Viewgraphs Presented at the Third Inertial Confinement Fusion Systems and Applications Colloquium, 9-11 November 1987, Madison, Wisconsin

R.R. Peterson, Compiling Editor

November 1987

UWFDM-748

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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VIEWGRAPHS PRESENTED AT THE THIRD INERTIAL CONFINEMENT FUSION SYSTEMS AND APPLICATIONS COLLOQUIUM

November 9-11, 1987

Madison, Wisconsin

Compiled December 1987

Robert R. Peterson
Compiling Editor

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1. Introduction

The third Inertial Confinement Fusion (ICF) Systems and Applications Colloquium was held in Madison, Wisconsin from November 11 to November 13, 1987. As the technical program indicates, the focus of this colloquium was drivers for commercial ICF reactors. The colloquium was divided into three plenary sessions, on laser drivers, light ion drivers and heavy ion drivers. Following the plenary sessions, concurrent workshops were held on each of the three driver options. Scientists from national laboratories, industry, government, and universities in the United States, and from several other countries attended the colloquium. A list of attendees is attached.

Here we have compiled viewgraphs presented at the plenary sessions. We have not included some photographs of equipment and some color viewgraphs that did not reproduce well. The viewgraphs are presented in the order that they appear in the program. One talk in the program, to be presented by Valentin Smirnov from the USSR, was not given and there are no viewgraphs for that talk. The talk by Walter Polansky of DOE was given, but we have no viewgraphs for that talk. The talk by Sheldon Kahalas of DOE made some opening remarks without viewgraphs, but he did provide us with a text containing his comments, which we have included.

We hope that these viewgraphs prove to be useful to the ICF community. Early in 1988, we will be publishing the proceedings of this colloquium. This will contain papers written by the speakers in the plenary sessions. The proceedings will also include summaries of the activities of the workshops that followed the plenary sessions. The viewgraphs compiled here should provide a helpful addition to the proceedings, once they are published.

11/6/87

TECHNICAL PROGRAM FOR 3rd INERTIAL CONFINEMENT FUSION SYSTEMS AND APPLICATIONS COLLOQUIUM

Monday, November 9, 1987

9:00 - 9:15	Opening Remarks by University of Wisconsin-Madison
9:15 - 9:30	Opening Remarks by Department of Energy

Plenary Sessions for Laser Fusion
Chairman - Roger Bangerter, Lawrence Livermore National Laboratory

9:30 - 10:00 a.m.	Howard Lowdermilk - Lawrence Livermore National Laboratory, "LLNL View of Commercial Drivers for Laser Driven Reactors"
10:00 - 10:30 a.m.	BREAK
10:30 - 11:00 a.m.	Dave Harris - Los Alamos National Laboratory "LANL View of Commercial Drivers for Laser Driven Reactors"
11:00 - 11:30 a.m.	Michel Andre - Centre d'Etudes de Limeil/Valenton "French View of Commercial Drivers for Laser Driven Reactors"
11:30 - 12:00 noon	Yasukazu Izawa/Takahisa Jitsuno - Osaka University "Japanese View of Commercial Drivers for Laser Driven Reactors"
12:15 - 1:30 p.m.	LUNCH - Wisconsin Center, South Dining Room 702 Langdon Street
1:30 - 2:00 p.m.	Steve Obenschain - Naval Research Laboratory "Beam Quality for Symmetric Illumination Commercial Laser Driven Reactors"

Plenary Sessions for Light Ion Beam Fusion
Chairman - Gunther Kessler, Kernforschungszentrum, Karlsruhe, FRG

2:00 - 2:30 p.m.	Don Cook - Sandia National Laboratory "Sandia View of Commercial Light Ion Fusion Drivers"
2:30 - 2:50 p.m.	Terry Crow - Sandia National Laboratory "Pulse Shaping for Light Ion Reactors"
2:50 - 3:10 p.m.	Rick Olson - Sandia National Laboratory "Relationship Between TDF and Commercial Drivers"
3:10 - 3:30 p.m.	BREAK

**TECHNICAL PROGRAM FOR
3rd INERTIAL CONFINEMENT
FUSION SYSTEMS AND APPLICATIONS COLLOQUIUM**

Monday, November 9, 1987 (Continued)

3:30 - 3:50 p.m.	Malcolm Buttram - Sandia National Laboratory "Repetative Pulsed Power for Commercial Reactors"
3:50 - 4:20 p.m.	Valentin Smirnov - Kurchatov Institute of Atomic Energy "USSR View of Commercial Drivers for LIB Fusion Reactors"
4:20 - 5:10 p.m.	Shuji Miyamoto - Osaka University "Japanese View of Commercial Drivers for LIB Fusion Reactors"
Evening	Open

Tuesday, November 10, 1987

<u>Plenary Session for Heavy Ion Beam Fusion</u>
Chairman - William Hermannsfeldt, Stanford University

9:00 - 9:30 a.m.	Walter Polansky - Department of Energy "Accelerator Research for HIB Fusion in the U.S."
9:30 - 10:00 a.m.	Denis Keefe/Thomas Fessenden - University of California-Berkeley, "Induction Linac Drivers for Commercial HIB Fusion"
10:00 - 10:30 a.m.	Rolf Muller - GSI/West Germany "RF Linac Driver for Commercial HIB Fusion"
10:30 - 11:00 a.m.	BREAK
11:00 - 11:30 a.m.	Edward Lee - University of California-Berkeley "Critical Issues of Accelerators for Commercial HIB Fusion"
11:30 - 12:00 noon	Donald Dudziak - Los Alamos National Laboratory and William Hermannsfeldt - Stanford University "Update of HIFSA: Implications for Commercial HIB Fusion"
12:00 - 12:15 p.m.	Instructions for Working Groups Greg Moses, University of Wisconsin
12:15 - 1:30 p.m.	LUNCH - Wisconsin Center, South Dining Room 702 Langdon Street

TECHNICAL PROGRAM FOR
3rd INERTIAL CONFINEMENT
FUSION SYSTEMS AND APPLICATIONS COLLOQUIUM

Tuesday, November 10, 1987 (Continued)

1:30 - 5:00 p.m. Working Groups on ICF Drivers

Coordinator	Driver System	Room
H. Lowdermilk	Laser	Rosewood
D. Cook	Light Ion Beam	Round Table
D. Keefe/ T. Fessenden	Heavy Ion Beam	Langdon

5:30 - 7:00 p.m. RECEPTION - Wisconsin Center, Alumni Lounge
702 Langdon Street

7:30 - 8:30 p.m. DINNER - University Club, 808 State Street

8:30 - 9:15 p.m. Arthur Hasler - University of Wisconsin, Limnology Department, "How Do Salmon Find Their Way Home?"

Wednesday, November 11, 1987

9:00 - 12:00 noon Working Groups

12:00 - 1:00 p.m. LUNCH - Open

1:00 - 3:00 Summary Reports and Conclusions
Chairman - Dave Bixler, Department of Energy

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Introductory Remarks

Remarks Prepared For

Third Inertial Confinement Systems and Applications Colloquium

held at University of Wisconsin, Madison, Wisconsin

November 9-11, 1987

Sheldon L. Kahalas

Office of Inertial Fusion

U. S. Department of Energy

Washington, D.C. 20545

Introduction

Good Morning. I would like to welcome you to the third ICF Systems and Applications Colloquium on behalf of the United States Department of Energy. This meeting is devoted to Advanced Drivers for Commercial Applications. We in the U.S. view commercial applications for energy as a long-term goal of our program as well as of the international program. So I am happy to welcome you here in Madison today. It is particularly opportune to hold this colloquium now, since it serves to underscore our continuing interest and commitment to the long-term energy goal.

I'd like to start by giving you my perspective of the current status of the U. S. inertial fusion program.

11/5/87

The inertial fusion program in the United States has undergone profound changes over the years, while maintaining a remarkable degree of stability and continuity of purpose. In the early seventies, the program was recognized to have two goals, near-term military and long-term civilian power applications. With the more recent perception that oil is plentiful, the present Administration has tended to place less emphasis on government development of new energy sources. But even though the program has recently been justified more because of its military applications, the goals of inertial fusion have not changed and the long-term energy goal continues to be a primary consideration. Furthermore, it is recognized that potential spinoffs may have applicability over a wide range of technology areas, both military and civilian. These include, for instance, laboratory x-ray lasers, which could have biological applications, and development of diagnostic instrumentation to measure phenomena occurring on very short timescales over very small distances.

Technical Achievements of the Program

The inertial fusion program has made excellent progress recently. Centurion/ Halite, a classified program, is a theoretical and experimental effort to investigate the design characteristics of high-performance ICF targets. This program was given highest priority in the 1986 National Academy of Sciences review of the inertial fusion program that took place under the chairmanship of Will Happer. I can say that excellent progress recently has been made, that could even be described as "historical" in accomplishment, and is thought by some to mark a turning point in demonstrating target behavior. Because this program is classified, I am unable to give you any details.

The glass laser experimental program using the NOVA laser has made significant progress. Its primary approach is with hohlraum targets. 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. While a great deal of work remains, no recognized process has been found that prevents laser fusion from working for 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 make PBFA II operate routinely. 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 Sandia researchers can now concentrate on the most important pulsed power issues, power concentration and beam focusing. We are not yet ready to undertake target compression experiments on PBFA II. We expect that it will probably take a few years to arrive at that point.

The University of Rochester and the Naval Research Laboratory are major participants in the direct drive program. 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 into the behavior of Rayleigh-Taylor instabilities that suggests the possibility of higher target performance using high aspect ratio (thin shells) targets 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, the Aurora laser, at Los Alamos, is to deliver focusable 5 ns, multi-kilojoule, 248 nanometer pulses on target. Aurora leads 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 incorporate induced spatial incoherence (ISI) techniques 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.

Future Direction of the Program - Laboratory Microfusion Capability

With the progress in target physics that has been made, program emphasis is shifting to longer-term planning for our next facility, currently called the Laboratory Microfusion Facility, or LMF for short. From the perspective of the long-term energy goal of a prototype reactor, the LMF is an intermediate facility. 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 the weapons program, for example, from experiments on materials at high density and temperature. There will also be benefits to the civilian energy program from experiments to make high gain targets work. The LMF is envisioned as a 5 to 10 megajoule, high gain, single shot facility, capable of about one shot per day. Maximum yield would be about 1000 megajoules. It is desirable that the driver characteristics be flexible, with a wide range of pulse lengths (3 to 10 nanoseconds) and a variety of pulse shapes and pulse energies. The goal is to build the driver at a cost less than $200/joule. Our new program planning is looking 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 planning, 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 was 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 target physics progress 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 pace of driver development, because in this past year the inertial fusion program has added enormously to the knowledge base that will show 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.

Session 1: Laser Fusion

1. Howard Lowdermilk (LLNL)
2. Dave Harris (LANL)
3. Michel Andre (Limeil)
4. Yasukazu Izawa (Osaka)
5. Steve Obenschain (NRL)

LLNL Viewpoint on Laser Drivers for ICF Commercial Power Reactors

W. Howard Lowdermilk

3rd ICF Systems and Applications Colloquium

Nov 9–11, 1987

University of Wisconsin

CW-1004-U-3740-1

The overriding requirement for a laser driver for ICF commercial power generation is working system efficiency $\eta_S > 10\%$

Required to:

1. Maintain core gain $\eta_S G > 10$ for reasonable pellet gain $G \sim 100$ (keeps recirculating power fraction <25%)

2. Keep driver cost reasonable (30-60 $/W)

3. Compete with heavy ion driver ($15\% < \eta_S < 40\%$)

60-00-1187-2573
CW-1004-U-3740-2

A successful, laser reactor driver must satisfy a number of requirements

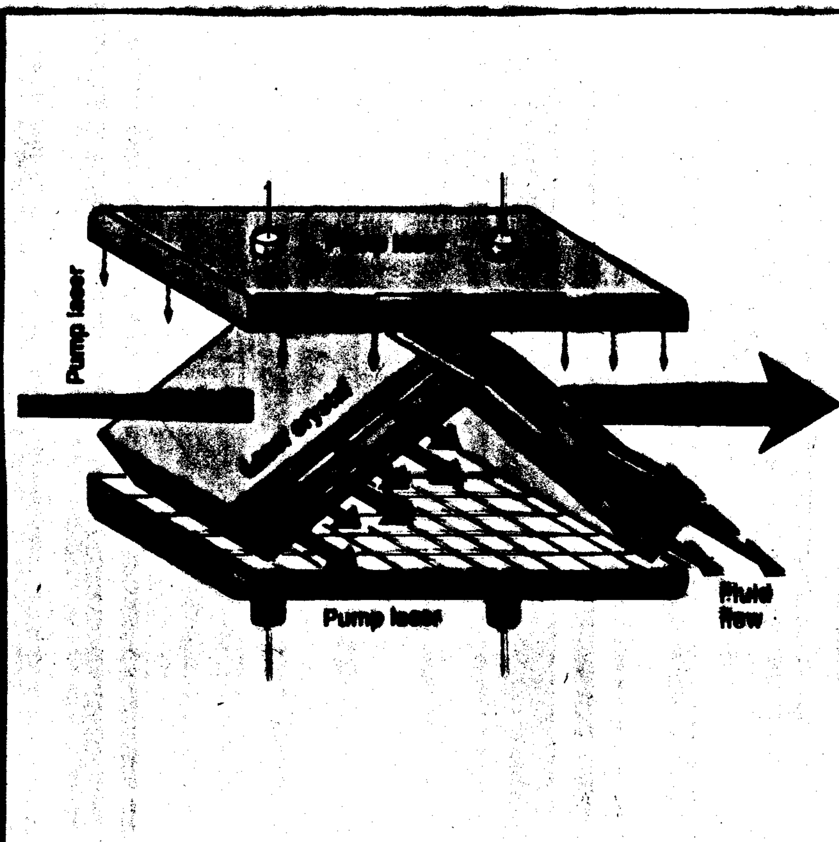
Efficiency	$\geq$10%
Pulse properties	
• Energy	3–6 MJ
• PRF	3–10 Hz
• Duration	5–10 ns
• Peak power	~500 TW
• Shape	Complex, ~20:1 contrast
Wavelength	Fixed, $\lambda < 500$ nm
Cost goal	30–60 $/W 150–300 $/J

No current laser will meet the goal of efficiency >10% with necessary pulse format for ICF reactor driver

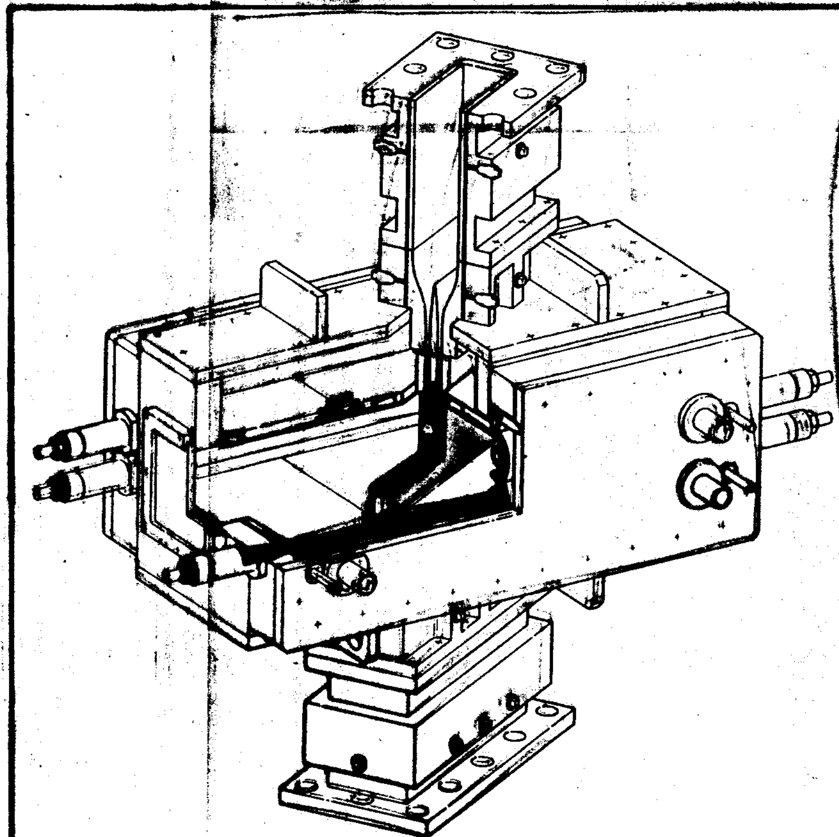
- **KrF** — Practical operating efficiency ~5–6%.
- **Solid State** — Ability to meet efficiency, power and beam quality requirements appears to us to be technically assured. The issue is cost.
- **IFEL** — Potential average power and efficiency (>20%) are promising. To be useful, requires practical method to accumulate energy and deliver at high peak power (~1000 TW)

Solid state lasers in the face pumped, gas cooled slab (GCS) geometry can achieve high average power with high beam quality

GCS concept



GCS testbed



Heat transport and medium optical quality currently under study (DARPA supported)

60-00-1187-2576
CW-1004-U-3740-5

The surface heat flux is surprisingly low in a solid state fusion driver amplifier

Gas flow-cooling channel
1–2 atm He;
M = 0.3

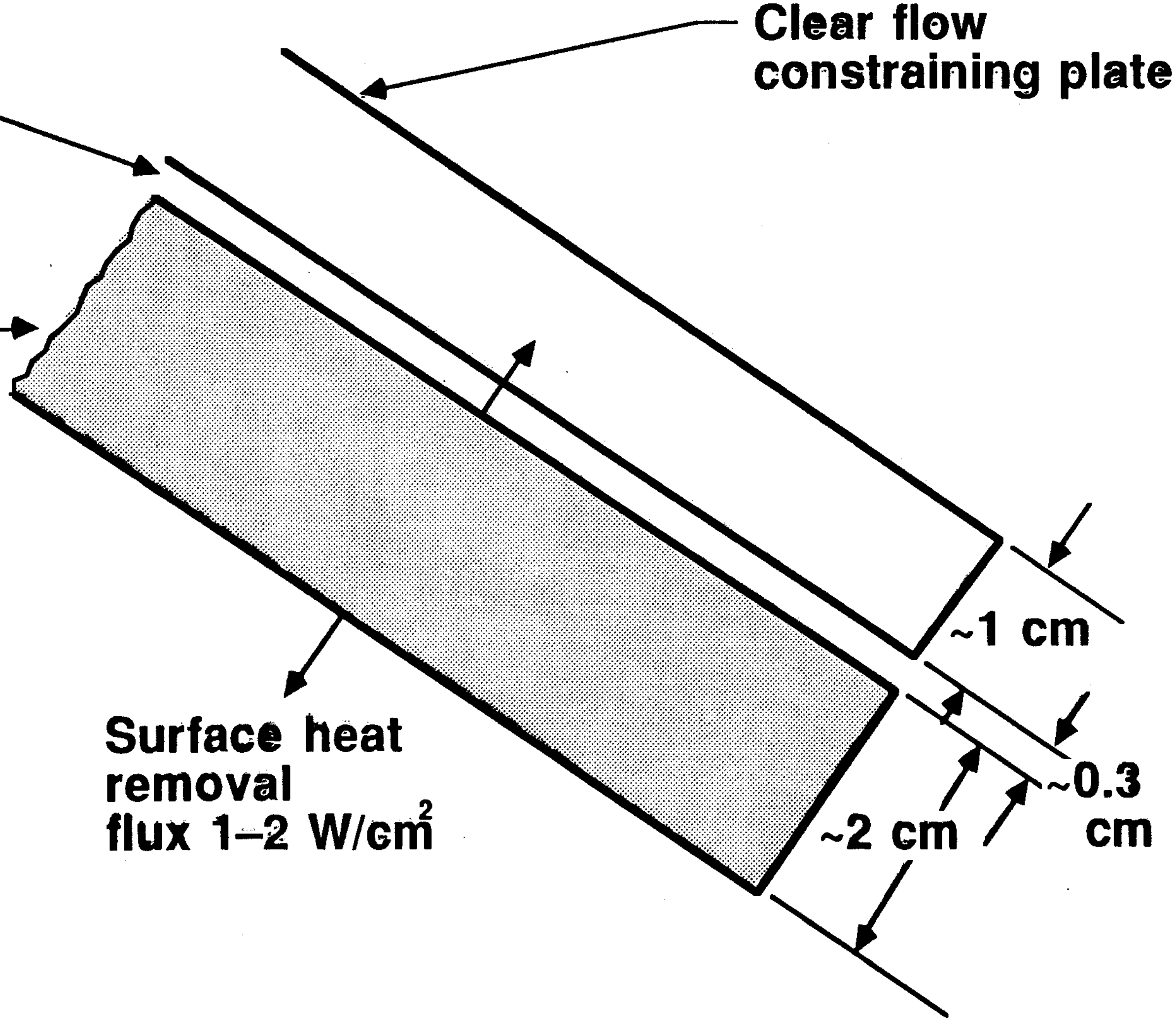
Gain medium

Optical energy density ~0.6 J/cc

Optical power density 3–6 W/cc

Waste heat density 1–2 W/cc

Repetition rate 5–10 Hz



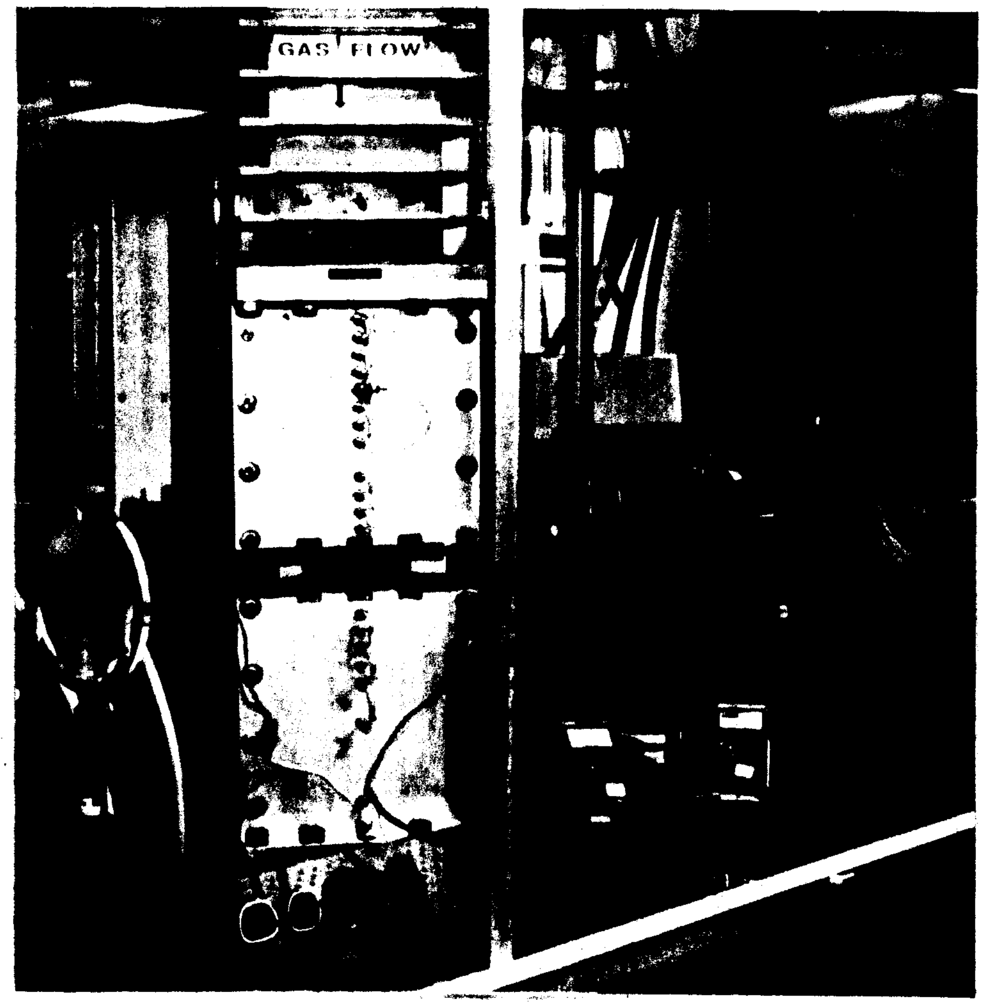
02-02-1087-2162
LD-002-2315-U-P1

GCS optical-beam gas-flow effects have been measured

- Wide range of conditions

Heat flux	→ 5 W/cm^2
Mach No.	→ 0.7
Channel width	→ 6 mm
Channel wedge	→ 0.05°
Pressure	→ 2 atm

- Quantitative scatter loss using Schlieren techniques



02-02-1087-2161

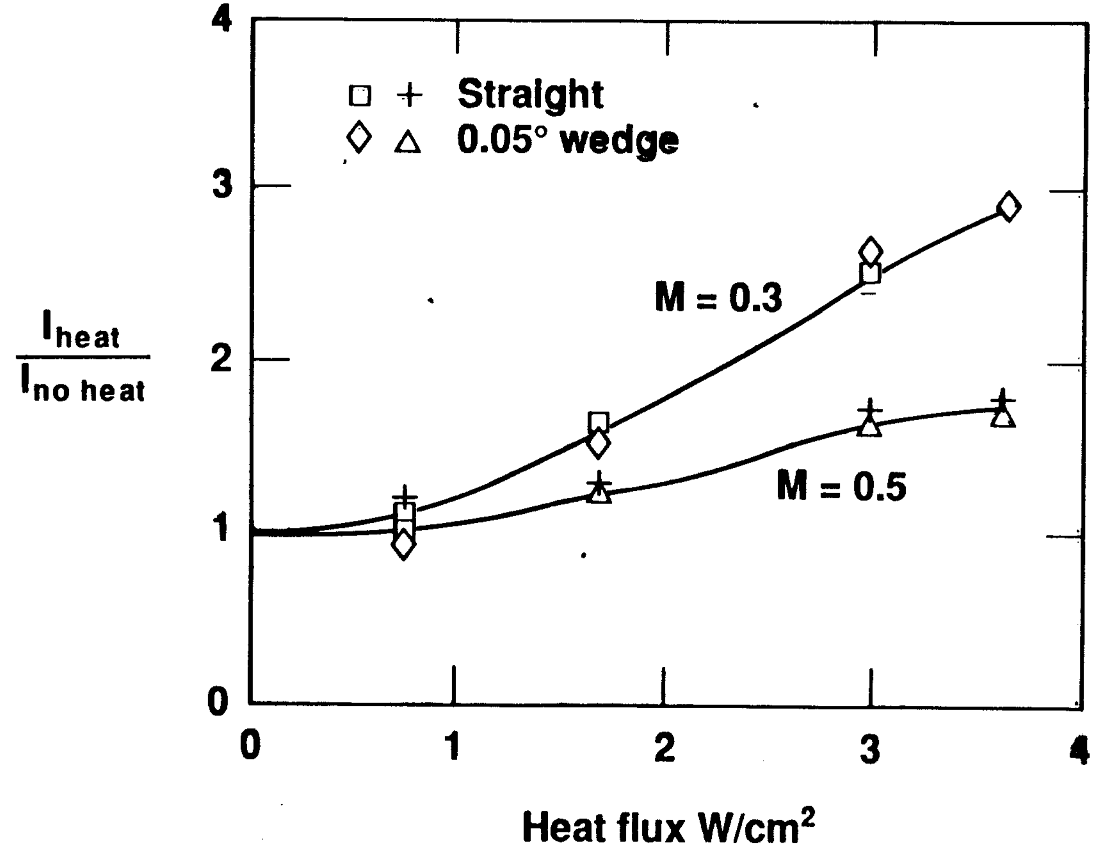
AH-089-U-2316-1

Turbulent gas-cooling effects on optical beam quality have been mapped over a wide range of conditions

Typical raw data

Heat flux 3 W/cm²
Mach No. 0.4
2 atm nitrogen
Channel width 3 mm

Channel width = 3 mm



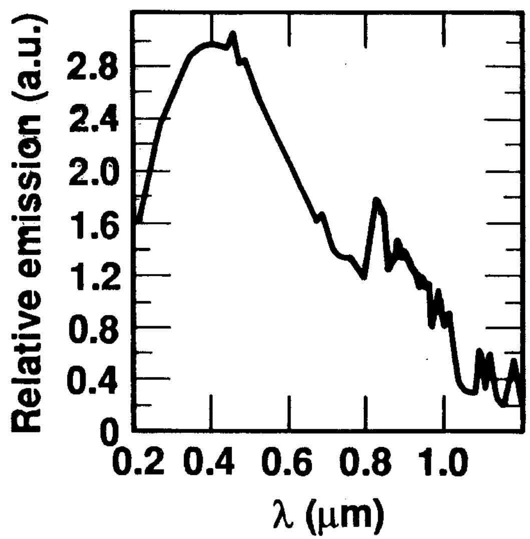
$I_{no\ heat} \lesssim 0.05\%$

02-02-1087-2158

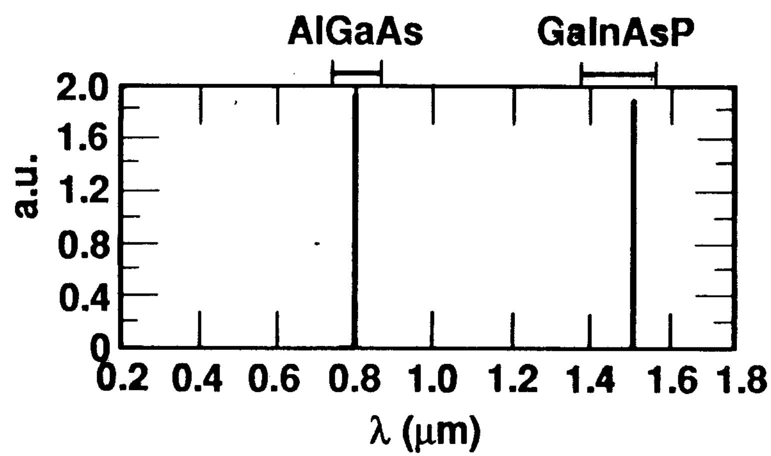
AH-079-U-2266-5

LDA and flashlamp pump sources are significantly different

Xenon flashlamp



Laser diode arrays



Typical Values	Flashlamp	Laser Diode Arrays
Emission solid angle	$4\pi\ \Omega$	$< \pi\ \Omega$
Total flux	60 kW/cm^2	3 kW/cm^2
Spectral flux	2.5 W/cm^2-nm	500 W/cm^2-nm
Mean wavelength	550 nm	800; 1550 nm
Efficiency	75%	40–50%
Cost unit energy	low	Very high

02-02-0987-2099
CW-1038-U-2147-3

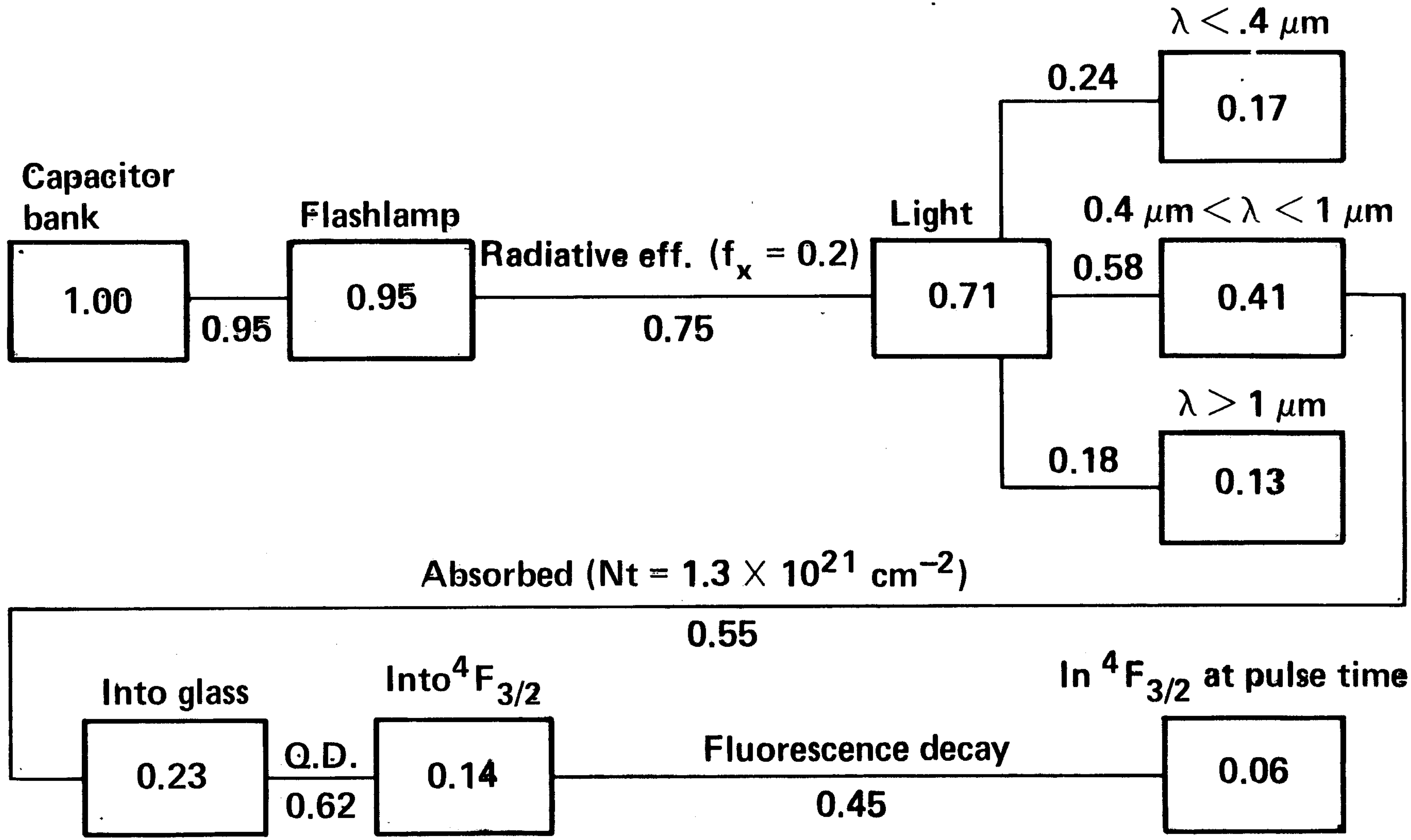
This advanced Nd:glass amplifier stores energy at above 6% efficiency – 2 1/2 fold higher than Nova

70-00-1186-4694B

10/87

AH-101-U-2329-5

Pumping efficiency of Nd-glass



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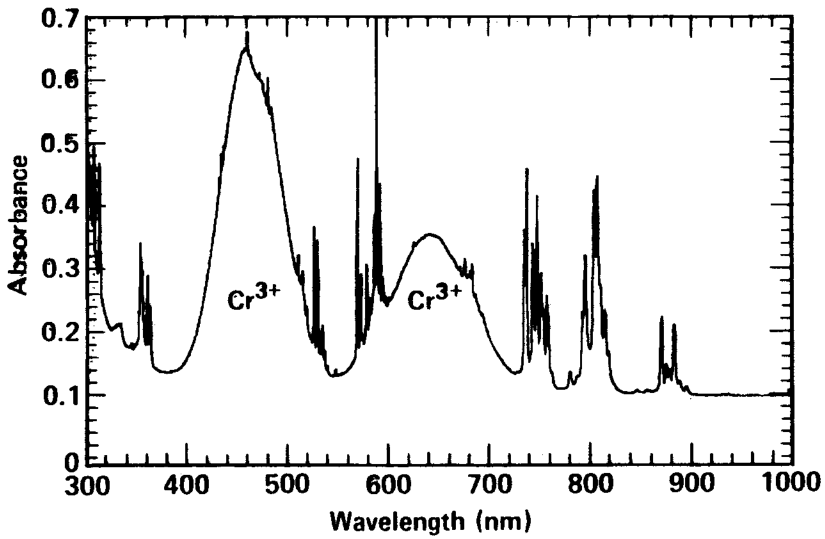
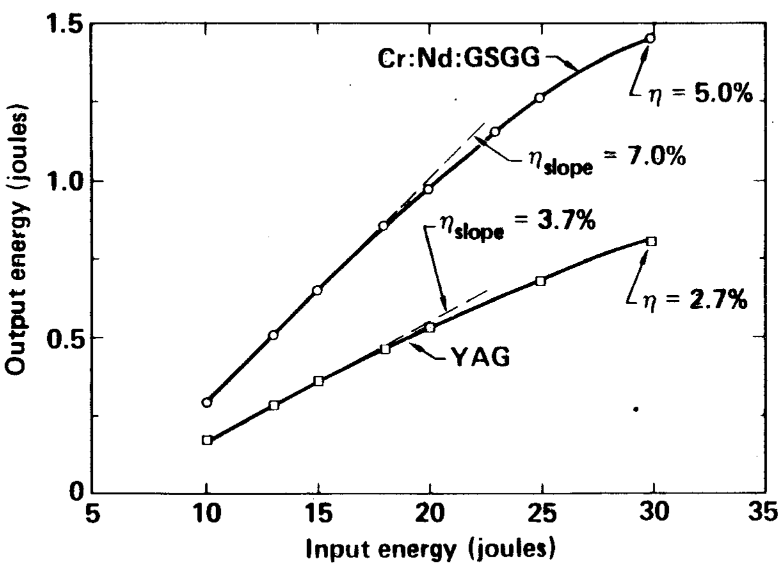
Cr → Nd sensitization in GSGG increases laser efficiency by 2X compared to Nd:YAG



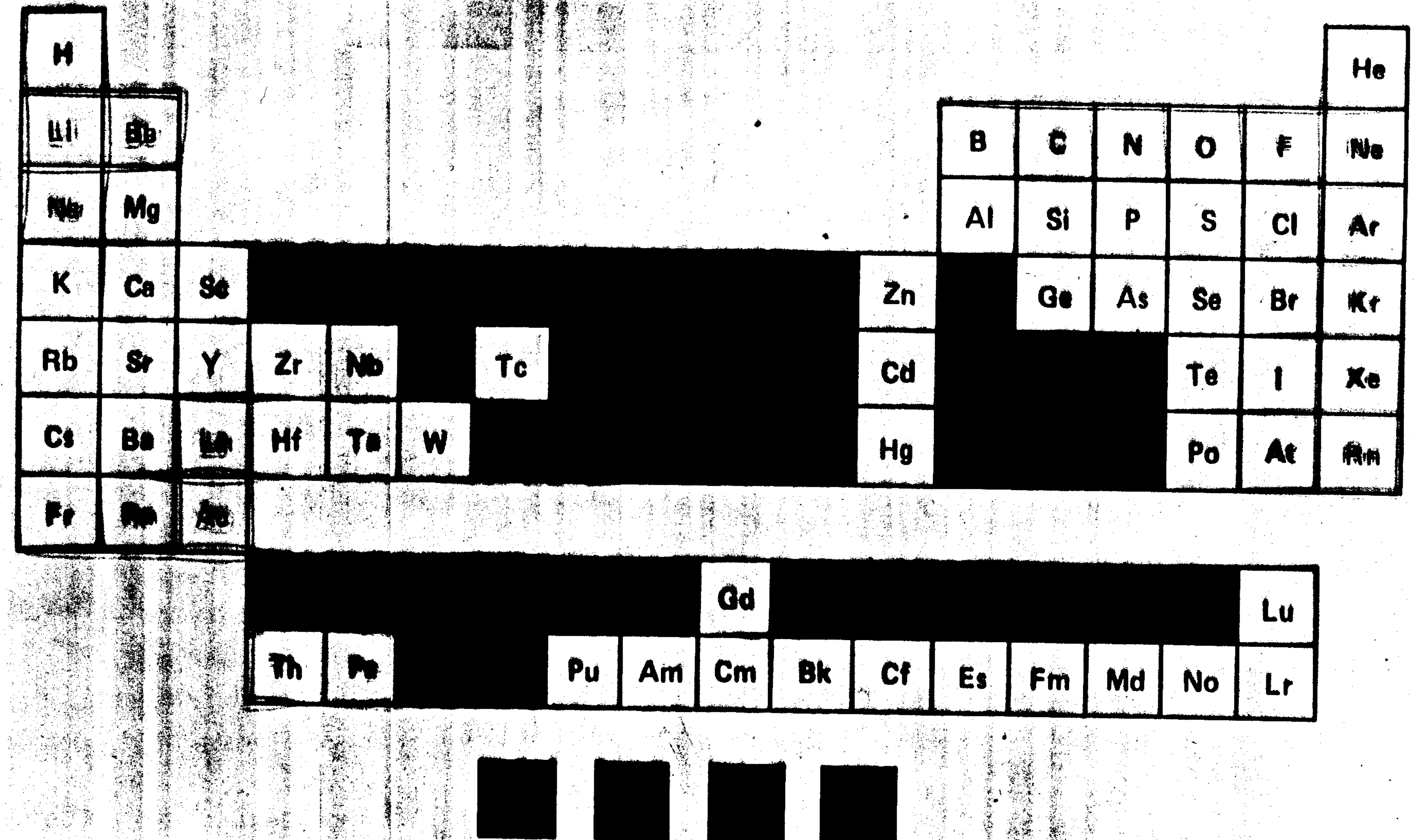


- This material illustrates the desired effect, but is not useful for fusion
- n_2 of GSGG is ~5X too large (8×10^{-13} esu)
- Stimulated emission cross-section is ~5X too large (1.3×10^{-19} cm^2)
- Fluorescence lifetime is ~5X too short (280 μsec)

Response:

- Seek Cr/Nd and other sensitizer/activator pairs in low-n_2 fluorides and phosphates

Probable activator and/or sensitizer ions



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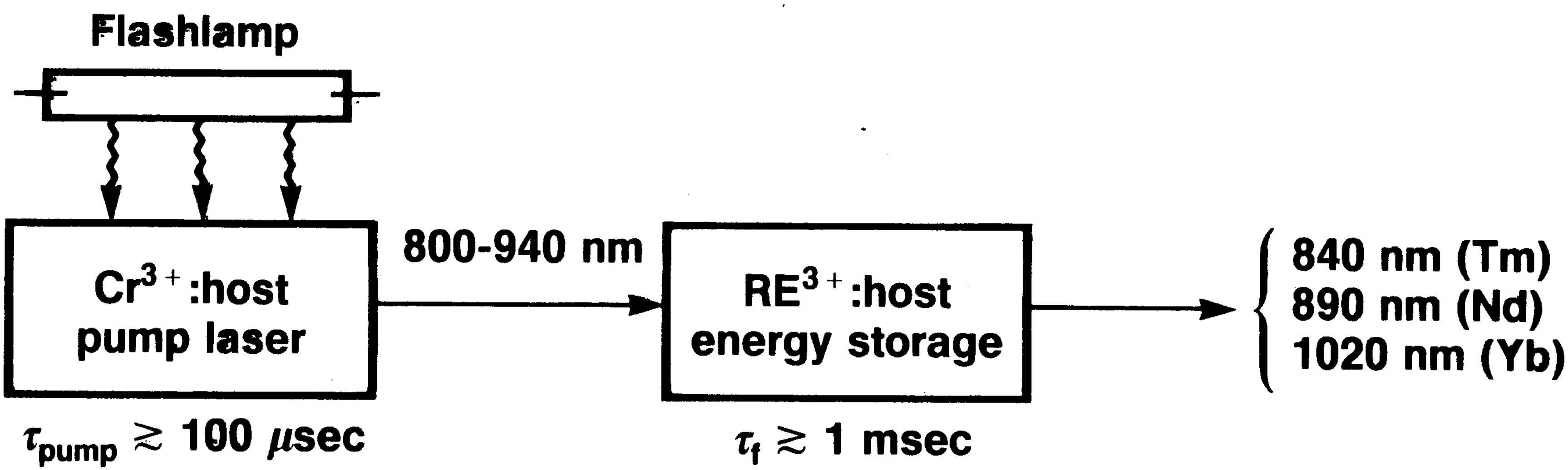
Laser pumped lasers are potential, high energy storage fusion lasers

Example



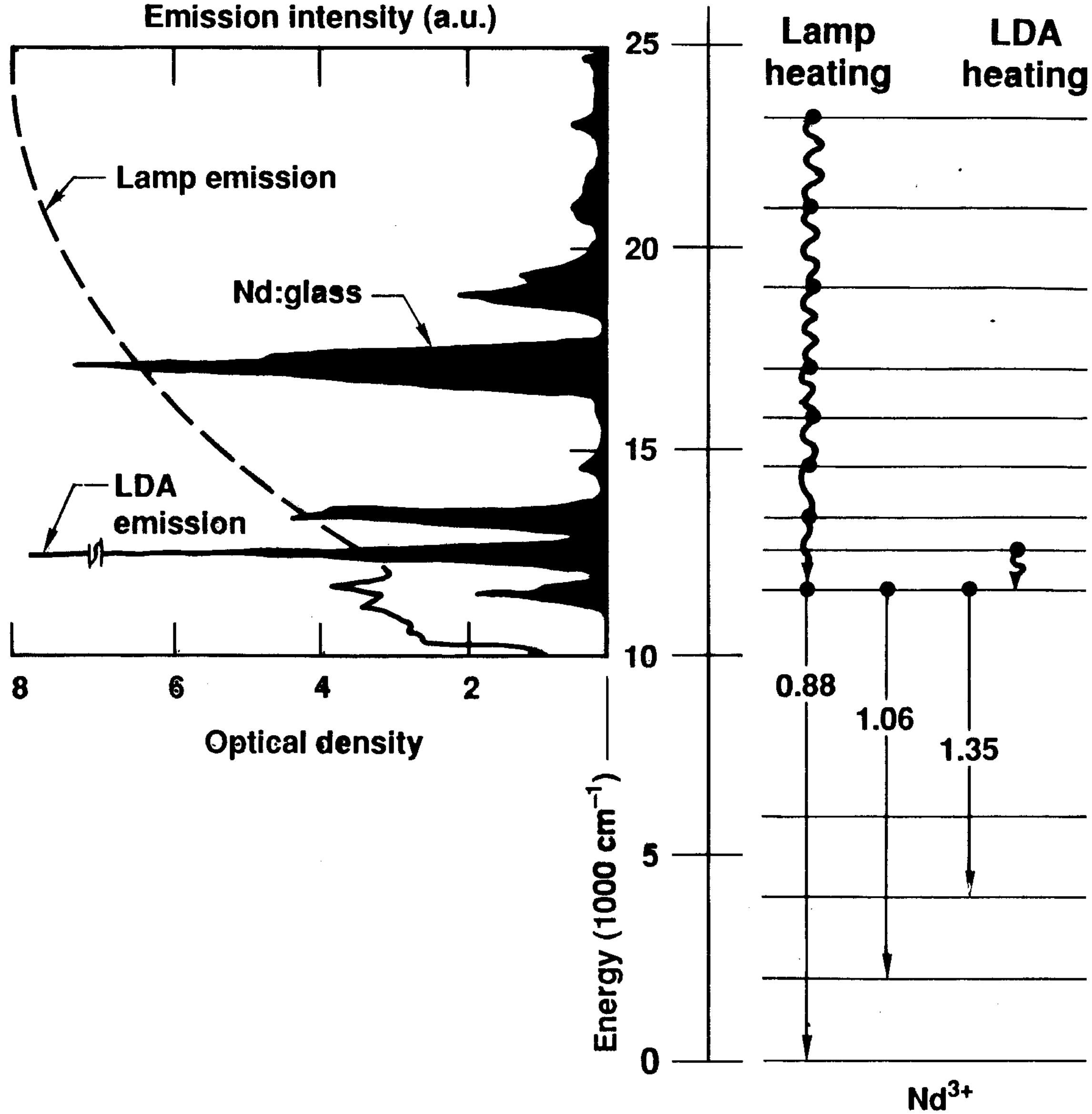
$$\eta_{laser} = \eta_{pump}\ \eta_{trans}\ \eta_{abs}\ \eta_{qd}\ \eta_{fluor}\ \eta_{ext}\ \eta_{fill}$$

$$0.042 = (0.10)\ (0.90)\ (0.90)\ (0.90)\ (0.90)\ (0.80)\ (0.80)$$

02-02-0587-1079A

6/87

LDAs have significant advantages as Nd laser pumps



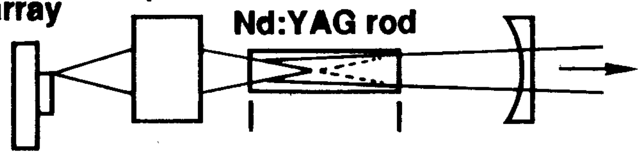
Major Advantages
• High optical coupling
• High spectral coupling
• Low lattice heating
• Use of gain materials with low Nd doping (low self-quenching)
• Potential for efficient 3-level laser action (saturation pumping)
• Anti-Stokes lasers

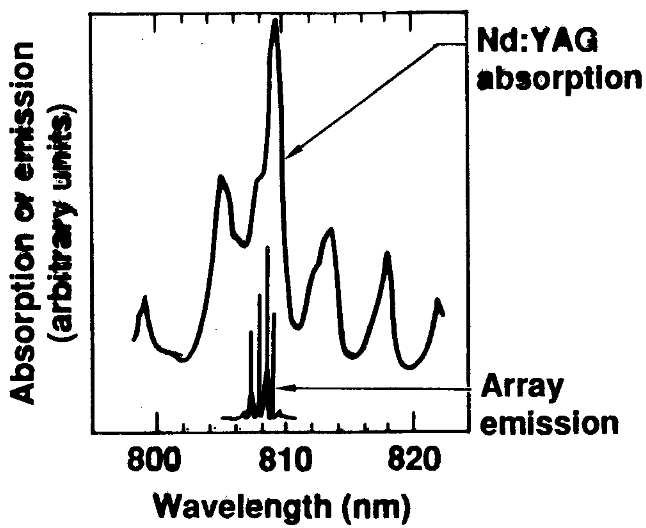
02-02-0987-2100

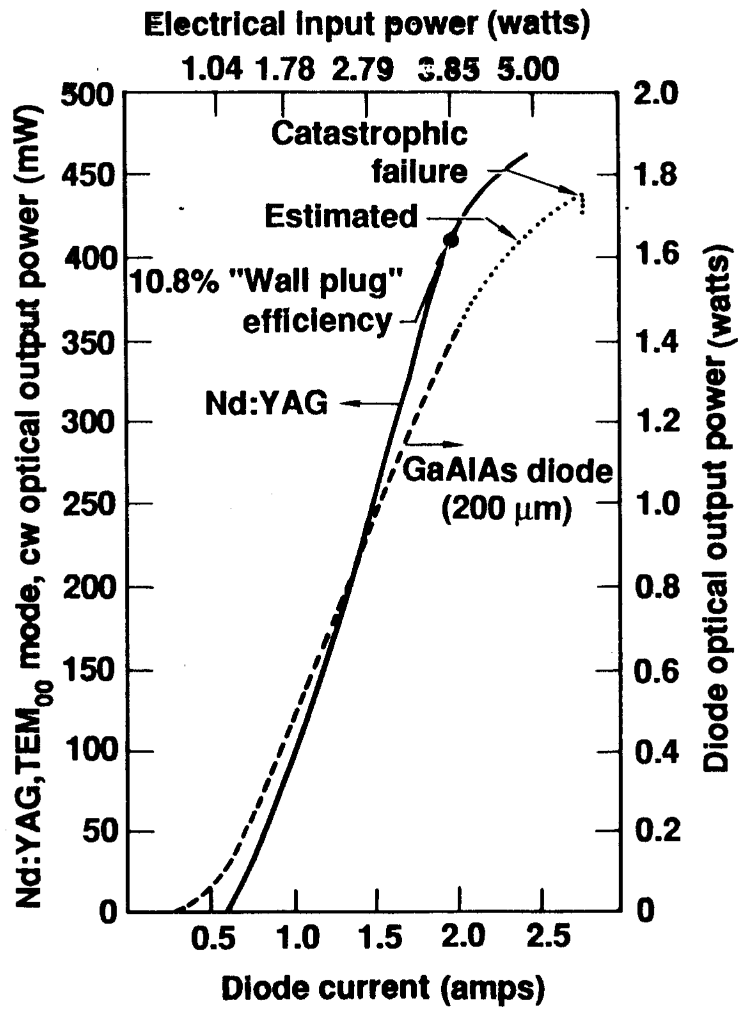
"Wall-plug" efficiency > 10% has been demonstrated

Data source: D. R. Scifres, et al., Spectra Diode Labs., unpublished

Nd:YAG end-pumped by an AlGaAs laser diode array







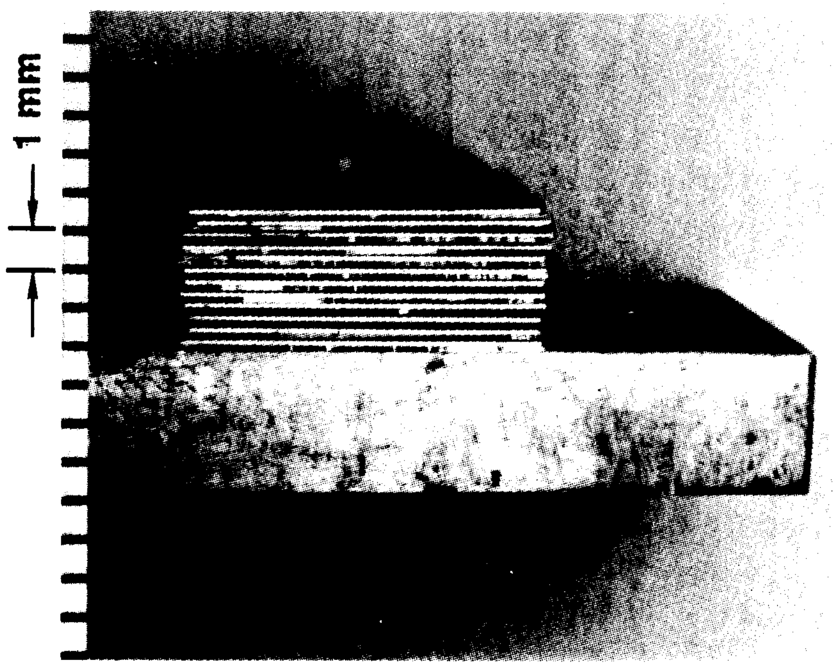
02-02-0987-2102

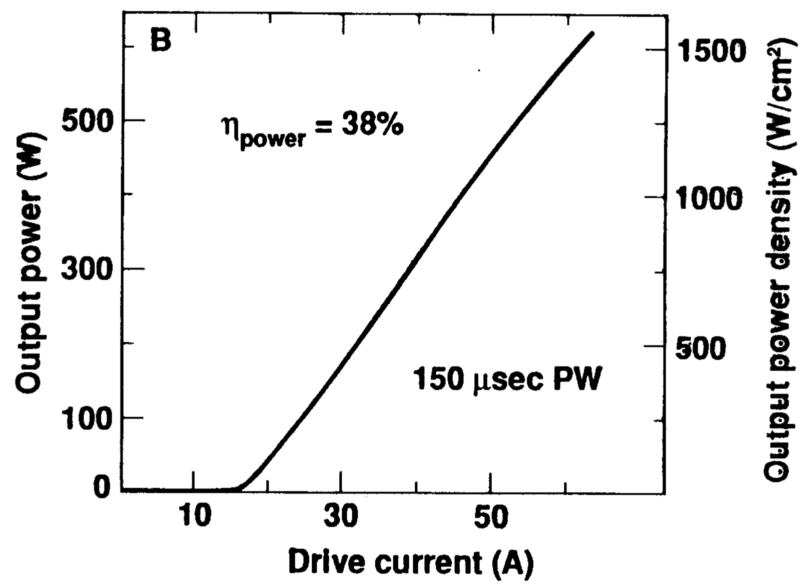
AH-087-U-2314-1

Spectra Diode Labs—2-D laser diode array*

*P. Cross, et al., Science, 237, 1305 (1987).

12 bars — 12,000 emitters





02-02-0987-2116

PY-1035-U-2145-2

Conclusions – solid state fusion drivers

A solid state fusion driver with appropriate wavelength, efficiency, average-power and beam quality appears to be technically feasible.

- The GCS geometry solves the waste heat issue.
- The diode array pump solves the efficiency issue.

Our greatest concern is about the cost of pump arrays. This concern can be resolved by:

- Mass manufacturing in a fusion power economy.
- Development of long-storage (τ_f >> msec) gain materials that permit high duty factor operation of pump arrays.

02-02-1087-2163
AH-131-U-3843-1

LANL VIEW OF COMMERCIAL DRIVERS FOR LASER-DRIVEN REACTORS

D. B. Harris, L. A. Rosocha, and D. C. Cartwright

Los Alamos National Laboratory

3rd ICF Systems and Applications Colloquium

Madison, Wisconsin

9-11 November 1987

Los Alamos

THERE CURRENTLY APPEARS TO BE A TOTAL OF SIX LASER CANDIDATES FOR COMMERCIAL APPLICATIONS

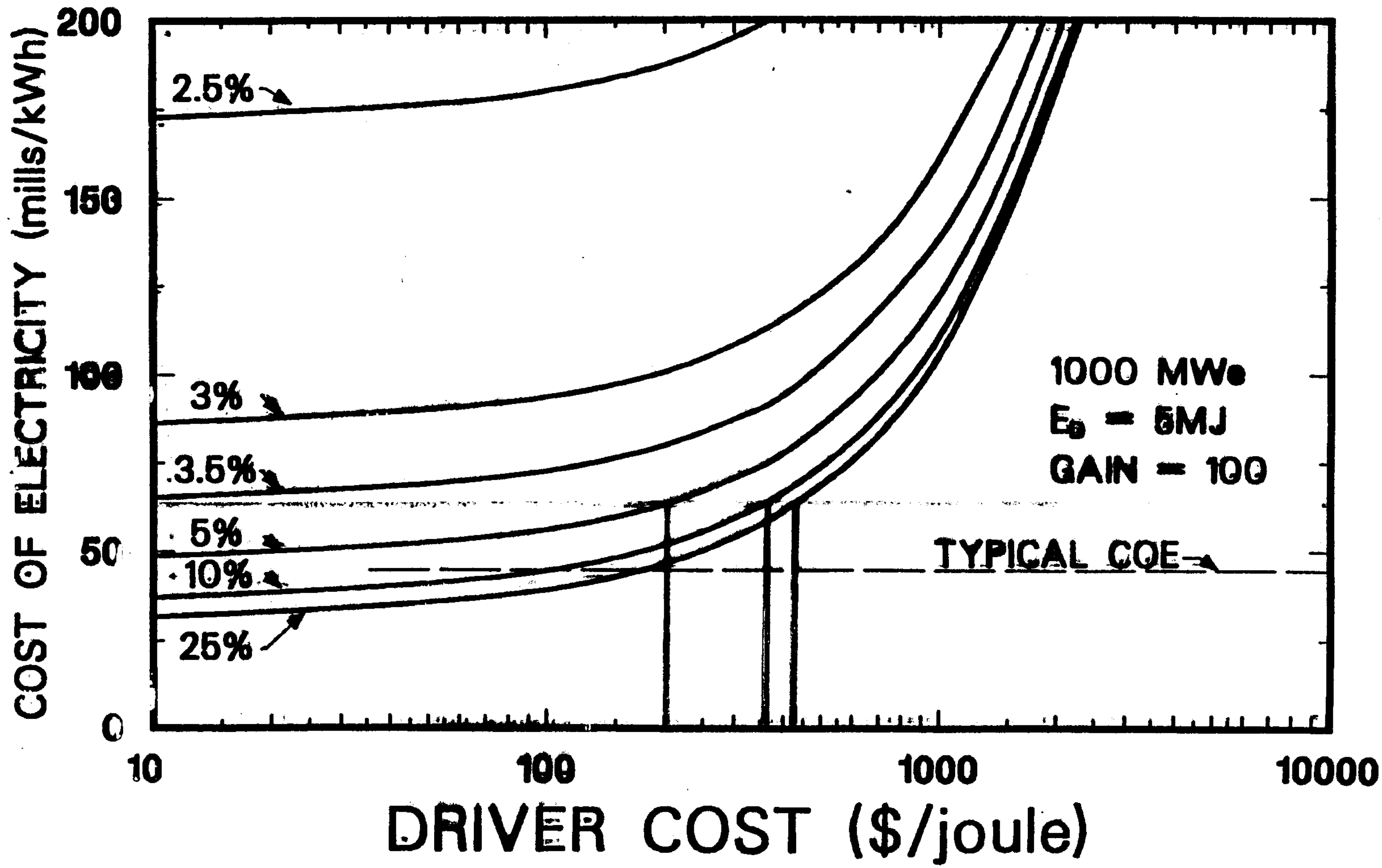
- Excimers (KrF, etc.)
- Advanced solid state
- Free electron lasers
- Iodine
- CO_2
- Chemical lasers (HF, DF)

COMMERCIAL ICF DRIVERS MUST *SIMULTANEOUSLY* SATISFY *ALL* OF THE FOLLOWING REQUIREMENTS

- High efficiency
- Low cost
- Efficient target coupling
- High pulse repetition rates
- Large pulse energies on target
- Reliability and robustness

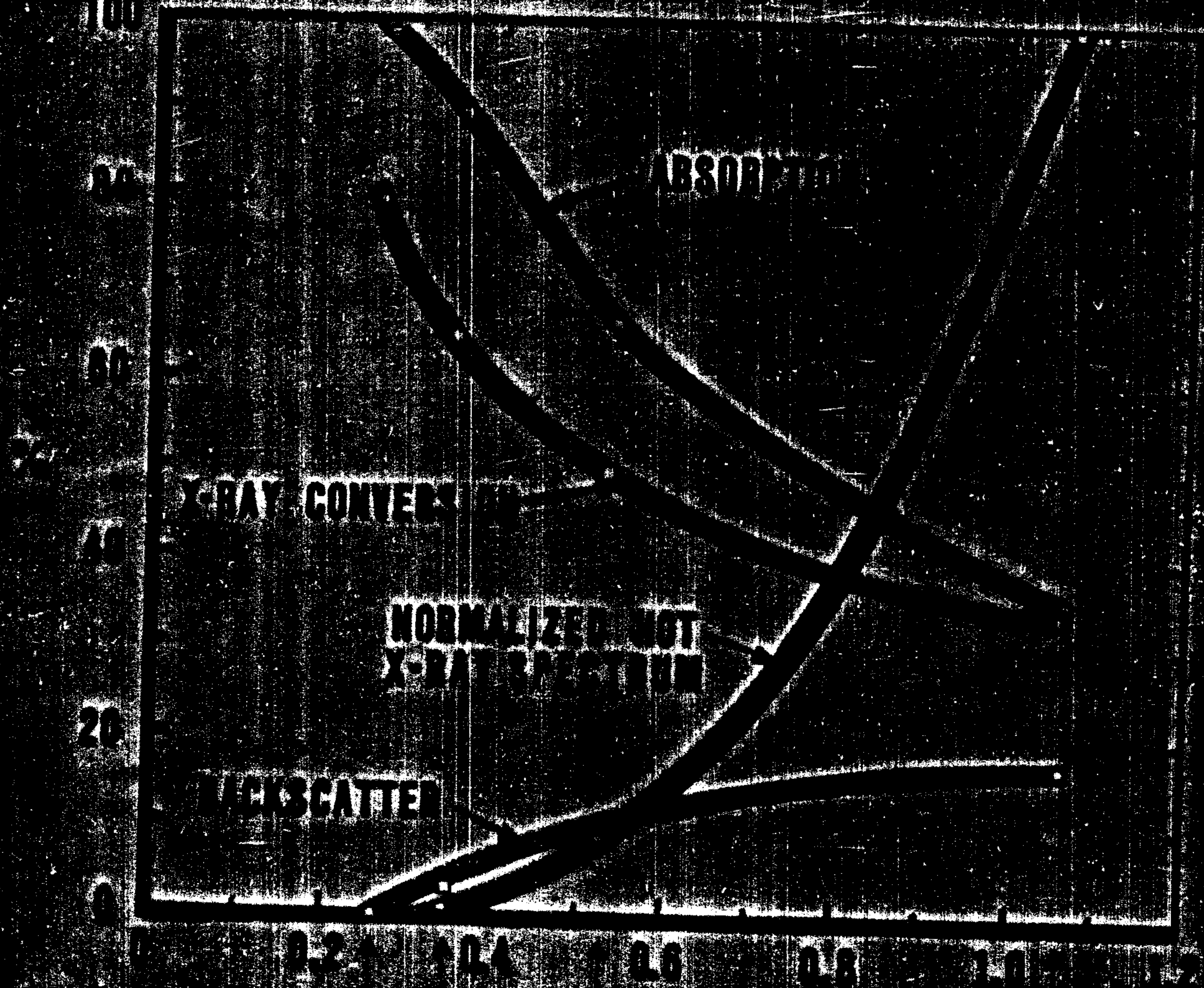
Los Alamos

LOW DRIVER COST AND HIGH DRIVER EFFICIENCIES CAN RESULT IN A COMPETITIVE COE



Los Alamos

LASER PLASMA COUPLING
AS THE LASER
IS DECREASED



Los Alamos

REMARKS ON "VIEWS" VIEWGRAPH:

- OPINIONS ON "POTENTIAL" - DOES NOT HAVE TO BE DEMONSTRATED
- COST ASSUMES AT REP RATE & HIGH EFFICIENCY
- A "+" MEANS LOOKS PROMISING
- A "?" MEANS QUESTIONABLE OR UNKNOWN
- A "-" LOOKS DAMN HARD OR FATAL FLAW
- ANY FATAL FLAW WILL <u>ELIMINATE</u> THAT DRIVER!

LOS ALAMOS VIEWS ON THE POTENTIAL FOR DIFFERENT DRIVER CANDIDATES

	EFFIC.	COST	TARGET COUPLE	REP RATE	ENERGY SCALE	RELIAB. ROBUS.
KrF	+	?	+	+	+	?
S.S. vitr / cryst	? / +	- / -	+ / +	- / +	+ / -	? / ?
FEL	+	-	-	+	-	+
Iodine	?	?	+	?	+	?
CO_2	+	+	-	+	+	+
HF	?	?	-	+	+	?

