Proceedings of the Third Inertial Confinement Fusion Systems and Applications Colloquium

R.R. Peterson, compiling editor

May 1988

UWFDM-749

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Proceedings of the Third Inertial Confinement Fusion Systems and Applications Colloquium

R.R. Peterson, compiling editor

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

May 1988

UWFDM-749

PROCEEDINGS OF THE

THIRD INERTIAL CONFINEMENT FUSION

SYSTEMS AND APPLICATIONS COLLOQUIUM

9-11 November 1987
Madison, Wisconsin

Robert R. Peterson

Compiling Editor

May 1988

UWFDM-749

TABLE OF CONTENTS

PAGE

PREFACE i

OPENING REMARKS

Future Directions in Inertial Fusion Research 1
Sheldon L. Kahalas

LASER FUSION

Japanese View of Commercial Drivers for Laser Driven Reactors 9
Y. Izawa, T. Jitsuno and S. Nakai

Los Alamos National Laboratory View of Commercial Drivers for Laser-Driven Reactors 29
David B. Harris, Louis A. Rosocha and David C. Cartwright

Achieving Adequate Beam Quality for Commercial Laser Fusion Reactors 86
S.P. Obenschain, R.H. Lehmberg, A.J. Schmitt and S.E. Bodner

LIGHT ION BEAM FUSION

Pulsed Power Driver Technologies for Inertial Confinement Fusion Power Reactors 106
D.L. Cook

The APEX Project: Ion Beam Pulse-Shaping Experiments on Sandia National Laboratories' Particle Beam Fusion Accelerator PBFA II 128
James T. Crow

Relationship Between the TDF and Commercial ICF Drivers 148
R.E. Olson

Repetitive Pulsed Power for Commercial Reactors 172
Malcolm T. Buttram

Japanese View of Commercial Drivers for LIB Fusion Reactors 191
S. Miyamoto, K. Imasaki, N. Yugami, T. Akibo, K. Emura, H. Takabe, K. Shimoura, M. Fukuda, K. Nishihara, S. Nakai and C. Yamanaka

TABLE OF CONTENTS
(Continued)

PAGE

HEAVY ION BEAM FUSION

Accelerator Research for HIB Fusion in the U.S 225
Walter M. Polansky

Induction LINAC Drivers for Commercial Heavy Ion-Beam Fusion 238
Denis Keefe

RF LINAC Driver for Commercial Heavy Ion Beam Fusion 256
R.W. Müler

An Overview of Heavy Ion Drivers for ICF 266
Edward P. Lee

Update of HIFSA: Implications for Commercial Heavy-Ion Fusion 281
D.J. Duziak, J.H. Pendergrass and W.W. Saylor

REPORTS ON WORKSHOPS AT COLLOQUIUM

Review of the Laser Fusion Working Group Session 311

Review of the Light Ion Fusion Working Group Session 316

Review of the Heavy Ion Working Group Sessions 319

LIST OF ATTENDEES 322

PREFACE

The Third Inertial Fusion Systems and Applications Colloquium was hosted by the Fusion Technology Institute of the University of Wisconsin and held on the Madison campus on November 9, 10, and 11, 1987. The theme of the meeting was "Advanced Drivers for Commercial Applications". The U.S. Department of Energy (DOE) sponsored the meeting to provide a forum for dialogue among the proponents of commercial inertial confinement fusion (ICF), specifically to take a fresh look at the state of development of the various driver options of ICF. The colloquium was divided into sessions covering lasers, light ion beam accelerators, and heavy ion beam accelerators, and included a workshop to highlight the issues involved with further development of each of the driver options.

The workshop discussions illustrated a diversity of opinions among the various driver proponents as to the suitability of a given driver for commercial fusion applications. There was, however, a mutual vision which nearly all participants shared; that is the production of fusion energy on a commercial scale.

In the United States, the potential for fusion is being developed in two major fusion programs: ICF and magnetic confinement fusion (MCF). The bulk of the funding for both programs is provided by the Federal Government and administered by DOE. The MCF program is funded through DOE's Office of Energy Research, whose mission it is to develop magnetic confinement fusion and determine its feasibility for energy production. Authorization for this program comes from Congressional committees whose chief responsibility lies in future sources of energy for the nation; whereas the ICF program receives its authorization from the Armed Services Committees of the Congress, whose chief responsibility is the military state of readiness. Hence, the primary mission of the U.S. ICF program is to provide support to the military weapons program.

However, it is also the mission of the ICF program to determine the feasibility of ICF for commercial energy applications. The Inertial Fusion Division of DOE, in keeping with this dual mission, maintains that at the current stage of development, ICF activities support both the military and civilian objectives, and that the civilian objectives are long-term. Since very few activities devoted solely to civilian applications are undertaken at this time, a casual observer could conclude that magnetic confinement is the only program dealing with fusion-generated energy.

DOE, however, recognizes the importance of maintaining ICF as a viable option for civilian energy applications; and all concerned with the program recognize this. All who are involved with determining the resources of the national ICF program have a responsibility to see that the military missions of the program are met. At the same time, virtually all involved with ICF recognize the potential value of ICF to the civilian sector and have, at one time or another, expressed the desire to see commercial fusion become a reality.

Out of its interests in the energy applications of ICF, DOE thus sponsors the Inertial Fusion Systems and Applications Colloquia. The purpose of these meetings is to focus only on the civilian applications of ICF. The meetings are not held on a set frequency; rather, they are called as the need exists. The first colloquium was held on March 7 and 8, 1985, at Lawrence Livermore National Laboratory and included about 30 scientists and engineers from the national laboratories as well as academia. The second meeting was held on October 2 and 3, 1985, at the University of Wisconsin. There were approximately 40 in attendance at that meeting, including representation from industry. The theme of both of these colloquia was "Systems Studies Needs for the Eighties". Both meetings were successful in creating a forum for airing the views of the different communities interested or involved in ICF, but the benefits were limited, because no provisions were made for publishing the proceedings of the meetings.

In an effort to make this, the third colloquium, as effective as possible, DOE expanded the program in two ways: (1) by publishing the complete proceedings of the meeting, and (2) by broadening the attendance to include the ICF participants from other nations.

Because of past contributions made by the Fusion Technology Institute of the University of Wisconsin to the fusion program, it seems appropriate that this first of the expanded colloquia be held at Madison.

David N. Bixler
Systems and Applications
Program Manager
Inertial Fusion Division
Office of Weapons Research,
Development, and Testing

FUTURE DIRECTIONS IN INERTIAL FUSION RESEARCH

Sheldon L. Kahalas
Department of Energy
Office of Inertial Fusion
Washington, DC 20545

INTRODUCTION

The inertial fusion has undergone profound changes over the years, while maintaining a remarkable degree of stability and continuity of purpose. In the early seventies, the program had two goals, near-term military and long-term civilian power applications. With the perception that oil is plentiful, the present Administration's attitude towards development of new energy sources has shifted. But, the goals of inertial fusion have remained constant, though there has been some shift in emphasis toward military application. Indeed, there have been useful spinoffs such as laboratory x-ray laser experiments, which could have biological applications, and there are also potential military applications to the Strategic Defense Initiative deriving from studies of high energy beam physics.

NAS REPORT ON INERTIAL FUSION - 1986

In 1985, Congress requested that the Executive Branch conduct a study of the inertial fusion program, oriented towards inertial fusion's military applications and looking particularly at its state of health and prospects for the future. This study was performed by the National Academy of Sciences (NAS), under the oversight of the Office of Science and Technology Policy. The NAS formed a panel that reviewed the entire program, both classified and unclassified. The panel consisted of a number of well-known experts in fusion, plasma physics, and nuclear weapons physics, with Dr. William Happer of Princeton University as chairman. The committee discussed the main technical issues that required resolution, in order to come to a decision over the five year period about proceeding with the next step, a high gain facility.

These issues were:

- Nature and practicality of the driver needed to ignite high gain pellets.
- Minimum mass of DT fuel that can be ignited and burned, and minimum energy required.
- Degree to which laser-plasma interactions and hydrodynamic instabilities can be controlled.
- Cost of the system compared to benefits.

The panel recommended that:

- The program be maintained at the current level for five years, in order to resolve the critical technical issues.

In addition, the panel recommended:

- A continuing high-level advisory committee be put in place.
- IF classification policy be reviewed to see if there were some portions that could be relaxed.

Finally, somewhat reluctantly, the committee enumerated its view of program element priorities:

- Centurion-Halite
- Use of Nova and PBFA II
- Support laboratories and direct drive
- Advanced ICF drivers

The technical recommendations were accepted by the Department and put in place to the extent possible under the budget constraints involved. The recommendations for the advisory committee and declassification are still under review with regard to appropriate action.

The recommendation to institute a Federal Advisory Panel has not been implemented by the Department because the program has classified areas and has close ties to weapons physics. The Federal Advisory Panel was recognized to be more appropriate for an open scientific program in an unclassified arena, such as the magnetic fusion program. Instead, the Department is currently constituting a group of independent technical advisors who will individually provide advice to the Department.

Recommendations concerning classification are being evaluated with a view toward implementation. This has been a slow process, since it involves review by a group well-versed in classification, and if approved by the Assistant Secretary for Defense Programs, it will be followed by further work to implement any of the specific recommendations for further declassification.

NAS REVIEW ON IF PROGRAM PLAN - 1987

More recently, in December 1986, a subgroup of the Happer panel met to review the new IF program plan that had been modified to reflect the panel's recommendations, within budget and programmatic limitations. They found that excellent progress had been made, albeit not as rapidly as had been hoped for at the time of the original report. The committee recognized that budget was a serious constraint on the program. However, the Committee reiterated its recommendation for a Federal Advisory Panel.

TECHNICAL STATUS OF THE INERTIAL FUSION PROGRAM

The inertial fusion program has made excellent progress in the past few years. The Centurion-Halite program is a theoretical and experimental effort to investigate the design characteristics of efficient ICF targets. It was given highest priority by the Happer panel. While this is a classified program, I can say that excellent progress has been made recently which could even be described as "historical" in accomplishment and is thought by some to mark a turning point for the program. Without apologizing for not being able to tell you more, I emphasize that those with access to classified information are obligated to observe the rules for access, so that I cannot elaborate further at this meeting.

The glass laser experimental program using the NOVA laser has made significant progress. Its primary approach is with hohlraum targets, the details of which are again classified. Results this past year have yielded an implosion with a convergence ratio of 30 in radius. This bodes well for our ability to compress pellets to a very small radius and, consequently, very high fuel density. Also, significant progress has been made in exploring plasma instabilities and x-ray conversion processes. While a high-gain target design with a specific driver has not yet been completed and while plasma interactions are likely to play an important role in the determining the details of such a design, no known process has been found that prevents laser fusion from working for the shorter wavelengths well below 1 micron.

The pulsed power program has made significant progress; starting with a first shakedown shot in December, 1985, work has continued to characterize and improve the power flow in PBFA II. Very recently, PBFA II performance exceeded the original design specifications for synchronization of the pulsed power modules. The 36 module timing spread was measured to be less than 15 nanoseconds. The program has reached the point that PBFA II operation is stable and reliable, and Sandia researchers can now concentrate on the most important light ion issues, beam generation, power concentration and beam focussing. We are not yet ready to undertake target compression experiments on PBFA II. We expect that it will take perhaps a few years to arrive at that point.

The direct drive program has the University of Rochester and the Naval Research Laboratory as its major participants. The University of Rochester is working toward achieving 200 XLD target compression using cryogenic targets on OMEGA with third harmonic light, a technique which they have pioneered. The Naval Research Laboratory has developed the induced spatial incoherence technique (ISI) for increased beam smoothing, a crucial issue for directly (and possibly indirectly) driven targets and are currently exploring ways to apply ISI to KrF lasers. Also, NRL has provided new insight to the behavior of Rayleigh-Taylor instabilities, leading to the possibility of using high aspect ratio targets (thin shells) for direct drive.

KMS Fusion, Inc. is a major supplier of targets for the program. Besides pioneering in the fabrication of cryogenic targets and developing new target fabrication techniques, they recently delivered the cryogenic target apparatus to be used at Rochester. Also, KMSF has made major contributions to the laser plasma experimental program at Lawrence Livermore, particularly in laser diagnostics and plasma instabilities.

The krypton fluoride gas laser program is an advanced driver technology demonstration involving Los Alamos and the Naval Research Laboratory. The major effort, Aurora, at Los Alamos, is to deliver focusable 5 ns, multi-kilojoule, 248 nanometer pulses on target. Aurora is the state of the art in large KrF laser optics, serving as a test-bed for the development of large scale optics for KrF fusion laser systems. In addition, Los Alamos and NRL are collaborating to investigate the benefits of incorporating the induced spatial incoherence (ISI) concept into Aurora to smooth the laser beam. Significant progress has been made in the fabrication and testing of hardware. The program is on schedule for putting 48 beams on target in December 1987 with the long term goal of completing the evaluation of this driver technology by 1992.

CURRENT STANDING OF INERTIAL FUSION PROGRAM WITHIN THE DEPARTMENT OF ENERGY

The inertial fusion program has always been directed by the Defense Programs Organization located within the Department of Energy. This is so for several reasons:

first, much of the program has bearing directly or indirectly on weapons-related phenomena; second, the program has always had highly classified aspects; and third, much of the program originated at the nuclear weapons laboratories, Los Alamos, Lawrence Livermore and Sandia. Even the early work of KMS Fusion, Inc. was "born" classified.

Because of its location within the Department and within the Departmental budget, the basic fact of life is that the inertial fusion program competes with nuclear weapon requirements for funds. This leads to a situation where the decision-makers within the Department and within Defense Programs must balance consideration for inertial fusion against resource requirements for the nuclear deterrent and for Strategic Defense research. This is an admittedly difficult task in which the judgments of the Department are tempered by political reality. Recently, the Defense Program management decided to support a level-of-effort budget for the inertial fusion program. This is a considerably different position compared to even last year when the Department was supporting a 25% cut in the inertial fusion program budget. The positive shift in support for the inertial fusion program is in good part related to the strong boost given to the program by the Happer panel findings. The shift is also derived from the Department's decision to take a more realistic view of the strong support that the inertial fusion program has enjoyed in Congress. However, with the excellent progress that has been made in the program, it would appear that increased resources to prepare for a Laboratory Microfusion Facility, the next large facility in the program, will be needed. To convince the Department and the Office of Management and Budget of the need for increased resources in the present budget climate will require a strong set of program accomplishments, a well laid-out program plan, and an effective presentation of inertial fusion's potential.

FUTURE DIRECTION OF THE PROGRAM

With the progress in target physics that has been made in the program, our attention is shifting to emphasize longer-term planning for our next facility, currently called the Laboratory Microfusion Facility or LMF for short. We are at the stage of conducting an internal Headquarters-run study of the requirements and conditions for such a facility, as well as its potential uses. We expect there will be benefits to both the weapons program, for example, from experiments on materials at high density and temperature as well as to the civilian energy program from experiments to ascertain high gain target behavior. The LMF is envisioned as a 5 to 10 megajoule, high gain, single shot facility, capable of as many as 10 shots per day. Maximum yield would be about 1000 megajoules. It is desirable that the driver be flexible, with a wide range of pulse lengths (3 to 10 nanoseconds), large range of pulse shapes, and wide range of pulse energies. The goal is to build the driver at a cost of less than $200/joule. In addition, we are putting together a new program plan that attempts to look beyond the early 1990's decision point, assumes a positive decision to go forward with the program, and projects out the next stage including plans to build an LMF. The plan, under ordinary contingencies, by the way, does not include immediate selection of a single candidate driver for the facility. Instead, we plan to intensify program efforts to develop our understanding sufficiently that an appropriate driver selection can be made.

CONCLUSIONS

The inertial fusion program has shown great progress over the past year. In the present program plan (for 1987-1991), the program has focussed on an early 1990's decision date, as suggested by the National Academy of Sciences report. While the exact nature of the decision was not defined, it was generally considered to be a go/no go with regard to a new major facility to achieve high gain. The program's emphasis during this period was consistent with the priorities enumerated by the NAS (Happer) panel and focussed on elucidating the conditions needed to achieve high gain. With the progress in target physics that has been made to date, we believe we are rapidly approaching a point when we will be able to say with confidence that a 5-10 megajoule facility will provide high gain. Because we are not quite there yet, we believe we must continue to pursue target physics issues vigorously. But, the IF program also needs to accelerate the developmental pace of drivers because in this past year the inertial fusion program has added enormously to its knowledge base that shows the feasibility of a high gain facility.

We now believe with the progress that has been made to date that the question is no longer if inertial fusion can be made to work, but when and for how much.

JAPANESE VIEW OF COMMERCIAL DRIVERS FOR LASER DRIVEN REACTORS

Y. Izawa, T. Jitsuno and S. Nakai
Institute of Laser Engineering
Osaka University
Yamada-oka, Suita 565, Japan

INTRODUCTION

The recent progress of laser fusion research is remarkable in obtaining the high density and high temperature compressed plasma and in understanding the implosion physics. The data bases of the implosion processes such as absorption, energy transport, ablation hydrodynamics and implosion stability have been accumulated and the technologies for the advanced experiments have been developed, both of which enable us to proceed the research step toward the fusion ignition experiments and the achievement of the breakeven condition.

We present the recent progress in the direct-drive implosion experiments by stagnation-free implosion and shell implosion with random phased laser, the scaling to the ignition condition and the design of the laser system for the future experiments.

RECENT PROGRESS IN DIRECT-DRIVE IMPLOSION EXPERIMENTS

Large High Aspect Ratio Target

In direct-drive implosion, laser illumination uniformity and implosion stability are very important. Rayleigh-Taylor instability amplifies asymmetry during the implosion. In the acceleration phase, the instability is strongly affected by ablation flow and thermal conduction. The growth rate is expected to be reduced from the classical value. On the other hand, it is recently recognized that the pusher-fuel contact surface is very unstable in the deceleration phase.

From such a point of view, so-called "stagnation-free implosion" has been proposed and investigated.[1,2] Target named LHART (Large High Aspect Ratio Target) was accelerated for a long distance up to a high velocity with the rising part of the Gaussian laser pulse from the GEKKO XII green laser. Successive shock waves generated during the acceleration collapse simultaneously at the center of the target. At this time, maximum compression occurs and results in the high implosion efficiency and high neutron yield.

The flow diagram for a typical example of the LHART implosion is shown in Fig. 1. This is for the case that the target with diameter of 1235μm, and wall thickness of 1.3μm filled with 6.2atm DT gas was irradiated by a Gaussian pulse of 13kJ/1ns.[3] The ILESTA-BG code with the flux limiter f=0.04 has been used in the simulation. In the figure, the dotted line shows the trajectory of the cut-off point. Closed circles, taken from the x-ray streak image, indicate the trajectory of the pusher in the implosion phase and that of shock wave in the expansion phase. Good agreements on the implosion time as well as the final core size is seen. In this laser shots, the neutron yield of 10^{13} and the coupling efficiency of 5.5% have been achieved.

Coupling efficiency and hydrodynamic efficiency for the LHART target are plotted in Fig. 2 against the DT fuel mass divided by the total target mass. The dependence of the efficiencies on the target parameters is theoretically analyzed and shows good agreement over the wide range of the variables.

Figure 3 shows the recent progress in neutron yield and pellet gain. The pellet gain of 0.2% was achieved.

Uniformity Improvement by Random Phased Laser

In order to smooth out the illumination non-uniformity, random phasing technique has been proposed.[4] A random phase plate (RPP), which consists of a two-dimensional

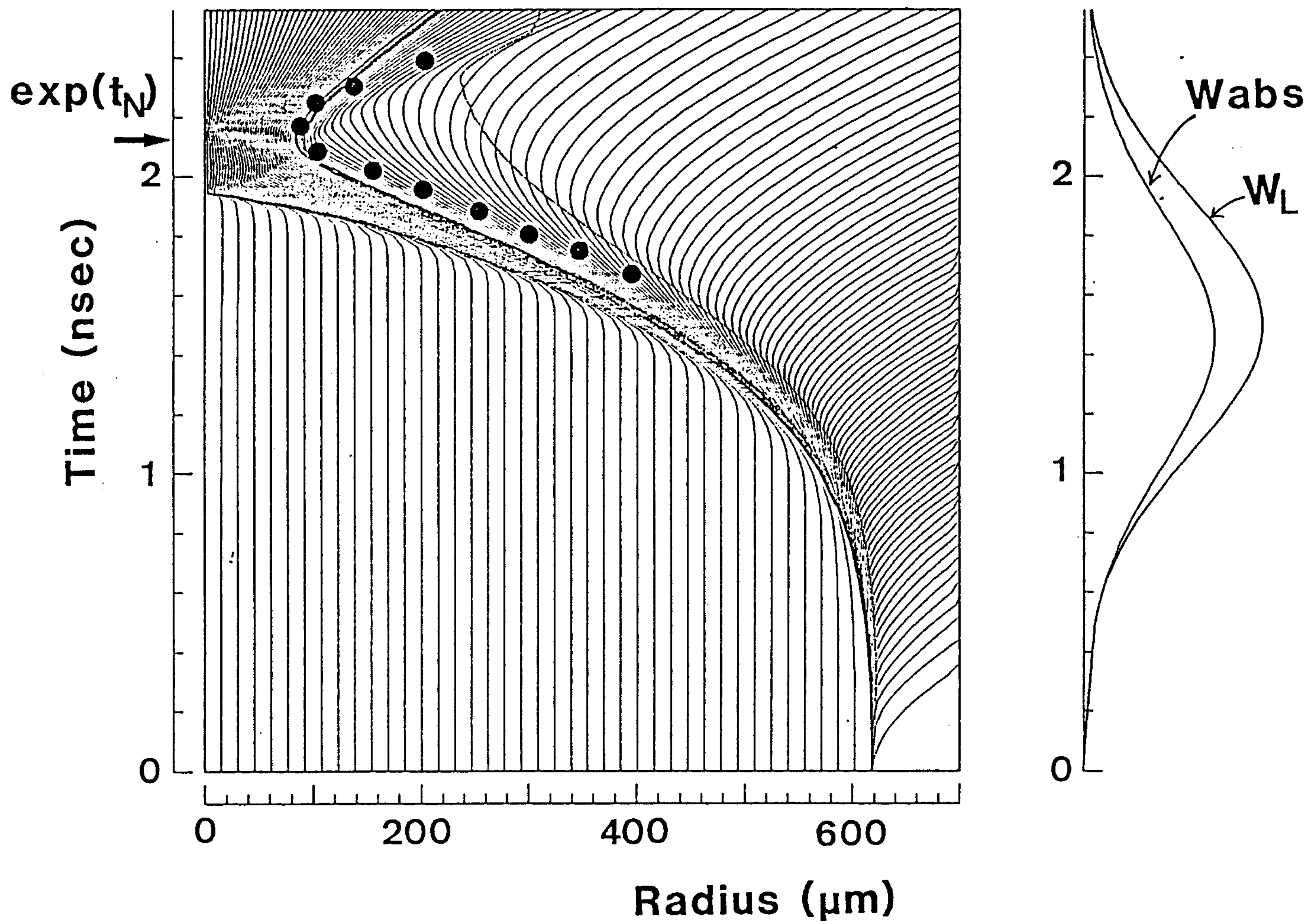


Fig. 1. Flow diagram of the LHART experiment which resulted 10^{13} neutron production. The simulation has been done with flux limiter f=0.04. The solid circles indicate the trajectory of peak intensity of X-ray emission measured by a streak camera. The arrow with indication exp(t_N) shows the time of neutron emission measured from a fast neutron detector.

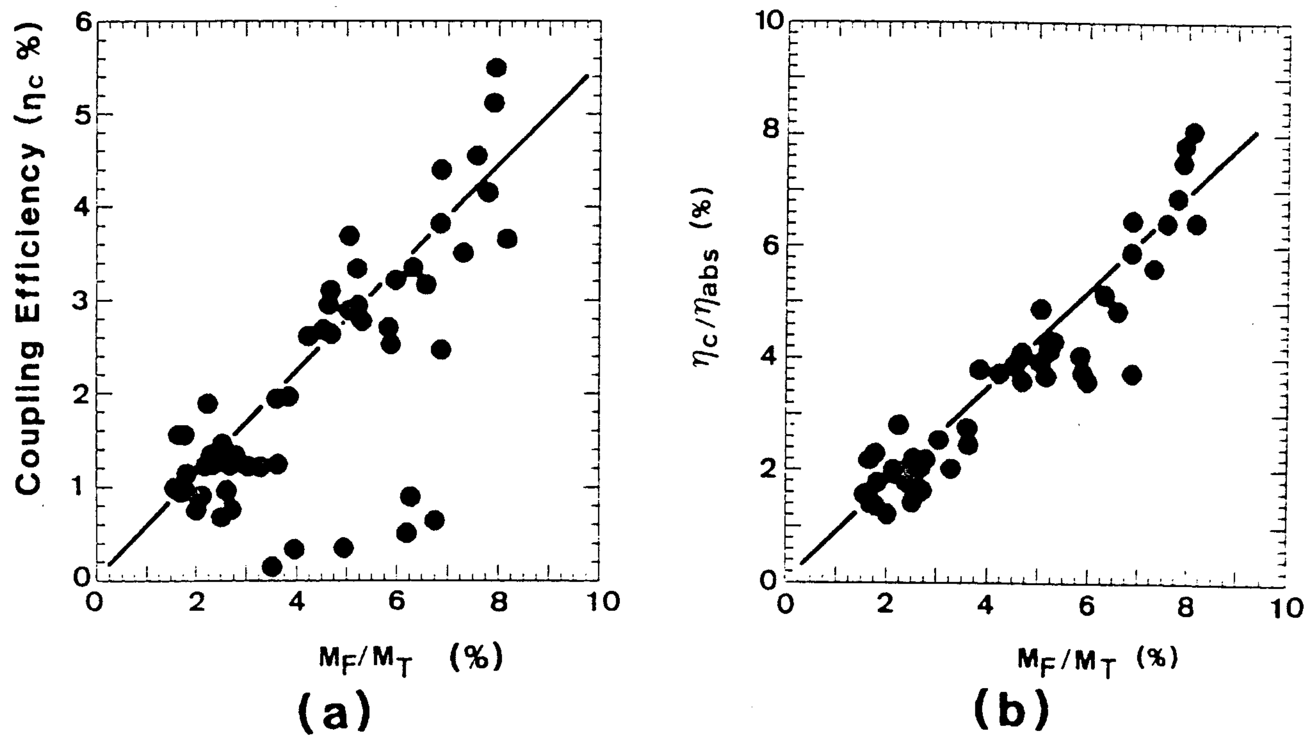


Fig. 2. Mass ratio dependence of coupling efficiency and hydrodynamic efficiency. M_F is a fuel mass and M_T is a total target mass.

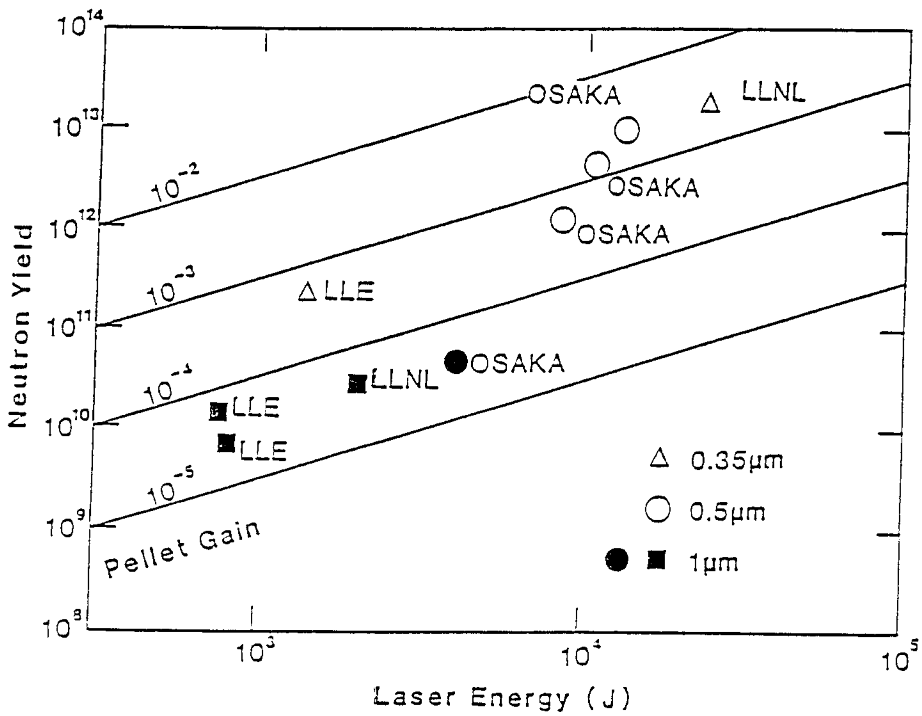


Fig. 3. Recent progress in neutron yield and pellet gain is plotted as a function of laser energy.

array of transmitting area coated on a glass plate, each of which applies a phase shift of either 0 or π radian, was placed in each laser beam of GEKKO XII.[5] The size of each segment to compose a 2-D array was 2x2 mm.

The intensity distribution of the laser beam on a target plane with and without RPP was measured, as shown in Fig. 4. Without RPP, the intensity distribution shows a central dip and the diffraction rings. These are caused by the diffusion plate on the focusing lens. A random phase plate eliminates completely these patterns but produces small scale intensity modulation. Intensity distributions in both cases were well reproduced by the 2-D simulation.

Figure 5 shows the x-ray pinhole images from a steel ball irradiated by 12 beams of 1.55kJ, 100ps laser. Because of time integration, detailed structure is not observed. But the improvement in illumination uniformity by RPP is clearly see.

A plastic shell target has been imploded by the random phased GEKKO XII green laser. The targets are deuterated polystyrene (CD) shells with diameters of 600-1000μm and shell thicknesses of 4-12μm.

Fuel area density ($\rho_D R$) measured by the secondary reaction technique is plotted against the CD shell thickness in Fig. 6. The solid line corresponds to the data by 10kJ/0.8ns laser without RPP. A high density compression of more than 40 times liquid density has been achieved, where ρR=30mg/cm^2 is almost the upper limit of secondary reaction measurement. The dashed lines are for the data by 5kJ/0.8ns laser with and without RPP. Random phasing improves the implosion uniformity and more than 10 times higher ρR is obtained.

SCALING TO THE IGNITION AND STRATEGY TO THE REACTOR

The criterial for ignition, where the α particle heating becomes predominant over the energy loss, is evaluated by the following energy equation.

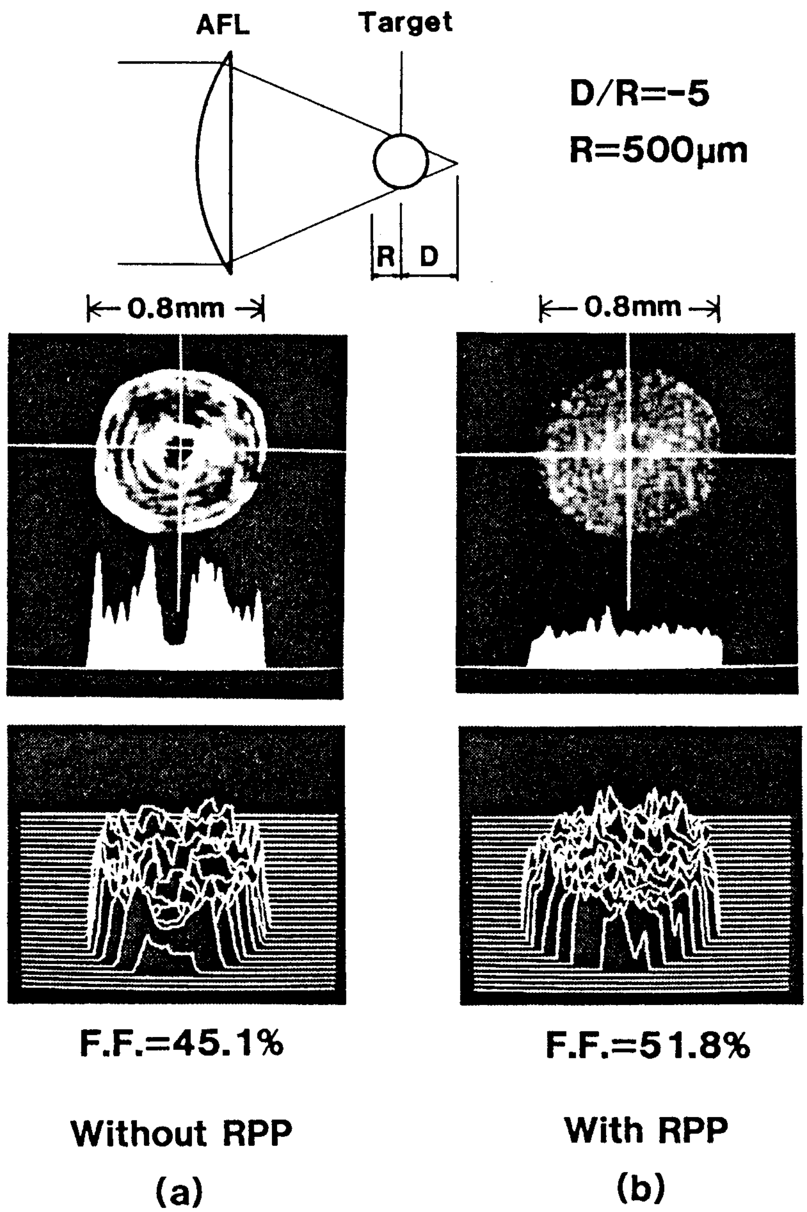


Fig. 4. Laser intensity distribution on a target plane without (a) and with (b) the random phase plate.

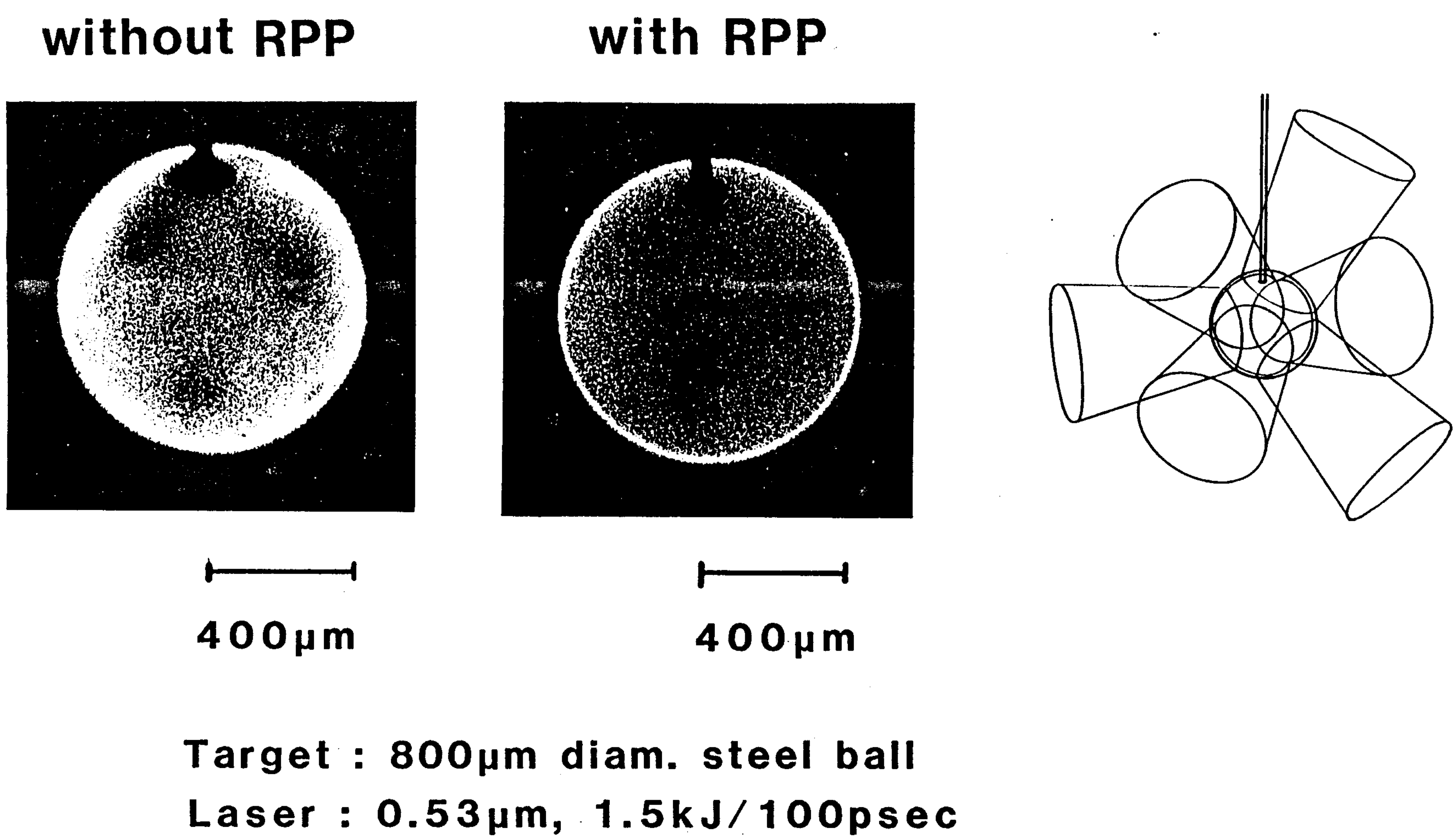


Fig. 5. X-ray pinhole pictures of steel ball target of 800μm diameter irradiated by 12 laser beams without (a) and with (b) the random phase plate.

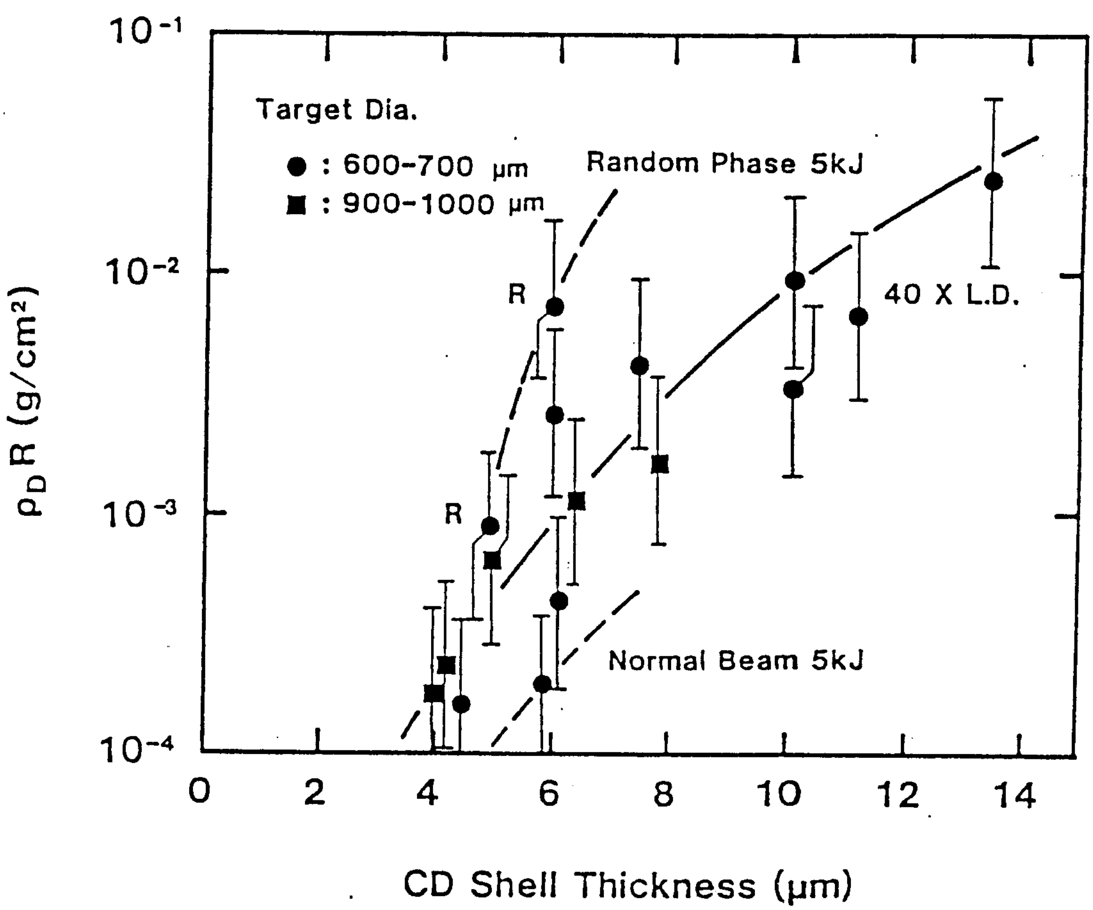


Fig. 6. Fuel area density measured from the secondary reaction as a function of CD shell thickness.

$$3 \frac{\rho}{m_i} \frac{dT}{dt} = - p\nabla u + \nabla K_e \nabla T - W_R + W_\alpha$$

where the first term in the right hand side represents the pressure work W_E due to compression or expansion, the second and the third are the energy loss by thermal conduction W_C and radiation and the last term is the a particle heating. The ignition condition is defined by $W_E + W_C + W_R < W_\alpha$. Calculated results [6] are summarized in Fig. 7. Here the lines with C, R, E and CR represent the criteria that the α heating W_α balances with the loss by thermal conduction (C), radiation (R), expansion [E) and conduction and radiation (CR) respectively. The bold solid line with ECR shows the ignition condition.

By using the experimentally obtained data on the physical processes of implosion and the well-developed simulation code, we can design the optimized fuel pellet at the available laser energy and predict the scaling to the ignition. The required laser energy achieving ignition and breakeven is predicted to be 100kJ in 3ω as shown in Fig. 8. In this evaluation, the illumination non-uniformity is considered to be less than 3%.

Beyond the ignition, there are several steps to reach the commercialization of the reactor. They are the demonstration of high gain, the development of the reactor technologies and then the demonstration of power reactor. The scenario to the ICF reactor is shown in Table 1.

GEKKO XII UP-GRADE AND MJ LASER

The glass laser is the most advanced driver and widely used for the implosion experiments. The advantages of the glass laser are in 1) high reliability of operation, 2) controllability of pulse shape, 3) good focusability, and 4) well developed optical components and technologies. The high efficiency of frequency conversion from IR (ω) to green (2ω), blue (3ω) and UV (4ω) is very effective to investigate the wavelength scaling of

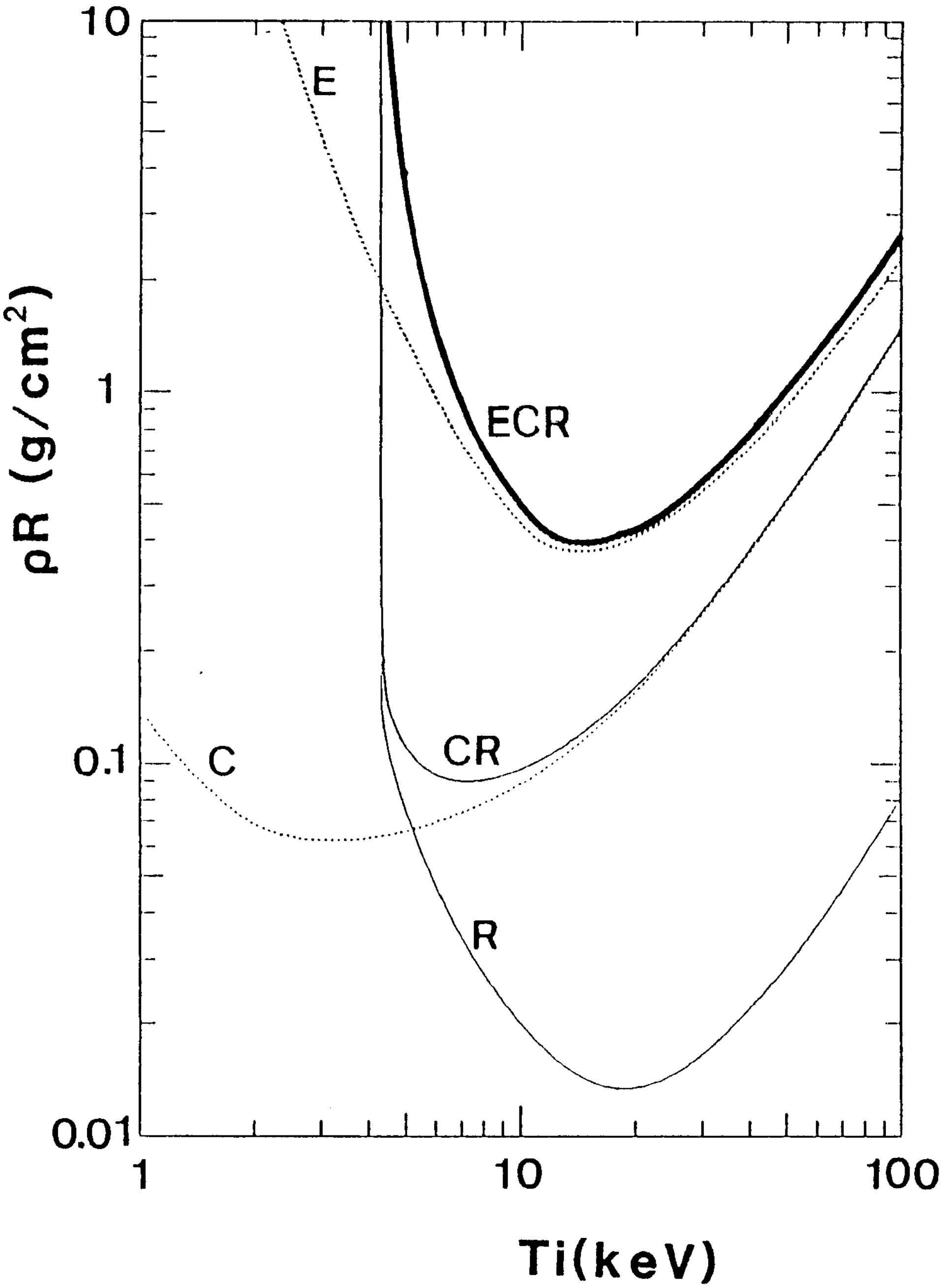


Fig. 7. Ignition condition as a function of ρR and Ti with different assumptions of loss mechanism.

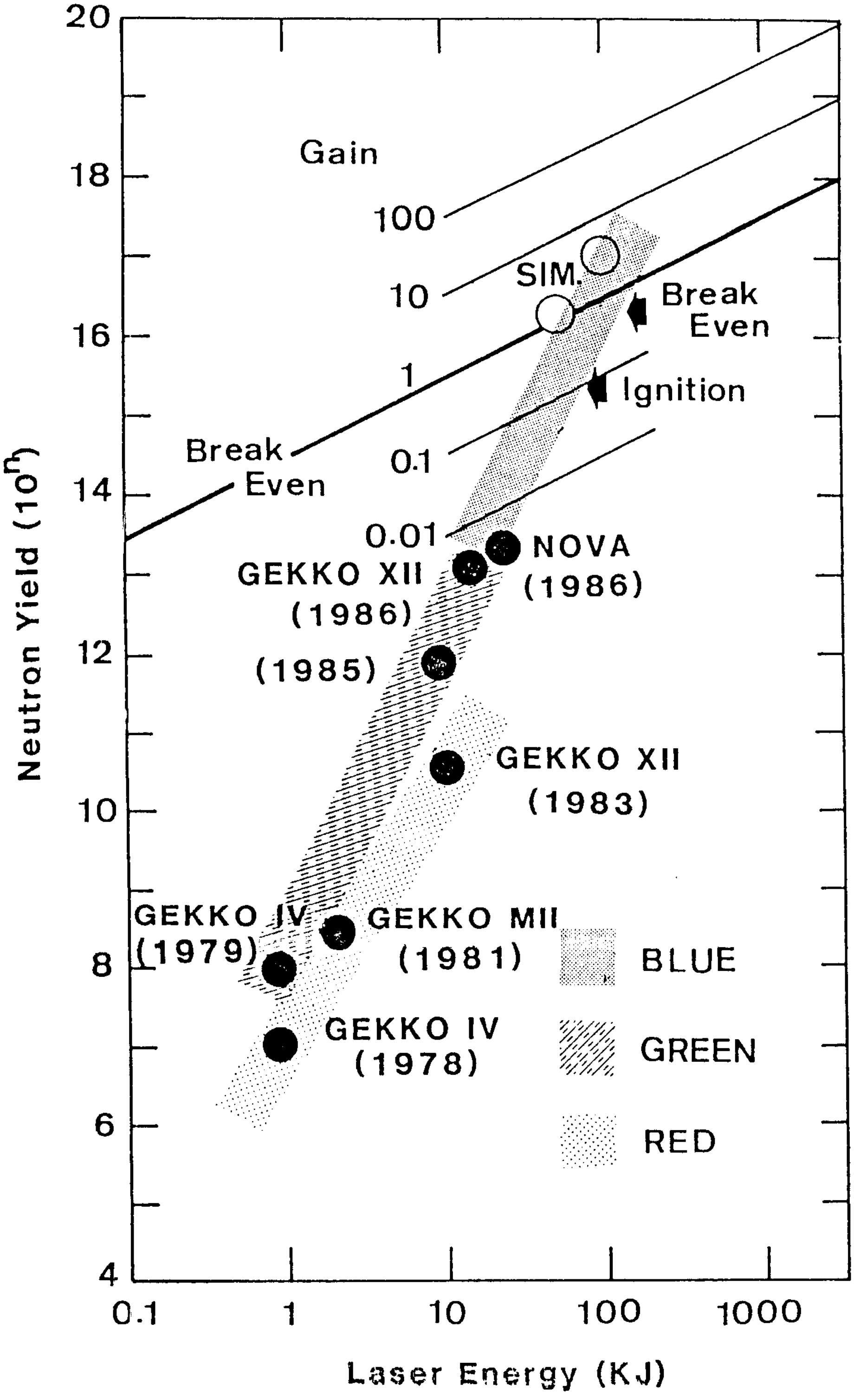


Fig. 8. Progress and prospect of laser fusion. The solid circles are from experiments with GEKKO XII and NOVA. Open circles are from one dimensional simulations. This suggests the feasibility of achieving ignition and breakeven by a 100kJ blue laser.

Table 1 Scenario to ICF reactor

	I Ignition Experiment	II L F C X	III L F E R	IV L F P R
Mission	Ignition (Scientific feasibility)	Burning (Engineering feasibility) · High gain pellet design · Reactor engineering · Intence neutron source	Reactor engineering test	Demonstration of power plant
Laser	Nd-glass 100 kJ Single shot	Nd-glass 500 kJ - 1 MJ Single - 1 shot/min.	500 kJ - 1 MJ 1 Hz	>4 MJ 1 Hz
Pellet	$Q = 1$ 10^{16} N/shot $\rho \geqq 1000\ \rho_0$(200 g/cm^3) $\rho R \geqq 0.3$ g/cm^2	$Q = 10 \sim 100$ $10^{18} \sim 10^{19}$ N/shot 5~50 MJ/shot $\rho \geqq 2000\ \rho_0$(400 g/cm^3) $\rho R \geqq 1$ g/cm^2	$Q = 10 \sim 100$ $10^{18} \sim 10^{19}$ N/sec 5~50 MWth	$Q = 50 \sim 500$ $10^2 \sim 10^3$ MWE $\rho \sim 2000 \sim 4000\ \rho_0$ (400~800 g/cm^3) $\rho R \sim 3 \sim 5$ g/cm^3

implosion. Considering these excellent features of the glass laser, it is reasonable to use the high power glass laser for the future research.

The GEKKO XII up-grade with the output of 100kJ at 0.35μm(3ω) has been designed. Optical arrangements of GEKKO XII and GEKKO XII up-grade system are shown in Fig. 9. In the up-grade system, disk amplifies with 350mm in diameter (DA350) are added after GEKKO XII. The specifications are as follows.

Output energy	:	100kJ
Wavelength	:	0.35μ
Pulse width	:	2ns
Beam diameter	:	50cm
Beam number	:	24 beams

The DA350 amplifier module, shown in Fig. 10, has been constructed and the amplification characteristics were measured. Performance characteristics of the GEKKO XII up-grade system was calculated by using the two dimensional computer code and the experimental data of amplification in DA350 as shown in Fig. 11. Figure 12 shows the calculated illumination non-uniformity σ and that with thermal smoothing σ_{th} as a function of the beam number. In the up-grade system, the illumination non-uniformity less than 2% is expected. The layout of the up-grade system is shown in Fig. 13.

Conceptual designs of MJ glass lasers are in progress. It is possible to scale the GEKKO XII up to a MJ system by increasing the beam number. However, the MOPA system is too large in scale and is not cost effective. Regenerative amplifier and/or multi-pass simplification schemes by using silicate, phosphate and fluoro phosphate laser glass are compared. Overall efficiency of 1.7% will be obtained by the regenerative amplification system with a phosphate laser glass pumped by Xe flashlamps. Laser diode pumping will improve the efficiency up to ~ 10%.

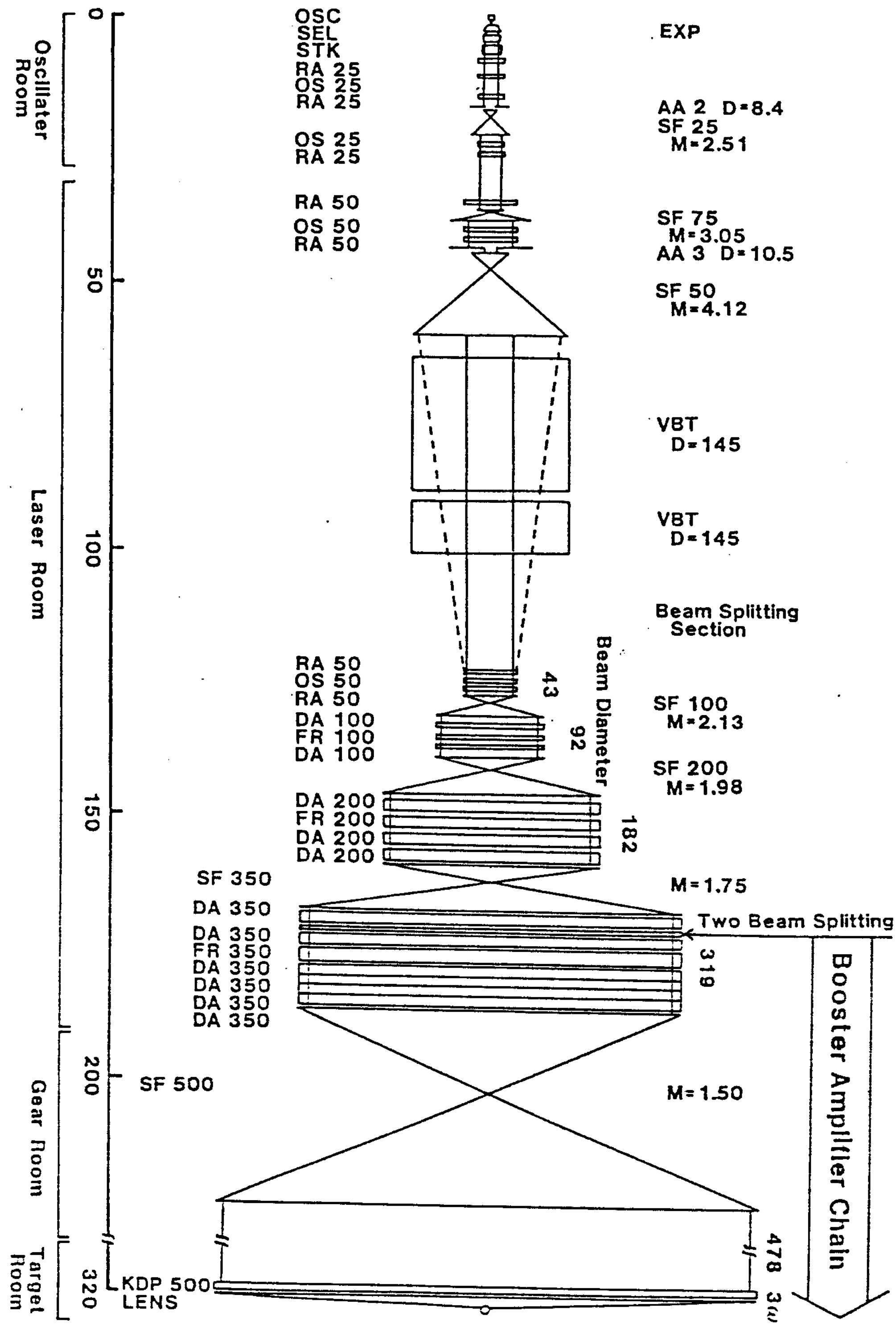


Fig. 9. Optical arrangements of GEKKO XII and GEKKO XII up-grade system.

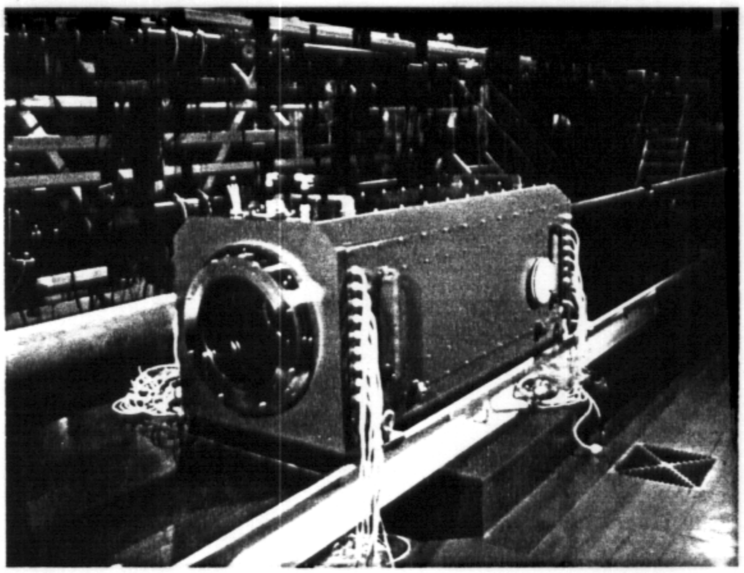


Fig. 10. Disk amplifier with diameter of 350mm. Monolithic laser glass is used.

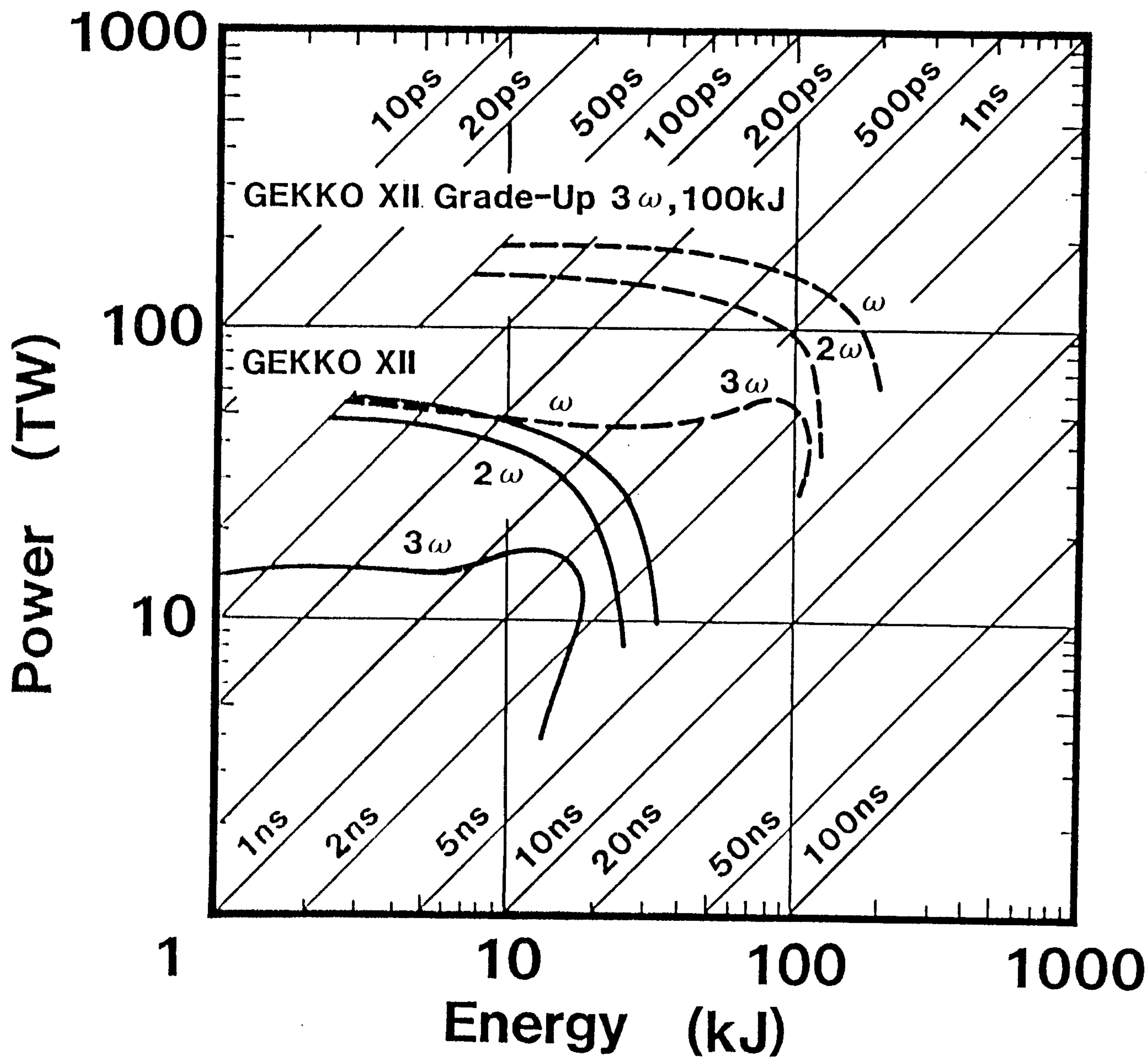


Fig. 11. Performance characteristics of GEKKO XII up-grade system.

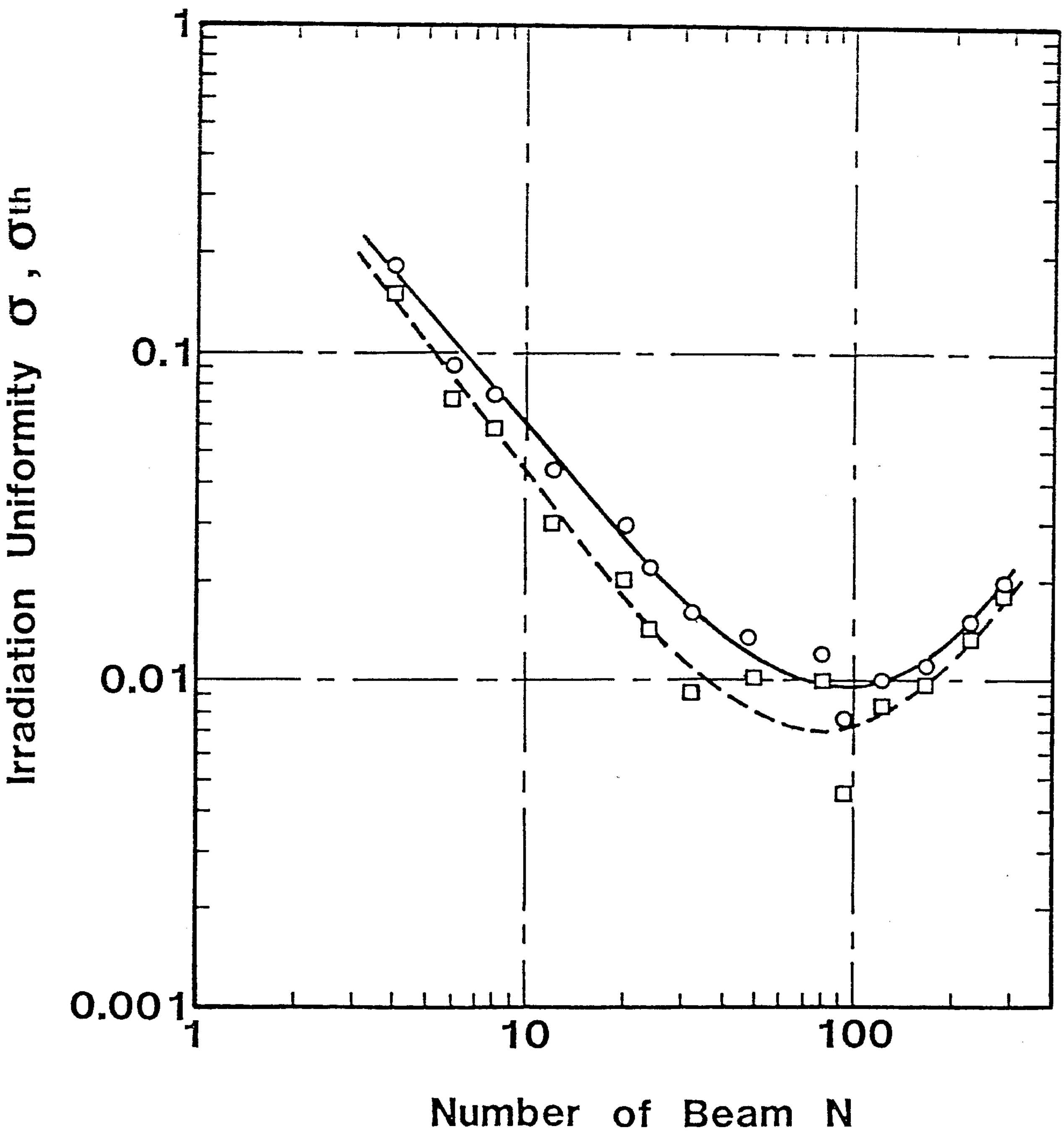


Fig. 12. Illumination non-uniformity calculated by 2-D simulation as a function of laser beam number.

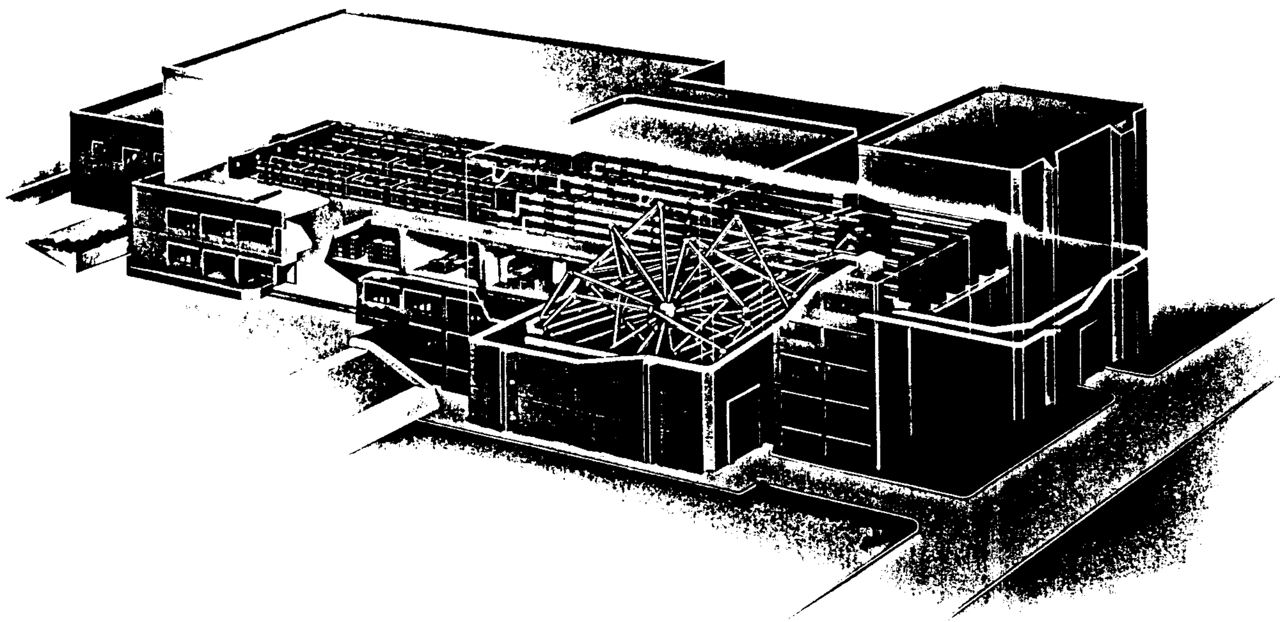


Fig. 13. Layout of the 100kJ blue laser system based on GEKKO XII.

REFERENCES

1. C. Yamanaka and S. Nakai, Nature 319 (1986) 757.
2. C. Yamanaka et al., Phys. Rev. Lett. 56 (1986) 1576.
3. H. Takabe, ILE Quarterly Progress Report, ILE-QPR-87-20 (1987).
4. Y. Kato et al., Phys. Rev. Lett. 53 (1984) 1057.
5. S. Nakai, ILE Quarterly Progress Report, ILE-QPR-87-22 (1988).
6. Y. Kato, ILE Quarterly Progress Report, ILE-QPR-87-21 (1987).

LOS ALAMOS NATIONAL LABORATORY VIEW OF COMMERCIAL DRIVERS FOR LASER-DRIVEN REACTORS*

David B. Harris, Louis A. Rosocha, and David C. Cartwright
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

An evaluation of the six main laser candidates for inertial confinement fusion (ICF) commercial application drivers has been performed. Each laser is rated in its ability to satisfy eight different driver requirements: cost, efficiency, target coupling, pulse shaping capability, focussing, repetition rate, energy scaling, and reliability/robustness. The result of the evaluation indicates that the KrF laser appears to be most attractive for ICF commercial applications. The KrF laser fusion program at Los Alamos National Laboratory is described, including the prototypical demonstration system called Aurora and technology development in areas such as optics, pulsed power, kinetics, and alignment systems. Also described are the results of conceptual designs and system studies.

INTRODUCTION

Many different types of laser systems have been proposed as drivers for commercial laser fusion reactors. Some of these have been dismissed as not being able to meet all of the requirements, some have always been in the list of candidates, and others are new and it is yet to be determined if they can meet the driver requirements. It is the intent of this manuscript to examine the current list of laser candidates, determine the one that appears to be the most qualified for a commercial reactor driver, and describe the development program for that laser.

---

* This work was performed under the auspices of the U.S. Department of Energy under Contract W-7405-ENG-36.

The main objective of the inertial confinement fusion (ICF) program is to develop ICF for military applications, with a secondary application being the development of commercial applications. In fact, it has been said that "the U.S. has a $300 million program in commercial fusion. It is called magnetic fusion" [1]. Even with secondary status for the U.S. ICF commercial program, researchers working in the field with the desire of developing ICF commercial applications should not despair. Many of the steps in the development program for ICF are common for both military and commercial applications [2]. The next major step in the development of ICF for either military or commercial applications is to build a facility to produce high gain. This major step will probably require one or more smaller steps to get from where we are now to where we need to be. This next major facility has been called by many names: the Target Development Facility, the Single-Pulse Test Facility, or the High-Gain Test Facility. Currently, this facility is being examined in a study organized by the U.S. Department of Energy under the name Laboratory Microfusion Facility (LMF) [3-10]. This facility will be a significant step towards ICF commercialization because it will develop high-gain targets. However, the main purpose of the facility is to do weapons physics and weapons-effects experiments. The result of this emphasis on military applications is that there is only a small ongoing effort in the ICF program examining commercial applications. Much of this small effort has been spent on developing ICF reactor concepts and performing system studies. Very little effort has gone into developing drivers for commercial applications, and this approach is probably appropriate in view of the fact that these high-efficiency, high-average-power drivers will not be required for many years, whereas the driver for the LMF will probably be needed within 10 to 15 years.

Our paper's title indicates that laser drivers for commercial applications will be examined with respect to their attractiveness for ICF commercial applications. There are many different potential commercial applications for ICF including electric power, process heat, synthetic fuel, and fission fuel production. This paper assumes that the commercial application of interest is electric power production. This application is perhaps the one with the most stringent set of driver requirements and thus the most difficult to achieve. On the other hand, if a driver can meet these requirements, it will probably be able to meet the requirements for any of the other applications. Additionally, this is the application that the public perceives as the one having the greatest need.

This paper identifies the commercial reactor driver requirements in Section II. The laser systems that are currently being considered are identified in Section III and are evaluated in Section IV with respect to the potential of meeting the ICF driver requirements. KrF lasers will be shown to be the most attractive laser candidate for a reactor driver. Section V will describe the KrF laser development plan and program at Los Alamos National Laboratory.

DRIVER REQUIREMENTS FOR COMMERCIAL APPLICATIONS

The driver requirements for ICF electric power production have been discussed many times in the past [2,11-13], and are subject to change as more information is obtained on target performance [14]. In particular, the predicted target gain as a function of driver energy has a significant impact on some of the driver requirements and has been changing significantly even over the past 5 years [15-17]. Laser coupling efficiency can also play a crucial role in determining target gain and thus also impacts the driver requirements [17]. Considerable uncertainty still exists in determining the proper target-coupling efficiency for ICF targets [18]. Because of these uncertainties, many of the driver requirements will be given in relative or nonabsolute terms.

The requirements for a driver for commercial applications can be stated in eight general terms. They are efficiency, cost, target coupling, pulse shaping, focussing, pulse repetition rate, energy scaling, and reliability/robustness. These requirements will be discussed individually.

Efficiency. The driver efficiency required for economic electric power production depends strongly on the assumed target performance. The higher the driver efficiency, the lower the driver recirculation fraction, which (all things being equal, which they seldom are) lowers the cost of electricity (COE). Absolute numbers have been quoted in the past, such as the driver efficiency, η_d, must be greater than 10% [12,13]. As mentioned before, the uncertainties in target gain make accurate estimates of the required driver efficiency impossible. It is preferable to quote requirements for the driver-efficiency target-gain product, $\eta_d G$. Previous authors have estimated this product needs to be greater than six [19], eight [20], ten [21], 15 [22], or 20 [23]. The reasons for these differences in the assumed requirement for $\eta_d G$ are the different assumed values for the thermal-to-electric conversion efficiency, η_t, and differences in the perceived cost tradeoffs between additional balance-of-plant capacity and a higher energy driver.

The Lawrence Livermore National Laboratory (LLNL) ICF reactor concept Cascade [24] has probably received more attention than any other ICF reactor concept. It assumes a somewhat optimistic target gain of 200 at 1.5-MJ driver energy, and estimates that η_t=55%. In this case, if an acceptable driver recirculation fraction is 25%, the driver efficiency only needs to be 3.6%. It is clearly impossible to accurately estimate the actual value of the driver efficiency or even the $\eta_d G$ that is required until accurate values of the target gain and thermal-to-electric conversion efficiencies are known. It will be shown in the next section that the driver efficiency and cost act together to determine the cost of electricity.

Cost. The cost of the driver for electric power production must almost certainly be less than 50% of the total capital cost of the plant and should be as small as possible. Comparison of laser-driven reactor plants to today's fission power plants is enlightening. The nuclear island in a fission plant is ~ 30-35% of the total capital cost [25]. The analogy of the fission nuclear island is the ICF reactor and reactor-related equipment. Thus, the two power plants are similar, except that the ICF plant requires a driver, which has no analogy in the fission power plant. If the ICF power plant is to compete with the fission power plant, the cost of the driver must be small. A representative value of the cost of electric power production today, from either nuclear or coal, is ~ 45 mills/kWh. A reasonable COE goal for fusion, with its unlimited fuel supply, and its potential to be less polluting than burning coal and the perception of being less dangerous than fission, might be ~ 60 mills/kWh. Therefore, a reasonable goal for the driver contribution to the COE might be ~ 15 mills/kWh [26].

Figure 1 examines the COE as a function of driver cost and efficiency. Assumed in this graph is the cost of targets at $0.50 each, driver energy of 5 MJ, target gain of 100, and standard assumptions on the cost of money, construction time, power plant size, etc. [27]. In order to meet our goal of 60 mills/kWh, a 5% efficient driver must cost less than $200/J, or $1 billion. Higher driver costs are allowable if the driver efficiency is higher. At 10% driver efficiency, the driver can cost up to $350/J to be less than our COE goal, and a 25% efficient driver can cost up to $420/J.

The results shown in Fig. 1 are representative in nature. In a more detailed study, one would calculate the COE as a function of the driver cost and efficiency. However, the situation is usually more complicated in that the driver cost is a function of the driver efficiency and both are typically functions of the driver energy and repetition rate. The target cost is also a function of the driver energy [28], and the target contribution to the COE is strongly dependent on the repetition rate [29]. Thus a detailed study will find a minimum COE as functions of all of these parameters. For the purpose of this manuscript, it will be assumed that the driver efficiency should be

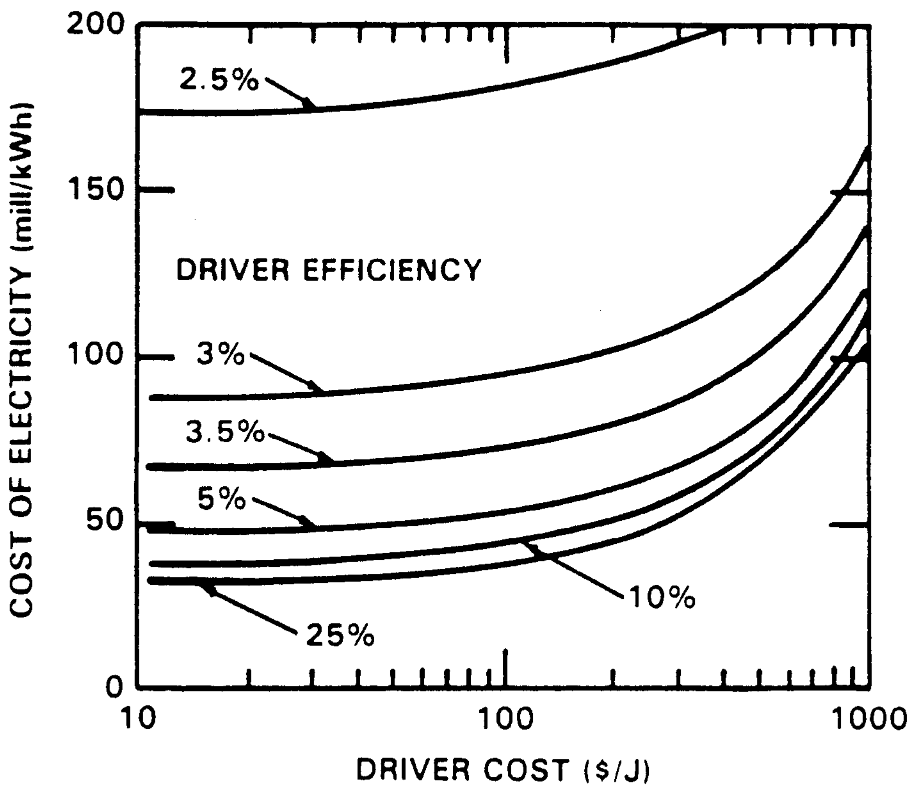


Figure 1. The cost of electricity production as a function of driver cost for different driver efficiencies. The target gain is assumed to be 100 with the driver energy fixed at 5 MJ. Targets are assumed to cost $0.50 each.

greater than 5% and the driver cost should be less than a couple hundred dollars per joule and that higher efficiency and lower cost is always better.

Target Coupling. Target coupling is another requirement that is difficult to quantify. The definition of target coupling used here is the product of the energy absorption and x-ray conversion efficiencies. Measurements of the laser absorption efficiency and x-ray conversion efficiency have been made [30], but there remain some uncertainties and inconsistencies [18]. Only recently have the coupling efficiencies been translated into different gain curves [17,18], where it is possible to assess the impact on the overall system.

For lasers, there are three clear implications of the target coupling efficiency data. First and obviously, higher coupling efficiencies result in higher target gain [17]; second, shorter wavelengths (in the intensity range of interest) result in higher coupling efficiencies [30]; and third, higher intensities result in lower coupling efficiencies [17]. The third implication leads to the fact that beam hot-spots will be detrimental to the coupling efficiency, and thus good beam quality will be important for high coupling efficiencies. Additional factors such as a broad bandwidth will also be beneficial and may be crucial.

Pulse Shaping. In order to achieve high gain, a target needs to be compressed with a particular pulse shape that is accurately reproducible [3,31]. Whereas it is very important for the LMF to have flexible pulse shaping for target development, the driver for commercial applications will need to produce only one pulse shape. The pulse-shape sensitivity that a laser has, possibly resulting from a large nonlinear gain medium, can give an indication of the ability of a laser to consistently generate the desired pulse shape within the required accuracy.

Focussing. A reactor driver will need to have its final optical element a good distance from the target in order to have a reasonable lifetime. Thus, focussing the laser with high f-numbers to the required small focal spots is needed. Beam quality and wavelength effects need to be considered.

Pulse Repetition Rate. The driver for an ICF electric power plant will probably be required to operate in the range of 1 to 10 pulses per second, depending on the target gain and the operating parameters where the COE is minimum. This minimum in the COE occurs because of tradeoffs between the driver cost and the per-target cost. The driver cost increases as the driver energy increases, driving the COE minimum to lower driver energies. On the other hand, the repetition rate increases dramatically as the driver energy and target gain decrease; therefore the number of targets and total cost increases. It is typical to find a broad minimum in the range of a few pulses per second resulting from these factors [26,32].

Energy Scaling. The cost and performance of current ICF drivers demonstrate that energy scaling is an important issue for commercial drivers. The most expensive ICF driver extant, the Nova laser system at LLNL, is currently limited to operation at 20-30 kJ (frequency tripled with 3 ns pulses) as a result of platinum inclusions in the laser glass [24]. The Nova output energy is lower than the approximate operating point of an electric power plant operating driver energy by a factor of ~ 250! A driver for an electric power plant needs to have very favorable energy scaling and cost effective architectures to be attractive in the several megajoule range expected to be required for electric power production.

Reliability and Robustness. A driver for a commercial electric power plant will need to be reliable and robust in order to have a competitive COE with other electric power production technologies. The sensitivity of the driver to cleanliness and controlled environments should be reduced as the driver will have to operate in an industrial setting instead of in a laboratory.

LASER CANDIDATES FOR COMMERCIAL APPLICATIONS

Six different laser candidates for ICF commercial applications have been identified that have received more than cursory attention. They are excimers such as KrF, solid state, free electron, iodine, CO_2, and chemical lasers such as HF.

Below is a brief discussion of some of the features of each of these six systems currently or previously proposed for laser-fusion drivers; they will be evaluated in Section IV with respect to their appropriateness as a driver for ICF commercial applications. Ion accelerators and other lasers that have received less attention in the past, such as the $O_2(^1\Delta)$-I_2 laser, will not be discussed in this paper. Note, however, that the $O_2(^1\Delta)$-I_2 laser has received some study [33] and has some attractive features: it can be pumped by fusion neutrons and can avoid the thermal-to-electric conversion losses required by electrically pumped lasers.

KrF Lasers. KrF lasers are a relative newcomer to the list of driver candidates, having been discovered in 1975 [34]. They were quickly recognized as an attractive driver for inertial fusion because they have a high intrinsic efficiency and because they use a gaseous lasing medium, which allows the simple removal of the laser waste heat. Indeed, they may be the "brand X" laser system that has often been assumed to be needed for commercial applications [35].

There are many different configurations for KrF laser fusion drivers, based on the type of amplifiers and method of pulse compression. Since the upper-state lifetime for KrF* is less than 10 ns, KrF lasers typically need to be pumped and continually extracted for more than 100 ns in order to minimize pulsed-power rise and fall time losses. Thus, some type of pulse compression is needed. Additionally, KrF lasers can be discharge pumped, e-beam pumped, or pumped by a combination of the two methods.

Many combinations of these different types of amplifiers and pulse compression techniques have been previously discussed. Some of the original complete system studies of KrF laser fusion systems used large e-beam-pumped amplifiers and pure angular multiplexing for pulse compression in either a single-pulse [36] or repetitively pulsed [37] mode. Later, a Bechtel/LLNL/Physics International study examined a system comprised of large e-beam-pumped amplifiers and backward Raman nonlinear pulse compression [38]. Recently, it has been proposed that e-beam-sustained discharge-pumped KrF amplifiers may have an even higher wall-plug efficiency than the e-beam-pumped amplifiers [39]. A study by Spectra Technology (formerly Math Sciences Northwest) has proposed that the optimum pulse compression system for the e-beam-sustained discharge lasers is with forward Raman beam combination followed by angular multiplexing. A detailed analysis has compared the large e-beam-pumped amplifier/angular-multiplexed approach with a discharge amplifier/forward Raman beam combination/angular multiplexing approach [26,40]. It was found that both approaches appeared nearly equally attractive as a driver for inertial fusion.

Solid-State Lasers. Solid-state lasers have been the mainstay of single-pulse drivers for inertial fusion, being used in the United States at LLNL, the University of Rochester, KMS Fusion, Inc., and the Naval Research Laboratory. The advanced solid-state laser appropriate for ICF commercial applications is significantly different from the single-pulse systems. The three most significant differences are due to the need for

(1) pulse repetition rates on the order of five per second,

(2) wall plug to laser light on target efficiencies ≥ 5%, and

(3) driver system costs on the order of a couple hundred dollars per joule.

It appears possible to independently achieve all of the driver requirements listed above with advanced solid-state lasers; however, it is questionable whether it is possible to achieve all of the requirements simultaneously [41]. In order to achieve the high average power required for ICF commercial applications, the solid lasing medium needs to be actively cooled. Two approaches have been proposed to do this [24]. The first concept is the gas-cooled slab geometry, where all of the laser material is close to the coolant. The second concept is the zigzag liquid-cooled laser. In this geometry, the laser material is edge cooled, and the beam propagates through the medium in a zigzag pattern in order to average the thermally induced optical aberrations. Reference 24 contains a complete description of the work LLNL is doing in this area.

Two pump sources have been proposed in order to achieve the efficiency requirements. The first is to pump the lasing medium with laser diodes; laser diodes have demonstrated efficiencies of about 40% for single diodes and 20% for 1- x 1-cm arrays [24]. The second proposed pump source is an advanced flashlamp with spectral output tailored to the needs of the lasing medium. One item that has yet to be discovered is the lasing medium that has the capability to operate at high efficiency and also has a high heat transfer coefficient. Nd:glass lasers have been typically used in single-pulse applications, but Nd:YAG is more efficient. Neither of these appear to be suitable for the high efficiencies and high average powers required for ICF commercial applications. Many solid-state lasing media have been proposed [12,24,42,43], but none have been found to meet all of the desired criteria [44].

Other Laser Systems. The KrF and solid-state lasers are the two laser-drivers currently receiving the most emphasis in the U.S. A few other laser systems received significant attention in the past but are receiving considerably less attention now. These will now be briefly described.

The free electron laser (FEL) has been proposed as a driver candidate for ICF commercial applications [41,45,46]. This system is based on the induction linac approach, which appears more suitable for the short pulses required for ICF than the radio frequency quadrupole approach. The FEL has been proposed for ICF commercial applications because it appears capable of operating at high efficiency and at high average power, and it theoretically has the ability to operate at any wavelength in the range of interest.

Iodine lasers were probably first proposed for ICF because of their gaseous lasing media, which can use simple heat exchangers for removing the laser waste heat. Most of the work on iodine lasers is done in Germany at the Max-Planck-Institut für Quantenoptic [47]. Iodine lasers have some flexibility in that they can be pumped by either flashlamps or e-beams.

CO_2 lasers also share the advantage of a gaseous lasing medium. System studies for CO_2 lasers have examined them in the form of a driver for a power plant, and at the time of the study they looked very attractive [11,48]. CO_2 lasers for inertial fusion were developed at Los Alamos until 1985, when it was positively determined that the wavelength is too long for efficient target coupling.

Finally, a small effort was undertaken at Los Alamos to examine HF lasers for single-pulse applications such as the LMF. In the form of an e-beam-initiated chemical laser, the HF laser can have a single-pulse total system efficiency of 325% [49]. For repetitively pulsed applications, it is important to include gas reprocessing and flow power requirements for calculating the system efficiency. The inclusion of these effects lowers the system efficiency considerably.

EVALUATION OF THE LASER CANDIDATES

There has been much effort through the years in examining different drivers and evaluating their ability to satisfy the requirements for ICF applications [e.g., 13]. These types of studies often suffer not because of the authors' biases but because the authors typically have much greater knowledge about certain drivers and some ignorance of other drivers. In order to avoid this problem, the authors of this paper have consulted a number of other experts with a wide range of experience on lasers for inertial fusion. As mentioned before, only lasers that have received considerable attention will be analyzed here.