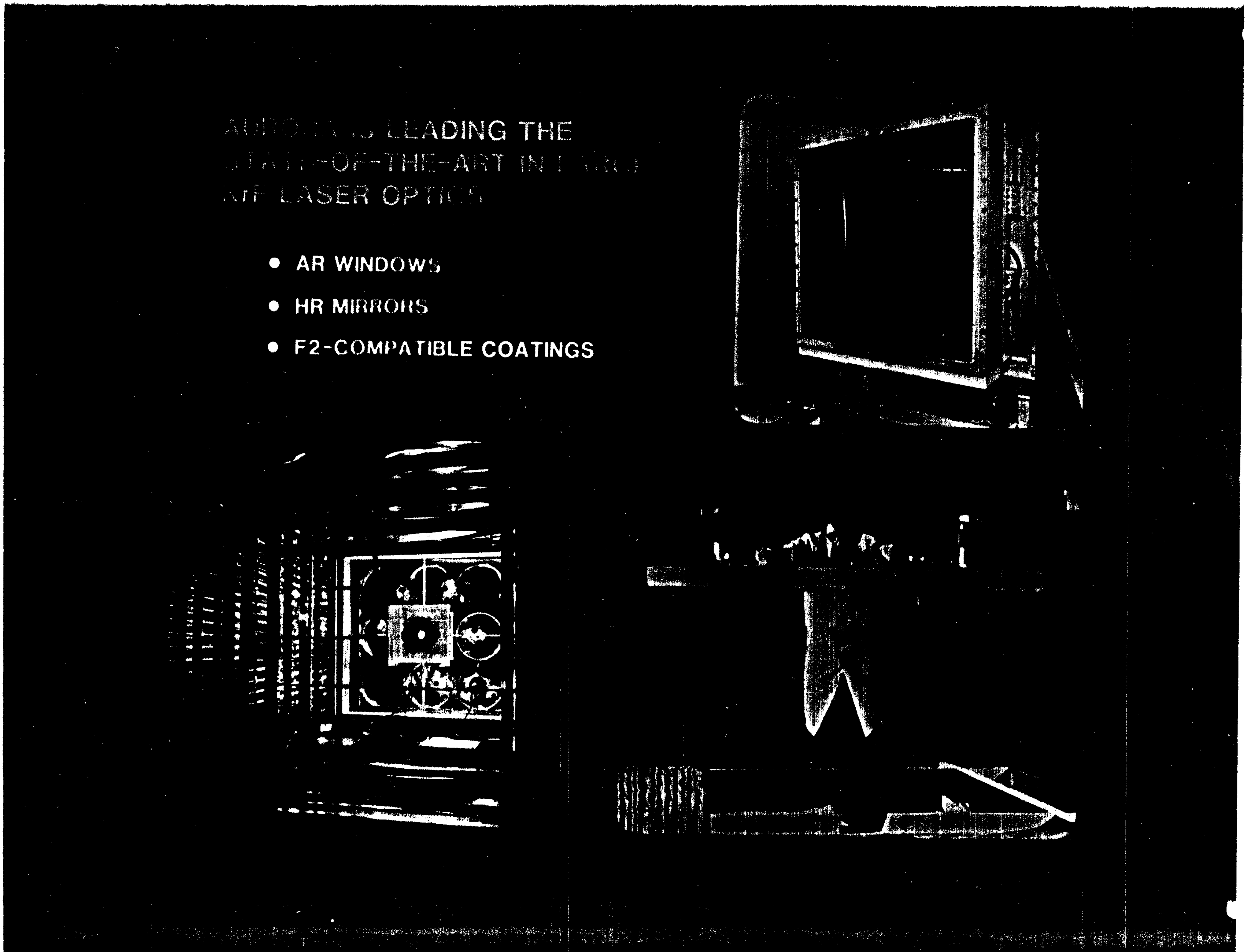
Los Alamos

LOS ALAMOS HAS A BALANCED PROGRAM TO DEVELOP KrF LASERS FOR INERTIAL-FUSION APPLICATIONS

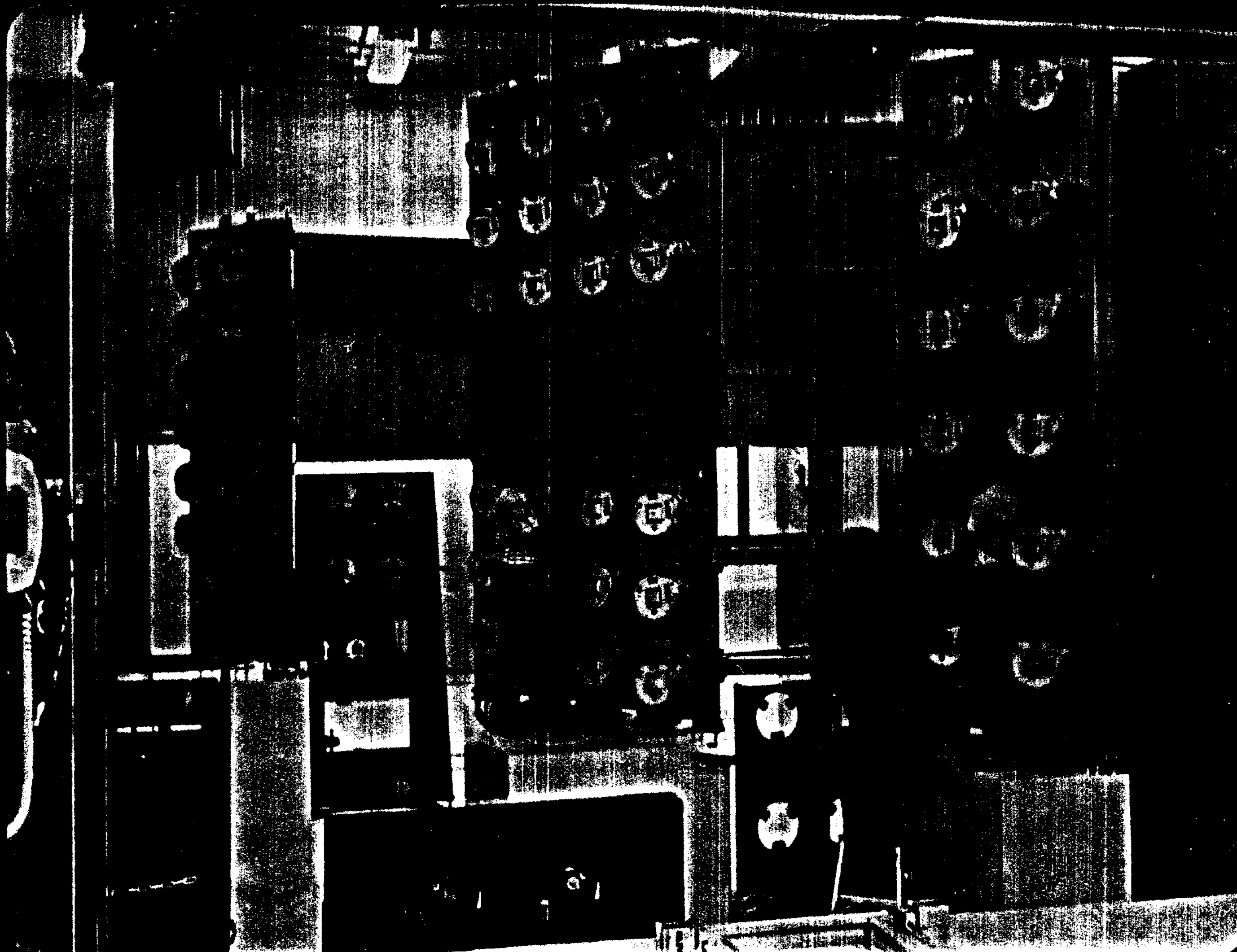
- CAPSULE PHYSICS
- LASER-MATTER INTERACTIONS
- DRIVER DEVELOPMENT

THE LOS ALAMOS DRIVER DEVELOPMENT PROGRAM ELEMENTS

- PROTOTYPICAL SYSTEM DEMONSTRATION (AURORA)
  - Scalable amplifier module
  - Optical multiplexing
  - Target-qualified optical beam
- KrF TECHNOLOGY DEVELOPMENT
  - Improved optical performance
  - Kinetics modeling/experiments
  - Pulsed power development
  - Alignment, controls, and diagnostics
- CONCEPTUAL DESIGN DEVELOPMENT
  - Conceptual designs/scaling & tradeoff studies
  - Cost estimates (capital and O&M)

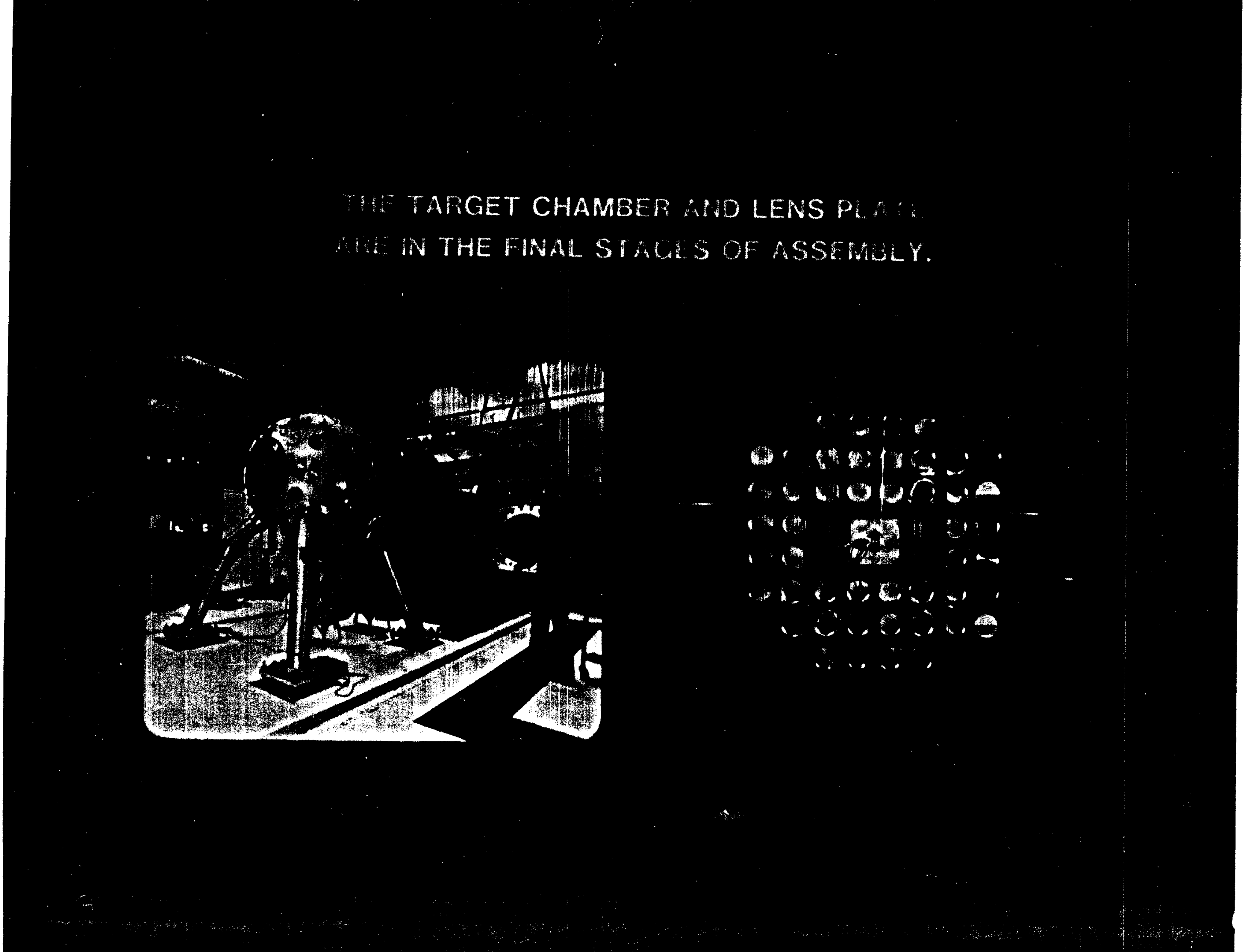

LEADING THE
OF-THE-ART IN
LASER
• AR WINDOWS
• HR MIRRORS
• F2-COMPATIBLE COATINGS

THE AIMING MIRRORS STAND THAT DIRECTS
BEAMS TO THE SET PLANE HAS BEEN INSTALLED



Los Alamos

CLS-VG 2943


THE TARGET CHAMBER AND LENS PLA
ARE IN THE FINAL STAGES OF ASSEMBLY.

AURORA STATUS - 9 NOV 87

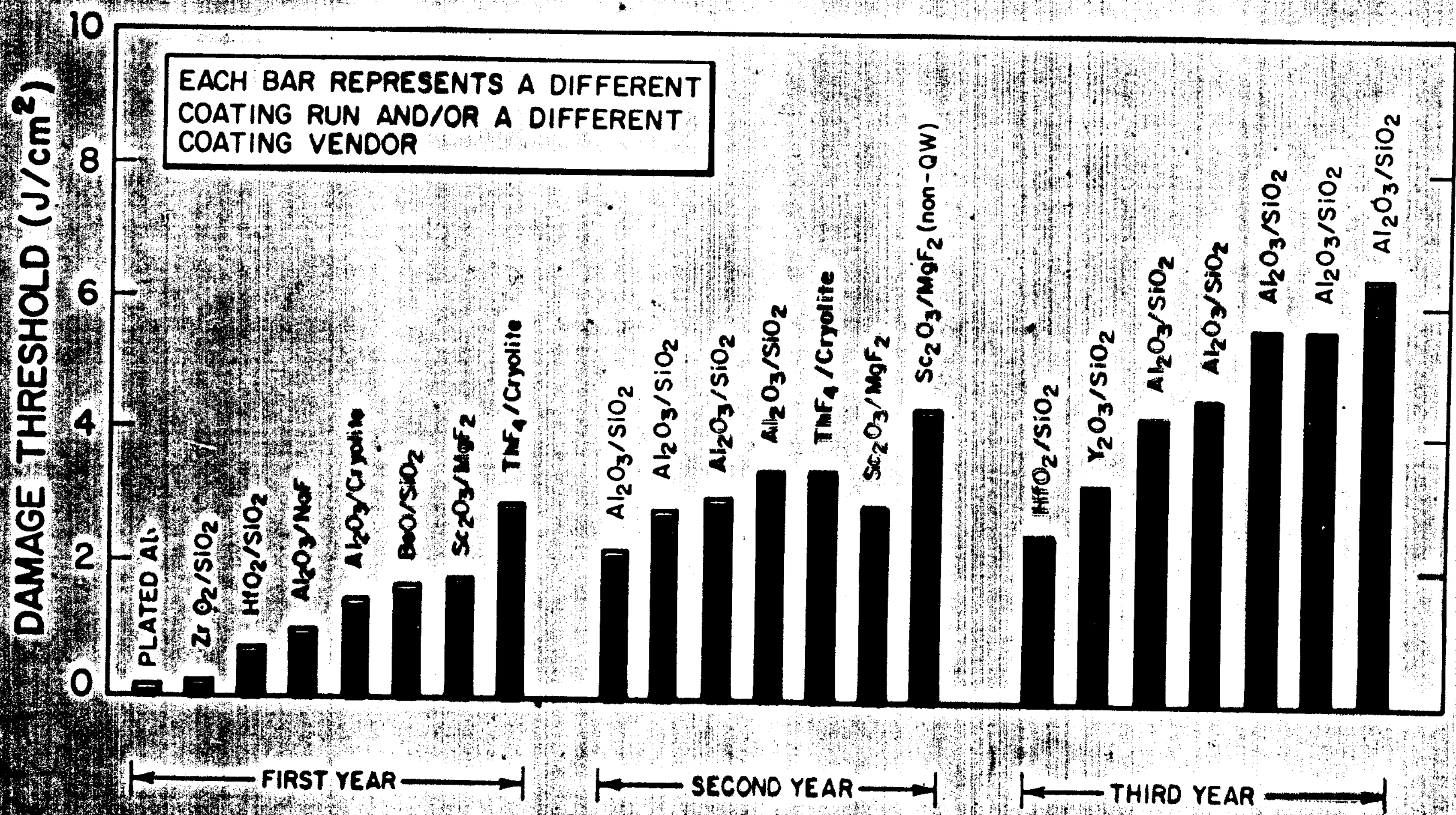
- 96 beams multiplexed, propagated, and amplified from front end through intermediate amplifier

- First energy delivered to target plane expected Dec. 87

- Multikilojoules on target expected mid-88

Los Alamos

OPTIMIZATION OF 248 nm REFLECTORS



Los Alamos

RECENT EXPERIMENTAL RESULTS CONFIRM HIGH INTRINSIC* EFFICIENCY OF KrF LASERS

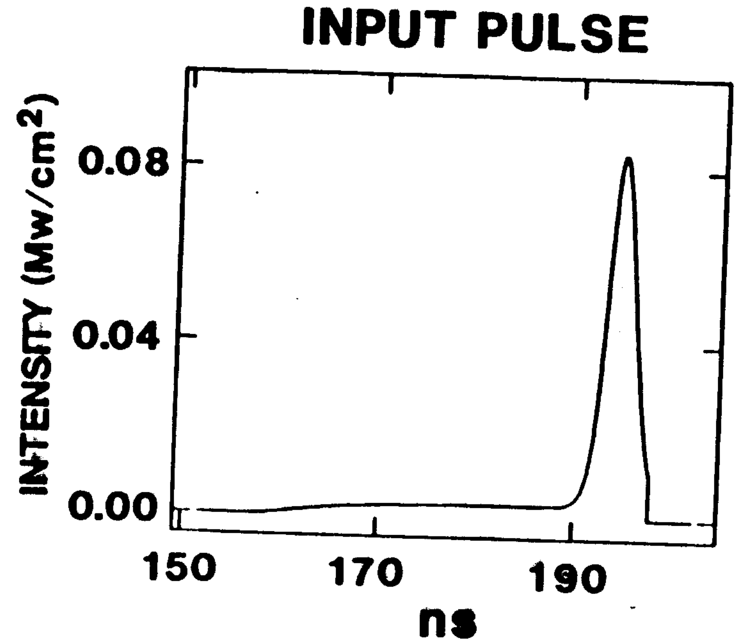
Under contract to LANL, Spectra Technology, Inc., recently measured an intrinsic efficiency* of 13 ±1% at pump rates comparable to AURORA lasers.

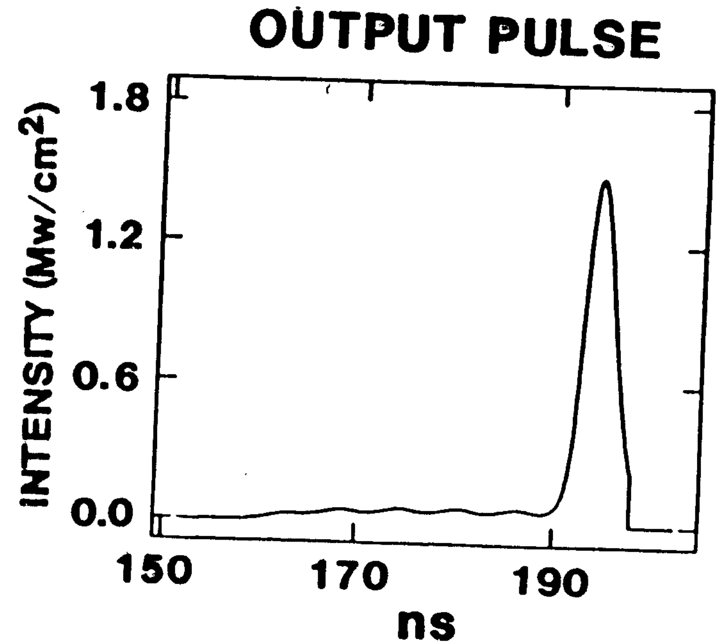
Previous measurements obtained ~12–14%

* Energy out (248 nm)/energy deposited in gas

Los Alamos

REQUIRED TEMPORAL PULSE SHAPES ARE EASILY ACHIEVED WITH KrF LASER SYSTEMS



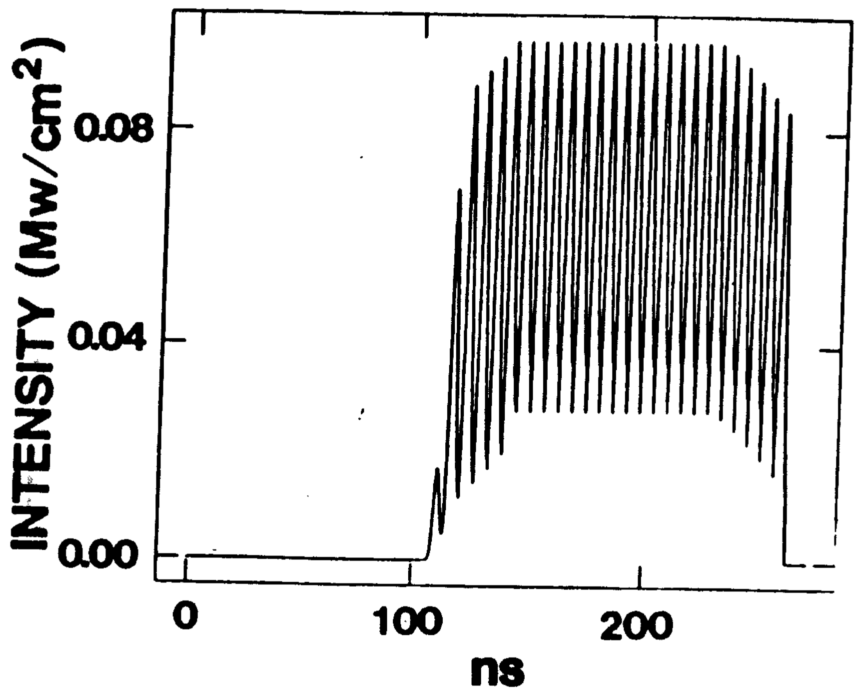


- 4 ns PULSES WITH ~30 ns FOOT
- PULSE SEPARATION ~6 ns
- DOUBLE PASS AMPLIFIER WITH STAGE GAIN OF ~20
- FRONT END PULSE SHAPE WHICH WILL PRODUCE THE DESIRED OUTPUT IS EASILY DEFINED

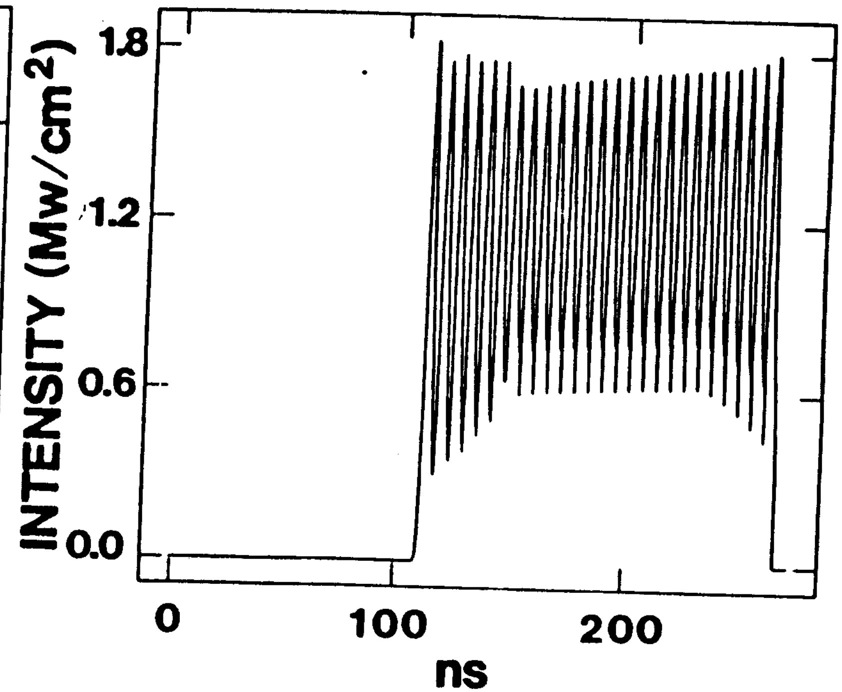
Los Alamos

SINGLE OR DOUBLE PASS KrF AMPLIFIERS BEHAVE LINEARLY WHEN SATURATED

INPUT PULSE TRAIN

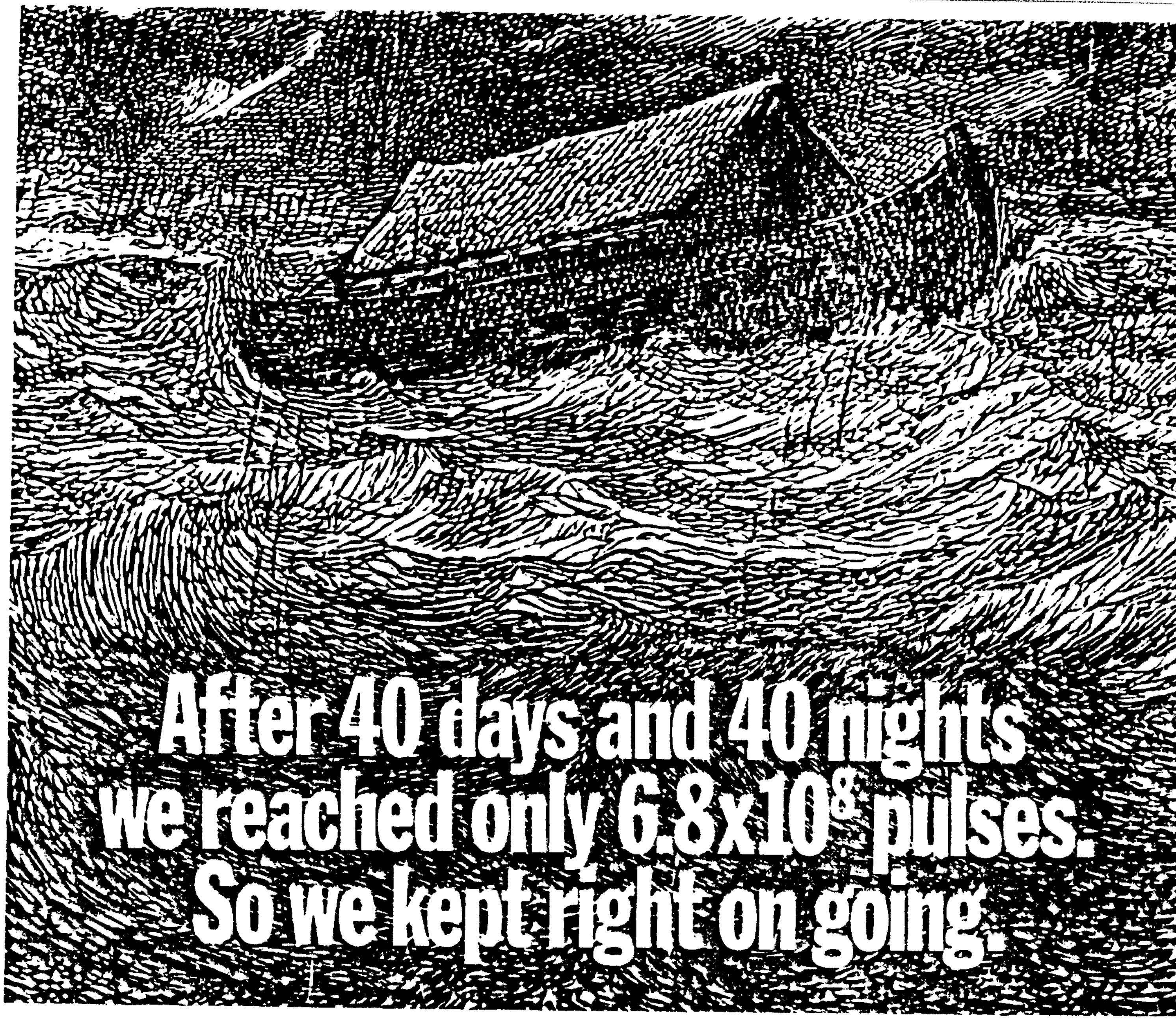


OUTPUT PULSE TRAIN



- FOR UP TO ~5ns PULSE SEPARATIONS, KrF MEDIA STORES ENERGY RESULTING IN MINIMAL LOSS OF EFFICIENCY

Los Alamos



Billion pulse reliability from Questek's excimer lasers.

We designed our Series 2000 Advanced Excimer Lasers to be survivors.

But to prove the point, we decided to put our laser to a tougher test than you ever will.

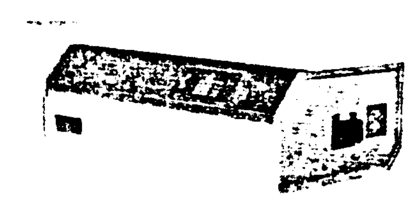
10^9 pulses.

At 250 Hz, that's 46 days of continuous operation, 24 hours a day. That's equivalent to over *5 years* of typical laboratory usage.

While our test ran 58 days due to maintenance and scheduled inspections each 10^8 pulses, we confirmed that our lasers perform for 10^9 pulses without replacement of the thyratron, the solid nickel electrodes, or a single capacitor or preionizer. No one else can say they have operated their excimer laser 10^9 pulses, much less 10^9 pulses without such component replacement.

The Series 2000 survived 40 days and 40 nights, and then some.

And no other excimer laser manufacturer is even in the same boat.



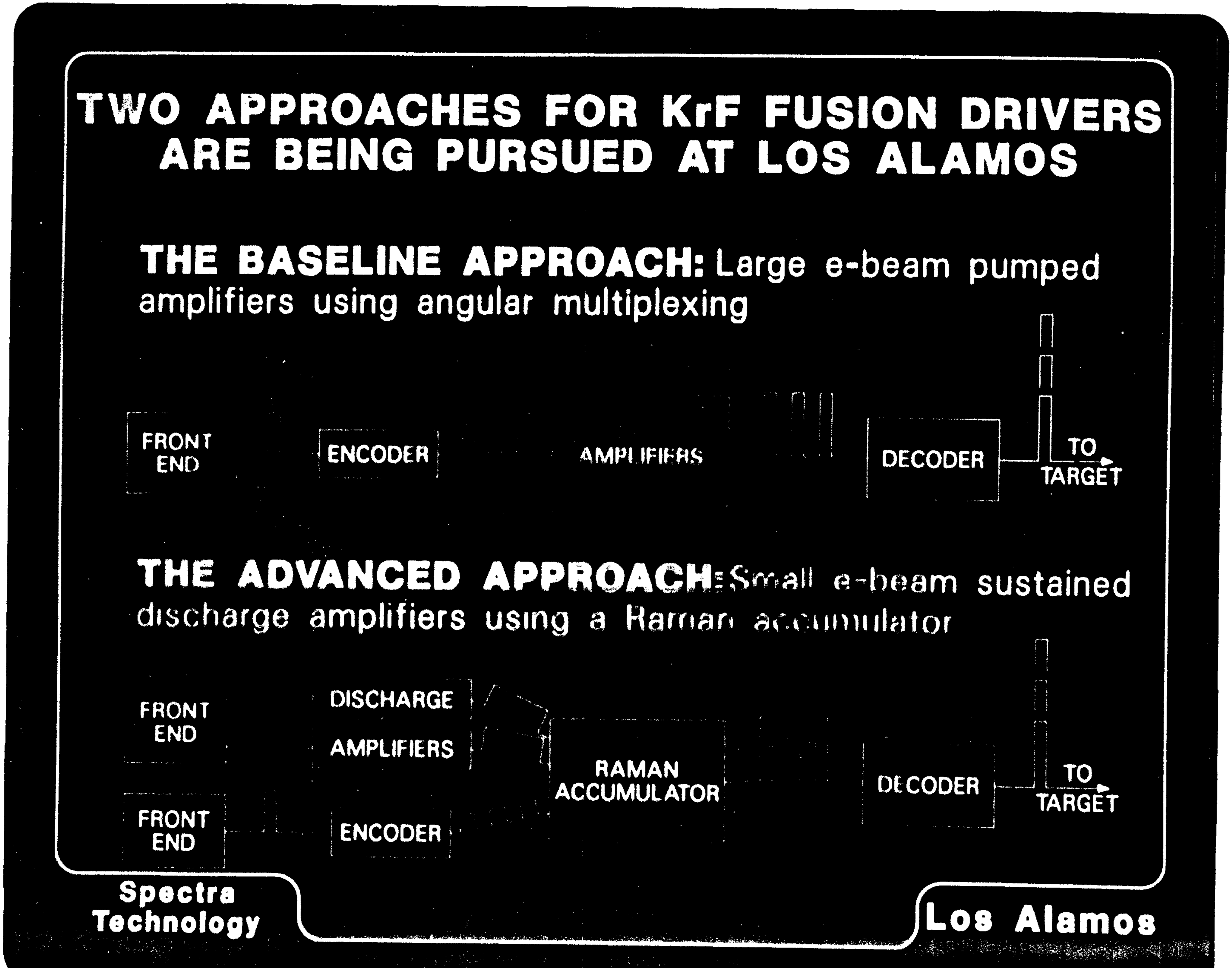
QUESTEK

Questek Inc. 44 Manning Road Billerica, MA 01821 Tel: (617) 667-6790 Tlx: 4971358 QUESTEK

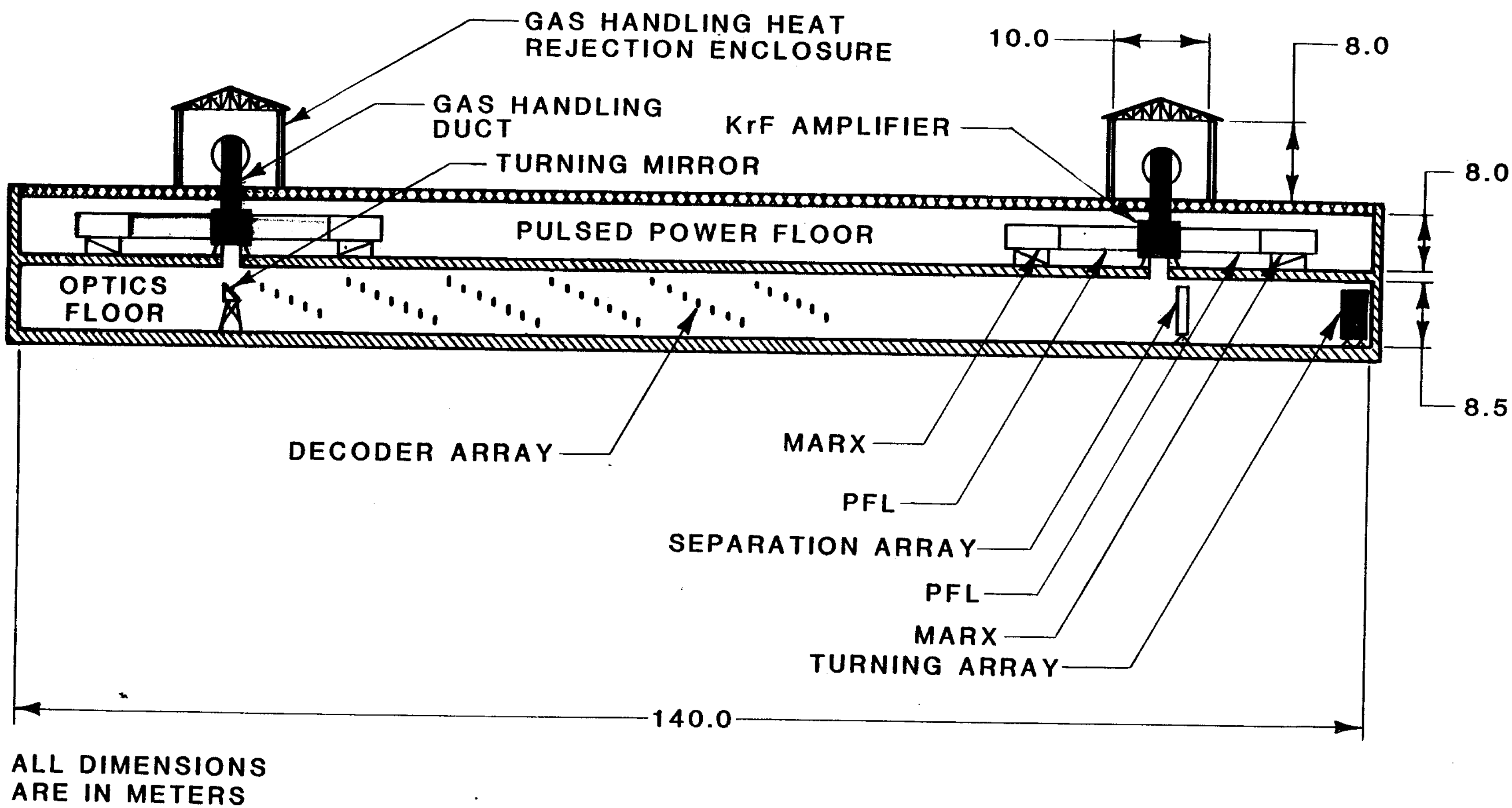
Canada: Technical Marketing Associates Ltd.—Mississauga (416)826-7752 **Europe:** Spectra-Physics GmbH—Darmstadt, W. Germany (06151)7080 **India:** Harvin Agencies—(842)32058 **Israel:** Isramex Company Ltd.—(3)243333 **Japan:** Shibuya Kogyo Company Ltd.—Kanazawa (07762)62-1201

CIRCLE NO. 12

• Advanced approach developed by Spectra Technology and Los Alamos.



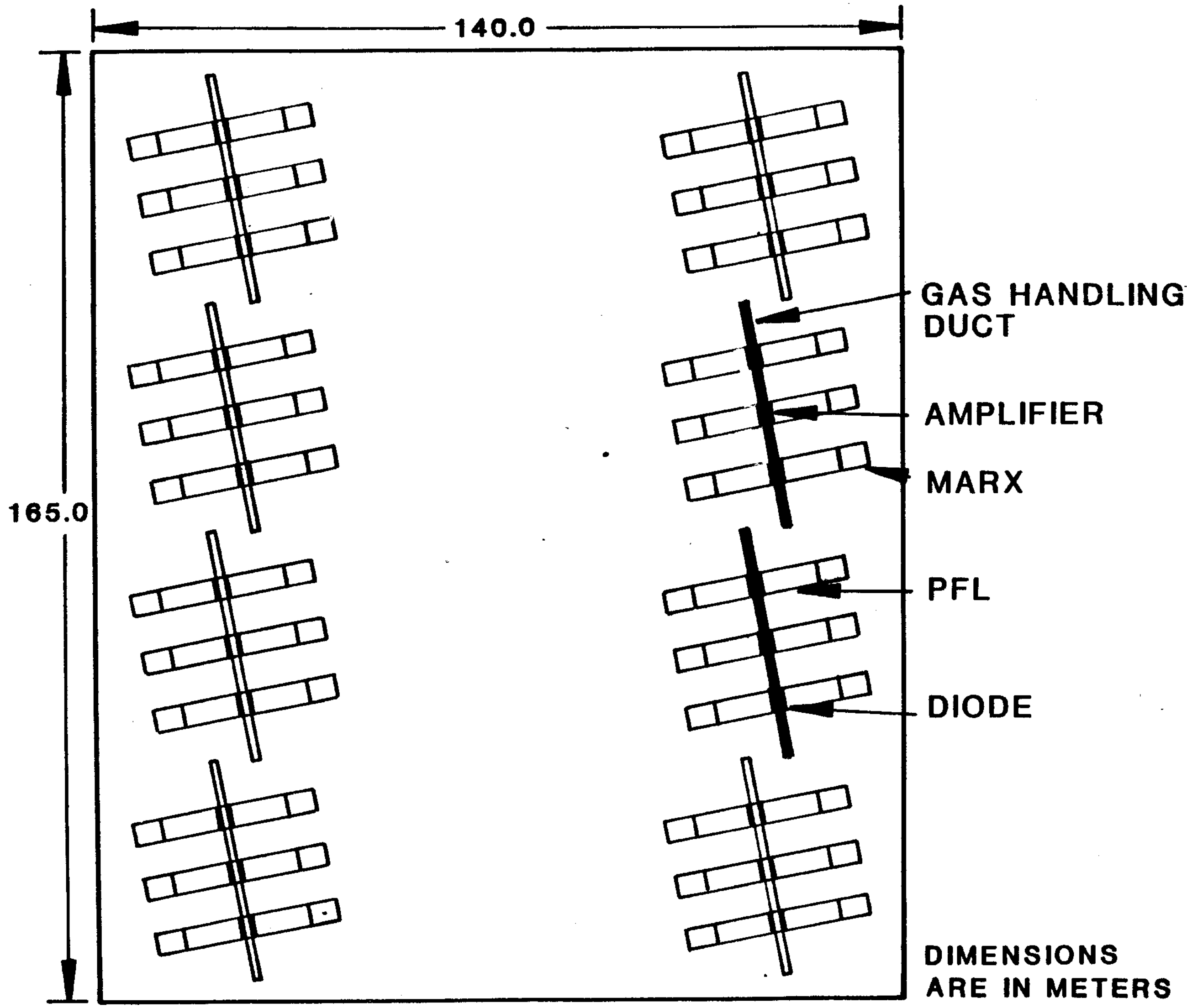
LASER BUILDING ELEVATION VIEW



MDAC

Los Alamos National Laboratory

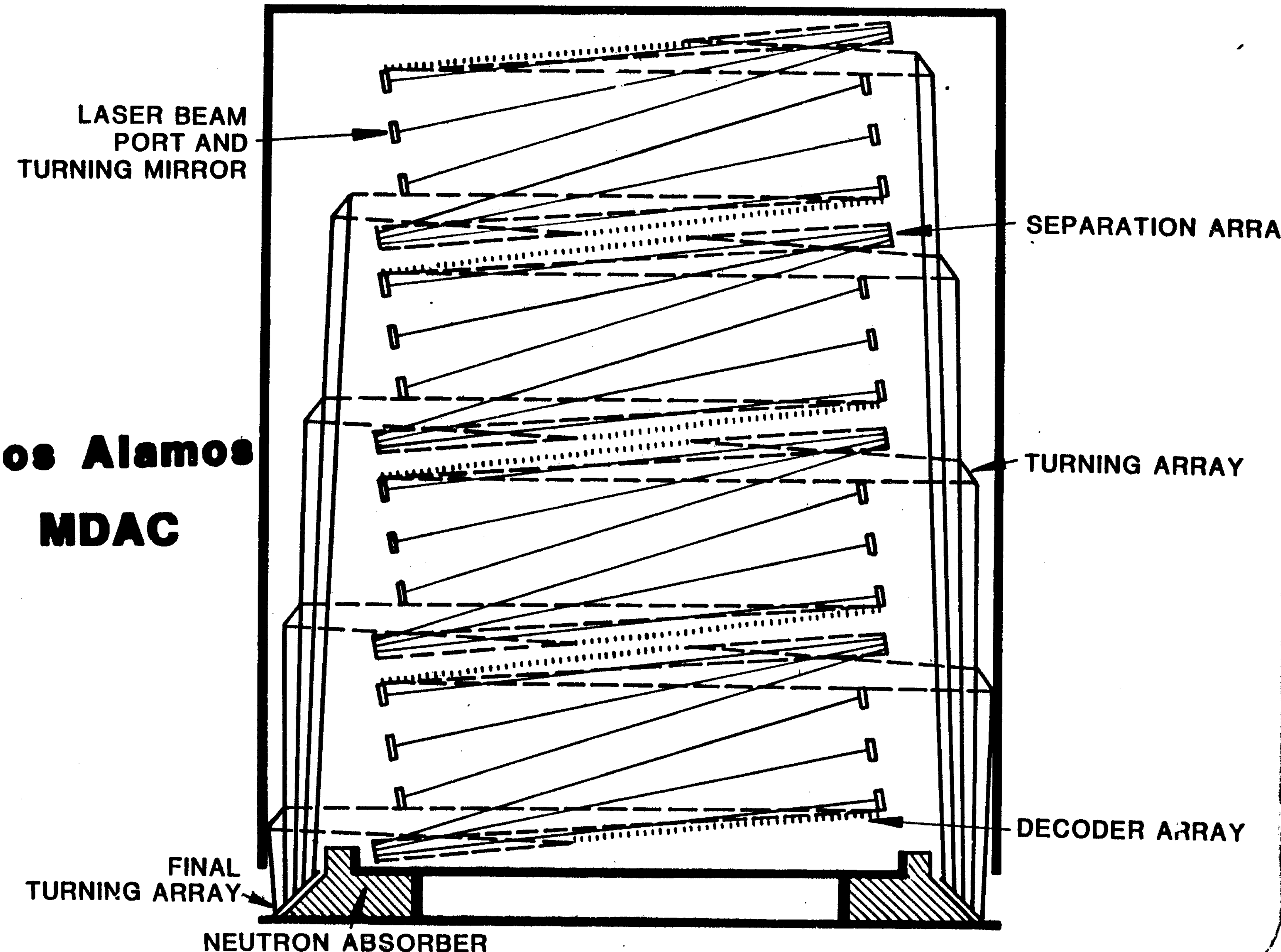
LASER BUILDING MAIN AMPLIFIER FLOOR



MDAC

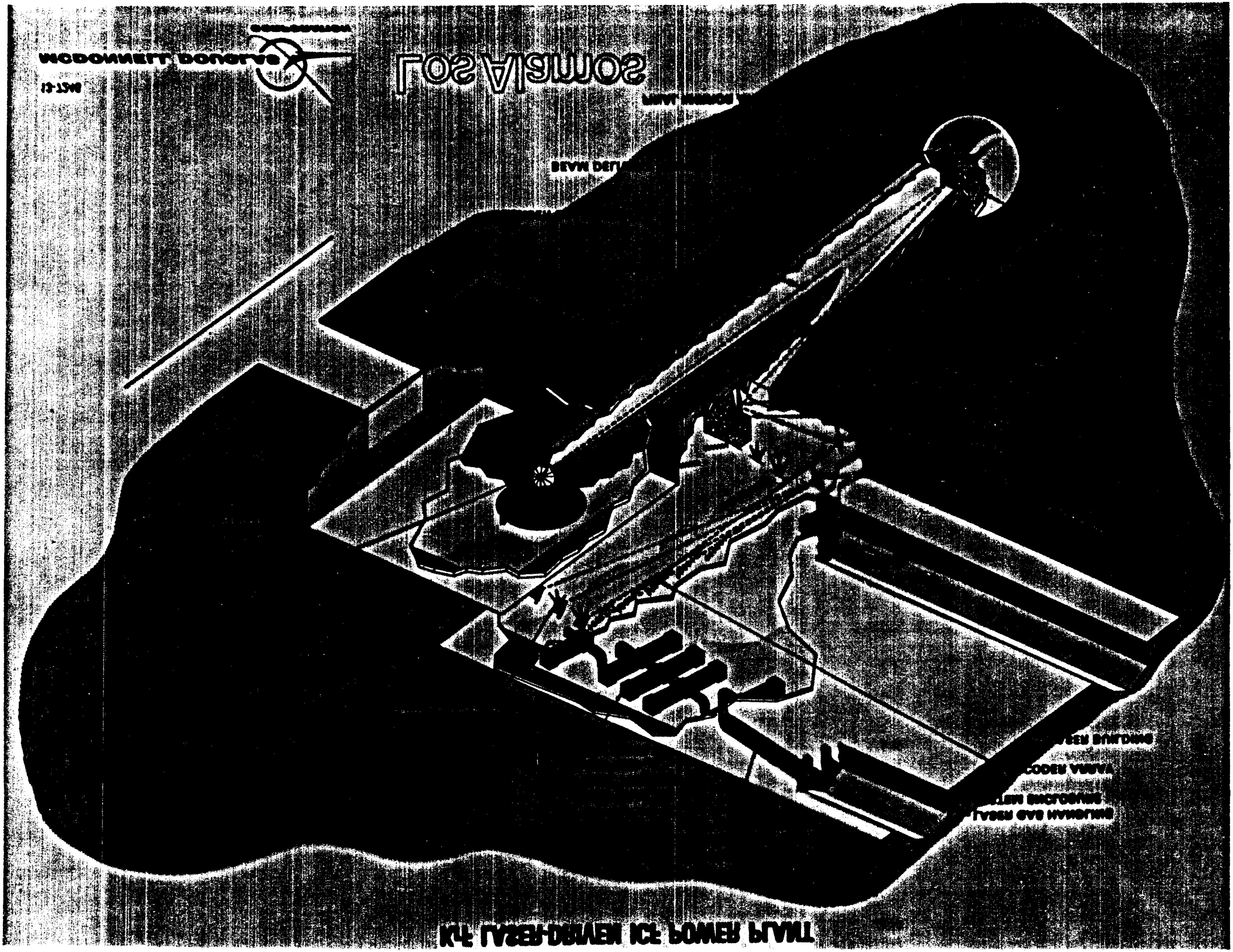
Los Alamos

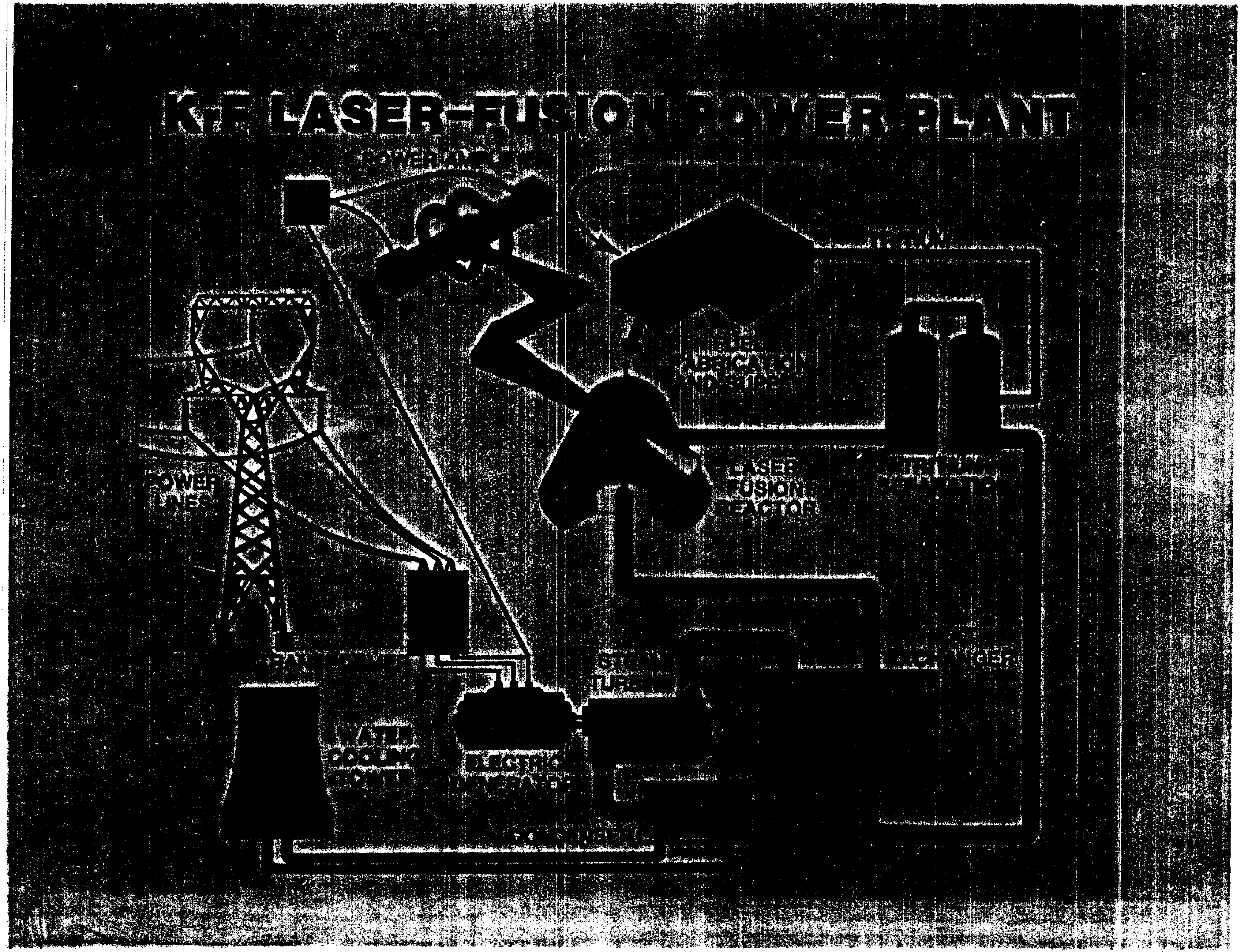
LASER BUILDING OPTICS LEVEL



Los Alamos

MDAC


Los Alamos
MCDONNELL DOUGLAS
KrF LASER-DRIVEN ICF POWER PLANT


KrF LASER-FUSION POWER PLANT
POWER LINES
LASER FUSION REACTOR
ELECTRIC

LASER SYSTEM EFFICIENCY IS *EFFECTIVELY* IMPROVED BY USING THE LASER "WASTE" HEAT AS FEEDWATER PREHEAT

- Original System Efficiency

$$\eta_{system} = \frac{P_{target}}{P_{laser} + P_{gas}}$$

- Effective Efficiency+

$$\eta_{effective} = \frac{P_{target}}{P_{laser} + P_{gas} - {}_{c}Q_{laser}}$$

- Sample Calculation

$$\eta_{sys} = \frac{25}{278+20} = 8.4\% \qquad \eta_{eff} = \frac{25}{278+20-0.4(208)} = 11.7\%$$

MDAC

+ Thanks to J. Pendergrass (Los Alamos)

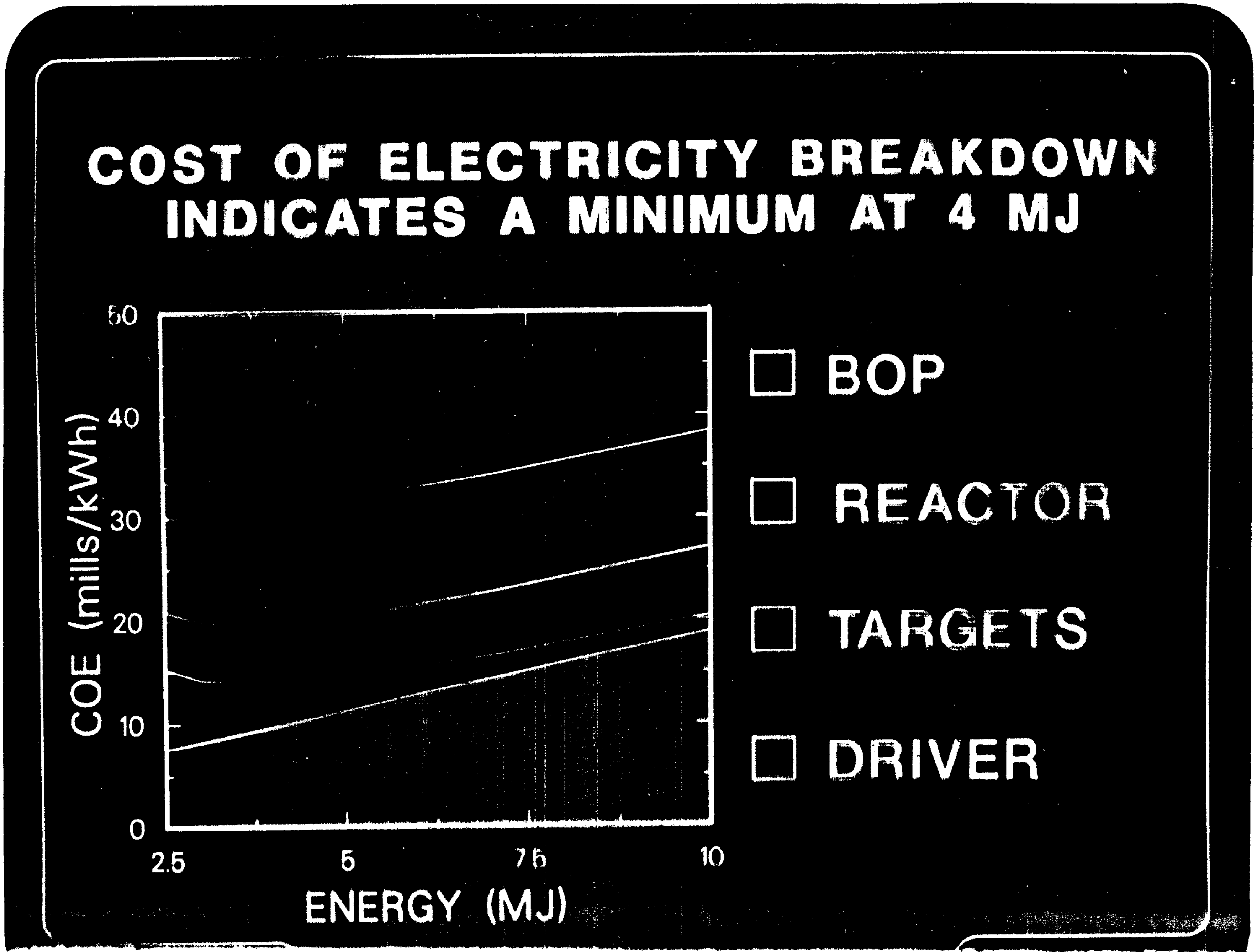
Los Alamos

ASSUMPTIONS USED FOR THE COE CALCULATION

- Optical fluence 4 J/cm^2 short pulse, 6 J/cm^2 long
- Derated Marx generator/water lines exist
- Cost of optics and amplifiers 25% of today's cost (excluding pulsed power and supercond. magnets)
- Single-shell gain curve (Lindl-Mark)
- 42.5% electric power generation efficiency
- 70% neutron energy fraction
- Neutron energy multiplication = 1.25
- 75% plant capacity factor
- Fixed charge rate = 0.10
- 2.5% nondriver recirculating power fraction
- O & M cost factor = 10% of annual capital charges
- Indirect capital cost factor = 0.30
- Target costs from model by Pendergrass, Harris, and Dudziak (Fusion Technology, May 1987)

MDAC Los Alamos

1.21


COST OF ELECTRICITY BREAKDOWN
INDICATES A MINIMUM AT 4 MJ
COE (mills/kWh)
50
40
30
20
10
0
2.5
5
7.5
10
ENERGY (MJ)
BOP
REACTOR
TARGETS
DRIVER

KrF LASERS HAVE GREAT POTENTIAL FOR COMMERCIAL REACTORS AND NEAR-TERM APPLICATIONS

- High projected efficiency (>10%)
- Low projected cost (<200 $/J)
- Efficient target coupling (249 nm, pulse shaping)
- High pulse repetition rates (gas laser)
- Scalable to high energies (replication of modules)
- Reliability and robustness (to be demonstrated)

THE LANL PROGRAM IS DESIGNED TO VERIFY THE POTENTIAL OF KrF LASERS FOR COMMERCIAL AND MILITARY APPLICATIONS

Los Alamos

COMMERCIAL DRIVERS FOR LASER DRIVEN REACTORS

FRENCH VIEW

COMMISSARIAT A L'ENERGIE ATOMIQUE

CENTRE D'ETUDES DE LIMEIL

MICHEL L.ANDRE

SOUVENIRS

1962

First oscillator at limeil

1963

Demonstration of multiphoton ionisation

1966

125 J, 30 ns, two beams laser
Aspherical lenses

1969

Fusion neutrons on cryo-target
100 J, 2 ns laser

1971

400 J, 2 ns, four beam laser
Most Powerfull laser in the world

SOUVENIRS (SUITE)

1973

First four beams experiment

1974

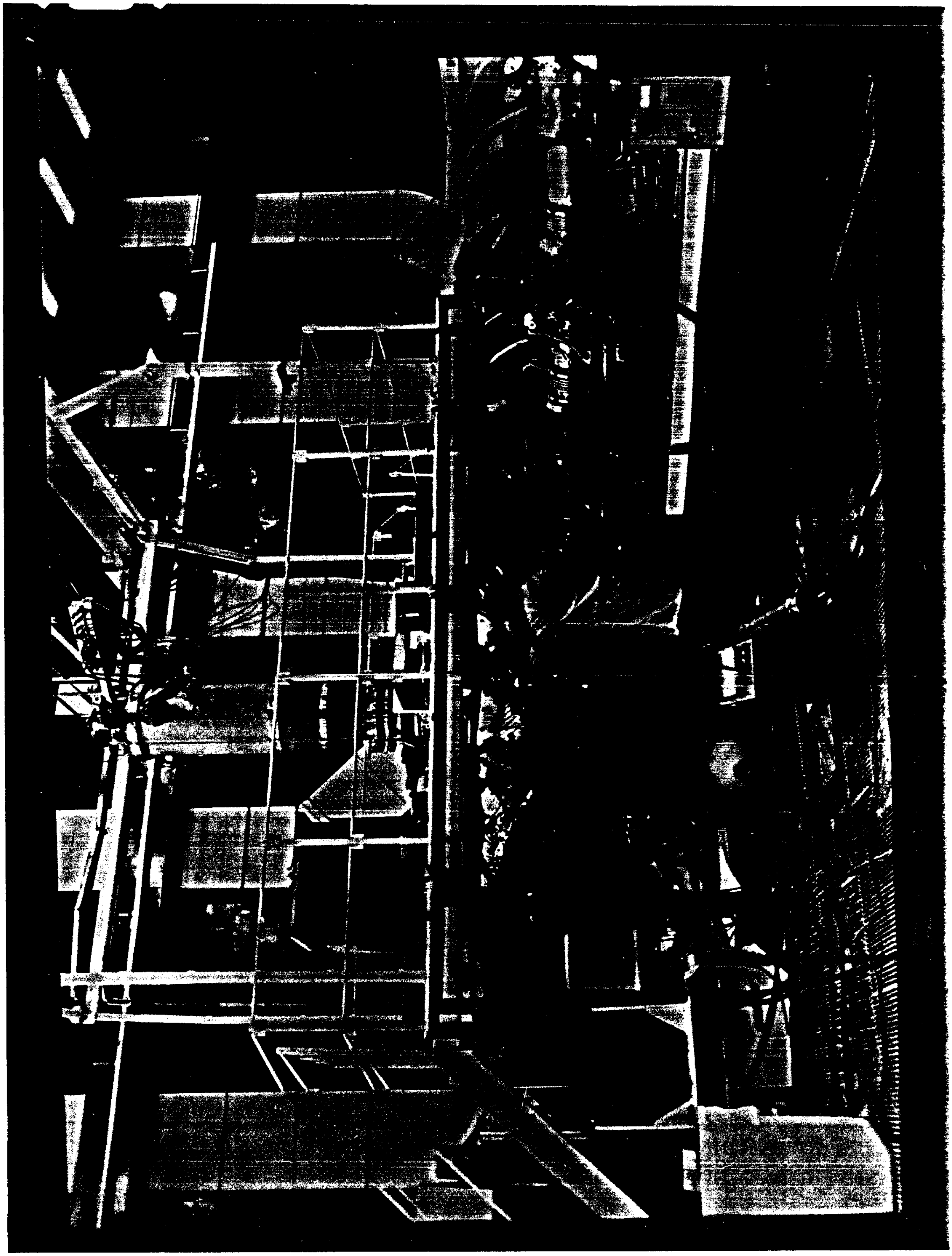
First green neutrons

1976

100 J, 100 ps, one beam laser

SOLID STATE LASERS AT LIMEIL

Name (working since)	Number of beams	Beam diameter (cm)	Maximum power (terawatt) of the different possible wavelength (um)			Pulse duration (ns)
			1,05	0,53	0,35	
P102 (1976)	1	9	0,1	-	0,03	0,05 - 1
OCTAL (1982)	8 (2 x 4)	12	2	-	0,7	0,2 - 2
PHEBUS (1986)	2	74	20	13	10	0,2 - 6



AFTER PHEBUS ?

- NEW PROJECT NECESSARY IN THE NEAR FUTUR
- TECHNICAL AND COST QUESTIONS TO BE ANSWERED
- LIMEIL GREAT INTEREST FOR A FUTUR BIG LASER
- R & D ACTIONS AND WISH FOR AN INTERNATIONAL COLLABORATION

NO OFFICIAL NATIONAL PROJECT

FRANCE IS ENGAGED IN MAGNETIC CONFINEMENT FUSION FOR ELECTRIC ENERGY PRODUCTION

PHYSICS OF I.C.F. IS NOT YET ESTABLISHED ... BUT HAS TO BE

REACTOR CONCEPT NEED DECISION ON THE DRIVER ... BUT ANYWAY POWERFUL DRIVER IS NECESSARY FOR PHYSICS AND PARTICULAR APPLICATIONS

QUESTIONS

WHICH LASER
- ACTIVE MEDIUM
- GENERAL STRUCTURE

WHAT PERFORMANCES
- DRIVER GOAL
- INTERMEDIATE STEP

EVALUATION OF COST
- STUDIES
- CONSTRUCTION

TIME ALLOWED
- FOR STUDIES
- FOR INTERMEDIATE STEP
- FOR DRIVER PROTOTYPE

LIMEIL INTEREST

(IN 1987)

PHYSICS OF I.C.F

CLASSIFIED APPLICATIONS

LASER TECHNOLOGY

TARGET DESIGN
TARGET FABRICATION
PLASMAS DIAGNOSTICS

R&D PHILOSOPHY

TO PREPARE A POSSIBLE FUTUR WHILE DEVELOPING NEW TECHNICS TO MAINTAIN PHEBUS

R&D ACTIONS

BEAM SMOOTHING TECHNICS

OPTICAL COMPONENTS QUALITY
- SOL GEL COATINGS
- OPTICAL REPLICAS

DIAGNOSTICS DEVELOPMENTS
- CALORIMETRY
- 20 NS PULSE MEASUREMENT

POWER CONDITIONNING
- LOW COST FLASHLAMPS

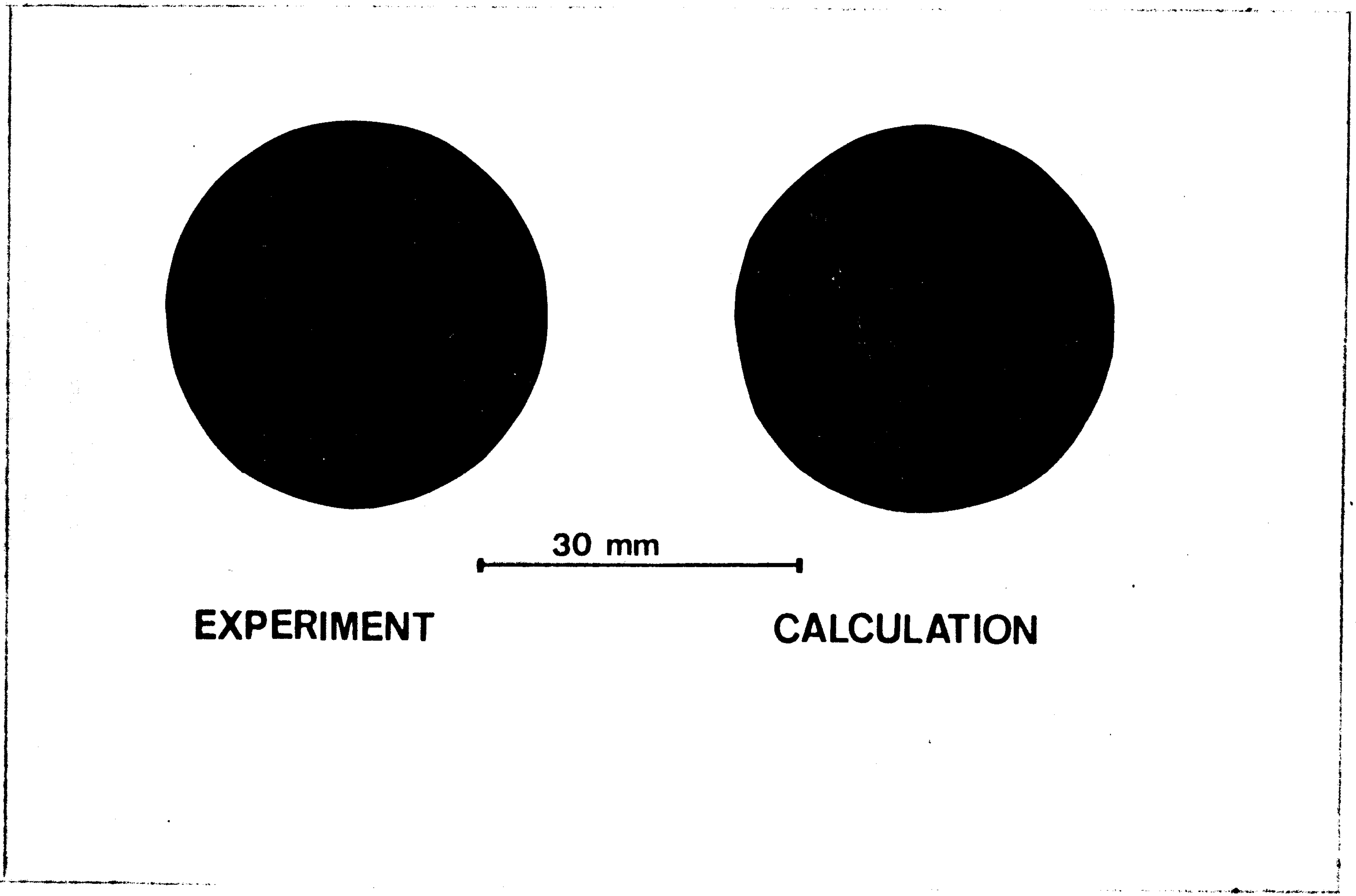
LIMEIL KNOWLEDGE

SIMULATION CODES
- Beam propagation
- Frequency conversion
- Laser design
- Optical design

LASER TECHNOLOGY
- Mechanical design
- Clean assembly
- Optics control
- Power Conditionning

TARGET CHAMBER TECHNOLOGY
- Chamber design
- Target positioner
- Plasma diagnostics
- High resolution optics

TARGET DESIGN-FABRICATION
- "Production" Targets
- "Hand-made" Targets


30 mm
EXPERIMENT
CALCULATION

SOL-GEL TECHNIQUE

ADVANTAGES

Low cost
Easily removable
High flux resistance
No size limitation

MID-TERM STUDIES

Material optimization
Deposition technique

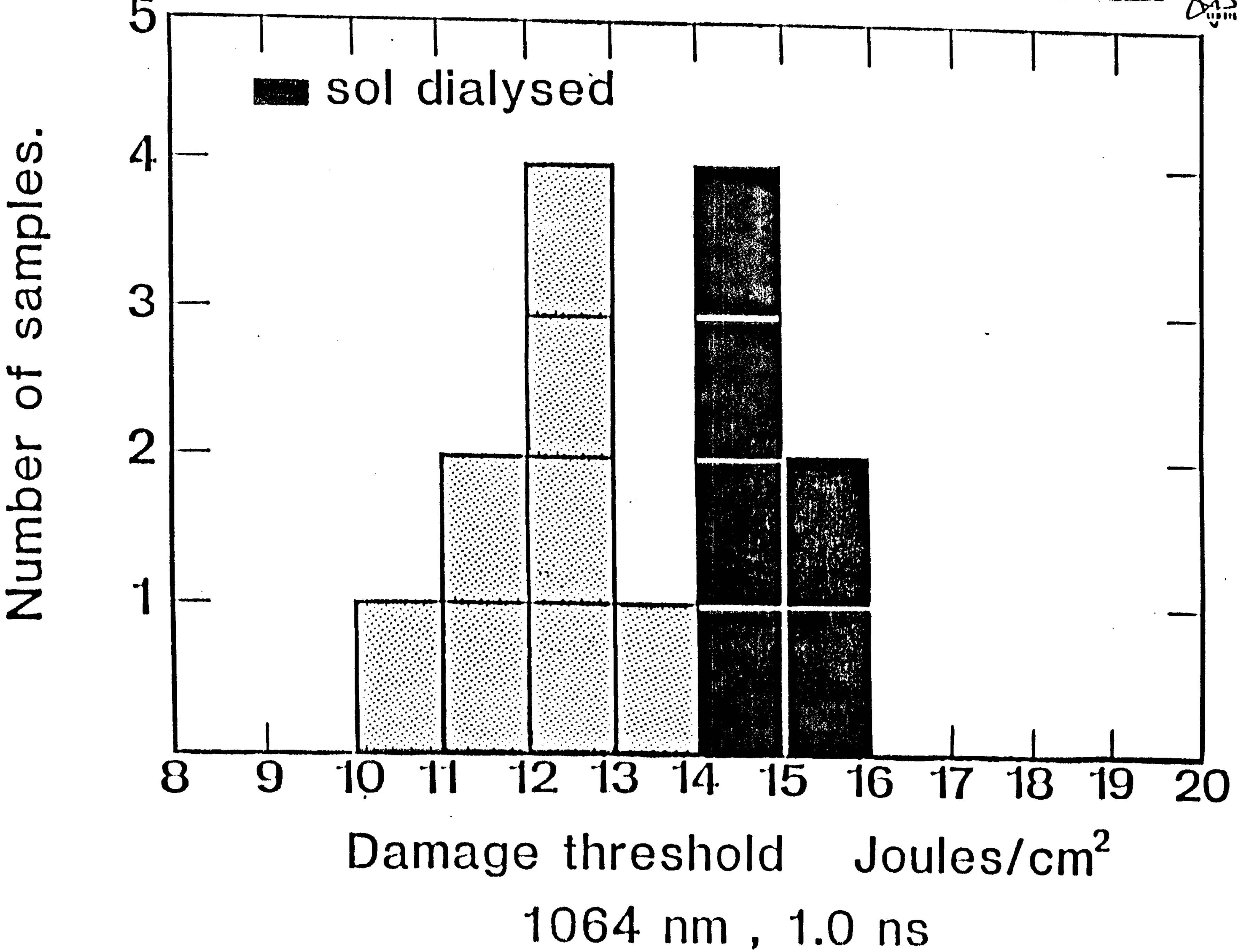
ThO_2 coating caracteristics.

1. Coating consists of layers of uniform ThO_2 spheres.

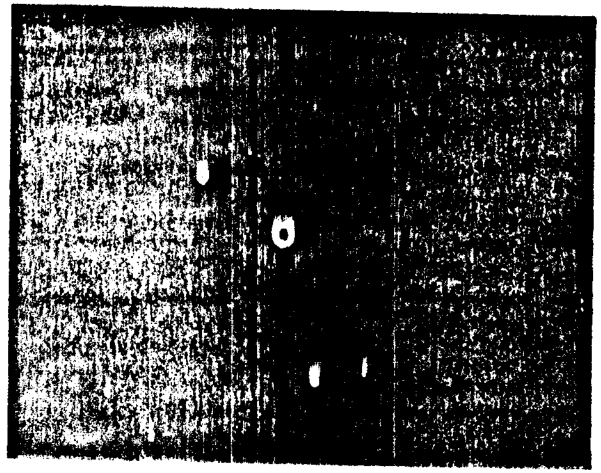
2. Coating is porous with a refractive index adjacent to 1.6–1.65.

3. Coating exhibits a low abrasion resistance.

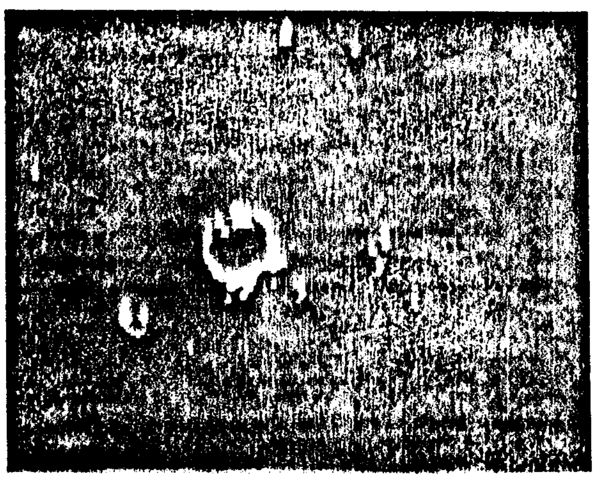
Damage thresholds of ThO_2 coatings from sols.



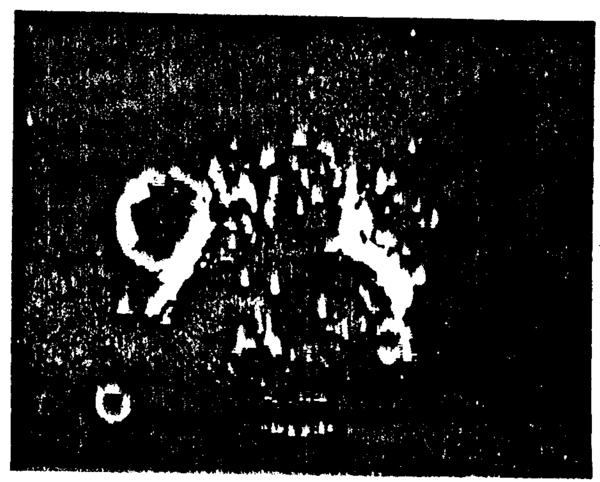
Typical damage evolution of ThO_2 coating at 1064 nm.



15.3 J/cm^2

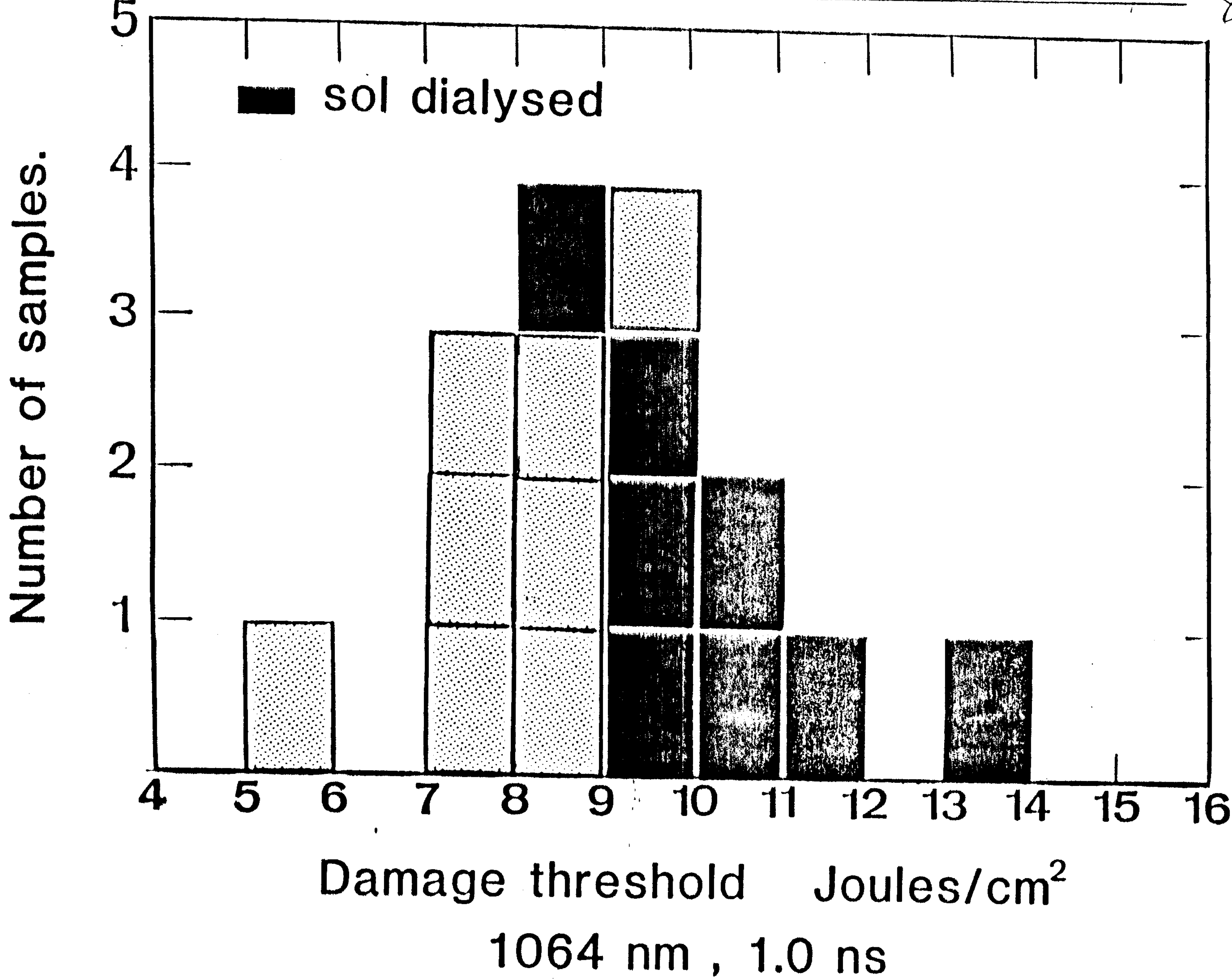


20.2 J/cm^2

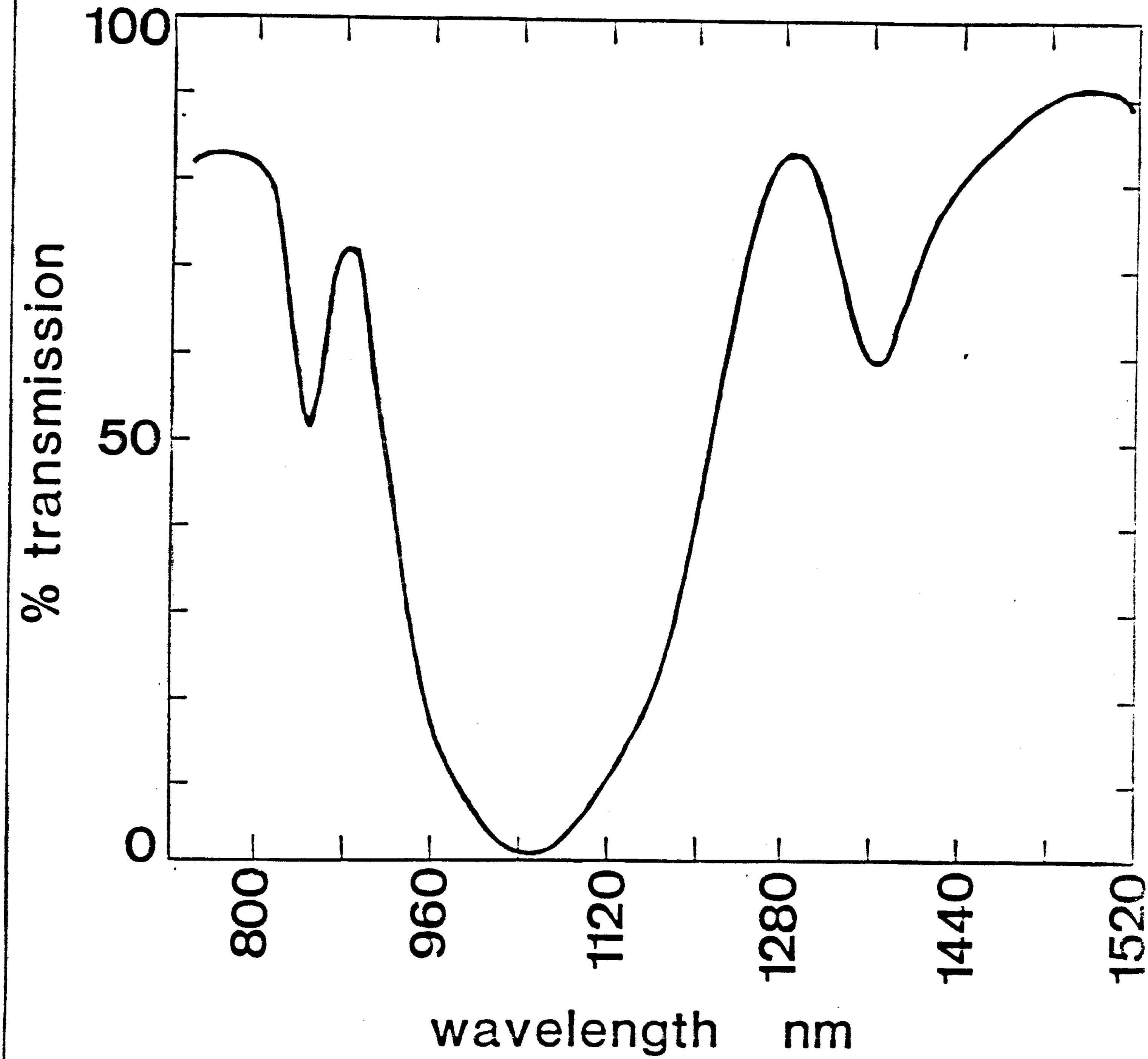


25.0 J/cm^2

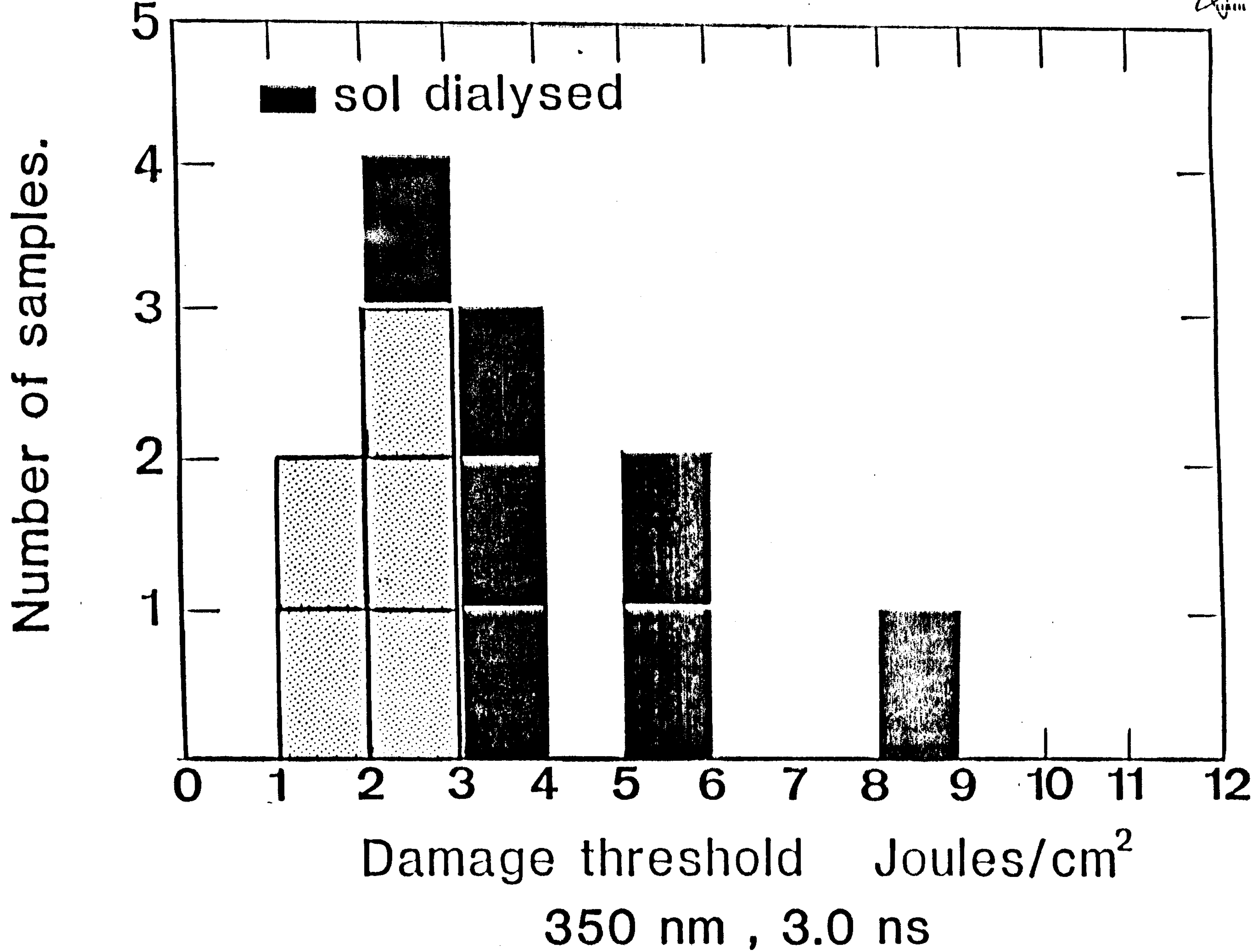
Damage thresholds of ThO_2-SiO_2 HR-coatings.



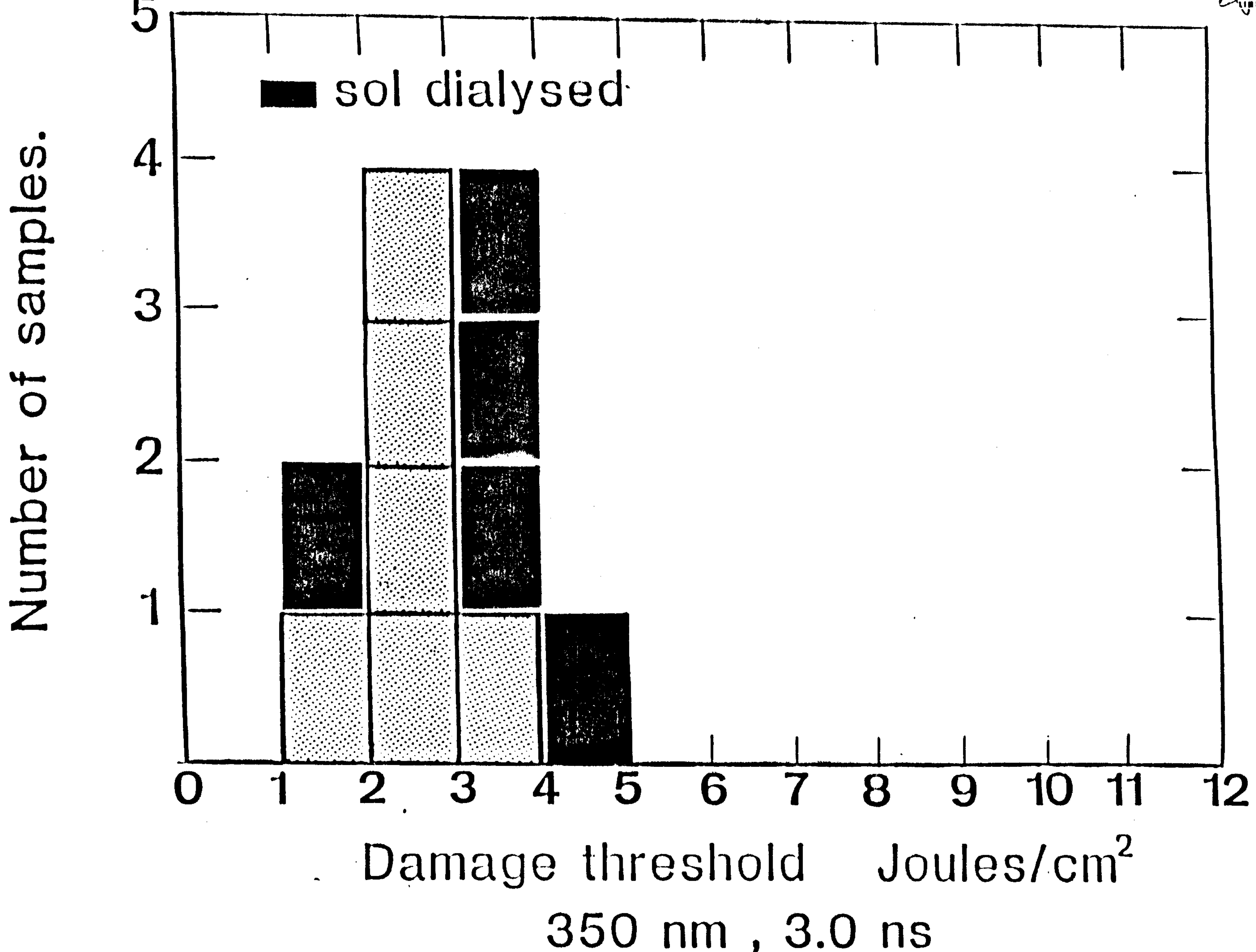
HR porous sol-gel coatings.
21 successive ThO_2–SiO_2 layers deposited from sols.



Damage thresholds of ThO_2 coatings from sols.



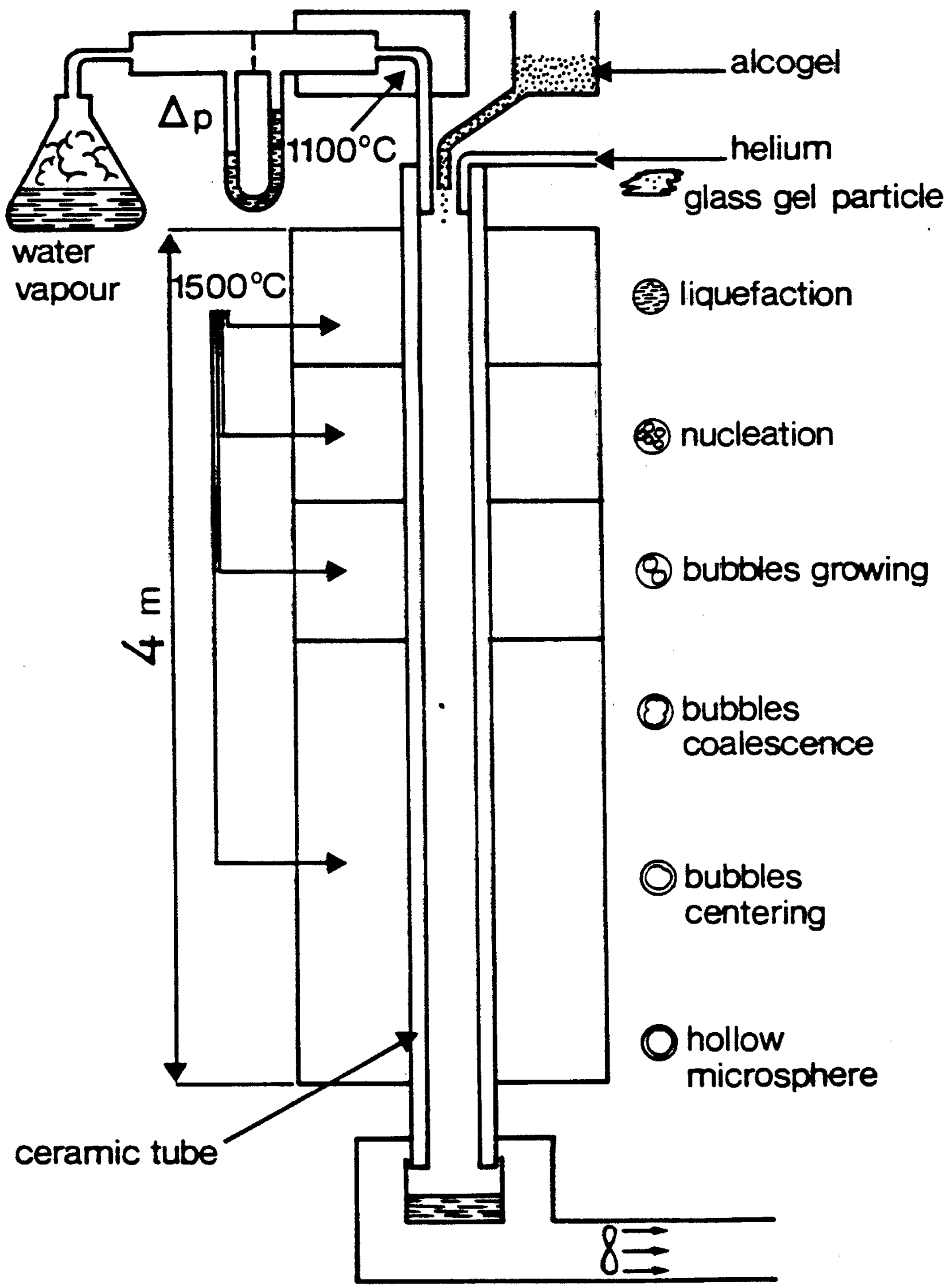
Damage thresholds of ThO_2–SiO_2 HR–coatings.



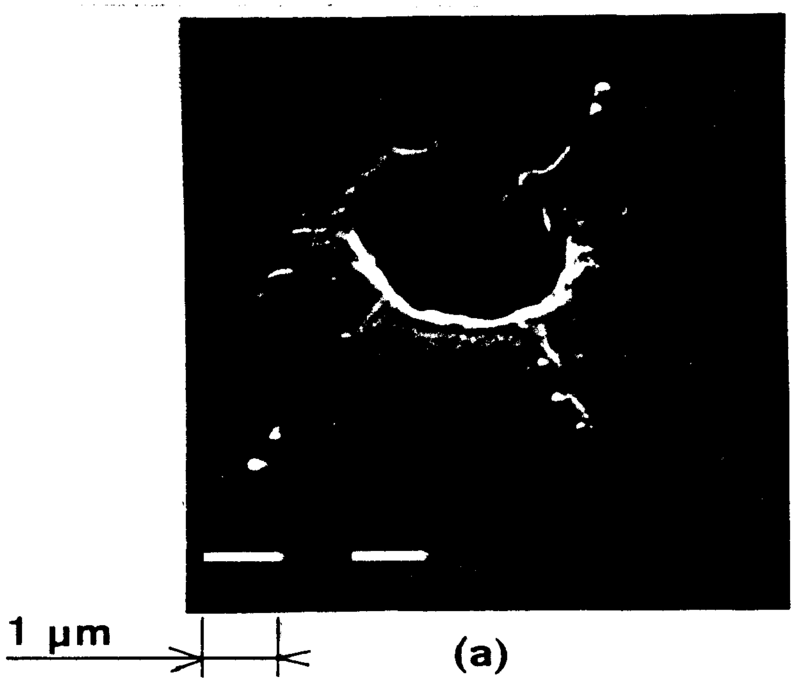
TARGET FABRICATION

- LARGE GLASS MICROBALLOONS
- LASER MACHINING
- LOW DENSITY FOAMS
- MICROLITHOGRAPHY

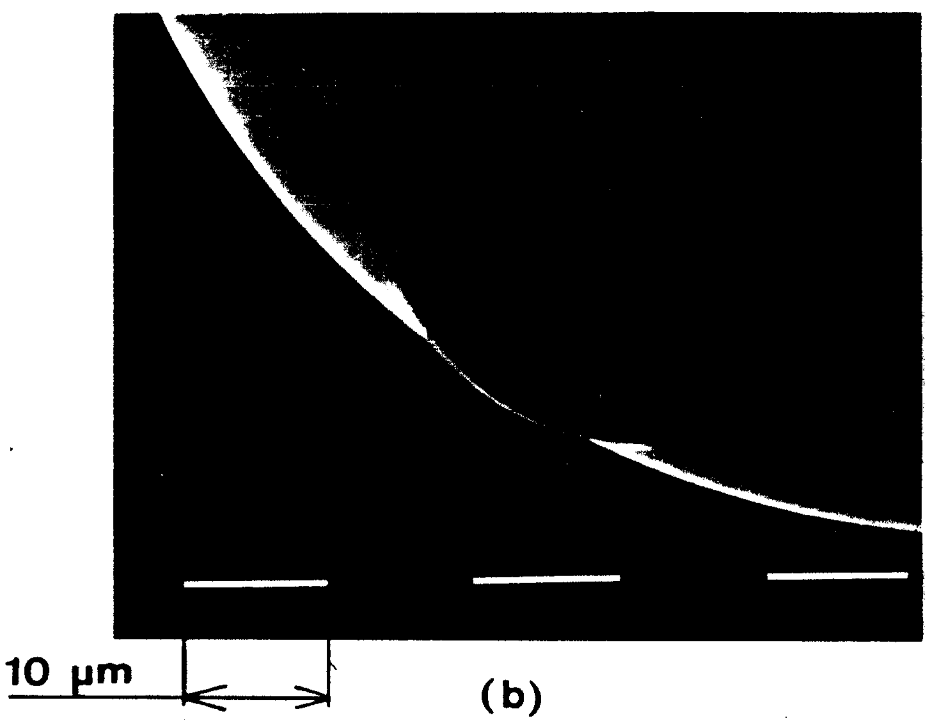
SCHEMATIC OF THE HIGH TEMPERATURE FURNACE



DRILL FILL AND PLUG



(a)

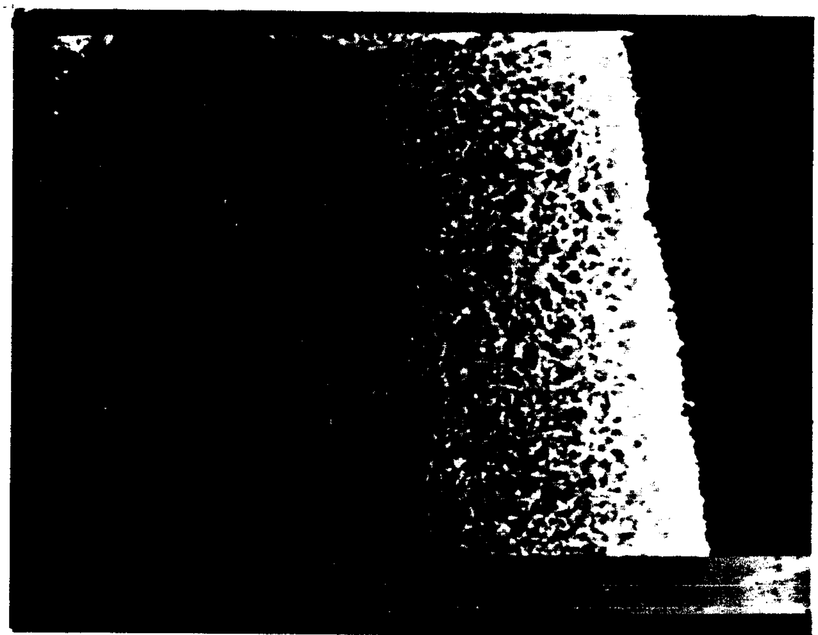


(b)

a–3 μm diameter hole drill in a glass microballoon

b–low glass temperature melted onto the ball

LOW DENSITY FOAM



10 µm

(a)

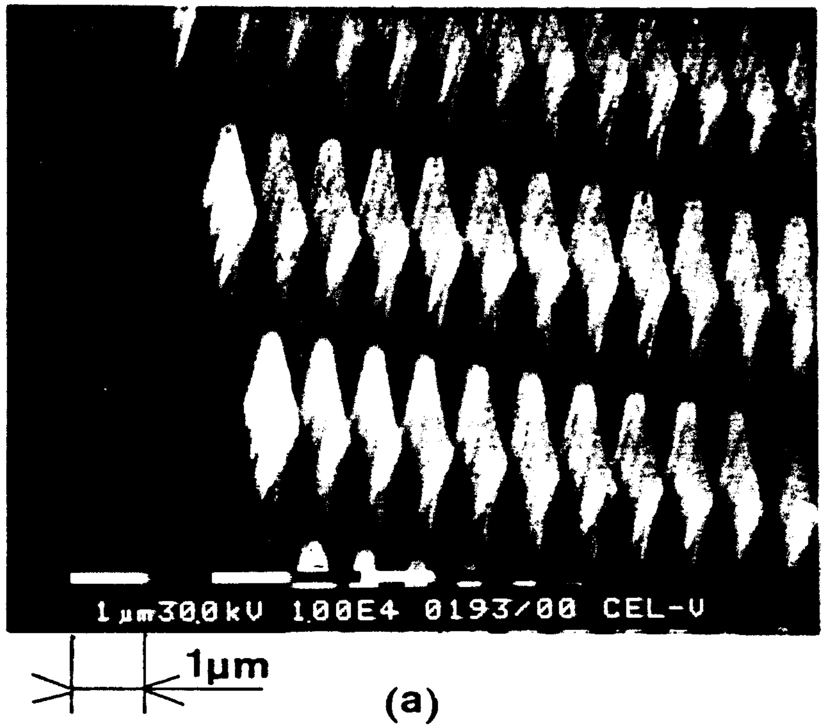
100 µm

(b)

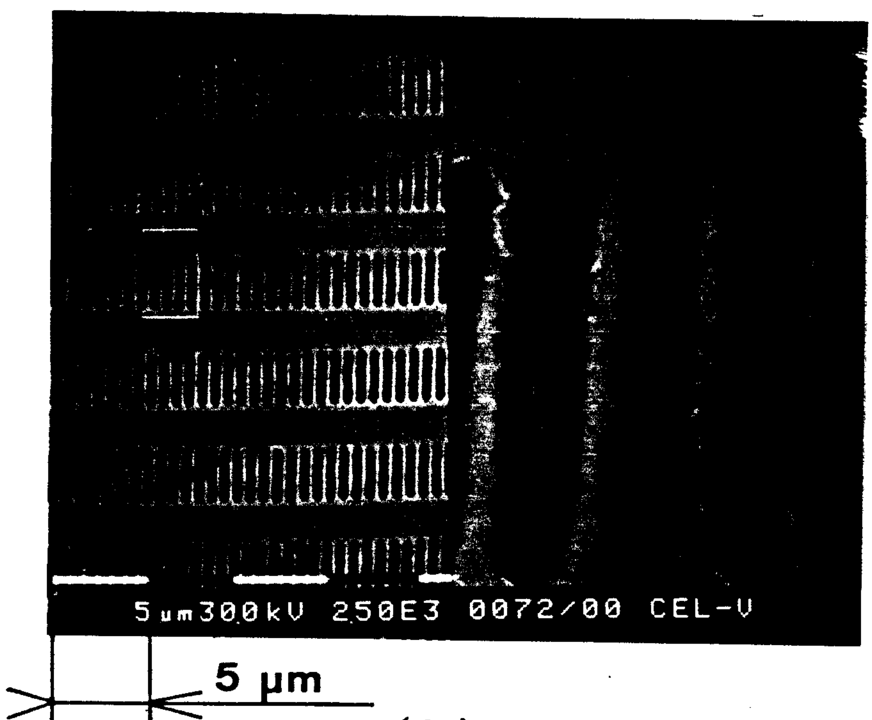
a–dextran foam 3.10^{-2} g.cm^{-3}

b–gold layer 3 g.cm^{-3}

ELECTRON MICROLITHOGRAPHY



(a)



(b)

a–SEM photomicrograph of a polyimide pattern

b–free standing gold TG 8000 Å spatial period

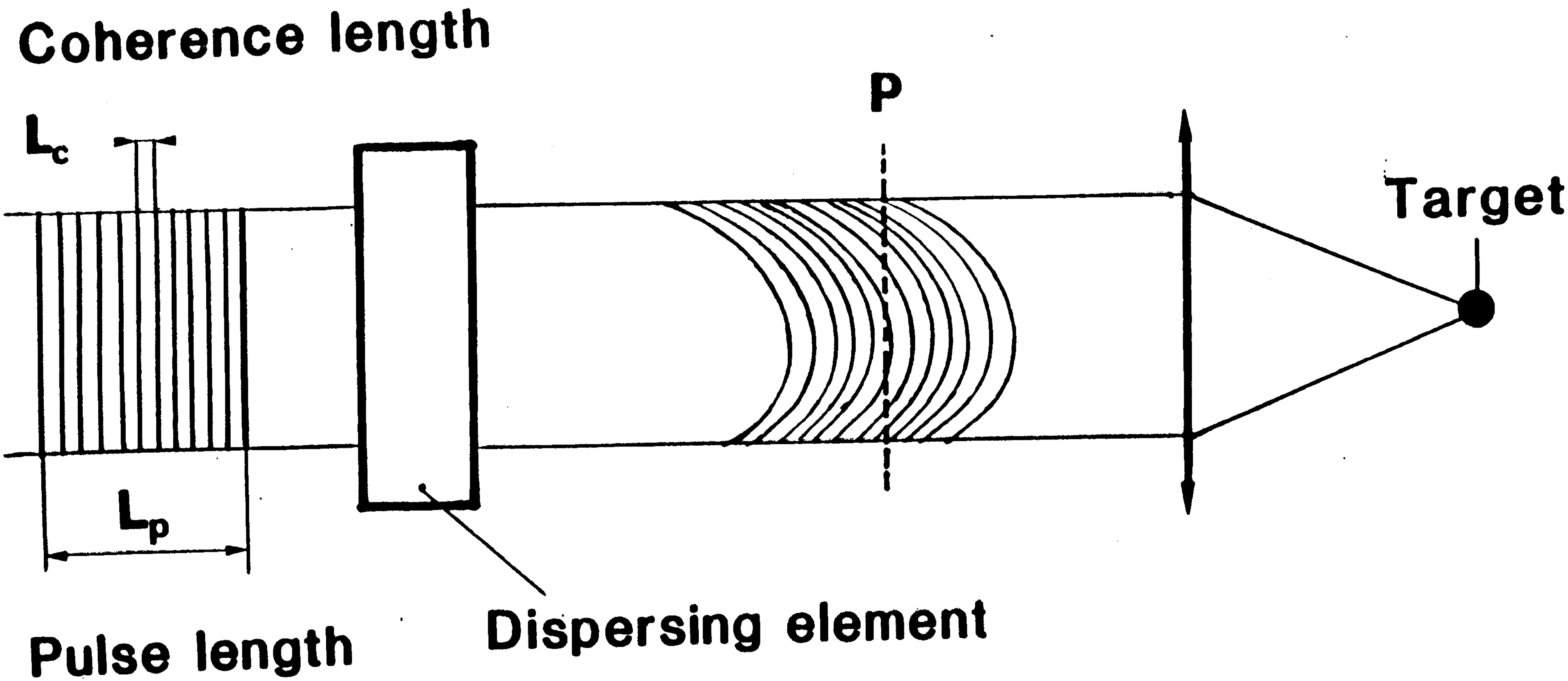
BEAM SMOOTHING

EXPERIMENTS ON P102

Broad band oscillator
50 meter optical fiber

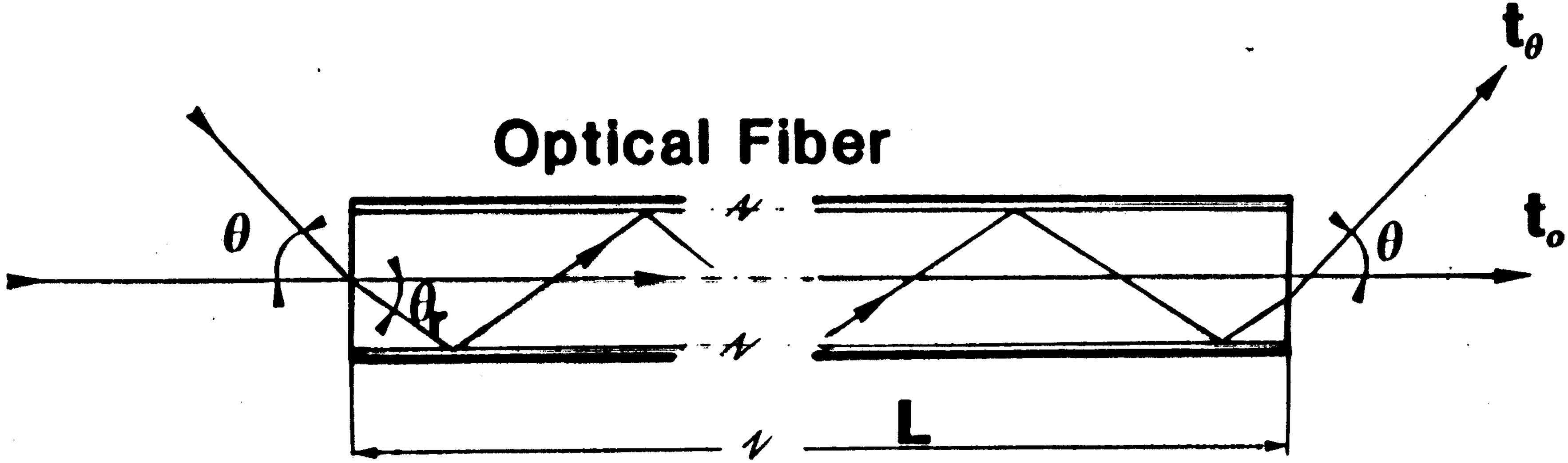
INSTALLATION ON PHEBUS

On X ray diagnostic beam
Oscillator synchronisation issue



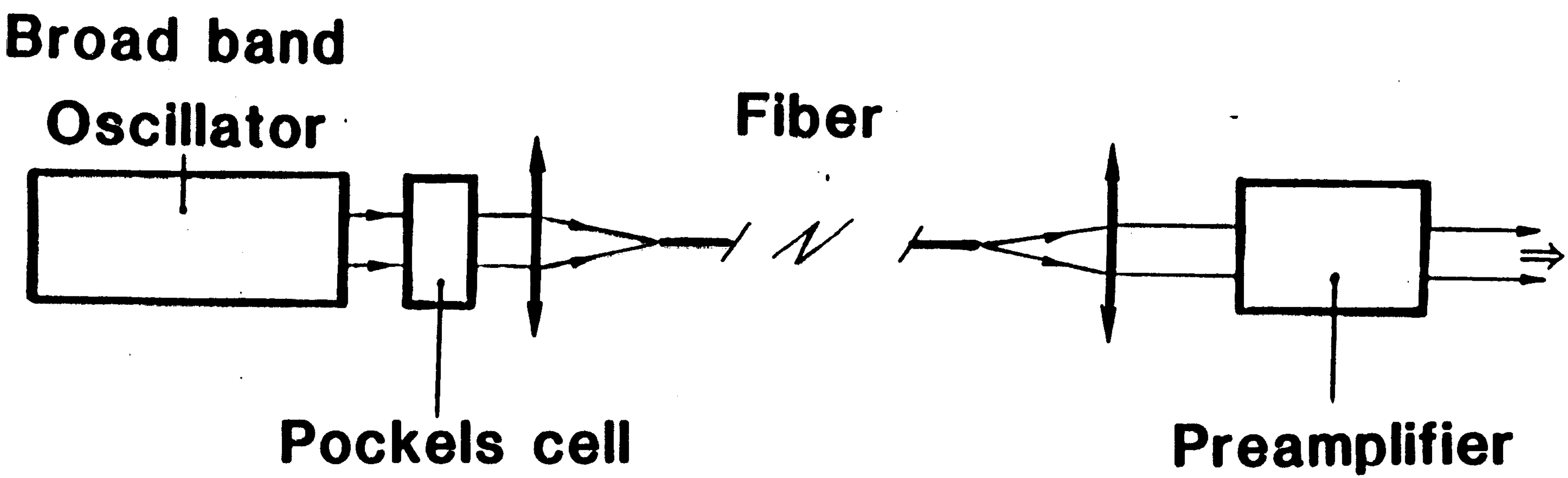
Principle of optical smoothing

The photons located in a plane P are all reaching
target at the same time. As P is crossing several cohere
layers of thickness L_c, a number of independe
interference patterns are simultaneously superimposed
the target. The result is a smoothing of the spatial ene
distribution.



Propagating time dispersion in an optical fiber

The travelling distance and thus the propagating time t_θ o photons is a function of their angle of incidence θ. Th minimum value of t_θ is for rays entering parallel to th fiber axis.

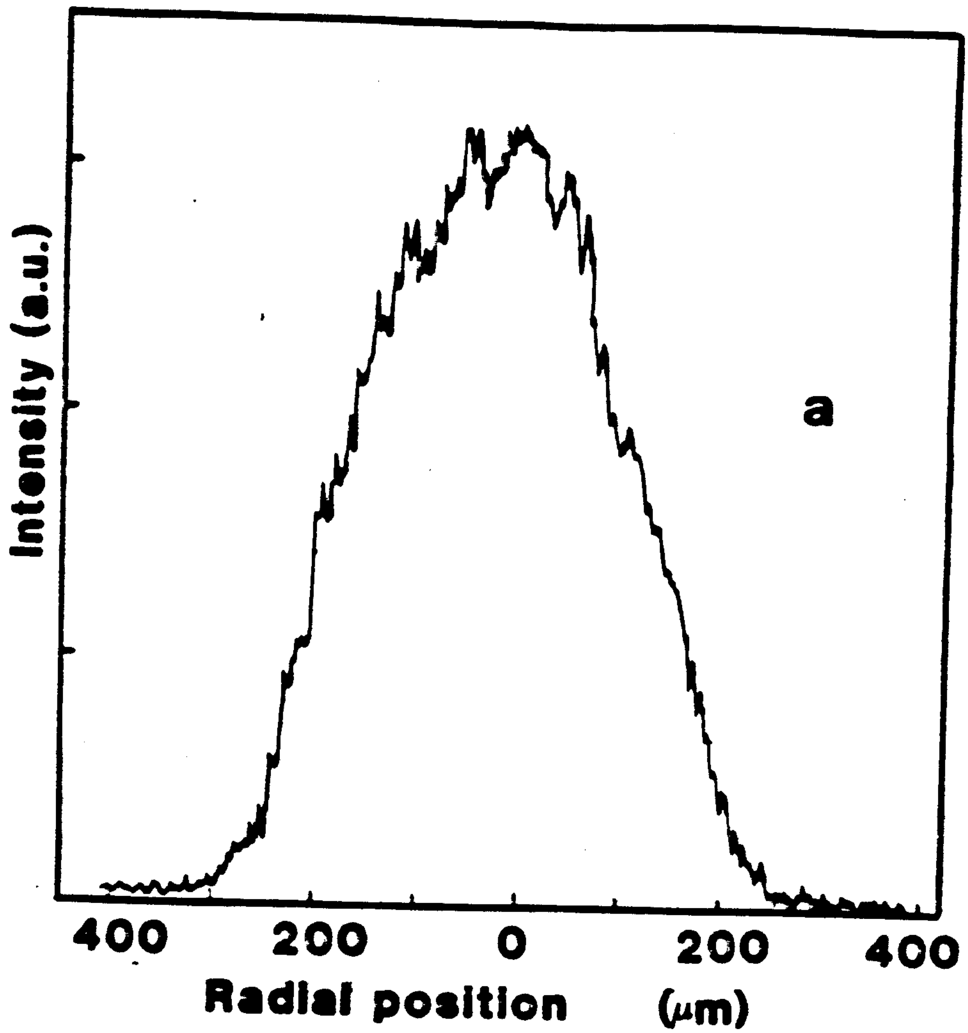


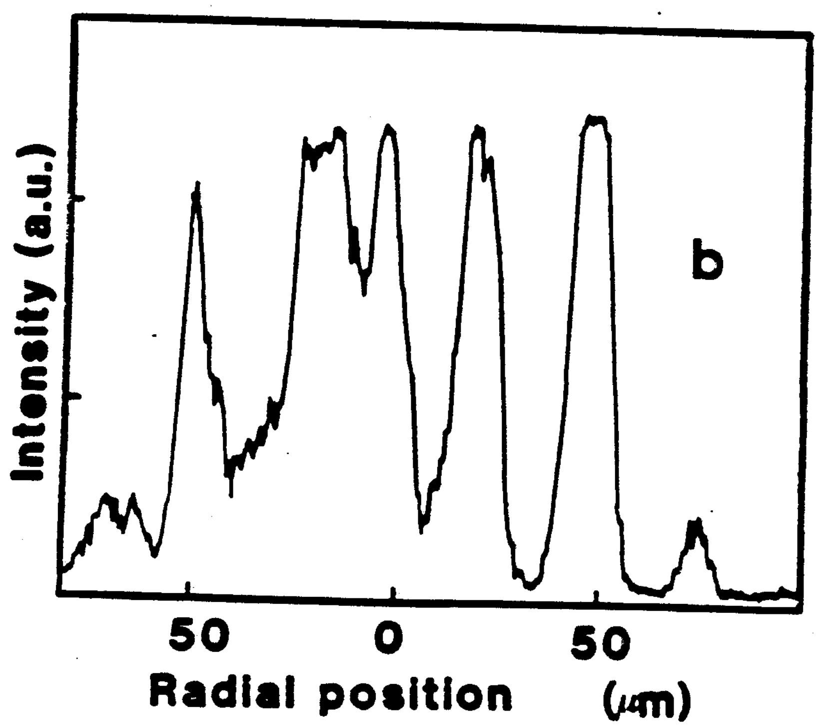
<u>Fiber optic pulse generator</u>

This pulse generator consists in a broadband oscillator coupled to an optical fiber. Suitable relaying optics, Pockels cell and pre-amplifiers complete the assembly.

Focal intensity profile

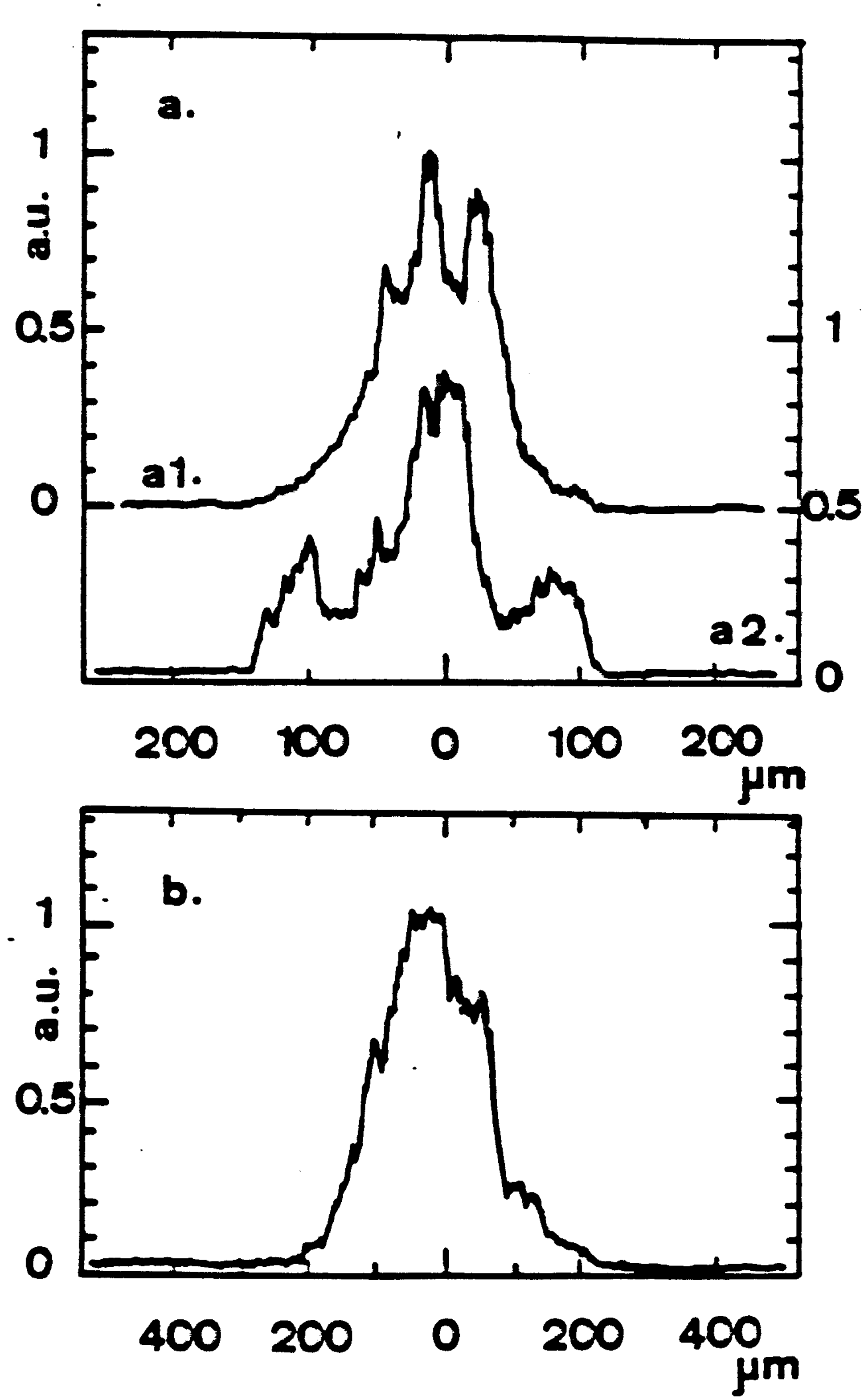
Data are from digitization of Vidicon images. In 4a, with optical fiber pulse generator, uniformity is greatly improved relative to 4b, with standard pulse generator.





Frame 4

Intensity profile of X-ray pinhole photographs obtained from gold targets, a : with standard pulse generator (a_1 - a_2 are analysis along two different axis), b : with optical fiber pulse generator ; modulations of less than 10 μm in width are due to the X-ray film.



STORAGE OF ENERGY BY SUPRACONDUCTIVITY

— —

1965 : Limeil demonstrated the storage of 0.1 Joule and the release of 5 watt.

1990 : We need to store and release several hundred million Joules

CONCLUSION

Limeil is developing several technological areas which will certainly be necessary for future laser commercial drivers.

Japanese View of Commercial Drivers for Laser Driven Reactotrs

3rd Inertial Confinement

Fusion Systems and Applications Colloquium

Institute of Laser Engineering

Osaka University

Outline

ILE Osaka

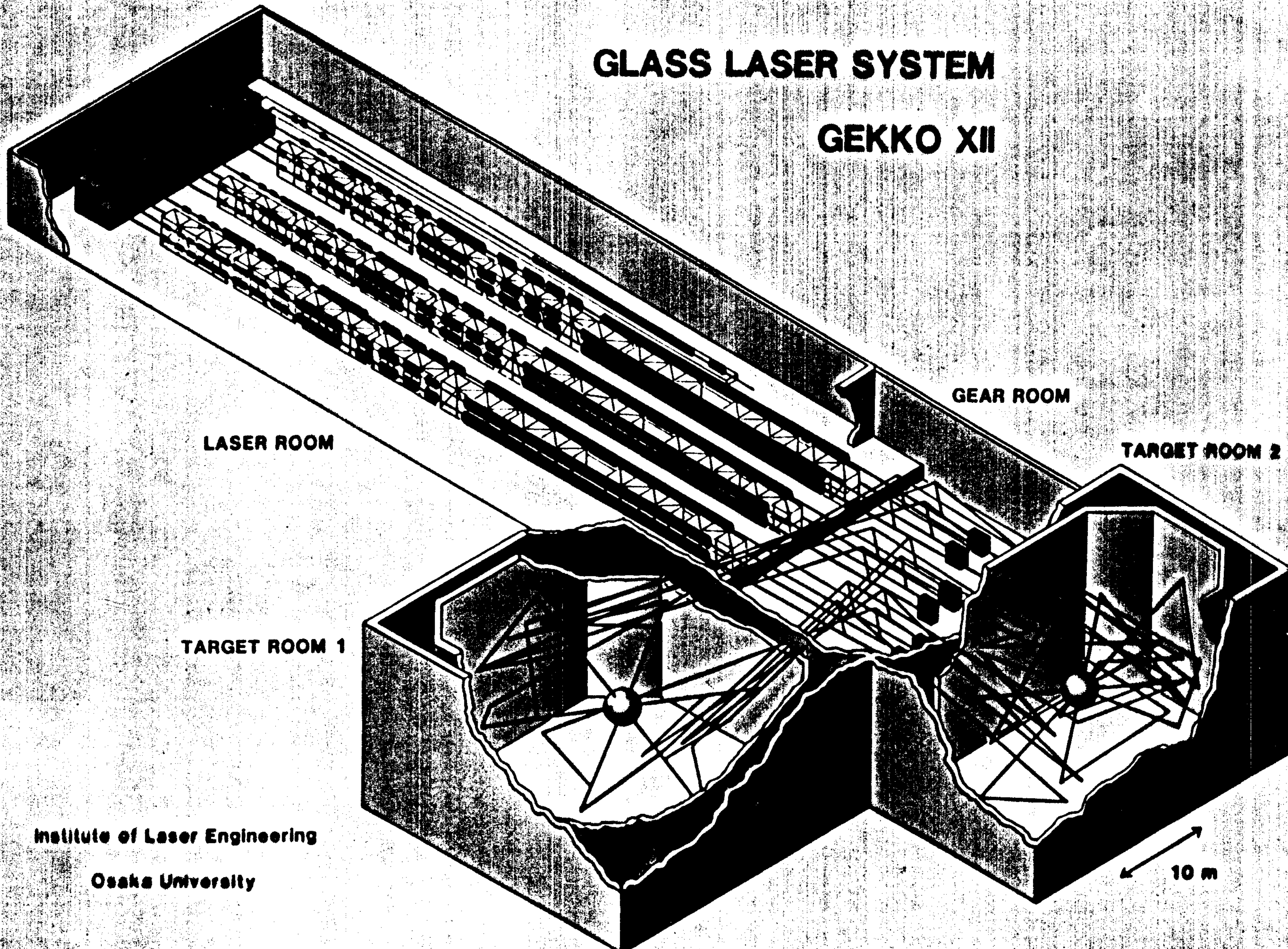
1 Progress in direct-drive implosion by GEKKO XII green laser

2 Approach to ignition and GEKKO XII up-grade

3 MJ laser design

GLASS LASER SYSTEM

GEKKO XII



Direct drive requires implosion stability and implosion symmetry

ILE Osaka

1. " Stagnation – free " implosion

    Large High Aspect Ratio Target (LHART)

    High neutron yield $n_y \sim 10^{13}$

    Coupling efficiency ~ 5.5 % , $Q \sim 0.2\%$

2. Random phased laser beam

    Smooth large scale illumination nonuniformity

    Higher ρR value achieved by RP laser

    $(\rho R)_{RP} > 10 \cdot (\rho R)$

High neutron yield experiments by LHART

ILE Osaka

GEKKO-XII Green laser

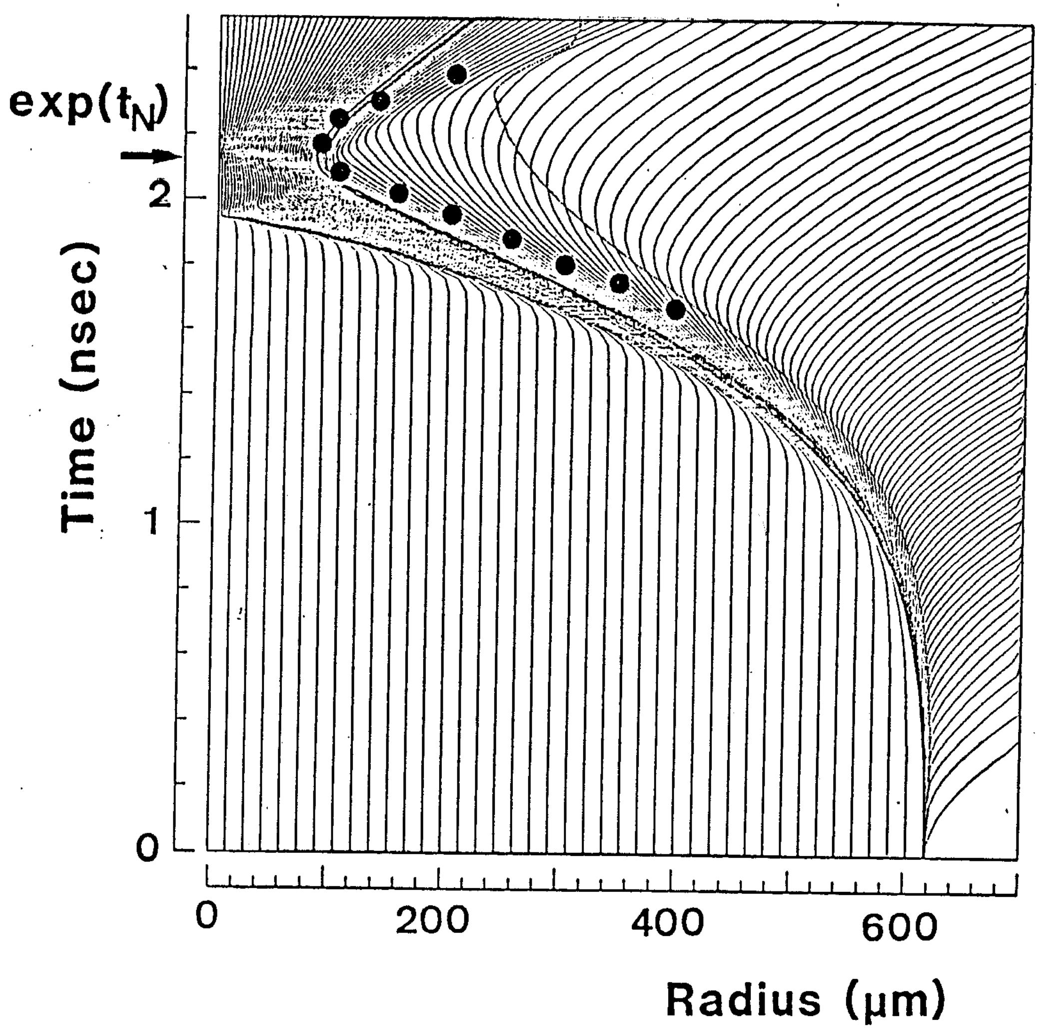
energy :	10 – 15 kJ
pulse width :	1 ns FWHM (Gaussian)

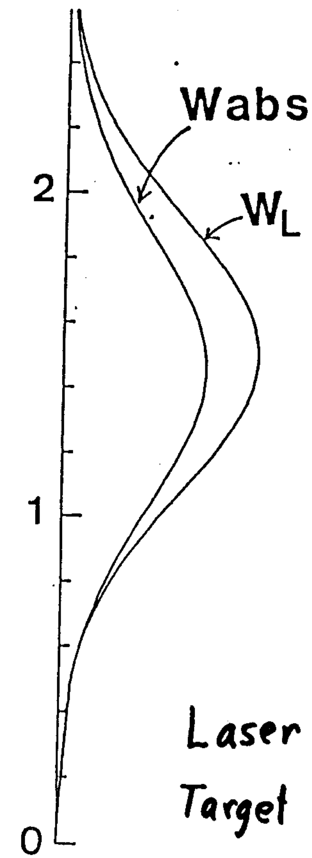
Target

diameter	700 – 1500 μm
wall thickness	0.9 – 2.5 μm
fuel pressure	1.5 – 8 atm (D-T)

ILESTA-BG code with flux limiter 0.04 well reproduces the observed implosion (shot #3826).

ILE Osaka





Laser 13 kJ/1 ns

Target 1235 μmϕ/1.31 μm

6.2 atm DT

(AR = 471)

Ny 9.8×10[12]

Neutron yield strongly depends on the target aspect ratio.

ILE Osaka

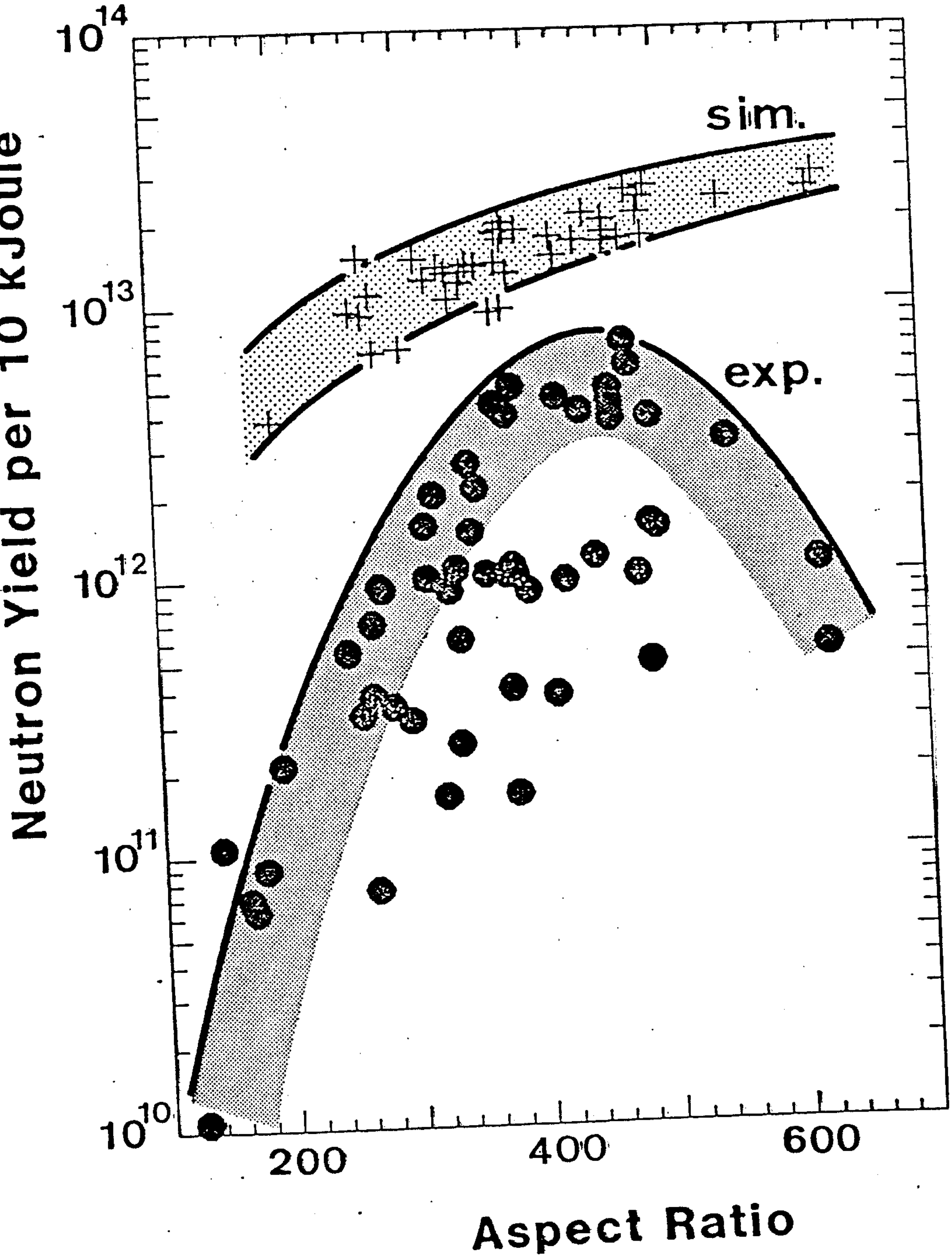
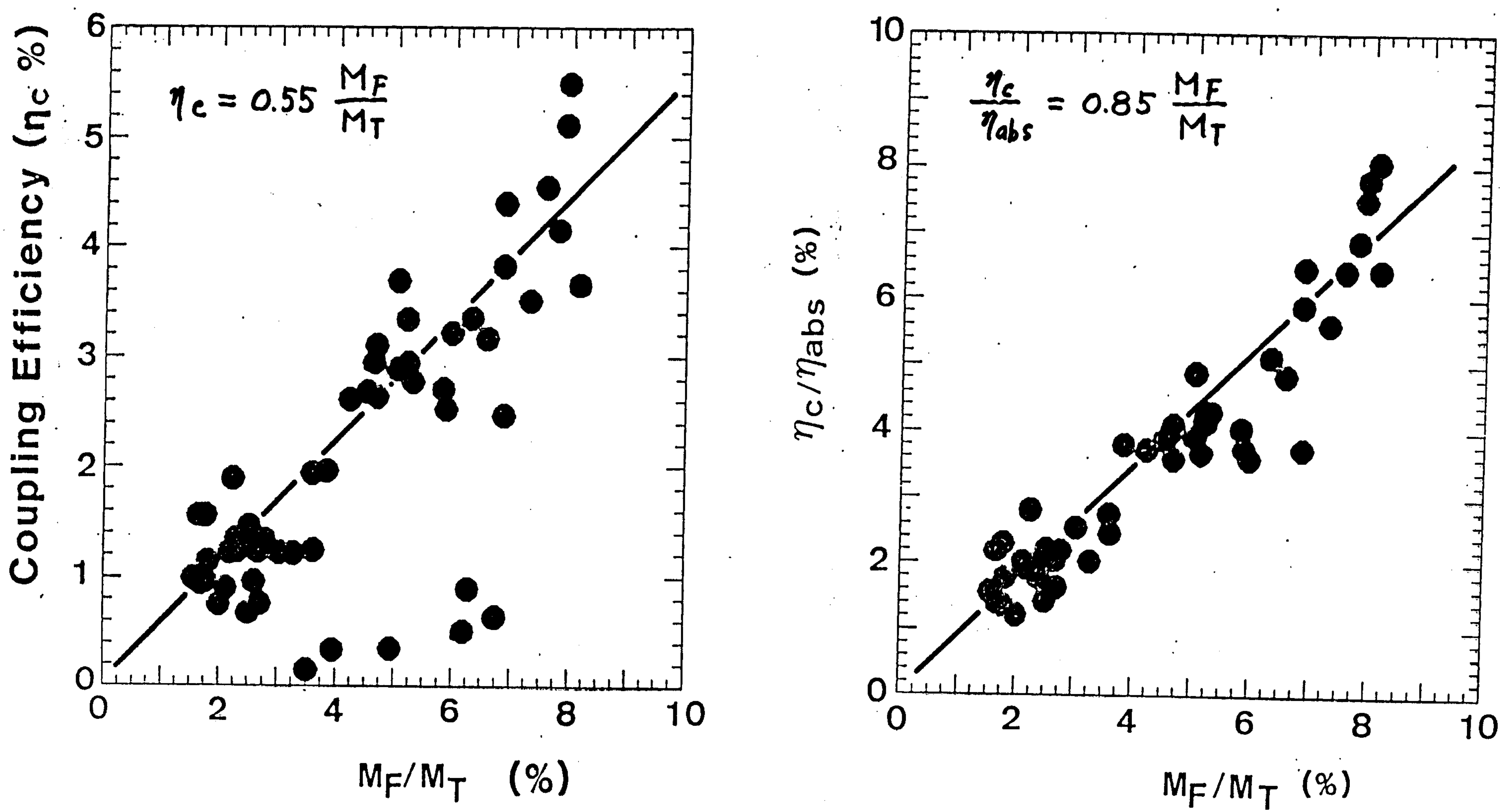


Fig. 4

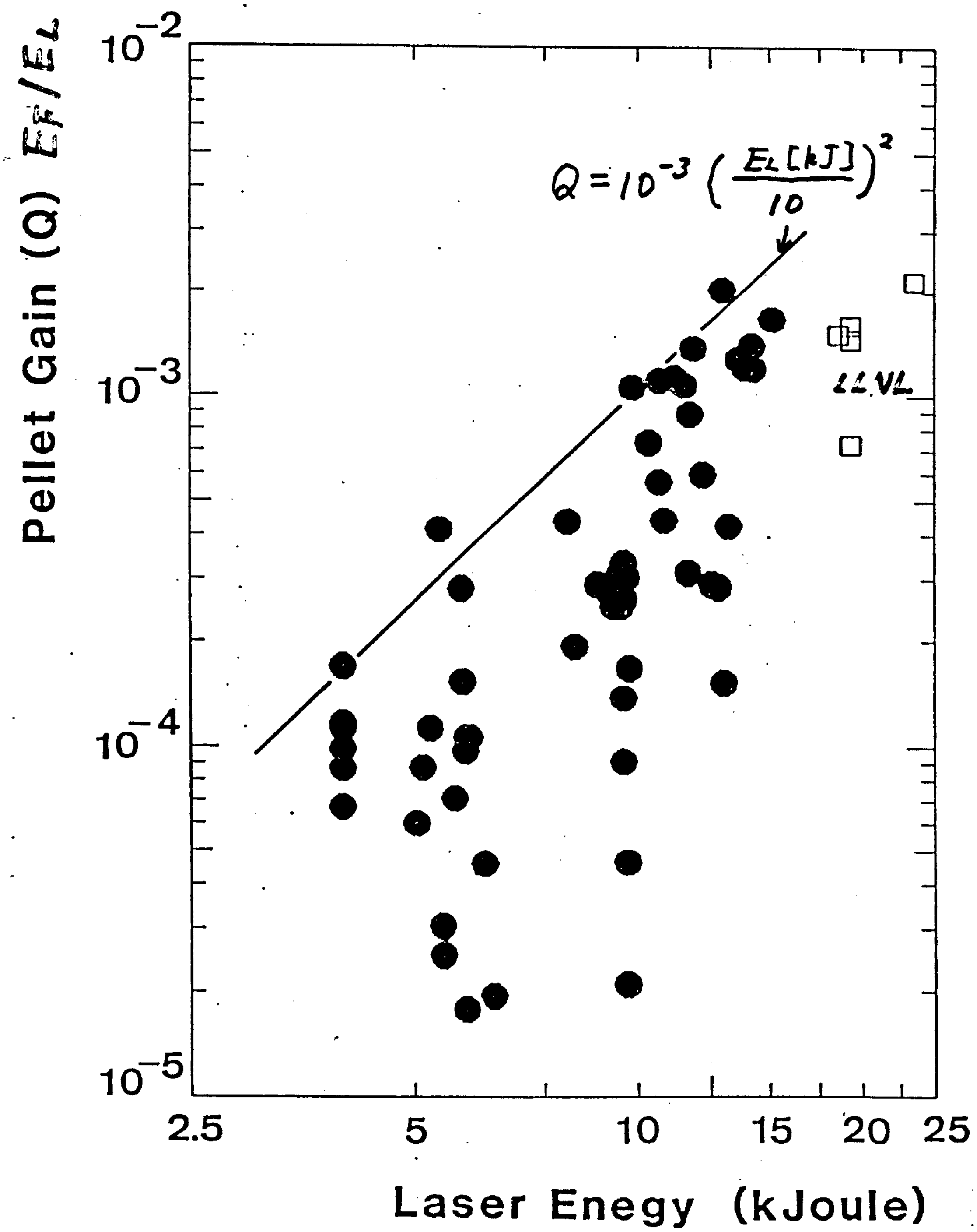
Coupling and transfer efficiency increase with a fraction of fuel mass.

ILE Osaka



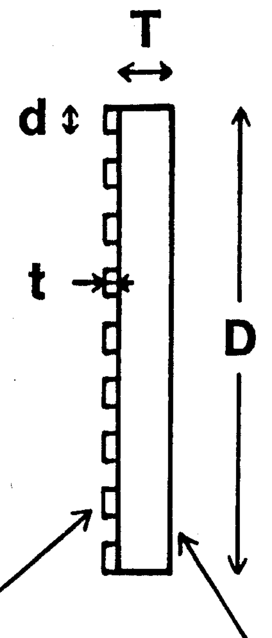
Pellet gain up to 0.2% has been achieved.