Figure 2 shows our analysis of the six different laser drivers being considered, broken down into the eight different driver requirements for electric power production that were described in Section II. For our analysis, a rating system of a "+", "?", and "-" have been used. A "+" means promising to achieve the requirement but not necessarily demonstrated. A "?" means questionable, unknown, or uncertain if the requirement can ever be satisfied. Finally, a "-" means unlikely to ever be able to achieve the requirement (perhaps a fatal flaw). Three additional comments are needed at this time. First, the rating system is estimated such that the rating for each category assumes that the driver is in a configuration to achieve all of the other requirements as well as possible. For example, the cost is evaluated for a laser operating as well as the system can; that is with high efficiency, high average power, long distance from the final optical element to the target, and using an appropriate pulse shape and wavelength for high target yields. Second, the authors believe that much innovation will occur for laser drivers over the next 50 years. It is very difficult to predict possible improvements at this time. That means that it will be important to revisit this analysis periodically in order to include these future innovations. The authors have considered the different laser systems in an architecture that is at present thought to be appropriate for ICF commercial applications. The third comment that is required now is that any single fatal flaw that is ultimately found will eliminate that driver. As the drivers become more developed, the "?"s will turn into "+"s and "-"s. This will then eliminate some, and possibly all, of the laser drivers. One thing that will impact the attractiveness of all of the laser systems would be the determination that the gain curves are actually lower than currently estimated. This is not without precedent. Lowering of the target gain will increase the efficiency requirements for the driver [29], possibly out of the range of all of the drivers

	EFFICIENCY	COST	TARGET COUPLING	PULSE SHAPING	FOCUSSING	REPETITION RATE	ENERGY SCALING	RELIABILITY AND ROBUSTNESS
KrF	+	?	+	+	+	+	+	?
S.S. Vitr.	?	-	+	?	-	-	+	?
S.S. Cryst.	+	-	+	-	?	+	-	?
FEL	+	-	+	-	+	+	-	+
IODINE	?	?	+	?	+	?	+	?
CO_2	+	+	-	?	?	+	+	+
HF	?	?	-	-	?	+	+	?

Figure 2. This chart evaluates the six main laser-driver candidates for eight different requirements for inertial confinement fusion electric power production. A "+" means that it looks promising for achievement of the requirement, a "?" means that it looks questionable or is unknown, and a "-" means that it does not look possible, even with favorable future projections. To be viable for ICF commercial applications, the driver must eventually have "+"s for all of the requirements. This evaluation is sure to change with time as developments and breakthroughs in driver technology are achieved.

except the FEL. Only time will ultimately determine the exact requirements and performance ability of the different driver candidates. The following section will explain the reasoning behind the rating of each driver and each requirement category.

Evaluation of the Different Laser Candidates

KrF Lasers. KrF lasers are being developed at Los Alamos. The Aurora laser system is the only full-scale test of a KrF laser for ICF. Aurora is at present under construction, with the first delivery of multikilojoules to the target plane expected in mid-1988. Aurora will be described in more detail later in this paper.

KrF lasers appear to be able to operate at high efficiency while simultaneously operating in a "best possible" mode for all of the other requirements. Recently, Spectra Technology, Inc. and Los Alamos measured a laser intrinsic efficiency of $13\pm1\%$. The definition of intrinsic efficiency used here is laser energy out divided by the total energy deposited in the gas. Computer results indicate that more favorable pump conditions can produce an intrinsic efficiency as high as 15-17% [50,51]. Three other efficiencies must be considered to determine the overall system efficiency. First, the efficiency from wall plug to energy deposited to the gas must be known. Single-pulse lasers are usually not designed for high efficiency. However, a 1980 Avco Everett Research Laboratory study estimated that with current (1980) technology this efficiency could be 60% and with projected improvements could be as high as 82% [36]. The second additional efficiency, losses in transport from the main amplifier to the target, was also estimated in the Avco study. They reported (again in 1980) that the current estimate is 90% transmission efficiency and with projected improvements could be as high as 94%. Without any improvements in intrinsic efficiency, this gives the estimate for a single-pulse system to be ~ 7% with current (1980) technology and ~ 10% assuming projected improvements. If 15% intrinsic efficiency can be realized, the single-pulse system efficiency can be as high as 11.5%. The third additional efficiency needed accounts for the power required to flow and condition the gas in a repetitive system. Estimates of the power required for this were done by McDonnell Douglas Astronautics Company and Los Alamos [52,53]. For an electric power plant, a credit is also allowed for the use of the "waste heat" for feedwater preheat [26,54]. The loss in efficiency resulting from circulating the gas is approximately cancelled by the credit for the feedwater preheat. Thus, overall system efficiencies projected for the future are approximately 10% wall plug to laser light on target. Thus, KrF lasers deserve a "+" for system efficiency.

The cost of KrF laser-fusion systems has been examined in detail [26]. It is projected that KrF lasers are an affordable driver if certain assumptions are made. These assumptions include

- laser operation with 4 J/cm^2 optical fluence for long-term reliable operation with 10-ns pulses,
- optical fluences of 6 J/cm^2 in a fluorine environment with 400-ns pulses,
- the cost of optical components, including blanks, coating, polishing, and mounts, is 25% of today's cost in constant dollars, and
- the cost of KrF amplifiers, excluding the superconducting magnets and pulsed power, is 25% of today's cost.

With these assumptions, KrF lasers can meet the cost requirements for ICF commercial applications. Because these modest but unproved assumptions had to be made to meet the cost requirement, KrF lasers are rated with a "?" for cost.

KrF lasers operate at a wavelength of 248 nm. This allows them a very high target coupling efficiency [30]. The broad bandwidth of KrF lasers also improves the target coupling [55-57] and allows them to be especially well suited for direct drive [58]. KrF lasers get a very high "+" for target coupling.

Pulse shaping is a critical issue for high target gain. Pulse shapes can be one of three types: multiple step, ramp, or picket fence [3,31]. There currently does not appear to be any significant advantage of one type over the other. KrF lasers appear to be able to propagate pulse shapes through the amplifier chain with only slight modification of the laser system [59]. Pulse-shape propagation in KrF lasers will be discussed in more detail in Section V of this manuscript. KrF lasers are rated "+" in pulse-shaping ability.

As mentioned before, because the final optical element will be in the direct "shine" of the target, it will need to be a long distance away from the target to extend the lifetime owing to damage from x-rays and neutrons. Data is lacking on exactly how far the final optic will need to be from the target, but estimates of 80-200 meters have been made [26]. At these distances, focussing to the desired spot size will require short wavelengths and good beam quality. KrF lasers appear to have these qualities and as indicated in Fig. 2, receive a "+" for focussing.

It appears to be a simple matter to operate KrF lasers in a repetitively pulsed mode. Because they are gas lasers, the waste heat can be removed by flowing the gas through a heat exchanger. Key issues are the type of pulsed-power system needed for this task and the ability of the gas-flow system to provide a uniform lasing medium. Studies of potential pulsed-power systems [52] indicate that there appear to be several options available. Experimental [60] and theoretical [26,52,61] studies of the gas flow system indicate that it is possible to obtain the required uniformity conditions in the laser for an affordable cost. Thus, KrF lasers receive a "+" for this requirement.

There do not appear to be any inherent limitations to scaling KrF lasers to the multimegajoule level. The best way to scale them is to determine the optimum module size, and replicate modules. Therefore, KrF lasers receive a "+" for energy scaling.

The reliability and robustness of a fusion laser system is a difficult thing to determine at this time. In order to have a minimum impact on the cost of electricity, the laser will need to fire on the order of 10^8 shots (~ 1 year) before it can shut down for on the order of 1 month for maintenance. Minor amounts of down time are permissible, but the driver must have an availability of ≥ 80% for the power plant to have a total availability ≥ 70%. Currently, it is unknown if KrF lasers can operate with the reliability and robustness required, so a "?" goes into that column in Fig. 2.

Solid-State Lasers. The row for solid-state lasers in Fig. 2 is divided into two rows to rate both vitreous (glass) and crystalline (e.g., YAG) lasing media. These two lasing media have such significantly different properties that the two rows are required. It will be assumed for both of these systems that diode laser pumping is used. It will also be assumed that the laser will have to be frequency tripled for adequate target coupling. There is some question about this, as evident by the range of wavelengths, 0.26-1.06 μm, desired for the multimegajoule single-pulse test facility [12].

The efficiency of flashlamp-pumped solid-state lasers for single-pulse ICF applications has typically been low, on the order of 1% or less. For a commercial ICF driver, the laser diode pumping will allow performance with higher efficiency. However, in order to operate with high average power in either the slab or zigzag architecture, the lasing medium must also have adequate thermal properties. This lasing medium has not yet been identified, and LLNL is currently performing an empirical search for a lasing medium that has the desired high efficiency and thermal properties [44]. There is no guarantee that this search will succeed. The authors and consultants of this paper, with the knowledge currently available to them, agree that a crystalline solid-state laser appears able to achieve the required efficiency for ICF commercial applications. This same group concluded that it is questionable if vitreous solid-state lasers can reach these efficiencies owing to the absorption cross sections of glasses.

The cost of single-pulse solid-state lasers has typically been high. Starting with the Janus laser constructed in the early seventies at a cost of slightly less than $10,000/J, costs have decreased [31]. However, the recently completed Nova laser fusion system at LLNL has cost $176 million, and it is assumed that it can operate (with platinum-free glass) at approximately 60 kJ frequency tripled, resulting in a unit cost of just under $3000/J. It has not been shown that a single-pulse, low-efficiency, solid-state laser can be constructed for less than the cost goal for ICF commercial applications of a few hundred dollars per joule; indeed, the solid-state laser medium has not even been identified. The high-efficiency, high-average-power laser will be significantly more expensive. The cost of the laser diodes required to pump the laser are today approximately a factor of 500 higher than thought affordable to meet the cost goals [44]! Combined with the complicated laser system with gas flow, it is the opinion of the authors and consultants that solid-state lasers, using either a crystalline or vitreous lasing medium, will almost certainly be too expensive for ICF commercial applications.

Target coupling from the output of frequency-tripled solid-state lasers should be adequate for high gain. If frequency-doubled laser light is found to be adequate, then solid-state lasers can also enjoy the benefits of broad bandwidth. It is possible that frequency-doubled laser light is not going to have a high coupling efficiency, and possibly frequency tripled may not be adequate. Solid-state lasers can frequency quadruple to get to near the wavelength of KrF lasers but will suffer an additional loss in efficiency. In this paper, it will be assumed that frequency-tripled laser light will give good target coupling efficiency, and thus both types of solid-state lasers receive a "+" .

As mentioned before, the laser system must be able to deliver a carefully shaped pulse to the target. Of the three types of pulse shapes [3,31], solid-state lasers will probably use the picket-fence approach. This approach limits the dynamic range required to about 10:1. Two areas complicate the propagation of pulse shapes in solid-state lasers. The first is the lasing medium gain sensitivity, which tends to amplify less intense pulses more than higher intensity pulses. This tends to destroy the desired pulse shape. The second difficulty is the frequency conversion process, which is also dependent on the pulse intensity [12]. It is the opinion of the authors that the vitreous approach results in questionable pulse shaping, and the crystalline approach, with the higher gain sensitivity, looks extremely difficult and is rated a "-".

Traditionally, solid state lasers have a reputation for poor beam quality. All solid-state laser-fusion systems currently built use low f-number target lenses. This allows them to focus to small spot sizes with poor beam quality. For an ICF electric power plant, the final optical elements will have to be a long distance away from the target, requiring high f-numbers. It is the authors' opinion that the beam quality from vitreous solid-state lasers will not be adequate for high f-number focussing, and thus are rated a "-". The crystalline solid-state lasers with better beam quality are rated as questionable.

In order to operate solid-state lasers at a high repetition rate, the waste heat must be efficiently removed from the solid lasing medium. Schemes to do this exist but require a high thermal transfer coefficient or very thin gain slices. Good thermal properties are just one of the desirable characteristics that are being examined in the LLNL search for a lasing medium. For the state of knowledge available today (with no suitable lasing medium yet identified), the authors' opinion is that a glass laser does not appear to have the necessary thermal properties and is thus rated with a "-" for repetition rate ability. Crystalline lasers have better thermal properties and are rated with a "+".

Scaling of high-efficiency, high-average-power solid-state lasers to high energies is a difficult problem. The authors feel that it is possible to scale vitreous lasers to high energy, and therefore they rate them with a "+". The crystalline lasers present a difficult problem with growing large numbers of large crystals, and it is felt that scaling to high energies is probably not achievable.

The reliability and robustness of solid-state lasers appropriate for an ICF electric power plant may be possible, but these attributes certainly need much development. Both types of solid-state lasers are rated as questionable in this area.

Free Electron Lasers. Free electron lasers (FEL) are considerably less developed than KrF or solid-state lasers for fusion applications. However, they have three unique advantages over all other laser systems that warrant their study. First, they appear easily capable of operating at high efficiencies. The FEL directly converts the kinetic energy of a relativistic electron beam to laser light, which avoids many of the losses involved with optical or electrical pumping schemes. Second, the FEL is basically an electron accelerator, which historically has been very reliable. Third, the FEL is almost as easy to run in a repetitive mode as the electron accelerator. Thus, with hardly any development required, the potential is there for a high-efficiency, repetitively pulsed, reliable laser-fusion driver. On the other hand, critical issues do need to be evaluated [45]:

- Can the laser beam be directed onto the pellet without focussing optics?
- Will two-dimensional effects substantially reduce the overall FEL efficiency?
- Can the requisite high current, high voltage, high brightness accelerator be built?

Clearly these issues need to be resolved in order to determine the feasibility of FELs for ICF commercial applications.

There is probably little question that FELs have the ability to operate at efficiencies suitable for ICF commercial applications. Prosnitz [45] estimates an overall efficiency of 14%, and thus FELs rate a "+".

Cost estimates for ICF FELs have received considerably less attention than some of the other laser systems. Though the estimates by Prosnitz meet the cost goal, the cost estimates for FELs in the Strategic Defense Initiative program are very large. Thus, the consensus of the authors is that FELs rate a "-" for affordability.

FELs get a "+" for target coupling because they have the ability to operate at the wavelength of their choice. Prosnitz [45] chose to operate at 250 nm in his study of FELs for ICF.

It is very uncertain if the FEL can provide the unique and highly accurate pulse shapes needed for ICF. This statement may also be true for all of the ion accelerator driver concepts for ICF. They are rated a "-" for pulse shaping.

The high beam quality and short wavelength output of an FEL should allow it to focus to the target. FELs are unique in that they will operate at intensities higher than optics can handle, and thus the output of the FEL must be directed towards the target with no optics in between. This has the system advantage that there are no final optics problems in the direct shine of the target output. There is a disadvantage that expensive portions of the driver are in the direct shine and will become radioactive. As for focussing the FEL, it is the opinion of the authors that it is a technical problem that can be overcome, and thus FELs receive a "+".

The FELs should have no problem operating at the repetition rates required for ICF commercial applications, and in this category are rated with a "+".

Scaling an FEL to the megajoule range at short wavelengths and short, shaped pulses appears to the authors to be very difficult. Prosnitz assumed 100-kJ modules and replicated them to get to the multimegajoule level. With the uncertainties associated with this, the authors rate FELs a "-" in energy scaling.

FELs are based upon electron accelerator technology, so they should be very reliable and robust. If shielding the FELs from the target neutrons is achieved, they should have little problem meeting the reliability goal of 108 shots before major maintenance. They deserve a "+" for reliability and robustness.

Iodine Lasers. The iodine laser for ICF is mainly being developed at the Max-Planck-Institut für Quantenoptic at Garching, Federal Republic of Germany. The Asterix IV laser is the latest iodine laser at Garching. It is designed to deliver 2 kJ of energy in 1 ns or a maximum power of 7 TW at 0.1 ns. The laser is pumped by photo-dissociation of gaseous perfluoroalkyls, e.g. C_3F_7I, which results in a laser transition at 1.315 μm [47]. The information available on Asterix IV will be used as a basis for our evaluation of the iodine laser.

The quantum efficiency of the atomic iodine laser is 21%; however, the typical system efficiency is only 0.1-0.2 % [62]. The ultimate efficiency of the high-average-power iodine laser is uncertain because the power required to reconstitute the laser gas needs to be considered. A LLNL report states that "the atomic I_2 system does not meet ICF objectives because the total system efficiency does not exceed 2 % when the costs of the chemical reprocessing are included" [41]. Not having studied iodine lasers and the efficiency associated with chemical reprocessing, we rate the efficiency of iodine lasers "?" for ICF commercial applications.

The cost of a high-efficiency, high-average-power iodine laser is also uncertain at this time. If laser diodes are needed for high efficiency, the cost will probably exceed the requirement for ICF commercial applications. Advanced flashlamps may be affordable. Because of this uncertainty, iodine lasers are rated "?" for cost.

Efficient target coupling appears possible with iodine lasers through the use of frequency multiplication techniques. With a fundamental wavelength of 1.31 μm, frequency tripling reduces the wavelength to 0.44 μm, which may be short enough. If not, frequency quadrupling is possible, but the effect on the cost and efficiency must be considered.

Like solid-state lasers, pulse shaping is questionable for iodine lasers because of the required frequency multiplication. They are thus rated with a "?" for pulse shaping.

Focussing with iodine lasers appears possible with the adequate beam quality and short wavelength. They are rated a "+" for focussing.

An uncertainty exists on the ability of iodine lasers to operate at the repetition rates required for ICF commercial applications owing to limitations on the gas flow rate [63]. They thus receive a "?" for pulse repetition rate.

There appears to be no fundamental reason why iodine lasers cannot be scaled to high energy, and thus are rated with a "+" for salability.

Finally, the reliability and robustness of iodine lasers, as with most other lasers, is uncertain. They are rated "?" for this category.

<u>CO_2 Lasers</u>. CO_2 lasers for inertial fusion have been developed at Los Alamos and in Japan. A comprehensive study of a CO_2 driver for ICF commercial applications was done in 1980 by the Avco Everett Research Laboratory [48]. Some of the results will be presented here, along with information obtained more recently.

The efficiency of CO_2 lasers appears adequate to meet the requirements for ICF commercial applications. Reference 11 summarizes the work from Reference 48. This work indicates that CO_2 lasers appear to have the potential of operating with an efficiency of approximately 8 %. They are therefore rated with a "+" for efficiency.

The cost estimate that Friedman of Avco performed [48] indicated the possibility for costs in the range of \$100-\$300/J, and therefore CO_2 lasers deserve a "+" for cost.

Target coupling is where CO_2 lasers suffer for ICF commercial applications. Because of the long wavelength, 10.6 μm, the laser is absorbed by processes other than inverse Bremsstrahlung and produces too many fast electrons to avoid fuel preheat. Thus, high target gain will not be possible. CO_2 lasers are rated a "-" for target coupling.

Because the CO_2 laser is highly nonlinear, it is uncertain if the desired pulse shapes can be delivered to the target. They are rated as "?" for pulse-shape capability.

Focussing the CO_2 laser from a long distance to the target may not be possible owing to the long wavelength. It is questionable if CO_2 lasers can meet this requirement and are rated "?".

CO_2 lasers appear capable of operating at the repetition rates required for ICF commercial applications. There is also a great deal of experience with commercial CO_2 lasers that operate at high repetition rates. CO_2 lasers deserve a "+" for repetition rate.

CO_2 lasers also appear capable of being scaled to large sizes and thus high energies [11]. This was demonstrated by the Antares laser system [64] built at Los Alamos. They rate a "+" for energy scaling.

Finally, it is the opinion of the authors that CO_2 lasers appear to have the capability of operating with the reliability required for ICF commercial applications. Therefore, they are rated a "+" in this category.

HF Lasers. Chemical lasers such as HF lasers have been investigated for ICF commercial applications drivers much less than some of the other laser candidates. A recent study of HF lasers for a single-pulse high-gain test facility [49] will be used to judge HF lasers for ICF commercial applications. This study assumed that the target yield of 1000 MJ is the main requirement for the facility. In order to accomplish this yield, calculations indicate that a 100-MJ laser using a nonoptimal pulse shape is needed. These calculations indicate that this will give a target gain of 10 and thus the desired 1000 MJ yield.

The efficiency of HF lasers at first appears excellent. In a single-pulse mode, the wall plug to laser light on target efficiency is 325%. For ICF commercial applications, the power required to reconstitute the gas must also be considered. Because of the uncertainties involved with the chemical process, exact target coupling, and our perceived lack of pulse-shape ability, it is uncertain if the efficiency is high enough for ICF commercial applications, and thus they are rated "?".

Because of the limited amount of development of HF lasers for ICF, the cost is certainly questionable. Reference 49 indicates that the cost of the 100-MJ lasers is acceptable, but the high-repetition rate and gas reprocessing requirements are not addressed. Because of these uncertainties, the laser must be rated as "?" for meeting the cost requirements for ICF commercial applications.

Target coupling does not appear attractive for ICF applications. Because of the long wavelengths, in the region of 2-4 μm, the coupling efficiency will be low. The multiline, broad bandwidth aspect of the HF laser is a benefit that will contribute to higher coupling than with a narrow-band laser. However, in the opinion of the authors, the wavelength is too long for adequate target coupling and the HF laser is rated a "-" in this requirement.

Pulse shaping is something that the authors consider difficult to do with the HF laser. This is part of the reason why Phipps [49] required 100 MJ of driver energy to obtain a target gain of 10. Pulse shaping is rated a "-" for HF lasers.

Focussing the HF laser on the target from a long distance is doubtful because of the long wavelength. HF lasers are thus rated with a "?" for focussing.

Because HF lasers use a gaseous lasing medium, they should have no difficulty (aside from gas reprocessing) in operating at the repetition rates required for ICF commercial applications. They thus deserve a "+" in this category.

There appears to be no inherent limitation on scaling HF lasers to the energy required for ICF applications [49]. They thus deserve a "+" in this category.

Finally, the reliability of the HF laser is uncertain, mainly owing to the lack of knowledge caused by the limited development. They are rated "?".

Summary of the Evaluation

The authors will be very surprised if advances in technology and/or clever innovations do not quickly change the results of the above analysis. The rate of development for lasers, although not at the level of computers, is staggering. We will make no projections on how long (after publication of this manuscript) our opinions will be unchanged.

Biasing and level of optimism are two items that can have an influence on the analysis. We attempted to eliminate biasing by including the opinion of other laser experts with experience with a variety of lasers for fusion. Additionally, we tried to be optimistic with our projections. When we had a difference of opinion on a requirement for a particular laser system that could not be worked out through discussion, we gave it the benefit of the doubt.

KrF lasers appear to be the most attractive lasers for ICF commercial applications at this time. The ability to satisfy two requirements, cost and reliability, are still uncertain. The cost of multimegajoule, several-pulses-per-second lasers is difficult to estimate. Cost estimates have been done for KrF lasers [26], and the cost was found to be in the affordable range if certain assumptions for cost reductions for optical components and certain parts of the e-beam-pumped amplifiers were made. It is not certain that these assumptions are achievable, which is why KrF lasers are questionable with respect to the cost requirement. The cost estimates, however, have made it possible to identify where research needs to be done. The second uncertain requirement is for the reliability and robustness of the laser system. This requirement was listed as uncertain for almost all of the laser systems and can be satisfied only through research and development. Because highly reliable, repetitively pulsed fusion lasers will not be needed for a long time, it is doubtful that work will be done in this area in the near future. Other applications require certain components of KrF lasers such as pulsed power and optics.

Therefore, some work on this aspect is being done on the side. However, it is likely that a definitive answer on KrF laser's reliability and robustness will be lacking for a long time.

Iodine lasers are the second-place finishers with no show stoppers ("-"). They have a difficulty to overcome that KrF lasers do not have: the long wavelength needs to be shortened through frequency multiplication. Additionally, further investigation on the chemical processing cost and efficiency needs to be considered.

Solid-state lasers for inertial fusion have received the most funding for development to date and have been successful (though expensive) as single-pulse research tools. It has been recognized [31] that the cost must be significantly reduced to be affordable for the multimegajoule single-pulse high-gain test facility. Solid-state lasers do not appear to be attractive for ICF commercial applications in architectures currently being considered for high average power. The main problem appears to be the costs associated with high efficiency and high average power. Only time will tell if high-average-power solid-state lasers can be made affordable enough for future applications.

LOS ALAMOS KrF LASER DEVELOPMENT PROGRAM

The U.S. national ICF program has three main thrusts (see Fig. 3). One major element is the capsule physics program, which goes under the name Centurion/Halite. A second element is driver technology. Three drivers are funded by the Office of Inertial Fusion (recently changed to the Inertial Fusion Division in the Office of Weapons Research, Development, and Testing): light ions, excimer lasers (mainly KrF), and solid-state lasers. A fourth driver, heavy ions, is funded by the Office of Energy Research. The third major element of the national program is the investigation of driver-matter interactions. This investigation includes both photon and high-energy ion interactions. Los Alamos participates in all of these activities but emphasizes work that involves KrF

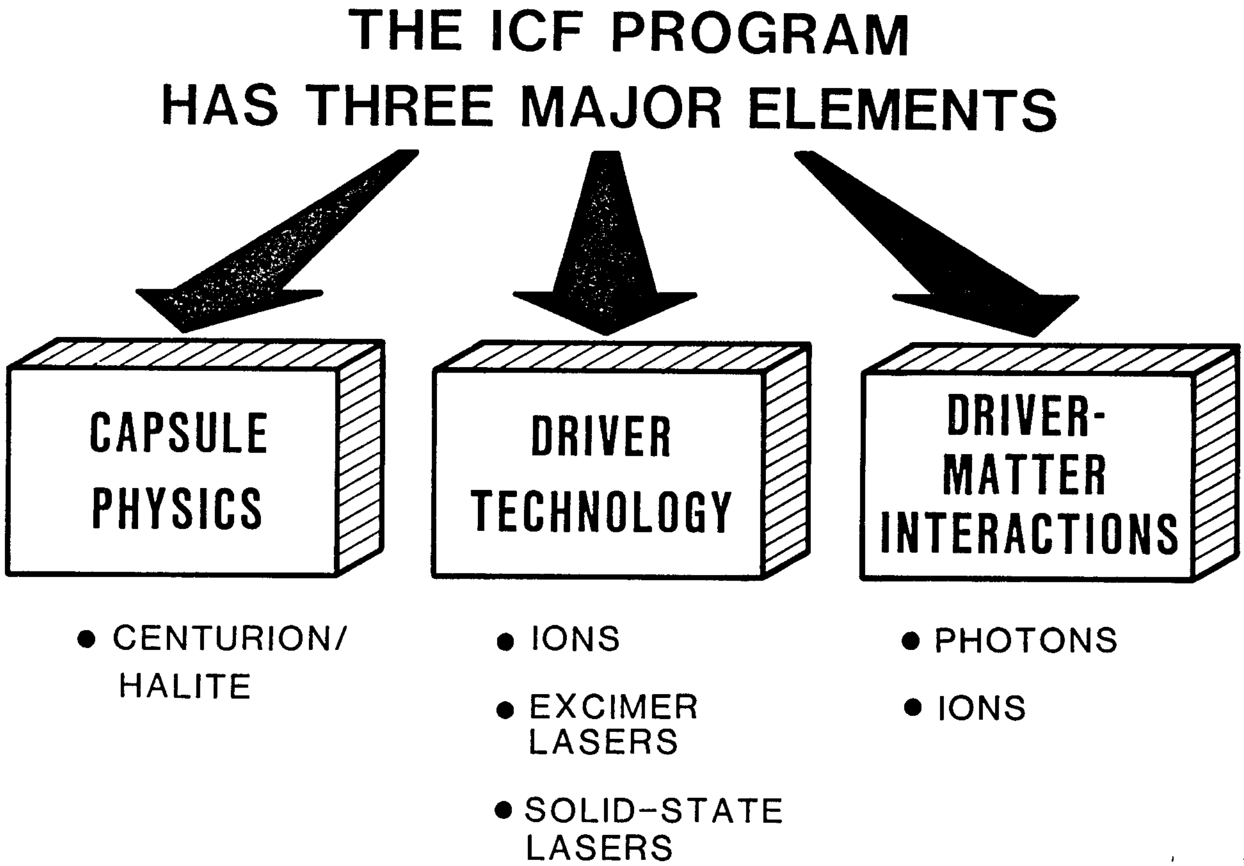


Figure 3. The U.S. inertial confinement fusion program has three major elements. Capsule physics is examined by the Centurion/Halite program. Driver technology development and driver-matter interactions, for both lasers and ion drivers, are the other two major elements.

lasers. This section will describe the driver technology development program at Los Alamos.

Commercial Applications Development Plan for KrF Lasers

The development plan for KrF lasers is simple and follows the plan Willke et al. defined in 1979 [65]. The Aurora KrF laser fusion system, described in the next section, will address almost all of the issues for the applicability of KrF lasers for ICF. One important issue that is not fully addressed by Aurora is the scaling of KrF laser amplifiers to larger module sizes that appear more affordable and the ganging of the output of more than one amplifier with a technique called aperture combination [26]. The next system will then need to address this issue. One plan currently under consideration is an upgrade of the Aurora system to the 200- to 400-kJ range. This upgrading could be accomplished by simply adding an additional stage of amplification to the output of Aurora. Preliminary plans for this upgrade have been completed.

After the Aurora upgrade, the KrF laser development plan would probably be the same as proposed by Willke. The next step is the multimegajoule single-pulse test facility, currently called the LMF. After Aurora and the Aurora upgrade, all of the technology required to construct and operate a KrF laser-driven facility of this scale will be in hand. The LMF will not only develop high-gain targets for commercial applications but will also be used for military applications such as weapons physics research and weapons effects experiments. Either during or after the LMF, a small-scale experiment called (by Willke) the systems integration facility (SIF) will be needed. The purpose of the SIF is to develop the technology for target injection, tracking, and targeting by the laser system. Additionally, the SIF will aid in pulsed-power-supply development, require the construction and testing of a prototype driver, and allow beam propagation studies.

Following the LMF and SIF will be facilities such as the following:

- The engineering test facility (ETF), which is required to test ICF reactor concepts and reactor-plant equipment such as tritium recovery and handling.
- The materials test facility (MTF), which is needed to test pulsed irradiation effects and to qualify materials for ICF applications.
- The pellet fabrication facility (PFF), which is required to develop mass-production fabrication of targets, to serve as a prototype for a target factory for ICF commercial applications, and to provide targets for the above facilities.
- The fusion pilot plant, which will serve as a prototype for an electric power plant. The pilot plant may be a fission-fusion hybrid in order to lower the fusion requirements and still make the plant cost competitive.

Finally, after all of these intermediate steps, the technology will be available and the risk should be acceptable for construction of an ICF power plant operated by the electric power industry.

The following sections will describe the work currently underway at Los Alamos for the development of KrF lasers for inertial fusion.

The Aurora KrF Laser System

Aurora, the goddess of the dawn, is an appropriate name for the first complete KrF laser-fusion system. But it is more than the dawning of a new type of laser system. It is also the dawning of a laser system that may be the "brand X" laser that ICF researchers have often assumed for commercial applications. In the words of George Miley, editor of *Fusion Technology*, "the time is rapidly approaching when a workable laser driver (versus the single-pulse, low-efficiency, glass lasers currently used for implosion experiments) must be developed, or the hope for a practical laser driver in time to compete for reactor use will vanish" [35]. This clearly defines the goal of the Los Alamos driver development program.

The Aurora laser system is depicted in Fig. 4. A 5-ns pulse generated in the front end is expanded and divided into two through the use of an apertured mirror. Each of these pulses are split into six in the beam slicer, making 12 total beams. These beams are then amplified in the small amplifier module (SAM). Each beam is then further divided into 8 beams through the use of beam splitters, producing the desired 96 beams with a 5-ns separation time. The beams are then directed to an angle encoder station, where each beam is given a slightly different angle for propagation through the amplifier sections. After being angle encoded, the beams are directed through the single-pass preamplifier (PA) and intermediate amplifier (IA) and then go to the large amplifier module (LAM) input array where they are amplified in the double-pass LAM. The LAM, shown from the front in Fig. 5, is pumped from each side by an e-beam diode, which is powered by Marx generators and two coaxial water-dielectric pulse-forming lines (Fig. 6). The 96 beams are then separated, the time delay is removed in the demultiplexer, and the beams are directed to final aiming mirrors (Fig. 7), and are directed through lenses to the target. The reader is encouraged to read the Rosocha et al. article [66] in the special issue of *Fusion Technology* devoted to KrF lasers for ICF for a much more detailed review of the Aurora laser system.

Mostly for financial reasons, current plans call for only 48 of the beams to be brought to one side of the target; however, all of the issues that could be answered by bringing all 96 of the beams to target can be addressed with the 48-beam system. If a later decision is made to bring the remaining beams to target, the existing target chamber, shown in Fig. 8, is able to accommodate them with little modification.

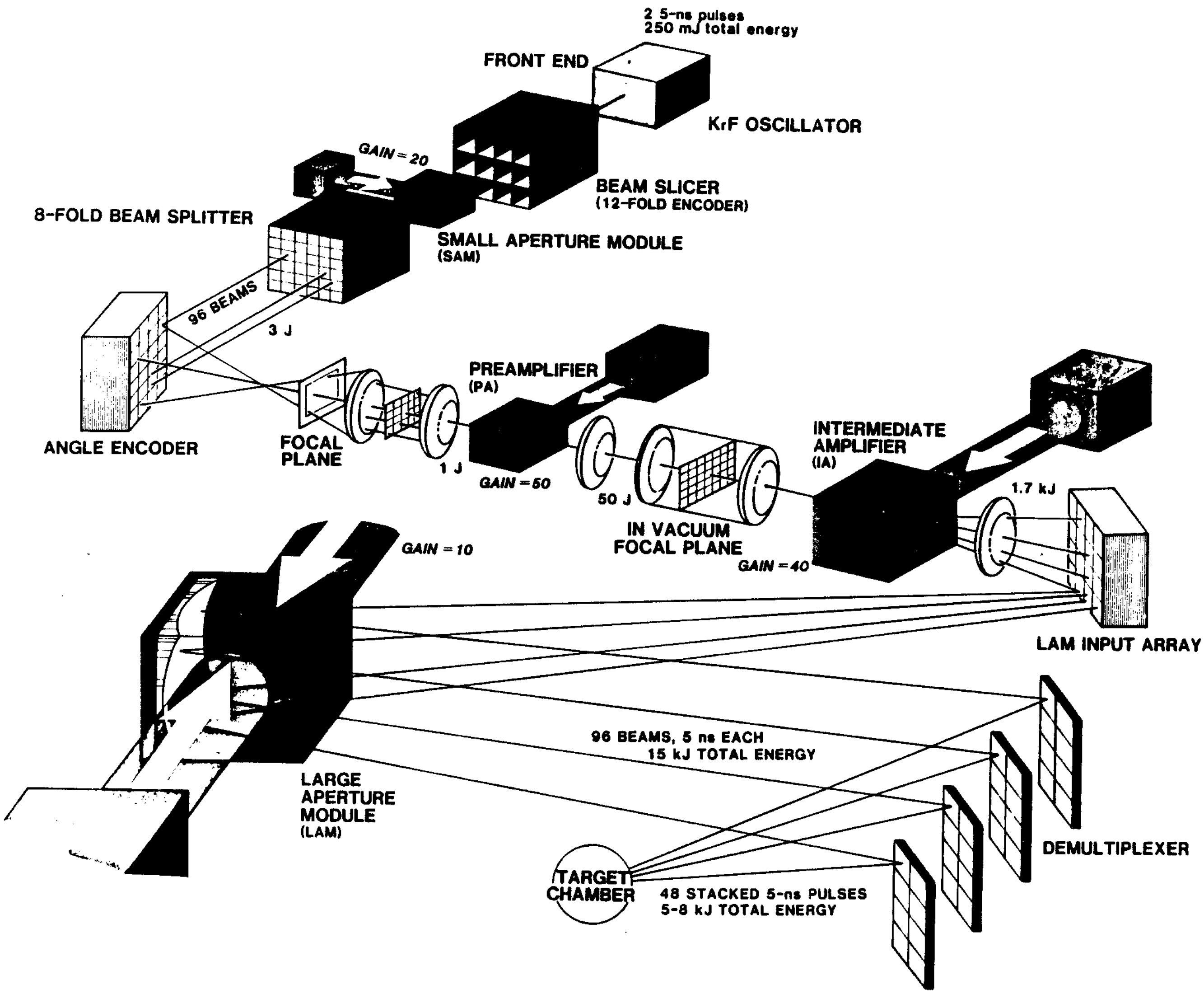


Figure 4. A conceptual layout of the Aurora laser system is illustrated. All of the main optical and laser elements from the front end through the final amplifier output and on to the target are shown. Stage gains, number of beams, and beam energy are indicated at various points along the beam path. A final output of 10-20 kJ in a 480-ns pulse composed of a 96-element train of 5-ns pulses is expected at the final large amplifier module amplifier. Typical delivered-energy at the target will be 5 to 8 kJ in 48 beams.

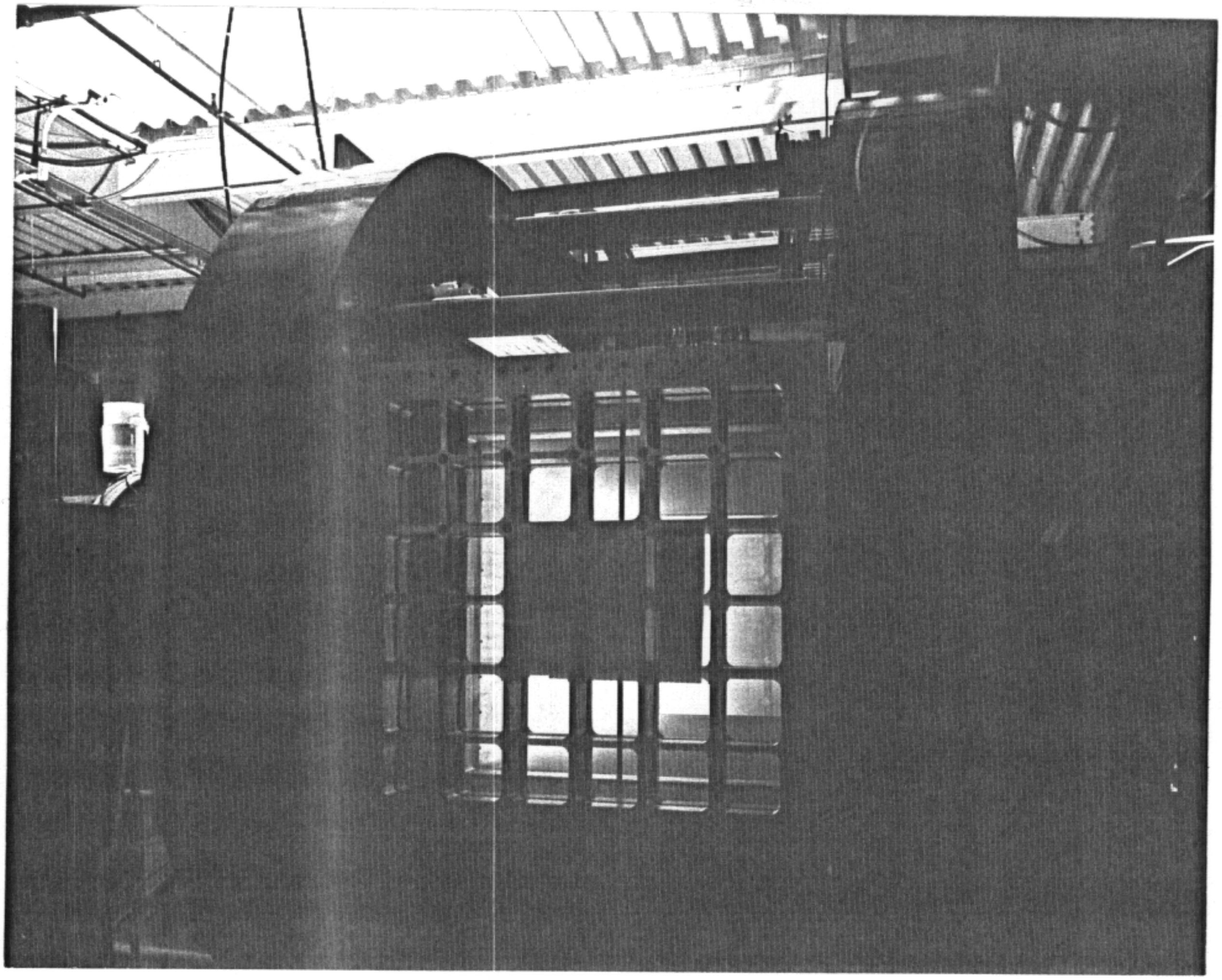


Figure 5. The large amplifier module is shown in an unstable optical resonator configuration with the e-beams being fired. For two-pass operation, the segmented window will be replaced with a monolithic fused-silica window.

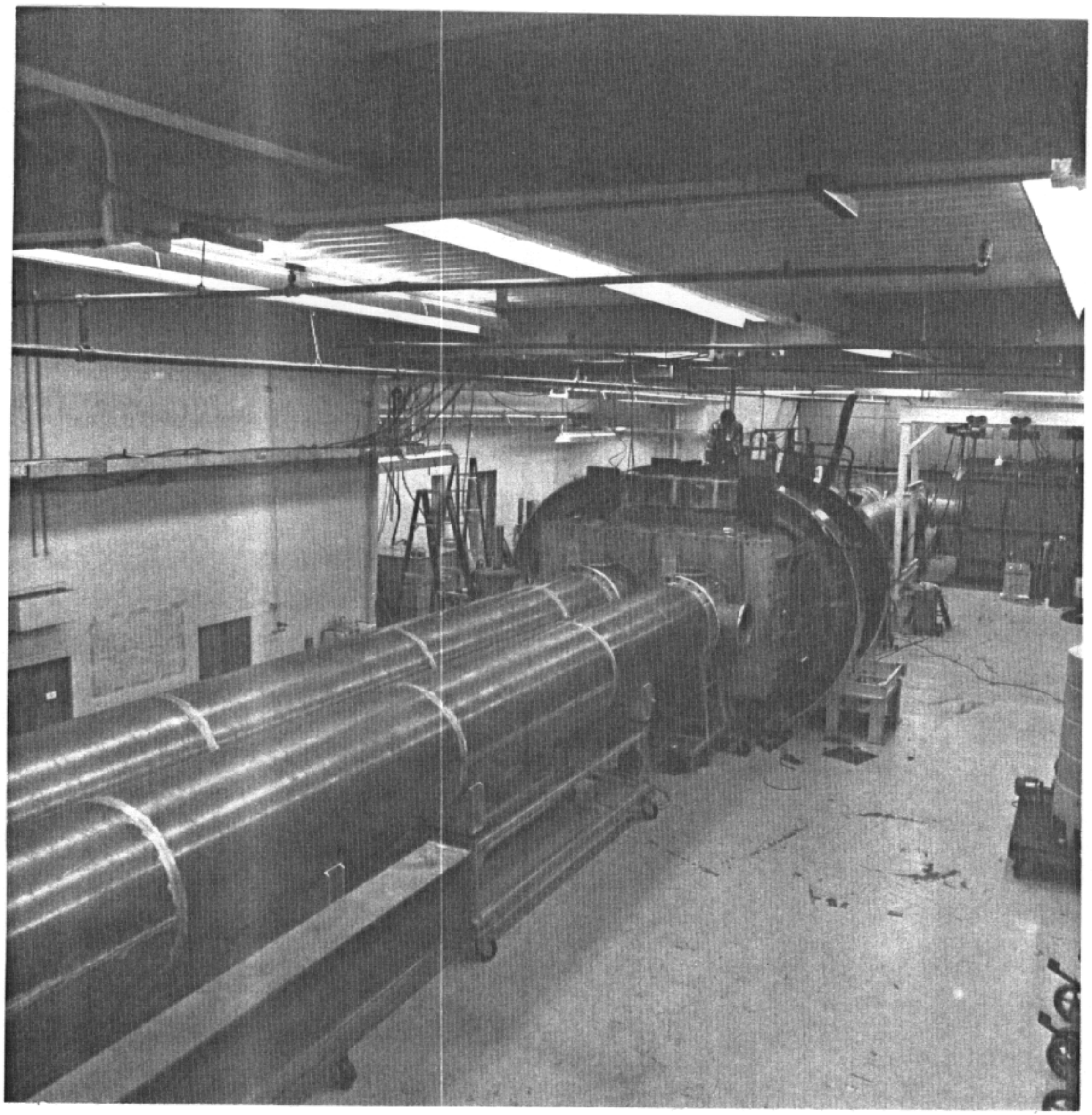


Figure 6. A photograph showing the Aurora large amplifier module in the latter part of its initial assembly phase. The main laser cavity, which is pumped by two opposed broad-area cold-cathode e-guns, is located between the coils that provide the guide magnetic field for the e-guns. The e-guns are housed in the vacuum enclosures adjacent to the laser chamber. Each e-gun is powered by a parallel combination of two coaxial water-dielectric pulse-forming lines (PFLs), which are clearly visible in the foreground. Each pair of PFLs is charged by a separate Marx generator; the tank visible in the background contains one Marx. On a routine basis, the e-guns deliver ~ 160 kJ into the laser gas at electron energies of 550 to 600 kV and current densities of 12 A/cm^2. So far, the 1- x 1-meter aperture large amplifier module has produced in excess of 10 kJ of 248-nm laser light when configured as an unstable optical resonator.

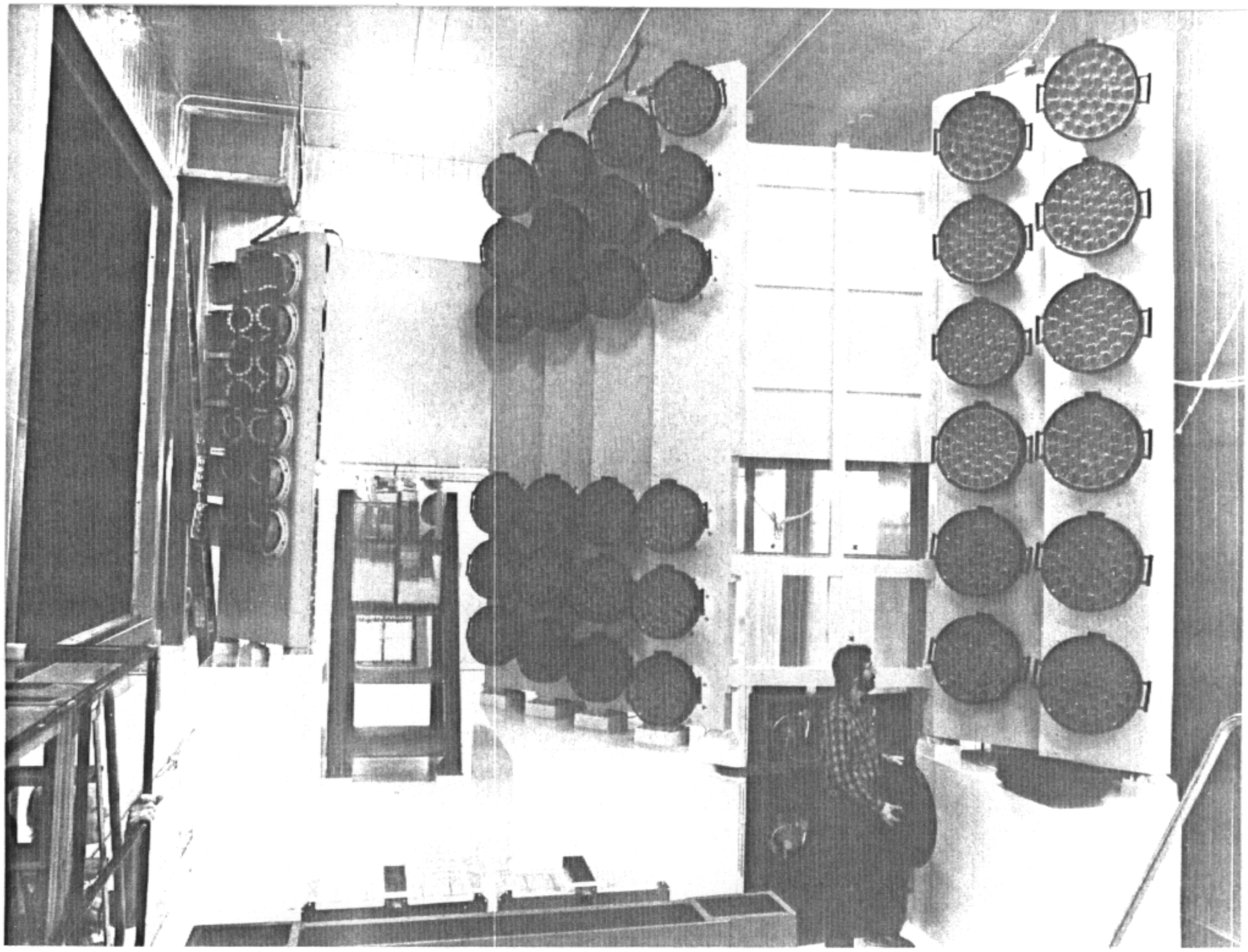


Figure 7. The final aiming mirrors have recently been installed. These mirrors will direct the 48 beams through final lenses to the target.

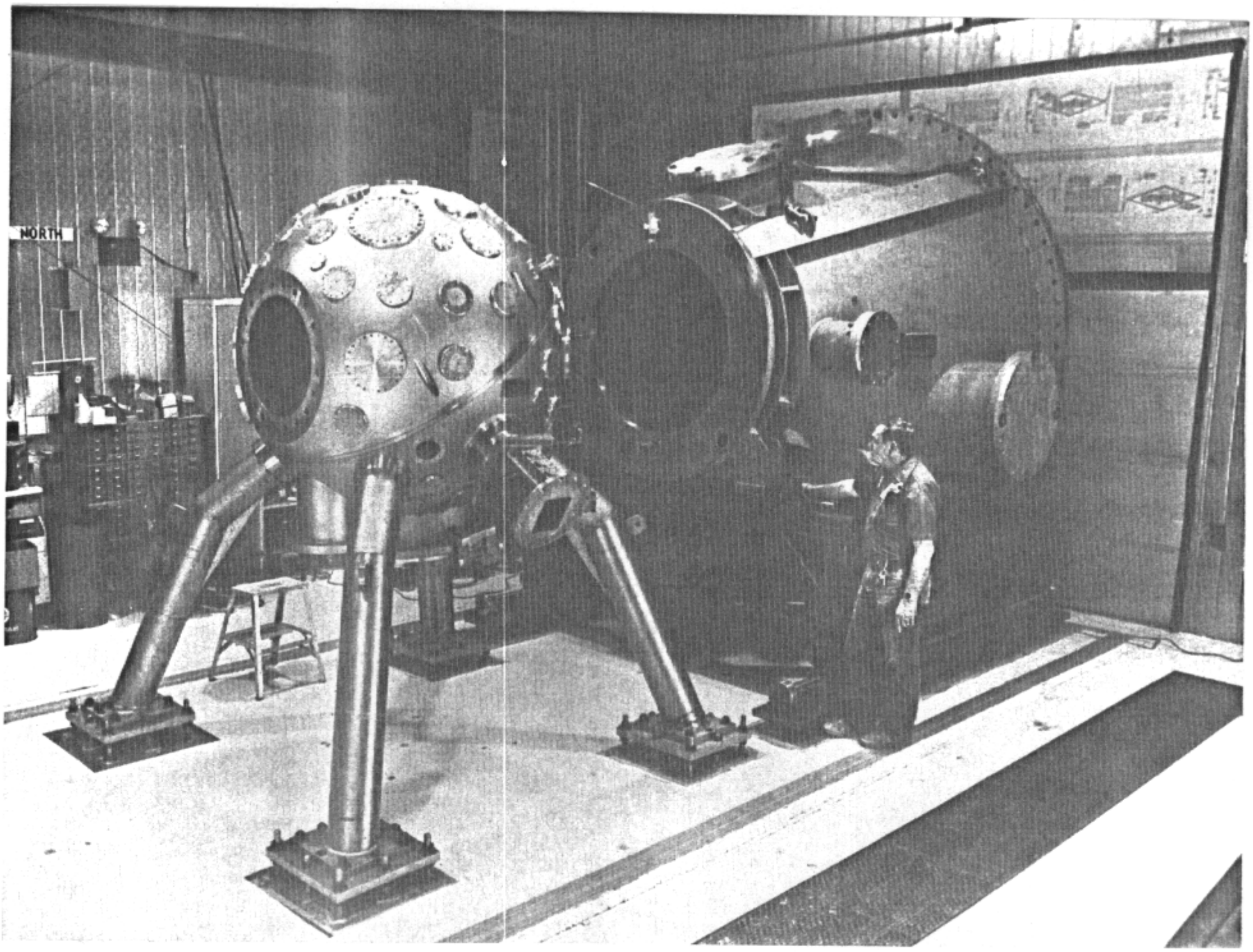


Figure 8. The target chamber and final beam cone shortly after installation. To facilitate collaboration and interchange of diagnostics, the target chamber size and port configuration is the same as the target chamber on the University of Rochester's Omega laser system.

KrF Technology Development at Los Alamos

Technology development for KrF lasers is also being done at Los Alamos. The goal here is to not only improve the feasibility of KrF lasers but to also develop technology in the areas with the highest cost leverage in order to reduce the cost of fusion laser systems. Key areas of technology development currently underway include KrF kinetics, optics, pulsed power, and alignment systems. These subjects will be described briefly in this section; see references 67-71 for complete descriptions of the Los Alamos work in these areas.

KrF Kinetics. There have been many papers published in the last 10 years describing experimental and theoretical studies of KrF kinetics (see References 50 and 51 and references therein). At Los Alamos, there have been three recent studies that will significantly impact KrF fusion lasers. The results of these studies will be briefly examined.

In a collaborative effort with Spectra Technology, Inc. [72], a series of experiments was performed to measure the KrF intrinsic efficiency. Here, the definition of intrinsic efficiency is the 248-nm laser energy out of the amplifier divided by the total e-beam energy deposited in the gas mixture. This definition of intrinsic efficiency includes pulsed power rise- and fall-time losses, losses owing to unpumped F_2 regions, and losses owing to imperfect optics. Because existing equipment was used for the experiments, they were not performed under the pump-power conditions predicted by computer analysis to be optimal. Operating at conditions as close to ideal as possible, an intrinsic efficiency of $13 \pm 1\%$ was measured. Even higher intrinsic efficiencies are expected under higher pump conditions [50,51].

Another collaborative effort with Spectra Technology, Inc. examined a wide range of KrF laser fusion systems with the goal of identifying the system configuration with the highest system efficiency. It was determined that e-beam-sustained discharge

(EBSD) KrF lasers can have a significantly higher wall-plug efficiency than purely e-beam-pumped amplifiers [26,73]. In part, this increase in efficiency results from the fact that the upper laser level is formed dominantly by excitation transfer between neutral species in EBSD lasers as opposed to being formed dominantly by ion-ion neutralization in e-beam-pumped lasers. The neutral channel is energetically more efficient than the ion channel which is why a higher intrinsic efficiency is expected. In addition, the wall-plug efficiency at which power can be deposited in the gas is higher for discharges than for e-beams. Electrical circuits for discharges typically have fewer stages of power conditioning, thereby having a higher overall charging and transfer efficiency. There are also losses associated with penetration of the e-beam through mechanical structures that are reduced with the EBSD approach.

The EBSD lasers, however, cannot be scaled to high output energies, being limited by discharge stability to a few kilojoules per amplifier. Thus, a few thousand amplifiers will be required to generate a few megajoules of laser energy. If pure angular multiplexing is to be used for pulse compression, the total number of beamlets will be of the order 100,000, which may be too large. A scheme was devised which used forward Raman amplifiers [74] utilizing rotational Raman scattering in hydrogen to provide the required beam combination and beam cleanup at high efficiency. This scheme would allow the EBSD lasers to operate with a single, 320-ns pulse and significantly reduce the total number of beams in the system. This system was analyzed in detail [26,40,73], and it was determined that it appeared equally attractive as a driver for ICF commercial applications as the e-beam-pumped/pure-angular-multiplexed approach.

The third recent result involves the propagation of pulse shapes through KrF laser-fusion systems. It has been found [59] that the pulse shapes required for high gain targets can be propagated through a chain of amplifiers with very little modification required. As shown in Fig. 9a, an input pulse similar in temporal characteristics to that required a)

b)

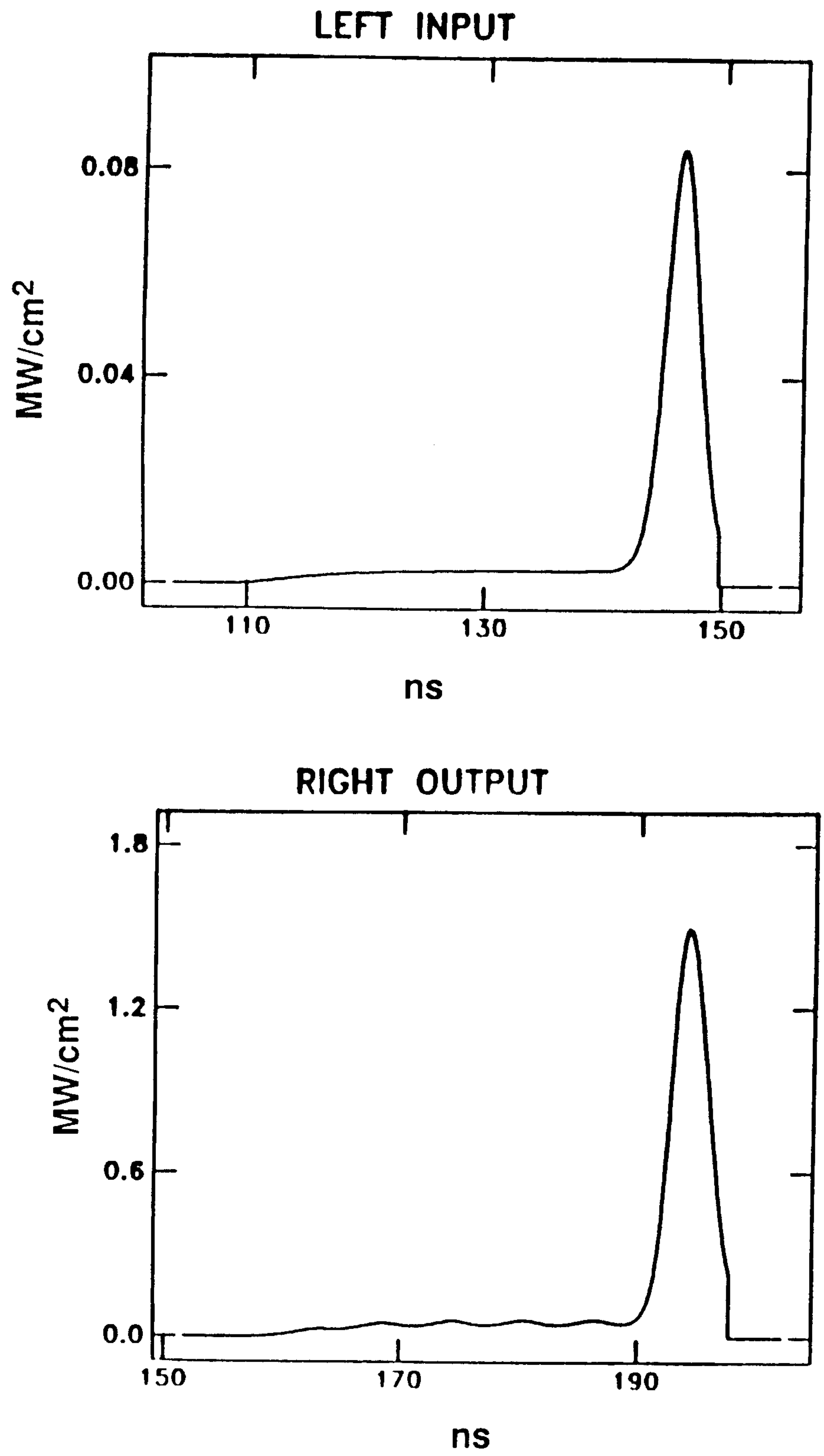


Figure 9. a) An input pulse, shaped like a western boot, is used as an approximation of the pulse shape required for high gain. b) The output pulse maintains the shape of the input pulse after amplification [59].

for high gain will be amplified with little loss in shape. The output pulse is shown in Fig. 9b. Similarly, Figs. 10a and 10b show a train of input and output pulses appropriate for a two-pass amplifier. The only modifications required of the input pulses is the removal of the "foot" of the first few, and the intensity of the first two pulses is attenuated. This gives the uniform pulse shapes and intensities shown in Fig. 10b. The target will see complete pulse shapes on all but a few pulses, which will deposit their energy only in the peak power portion of the pulse.

Optics Development. It has been determined that optical components are a high-leverage-cost item for KrF laser-fusion systems [26]. Two improvements can substantially reduce the impact of the cost of optics on the total system: optics that operate at higher fluences and optics that cost less. Los Alamos is pursuing both of these areas.

Los Alamos has long had an optics damage-testing program [69,75,76]. Its goal is to determine which coatings are best for 248 nm and which coating techniques are best. Figure 11 shows a sample of the progress that has been made for mirror coatings. The progress that has been made is easily seen.

Los Alamos has also been involved in developing low-cost optics. One especially significant innovation is the lightweight mirrors developed in conjunction with the University of Arizona Mirror Fabrication Group in the Astronomy Department [69]. These large-area mirror blanks are manufactured using a novel Pyrex-fusion technology and have been found to be satisfactory for use with Aurora. Innovations such as these can significantly reduce the cost of KrF laser-fusion systems.

Pulsed-Power Development. Many aspects of pulsed power are being examined at Los Alamos. A detailed description of this work can be found in Reference 70 and references therein.

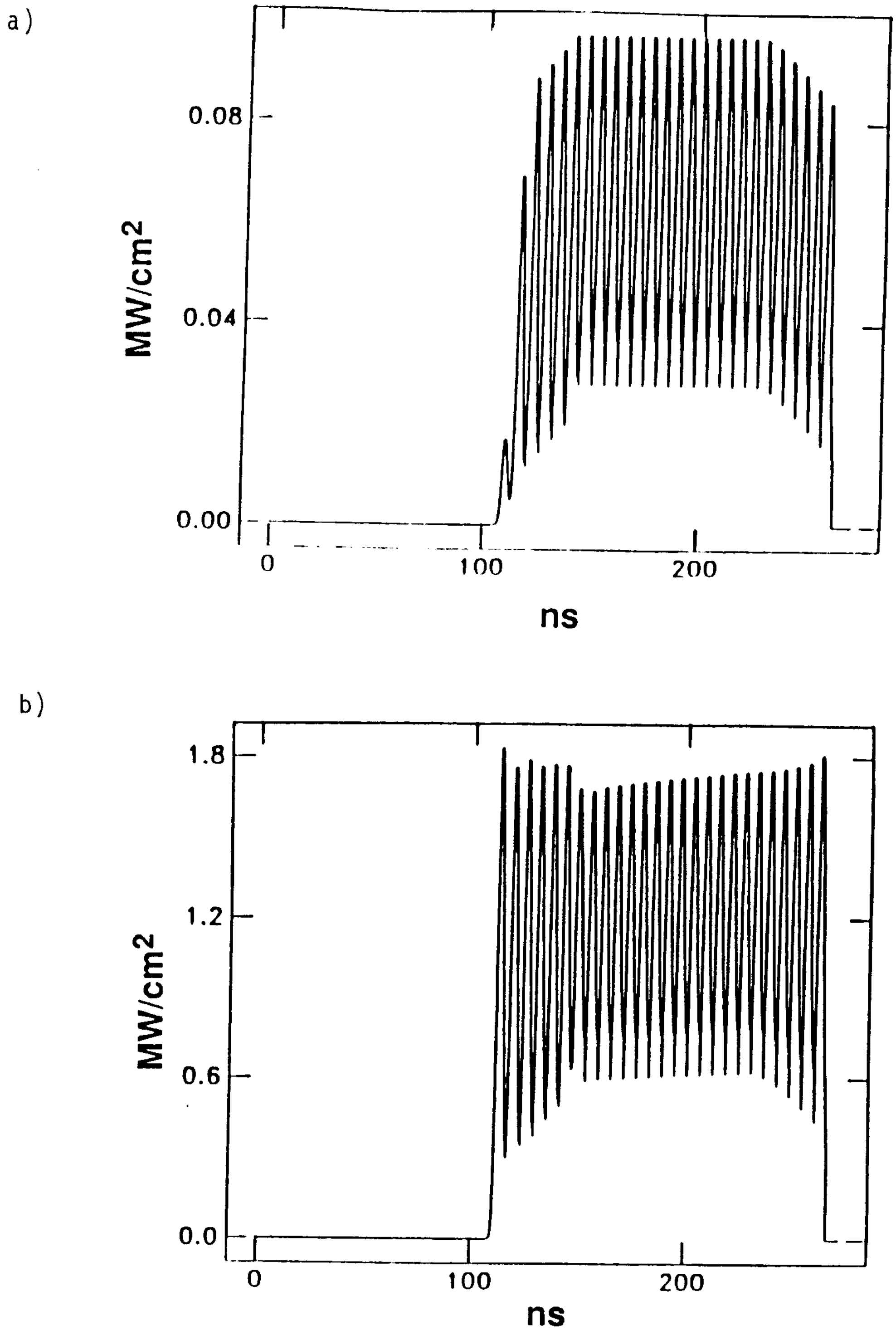


Figure 10. a) A series of input pulses is sent into the double-pass amplifier. Note that the intensity of the first two pulses is reduced, and the first six pulses have no "foot" portion of the western boot. b) After amplification, the intensity of the pulses is uniform [59]. The pulse shape is maintained through the amplifier, showing that a pulse shape generated in the front end can be propagated through the amplifier chain.

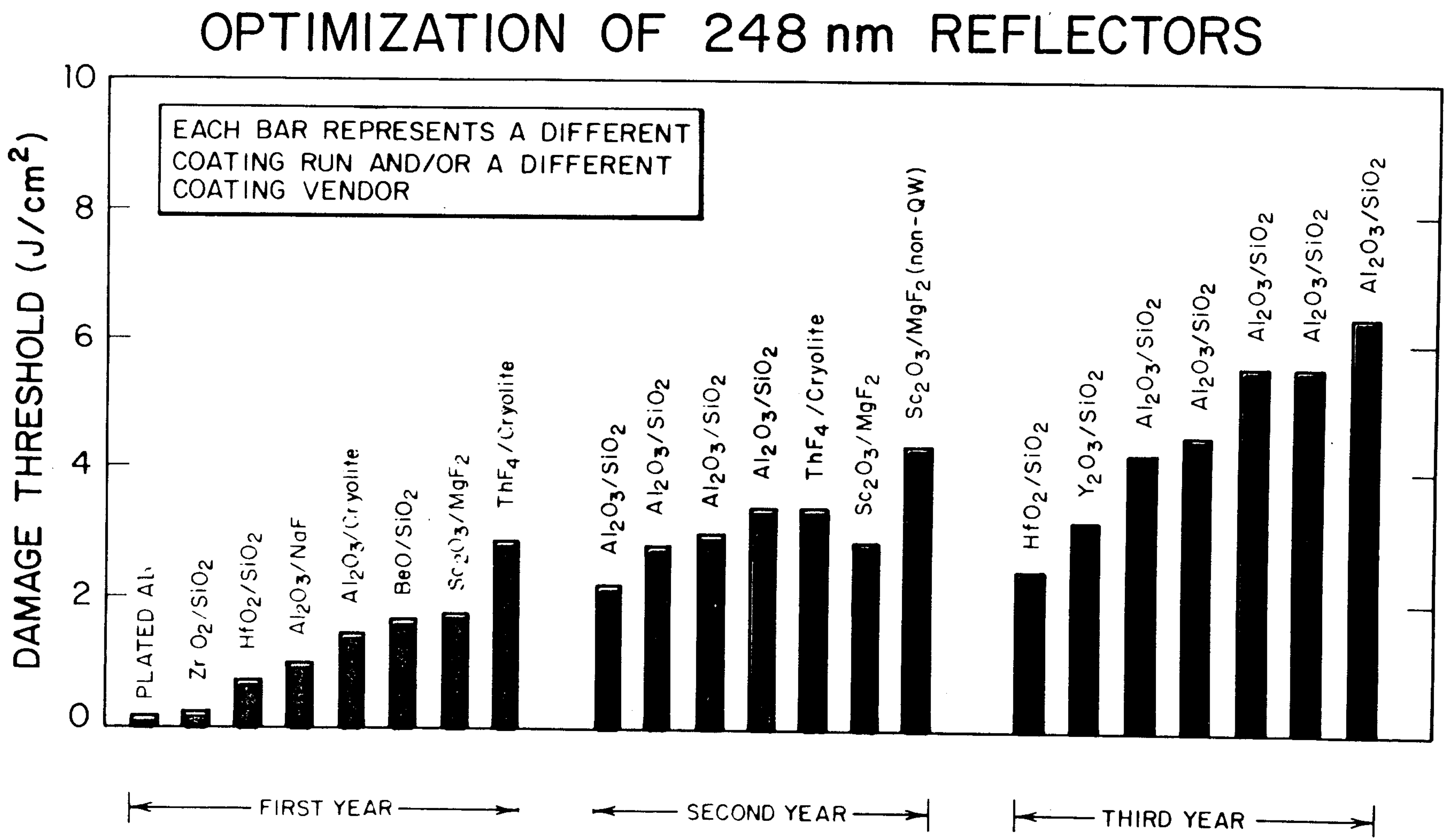


Figure 11. Much progress has been make in the area of optical coatings at 248 nm. Shown is a sample of the results for mirror coatings, indicating the rate of progress.

Because of the intrinsic efficiency of KrF gas mixtures, maximization of the pump efficiency is crucial for ICF commercial applications that require high-driver efficiencies. The pump source for KrF lasers can be divided into three areas: the Marx generator and charged-coaxial water-dielectric pulse-forming lines (PFLs); the switch, bushing, and diode; and the hibachi and foil.

The Marx generator, coaxial water PFL combination has been determined to be the best of all of the options for large, single-pulse KrF lasers with pump times less than ~ 1 μs. The Marx generator is the simplest form of energy storage but requires an intermediate energy storage stage because of the high internal inductance. Water PFLs are suitable owing to the high allowable energy density, ~ 20 kJ/m^3, the high dielectric constant, and the self-healing property of liquids. Repetitively pulsed systems may or may not use a different technology. Very little work is being done investigating these systems because of the lack of need at this time. The issue of which type of pulsed power system is best for repetitively pulsed systems is still unanswered [52].

Single-pulse e-beam devices typically use cold cathodes, which produce high-current relativistic electron beams by field emission and subsequent plasma processes. Los Alamos has investigated cathode-emitter materials for these applications. Aurora uses a graphite felt fabric. It has also been found that velvet has suitable properties. This work is ongoing.

The hibachi is used to support a foil that provides an interface between the laser gas and the vacuum diode. The goal of research in this area is to minimize the losses resulting from electrons intersecting the hibachi supports and from backscattering from the foil. Hibachi designs with smaller supports and research into foil material and thickness choices is ongoing at Los Alamos.

Design studies of advanced pulsed-power systems have also been done [22,77]. A study of the pulsed power for a 100-kJ amplifier looked at expanding-flow diodes, which appear to offer higher efficiency. These systems are currently under study at Los Alamos.

Alignment System. An innovative concept for an alignment system for KrF lasers has been developed at Los Alamos [71]. The alignment system won an *Industrial Research* "IR 100" award in 1986. The alignment system, developed for Aurora, can align 96 beams to within a pointing accuracy of 5 μrad within 5 minutes and maintain the alignment in real time. The alignment system performance is possible through a novel use of random noise.

System Studies

Los Alamos has had an ICF systems effort for many years. Currently, the main thrust is on scaling KrF lasers to higher energies at an affordable cost. Much of this work has been done and published [26]. A joint Los Alamos/McDonnell Douglas Astronautics Company study [52] developed the design for a KrF laser for ICF electric power generation shown in Fig. 12. The laser system design uses three levels: the top level for gas handling equipment such as compressors and heat exchangers; the middle level for amplifiers; and the lower level for downstream optics. The beams are directed through a neutron pinhole to reduce dose rates in the laser hall. Two issues remain to be resolved. First, the distance required from the target to the final optics (for the optics to have a sufficiently long lifetime being subjected to the target output) is unknown. Much more work is needed to determine the optical damage from the target output and possible shielding techniques. The second issue is that the illumination geometry may be narrower than currently thought required for optimum target performance. These issues will need to be addressed before commercial laser fusion becomes a reality.

One recent development is the determination that the waste heat from a KrF laser fusion driver can be recovered and used in a power plant [54]. Although a number of

KrF LASER-DRIVEN ICF POWER PLANT

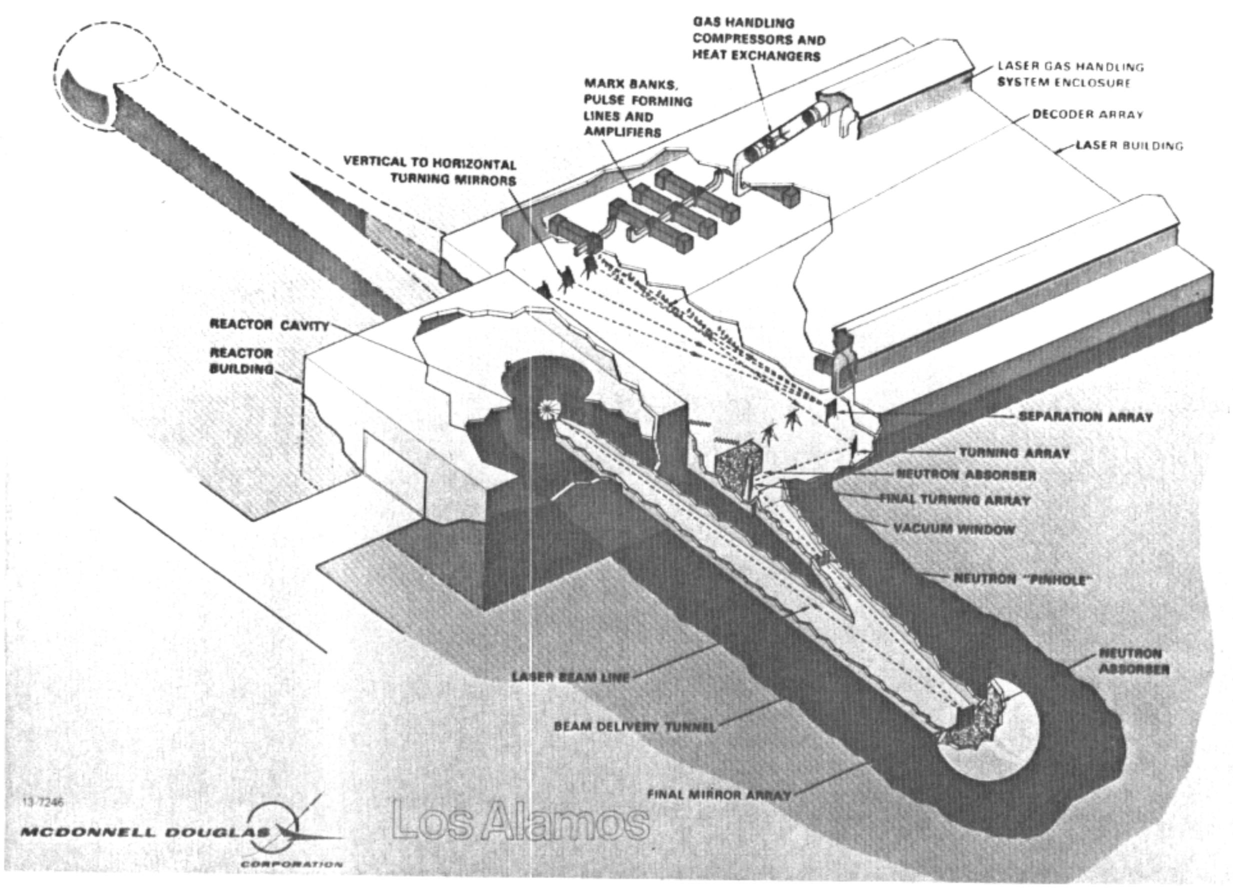


Figure 12. Conceptual design of a KrF laser appropriate for inertial confinement fusion commercial applications. The laser uses three levels. The top level encloses the gas handling equipment. The middle level contains the amplifiers, and the lower level the downstream optics. The major components of the system are shown.

applications are possible, the waste heat appears especially suitable for feedwater preheat in a power plant. This reduces or eliminates the high-temperature steam that would otherwise be diverted for this task, increasing the thermal-to-electric conversion efficiency. Because the driver deserves the credit for this improvement, an "effective" driver efficiency has been defined. For a KrF laser, this effective efficiency can be ~ 3% higher than the normal efficiency, i.e., 11% wall-plug efficiency instead of 8%. This simple concept adds more credence to the claim that KrF lasers have adequate efficiency for ICF commercial applications.

For ICF commercial applications such as electric power generation, a fuel cycle, a reactor, and a balance of plant is needed in addition to the driver (Fig. 13). Los Alamos has conducted a major review and update of projected target manufacturing processes and associated costs [28]. A review of reactor concepts can be found in References 78-80. The results of a study that included the latest cost information on the KrF lasers, targets, reactors, and a balance of plant indicate that a KrF laser-driven electric power plant is competitive in cost with other sources of electricity [26]. The breakdown of the cost of production of electricity as a function of the driver energy is given in Fig. 14. The minimum in the total COE occurs because at low driver energies, the gain is low and thus a large number of targets is needed. The cost of targets is high in this regime. Increasing the driver energy increases the driver cost but significantly decreases the cost of targets. The minimum in the cost of electricity occurs at 4 MJ and 4.5 Hz, where the cost of electricity is 31 mills/kWh for a 1000-MWe plant.

SUMMARY

Laser candidates and requirements for ICF commercial applications have been identified. A rating system has been devised that evaluates the different drivers in eight different categories. The rating system used a "+" if it is thought the laser can

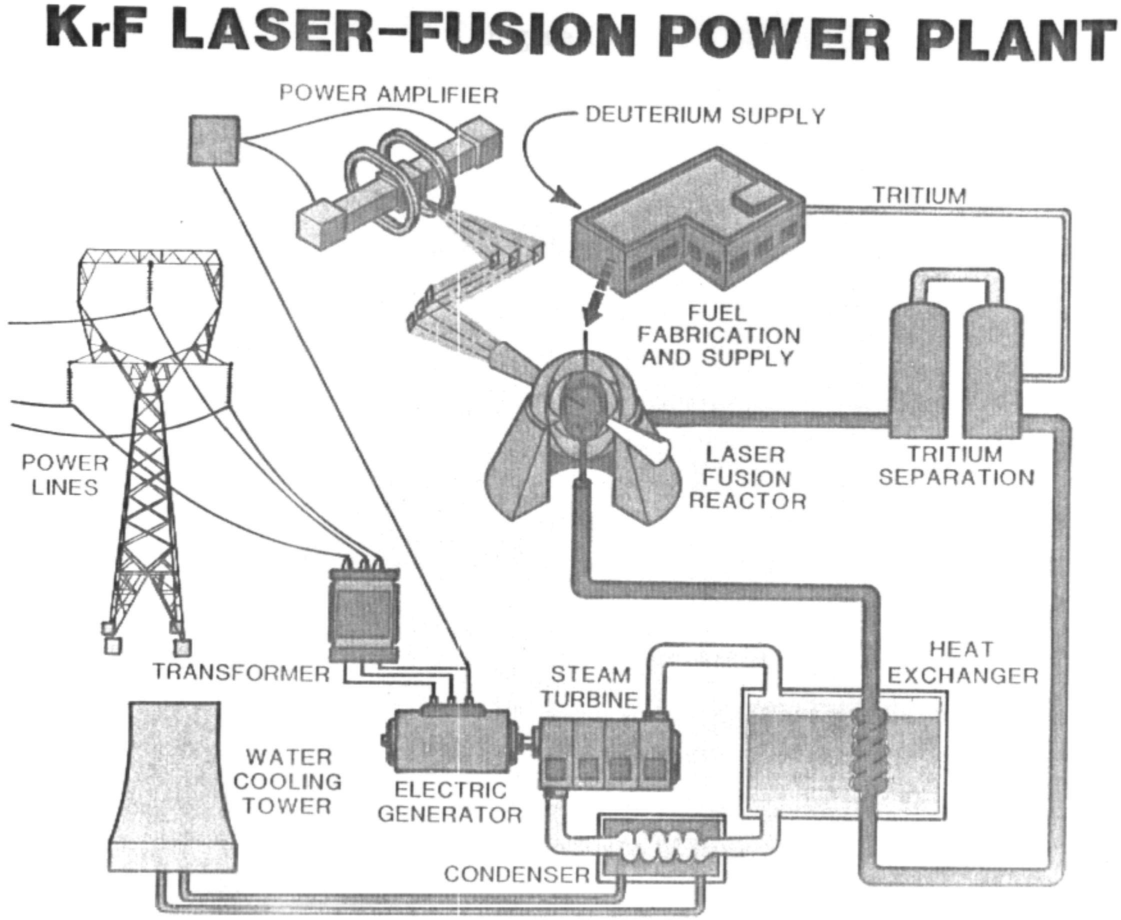


Figure 13. Systems in addition to the driver are required for inertial confinement fusion applications such as electric power productions. Los Alamos has performed studies in all of the required areas. A fuel cycle is needed to recover bred and unburned tritium and manufacture targets. A reactor is needed to contain the microexplosions and convert the target output to heat. Finally, a balance of plant is needed to turn the heat into electricity.

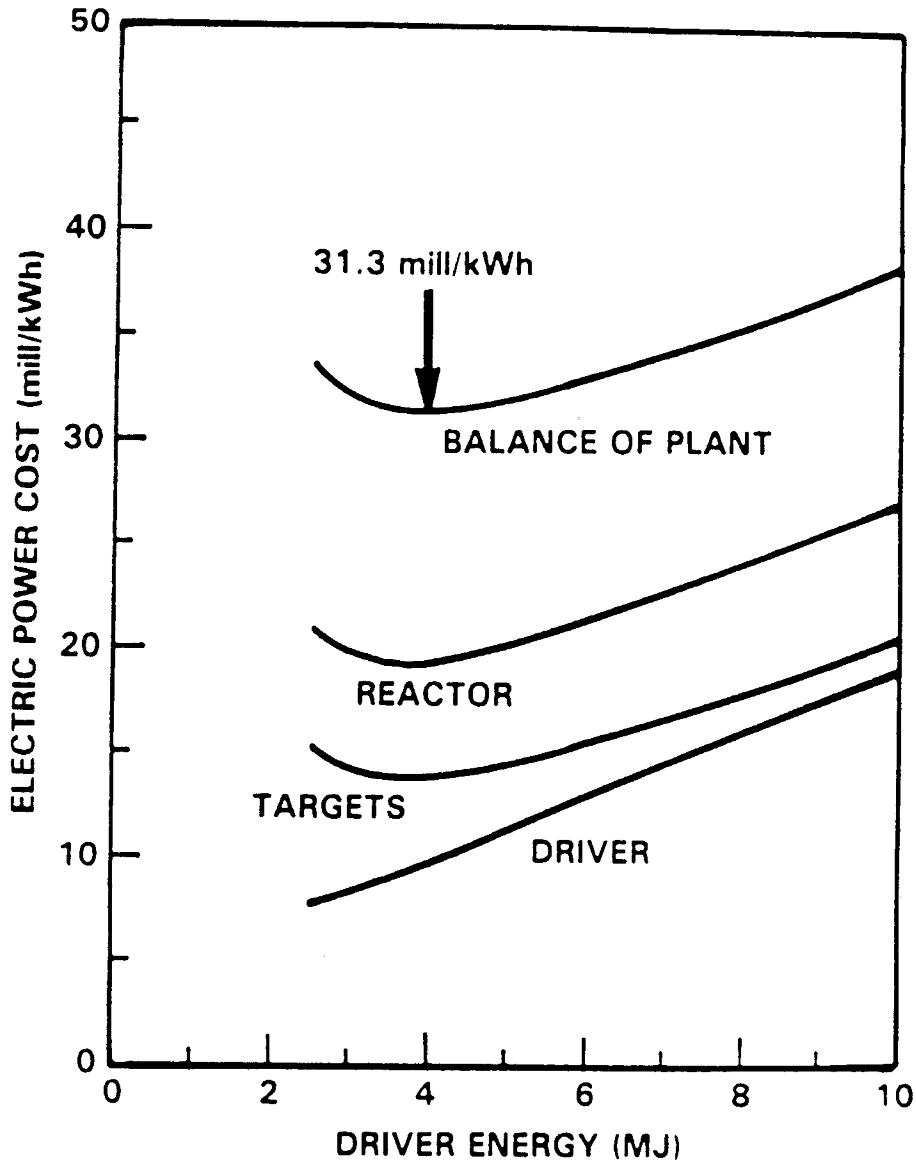


Figure 14. The electric power production cost breakdown is shown as a function of the driver energy. A minimum in the cost of electricity occurs at 4 MJ.

accomplish the requirement, a "?" if it is uncertain or unknown if the laser system can ever accomplish the requirement, and a "-" if it looks like projections for the laser indicate that it appears very unlikely that the laser will ever be able to satisfy the requirement. The categories include the driver's perceived ability to simultaneously operate at high efficiency, have a low capital cost, have good target coupling, deliver the desired pulse shape, be able to focus on the target from a long distance, operate at several pulses per second, scale to several megajoules laser output, and operate reliably and with robustness. Ultimately, if the laser system cannot satisfy all of the criteria, it will probably be eliminated. An example of this is the CO_2 laser, where it appears attractive in all areas except for target coupling because of its long wavelength. It has basically been eliminated from the U.S. ICF program.

The results of the rating indicate that the KrF laser appears to be the most attractive laser driver for ICF commercial applications. Only two lasers did not receive a "-" rating in at least one category. They are KrF lasers and iodine lasers. Iodine lasers received three "+" ratings and five "?". KrF lasers received six "+" and only two "?" ratings. Iodine lasers are being developed at Garching. Los Alamos is actively developing KrF lasers for inertial fusion.

A number of recent results and developments have continued to reaffirm our belief that KrF lasers are attractive for ICF commercial applications. The Aurora laser system will soon be operational and delivering multikilojoules of energy to a target. Aurora will demonstrate almost all of the technologies needed for a KrF fusion laser. As part of the Aurora system development, advances in alignment system technology, improvements in optical coatings to withstand higher fluences, development of low-cost mirror blanks, and improvements in pulsed power and electron-beam diodes have been accomplished. Experimentally, high intrinsic efficiencies have been measured. Additionally recent studies indicate that it will be a simple matter to propagate complicated pulse shapes through the amplifier chain. Also, system studies indicate that if the cost of optics and amplifiers can be reduced to 25% of today's cost, the cost of electricity from a KrF laser-driven power plant will be attractive.

While KrF lasers appear to be attractive for ICF applications, it should be made clear that much development is still required. Key areas of development remaining include scaling of modules to affordable sizes, optical coating studies, optical manufacturing, repetitive pulsed power development, kinetics studies, and beam propagation experiments. Additionally, development is required in the areas of low-cost ICF target mass production and ICF reactors. Los Alamos will continue to work in these areas and others.

ACKNOWLEDGEMENTS

The authors would like to thank all of the people working in the KrF program at Los Alamos. Also, much of this work would not be possible without the collaborative efforts of Spectra Technology, Inc., McDonnell Douglas Astronautics Company, Sandia National Laboratory, and Avco Everett Research Laboratory. Our appreciation also goes to Larry Blair, the Los Alamos KrF laser program manager.

Special recognition for contributions goes to Jay Ackerhalt, David Cartwright, Donald Dudziak, Charles Fenstermacher, Jack Hanlon, David Hanson, Reed Jensen, Michael Kang, Birchard Kortegaard, Norman Kurnit, John McLeod, John Pendergrass, Evan Rose, Edward Salesky, Sidney Singer, J. Allan Sullivan, and Douglas Wilson. Many others deserve our appreciation. Finally, probably everyone in the program owes thanks at one time or another to Irene Bubernak, who does many things for the program which often go without recognition.

REFERENCES

1. Comment made at the 3rd ICF Systems and Applications Colloquium, Madison, Wisconsin, 9-11 November 1987. Author wished to remain anonymous.

2. W.J. Hogan, "A Multi User Development Scenario for ICF," Lawrence Livermore National Laboratory report UCRL-93568 (October, 1985).

3. D.J. Dudziak, D.B. Harris, and J.H. Pendergrass, "Goals, Requirements, and Desirable Characteristics of the LMF Inertial Fusion Driver," 12th IEEE Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

4. R.E. Olson, "Conceptual Design of a 10 MJ Driver for a High Gain Target Development Facility (TDF)," 12th IEEE Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

5. J.H. Pitts, "Using the Nova Target Chamber for High-Yield Targets," 12th IEEE Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

6. M.T. Tobin, "Neutronics Issues for a Laboratory Microfusion Capability," 12th IEEE Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

7. W.J. Hogan, "Design Issues for a High Gain Fusion Facility: Implications of Recent Program Results," 12th IEEE Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

8. C. Orth, "Calculations of Ablated Mass and Ablation Momentum Transfer for the First Walls of ICF Facilities," Bulletin of the American Physical Society, 32, 9, 1788 (1987).

9. W.J. Hogan, "Target Chamber Design Issues for a High-Gain Inertial Fusion Test Facility," Bulletin of the American Physical Society, 32, 9, 1788 (1987).

10. D.B. Harris and D.J. Dudziak, "Major Cost Factors," Los Alamos National Laboratory report LA-UR-87-4142 (December, 1987). Prepared for inclusion in the Laboratory Microfusion Facility Phase I Final Report.