ILE Osaka



FABRICATION OF RANDOM PHASE PLATES FOR GEKKO XII

ILE OSAKA

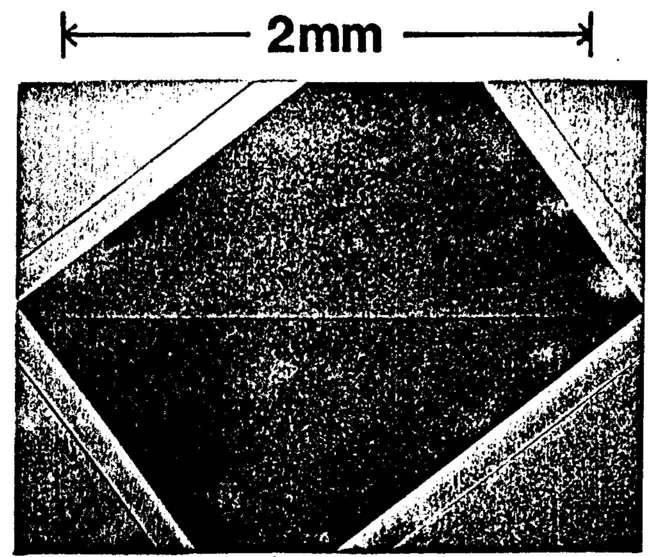


$D = 380mm$

$T = 15mm$

$d = 2mm$

$$(n-1)t = \frac{\lambda}{2}(1+\varepsilon)$$

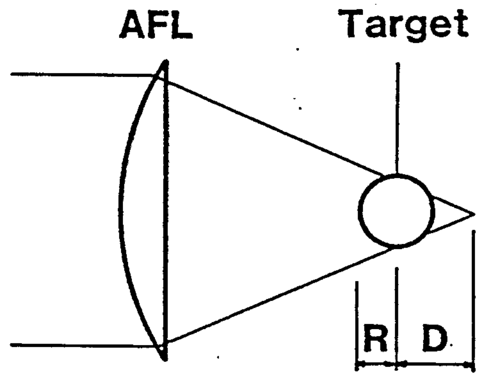


Performance

Thickness error	$\varepsilon = 0.03$	
Transmittance	$T = 0.95$	(526nm)
Laser damage	RP: $1.6-2.0J/cm^2$ AR: $2.5-3.0J/cm^2$	(526nm ,1ns)

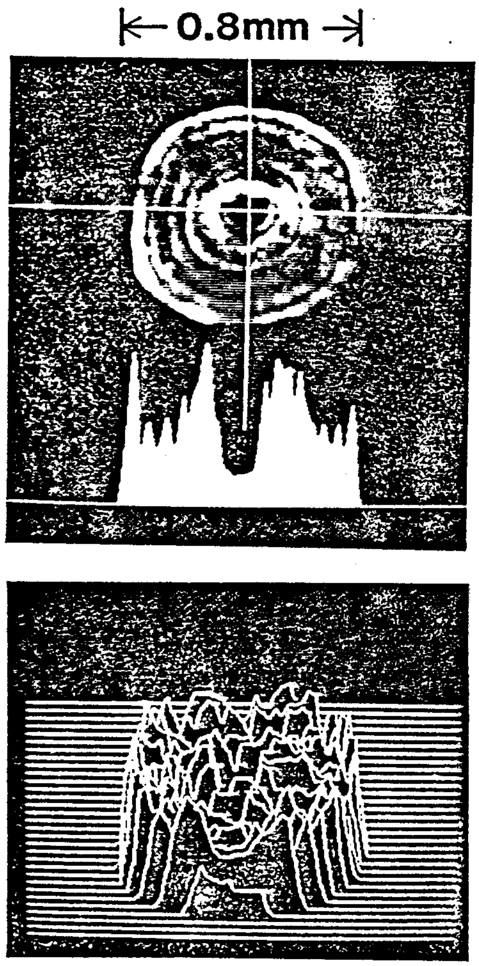
FOCUSING PROPERTY OF RANDOM PHASED WAVE

ILE OSAKA



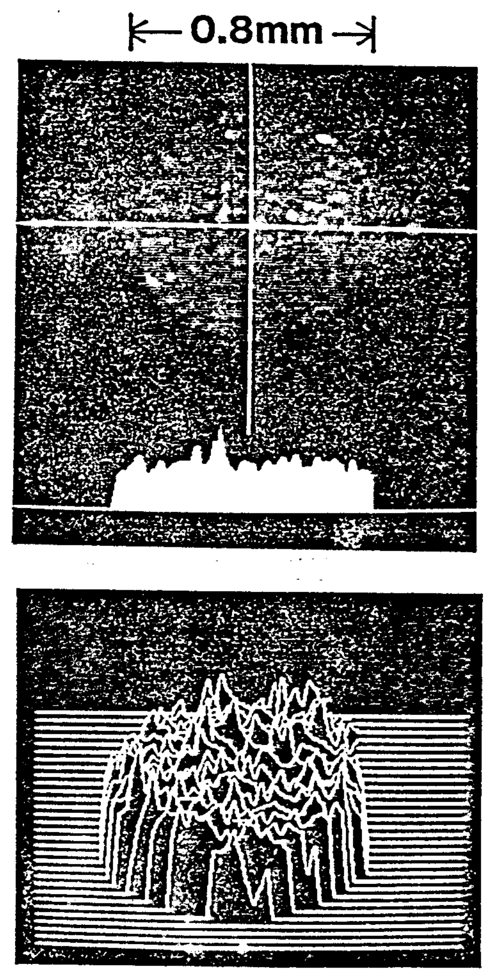
D/R=-5

R=500μm



F.F.=45.1%

Without RPP



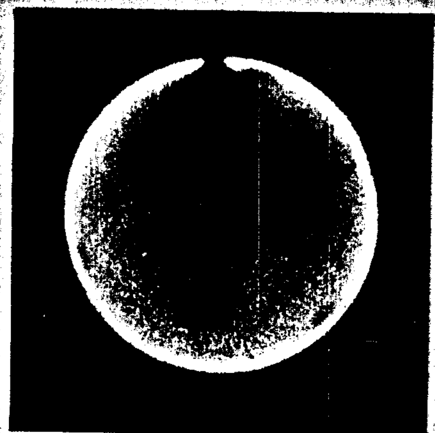
F.F.=51.8%

With RPP

Random Phase Plate Improves Irradiation Uniformity

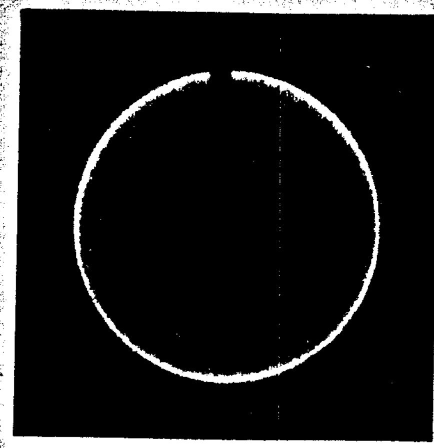
ILE Osaka

without RPP

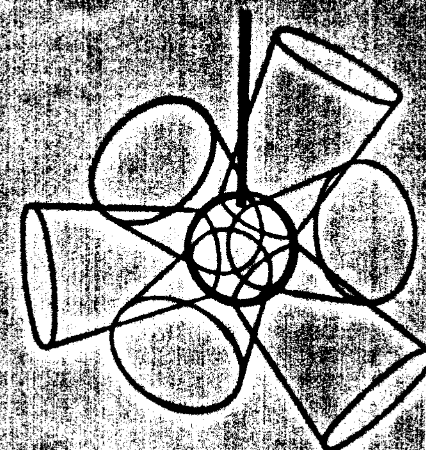


400μm

with RPP



400μm



Target : 800μm diam. steel ball

Laser : 0.53μm, 1.5kJ/100psec

Fuel ρR for CD Shell Targets

ILE Osaka

Target

Deuterated PS shell

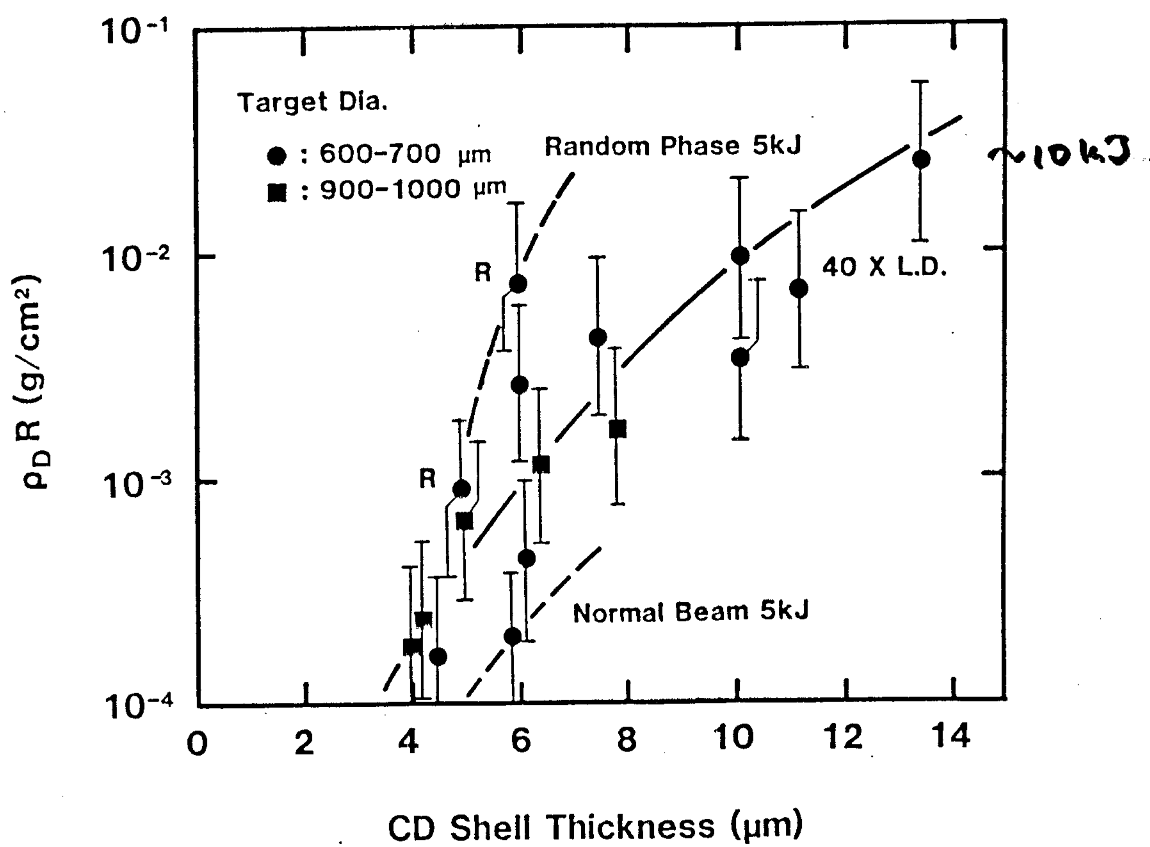
Laser

10kJ/0.8ns

(w/o RPP)

5kJ/0.8ns

(w and w/o RPP)



Approach to Ignition and Break Even at ILE

Direct Drive

LHART (Large High Aspect Target) : gas fuel

↓ $\eta_c \sim 6\%$, $Q \sim 0.2\%$, $N_y \sim 10^{13}$

CD shell target

↓ $\rho_D \sim 40 \times$ liquid density, (estimated) $\rho_D R \sim 25\ mg/cm^2$ (measured)

($\rho_{CD} R \sim 175\ mg/cm^2$)

Foam cryogenic target

GEKKO XII Laser

↓ $20\ kJ / 2\omega_0 / 1\ ns$, (10~15 kJ) $18\ kJ / 3\omega_0 / 1\ ns$ (1988 March)

Up-grade

$100\ kJ / 3\omega_0 / 2\ ns$

uniformity

beam number and balance, beam patern, random phasing

Development scenario to ICF reactor

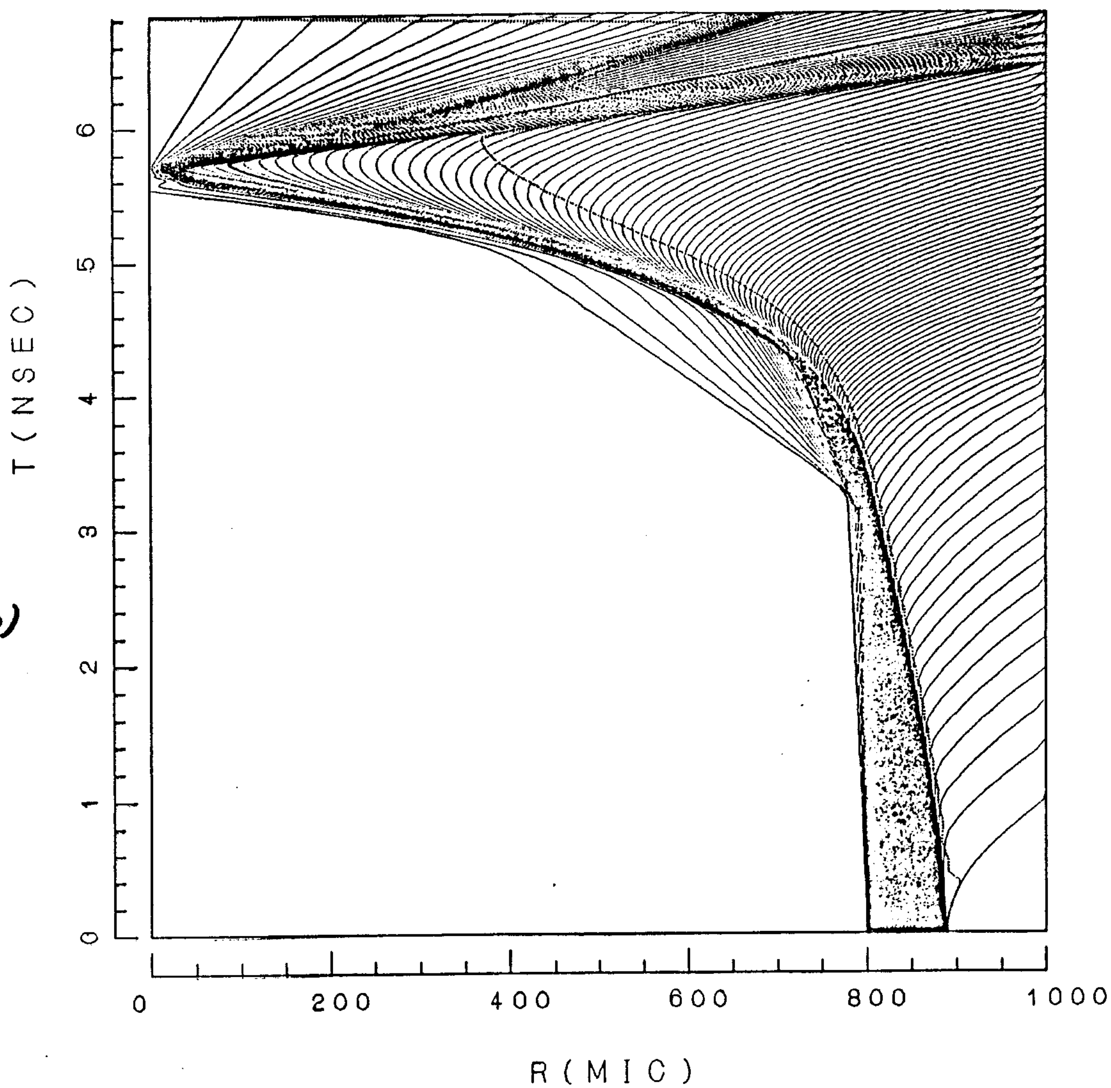
	I Ignition Experiment	II LFCX	III LFER	IV LFPR
Mission	Ignition (Scientific feasibility)	Burning (Engineering feasibility) · High gain pellet design · Reactor engineering · Intence neutron source	Reactor engineering test	Demonstration of power plant
Laser Pellet	Nd-glass 100 kJ Single shot Q = 1 10^{16} N/shot $\rho \geqq 1000\ \rho_0$(200 g/cm^3) $\rho R \geqq 0.3$ g/cm^2	Nd-glass 500 kJ - 1 MJ Single - 1 shot/min. Q = 10~100 10^{18}~10^{19} N/shot 5~50 MJ/shot $\rho \geqq 2000\ \rho_0$(400 g/cm^3) $\rho R \geqq 1$ g/cm^2	500 kJ - 1 MJ 1 Hz Q = 10~100 10^{18}~10^{19} N/sec 5~50 MWth	$\gtrsim$4 MJ 1 Hz Q = 50~500 10^2~10^3 MWE ρ~2000~4000 ρ_0 (400~800 g/cm^3) ρR~3~5 g/cm^3

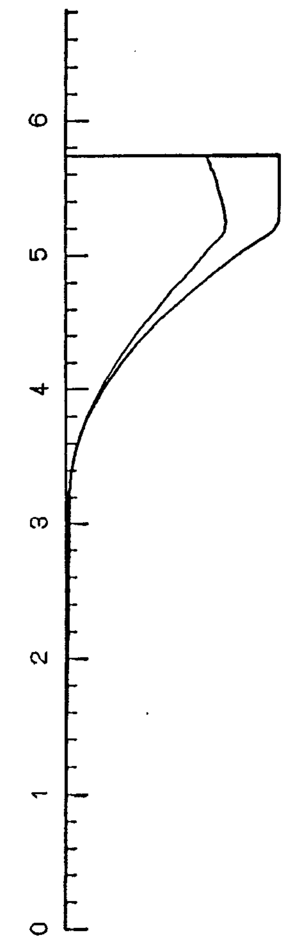
```
DATE=     87-08-03
TIME=     16:49:40
DATE     =0
STNO     =1000

*TARGET
  RO(MIC)=815.0
  TDTNO   =1.58x10^19
   MTL(1)  =1
   MESH(1)=40
   DR(MIC)=15.00
   FLLM    =0.100
   MTL(2)  =1
   MESH(2)=100
   DR(MIC)=75.00
   FLLM    =0.100

*LASER
  EL(KJ)  =50.00
  PW(NS)  =2.00
  WL(MIC)=0.35
  -D/R    =1.0

*PHYS.PARM
  F PRH   =0.000
  P PRH   =0.000
  IALPHA =1
  IAVI    =2
  IRAD    =1
  EO(KEV)=0.010
  E1(KEV) 20.000
```





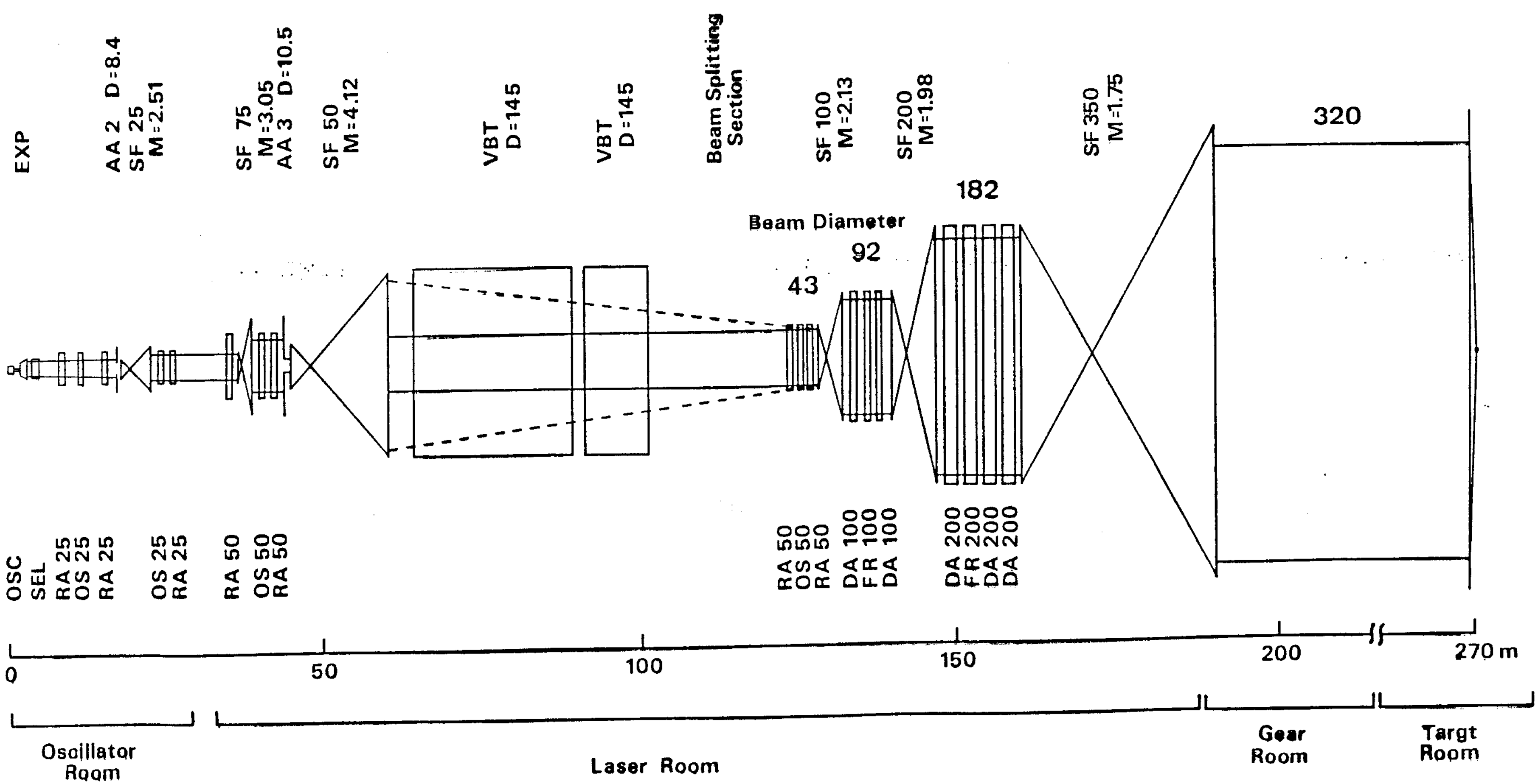
Laser
100kJ/2ns (3ω)
shaped pulse

Target
$R_0 = 880\mu m$
$A_0 = 10$
cryogenic

Core plasma
$T_i > 5keV$
$\rho R > 0.3\ g/cm^2$

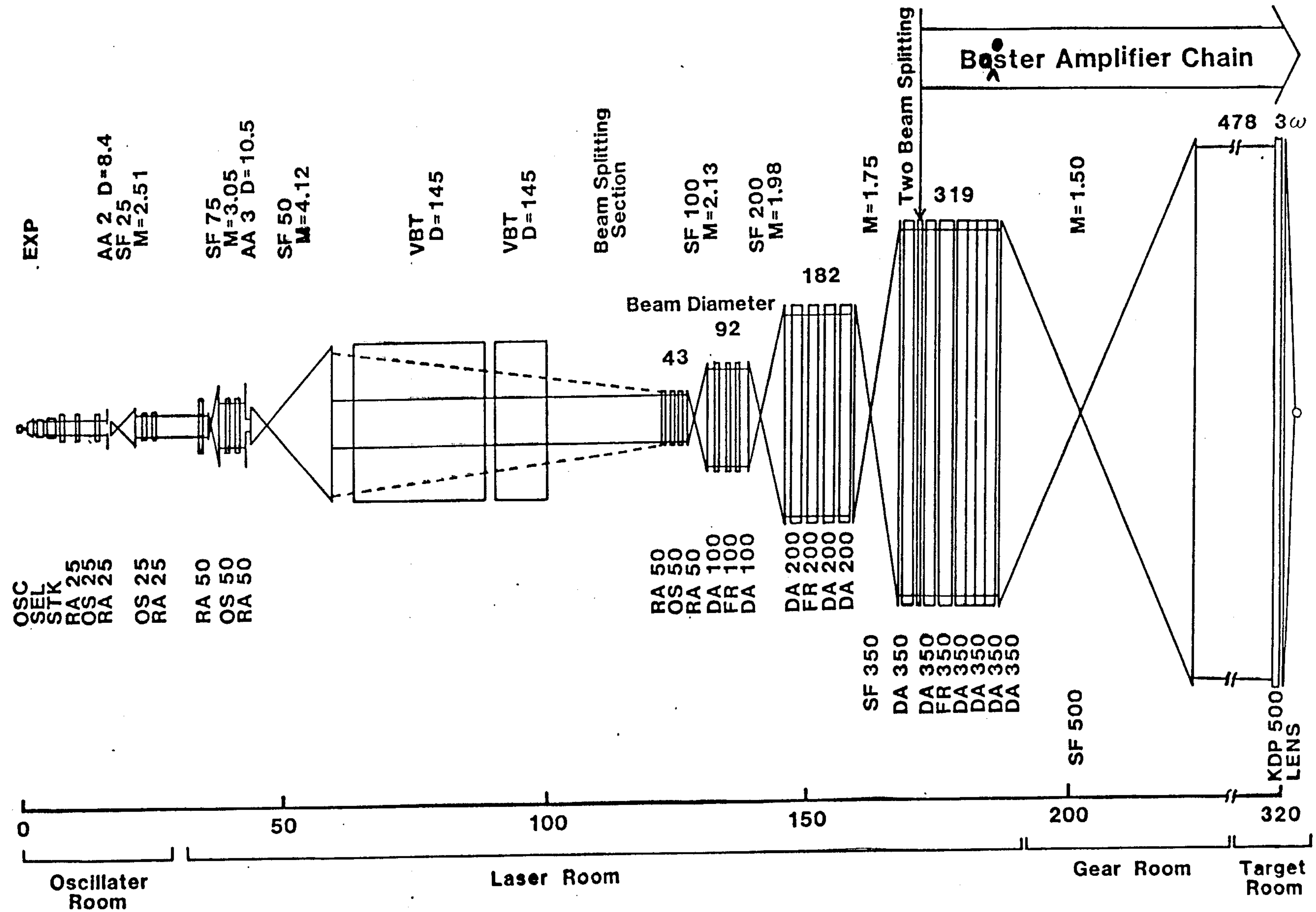
OPTICAL ARRANGEMENT OF GEKKO XII

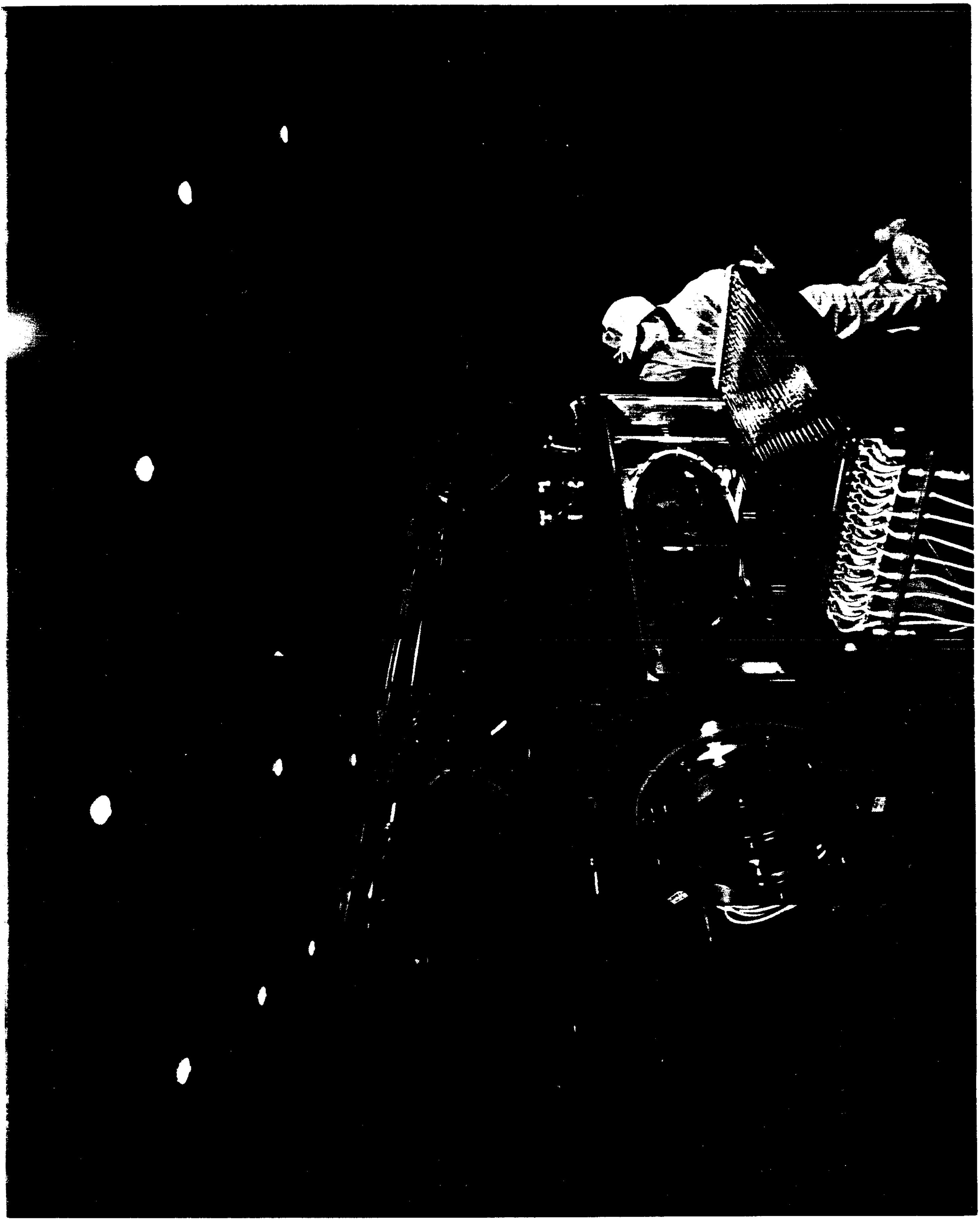
Institute of Laser Engineering Osaka University



OPTICAL ARRANGMENT OF GEKKO XII UP GRADE SYSTEM 3ω100kJ

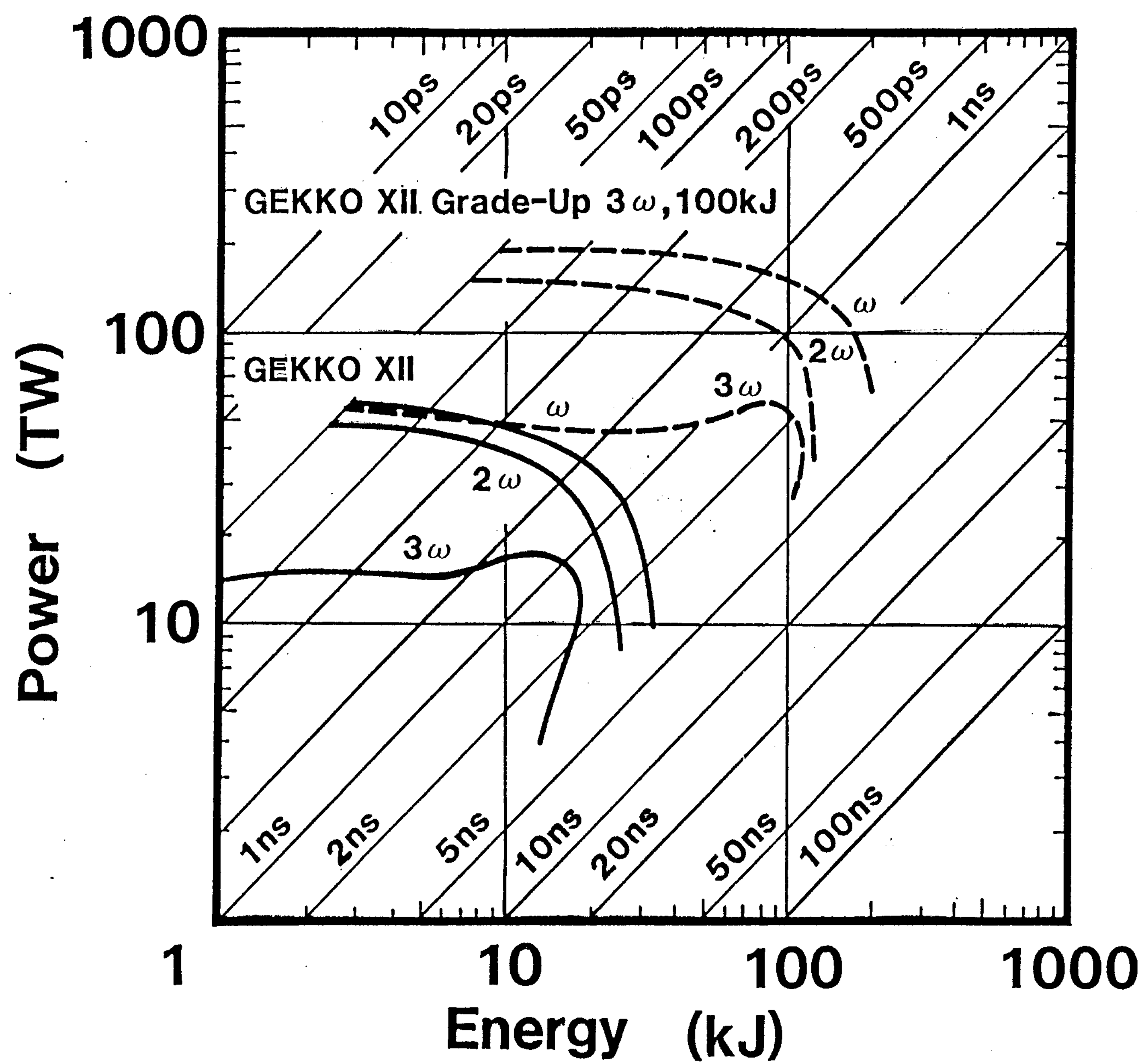
ILE OSAKA





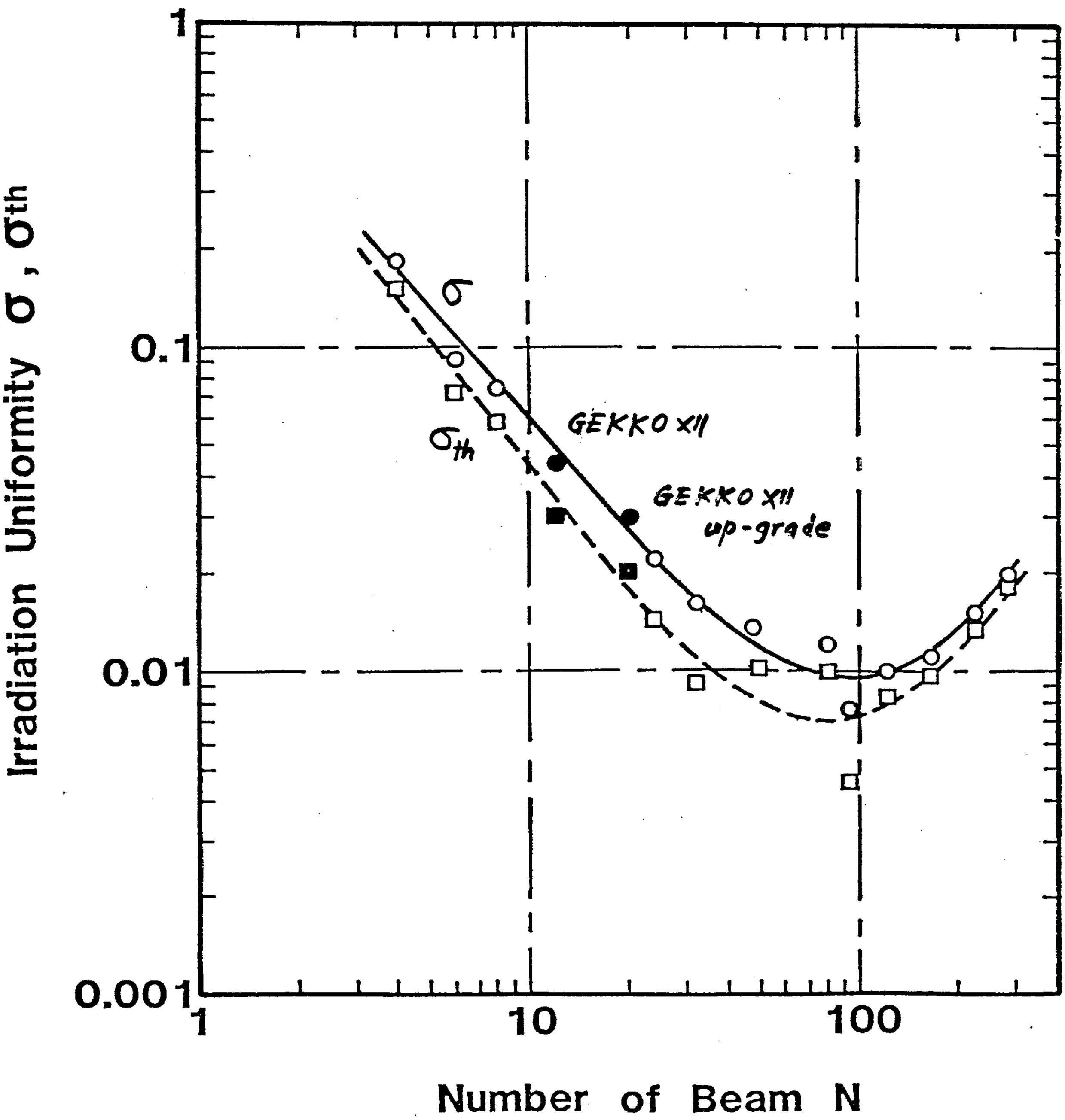
GEKKO XII Grade-up 3ω 100kJ System & GEKKO XII ω, 2ω, 3ω Performance

ILE OSAKA



Irradiation Uniformity

ILE OSAKA



(a) Energy	1MJ
(b) Peak Power	500TW
(c) Wavelength	0.35μm, 0.5μm, 1μm
(d) Pulse Shape	10ns Tailored pulse
(e) Efficiency	>1%

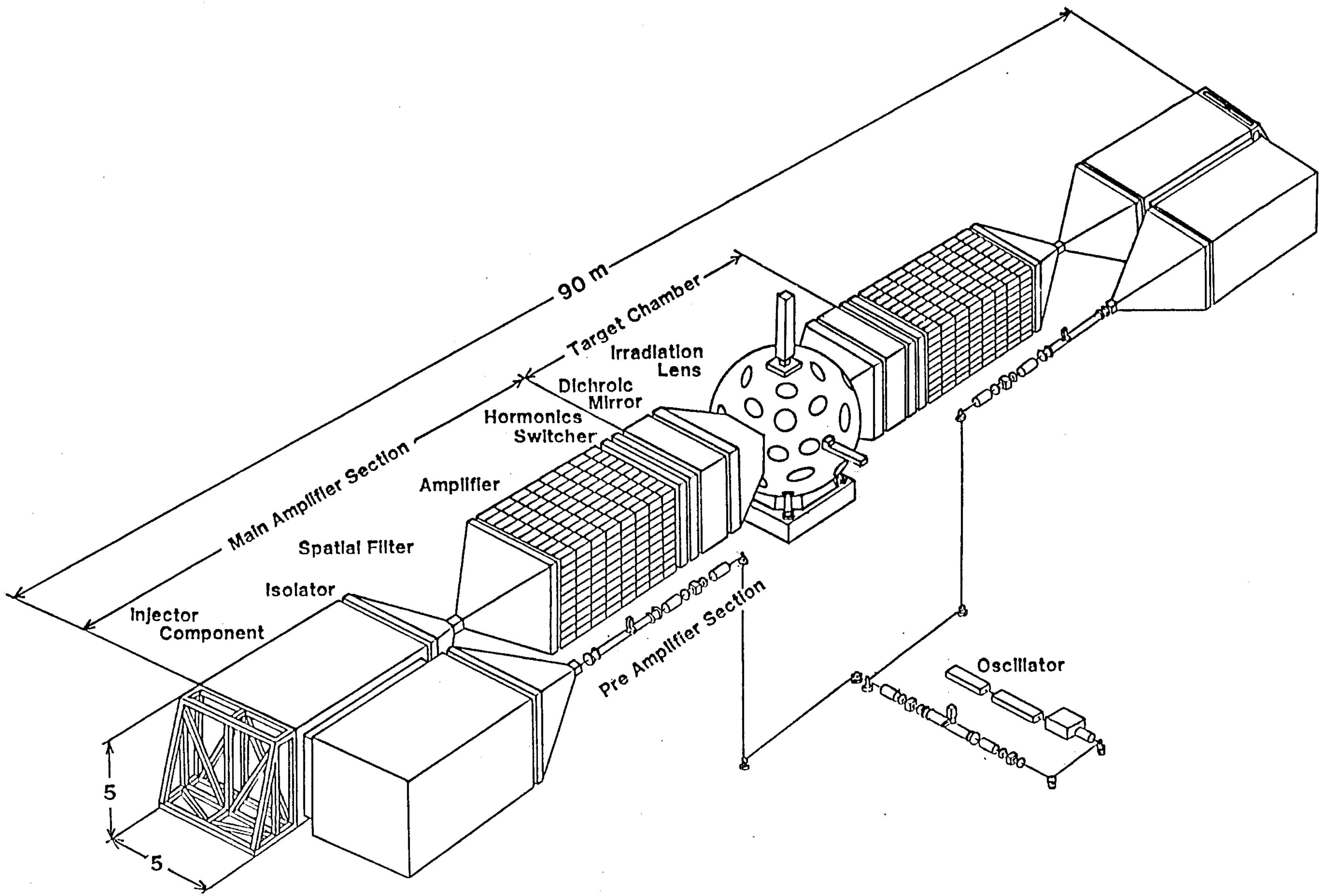
性能比較

System	GEKKOXII	GEKKOXII Up-Grade	MOPA G-XIIUpx10	Regenerative Amplifier
Energy 1 μm	30kJ	200kJ	2MJ	2MJ
0.35μm	15kJ	100kJ	1MJ	1MJ
Architecture	350mmφ	500mmφ	500mmφ	350x350mm
	200mmφ AMP	350mmφ AMP	350mmφ AMP	200segment
	12beam	24beam	240beam	2beam
Electro-Capacity	22MJ	74MJ	743MJ	116MJ
Efficiency	0.14%	0.27%	0.27%	1.72%
Size of system	20x120x5m	20x120x5m	100x120x5m	20x120x5m

	$\sigma\,10^{-20}$ [cm^2]	E_s [J/cm^2]	$n_2\,10^{-13}$ [esu]	Gain G	g_0 [%/cm]	Q_s [J/cm^3]	E_E [kJ]	Energy [kJ]	η_L [%]
LHG8	4.0	3.75	1.13	7	4.05	0.192	581	10.8	1.72 → 8.4%
LSG91H	2.7	4.12	1.58	6	3.73	0.261	792	10.8	1.26
LHG10	2.7	4.9	0.61	5	3.35	0.235	713	11.1	1.40

Mega Joule Glass Laser System

ILE OSAKA



Summary

ILE Osaka

1. "Stagnation-free" implosion showed good implosion properties
   → high Y_n, η_c, Q

2. Random phasing improved illumination nonuniformity
   → higher ρR

3. 100kJ "GEKKO XII up-grade" is expected to reach ignition condition.

4. MJ laser is designed with efficiency > 1%.

Achieving Adequate Beam Quality for Commercial Laser-Fusion Reactors

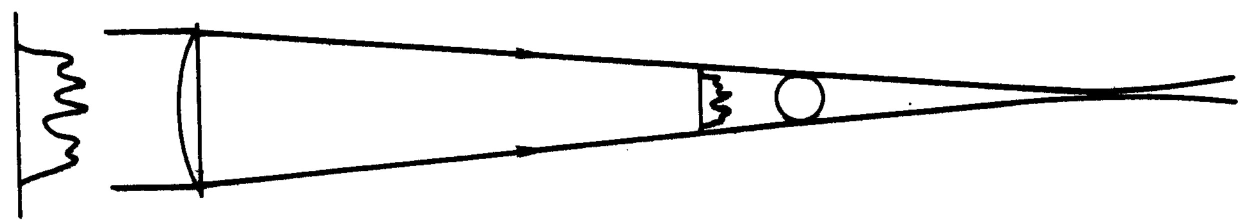
S.P. Obenschain, R. H. Lehmberg, A.J. Schmitt, S.E. Bodner

U.S. Naval Research Lab

1. Currently proposed beam-smoothing techniques

2. Constraints on the techniques for commercial reactors.

3. Effects of the constraints on the applicability of the beam-smoothing techniques.



PELLETS NORMALLY IN "QUASI-NEAR-FIELD"

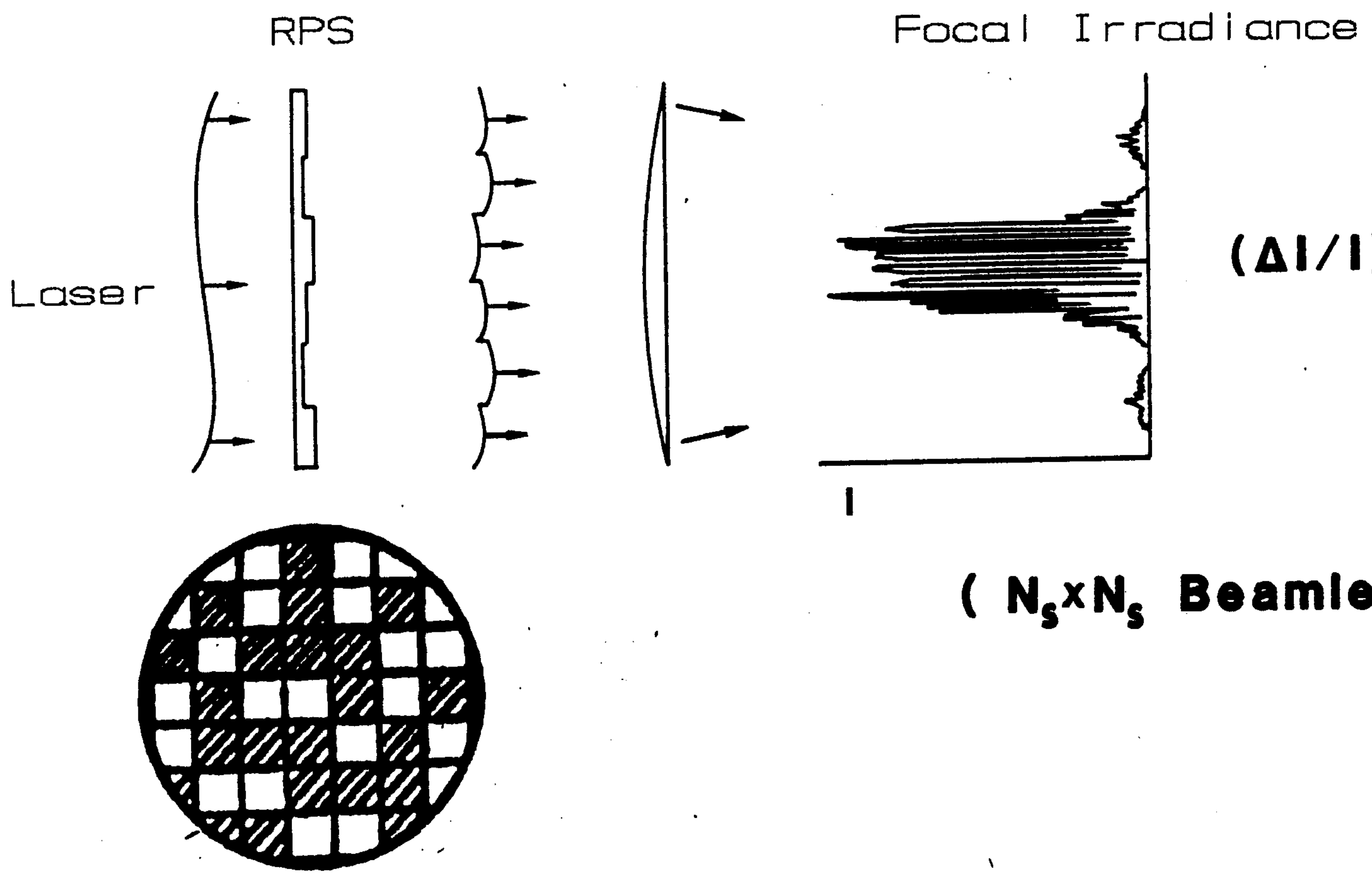
LASER NONUNIFORMITIES MAPPED ONTO PELLET

Lasers have much more coherence than is needed for Inertial Fusion.

CAN WE EXPLOIT THIS?

NRL

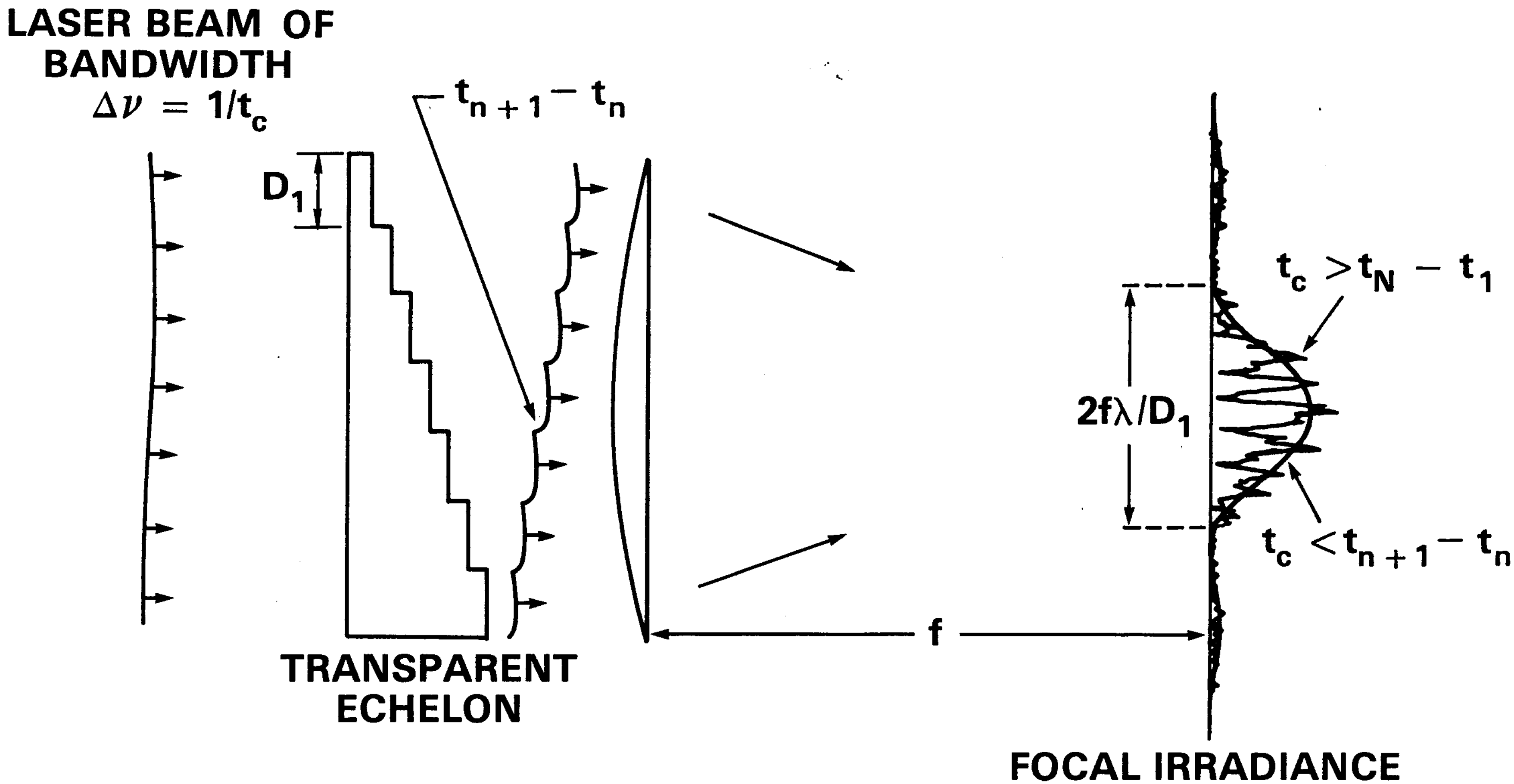
Beam Smoothing By a Random Phase Screen (RPS)



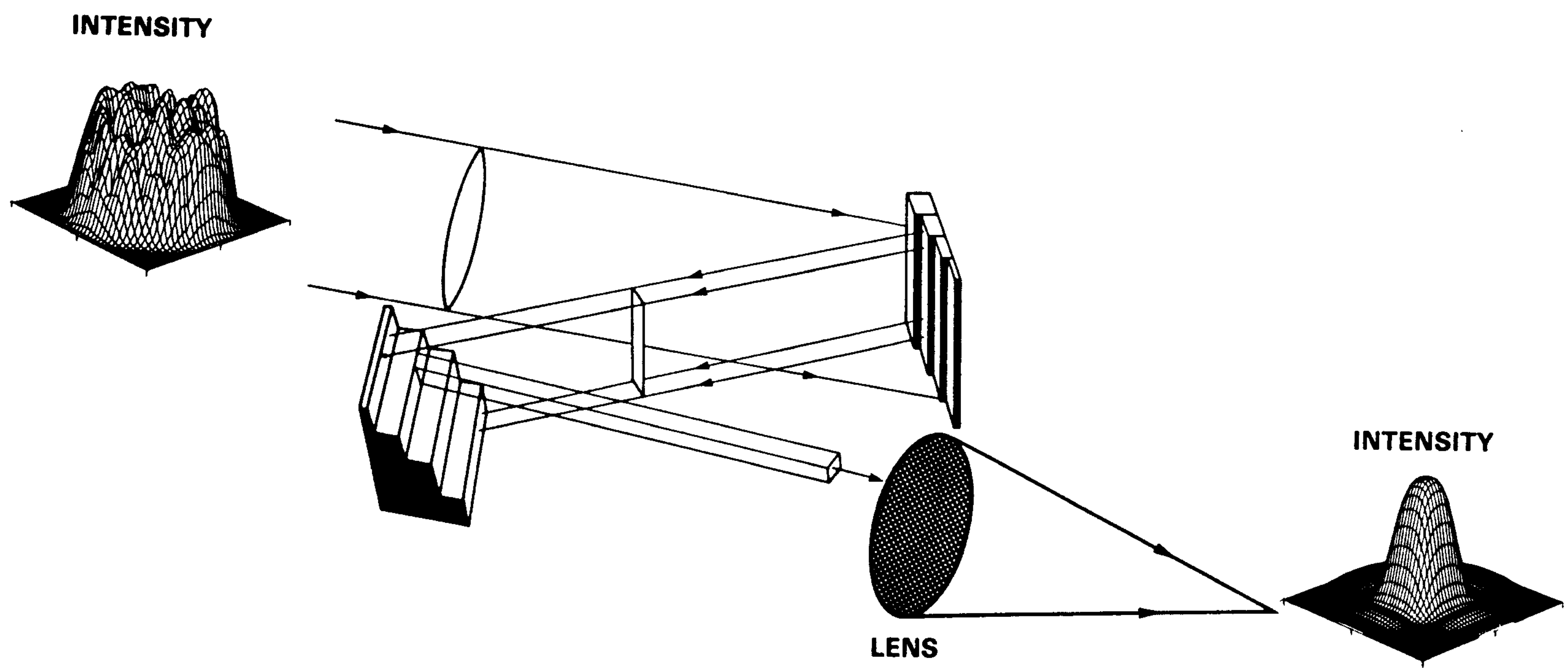
$(\Delta I/I)_L \propto 1/N_S$

($N_S \times N_S$ Beamlets)

BEAM SMOOTHING BY INDUCED SPATIAL INCOHERENCE (I.S.I.)

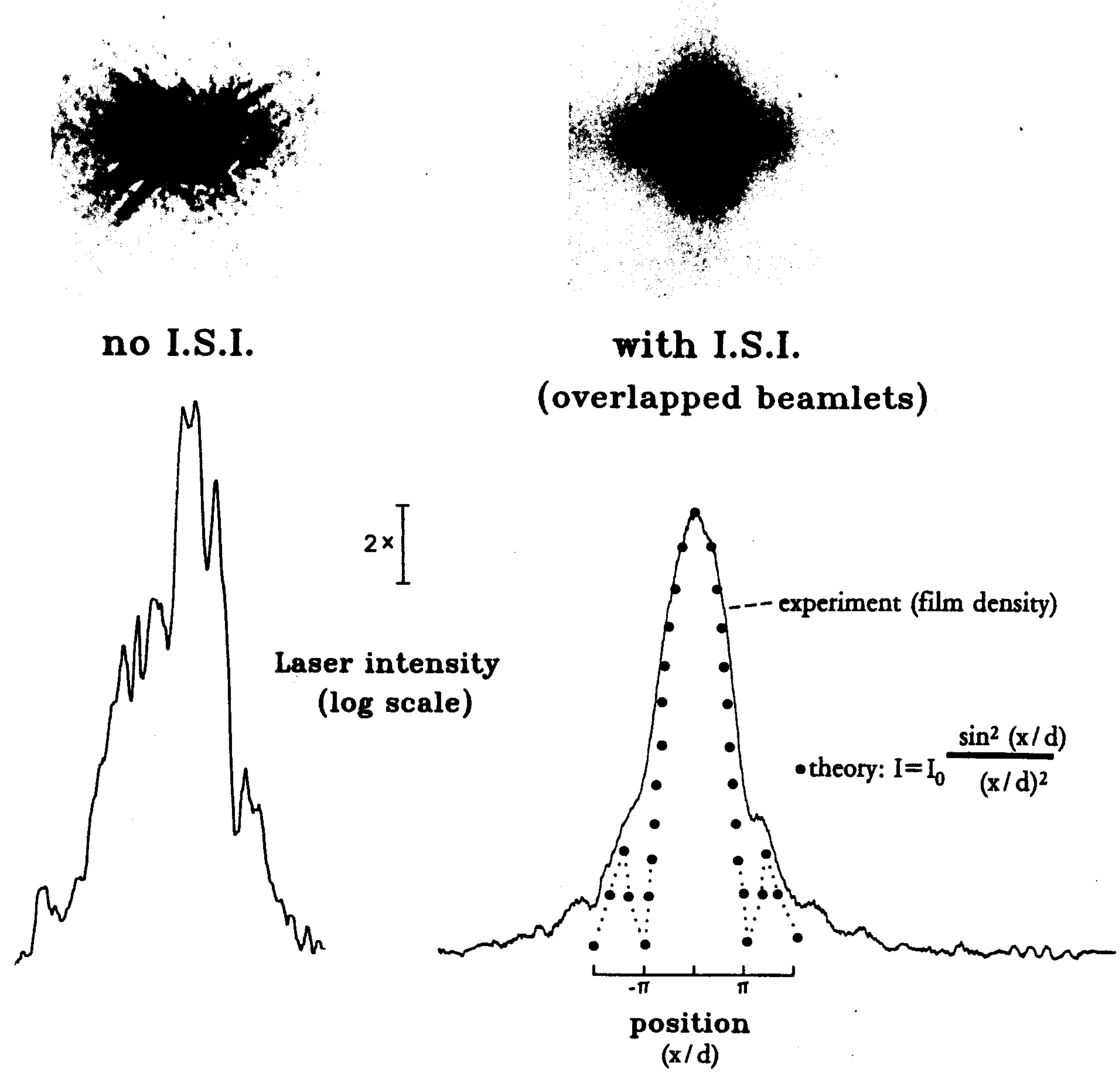


I.S.I. IN TWO TRANSVERSE DIMENSIONS
(REFLECTION MODE)



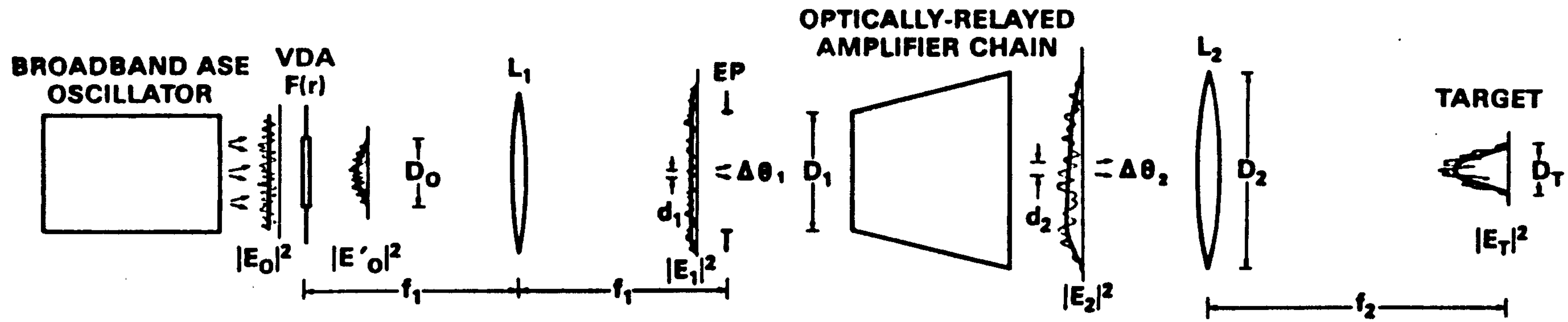
Focal Distributions with and without I.S.I.

(green laser)

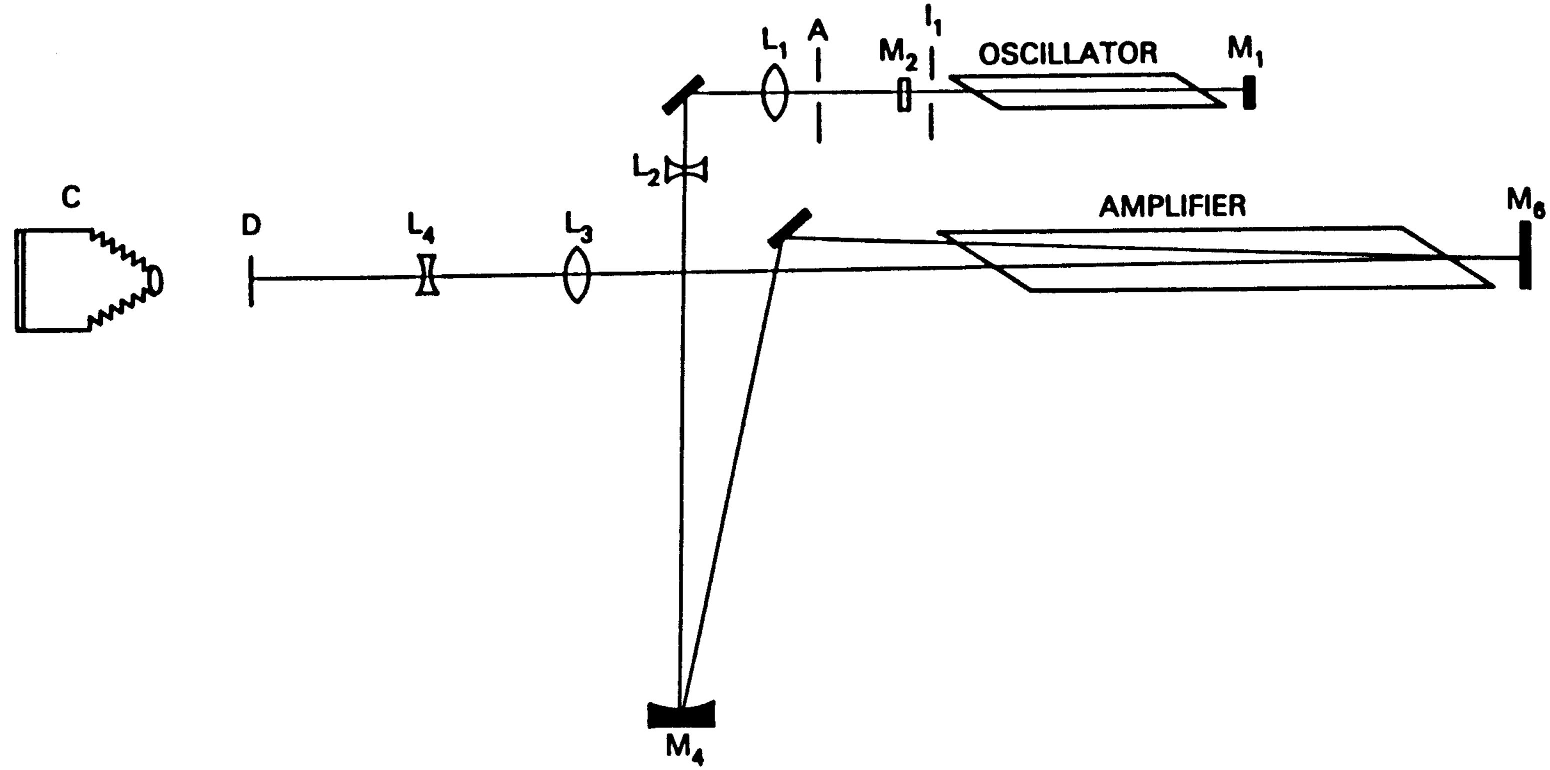


ECHELON–FREE ISI:

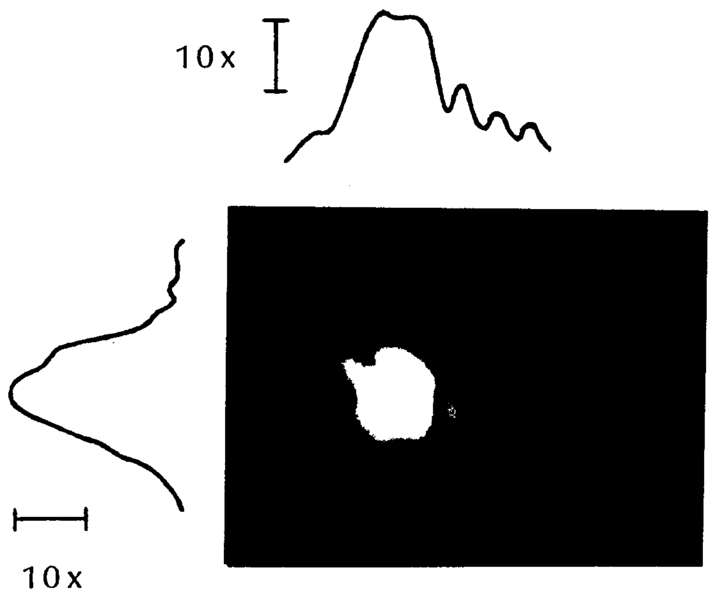
INFORMATION NEEDED TO REPRODUCE F(r) IS TRANSPORTED THROUGH THE ABERRATED LASER BY A MULTITUDE OF SMALL COHERENCE ZONES



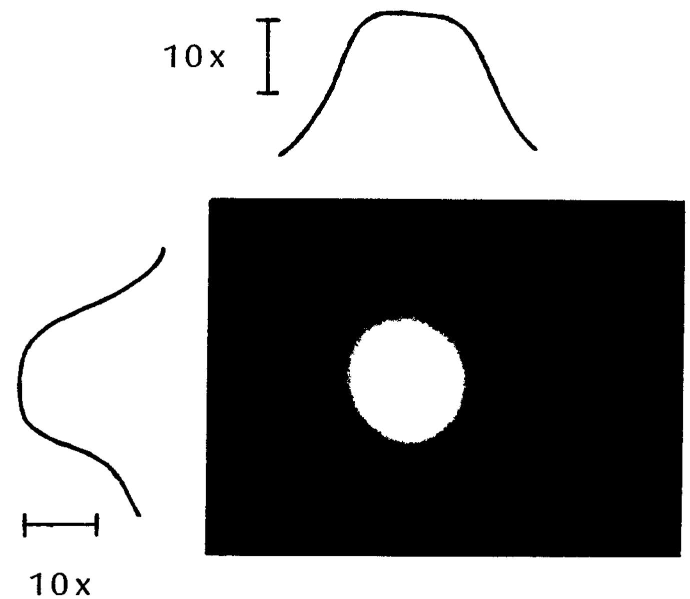
BROADBAND OSCILLATOR/AMPLIFIER SETUP WAS USED TO TEST INCOHERENT BEAM SMOOTHING WITHOUT ECHELONS



OUTPUT PROFILES SHOW BEAM SMOOTHING WITH SPATIALLY INCOHERENT APERTURE ILLUMINATION



coherent illumination



incoherent illumination

Constraints on the Laser for Beam-Smoothing

RPS: beam near perfect on spatial scale of the diffraction elements

ISI: above requirement plus broad laser bandwidth

Echelon-Free ISI: above requirements plus the nonlinear phase shifts must be small and diffraction of the small beamlets propagating through the laser system must be controlled

Applicability of Beam Smoothing to Current Lasers

RPS: can work with all current laser drivers
(glass and 2nd,3rd and 4th harmonics, KrF)

ISI: glass and 2nd harmonic of glass, KrF

Echelon-free ISI: KrF

Constraints on Beam Smoothing Techniques for Commercial (direct drive) Reactors

1. The final focusing optics must present a small solid angle to the target (large F#'s)

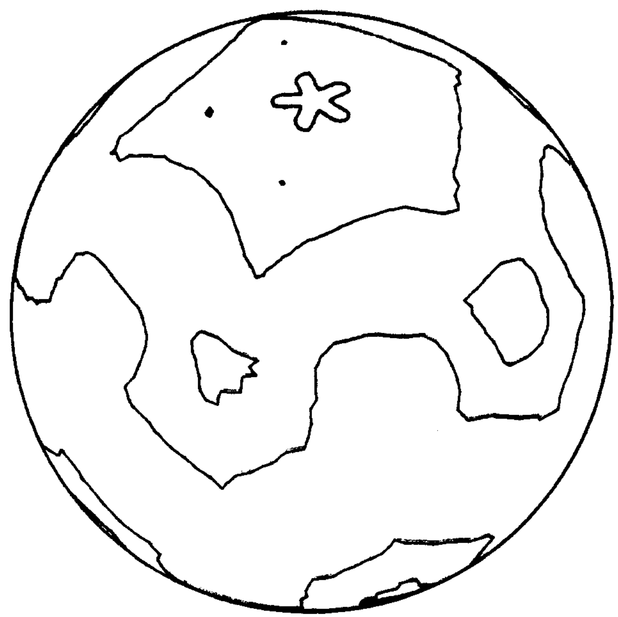
2. Ability to produce 1% or better ablation pressure uniformity on the pellet

3. Benign effects on interaction physics

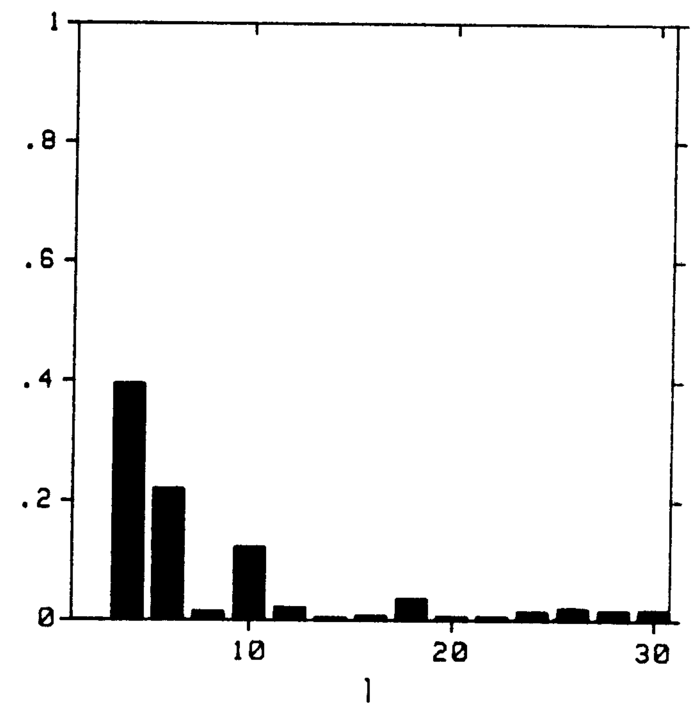
4. Costs match benefits

Calculations indicate highly uniform ablation pressures can be obtained with I.S.I. in spherical geometry

Pressure Distribution
(0.5% contours)



Spherical
Harmonic
Coefficients
(%)

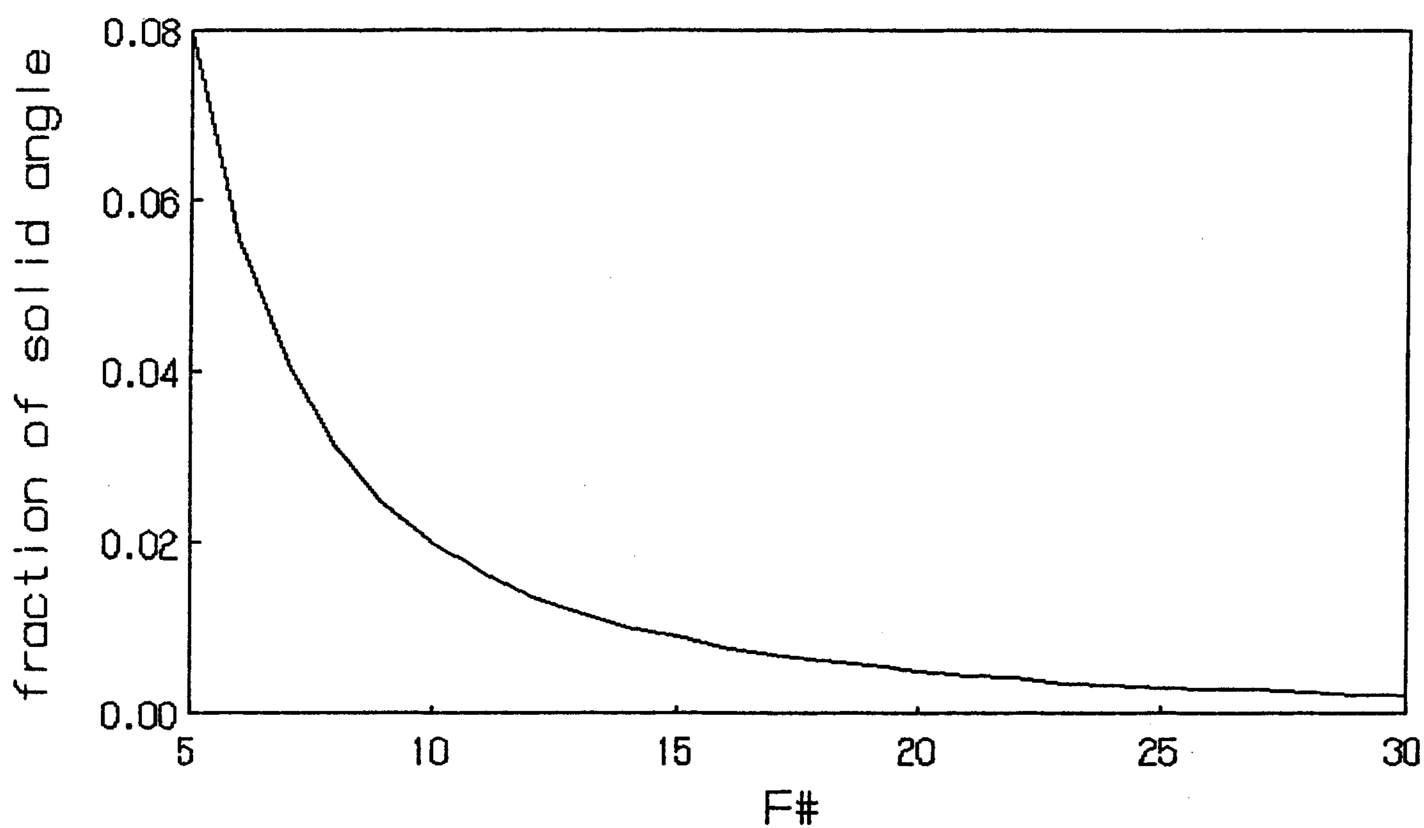


(32 beams, 250 nm laser)

What Are "Large" F#'s?

F# = focal-length / diameter of optic

The fraction of solid angle subtended by the final focussing optics is plotted below as a function of F# for the case of 32 laser beams.
Fractions below 1% require F#'s larger than 14.



With ISI, the pressure variation at the ablation surface is small, even with high F# optics.

$$\frac{\Delta P_{rms}}{P} \simeq \left(\frac{t_c}{\tau}\right)^{1/2} \left(\frac{F\lambda}{\sqrt{2}\pi d}\right)$$

(where d is the separation between the absorption and ablation radii)

$$\simeq \left(\frac{1ps}{1000ps}\right)^{1/2} \left(\frac{100 \times 1/4\mu m}{1.4 \times \pi \times 30\mu m}\right) \simeq 0.6\%$$

With RPS, the pressure variation is only small with low F# optics.

$$\frac{\Delta P_{rms}}{P} \simeq \left(1\right)^{1/2} \left(\frac{3 \times 1/4\mu m}{1.4 \times \pi \times 30\mu m}\right) \simeq 0.6\%$$

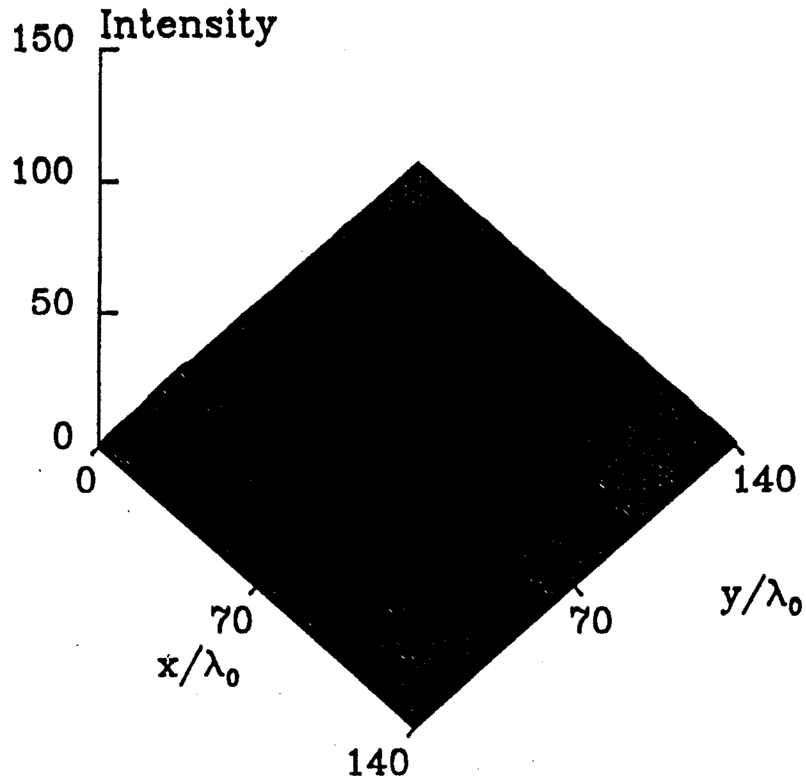
ISI suppresses filamentation

$\lambda_0 = 1\mu m$

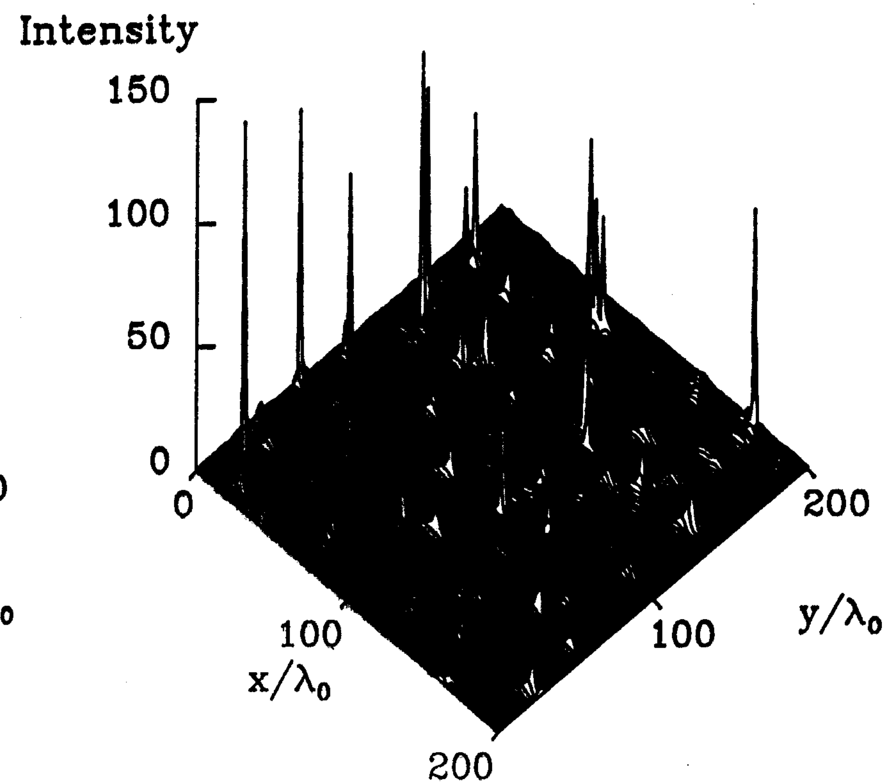
$I_0 = 10^{14} W/cm^2$

$n_e = 0.5 n_{crit}$

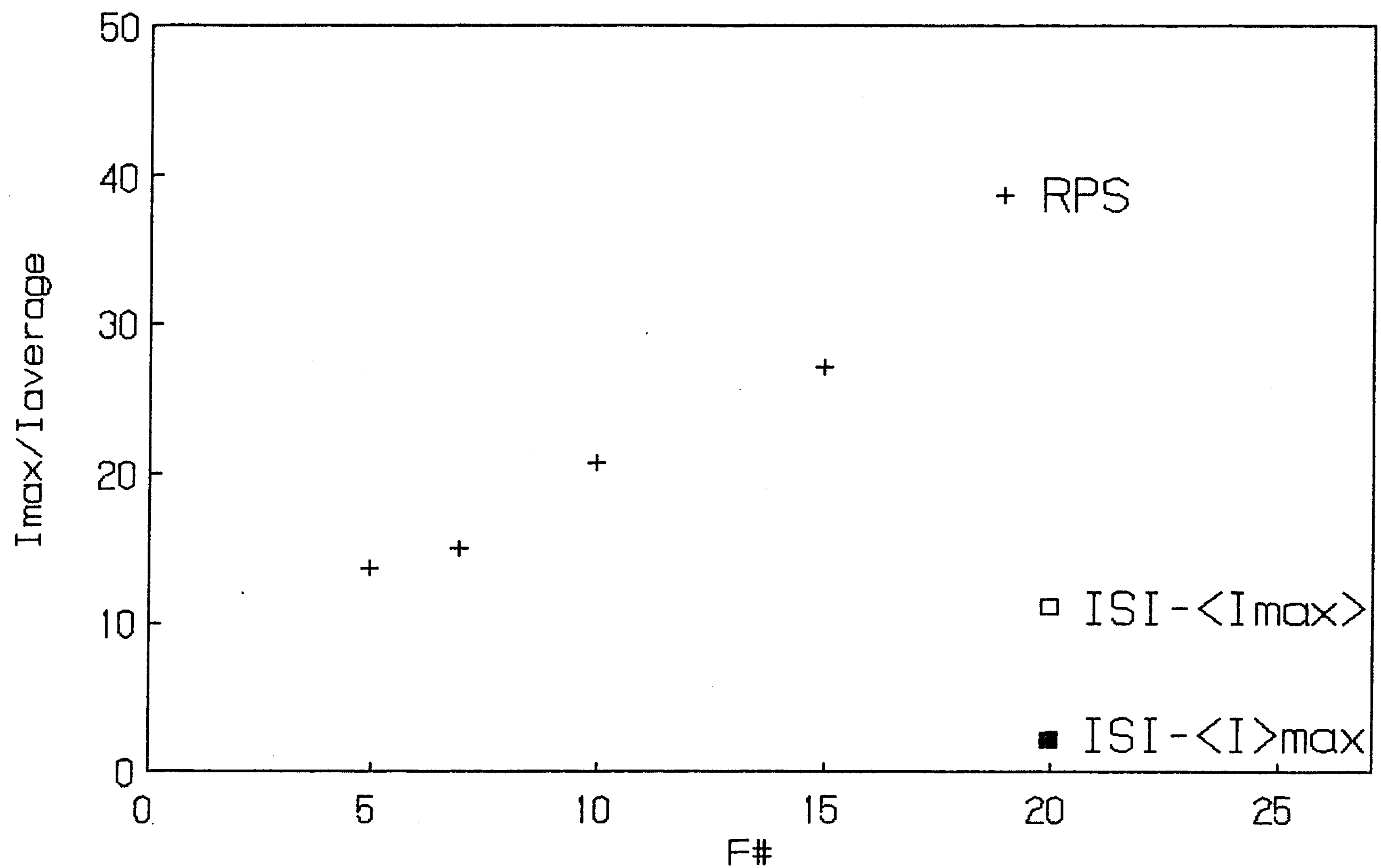
ISI: $100t_c$ time average



NO ISI



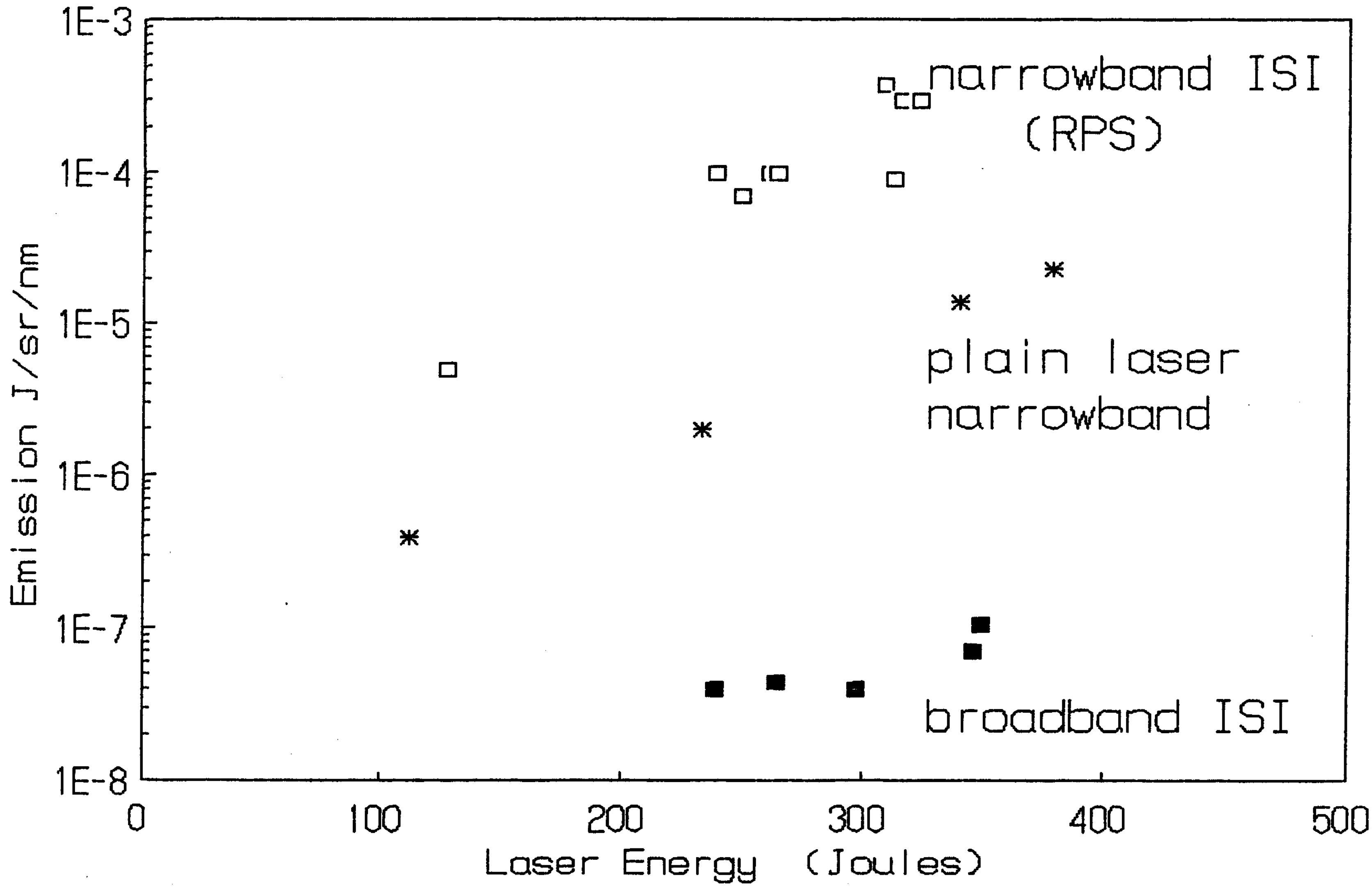
2-dimensional simulations of laser-target interaction with a single 250 nm laser beam indicate that filamentation occurs with RPS at large F#'s



Raman Emission With and Without ISI

1054 nm Laser, F#=10

<Intensity>= 1.2 E14 W/cm^2 at 300 Joules



Effects of Commercial Reactor Constraints

The high F# requirement limits the beam-smoothing techniques to schemes with both temporal and spatial averaging such as ISI or echelon-free ISI.

RPS, which utilizes spatial averaging only, requires low F#'s to obtain the ulta-uniform pressures required for direct drive and it probabably requires low F#'s to avoid laser-plasma instabilities.

Session 2: Light Ion Beam Fusion

1. Don Cook (SNL)
2. Terry Crow (SNL)
3. Rick Olson (SNL)
4. Malcolm Buttram (SNL)
5. Shuji Miyamoto (Osaka)

87TDD1000.23

PULSED POWER DRIVER TECHNOLOGIES FOR INERTIAL CONFINEMENT FUSION POWER REACTORS

D.L. COOK

Sandia National Laboratories

NOVEMBER 9-11, 1987

3rd INERTIAL CONFINEMENT SYSTEMS
AND APPLICATIONS COLLOQUIUM

ICF DRIVERS FOR POWER REACTORS FACE STRINGENT REQUIREMENTS

- 5 - 20 MEGAJOULES ENERGY
- $>$ 10% EFFICIENCY
- $>$ 100 TW/cm^2 POWER CONCENTRATION
- ADEQUATE PULSE SHAPING
- ENERGY DEPOSITION WITHOUT FUEL PREHEAT
- 1 - 5 Hz PULSE REPETITION RATE
- 10^9 SHOT LIFETIME
- $<$ $500 MILLION COST

87TDD1000.43

SEVERAL DRIVERS SHOW PROMISE FOR POWER GENERATION APPLICATIONS

- LIGHT IONS $(1 < z < 20)$
- HEAVY IONS $(z > 80)$
- WELTERWEIGHT IONS $(20 < z < 80)$
- EFFICIENT LASERS $(\eta > 10\%)$

87TDD1000.45

LIGHT ION DRIVERS SHOW PROMISE BUT MUST DEMONSTRATE VIABILITY

PROMISING ELEMENTS:

- LOW COST
- ENERGY DEPOSITION WITHOUT PREHEAT
- ION / ENERGY TRADEOFF FOR IDEAL RANGE IN TARGET
- PULSED POWER REPETITION RATE CAPABILITY

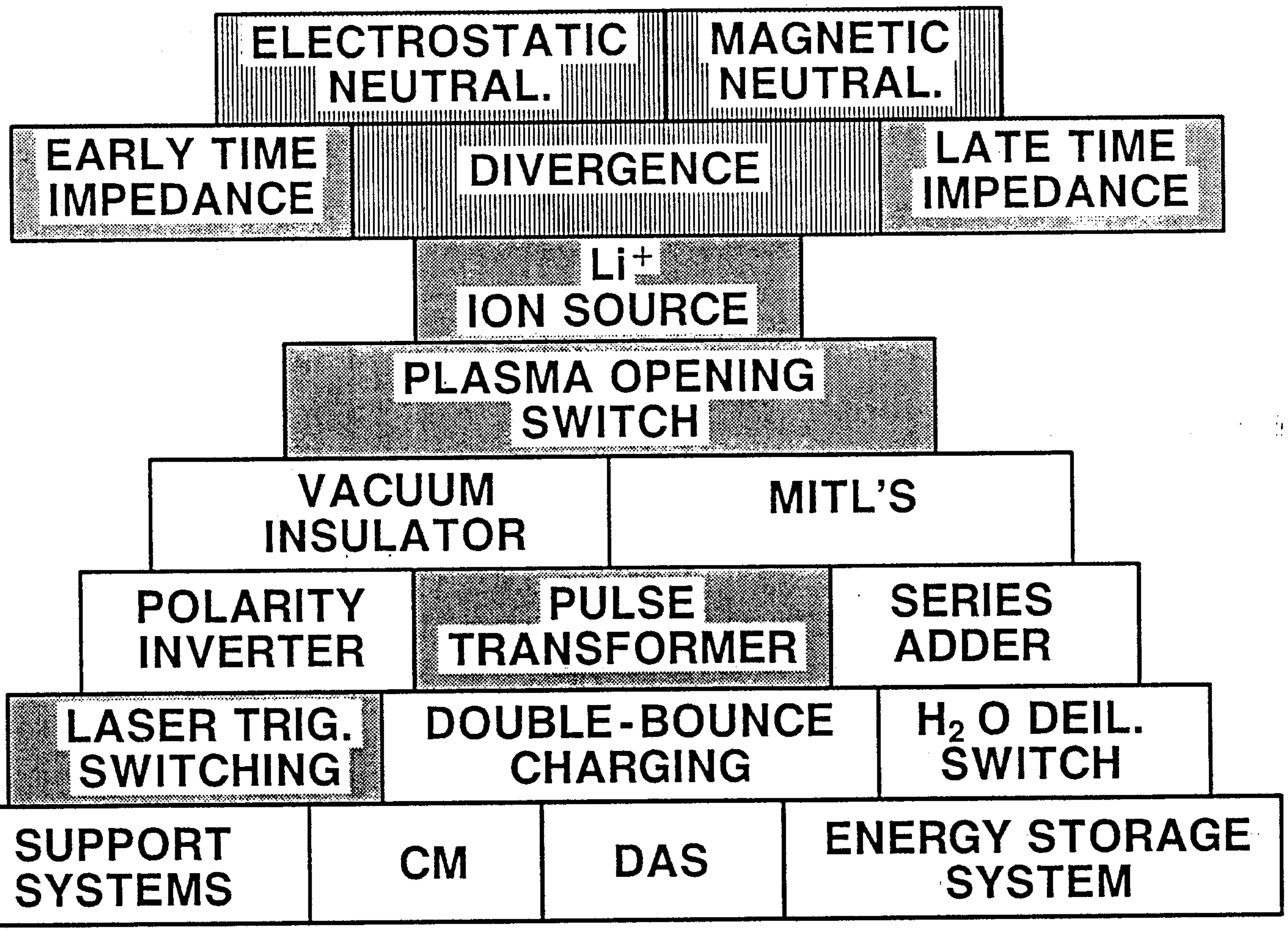
NEEDED FOR VIABILITY “PROOF”:

- FOCUSING TO >100 TW / cm^2
- ADEQUATE PULSE SHAPING
- STANDOFF

87TDD1000.44

86TX1000.56

PBFA II DRIVER DEVELOPMENT IS AN ACCELERATOR EXPERIMENT



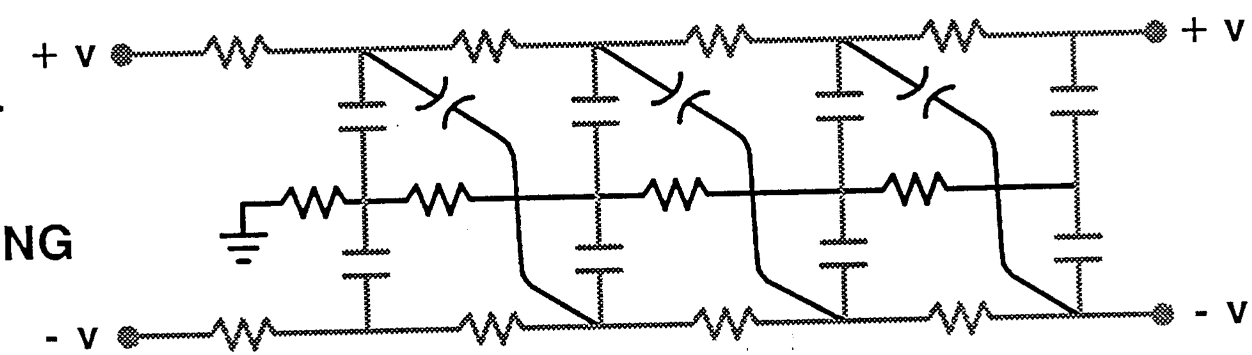
PULSED POWER INCORPORATES MANY ELECTRICAL STORAGE AND SWITCHING TECHNOLOGIES

- 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

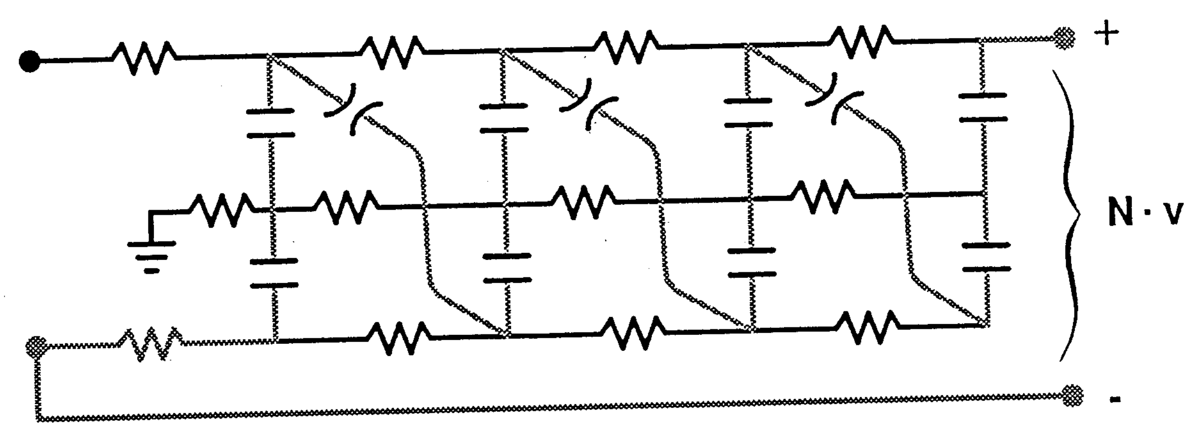
87TDD1000.28

MARX GENERATORS ARE CHARGED IN PARALLEL AND DISCHARGED IN SERIES TO AMPLIFY VOLTAGE

CIRCUIT
DURING
CHARGING

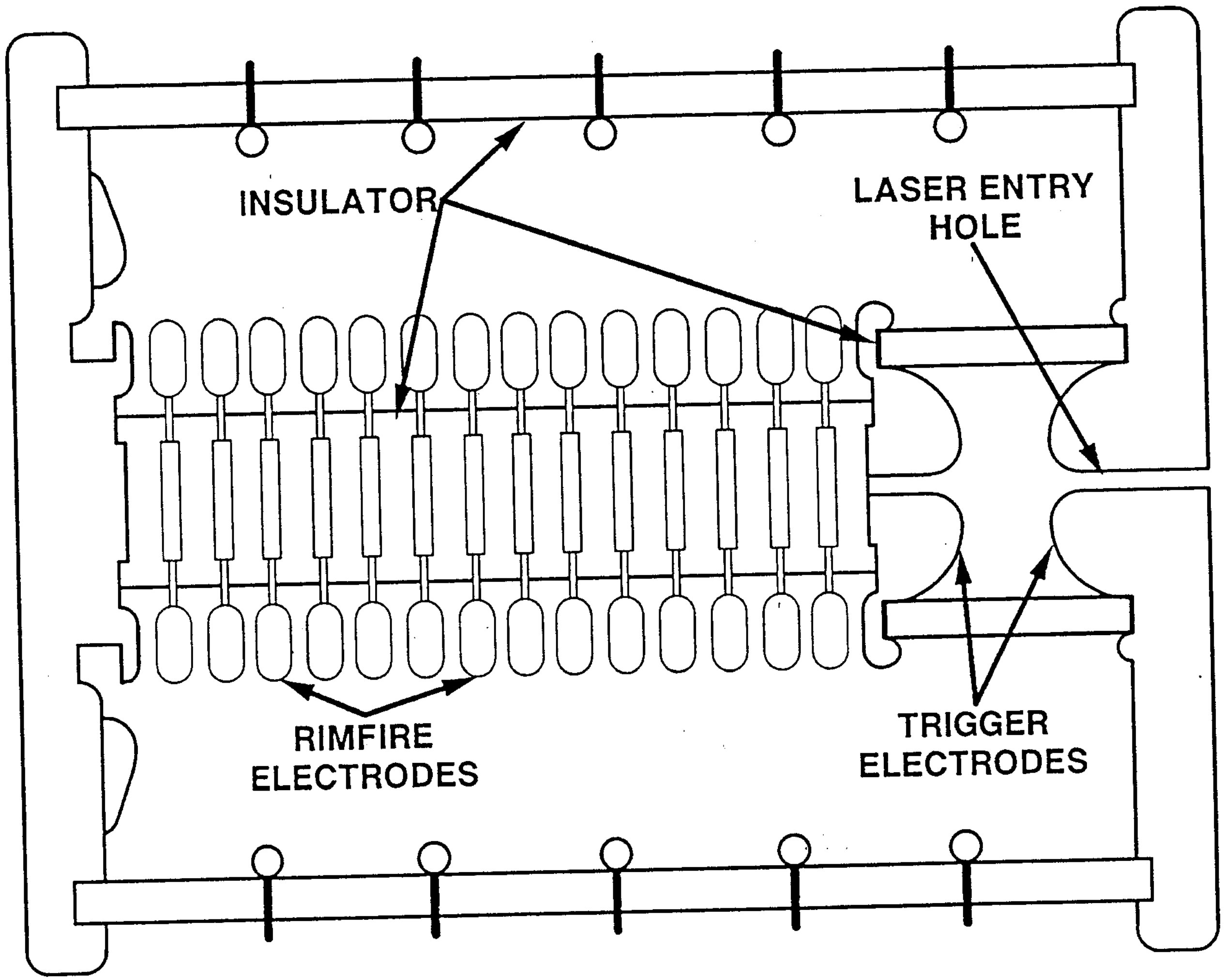


CIRCUIT
DURING
FIRING



87TDD1000.24

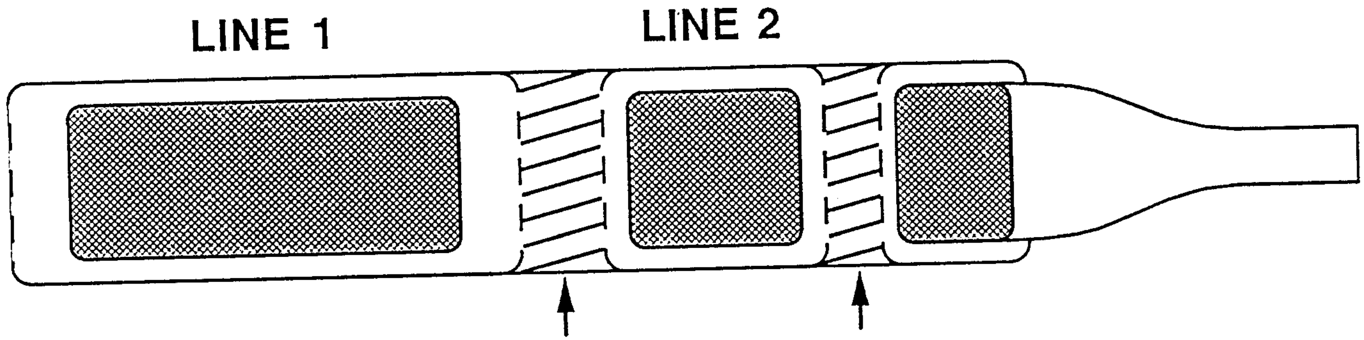
LASER-TRIGGERED GAS-INSULATED SWITCHES ARE EXTENDABLE TO HIGH VOLTAGE AND HIGH REPETITION RATE



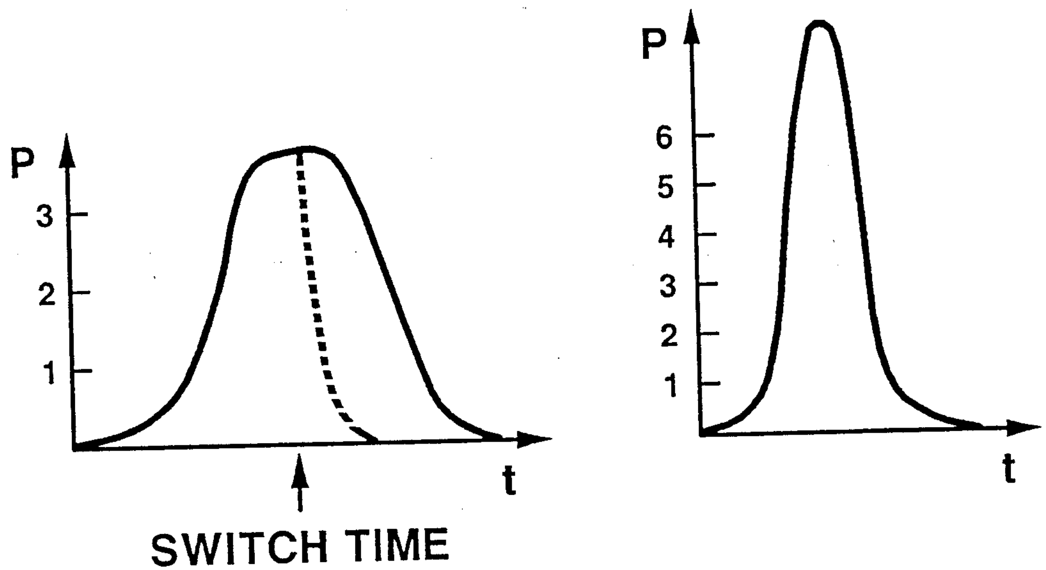
87TDD1000.36

WATER-DIELECTRIC PULSELINES ARE USED TO COMPRESS ENERGY IN TIME, AMPLIFYING POWER

PULSELINE GEOMETRY

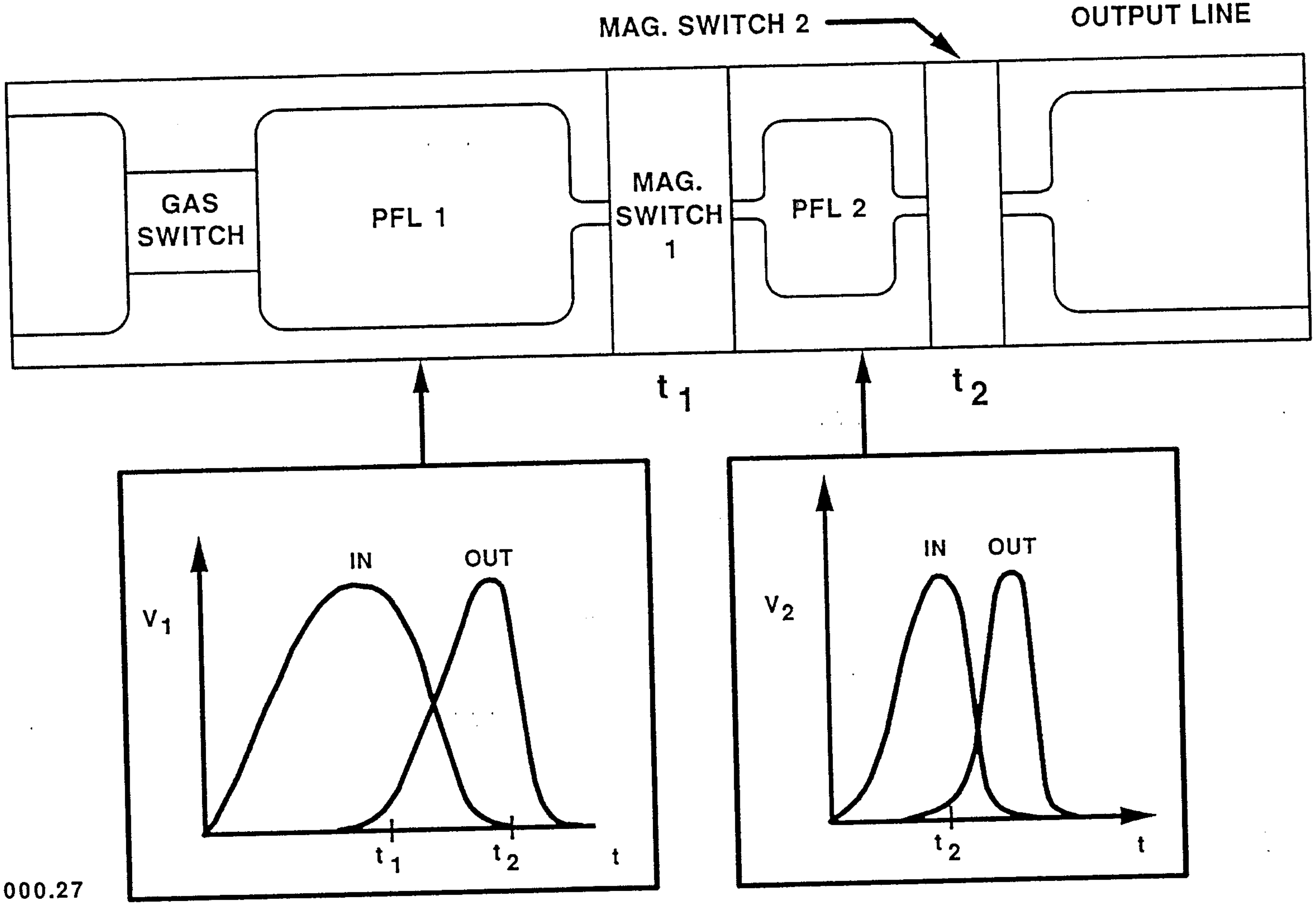


PULSELINE POWER



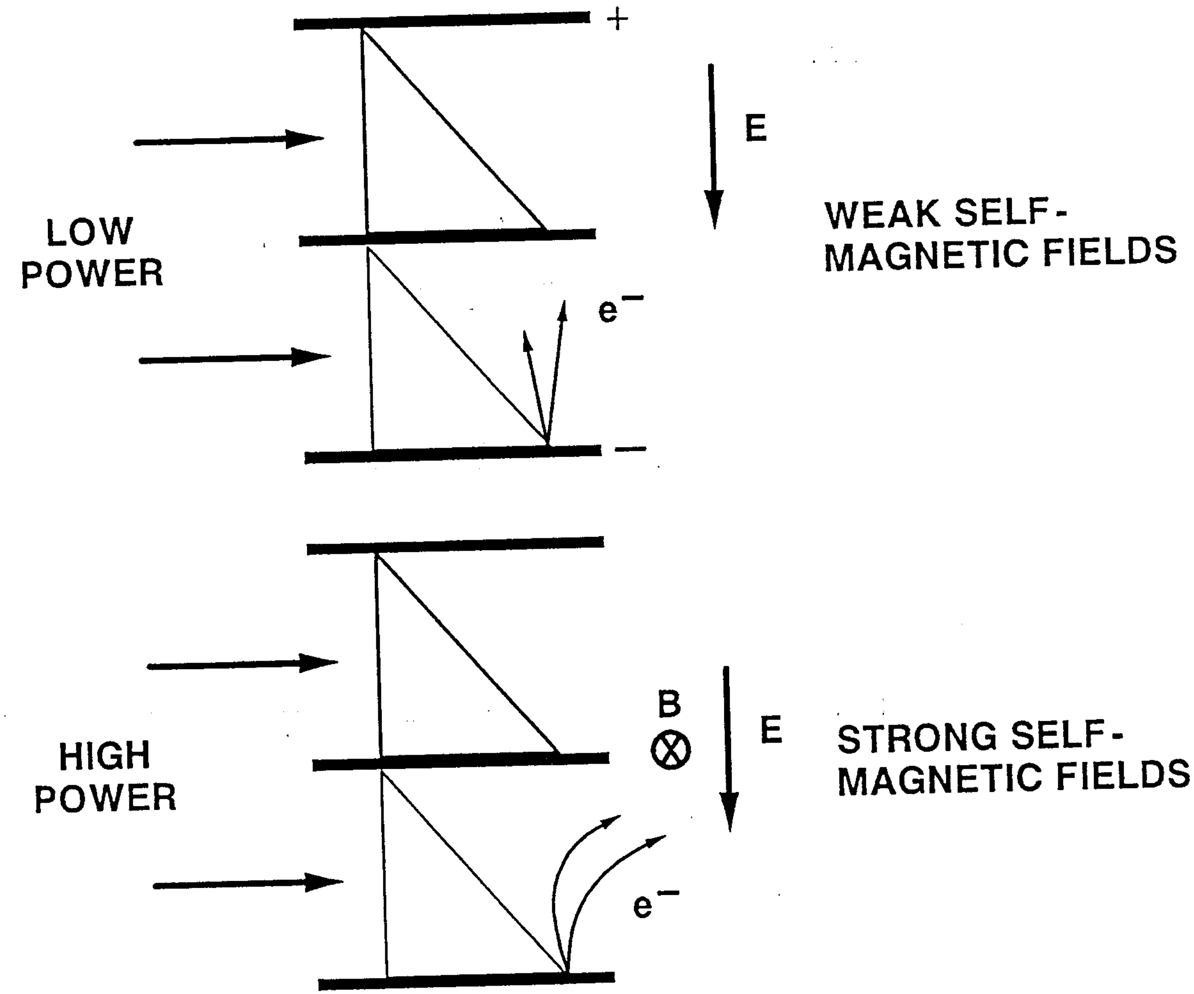
87TDD1000.25

SATURABLE CORE (MAGNETIC) SWITCHES ALLOW EFFICIENT PULSE COMPRESSION AT HIGH REPETITION RATE



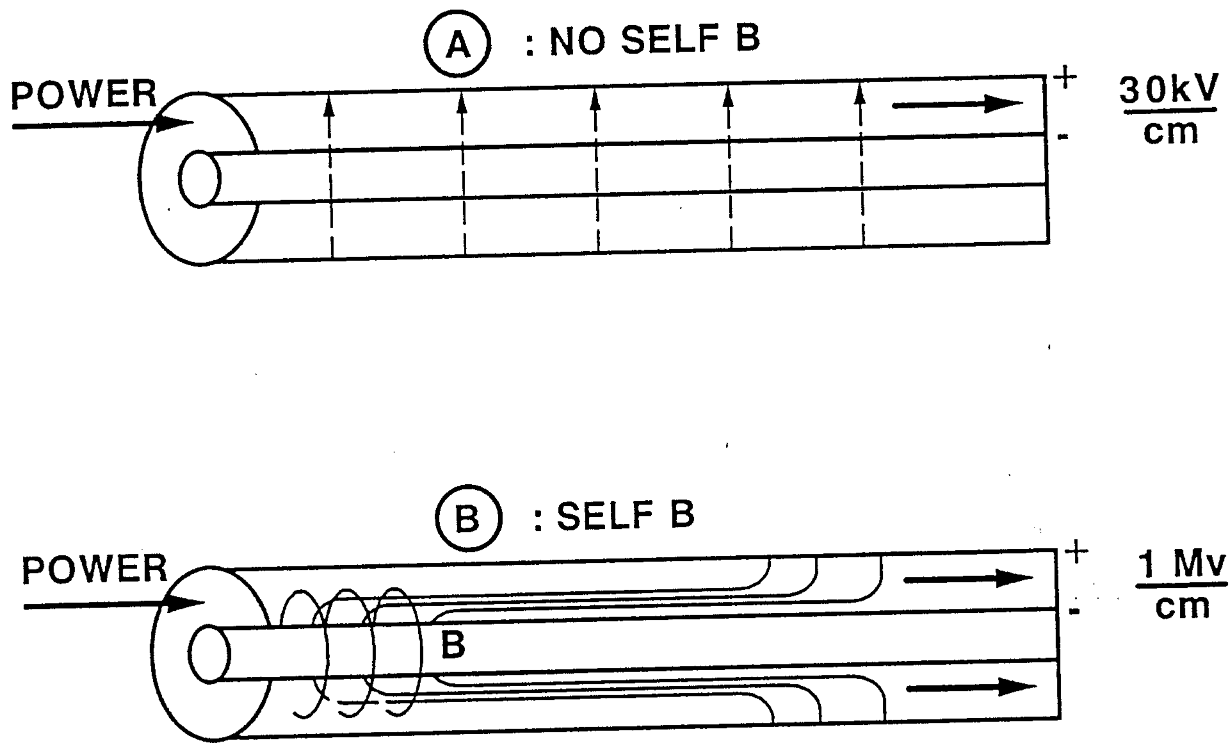
87TDD1000.27

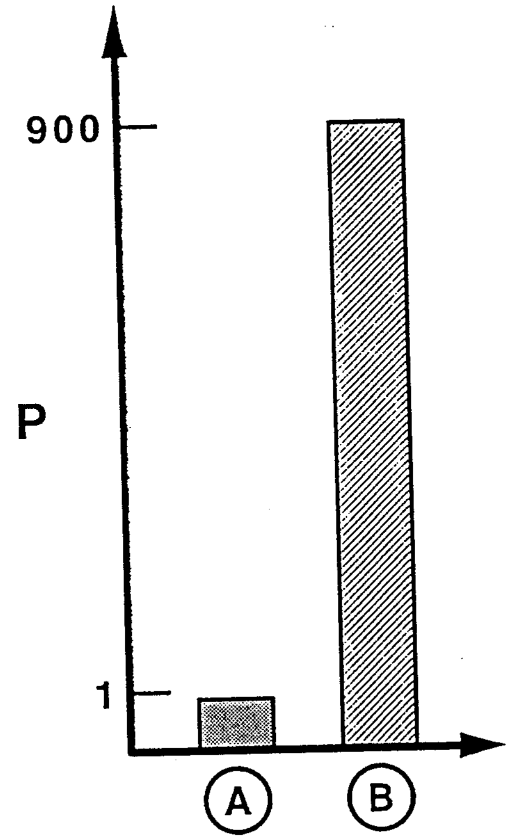
CREATIVE USE OF SELF-MAGNETIC FIELDS CAN RESULT IN MAGNETIC FLASHOVER INHIBITION (MFI)



87TDD1000.41

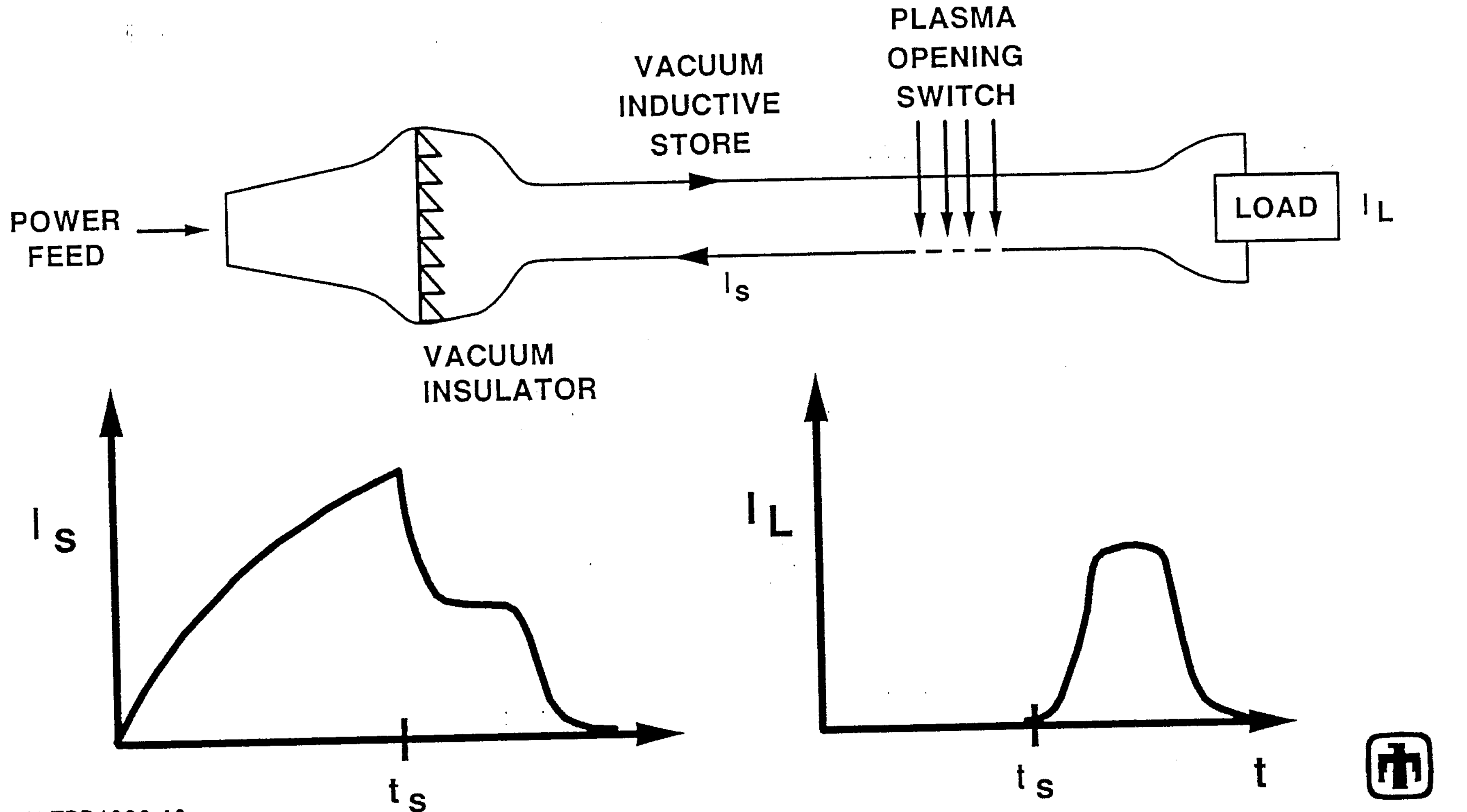
VACUUM SELF-MAGNETIC INSULATION ALLOWS VERY HIGH POWER PULSES TO BE TRANSPORTED EFFICIENTLY





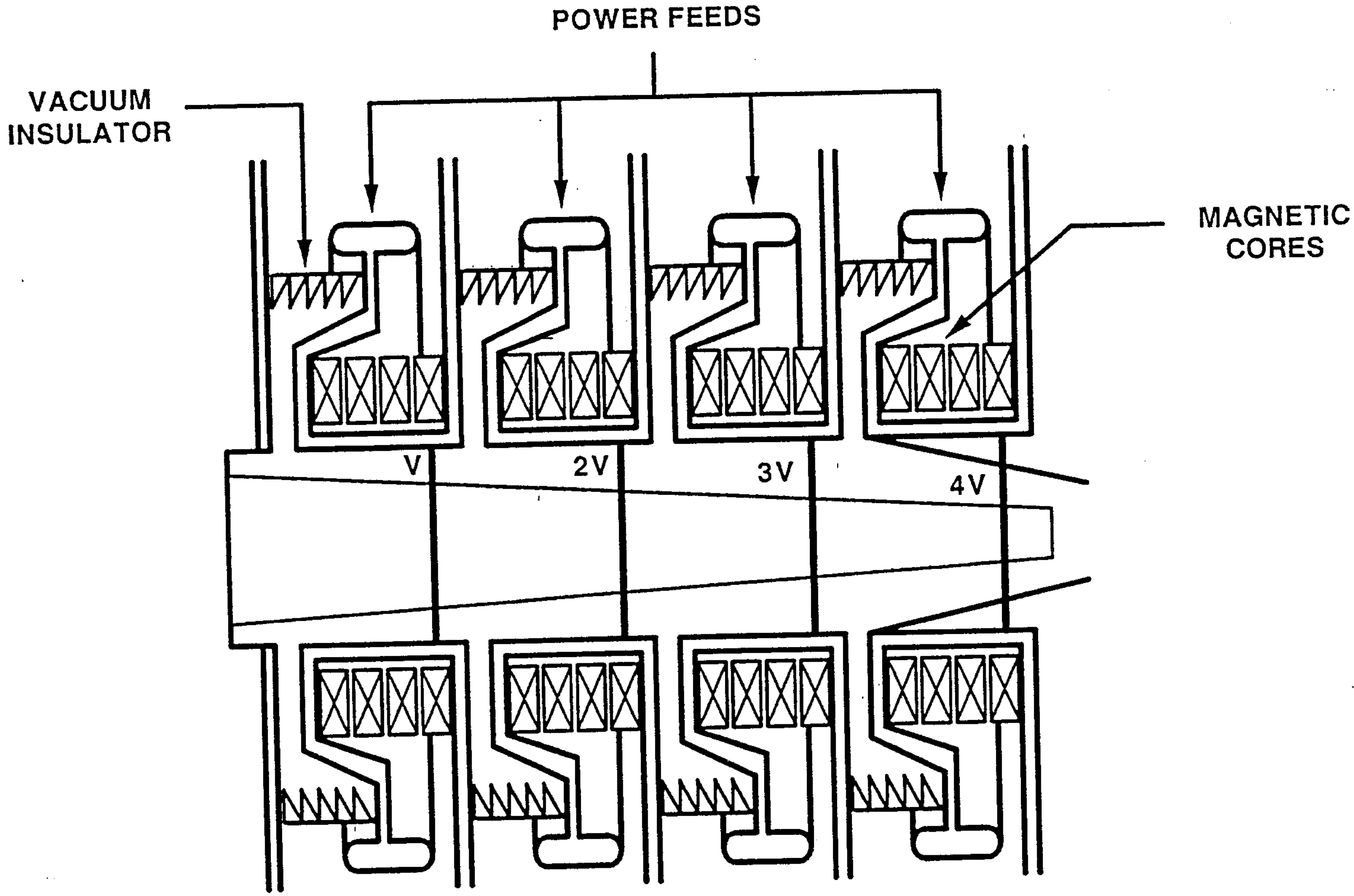
87TDD1000.42

VACUUM INDUCTIVE STORES CAN BE USED WITH OPENING SWITCHES TO PROVIDE PULSES ~ 10ns



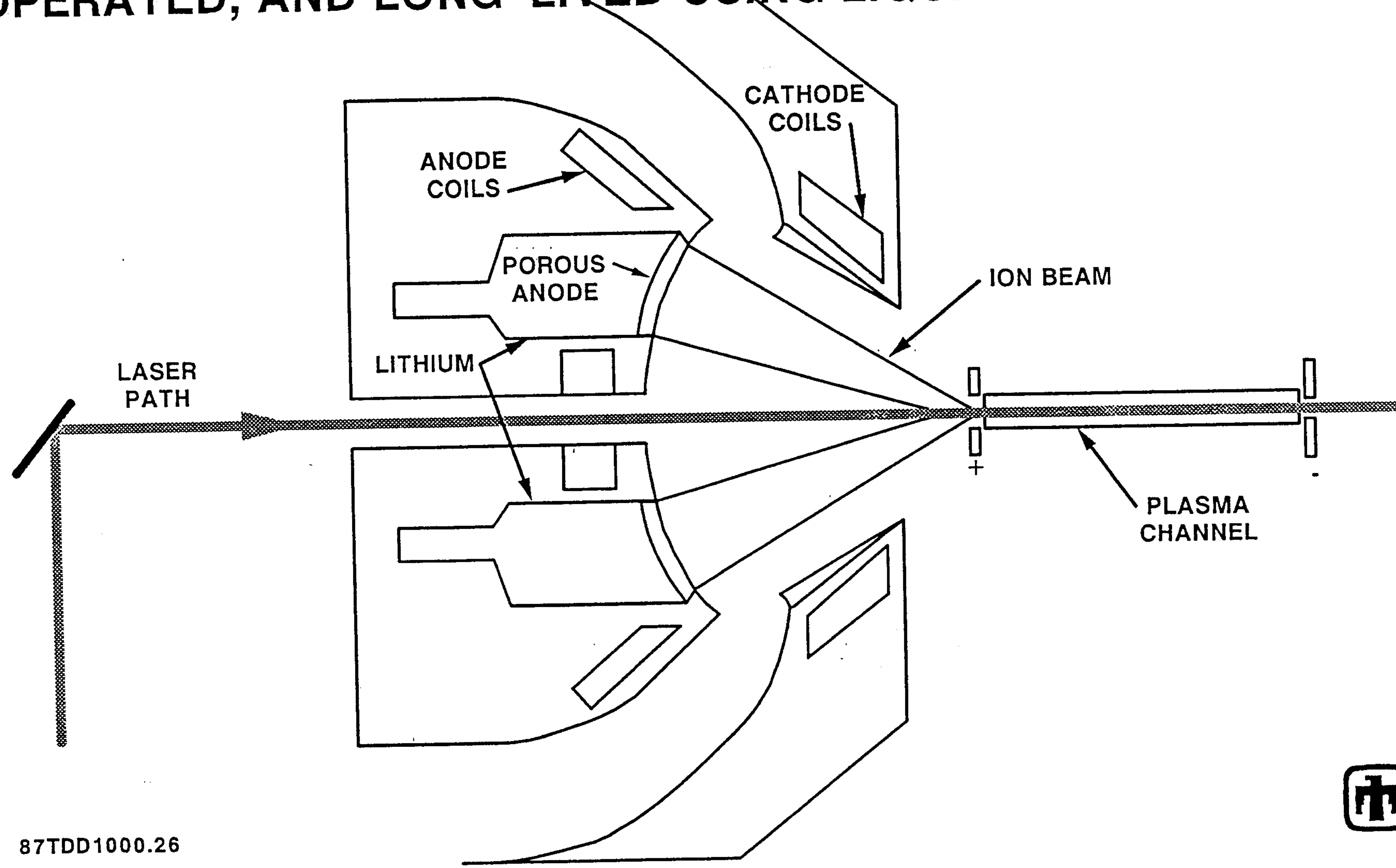
87TDD1000.40

INDUCTIVE VOLTAGE ADDITION RESULTS IN HIGH VOLTAGE OUTPUT USING LOWER VOLTAGE MODULES



87TDD1000.37

EXTRACTION ION DIODES CAN BE EFFICIENT, REPETITIVELY OPERATED, AND LONG-LIVED USING LIQUID METAL SOURCES

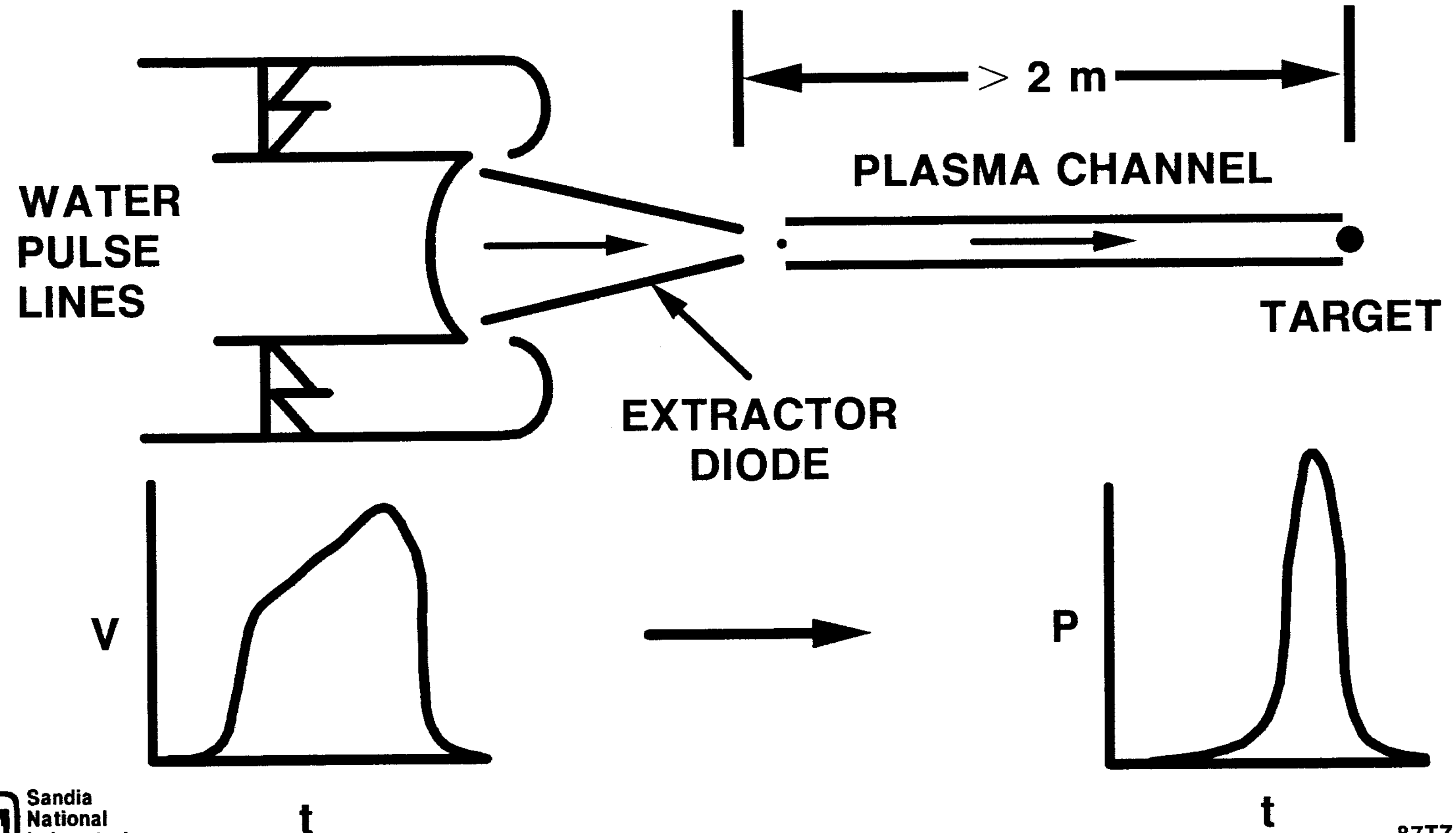


87TDD1000.26

PULSE-SHAPING TECHNIQUES ARE BEING DEVELOPED FOR PULSED POWER

- PULSE-SHAPING IS AT THE EXPLORATORY DEVELOPMENT STAGE
- EXTRACTOR DIODE SIMULATIONS HAVE BEEN DONE
- EXTRACTOR DIODE EXPERIMENTS ARE IN PROGRESS
- SINGLE-SIDED DIODE POWER FEED EFFICIENCY IS PROMISING
- BEAM PROPAGATION CHANNEL EXPERIMENTS ARE BEING PLANNED AND SET UP
- SCALED PROTOTYPE TESTS WILL BE DONE ON MITE, SuperMITE, DEMON, HERMES III BEFORE FULL-SCALE IMPLEMENTATION ON PBFA II

BEAM BUNCHING REQUIRES WATER SECTION PULSE SHAPING AND SUFFICIENT BEAM TRAVEL



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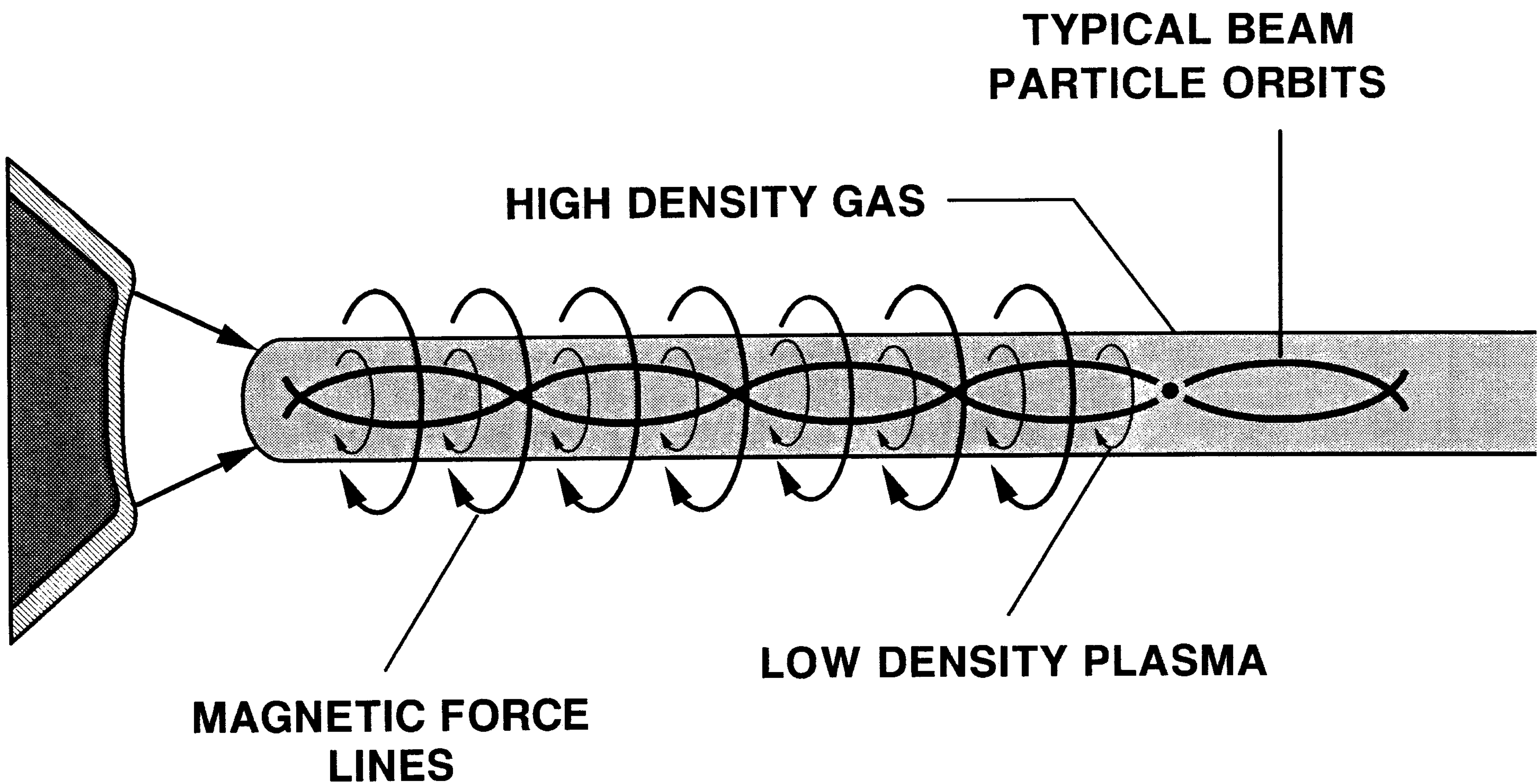
87TZ1000.34



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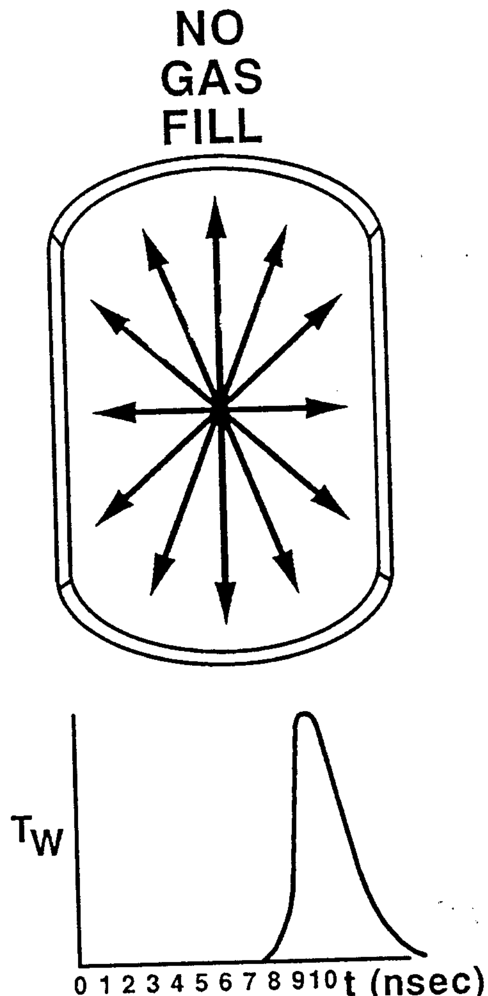
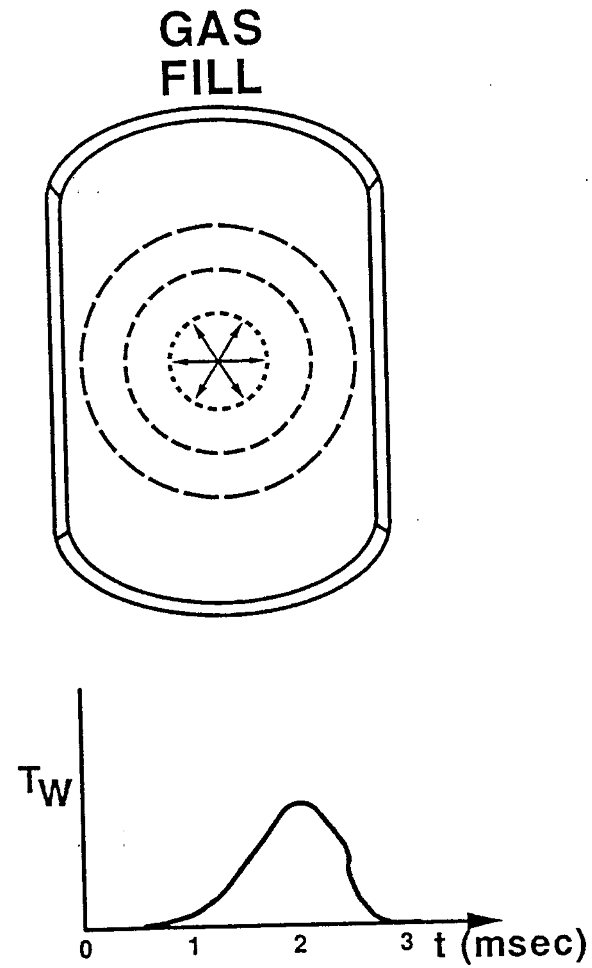
GAS-FILLED TARGET CHAMBERS PROVIDE FIRST WALL PROTECTION FROM LARGE THERMAL TRANSIENTS





87TDD1000.38

PULSE SHAPING FOR LIGHT ION ICF: THE APEX PROJECT

J. T. Crow

Sandia National Laboratories
Albuquerque, New Mexico

APEX Project Goals

Sandia National Laboratories

The APEX Project will demonstrate the capability of generating, transporting, and focusing an ion beam which has a pulse shape appropriate for driving a fusion target.

Light Ion ICF Reactors Will Combine Standoff and Pulse Shaping

Sandia National Laboratories

* Pulsed power using magnetic and electric energy storage can efficiently deliver pulses ~50 ns to an ion diode (ion accelerator).

* The ion beam transport system which provides standoff can be used to ballistically bunch the ion beam for pulse compression and shaping.