11. E.E. Stark, "The Status of Laser Drivers for Inertial Confinement Fusion," The Technology of Controlled Nuclear Fusion, Proceedings of the Fourth Topical Meeting, King of Prussia, Pennsylvania, 14-17 October 1980, p. 1373.

12. "1984 Laser Program Annual Report," Lawrence Livermore National Laboratory report UCRL-50021-84 (June, 1985).

13. W.J. Hogan, "ICF Drivers: A Comparison of Some New Entries and Old Standbys," Fusion Technology, 10, 649 (1986).

14. A.W. Maschke, "Laser Fusion/The Light That Failed," White Paper, 12 February 1979.

15. R.O. Bangerter, J.W-K. Mark, and A.R. Thiessen, "Heavy Ion Inertial Fusion: Initial Survey of Target Gain Versus Ion-Beam Parameters," Physics Letters, 88A, 225 (1982).

16. J.D. Lindl and J.W-K. Mark, "Recent Livermore Estimates on the Energy Gain of Cryogenic Single-Shell Ion Beam Targets," Lawrence Livermore National Laboratory report UCRL-90241 (February, 1984).

17. J.D. Lindl, R.O. Bangerter, J.W-K. Mark, and Y-L. Pan, "Review of Target Studies for Heavy Ion Fusion," American Institute of Physics Conference Proceedings 152, The 1986 International Symposium on Heavy Ion Inertial Fusion, Washington, D.C., 27-29 May 1986.

18. W.C. Mead and P.D. Goldstone, "Impact of Coupling Physics of ICF Driver Requirements," Los Alamos National Laboratory memorandum X-1(11/84)14, November 1984.

19. R.J. Jensen et al., "Los Alamos Krypton Fluoride Laser Program," Laser and Particle Beams, 4, 3 (1986).

20. W.J. Hogan and E. Storm, "Progress in Inertial Fusion," Lawrence Livermore National Laboratory report UCRL-92434 (1985).

21. "KrF Laser System for Inertial Confinement Fusion," Los Alamos National Laboratory report LA-UR-86-620 (February, 1986).

22. J.A. Sullivan and C.W. von Rosenberg, "High Energy Krypton Fluoride Amplifiers for Laser-Induced Fusion," Laser and Particle Beams, 4, 91 (1986).

23. A.J. Glass, "An Historic Overview of Inertial Confinement Fusion: What Have We Learned," Journal of Vacuum Science and Technology A, 4, 1098 (1986).

24. "1985 Laser Program Annual Report," Lawrence Livermore National Laboratory report UCRL-50021-85 (November, 1986).

25. J.G. Delene, G.R. Smolen, H.I. Bowers, and M.L. Myers, "Nuclear Energy Cost Data Base--A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generator Cost Analysis," U.S. Department of Energy report DOE/NE-0044/2 (March, 1984).

26. D.B. Harris et al., "Future Developments and Applications of KrF Laser-Fusion Systems," Fusion Technology, 11 705 (1987).

27. W.R. Meier, "A Standard Method for Economic Analyses of Inertial Confinement Fusion Power Plants," Fusion Technology, 10, 1557 (1986).

28. J.H. Pendergrass, D.B. Harris, and D.J. Dudziak, "Heavy-Ion Fusion Target Cost Model," Fusion Technology, 13, 375 (1988).

29. D.B. Harris, "KrF Laser-Fusion Power Plant Cost of Electricity Sensitivity to Target Cost and Gain," Bulletin of the American Physical Society, 31, 1411 (1986).

30. J.F. Holzrichter, E.M. Campbell, J.D. Lindl, and E. Storm, "Research with High-Power Short-Wavelength Lasers," Lawrence Livermore National Laboratory report UCRL-53623 (March, 1985).

31. W.J. Hogan, "Progress in the ICF Program at the Lawrence Livermore National Laboratory," Lawrence Livermore National Laboratory report UCRL-94321 (May, 1986).

32. D.J. Dudziak, W.B. Herrmannsfeldt, and W.W. Saylor, "HIFSA Heavy-Ion Fusion Systems Assessment Project, Volume I: Executive Summary" Los Alamos National Laboratory report LA-11141-MS, Vol. I (December, 1987).

33. G.H. Miley, "Review of Nuclear Pumped Lasers," Laser Interaction and Related Plasma Phenomena - Volume 6, H. Hora and G.H. Miley, eds. (Plenum Press, N.Y., 1984) pp. 47-72.

34. J.J. Ewing and C.A. Brau, "Laser Action on the Bands of KrF and XeCl," Applied Physics Letters, 27, 350 (1975).

35. G.H. Miley, "Editor's Comments," Fusion Technology, 11, 475 (1987).

36. J.H. Parks, "Conceptual Design for an Angularly Multiplexed Rare Gas Halide Laser Fusion Driver," DOE/DP/40113-1, Avco Everett Research Laboratory, 1980.

37. "Conceptual Design of a KrF Scaling Module," DOE/DP/40104, Mathematical Sciences Northwest, Inc., 1980.

38. J. Caird et al., "Conceptual Design of a 1.5-MJ, 2-Hz KrF Fusion Laser System," Lawrence Livermore National Laboratory report UCRL-53077 (1980).

39. E.T. Salesky and S. Singer, "High Efficiency KrF* Laser Using Electron Beam Sustained Discharge Pumping of KrF_2 Laser Mixtures," presented at 38th Gaseous Electronics Conference, Monterey, California, 15-18 October 1985.

40. D B. Harris et al., "KrF Lasers as Inertial Fusion Drivers," Proceedings of the 11th IEEE Symposium on Fusion Engineering, Austin, Texas, 18-22 November 1985.

41. "Drivers for Inertial Fusion Power Production," unauthored, unnumbered Lawrence Livermore National Laboratory report (March, 1985).

42. J.L. Emmett, W.F. Krupke, and J.B. Trenholme, "Future Developments of High-Power Solid-State Laser Systems," Soviet Journal of Quantum Electronics, 13, 1 (1983).

43. J.L. Emmett, W. F. Krupke, and W. R. Sooy, "The Potential of High-Average-Power Solid State Lasers," Lawrence Livermore National Laboratory report UCRL-53571 (September, 1984).

44. H. Lowdermilk, comments made at the 3rd ICF Systems and Applications Colloquium, Madison, Wisconsin, 9-11 November 1987.

45. D. Prosnitz, "High Intensity Free Electron Lasers for Inertial Confinement Fusion," Laser Interaction and Related Plasma Phenomena - Volume 6, H. Hora and G.H. Miley, eds. (Plenum Press, N.Y., 1984) pp. 193-200.

46. D. Prosnitz and R. Haas, "The Free Electron Laser ICF Driver," Transactions of the American Nuclear Society, 46, 188 (1984).

47. S. Witkowski, "Research Relevant to Laser Fusion at Garching," Nuclear Fusion, 25, 1339 (1985).

48. H.W. Friedman, "Fusion Driver Study--Final Technical Report," U.S. Department of Energy report DOE/DP/40006-1 (April, 1980).

49. C.R. Phipps, "Conceptual Design for a 100-MJ Single-Pulse Hydrogen Fluoride Laser and Fusion Target Irradiation Facility," Los Alamos National Laboratory report LA-CP-87-67 (1987).

50. M. Tanimoto et al., "Prospect of Efficient High-Power-Density Operation of KrF^*-Excimer for Fusion Driver: Characteristics in Kr-Rich Mixtures," Laser and Particle Beams, 4, 71 (1986).

51. F. Kannari, A. Suda, M. Obara, and T. Fujioka, "Theoretical Evaluation of Electron-Beam-Excited KrF Lasers Using Argon-Free Mixtures at One Atmosphere," Applied Physics Letters, 45, 305 (1984).

52. L.M. Waganer, D.S. Zuckerman, and D.A. Bowers, "KrF Laser System Studies," McDonnell Douglas Astronautics Company final report (1986).

53. D.B. Harris, L.M. Waganer, D.S. Zuckerman, and D.A. Bowers, "Conceptual Design of a Large Electron-Beam-Pumped KrF Laser for ICF Commercial Applications," Transactions of the American Nuclear Society, 52, 146 (1986).

54. J.H. Pendergrass, "Improving Inertial Confinement Fusion Power Plant and Effective Driver Efficiencies by Generating Electricity from KrF Laser Reject Heat," Fusion Technology, 11, 732 (1987).

55. D.W. Forslund, J.M. Kindel, and E.L. Lindman, "Plasma Simulation Studies of Stimulated Scattering Processes in Laser-Irradiated Plasmas," Physics of Fluids, 18, 1017 (1975).

56. K. Estabrook, W.L. Kruer, and B.F. Lasinski, "Heating by Raman Backscatter and Forward Scatter," Physical Review Letters, 45, 1399 (1980).

57. R. Jensen and P. Goldstone, "KrF for Fusion: Target and Laser Issues," Los Alamos National Laboratory report LA-UR-86-676 (1986).

58. R.H. Lehmberg and J. Goldhar, "Use of Incoherence to Produce Smooth and Controllable Irradiation Profiles with KrF Fusion Lasers," Fusion Technology, 11, 532 (1987).

59. D. Hanson and J. Ackerhalt, "Pulse Shaping and KrF as a Storage Laser: Consequences for Aurora," Los Alamos National Laboratory memorandum T-12(87)DH32 (1987).

60. P.M. Hurdle, J.H. Morris, S.C. Crow, and H.D. Hogge, "Experimental Investigation of Flow and Acoustics in Pulsed Excimer Lasers," Poseidon Research report 22 (June, 1979).

61. H.D. Hogge, S.C. Crow, J.H. Morris, and P.M. Hurdle, "Modeling and Simulation of Flow and Acoustics in Pulsed Excimer Lasers," Poseidon Research report 21 (February, 1979).

62. J.F. Holzrichter et al., "High Power Pulsed Lasers," Journal of Fusion Energy, 2, 5 (1982).

63. J.H. Lee, W.R. Weaver, D.H. Humes, M.D. Williams, and M.H. Lee, "Solar-Pumped Photodissociation Iodine Laser," Advances in Laser Science - I, eds. W.C. Stroalley and M. Lapp, Proceedings of the First International Laser Science Conference, Dallas, Texas, 1985, p. 179.

64. H. Jansen, "A Review of the Antares Laser Fusion Facility," IAEA Technical Committee Meeting on Advances in Inertial Confinement Fusion Research, Kobe, Japan, (1983) p. 284.

65. T. Willke et al., "A Plan for the Development and Commercialization of Inertial Confinement Fusion," Argonne National Laboratory report ANL-79-41 (1979).

66. L.A. Rosocha et al., "Aurora Multikilojoule KrF Laser System Prototype for Inertial Confinement Fusion," Fusion Technology, 11, 497 (1987).

67. S.J. Czuchlewski, D.E. Hanson, B.J. Krohn, A.L. Larson, and E.T. Salesky, "KrF Laser Optimization," Fusion Technology, 11, 560 (1987).

68. J. McLeod, "Output Optics for Aurora: Beam Separation, Pulse Stacking, and Target Focusing," Fusion Technology, 11, 654 (1987).

69. J.A. Hanlon and J. McLeod, "The Aurora Laser Optical System," Fusion Technology, 11, 634 (1987).

70. L.A. Rosocha and K. B. Riepe, "Electron-Beam Sources for Pumping Large Aperture KrF Lasers," Fusion Technology, 11, 576 (1987).

71. B.L. Kortegaard, "PAC-MAN, A Precision Alignment Control System for Multiple Laser Beams Self-Adaptive Through the Use of Noise," Fusion Technology, 11, 671 (1987).

72. W. Kimura et al., Spectra Technology, Inc., to be published.

73. J.J. Ewing et al., "New Techniques for KrF Fusion Laser Systems," Spectra Technology, Inc. final report (1986).

74. M.J. Shaw et al., "High-Power KrF-Laser-Pumped Raman Amplifier," presented at the Conference for Lasers and Electro-Optics, Baltimore, Maryland, 21-24 May 1985.

75. S.R. Foltyn and B.E. Newnam, "Multiple-Shot Laser Damage Thresholds of Ultraviolet Reflectors at 248 and 308 nm," NBS Special Publication 620, p. 265, U.S. National Bureau of Standards (October, 1980).

76. B.E. Newnam, S.R. Foltyn, and L.J. Jolin, "Multiple-Shot Ultra-Violet Laser Damage Resistance of Nonquarterwave Reflector Designs for 248 nm," NBS Special Publication 638, p. 363, U.S. National Bureau of Standards (October, 1981).

77. J.A. Sullivan, "Design of a 100-kJ Power Amplifier Module," Fusion Technology, 11, 684 (1987).

78. M.J. Monsler, J. Hovingh, D.L. Cook, T.G. Frank, and G.A. Moses, "An Overview of Inertial Fusion Reactor Design," Nuclear Technology/Fusion, 1, 3, 302 (1981).

79. W.J. Hogan and G.L. Kulcinski, "Advances in ICF Power Reactor Design," Fusion Technology, 8, 2A, 717 (1985).

80. "1985 Laser Program Annual Report", Lawrence Livermore National Laboratory report UCRL-50021-85 (November, 1986).

ACHIEVING ADEQUATE BEAM QUALITY FOR COMMERCIAL LASER FUSION REACTORS

S.P. Obenschain, R.H. Lehmberg, A.J. Schmitt, and S.E. Bodner
Naval Research Laboratory
Washington, D.C. 20375

INTRODUCTION

Commercial applications of laser fusion will require very high energy gain because of the inherent inefficiency of existing high power, short wavelength lasers. The pellet implosion must be highly symmetric to achieve this high energy gain; nonuniformities in the implosion velocity cannot exceed one or two per cent.[1] We will discuss techniques for obtaining the highly uniform pellet illuminations required for symmetric implosions for the case where the laser beams directly illuminate the pellet.

Achieving sufficiently uniform pellet illumination presents a major challenge for laser technology. Theoretical studies have shown that such uniformities can be achieved by overlapping a few dozen laser beams onto the pellet.[2,3,4] High illumination uniformity requires precise aiming of the beams and energy balance, but the most challenging requirement is that each of the laser beams have high focal uniformity. Unfortunately, high-power lasers have too many transmissive and reflective components to produce perfect, diffraction-limited beams; the inevitable beam imperfections distort the focal pattern and preclude uniform illumination of a target. In the last few years several laser beam-smoothing techniques have been proposed and implemented on research lasers to solve this problem, and to produce uniform illumination of targets starting with imperfect lasers. Here, we will review these beam smoothing techniques and discuss the constraints that must be placed on these techniques if they are to be implemented on commercial fusion reactors.

BEAM SMOOTHING TECHNIQUES

There is a conceptually simple way to overcome the beam uniformity problem: introduce into the laser beam large amounts of controlled "imperfections" that dominate over the uncontrolled imperfections arising from the laser system. This simple idea has led to several different optical smoothing techniques.

Figure 1 illustrates the random phase screen (RPS) technique for obtaining a smooth focal envelope.[5] In current implementations, the RPS consists of a transmissive plate that is divided into small squares or hexagons where the lateral dimensions of these elements is chosen to be small compared to the size of the phase and amplitude disturbances in the initial laser beam. The squares or hexagons are designed to randomly add a phase delay of either 0 or pi radians to the incident laser beam; hence the RPS breaks the beam into numerous beamlets that randomly differ in phase by pi. These beamlets are then overlapped onto the target by a single lens. Although the overlapped beamlets interfere to produce large amplitude modulations in the focal intensity, with numerous beamlets the envelope of the focal pattern converges on a smooth distribution determined by the diffraction pattern of the RPS elements. The short-wavelength interference pattern can be smoothed by thermal conduction in the blowoff plasma. It has been implemented on two large laser systems: The GEKKO XII laser at Osaka and more recently on the Omega laser at the University of Rochester.

Figure 2 illustrates the induced spatial incoherence (ISI) technique for obtaining smooth beams.[6] A broadband laser beam with a short coherence time ($t_c=1/\Delta\nu$) is broken up into numerous differentially delayed beamlets by a transmissive echelon; these beamlets are then overlapped onto the target by a single lens. With a narrowband laser, the beamlets would interfere and produce the same type of profile as the RPS technique. ISI eliminates this interference pattern in a time-averaged sense by arranging the differential delays between beamlets to be longer than the laser coherence time so that

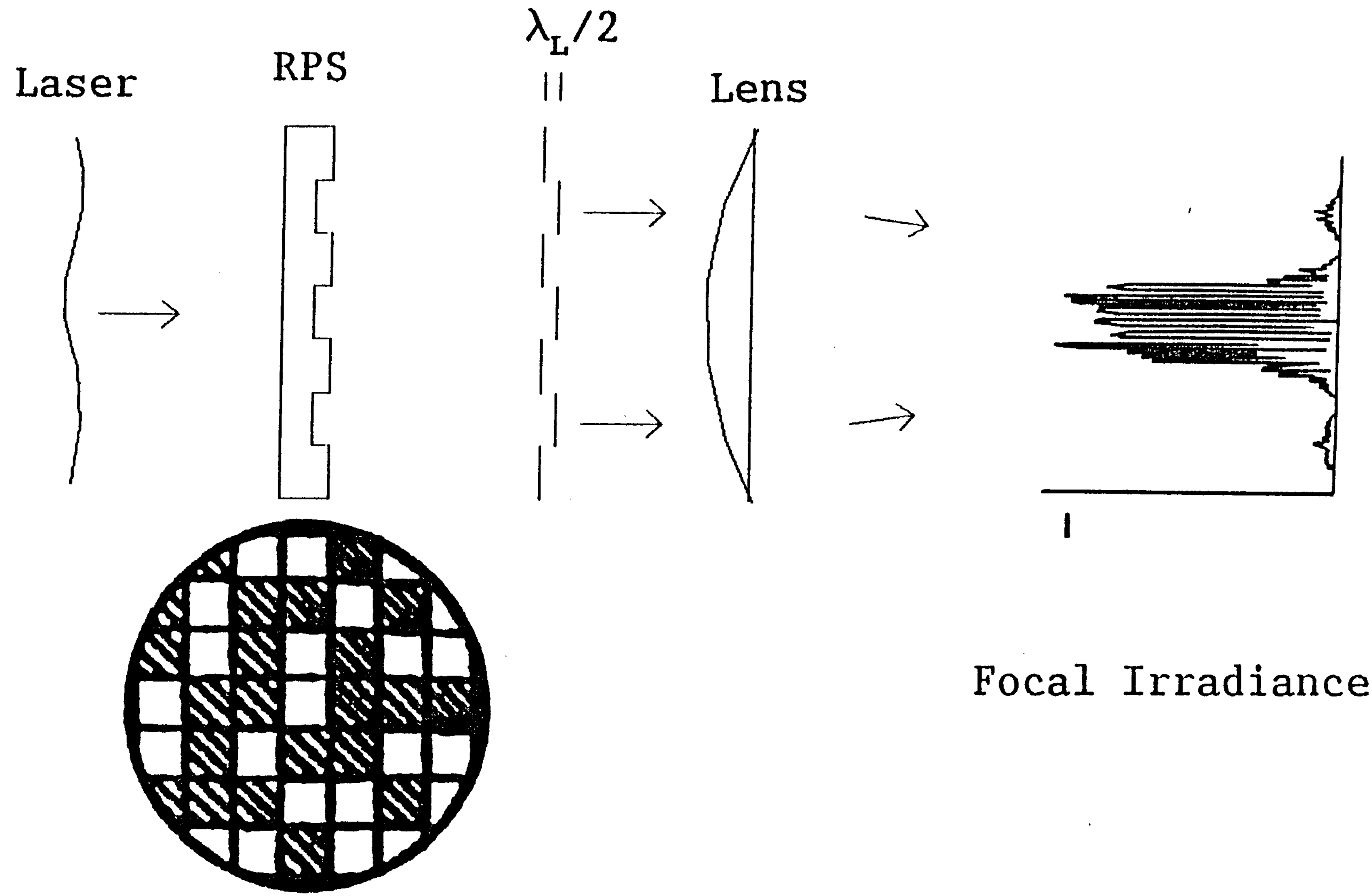


Figure 1. The random phase screen (RPS) technique for beam smoothing produces a stationary interference pattern with a smooth intensity envelope.

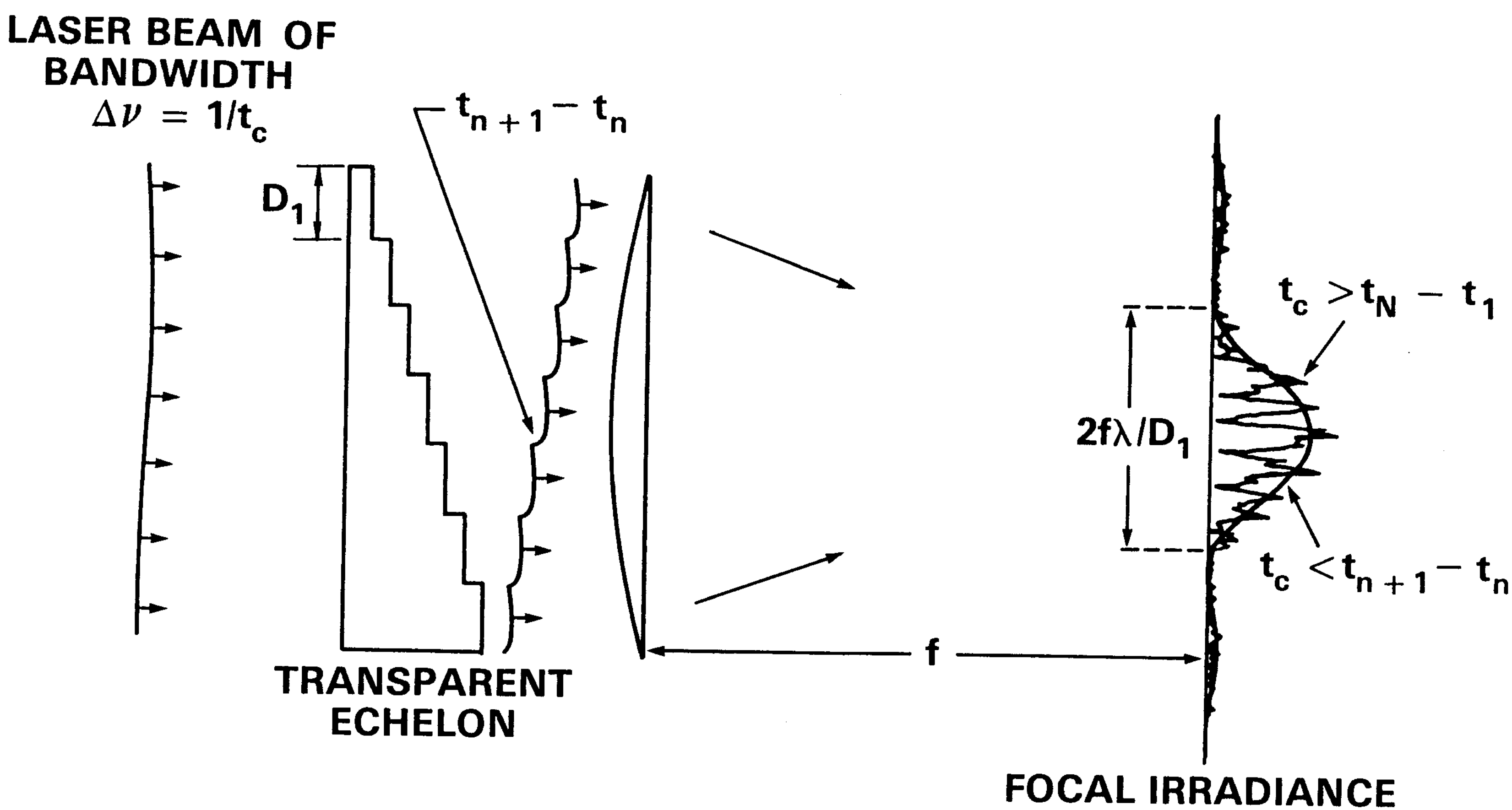


Figure 2. The induced spatial incoherence (ISI) technique for beam smoothing produces a time-varying interference pattern that approaches a smooth profile when the time averaging interval is long compared to the laser coherence time (t_C).

the beamlets are statistically independent. For this technique to benefit the implosion uniformity, t_c must be short compared to the hydrodynamic times for the pellet implosion. Current high power lasers have sufficient bandwidth to obtain $t_c<1$ psec, while the pellet implosion occurs on multi-nanosecond time scales. Implementation of ISI over both lateral dimensions of a laser beam is shown in Fig. 3. Figure 4 shows measurements of the focal uniformity obtained with and without ISI using the frequency-doubled output of one beam of the Pharos III glass laser. The improvement in focal quality with ISI is obvious; the ISI pattern approaches the ideal predicted by theory.

An echelon-free ISI scheme is illustrated in Fig. 5. The aim of this technique is to obtain a beam whose focal properties are determined by spatial incoherence as in ISI, but without the echelons.[7,8] In the configuration shown in Fig. 5, the beam from a broadband, spatially-multimode oscillator uniformly illuminates a filter. The intensity profile of the filter is then imaged onto the target through the amplifier system. The optical information required to produce the focal pattern is carried through the system in small coherence zones. If the laser does not significantly distort these coherence zones, the image on the target will faithfully reproduce the pattern determined by the filter. This technique has been successfully demonstrated on a small KrF laser,[7] and is now being implemented on a few-kilojoule KrF laser at NRL.

The constraints on the laser increase as one changes from RPS, to ISI, to echelon-free ISI. The RPS technique only requires that the laser beam be near perfect on the spatial scale of the small diffraction elements of the screen. It is applicable to all currently used lasers including Nd-glass, the second, third and fourth harmonics of Nd-glass, iodine, and KrF. The ISI technique has the same constraint, plus the need for broad laser bandwidth. This restricts the list of lasers to Nd-glass, its second harmonic, and KrF. Existing harmonic generation crystals have too much color dispersion to efficiently produce the third and higher harmonics of Nd-glass with broad bandwidth. The

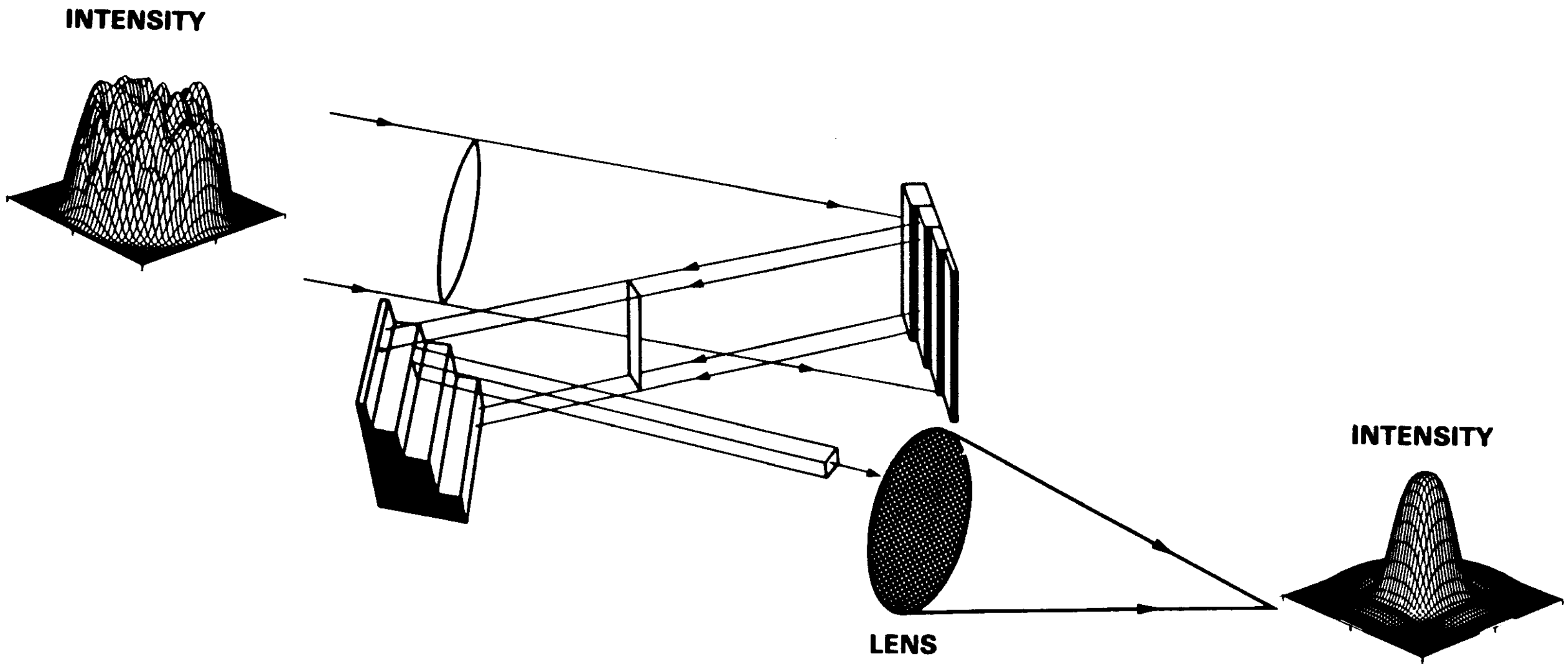


Figure 3. A pair of reflecting ISI echelons are shown here producing a 2-dimensional array of beamlets.

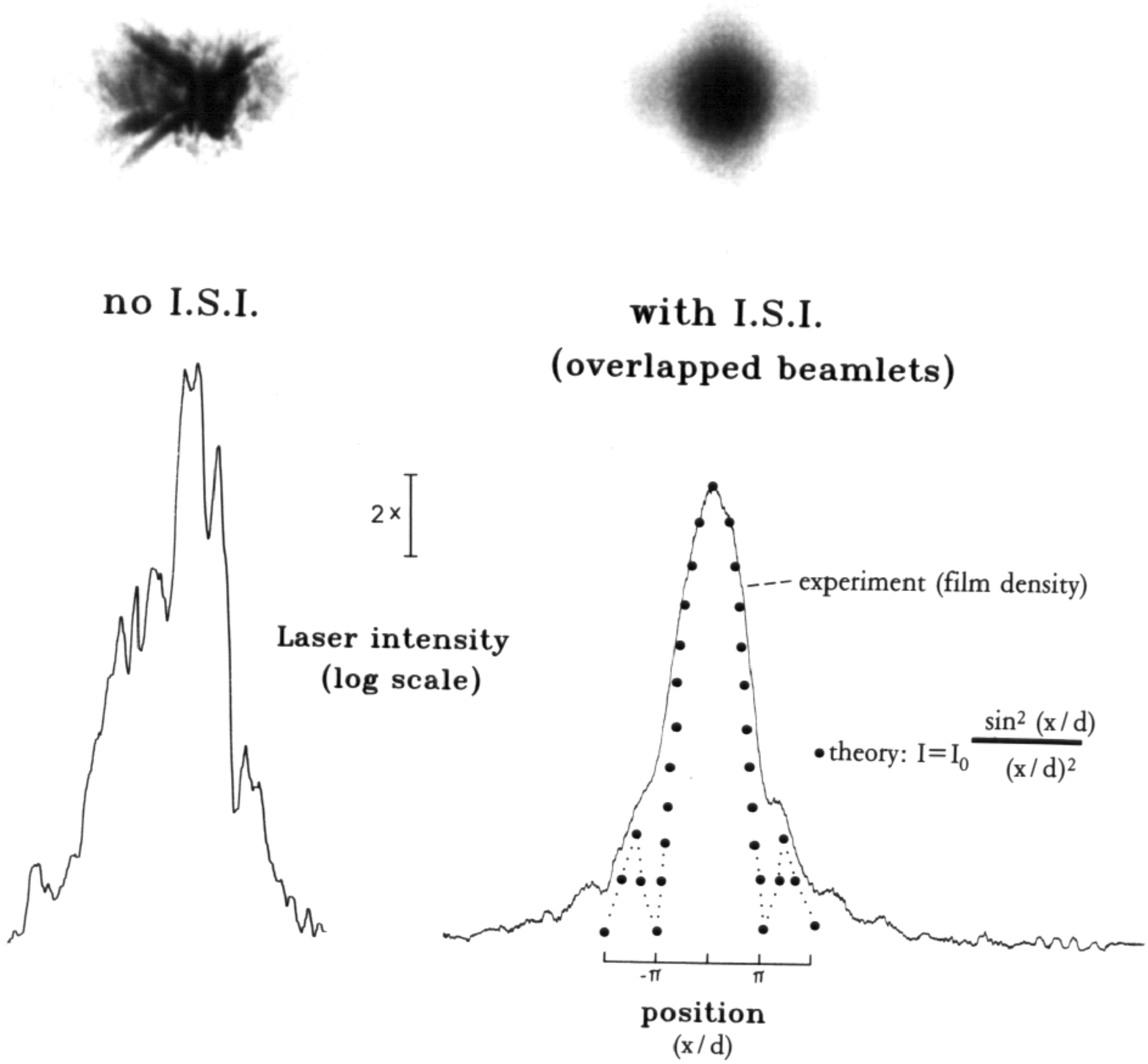


Figure 4. Measured focal distributions, with and without ISI, on the NRL Pharos III laser.

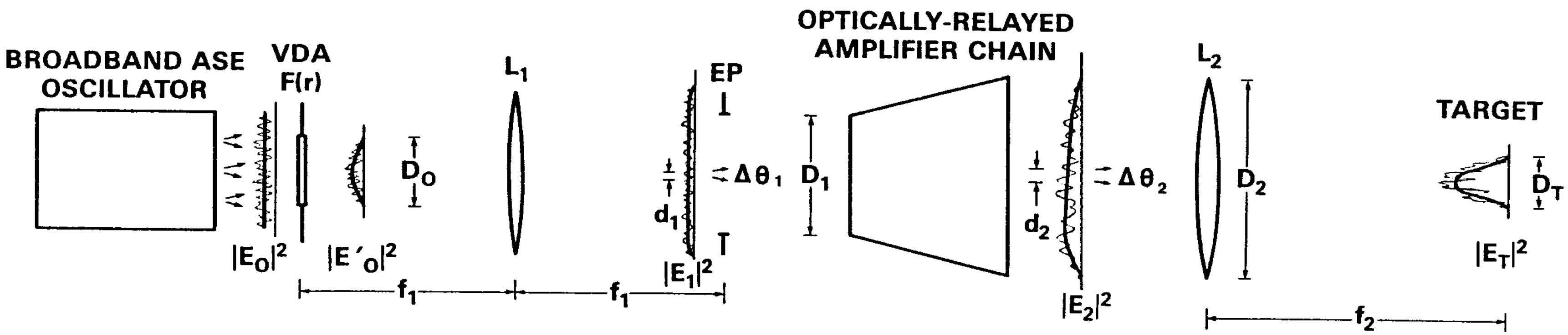


Figure 5. Echelon-free ISI images the smooth pattern produced by the variable density filter (VDA) through the laser system and onto a target. The fine line profiles show typical instantaneous intensities, while the heavy lines show the time averaged intensities. Beam relaying through the amplifiers is helpful in obtaining a replica of the VDA pattern on target, but design studies at NRL indicate that relaying is not absolutely required for angularly multiplexed KrF lasers.

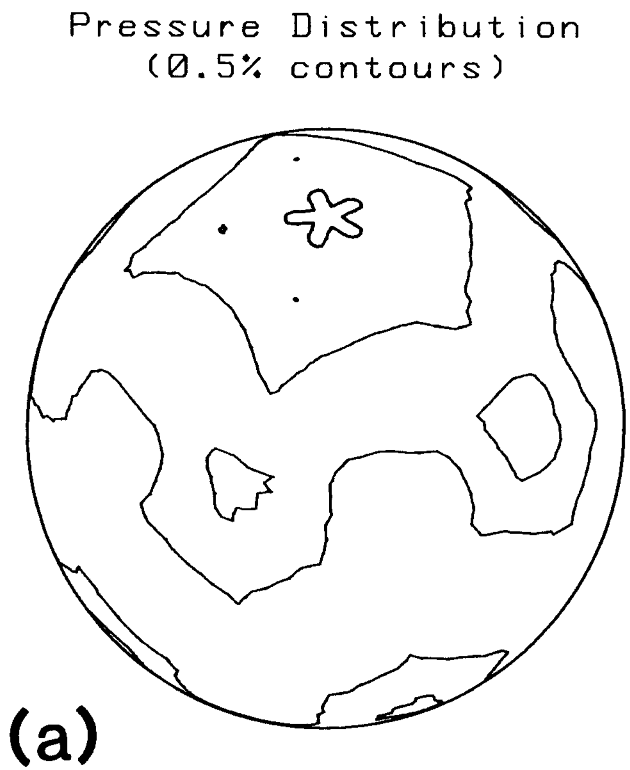
additional constraints on the laser for the echelon-free ISI have been studied in detail. The major restriction is that the nonlinear phase shifts must be small. This limits echelon-free ISI to systems where the nonlinear index of the gain media is small and the peak power loading on the transmissive optics is low. Of the above list of lasers, this last constraint is only satisfied by angularly-multiplexed KrF systems.

Finally, there are three other techniques for beam smoothing that do not rely on spatial incoherence. Arrays of lenses placed in the laser beam have been used to smooth the focal profile.[9] This technology is probably not applicable to commercial fusion reactors and is discussed briefly in appendix A. Two other schemes use nonlinear optical techniques (phase conjugation and Raman beam cleanup) to create a nearly diffraction-limited beam. Calculations indicate that these approaches would have difficulty in achieving a sufficiently uniform target illumination.[10]

CONSTRAINTS ON BEAM-SMOOTHING TECHNIQUES FOR COMMERCIAL REACTORS

The commercial reactor application places several additional constraints on the beam smoothing technologies. First, the final focusing optics must subtend a small fraction of the solid angle surrounding the target. This implies the use of large f-number final focussing optics. Second, for the case of high-gain directly-illuminated pellets, the smoothing technique must be able to produce 1% or better ablation pressure uniformity. Third, the smoothed beam must have acceptably benign effects on the interaction physics. Finally, the costs of implementing the technology must match the benefits. The remainder of this paper will deal with how the various beam smoothing techniques meet these constraints.

Figure 6 shows the calculated pressure contours and harmonic coefficients obtained for a reactor-sized pellet illuminated by thirty-two laser beams.[4] The laser wavelength



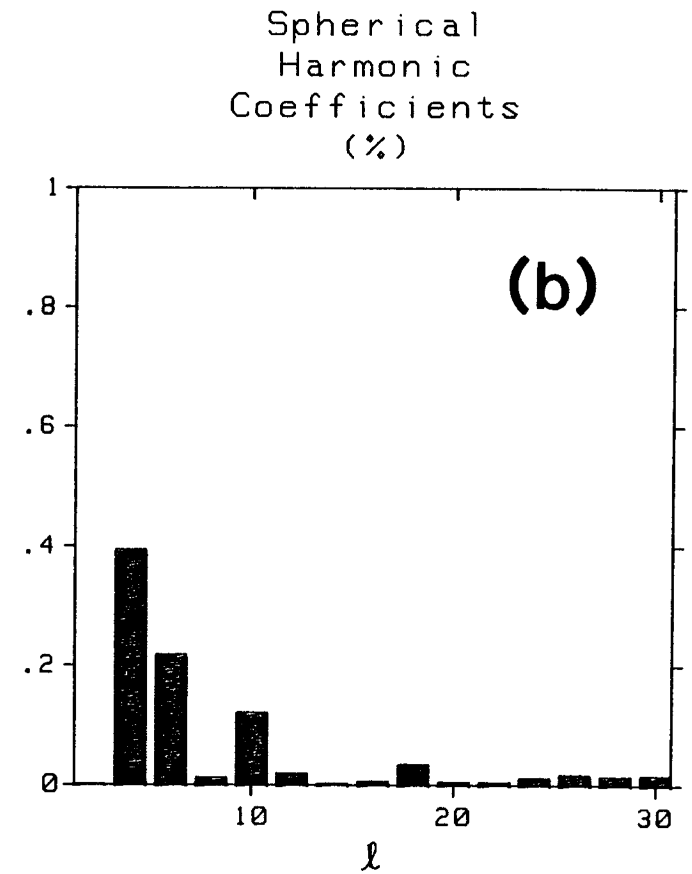


Figure 6a. Contour plots of the pellet's ablation pressure distribution when illuminated by 32 beams with a quadrature ISI profile.

Figure 6b. Harmonic coefficients of the pressure distribution as a function of mode number.

is 250 nm and the focal profile was chosen to match a quadrature overlap envelope that can be achieved by either ISI or RPS.[10] Good ablation pressure uniformity can be produced with harmonic coefficients well below 1%. These calculations dealt only with the envelope of the focal distributions. The question of whether the beam smoothing techniques can produce uniform enough focal distributions will be discussed below.

Figure 7 shows the fraction of solid angle subtended by the final focussing optics as a function of f-number, for the case of 32 beam illumination of a pellet. The fraction of solid angle subtended by the optics falls below 1% for an f-number>14. One would probably want f-numbers substantially larger than this, for fixed optical surface area, in order to limit neutron damage to the optics.

The focal spot diameter at the target for either ISI or RPS is determined by diffraction of the beam and is proportional to the f-number of the final focussing optic and inversely proportional to the the diffractive element (beamlet) diameter. Thus with either RPS or ISI one can choose from a range of combinations to obtain the desired focal envelope; e.g. fewer beamlets and larger f-numbers or more beamlets and smaller f-numbers. There are differences in wavelength of the interference pattern within the envelope as these parameters are varied. The interference pattern is concentrated at higher spatial frequencies with lower f-numbers; it can therefore be smoothed more effectively by lateral energy flow in the blowoff plasma. The following equations describe the ablation pressure nonuniformity due to this interference pattern as a function of f-number for the case of RPS and ISI:[10]

Eq. 1. $$\frac{\Delta P_{rms}}{P} \simeq \frac{\lambda_L \cdot F\#}{4.4 \cdot S} \quad \text{(with RPS)}$$

Eq. 2. $$\frac{\Delta P_{rms}}{P} \simeq \left(\frac{t_c}{\tau}\right)^{1/2} \cdot \left(\frac{\lambda_L \cdot F\#}{4.4 \cdot S}\right) \quad \text{(with ISI)}.$$

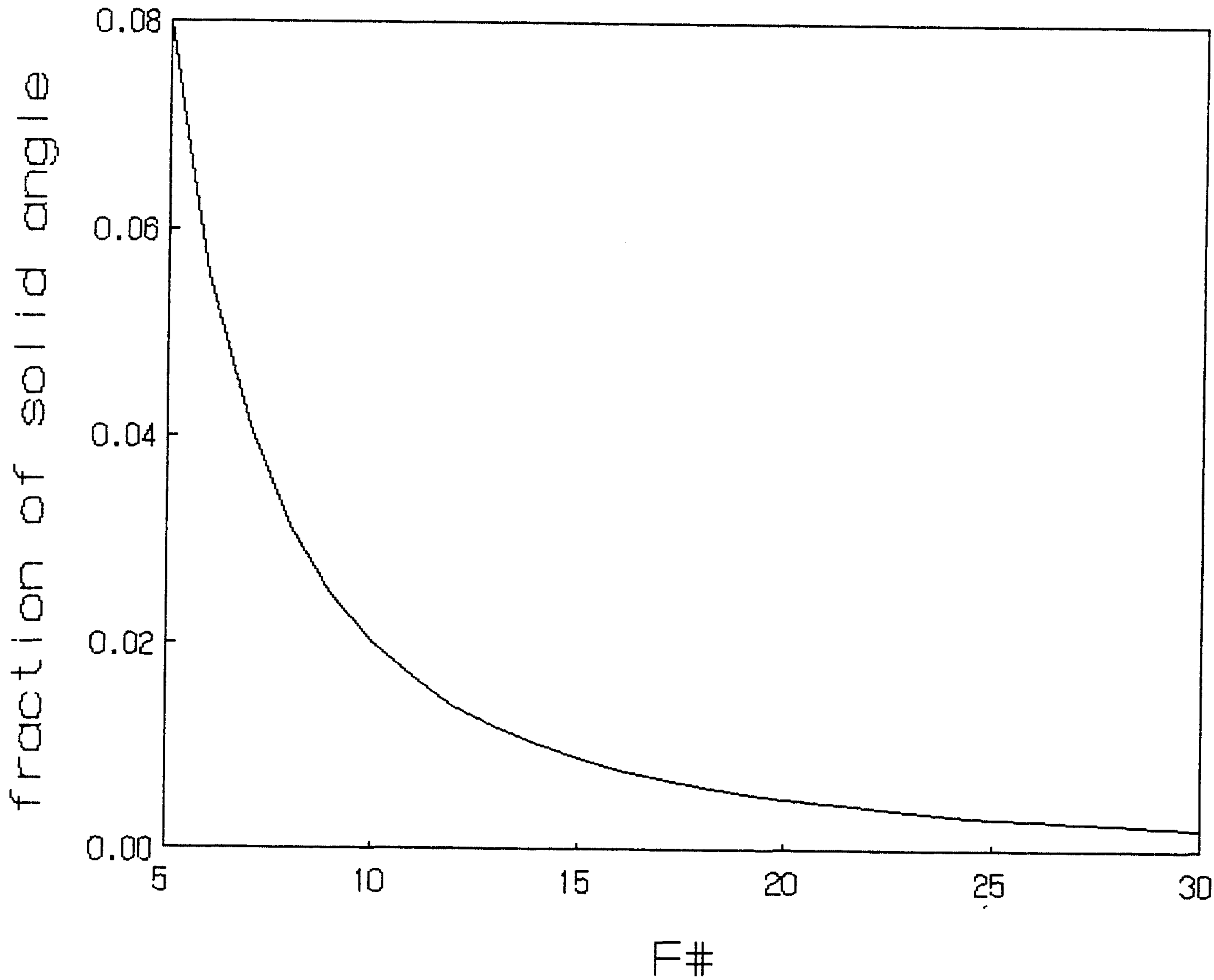


Figure 7. Fraction of solid angle subtended by 32 beams illuminating a pellet as a function of f-number.

Here S is the separation between the absorption and ablation regions which produces lateral smoothing of pressure variations for both RPS and ISI. The extra term in Eq. 2 accounts for temporal smoothing over the averaging interval τ. (ΔP_{rms} is thus a time averaged quantity in Eq. 2.) For λ_L=250 nm illumination of a pellet, NRL computer simulations predict an absorption-ablation separation of approximately 25 μm. If τ=400 ps, t_c=1 ps, and f-number=60, Eq. 2 predicts a 0.6% RMS nonuniformity. The RPS scheme requires f-number=3 to obtain the same level of uniformity; it cannot achieve low-ablation-pressure nonuniformity with high f-number focussing optics.

The laser-plasma interaction physics differs from an ideal beam because of the stationary short scalelength nonuniformity with RPS and because of the instantaneous nonuniformity with ISI. One instability of particular concern is filamentation. Hot spots in the laser beam can expel plasma and thereby increase the refractive index in the center of the hot spot. This phenomenon can have the effect of concentrating the hot spot to still higher intensity. This filamentation is particularly likely to occur with high f-number optics where the focal hot spots will have relatively long axial extents. Filamentation can produce very high laser intensities that can then excite other undesirable instabilities. Figure 8 shows the calculated intensity distributions obtained at half-critical density for the cases of ISI, and of an ordinary laser beam with an initially 25% rms amplitude nonuniformity. The ordinary laser beam nonuniformities are enhanced by several orders of magnitude, while the ISI beam shows a much smaller effect. A detailed computer study has shown that the combination of temporal and spatial smoothing of nonuniformity that is obtained with ISI suppress filamentation, provided the laser coherence time is short compared to the growth time of filamentation. Coherence times of a few picoseconds were adequate for this suppression in the simulations.[11]

RPS has a stationary interference pattern that can more easily seed filamentation. Figure 9 shows 2-dimensional calculations of the enhancement of the intensity for

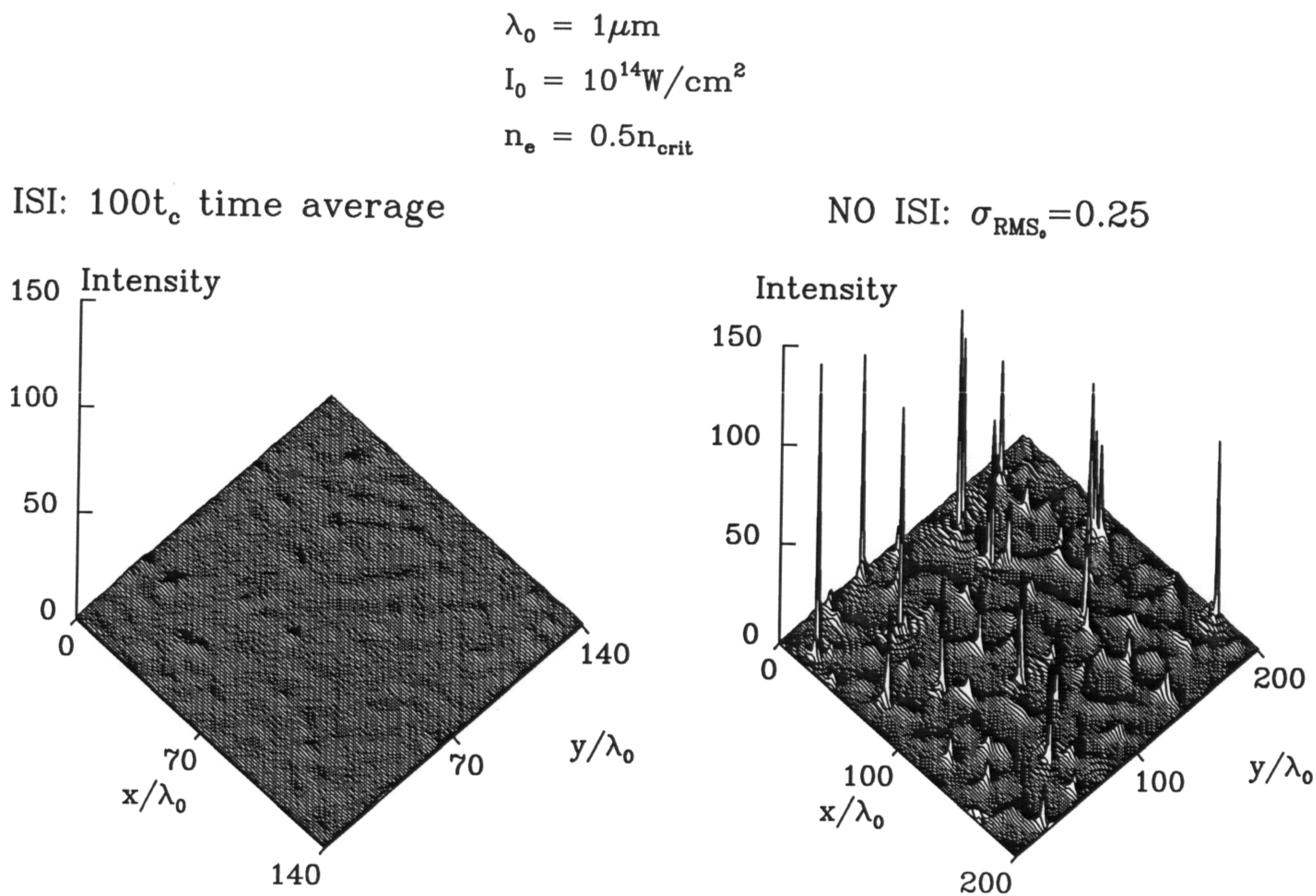


Figure 8. Calculated laser intensity distributions obtained with and without ISI at half-critical density. The ordinary beam with an initial 25% RMS amplitude modulation shows severe filamentation, while the ISI beam shows virtually no filamentation.

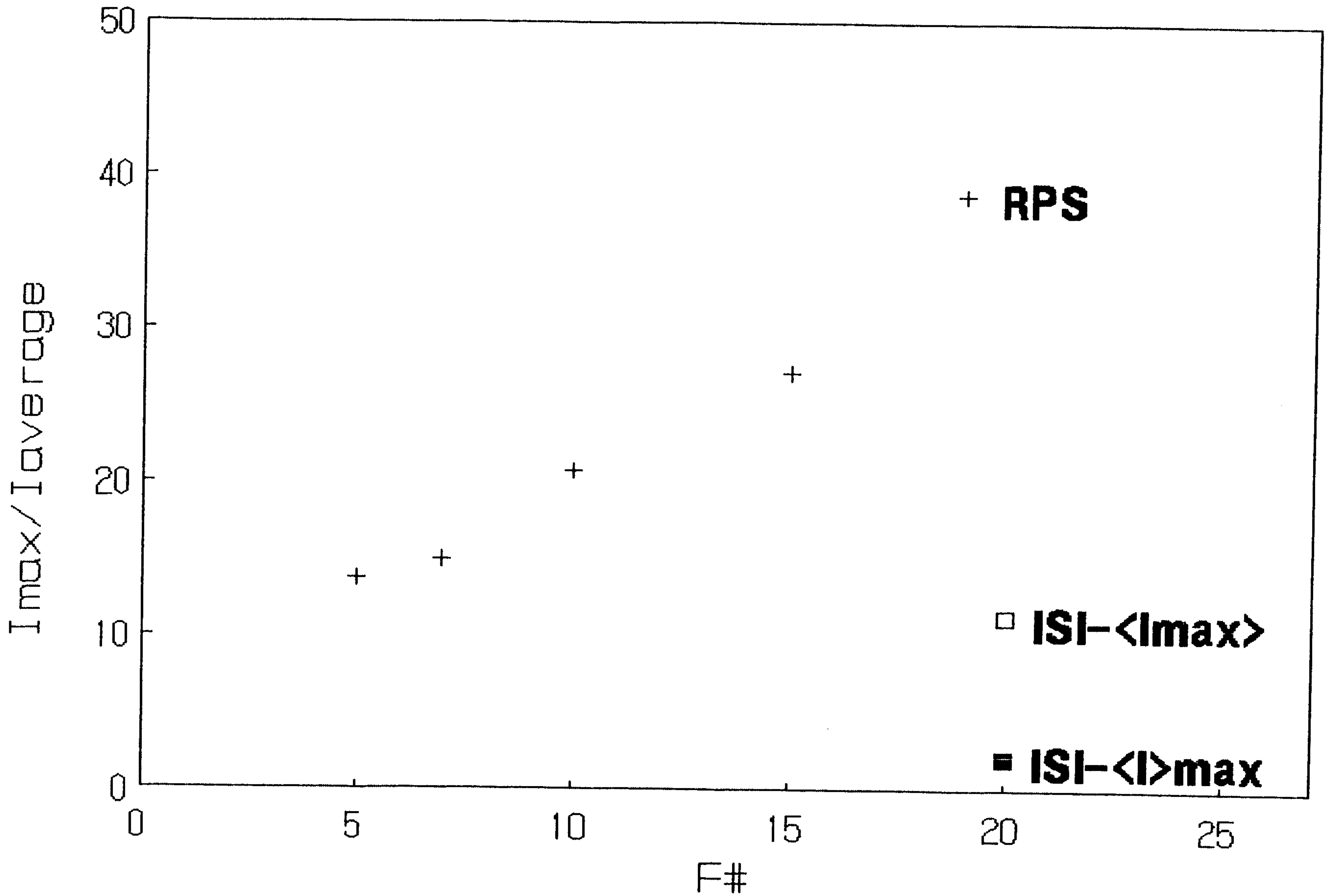


Figure 9. Comparison of the maximum intensity achieved inside the blow-off plasma as a function of lens f-number.

the case of RPS and ISI as a function of f-number. At lower f-numbers the enhancement in intensity is small even with RPS. However at large f-numbers where the interfering beamlets are nearly parallel as they approach the target, filamentation enhances the peak intensities with RPS much more than with ISI.

We have carried out experimental studies of the effects of ISI on laser-plasma interaction. Figure 10 shows the Raman scattering obtained in a laser-target interaction experiment with λ_L=1053 nm and f-number=11 for the cases of an ordinary laser beam, an ISI smoothed laser beam, and a narrowband laser beam with the ISI echelons. The last case simulates a coarsely gridded RPS. The Raman scattering was largest for the case of RPS and smallest for the case of ISI. We believe that this effect occurs because ISI suppresses filamentation, thereby suppressing the filamentation-enhanced Raman scattering. We have also observed that ISI suppresses other undesirable plasma instabilities.[12,13]

CONCLUSIONS

A commercial reactor must have final focussing optics with high f-number; this limits the beam-smoothing techniques to schemes that utilize both temporal and spatial averaging, such as ISI or echelon-free ISI. RPS, which utilizes spatial smoothing only, needs low f-numbers to obtain the ultra-uniform illumination required for high gain. RPS probably also requires low f-numbers to avoid deleterious instabilities in the laser-plasma interaction.

The main conclusion of this paper is that both spatial and temporal beam-smoothing are required for the commercial application of laser fusion. Of the currently available technologies, echelon-free ISI is probably the best choice. It eliminates the cost and complication of having echelons on numerous beams, and it offers the greater flexibility towards obtaining arbitrary focal patterns, including the capability of zooming the focus to follow an imploding pellet.

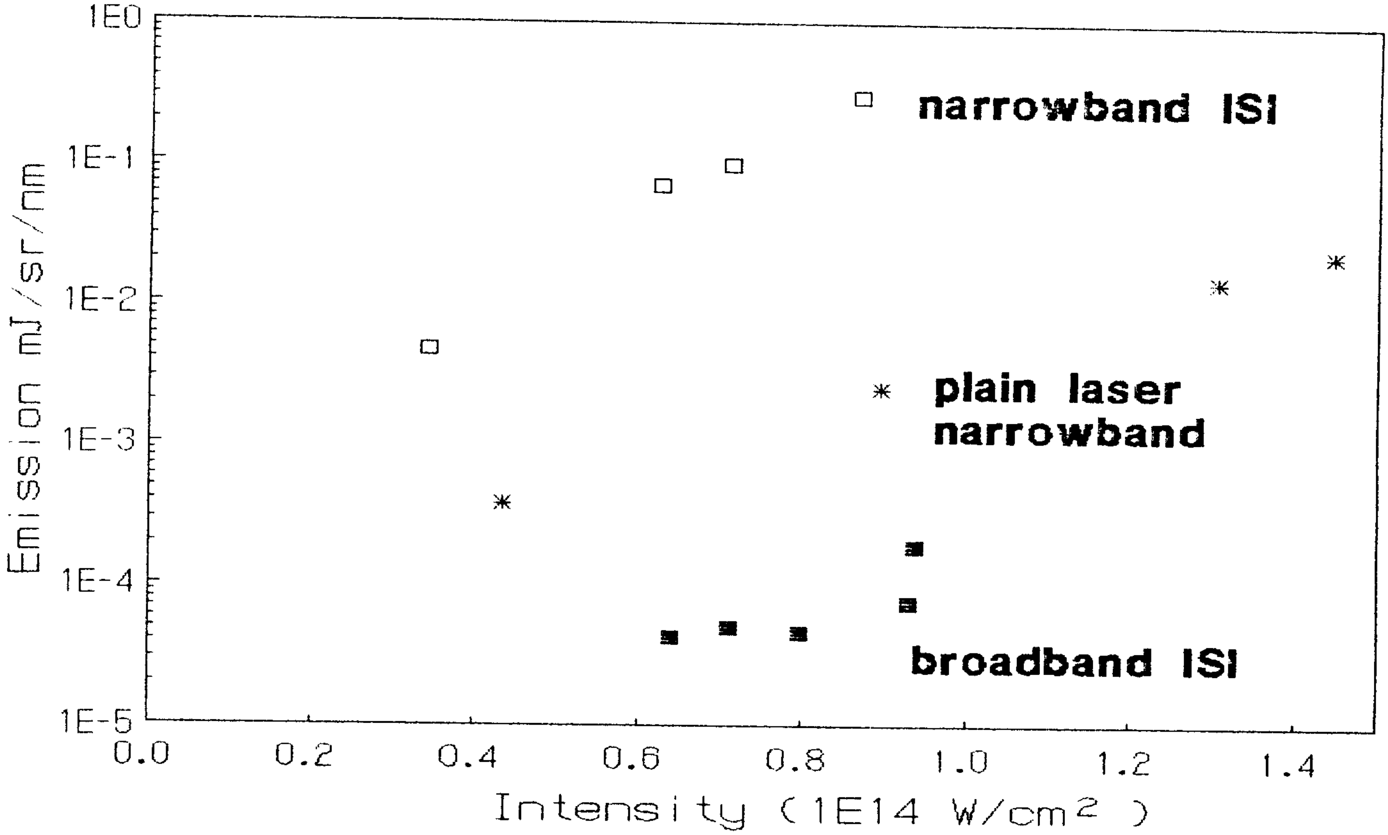


Figure 10. Raman emission (near 1.6 λ_L) from a laser irradiated target with ISI, with an ordinary laser beam, and with the echelons but with a narrow-bandwidth laser.

APPENDIX-A

The RPS and ISI techniques rely upon diffraction of many beamlets to produce a controlled, uniform focal distribution, with the target placed in the far-field of the focussing optic. An alternate strategy is to break the laser beam into numerous parallel beamlets which are individually diverging or converging by means of a lens array.[9] A second lens is then used to overlap the beamlets in the quasi-near field, thereby producing an averaging effect. The interference pattern among the overlapped beamlets can be eliminated by using a broad-bandwidth laser and arranging for differential delays among the beamlets, as in ISI. The edges of the lens array elements introduce diffraction ripples in the intensity at the target, but this could be remedied to some extent by placing soft-aperture edges on the lenses.

We have begun implementation of an alternate lens array scheme as illustrated in Fig. 11 which is optimized for use on a KrF laser. Here the lens array is illuminated by a spatially incoherent laser whose coherence zones are much smaller than the lens elements, but where the divergence introduced by the lens elements is larger than the divergence determined by the spatial incoherence. The spatial incoherence ameliorates the effects of diffraction by the lens array edges. The spatial incoherence should also make it easier to obtain a fairly uniform beam at the lens array, and thereby produce a more uniform quasi-near field focus for the individual beamlets. This technology can provide highly-uniform top-hat-shaped profiles at the target and should therefore be useful for near-term experiments using planar targets.

There are two serious limitations to the application of the lens array technique in a commercial fusion reactor. First, the lens array requires lower f-number final focussing optics than ISI because the target must be placed in the quasi-near field of the lens array elements. Secondly, the lens array cannot produce the shaped focal profiles that are preferred to obtain the best uniformity on spherical targets.

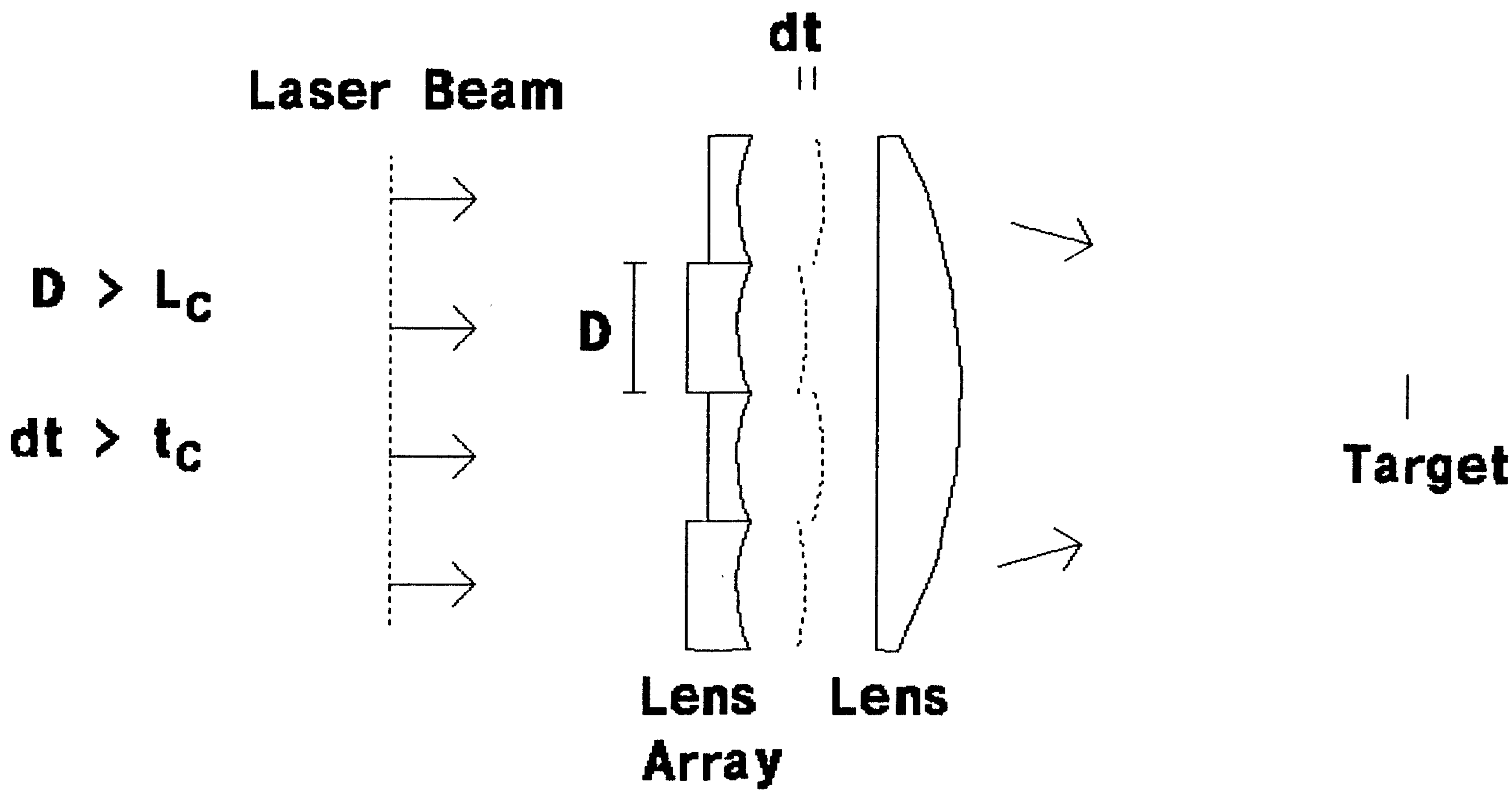


Figure 11. Lens array scheme for obtaining uniform illumination using a laser with a short coherence time (t_c) and a short lateral-spatial-coherence length (L_c). This technique is described in Appendix A.

REFERENCES

1. S.E. Bodner, J. Fusion Energy 1, 221 (1981).

2. S. Skupsky and K. Lee, J. Appl. Phys. 54 371 (1983).

3. J.E. Howard, Appl. Opt. 16, 2764 (1977).

4. A.J. Schmitt and J.H. Gardner, J. Appl. Phys. 60, 6 (1986).

5. Y. Kato, K. Mima, M. Miyanaka, S. Aringa, Y. Kitagawa, M. Nakatsuka, and C. Yamanaka, Phys. Rev. Lett. 53, 1057 (1984).

6. R.H. Lehmberg and S.P. Obenschain, Opt. Commun. 46, 27 (1983).

7. R.H. Lehmberg and J. Goldhar, Fusion Technol. 11, 532 (1987).

8. Somewhat similar techniques but applied to glass lasers are discussed in the following references. These techniques only work with small f-number optics in order to suppress filamentation in the laser. H. Schonnagle, H. Gunkel, and J. Grzanna, Lasers and Particle Beams 4, 453 (1986); V.V. Alexandrov, M.V. Brenner, S.V. Loburev, N.G. Koval'skii, and A. Rubenchik, Sov. J. Quantum Electron. 16, 443 (1986); D. Vernon, H. Ayral, C. Gonedard, D. Husson, J. Lauiou, O. Martin, B. Meyer, M. Rostaing, Opt. Commun. (in press).

9. Ximing Deng, Xiangchun Liang, Zezun Chen, Wenyan Yu, and Renyong Ma, Applied Optics 3, 377 (1986).

10. R.H. Lehmberg, A.J. Schmitt and S.E. Bodner, J. Appl. Phys., 62, 2680 (1987).

11. A.J. Schmitt (to be published Phys. of Fluids).

12. S.P. Obenschain, J. Grun, M.J. Herbst, K.J. Kearney, C.K. Manka, E.A. McLean, A.N. Mostovich, J.A. Stamper, R.R. Whitlock, S.E. Bodner, J.H. Gardner, and R.H. Lehmberg, Phys. Rev. Lett. 56 2807 (1986).

13. A.N. Mostovych, S.P. Obenschain, J.H. Gardner, J. Grun, K.J. Kearney, C.K. Manka, E.A. McLean and C.J. Pawley, Phys. Rev. Lett. 59, 1193 (1987).

PULSED POWER DRIVER TECHNOLOGIES FOR INERTIAL CONFINEMENT FUSION POWER REACTORS*

D.L. Cook
Sandia National Laboratories
Albuquerque, New Mexico

ABSTRACT

Pulsed power technology offers an efficient, low-cost, and repetitive means for generating intense light ion beams for Inertial Confinement Fusion (ICF). The technology produces a beam that couples well to matter and is scalable to very high power levels. The basic elements of pulsed power technology include capacitive energy storage, water dielectric pulse formation, vacuum inductive voltage adding, liquid metal and liquid dielectric ion sources, extraction ion diodes, plasma propagation channels, ballistic ion bunching, and gas-filled target chambers. Many of these technologies are applicable not only to production of intense light ion beams, but also may be useful for production of intense heavy ion beams and middleweight ion beams. These emerging technologies form the basis for flexible driver systems for powering inertial confinement fusion reactors in the next century.

INTRODUCTION

ICF drivers for power reactors face stringent requirements. These requirements are shown in Table 1.

---

*This work supported by the U.S. Department of Energy under Contract DE-AC04-76DP00789.

Table 1

Requirements of ICF Drivers for Power Reactors

10-20 MJ energy on target

> 10% efficiency

> 100 TW/cm^2 power concentration

Adequate pulse shaping

Energy deposition without fuel preheat

1 to 5 Hz pulse repetition rate

10^9 shot lifetime

< $500 million cost

Brief justification for each of these requirements is given below.

1. 10 to 20 MJ of Energy on Target

The present theoretical and experimental database for target behavior indicates that from 10-20 MJ of driver energy must be delivered to the target in order to drive a high-gain implosion. This range of driver energies is relatively independent of the type of driver.

2. > 10% Efficiency

Power reactor economics requires that the recirculating fraction of power in a reactor system be < 25%. With a plant thermal efficiency of 33%, this requirement establishes a minimum level of the product of driver efficiency and target gain equal to 12. If the yield from the target explosion is constrained to be not much larger than 1 GJ (i.e., gain of 100 with 10 MJ on target), then driver efficiency must exceed 10%.

3. > 100 TW/cm^2 Power Concentration

Efficient hydrodynamic implosions require a minimum implosion velocity. Establishing this velocity requires a power density for the beam at the target exceeding 100 TW/cm^2.

4. Adequate Pulse Shaping

High-gain implosions can only be achieved if a small amount of the DT fuel is brought to ignition temperature, and the resulting spark is propagated into cold, dense fuel. Establishment of the necessary temperature and density profiles in the target requires careful shaping of the power pulse driving the implosion.

5. Energy Deposition Without Fuel Preheat

The amount of energy required for an efficient implosion is a function of the fuel adiabat at the beginning of the compression. The driver energy required is minimized if the initial adiabat is low. In order to keep the initial fuel adiabat low, absorption of the driver beam energy must occur without generating hot electrons or penetrating X rays.

6. 1 to 5 Hz Pulse Repetition Rate

In ICF reactors, the pulse repetition rate establishes the reactor thermal power level given the target yield. For a yield of 1 GJ, the range of pulse repetition rate from 1 to 5 Hz produces a thermal power of 1 to 5 GWth, or about 300 to 1500 MWe.

7. 10^9 Shot Lifetime

A reactor pulse rate of 1 Hz and a 30 year operational lifetime require 10^9 driver pulses. A higher pulse repetition rate requires a correspondingly higher shot lifetime. Some elements of driver and target systems may have shorter lifetimes, requiring replacement, but most reactor elements must have at least a 10^9 shot lifetime.

8. $\leq$ \$500 Million Cost

In order to compete economically with fossil-fueled power reactors, ICF reactors must cost less than \$2/watt (or \$2 billion for a 1000 MWe plant) in current dollars. Since the balance-of-plant for ICF systems is expected to be approximately two-thirds of the total cost, and since the target production and yield containment system are likely to cost several hundred million dollars, the cost of a driver for a 1000 MWe plant must be less than $500 million if it is to be economically useful. Smaller power plants require even lower driver costs.

Several drivers show promise for power generation applications. These include ion drivers of different types and efficient lasers ($\eta > 10\%$). The ion drivers can be classified into three categories, according to atomic number (Z) of the ion. Since the energy of the ion which corresponds to an ideal range in the target is given very approximately by $E(MeV) \approx 4.5\ Z\ A^{1/2}$, where A = ion atomic weight, then these categories can also be characterized by ranges of accelerating voltage. Light ions ($1 < Z < 20$) have energies ranging from about 4.5 to about 500 MeV. Heavy ions ($Z > 80$) have energies > 5 GeV. Ions between these two, "welterweight" ions ($20 < Z < 80$), have energies from 500 MeV to 5 GeV.

The remainder of this paper will describe the pulsed power technologies under development for producing intense beams of light ions. The pulsed power technology for driving light ions shows significant promise, but viability of light ion systems must still be demonstrated. The promising elements of these systems include their low cost, the classical nature of ion energy deposition without preheat, flexibility for making the voltage/current trade-off necessary to obtain the ideal ion range in the target at very high power levels, and the capability of pulsed power systems to be operated at high repetition rates. Three features stand out as being necessary for a proof of viability: (1) beam focusing to > 100 TW/cm^2, (2) production of an adequately shaped power pulse for high gain implosions, and (3) development of techniques for diode "standoff" from high-yield targets.

PULSED POWER TECHNOLOGIES FOR FUSION REACTORS

The pulsed power for light ion ICF drivers incorporates many electrical switching and storing technologies. A list of these technologies is given in Table 2. Below, each of these technologies is described briefly and the principle of operation is shown schematically in a figure.

Table 2

<u>Pulsed Power Technologies for Light Ion ICF Drivers</u>

Marx Generators
Water-Dielectric Pulselines
Laser-Triggered, Gas-Insulated Switches
Saturable-Core Magnetic Switches
Vacuum Insulators
Self-Magnetic Insulation
Vacuum Inductive Storage
Inductive Voltage Addition
Liquid Metal and Liquid Dielectric Ion Sources
Repetitive Extraction Ion Diodes
Plasma Beam Propagation Channels
Transit-Time Ion Bunching
Gas-Filled Target Chambers

1. Marx Generators

Marx generators are capacitive arrays which are charged in parallel and discharged in series in order to amplify voltage. Schematics of the circuit during charging and the circuit during firing are shown in Fig. 1. Once the spark gap switches (shown as diagonal elements) are triggered, energy from the capacitors flows out to the load through the spark gap switches. In principle, Marx generators have shown high enough reliability to be used in power reactors. In practice, however, the inherent complexity of Marx generators may require that they be replaced by kinetic or inductive energy stores and transformers.

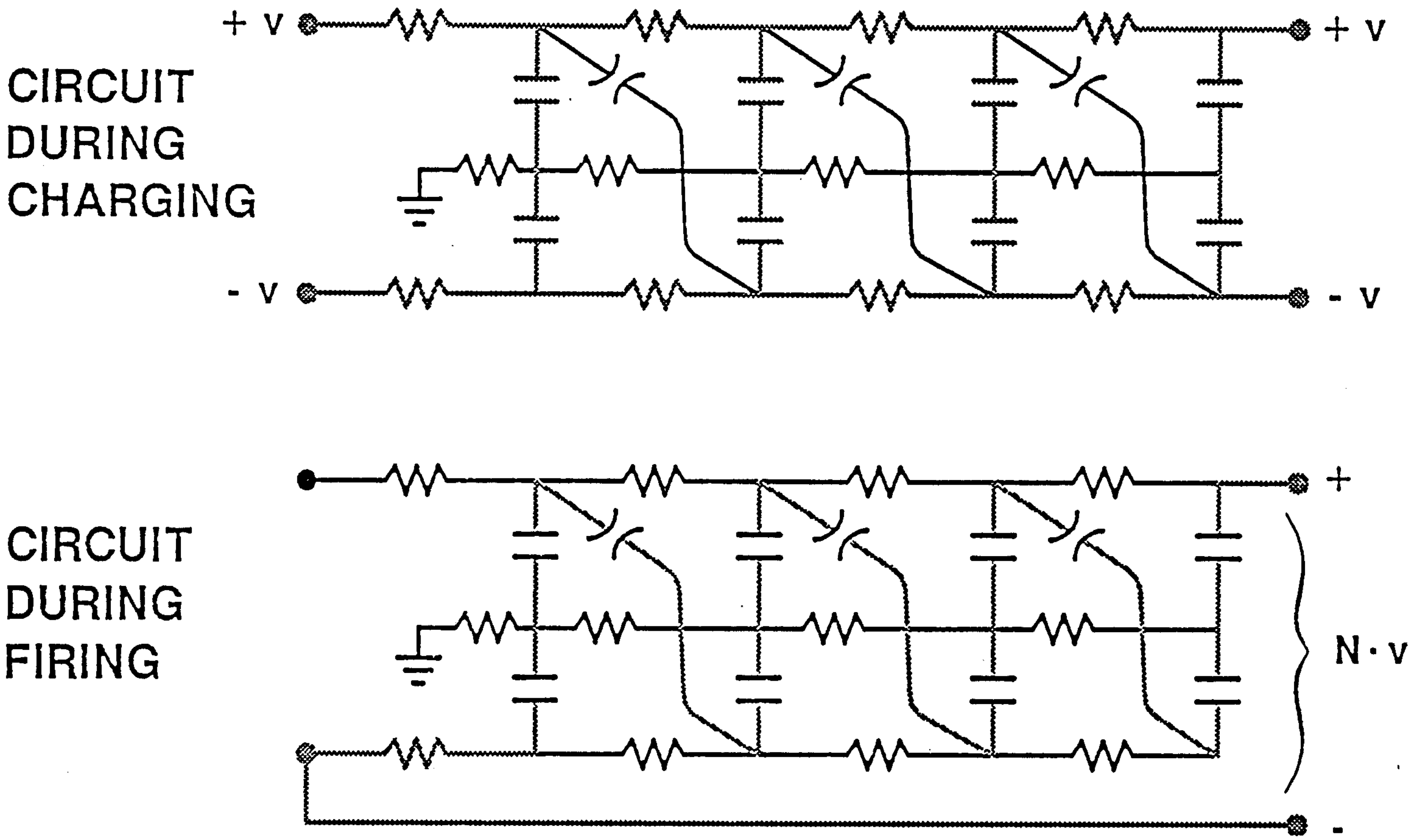


Fig. 1. Marx generator circuit configurations during charging (parallel) and discharging (series).

2. Water-Dielectric Pulselines

Water-dielectric pulselines are used to compress energy in time, amplifying power. The first stage of the water-dielectric pulseline is typically an intermediate storage capacitor. This element is used to compress energy from the 1-μs output pulse of the Marx generator to a typically 300-ns pulse. A switch, which is initially an open circuit and later a short circuit, is placed at the output of the intermediate storage capacitor. For multi-module machines, this switch is critically important for achieving good timing synchronization from module to module. Figure 2 shows a laser-triggered, multistage gas-insulated switch which can be used for synchronization. The switch shown is extendable to high voltage and high repetition rate. It resides inside the water dielectric between the intermediate storage capacitor and the main pulse-forming line. As shown, the switch is pressurized with several atmospheres of an insulating gas, typically SF_6. During operation, a laser beam which enters from the right causes the trigger gap to break down. The voltage across the switch is then shifted to the chain of smaller electrodes mounted on the center column. The electrode gap spacing is designed to be smaller than that needed to support the full voltage across the switch, and the breakdown proceeds from the right to the left along the outside rim of the electrodes, hence the name Rimfire(1) gas switch. When switch closure is completed, energy flows out from the intermediate storage capacitor, through the gas switch, and into the water dielectric pulseline shown in Fig. 3. Figure 3 shows that the output pulse from Line 1 (with width equal to the two-way longitudinal transit time of Line 1 in water) is further compressed after switching into Line 2, since Line 2 is shorter still. When this store-switch-store-switch sequence is carried out efficiently, the power increases as the time interval decreases. At each step, the incoming pulsewidth is smaller than in the prior step, so the electrodes of the storage unit can be placed more closely together without suffering electrical breakdown. This closer electrode spacing results in a smaller unit

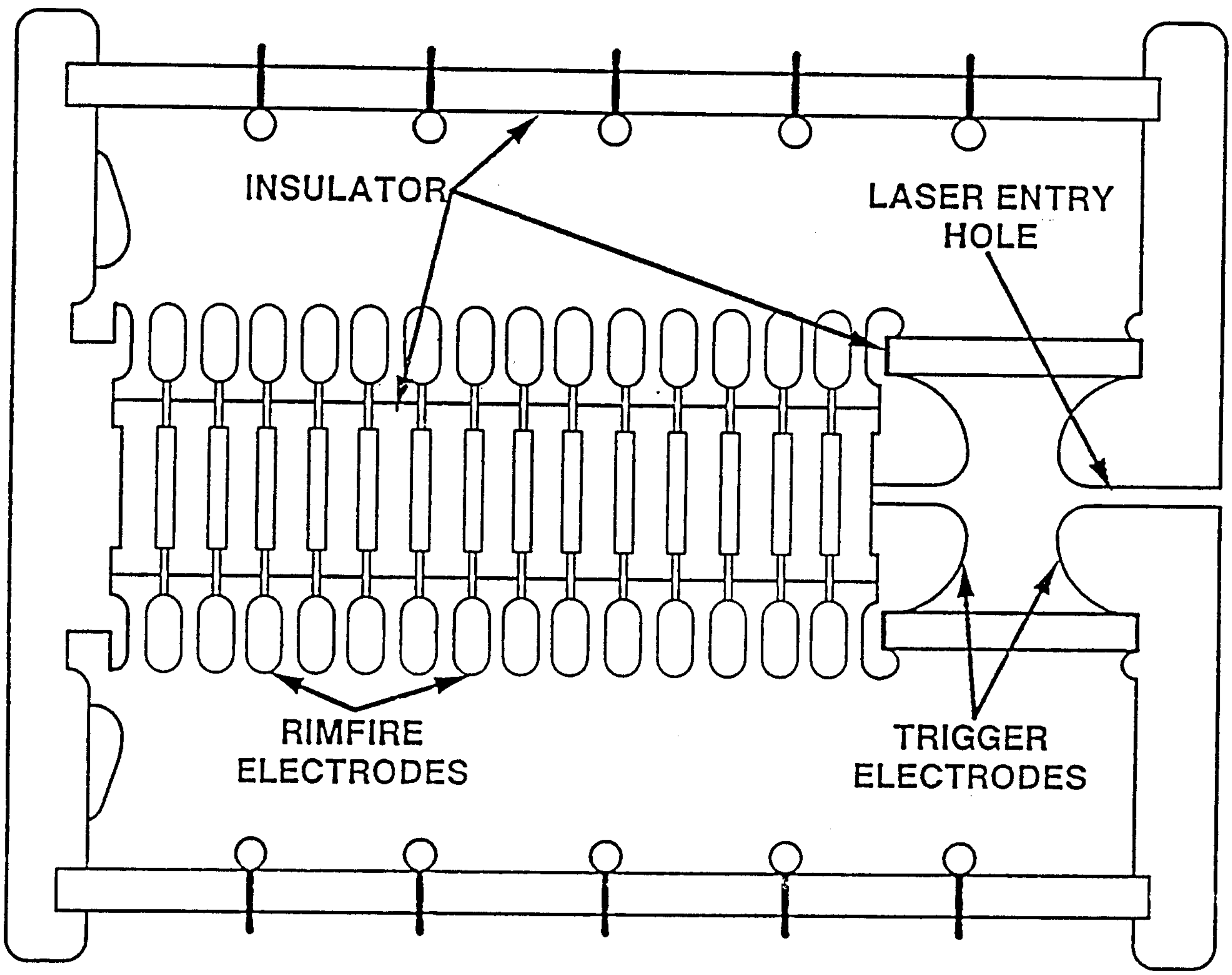


Fig. 2. Laser-triggered, multistage gas-insulated switch used for module timing synchronization.

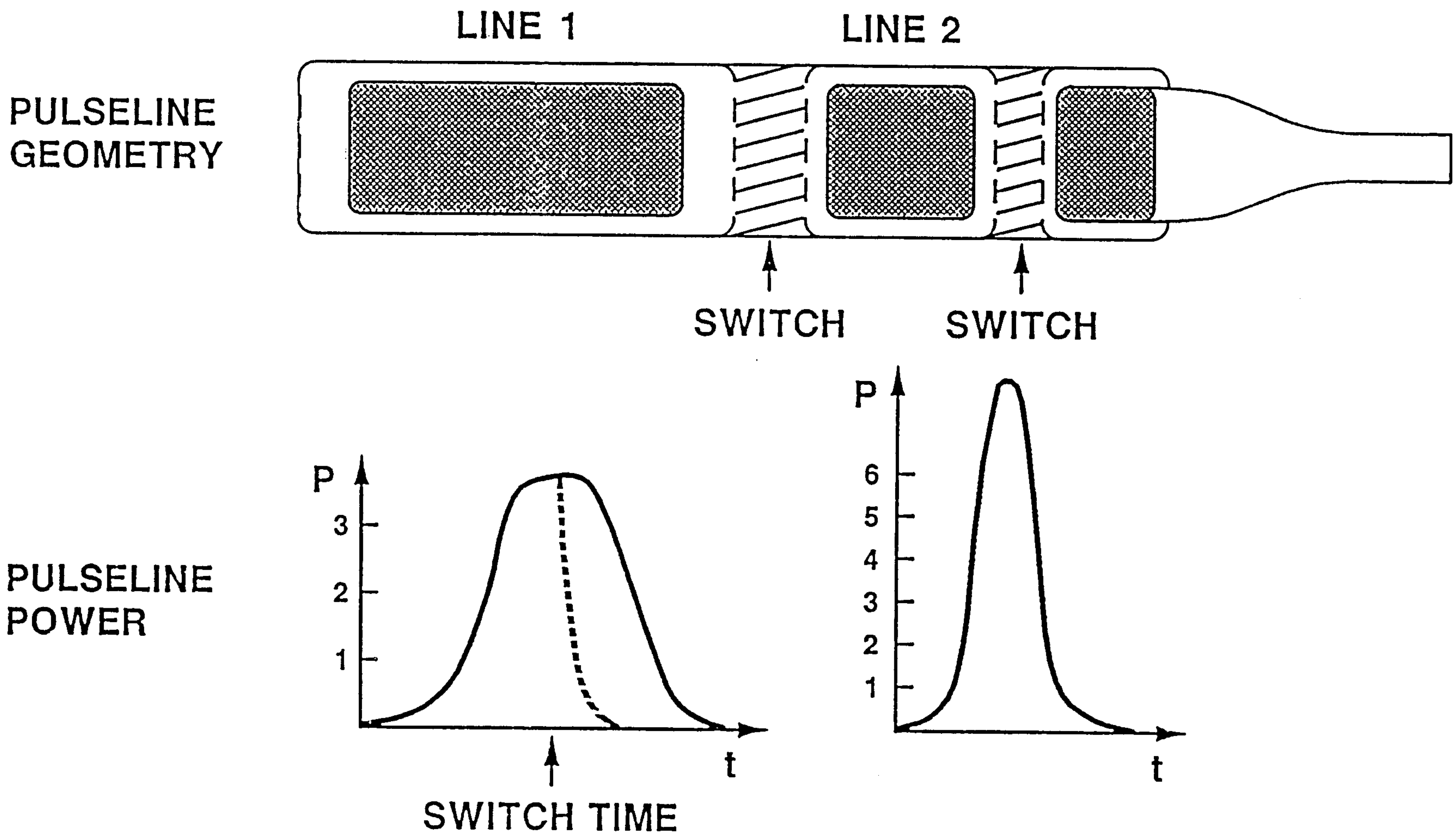


Fig. 3. Water-dielectric pulseline used for pulse compression.

inductance and, consequently, a higher output current with the smaller output pulse duration. The types of switches used in water-dielectric pulselines in present machines are typically field-enhanced, water-dielectric pin switches. Although such switches are inexpensive and easy to construct, the water arc produced by high current passage couples to pulselines and tanks as a strong acoustic wave. This switch is not compatible with very high repetition rate or very long lifetime.

3. Saturable-Core Magnetic Switches

Saturable-core magnetic switches allow efficient pulse compression at high repetition rate. They can be used at high repetition rate, since the energy dissipated in the switching action is very small. The use of saturable-core switches for high average RF power modulation was developed during and after World War II for powerful radar units. The configuration shown in Fig. 4 depicts the replacement of water-dielectric switches with magnetic switches in a high-power pulse-forming line. A pulse-forming line at the 1.8-TW, 200-kJ unit size has been constructed and shown to operate efficiently in a single-pulse mode in the SuperMITE accelerator(2) at Sandia National Laboratories. Saturable-core switches have also been used at the high repetition rate (10 kHz), 1-kJ level(3) on the ATA accelerator at the Lawrence Livermore National Laboratory.