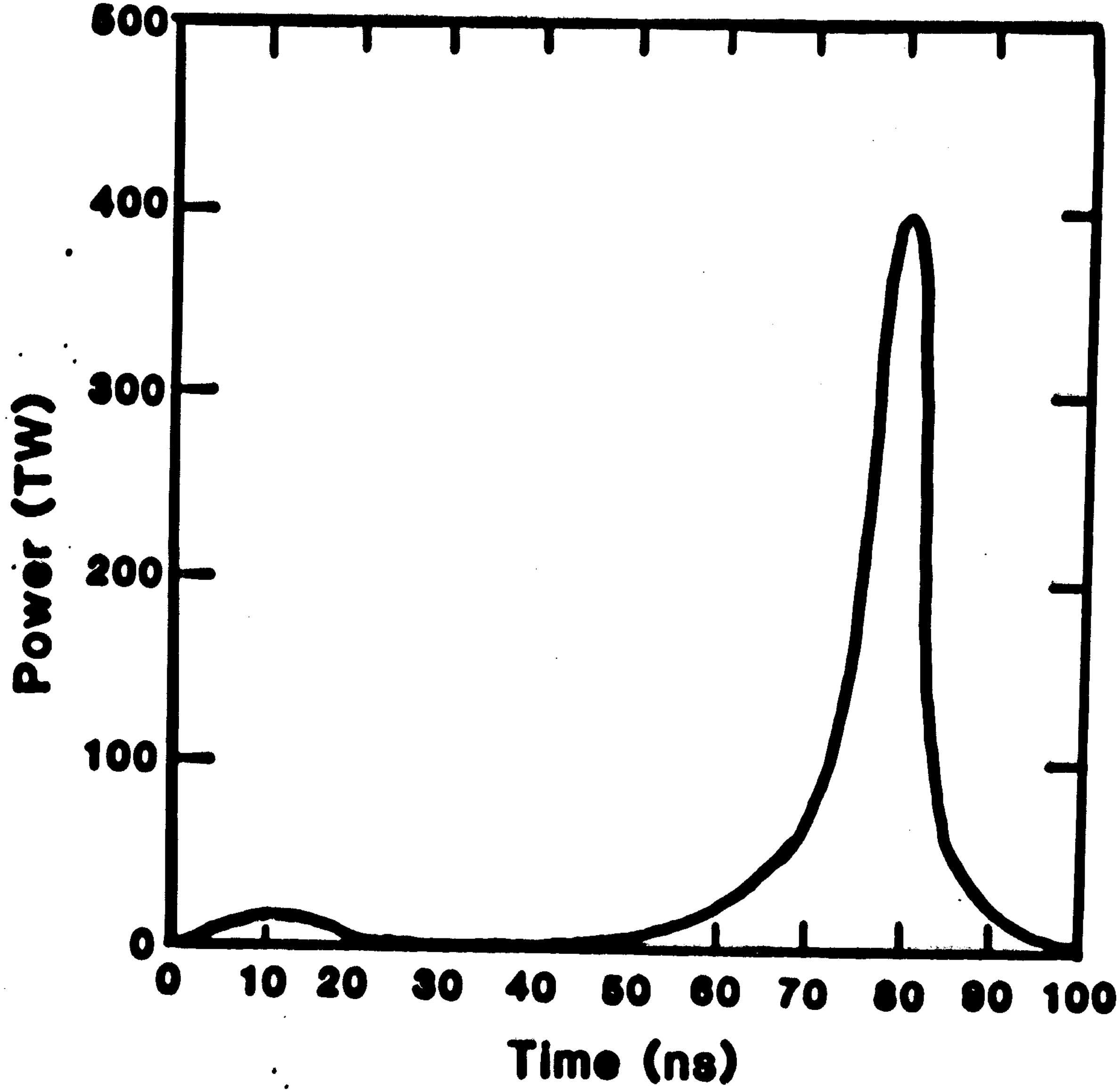
APEX Will Demonstrate Some Characteristics Needed for Energy-Generating Fusion Reactors

Sandia National Laboratories

- Pulse shaping system
- Efficient extraction ion diode
- Efficient ion beam transport
- Beam focusing

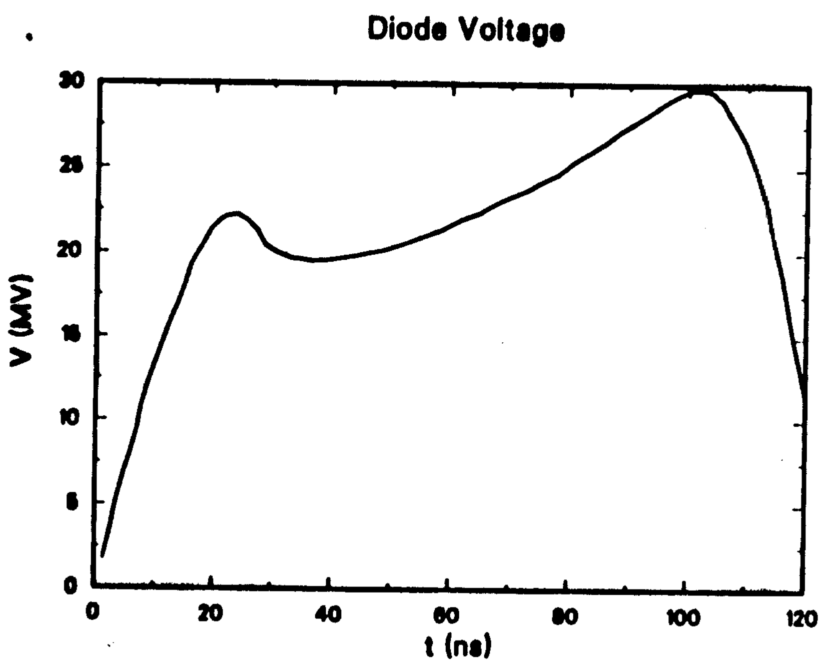
Not at high repetition rate, but the ion diode and transport channel are bases for development of high rate systems.

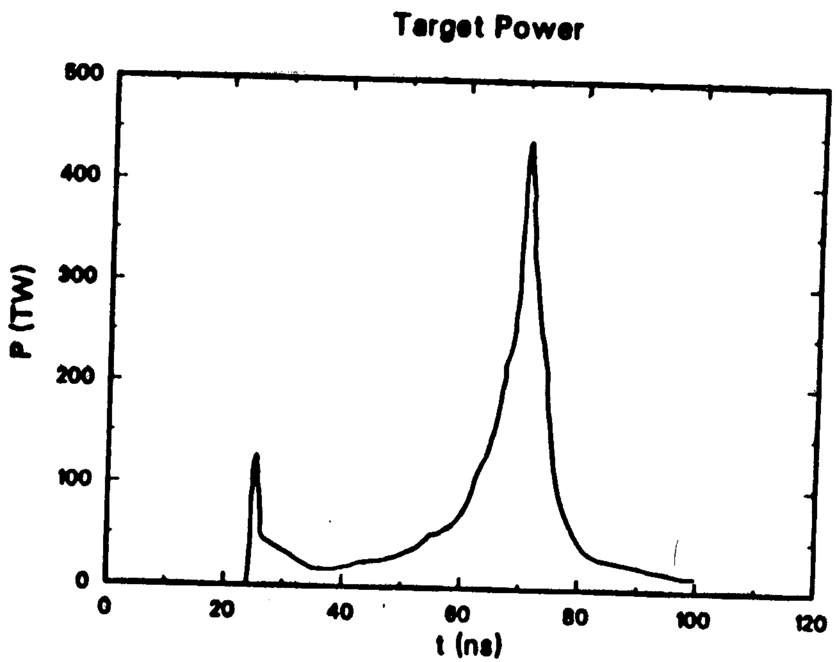
Fusion Targets Require Complex Pulses



Modest Pulse Shaping Can Produce Two Pulses

Sandia National Laboratories

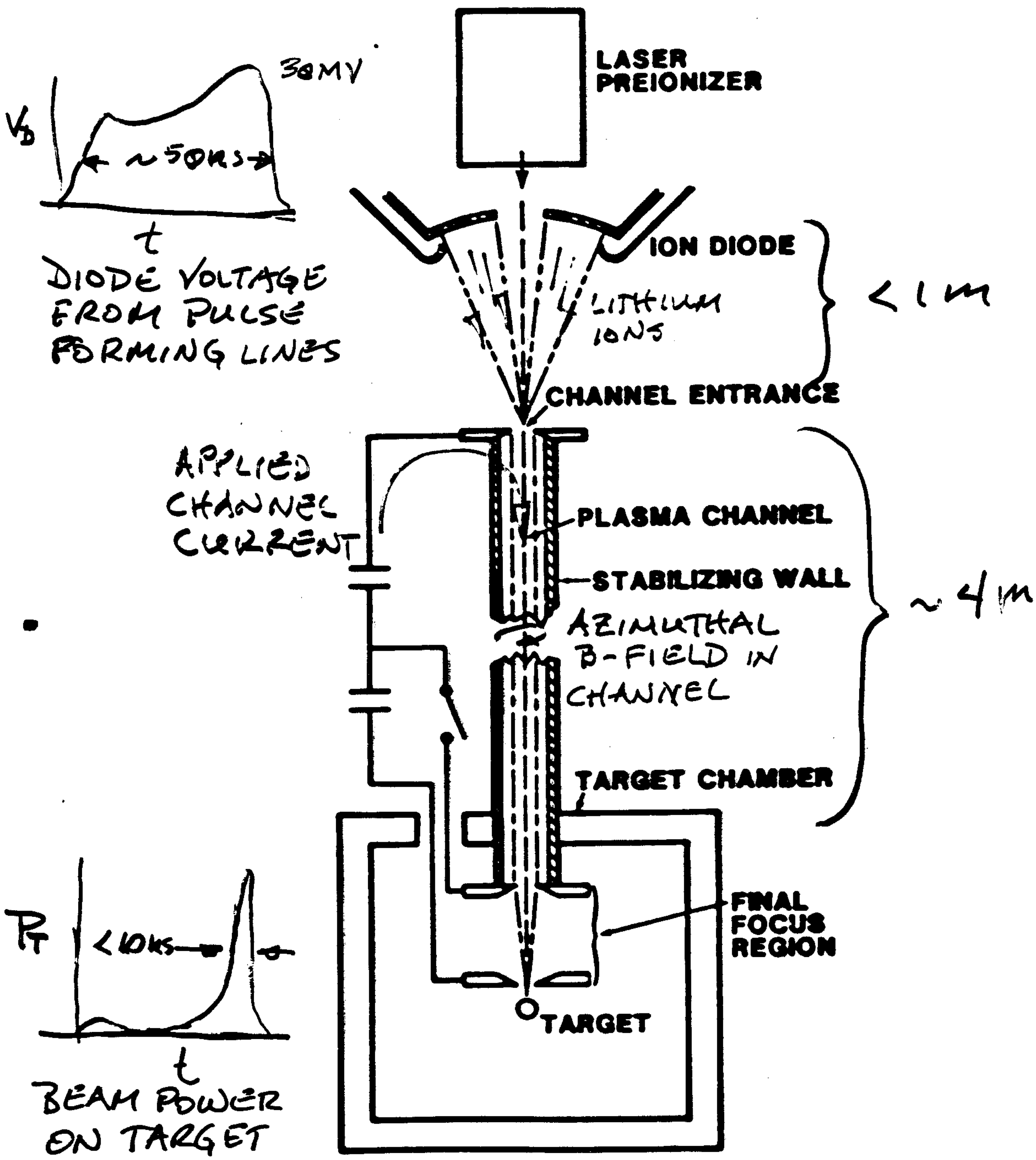


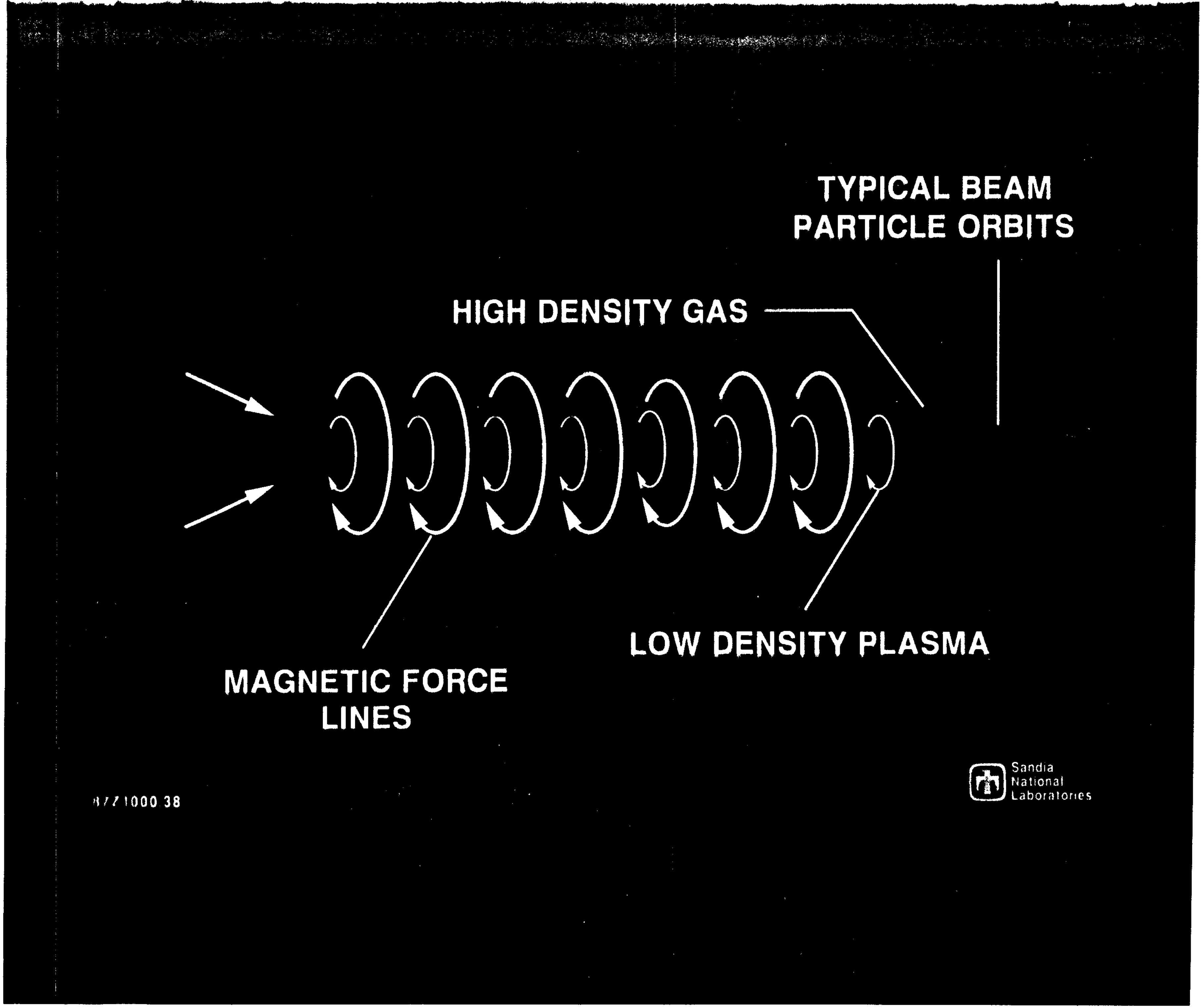


jtc 10/85

Basic APEX Pulse-Shaping System

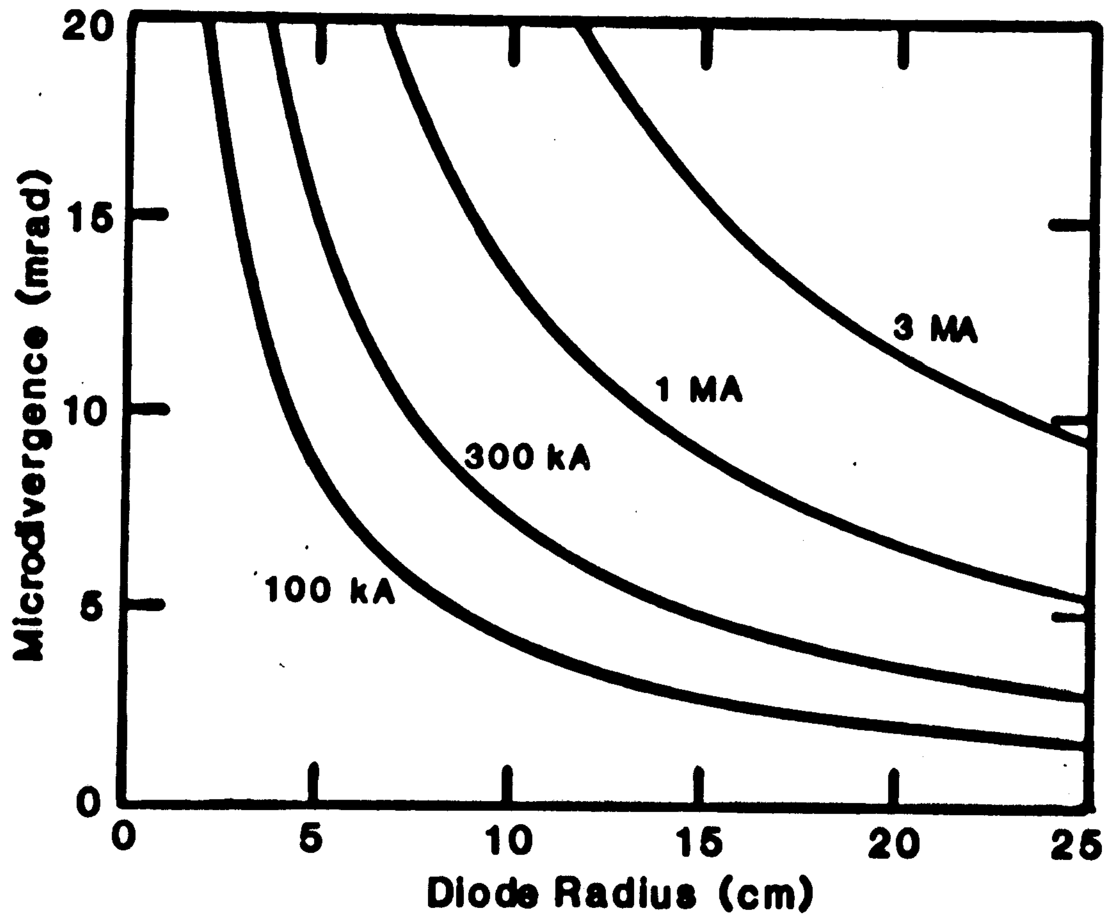
Sandia National Laboratories




TYPICAL BEAM
PARTICLE ORBITS
HIGH DENSITY GAS
LOW DENSITY PLASMA
MAGNETIC FORCE
LINES
Sandia
National
Laboratories
1000 38

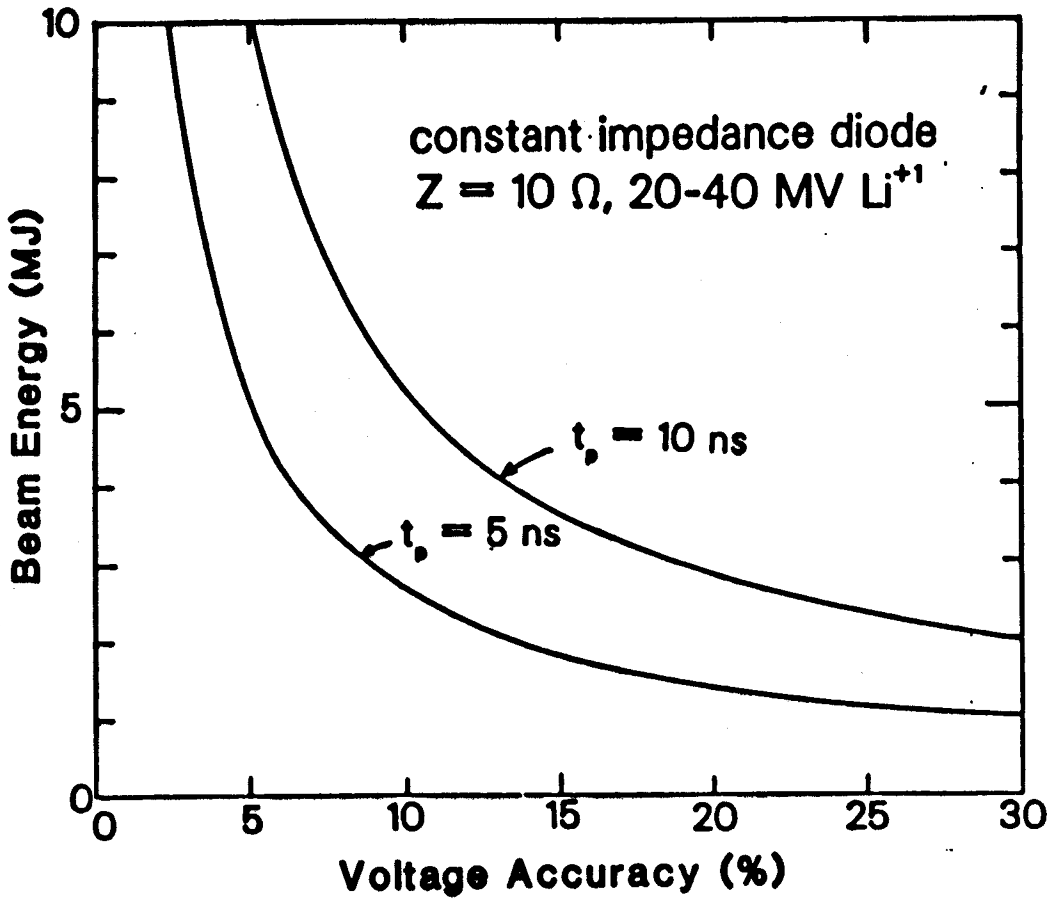
Channel (or Final Focus) Current Is a Function of Diode Radius and Divergence

Sandia National Laboratories



Long Channels Require More Accurate Waveforms

Sandia National Laboratories



Channel Transport Experiments Show Efficient Transport at Low Power Densities

Sandia National Laboratories

Experimenter	length (cm)	r_c (cm)	I_c (kA)	I_b (kA)	V_b (MV)	P_b (TW)	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

Two Diode Options Are Being Investigated

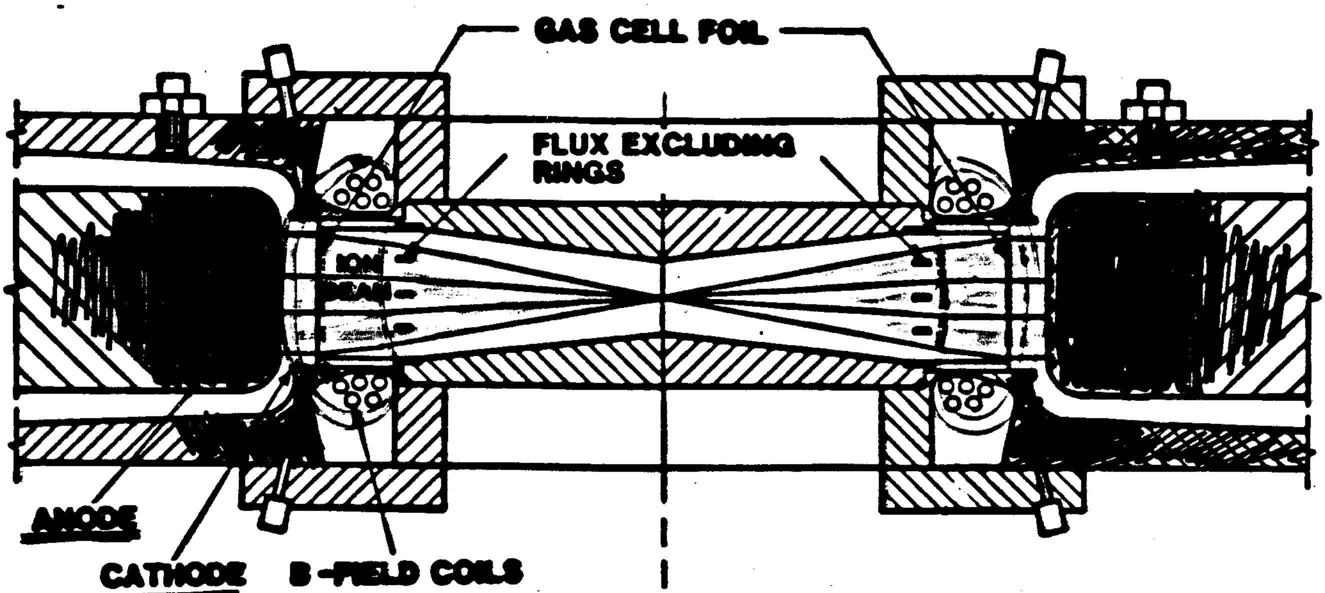
Sandia National Laboratories

* Single-stage applied-B (with Slutz/Seidel B-field)

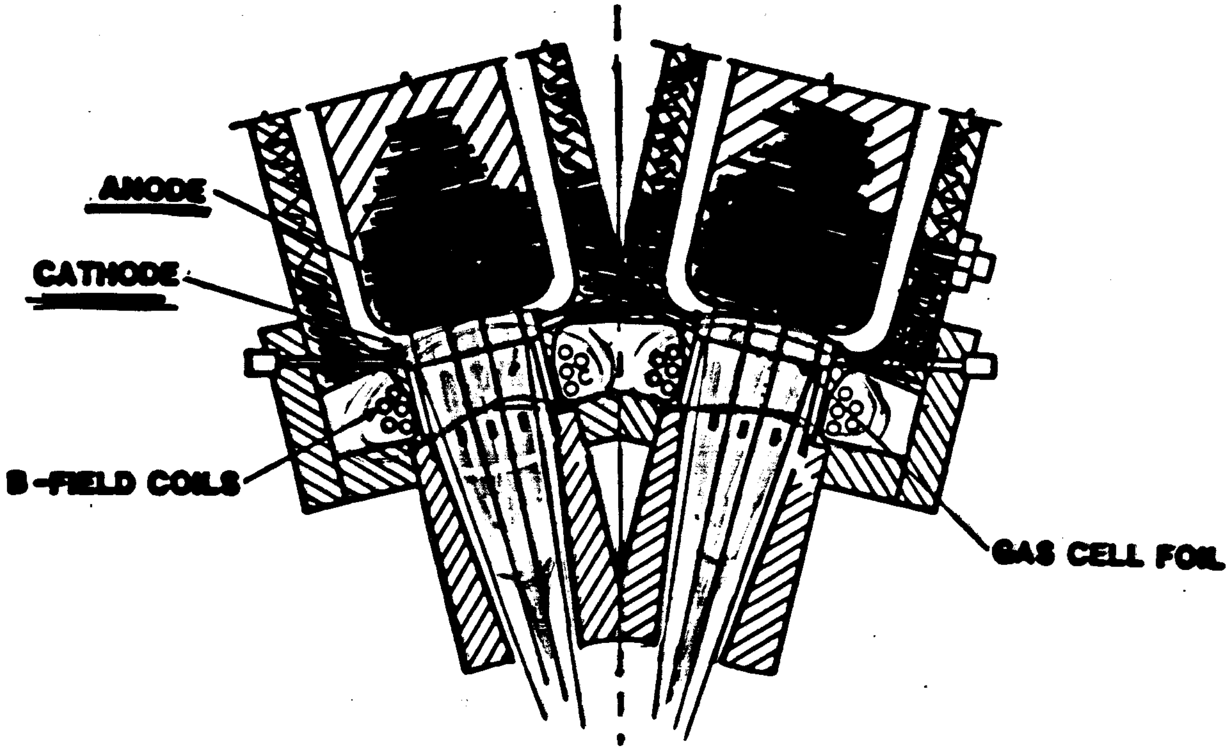
* Two-stage charge-stripping applied-B (Stripper)

Barrel and Extraction Diodes Are Topologically Identical

Sandia National Laboratories

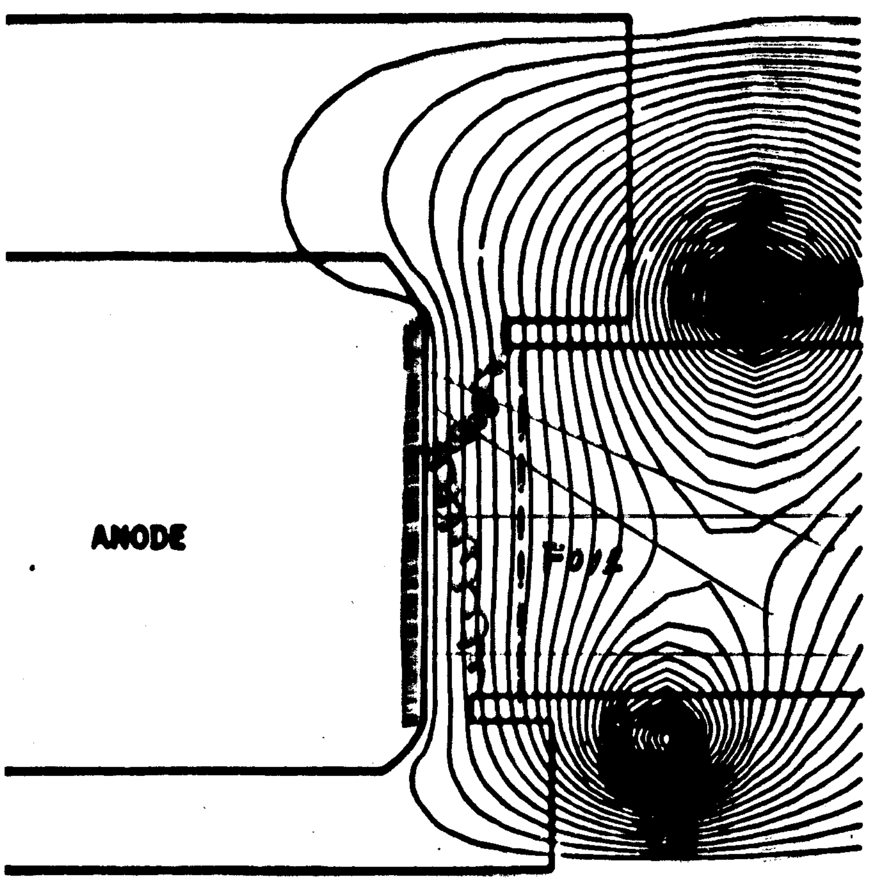


Barrel Diode

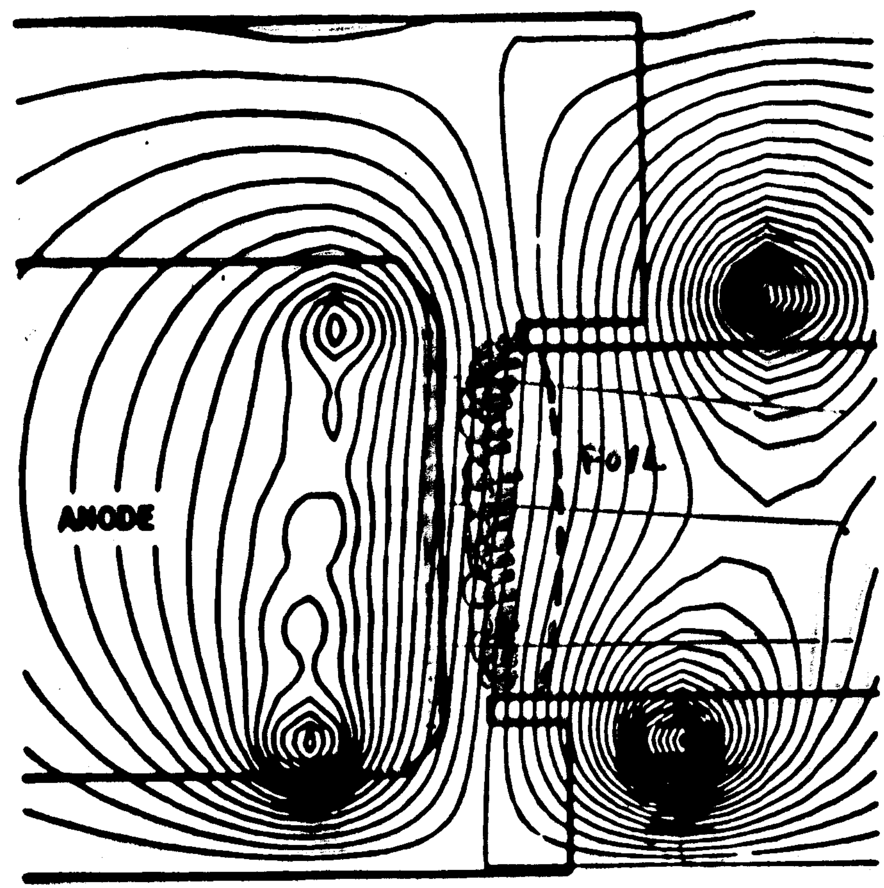


Extraction Diode

EXTRACTION DIODES SHOULD NOW BE EFFICIENT AND FOCUSABLE



OLD



NEW

Extractor Diode Results Are Encouraging

Sandia National Laboratories

- Early experimental results show good efficiency. However, diagnostics are as yet only B-dots and spall targets.

- Simulations indicate both coax and triax diodes can operate at high efficiencies (>80% in steady-state)

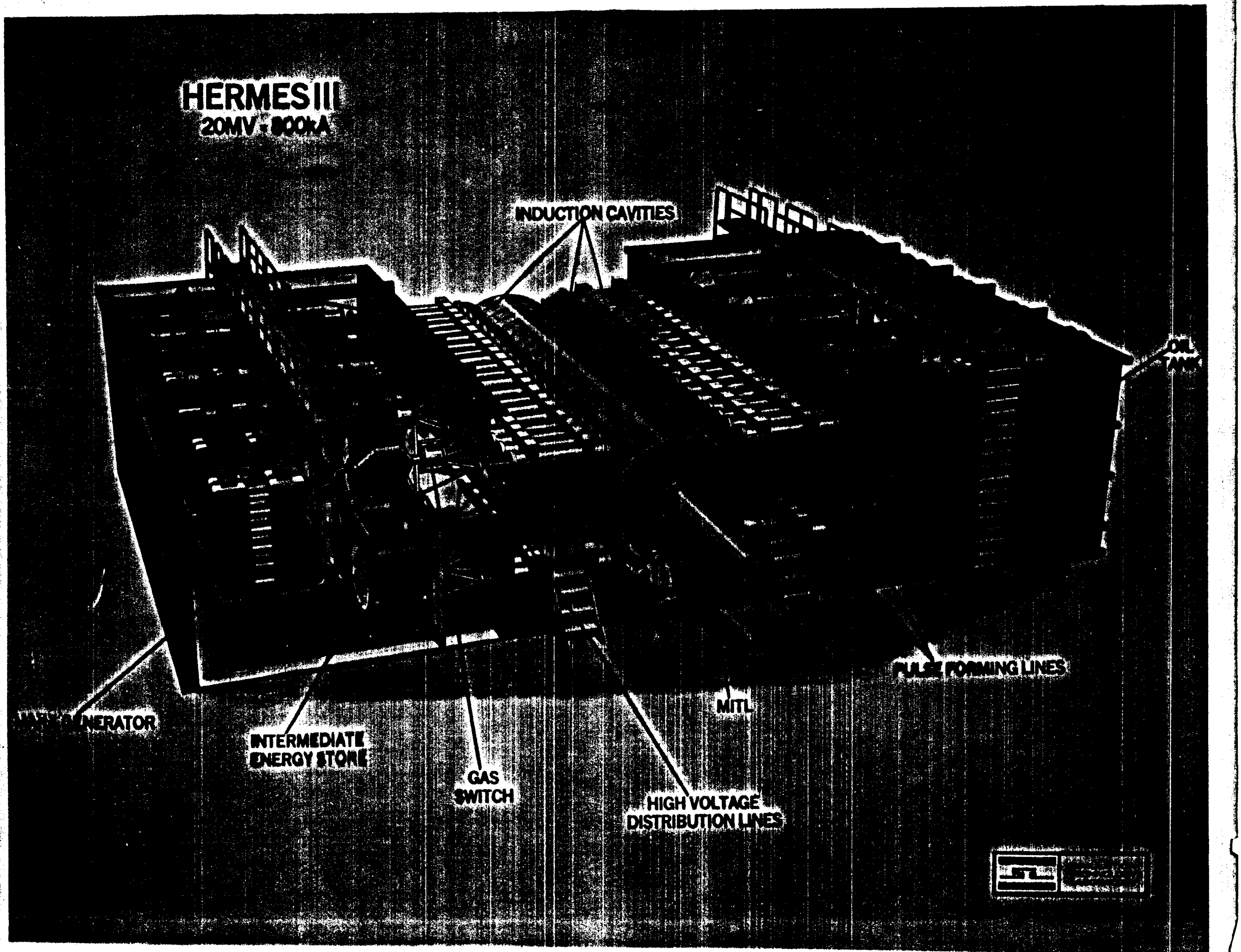
- Early experimental results show coax somewhat more efficient than triax.

- Beam is not yet uniform, but B-field errors exist due to coil winding and placement inaccuracies. Fields are now being mapped and corrected.

APEX Will Demonstrate Pulse Shaping

Sandia National Laboratories

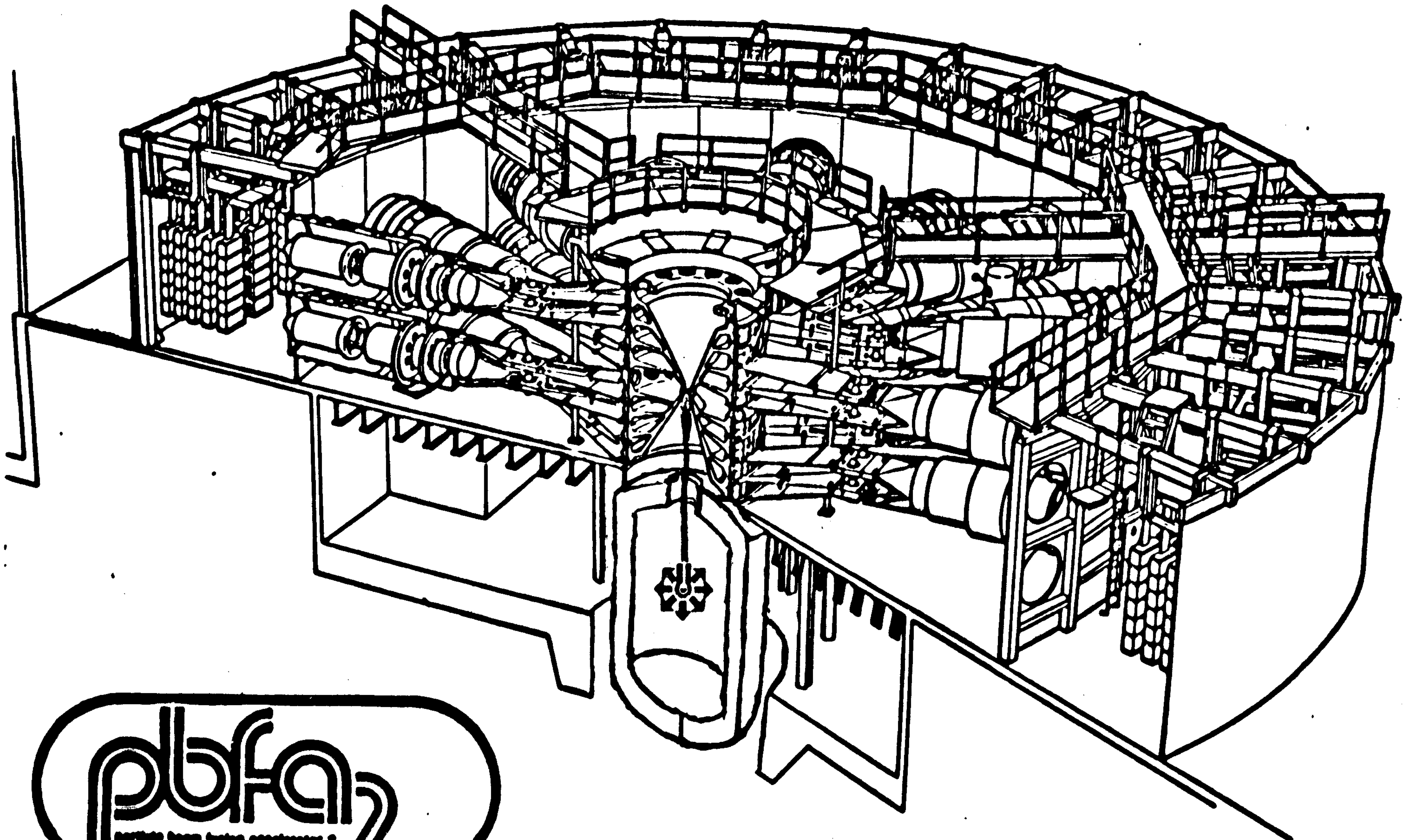
- Diode development on MITE and SuperMITE(now)
- Plasma channel development(now)
- SuperMITE beam-channel tests, protons, no pulse shaping (1988)
- Hermes III beam-channel tests, lithium, pulse shaping (1990, 91)
- Hermes III include final focus, hohlraum experiments (1991)
- PBFA II extraction diode, pulse shaping, target experiments


HERMES III
20MV · 800kA
INDUCTION CAVITIES
PULSE FORMING LINES
MITL
INTERMEDIATE
ENERGY STORE
GAS
SWITCH
HIGH VOLTAGE
DISTRIBUTION LINES

Moderate Gain May Be Possible on PBFA II with APEX Retrofit

Sandia National Laboratories

- Simulations indicate target would need >3 MJ.
- Stored energy in marx must be increased to >30 MJ.
- Since PBFA II was not designed as a nuclear facility, the number of high-gain shots would be limited.



pbfa 2

particle beam fusion accelerator 2

APEX

PRELIMINARY TARGET CHAMBER STUDY INDICATES SYSTEM REQUIREMENTS

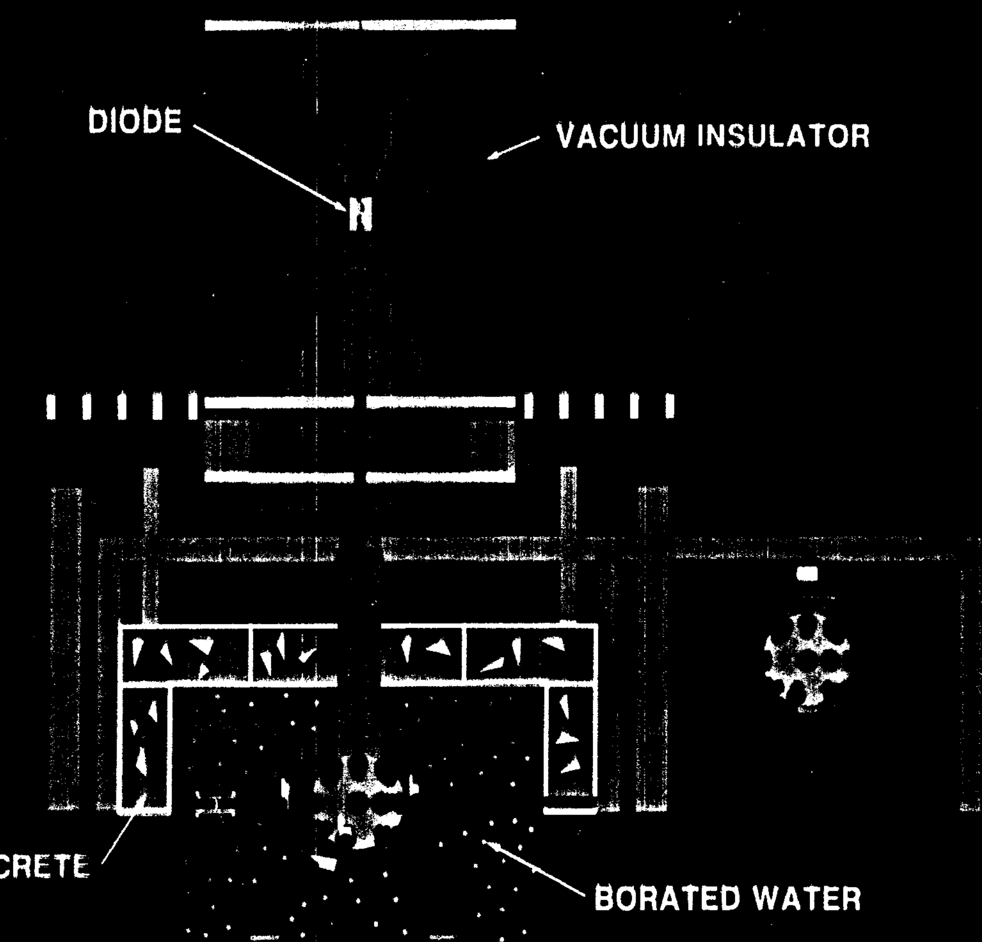
STUDY OF CHAMBER / SYSTEM FOR THIRTY 100 MJ SHOTS WITH DIAGNOSTIC TARGET EXPERIMENTS BETWEEN HIGH-OUTPUT SHOTS

- $1.8 M TOTAL COST, INCLUDING ALL FACILITY MODS, EXCLUDING TRITIUM HANDLING.
- TARGET CHAMBER, 1 m DIA., 5 cm THICK ALUMINUM REPLACED AFTER EACH HIGH-OUTPUT SHOT. ($226,000 COST)
- TEN-DAY COOLDOWN AFTER 100 MJ SHOT TO 0.5 Mrem / HR AT SHIELD WATER SURFACE, 50 Mrem / HR AT CHAMBER.

(PRELIMINARY STUDY BY TRW SPACE AND TECHNOLOGY GROUP, UNIV. OF WISCONSIN, AND FUSION SYSTEMS ENGINEERING CORP.)

87U1000.25

APEX TARGET CHAMBER BELOW PBFA II



The Next Light Ion Fusion Accelerator Will Use Techniques Refined in APEX

Sandia National Laboratories

- Efficient, uniform, focusing extraction diodes
- Ballistic ion beam bunching/pulse shaping
- Plasma transport channels
- High levels of waveshape and timing accuracy
- Knowledge of system and component interactions

Key Issues Are Addressed in APEX

Sandia National Laboratories

	Theory	Experiment
• Targets		
Beam energy	Allshouse	
Beam waveshape	"	
Symmetry	"	
Coupling efficiency	"	
• Beam		
Channel type	C.Olson	Crow
Channel stability	"	"
Transport efficiency	"	"
Phase-space control	"	"
Final focus	C.Olsen/NRL	NRL
• Diode		
EHD ion source	Pregenzer	Lab/Crow, S-MITE/Slutz,Bieg
Beam brightness	?	PBFA II/?, S-MITE/Slutz
Impedance control	Rosenthal	PBFA II/Mendel, S-MITE/Slutz
Extractor efficiency	Slutz	S-MITE/Slutz
Two-stage	Crow	?
• Pulsed Power		
Voltage programming	PSI/Smith	DEMON/Neau
PFL energy	W.Johnson	DEMON/Neau
Voltage stacking	Schneider	?
PFN timing/symmetry	Martin	PBFA II/?

RELATIONSHIP BETWEEN THE TDF AND COMMERCIAL ICF DRIVERS

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

Target Development Facility

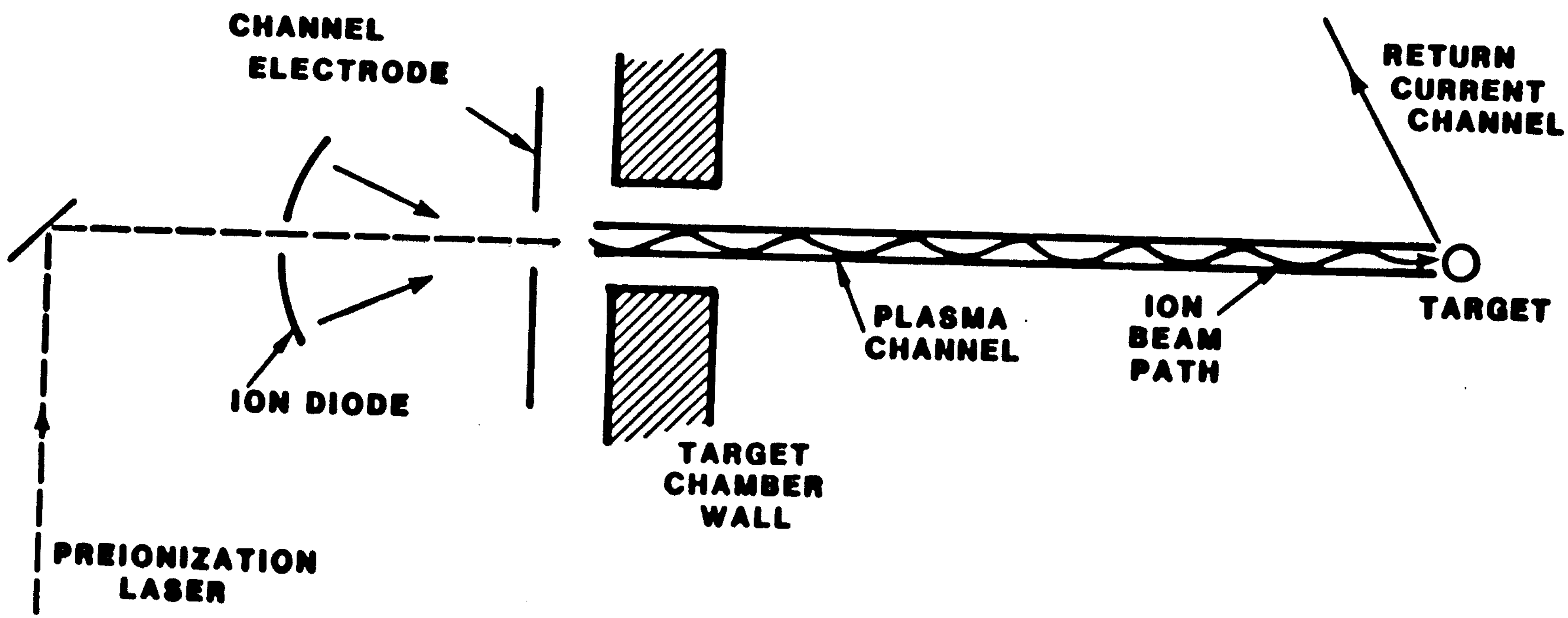
- A testbed for the R & D of high gain ICF targets
- Next step after PBFA-II
- Preliminary conceptual design

TDF Requirements

- 10 MJ on target
- Time-shaped pulse
- 50 to 1000 TW
- Adequate symmetry
- Nuclear Facility
  (100 to 1000 MJ per shot)
- Several shots per day
- 5 to 10 year lifetime

Channel Formation and Beam Propagation Concepts

BASIC CONFIGURATION



Basic Plasma Channel & Ion Beam Parameters

- "Free standing" channels
  - about 3 to 4 m long
  - about 1 cm diameter
  - $I_c < 70$ kA
- Extraction ion diode
  - Li^{+1} at 30 MV, nominal
  - $\Delta\theta > 5$ mrad
  - $J_a < 10$ kA/cm^2

<u>Conclusion</u>: Maximum trappable power at channel entrance is about 45 TW (conservation equations).

Number of Main Pulse Beams

Assumptions:

- Bunching factor = 3
- Beam generation and focusing efficiency = 80%
- Channel transport efficiency = 50%

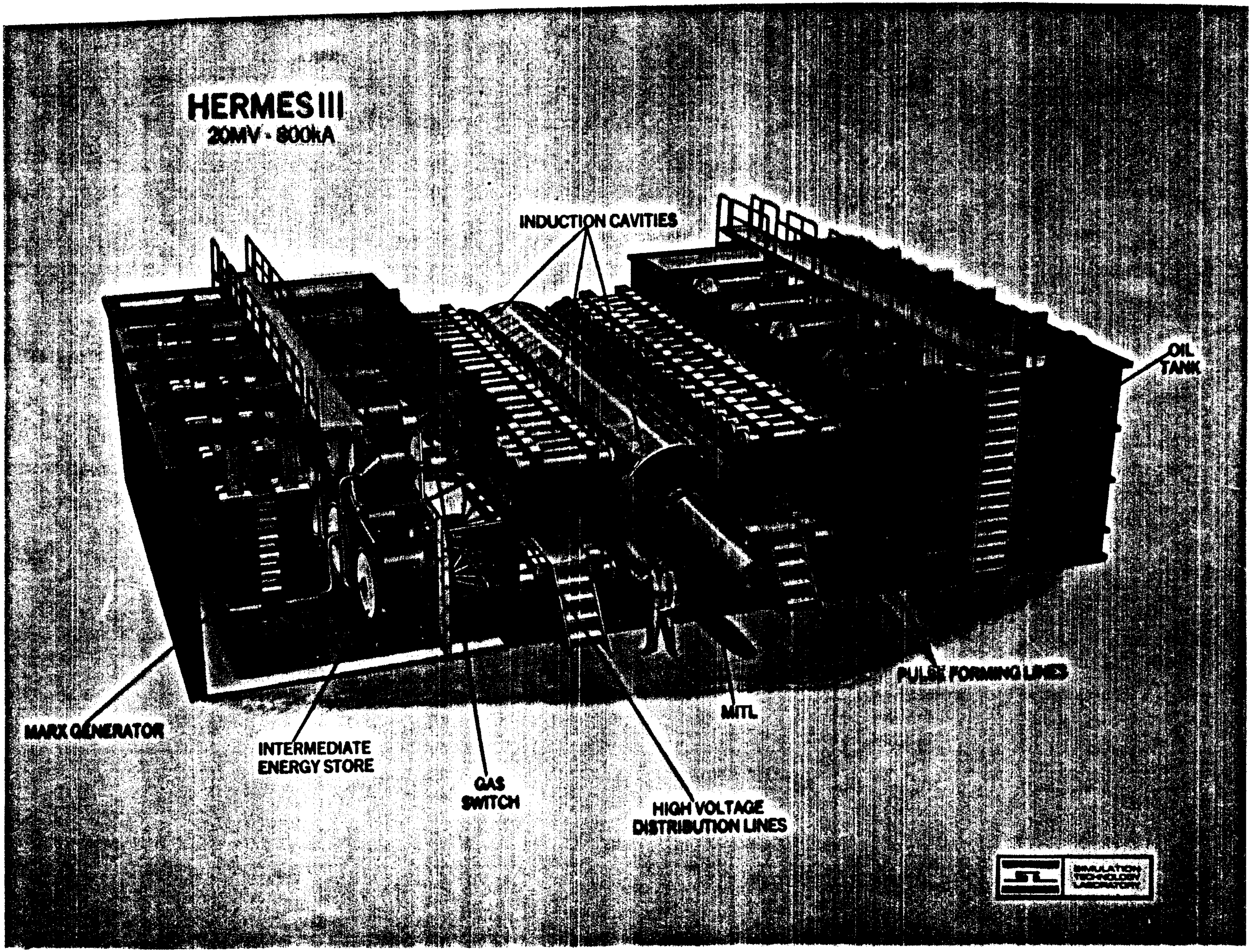
$$\frac{0.8 \times 1000 \text{ TW}}{N \times 3 \times 0.5} = 45 \text{ TW}$$

$$N = 12$$

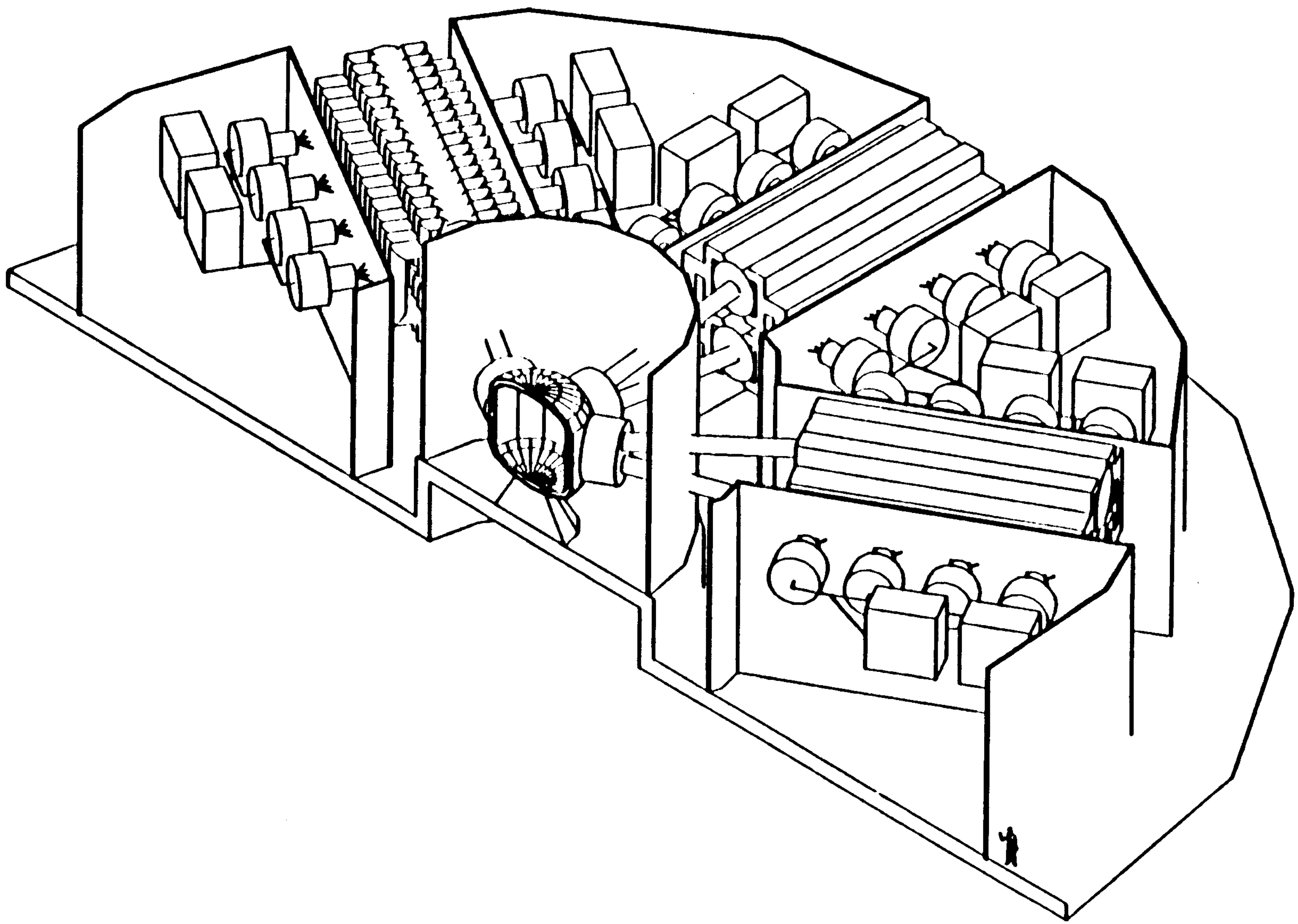
- Main pulse requires 12 beams

note: overlap & complexity issues argue for minimum number of beams

Conclusion: Conservative concept (pulsed power viewpoint) would supply a 1.8 MA, 30 MV (nominal) diode feed.


HERMES III
20MV - 800kA
INDUCTION CAVITIES
OIL TANK
MARX GENERATOR
INTERMEDIATE ENERGY STORE
GAS SWITCH
HIGH VOLTAGE DISTRIBUTION LINES
MITL
PULSE FORMING LINES
SIMULATION TECHNOLOGY LABORATORY

Light Ion Target Development Facility (TDF) Concept



Extrapolations from Present Technologies

Basic Components:

- Marx generators
- l. t. gas switches
- water PFL's
- magnetic switching
- Helia voltage addition
- MITL's
- extraction ion diodes
- laser-initiated plasma channels

10 MV, 2.4 MJ Marx Generator

- 96 capacitors:
  25 kJ, 100 kV, 5 μF
  15" x 15" x 30"
  30 nh per can
- 48 spark gaps:
  200 kV
  20 nH per switch
- basic arrangement:
  6 rows, 8 stages, 300 kV/in
  110 nH (geometrical) per stage
- overall parameters:
  11'-9" x 11'-9" x 6'-6"
  L_{eq} = 9.5 μH
  C_{eq} = 52 nF
  Z = 13.8 ohms
  I = 400 kA

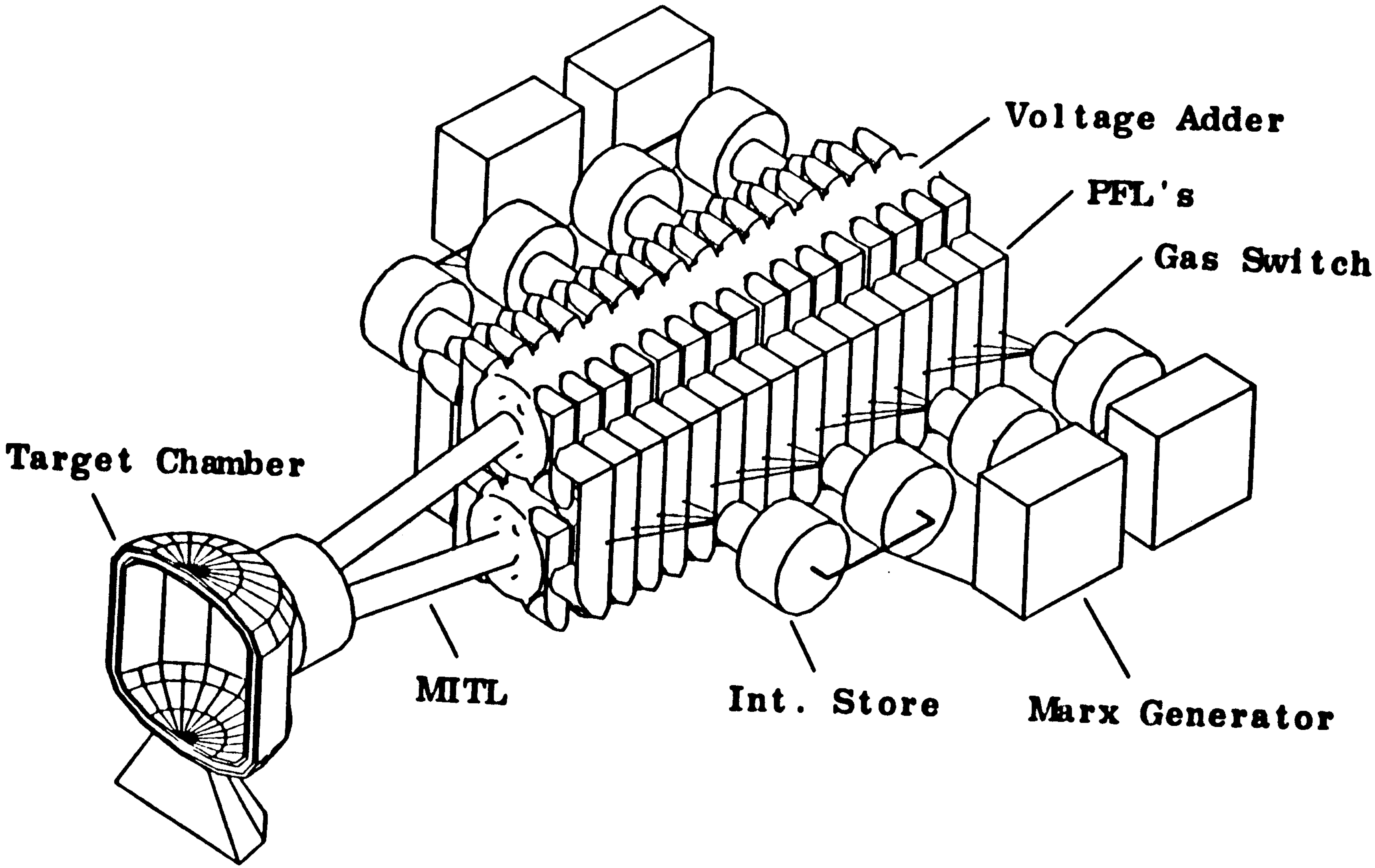
Intermediate Storage Capacitors

- 2.8 m O. D.
  (9'-2")
- 1.8 m I. D.
- 2.2 m length
- 20 MV/m maximum stress
- 22 nF
- 1 MJ
- 2.9 ohms

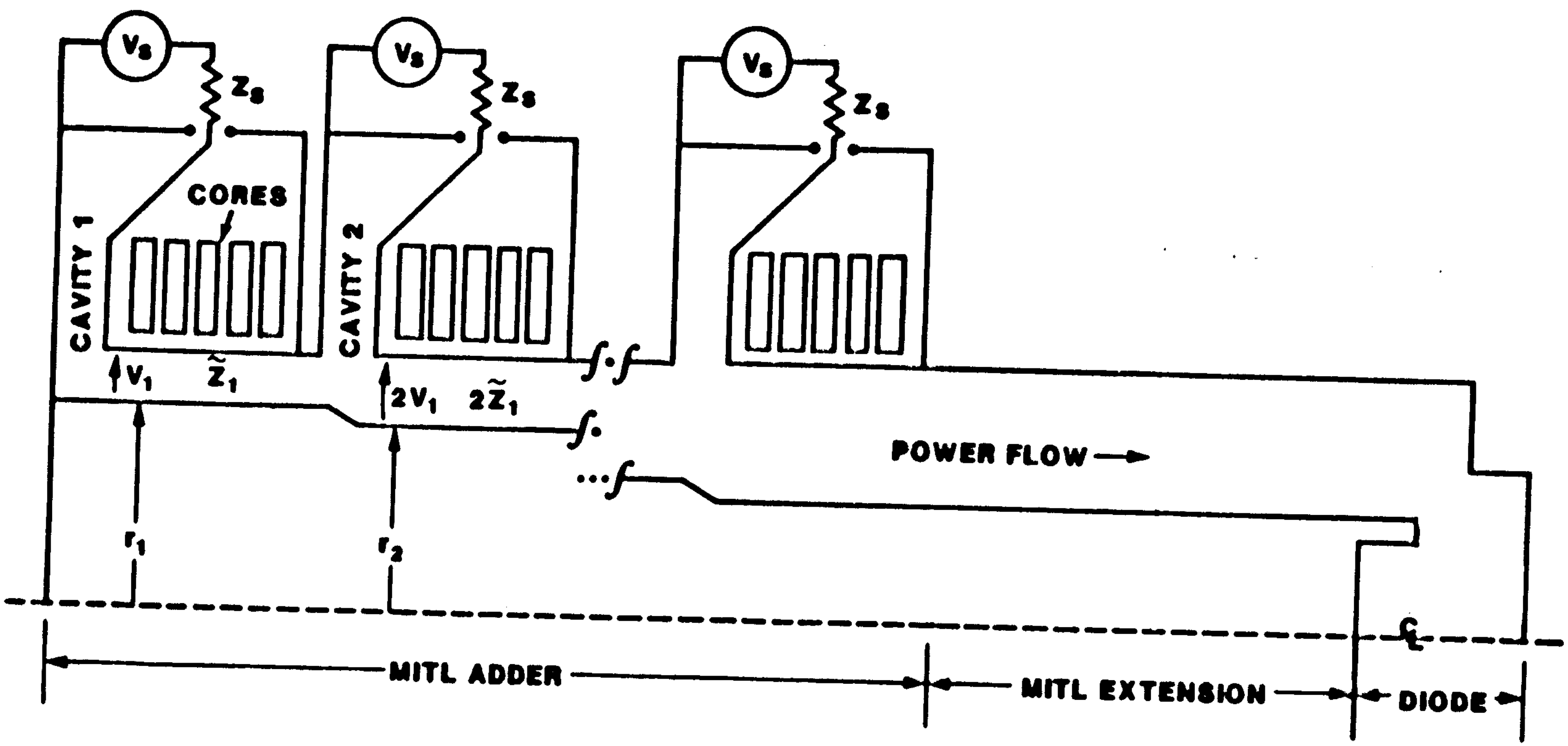
Mutistage Laser Triggered Gas Switches

- Nominal 10 MV
  ($\sim$ 8.5 MV, operational)
- length = 2.2 m
- 400 kA, 300 nH
- jitter $\sim$ 500 ps

TDF pulsed power system



TDF Voltage Addition Concept



TDF will involve significant scaleups from PBFA-II, Hermes-III, and other present-day technologies:

	Present Technology	TDF Concept
Marx Generators	6 MV, 0.4 MJ	10 MV, 2.4 MJ
L. T. 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	30 MV, 2 MV/cavity
Extraction Diode+	1.2 MV, 0.3 MA	30 MV, 1.5 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

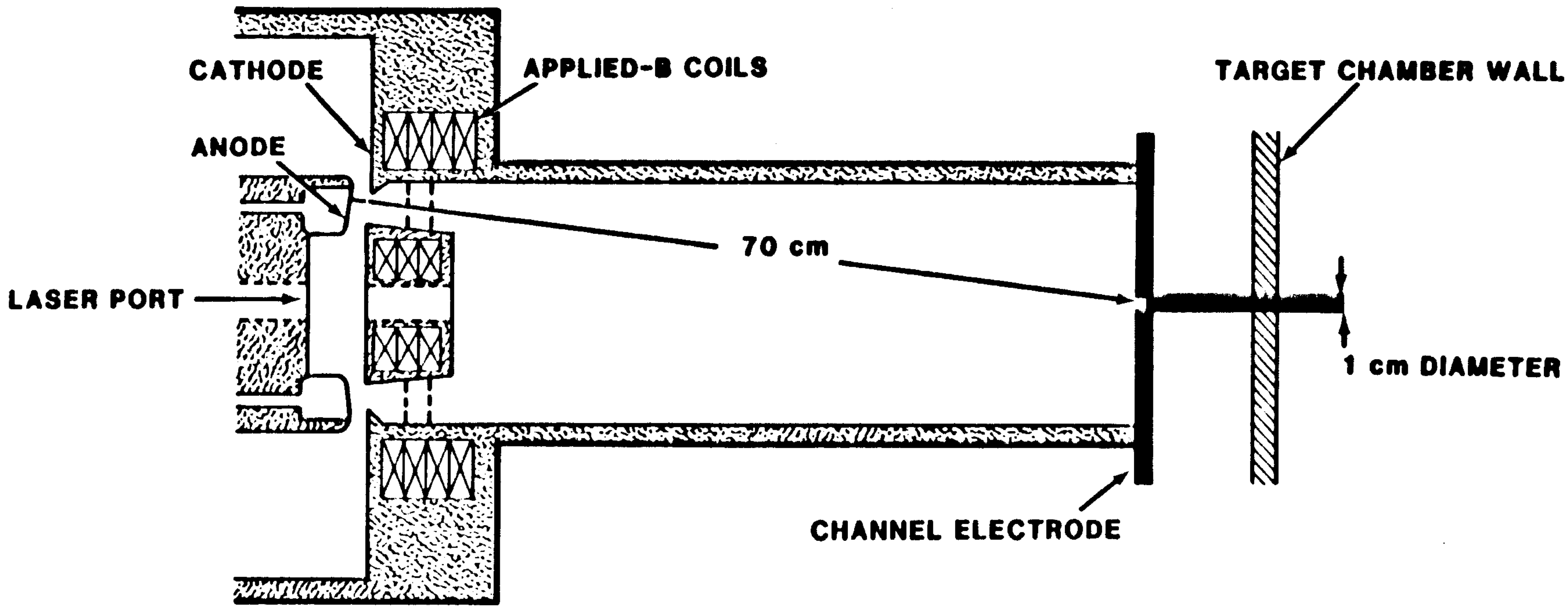
TDF extrapolations from Hermes-III technology

Hermes-III	TDF Voltage Adder
20 MV	30 MV
800 kA	1.8 MA
40 ns	30 ns
negative polarity	positive polarity
2 MJ stored energy	4.8 MJ stored energy
η = 32%	η = 34%

TDF Diode Concept

- Single gap
- Single-sided feed
- Applied-B insulation
- Field evaporation / ionization source of Li^{+1} ions

TDF Diode Concept

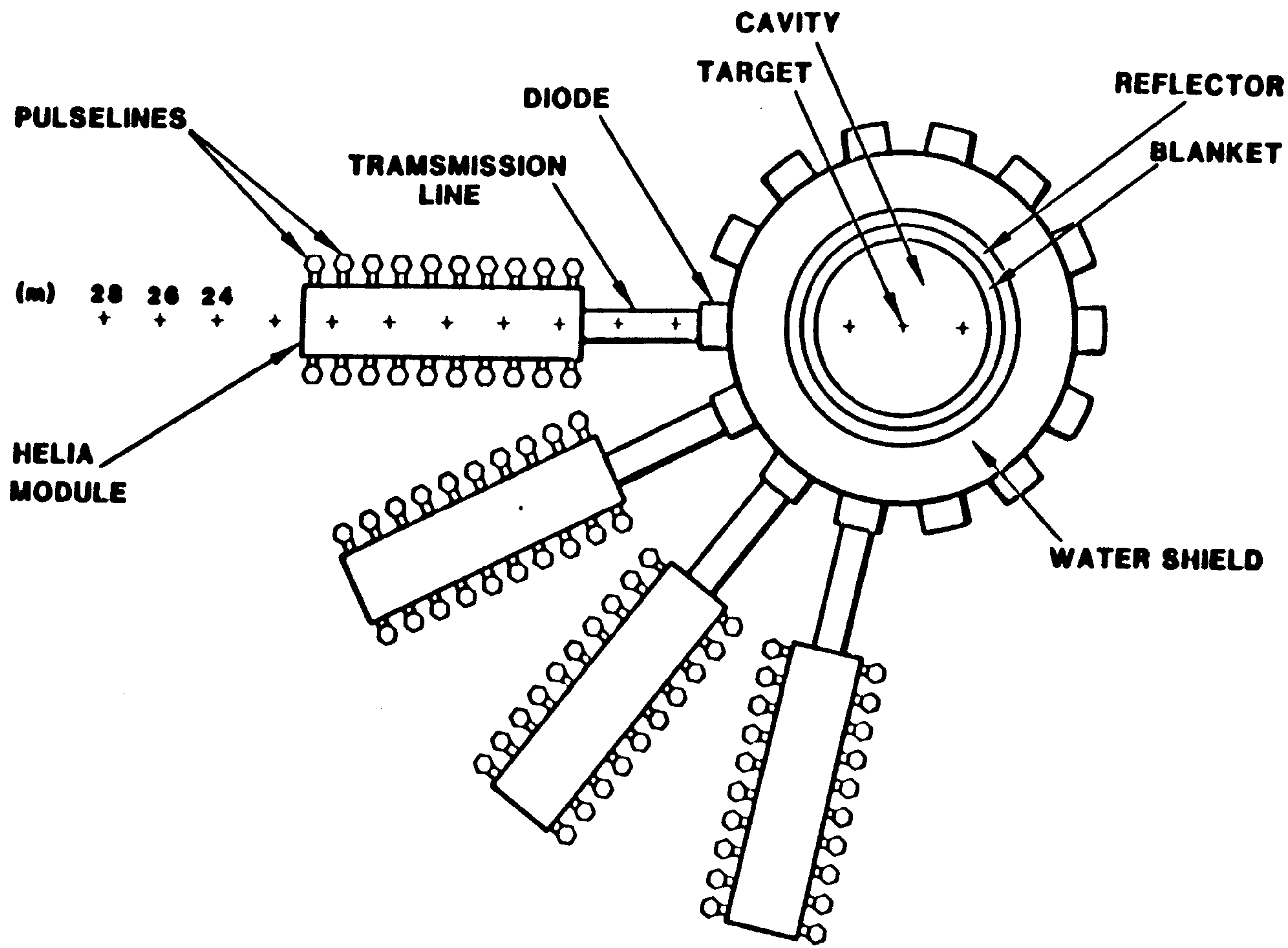


TDF Diode Parameters

Some optimistic, but reasonable assumptions:

V_{diode}	=	30 MV (nominal)
I_{diode}	=	1.8 MA "
Z_{diode}	=	17 ohms "
J_a	=	10 kA/cm^2
$\Delta\theta$	=	5 mrad
d	=	2 cm
B / B_c	=	1.5
B_{ap}	=	7 T
R_o	=	10.5 cm
R_i	=	7 cm
F	=	70 cm

LIBRA Concept



TDF Technologies Relevant to Commercial ICF Drivers

General:

- Target Physics
- Pulse Shape Requirements

LIBRA:

- Extraction ion diode
- Plasma channel transport
- Voltage Addition (MIVA)
- Cavity gas behavior
- Magnetic switching (?)
- Target injection & tracking (?)