4. Vacuum Insulators

The transition from the water-dielectric pulse-forming line to the magnetically-insulated vacuum transmission line is typically one of the weakest points in pulsed power systems. The weak point occurs on the vacuum side of the insulating material used to separate water from vacuum. This region is shown in Fig. 5. Electrons which are emitted from the triple point (the point of intersection for the metal grading ring, the plastic insulator, and the vacuum) can avalanche across the surface of the plastic insulator causing "flashover." At high power, creative use of self-magnetic fields can result in magnetic flashover inhibition (MFI).(4,5) This configuration, shown in the

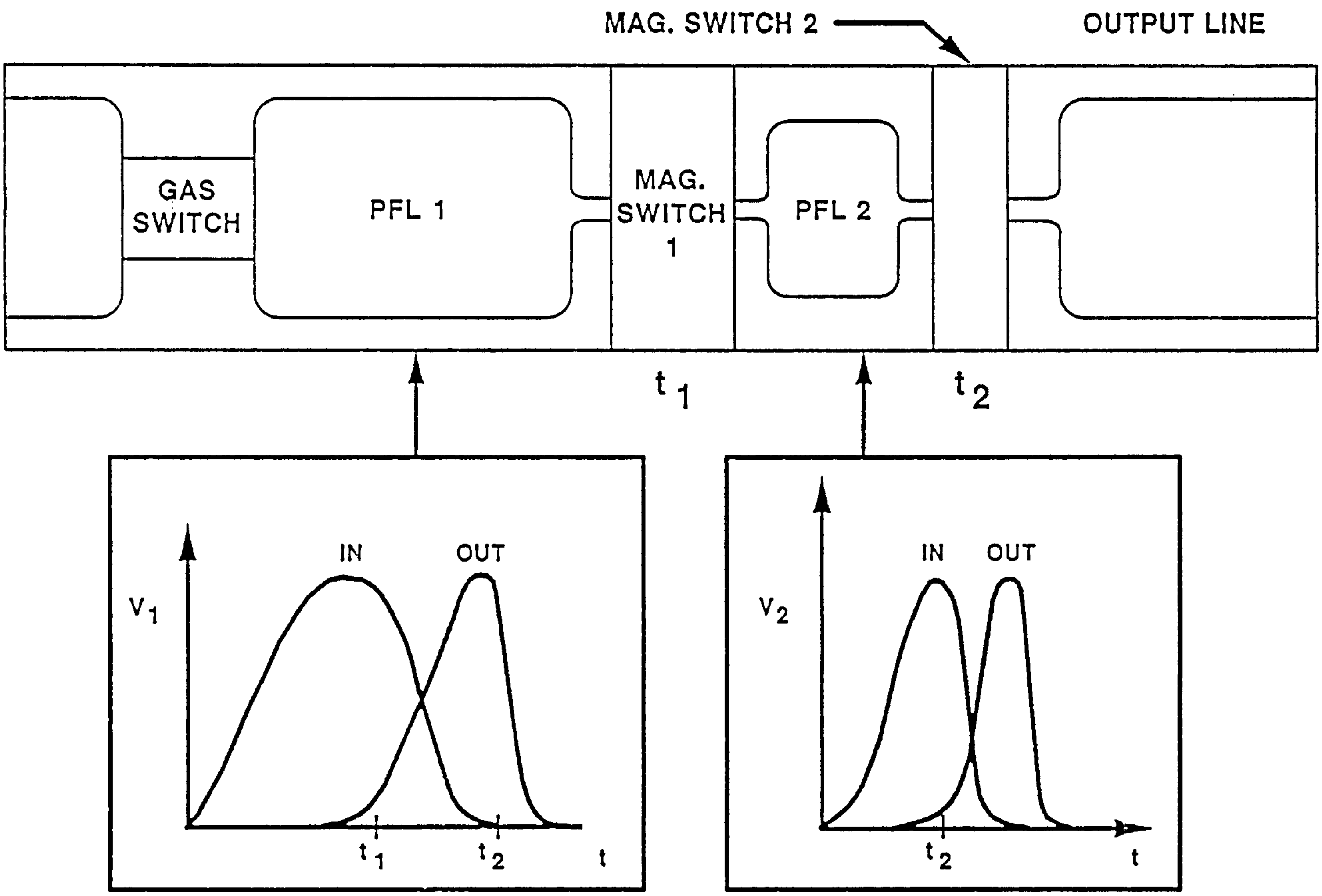


Fig. 4. Water-dielectric pulse forming line using saturable-core magnetic switches for high repetition rate.

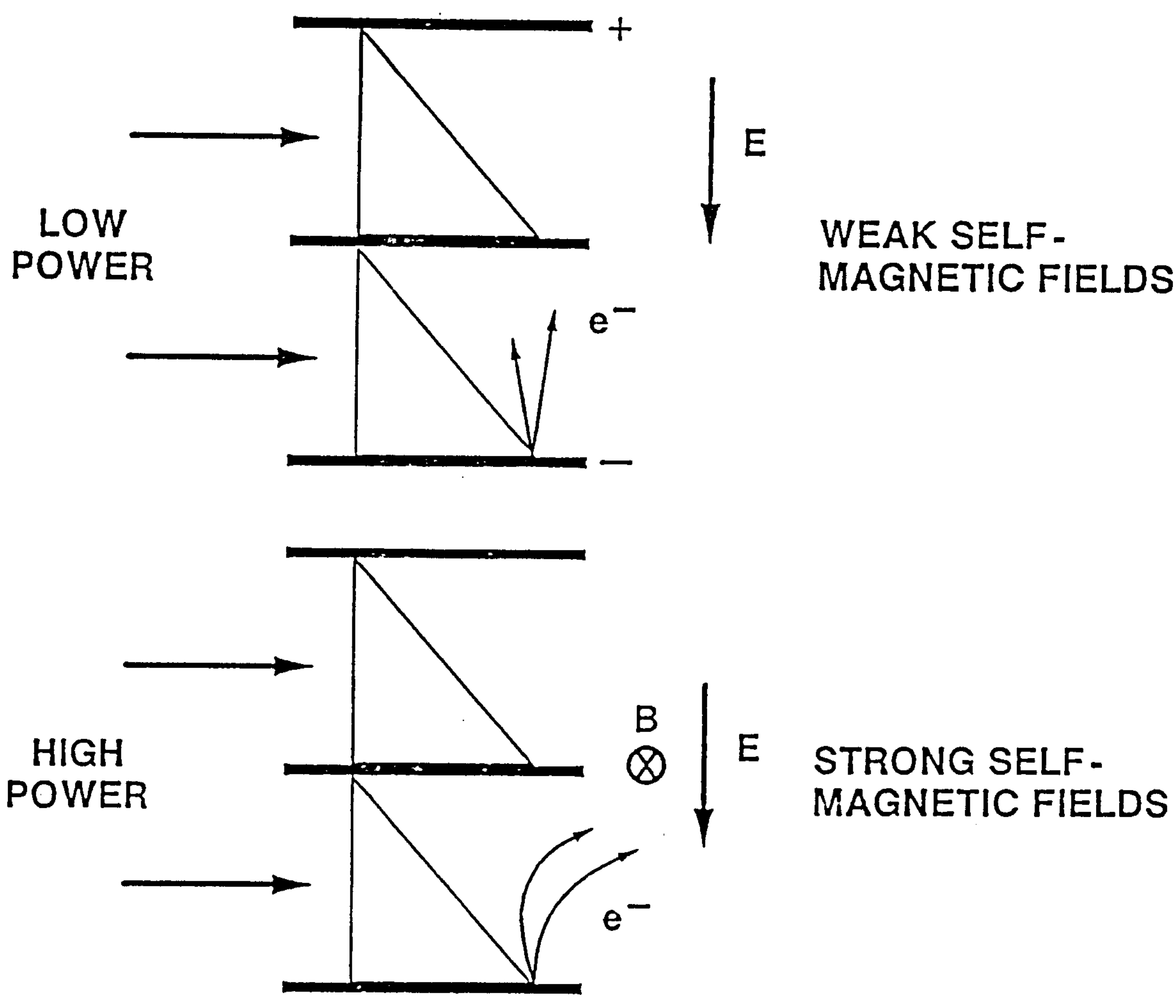


Fig. 5. Vacuum insulator regions without (top) and with (bottom) self-magnetic fields.

lower half of Fig. 5, uses the self-magnetic field of the high-power pulse to turn electrons away from the insulator surface. Insulators which work in the MFI regime may be useful at higher electric field levels than non-MFI insulators.

5. Self-Magnetic Insulation

In a way similar to the use of self-magnetic fields at insulator surfaces, self-magnetic fields can be used to insulate power flow in vacuum transmission lines. In Fig. 6, electron flow and transportable power levels are shown for a transmission line in which the self-magnetic field is not significant (top), and one in which the self-magnetic field is dominant (bottom). In the top figure, electrons freely stream from the cathode to the anode, limiting the voltage and transportable power to a low level. In the bottom figure, self-magnetic fields created by current loss at the head of the power flow wave turn electrons and prevent them from reaching the anode. Since the magnitude of transportable power is proportional to the product of the electric field and the current (which is again proportional to electric field for a resistive load), the use of self-magnetic insulation can allow very high power pulses to be transported efficiently.

6. Vacuum Inductive Storage

Once the power pulse is in vacuum, it can be further compressed in time through the use of an inductive store and an opening switch. The use of inductive stores and opening switches for pulse compression in vacuum is analogous to the use of capacitive stores and closing switches in the water-dielectric section of these accelerators. A schematic of an inductive storage pulse compressor is shown in Fig. 7. Energy is initially stored in the inductance located between the vacuum insulator and the plasma switch while the plasma switch is conducting current. Near the peak of the current waveform, the plasma switch opens and energy stored inductively is delivered to the load. This technology may have significant leverage for the future, particularly if plasma switches can be developed to conduct current for > 1 μs and to open in < 10 ns.

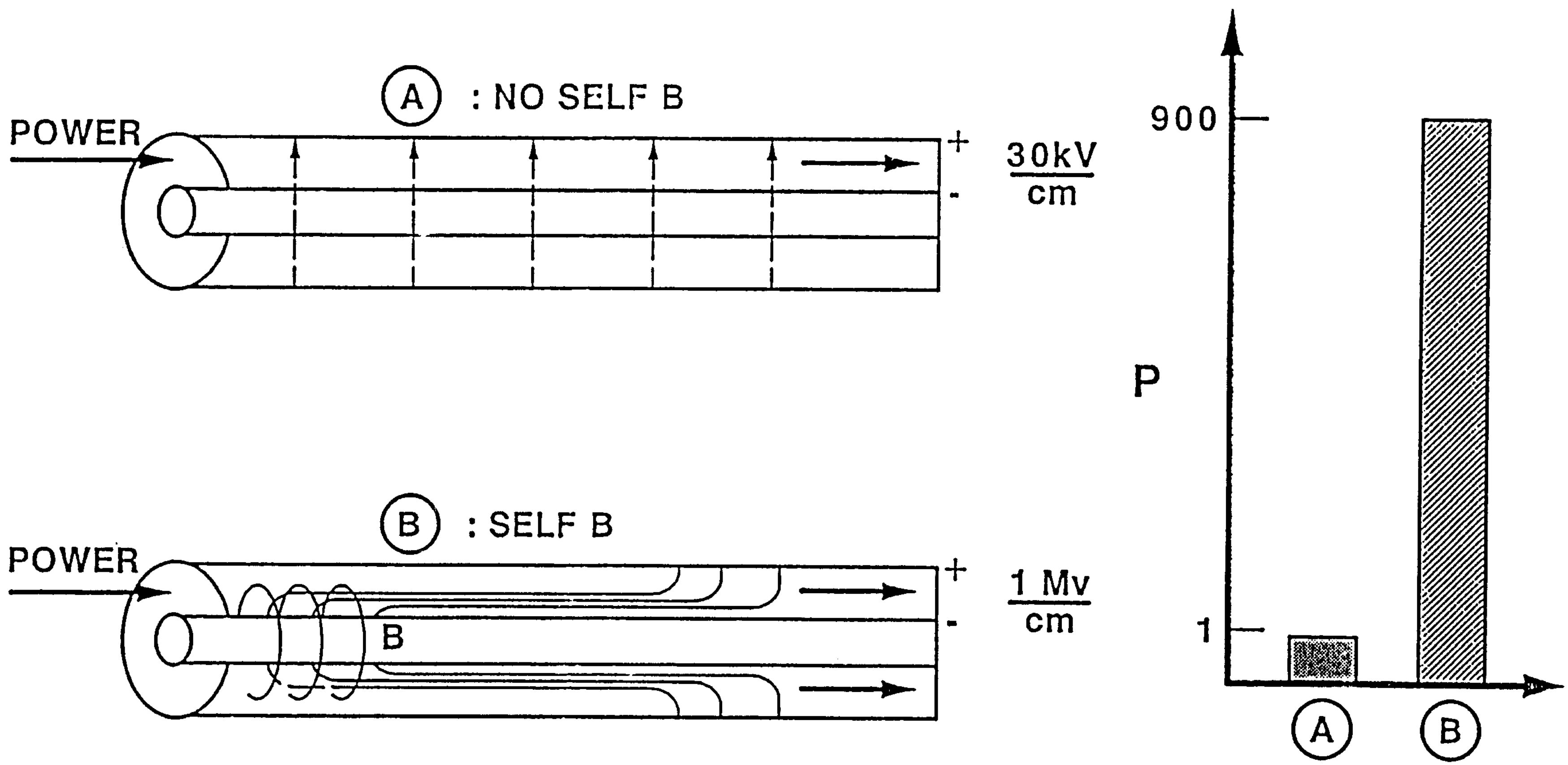


Fig. 6. Electron flow and transportable power levels for coaxial transmission lines without (top) and with (bottom) self-magnetic insulation.

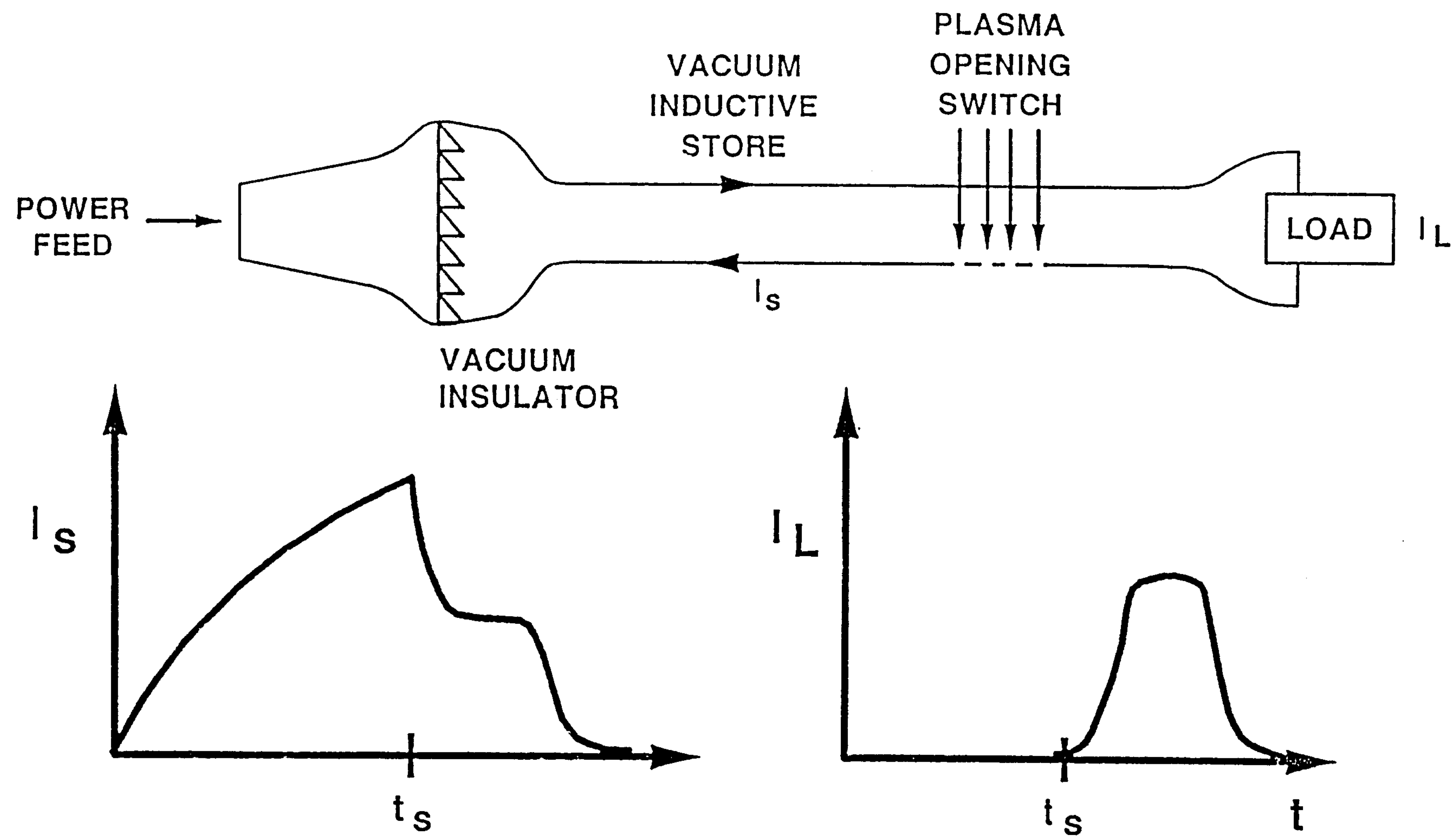


Fig. 7. Inductive storage and pulse compression using a magnetically insulated vacuum transmission line and a plasma opening switch.

7. Inductive Voltage Addition

We have recently constructed large accelerators[6] which achieve high voltages by using inductive addition in vacuum. This principle is shown in Fig. 8. Magnetic cores, designed to support voltage without saturating, isolate the power feeds and allow voltages from each module to be added in series. This addition, as shown in the figure, occurs as the addition of electromagnetic waves along a central conducting stalk. The voltage addition is similar to that in a linear induction accelerator (LINAC) where the energy in a propagating beam is increased by voltage applied to each accelerating stage. In the inductive voltage adder, a high-voltage electromagnetic output pulse can be achieved using low voltage modules. This voltage addition technique appears scalable to very high voltage levels, and may be a way to reach the levels required to drive "welterweight" ions for ICF.

8. Repetitive Extraction Ion Diodes

Two inventions made recently have enabled the conceptual definition of a repetitive extraction ion diode. The first of these is a geometry for the applied magnetic field of an extractor diode which uses a diffusive anode.[7] Such a geometry allows for uniform magnetic insulation of the anode-cathode gap. The second invention is the idea of using an electrohydrodynamic (EHD) instability on the surface of a liquid metal or liquid dielectric mounted on the anode and exposed to the very high electric field in the AK gap.[8] Use of liquid sources enables this basic diode concept to be made repetitive, with replacement of the front surface of the anode possible between shots. The use of liquid metals or liquid dielectrics in the anode also permits energy lost in the form of high voltage electrons to be removed between shots. For example, the range of a 30-MeV electron in lithium is about 11 cm, so flowing liquid lithium or a liquid lithium compound through the anode can remove the lost energy. A diode concept using these ideas is shown in Fig. 9.

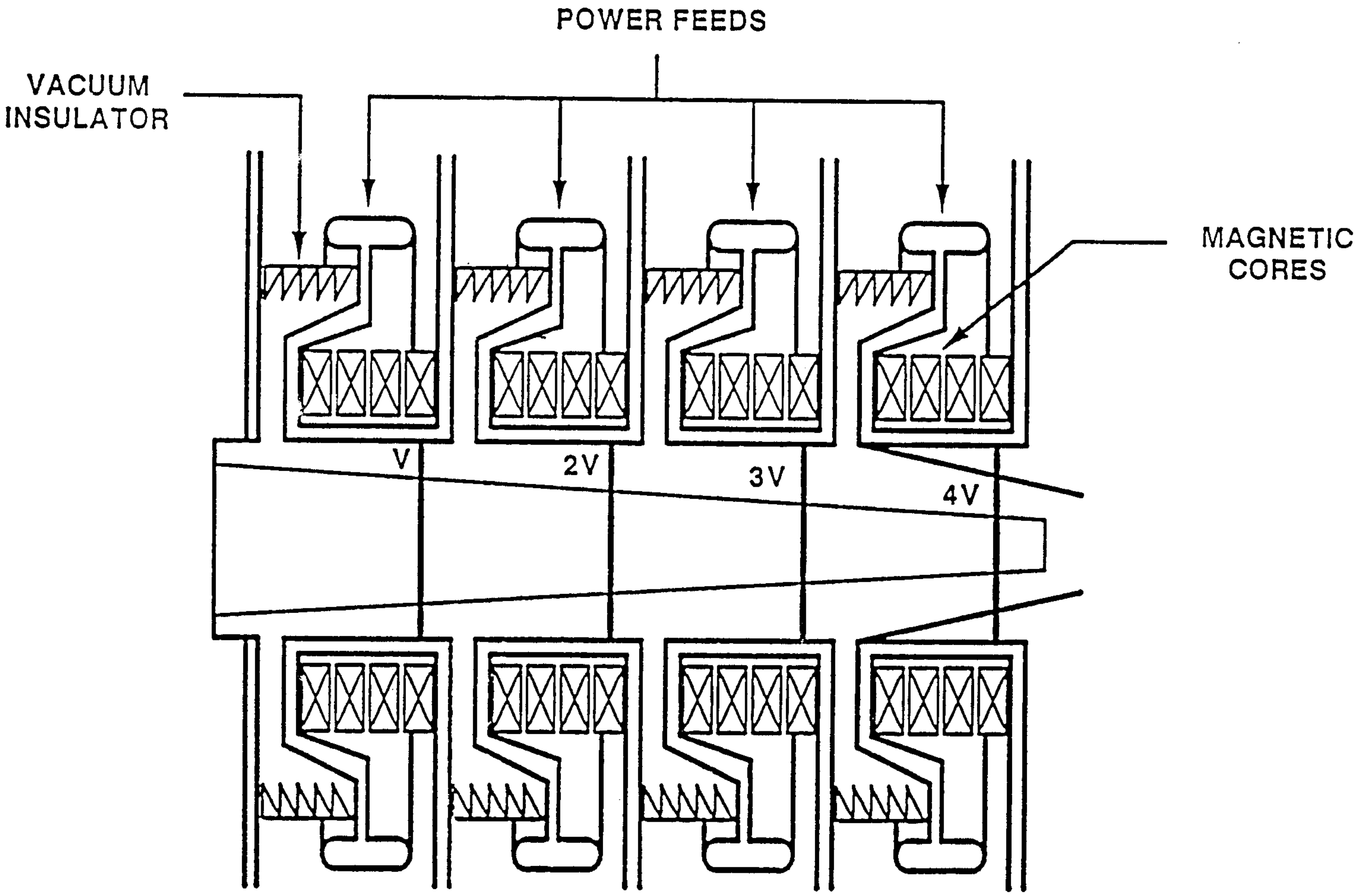


Fig. 8. Inductive addition of voltage in vacuum along a central stalk.

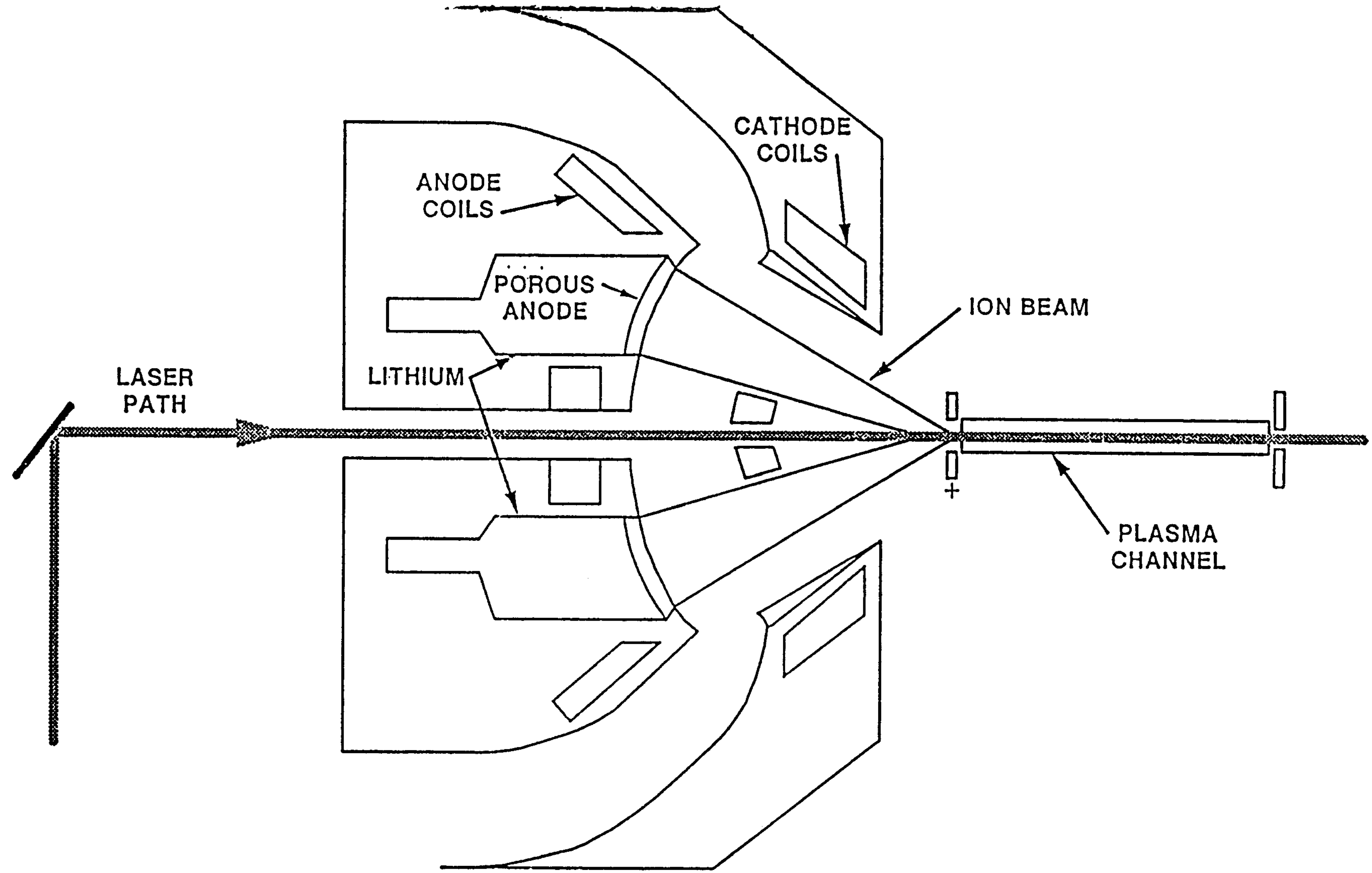


Fig. 9. Conceptual drawing of a repetitive extraction ion diode.

9. Plasma Beam Propagation Channels and Transit-Time Ion Bunching

The use of a light gas fill inside the reactor chamber of an ion-driven reactor enables beam propagation from the diode to the target in the following way. A low-energy laser is directed through a hole in the diode, as shown in Fig. 9, and ionizes a path from the diode focal region to the target. When a capacitor bank is discharged through this low-density plasma, a shock wave is created expanding the plasma outwardly in a radial direction. The magnetic field associated with the channel current confines the ions entering the channel to the rarefied plasma region, allowing them to be propagated down to the target. In turn, the high density gas at the periphery of the plasma channel constrains the pressure of the magnetic field and, in turn, the ion transverse momentum. With a suitable pulse shape provided at the ion diode, ballistic transit-time bunching of the ions can be accomplished. Ions which are created later in the power pulse, having a higher energy, can catch up with the lower energy ions created early in the power pulse. When properly arranged, the ion power pulse shape at the target will be correct for driving high-gain implosions. As shown in Fig. 9, the low-energy laser is important for targeting, since the initial laser path controls the plasma channel which, in turn, controls the high-power ion beam. This targeting can take place in less than 1 μs, permitting an injected target moving at 500 m/s to be struck with an accuracy better than 0.5 mm.

10. Gas-Filled Target Chambers

Gas-filled target chambers can provide first-wall protection from large thermal transients. As shown in Fig. 10, the temperature excursion induced by X rays and debris ions at the first wall of a vacuum reactor chamber occurs on the time scale of the burn duration, or 0.1 to 1 ns. If several torr of gas can be placed inside the target chamber, then as shown in Fig. 9, the gas can act as a thermal capacitor, converting the 1-ns x-ray pulse to a 0.1- to 5-ms thermal pulse and hydrodynamic overpressure.[9,10] The

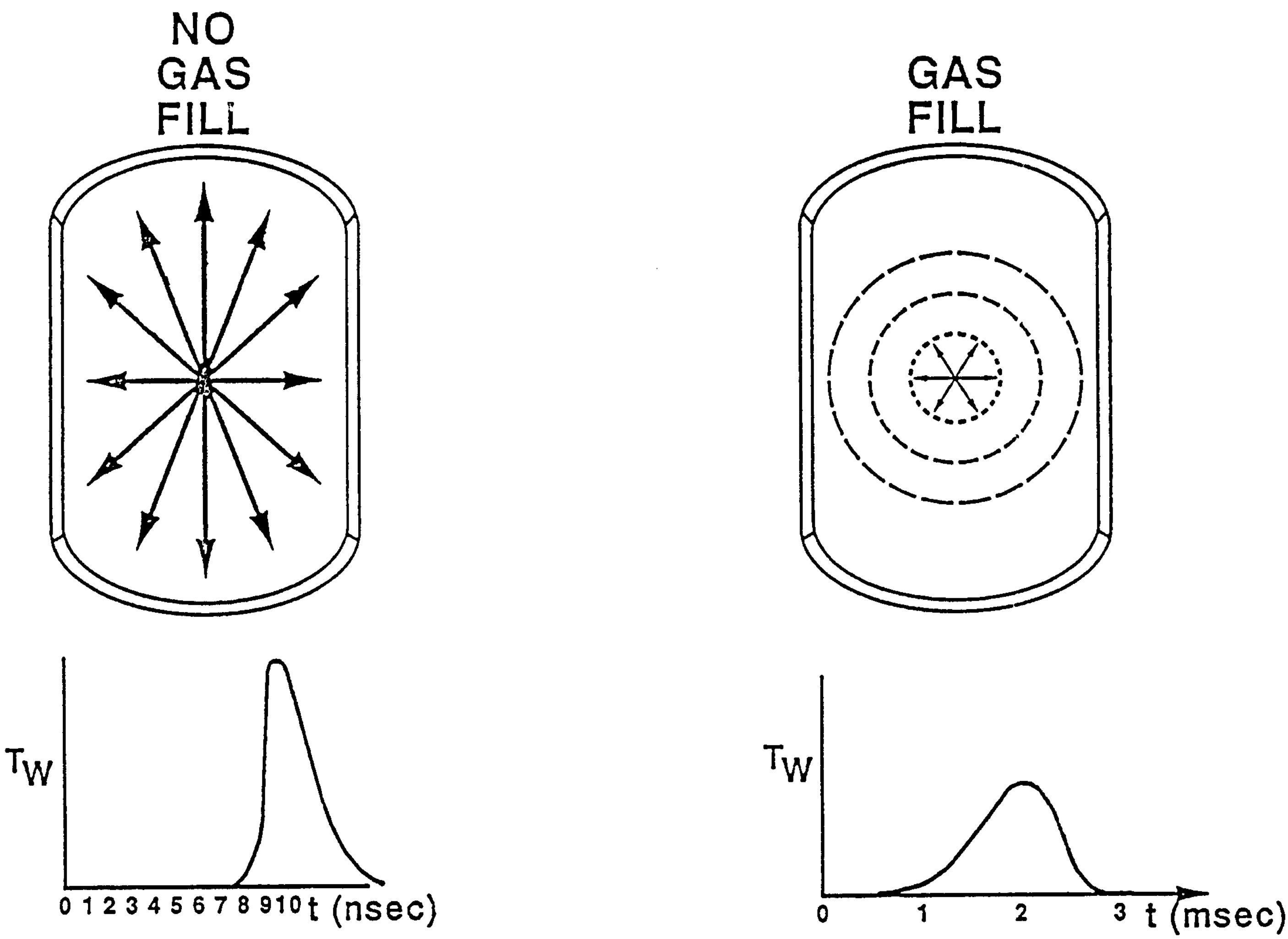


Fig. 10. First wall temperature excursions without (left) and with (right) a rarefied gas fill in the target chamber. The temperature excursion with the gas fill is more than one order of magnitude smaller and occurs over a much longer time, avoiding ablation and reducing wall stresses greatly.

overpressure, which sets minimum thicknesses for first-wall components, is much easier to contain without damage than the 1-ns x-ray pulse which would otherwise strike the wall. Interestingly, the level of thermal wall loading and hydrodynamic overpressure expected in a light-ion-driven fusion reactor chamber having a radius of 3 m and containing a yield of 800 MJ are comparable to those in an internal combustion engine.

SUMMARY

Pulsed power technologies being developed for the Inertial Confinement Fusion program are operating reliably at the MJ energy level. These technologies enable generation of very intense ion beams at reasonable costs due to high component efficiencies. Conceptual approaches for delivering these high-power beams to a target at a distance have been developed and experiments are beginning. If these experiments are successful, it should be possible to take advantage of the use of a rarefied gas fill in a target chamber offered by light ions. While very much remains to be done before light ion fusion energy becomes a reality, the progress being made in addressing the necessary technologies for fusion energy generation is continuing at a rapid pace.

REFERENCES

1. D.R. Humphreys, K.J. Penn, J.S. Cap, R.G. Adams, J.F. Seamen, and B.N. Turman, Proc. 5th IEEE Pulsed Power Conf., Arlington, VA, June 10-12, 1985, p. 262 (1986).

2. E.L. Neau, Proc. 4th IEEE Pulsed Power Conf., Albuquerque, NM, June 6-8, 1983, p. 246 (1984).

3. D.L. Birx, E. Cook, S. Hawkins, S. Poor, L. Reginato, J. Schmidt, and M. Smith, Proc. 4th IEEE Pulsed Power Conf., Albuquerque, NM, June 6-8, 1983, p. 231 (1984).

4. K.D. Bergeron and D.H. McDaniel, Appl. Phys. Lett. 29, 534 (1976).

5. J.P. VanDevender, Proc. 3rd IEEE Pulsed Power Conf., Albuquerque, NM, June 1-3, 1981, p. 248 (1982).

6. J.J. Ramirez, K.R. Prestwich, R.A. Hamil, D.L. Johnson, L.X. Schneider, E.L. Burgess, T.W.L. Sanford, G.A. Zawadzkas, J.P. Furaus, and L.O. Seamons, Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, June 29-July 1, 1987 (1988).

7. S.A. Slutz and D.B. Seidel, J. Appl. Phys. 59, 2685 (1986).

8. A.L. Pregenzer, J. Appl. Phys. 58, 4509 (1985).

9. R.R. Peterson, G.A. Moses, R.L. Engelstad, D.L. Henderson, G.L. Kulcinski, E.G. Lovell, M.E. Sawan, I.N. Sviatoslavsky, J.J. Watrous, R.E. Olson, and D.L. Cook, Fusion Technology 8, 1895 (1985).

10. G.A. Moses and R.R. Peterson, Nuclear Fusion 20, 849 (1980).

THE APEX PROJECT: ION BEAM PULSE-SHAPING EXPERIMENTS ON SANDIA NATIONAL LABORATORIES' PARTICLE BEAM FUSION ACCELERATOR PBFA II*

James T. Crow
Sandia National Laboratories
Power Flow Research Division

INTRODUCTION

The goal of the Inertial Confinement Fusion (ICF) program is to develop a system that will deliver enough power and energy to a fusion target to compress and heat the fuel sufficiently to begin a thermonuclear reaction. With proper driver and target design, it appears possible to achieve target gains (energy generated in the reaction divided by energy used to compress and heat the target) of up to several hundred. Such a system could be used in a repetitive system to generate power.

Sandia National Laboratories' efforts in ICF are concentrated on systems which will accelerate light ions (e.g. lithium) to produce the high power pulse on the target. Light-ion accelerators have the potential of achieving high efficiencies (> 20%, wall-plug to ion beam) so only a modest target gain is needed in a system which could produce net usable power output. Energy-producing ICF systems that use moderate-gain rather than high-gain targets could use simpler and more reliable beam generation and simpler and cheaper targets. Sandia National Laboratories Particle Beam Fusion Accelerator PBFA II is the world's most powerful light ion fusion accelerator. In its present configuration using a 15 cm radius "barrel" ion diode and lithium ions PBFA II might produce significant burn in a fusion target.

* This work was supported by the U.S. Department of Energy under Contract No. DE-AC04-76DP00789.

Careful shaping of the power pulse on target will be required to achieve high gain from a fusion target. In addition, use of moderate- or high-gain targets, particularly in high-repetition-rate systems that are intended to produce net energy output, will require adequate separation between the ion accelerator and the target to protect the accelerator from blast and radiation.

Conceptual designs [1,2] of light ion fusion reactors generally have several electrical pulse-forming sections feeding ion diodes which focus ion beams into plasma channels for propagation to a fusion target. The propagation channels are rarefied plasmas with applied currents that produce magnetic fields which trap the ion beams and direct them to the target. The plasma channels have the dual function of providing standoff from the target, and a means for shaping the ion beam pulse. Pulse shaping and compression are accomplished in the plasma channels by applying a properly ramped voltage to the ion diodes, so that the higher-energy ions emitted later in the pulse overtake the earlier ions during their transit down the channels.

We are developing a modification for PBFA II that will generate pulse-shaped ion beams and transport them to a fusion target. This system will include water-dielectric pulse-forming lines modified to provide a ramped output pulse, an efficient extraction ion diode, and a single plasma channel which will transport a lithium ion beam to a fusion target in a target chamber located beneath the accelerator. This PBFA II revision will allow experiments on the physics of high power ion diodes, plasma channels, and fusion targets in high compression and high temperature regimes, and it has the possibility of driving fusion targets to moderate gains. As a step toward a PBFA II design, an experiment will be designed for the Hermes III accelerator that will demonstrate the essential principles of ion beam pulse shaping, but without the possibility of target gain.

Conceptual design studies for light ion fusion (LIF) reactors have indicated that LIF reactors can be economically attractive for commercial generation of energy. Some of the characteristics which such a system must have are:

1. A system of pulsed power, ion acceleration, and beam transport that will produce the tailored power pulses needed by high-gain fusion targets.
2. An efficient generation system (ion source and diode) for the ion beams which will focus to > 100 TW/cm^2.
3. An efficient system of ion beam transport from the ion diodes to the target, at the appropriate beam power densities (> 100 TW/cm^2).
4. Relatively simple, inexpensive fusion targets with gains of 50 - 200 at ion beam energies of 3 MJ - 10 MJ.
5. A repetitive pulsed power system with low component failure rates and a lifetime of more than ten years at a shot rate of a few Hz.
6. Reliable ion diodes which will operate at a rate of a few Hz.

The pulse-shaping project planned for PBFA II will develop a system which has the first three of these characteristics. The components for this system will not be capable of high repetition rate operation, but the applied-B ion diode and the plasma channel to be developed can be the bases for similar elements operating at high repetition rates. In addition, experiments can be done on targets at temperatures and compressions appropriate to fusion, and will be an important step in target development.

BASELINE APEX SYSTEM

The basic APEX system is shown schematically in Fig. 1. The existing PBFA II barrel diode will be replaced with a diode that has an extraction configuration which will focus a lithium ion beam into a plasma channel. The ion beam is confined in the channel by azimuthal B-fields produced by a current in the channel that is driven by

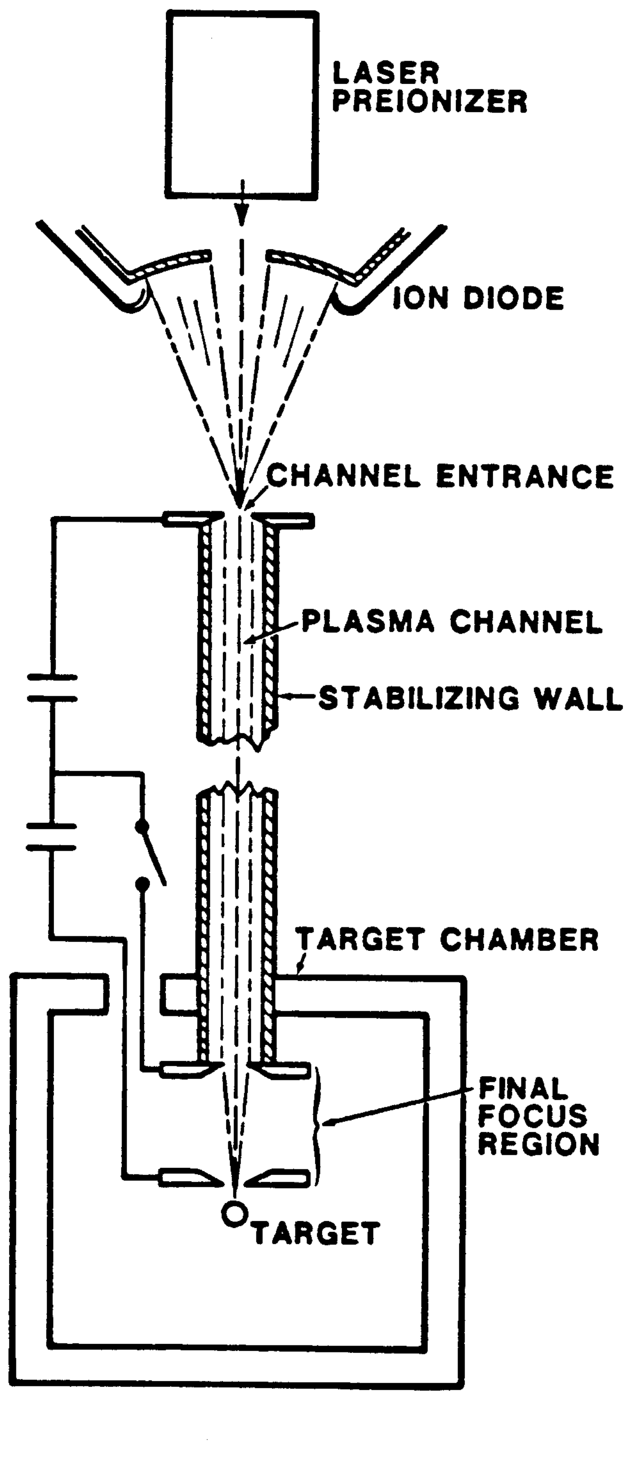


Fig. 1. Schematic drawing of the basic APEX pulse-shaping system.

external capacitor banks. The PBFA II water-section pulse forming lines will be modified to provide an upwardly-ramped voltage pulse to the diode. The ion beam pulse is then compressed by ballistic bunching while propagating in the channel. A target chamber will be installed below the PBFA II vacuum insulator stack. The overall configuration of the modified PBFA II is shown schematically in Fig. 2.

The PBFA II APEX Project is now in the exploratory development phase. This phase is investigating targets for single-sided drive, plasma channels for transport of fusion-quality ion beams over distances sufficient for ballistic ion beam bunching, efficient ion diodes in an extraction configuration, and methods for accurate pulse shaping that combine water-insulated pulse forming lines with ballistic bunching of the ion beam. In addition, a target chamber must be designed to contain the output of the fusion targets to be tested, including consideration of handling of activated material. This exploratory development will also provide cost/benefit data for consideration of an accelerator energy upgrade.

EXTRACTION ION DIODES

In experiments performed prior to 1987, applied-B ion diodes in the extraction configuration have been inefficient. Although barrel and extraction diodes are topologically identical, as seen in Fig. 3, flux surfaces cannot conform to the anode surface of an extraction diode as they do in the barrel geometry, since, in an extraction geometry, the azimuthal component of self-magnetic field is dependent on radial position in the diode. The effect of ignoring this difference by using conducting anodes in extraction diode experiments has been strong magnetic insulation of the anode-cathode gap near the center of the diode, and weak insulation at large radius, producing losses and poor focus.

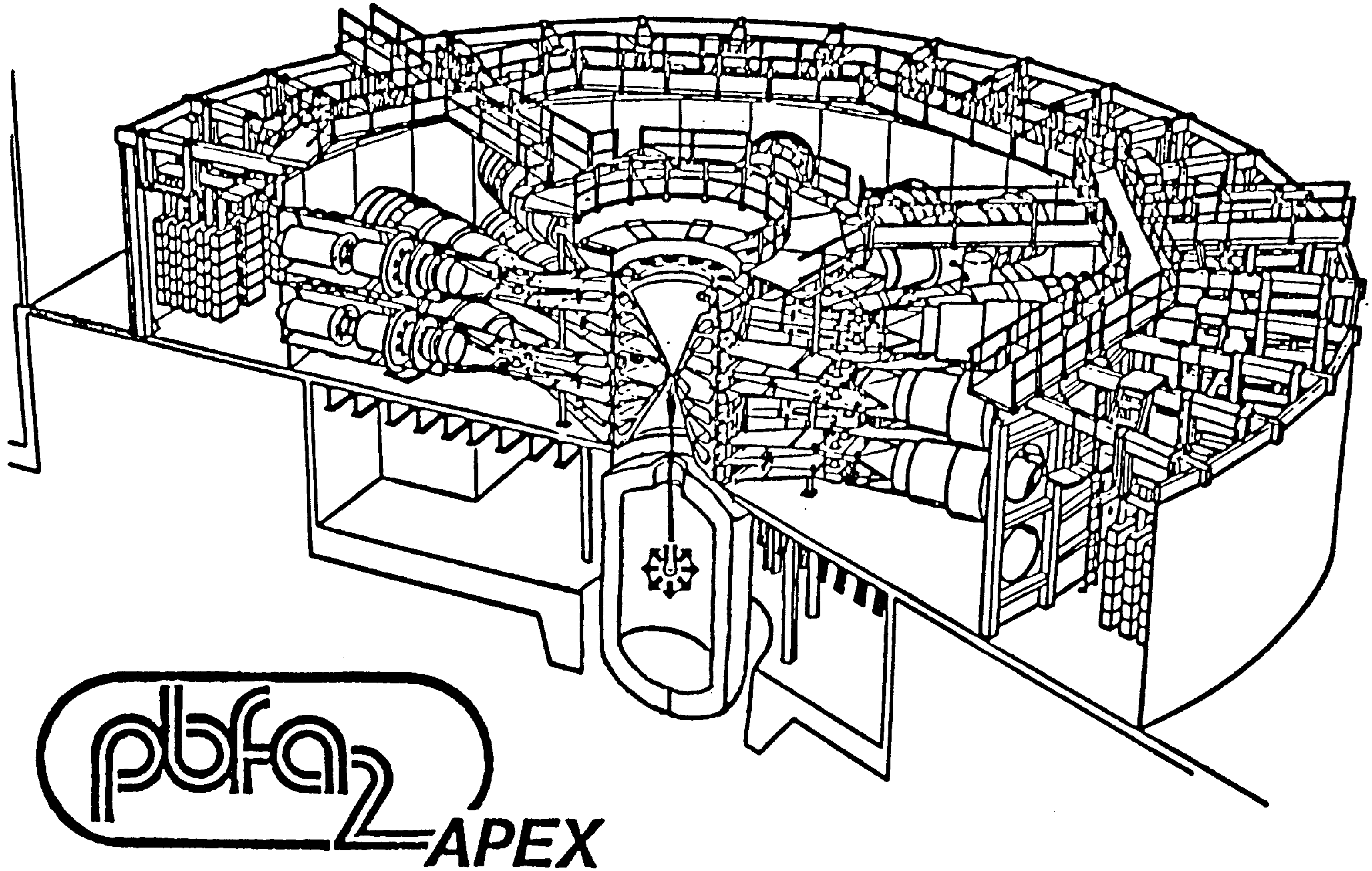


Fig. 2. The APEX pulse-shaping system installed on PBFA II.

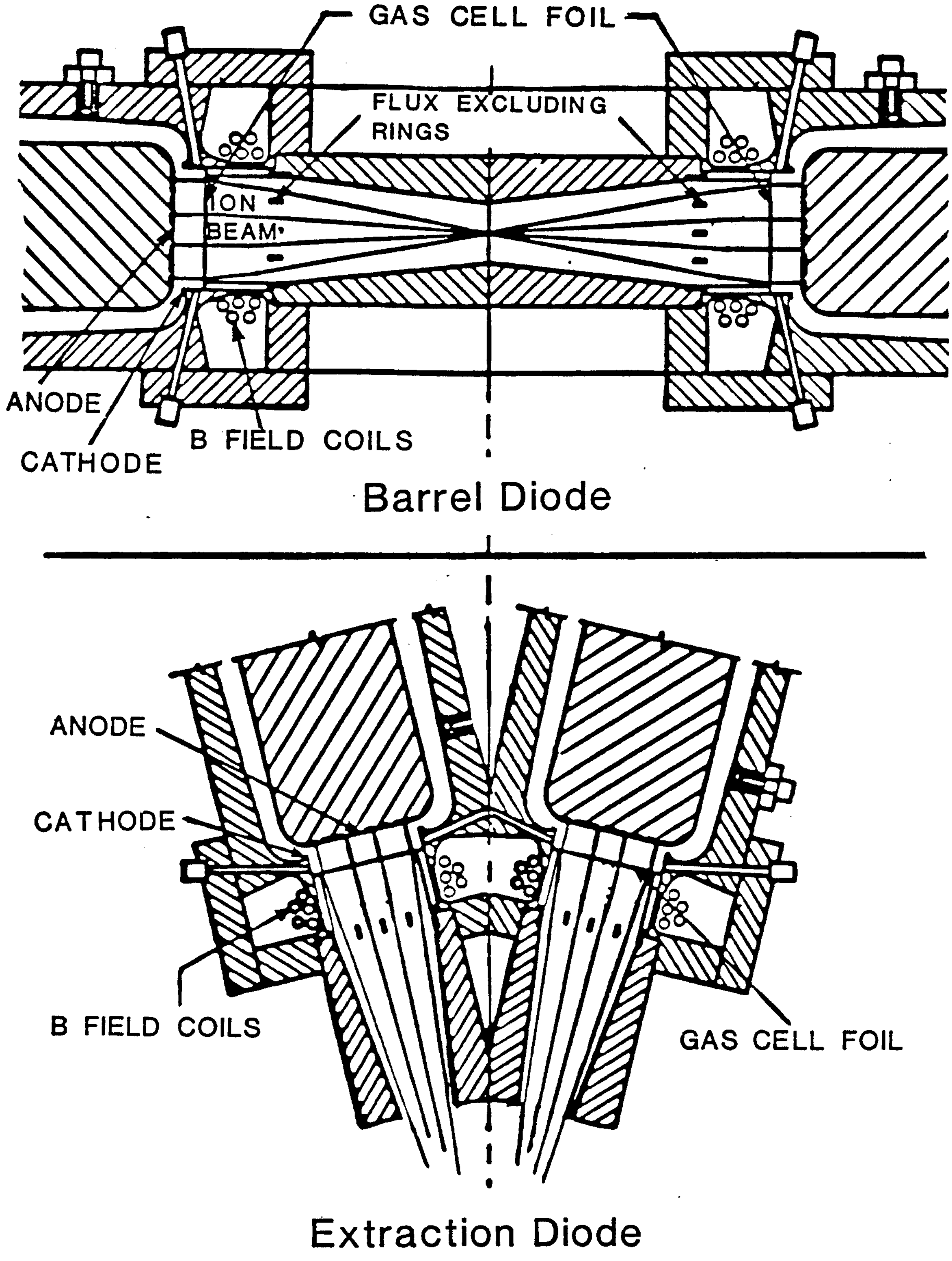


Fig. 3. Barrel and extraction diodes are topologically identical.

A solution proposed by Slutz and Seidel at Sandia National Laboratories [3] is to allow controlled penetration of the magnetic field into the anode structure, so that the magnetic insulation of the virtual cathode (electron) sheath is uniform across the entire anode surface. Canonical angular momentum is then different for ions emitted at different radii preventing focus of the beam on axis, but this can be corrected by proper location of a charge-stripping foil when using lithium (or higher-Z) ions.

The magnetic field configuration and foil location are shown in Fig. 4. Development of an efficient extraction diode with uniform ion emission is critical to the APEX project and to future light ion reactor systems. This configuration is expected to produce uniform emission and efficient operation. Tests by Slutz of a diode using this magnetic field geometry are in progress on Sandia National Laboratories MITE accelerator. Preliminary results show an improvement in uniformity and good efficiency, although the field configuration has not yet been optimized.

The ion source planned for use in the APEX diode (and in the present PBFA II barrel diode) is a liquid lithium metal or lithium salt ion source that depends on an electrohydrodynamic instability to produce surface cusps in the high electric field at the anode. The cusps field-emit ions, or neutrals which are then field ionized. This source can be very high purity, and is potentially self-renewing, which is an important characteristic for extrapolation to a high-repetition-rate system.

ION BEAM PROPAGATION AND PLASMA CHANNELS

The baseline approach to confinement of the propagating ion beam between the diode and the target will be a Z-pinch plasma channel, as seen in Fig. 1. This method has been studied at Sandia National Laboratories [4], Naval Research Laboratory [5], Osaka University [6], and at Nagaoka University [7]. Ion beam and channel parameters

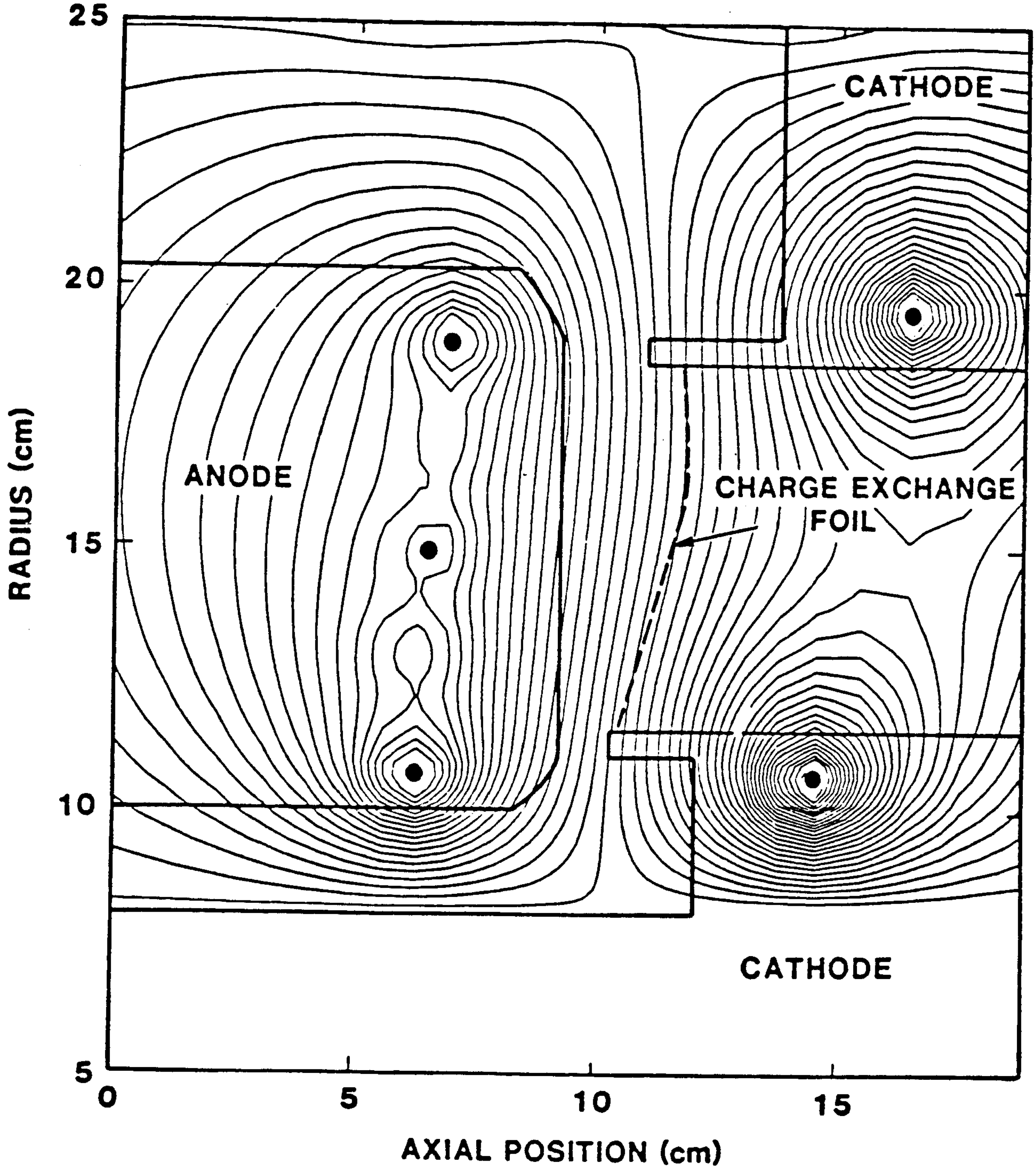


Fig. 4. New magnetic field configuration for efficient, uniform extraction ion diodes.

required for APEX are shown in Table 1. Results of some ion beam transport experiments are shown in Table 2. The APEX system will probably use a main channel 2 to 3 cm diameter, followed by a final focus cell. Naval Research Laboratory is presently conducting experiments on final focus cells to determine compressions achievable. They are also supporting the APEX effort with channel theory and simulations.

The pulse shape required at the target is somewhat more complex than the simple parabolic shape needed to produce complete bunching. An initial primer pulse is needed, and the main power pulse must be carefully tailored. An example of an ion energy (diode voltage) waveform at the input (diode end) of the transport channel and the corresponding channel power output (at the target) is seen in Fig. 5.

The applied current required in a transport channel (or final focus cell) for a target with a given radius depends strongly on diode parameters, increasing as the square of the product of diode radius and beam microdivergence. This dependence is shown in Fig. 6 for a specific APEX case.

Applied currents in excess of 100 kA in the channel or 400 kA in the final focus region are difficult to achieve, since MHD instabilities rapidly disrupt the plasma channel at high currents. Measurements of the ion beam produced by the present PBFA II barrel diode will provide information on the relation of diode current density and microdivergence in the range of 15-30 MV peak, and will provide a basis for the APEX channel currents needed. High channel currents require high gas densities, and beam losses rapidly become unacceptable. The inductance of a free-standing channel is about 1 μH/m. This will require a high applied voltage if fast channel current risetimes are required for channel stability. Since the APEX system is intended for low repetition rate, we can use wall- or applied-field-stabilized channels to reduce the need for fast risetimes and high voltage, but this issue must be addressed in high-repetition-rate systems.

Table 1. Baseline APEX Beam and Channel Parameters

beam (at the diode):	
ion energy	20 - 36 MeV (ramped)
ion current	2 - 3 MA (ramped)
pulse length	50 - 80 ns
total energy	3 MJ (>6 MJ, Marx upgrade)
peak power	70 - 120 TW
channel:	
length	3 - 6 m
current	75 - 250 kA
plasma density	10^{17} - 10^{18} cm^{-3}
beam density (Li)	10^{14} - 10^{15} cm^{-3}
input diameter	2 - 3 cm
inductance	about 1 μH/m
channel L*Idot	about 10^5 V/m
final focus:	
input:	
diameter	2 - 3 cm
power density	100 - 200 TW/cm^2 peak
output:	
diameter	1 cm
power density	400 - 600 TW/cm^2 peak
energy	1.2 MJ (>3 MJ with upgrade)

Table 2. Results of Some Channel Experiments Show Efficient Transport

Experimenter	channel length (cm)	channel radius (cm)	channel cur. (kA)	beam cur. (kA)	beam accel. (MV)	beam power (TW)	transp. eff. (%)
J.N. Olsen, SNL	50	1	40	300	0.8	0.24	80-90
J.N. Olsen, SNL	100	...	15-40	70	0.8	0.56	50-60
F.L. Sandel, NRL (wall confined)	to 500	.8-2.3	30-50	500	1.4	0.7	to 100
S. Miyamoto, Osaka U.	40	.75	...	200	0.8	.16	70

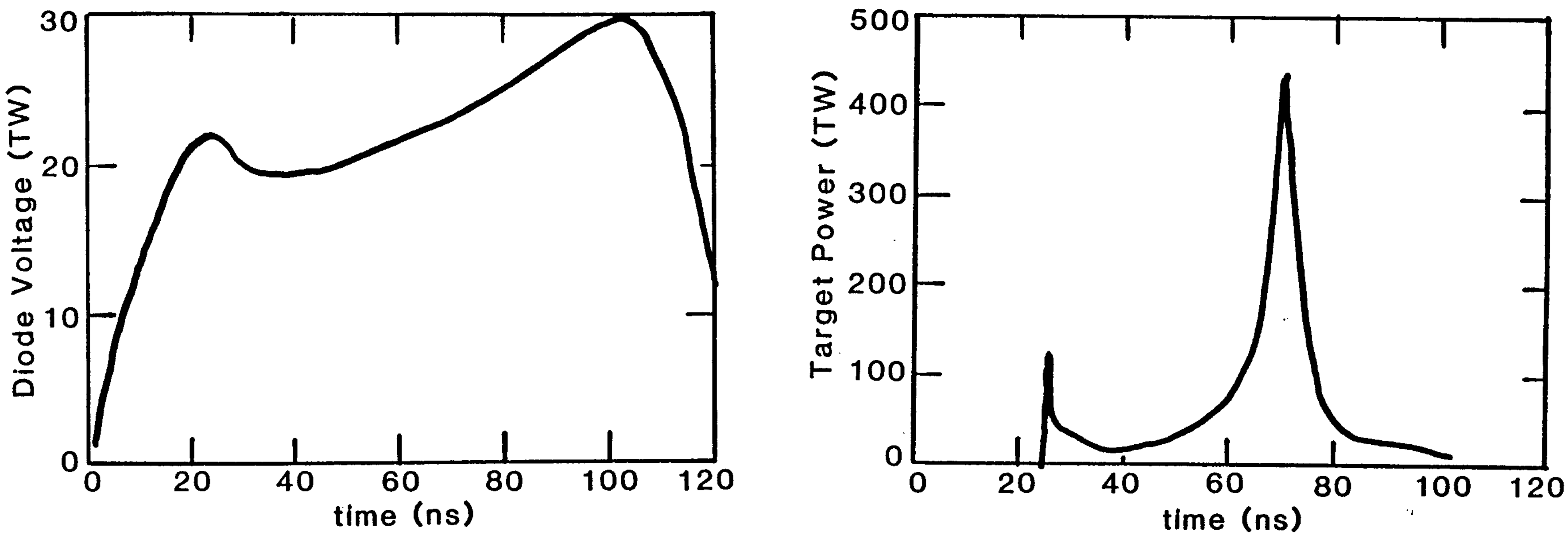


Fig. 5. The required power pulse on target can be achieved by ballistic bunching in the transport channel. For this specific example, the target power shown assumes a constant diode impedance.

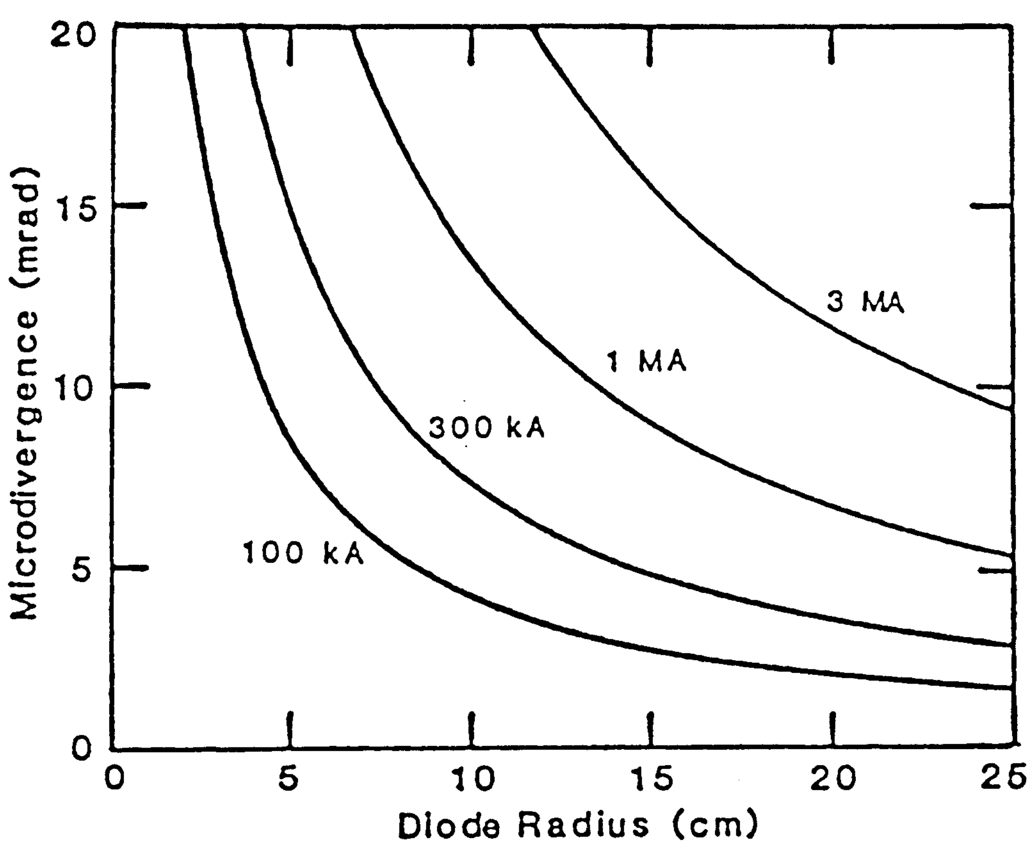


Fig. 6. Curves of channel current required to trap an ion beam of given microdivergence produced in a diode of given radius. The applied current required varies as the square of the product of microdivergence and diode radius.

WATER-SECTION PULSE-FORMING

Pulse shaping will be achieved in the water section of PBFA II using a combination of stubs and tapered lines. These networks must produce the approximately parabolically-ramped voltage required at the ion diode to achieve the proper ballistic bunching. Pulse-forming lines for APEX are being investigated by Pulse Sciences, Inc., San Leandro, CA.

The Marx generators (the primary energy storage) in PBFA II store 13 MJ. We expect the new pulse-forming system to be 25-30% efficient, with approximately 4 MJ delivered to the vacuum insulator from the water lines. Total diode and beam propagation efficiencies are expected to be 30% or better in the APEX system, so that approximately 1.2 MJ will be available on the target. The probability of achieving gain in a fusion target improves rapidly with increasing energy available on target [8]. In conjunction with the redesign of the PBFA II water-insulated pulse-forming lines to provide the appropriate ramped waveform, we will study the cost and benefit of an upgrade of the Marx generators and intermediate storage capacitors to provide a factor of 2 - 3 energy increase.

TARGET CHAMBER

The target chamber must contain the target blast and moderate the radiation output, if significant target outputs are achieved. The surrounding environment must also be designed to confine output radiation and minimize activation. The system must have reasonable accessibility for diagnostics and modifications. The APEX retrofit for PBFA II will be designed for approximately one small yield target shot per month with frequent diagnostic (D-D target) shots between. This makes a small, replaceable target chamber feasible. A preliminary study by TRW [9] has produced a design for a target chamber subsystem which includes a chamber replaced after each high-output shot. This design is shown schematically in Fig. 7.

Since it is not certain that this developmental system will produce the beam necessary for target gain, the system will be assembled and tested through the beam propagation and final focus stages before installation of the full confinement target chamber subsystem.

SYSTEM CONSIDERATIONS

Preliminary target simulations coupled with calculations of ion beam bunching in the transport channel show that a waveform accuracy of 5-10% will be required at the ion diode. The specific accuracy depends on the pulse length and on the channel length needed for a given energy as seen in Fig. 8. Since PBFA II has 36 separate modules which use laser triggered gas switches for timing, the waveform accuracy requirement will place requirements on the synchrony and repeatability of the system. These requirements will be determined by system studies that will include channel propagation effects and the pulse smoothing effects of power flow combination in the vacuum transmission lines feeding the ion diode. In addition, the waveform needed at the target cannot be defined with accuracy by simulations, so the pulse-forming system must be adjustable over 10-20% in voltage output.

Target simulations will determine the pulse shape needed on target, which drives the design of the rest of the system. These simulations will also indicate the probability of achieving gain from a D-T target with PBFA II-APEX, and will be a major factor in the decision to upgrade PBFA II energy storage capability.

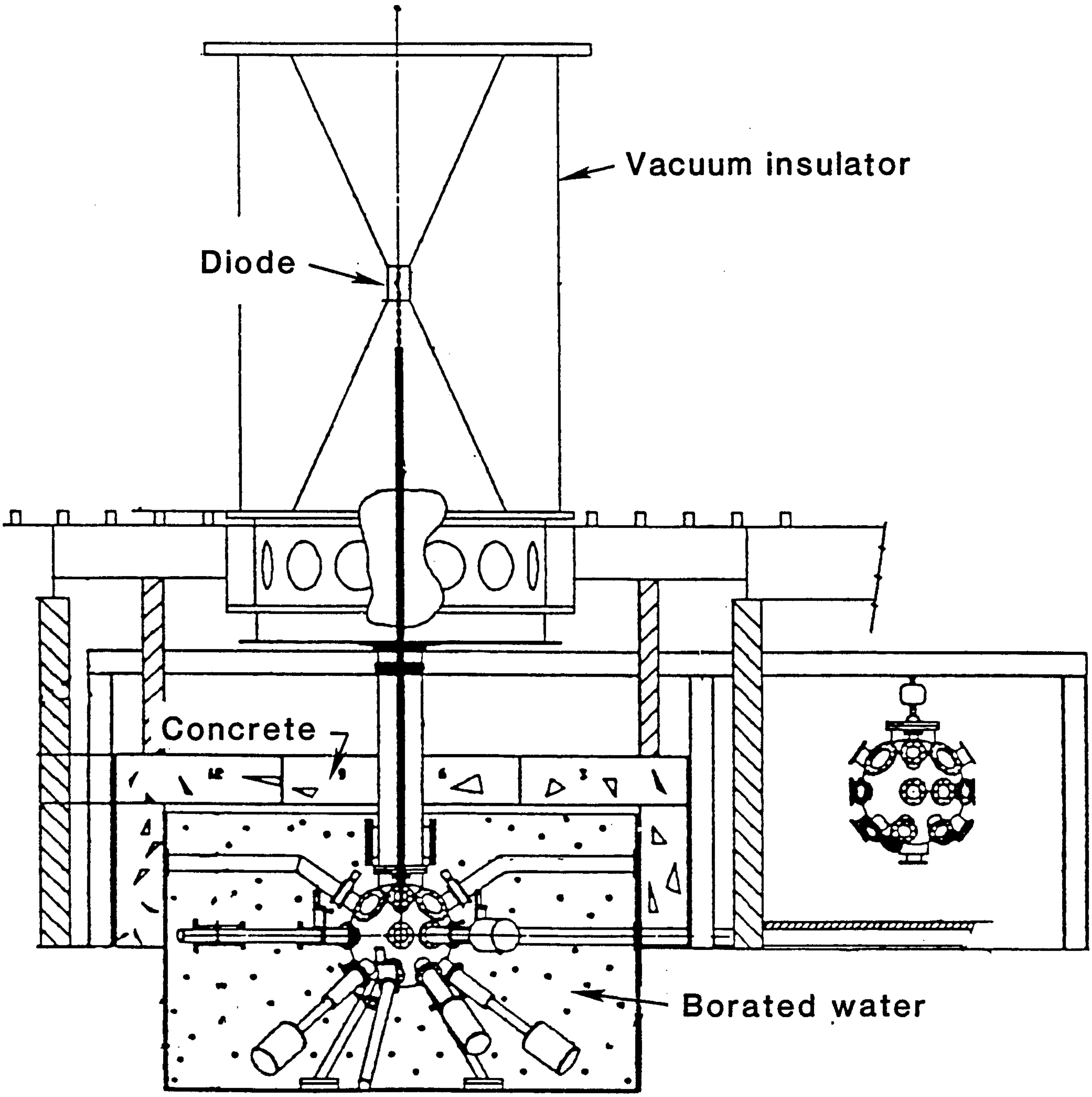


Fig. 7. Schematic diagram of a target chamber installed below PBFA II.

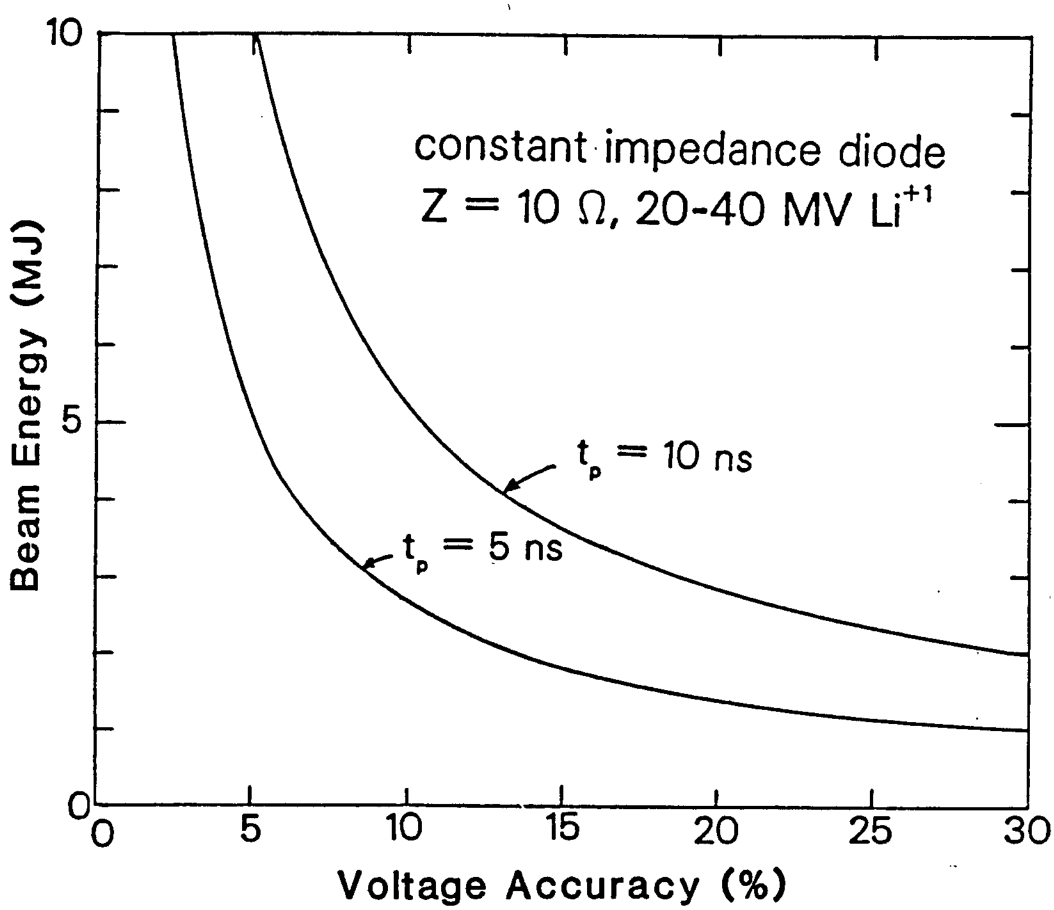


Fig. 8. Voltage accuracy needed at the ion diode as a function of channel length. In this plot, channel length is translated to beam energy, since higher beam energy in the PBFA II application requires a longer diode pulse and a longer channel.

PULSE-SHAPING SYSTEM DEMONSTRATION

As an intermediate step between tests of individual components and installation of the APEX system on PBFA II, we plan to conduct pulseforming experiments on the Hermes III accelerator [10]. This accelerator uses the same pulse power technology tentatively planned for the next generation light ion fusion accelerator [2]. These tests will combine a focusing extraction lithium ion diode with beam propagation and bunching in a plasma channel and focusing on a diagnostic target.

The ion diode will be driven by a shaped power pulse that will have voltage approximately half and energy approximately one third that planned for the next generation accelerator.

SUMMARY

The PBFA II APEX project will develop techniques for producing an ion beam with the pulse shape appropriate for achieving significant gain and energy output from a fusion target. These techniques will be tested on PBFA II, the world's most powerful light ion fusion accelerator, and will be used to study the physics of fusion target compression and heating, with a possibility of achieving target energy gain.

Development of ion beam pulse shaping, efficient extraction ion diodes, and efficient plasma channel transport are essential to progress toward an energy-producing light ion fusion reactor. The APEX project will develop these systems and test them at power and energy levels expected in energy-producing reactors. The ion diode and plasma channel to be used in APEX are types which can be the bases for high-repetition-rate systems. The PBFA II APEX project will be a significant proof-of-principle demonstration of a light-ion pulsed-power module for a fusion energy producing system.

REFERENCES

1. H. Madarame, S. Iwata, S. Kondo, A. Suzuki, K. Miya, Y. Oka, S. Tanaka, M. Akiyama, and M. Uesaka, Nuclear Engineering and Design/Fusion 1, 387 (1984).

2. R.E. Olson, Proc. 11th Symp. on Fusion Eng., Austin, TX, Nov. 18-22, 1985.

3. S.A. Slutz and D.B. Seidel, J. Appl. Phys. 59, 2685 (1986).

4. J.N. Olsen and R.J. Leeper, J. Appl. Phys. 53, 3397 (1982).

5. P.F. Ottinger, D. Mosher, and S.A. Goldstein, Phys. Fluids 23, 909 (1980).

6. T. Ozaki, S. Miyamoto, K. Imasaki, S. Nakai, and C. Yamanaka, J. Appl. Phys. 58, 2145 (1985)

7. K. Yatsui, K. Masugata, T. Nakayama, and M. Matsui, Phys. Lett. 89A, 235 (1982).

8. J.D. Lindl and J.W-K. Mark, Proc. Int. Symp. on Heavy Ion Accelerators and Their Application to Inertial Fusion, Tokyo, Japan, Jan. 23-27, 1984.

9. Final Report, APEX Target Chamber Preliminary Design Project, TRW, University of Wisconsin, and Facilities Systems Engineering Corp., July, 1987.

10. J.J. Ramirez, K.R. Prestwich, E.L. Burgess, J.P. Furaus, R.A. Hamil, D.L. Johnson, T.W.L. Sanford, L.O. Seamons, L.X. Schneider, and G.A. Zawadzkas, Proceedings of the Sixth IEEE Pulsed Power Conference, Arlington, Virginia, June 29-July 1, 1987.

RELATIONSHIP BETWEEN THE TDF AND COMMERCIAL ICF DRIVERS

R.E. Olson
Target Experiments, Division 1263
Sandia National Laboratories
Albuquerque, NM 87185
(505) 846-6892

ABSTRACT

The Target Development Facility (TDF) is envisioned as a testbed for the development of high gain inertial confinement fusion (ICF) targets. A 10 MJ, 300 to 1000 TW light ion TDF driver concept based upon extrapolations from present-day pulsed power technology is described in the present paper. This description is followed by a discussion of the relevance of TDF technology to the eventual commercialization of ICF.

INTRODUCTION

Commercial application of inertial confinement fusion (ICF) will require high gain (>80) fusion targets. It is thought that the development of such targets will require a 5 to 10 year effort utilizing a dedicated nuclear research facility with a driver capable of providing a 10 MJ, 300 to 1000 TW pulse of on-target energy at the rate of at least one target shot per day. This may be accompanied by several "driver" (non-target) shots per day. The high gain Target Development Facility (TDF) is a light ion driven concept for such a facility.[1,2] Some basic parameters of the TDF conceptual design are given in Table 1.

Beyond TDF, progress toward commercial ICF will probably involve an Engineering Test Reactor (ETR)[3] and a demonstration power reactor (DEMO).[4] The ETR will demonstrate the integrated repetitive (~ 1 to 5 Hz) performance of a driver, a fusion target and a reaction chamber under conditions representative of those expected in a commercial power generation system. It is likely that the ETR will, in turn, be followed

Table 1. Basic TDF Parameters

Energy on target	10 MJ
Accelerated ion species	Li^{+1}
Nominal ion energy	30 MeV
Number of main pulse beams	12
Target yield	50 to 800 MJ
Experiment rate	Several driver shots and at least one target shot per day
Target chamber radius	3 m
Target chamber height	6 m
Chamber structural material	Al 6061-T6
Fatigue lifetime	15,000 shots
Service lifetime	7 years

by a DEMO facility in which an integration of the driver and reaction chamber with the balance of plant systems will be demonstrated. Commercial ICF power plants will be developed after successful TDF, ETR, and DEMO programs. This basic progression of research facilities is summarized in Table 2.

The present paper contains a description of a 10 MJ, 300 to 1000 TW light ion TDF driver concept. The design is based upon extrapolations from existing pulsed power technology and might be viewed as a first step in the progression of Table 2. This description is followed by a discussion of the relationship between the TDF pulsed power system and the repetitive driver systems envisioned for light ion versions of the ETR, the DEMO, and commercial ICF power plants.

OVERVIEW OF THE TDF PULSED POWER CONCEPT

The basic layout of the light ion TDF concept is illustrated in Figure 1. Target explosions are contained within a strong target chamber which is, for shielding purposes, immersed in a tank of borated water. Ion extraction diodes are located outside of the chamber, and ion beams are transported through beamports in the chamber wall. The target is located in the center of the chamber and is driven by twelve ion beams which are confined and directed to the target by means of current-carrying plasma channels.

The TDF pulsed power concept[5] (Figure 2) is based upon an upgraded version of the new Hermes-III pulsed power and voltage addition technology.[6] It is anticipated that, for the TDF, magnetic switching technology[7] might be used in place of water switching and that an anode stalk will be used in the voltage addition cavities. The present Hermes-III (Figure 3) is designed to deliver a 16 TW (800 kA at 20 MV), 35 ns power pulse to an electron beam diode. Each beamline in the TDF conceptual design delivers an approximately 55 TW, 30 ns pulse to a Li^{+1} extraction ion diode. The vertically stacked beamline pairs and general pulsed power arrangement depicted in Figure 2 will require

Table 2. Major Facilities Enroute to Commercial ICF

High Gain Target Development Facility (TDF)

- develop high gain (>80) ICF targets
- up to 10 MJ on target
- 300 to 1000 TW, flexible pulse shape
- several shots per day for the driver; at least one target shot per day
- nuclear facility

Engineering Test Reactor (ETR)

- integration of repetitive driver, target, and reaction chamber
- up to 1 Hz rep. rate
- 3 to 4 MJ on target
- low yield targets

Demonstration Power Reactor (DEMO)

- repetitive (3 Hz) driver
- 300 MJ yield
- balance of plant systems
- 300 to 400 MW_e

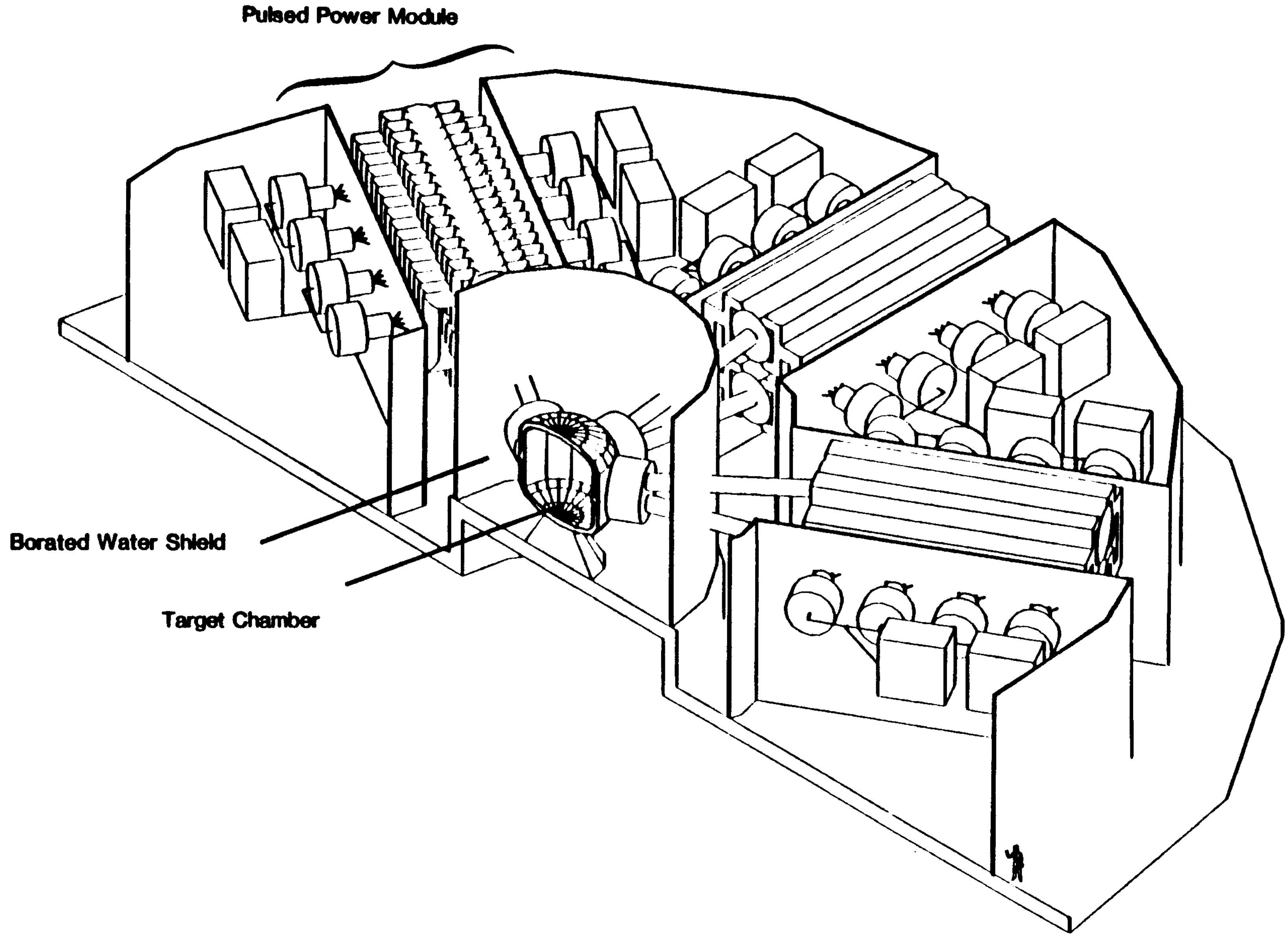


Figure 1.   The light ion high gain TDF concept.

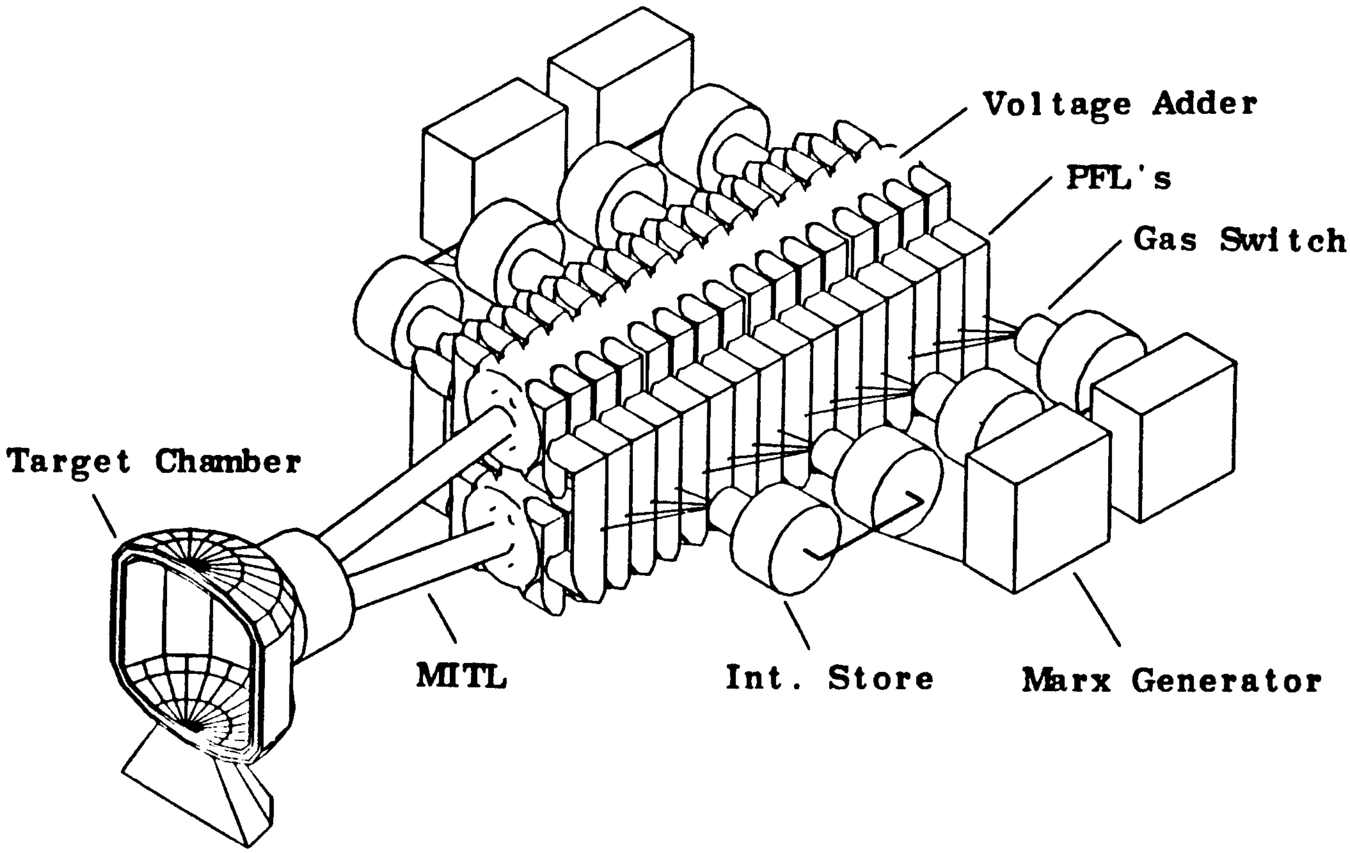


Figure 2. A TDF pulsed power module.

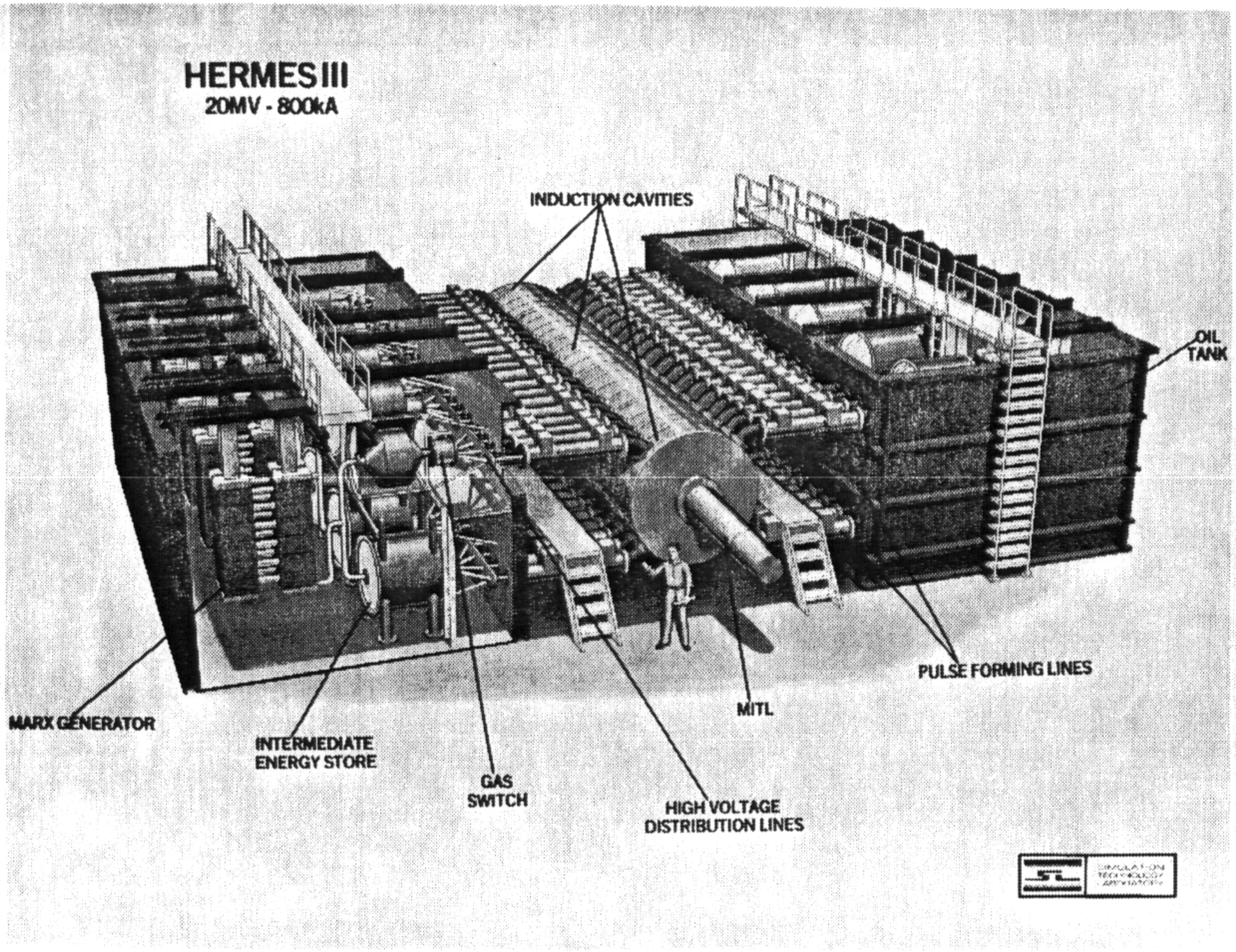


Figure 3. A schematic drawing of the Hermes-III accelerator.

significant advances in all areas of pulsed power technology. Some of the more significant extrapolations from PBFA-II and Hermes-III technology are summarized in Table 3. As indicated in the table, major advances will be required in the areas of positive polarity inductive voltage addition, extraction ion diode technology, ion beam transport in plasma channels, and magnetic switching (if used). Relatively modest advances will be required in the areas of high voltage Marx generators, laser triggered gas switches, and water dielectric pulse forming lines. Simultaneous operation of 12 Hermes-III class accelerators is, of course, a major technological extrapolation in itself.

Each of the TDF extraction diodes focuses into an individual plasma channel. The basic concept is illustrated in Figure 4. Assumptions pertaining to achievable anode current density (7 kA/cm^2), ion source (Li^{+1}), diode voltage (25-35 MV), beam divergence (10 mrad), and pulse width at the diode (30 ns) are similar to those expected for the PBFA-II barrel diode.[8,9] A comparable ion extraction diode is to be developed within the APEX program.[10] It is assumed that each TDF plasma channel (1 to 2 cm diameter, 3 m length) can trap and transport the intense beam of 25-35 MV ions at a reasonably high efficiency (~ 70%) and that a voltage ramp at the diode will result in a "bunching" of the ion beam during its transit through the channel. For the TDF conceptual design, it is assumed that inefficiencies associated with beam generation, focusing, transport, and channel overlap will result in an overall diode-to-target energy loss of about 50%.

PRIME ENERGY STORAGE

Overall, the pulsed power system is expected to be about 35% efficient in its delivery of energy to the ion diodes. Thus, the provision of about 20 MJ to the diodes will require the storage of about 57 MJ in the prime energy store of the accelerator. In the present design concept, this energy is stored in twenty-four 10 MV Marx generators

Table 3. TDF Scaleups from PBFA-II and Hermes-III Pulsed Power Technologies

	Present Technology	TDF Concept
Marx Generators	6 MV, 0.4 MJ	10 MV, 2.4 MJ
Laser Triggered Gas Switches	6 MV, 400 nH	10 MV, 300 nH
Magnetic Switches*	0.2 V s, < 10^2 shots	0.4 V s, > 10^4 shots
Voltage Addition	20 MV, 1 MV/cavity, negative polarity	30 MV, 2 MV/cavity, positive polarity
Extraction Diode⁺	1.2 MV, 0.3 MA	30 MV, 1.8 MA
Plasma Channels	30 kA, 1 m	100 kA, 3 m
Beam Transport	0.06 MA, 0.8 MeV (protons)	1.5 MA, 30 MeV (lithium)

---

*water switching may be adequate for the TDF driver

⁺a 30 MV, 5 MA barrel diode is being developed in PBFA-II

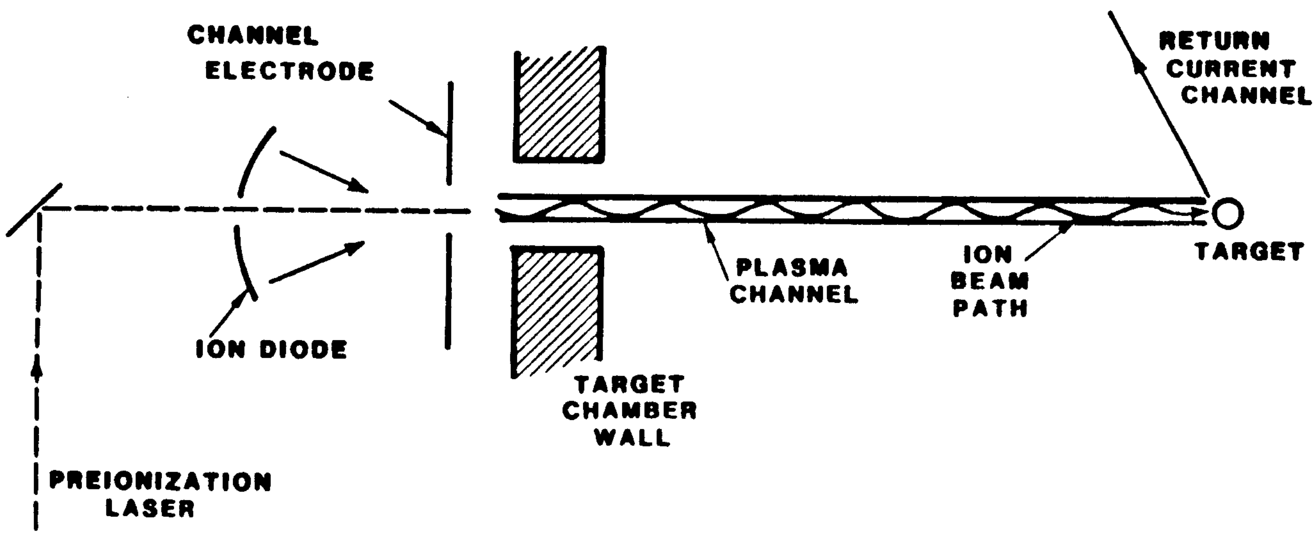


Figure 4. Channel formation and ion beam propagation concepts.

(four Marxes per beamline pair). Each Marx is constructed of ninety-six 5 μF, 100 kV capacitors along with forty-eight 200 kV spark gaps.

The Marxes are configured as 48 stages hung from insulating supports in six rows of eight stages. The overall dimensions of such a Marx will be approximately 3.6 m high x 3.6 m long x 1.8 m wide. Assuming a 30 nH internal inductance per capacitor, a 20 nH inductance per switch, and a geometric inductance of 110 nH per stage, leads to an estimate of 9.5 μH total inductance per Marx. With output switches in the armed position, the Marx is connected to a pair of oil-dielectric transfer lines which feed two of the eight water-dielectric intermediate storage capacitors associated with each beamline pair.

INTERMEDIATE STORES AND GAS SWITCHES

Each intermediate storage capacitor is approximately 2.8 m in diameter and 2.1 m long. The inner conductors are 1.8 m in diameter and are held in place via oil-water barriers at either end. The overall capacity of each intermediate store is about 26 nF. The inner conductor of each intermediate store terminates in a multistage, multichannel laser triggered gas switch of the PBFA-II "Rimfire"[11] type of construction.

The TDF triggered switches must be designed to hold off a rising (10 MV, peak) voltage for over 1 μs and to switch on command with a jitter of less than 1 ns. Each switch must pass a peak current of about 400 kA through an inductance of ≤ 300 nH. A brief design study of a comparable switch concept was recently conducted for the Aurora accelerator program.[12]

PULSE COMPRESSION LINES AND MAGNETIC SWITCHES

Each laser-triggered switch is connected to the inner conductors of four coaxial, water-dielectric transmission lines. Each of these 6 ohm lines (1.2 m O.D., 0.5 m I.D.)

leads to a pair of "first" magnetic switches. A "double bounce" charging scheme[13] is used to charge these lines to about 6.5 MV.

The first magnetic switch must hold off the rising voltage wave for approximately 140 ns. Thus, a conservative design calls for a 0.4 V s holdoff. Output from the first magnetic switch feeds into a pair of 4 ohm (1.0 m O.D, 0.5 m I.D.) second PFL's. These lines are double bounce charged to a 4.4 MV peak voltage and are terminated in a pair of 0.2 V s magnetic switches.

The TDF magnetic switch V s requirements represent a relatively modest extrapolation from COMET-II hardware.[7] The TDF magnetic switch lifetime requirements do, however, call for an ambitious research effort.[14]

INDUCTIVE VOLTAGE ADDITION

The TDF voltage addition scheme is based upon the concept of inductive voltage addition with time isolation provided by magnetic Metglas cores[15] (as in Hermes-III). Each cavity is 1.3 m long with an O.D. of 3 m. The ferromagnetic region of each cavity consists of four Metglas cores (0.3 m long, 1.8 m O.D., 1.1 m I.D., 0.5 packing fraction). The voltage feed gaps are located at a radius of 46 cm from the centerline of the magnetically insulated transmission line (MITL). The "outer" end (the end farthest from the target chamber) of the anode stalk is 44 cm in radius. Moving inward (towards the target chamber), the stalk tapers to a radius of 26 cm. In this manner, the MITL impedance gradually increases so as to match the effective output impedance of the cavities added in series. Each beamline is fed by sixteen 2 MV induction cavities. A voltage ramp is generated by means of a delayed feed to the final four cavities. This TDF voltage addition scheme represents a fairly significant scaleup of the existing 20 MV, 800 kA Hermes-III accelerator.[6] The concept of efficient voltage addition in positive polarity (Hermes-III is designed for negative polarity) will require experimental verification.

This question will be addressed in upcoming experiments on the Helia and Hermes-III accelerators.

EXTRACTION DIODE PARAMETERS

An ion extraction diode is attached to the end of each 16 ohm (effective impedance) MITL. The anode annulus has an O.D. of about 20 cm and an I.D. of 14 cm (Figure 5). The diode is driven by a 1.8 MA, ramped voltage (25-35 MV) pulse of about 30 ns duration. An applied radial B-field insulates the anode and establishes a virtual cathode of electrons. It is envisioned that Li^{+1} ions will be emitted from a liquid lithium coated anode surface via an electrohydrodynamic (EHD) process.[16] The Li^{+1} beam is ballistically focused over a distance of about 75 cm to the entrance of a current-carrying plasma channel (Figures 4 and 5).

A diode such as the one envisioned above represents a very large extrapolation from the present technology base. Recent applied-B extraction diode experiments have operated at the 1.2 MV (protons), 0.3 MA level.[17] The high energy (25 to 35 MV), high intensity (anode current density 7 kA/cm^2), low microdivergence (10 mrad) TDF parameters are, however, very similar to the anticipated performance levels of the PBFA-II applied B barrel diode.[9] Issues related to the extraction of a high power ion beam, EHD ion sources, and focusing into a current-carrying plasma channel will be addressed within the APEX program.[10]

PLASMA CHANNEL TRANSPORT

The laser-guided plasma channel and ion beam transport concepts envisioned in the TDF design represent the technologies that are probably the furthest removed from the present technology base. The concept (illustrated in Figure 4) relies upon the scheme of laser-reduced breakdown voltage in a 5-20 torr background gas. Following breakdown,

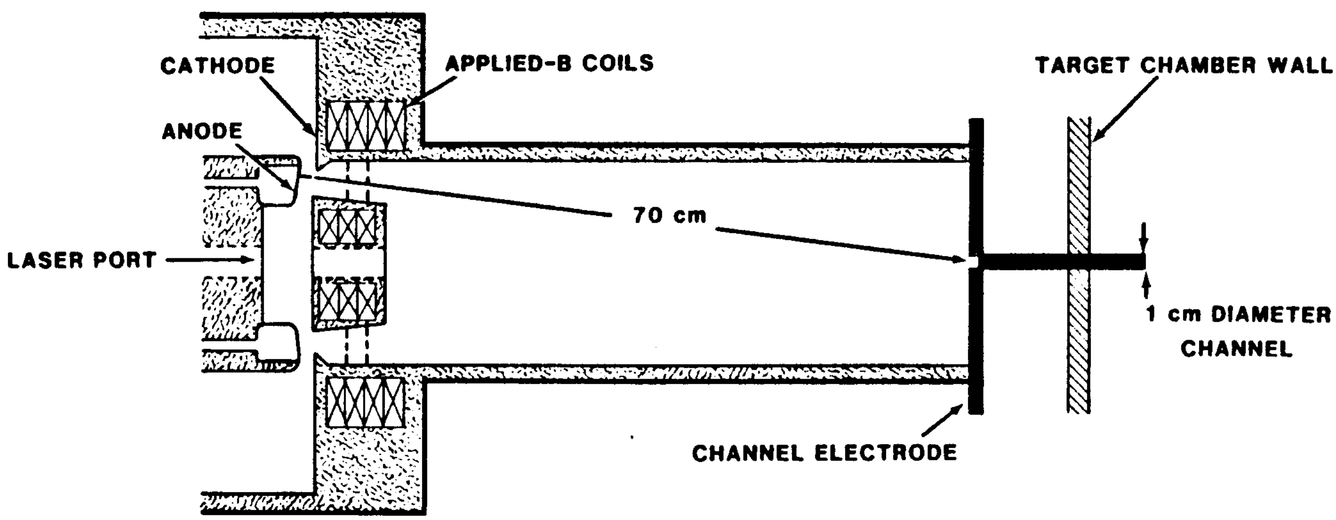


Figure 5. The TDF ion diode concept.

the channel current is ramped up to about 100 kA (a current which is sufficient to confine a 30 MV, fully-stripped Li^{+3} ion in a 1 to 2 cm diameter channel). Assuming a focusing efficiency of 80%, approximately 44 TW of high energy ion beam power is trapped at the entrance of each plasma channel.[18] It is anticipated that each beam will bunch to an idealized level of 100 TW during its transit through the 3 m long plasma channel, but that energy loss mechanisms will degrade the beam's peak power to about 80 TW.

In theory, it would appear that there are several fundamental limitations on the beam power transportable in a plasma channel.[19] It is thought that such limitations might be imposed by induced E-field and collisional energy loss, JxB expansion of the channel, or beam-channel instabilities. There is, of course, also the possibility that the channel will become MHD unstable prior to reaching the required driven current level. The required plasma channel and beam transport technologies are beyond the "proof-of-principle" stage (i.e., 0.05 TW in a 1 m laser-initiated channel has been demonstrated[20]), but are about two orders of magnitude removed from present-day capabilities. A research program with the goal of developing a PBFA-II channel transport system that meets TDF requirements is, however, presently underway.[10]

PULSE SHAPING

High gain ICF targets will require a precisely shaped driver pulse. As a testbed for such targets, the TDF driver should be extremely flexible in its pulse shaping capability. In principle, shaped pulse forming lines can be used to generate an on-target light ion beam pulse consisting of an initial primer pulse (< 100 TW) followed by a carefully tailored main power pulse (300 to 1000 TW). Calculations demonstrating the feasibility of such a "two pulse" output for a system of stubs and tapered lines in the PBFA-II water section have been presented in Reference 10. For the TDF, additional pulse shaping flexibility might be provided through staggered timing of the individual beamlines or a modification of the voltage adders to provide a secondary, low voltage primer pulse diode system. An ongoing research program with the goal of demonstrating appropriate light ion pulse shaping technologies is described in References 10 and 21.

EXTRAPOLATION TO ETR, DEMO, AND COMMERCIAL ICF DRIVERS

Clearly, the development of high gain ICF targets and the establishment of driver pulse shape requirements are necessary steps toward the commercialization of ICF. In addition, information concerning high gain target neutronics, wall loading, material vaporization, and cavity gas behavior[22,23] will supply important input for any commercial ICF reactor chamber design. Thus, as a testbed for the development and understanding of high gain targets, the TDF will play a key role enroute to an ICF power reactor -- regardless of driver choice (e.g., gas laser, glass laser, heavy ions, or light ions).

For the light ion ETR,[3] DEMO,[4] and LIBRA power reactor[24,25] concepts, TDF-related advances in light ion driver technology will be of great significance. As might be expected, these design concepts utilize a number of the above-described TDF pulsed power technologies. Water pulse forming lines, magnetic switching, magnetically insulated inductive voltage addition, and magnetically insulated transmission lines are key components of the pulsed power systems. The development of high power extraction ion diodes and plasma channel ion beam transport techniques will also be required for the ETR, DEMO, and LIBRA concepts.

The basic operating parameters of the ETR (depicted in Figures 6 and 7) are summarized in Table 4. The concept utilizes eight magnetically insulated extraction ion diodes which focus 30 MeV lithium ion beams into laser initiated plasma channels. The channels concentrate the ion beam power onto a low yield ICF target. The ion source is

Table 4. Engineering Test Reactor Parameters (from Reference 3)

Target Yield	30 MJ
Target Gain	10
Energy Absorbed at Target	3 MJ
Accelerated Ion Species	Li^{+1}
Nominal Ion Energy	30 MeV
Beam Transport	preformed plasma channels
Transport Distance	3 m
Number of Beams	8
Repetition Rate (burst mode)	1 Hz
Neutron Flux (burst mode)	0.5 MW/m^2
Lifetime Neutron Fluence	0.15 $MW\text{-}y/m^2$

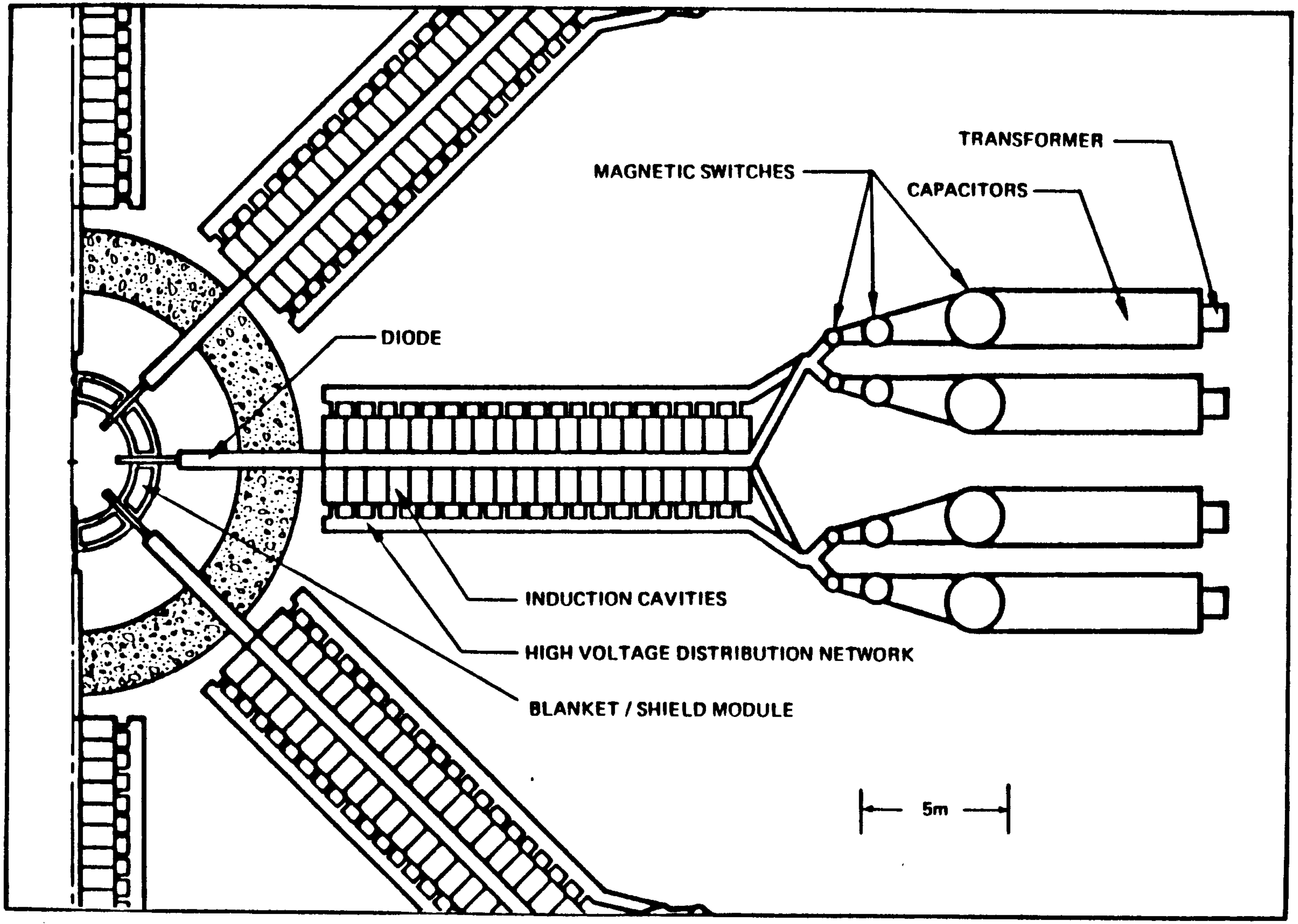


Figure 6. Overhead view of the ETR concept (from Reference 3).

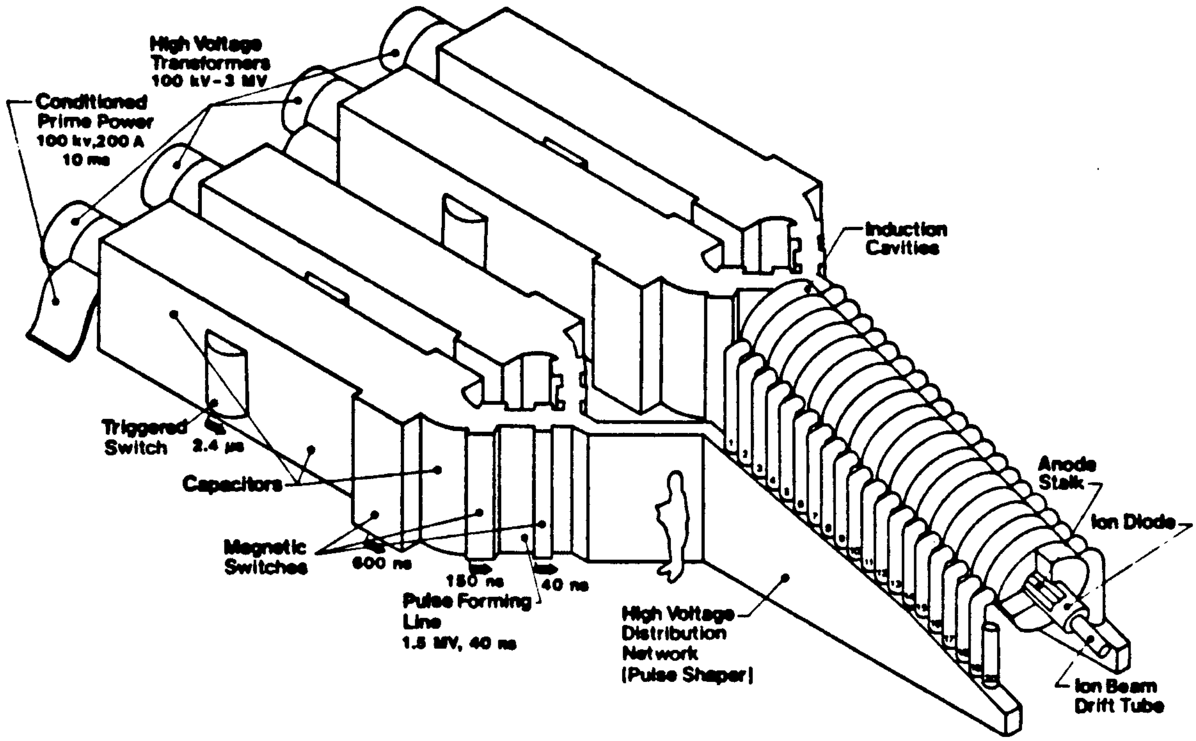


Figure 7. Illustration of an ETR pulsed power module (from References 3 and 26).

a continuously replaceable liquid lithium film, and the diode is cooled by circulating the lithium. As described in References 26 and 27, a 30 MV electrical pulse is supplied to the diode via a magnetically insulated transmission line from a linear induction voltage adder. The twenty stage adder receives 40 ns pulses at 1.5 MV from a series of magnetically switched pulse forming networks. The prime power is delivered by rotating energy storage, conditioned by step-up transformers, and synchronized with laser-triggered gas switches. It is envisioned that each pulsed power module in the ETR concept will provide a 25 TW electrical pulse to its ion diode load.

In the DEMO and LIBRA concepts, an integration of the ETR functions of repetitive driver, fusion target, and reaction chamber with the balance of plant systems will be required. The LIBRA concept (which is currently an ongoing conceptual design study) utilizes a number of the aforementioned TDF pulsed power components. These include water pulse forming lines, magnetic switches, magnetically insulated voltage adders, extraction ion diodes, and plasma channel ion beam transport. Thus, although the TDF (~ several high gain experiments per day) is not a high rep-rate facility, it will be a key facility in the development of commercially relevant ICF pulsed power technologies.

CONCLUSIONS

A 10 MJ, 300 to 1000 TW light ion beam pulsed power driver concept for application in a high gain TDF has been described. The pulsed power concept is based upon the new Hermes-III[6] high power voltage addition technology. The system converts a 57 MJ prime energy store into twelve 30 ns, 1.65 MJ (20 MJ total) ramped voltage (25 to 35 MV) extraction ion diode feeds. It is anticipated that appropriate ion extraction diode and plasma channel technologies will be developed in conjunction with the ongoing APEX program.[10,21]

The TDF is viewed as a major step enroute to commercial ICF. A number of TDF pulsed power technologies are envisioned as key components in the design of light ion driven ETR, DEMO, and ICF reactor concepts. In addition, TDF target physics, neutronics, and wall loading information will most certainly be crucial in the design of any ICF power plant -- regardless of driver choice.

ACKNOWLEDGMENTS

Helpful comments and suggestions were provided by D.L. Cook of Sandia National Laboratories, and G.A. Moses and R.R. Peterson of the University of Wisconsin.

REFERENCES

1. D.L. Cook, "Preliminary Conceptual Design and Engineering Aspects of a Light Ion Fusion Target Development Facility (TDF)," Proc. 9th Symp. on Eng. Problems of Fusion Research, IEEE Pub. 81CH1715-2, p. 664 (1981).

2. R.E. Olson, D.L. Cook, G.A. Moses, D. Bruggink, R.L. Engelstad, D.L. Henderson, E.G. Lovell, R.R. Peterson, M.E. Sawan, O. Yasar, "Conceptual Design of a High Gain Target Development Facility," Proc. 12th Symp. on Fusion Engineering, Monterey, CA, Oct. 12-16, 1987.

3. S.L. Thomson, D.L. Cook, R.R. Peterson, W. Allen, "Light Ion System Analysis and Design -- Engineering Test Reactor Development Plan," EPRI Rpt. EPRI AP-3853-2, March, 1985.

4. J. Benford, W. Allen, "Light Ion System Analysis and Design -- Commercial Demonstration Reactor Preconceptual Design," EPRI Rpt. EPRI-3853-1, March, 1985.

5. R.E. Olson, "Conceptual Design of a 10 MJ Driver for a High Gain Target Development Facility," Proc. 12th Symp. on Fusion Engineering, Monterey, CA, Oct. 12-16, 1987.

6. J.J. Ramirez, K.R. Prestwich, E.L. Burgess, J.P. Furaus, R.A. Hamil, D.L. Johnson, T.W.L. Sanford, L.O. Seamons, L.X. Schneider, G.A. Zawadzkas, "The Hermes-III Program," Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, June 29, 1987.

7. E.L. Neau, T.L. Woolston, K.J. Penn, "COMET-II: A Two-Stage, Magnetically Switched Pulsed Power Module," Proc. 16th IEEE Power Modulator Symp., IEEE Pub. 84CH2056, p. 292 (1984).

8. B.N. Turman, T.H. Martin, E.L. Neau, D.R. Humphreys, D.D. Bloomquist, D.L. Cook, S.A. Goldstein, L.X. Schneider, D.H. McDaniel, J.M. Wilson, R.A. Hamil, G.W. Barr, J.P. VanDevender, "PBFA-II, A 100 TW Pulsed Power Driver for the Inertial Confinement Fusion Program," Proc. 5th IEEE Pulsed Power Conf., Arlington, VA, June 10-12, 1985.

9. J.P. VanDevender, J.A. Swegle, D.J. Johnson, K.W. Bieg, E.J.T. Burns, J.W. Poukey, P.A. Miller, J.N. Olsen, G. Yonas, "Decreased Beam Divergence in Proof-of-Principle Experiment for the Light Ion Beam Fusion Facility PBFA-II," Laser and Particle Beams, 3, 93 (1985).

10. J.T. Crow, G.O. Allshouse, E.L. Neau, C.L. Olson, S.A. Slutz, "The APEX Pulse Shaping Project for PBFA-II," Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, June 29, 1987.

11. D.R. Humphreys, K.J. Penn, J.S. Cap, R.G. Adams, J.F. Seamen, B.N. Turman, "Rimfire: A 6 MV Laser-Triggered Gas-Filled Switch for PBFA-II," Proc. 5th IEEE Pulsed Power Conf., Arlington, VA, June 10-12, 1985.

12. B.N. Turman, D.R. Humphreys, R.A. Hamil, J.F. Seamen, K.R. Prestwich, T.H. Martin, F.T. Warren, G. Frazier, "Design Study for a 12 MV, Low-Jitter Switch for Aurora," Sandia Lab. Rpt. SAND86-0061 (1986).

13. I.D. Smith, "Rapid Pulse Charging of Transmission Lines," Pulse Sciences, Inc. Rpt., April, 1981.

14. H.C. Harjes, et al., "Investigations into the Design of Multi-Terawatt Magnetic Switches," Proc. 6th IEEE Pulsed Power Conf., Arlington, VA, June 29, 1987.

15. I.D. Smith, "PIB Reactor-Driver Design Based on Small Sub-Modules," Pulse Sciences, Inc. Rpt., August, 1979.

16. A.L. Pregenzer, "Electrohydrodynamically Driven Large Area Liquid Metal Ion Sources," J. Appl. Phys., 58, 4509 (1985).

17. D.J. Johnson, J.P. Quintenz, M.A. Sweeney, "Electron and Ion Kinetics and Anode Plasma Formation in Two Applied B_r Field Diodes," J. Appl. Phys., 57, 794 (1985).

18. J.J. Watrous, R.E. Olson, "Ion Beam Trapping in Plasma Channels for Light Ion ICF," Fusion Technology, 10, 664 (1986).

19. P.F. Ottinger, S.A. Goldstein, D. Mosher, "Constraints on Transportable Ion Beam Power," NRL Mem. Rpt. 4948, Nov., 1982.

20. J.N. Olsen, R.J. Leeper, "Ion Beam Transport in Laser Initiated Discharge Channels," J. Appl. Phys., 53, 3397 (1982).

21. J.T. Crow, "Pulse Shaping for Light Ion ICF: The APEX Project," these proceedings.

22. R.R. Peterson, R.L. Engelstad, D.L. Henderson, E.G. Lovell, G.A. Moses, M.E. Sawan, O. Yasar, "Target Chamber Designs for the Light Ion Fusion Target Development Facility," Proc. 12th Symp. on Fusion Engineering, Monterey, CA, Oct. 12-16, 1987.

23. O. Yasar, M.E. Sawan, D.L. Henderson, G.A. Moses, "Neutron Activation in the Light Ion Fusion Target Development Facility," Proc. 12th Symp. on Fusion Engineering, Monterey, CA, Oct. 12 16. 1987.

24. B. Badger et al., "Annual Progress Report for the LIBRA Light Ion Beam Fusion Reactor Project," Fusion Power Associates Rpt. FPA-85-5, Dec., 1985.

25. I. Smith, D. Garofalo, H. Nishimoto, W. Weseloh, "Design of a 20 MV, 240 TW Ion Beam Driver for an Inertial Fusion Reactor," Pulse Sciences, Inc. Rpt. PSI-TR-224-1, Sept., 1985.

26. K.R. Prestwich, M.T. Buttram, "Repetitive Pulsed Power Technology for Inertial Confinement Fusion," Nuclear Technology/Fusion, 4, 945 (1983).

27. M.T. Buttram, "Repetitive Pulse Accelerator Technology for Light Ion Inertial Confinement Fusion," IEEE Trans. on Nuclear Science, NS-32, 1571 (1985).

REPETITIVE PULSED POWER FOR COMMERCIAL REACTORS

Malcolm T. Buttram
Sandia National Laboratories, Div. 1248
P. O. Box 5800
Albuquerque, NM 87185

INTRODUCTION

This paper will attempt an extrapolation from today's state-of-the art in pulsed power to pulsed power systems suitable for operation of a commercial ICF reactor. A reactor grade pulsed power system will be defined as one delivering 10 MJ to the target in a shaped 10 ns pulse at several 10's of megavolts. This would be repeated at a rate up to 10 Hz. Furthermore, the system would have to be efficient, long lived, and require a minimum of maintenance.

"Efficient" can be quantified somewhat because it is coupled to reactor economics through the recirculated power fraction, F. Generally, it is unacceptable for the recirculated power to exceed 25% of the total electrical output of the reactor. The product of F with the efficiency for converting the recirculated power to beam on the ICF target (E_c) times the target gain (G) times the thermal-to-electrical conversion efficiency (E_t) is constrained by the relation

$$F\, E_c\, G\, E_t = 1\,. \tag{1}$$

For typical values (G=50, E_t=0.35), E_c must exceed 23%. A big uncertainty exists in the efficiency E_c which is the product of the pulsed power efficiency with the efficiencies for beam production, transport, and targeting. If we assume that each of these latter three processes is approximately 70% efficient, then the pulsed power system efficiency for converting "wall plug" power to a power pulse at the diode will be satisfactory if it equals at least 70% as well.

"Long lived" and "minimum maintenance" are much harder to quantify. At 10 Hz, a reactor would produce 864,000 pulses per day. One might assume that long lived means a large multiple of this number, $3x10^8$ to $6x10^9$ for 1 to 20 years, for example. However, a long life might be achieved with periodic servicing, such as exchanging old switches. At this point it becomes very difficult to quantify the amount of servicing that is acceptable. This will be discussed with regard to some specific components in the remainder of the paper.

There are two data bases which may be used to extrapolate from state-of-the-art to the ICF pulsed power reactor requirements. The first comes from the high power single pulse machines such as PBFA [Turman, 1985], Blackjack [Miller, 1983], and Pithon [Sincerny, 1983]. All use Marx generators (which employ gas spark gaps as their switching elements), water pulse forming lines for low impedance, liquid spark gap switches as the fast pulse forming element, and plastic liquid-vacuum interfaces that are the weak link in the flow of power to the load. These single shot systems have been developed with energies that are within an order of magnitude of the energy and power required for ICF, but they are designed with some components that do not extrapolate to reactors, typically liquid spark gap switches. Furthermore, they do not generate 10 ns pulses nor have they demonstrated the voltage control required for bunching to 10 ns as of this time. The second data base comes from repetitive pulsed power systems. These devices generally will perform at 10 Hz but are three or four orders of magnitude too low in energy and power. The requisite pulse length and/or voltage waveform control have yet to be demonstrated. Nevertheless, it is necessary to design with components that have demonstrated repetitive capability when developing a reactor concept, recognizing that the number of such components required raises the question of whether they have the reliability for this service.

Neither data base contains information on the operation of systems with the multiple 10's of megavolts rating. The first opportunity to gain that type of data will come with operation of the HERMES III 20 MV system during the next year [Ramirez, 1987]. "HERMES III" in this context is a technology for taking N identical pulses and adding them to produce N times the voltage of a single pulse at the single pulse current. It does not address how those pulses were formed in the first place. Because the HERMES III technology looks like the best candidate to achieve the very high voltages required for light ion ICF, the remainder of this paper will discuss repetitive pulsed power in the context of a HERMES III based ICF reactor accelerator.

GENERATION OF HIGH VOLTAGE, SHAPED PULSES

HERMES III is a gamma ray simulator; that is, it is an electron accelerator as it is being built at present. The basic design is illustrated in Fig. 1 which shows 20 cavities, each pulsed by a driver (voltage V_S, internal impedance Z_S), and each delivering its pulse to a common transmission line which is referred to as a MITL (magnetically insulated transmission line) in the figure. The pulse is actually "shorted" by an alternate path to ground in each cavity, but the path encloses a ferromagnetic core as shown in the leftmost cavity of Fig. 1. These cores prevent the "short" from drawing significant power by rendering it very inductive. Thus this type of structure is generally referred to as an induction accelerator. (The voltage in the cavity is "supported" by the magnetic flux change in the ferromagnetically loaded cavities.) Ideally, the MITL impedance increases by Z_l (Z_l=Z_S) at each cavity which results in all of the input power flowing forward toward the load in a wave having a current equal to $V_S/2Z_S$ and a voltage equal to $20(V_S/2)$ at the end of the MITL. In reality, this idealization can be very nearly achieved as has been demonstrated on a 4 MV prototype of HERMES III called HELIA [Ramirez, 1985].

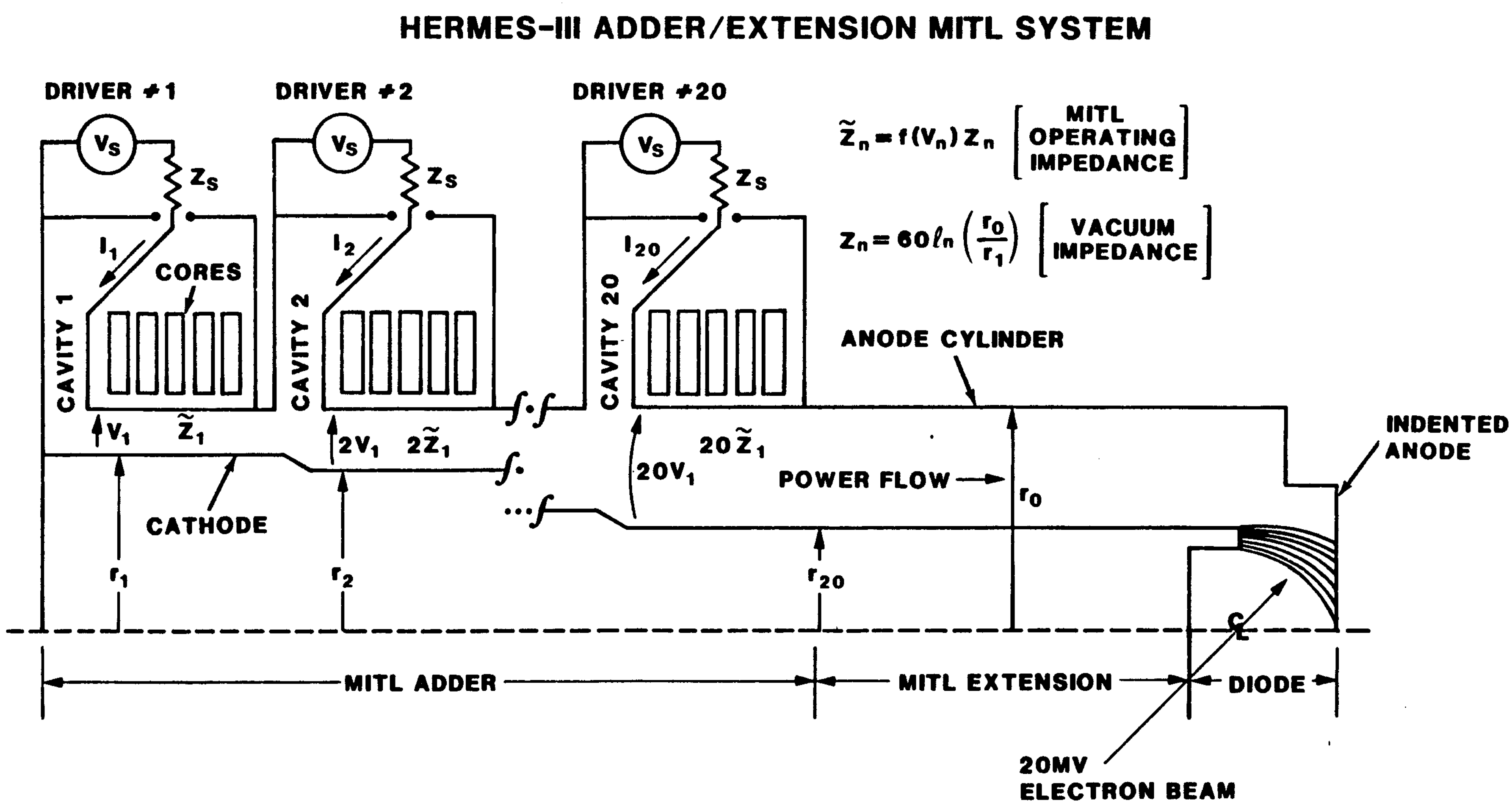


Figure 1. Schematic of the HERMES III adder including the isolation cavities, magnetically insulated transmission line (MITL) and an electron beam load.

In HERMES III, V_S=2 MV, Z_S=1.25 ohm, and the current is 800 kA. Altogether there are 20 stages of adder for a output voltage of 20 MV nominal. The output pulse width is about 40 ns (FWHM) and the energy per pulse is projected to be 650 kJ. Increasing the number of cavities by 50% (to 30) would increase the voltage to 30 MV as required for ICF using lithium ions. The pulse energy would then be 1 MJ. For the efficiency factors assumed earlier, the total electrical energy delivered to the reactor beam diode(s) would have to be 30 MJ; so the proposed baseline system would require 30 enhanced HERMES IIIs operating in parallel at 10 Hz. Limitations on the number of beams that can be targeted might force the size of the individual modules to be increased, but overall this does not appear to be an unreasonable goal. For the purposes of this paper it is assumed that this type of device can be made to meet these specifications in positive polarity load, as is required for ICF. (It will be tested in negative polarity, as required for a simulator, initially. Negative polarity is more conducive to stable magnetically insulated power flow in this type of structure than is positive polarity; so this may not be a stringent test.)

In this proposed design, there are a total of 900 individual cavities, and each needs to have a "pulser" to provide its power. Nominally each pulser is to deliver 1 MJ at 1 MV within 10 ns to a matched load. In fact, there are at least two complications. The power pulse on target needs to be carefully shaped to drive the target with a minimum of energy. The general shape required is an upward ramp in the power as a function of time. This could be accomplished by generating a somewhat triangular pulse, but this results in wasting the half of the pulse energy that arrives after the power peak, which is undesirable. The second complication arises because current pulser technology cannot generate shaped (or unshaped) 10 ns pulses. As a result, typical system designs use a longer pulse (around 40 ns) with a voltage waveform that ramps upward. Ions generated later in the pulse overtake those that were generated early in order to create a 10 ns pulse on target (a process referred to as "bunching"). Of course, the ions must be bunched to arrive at the target with the carefully tailored 10 ns shape referred to above, which could be very difficult to accomplish. Fortunately, it is possible to avoid part of the shaping that might otherwise be required of the pulses at the individual cavities by suitably tailoring their arrival times [Prestwich, 1983; Buttram, 1985]. Thus the problem is reduced to the generation of 900 identical pulses with suitable synchrony. How that might be accomplished is the subject of the remainder of this paper.

GENERATION OF MEGAVOLT PULSES

There are two generic extreme approaches for the design of the megavolt pulsed power system for this application. One could generate a few (N) synchronized pulses totalling 30 MJ, then split them into 900 parts and inject those pulses into the adders. This is Option 1. Included in it is the possibility of producing many small pulses which are added to form the large pulses then split [J.J. Ramirez, private communication]. This apparently awkward scheme has the advantage of homogenizing the outputs from the several pulsers so that each of the power pulses at the beam diodes is identical with all the other power pulses and all are synchronized with essentially arbitrarily good accuracy. This is extremely important because the bunched beams must arrive at the target with a timing spread that is some small fraction of their 10 ns width.

Option 2 is to generate each of the 900 pulses separately, probably at the cavities. In this case, timing jitter in the switching translates into pulse distortion and into jitter among the 30 accelerator outputs. The advantage of this scheme is that the complicated problem of adding and/or splitting multiple 1 MV, 40 ns pulses is avoided.

To evaluate Option 1 further, consider the scenario diagrammed in Fig. 2. For the sake of clarity, define each of the 30 HERMES III adder assemblies to be a module, and define each of the 30 cavities that make up a module to be a submodule. In Fig. 2 one

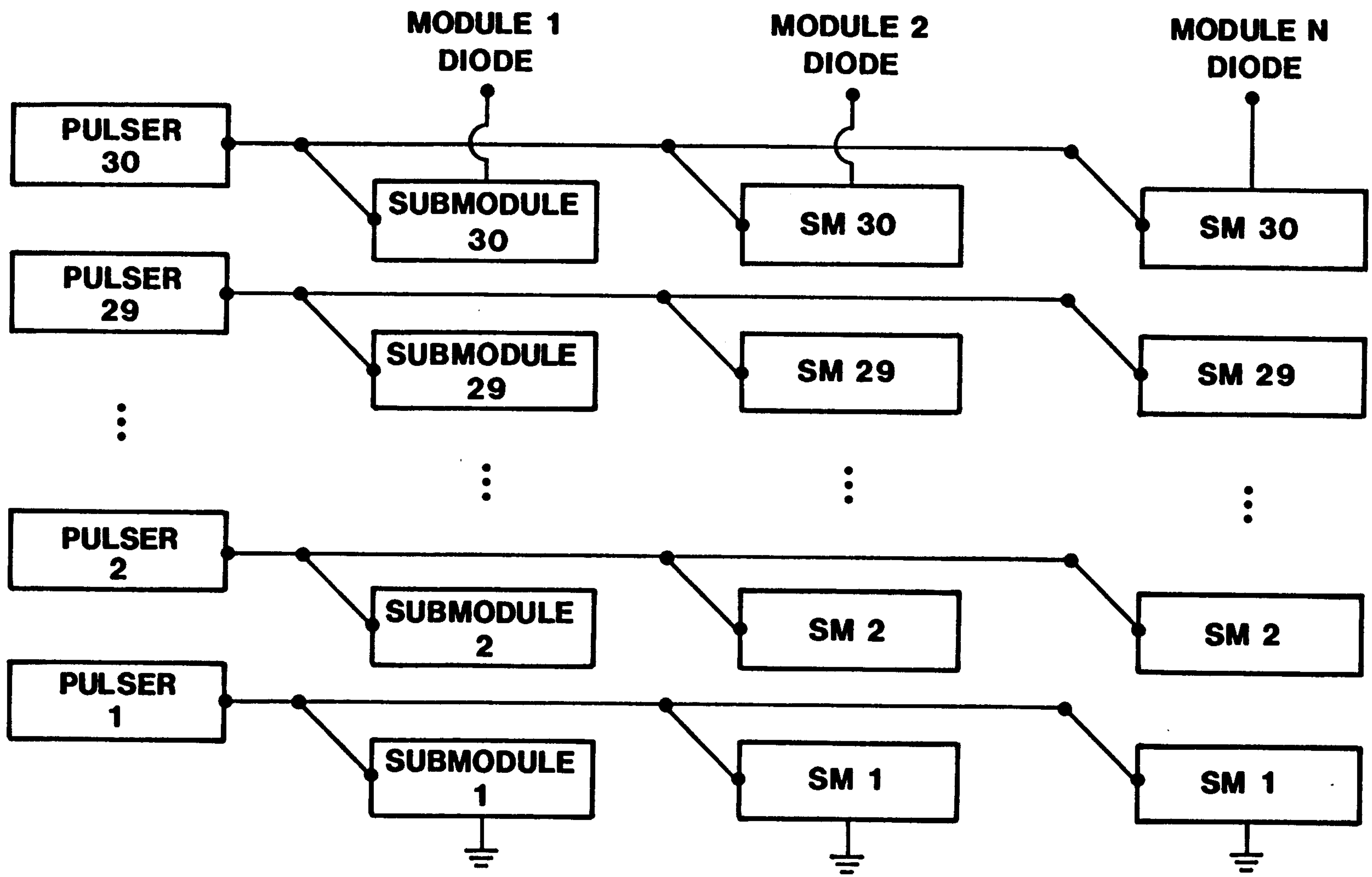


Figure 2. Schematic of a design that guarantees that all of several HERMES III adders receive the same electrical pulse. In this scheme, one pulser drives the same stage of all of the adders.

pulsed power system drives all of the equivalent submodules, that is one pulser drives all of the low end cavities, a second drives all of the second cavities, etc. There are a total of 30 pulsers. With this scheme, each of the 30 modules produces precisely the same output pulse provided the beam diodes behave identically. That pulse may be distorted by imperfections in the pulsed power system, but at least all the pulses are identical and properly timed.

Each of the 30 pulsers starts with a 2 MV, 1 MJ capacitor (1 μF) which is switched into a second capacitor with the switching element that performs the synchronization function. That second capacitor is switched into a third using a saturable inductor and so forth until the last set of saturable inductors switch the final 1 MJ, 40 ns pulses into their respective submodules. We will assume that the saturable inductors perform as required, that is, that they have no problem with repetition rate, life, or jitter. In effect, they can be ignored in the following analysis if they do so.

The candidate switches for the synchronizing element include thyratrons, ignitrons, spark gaps, and perhaps even solid state switches (SCRs). If a single spark gap is to serve as the synchronizing switch, we may assume that it can operate at 2 MV, 100 kA, and 10 Hz for an extended duration. For a simple capacitor-inductor-capacitor circuit at 1 MJ and 2 MV, the capacitance is 0.5 μF, the pulse impedance is 20 ohm, the inductance is 100 μH, and the transfer time is 16 ns. The spark gap transfers 1 coulomb per switching operation, or about 10^6 coulombs per day, eroding about 100 g from the electrodes [Donaldson, 1986]. If such a switch could be designed, all thirty might have to be replaced once a day. With proper design, that would seem to be an acceptable level of maintenance.

To use thyratrons or ignitrons, it would be necessary to reduce the switched voltage; that is, the switch would have to operate in the primary of a dual resonance transformer to charge the initial capacitor in the magnetic compression string. Assuming a working voltage of 50 kV, the switched current would be increased by a factor of forty if the switched energy and time were to be unchanged. At 4 MA, from 100 to 10^4 parallel switches would be required, rendering this option less desirable than the single spark gap.

With 30 spark gaps, timing becomes a serious issue. Without a detailed analysis, one might assume that if the ions are to arrive at the target in a shaped 10 ns pulse, that the pulses from the 30 pulsers should not have a spread of more than 1 ns about their respective optimal times. The standard deviation in their timing then would have to be on the order of 0.25 ns. This is quite severe. Spark gaps have been synchronized to laser triggers with a jitter of about 2 ns at 4 MV in single shot systems [Denison, 1987; Wilson, 1987]. Attempts to achieve equivalent performance at 10 Hz have not been made. On the other hand, spark gaps operating at several kilojoules and 1 MV have been run to 10 Hz for extended periods [Rohwein, 1986]. The challenge is to combine the high energy, modest repetition rate and long life with even more precise triggering.

As an alternative, one might turn to the photoconductive semiconductor switch (PCSS). PCSS uses intrinsic semiconductors which are good insulators under normal conditions for pulsed power purposes. Switching is initiated by using laser photons to produce carriers in the semiconductors, rendering them conductive [Nunnally, 1985; Zutavern, 1987]. There is essentially no jitter in the creation of the conductivity in the PCSS and therefore there is no switching jitter. PCSS have been operated to several kiloamperes and 100 kV to 200 kV at repetition rates of at least 1 Hz. Extensions to the 100 kA, 1 MV are planned for the immediate future at Sandia. Should this technology prove to meet the current, voltage, and repetition rate requirements for ICF, it would almost certainly be suitable for the long term reactor scenarios in terms of lifetime and reliability.

Perhaps of greater importance, PCSS open the possibility of building a device of the Option 2 type. Option 2 requires at least one pulser for each of the 900 submodules.

Each submodule produces a 1 MV, 33 kJ pulse. If bunching is to be employed, each of the pulsers must generate a properly timed 30 ns to 40 ns pulse. An interesting variant, however, that does not put such a severe strain on transport and bunching is to generate a relatively short pulse directly. This is possible, in principle, because the PCSS has no "turn-on" phase. If the parasitic inductances and capacitances associated with the pulse forming lines can be sufficiently minimized, then 3.3 MA, 10 ns, 1 MV, 3.3 TW pulses should be a reasonable near term goal for PCSS research.

An advantage for the Option 2 design is that the pulse forming system could be located inside the cathode stalk (the inner MITL line in Fig. 1). This may prove to be a necessity for ion accelerators in order to prevent severe electron losses between the anode and cathode in the MITL. In an electron accelerator, like HERMES III, the polarity of the inner electrode is negative. Power is fed into this region from openings in the positive electrode so there is no need to have openings in the negative electrode structure. This is important because the fields in these devices are such that the negative electrode is surrounded by a cloud (sheath) of electrons held against the cathode by the magnetic field of the MITL current. If that containment is lost, significant electron currents might cross the adder anode-cathode gap resulting in an inefficiency in the power flow to the load. Ample data seem to suggest that containment will be adequate with the geometry of Fig. 1 and negative polarity. However, simulations [J.W. Poukey, private communication] show that containment is lost to some extent if the electrons are required to flow across the mouth of a cavity as they would be if they were confined to the outer wall in a positive polarity (ion) accelerator. This problem would be solved if the pulsed power could be inside the inner (positive) electrode structure. This configuration is more reasonable for a 10 ns pulser than for a 30 ns to 40 ns device. Thus Option 2 (and PCSS) may have an advantage in this regard.

One final technology that seems to fit most reasonably into Option 1 is the plasma opening switch (POS). It is a major component of the PBFA II program, being required for pulse length reduction and power (voltage) multiplication. It is perhaps the only switch that could relieve the stringent voltage waveform requirements imposed by beam bunching in Option 1, that is, it could be used to reduce the pulse length below that which can be achieved with magnetic switches in the near term. From the reactor viewpoint, it might be attractive because it is a vacuum device. Generally, vacuum switches are more amenable to repetitive operation than other plasma switches. This capability has yet to be demonstrated, however. Neither has the potential for long lifetime coupled with precise timing and pulse shape control.

CHARGING SYSTEMS AND DIELECTRICS

In the scenarios discussed above, either a set of 30 capacitors must be charged to 1 MJ and 2 MV for Option 1 or a set of 900 pulse forming lines must be charged to 2 MV and 33 kJ for Option 2. Typical single shot ICF devices use Marx generators. They will almost certainly have to be replaced because their use would result in a proliferation of spark gaps that would appear to be highly undesirable. In their place, one would have to use transformers. This matter was addressed above with regard to the use of thyratrons as the timing switch for Option 1. The point was made that the total currents in the transformer primaries can be very large. If this were to force the use of multiple spark gaps, then this option might be objectionable for the same reason as the Marx generator option. Accordingly, at Sandia we are looking at using SCRs in the primary of a very slow transformer, one that charges the high voltage capacitor in 1 ms. SCRs do appear capable of this service, and their capabilities are being improved continuously. Accordingly, they seem to be a good switch candidate. However, this option does stress the capacitor for a very long time, and it is yet to be shown whether this potential dielectric problem will be more or less severe that the problem of switching very large currents to charge the high voltage capacitors more rapidly.

This is but one example of the generic problem of finding suitable dielectrics for very large, repetitive pulsed power systems. Modern single shot systems invariably use mineral oil for bulk insulation and deionized water for insulation in pulse capacitors and pulse forming lines. There seems to be no reason to go away from oil and water as dielectrics; however, it will almost certainly be necessary to reduce their working electric stress. There is no data to date on the stress that very large water capacitors, for example, can survive with essentially a zero probability of faulting, but it has been shown that water cannot in general be operated to the stress levels used in single pulse devices because the dielectric degrades with accumulated shots. Working stress levels around 100 kV/cm are typical in Sandia's small repetitive systems, but there is no data base for making definitive statements about what is allowable in systems of the ICF size. In fact, if there is one area of technology that is crucial to the development of a light ion ICF reactor that is not being addressed, it is the area of dielectrics.

The final pulsed power issue to be discussed is the interface to the recirculated AC power from the reactor. Conventionally, the power would be put through a high voltage DC power supply to charge a bank of energy storage capacitors. Substantial improvement will be needed in the design of energy storage capacitors before long life reactor service can be confidently projected. At Sandia, we are looking at pulsed alternator technology as a replacement for the capacitors.

REPETITIVE DIODE ISSUES

Finally there is the issue of the beam diode. Being vacuum devices, diodes generally are suitable for repetitive operation in the sense that they do recover between shots at 10 Hz rates, provided that they do not suffer significant damage when pulsed. "Damage" comes in at least two forms. The more obvious is due to "arcing". In electron beam diodes at low power, arcing is due to closure of the diode's anode-cathode vacuum gap by plasma from one or both of the electrodes. Such closure will occur. It is, therefore, necessary to ensure that there is no substantial energy left in the pulser at that time. This argues, at a minimum, for very efficient pulsed power systems. It may also require some forms of damping. The second form of "arcing" is the formation of electron beams that leak around the magnetic confinement in the diode and damage the anode. This type of "arc" is the subject of ongoing research because it represents a parasitic power loss during the operation of single pulse diodes as well as a damage mechanism.

The second diode damage mechanism is the loss of emission. It has been shown that electron emitters lose their emission capability under repetitive short pulse operation [Buttram, 1979]. This may be relevant both to the maintenance of stable magnetic insulation in MITLs and to the formation of electron cloud "cathodes" (virtual cathodes) in the diode itself. Likewise, one might expect the ion source to become exhausted in certain designs. The use of replenishable lithium liquid surfaces seems to be one answer to this problem, whereas sources using solid surfaces might be expected to have a short life. Of course, it may be necessary to limit the amount of pooled lithium to prevent contamination of the diode over long periods of use. At some point these issues will have to be addressed, but that will not be possible until suitable pulsers are available.

CURRENT RESEARCH

The development of the HERMES III adder is crucial to this concept. HERMES is an outgrowth of the LIA development that has been ongoing, largely at Lawrence Livermore National Laboratories, for many years. Specifically, it resembles the injector for accelerators such as ETA and ATA [Reginato, 1983]. The crucial difference is one of size. The injectors are typically only 2.5 MV and 10 kA. At such levels issues like magnetic insulation do not dominate the design as they do at HERMES levels. The HERMES III design concept has been tested in a 4 MV prototype accelerator called HELIA [Ramirez, 1985]. (The original HELIA experiment was suggested by I.D. Smith and was performed as a collaboration between Pulse Sciences Inc. and Sandia.) Figure 3 shows the theoretical load line for HELIA as compared to the data. The agreement of the two illustrates the viability of the HERMES III concept for a high power case where magnetic insulation is an absolute requirement. These data give confidence in the ultimate success of HERMES III which, in turn, could be a stepping stone toward a light ion ICF system.

Magnetic switches are crucial in almost all light ion ICF reactor scenarios as well. Other approaches to switching require such a large number of individual switches that the credibility of the design suffers. (The exception may be the PCSS.) Magnetic switches have been demonstrated for long life and high repetition rate operation at low energy per pulse [Birx, 1984] and for single shot operation at high energy and power [Neau, 1983]. At present the magnetic core electrical stress used for the long life work is incompatible with the very high powers required for ICF. The high power work has resulted in very short core lifetimes. Experiments underway to identify the problems in high power cores are showing promise of making substantial improvement. One particular problem already identified is that the very thin plastic insulating foils required for high peak power cores (to achieve small packing fraction and minimal saturated

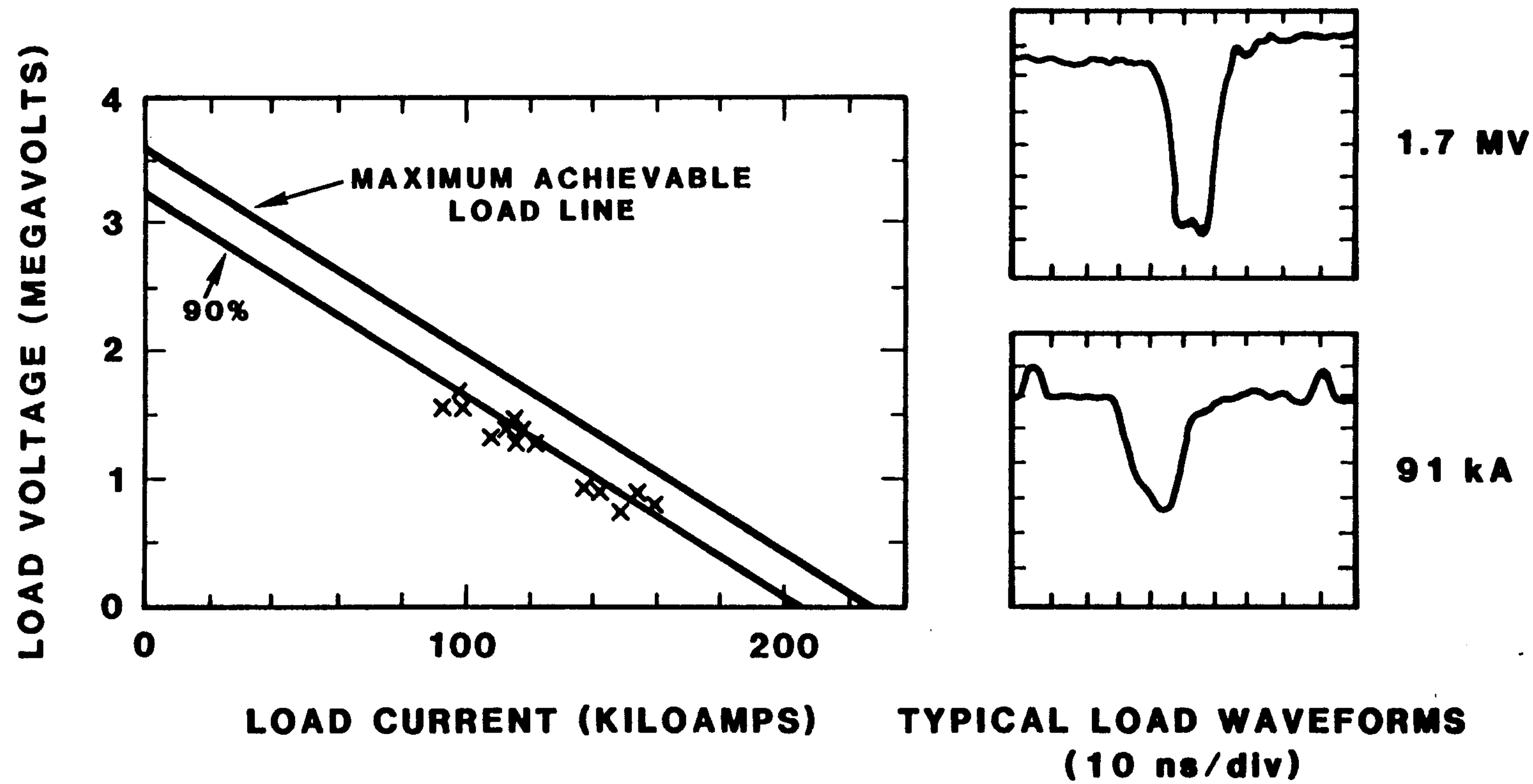


Figure 3. Load line for the HELIA experiment, a prototype for HERMES III, illustrating at least 90% efficiency in generating the theoretical output value (load line value).

inductance) are damaged by the rough Metglas surface when the cores are wound. Experiments to improve the quality of the Metglas finish are underway and are showing progress. In addition, thinner Metglas, which should reduce core losses and permit faster pulse risetimes, is being developed [Harjes, private communication].

Spark gaps, such as would be required for the timing switch in Option 1, have not been developed. Devices that meet or exceed the voltage, current and timing requirements have been demonstrated on single short pulsers. These spark gaps do not pass the required energy or coulombs, however, because the pulse length is much shorter. The degradation of the timing and lifetime of such spark gaps as a result of the higher energy/coulomb transfer and of repetitive operation is an unresolved issue. Spark gaps have been operated at 10 Hz (and at much higher rates) routinely but at lower energy per pulse. There is no ongoing work to bridge the gap between the state-of-the-art in spark gap switches and the light ion ICF requirement.

At Sandia, we have chosen to develop PCSS for use in place of the spark gaps in this application. PCSS was suggested for pulsed power applications initially by Nunnally [1985]. It has been refined somewhat over the past few years to the point that for some applications, like ICF, the laser requirements have been reduced by at least two orders of magnitude [Zutavern, 1987]. State-of-the-art PCSS switches still operate at very low voltage and current relative to the ICF requirement, however, and their typical geometry is still a wafer of semiconductor in a strip line. We are beginning an experiment to extend the range of PCSS to 50 kJ and 1 MV at 10 Hz this year. The primary goal of that experiment is to develop the technology for operating large numbers of individual GaAs PCSS in parallel in a high power environment. Considerable work will also be required in semiconductor-to-metal contact development and in development of alternatives to the wafer geometry, alternatives more useful for switching extended pulsed power structures.

We have begun a series of experiments that should culminate in a 5 MV, 50 kJ, 10 Hz adder that would be a prototype of the Option 1 concept. For the initial power conditioning, we have chosen a 50 kJ pulsed alternator that will be switched with SCRs into a transformer for charging a 1 MV capacitor. The charging period will be 1 ms. This part of the system should be in place by the summer of 1988. The next stage of compression will use PCSS to transfer the energy to a magnetic compression system. The final stage will feed a 1:10 adder for a 5 MV output. A second experimental program to extend this technology to 500 kJ per pulse is also being started.

CONCLUSION

This paper has presented a viable concept for ICF reactor grade light ion pulsed power. It is based on the HERMES III adder concept. This will have been tested with negative polarity within a year, and plans for positive polarity tests are being formulated. Other elements of the design, such as saturable magnetic switches, seem to be reasonable extrapolations of what has been or is being done. Timing switches are a critical concern, whether they be spark gaps or the less developed PCSS option. Other switch options are becoming available as well, options that generally can be used to generate shorter electrical pulses permitting some of the bunching requirements of the mainline designs to be relaxed. Among these options are PCSS and POS. Experiments to look at the first stages of power conditioning, the AC interface, are now underway. They are scheduled to culminate in 50 kJ and 500 kJ repetitive prototypes of the required ICF system.

Clearly, significant development in pulsed power will be required before a light ion ICF reactor can be built. Nevertheless, with the work done to date and what is ongoing, the prospects for success, without the necessity for the invention of totally unanticipated new technologies, seem quite good. The development of pulsed power will be a stepping stone toward the development of repetitive ion sources and transport which are the next items to be investigated enroute to a reactor.

REFERENCES

D.L. Birx, et al., "A Multipurpose 5-MeV Linear Induction Accelerator," Proc. IEEE 16th Power Modulator Symposium, Alexandria, VA, 1984, p. 186.

M.T. Buttram, "Repetitive Pulse Accelerator Technology for Light Ion Inertial Confinement Fusion," IEEE Trans. NS, Vol NS-32, Oct. 1985, p. 1571.

H.T. Buttram, "Repetitively Pulsed Electron Beam Diode Lifetime and Stability," Proc. 2nd IEEE International Pulsed Power Conference, Lubbock, TX, 1979, p. 61.

G.J. Denison, et al., "A High Voltage Multistage Laser Triggered Gas Switch," Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, 1987.

A.L. Donaldson, et al., Proc. IEEE 17th Modulator Symposium, Seattle, WA, 1986, p. 146. The extrapolation of erosion data is very imprecise. The estimate given in the text is an attempt to be conservative.

A.R. Miller, Proc. 4th IEEE Pulsed Power Conference, Albuquerque, NM, 1983, p. 594.

E.L. Neau, "COMET, a 6 MV, 400 kJ, Magnetically-Switched Pulse-Power Module," Proc. 4th IEEE Pulsed Power Conference, Albuquerque, NM, 1983, p. 246.

W.C. Nunnally, Proc. of the 5th IEEE Pulsed Power Conference, Arlington, VA, 1985.

K.R. Prestwich and M.T. Buttram, "Repetitive Pulsed Power Technology for Inertial Confinement Fusion," Proc. 5th Topical Meeting on Fusion Energy Technology, Knoxville, TN, 1983.

J.J. Ramirez, et al., "The Four Stage HELIA Experiment," Proc. 5th IEEE Pulsed Power Conference, Arlington, VA, 1985, p. 143.

J.J. Ramirez, et al., "The HERMES III Program," Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, June 1987.

G.J. Rohwein, et al., "The TEMPO Machine," Proc. IEEE 17th Power Modulator Symposium, Seattle, WA, 1986, p. 226.

L. Reginato, et al., "The Advanced Test Accelerator (ATA), a 50-MeV, 10 kA Induction Linac", IEEE Trans N S, Vol. NS-30, No. 4, 1983, p. 2970.

P. Sincerny, et al., Proc. 4th IEEE International Pulsed Power Conference, Albuquerque, NM, 1983, p. 478.

B.N. Turman, et al., "PBFA II, a 100 TW Pulsed Power Driver for the Inertial

Confinement Fusion Program," Proc. 5th IEEE Pulsed Power Conference, Arlington, VA, 1985, p. 155.
J. Michael Wilson and Guy L. Donovan, "Laser Triggered Gas Switch Improvements on PBFA II," Proc. 6th IEEE Pulsed Power Conference, Arlington, VA, 1987.

F.J. Zutavern, et al., "Recent Developments in Opening and Avalanching Photoconductive Semiconductor Switches," Proc. of the 6th IEEE Pulsed Power Conference, Crystal City, VA, 1987.

JAPANESE VIEW OF COMMERCIAL DRIVERS FOR LIB FUSION REACTORS

S. Miyamoto, K. Imasaki, N. Yugami, T. Akiba, K. Emura, H. Takabe,
K. Shimoura, M. Fukuda, K. Nishihara, S. Nakai and C. Yamanaka
Institute of Laser Engineering, Osaka University
Institute of Laser Technology
Suita, Osaka 565, Japan

INTRODUCTION

Recent progress in inertial confinement fusion (ICF) research makes it possible to achieve the ignition condition of pellet implosion in the near future. Small target implosion experiments have been successful using high power lasers such as the Gekko XII glass laser system. The scaling law of implosion fusion experiments indicates that several MJ energy drivers will be needed for ICF reactors. A light ion beam generated by pulse power technology is the promising energy driver for ICF due to its high generation efficiency; it is easy to generate the large energy beam at relatively low cost.

A conceptual design of a LIB-ICF reactor ROKKO I [1] has been performed as a reference for the analysis of the key issues. The schematic drawing shown in Fig. 1 is based on the laser ICF reactor SENRI where a thick liquid Li blanket directly facing the pellet fusion is adopted on the inner surface of the structural wall to decrease the neutron fluence, activation and mechanical pulse loading. These features of the reactor chamber minimize the size which is desirable especially for particle beam fusion to get shorter propagation length.

Beam parameters such as optimum beam particle energy, pulse width or waveform, power density on target or focus spot size, and total beam energy injected on the target are dependent on the ion species, the beam focusability and also the target design.

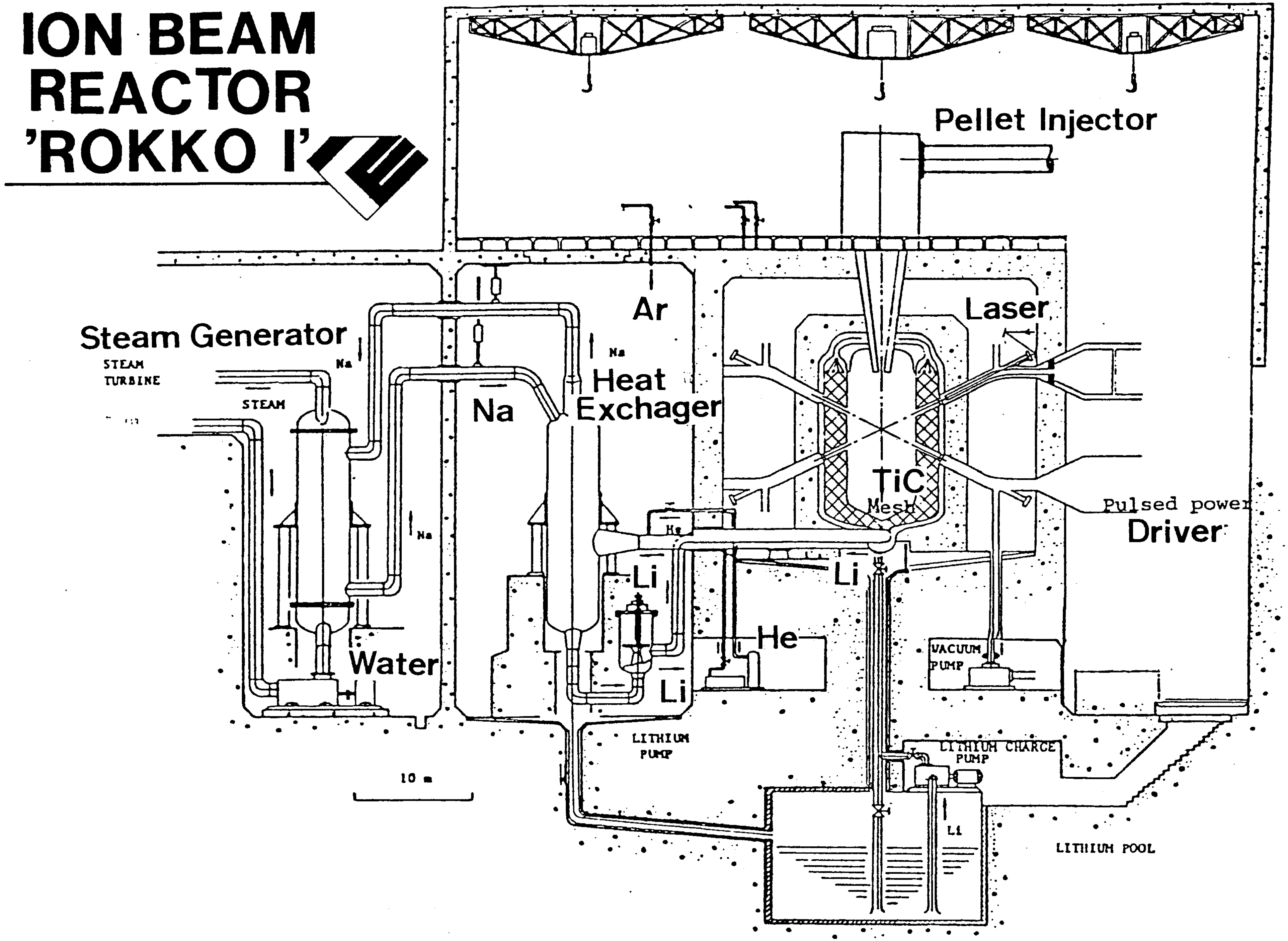


Fig. 1. The conceptual design of the LIB-ICF reactor ROKKO I.

POWER FLOW

Figure 2 shows a simplified power flow diagram of a LIB reactor system. The following condition may be required to obtain adequate output,

$$\eta_p \cdot \eta_B \cdot \eta_T \cdot \eta_G \cdot Q_T \cdot Q_B \gtrequal 3. \tag{1}$$

Here η_p, η_B, η_T and η_G are the efficiencies of the pulse power system, beam generation, beam transport and electric generator, respectively. Q_T and Q_B are the gain of the target and reactor blanket, respectively. The typical parameters may be as follows, $\eta_p \gtrequal 0.7$, $\eta_B \gtrequal 0.7$, $\eta_T \gtrequal 0.5$, $\eta_G \gtrequal 0.3$ and $Q_B \gtrequal 1.1$. Then the required target gain becomes $Q_T > 40$.

The required beam energy for achieving the high gain is strongly dependent on the nonuniformity of the imploding target. This restriction can be relaxed by using a low-compression-ratio target. Figure 3 shows a schematic of a cannonball target for ion beams [2]. Ion beams pass through the outer solid gold and deposit the energy to the radiator. Sufficient smoothing occurs to maintain uniformity during the implosion. The implosion efficiency is expected to be 8% with a beam power density of 10^{14} W/cm^2 and pulse length of 10 ns.

The target gain can be described using an energy conservation relation. The result is [3]

$$Q_T = 0.21\,(\varepsilon_b/E_b\beta)\,(\mu/\varepsilon_c{}^2)^{2/3}$$

$$\cdot\,\{\eta_I E_b - 102 \cdot a^3(\varepsilon_h - \varepsilon_c)\}^{4/3} \tag{2}$$

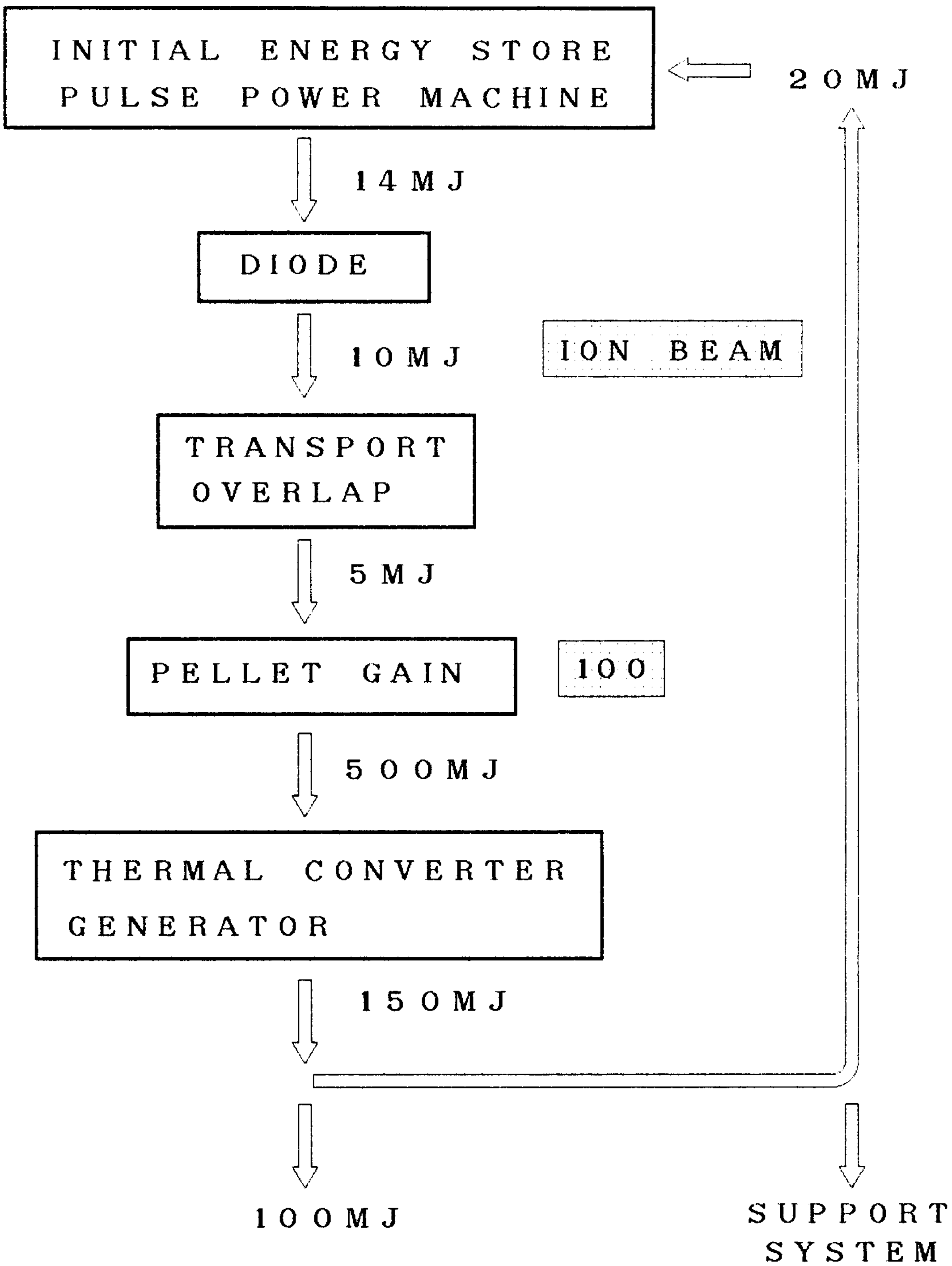


Fig. 2. The power flow diagram of a LIB reactor system.

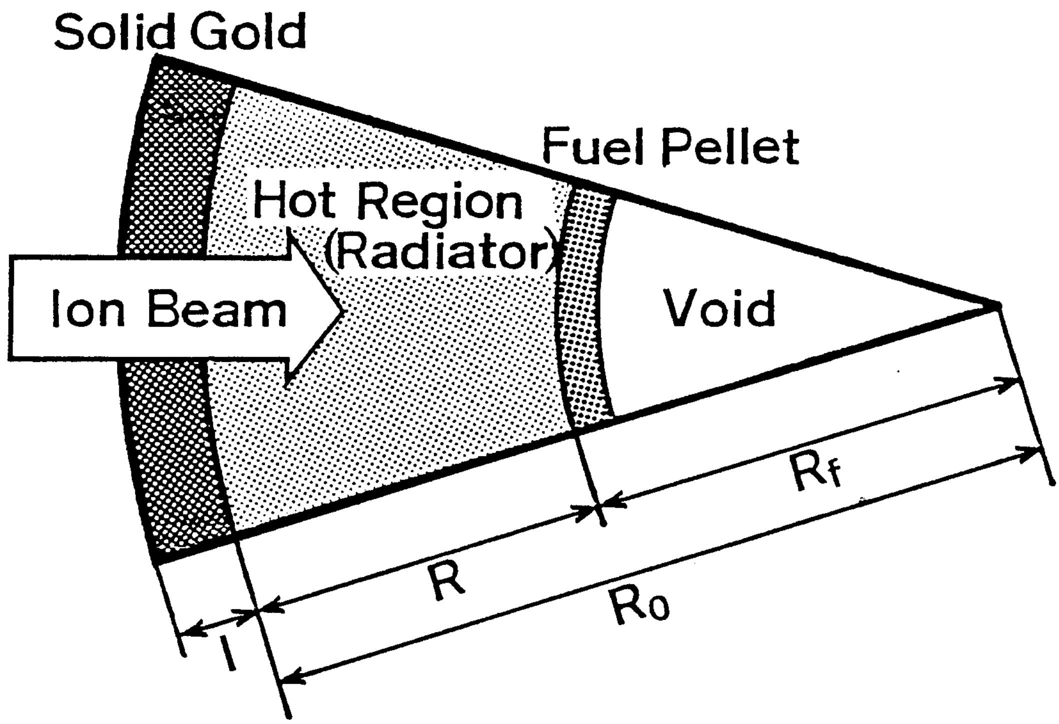


Fig. 3. The schematic of a cannonball target for ion beam fusion.

where E_b is the beam energy injected to the target, ε_b is the released energy from the whole fuel burning, $\beta = T^{1/2} / \langle \sigma V \rangle$, T is the temperature of the burning fuel, a is the ρR at ignition, and η_I is the implosion efficiency, μ is the compression rate, ε_h is the fuel energy for ignition, and ε_c is the energy required to compress the fuel to ρ.

The implosion efficiency can be described as

$$\eta_I = \eta_a + \eta_h + \eta_c \tag{3}$$

where η_a, η_h, and η_c are the efficiencies of absorption, hydrodynamics and conversion, respectively. The hydrodynamic efficiency can be obtained from a simple flat deposition model as

$$\eta_h = E_b/(2\, E_b + 5 \times 10^9\, R^3 l^2) \tag{4}$$

where R is the target radius and l is the length of absorption. From Eqs. (2-4), the gain curves are estimated as shown in Fig. 4 in which the efficiency $\eta_a + \eta_c = 0.5$ was used.

TARGET INTERACTION AND REQUIRED BEAM INTENSITY

Beam target interaction experiments have been performed [4]. Figure 5 shows a shadowgraph of the layered target. The target is composed of a 90 μm polyethylene foil sandwiched between rear and front copper foils of 10 μm and 20 μm thickness, respectively. The power density and energy spectrum of the incident proton beams were estimated from the neutron number and spectrum from the $^{65}Cu(d,n)^{65}Zn$ reaction. This deuterium is naturally contaminated with protons.