Conclusion: TDF is a major step enroute to commercial ICF, but does not address repetitive (› 1 Hz) pulsed power issues.

Sandia National Laboratories

[redacted] PULSE ACCELERATOR TECHNOLOGY FOR LIGHT ION INERTIAL CONFINEMENT FUSION

Malcolm T. Buttram
Sandia National Laboratories

REPRESENTATIVE REPETITIVE SYSTEMS

ATA	35 kJ	1 Hz	(1000 Hz)
RAVEN/TEMPO	10 kJ	10 Hz	
(AVCO)	20 kJ	125 Hz	
RHEPP I	50 kJ	10 Hz *	
II	500 kJ	10 Hz *	

* proposed

MODIFICATIONS FOR REPETITIVE OPERATION

LOWER THE ELECTRIC STRESS

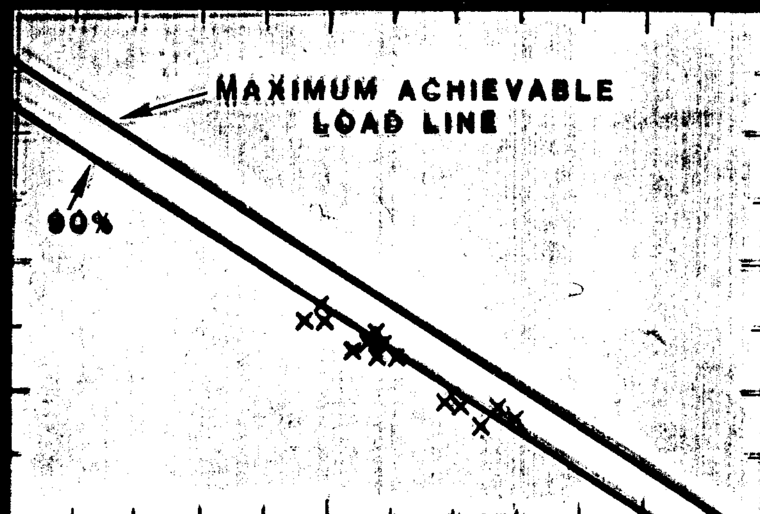
BEWARE OF OVERHEATING

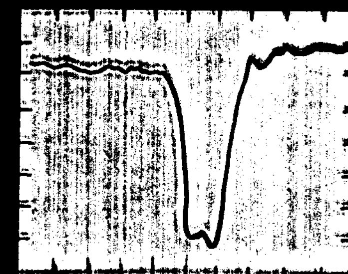
MINIMIZE FAULTS AND/OR THEIR CONSEQUENCES

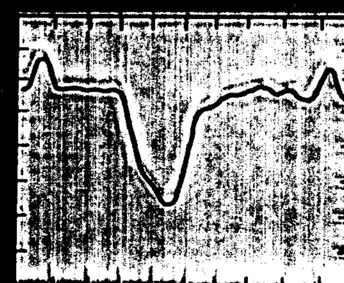
- POWER SOURCE
- ISOLATED MODULES

CHANGE SWITCHING AS NECESSARY

Inital half voltage tests on HELIA are promising.







ADDER ENERGY EFFICIENCY ≥ 80%

CHARGING SYSTEM EFFICIENCY ≥ 90%

OVERALL PULSE POWER EFF > 70%

IMPORTANCE:

$$\epsilon_{TH} R \, \epsilon_{power} \, \epsilon_{BEAM} \, \epsilon_{tgt} \, G = 1$$

COMPONENT LIFE.

ADDER ISSUES

WILL MAGNETICALLY INSULATED ADDER WORK IN + POLARITY ?

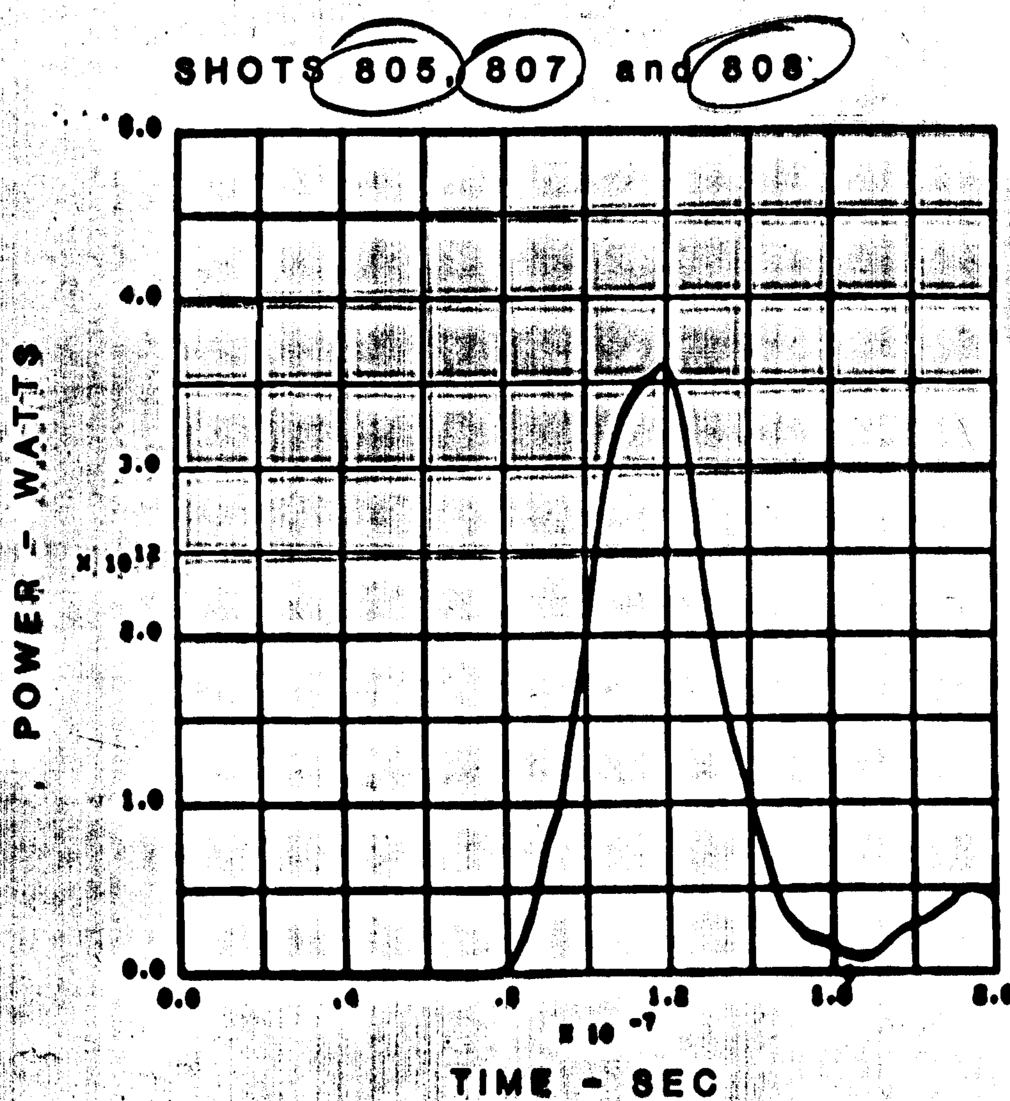
WILL MAGNETIC INSULATION "WEAR OUT" ?

CAN POST-PULSE ARCS BE AVOIDED ?

WHERE DO THE PULSES COME FROM ?

OPTION 1	TIMING SWITCH + SATURABLE MAGNETICS
OPTION 2	PCSS

MAGNETICALLY SWITCHED MODULE OUTPUT IS REPRODUCIBLE



ELN 1/15/85

MAGNETIC SWITCHES ARE:

IDEAL

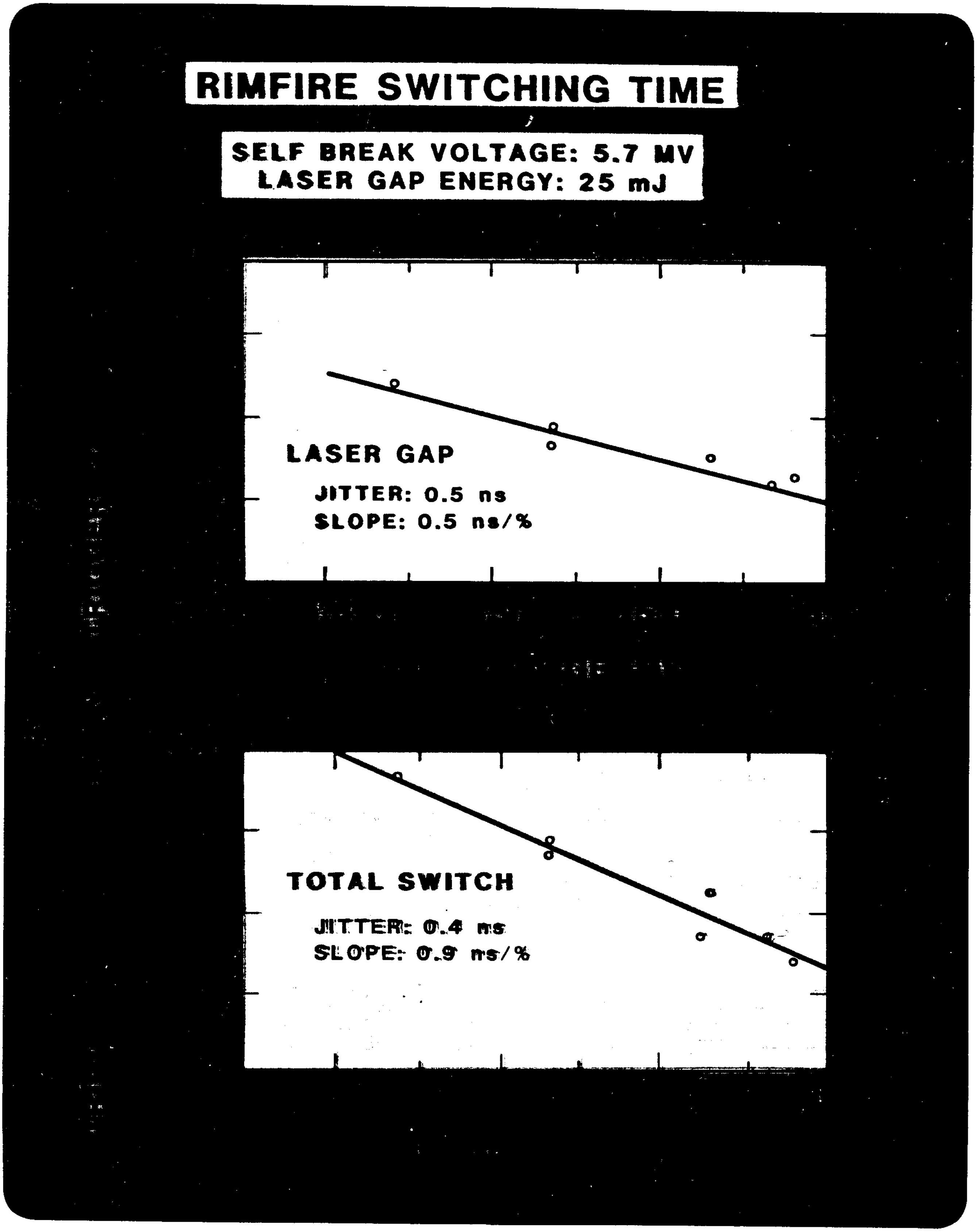
- REPETITIVE (300 kV, 1 kHz, 10^{10} watt demonstrated)
- HIGH POWER (2.7 MV, 3.7×10^{12} watt demonstrated)

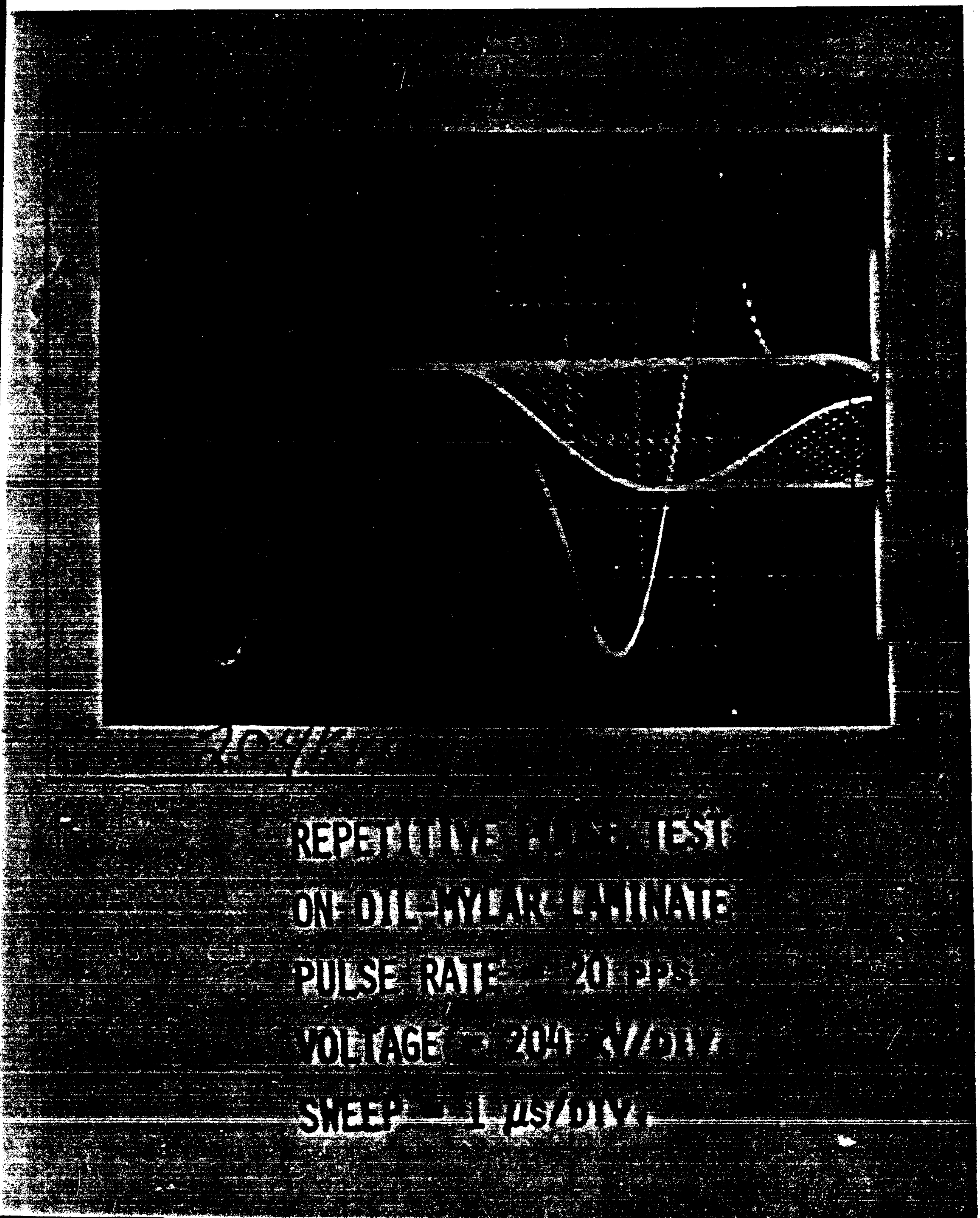
NON-IDEAL

- BIG, HEAVY
- NEED A TIMING SWITCH
  - Spark Gap
  - PCSS

HYPOTHETICAL TIMING SWITCH NEEDS

2 MV	CHARGE VOLTAGE
200 kA	PEAK SWITCHED CURRENT
1 COULOMB/PULSE	CHARGE TRANSFER
10^{6} SHOT	LIFE TO REPLACEMENT
0.25 ns	JITTER


RIMFIRE SWITCHING TIME
SELF BREAK VOLTAGE: 5.7 MV
LASER GAP ENERGY: 25 mJ
LASER GAP
JITTER: 0.5 ns
SLOPE: 0.5 ns/%
TOTAL SWITCH
JITTER: 0.4 ns
SLOPE: 0.9 ns/%


ON OIL-MYLAR LAMINATE
PULSE RATE – 20 PPS
SWEEP – 1 µs/DIV


WINDOW
SUPPORTING FOILS

ALTERNATOR → SCR → TRANSFORMER → PCSS → MAGNETIC COMPRESSION → ADDER

PHASE I : 50 kJ 1MV 10 Hz [~ 1½ YR]

PHASE II 500 kJ >1MV 10 Hz [~ 1993]

PHASE III 5000 kJ ?

SPARK GAPS:

HAVE DEMONSTRATED VOLTAGE, CURRENT, TIMING

HAVE DEMONSTRATED RATE AND SHOT LIFE

HAVE NOT DEMONSTRATED PARAMETERS SIMULTANEOUSLY

PCSS:

HAVE DEMONSTRATED RATE, LIFE, AND TIMING

HAVE NOT DEMONSTRATED VOLTAGE OR CURRENT

ASSESSMENT:

THE BIG PAYOFF IS IN PCSS.

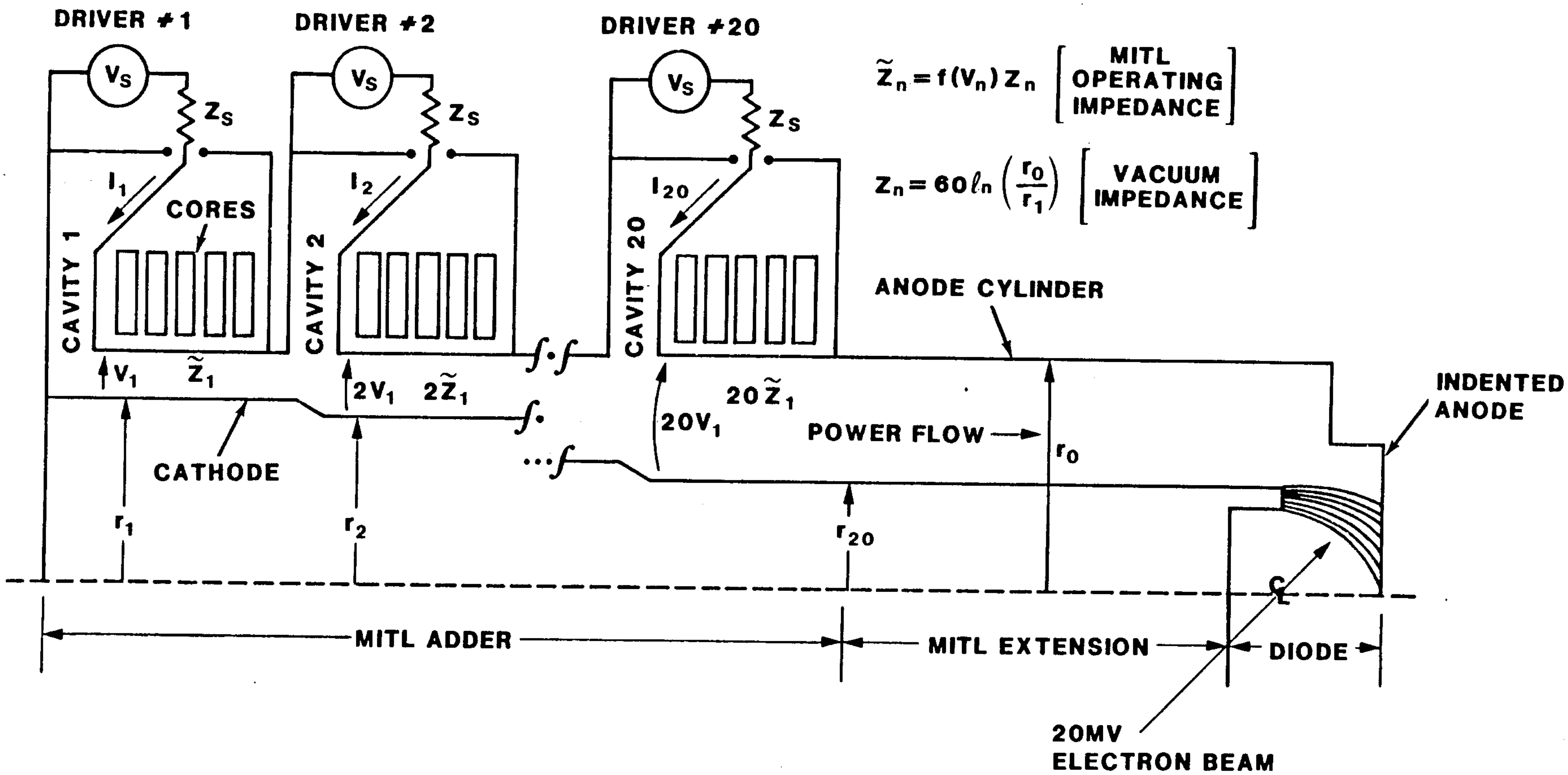
OPTION 2

FORM 10 NS PULSES (REQUIRES PCSS)

PLACE THE PULSE FORMING ELEMENTS IN THE (+) MITL SHANK

LONG TERM OPTION

HERMES-III ADDER/EXTENSION MITL SYSTEM



SUMMARY:

THE HERMES III ADDER SEEMS AN IDEAL BASIS FOR BUILDING A REPETITIVE LIGHT ION ICF PULSER SYSTEM

MAGENTIC SWITCHES ARE CLOSE TO THE REQUIRED PARAMETERS

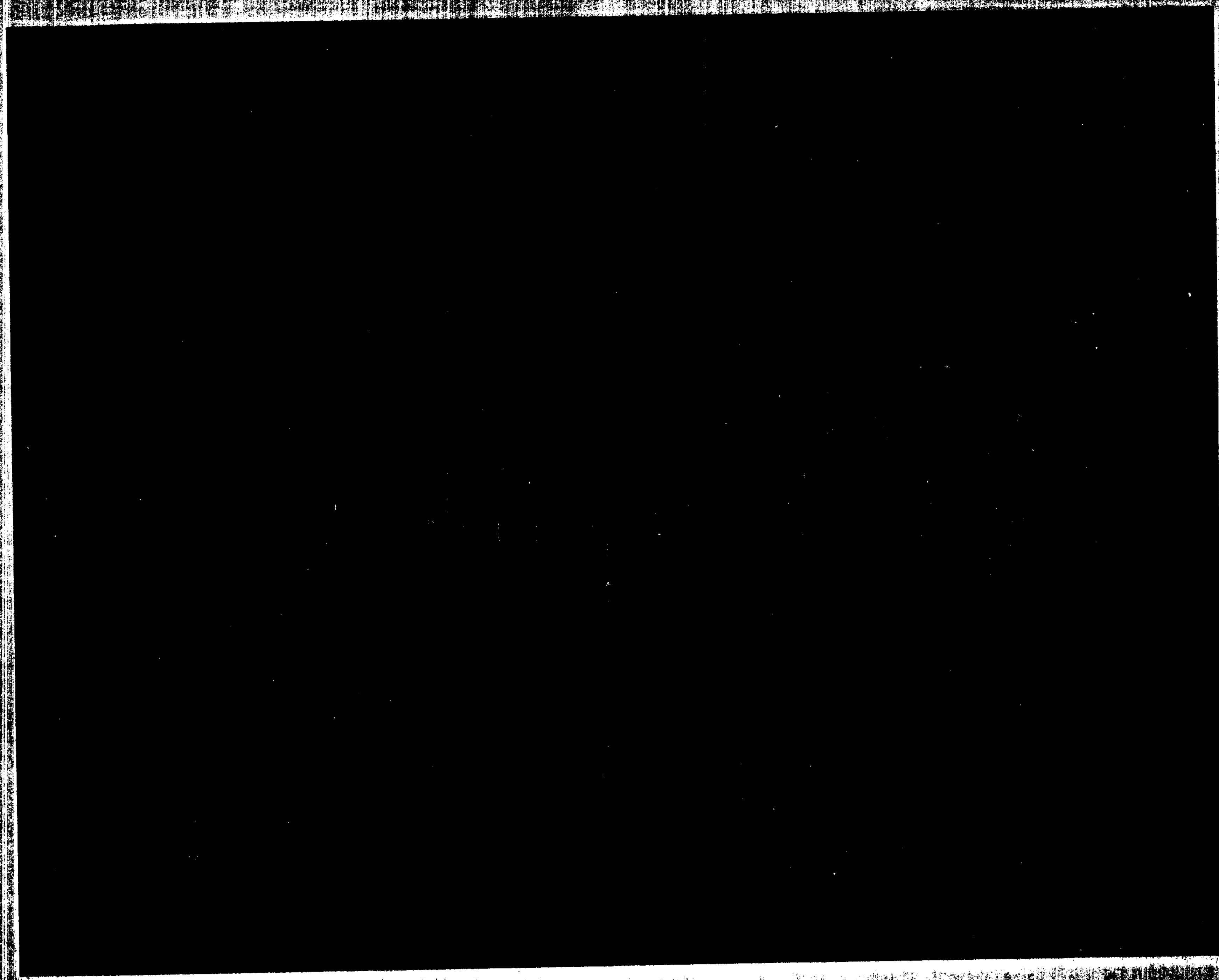
THE TIMING SWITCH NEEDS WORK

- SPARK GAPS ARE THE LEADING CONTENDER
- PCSS MAY BE BETTER IN THE LONG RUN

WE CAN BUILD THE LIGHT ION ICF DRIVER WITH COMPONENTS THAT WE ARE WORKING ON TODAY. WE DO NOT NEED ANY UNFORESEEN NEW DEVELOPMENTS.

K&M Company
TORRANCE, CA 90503

POLY - VU
#PV119



Commercial Drivers for LIB Fusion Reactor

ILE Osaka

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Institute of Laser Engineering , Osaka University
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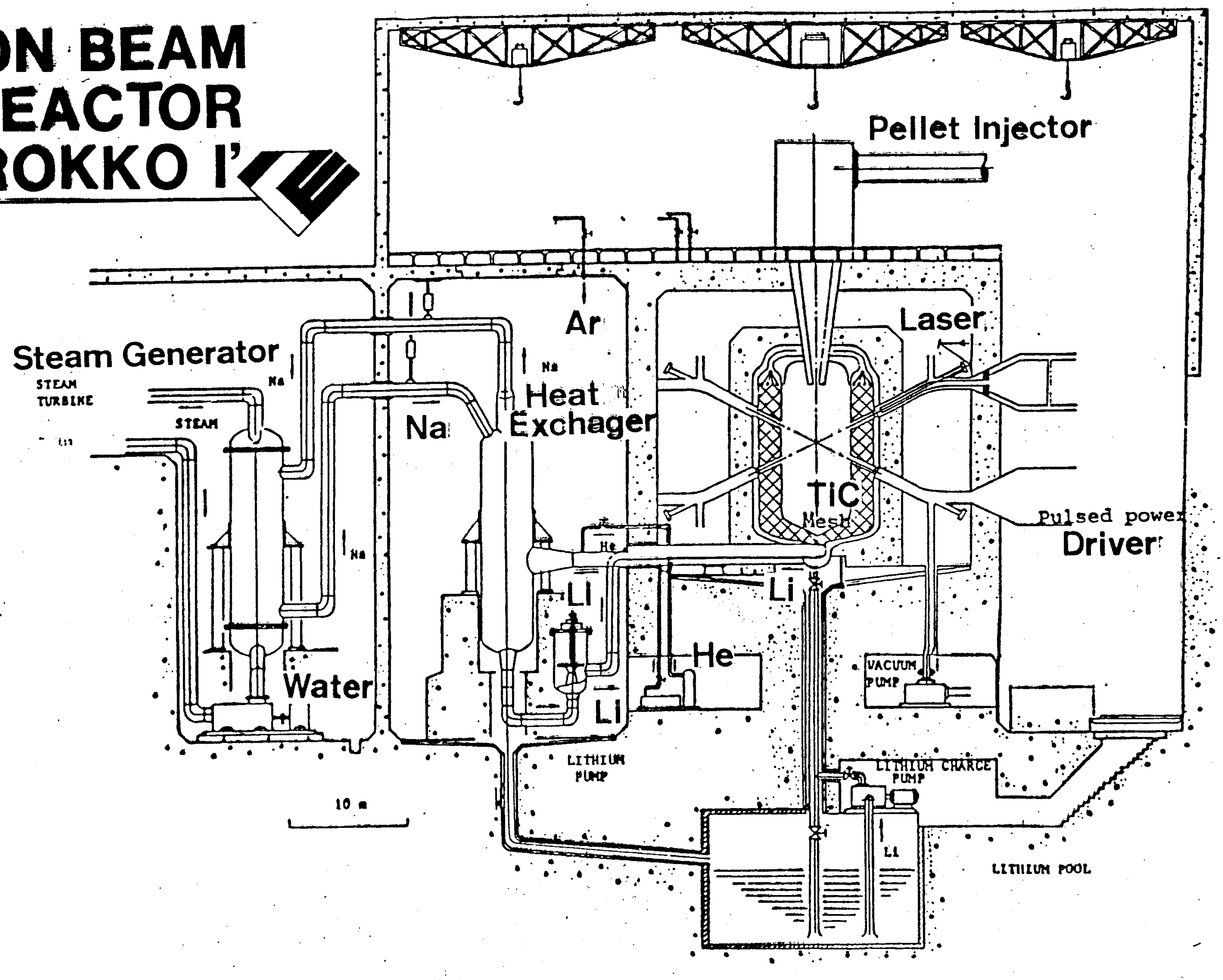
Suita , Osaka , Japan

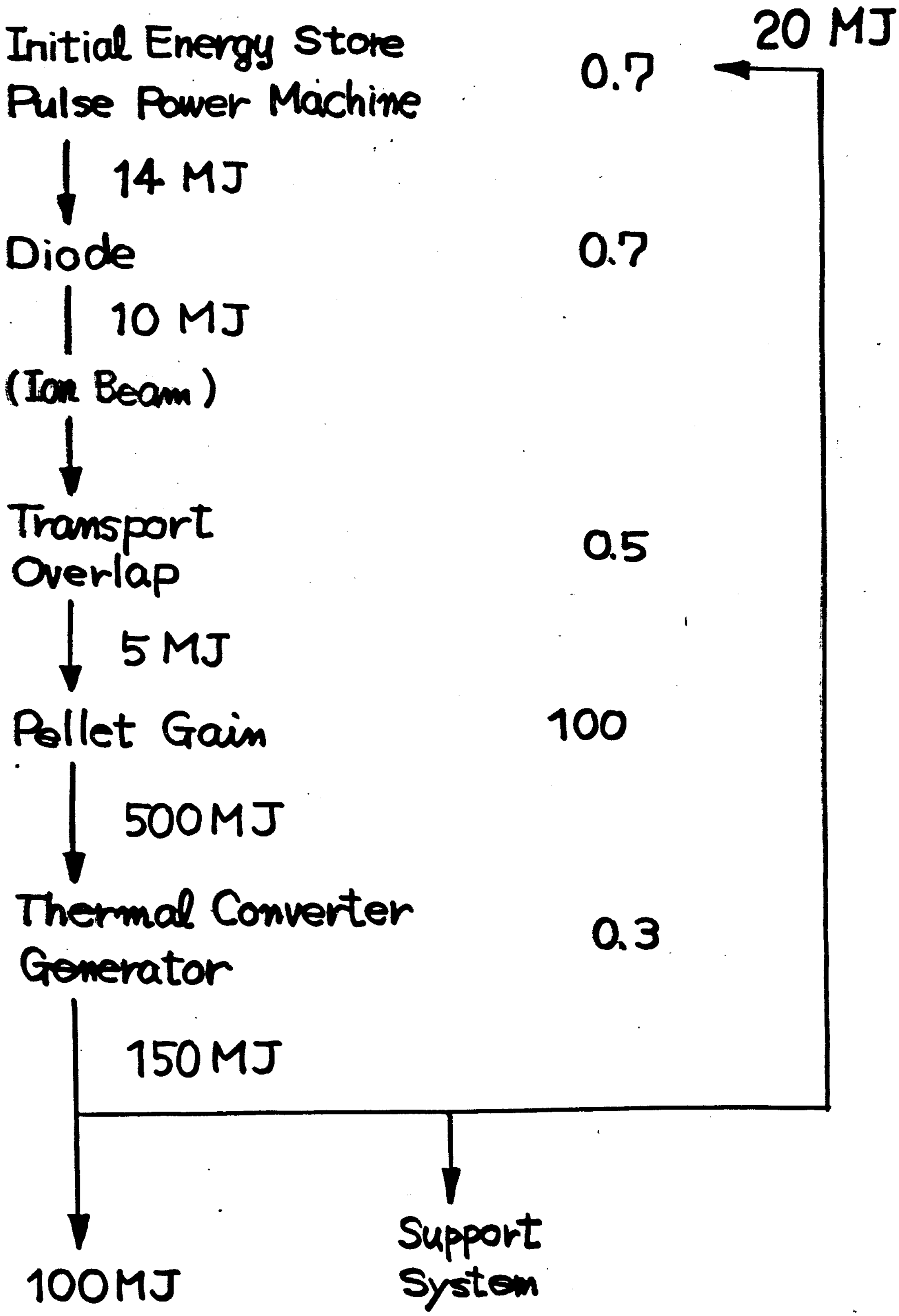
Outline

1. Reactor System
    - Power Flow
2. Energy Driver
    - Target
    - Beam Transport (Reacter Chamber)
    - Ion Diode
    - Pulse Power Machine
    - System Parameters

ION BEAM REACTOR 'ROKKO I'



Power Flow : smallest system

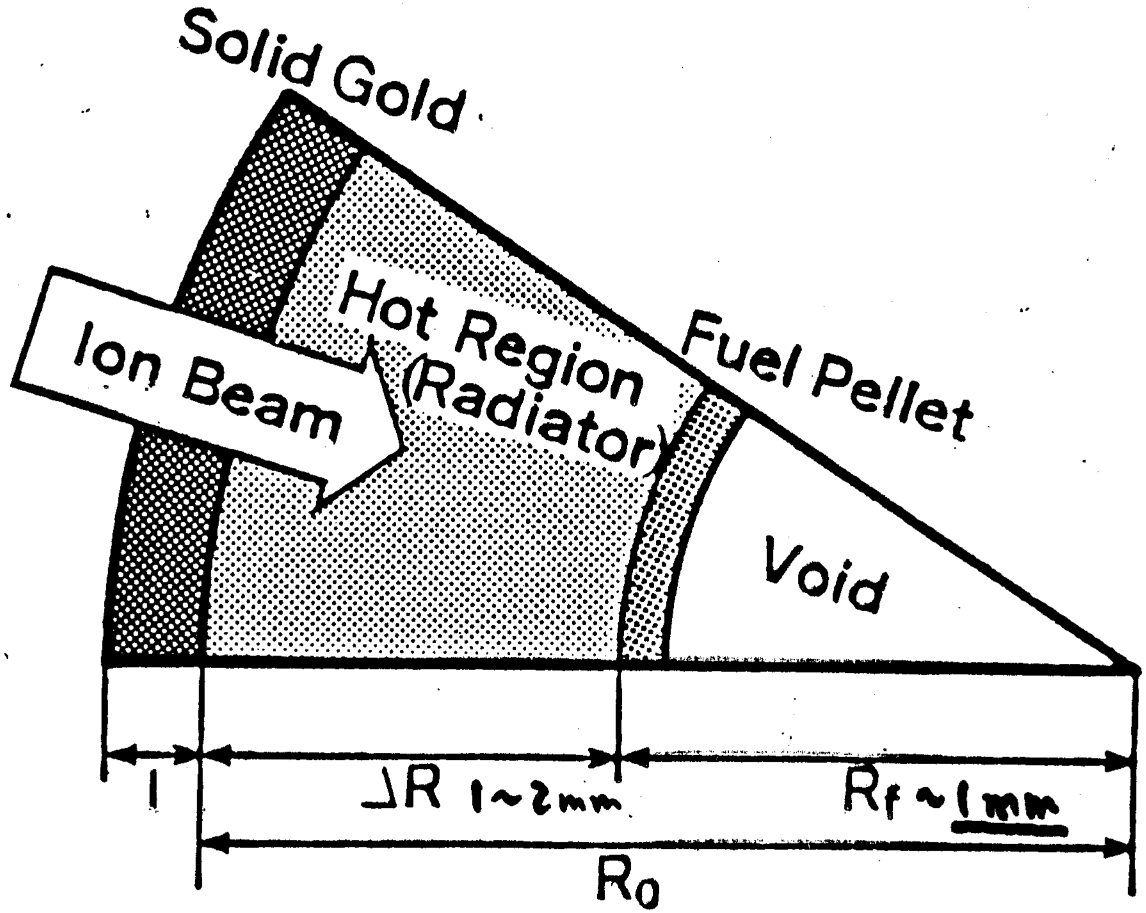


Block Diagram : Driver System

Pulse Power	Diode	Transport	Target
Energy Storage	Ion Source	Power Limit	Interaction
Pulse Compression	Generation Efficiency	Irradiation Geometry	Energy Transport
Repetition ,Life	Focusing	Efficiency	Implosion
	Repetition,Life	Overlap	
		Bunching	

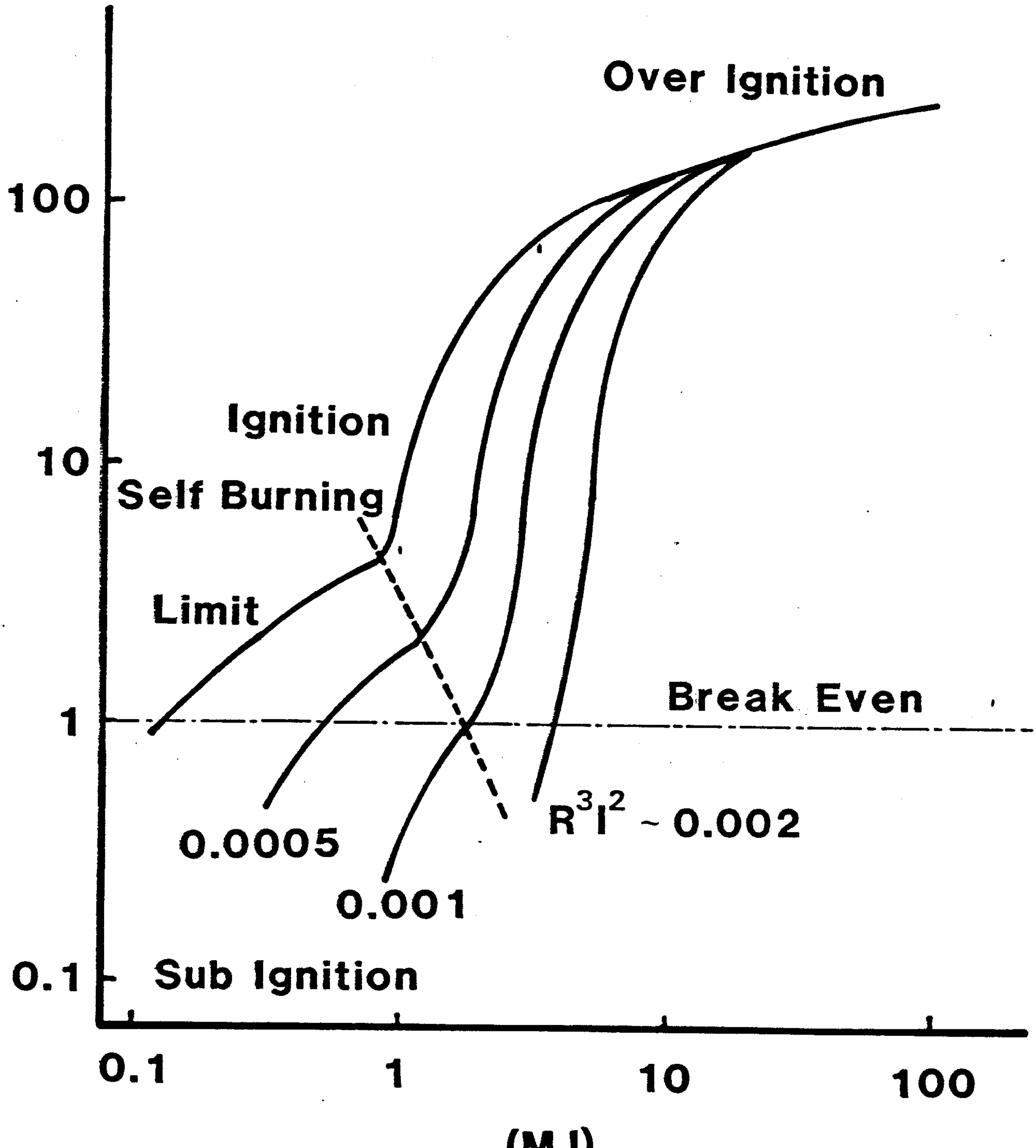
Cannonball Target for Ion Beam

ILE

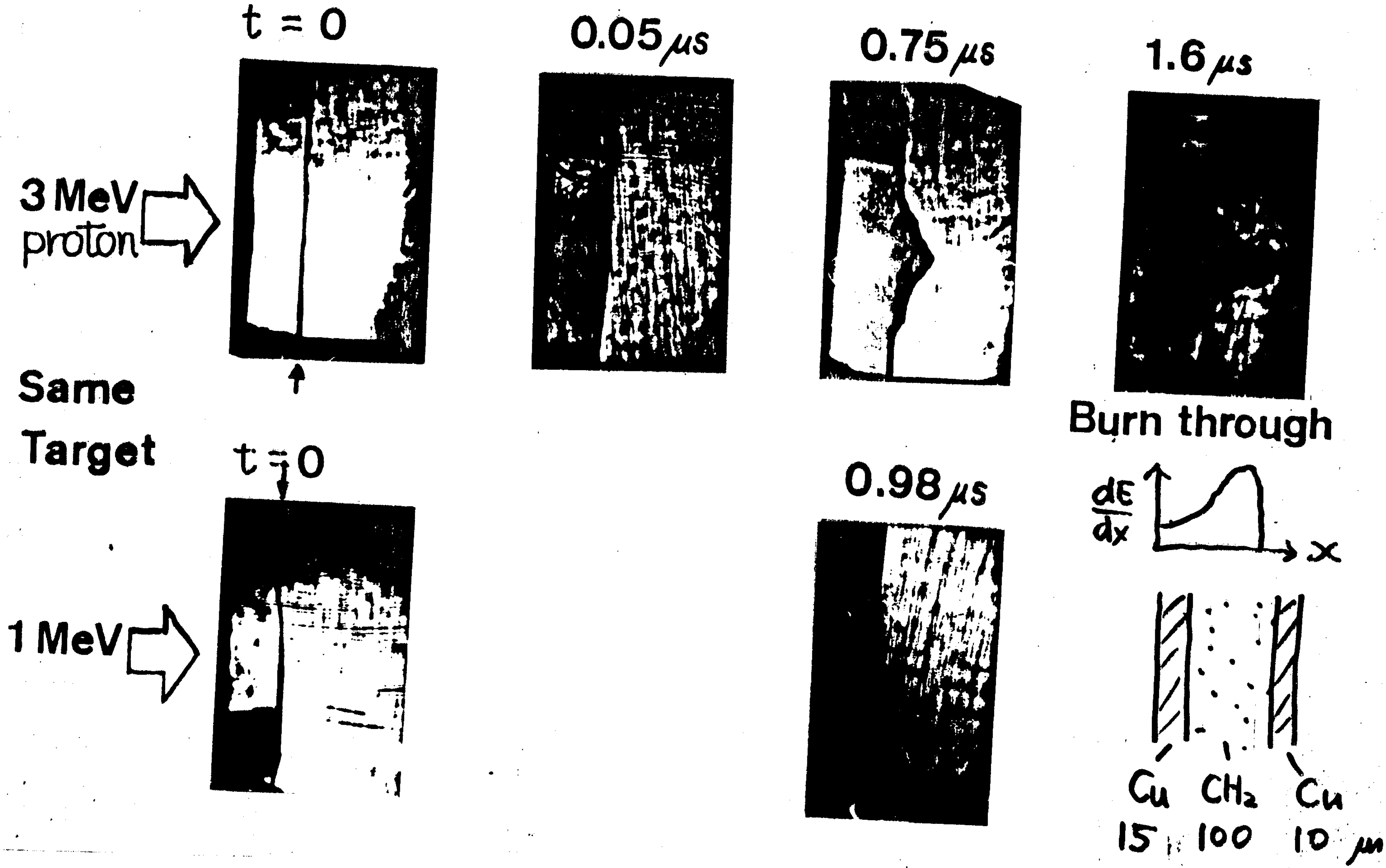


Schematic description of Mahobin target

GAIN CURVE FOR ION BEAM DRIVEN TARGET



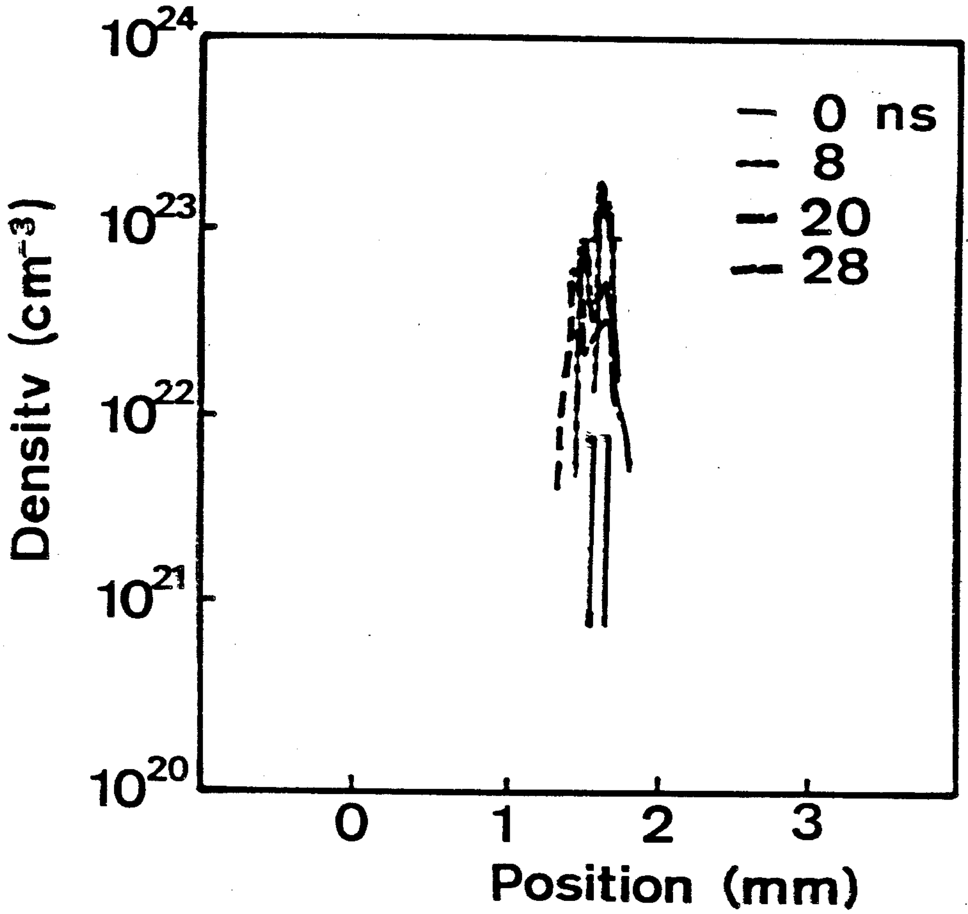
N_2 Laser Shadowgraph



Velocity Simulation by HISHO CODE

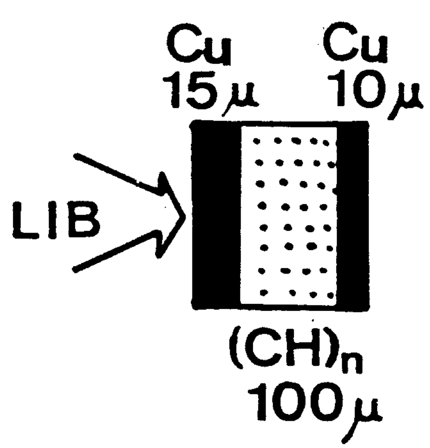
The HISHO CODE

- Hydrodynamic
- Light Ion Beam Interaction : Bethe-Bloch
- Radiation Transport



rear velocity

5×10^5 cm/s



$I = 10^{11}$ W/cm^2 3 MeV

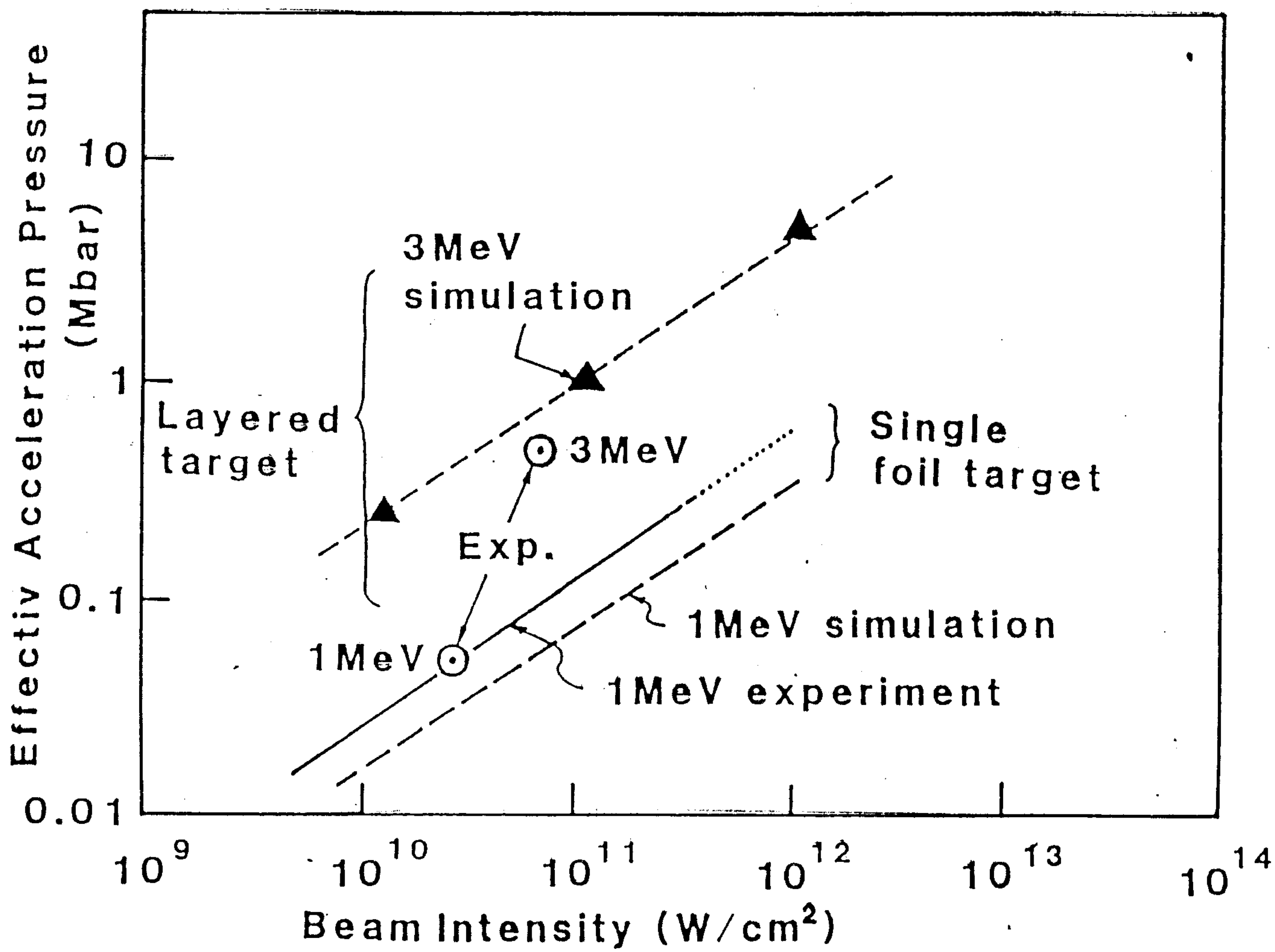
$\tau \sim 15$ ns

$\theta = 30°$

same as the expeliment

BEAM TARGET EXPERIMENTS

Acceleration Pressure Scaling



Beam Transport

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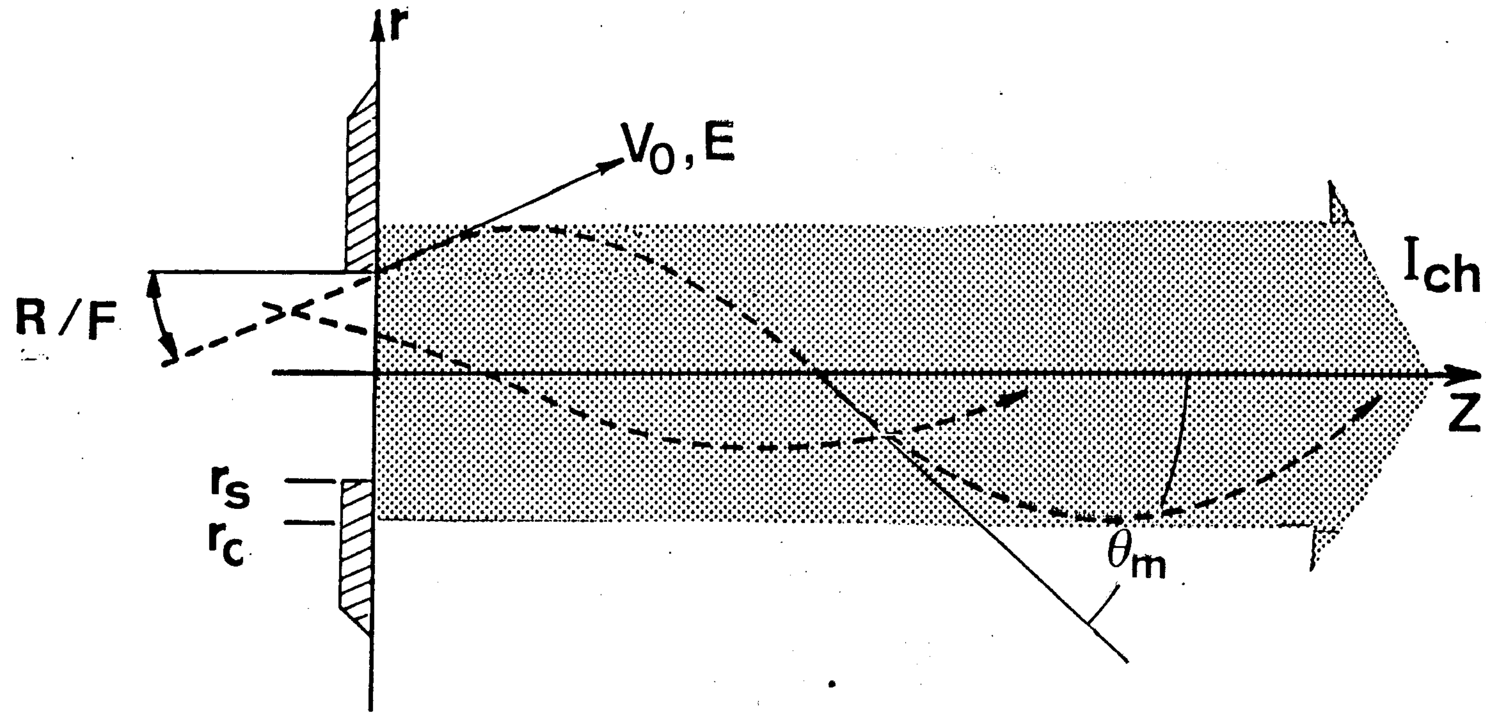

$$I_{ch}\ (kA) > 724\ \frac{\sqrt{AE(MeV)}\ (R/F)^2}{1-(r_s/r_c)^2}$$

$$\tan\theta_m = 0.203\sqrt{\frac{I_{ch}}{\sqrt{E}}}$$

Transportable Power Limit

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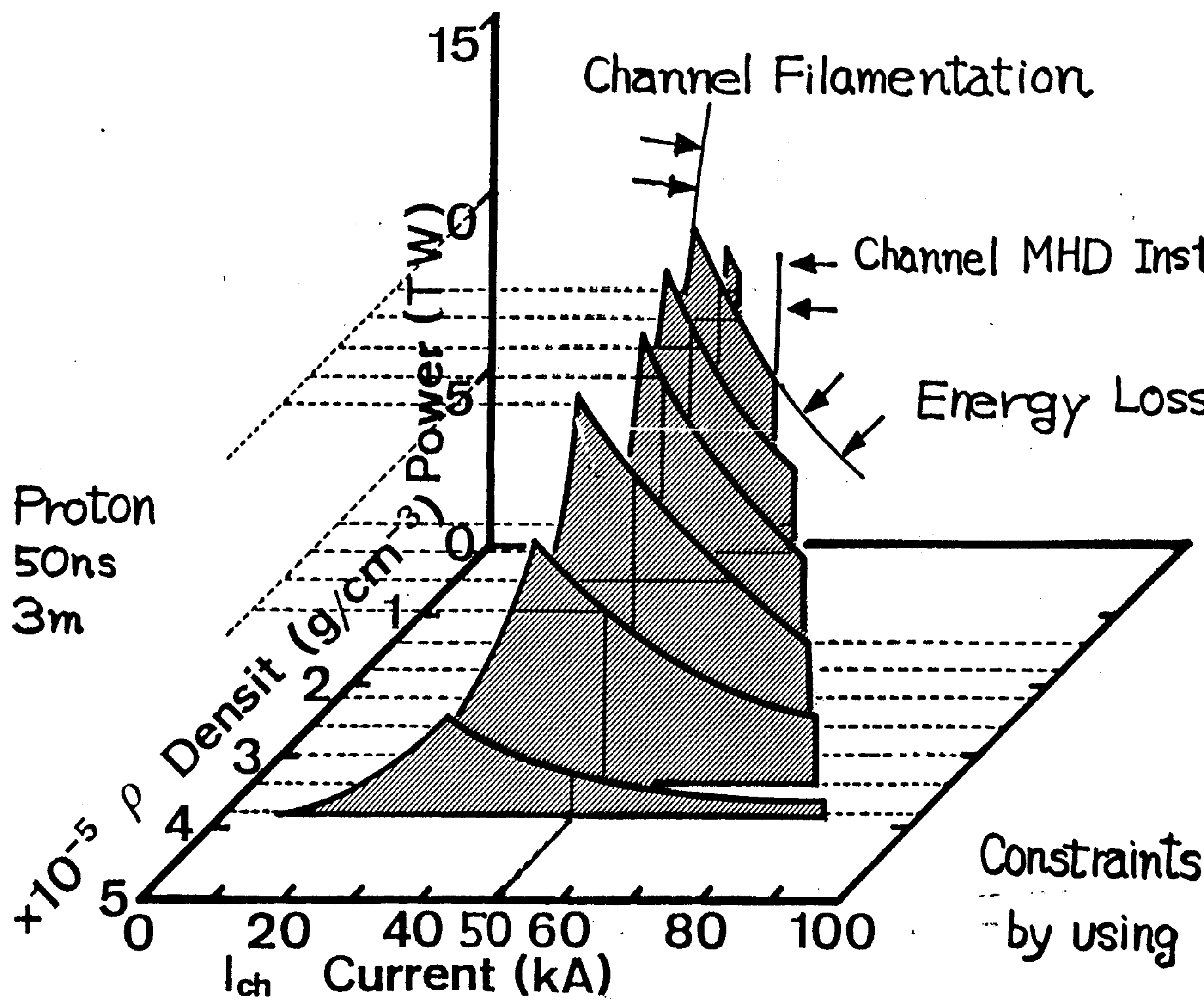
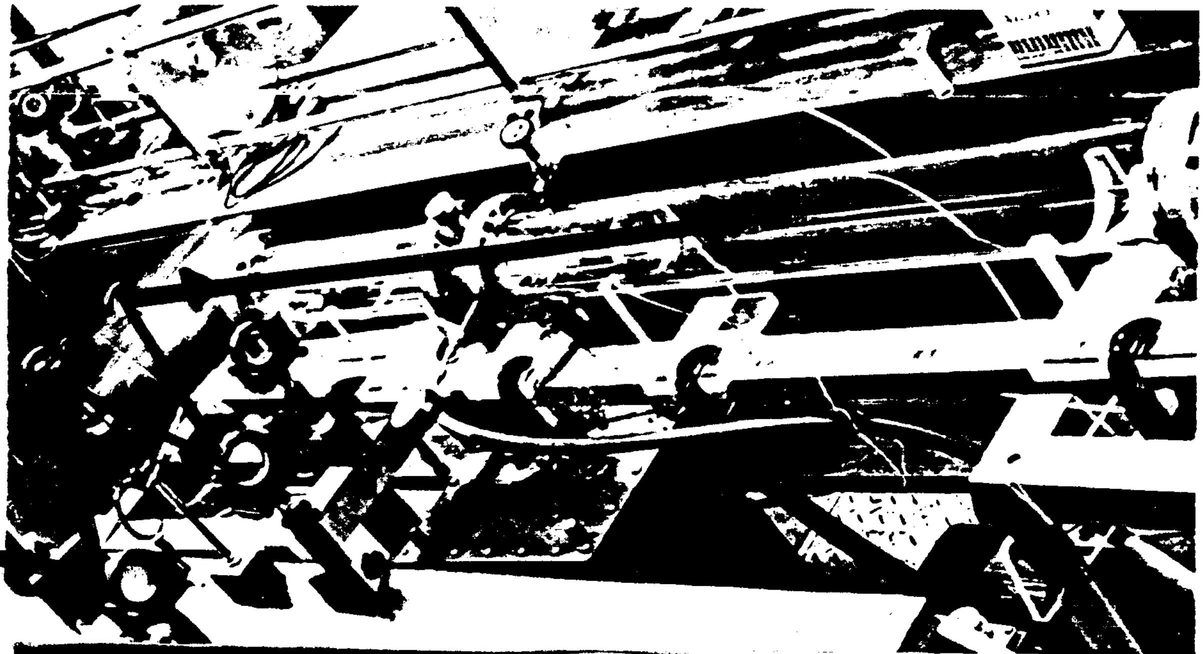
- Proton
- 50ns
- 3m



Constraints are relaxed by using heavyer ion.