The acceleration pressure of the target was estimated from the behavior of the target. The estimated pressure was 0.5 Mbar in the case of 3 MeV protons and a

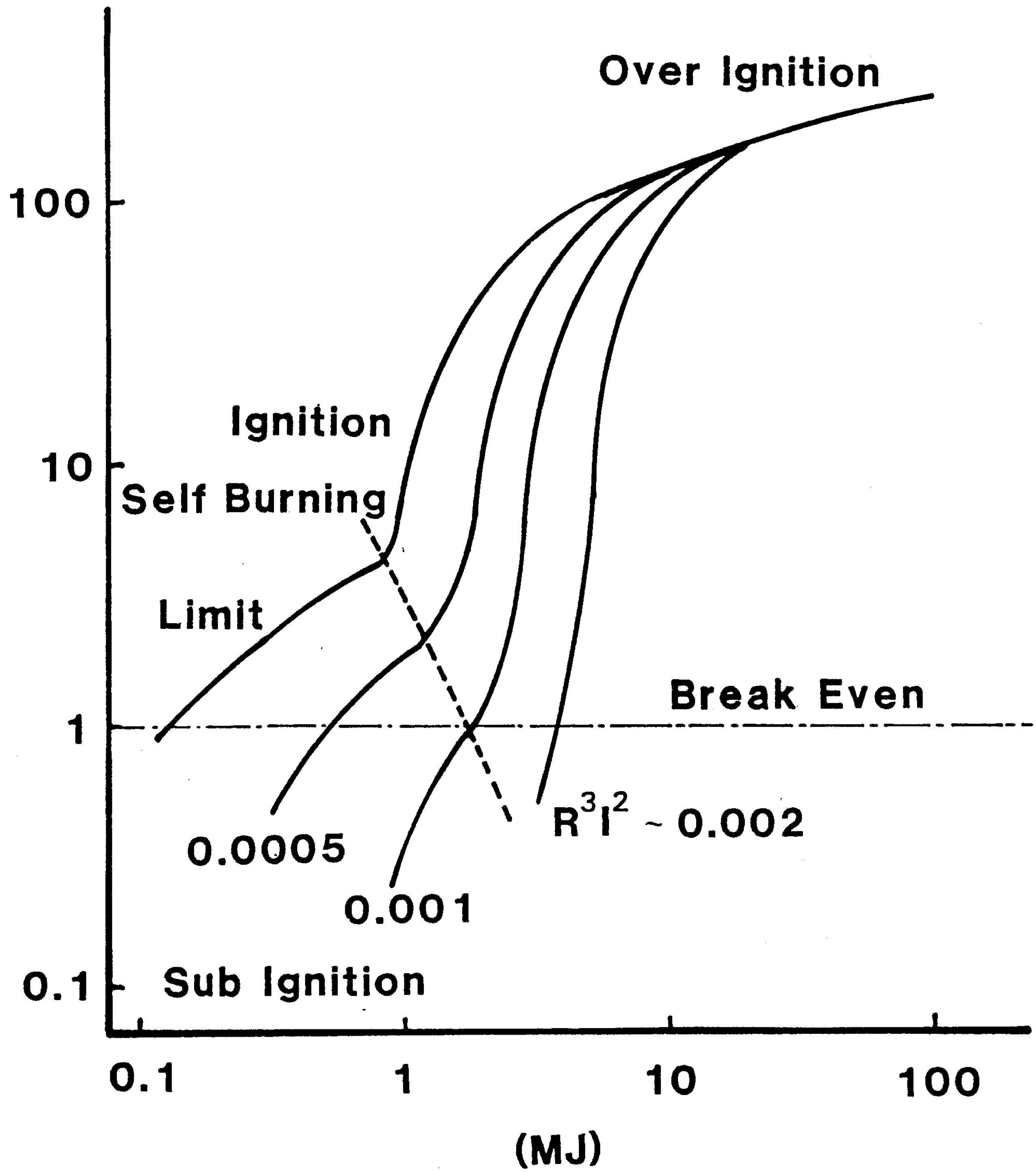


Fig. 4. The gain curves of implosion targets. The parameter is the target radius of R and the beam absorption length of l.

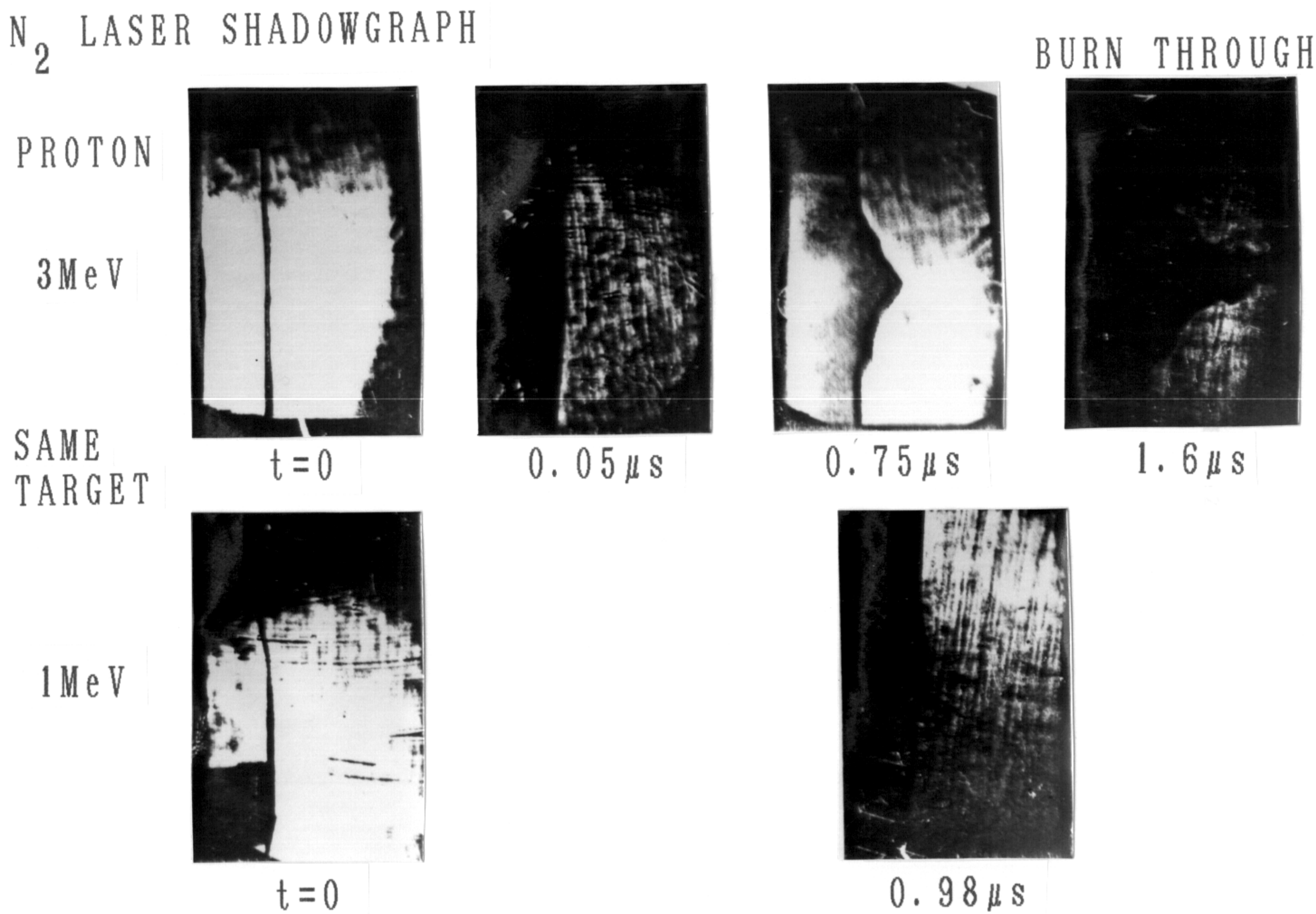


Fig. 5. N_2 laser shadowlength of a layered target of copper 10 μm - polyethylene 90 μm - copper 20 μm irradiated by 3 MeV and 1 MeV proton beams.

intensity of 1 x 10^{11} W/cm^2. When the same target was irradiated with a 1 MeV proton beam at a power density of 5 x 10^{10} W/cm^2 the pressure was 0.08 Mbar. In this case the ion beam was stopped in the first foil and therefore there was no effect of the cannonball shape of the target.

A computer simulation with the HISHO code [5] was performed. The energy deposition was calculated on the basis of the classical interaction processes including the free electron contribution and the beam incident angle of 30° was the same as in the experiment. The experiment and simulation results are summarized in Fig. 6. The ablation pressure scalings obtained with the single foil and layered foil are indicated. The results of the layered target with a 1 MeV beam correspond well with the results for the single foil target [6]. In the case of 3 MeV proton beam irradiation, the pressure obtained was 5-6 times higher than in the 1 MeV case. This fact shows the high hydrodynamic efficiency of the tamper target. This experimental scaling of acceleration pressure indicates the required pressure of several tens of Mbar may be achieved by an intensity of 5-10 x 10^{13} W/cm^2.

BEAM TRANSPORT [7]

The focused ion beams must be transported from outside of the reactor vessel to the fusion fuel pellet at the reactor center. Beam particles travel using multiple current-carrying plasma channels. Power and power density enhancement are expected due to beam bunching and beam overlapping. It is possible to obtain the required power density of 100 TW/cm^2 on the pellet or the sufficient implosion velocity. A transport length of 3-5 m is required for beam bunching and first wall survivability.

The plasma channel in a fusion reactor has to satisfy the following conditions to transport the ion beam [8]:

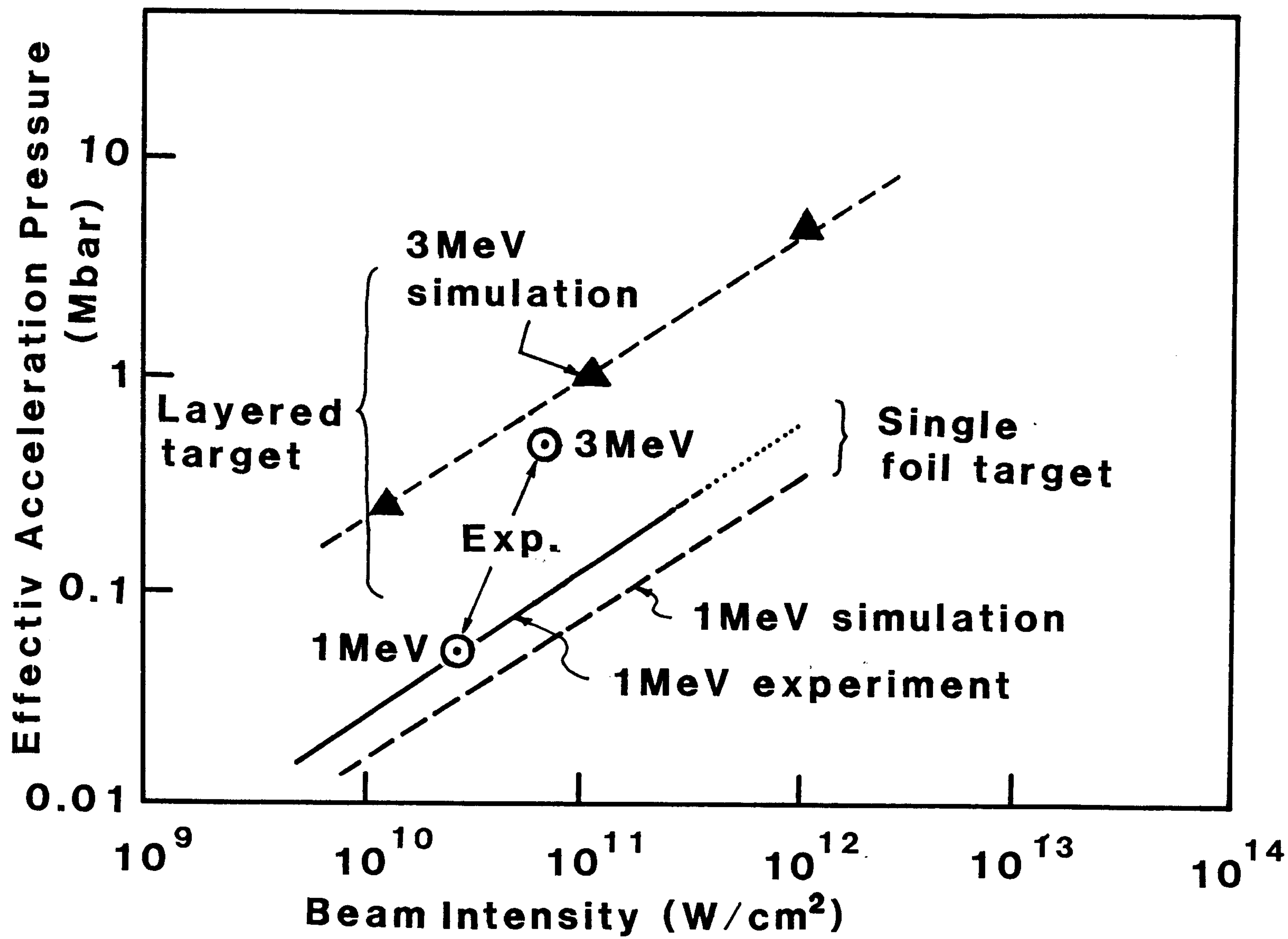


Fig. 6. The experimental and the simulation results of effective acceleration pressure scaling to beam intensity.

(1) The channel current to confine the ion beam within the channel I_{ch} is determined by the beam velocity v, the maximum injection angle α, and channel radius r_{ch} from the single-particle orbit model. If uniform current density is assumed, the required channel current for the proton beam [9] is

$$I_{ch} > 1.57 \times 10^{7}\, v\alpha^{2}/c(1 - r_s^{2}/r_{ch}^{2})^{-1}, \tag{5}$$

where r_s is the beam focal size at the injection into the channel and c is the velocity of light in vacuum.

(2) The kink instabilities of the channel are the most critical problem in the macroscopic instabilities. The growth rate of these instabilities Γ is estimated by Manheimer et al. [10] assuming that the wavelength of interest is the channel radius,

$$\Gamma = 1.26 \times 10^{5}\, I_{ch}/(r_p\sqrt{\rho g}), \tag{6}$$

where r_p is the radius of the current flowing region and ρg is the pressure of the background gas.

(3) The two-stream instability, and the beam and channel filamentation instabilities can be considered in the microscopic instabilities [11].

(4) The channel is expanded by a j x B force, where j is the channel return current.

(5) The small energy loss of the beam requires a low plasma density. The channel gas can be rarefied by the shock wave keeping the high background gas macroscopically to stabilize the channel. The decelerating electric field due to the channel expansion is important to consider.

Assuming an acceptable instability growth rate of 10^6, an energy loss of 25%, a channel expansion 1.5 times the 3 m channel length, and $r_s = 0.75\ r_{ch}$, the transportable power P can be obtained for the channel mass density and the channel current. For example, the transportable window is plotted in Fig. 7 for the case of a channel radius of 0.5 cm, a proton beam energy of 10 MeV, and a pulse width of 50 ns.

Figure 8 shows the demonstration of the transport channel formation by laser guiding. The CO_2 laser beam (2 J/100 ns) was axially injected in the ethylene gas between electrodes. The laser was focused to less than 0.5 cm on the ground electrode by a focusing mirror of f = 200 cm. The negative high voltage of up to 40 kV was applied to another electrode. The channel gas was C_2H_4 at 20 mbar. The straight and stable free standing channel could be obtained. The electric field required to form the channel was only 10 V/cm mbar when the absorbed laser energy was 2 mJ/cm^3mbar.

Beam transport experiments were performed using the pinch-reflex ion diode on Reiden IV (1 MV, 0.8 MA, 60 ns). The experimental setup is shown in Fig. 9. The proton beam energy of 0.8 MeV and the power of approximately 10^{10} W was transported through a 40 cm channel with a particle efficiency of better than 90% and with the energy efficiency of 80%. The calculated energy loss of 160 keV, which was mainly the classical collision with these experimental conditions, was in good agreement with the experimental energy loss of 150 keV.

BEAM OVERLAPPING

It is necessary to overlap several beams on the pellet in order to achieve higher beam intensity. The beam intensity multiplication on the pellet in the multi-channel system (Fig. 10) is expressed by the beam overlap gain,

$$G_{ol} = f(r_{ch}/r_t)^2 N/4, \qquad (7)$$

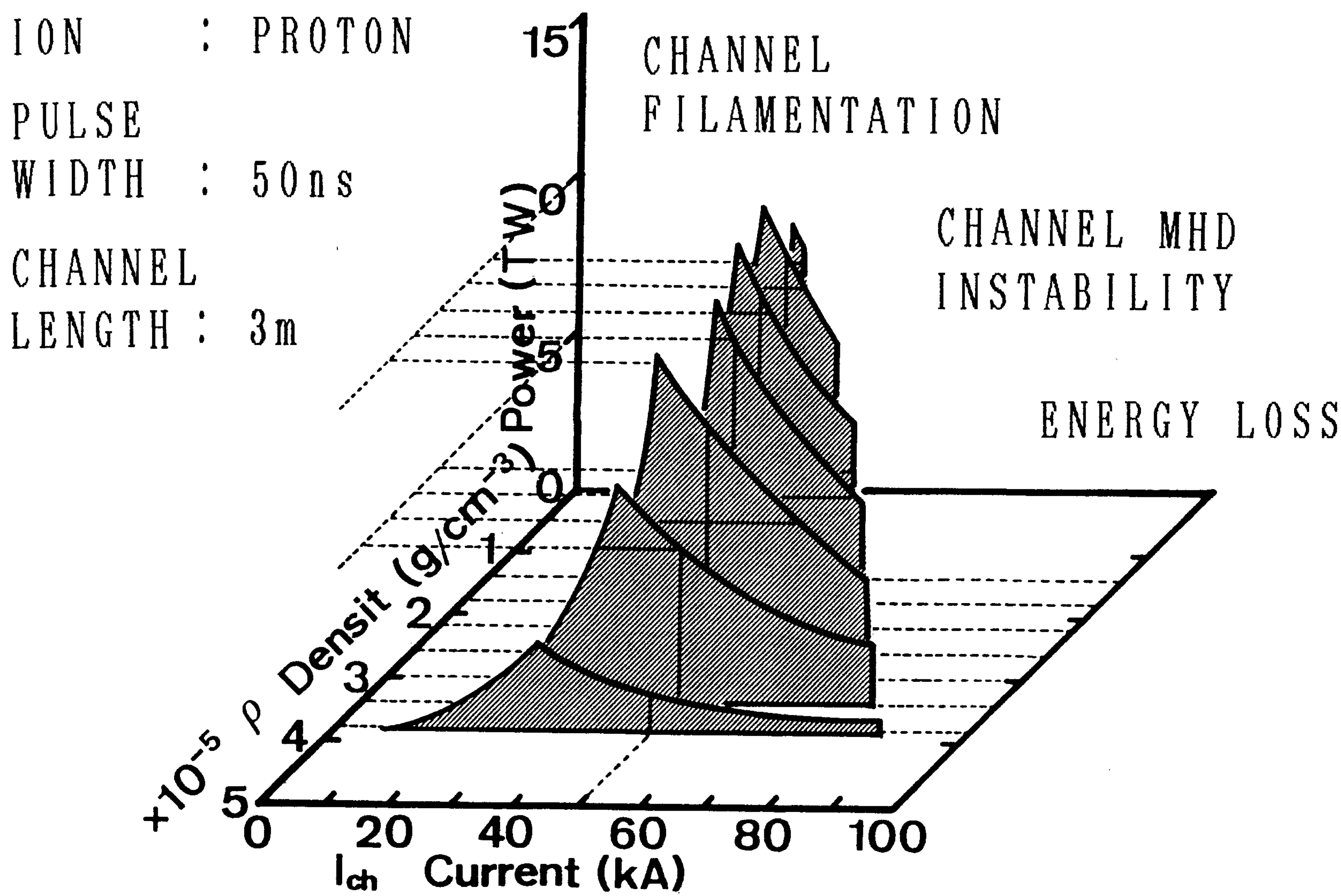


Fig. 7. The example of the transportable power window for the channel mass density and the channel current. A proton beam energy of 10 MeV and a pulse width of 50 ns.

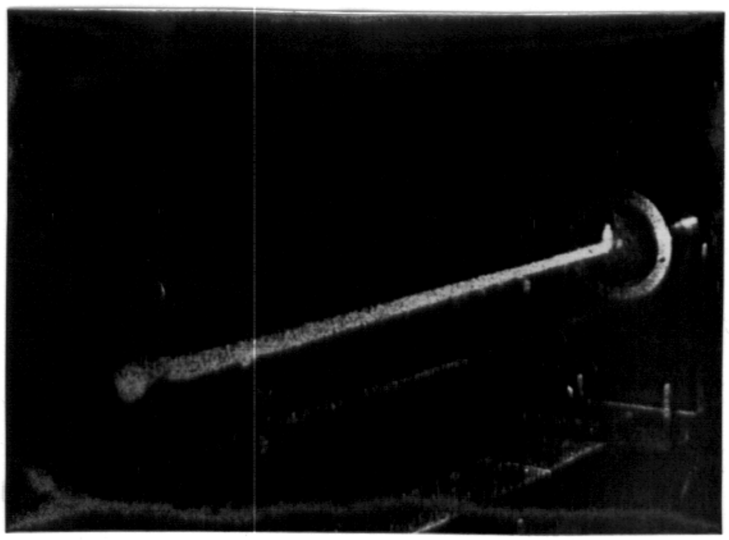


Fig. 8. Photograph of the CO_2 laser-guided plasma channel.

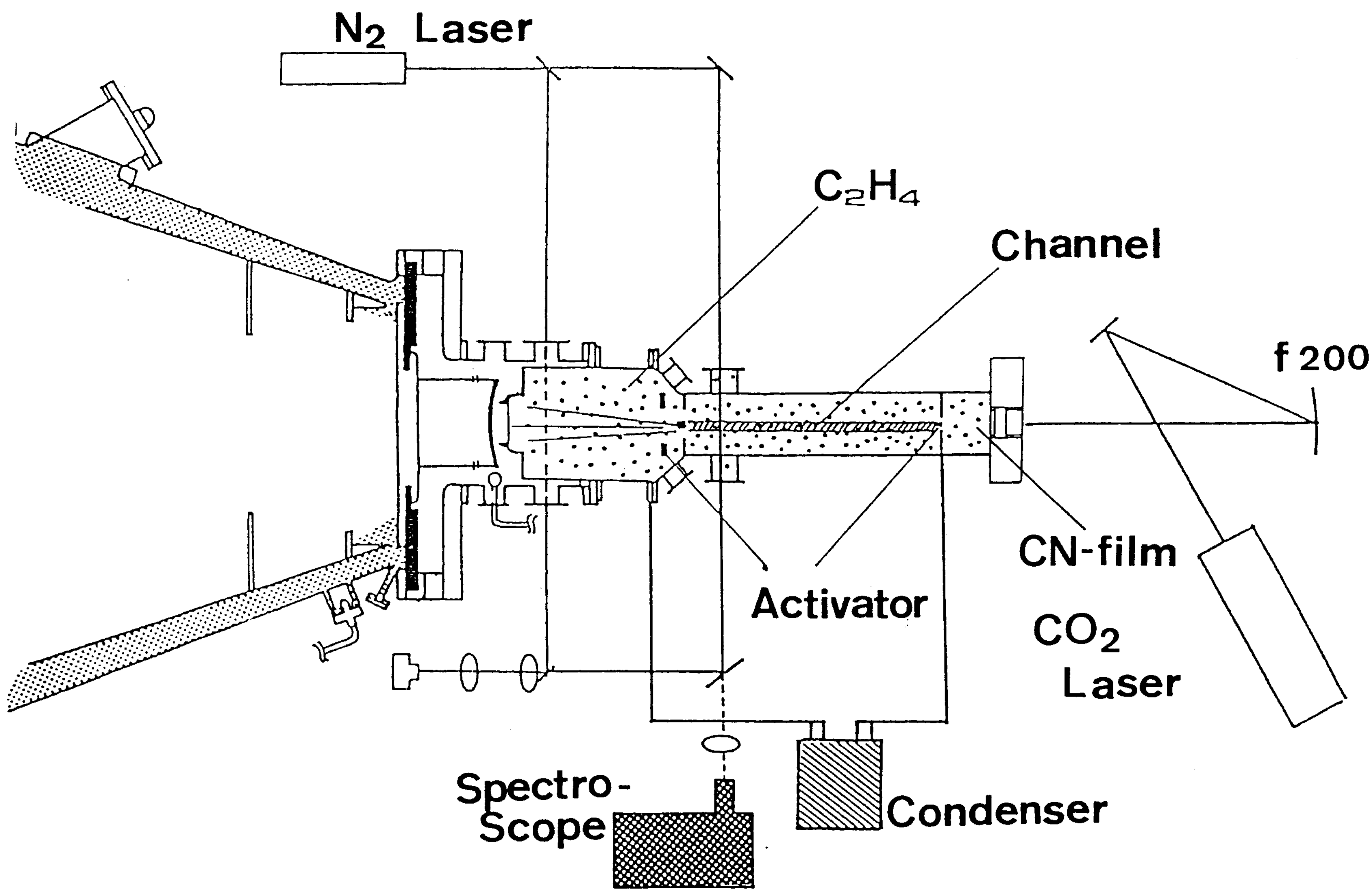


Fig. 9. Experimental setup for the channel formation and the beam transport.

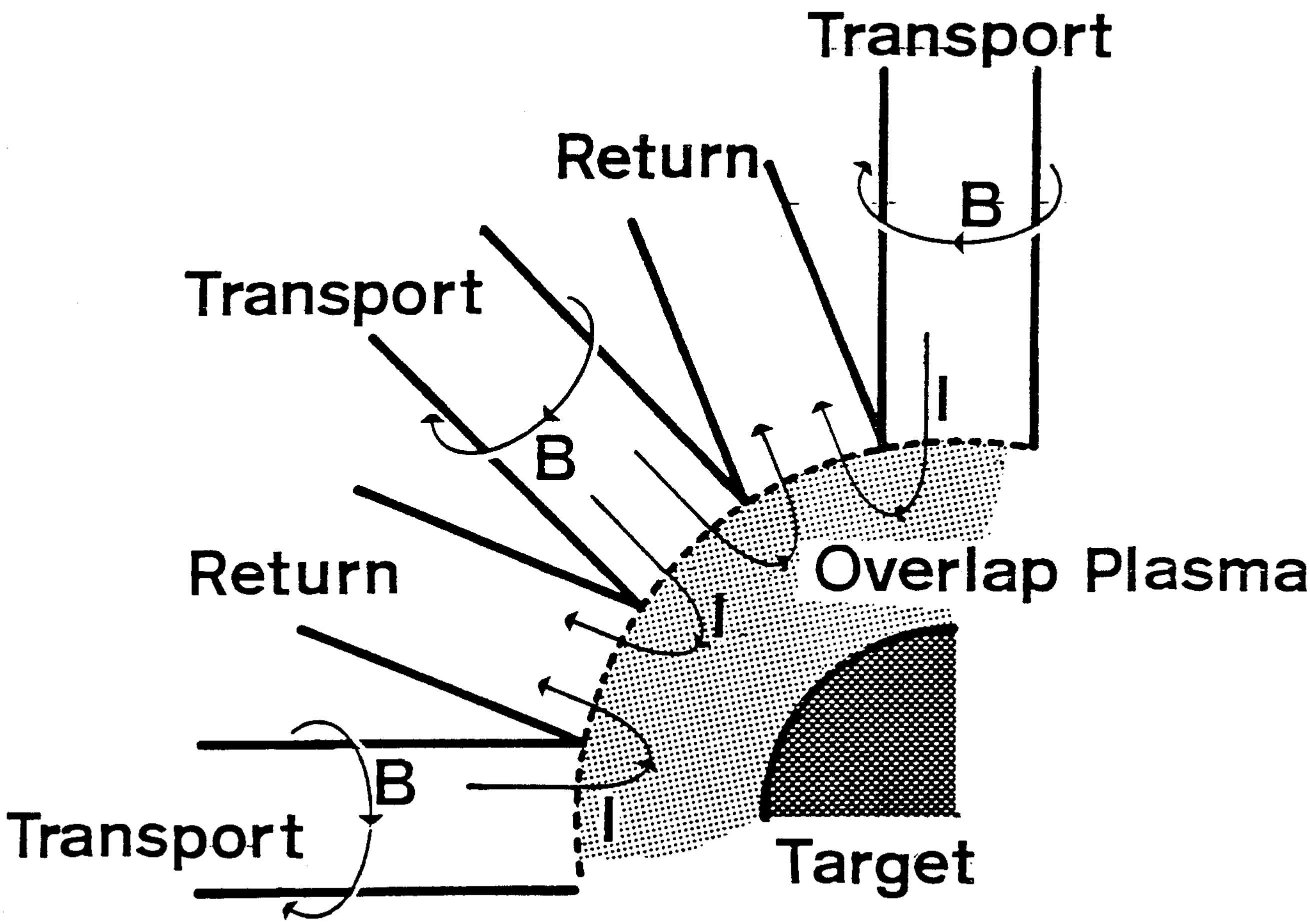


Fig. 10. A schematic drawing of beam overlap around the target.

where f is the fraction of the injected beam which is incident on the pellet. In the beam overlap, the return paths, which may be preferred by the plasma channel initiated by the laser guidance, give the large effect of overlap gain. We have proposed the uniform irradiation reactor channel system [7]. Figure 11 shows the geometry of the irradiation system. In this system, 30 beam channels and 32 return paths channels are arranged on a dodecahedron. The inductances are estimated to be about 3 μH/channel, when the reactor radius is 3 m. This low inductance geometry relaxes the insulation voltage of channel formation at the entrance of the reactor to less than 100 kV for a channel current of 50 kA.

Figure 12 shows the calculated fraction of the target irradiation to injection beam particles and the overlap gain as a function of the ratio of the target radius to the channel radius. The higher overlap gain could be obtained at the smaller ratio of the target to the channel radius because the beam profile on the target has a peak around the center. The irradiation flux normalized to the average flux is shown as a function of the zenithal angle from the equator to the pole in Fig. 13. The flux asymmetry is 4.5%.

We also studied the triple wire-exploding channel formation and beam transport in the multi-channel system [7]. This channel consisted of one transport channel and two return paths as shown in Fig. 14. The experimental results indicate that the overlap gain of $G_{ol} \sim 7.3$ is expected if 30-32 channel returns are alternately arranged.

DIODE BRIGHTNESS

Figure 15 shows the experimental scaling of the ion diode brightness on the diode acceleration voltage. The data points are the results with the applied magnetic field diode on Reiden III [12] (white circle), with the conical pinched electron beam ion diode [13] (white square), with the pinch-reflex ion diode [14] (black square) and with the applied magnetic field inverse pinch ion diode using the inductive pulse compression with

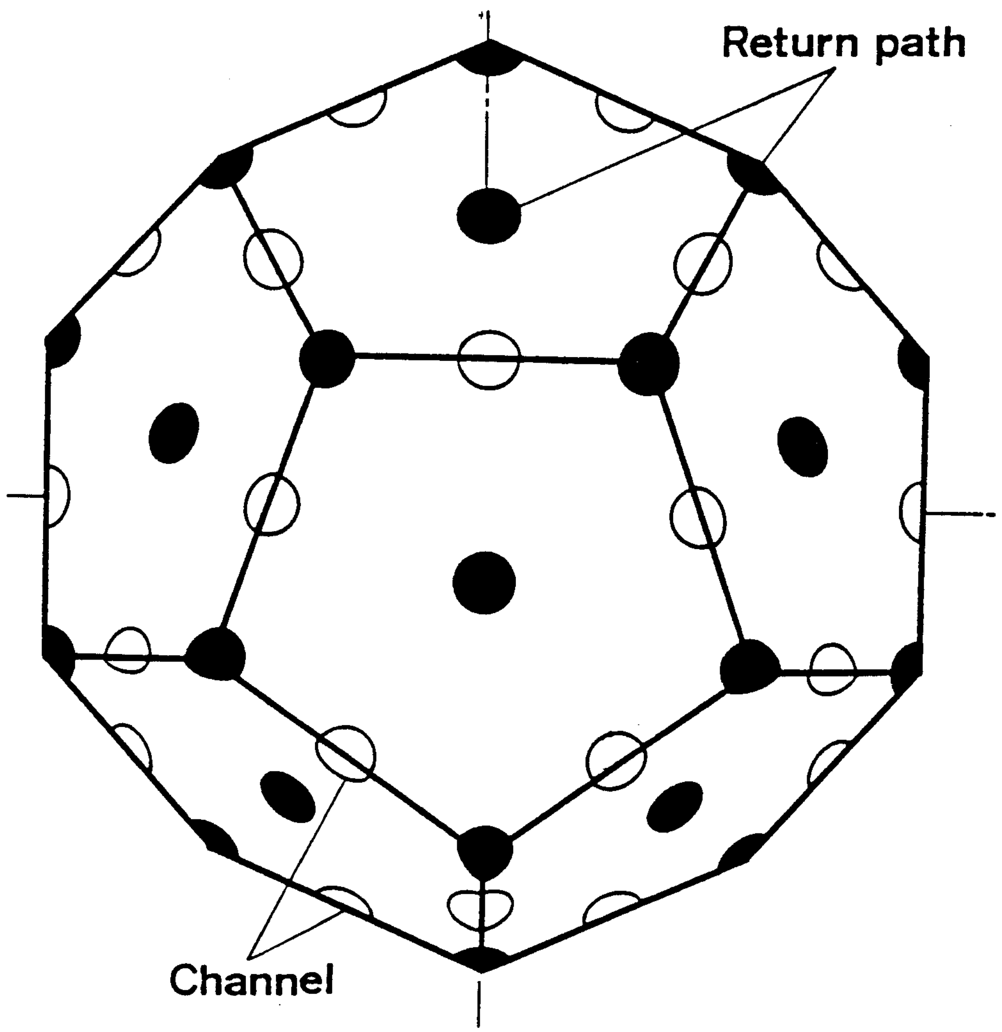


Fig. 11. Dodecahedral configuration for the overlap reactor channel system.

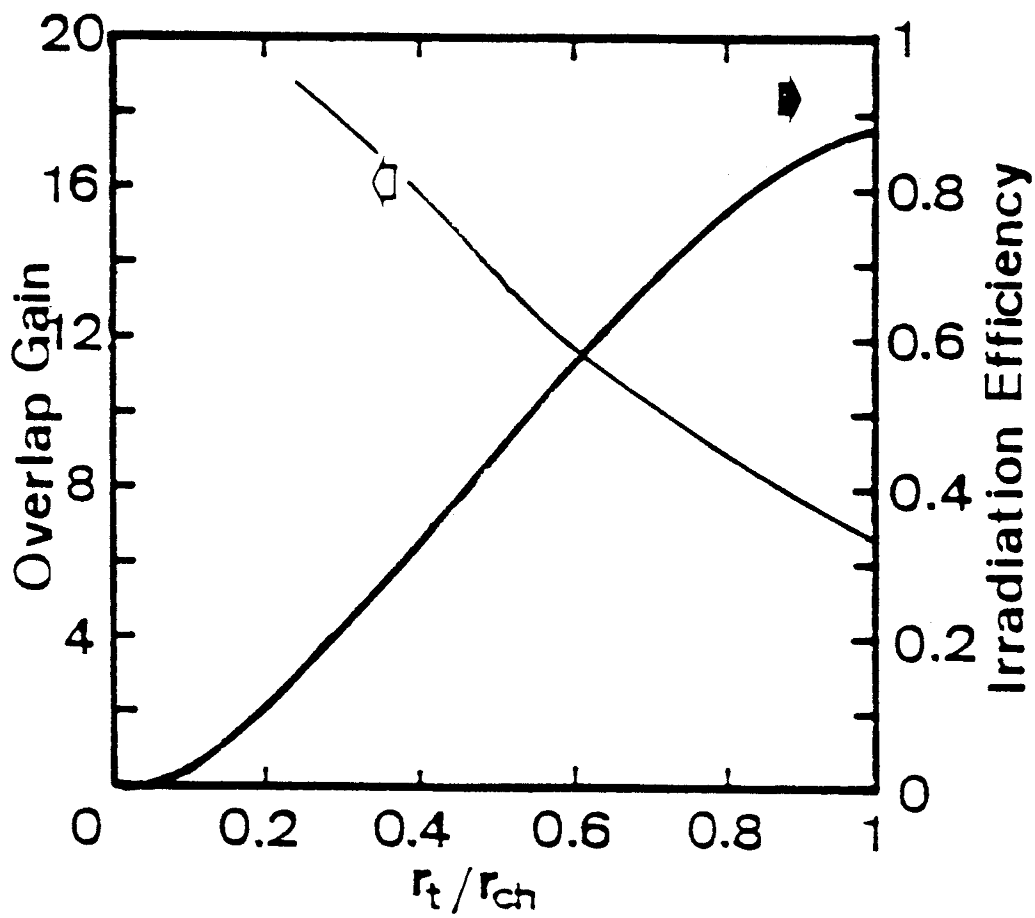


Fig. 12. Fraction of the beam irradiation efficiency and the overlap gain as a function of r_t/r_{ch}.

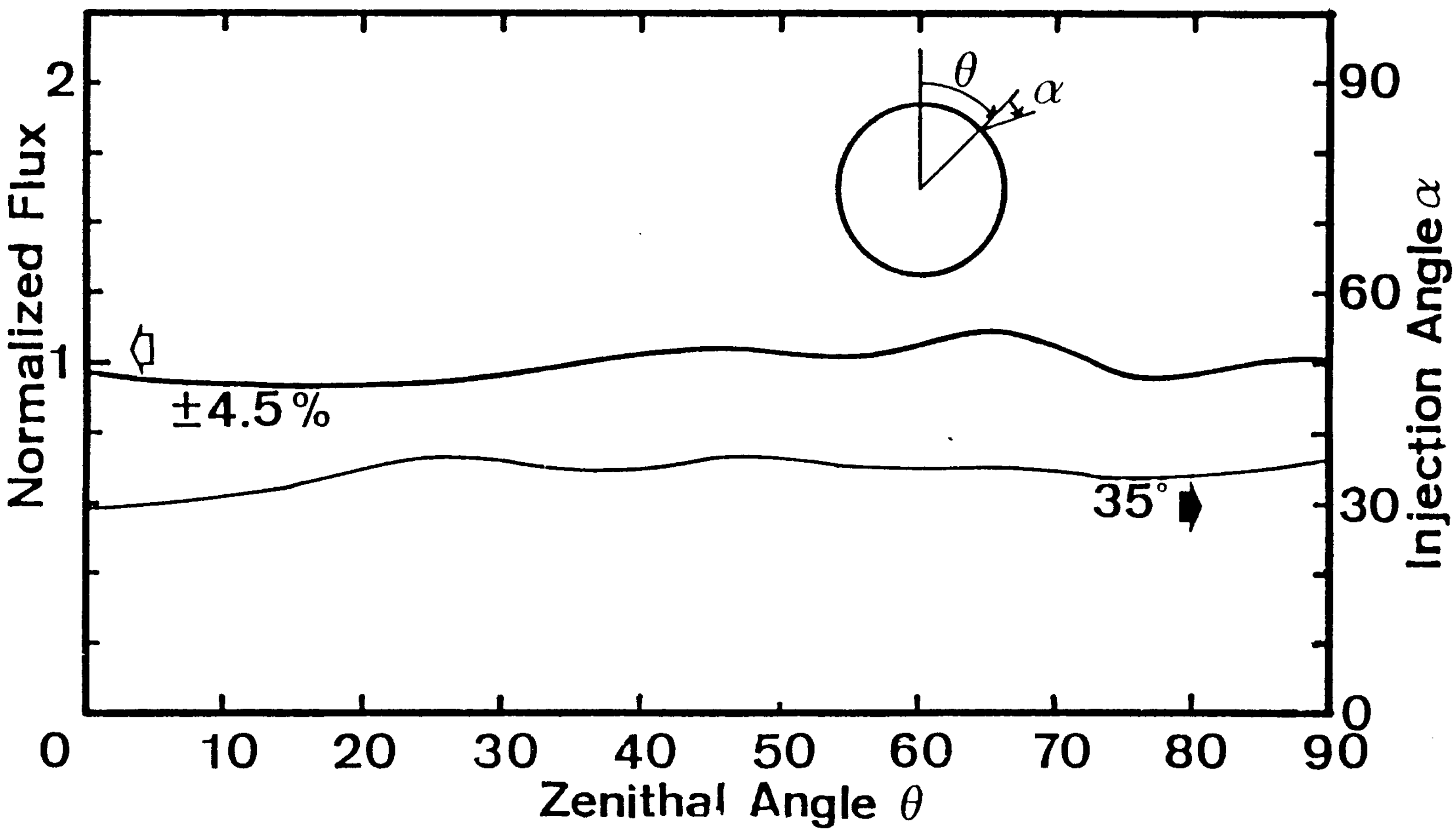


Fig. 13. Irradiation flux and the average injection angle onto the pellet target as a function of the zenithal angle from the equator to the pole of the pellet.

Fig. 14. Photograph of the triple-wire channel. This channel consisted of one transport channel and two return paths.

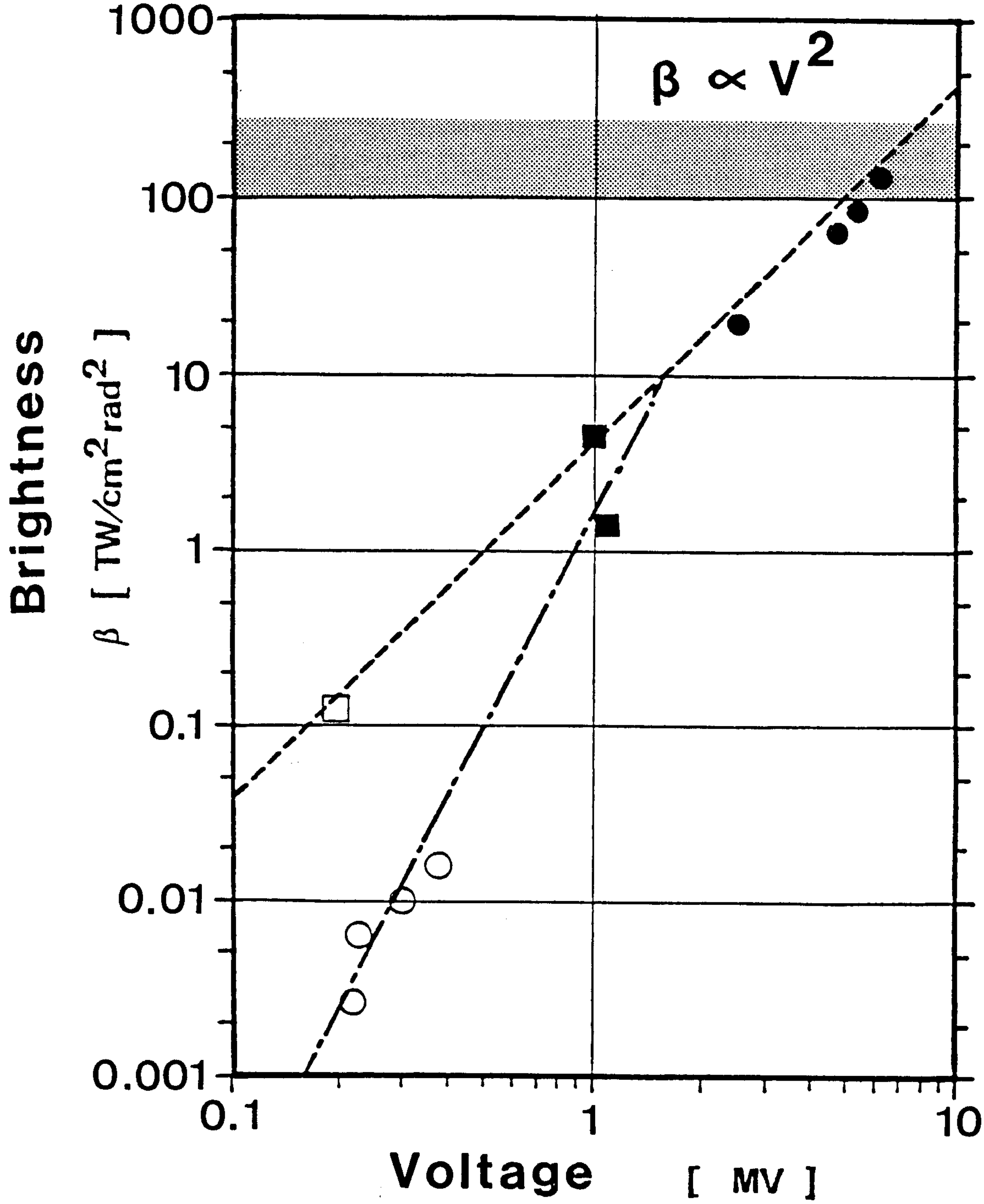


Fig. 15. The experimental scaling of the ion diode brightness on the diode acceleration voltage.

a plasma erosion opening switch [15] (black circle) on Reiden IV. These results show that the brightness dependence on the diode voltage is stronger than the square power.

The beam transport and irradiation system requires sufficient brightness of the ion diode. This requirement depends on the ion mass for a fixed ion range. Figure 16 shows the ion energy and required beam brightness for several ion species with a target range of 100 mg/cm^2. The conservative brightness scaling on diode voltage (brightness $\propto V^2$) is also shown. With this scaling, the required brightness should be achieved for ions heavier than Li.

LIB-ICF DRIVER

The target irradiation parameters are shown in Table 1. The total beam power of 200 TW and beam energy of 10 MJ are focused and transported to the target as independent 30 beams. The beams are bunched during the transport and overlap at the target. Table 2 shows the beam focusing and transport parameters for Li^+ and C^{4+} ions. The beam transport requires a high bright beam of approximately 10^4 TW/cm^{2}rad^2.

The induction accelerator shown in Fig. 17 is a candidate for the LIB-ICF driver for fusion reactors. The outputs of 1-2 MV from small pulse forming line modules are combined and added by the induction cavities. The high voltage output would be applied to one or more stages of applied magnetic field ion diodes. The advantages of this type of

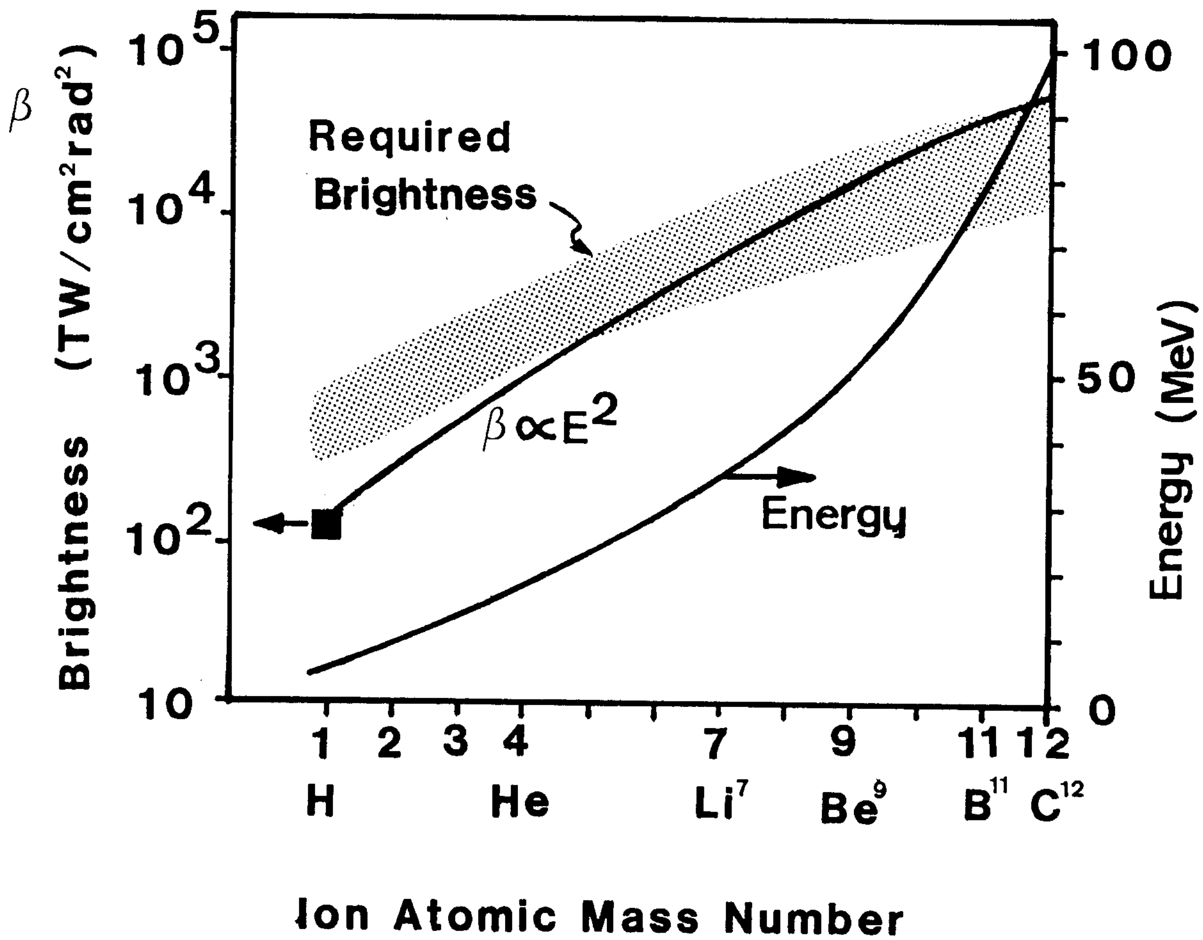


Fig. 16. The required ion energy and beam brightness on the diode acceleration voltage.

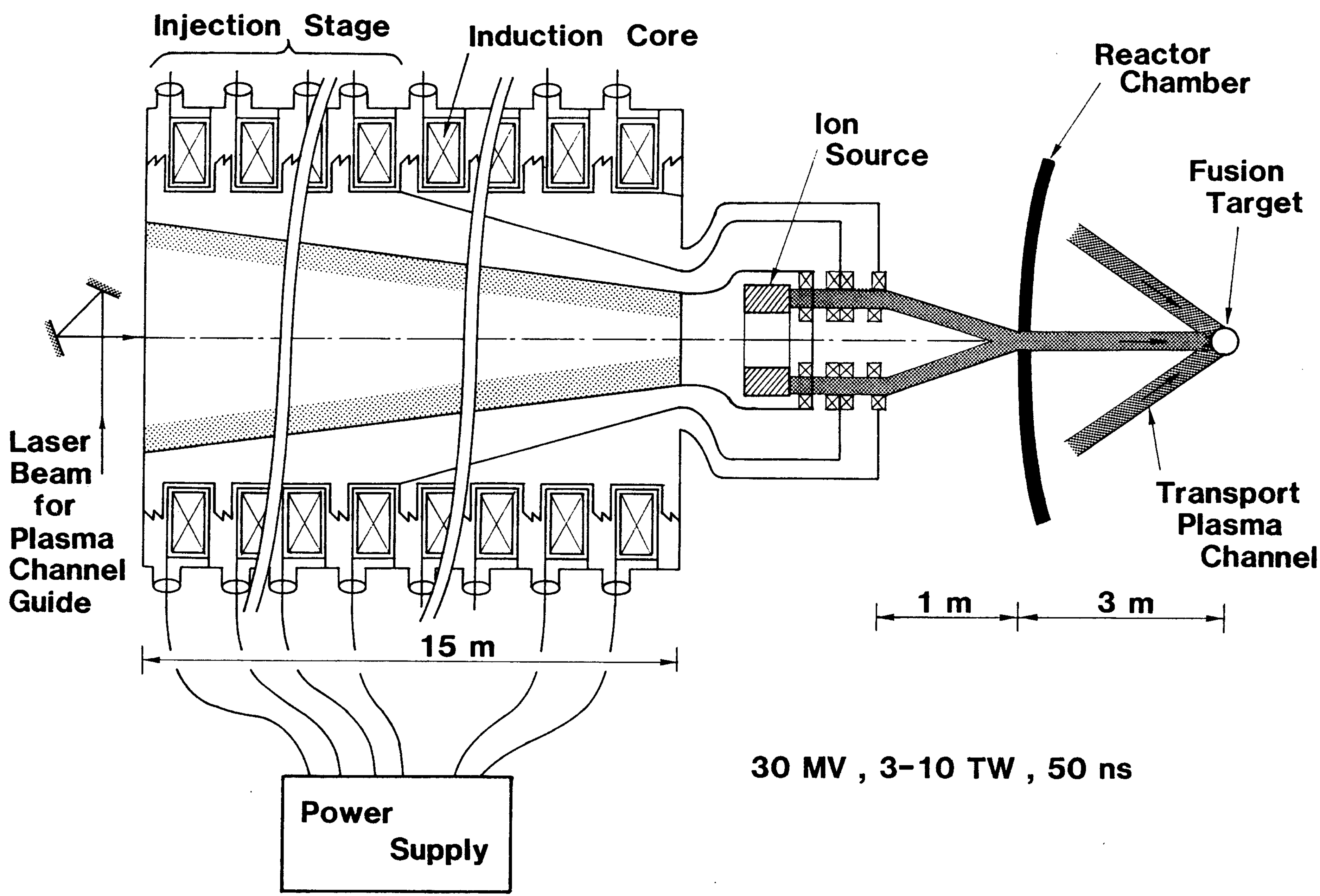


Fig. 17. Induction accelerator LIB-ICF driver system.

Table 1. Beam Parameters of LIB Reactor System

Total Power	200 TW
Pulse Width	50 ns
Total Energy	10 MJ
Voltage	> 30 MV
Beam Number	30 Beams
Beam Power	6.7 TW/Beam
Focal Radius	0.35 cm
Channel Radius	0.5 cm
Target Radius	0.4 cm
Bunching Gain	5
Overlap Gain	8
Transport Efficiency	0.75
Irradiation Efficiency	0.7
Power on Target	510 TW
Intensity on Target	250 TW/cm^2
Energy on Target	5.1 MJ

Table 2. Beam Focusing Parameters

Ion	C^{4+}	Li^{+}
Focal Radius (cm)	0.35	0.35
Channel Radius (cm)	0.5	0.5
R/F (rad)	0.075	0.085
(deg)	4.3	4.9
Channel Current (kA)	50	50
Focusing Length (cm)	108	96
Required Divergency Angle (mrad)	3.2	3.6
Required Diode Brightness (TW/cm^2sr)	9200	7100

driver are ease and reliability of generation of high voltages and controllability of the voltage waveform. The voltage waveform of $V = (L^2M/2Ze)/(t_{TOF}-t)^2$, where L is the transport length between the diode and the target, M and Ze are the ion mass and charge and t_{TOF} is the time of flight of the ion accelerated by the voltage at t = 0. The high bunching gain required an accurate voltage waveform. The adapted voltage waveform can be generated by adjusting the transit time of the power supply line from the pulse forming modules to the voltage adding cavities.

The impedance of the ion diode, which is the load of the induction accelerator, must be controlled in time to obtain a precise diode waveform. The time evolution of diode impedance characteristics strongly depends on the diode geometrical parameters and also type of ion source. In proton beam diodes, the flashover type ion sources were often used. The ion current density of this type of ion source is

$$Ji \sim 0.4\, n_i Ze(2kT/M)^{1/2}, \qquad (8)$$

where n_i, Ze and M are the ion density, the ion charge and the ion mass, and kT is the plasma temperature. The temperature should be lower than several eV to avoid the multiple ionization of ions and the thermal divergence of ion beams. For example, a plasma density of $10^{17}/cm^3$ is required to achieve an ion current density of 3.3 kA/cm^2 for a Li^+ plasma of T = 1 eV. Flashover type plasma sources release as much neutral gas as plasma. The neutral gas enters the diode gap freely and is ionized by collisions with ions and electrons. This ionized neutral gases cause the impedance collapse of the diode at later time.

An injection plasma or an injection ion beam are considered as an ion source of the inductive acceleration ion driver. The injection plasma ion source can be used for an operation of plasma fill ion diode. This type of diode has the characteristic of rising impedance with time, which is favorable for beam bunching. The ion current density in the plasma fill diode is

$$j_i > n_i Zev_d, \tag{9}$$

where v_d is an injection velocity of plasma. The inequality of the above equation shows that the impedance of the plasma fill diode cannot be controlled directly.

If constant impedance operation or constant current operation can be realized, voltage waveform control by inductive voltage adders will be easily performed. A prototype experiment with an inductive accelerator is underway to study diode impedance control by the injection plasma or the injection ion beam. The schematic configuration of the inductive accelerator Reiden IV-IA is shown in Fig. 18. The output of the second pulse forming line of Reiden IV (voltage of 500 kV and pulse width of 100 ns) was divided into 32 high voltage cables. The impedance of the cables is 50 Ω. The prototype induction accelerator (SHVS) [16] consists of eight stages of induction cavities with each cavity fed by 4 cables. Figure 19 shows the induction cavities. The induction voltages are added by the inner conductor extended from both sides to the center of the SHVS. One stage (4 MV) and two stage (2 MV + 2 MV) ion diodes are set at the center of the SHVS. The experimental setup of a two stage ion diode is shown in Fig. 20. The parameters of the ion source and the ion diode for the inductive accelerator LIB-ICF driver are shown in Table 3.

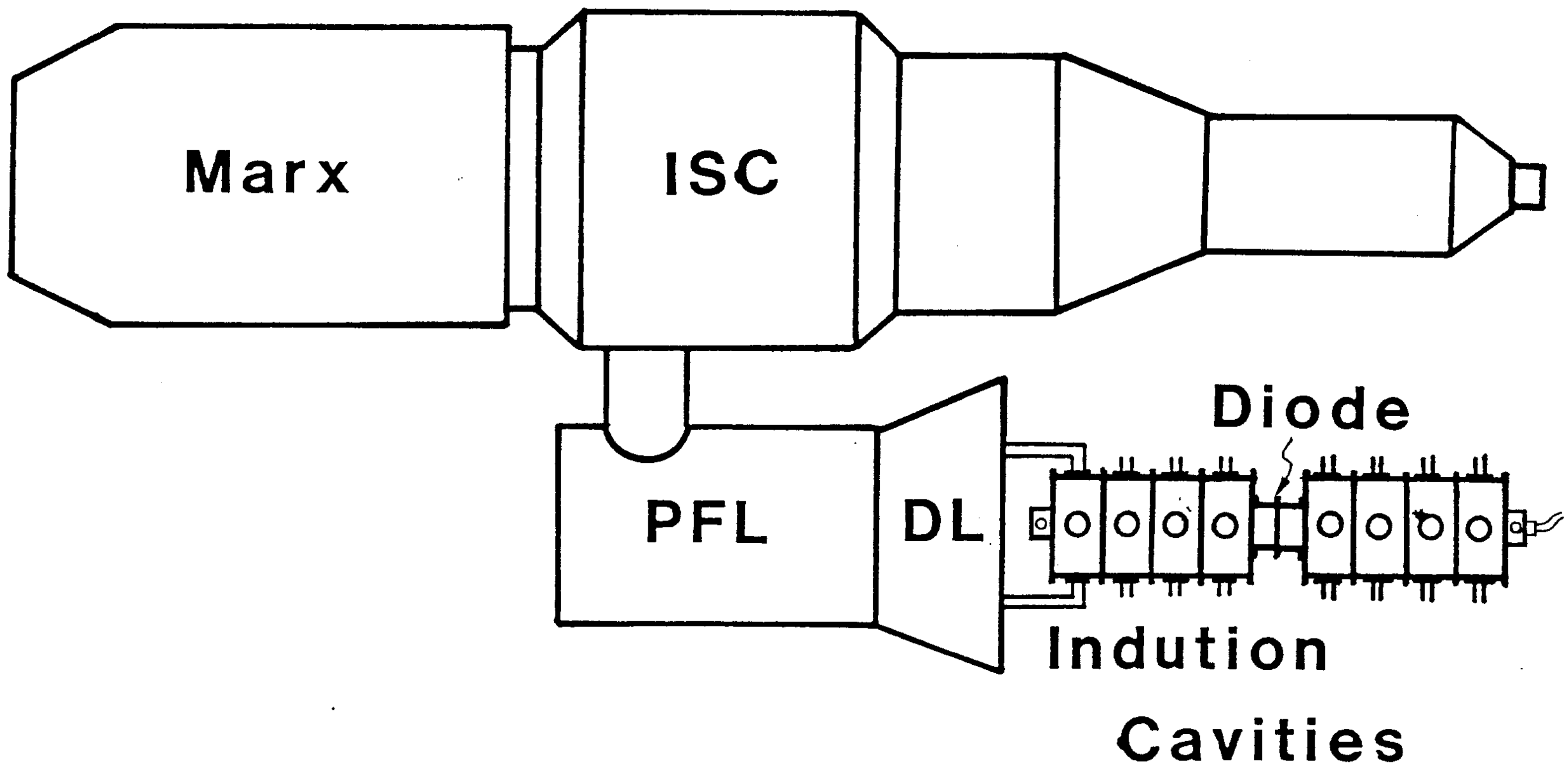


Fig. 18. The schematic configuration of inductive accelerator Reiden IV-IA.

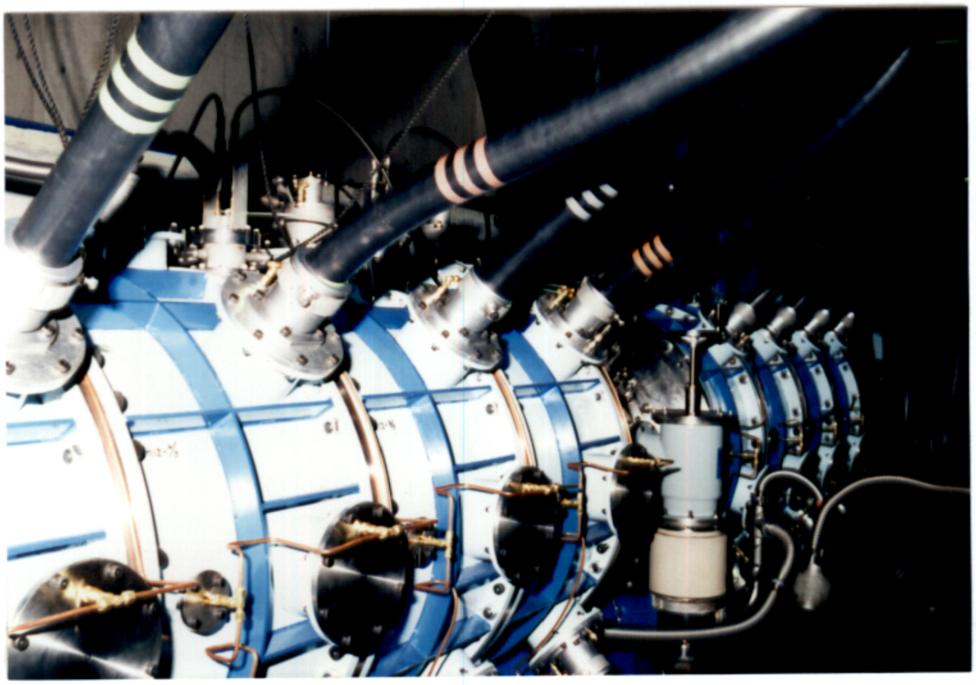


Fig. 19. Photograph of the eight stage induction cavities of Reiden IV-IA.

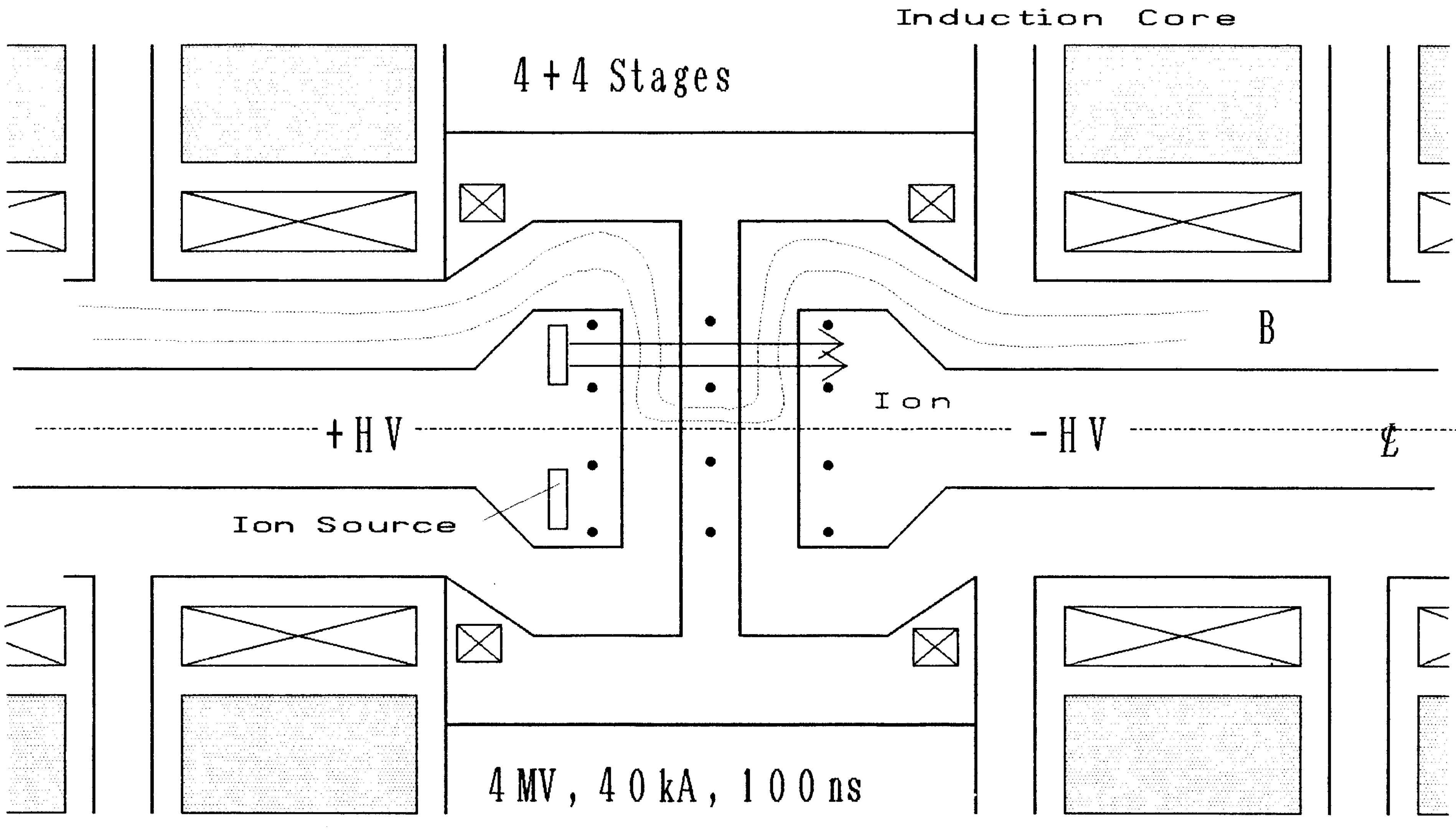


Fig. 20. The experimental setup of two stage ion diode on Reiden IV-IA.

Table 3. Ion Source and Diode Parameters

- Ion Source

Ion	C^{4+}	Li^{+}
Plasma Density ($/cm^3$)	5×10^{14}	1×10^{15}
Injection Velocity (cm/s)	1×10^{7}	2×10^{7}
Ion Current Density (kA/cm^2)	3.2	3.2

- Diode

Hollow Beam	Outer radius	8 cm
	Stages	2 ~ 4
	Voltage	15 ~ 7.5 (MV)
	Current	0.3 (MA)

REFERENCES

1. K. Imasaki et al., ILE Research Report, ILE 8130P (1981).

2. K. Imasaki et al., J. Phys. Soc. Jpn. 50, 3847 (1981).

3. K. Imasaki et al., "Proceedings of 8th Symposium on ISIAT," Tokyo, 143 (1984).

4. S. Miyamoto et al., "Laser Interaction and Related Plasma Phenomena," Vol. 7, Plenum Publishing Co., 619 (1986).

5. K. Nishihara et al., Proc. Japan-US Seminar on Theory and Application of Multi-Ionized Plasma Produced by Laser and Particle Beams, Nara (1982).

6. S. Miyamoto et al., Jpn. J. Appl. Phys. 21, L83 (1982).

7. T. Ozaki, S. Miyamoto, K. Imasaki, S. Nakai, and C. Yamanaka, J. Appl. Phys. 58, 2145 (1985).

8. P.F. Ottinger, S.A. Goldstein, and D. Mosher, Naval Research Laboratory Memorandum Report No. NRL MR-4948 (1982).

9. P.F. Ottinger, D. Mosher, and S.A. Goldstein, Phys. Fluids 23, 909 (1980).

10. W.M. Manheimer, M. Lampe, and J.P. Boris, Phys. Fluids 16, 1126 (1979).

11. P.F. Ottinger, D. Mosher, and S.A. Goldstein, Phys. Fluids 22, 332 (1979).

12. S. Miyamoto et al., Proc. of 4th Symposium in Ion Sources and Ion Appl. Tech. ISAT80, 215 (1980).

13. Y. Matsukawa et al., Jpn. J. Appl. Phys. 21, L675 (1982).

14. S. Miyamoto, T. Ozaki, A. Yoshinouch, S. Higaki, K. Imasaki, S. Nakai and C. Yamanaka., "Laser Interaction and Related Plasma Phenomena" Vol. 6, Plenum Publishing Co., 981 (1986).

15. K. Imasaki, S. Miyamoto, T. Ozaki, H. Fujita, N. Yugami, S. Higaki, S. Nakai and C. Yamanaka, Proc. 10th Int. Conf. on Plasma Phys. and Controlled Nuclear Fusion Research, London, IAEA-CN-44/B-II-2 (1984).

16. T. Akiba et al., Nuclear Instrum. and Methods in Phys. Research A259, 115 (1987).

ACCELERATOR RESEARCH FOR HIB FUSION IN THE U.S.

Walter M. Polansky
Office of Basic Energy Sciences
U.S. Department of Energy
Washington. D.C. 20545

The U.S. program in heavy ion beam (HIB) fusion emphasizes research on linear induction accelerators. This approach emerged in 1983, when the Department of Energy established the Heavy Ion Fusion Accelerator Research (HIFAR) effort to acquire an appropriate data base for future decisions in heavy ion fusion. Since its inception, HIFAR has advanced the understanding of high-current, ion beam transport and accelerator technology through laboratory scale experiments and supporting theoretical studies. But existing experiments do not have the capability to supply a major component of the remaining data needed to adequately satisfy the HIFAR objective; hence, the program is at a crossroads. Technically, HIFAR appears ready to proceed with the next program phase. However, the realities of the budget perspective, and the complications surrounding it, cannot be ignored. Affordable energy prices and the perception of abundant oil supplies have reduced the motivation to develop long-term energy solutions based on inexhaustible fuel supplies. As a consequence, the development of a commercial fusion capability does not at this time rank high among National priorities. Obviously HIFAR must overcome this obstacle before proceeding into the next program phase. In this regard, however, it is probably not alone among promising fusion and other long-term energy programs.

In 1977, the U.S. Department of Energy (DOE) initiated a heavy ion fusion program under the joint sponsorship of Defense Programs' Office of Inertial Fusion (OIF) and Energy Research's Office of High Energy and Nuclear Physics. Research on heavy ion fusion was a modest component of the inertial fusion program; its budget stabilized at a level of \$3 M/y. In response to a Congressional initiative in 1983, the Department transferred the accelerator research portion of the heavy ion fusion effort to Energy Research and HIFAR was underway. The OIF retained responsibility for target designs and fusion systems studies.

ACCELERATORS FOR INERTIAL FUSION

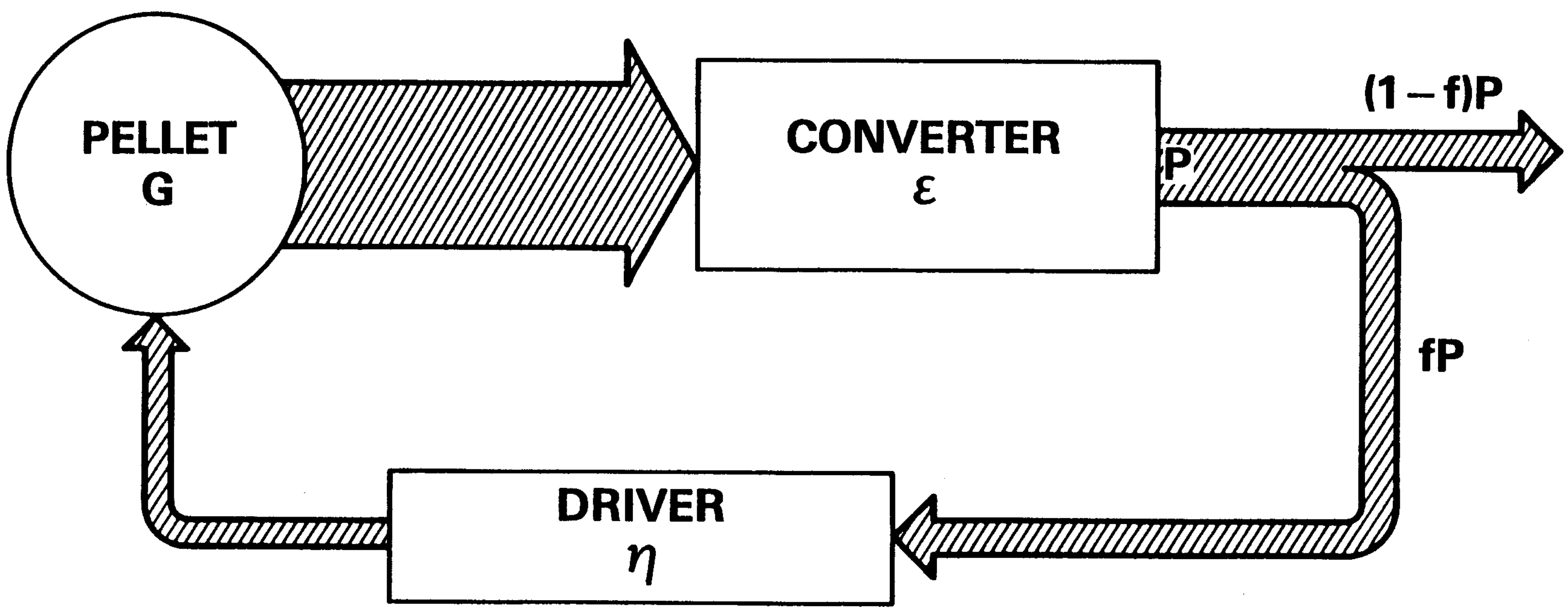
Based on present understanding,[1] an inertial fusion driver must be able to deliver nominally 200 TW/cm^2 in a 10-30 ns pulse to a fusion target that is several millimeters in diameter. For particle beams, this energy needs to be deposited in a layer corresponding to an ion range of 0.1 g/cm^2 to produce suitable fusion yields. For commercial applications, this performance must be reliably repeated several times each second.

Heavy ions (A=200) would need an energy of about 10 GeV to meet the range and energy deposition requirements of the fusion target. To satisfy irradiance conditions, the beam current should be about 20 kA for singly charged ions. While this is a large value, it nevertheless is in a range that leads one to consider adapting conventional accelerator technology to a heavy ion driver. Furthermore, accelerators have other features that could be advantageous for fusion applications. Accelerator facilities are reliable operations. The technology lends itself to pulsed operation with high efficiency. Also, the ion beams propagate through an accelerator in vacuum; no material "lenses" have to be placed in the beam path for transporting and focusing.

These may become important factors when considering electric power production, as shown in Figure 1. The driver efficiency η, is the energy/pulse delivered to the target divided by the electrical energy required to produce that pulse. Of the electrical power converted from the fusion reaction, a fraction must be recirculated to operate plant systems. The remainder, (1-f)P, represents the net generating capacity of the system. The power balance for the overall system is:

Figure 1

POWER BALANCE



$$P = \eta G \, fP\varepsilon$$

$$P=\eta G f P \varepsilon \quad (1)$$

Let's make a few assumptions to gather some insight into this expression. Thermoelectric conversion should have an efficiency of 33%. If we recirculate 25% of the total electrical power produced (333 MWe for a 1 GWe plant), then $\eta G=12$. For a driver that is 20% efficient, the target gain is 60, which should be in the performance range of simple, low-cost target designs. Employing lower yield targets in a fusion reactor may offer additional flexibility in terms of designs and materials. When considering commercial applications of inertial fusion a key figure of merit is (ηG), the product of driver efficiency and target gain.

The eventual ion of choice in an HIB fusion driver would emerge from assessments between actual target requirements and available ion accelerator technology, within acceptable economic and other bounds. As you may be aware, there are several methods for accelerating ions. In an inertial fusion context, one must evaluate which method can be modified and scaled to produce 20 kA currents of 10 GeV heavy ions. In addition, the output beams must have sufficiently good quality (measured in terms of the six dimensional phase space) to be focused over a distance of several meters to the center of the reactor chamber onto a fusion target.

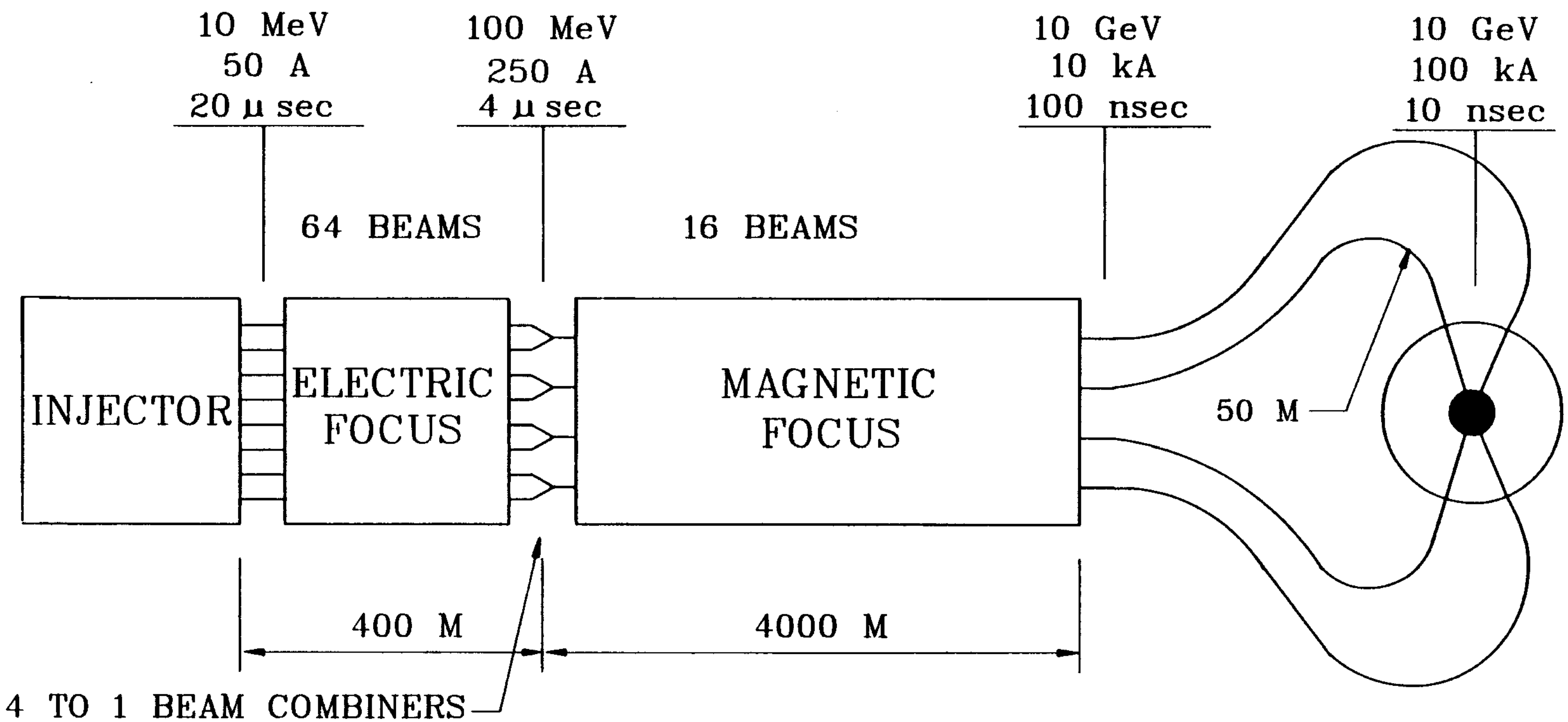
The relative merits of ion accelerator concepts for an inertial fusion driver have been reviewed in the U.S. by specialists through a series of workshops. Two distinct accelerator system designs emerged as viable candidates. One uses an rf-linac with storage rings patterned from fairly conventional designs to accelerate about 100 mA of heavy ions at constant current to full energy, followed by current amplification by multiturn stacking and bunching in the storage rings. National heavy ion fusion programs in Europe and Japan are pursuing this approach. Dr. Müller will be describing this approach during his presentation on the West German heavy ion program.

The other approach, the induction linear accelerator, has been adopted by the U.S. program. The decision to limit the U.S. program to a single accelerator approach was driven by budgetary considerations. This decision was made easier by the knowledge that the rf-linac/storage ring approach would not remain unexplored, since it was being examined elsewhere. Although the available data base for this decision was incomplete, several factors supported the induction linac method. First, an induction linac would be conceptually simpler than an rf-linac as an inertial fusion driver since fewer beam manipulations would be involved. Second, considerable experience has accrued in employing induction linac technology for the acceleration of high-power electron beams. Finally, the key technical issues confronting induction linac development such as multiple beam transport and beam stability can be studied in integrated experiments with modest size accelerator apparatus. Denis Keefe and Ed Lee will provide details on the induction linac approach in subsequent presentations.

An induction linac uses ferromagnetic cores to accelerate an ion beam bunch through transformer action. Unlike the case of an rf-linac, in which the beam current remains constant, amplification of the beam current can be achieved during acceleration by properly choosing the waveform voltages on the induction cores to control bunch length. The design philosophy for a heavy-ion induction linac driver (Figure 2) would consist of simultaneously transporting multiple beamlets through closely spaced, parallel channels that lie within a common series of accelerating cores. At the front end of the accelerator, a multiple-beam ion source would produce heavy ion beams at the levels of electrical charge/pulse to meet pellet implosion requirements. The current in each beamlet is constrained by transport limits within the lattice. As ion speed increases, the focusing system changes from electrostatic to magnetic quadrupoles with a corresponding increase in the maximum allowable current. At this point, beams can be combined to decrease the size and cost of the subsequent accelerator structure. A final

Figure 2

INDUCTION LINAC DRIVER (A=200, q=3)



power amplification of about a factor of 10 would occur by beam bunching action in the drift compression section just before the beams are focused onto the target.

HIFAR PROGRAM DESCRIPTION

HIFAR addresses the generation of high-power, high-current density beams of heavy ions, the understanding of scaling laws in this previously unexplored regime and the validation of accelerator concepts. Lawrence Berkeley Laboratory (LBL) is responsible for conducting the HIFAR program. Supporting efforts have been provided by Los Alamos National Laboratory, Lawrence Livermore National Laboratory, Naval Research Laboratory, Stanford Linear Accelerator Center, and Argonne National Laboratory. The HIFAR program structure and budget history appear in Tables 1 and 2, respectively.

The program strategy calls for a series of experiments to test beam physics issues under conditions that become progressively representative of an inertial fusion driver. HIFAR researchers have designed and fabricated the first three elements in this series; all are located at LBL. The first element is the Single Beam Transport Experiment[2] (SBTE) which has been operational since 1983. The SBTE apparatus contains a thermionic cesium source, an injector, a matching section that consists of 5 electrostatic quadrupoles, a transport section of 41 focusing-defocusing pairs of electrostatic quadrupole lenses, and a chamber for beam diagnostics. Typical values for ion kinetic energy and beam current are 150 keV and 20 mA, respectively. The SBTE was used by LBL researchers to transport beam currents three times as high as those previously thought possible in beams dominated by their own space charge. Figure 3 shows the electrostatic quadrupole lenses that provide the focusing fields for stable beam transport. For scale, the outer vacuum chamber of the SBTE is about 30 inches wide.

The next step beyond SBTE is an experiment[3] called the MBE-4 that will test the electrostatic features of a multiple beam induction linear accelerator. MBE-4 (Figure 4)

TABLE 1

HIFAR Program Structure

(FY1987 Operating Budgets)

* Lawrence Berkeley Laboratory ($3.9 M)

  - Single and Multiple Beam Experiments
  - Accelerator Theory and Design
  - Technology Development

* Los Alamos National Laboratory ($0.9 M)

  - Multi-Beam Source Research
  - Injector Development

* SLAC, NRL, LLNL, and ANL ($0.5 M)

  - Supporting Studies

TABLE 2

HIFAR Budget History

($ in Millions)

	FY84	FY85	FY86	FY87
Capital	0.2	0.6	0.6	0.6
Operating	4.8	5.0	4.6	5.3
Total	5.0	5.6	5.2	5.9

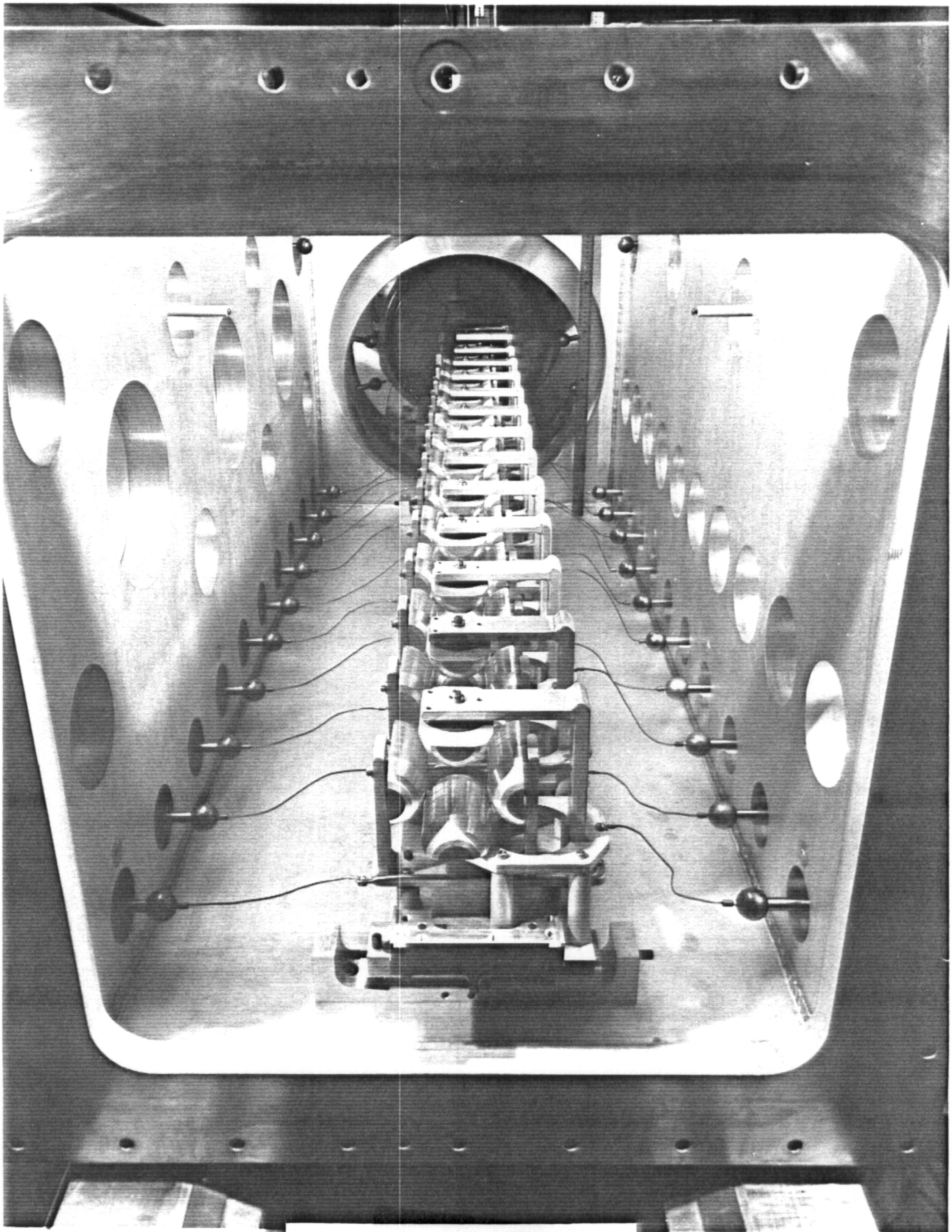


Figure 3: Interior of SBTE Apparatus

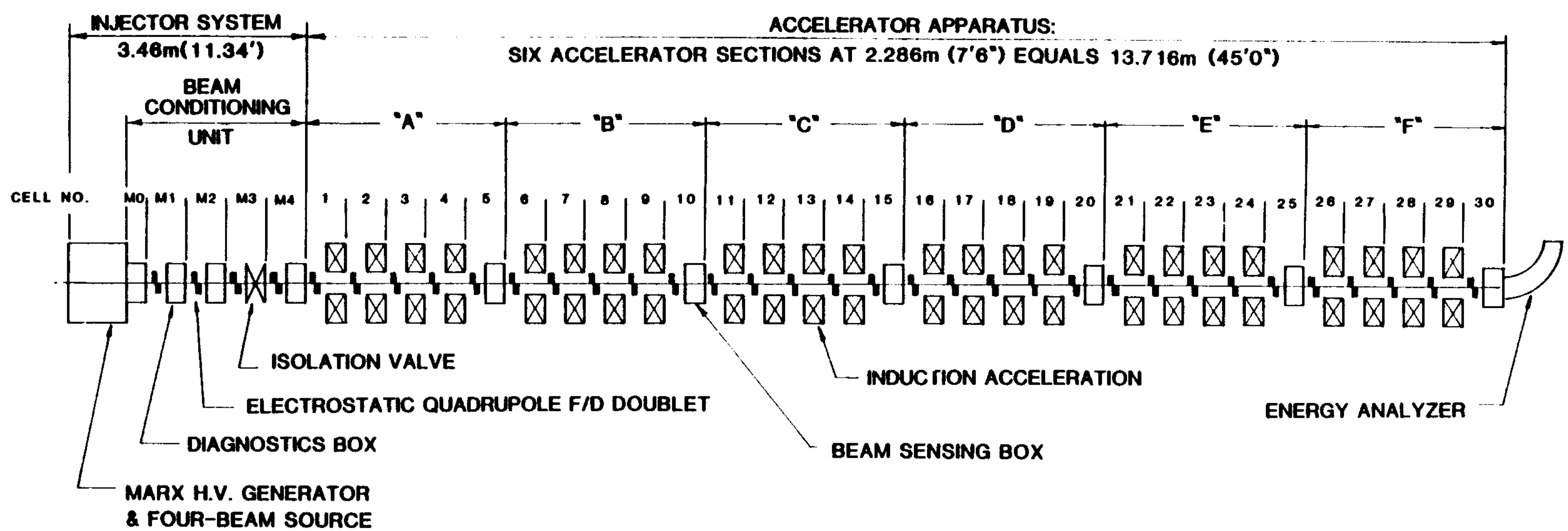


Figure 4. MBE-4 Diagrammatic Layout

integrates both focusing elements and accelerating electrodes that accommodate four ion beams in a single accelerating structure. This apparatus is fully operational and provides a basis for scaling to additional beams in the electrostatic portion of a driver. Magnetic induction cores, which accelerate all of the beams simultaneously, surround the lens arrays. Electrical pulses to the cores are tailored to preferentially accelerate the tails of the beams. As a result, the beam pulse length decreases as the beamlets travel through the linac and the current increases a factor of six over its value at the injector. MBE-4 tests have demonstrated the feasibility of the multiple beam concept and much of the longitudinal acceleration physics of a much longer induction linac.

In addition to the single- and multiple-beam experiments, HIFAR researchers at Los Alamos and the University of New Mexico have been developing ion source and injector technology to generate sixteen beams of singly or doubly charged ions at 2 MV for future experiments. During 1987, the injector apparatus, that was the keystone of this effort, was shipped to LBL so that remaining injector development could be fully integrated within the overall experimental program. The performance specifications on the ion injector apparatus represented a bold undertaking that will result in substantial benefit to HIFAR. The program owes a debt of gratitude to the members of the HIFAR team at Los Alamos for their efforts.

SUMMARY

The heavy-ion option must not be overlooked when the time comes for evaluating methods for establishing a commercial inertial fusion capability. HIFAR has made substantial progress toward understanding the potential of the induction linac approach, although much work remains to be performed. Furthermore, HIFAR appears to be on the right track. An internal assessment of the induction linac option for commercial power generation found that the induction linac method is economically comparable to magnetic fusion options over a range of driver parameters and for several choices of both reactor and target concepts. Bill Herrmannsfeldt and Don Dudziak will describe this study later in this session. Additional support on HIFAR status and the prospects[5] for heavy-ion fusion comes from a 1986 JASON panel review. The panel gave the program high marks and stated, "...one can argue that heavy ions are more attractive for driving an ICF target than lasers or light ions...for commercial power generation."

This symposium should provide relevant information to guide National policy decisions so that power production from inertial fusion can become a reality. In the meantime, we must continue to address the major technical issues on drivers to the extent possible within available funds. Thank you for your attention.

REFERENCES

1. D. Keefe, "Inertial Confinement Fusion," Ann. Rev. Nucl. Part. Sci., 32:391-441, (1982).

2. W. Chupp et al., "A Quadrupole Beam Transport Experiment for Heavy Ions Under Extreme Space Charge Conditions," IEEE Trans. Nucl. Sci., NS-30(4), 3669, (1983).

3. R.T. Avery, "Program Plan for the MBE-4 Multiple Beam Experiment," LBL Report No. 19592, (Feb. 1985).

4. D.J. Dudziak and W.B. Herrmannsfeldt, "Heavy Ion Fusion Systems Assessment Study," Heavy Ion Inertial Fusion, Washington, DC, Editors M. Reiser, T. Godlove and R. Bangerter, AEP Conf. Proc., Series No. 152, (1986).

5. D. Hammer et al., "Heavy Ion Fusion," JASON Report No. JSR-86-302, (July 1986).

INDUCTION LINAC DRIVERS FOR COMMERCIAL HEAVY-ION BEAM FUSION*

Denis Keefe
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 USA

INTRODUCTION

To achieve the desired range (0.1-0.2 g/cm^2) in the fusion target a heavy ion ($A \approx 200$) must have a kinetic energy in the region of 10 GeV -- more than a thousand times that for a proton of the same range. For a given pulse length (10-20 ns) the particle beam current can therefore be less by a corresponding factor. Also, damaging collective phenomena tend to scale with the ratio (Current/Mass) so that an additional factor of ~ 200 due to the mass also works in favor of heavy ions. Nonetheless, the particle beam current needed at the target is very large -- 20 kA for ions with charge-state, q, of unity -- compared with standard accelerator experience. The questions of handling very high beam-currents and, at the same time, maintaining high-optical quality on the target -- have been, and remain, central to the heavy-ion fusion accelerator research (HIFAR) efforts. (In accelerator parlance, good optical quality corresponds to low beam emittance; emittance being measured by the product of the transverse size of the beam and the maximum transverse velocity components of the particles.)

A multigap accelerator for heavy ions, relying on the physics and engineering base of research accelerators, offers a unique combination of several advantages as a driver for fusion energy in the following regards:

i) Efficiency

ii) Repetition rate

iii) Reliability

iv) Long stand-off distance for the final focus.

* This work was supported by the Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy, under Contract No. DE-AC03-76SF0098

DRIVER CONFIGURATIONS

As mentioned in the previous talk by W. Polansky, two generically different heavy-ion accelerator driver systems to deliver high current beams of heavy ions (A = 200) with kinetic energy about 10 GeV are under study at present.

The rf/storage ring method (to quote from the HIBALL study report) starts with eight low-β accelerators, the beams being sequentially combined in pairs--after some stages of acceleration--to deliver a high current beam (160 mA) to the main linac (Badger et al., 1984). In an rf linac, the current remains constant since the length of the bunch expands in direct proportion to the speed during acceleration. When acceleration to 10 GeV is complete, the current is amplified from 160 mA in a sequence of manipulations in storage rings, including multiturn injection and bunching, to 20 kA to be delivered finally to the target in some ten to twenty separate beams.

The induction linac system, by contrast, relies on amplifying the current simultaneously with acceleration to keep pace with the kinematic change in the space-charge limit (Keefe, 1976; Faltens et al., 1981). It is convenient to think of sixteen beams accelerated in the same structure with independent transport systems from source to target; this approach would represent the simplest single-pass system.

While a knowledge of the space-charge limit for beam current is crucial in the design of just the low-β parts of the rf/storage ring system, it is clearly central to the design of the induction linac at every point along its length.

The importance of obtaining high current can be illustrated as follows. The target requirements set the kinetic energy (i.e. range) of the ion -- say, 10 GeV -- and also the total beam energy -- say W = 3 MJ. Thus the amount of beam charge (for singly-charged ions) is determined as 3 MJ/10 GeV = 300 microcoulombs. In supplying the 3 MJ over the length of the accelerator it is advantageous to supply as much energy as one can at each gap in the multigap structure. If the voltage added per gap is ΔV, the energy added per gap is $\Delta W = I\tau\Delta V$. The product $\tau\Delta V$ is simply the volt-seconds product of the induction core supplying the voltage increment, and is related to the volume and hence the cost of the unit. Therefore, maximizing the current, I, at each accelerating station can result in lower core cost; in addition a large beam current can heavily load the driving circuitry and lead to high electrical efficiency.

THE CURRENT-AMPLIFYING INDUCTION LINAC

The basic idea of a heavy-ion induction linac using current amplification is to inject a long beam bunch (many meters in length, several microseconds in duration) and to arrange for the inductive accelerating fields to supply a velocity shear so that, as the bunch passes any point along the accelerator, the bunch tail is moving faster than the head. As a consequence, the bunch duration (and usually, but not necessarily, the spatial length) will decrease and the current will be amplified from amperes at injection to kilo-amperes at the end of the driver (10 GeV). The current is further amplified by a factor of about 10, and the pulse duration shortened correspondingly to about 10 nanoseconds, by beam bunching in the drift section between the accelerator exit and the final focussing lenses. Disruptive transverse space-charge forces are large enough that some sixteen parallel beams are needed to handle the ions in the drift-compression and focus sections. In the drift section, one is relying on the longitudinal space-charge self force in the beam bunch to slow down the faster-moving tail and speed up the slower-moving head and, thereby, to remove the velocity shear so that chromatic aberration does not spoil the final focussing conditions.

Assembly of a proof-of-principle experiment, called MBE-4, has just been completed at Berkeley (see Fig. 1.) The aim is to prove the principle of current amplification while keeping the longitudinal and transverse beam dynamics under control (i.e. adequately small emittance) and, in addition, to face the additional complication of handling

Fig. 1. The recently completed MBE-4 apparatus; the induction cores are housed in the square boxes.

multiple beams (four in MBE-4). Four surface ionization sources supply 20 mA apiece of cesium ions at 200 kV. When completed, the apparatus will have 24 accelerating gaps and should achieve a current amplification of a factor of six. For comparison, in the few-thousand-meter length of a driver the current amplification factor needed is a few hundred.

The transverse beam dynamics in MBE-4 is strongly space-charge dominated in that the betatron phase-advance per focussing-lattice period for each beam is strongly depressed -- from $\sigma_0 = 60°$ down to about $\sigma \sim 12°$ (see Fig. 2 for a definition of these terms.) For a monoenergetic beam without acceleration the Berkeley Single Beam Transport Experiment (SBTE; see below) has shown stable beam behavior to lower values of σ (7°-8°). New issues in transverse dynamics, however, arise in MBE-4 because of (a) the difference in velocity along the bunch as it passes through a given lens, which results in values for σ_0 and σ that vary along the bunch length, and (b) the discrete accelerating kicks which can cause envelope-mismatch oscillations.

For the longitudinal dynamics, two separate features arise in MBE-4. Space charge effects throughout the body of each long bunch (about 100 cm long and 1 cm radius) are strong enough that the dynamical response to velocity kicks or acceleration errors is described in terms of space-charge (Langmuir) waves rather than in single-particle terms. Secondly, the tapered charge density that occurs at the ends of the bunch will result in collective forces that are accelerating at the head and decelerating at the tail and, if not counteracted, will make the ends of the bunch spread both in length and in momentum. A major part of the experimental effort is centered on designing and successfully deploying the electrical pulsers to handle the correcting fields at the bunch ends.

SPACE-CHARGE DEPRESSES THE BETATRON PHASE ADVANCE PER CELL

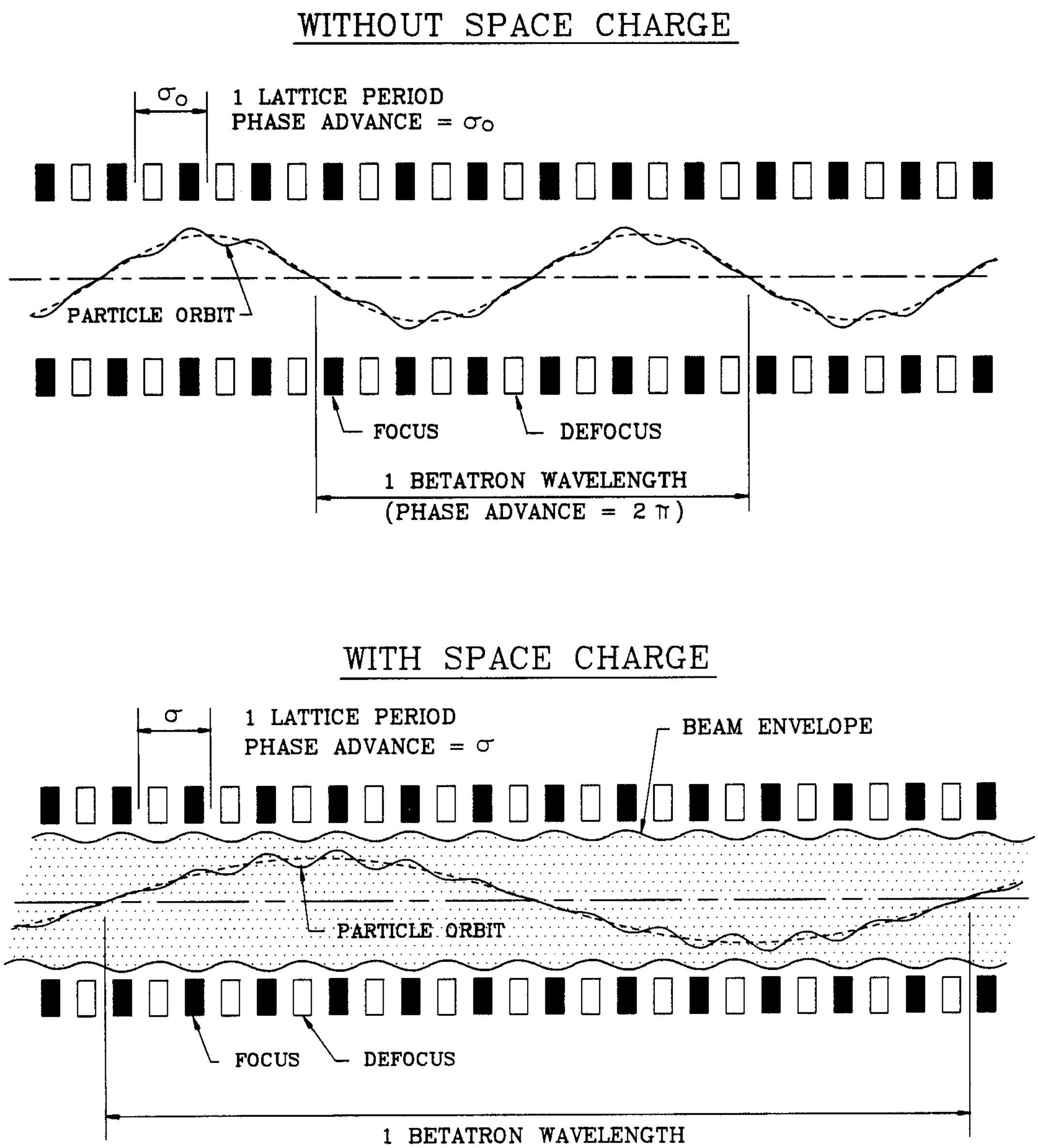


Fig. 2. In a strong-focussing lattice (alternating focussing and defocussing quadrupoles) a single particle executes quasi-sinusoidal betatron oscillations (upper). Its motion is characterized by the phase advance of the sinusoid per repeat length of the structure, σ_0. With space-charge present -- a defocussing force -- the phase advance, σ (or oscillation frequency) is decreased (lower).

Figure 3 shows an example of current amplification results obtained some months ago when only 12 of the 24 accelerating gaps were in place. It can be seen that the pulse duration has been shortened by a factor of three and the current correspondingly increased (Fessenden et al., 1987). Because MBE-4 operates at relatively low energy (accelerating from 200 keV to 1 MeV), we can try rather aggressive schedules for current amplification, which correspond to setting up a large velocity shear, $\Delta\beta/\beta$. We do not have a precise argument for exactly how large a velocity-shear may be and still be considered tolerable. An experiment with $\Delta\beta/\beta = 0.4$ has been completed; this is much more than will be needed in a driver.

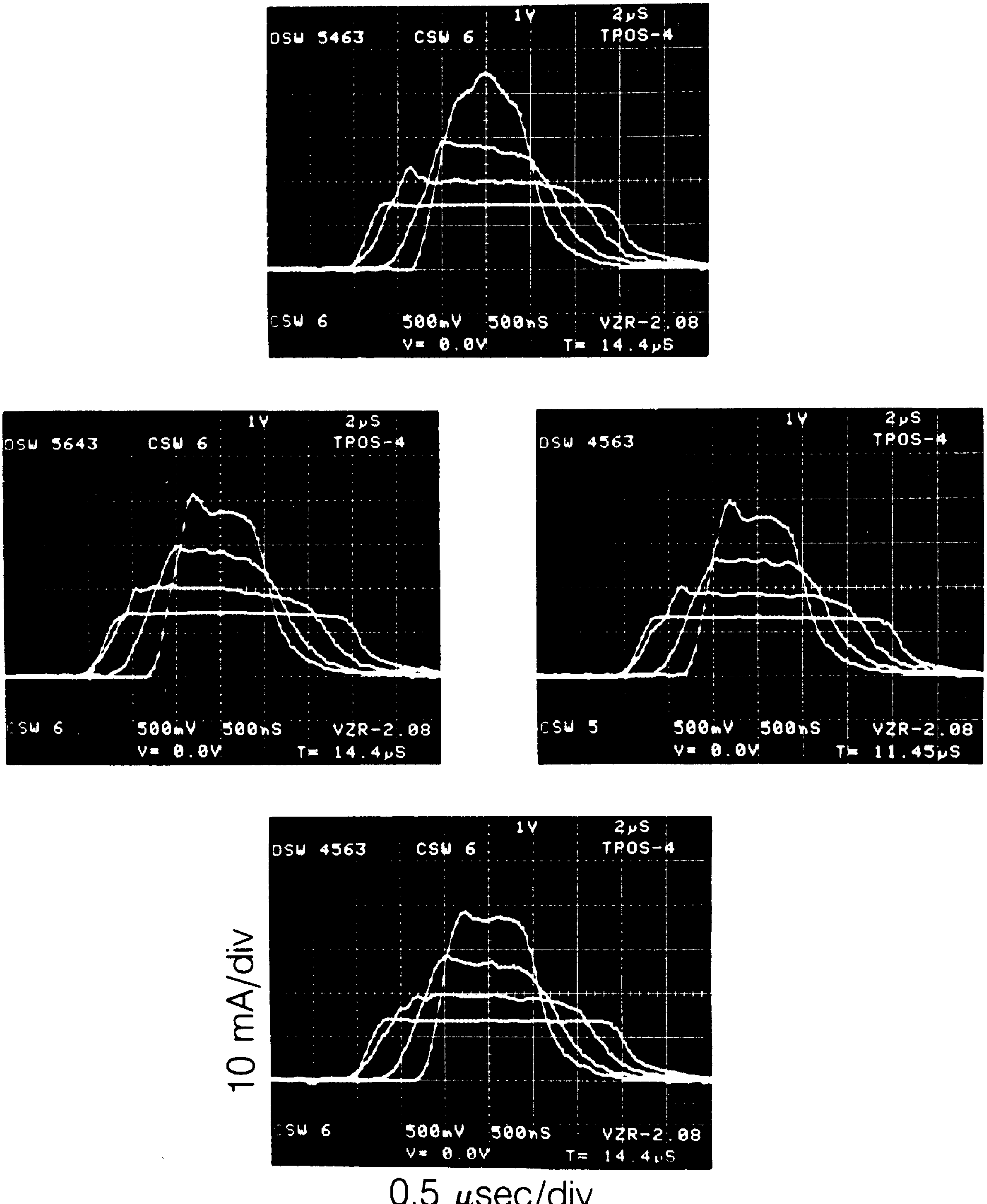
HIGH CURRENT BEAM BEHAVIOR AND EMITTANCE GROWTH

The Single Beam Transport Experiment (SBTE)

The Single Beam Transport Experiment (SBTE) is the most extensive experiment of its kind on the propagation of space-charge-dominated ion beams in a long quadrupole-focussed transport channel. It consists of 87 alternating-gradient electrostatic quadrupoles -- this is about one-tenth of the number of lenses needed in a driver. A beam of cesium ions is supplied from a hot zeolite emitter and injected into the channel from an injector which can be varied in voltage from 120 to 200 kV. Both the beam current and the beam emittance can be independently varied at the injector to study beam behavior for a variety of conditions. Empirically, the propagation is judged "stable" if both the beam current and the beam emittance are the same at the end of the channel as at the beginning.

The results are shown in Fig. 4; at the highest currents and lowest emittance values obtainable from the 120-200 kV cesium injector, no growth in emittance or loss in current were observed in the transport channel provided σ_0 did not exceed 88° (Tiefenback & Keefe, 1985; Tiefenback, 1986). A threshold value of current above which emittance

MBE-4 Beam Currents at Stations 0, 5, 10, 15



XBB 873-1799

Fig. 3. Oscillograms for all four beams in MBE-4 show the injected current trace (lowest amplitude, longest duration) and the amplified current traces after four, eight, and twelve accelerating units.

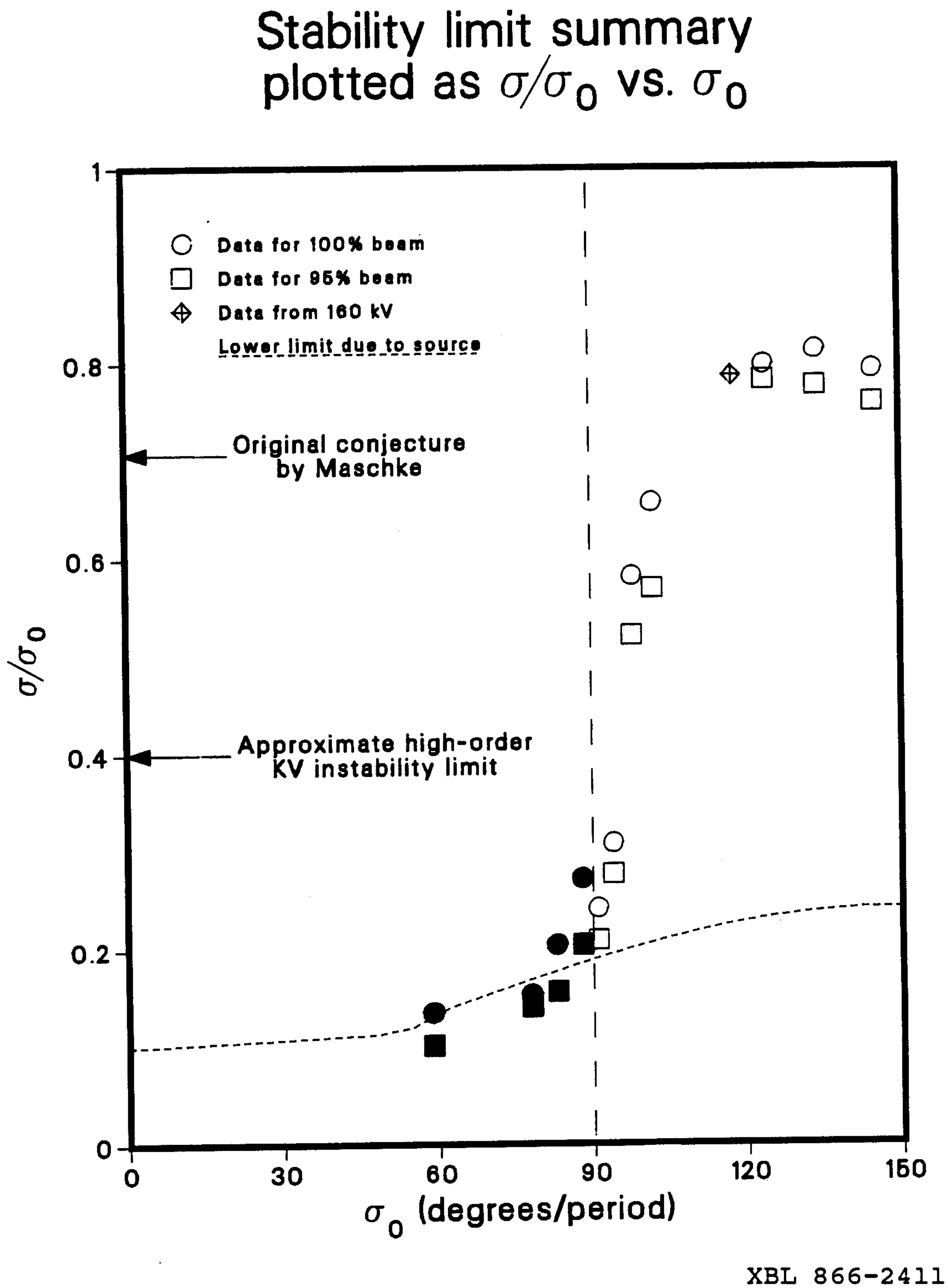


Fig. 4. Results from the Single Beam Transport Experiment. The solid data points are for cases where no emittance growth or current loss could be detected. The dashed curve indicates the lower limit on σ/σ_0 that could be reached because of ion-source limitations. Above $\sigma_0 = 88°$, emittance growth and current loss can be avoided only for values of σ/σ_0 lying above the open data points.

growth occurs could, however, be measured for values of σ_0 in excess of 88°. Since the transportable current is greatest for $\sigma_0 < 88°$, the design of drivers will be restricted to σ_0 values in this range.

Earlier theoretical work on beam current limits in AG focussing systems utilizing an idealized distribution (the Kapchinskij-Vladimirskij or K-V) indicated that it could be dangerous to use σ_0 greater than 60°, and that σ could probably be depressed from that value down to 24°, but not below (Hofmann et al., 1983). The experimental limits from SBTE shown in Table 1 can be seen to be much more encouraging.

Table 1. Experimental Limits on σ_0, σ.

σ_0	60°	78°	83°
σ	< 7°	< 11°	< 15°

In his original consideration of high current limits in magnetic AG systems Maschke showed that the limiting particle current could be written (nonrelativistically) as:

$$I_p = K(\eta B)^{2/3}(\varepsilon_N)^{2/3}V^{5/6} \quad q^{1/2}A^{1/2} , \tag{1}$$

with B the limiting pole-tip field, η the fraction of length occupied by magnetic lenses, qV the ion kinetic energy, ε_N the normalized emittance, and A and q the ion mass and charge state respectively. It is useful to use the "smooth approximation" (Reiser, 1978) to write the explicit dependence of K on σ_0 and σ, viz:

$$K \propto \sigma_0^{2/3} \quad (\sigma/\sigma_0)^{2/3} \; . \qquad (2)$$

The coefficient, K, originally selected by Maschke was for an implicit conjecture that σ/σ_0 could not be less than 0.7. The fact that we can use a somewhat higher value of σ_0 and a significantly lower value for (σ/σ_0) than thought possible a few years ago has led to reduced capital cost and increased electrical efficiency for heavy ion driver designs.

NEW CONSIDERATIONS FOR DRIVER DESIGN

Much of the early design work for induction linac drivers was restricted to considering (a) that ions with charge state q = 1 were most suitable and (b) that σ/σ_0 = 24°/60° = 0.4 was a limiting value. The driver design program, LIACEP (Faltens et al., 1979) did, however, indicate that capital savings could ensue if either condition could be relaxed, but at the cost of additional complications, as perceived then, such as the following:

i) Reduced particle beam current at any point (V) in the driver (see Eq. 1 for q-dependence).

ii) Generating ions with q > 1, which was visualized to be done by stripping a beam with q = 1 at some intermediate energy.

iii) An increased number of beam lines in the drift-compression section.

The results from SBTE and simulations have altered our thinking and encouraged us to re-open the matter of using ions with charge state q > 1. As an illustration, imagine that (σ/σ_0) has no lower limit; then, by going up in charge state, q, we can maintain the same particle current (Eqs. 1 and 2) by choosing a lower value for (σ/σ_0). Now the total voltage of the accelerator can be cut from 10 GV (for q = 1) to (10/q) GV, resulting in a shorter and less expensive driver. This argument alone would suggest selecting the highest possible charge state to minimize size and cost. A limitation occurs, however, beyond $q = 3$ (for $A = 200$) because the increased perveance (i.e., space-charge) in the final drift lines rises as q^2 and the increased cost of the larger number of final beam lines that will be needed overrides the cost reduction in the accelerator. This argument is given in more detail by Lee (1986).

It now appears that the direct generation of adequately high currents of ions with $q > 1$ from a source is possible as a result of work by Brown with the MEVVA source (Brown, 1986). Using a similar source, Humphries has shown how to avoid plasma pre-fill of the extraction region, and thus has solved the problem of rapid turn-on of the source (< 1 μs) needed for an induction linac driver (Humphries and Burkhardt, 1986).

With ions of $q = 1$, the low velocity end of the linac (< 250 MeV) represented only 10% of the cost [Faltens et al. (1981)]. With ions of $q = 3$, the bulk of the accelerator has been shortened from 10 GV down to 3.3 GV and the cost of the front end represents a much more significant fraction of the overall cost; hence, it is now receiving more design attention. With higher charge state we visualize a driver starting with as many as 64 beamlets up to the 250 MeV point, whereupon they are combined in sets of four to provide 16 beams that undergo the bulk of the acceleration (see Fig. 5). Before this strategy can be established as a viable one, however, the emittance growth in combining high-current beams must be better understood.

THE HEAVY ION FUSION SYSTEMS STUDY (HIFSA)

The first systems assessment for a power plant based on an induction linac driver has been completed under the auspices of EPRI and the DOE Office of Program Analysis and Office of Basic Energy Sciences (Waganer et al., 1986). The major participants include McDonnell-Douglas (MDAC), LANL, LBL, and LLNL. The main emphasis as expressed in the term "Assessment" is not on developing a point design such as HIBALL

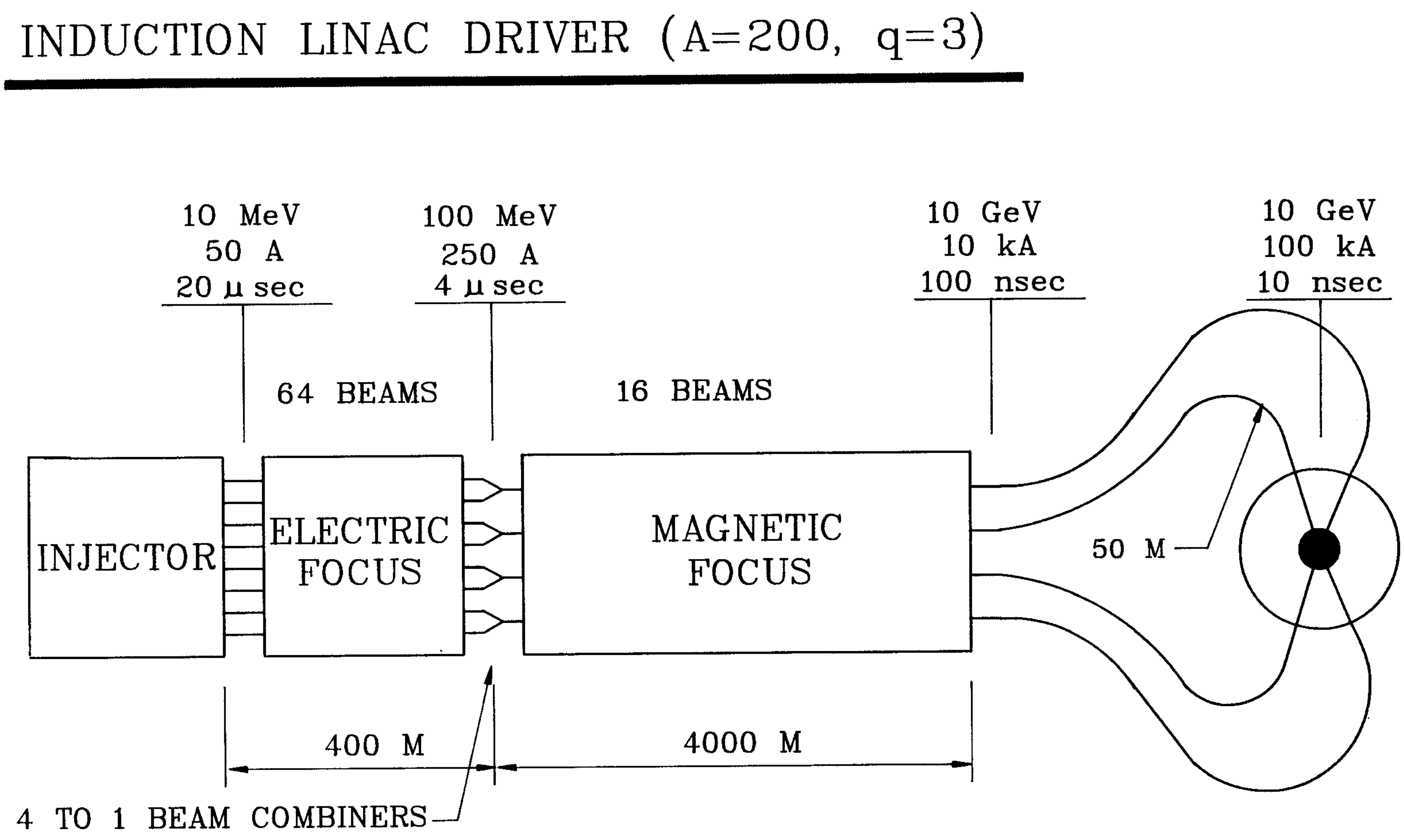


Fig. 5. Schematic of present concept for a driver using ions with charge state 3. The total beam current shown is in electrical (not particle) amperes.

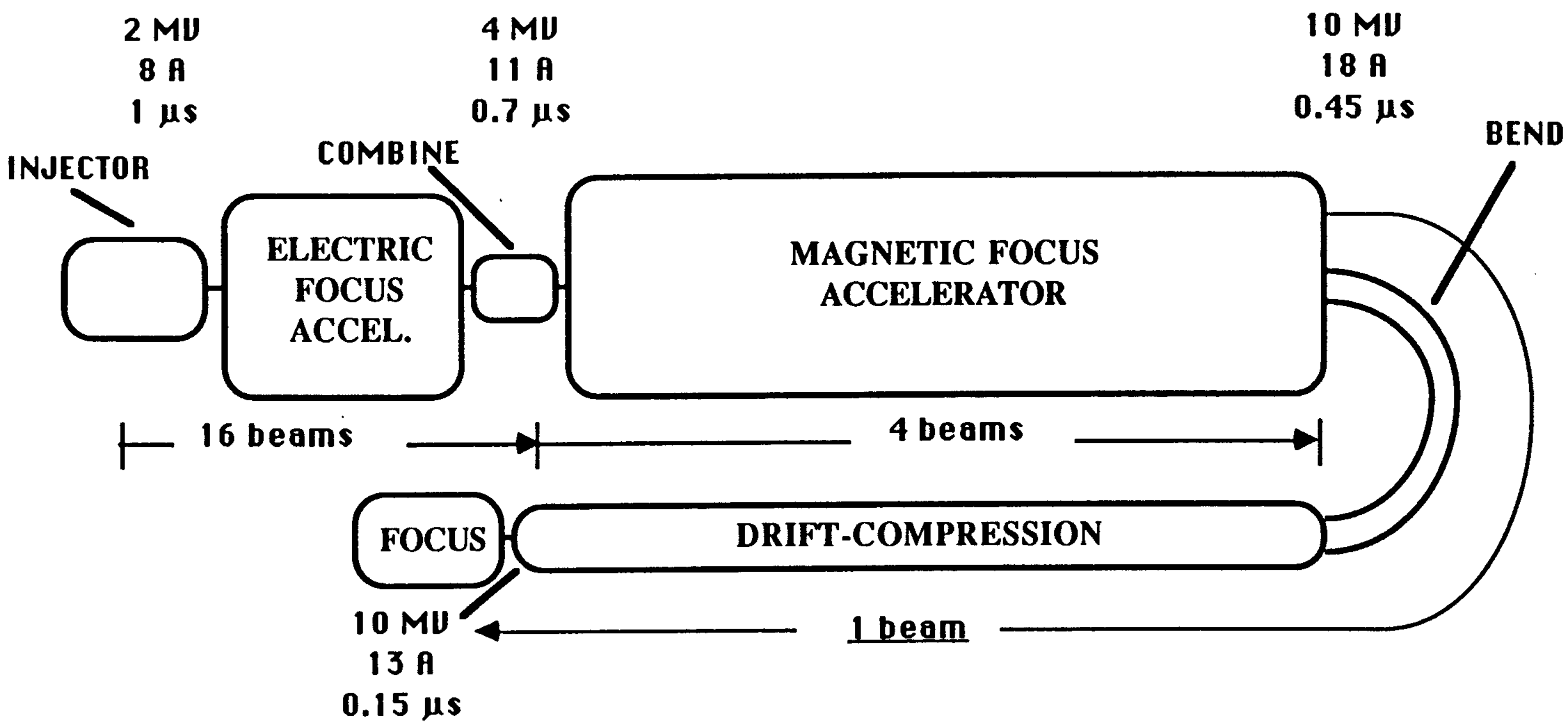
(Badger et al., 1984) but on exploring a broad range of parameters to establish general conclusions (a wide variety of point designs can, of course, be generated from the results).

Four different reactor types and five different target designs are included in the examination. The driver parameters range from a kinetic energy of 5 GeV to 20 GeV, a beam energy from 1 MJ to 10 MJ, a repetition rate of 2 Hz to 10 Hz, and an electrical efficiency in the range 20-40%. Results to date show that a cost of electricity of 5.5 cents/kWh seems quite reasonable to expect for a 1000 MWe plant that uses ions with A = 200, q = 3. The familiar "economy-of-scale" effect is also apparent, with the cost of electricity being less (4.5 cents/kWh) if a 1500 MWe plant is considered, or more (9.5 cents/kWh) for a 500 MWe plant. One of the more interesting results is that such values of electric energy cost can be realized for a very broad range of driver parameters and for several choices of both reactor and target designs.

FUTURE STUDIES

Certain manipulations will be needed in a driver that have yet to be modelled in the laboratory both to test the beam physics realistically and to establish the technology. We have proposed incorporating several relevant experiments in a sequential way in an apparatus called ILSE (see Fig. 6.) The purposes include:

i) Scaling up the injector technology from the few-hundred kV level to 2 MV; also scaling up the number of multiple beams from 4 to 16. A 2 MV injector designed and partially fabricated at LANL is now being completed at LBL and could provide the ILSE injector.



XBL 8711-4802

Fig. 6. A schematic of ILSE. After acceleration just one of the four beams is used for the bend, drift-compression, and focus experiments.

ii) After acceleration from 2 MeV to 4 MeV, transverse stacking of the beams in sets of four to reduce the number of beams from 16 to 4. Such a manipulation is well-known to result in an increase in emittance by just over a factor of two for low-current beams. It has been recognized in the past three years that the increase can be much more for space-charge dominated beams. It is important to study the physics of this process in the laboratory to see if the actual emittance growth can be kept within tolerable limits for a driver.

iii) Magnetic focussing of the beam during acceleration from 4 MeV to 10 MeV. A light ion (carbon) has been selected for use in ILSE so that at the 4 MeV point the ion velocity is large enough that the ($\underset{\sim}{v} \times \underset{\sim}{B}$) force allows the use of reasonably proportioned magnetic quadrupoles.

iv) Bending of one of the beams through a large angle (180°) to model the bending that takes place between the end of a driver and the reaction chamber. Such achromatic bends are well tested and understood for low current beams but some new physics questions arise for space-charge-dominated beams.

v) Drift-compression physics. When it exits the accelerator the beam has a velocity shear from head to tail which causes the tail to catch up with the head and bunching to occur. Because of longitudinal space-charge the head is collectively accelerated and the tail decelerated and the velocity tilt virtually removed by the time the final focus lens is reached. While the process has been simulated with 2-1/2 D PIC codes, the physics is complicated enough that it needs exploration in the laboratory.

vi) Final beam focus to a target a few millimeters in size. The ILSE parameters should result in heating of the target to a few eV and production of plasma. There is a wide range of experiments related to propagation and focussing in a reactor that can be performed in the final focus section.

While the scale of ILSE is too small to produce a high-temperature target plasma, it can test the physics and technology of key driver parameters at a scale of one-tenth (or greater in some cases).

SUMMARY

Experimental progress to date has strengthened our belief in the soundness and attractiveness of the heavy ion method for fusion. What surprises that have shown up in the laboratory (e.g., in SBTE) have all been of the pleasant kind so far.

The systems assessment has supported the view that the heavy ion approach can lead to economically attractive electric power and that a wide variety of options exists in all parameters. The systems work has also been of great help in pointing the way for research and development activities.

REFERENCES

1. Badger, B. et al., 1984, "HIBALL-II, An Improved Heavy Ion Beam Driven Fusion Reactor Study," Univ. of Wisc. Rep. No. UWFDM-625.

2. Brown, I., 1986, *Proc. Int. Symp. on Heavy Ion Fusion*, AIP Conference Proceedings No. 152, 207.

3. Faltens, A., E. Hoyer, D. Keefe and L.J. Laslett, 1979, *Proc. Workshop on Heavy Ion Fusion*, Argonne 1978, Argonne Natl. Lab. Rep. ANL-79-41, p. 31.

4. ltens, A., E. Hoyer, D. Keefe, 1981, *Proc. 4th Int. Top. Conf. on High-Power Electron and Ion-Beam Res. and Tech., Palaiseau*, (ed. H.J. Doucet and J.M. Buzzi) 751.

5. Fessenden, T.J., D.L. Judd, D. Keefe, C. Kim, L.J. Laslett, L. Smith and A.I. Warwick, 1986, *Proc. Int. Symp. on Heavy Ion Fusion*, AIP Conference Proceedings No. 152, 145.

6. Hofmann, I., L.J. Laslett, L. Smith and I. Haber, 1983, *Particle Accelerators* 13 165.

7. Humphries, S., Jr. and C. Burkhardt, 1986, *Particle Accelerators*, 20, 211.

8. Keefe, D., 1976, *Proc. 1976 Proton Linear Accel. Conf. (Chalk River)*, Atomic Energy of Canada, Ltd., Rep. No. AECL-5677, 272.

9. Lee, E.P., 1986, *Proc. Int. Symp. on Heavy Ion Fusion*, AIP Conference Proceedings No. 152, 461.

10. Reiser, M., 1978, *Particle Accelerators*, 8, 167.

11. Tiefenback, M.G., and D. Keefe, 1985, *IEEE Trans. Nuc. Sci.* 32, 2483.

12. Tiefenback, M.G., 1986, "Space-charge Limits on the Transport of Ion Beams in a Long A.G. System" (Ph.D. Thesis), Lawrence Berkeley Laboratory Report No. LBL-21611.

13. Waganer, L.M., D. Driemeyer and D.S. Zuckerman, 1986, *Proc. Int. Symp. on Heavy Ion Fusion*, AIP Conference Proceedings No. 152, 482.

RF LINAC DRIVER FOR COMMERCIAL HEAVY ION BEAM FUSION

R.W. Müller
GSI Darmstadt, FRG

Heavy ions are a promising driving medium for ICF because of their high stopping power, or short range, or their good energy coupling to the target ablator which is expected to become even stronger at high target temperature. In contrast to light ions, the energy may be as high as 50 MeV/mass unit, and therefore the current may be moderate. Transport and focussing may be conventional without compensation by electrons, with a few exceptions.

Making full use of now existing linac technology, and using, e.g. Bi ions in the 1^+ charge state, a linac of a few miles length can produce the required driver energy of 5 MJ within 4 ms, contained in 3×10^5 short ion pulses. A chain of these pulses, if they would exist all at a time in one beam tube, would be 400 km long. Ninety percent or more of this length is empty space which, however, cannot simply be taken out because of the fixed bucket frequency of a linac.

A very straightforward idea to solve the problem of compression in time is to let the bunches wait, running down a helix-shaped beam line, and kick them towards a target all at one time. Figure 1 shows such a scheme, now somewhat prehistoric; it is, however, not applicable for pulse trains as long as those needed.

It is better to let the beam forget its microbunch structure by actively debunching it. Actively means that a fraction of the 90% empty space between microbunches is used to improve the momentum definition of the beam, or reduce the momentum width. Small momentum width is needed when finally the beam is compressed in time; otherwise the resulting momentum spread would become intolerably big. On the other hand, small momentum width can give rise to microwave instabilities in the storage rings by lack of so-called Landau damping. We found a gap between both limitations.

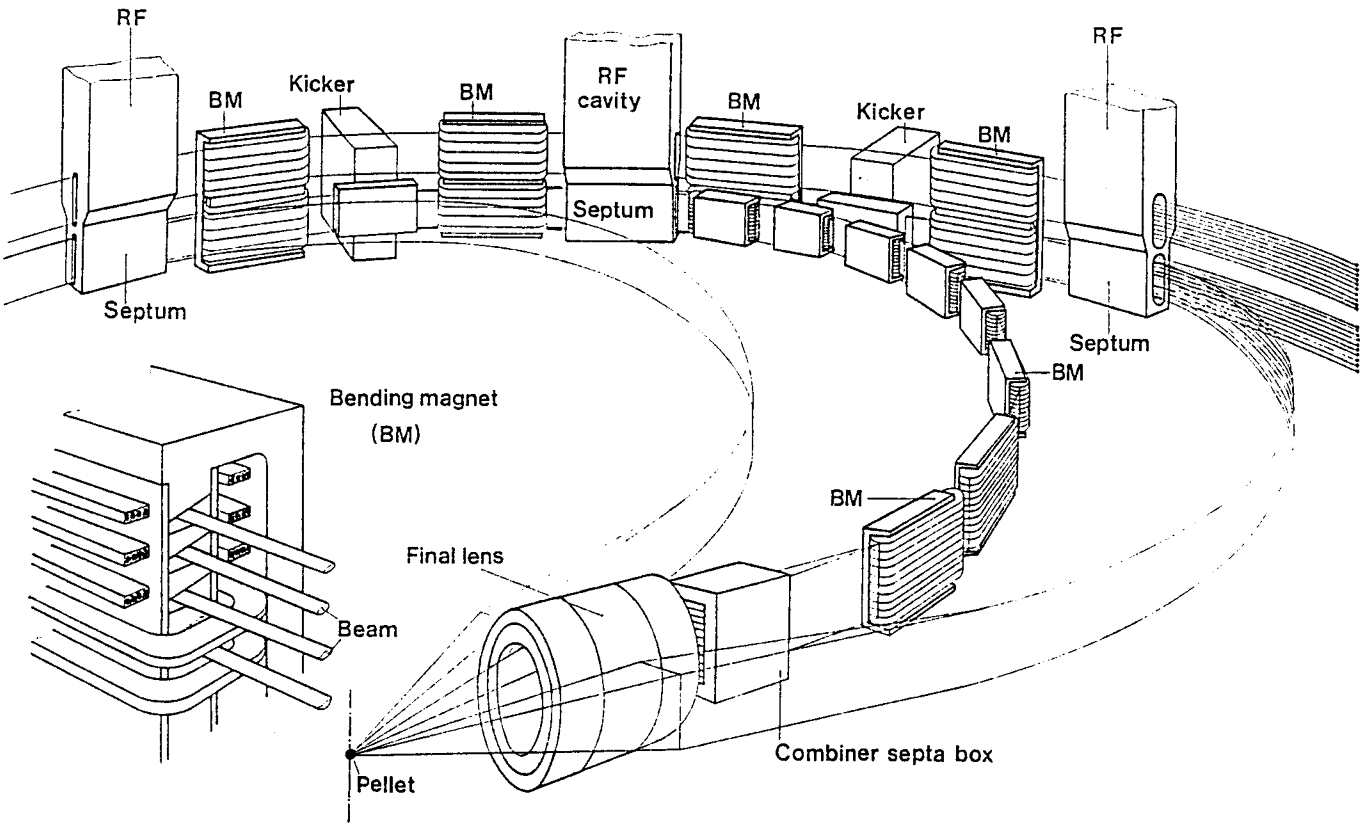


Fig. 1. A naive scheme: The helix beam line with beam combination after extraction.

Longer bunches of 2 μs length with 2 μs pauses are now formed by alternatively kicking the beam into two different channels and rings. To reduce losses during kicking, short gaps of 0.4 μs length every 2 μs must be programmed into the linac beam right at the ion sources.

The task now is to fold these 1920 2 μs-pulses into 20 pulses (= 20 beam lines), so we need a folding or stacking factor of $96 = 3 \times 2^5$. HIBALL-I[1] used conventional transverse stacking techniques for this task. This required one very big storage ring, followed by smaller ones (see Fig. 2). For reasons of stability of the stored beams we now prefer Bi^+ over Bi^{2+} ions (reduced space-charge). In this case the old design would have become too expensive. The new scheme of HIBALL-II[2] is more economic, avoiding super-large rings, and minimizing the number of smaller rings; see Fig. 3.

The first pair of accumulator rings (AR) stores only 122 μs-pulses each, and has to be used repetitively every 48 μs, i.e. 80 times per pellet-shot cycle, or 8 times to fill one of the 10 storage rings. The remaining folding factor of $8 = 2^3$ is achieved by 3 waiting rings (WR) and an in-flight combination of retarded and unretarded pulses. So five rings of a reasonable diameter, less than 500 m, plus a delay-line of 185 m length, which can be housed in one tunnel, do the job of a 48-fold-stacking.

The beams are then deposited in 10 storage rings. At the entrance there is another factor-of-two folding by two-turn injection. For these storage rings we think of superconducting magnet technology which is in the stage of development now. It is not vital for the scheme. An alternative could be five warm storage rings plus another waiting ring, all of identical size. This choice may even be a little cheaper, but the geometry of placing the storage rings around the reactors is more sophisticated. The geometry with superconducting rings is given in Fig. 4.

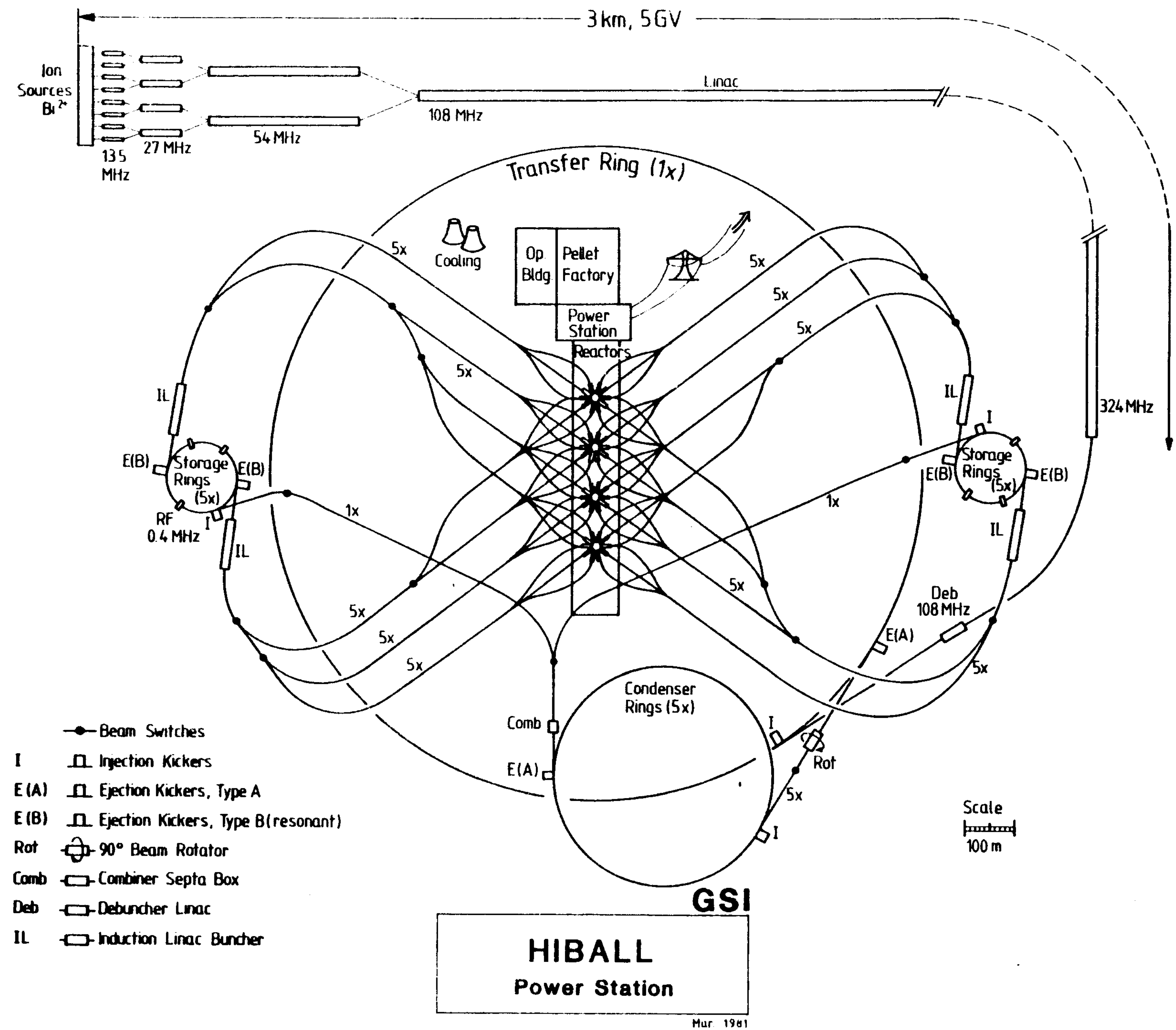


Fig. 2. HIBALL-I scheme and ground-plan.

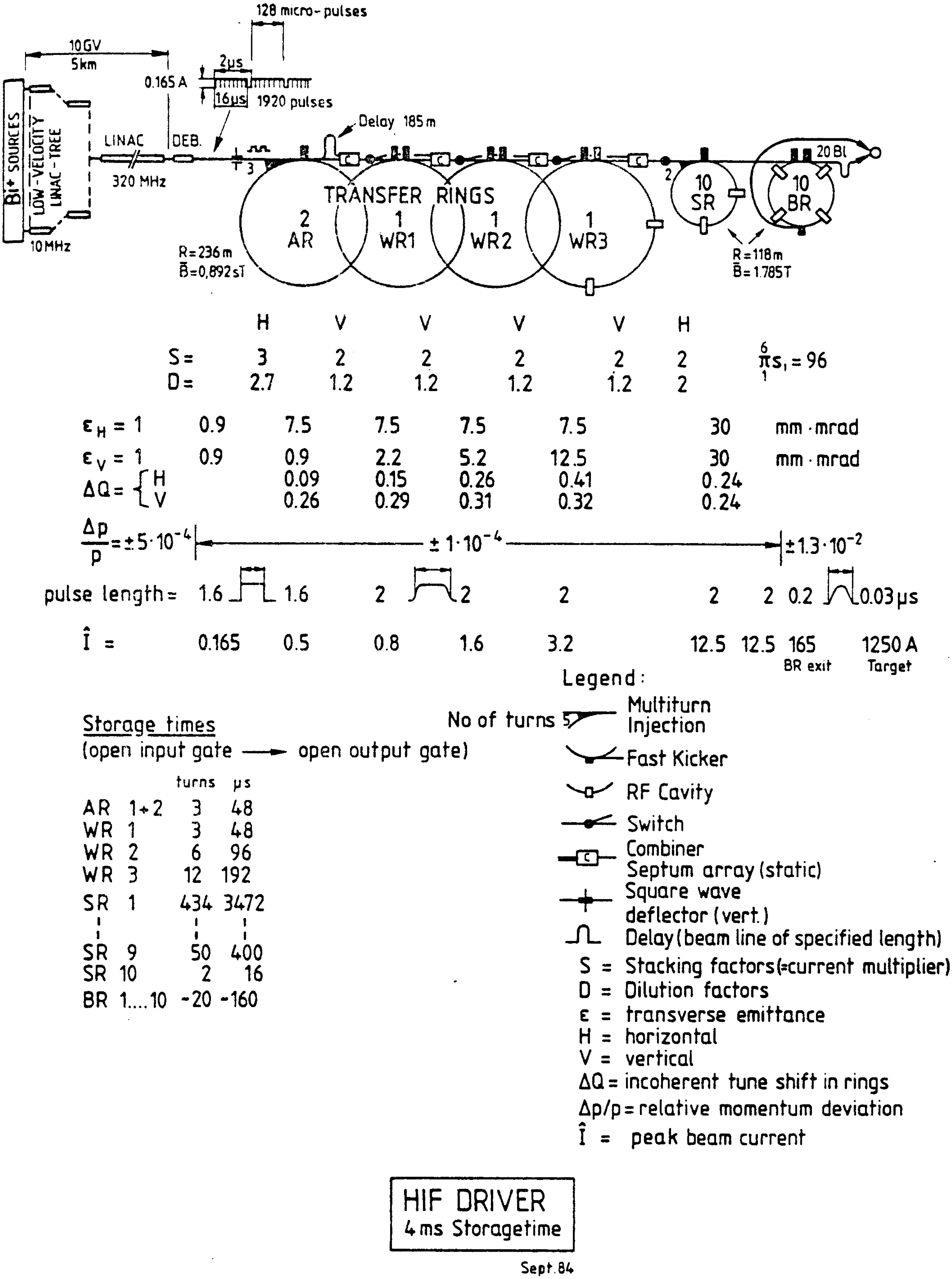


Fig. 3. HIBALL-II scheme. 2 μs beam pulses are folded 96 times by retardation and transverse combination, 20 folded pulses are stored in 10 storage rings. Before shooting they are compressed to a length of 30 ns (basis) or 20 ns (half width); the beam current then is 1250 A per channel (20 channels).

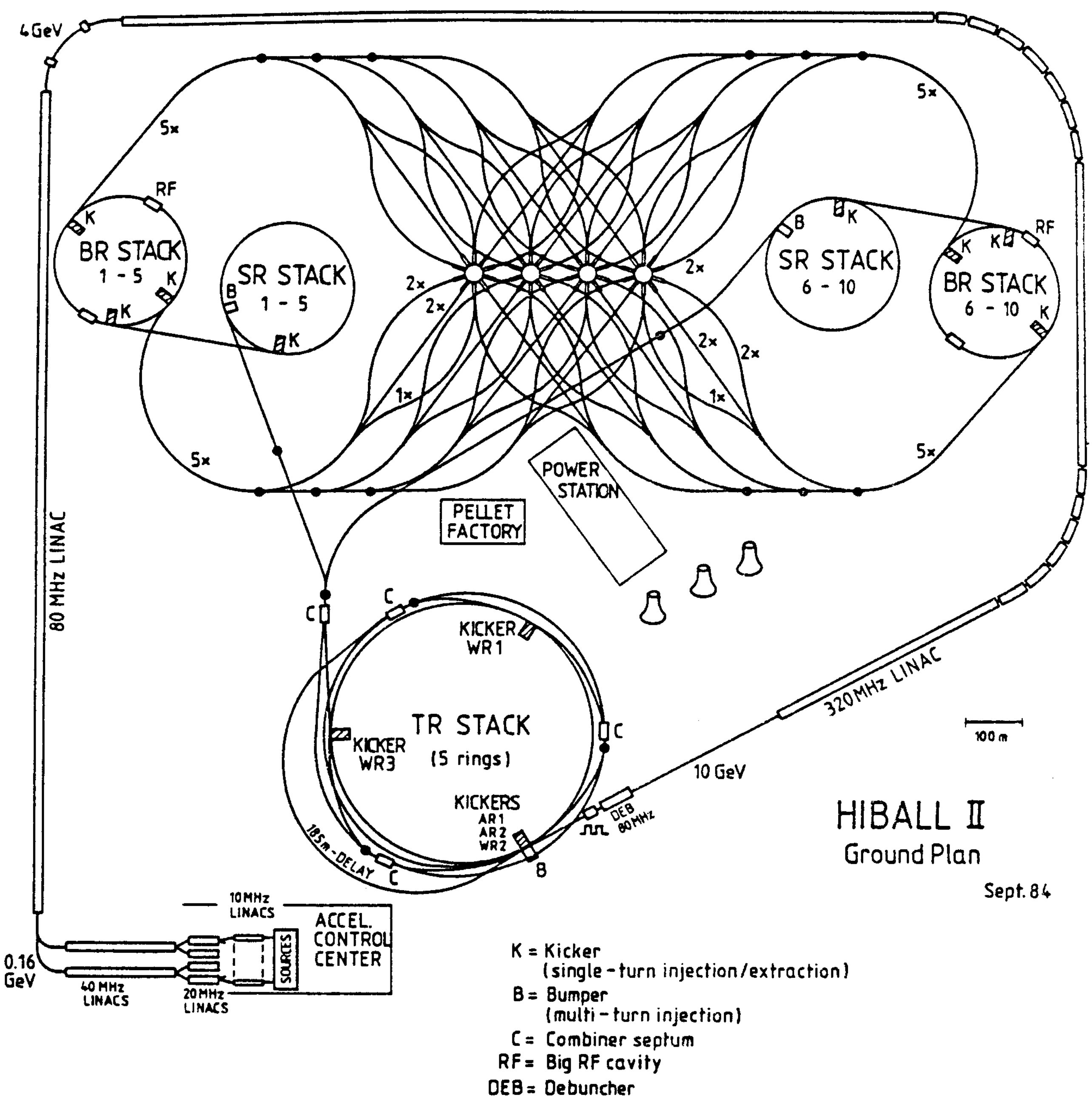


Fig. 4. HIBALL-II ground plan.

Whereas HIBALL-I used linear induction devices to compress the beam pulses from 2 μs down to 20 ns length, we now prefer compressor rings. For this bunching procedure a high RF voltage is needed, and the only way to produce it is with high-Q cavities which must be already fully excited when the beam is entering. It is the so-called "bunch-into-bucket" mode of operation which is, e.g., used in the CERN Antiproton Collector ring for an inverse purpose, namely "debunching" a short beam pulse with high $\delta p/p$ into a long pulse with low $\delta p/p$. The linear induction devices had turned out to be too expensive. They are a waste of money unless they are not combined with an acceleration task, as they are in the case of an induction linac.

All the single elements are at hand, though they have to be pushed to their frontier of performance. GSI has undertaken the demonstration of the first piece of a HIBALL linac; it is the RFQ linear accelerator MAXILAC (Fig. 5) which is able to accelerate milliampere beams of ions as heavy as Xe^{+}. A similar accelerator has been constructed at Moscow by Professor Kapchinskij and his team.(3) A high-intensity ring accelerator technique for heavy ions will also be pushed forward by GSI by constructing SIS to which a high-current injector of the type of MAXILAC will be a high-current injector.

High temperature target experiments have already begun at GSI. Power densities of as much as 1 GW/g have been deposited on solid targets to generate a plasma of a temperature of 1 to a few eV. Arnold and Meyer-ter-Vehn(4) have developed a diagram showing the relationship of temperature and specific heating power, Fig. 6. The result of our first experiment is the first experimental data point on that line. It demonstrates the long way we have to go: 10^{14} W/g rather than 10^{9} W/g, and a temperature of 500 eV on the pellet surface rather than 1 eV. SIS will settle just on the middle of the way.

As a conclusion we may say that heavy-ion driven inertial fusion is not exotic at all, or "science fiction" as many colleagues believe. It requires bringing every single element to its best performance. And it is expensive, but in the HIBALL study we have

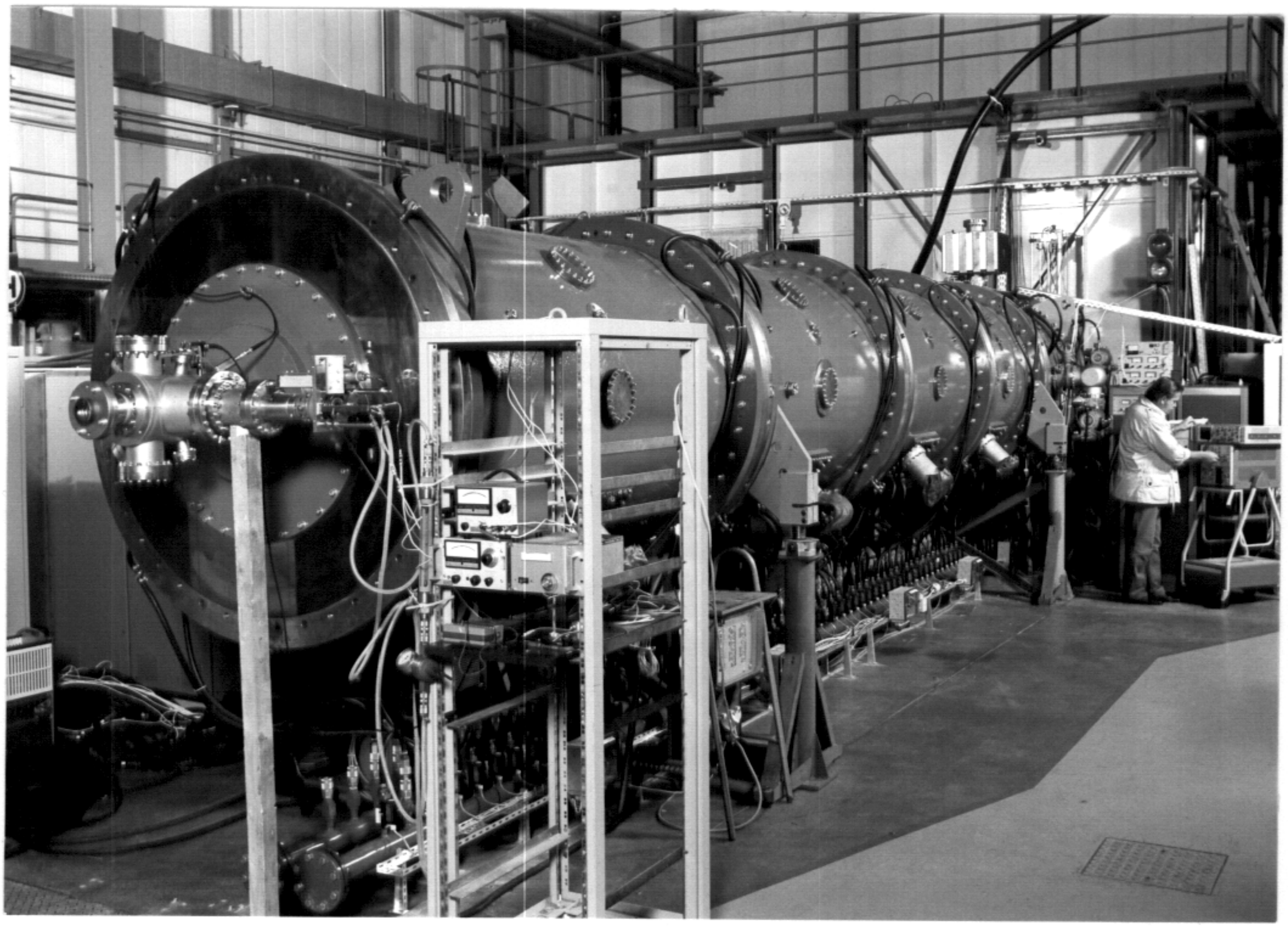


Fig. 5. 13.5 MHz RFQ Linac "MAXILAC" at GSI, Darmstadt.

Figure 6

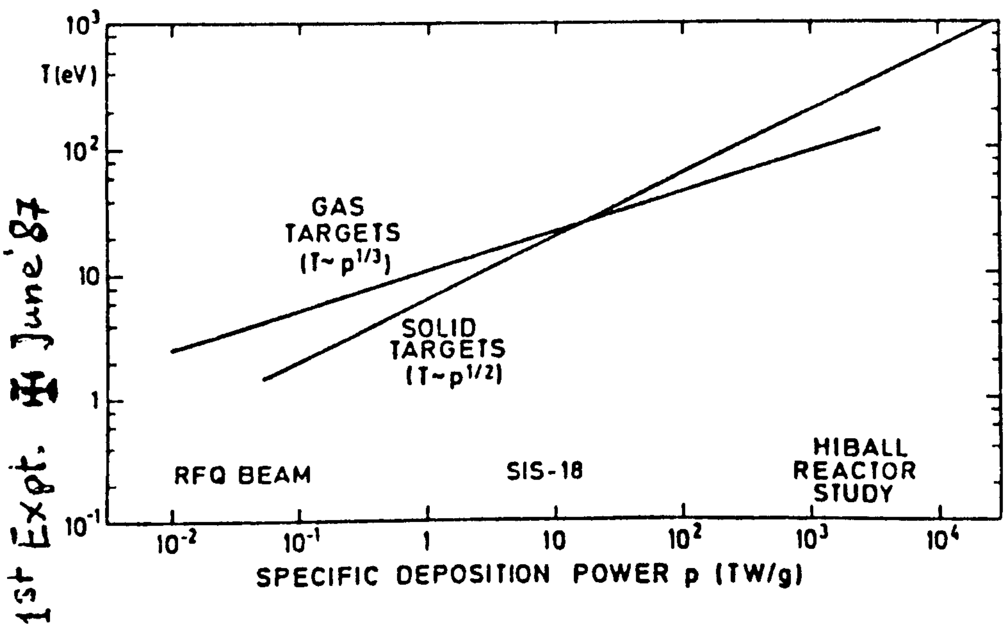


Fig. 6. Calculated plasma temperature vs. power density. Gases and solids behave differently with respect to hydrodynamic response. The first data point has been taken with the MAXILAC beam in June, 1987, on a W target. Apparently the W vapor behaves like a gas (R. Arnold, J. Meyer-ter-Vehn).

shown that there is a reasonable return of the invested money. Every dollar spent for developing acceleration technology for higher performance is also a dollar spent for fusion.

REFERENCES

1. HIBALL, KfK 3202, UWFDM-450 (2 Vol.) (Dec. 1981).

2. HIBALL-II, KfK 3840, FPA-84-4, UWFDM-625 (July 1985).

3. I.M. Kapchinskij et al., "RF Linac for HIF Driver," 1986 Linac Conf. Stanford, SLAC-303 (1986), p. 318 ff.

4. R. Arnold, J. Meyer-ter-Vehn. GSI-86-13, p. 53.

AN OVERVIEW OF HEAVY ION DRIVERS FOR ICF*

Edward P. Lee
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 USA

ABSTRACT

An overview of conceptual Heavy Ion Induction Linac Drivers for commercial ICF is given. Emphasis is placed on models, issues and scale relations.

INTRODUCTION

Inertial confinement fusion (ICF) requires very high power irradiance and energy deposited on the fusion target which are nearly independent of the driver type. In addition, the depth of deposition must be small (typically ~ .1 g/cm^2 in a stopper material) to produce the high fusion yields required for an economically attractive power plant. The range condition can be met in principle by any ion species, accelerated sufficiently to match the range-energy relation, as well as by short wavelength (< 300 nm) photons. For the heavy-ion driver approach to ICF two conventional but very high current accelerator technologies are being explored. These are the rf linac/storage ring system now studied in W. Germany and Japan, and the induction linac approach of the USA. For both accelerator types the combined considerations of space charge limits and range in dense matter lead to the use of heavy ions of high kinetic energy.

A typical set of final beam parameters suitable for a power reactor, which was adopted in the HIBALL-II study,[1] applies equally well to either of the two heavy ion driver types (see Table 1). It must be emphasized that cost tradeoffs among the many

* This work was supported by the Office of Energy Research, Office of Basic Energy Sciences, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Table 1 - Selected HIBALL-II Parameters

Pulse Energy	5.0 MJ
Particle Energy	10 GeV
Particle Type	Bi^{+} (A = 209)
Pulse Power	250 TW
Pulse Length	20 ns
Rep. Rate per Reactor	5 Hz
Number of Beams per Reactor	20
Net Pulse Charge	500 μC
Relativistic Factor ($\beta\gamma$)	.325
Final Emittance (unnormalized)	3×10^{-5} m-r
Momentum Width at Final Lens	$\pm$ 1%
Spot Radius	4 mm
Range in Pellet (Pb+Li Layers)	.19 g/cm^2
Convergence Half Angle	$\simeq$ 10 mr
Standoff to Final Magnet	8.5 m
Target Gain	87
Net Electric Power (4 Reactors)	3.784 GW
1984 Cost of Electricity (4 Reactors)	47.9 mill/kWh
Direct Cost of Entire Plant	5100 M$
Direct Cost of Driver	2432 M$

components of a complete power plant allow a broad range of system parameters (such as repetition rate) to be considered with minor effect on final cost of electricity (COE). Some cost data for HIBALL-II are also included in Table 1. It should be noted that, although its 47.9 mill/kWh COE is about double that available from existing, on-line coal or fission plants, it is comparable with the estimates from other fusion system studies (e.g. 59.1 mill/kWh for the STARFIRE tokamak in 1984 dollars using current costing methods). The primary concern at present is not so much the COE, but the magnitude of generating capacity and capital investment of the plant. A 500-1000 MWe fusion plant with this COE is of considerable interest, but it is difficult to achieve, primarily because of the economy of scale associated with all nuclear electric plants. Both the rf linac/ storage ring and the induction linac drivers provide a substantial fraction of total direct capital costs of a plant and scale poorly for lower net electric power. The HIBALL-II driver cost is "only" about 48% of total direct capital cost largely because the high repetition rate capability of the accelerator has been exploited in a large (multi-GW) plant with four reactors. Magnetic fusion systems are also very large for reasons of economy of scale as well as physical constraints imposed by the use of low density plasma.

A goal of the recently completed Heavy Ion Fusion Systems Assessment[2] (USA) was to find ways of reducing the cost of the induction linac driver and other plant components to the point where 500-1000 MWe plants were attractive. Another related goal of Heavy Ion Fusion, not covered by the Assessment, is to find a path of development which will lead from the current research to a fusion plant with a minimum of risk and expense. Cost reductions can be achieved in several directions:

a. Reduced cost of materials

b. Innovative use and manufacture of components

c. Optimized match of major system components (e.g. high rep. rate reactor to high rep rate accelerator)

d. Changes in design limitations resulting from improved understanding of physical constraints.

INDUCTION LINAC SYSTEM

An induction linac driver is now envisioned as a multiple beamlet transport lattice consisting of (N) closely packed parallel channels comprised of quadrupole lenses (electric or magnetic). Surrounding the lattice are massive induction cores of ferromagnetic material and associated pulser circuitry which apply a succession of long duration, high voltage pulses to the N parallel beamlets. Longitudinal focussing is also achieved through the detailed timing and shape of the accelerating waveforms (with feedback correction of errors). A multiple beam source of heavy ions operates at 2-3 MV, producing the net charge per pulse required to achieve the desired pellet gain. Initial current (and therefore initial pulse length) are determined by transport limits in the lattice at low energy. The use of a large number of electrostatic quadrupole channels (N ~ 16 - 64) appears to be the least expensive focussing option at low energies (below ~ 50 MV). This is followed by a lower number of superconducting magnetic channels (N ~ 4-16) for the rest of the accelerator. Merging of beams may therefore be required at this transition. Furthermore, some splitting of beams may be required after acceleration to stay within current limits in the final focus system.

The rationale for the use of multiple beams is that it increases the net charge which can be accelerated by a given cross section of core at a fixed accelerating gradient. Alternatively a given amount of charge can be accelerated more rapidly with multiple beams since the pulse length is shortened and a core cross section of specified volt-seconds per meter flux swing can supply an increased gradient. However, an increase in the number of beamlets increases the cost and dimensions of the transport lattice and also increases the cost of the core for given volt-s product since a larger core volume is required. For a given core cross section ($\propto$ volt-seconds/m), the volume of ferromagnetic material increases as its inside diameter is increased. Hence there is a tradeoff between transport and acceleration costs with an optimum at some finite number of beamlets. The determination of this optimum is a complex problem depending on projected costs of magnets, core, insulators, energy storage, pulsers and fabrication. The induction linac design code LIACEP[3] is used for this purpose.

The choice of superconducting magnets for the bulk of the linac is mandated by the requirement of system efficiency; this must be at least ~ 10% in an ICF driver and ideally > 20% to avoid large circulating power fractions (which result in a high COE). Induction cores are most likely to be constructed from thin laminations of amorphous iron, which is the preferred material due to its excellent electrical characteristics and flux swing. At a projected cost of ~ 4 $/lb (insulated and wound) this is a major cost item for the first 2-4 GV of a typical linac. At higher voltage the cost of pulsers and fabrication of the high gradient column with insulators dominates.

Several fundamental issues of beam dynamics and control are posed by the acceleration scheme outlined above and are the focus of the USA Heavy Ion Fusion Accelerator Research (HIFAR) program.[4] Foremost among these is the feasibility of simultaneously accelerating a large number of beams in a single structure. Is the interaction among beams in the acceleration gaps harmless, and can steering and wave-form corrections be applied with sufficient accuracy? The currently operating four beam accelerator MBE-4 is designed to address these issues.[5] Combination of beams is predicted to cause a large increase in their transverse phase area. This is predicted to be tolerable for driver scale parameters, however, a test of concept is desired at an early stage. This will be one of the earliest experiments performed with the proposed

Induction Linac Systems Experiment (ILSE)[6] and also possibly with MBE-4. Another component under development is the high voltage multiple beam injector, which must supply currents of sufficient intensity and brightness matched to an accelerator of reasonable physical dimensions. The ILSE injector,[7] now under construction, addresses this point.

FINAL TRANSPORT AND FOCUS

Between the accelerator and the fusion reactor the beamlets are separated and also, if necessary, split. The drift lines leading to the final focus area are 200-600 m in length and used for ballistic compression as well as matching to the final focus configuration of the reactor. The transport lattice is composed of cold bore superconducting quadrupoles, bends, and possibly higher order elements needed to control dispersion. As the beamlets compress, the transport of the high current becomes increasingly demanding, with the large apertures and the close packing of elements especially pronounced immediately before the final focus train.

At the end of acceleration the ion pulse is typically 100-400 ns in length, which is well matched to the bandwidth of the accelerator pulse forming system. Subsequent reduction to the desired 5-20 ns length desired for the fusion pellet implosion is achieved by the mechanism of drift compression in the transport lines leading to the final focus system. If the initial pulse length (in m) is ℓ_0 and the drift lines have length Z_0, then a head to tail velocity tilt of approximately

$$\frac{\Delta v}{v} = \frac{\ell_0}{Z_0}$$

must be applied in the final stages of acceleration. If, for example, ℓ = 20 m and Z_0 = 400 m then the pulse tail must move 5% faster than the head in the transport lines. There are several important considerations in this approach:

(a) The bends in the transport system must handle the velocity tilt and space charge with a minimum of dispersive effects. There have been only rudimentary (but encouraging) calculations of a design to accomplish this.

(b) Longitudinal space charge forces reduce the velocity tilt as the pulse compresses; the initial tilt must be large enough that it is not entirely removed before the desired final pulse length is reached.

(c) Any residual tilt remaining in the pulse at the time of final focus will result in a potentially severe second order chromatic aberration at the pellet. It is assumed that this can be compensated by the use of rapidly pulsed quadrupoles in an upstream location. These pulsed quadrupoles would impose a time dependent envelope oscillation which would cancel the time dependent aberration resulting from the remaining tilt.

(d) The generation of longitudinal momentum spread by the inhomogeneous fields acting during compression is minimal (ideally $\Delta p/p \leq 10^{-3}$ in final focus). A recent, and preliminary particle-in-cell simulation of compression dynamics indicates that the final momentum spread can be on the order of 10% of the initial tilt.[8] This is larger than desired by a factor of several.

The final focus system itself has parameters determined largely by the requirements of spot size on target, reactor size, and the neutron, x-ray, and gas fluxes from the reactor. The final focus quadrupole triplets described by R. Martin[9] are well suited as the basic beam line components. HIBALL-II uses magnet trains consisting of a pair of triplets separated by a pair of weak bends used to remove line-of-sight neutrons from the beam transport line. A detailed discussion of shielding requirements for this system is also presented in the HIBALL-II study.

To produce a small radius (r) on the target, the beamlet emittance (transverse phase area ε), must satisfy

$$\varepsilon < r\theta$$

where θ is the beamlet convergence cone half-angle. For HIBALL ($r = 4$ mm, $\theta = 10$ mr) this condition is $\varepsilon < 4\times10^{-5}$ m-r, which is 33% larger than the design value of 3×10^{-5} m-r. Allowance must also be made for the effect on spot size of momentum dispersion, various forms of jitter, and space charge induced blow up. A final focus system comprised of quadrupoles and weak bends has dispersion at the target which leads in a practical design based on a pair of triplets to increased spot radius:

$$\Delta r \approx 8\ L\theta\ \frac{\Delta P}{P}\ ,$$

where L is the distance from the pellet to the center of the final quadrupole. Without compensation by higher order elements it is desirable to keep $\Delta P/P \lesssim 10^{-3}$. This is a severe requirement to be met by the accelerator system.

In summary, the requirement of small spot size on target is met by small specified emittance and a set of other focal and reactor constraints which are not currently well understood. The cone half angle θ is set at a value which is determined by a trade-off between factors which drive it towards a low value and those which drive it to a high value. In the first category are dispersion, aberrations, magnet costs, reactor constraints, shielding and beam line vacuum. In the second category are the emittance limit, space charge effects, and jitter control. The range $\theta = 10$-20 mr is the result of compromises among these factors. Aside from the spot size condition, it is economically desirable to make the emittance large, since the limit on transport of high current is found to vary as $\varepsilon^{2/3}$.

Transport within the reactor vessel has, in most studies, been assumed to take place in near vacuum ($P \lesssim 10^{-4}$ torr Li) to avoid disruption by the two-stream instability, or in a high pressure window ($P \sim 10^{-1} - 10$ torr), where the beam is also thought to be stable.[10] HIBALL specifies $P < 10^{-5}$ torr Pb vapor to avoid stripping of beam ions, which would lead to reduced irradiance due to the beam's electric field. Unfortunately, several attractive reactor concepts (CASCADE,[11] HYLIFE[12]) have residual gas pressures in the range $10^{-2} - 10^{-3}$ torr Li at reasonable rep rates; this pressure must be taken into account both for transport in the reactor and in maintaining vacuum in the final focus lines.

It is essential that the residual pressure in the reactor chamber ($P \sim 10^{-2} - 10^{-3}$ torr Li) be attenuated by a large factor between the reactor and the final focus train. Otherwise the bulk of the beam ions are stripped before the focal process is completed and is thereby misdirected. It was assumed in HIFSA that this can be achieved with a combination of fast shutters and pumping in a transition region of about 1.0 m in length located between the final quadrupole and the reactor shield. Some estimates of the requirements follow.

The stripping length $\ell_s = (n_g \sigma_s)^{-1}$ should be at least 300 m in the final magnet if beam loss is to be kept below ~ 1%. There is further pumping upstream so ℓ_s gets longer rapidly as one moves away from the reactor. The stripping length is approximately

$$\ell_s \approx \frac{1.0 \text{ cm}}{P_{torr}} \left(\frac{92}{Z_i}\right) ;$$

we require (for U^{238} on Li)

$$P \lesssim 3 \times 10^{-5} \text{ torr} ,$$

which is a factor of 30 to 300 below the pressure in the chamber. High speed shutters (for example spinning disks with holes) could open a 10 cm diameter hole for a period as short as 2 ms, so the beam line would only be open for 1% of the time if the system rep rate was 5 Hz. It is only open for the low pressure residual gas, i.e., the high pressures following the explosion are blocked.

The gas volume which is passed by the open shutters is characterized by molecular flow (long mean free path) and can be readily removed by pumping except for the line of sight fraction. This fraction can be reduced to a few percent of the passed volume if the transition zone is long enough; the development of transition zone design is a critical item for HIF.

THE REACTOR ENVIRONMENT

The reactor chamber of 5 - 10 m radius is surrounded by a Li blanket and shielding of total thickness ≅ 2 m. The beamlets must pass through whatever residual gas remains in this zone as they converge towards the pellet. As mentioned, an additional beam line length of ~ 1 m between the final magnet and the shielding is occupied by pumping ports and shutters required to prevent a significant amount of gas from reaching upstream into the final focus lenses. Since pressures in the range 1-10 torr appear immediately following an explosion this implies the presence of a very powerful self pump-down of the chamber to match the repetition rate of 1-10 Hz. The difficulties associated with densities higher than 3×10^{14} cm^{-3} Li are: (a) gas flux into final focus lenses, (b) filamentation instability and possibly the two-stream instability, and (c) possible beam spot spreading from stripping. Limitations due to beam scattering and energy loss set in at $n_g \geq 3 \times 10^{16}$ cm^{-3} and are not relevant here. Fortunately several reactor types

[Granular Wall, Wetted Wall, HYLIFE (Li jets), and Magnetically Protected Dry Wall] all appear to be potentially capable of meeting this pressure requirement. An interesting contrast is provided by the HIBALL chamber, which employs a Li-Pb layer. This special surface pumps down the chamber to ~ 10^{11} cm^{-3} Pb vapor at a 5 Hz shot rate. A brief discussion of stability and stripping follows.

The cross section for gas stripping of the beam ions is approximately given by

$$\sigma_s \approx \frac{2.45 \times 10^{-18} cm^2}{\beta^2} \left(\frac{Z_i}{92}\right) \exp(-.063Z^*) \ ,$$

Z = atomic number of ion ,

Z* = stripped state of ion .

Here we have used the numerical fit by Stroud[13] for U^{238} on Li, generalized to apply to other heavy ions by incorporating the factor (Z_i/92). For low Z*, a typical value is (10 GeV, U^{238}).

$$\sigma_s \approx 2.7 \times 10^{-17} cm \ .$$

A stripping length is defined:

$$\ell_s = \frac{1}{n_g \sigma_s} = (370 \text{ cm}) \frac{10^{14}}{n_g}$$

An average stripped state of approximately

$$\overline{Z^*} = Z^*_{initial} + \frac{L}{\ell_s}$$

results as the ions approach the pellet. If n_g is taken as $3 \times 10^{14} cm^{-3}$ then, since transport in gas is expected to be on the order of 10 m, it is clear that as many as ten electrons are removed in addition to the initial state q.

The consequences of stripping in the chamber are unclear at present. The beam current increases as Z*, and the electrical rigidity decreases as 1/Z*. Hence we expect the stripped ion beam to be more easily disrupted by beam-plasma instabilities. These are discussed below. A second concern is that the beam will not focus to the desired small spot radius due to increased space charge forces. The few estimates made to date of this effect suggest that the problem is reduced or eliminated by the fact that electrons stripped from the ions travel with the beam and neutralize the increased space charge and current. The dangerous possibility is that, since there will be a spread in charge states, the ions will be deflected by varying amounts in the residual self electric field of the beam and the spot size will be spread. Research on this topic--dynamics of the beam envelope in the gas environment including the statistical effects of stripping and neutralization -- has been inadequate and was identified by HIFSA as one of the most important areas for future simulation and experiment. If stripping is found to be unacceptable in the reactor designs considered then either some other propagation mode which is insensitive to stripping must be found, or a reactor chamber of the HIBALL type ($n_g \ll 10^{14}$) must be considered.

Filamentation Instability

The filamentation mode is a serious concern for high pressure reactors ($P \geq 10^{-2}$ torr Li). If the beam ions strip to a sufficiently high average charge state and the beam is also neutralized by background electrons, then microscopic magnetic pinches within the beam pulse can grow during propagation to the pellet and disrupt the convergence processes. A previous analysis of this phenomenon[14] gave the safety condition

$$\alpha = \frac{\omega_b R_c}{c} \leq 3 \ ,$$

where ω_b is the plasma frequency of the beamlet evaluated at the chamber wall, c is the speed of light, and R_c is the chamber radius. Because of convergence effects the total mode growth is only on the order of exp $(\alpha) < 20$. The mean stripped charge state Z^* is used to evaluate ω_b

$$\omega_b = \frac{n_b Z^{*2} e^2}{\varepsilon_o m_o A}^{1/2} \ ,$$

where n_b is the beamlet's number density. Using convenient system parameters we have the safety condition

$$W_{beamlet} \leq (33 \text{ MJ}) \left(\frac{A}{Z^*}\right)^2 \beta^3 \tau_{ns} \theta^2 \ ,$$

where θ is the half angle of the beam cone. There is little problem provided $A/Z^* \geq 20$. We estimate for stripping by Li vapor

$$\frac{A}{Z^*} \gtrsim \frac{2.5 \text{ m}}{R_c \ P_{torr}} \ ,$$

so no problem is expected below ~ 10^{-2} torr, which is normally the case. If higher pressures are contemplated then this subject should be given renewed attention.

Two Stream Mode

Prior to 1985 it was generally believed that unstable two-stream modes eliminated the possibility of heavy ion beams propagating in a background pressure of 10^{-4} - 10^{-1} torr Li. The analysis of converging beams by P. Stroud[13] has reversed this opinion and we now (optimistically) assume that there is no restriction on pressure from this consideration.

The standard analysis for non-converging beams uses a Fourier decomposition in longitudinal variable (z) and time (t):

$$\text{Perturbed Quantities} \sim \exp(ikz - \omega t) ,$$

where k is the wave vector and ω is the frequency. The resulting dispersion relation for the plasma electron-beam ion mode is

$$1 = \frac{\omega_p^2}{\omega^2} + \frac{\omega_b^2}{(\omega - kv)^2} ,$$

where ω_b and ω_p are respectively the beam and electron plasma frequencies, and v is the beam velocity. Rapid growth occurs for $\omega \approx \omega_p$ and

$$k \approx \omega/v .$$

The maximum growth rate in this case is (.6873) $(\omega_p \omega_b^2)^{1/3}$, and only nonlinear effects can result in saturation. When convergence of the beam envelope is taken into account this simple (and disastrous) picture is changed because the resonant condition does not persist with distance. The plasma frequencies (ω_b, ω_p) both increase as the beam converges and any particular unstable wave number k is quickly swept through resonance. The reader is referred to the article by Stroud for details; the primary conclusion is that at typical HIF parameters, less than 1% of beam ions are deflected from the desired spot at pressures at least up to 3×10^{-3} torr Li.

REFERENCES

1. "HIBALL-II, An Improved Heavy Ion Beam Driven Fusion Reactor Study," Fusion Power Associates report FPA-84-4, Kernforschungszentrum-Karlsruhe report KfK-3840 and University of Wisconsin report UWFDM-625, (1984).

2. D. Dudziak and W. Herrmannsfeldt, "Heavy Ion Fusion System Assessment Study," Proc. Int. Symposium on Heavy Ion Fusion, AIP Conference Proceedings, 152, p. 111, American Institute of Physics, New York (1986) (M. Reiser, T. Godlove and R. Bangerter, eds.).

3. A. Faltens, E. Hoyer, D. Keefe, and L.J. Laslett, "Design/Cost Study of an Induction Linac for Heavy Ions for Pellet-Fusion," IEEE Trans. Nuc. Sci., NS-26, No. 3, p. 3106, (1979).

4. R. Gajewski, "Overview of Heavy Ion Fusion Accelerator Research Program at the U.S. Department of Energy," Proc. Int. Symposium on Heavy Ion Fusion, AIP Conference Proceedings, 152, American Institute of Physics, New York (1986) (M. Reiser, T. Godlove and R. Bangerter, eds.).

5. T.J. Fessenden et al., "Preliminary Results from MBE-4, A Four Beam Induction Linac for Heavy Ion Fusion Research," Proc. Int. Symposium on Heavy Ion Fusion, AIP Conference Proceedings, 152, p. 26, American Institute of Physics, New York (1986) (M. Reiser, T. Godlove and R. Bangerter, eds.).

6. T.J. Fessenden et al., "Preliminary Design of a 10 MeV Ion Accelerator for HIF Research," LBL Report LBL-21194 (1986).

7. E.O. Ballard et al., "Design Status of Heavy Ion Injector Program," IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, p. 1788.

8. J. W-K. Mark et al., "Studies on Longitudinal Beam Compression In Induction Accelerator Drivers," Proceedings of the International Symposium on Heavy Ion Fusion, AIP Conf. Proc. 152, p. 227.

9. Ronald L. Martin, Nuclear Instruments and Methods 187, 271-280, (1981).

10. Proceedings of the Heavy Ion Fusion Workshop, W.B. Herrmannsfeldt (ed.), held October 1979 in Berkeley, CA, issued as LBL-10301, SLAC-PUB-2575, p. 403.

11. J.H. Pitts and I. Maya, Lawrence Livermore Laboratory report UCRL-92558, (1985).

12. J. Blink et al., Lawrence Livermore Laboratory report UCRL-53559, (1985).

13. P. Stroud, LANL report LA-UR 85-2809, (1985).

14. E.P. Lee, et al., "Filamentation of a Heavy-Ion Beam in a Reactor Vessel," Phys. Fluids 23 (10), p. 2095, 1980.

UPDATE OF HIFSA: IMPLICATIONS FOR COMMERCIAL HEAVY-ION FUSION

D.J. Dudziak, J.H. Pendergrass and W.W. Saylor
University of California
Los Alamos National Laboratory
P.O. Box 1663, Mail Stop F611
Los Alamos, NM 87545

ABSTRACT

An overview of the Heavy-Ion Fusion Systems Assessment (HIFSA) study is presented. This *ad hoc* study, led by Los Alamos National Laboratory, was conducted during a period of over two years by a consortium including national laboratories, an industrial contractor, and a university. Results of the study have been presented in many conference papers, a final report, and a special issue of the journal ***Fusion Technology***. Here we present a review of the major subsystem options considered for an induction-linac driven power plant, the performance resulting from a study of the various system configurations, and a cost optimization and sensitivity study. Key results and conclusions are discussed, and recommendations for research and development required to achieve the projected performance are made. The cardinal conclusion of the study is that conceptual 1-GWe commercial heavy-ion fusion power plants have estimated cost-of-electricity (COE) values comparable to those for other magnetic- and inertial-confinement fusion reactor concepts; in addition, the conceptual designs are robust in that they have broad minima in COE.

THE HIFSA PROJECT

The Heavy-Ion Fusion Systems Assessment (HIFSA) project was an assessment of the potential for heavy-ion fusion (HIF) commercial electric power using induction-linac drivers. It was conceived and initiated in 1984, with funding provided by DOE and EPRI for the two years 1985-1986. Led by Los Alamos National Laboratory (LANL) under the guidance of a Steering Committee chaired by W.W. Herrmannsfeldt, the project included participation by Lawrence Berkeley Laboratory (LBL), McDonnell Douglas Astronautics Co. (MDAC), Lawrence Livermore National Laboratory (LLNL), the University of Wisconsin (UW), and Sandia National Laboratories (SNL).

Many of the existing ICF reactor and balance-of-plant (BOP) concepts developed for laser fusion apparently require only minor modifications for HIF. There are also a few reactor concepts developed specifically for HIF. Much effort has been devoted to development of these concepts over the past decade. These considerations led to concentration of limited HIFSA project resources on:

- innovations and cost/performance modeling for HIF target, accelerator, and final beam transport concepts; and
- an HIF commercial power plant systems code to identify key cost/performance issues, explore significant tradeoffs, quantify parameter sensitivities, and search for global optima.

The principal figure of merit used in the HIFSA studies to characterize commercial HIF power plants is unit cost of electricity. The total capital cost, which largely determines COE in capital-intensive HIF power plants and also is a measure of the difficulty of financing the construction of an HIF plant, is an important secondary figure of merit.

The HIFSA project was an *ad hoc* effort during a period of about two years. An ongoing HIF research and development program is exclusively devoted at present to accelerator R&D. However, much of the work on targets, reactors, and other systems in both US and non-US laser and light-ion fusion programs is directly applicable to HIF. Although the HIFSA project is small compared to other fusion programs, the results of the HIFSA studies are expected to play a vital role in providing guidance for HIF program planning through identification of promising commercial plant subsystem concepts and operating parameter space.

Perhaps the best prior overall design studies of commercial HIF are the HIBALL studies [1,2]. During the HIBALL studies, a technically credible commercial HIF power plant scenario with competitive projected COE was developed. The results of the HIBALL study, while not entirely satisfactory because of the plant scale (4000 MWe) required for competitive COE, are widely viewed as having established the technical feasibility of commercial HIF, provided that high-gain targets and affordable target mass production methods are also demonstrated. In particular, the HIBALL radio-frequency (rf) driver appears to require little new fundamental technology. Of course, considerable development will be required to qualify reliable, affordable commercial systems. Also, some details of accelerator design, beam merging, final focus, etc., may be different than presently envisioned.

Once technical feasibility is established and economic promise is indicated, support for the R&D required to realize the potential of HIF must be provided. HIF is faced with the same cruel dilemma confronting all fusion in the US today -- several factors have diminished, at least for the present, the interest of government, the public, and public utilities in long-range new energy technologies. These include: (1) intense competition for federal R&D funding; (2) perceptions of fusion as too difficult, too far in the future, too big, and too expensive; (3) the cost of the next generation of R&D facilities; (4) the problems of fission; and (5) temporary easing of the energy "crisis."

Past and present US HIF Program R&D funding levels have been adequate for investigating beam transport and accelerator physics and design issues theoretically, with some small supporting experiments. The present level of funding is not adequate for extending the experiments for examination of the parameter space for commercial applications of HIF or for engineering and constructing large prototype induction-linac components.

For ICF the short-term answer to the funding dilemma is the development of less costly concepts for the next generation of R&D facilities. For the longer term, the attractiveness of ICF with respect to cost, reliability, and safety must be even more firmly established. In order to enhance the attractiveness of HIF relative to other approaches to ICF:

- accelerator capital cost, which is still the largest contributor to COE for an HIF power plant, must be reduced;
- commercial plant scale for competitive COE must be reduced below the 4000-MWe level of the HIBALL studies; and
- the projected efficiency and reliability advantages of heavy-ion accelerators over other drivers should be verified.

HIFSA ACCELERATOR STUDIES

Heavy-Ion Induction Linac Technology

The proposed technology for heavy-ion induction linacs is an extension of well-established electron induction linac technology developed at LBL, SLAC, and elsewhere. High repetition rates, high current transport, and operational reliability have been demonstrated for electron induction linacs. HIF induction linac design is complicated by non-relativistic particle velocities that change significantly throughout the acceleration of the ions. The accelerator comprises a high-brightness ion source, a high-current injector, a low-energy accelerating section, a main induction accelerating section, and a final pulse compression section. The main accelerating section is the most costly, with the cost of the other sections about one-fourth of the total. In the proposed concept, multiple beamlets are accelerated by common induction cores, allowing a large total current to be transported within a single accelerating structure.

The ion source may be either a conventional, albeit large-pulse, multiple-beamlet source with electrostatic focusing or an advanced metal vapor source of the type developed and tested at LBL during the period of the HIFSA study. These new metal-vapor sources can provide intense beams of multiply charged ions, with high selectivity in some cases. The injector and low energy section of the accelerator match the ion source of the main induction accelerator section through the use of pulsed drift tubes.

The main accelerator section includes a series of induction cores that operates at a fixed voltage step per module and are driven by pulsers whose pulse duration decreases as ion velocity increases. In simple terms, the ion beam acts as one side of a transformer with a single turn and the induction cores as many turns on the other side. The pulse length varies from a few microseconds to about 100 ns and the design of the induction cores and pulsers must vary from one end to the other of the main accelerator section. The inductor core material may be ferritic steel, iron, or amorphous iron (metallic glass -- metglas™), with the optimum selection based on considerations of module performance and cost. Rapidly decreasing metglas costs have made cost-effective the use of this material for induction linacs. The shape of the voltage pulse applied at each acceleration step is approximately trapezoidal with a slight voltage "tilt" that applies a longitudinal compressive force to the ion pulse.

At the high-energy end of the main accelerator section, a final "kick" must be given to the back end of the ion pulses so that they will be compressed during final transport to the target. The ion pulse energies exiting the main accelerator section are typically 5 to 15 GeV, with pulse lengths of 60 to 100 ns decreasing to approximately 10 ns at the target. The compression section consists of induction modules that provide the appropriate voltage pulse profile to compress the ion pulse.

More details of the induction linac technology studies during the HIFSA project are published elsewhere [3]. Estimated costs and performance over wide ranges are also given.

Accelerator R&D Issues

For purposes of the HIFSA study, principal accelerator design parameter values were allowed to vary over ranges believed reasonable and achievable. The systems integration code described below was used to create a database that was then searched for optima. These parameters (and ranges) included pulse energy (1 to 10 MJ), ion species (130 to 210 amu), number of beamlets in the accelerator (4 to 16), and output emittance (15 to 30 microrad-m). Other accelerator design parameters were fixed at values regarded as near optimum or reasonable. For example, undepressed tune (the phase angle between a single ion passing through an inductor and the accelerating electromagnetic wave) was set at 60° and depressed tune (phase angle for a large ion pulse as determined by collective space-charge effects) at 8°. In effect, the greater the tune depression with stable transport, the greater the current that is being stably accelerated. In the past, theoretical analyses indicated that a depressed tune angle of 24° was the minimum that could be expected with stable transport. Experiments conducted at LBL during the period of the HIFSA project demonstrated stable transport at a depressed tune of 8°. Improvements to the theoretical analysis gave agreement between theory and experiment. The suggestion has been made that beginning with larger undepressed tune angles, perhaps 85°, could permit even higher tune-angle depressions and acceleration of even greater charges in a single beam line. This topic has been identified as an R&D need that should be assigned modest priority.

Examination of cost/benefit for different ion charge states, particularly the intermediate +2 state and higher charge states up to at least +4, with medium priority is indicated because, as is discussed in the section on integrated-plant studies, a change from +1 to +3 significantly reduces accelerator capital cost and COE. The principal reason is that +3-charge ions can be accelerated to the same energy in roughly one third the length of the main accelerator required with +1-charge ions if the voltage increment per accelerator module is the same.

The practicality of acceleration of higher charge states, previously thought to involve severe limitations on the current that could be stably transported, has been demonstrated in recent experiments. However, the vacuum requirements for focusing and transport in reactor chambers may be more stringent and an examination of this question with medium priority is indicated.

Adequate higher-charged-state ion sources are also necessary if higher-charge-state commercial HIF induction linac drivers are to be practical. Requirements include a large fraction of ions generated with the desired charge and low emittance. Therefore, if higher-charge-state HIF is to be pursued, then development of suitable sources must be accorded high priority.

Although HIF could be made to work without beam neutralization, the cost/performance benefits of neutralization for focusing and final transport are very large. Neutralization becomes even more important if higher ion charge states are used. For the HIFSA studies, neutralization sufficient to obtain the anticipated benefits at negligible additional cost was assumed. Because of the importance of this issue, R&D to develop and demonstrate cost-effective charge neutralization is assigned highest priority.

Estimated COE for commercial HIF power plants does not seem to be very sensitive to ion mass over the broad range 130 to 210 amu for fixed ion charge state. It would be interesting to extend the range of ion masses studied to lower values to establish the practical limits. More important, ions with charge +1 and of mass much lower than the lower end of the range examined in the HIFSA study may meet target requirements nearly as well as 210-amu ions with +3 charge. The difference can be compensated for by small improvements in accelerator beam emittance. For low ion masses, beam neutralization is crucial for cost-effective final beam transport and focusing. If cost benefits similar to those estimated for going from +1 charge to +3 charge with 210-amu ions can also be achieved by going to +1-charge, 70-amu ions, problems that might arise in developing higher-charge-state ions sources could be avoided. High priority for experiments and analysis of this alternative is recommended.

The optimum number of beamlets varies with position in the accelerator as ion energy changes. Development of low-cost methods for splitting and combining beamlets with small beam energy losses could permit modest reductions in accelerator cost. The HIFSA project team concluded that development of better understanding of beam transport and bending through simulation and experiment is required with medium priority. The team members are also of the opinion that substantial additional cost reductions and performance improvements for inductor cores, pulsers, and insulators are possible and recommend further R&D in these areas with high priority.

In multipulsing, two or more ion pulses are accelerated through the linac close together in time, with the interval determined by the time required to reset the induction cores. The pulses are simultaneously delivered to the target along beam-transport lines of different lengths. The potential modest benefit is accelerator cost savings due to halving of the current that the linac is required to accelerate plus potential improvements in efficiency as a result of higher duty factors. Offsetting these benefits in part is increased cost for additional beam transport line length and some loss in efficiency resulting from the requirement for fast reset of the induction cores. With two-sided or more symmetric target illumination, the additional beam transport line length required for double-pulsing is not very great.

In multipassing, the same ion pulse is passed through the main accelerator more than once to achieve the final ion energy. The saving in accelerator cost due to reduction in length seems potentially larger than that resulting from reduction in current for multipulsing. Higher duty factors can help efficiency. Efficiency loss resulting from the requirement for fast reset of the induction cores and the cost of extra beam-transport-line length will offset some of the potential gain. In addition, pulsing circuits for each inductor must be designed to accelerate ions at different energies in successive passes. Higher cost and/or reduced efficiency may be associated with these increased requirements. On the other hand, length scaling of the accelerator is expected to be more favorable than current scaling. A thorough assessment of this design option requires resources greater than those available for the HIFSA project.

HIFSA REACTOR/BALANCE OF PLANT (BOP) STUDIES

Only adaptation of a few existing laser fusion concepts with which HIFSA team members have substantial experience was considered. For lack of effective advocates on the HIFSA team, other promising concepts [1,2,4-6] developed for laser fusion and/or specifically for HIF were not included in the HIFSA studies. A combination of concepts providing a wide range of reactor repetition rates, capable of accommodating a wide range of target yields, and compatible with both conventional steam cycles and advanced power generation was desired to permit thorough exploration of the attractive characteristics of heavy-ion induction linac drivers -- high pulse repetition rates at little additional cost and high efficiency.

HIFSA reactor/BOP studies focused on:

- identification and quantification of additional design requirements for HIF, areas where HIF requirements are less constraining, and required interfaces between HIF reactors and drivers, fuel cycle, and BOP;

- identification and quantitative exploration of significant tradeoffs between reactor and driver, fuel cycle, and BOP design requirements and desirable features; and
- formulation of cost/performance models suitable for incorporation in the commercial HIF power plant systems code.

All reactor plant and BOP structures, interfaces, and equipment were treated.

Four classes of ICF reactor plant/BOP concepts were selected for the HIFSA studies: (1) a granular-wall concept (a variant of the LLNL CASCADE concept [7]; (2) a liquid-metal-jet concept (a variant of the LLNL HYLIFE concept [8]; (3) a wetted-wall concept (a variant of the Los Alamos wetted-wall concept [9]; and (4) a magnetically protected dry-wall concept (a variant of the Los Alamos magnetically protected concept [10]).

The first of these includes first-wall protection by a thick bed of solid particles in a rotating vessel for structure protection from all target emissions, a high-temperature, high-efficiency (55%) Brayton cycle, minimal containment, a pulse repetition rate up to 10 Hz, and two-sided target illumination. The second concept uses a thick array of liquid-metal jets to protect reactor structure from all target emissions, a conventional steam cycle, and conventional containment and is limited to about 2 Hz and few-sided illumination. The third reactor-plant/BOP concept employs thin liquid-metal films injected tangentially at high speed onto inexpensive, easily replaced curved reactor cavity walls to protect from target x-rays and debris ions and allow separation of reaction chamber and blanket functions; a conventional steam cycle; and conventional containment. It provides up to 10-Hz repetition rates and few-sided through semi-symmetric illumination. The last concept involves a very large dry-wall reaction chamber with diversion of target-debris ions away from exposed surfaces through direct-conversion systems for higher efficiency and removal; a conventional steam cycle for blanket energy conversion; and conventional containment to provide repetition rates up to 20 Hz, symmetric target illumination, and low neutron damage rates.

The HIFSA reactor-plant/BOP studies were not intended to be a final contest between concepts. The concepts studied involve different degrees of optimism. The differing degrees of optimism were retained to permit exploration of the potential benefits and/or penalties. To a large extent, differences in state of development of the concepts were ignored.

HIFSA FINAL BEAM TRANSPORT ANALYSIS AND MODELING

Introduction

The technological requirements for transport of heavy-ion beams from final focusing magnets to targets in HIF reactor cavities have been analyzed as part of the HIFSA project. Excessive disruption of focused beams will limit driver energy delivered appropriately to targets, and hence target performance. Conversely, for specified target performance, constraints may be placed on allowable values for other HIF system parameters, such as (1) beam emittance, momentum tilt, pulse energy, and peak power; (2) ion energy, mass, and charge; (3) cavity radius and gas density; (4) number of beams and beam port radius; and (5) target spot radius. An important factor that drives beam disruption is the growth of instabilities resulting from interactions of the beam with gas in the cavity. Meaningful cost/performance analysis requires a thorough understanding of the tradeoffs involved.

Beam Disruption by Streaming Instabilities

Heavy-ion beams traversing HIF reactor cavities stream through gas that remains after the cavity is cleared in preparation for injection of the next target. The residual gas may comprise target debris, fusion neutron transmutation products, and materials evaporated and sputtered by target emissions. Some of the residual gas becomes ionized through collisions with the beam ions. The ion beam/cavity gas system is dynamically unstable and charge clumps start to grow. Growing electric fields drive the ion beam to expand radially.

The principal objective of the analysis briefly described below was estimation of ion beam, reactor, and target parameter value ranges for which heavy-ion beams would not be unacceptably disrupted by interaction with residual cavity gas. The first step in the analysis was development of an improved model for beam evolution in time as heavy ions traverse a reactor cavity. The heavy ion charge state distribution, the ion density in the background gas around the ion pulse, and the density and velocity distributions of the electrons liberated by the interactions of the heavy-ions with the background gas are treated. This model includes the application of Maxwell's equations, kinetic equations for charge transfer, and a continuum fluid-dynamical model for the electron motions. The radial electrical fields driving instability growth are computed. A dispersion relation is solved for growth rates of the streaming instabilities as functions of mode number, time, and position. Finally, the perturbation of the beam ion distribution at the target is calculated to obtain the fraction of the beam energy deposited on the target as a function of the parameters listed above.

Summary of Computed Results

Figure 1 shows the final transport length (distance from final focusing quadrapole to target) for which 99 % of a 0.5-MJ pulse of 10-GeV ions injected through a quadrapole of 10 cm bore will be deposited on an 0.2 mm-radius target as a function of cavity gas (lithium vapor) number density. Efficient beam transport is also assured for any smaller transport distance. These results suggest that streaming instabilities are much less disruptive to transport of heavy-ion beams through HIF reactors than previous studies

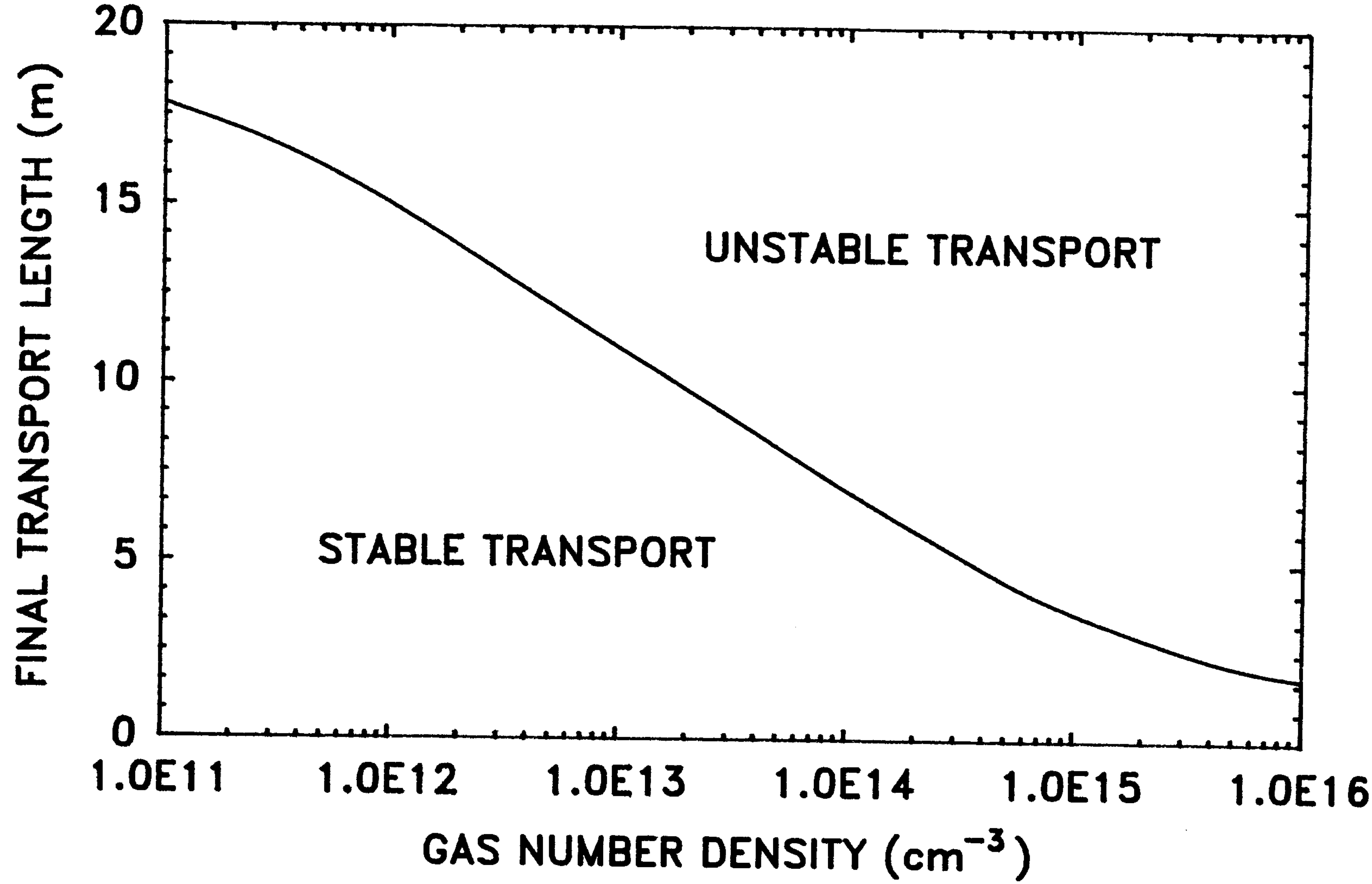


Figure 1. Final beam-transport length for which 99 % of +1, 10-GeV, mercury ions in a 10-ns, 0.5-MJ pulse focused by a 10-cm-bore final quadrupole magnet strike a 2-mm radius target as a function of lithium vapor number density in an HIF reaction chamber.

had indicated. In the stable regime the instabilities simply do not grow fast enough to disrupt the beams as they traverse the cavity. Constraints on reactor, accelerator, and target design can be relaxed in several directions. The density of gas remaining in reaction chambers after cavity clearing could be increased substantially, resulting in faster cavity clearing. Some reactor concepts that otherwise could not be efficiently used for HIF (e.g., those with high-vapor-pressure materials in the reaction chamber) would become more attractive. Transport at lower ion energy, higher ion charge, and/or higher beam emittance is also an option that could significantly reduce accelerator cost. In particular, a combination of (1) background gas densities as large as $10^{15}/cm^3$ (corresponding to equilibrium of pure lithium at 550°C), (2) ion charge as great as +4, and (3) ion energy as low as 4 GeV may be feasible.

Details of the beam transport model and additional computed results have been published elsewhere [12,13]. Experimental verification of the predictions of the new beam transport model in the near future is important.

HIFSA TARGET COST/PERFORMANCE MODELING

With the exception of targets with spin-polarized fuel, no fundamentally new, credible concept seems to have been conceived in nearly a decade. Therefore, only calculations to extend the credible target design parameter space to give accelerator designers as much freedom as possible were done for HIFSA. Concepts that were considered in greatest depth involve (1) conventional single-shell and double-shell fuel capsules, (2) direct drive with symmetric illumination, and (3) indirect drive with planar-symmetric, two-sided, and single-sided illumination. High-density ablators and tampers, magnetic insulation, and spin-polarized fuel were studied less intensively.

The approach adopted for the HIFSA studies was to fit with simple polynomial expressions existing best-estimate gain curves computed using detailed target-physics codes (gain/driver-pulse-energy relationship with a function of spot size and ion range as a parameter), such as those in Fig. 2 [14]. Best estimate gain curves were adjusted parametrically to reflect different degrees of optimism concerning target physics. Best estimate variations about the reference gain curves were performed using the scaling relationships of the Meyer-ter-Vehn model [15] and an alternative formulation developed during the HIFSA target studies for some of the target concepts [16]. In some instances, arbitrary assumptions were made concerning potential future advances in materials properties.

An improved HIF commercial-applications target cost model [17] has been developed through consultation with an *ad hoc* panel of experts as part of the HIFSA project. The model treats significant differences in costs for a wide variety of distinctly different target concepts. Target costs are scaled with important ICF plant parameters such as driver pulse energy and repetition rate and total fusion plant capacity. The generic formulation can be conveniently interfaced with cost models for other fusion plant systems. Although the emphasis in HIFSA is on HIF deuterium-tritium targets, the same general principles and many specifics are directly applicable for laser and light-ion fusion and other fuels.

In general, assumed superior target performance with no changes in target cost will lead to lower estimates of COE. For different target designs with the same degree of physics optimism, some of the improved performance of the more complex targets usually will be offset by increased cost of manufacture. Comparisons of COE for various target designs are presented in the section on integrated-plant systems studies. More details of target performance are published elsewhere [18].

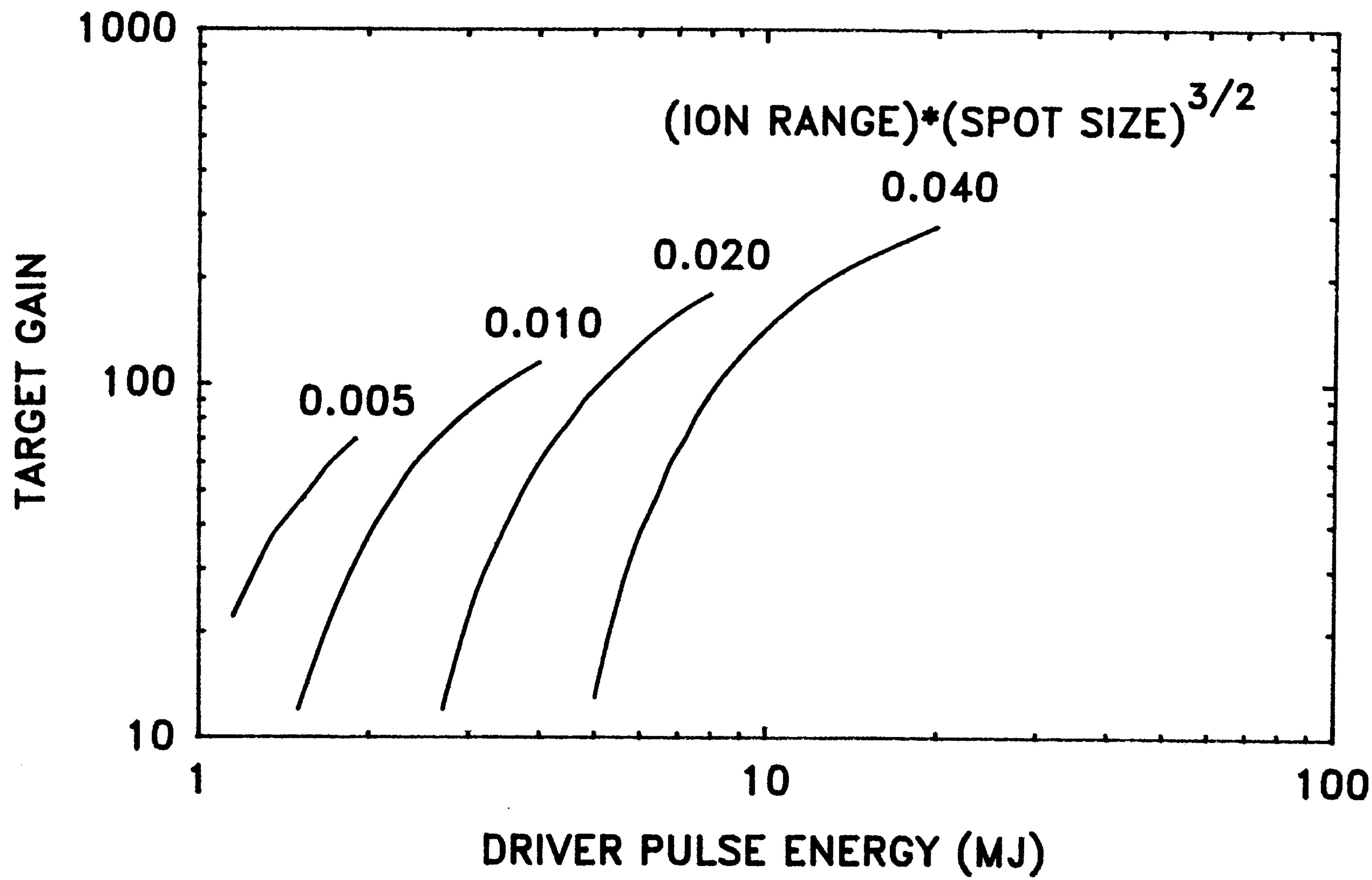


Figure 2. Single-shell HIF target gain as function of driver pulse energy with (ion range)X(spot size)$^{3/2}$ in g/cm$^{1/2}$ as parameter.

INTEGRATED PLANT SYSTEMS STUDIES

Introduction

To permit efficient exploration of the large design parameter space, MDAC developed a personal computer commercial power plant systems code for design tradeoff, parameter sensitivity, and cost optimization studies [19-20]. This code requires inputs in the form of (1) computed results from a more detailed induction linac design/performance code (LIACEP [3]) developed at LBL and fit with simple scaling relations by MDAC; and (2) target performance, fuel-cycle, and reactor design and cost scaling relationships provided by LANL and LLNL.

Summary of Representative Cost/Performance Results

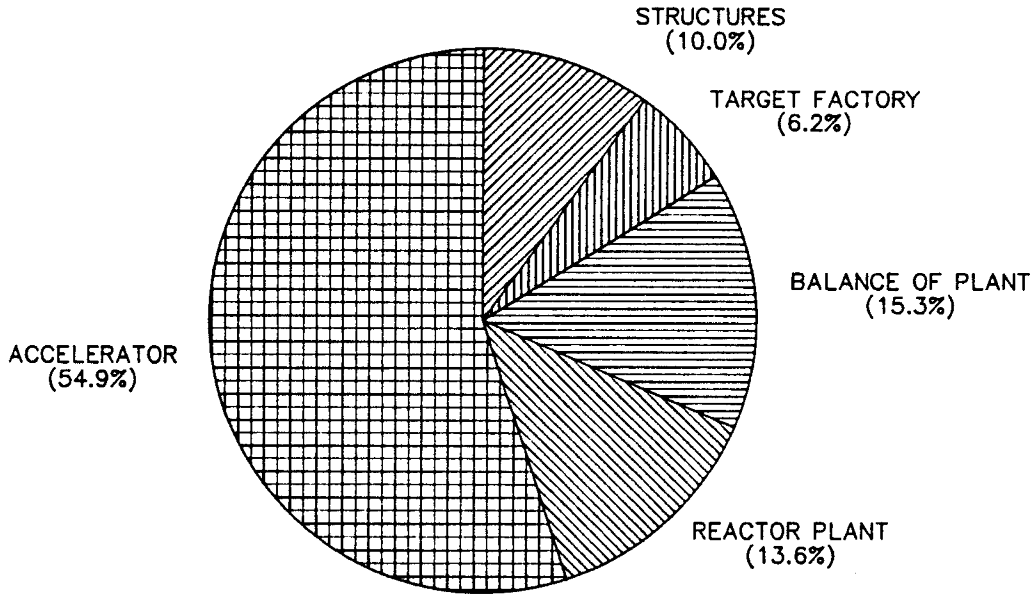
Except where otherwise noted, all of the HIF power-plant COE estimates presented are for 1000-MWe, one-reactor plants in which single-shell targets are illuminated from two sides with 16 beams of +3 charge-state, 130 amu ions with (ion range) (spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

Substantial reductions in optimum COE can be obtained by switching from acceleration of +1 charge ions to acceleration of +3 charge ions. The magnitude of the COE benefits is indicated in Fig. 3. Also shown in Fig. 3 is the breakdown into contributions to total COE of major plant subsystems. The difference in COE for the two charge states is almost entirely due to the difference in driver cost. For such capital-intensive plants, COE is largely determined by capital charges.

The scaling of COE with pulse repetition rate is illustrated in Fig. 4 for the four reactor-plant/BOP concepts included in HIFSA studies. In general, the COE minima are very shallow. The minimum COE for none of them is prohibitively large.

The inherent low-pulse-repetition-rate/large-target-yield character of the liquid-metal-jet reactor concept severely restricts the operational parameter space accessible

+1 Ions
(75.2 mill/kWh)



+3 IONS
(58.8 mill/kWh)

a)

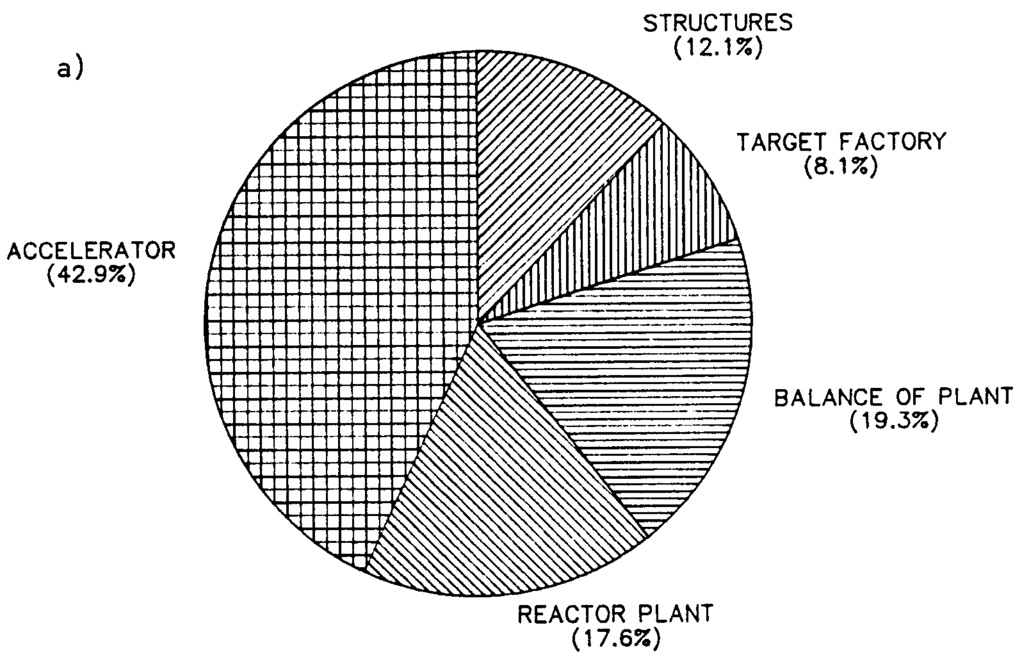


Figure 3 and 3a. Comparison of minimum COE and major-system capital-cost breakdown for induction linacs accelerating +1 and +3 ions and wetted-wall reactor-plant/BOP concept in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of 130 amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

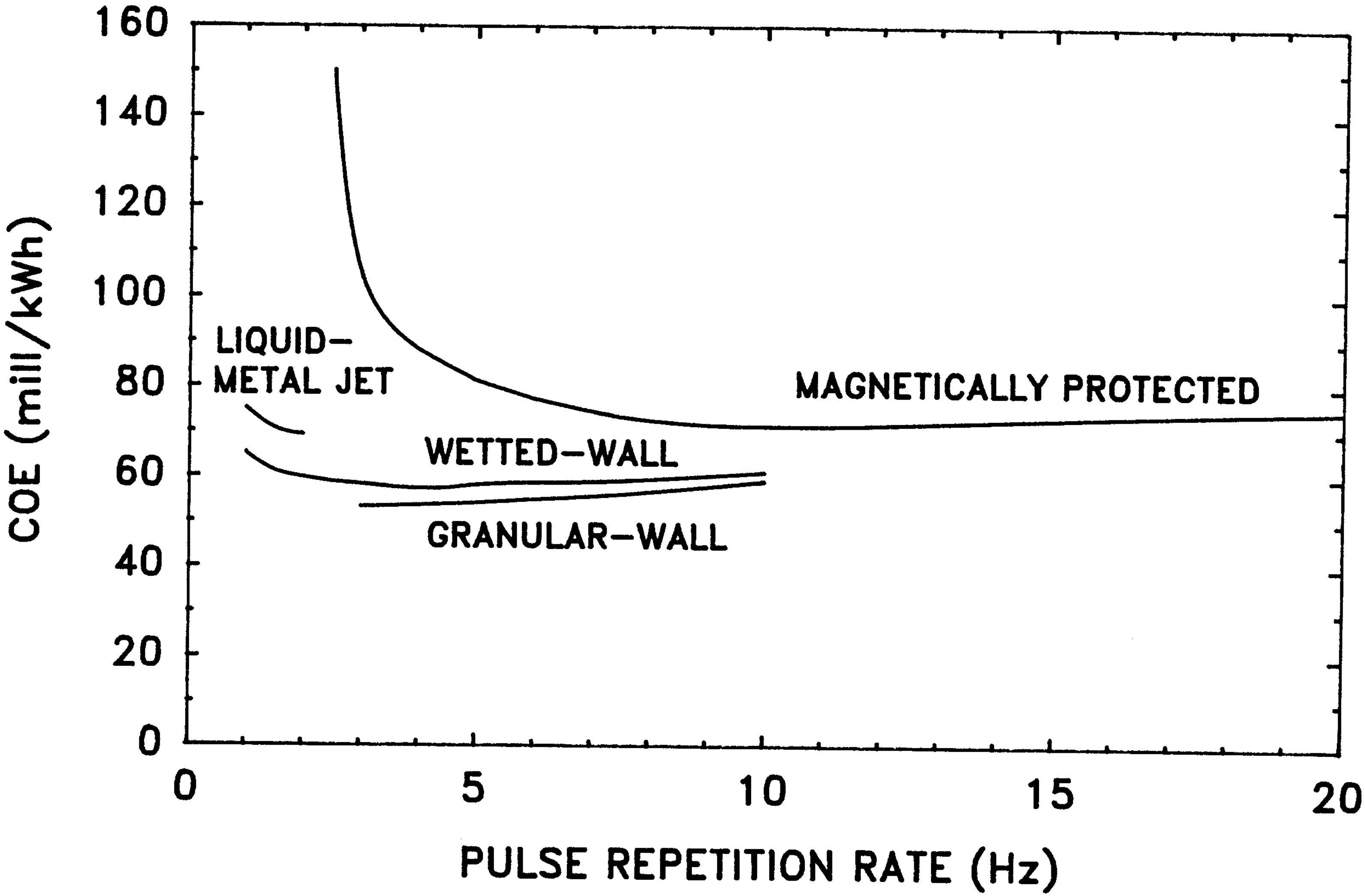


Figure 4. COE as function of pulse repetition rate for HIFSA reactor-plant/BOP concepts in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

to it. This, the large size of the reaction cavity, the complexity of the reactor structure, and the safety-related and electric-power-generation-related design conservatism of the reactor plant and BOP result in a relatively high COE for this concept. The magnetically protected dry-wall concept has near-optimum COE over a very wide pulse-repetition-rate range. However, the very large reaction cavity required even with small target yields, plus similar safety-related and power-generation-related conservatism, result in a similar minimum COE. The wetted-wall and granular-wall reactor concepts also have relatively large near-optimum pulse-repetition-rate operating ranges.

The wetted-wall concept assumes similar design conservatism. Nonetheless, COEs significantly lower than those for the first two reactor concepts are achieved through much smaller reaction cavities and simpler construction. The results for the granular-wall reactor concept illustrate the magnitude of the savings in COE that can be obtained if expensive containment structures and intermediate loops can be eliminated and higher power generation efficiencies can be achieved. Success in establishing credibility for the advantageous modifications to conventional ICF reactor plant and BOP designs embodied in the granular-wall reactor plant concept clearly can be important for economically attractive HIF power production. The other HIF reactor-plant/BOP concepts appear to be compatible with some of the improvements assumed for the granular-wall reactor.

Optimum COEs for the four reactor plant concepts for single-shell, double-shell, symmetric-illumination, and advanced targets are given in Fig. 5. The differences for the five target concepts are perhaps somewhat less than might have been predicted *a priori*, but as expected the two optimistic target concepts (the range multiplier and the advanced) give the lowest COEs. The reason for this relative independence of target concept is that for fixed values of (ion range) (spot radius)$^{3/2}$, the gain curves are relatively steep with similar slopes and start at nearly the same driver pulse energy, so that the pulse energy at which high gain is attained is nearly the same.

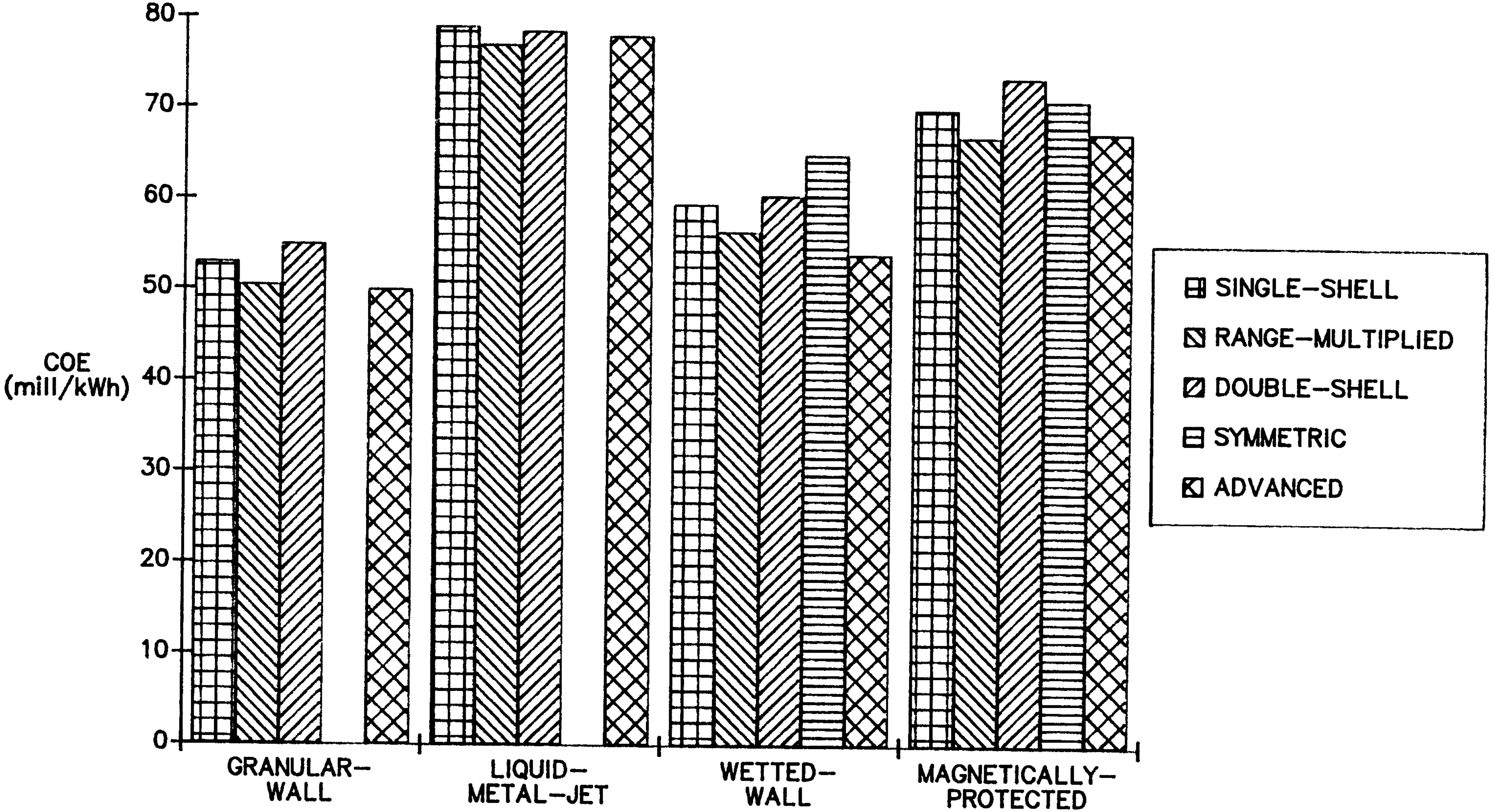


Figure 5. Minimum COE for four HIFSA reactor-plant/BOP concepts in 1000-MWe, single-reactor HIF power plants and for five HIF targets illuminated by beams of +3, 130-amu ions.

The optimum COE values for ion masses of 130 and 210 amu and (ion range) (spot radius)$^{3/2}$ values of 0.01 (0.01) 0.04 g/cm$^{1/2}$ in Fig. 6 indicate that the dependences of optimum values of COE on these two parameters are relatively weak. The results of the systems study showed disappointingly small difference in the COE for single-pulse linacs compared to double-pulse linacs. Costs for additional beam transport lines and the relatively flat scaling of linac cost with beam current are the principal cause for this result. Up to 1500 MWe, the maximum plant size for which the cost database is considered to be accurate, one reactor is optimum. At sufficiently large plant capacity, more than one reactor will be optimum.

Scaling of COE with plant net electric power is illustrated in Fig. 7 for the wetted-wall reactor-plant/BOP concept and +3 ions. Using scaling relationships consistent with those used in the HIFSA studies, the +1-ion HIBALL-II plant was scaled down to 1000 MWe from the original 4000-MWe point design and corresponding COE values are also plotted in Fig. 7. The strong economy of scale displayed depends on the assumptions that construction time does not increase with plant size and that other factors do not erode the projected economies of scale.

Near-Optimum Parameter Ranges

One of the most encouraging results of the HIFSA studies is that unexpectedly broad design parameter ranges for which COE is near the minimum were found. Ranges of values for some key design parameters for which the calculated COE was within 5% of the minimum COE are listed in Table 1 for the case of one-reactor, 1000-MWe net electric plants with targets illuminated by +3, 130 amu ions. It is important to recognize that arbitrary combinations of parameter values within the listed ranges are not always feasible. However, if one parameter value is set arbitrarily, then some value within the listed ranges for each of the other parameters is consistent with the specified value.

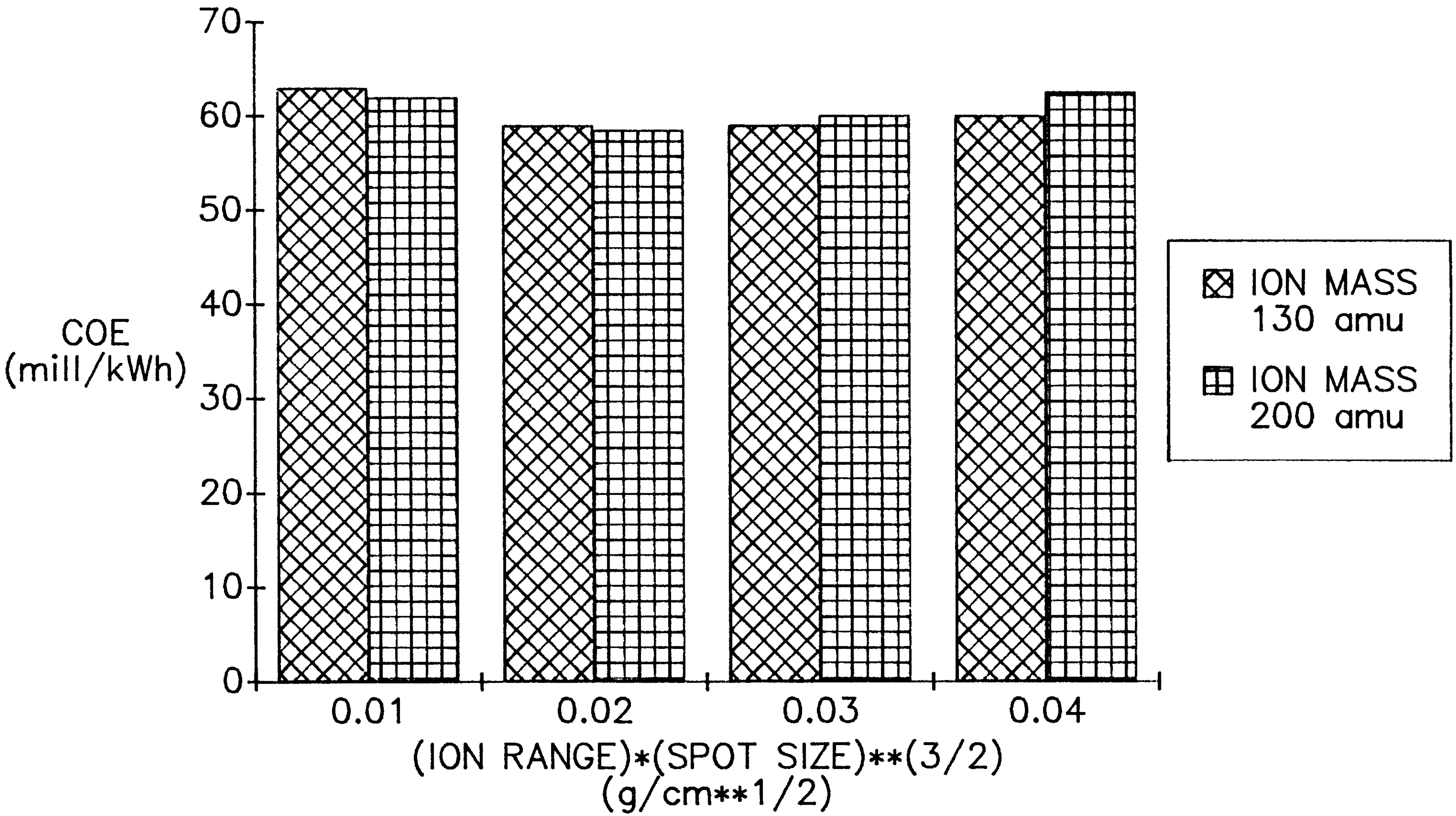


Figure 6. Minimum COE as function of ion mass and (ion range)X(spot radius)$^{3/2}$ for wetted-wall reactor-plant/BOP concept in 1000-MWe, single-reactor HIF power plants with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions.

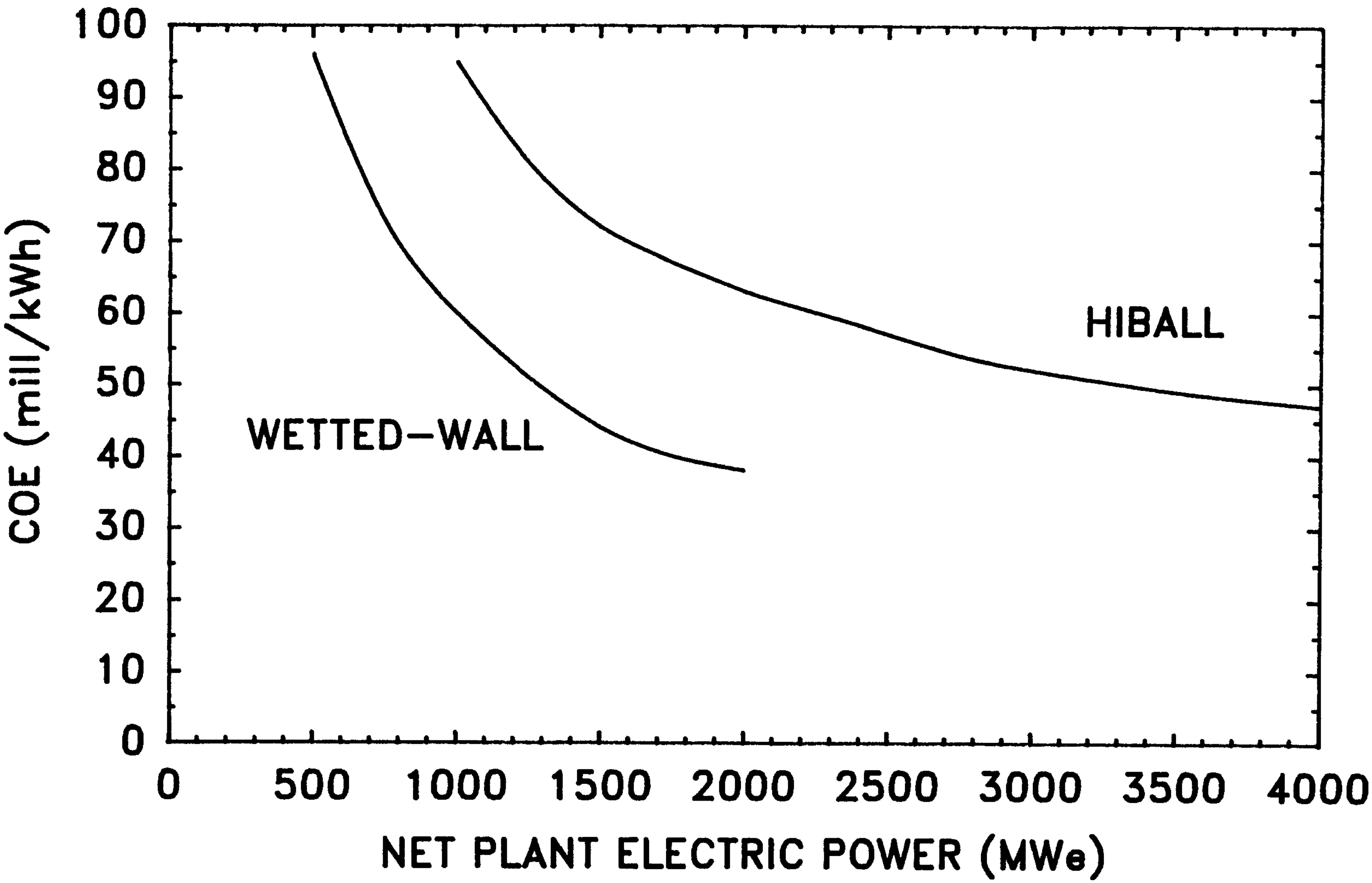


Figure 7. COE as function of single-reactor HIF power plant size for wetted-wall reactor-plant/BOP concept with single-shell targets illuminated from two sides by 16 beams of +3, 130-amu ions with (ion range)X(spot radius)$^{3/2}$ = 0.03 g/cm$^{1/2}$.

Table 1. Design parameter value ranges for which estimated COE is within 5 % of minimum COE (one-reactor, 1000-MWe net electric plants with targets illuminated by +3 ions).

	Magnetically Protected	Liquid-Metal Jet	Granular Wall	Wetted Wall
Repetition Rate (Hz)				
Single-Shell	9-19	1-2	3-9	3-9
Double-Shell	7-19	1-2	3-9	3-7
Symmetric	13-19	NA	NA	5-9
Range-Multiplier	9-19	1-2	3-9	3-9
Advanced	7-19	1-2	3-9	1-9
Target Gain				
Single-Shell	20-45	125-200	50-125	50-150
Double-Shell	25-50	125-175	50-100	50-120
Symmetric	25-50	NA	NA	50-100
Range-Multiplier	50-75	175-200	50-125	75-150
Advanced	50-100	175-375	75-150	75-400
Pulse Energy (MJ)				
Single-Shell	2.25-5.00	7.25-11.25	3.00-7.25	3.50-8.00
Double-Shell	3.25-6.00	7.00-9.00	3.50-8.00	4.00-8.75
Symmetric	2.75-4.75	NA	NA	4.00-11.00
Range-Multiplier	1.75-4.00	7.00-9.50	2.75-5.25	3.25-6.00
Advanced	2.00-4.50	4.75-8.50	2.00-6.00	2.25-7.50
Ion Energy (GeV)				
Single-Shell	6-12	8-15	6-12	6-13
Double-Shell	5-11	8-14	5-12	5-12
Symmetric	7-9	NA	NA	5-11
Range-Multiplier	6-13	8-14	7-12	6-13
Advanced	5-10	6-14	5-11	5-12
Number of Beams				
Single-Shell	10-50	16-50	12-50	12-52
Double-Shell	8-30	8-20	8-36	8-40
Symmetric	22-50	NA	NA	18-60
Range-Multiplier	8-50	15-49	12-30	12-50
Advanced	10-44	10-60	12-52	10-60
(Ion Range) (Spot Radius)$^{3/2}$ (g/cm$^{1/2}$)				
Single-Shell	0.01-0.03	0.02-0.04	0.01-0.04	0.02-0.04
Double-Shell	0.01-0.03	0.01-0.03	0.01-0.04	0.01-0.04
Symmetric	NA	NA	NA	NA
Range-Multiplier	0.01-0.04	0.03-0.04	0.02-0.04	0.02-0.04
Advanced	0.01-0.03	0.02-0.04	0.01-0.04	0.02-0.04

This result suggests that if for some unforeseen reason some part of design parameter space turns out to be inaccessible or unattractive, then other feasible or attractive designs can be found. Detailed data for linac performance for a wide variety of plant configurations are listed in Table 2 to further illustrate the large attractive HIF parameter space.

SUMMARY OF HIFSA PROJECT ACCOMPLISHMENTS, RECOMMENDATIONS AND PROJECTIONS

Key technical issues in the design and cost/performance modeling of induction linacs, reactors, targets, beam transport, BOP, and integrated commercial HIF power plants have been identified. A commercial power plant systems model that runs on personal computers was developed to facilitate wide-ranging tradeoff, sensitivity, and optimization studies. This model has been used to measure the relative value of improvements in physics understanding, conceptual designs, and technology. Limited only by the present understanding of HIF and the imagination of the project team, promising commercial HIF power plant configurations involving different degrees of optimism have been developed. Some of the insights gained in the development of cost/performance models have applications to ICF in general. Some of the models are directly applicable to laser and light-ion fusion. Also, extensive interactions between reactor, accelerator, and target scientists and engineers have led to better understanding of the requirements and issues.

A consistent commercial HIF induction linear accelerator concept has been developed that incorporates the latest physics understanding and technological advances. A comprehensive, detailed cost/performance code has been used to develop a wide-ranging, multidimensional accelerator cost/performance database. Substantially lower linac capital costs than those estimated in previous studies are projected as a result of

Table 2. Optimum-configuration commercial HIF power plant induction linac driver efficiencies (ion mass fixed at 130 amu and (ion range) (spot radius$^{3/2}$ fixed at 0.03).

Reactor Concept	Plant Scale (MWe)	Ion Charge State	Ion Energy	Target Concept	Illumination Geometry	Pulse Rate (Hz)	Pulse Energy (MJ)	Linac Efficiency (%)
magnetically protected	1000	+3	7	single-shell	two-sided	11	4.7	41.2
liquid-metal jet	1000	+3	8	single-shell	two-sided	2	8.2	28.2
granular-wall	1000	+3	8	single-shell	two-sided	5	5.3	37.1
wetted-wall	1000	+3	8	single-shell	two-sided	5	5.8	37.0
wetted-wall	1000	+1	7	single-shell	two-sided	5	5.9	25.4
wetted-wall	500	+3	8	single-shell	two-sided	3	5.7	33.5
wetted-wall	1500	+3	8	single-shell	two-sided	5	6.7	36.7
wetted-wall	1000	+3	8	advanced	two-sided	3	5.2	33.7
wetted-wall	500	+3	8	advanced	two-sided	1	5.8	22.1
wetted-wall	500	+3	8	range-multiplier	one-sided	5	4.5	36.6
wetted-wall	500	+3	8	single-shell	one-sided	5	5.8	37.0
wetted-wall	500	+3	5	symmetric	planar symmetric	7	5.6	37.4
wetted-wall	500	+3	8	double-shell	two-sided	3	5.6	32.3
wetted-wall	500	+3	8	advanced	two-sided	3	4.6	33.8
wettted-wall	500	+3	8	range-multiplier	one-sided	3	4.1	33.7
granular-wall	500	+3	7	advanced	one-sided	3	3.4	35.5

advances in induction linac science and engineering, materials, and industrial capability in recent years. The driver capital cost is now comparable to the sum of reactor plant and BOP capital costs for 1000 MWe plants, rather than completely dominating plant capital cost. The data has been fit with simple expressions to permit its incorporation into an integrated power plant systems code for performing design-tradeoff, parameter-sensitivity, and optimization studies. The integrated plant studies have revealed several important trends, including near-optimum COEs over wide ranges of linac design parameter values and substantial cost savings by operation with +3 charge state.

Accelerator-related R&D needs have been identified and priority recommendations have been made, with charge neutralization being assigned the highest priority and high priorities assigned to pulse shaping and compression and the use of much lighter ions with +1 charges. Additional opportunities for significant reductions in accelerator costs were identified.

Although great advances in target design did not result from HIFSA target studies, important benefits were obtained nonetheless. In particular, HIFSA target studies led to the formulation of target-performance models that relate important accelerator, reactor, and target performance parameters for a wide variety of target concepts in simple, convenient, accurate ways to facilitate integrated HIF power plant studies. These models and the HIFSA target cost model are useful for laser fusion and light-ion fusion as well.

REFERENCES

1. "HIBALL - A Conceptual Heavy Ion Beam Fusion Reactor," University of Wisconsin report UWFDM-450/KfK-3202 (1981).

2. "HIBALL-II, An Improved Heavy-Ion-Beam-Driven Fusion Reactor Study," Fusion Power Associates/Kernforschungszentrum Karlsruhe/University of Wisconsin report FPA-84-4/KfK-3840/UWFDM-625 (1984).

3. Jack Hovingh, Victor O. Brady, Andris Faltens, Denis Keefe, and Edward P. Lee, "Heavy-Ion Linear Induction Accelerators as Drivers for Inertial Fusion Power Plants," Fusion Technol., 13, 255 (1988).

4. M.J. Monsler, J. Hovingh, D.L. Cook, T.G. Frank, and G.A. Moses, "An Overview of Inertial Fusion Reactor Design," Fusion Technol./Fusion, 1, 302 (1981).

5. W.J. Hogan and G.L. Kulcinski, "Advances in ICF Power Reactor Design," Fusion Technol., 8 (1, Part 2 [A]), 717 (1985).

6. "Heavy Ion Fusion Reactor - Hiblic-I," Nagoya University report IPPJ-663 (1984).

7. J.H. Pitts, "The Development of the Cascade Inertial-Confinement-Fusion Reactor," Fusion Technol., 8 (1, Part 2 [A]), 1198 (1985).

8. J.A. Blink, "The High-Yield Lithium Injection Fusion Energy (HYLIFE) Reactor," Lawrence Livermore National Laboratory report UCRL-5399 (1985).

9. J.H. Pendergrass et al., "A Modified Wetted-Wall Inertial Fusion Reactor Concept," Proc. 4th Top. Meet. on the Technology of Controlled Nuclear Fusion (October 14-17, 1980, King of Prussia, PA), U.S. Dept. of Energy report Conf-80101011, Vol. 2, p. 1131 (1981).

10. J.B. Cornwell and J.H. Pendergrass, "Inertial Fusion Reactors and Magnetic Fields," Fusion Technology, 8, (1, Part 2 [B]), 1961 (1985).

11. John H. Pendergrass, "Heavy-Ion Fusion Systems Assessment Implications for Reactors," Fusion Technol., 13, 290 (1988).

12. P. Stroud, "Heavy-Ion Beam Transport through Liquid-Lithium First Wall ICF Reactor Cavities," in Los Alamos National Laboratory report LA-11141-MS, Vol. II (D.J. Dudziak, Ed.), (1987).

13. P. Stroud, "Streaming Modes in Final Beam Transport in Heavy-Ion Beam Fusion," Laser and Particle Beams, 4, 2 (1986).

14. J.D. Lindl and J.W-K. Mark, "Recent Livermore Estimates on the Energy Gain of Cryogenic Single-Shell Ion Beam Targets," Lawrence Livermore National Laboratory report UCRL-90241 (1984).

15. J. Meyer-ter-Vehn, "On Energy Gain of Fusion Targets: The Model of Kidder and Bodner Improved," Nuclear Fusion, 22, 561 (1982).

16. Glenn R. Magelssen, "Gain Scaling Relationships -- Heavy-Ion Targets," Fusion Technol., 13, 339 (1988).

17. John H. Pendergrass, David B. Harris, and Donald J. Dudziak, "Heavy-Ion Fusion Target Cost Model," Fusion Technol., 13, 375 (1988).

18. Roger O. Bangerter, "Targets for Heavy-Ion Fusion," Fusion Technol. 13, 348 (1988).

19. David S. Zuckerman, Daniel E. Driemeyer, Lester M. Waganer, and Donald J. Dudziak, "An Induction Linac Driven Heavy-Ion Fusion Systems Model," Fusion Technol., 13, 217 (1988).

20. Donald J. Dudziak, William W. Saylor, and William B. Herrmannsfeldt, "U.S. Heavy-Ion Fusion Systems Assessment Project Overview," Fusion Technol., 13, 207 (1988).

REVIEW OF THE LASER WORKING GROUP SESSIONS

The laser working group was chaired by H. Lowdermilk, and had representatives from LLNL (solid state lasers), LANL (KrF lasers), KMS Fusion (chemical lasers), DOE, Japan (solid state) and France (solid state). There were no experts in the field of free electron lasers, but FELs were included as one of the concepts in discussion.

The session started with questions directed at DOE people to clarify what needed to be done. They reiterated that a rating of all ICF drivers needed to be produced using the format used in the LANL talk on KrF lasers and commenting each choice. The pathway to the LMF and beyond, up to commercial capability, should be charted, with key technologies and milestones/demonstrations identified. The driver energy on target requirements should be in the range 5-10 MJ. In order to sell, a program would need total credibility. An assessment of relative status of various laser drivers would be needed as well.

It was decided that in order that the session be more efficient and fair, there would be just one working group discussing aspects of various laser concepts, instead of breaking up into smaller groups composed of experts and proponents of given concepts.

Potential Problem Areas

The work started by identifying potential problem areas for various laser concepts. The two mainline concepts (excimer and solid state) were discussed in detail, as well as the overall laser technology vis à vis other driver technologies (LIB and HIB). There was also considerable discussion of FELs, but since there were no FEL experts on the panel, the conclusions are somewhat tenuous.

For the solid state lasers, the problems identified are: necessity of finding a medium with a reasonably high efficiency (> 10% wall plug to target), optics damage and related cost of the system, need to find an affordable pump source, problem of bandwidth and short wavelengths and focal beam quality. On the other hand, there is a benefit to going to wavelengths longer than 4000 A, because the optical materials are more transparent and there is less damage to the optics.

For KrF lasers the main issues identified are: damage/cost (this would be more of a problem than for glass lasers due to the shorter wavelength), need to demonstrate reasonable efficiency, the optical train is complex, component lifetime and density of the medium has to be uniform to 0.0001 for acceptable beam quality (and for higher rep rates this problem will get worse). Under optical train complexity, angular multiplexing and demultiplexing needs to be done, but beams can be combined through amplifiers. If 5 MJ is needed on target, a lot of beams will be needed; however, passive optics need not be broken down into subapertures.

The disadvantages of the FELs are that the spot size is too large (1 cm) and it would be tough to go directly from wiggler to target, the required short wavelengths would not be easy to achieve, problem of high fluences (beam handling) and focusing and the fact that this is a less well developed technology. An advantage of FELs is their high efficiency.

Overall, the lasers are perceived to have problems with respect to photon damage, large optics fabrication, focal beam quality, radiation damage on optics, efficiency, reliability, lifetime. Heavy ion fusion is expected to be the main competitor for a commercial ICF reactor. The HIF drivers have the advantage of easily achieving repetitive operation, and related to that the fact that in order to get to a reactor driver, only one step is necessary, whereas for lasers two steps are needed (one to demonstrate a single shot driver at the required energy, and the other to demonstrate rep-ratability at that energy). Some of the problem areas for lasers are being addressed in the SDI program (damage, fabrication of large optics, use of phase conjugation to compensate for non-ideal optics). In the area of cost, the figure quoted was $0.5B for an acceptable 5 MJ driver.

What Must Be Done To Get Where We Want To Be?

For solid state lasers, we have to do the following:

a) Find the medium with high intrinsic efficiency (a semi-empirical process, so there are a lot of combinations);
b) Damage/cost research (a lot more needs to be done in this area);
c) Development of an affordable pump source. Rate of development in this area is high -- one year progress of 100 mW to 1 W per facet and from 10 diodes to 1000 diodes per array has been reported. A lot of work is under SDI and other programs, so the fusion program need not pay for this now. Cost reduction needed is from $50k/sq cm now to $100/sq cm. The issue of 2-D monolithic array fabrication and cooling are the two issues that need to be addressed;
d) Solve the problem of bandwidth and short wavelength (for indirect targets, there is efficient coupling, and conversion efficiency from laser to X-ray is high -- 70%, with 80% achievable with smoothing techniques;

e) Solve the beam quality problem (this is unlikely to be a serious issue for indirect drive devices). However, uniformity of x-ray conversion is an issue, albeit significantly lower in difficulty than items a), b) and c) for indirect drive. For direct drive, laser light pattern should be corrected by ISI techniques or some other method;

f) Energy scaling. This is not a physics problem but a production problem because we need to grow crystals of the required size quickly and economically. The size needed is 20-30 cm aperture vs. currently available 10 cm aperture. Non-optical quality crystals (e.g. CaF_2) in the 30-60 cm range have been grown. A 10-year program is envisaged to solve this problem;

g) Frequency conversion at high PRF. Handling techniques for average power through the amplifier are extendable to frequency converter, but technical problems need to be solved -- e.g. the intensity dependent polarization rotation problem. Ideal efficiency should be around 85%, but 35% achieved at Osaka.

For KrF lasers, the problems worked on are:

a) Damage/cost for 0.25 micron light. Not as much effort is being put into this problem as at LLNL for their laser. While this is a small program, it is the most highly leverage item for the cost of KrF laser system (single pulse included). The experimental damage limit achieved has gone from 2 J/sq cm to 6 J/sq cm with small samples achieving 10 J/sq cm (scaled to 20-30 ns). It would seem reasonable that practical damage limits of 5 J/sq cm are achievable. Fluorinated long term optics need to be emphasized;

b) Efficiency. Laser intrinsic efficiency in a medium of 13% ± 1% has been measured with non-optimal pumped power pulse duration, so potential exists for 15%. Pulsed power efficiency can be increased by eliminating the guide magnets, which are energy users. In the power plant we would use superconducting magnets -- in the Aurora experimental facility replacing regular magnets with superconducting magnets would cost $100/J, so it remains to be seen what the cost impact of that strategy would be on the power plant -- e.g. can we use single size magnets for several modules? Beam transport issues are mostly engineering (there are no physics issues involved). At Sandia's PBFA-II facility, the pulsed power portion of the machine is achieving high efficiency and there are no fundamental physics limitations. For KrF lasers there may be cost differences between the e-beam method and the discharge method of laser pumping. One study found that the discharge laser option would be a little higher in cost and efficiency. In summary, the wall plug efficiency components are: kinetic efficiency (up to 15%), pulse power efficiency (75-80% for rep-rated Marx technology, including beam transport), optical transport efficiency from the final amplifier to the target of 90-95%. Gas pumping and handling will result in a loss of 1% of efficiency, so potential exists for an overall efficiency of 8-9%. The Aurora facility has an intrinsic efficiency of 7%. Overall KrF system efficiency can be increased if the waste heat can be used for feedwater heating in the power plant;

c) Issue of complex optical train for KrF lasers is being studied in a LANL program for system architecture. There would be 6 optical surfaces between the main amplifier output window and target, which is similar to the number at the Nova facility. In the power plant situation, one is concerned with the neutrons streaming back, which is a problem for all lasers;

d) Issue of component lifetime. This would encompass the components of the pulsed power supply and the optics. The pulsed power and diode work at Sandia can answer similar questions for the laser systems. One problem for e-beam pumped systems is how the e-beam coils would be cooled; if this can't be answered, then the discharge pumping should be chosen, although a lot of amplifiers would be necessary. Progress is being made in the areas of reliability and availability of the pumping sources. The laser refurbishment could be done when the power plant is down. Is it possible that the final mirrors be annealed? Damage and cost of optics is a high leverage item (LAM window costs $0.5M);

e) Beam quality issues; there is difference in this area between a single pulse facility and one which has flowing gas to remove the heat. For instance, for 3 MJ at 10 Hz, we'll need almost 300 MW of cooling (at 10 Hz efficiency), which is non-negligible. Laminar flow in the amplifier would be needed in order to satisfy beam quality requirements. Money needs to be applied to the KrF laser problems -- for instance while $200-300M has been spent on the 3rd generation device like Nova, only $40M has been spent on the 1st generation device at Los Alamos.

High Leverage Technology Issues

These are areas of make or break. They are: damage, low cost large optics fabrication, effects of spatial and temporal incoherence, radiation resistant optical materials and advanced materials (e.g. fluorine resistant materials for KrF lasers), practical application of phase conjugation (this would relax requirements for homogeneity and surface finishing and would get rid of expensive alignment hardware to make optics inexpensive and reliable), efficient pumping scheme, pulse shaping (this is a strong point vs. heavy-ion beam and light-ion beam drivers) and international collaboration. KrF program needs to demonstrate the needed pumping efficiency.

How to Reduce Risk and Increase Credibility

a) Fully integrated demonstration of a specified efficiency is necessary. This efficiency would have to be agreed on and would likely be about 10%.

b) Design a credible cost model.

c) Demonstrate average power capability.

d) Need to demonstrate mass produced target performance. For direct drivers, we need to demonstrate the required uniformity (1-2%?).

Do we need to settle the question of indirect drive vs. direct drive to enhance credibility? Yes, this question should be answered soon. We need a device to test both concepts (would LMF do this?). Also, we should design a driver that can do commercial power credibly today in the unlimited resource scenario. The parameter space should be narrowed. The issue of bandwidth should be addressed. A lab driver to drive a high gain pellet is needed. An optimization should be done concerning cost of electricity, availability and environmental cost.

Near Term Key Issues

These are the key technical issues to be resolved in the near future (2-5 years and before decision on the 10 MJ laser):

a) Effects of spatial and temporal incoherence;

b) Effects of pulse shaping;

c) Question of the right wavelength;

d) Damage to optics;

e) Low cost, high performance driver for LMF -- credible design and analysis should be performed.

International Collaboration

As the scale and cost of planned facilities go up, more collaboration may be necessary. However, the classification problem will impede this. Perhaps, there could be cooperation in the area of component development. Workshops can be held under DOE and other sponsorships. The collaboration would also be important from the standpoint of credibility, because several labs would be working on problems and checking results.

REVIEW OF THE LIGHT ION FUSION WORKING GROUP SESSIONS

The light ion fusion (LIF) working group was chaired by Don Cook of Sandia National Laboratory. Members of the group included M. Buttram (SNL), G. Chenevert (DOE), T. Crow (SNL), S. Dean (FPA), N. Hoffman (ETEC), G. Kulcinski (UW), S. Miyamoto (Osaka), R. Olson (SNL), R. Peterson (UW), and J. MacFarlane (UW).

The working group identified the major technical issues facing LIF, and established lists of near term and long term priorities. These lists are shown in Tables 1 and 2. The near term research and development priorities are more specific, and Table 1 shows a dual-track experimental program that can more or less proceed in parallel. PBFA II can initially be used for unshaped pulse experiments for understanding beam focussing and target coupling. At the same time, the Supermite and Hermes III devices can proceed with shaped pulse experiments for beam focussing and beam transport. For both the shaped and unshaped pulse tracks, beam focussing is a top priority. After PBFA II has achieved 30 MV operation and the shaped pulse experiments have been completed on Hermes III and Supermite, PBFA II can be modified for pulse shaping, and target experiments performed.

The longer term issues critical to LIF reactors are listed in Table 2. The transport of ions through freestanding plasma channels over a "standoff" distance of a few meters must be demonstrated for reactor operation, and the physics of overlapping channels near the target understood. In addition, a repetitive (~ 1 Hz) diode and pulse module must be developed.

Other issues discussed by the working group included: (1) popular appeal and understanding of LIF, (2) additional R&D for the LIF program if funding was unlimited, (3) international collaboration, (4) information funding agencies need to support programs, and (5) potential markets for pulsed power. A brief summary of each of these items is given below:

- Popular appeal and support for LIF may have problems due to the perceived complexity of pulsed power systems. Also, the pulsed power systems are often run near their design limits, leading to a breakdown of components. This "pushing the limits" of the system can lead to an overly pessimistic view of LIF reliability.

- In the unlimited funding scenario, the LIF program could be expanded by increasing the number of sites working in the area of pulsed power, as well as increasing parallel efforts on selected items to reduce potential risks.
- The Japanese program would like increased collaboration with the U.S. program. Although it is not likely that the U.S. would interact in areas of target physics, collaboration at the driver component level might become possible.
- G. Chenevert (DOE) pointed out that funding agencies like to see technical accomplishments in order to support programs. He pointed to successful laser fusion target experiments as an example.
- Potential markets for pulsed power were discussed. Possible market areas include: small size ICF due to LIF's low cost and high efficiency; tritium production; materials and food processing; and astrophysical, high energy density research.

In the final workshop session, each group rated the potential strong and weak points of each of the ICF drivers. In regards to light ion fusion, all groups generally agreed that the major difficulties facing LIF are the demonstration of beam focussing and high rep rate operation. The major advantage of LIF was seen to be its low cost relative to laser and heavy ion fusion.

Table 1. Near Term LIF Issues.

Unshaped Pulse	Shaped Pulse
1. Beam focussing. (H+, Li+; PBFA II)	1. Beam focussing with extractor diode. (H+, Li+; Supermite, Hermes III)
2. Target coupling demonstration. (PBFA II)	2. Transport channel creation. (off-line)
3. Generate 30 MV potential at diode. (PBFA II)	3. Beam transport in channels. (H+, Li+; Supermite, Hermes III)
4. Perform implosion experiments. (PBFA II)	4. Target coupling experiments. (Hermes III)
5. Attempt ignition. (PBFA II)	
6. Modify PBFA II for pulse shape.	
7. Perform pulse shaped target experiments.	

Table 2. Long Term LIF Issues.

1. Demonstrate freestanding transport channels for "standoff".

2. Investigate multiple channel overlap.

3. Develop a reusable ion diode.
(30 MV, 1-2 MA, 20 shot lifetime)

4. Develop a repetitive pulse module.
(30 MV, 1-2 MA, 1 Hz, 300-600 kW)

5. Develop a repetitive diode.

REVIEW OF THE HEAVY ION FUSION WORKING GROUP SESSIONS

The heavy ion fusion (HIF) working group was chaired by Tom Fessenden of Lawrence Berkeley Laboratory. Among the members of this working group were Roger Bangerter (LLNL), Dave Bixler (DOE), Don Dudziak (LANL), Bill Hermannsfeldt (SLAC), Jim Mark (LLNL), Rolf Müller (GSI), Walter Polansky (DOE), Mohamed Sawan (UW), Igor Sviatoslavsky (UW), and Layton Wittenberg (UW).

The group began by listing the important questions for HIF. The group then discussed each of these questions, some in more detail than others. The group then summarized the discussions and prepared viewgraphs to present to the rest of the colloquium. This summary began with a statement that the advantages of HIF are the efficiency, rep rate and reliability with high confidence. Seven issues were then discussed.

1. Could heavy ion beams be the LMF driver?

   Heavy ion beams could be the LMF driver, but technical development of heavy ion drivers is behind some other candidates. A large increase in the funding level for the development of heavy ion drivers would be required to bring this technology up to the levels of the other candidate drivers. Only then could one realistically assess the merits of heavy ion beams as a possible LMF driver.

2. What would be the advantages of commercial ICF?

   Fission is the perceived main competition to fusion and fusion has environmental and safety advantages over fission. Currently, magnetic fusion is perceived as the commercial fusion program. ICF is a military program in the United States and a basic science program in Europe. An objective comparison between ICF and magnetic fusion could show that ICF is competitive with magnetic fusion for commercial power production, but there are political reasons, both in the U.S. and in Europe, for avoiding this comparison.

3. Are there new ideas that may favor heavy ion drivers?

   The high driver efficiency and precise focussing possible with heavy ion beams allows the consideration of target concepts that are not possible for other drivers. Advanced fuel targets using fusion fuels that produce reduced amount of neutrons, and therefore may activate the target reaction chamber to a lower degree, may have smaller burn fractions leading to lower gains. The high driver efficiency means that a lower target gain would still be acceptable for economic power production. Some target concepts require beam focal spots of 1/4 mm in size, which is possible in heavy ion drivers but probably not in light ion drivers. These targets are predicted to have increased gain and lower input energy requirements, which makes them potentially very attractive for commercial fusion.

One advantage of heavy ion beams that is not part of a new idea but that came up in the discussion is the final focussing optics for heavy ion beams. These final focussing magnets are not in the line-of-sight of target generated neutrons, x-rays, and debris. In both laser and light ion beam concepts there may be sensitive structures within the line-of-sight of the target and within several meters of the target, which could lead to the problem of frequent component replacement. The HIBALL study showed how it is possible to shield heavy ion final focussing magnetics so they could last the life of the plant.

4. <u>What are the high risk areas for heavy ion drivers?</u>

Because of the slower development of heavy ion beam drivers for fusion compared to lasers and light ions, there are some uncertainties for heavy ion drivers that are critically important to the concept. There are large uncertainties in the transmission of ion beams in the target chamber that could have a strong impact on the design and operation of the target chamber. Specifically, ion beam propagation will place some limits on the density of gas in the target chamber. Depending on the target chamber design and the choice of target, material may be vaporized off of the target chamber walls, which will take some amount of time to condense out. Estimates of this condensation time range from below .1 s to above 1 s, meaning that the target chamber rep rate could range from the more than acceptable 10 Hz to the probably not acceptable 1 Hz. There are also issues in the driver performance. Emittance conservation is an issue for both RF and induction linac type heavy ion drivers. Also, there may be problems of energy definition for induction linacs and transvere emittance controls in RF linacs. Research into all of these issues could use more funding.

5. <u>Are heavy ion drivers too expensive</u>

There is a perception that heavy ion drivers would be very expensive, at lease initially. This would lead to high construction costs per unit of delivered beam energy compared with other type of drivers. This is more of a problem for induction linacs than for RF linacs. One idea that could reduce the cost of induction linacs would be to use a 100 MeV injector such as a Pulselac.

There were two questions that were not addressed because of lack of time. Can we find or do we want other customers for ICF? Can we borrow or contribute useful technologies or concepts?

The group devised a possible HIF development plan. This plan is specific to induction linacs, though something similar could be done for RF. The driver development would proceed in increments in ion energy. The first major step would be the development of the Induction Linac System Experiment (ILSE), which would have an ion energy of 10 MeV. It would address the merging of beams, magnetic focussing in accelerators and transport, the bending of space-charge-dominated ion beams, drift-compression physics, and final focus physics. The next steps would be at ion energies of 100 MeV, 1 GeV, and finally 10 GeV, which is that required for a commercial driver.

LIST OF ATTENDEES

Monsieur Michel Andre
Centre d'Etudes de Limeil/Valenton
BP 27
94190 Villeneuve-St. Georges
France

Dr. Roger Bangerter
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Dr. David N. Bixler
Office of Inertial Fusion, DP-231
U.S. Department of Energy
Washington, DC 20545

Dr. Malcolm T. Buttram
Sandia National Laboratory
Pulsed Power Sciences Directorate
Organization 1200
Albuquerque, NM 87185-5800

Dr. Gary Chenevert
Office of Inertial Fusion, DP-231
U.S. Department of Energy
Washington, DC 20545

Dr. Donald Cook
Organization 1200
Sandia National Laboratory
P.O. Box 5800
Albuquerque, NM 87185-5800

Dr. J. Terry Crow
Sandia National Laboratory
Pulsed Power Sciences Directorate
Organization 1200
Albuquerque, NM 87185-5800

Dr. Stephen O. Dean
Fusion Power Associates
2 Professional Drive
Suite 249
Gaithersburg, MD 20760

Dr. Donald Dudziak
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Roxi L. Engelstad
University of Wisconsin
509 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Thomas Fessenden
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, CA 94720

Dr. David Harris
Los Alamos National Laboratory
Analysis and Assessment Division
P.O. Box 1663
Los Alamos, NM 87545

Dr. William B. Hermannsfeldt
Stanford Linear Accelerator Center
Stanford University
P.O. Box 4349
Stanford, CA 94305

Dr. Nate Hoffman
ETEC
P.O. Box 1449, M-Stop T-036
Canoga Park, CA 91304

Dr. Yasukaza Izawa
Institute of Laser Engineering
Osaka University
Suita, Osaka 565
Japan

Dr. Takahisa Jitsono
Institute of Laser Engineering
Osaka University
Suita, Osaka 565
Japan

Dr. Sheldon Kahalas
Office of Inertial Fusion, DP-231
Department of Energy
Washington, DC 20545

Professor Gunther Kessler
INR Kernforschungszentrum
P.O. Box 3640
D-7500 Karlsruhe
West Germany

Dr. Terry Kessler
University of Rochester
Laboratory for Laser Energetics
250 East River Road
Rochester, NY 14623

Prof. Gerald L. Kulcinski
University of Wisconsin
443 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Demos Kyrazis
Lawrence Livermore National Laboratory
P.O. Box 5508, L-493
Livermore, CA 94550

Dr. Edward Lee
University of California
Lawrence Berkeley Laboratory
One Cyclotron Road
Berkeley, CA 94720

Dr. Edward Lovell
University of Wisconsin
3352 Engineering Bldg.
1415 Johnson Drive
Madison, WI 53706

Dr. W. Howard Lowdermilk
Lawrence Livermore National Laboratory
Y-Division, P.O. Box 5508
Livermore, CA 94550

Dr. Joe MacFarlane
University of Wisconsin
537 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. James Mark
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Dr. Shuji Miyamoto
Institute of Laser Engineering
Osaka University
Suita, Osaka 565
Japan

Professor Gregory A. Moses
University of Wisconsin
433 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Rolf Muller
GSI
D-6100 Darmstadt
West Germany

Dr. Zoran Musicki
University of Wisconsin
519 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Stephen Obenschain
Naval Research Laboratory
Code 2610
4555 Overlook Avenue, S.W.
Washington, DC 20375-5000

Dr. Richard Olson
Sandia National Laboratory
Pulsed Power Sciences Directorate
Organization 1200
Albuquerque, NM 87185-5800

Major Tom Owen
Office of Inertial Fusion
U.S. Department of Energy
Washington, DC 20545

Dr. Robert R. Peterson
University of Wisconsin
533 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Walter Polansky
Office of Basic Energy Sciences
U.S. Department of Energy
ER-16
Washington, DC 20545

Dr. Howard Powell
Lawrence Livermore National Laboratory
Y-Division, P.O. Box 5508
Livermore, CA 94550

Dr. Louis Rosocha
Los Alamos National Laboratory
Chemistry Division
P.O. Box 1663
Los Alamos, NM 87545

Dr. Mohamed E. Sawan
University of Wisconsin
517 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Igor N. Sviatoslavsky
University of Wisconsin
525 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Otho Ulrich
KMS Fusion, Inc.
P.O. Box 1567
Ann Arbor, MI 48106

Dr. Layton J. Wittenberg
University of Wisconsin
535 Engineering Research Bldg.
1500 Johnson Drive
Madison, WI 53706-1687

Dr. Thomas Wright
Office of Inertial Fusion, DP-231
U.S. Department of Energy
Washington, DC 20545