C_2H_4 gas

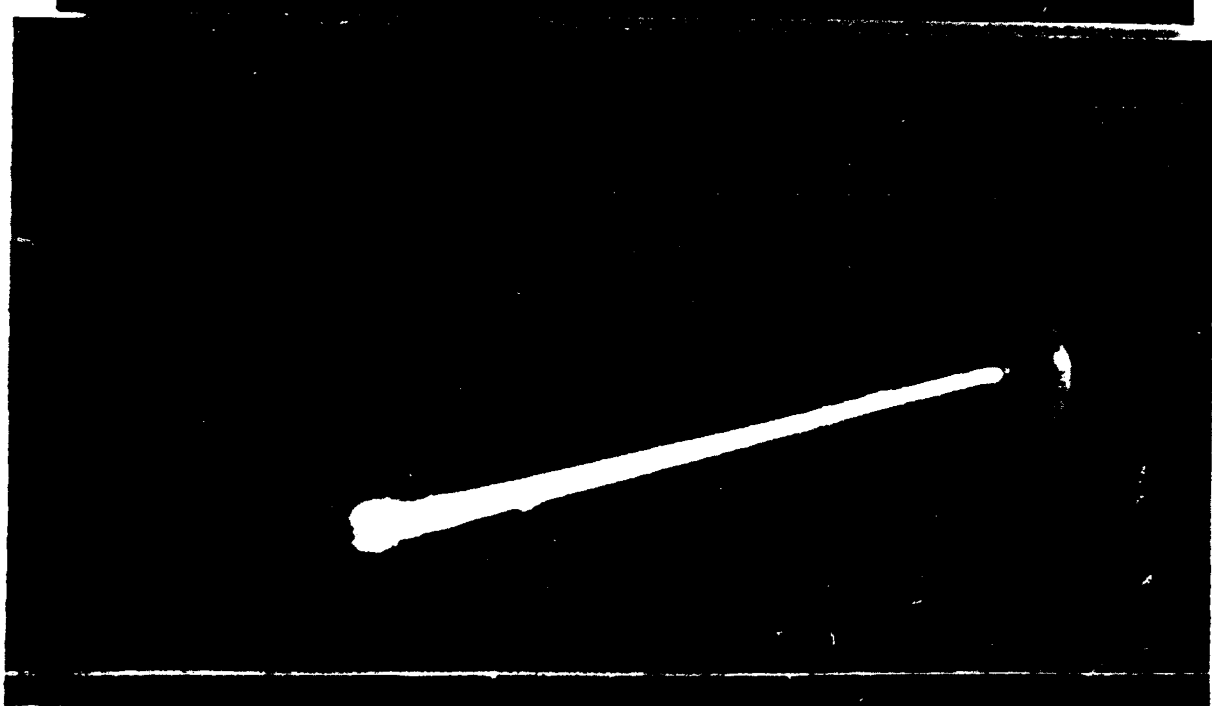
2J, 100ms CO_2 laser pass

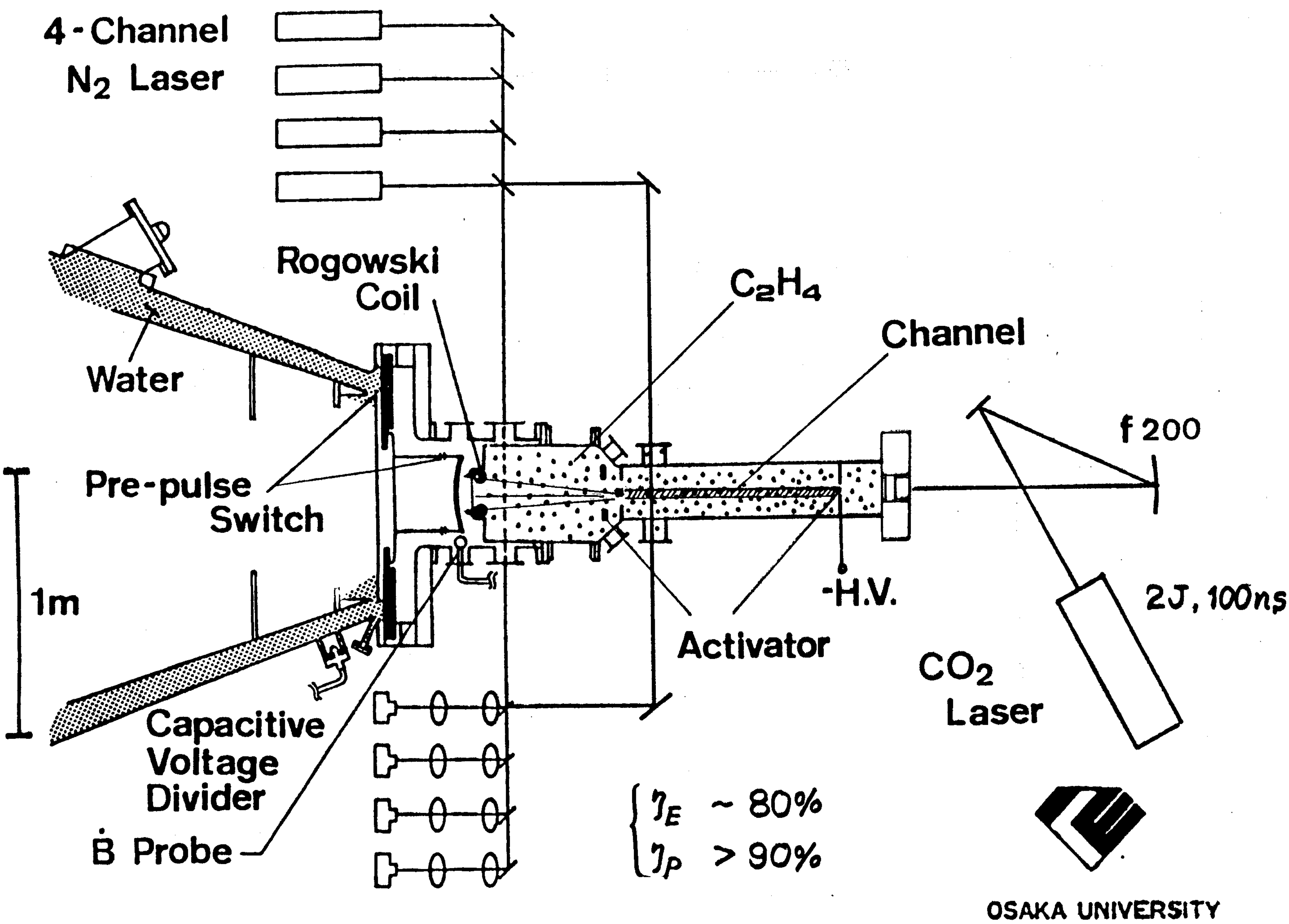


No laser

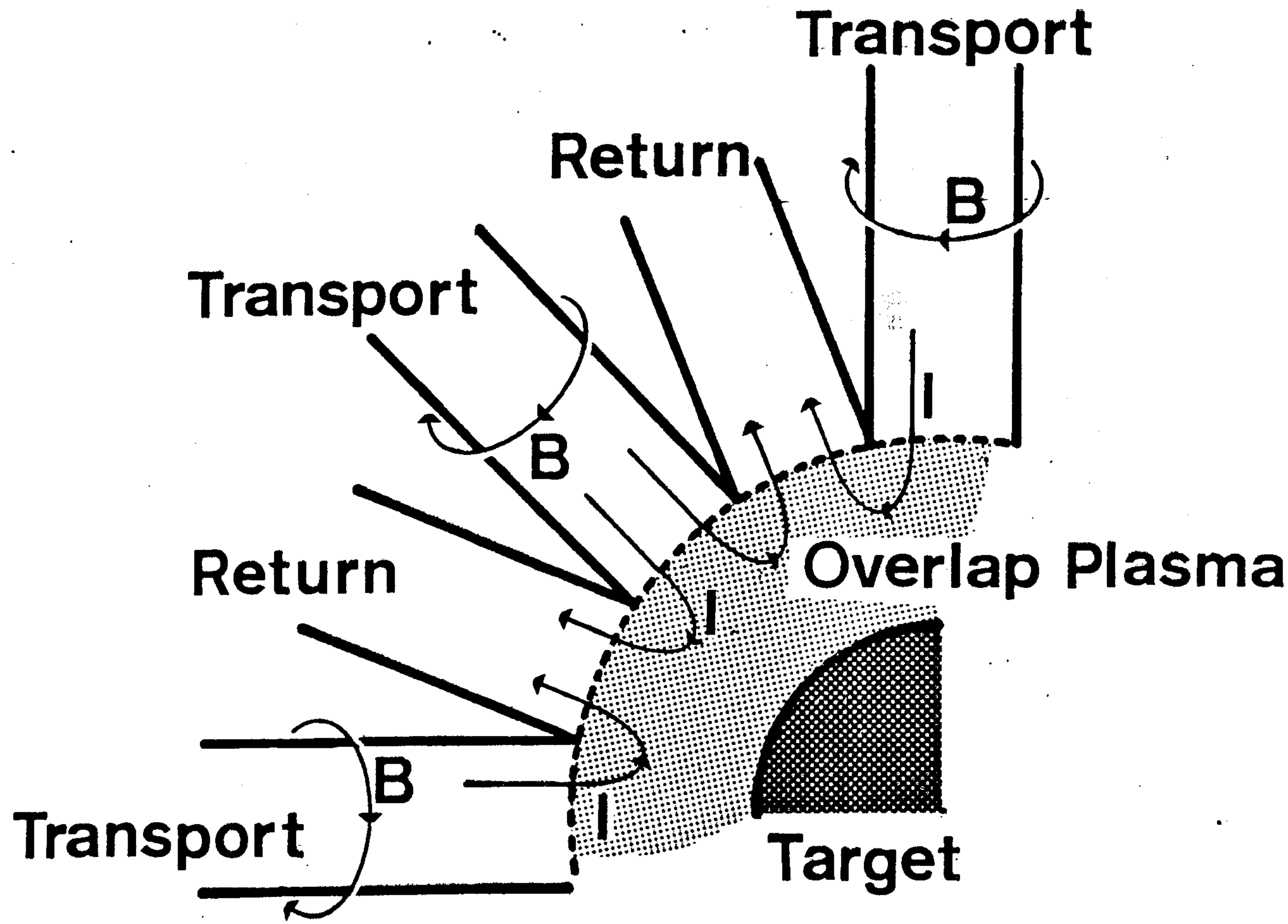
10 Vcm $Torr^{-1}$

With laser 2.4mJ cm^{-3} $Torr^{-1}$




4-Channel
N2 Laser
Rogowski
Coil
C2H4
Channel
Water
f 200
Pre-pulse
Switch
-H.V.
1m
2J, 100ns
Activator
CO2
Laser
Capacitive
Voltage
Divider
ηE ~ 80%
ηP > 90%
Ḃ Probe
OSAKA UNIVERSITY

Beam Overlap Configuration



Irradiation Arrangement 30–32

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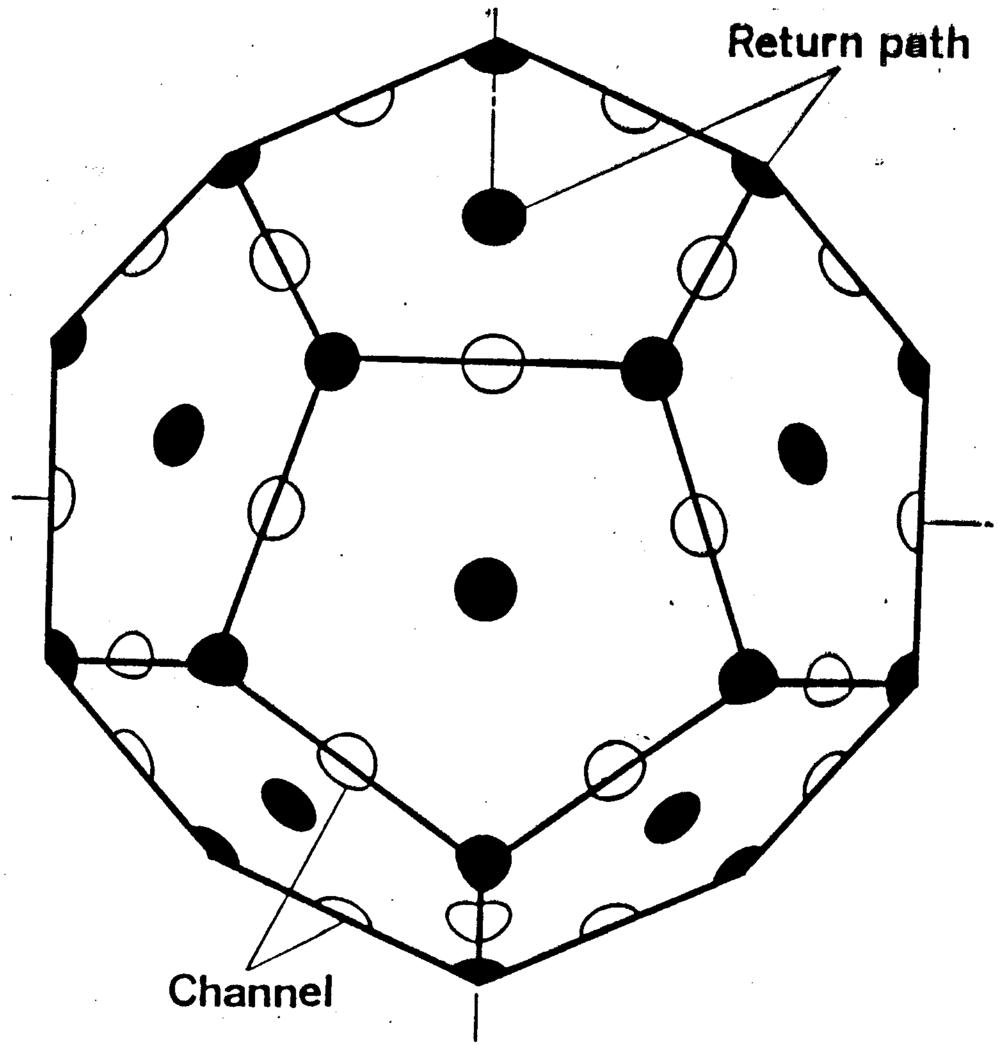

Uniformity and Average Incident Angle of Target

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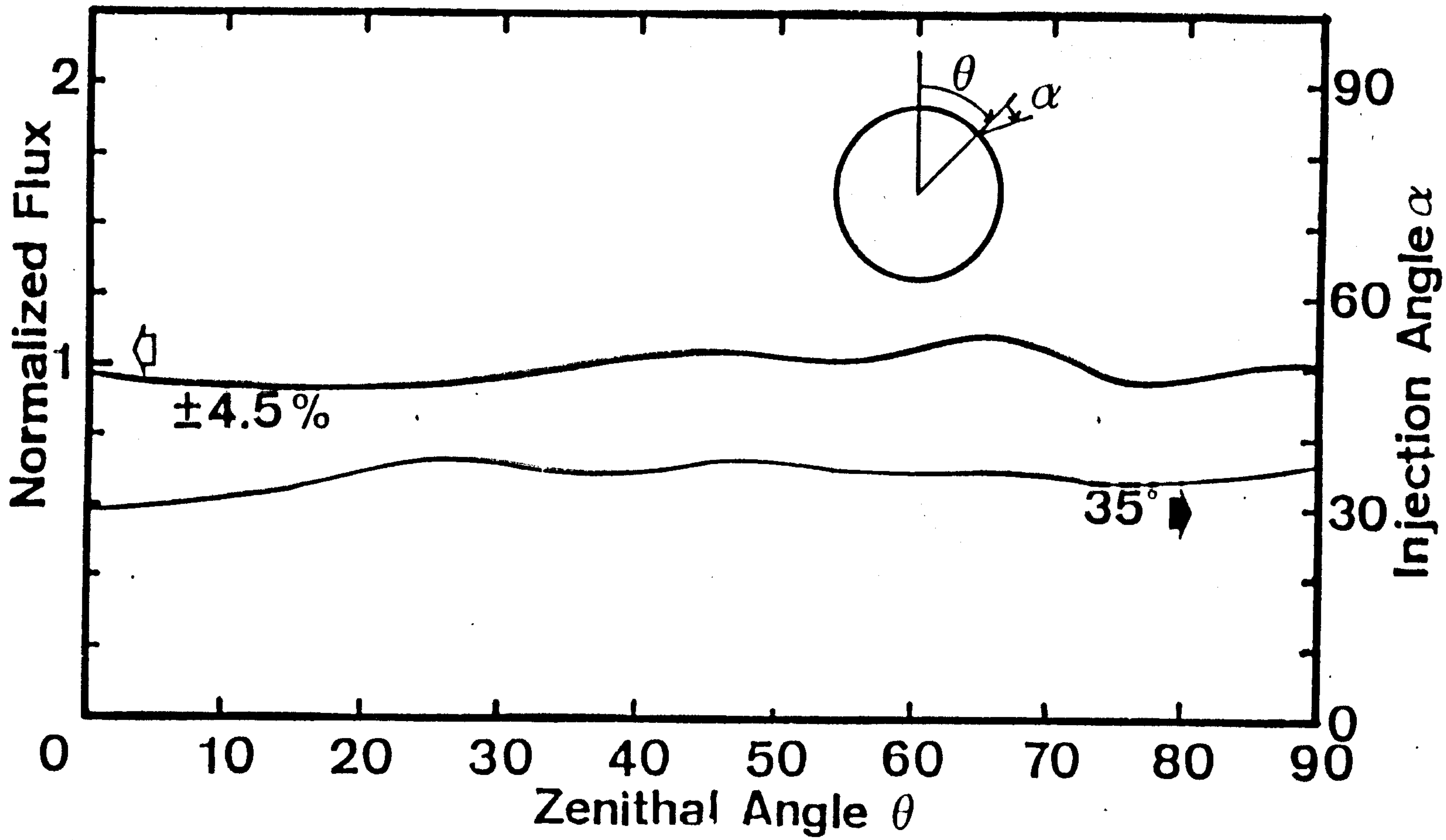
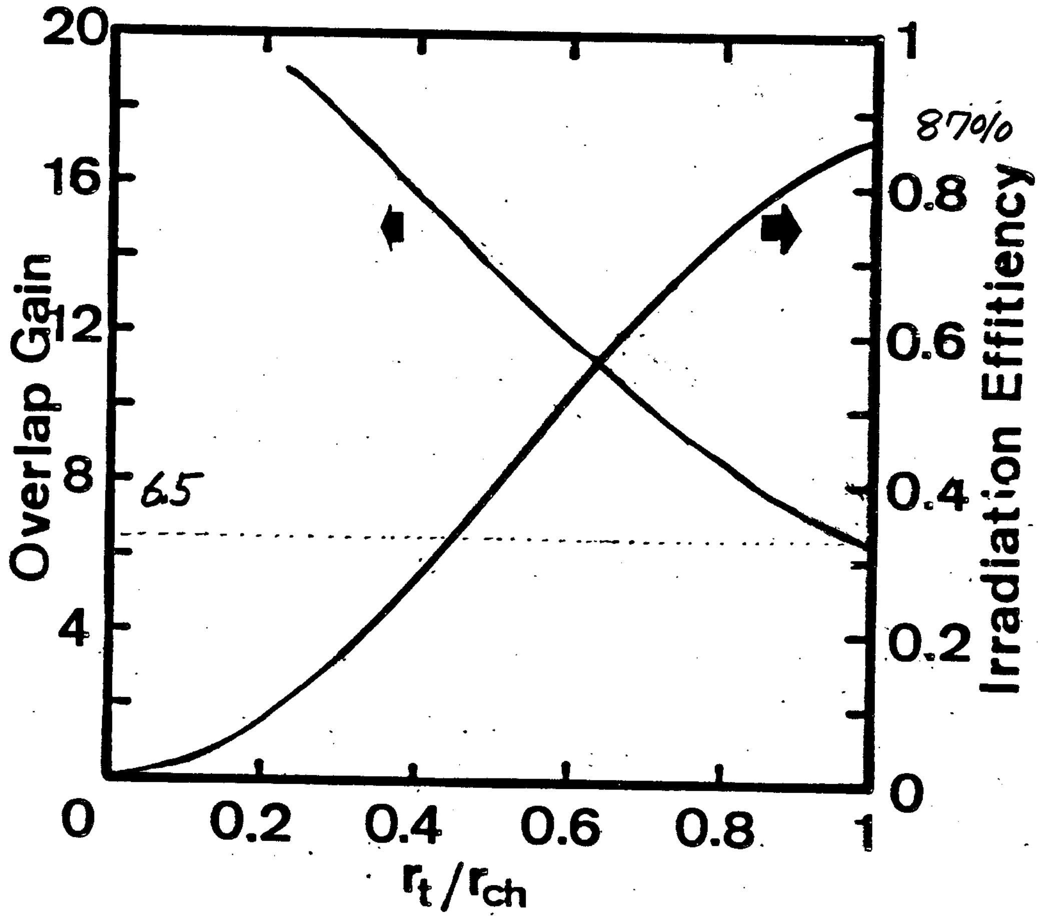


Beam Irradiation Efficiency and Beam Overlap Gain

ILE

Orbit Calculation 30 ch - 32 return



Triple Channel Transport Experiment

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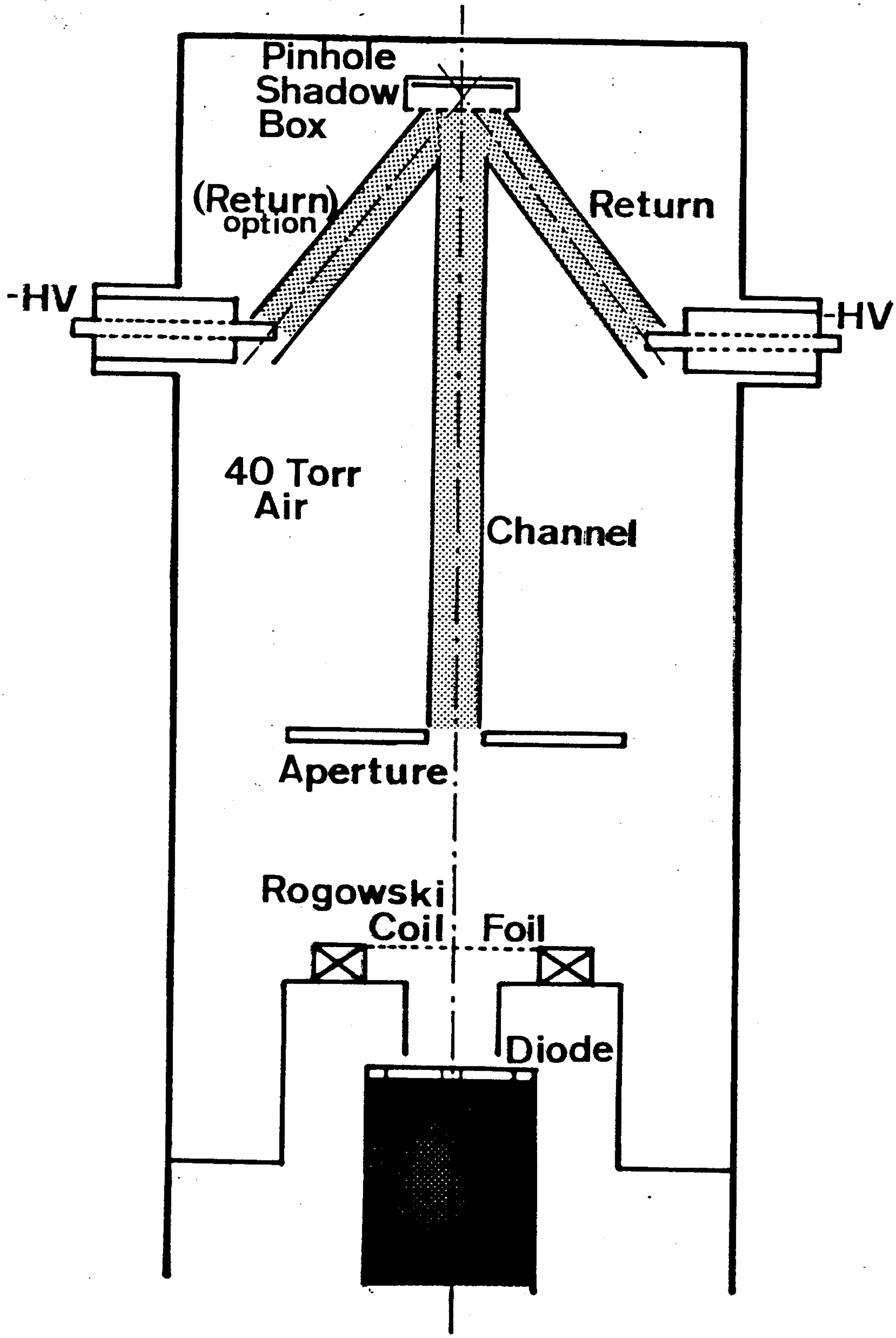
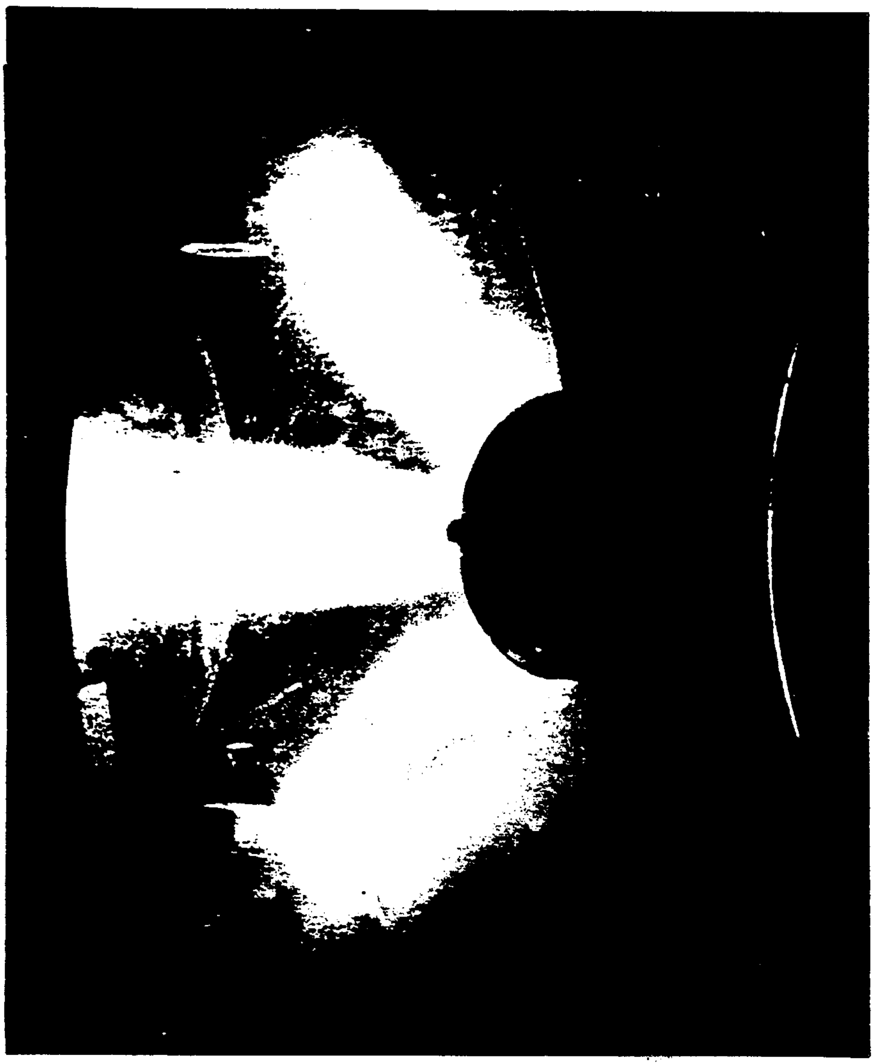
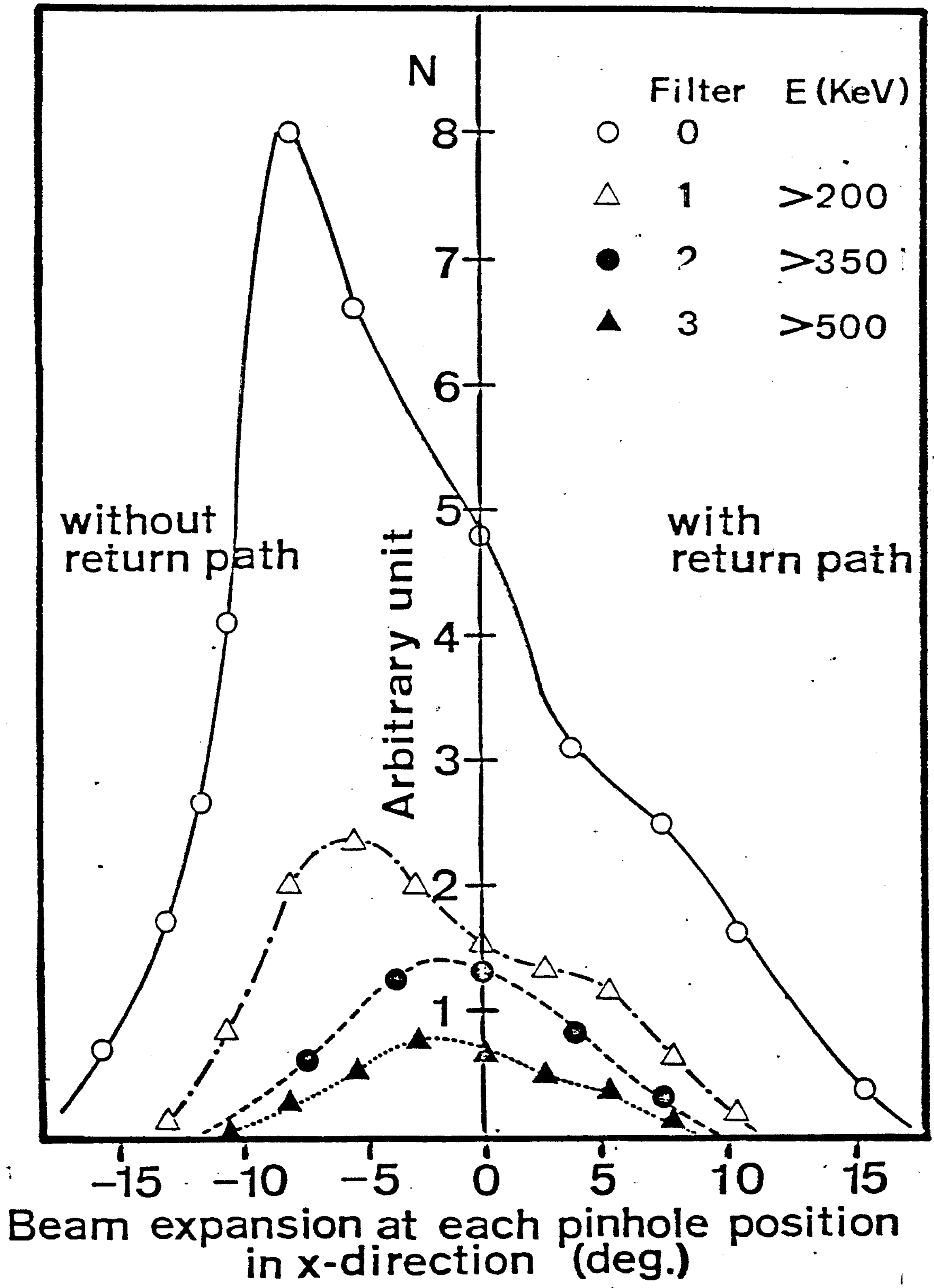


TRIPLE WIRE CHANNEL



BEAM EXPANSION IN OVERLAP REGION



Experimental expected overlap gain was 7.3

BEAM TRANSPORT BY LASER GUIDED PLASMA CHANNEL

Experiments	Reactor
(1) Channel Formation	
• C_2H_4 20 mbar	10 mbar
• CO_2 P(20) 10.6 μm Laser	
• 10 V/cm·mbar	30 kV
• 2 mJ/cm^3·mbar	40 J
• 0.4 ~ 1 m	3 m
• $n_e \sim 5\times10^{17}/cm^3$, $T_e \sim 1.8$ eV	
• I_{ch}=10 ~ 40 kA	
(2) Transport	
• Energy Transport Efficiency	
~ 80 % (0.4 m)	$\left.\frac{dE}{dx}\right\|_{loss} = \frac{10^9 \rho_0}{E}$
• Particle Transport Efficiency	
>90 % (0.4 m)	$I_{ch} > K(R/F)^2\sqrt{AE}$
• Guide up to 10^{10} W/cm^3	
(3) Beam Overlapping	
• Alternate Arrangement beam & return channel	Arrangement 30-32 Overlap Gain >6.5

Brightness Scaling

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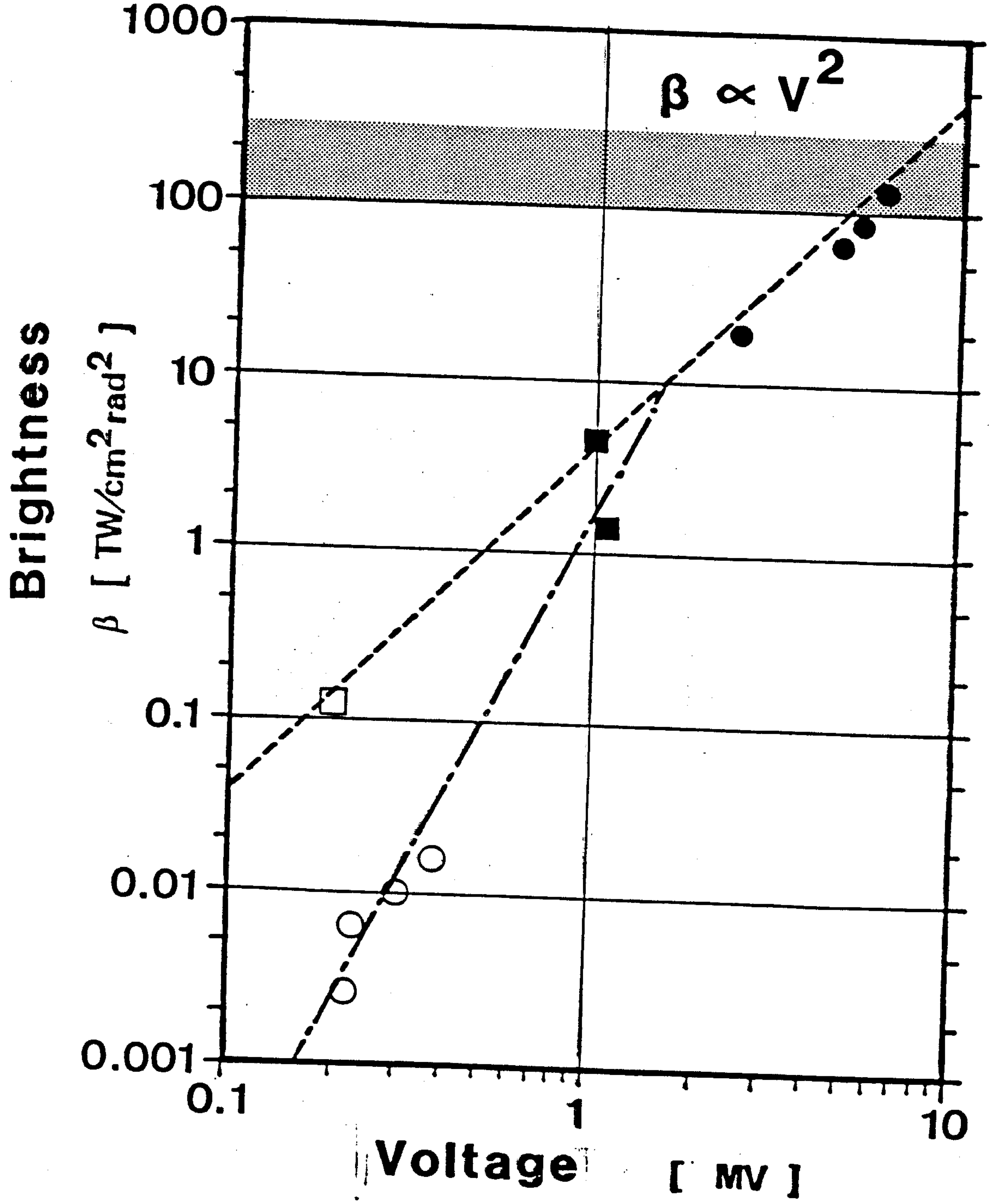
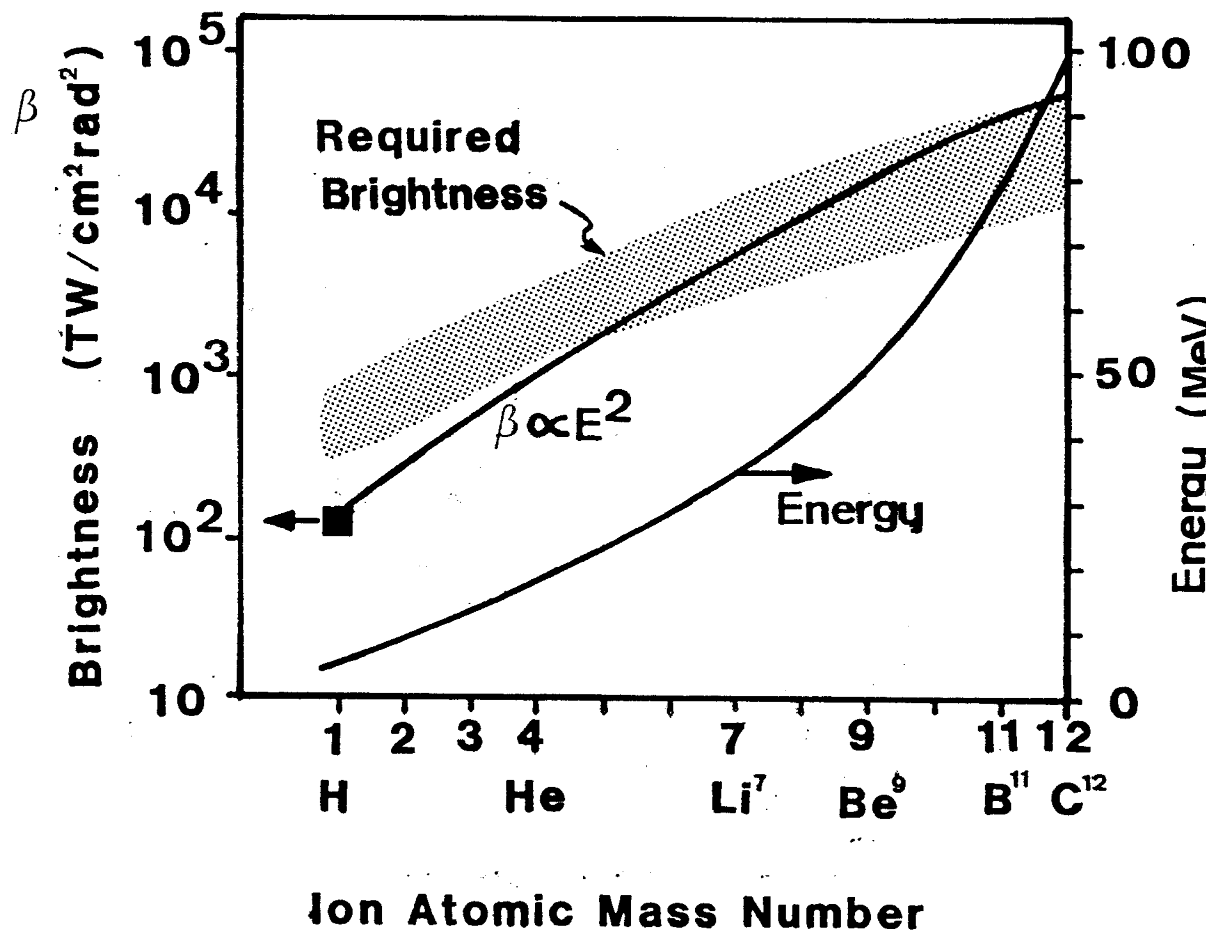


THE BRIGHTNESS REQUIREMENT



Target Range of $100 mg/cm^2$

LIB-ICF DRIVER : Stacked Ion Diode by Induction Linac

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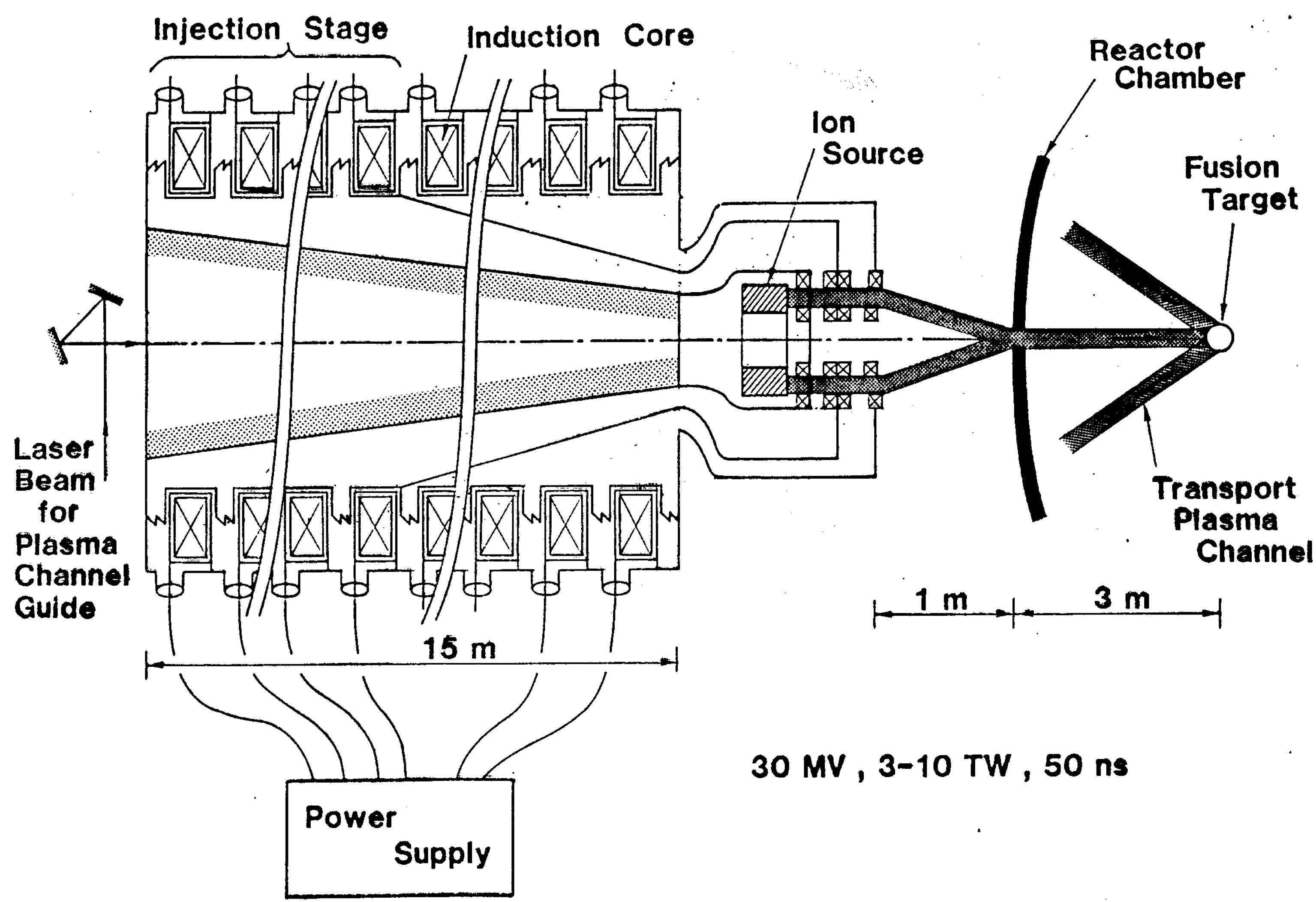

30 MV , 3-10 TW , 50 ns

Ion Source

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- **Stationary Plasma**

  Bhom Current $J_i \sim 0.4eZn_i(2kT/m_i)^{1/2}$

  ex) Li, $T \sim 1\,\mathrm{eV}$, $n_i \sim 1 \times 10^{17}\ /\mathrm{cm}^3$

  $J_i \sim 3.3\ \mathrm{kA/cm^2}$

  $d > 0.1$ mm for 50ns pulse

- **Injection Plasma** Repitition

  Current Density $J_i = n_i e Z v_d$

  ex) Li, $v_d \sim 2 \times 10^7\,\mathrm{cm/s}$, $n_i \sim 1 \times 10^{15}/\mathrm{cm}^3$

  $Ji = 3.2\ \mathrm{kA/cm^2}$

  $d = 1\mathrm{cm} = v_d \tau$

  → Impedance control by density modification?

- **Plasma Fill**

  Erosion $J_i > n_i e Z v_d$

  Expanding gap spacing

  Increasing Diode Voltage

THE SCHEMATIC CONFIGURATION OF REIDEN IV-IA

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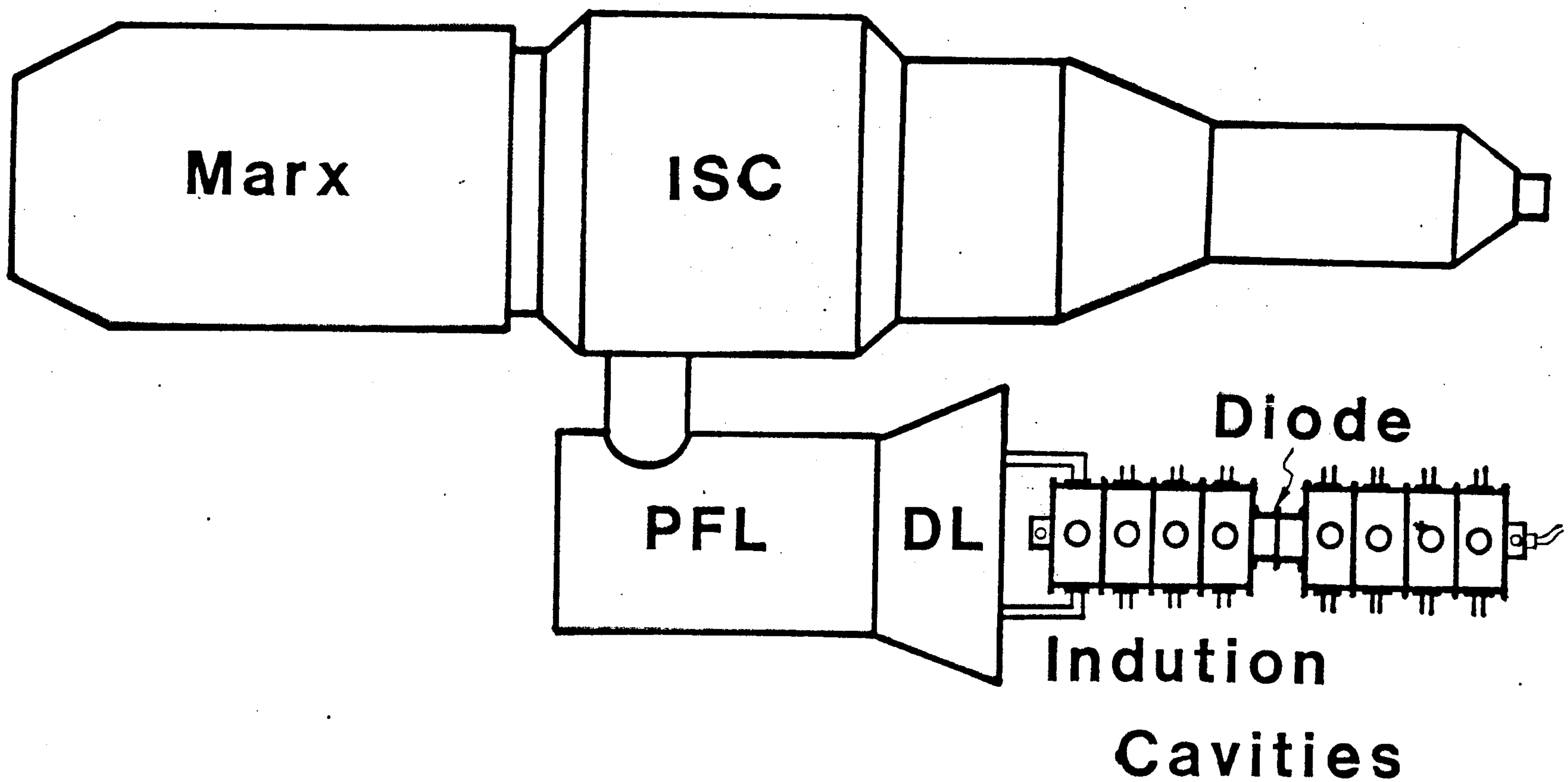
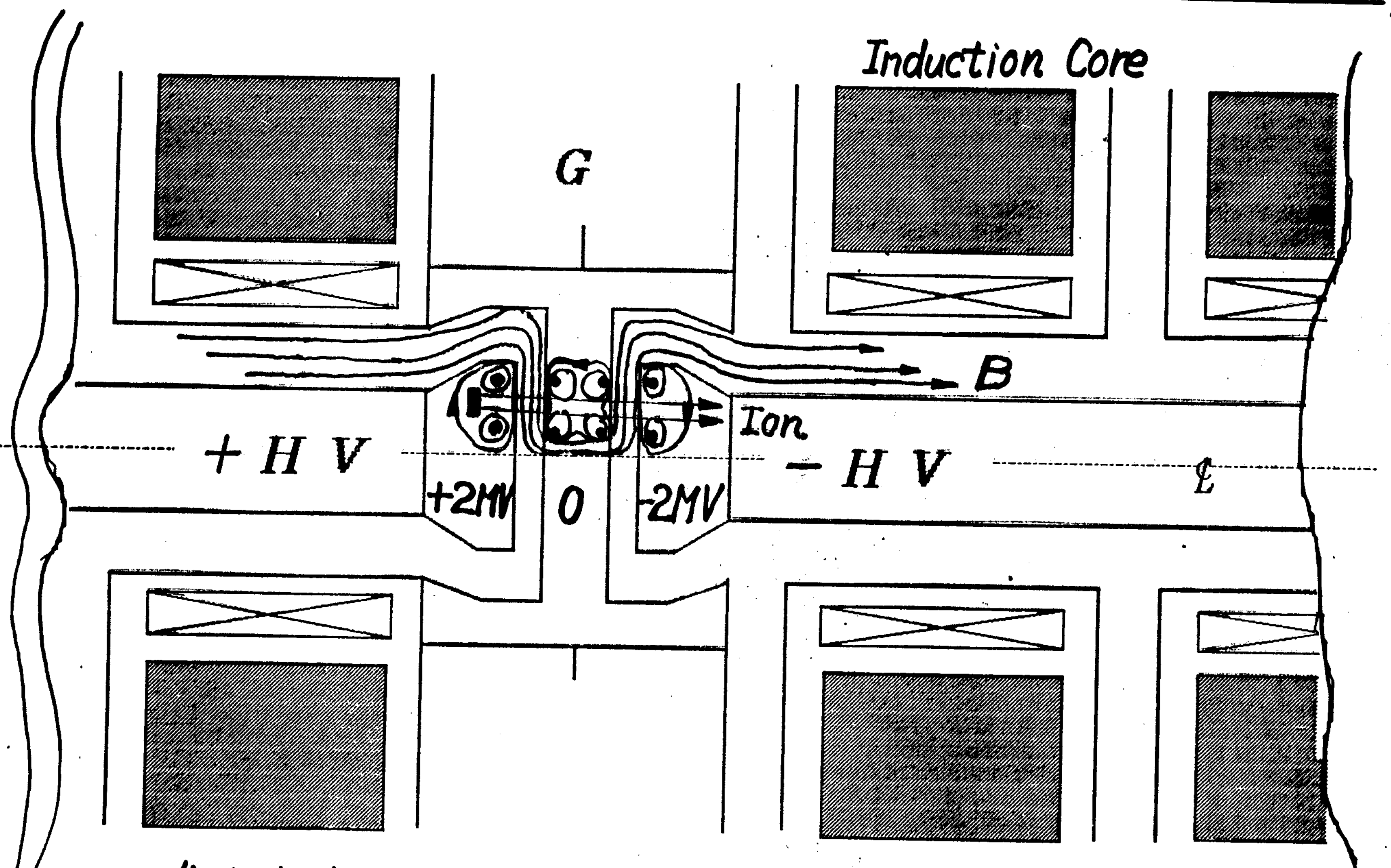


Experimental setup of stacked ion diode



4 + 4stages 4MV, 40kA, 100ns

Irradiation Parameter

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Total Power	200 TW
Pulse Width	50 ns
Total Energy	10 MJ
Voltage	30 MV (change with ion)
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/cm²
Energy on Target	5.1 MJ

Transport Parameters

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

Ion Source and Diode

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●Ion Source

Ion	C^{4+}	Li^{+}
Plasma Density (/cm³)	5×10^{14}	1×10^{15}
Injection Velocity (cm/s)	1×10^{7}	2×10^{7}
Ion Current Density (kA/cm²)	3.2	3.2

●Diode

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

Session 3: Heavy Ion Beam Fusion

1. Walter Polansky (DOE)
   (no viewgraphs available)

2. Thomas Fessenden (LBL)

3. Rolf Müller (GSI)

4. Edward Lee (LBL)

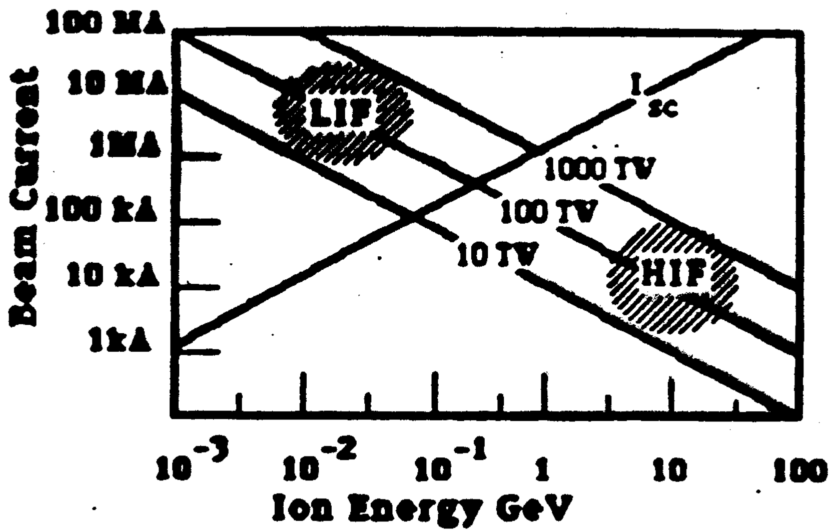
5. Donald Dudziak (LANL)

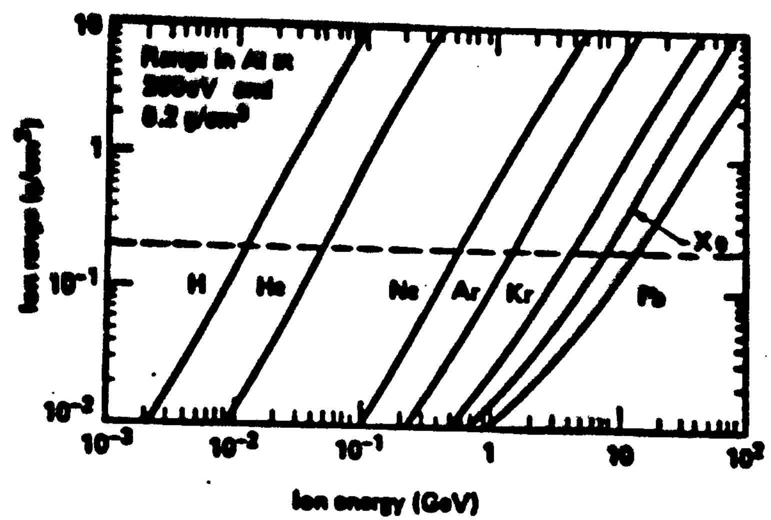
INDUCTION LINAC DRIVERS FOR COMMERCIAL HIB FUSION

Tom Fessenden
Substituting for D. Keefe

Lawrence Berkeley Laboratory

Why Heavy Ions?



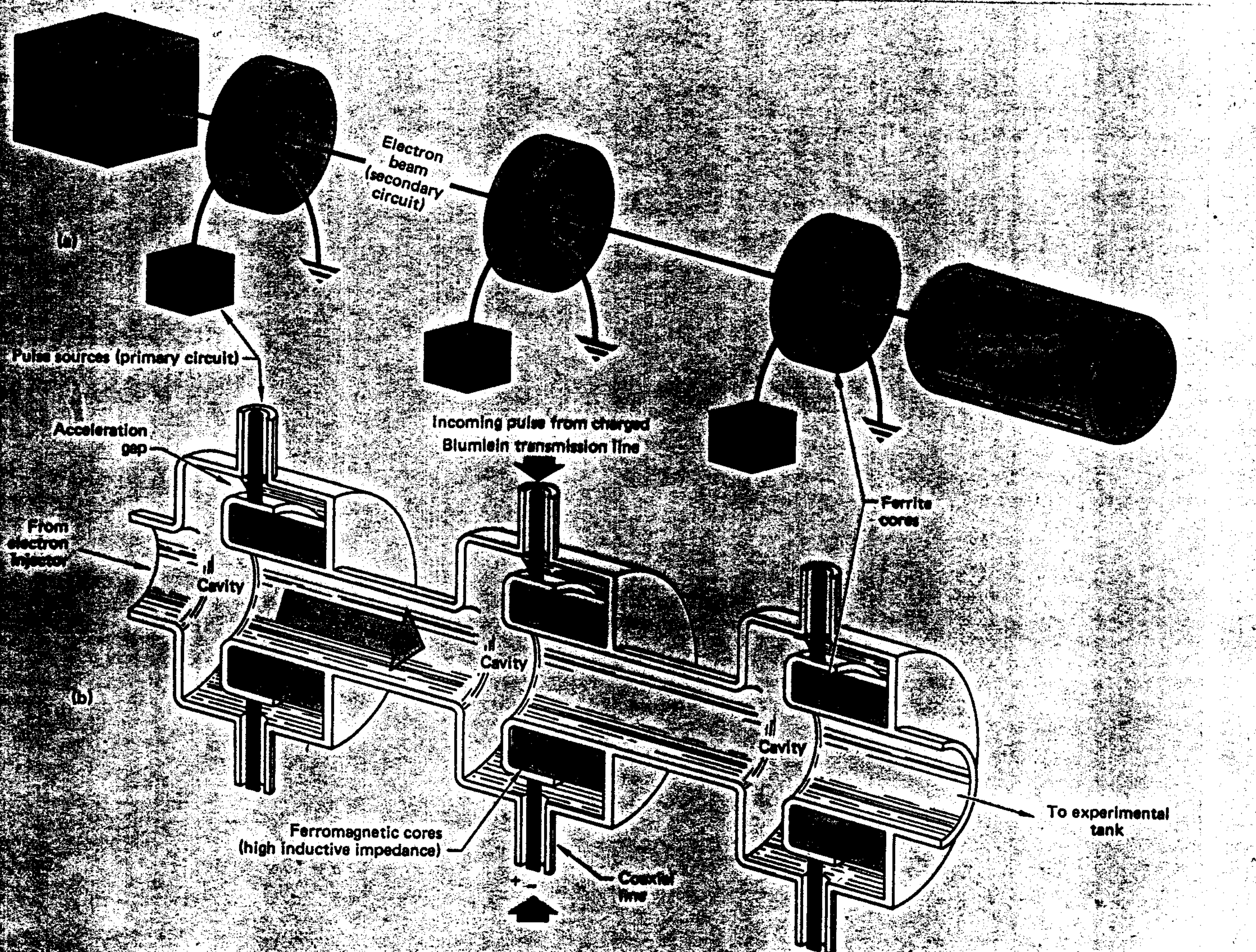


- Ion kinetic energy is high: T = 10 GeV = .02 ergs/ion
- Beam current is "low" $I_f = 10$ kA
- Beam neutralization for transport is not required
- Accelerator technology is suitable and well-understood

AFRD 0785-7004

Heavy ion accelerators may be the most attractive driver option for inertial confinement fusion (ICF)

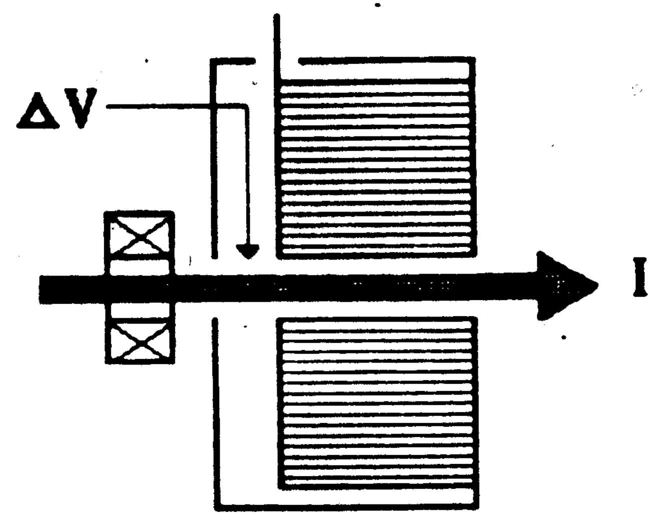
- Accelerators have a broad technology base
- Multi-gap heavy ion accelerators have advantages over laser and light-ion drivers
  - Repetition rate
  - Efficiency
  - Reliability
  - Long stand-off focal distance
- Germany, USSR, and Japan study RF linacs with storage rings
- U.S. studies multiple-beam induction linacs for ions



(a)
Electron beam (secondary circuit)
Pulse sources (primary circuit)
Acceleration gap
From electron injector
Cavity
Incoming pulse from charged Blumlein transmission line
Ferrite cores
(b)
Cavity
Cavity
Ferromagnetic cores (high inductive impedance)
Coaxial line
To experimental tank

60A-8

Each Accelerating Gap Must Add Both Volts and Joules to the Beam



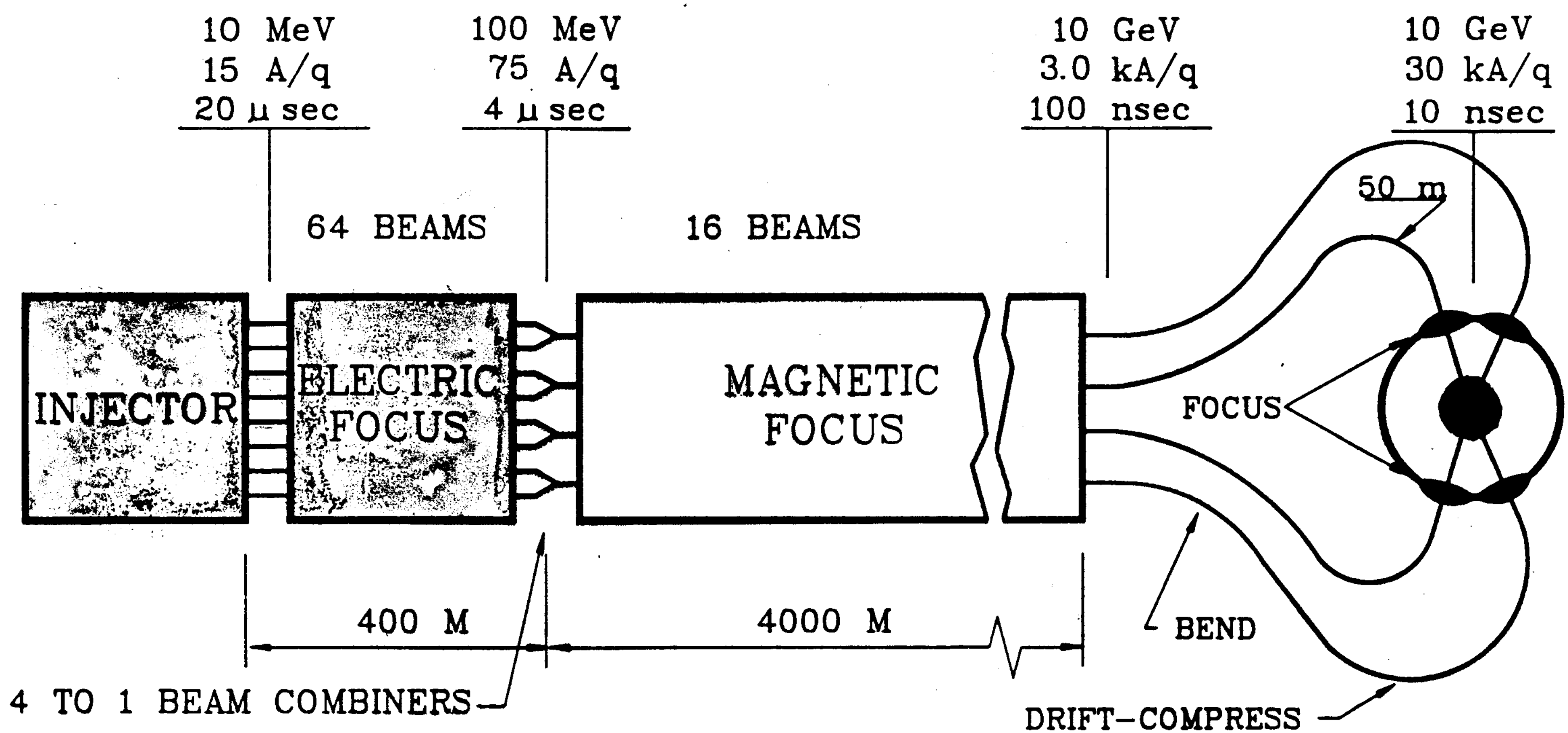
Joules added per gap = $I \times \Delta V \times \tau$

Since $\Delta V \times \tau$ = core volt-seconds, and is costly: I should be as large as is reasonable

Also, large I improves electrical efficiency (20-30%)

AFRD 0186-0103

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



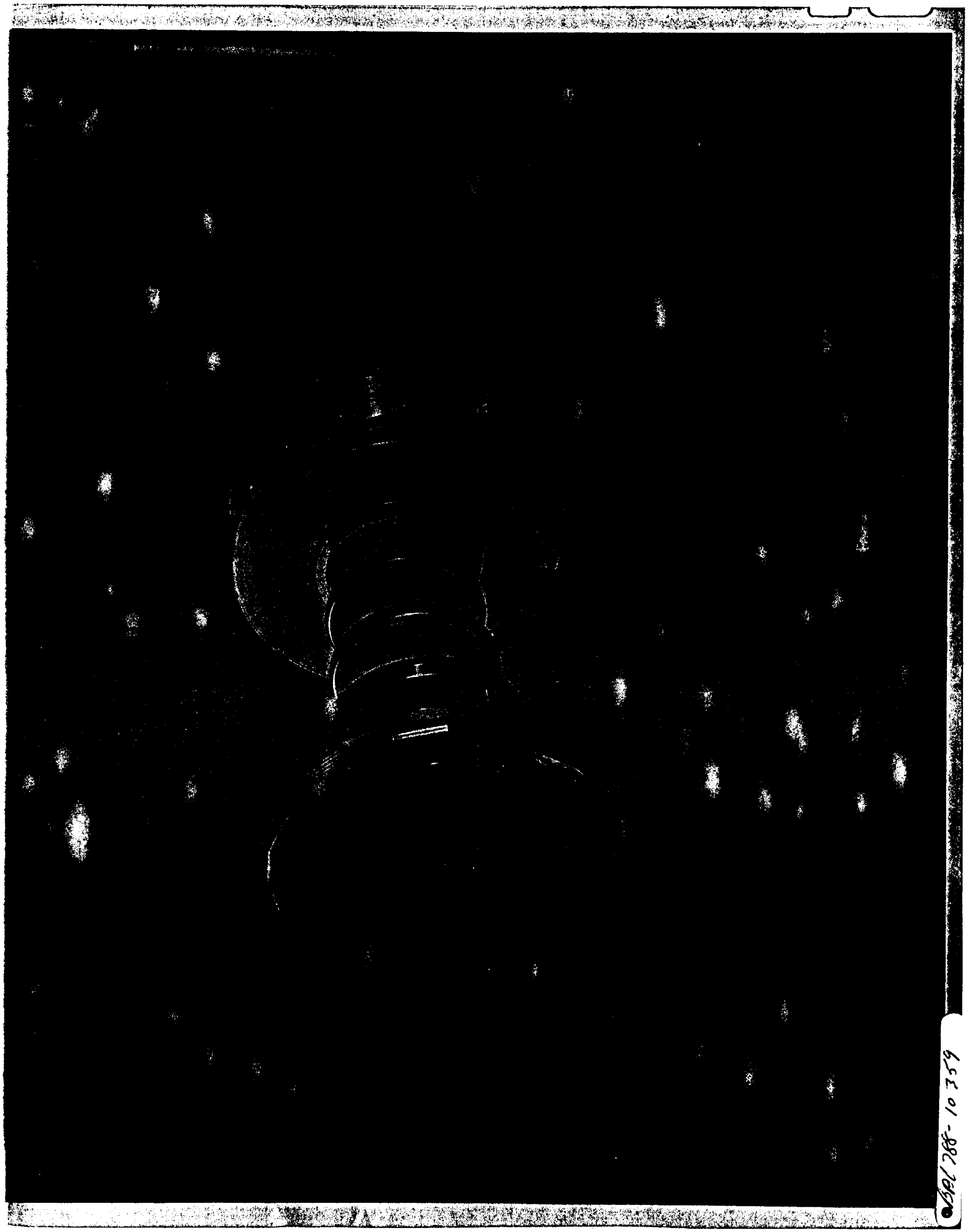
The HIFAR program to date has been highly successful

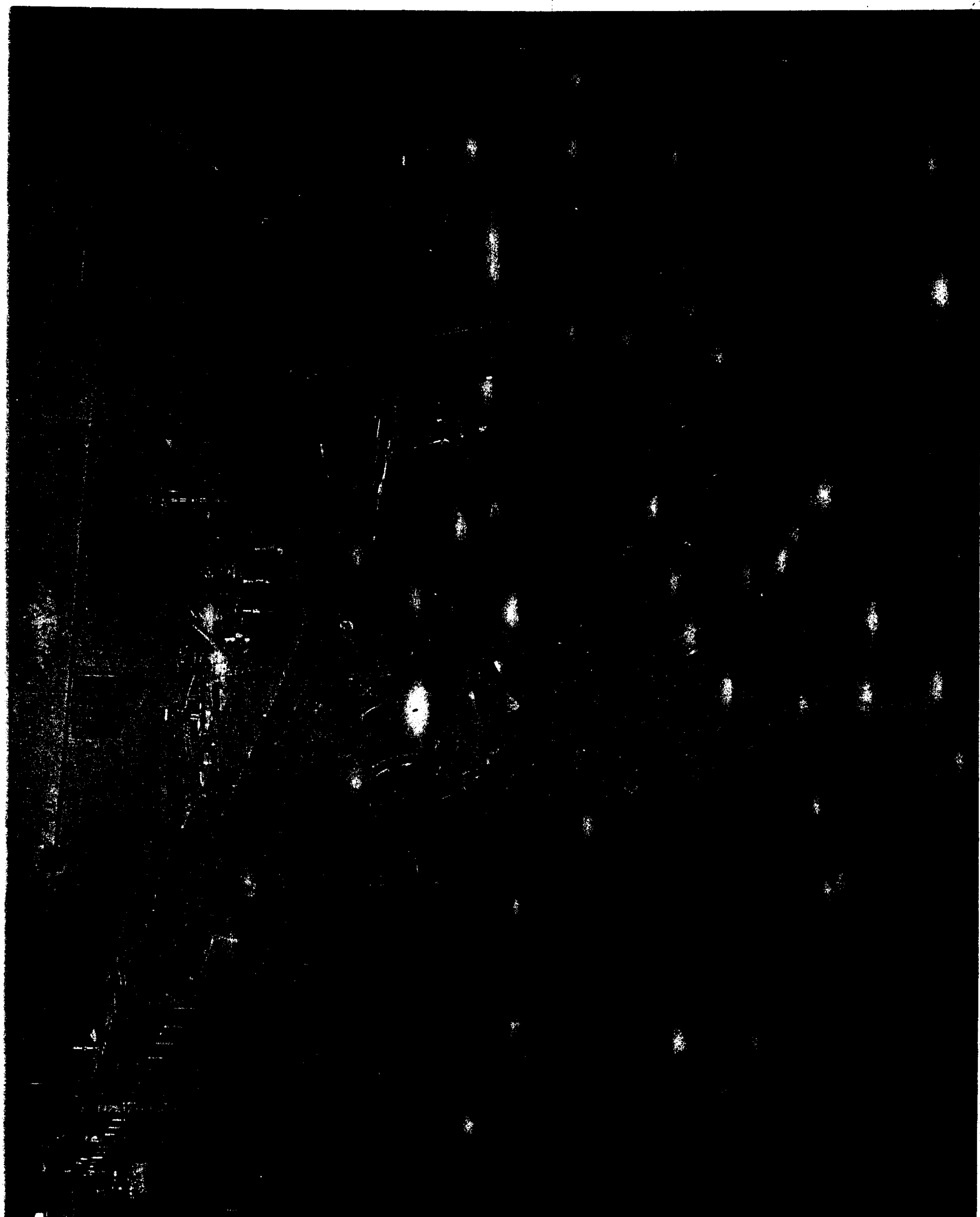
- Sources with high-current ion beams (Xe, Cs, Hg) with more than adequate optical quality have been built

- Extensive measurements on high-current ion beam transport have revealed that we can transport, without degradation, much higher currents than thought possible; this cuts the cost of the driver
  - These results have opened up a new sub-field of accelerator physics: "space-charge-dominated" beams

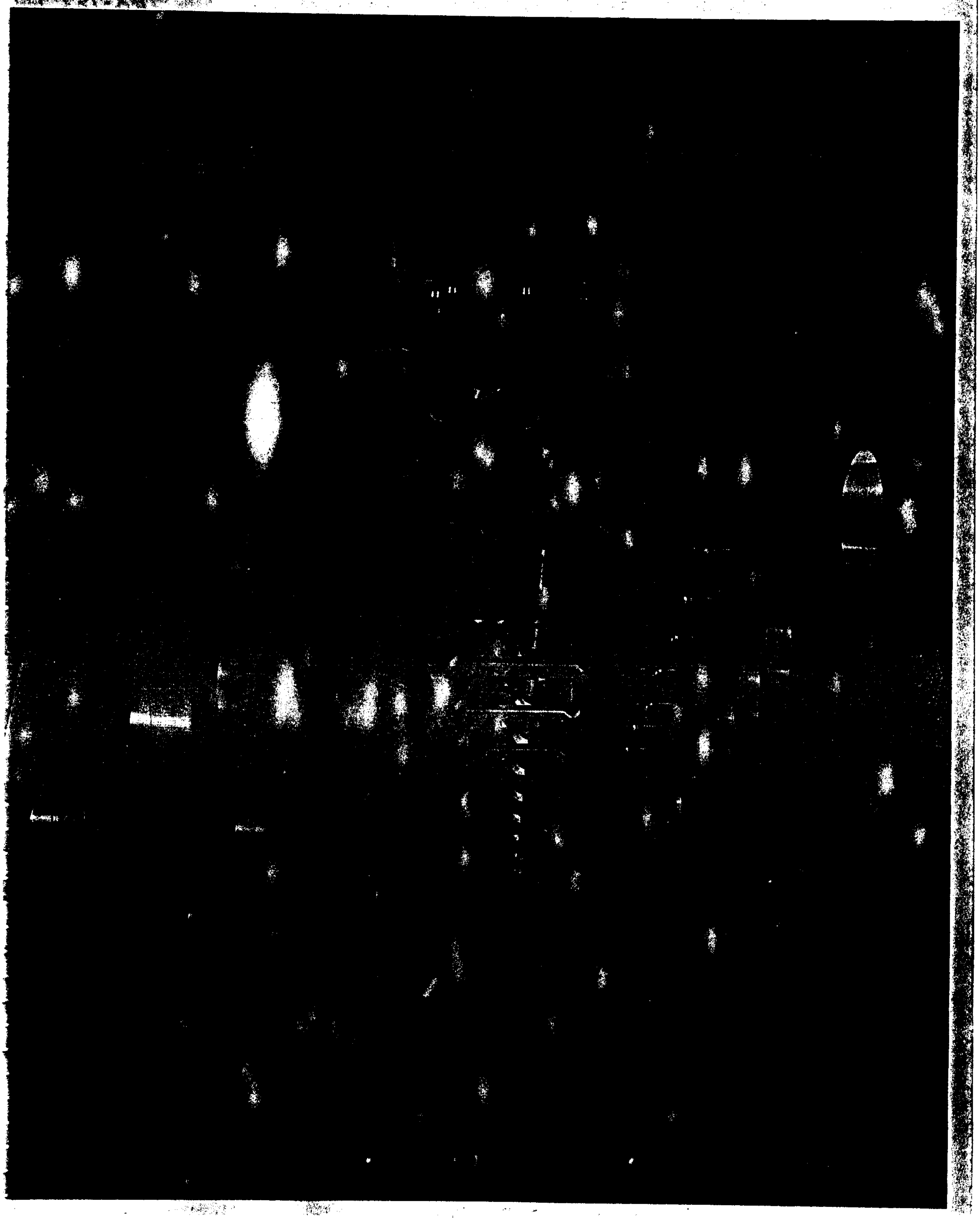
- The Multiple Beam Experiment (MBE-4) is showing how to achieve controlled current amplification in an ion induction linac with multiple beams

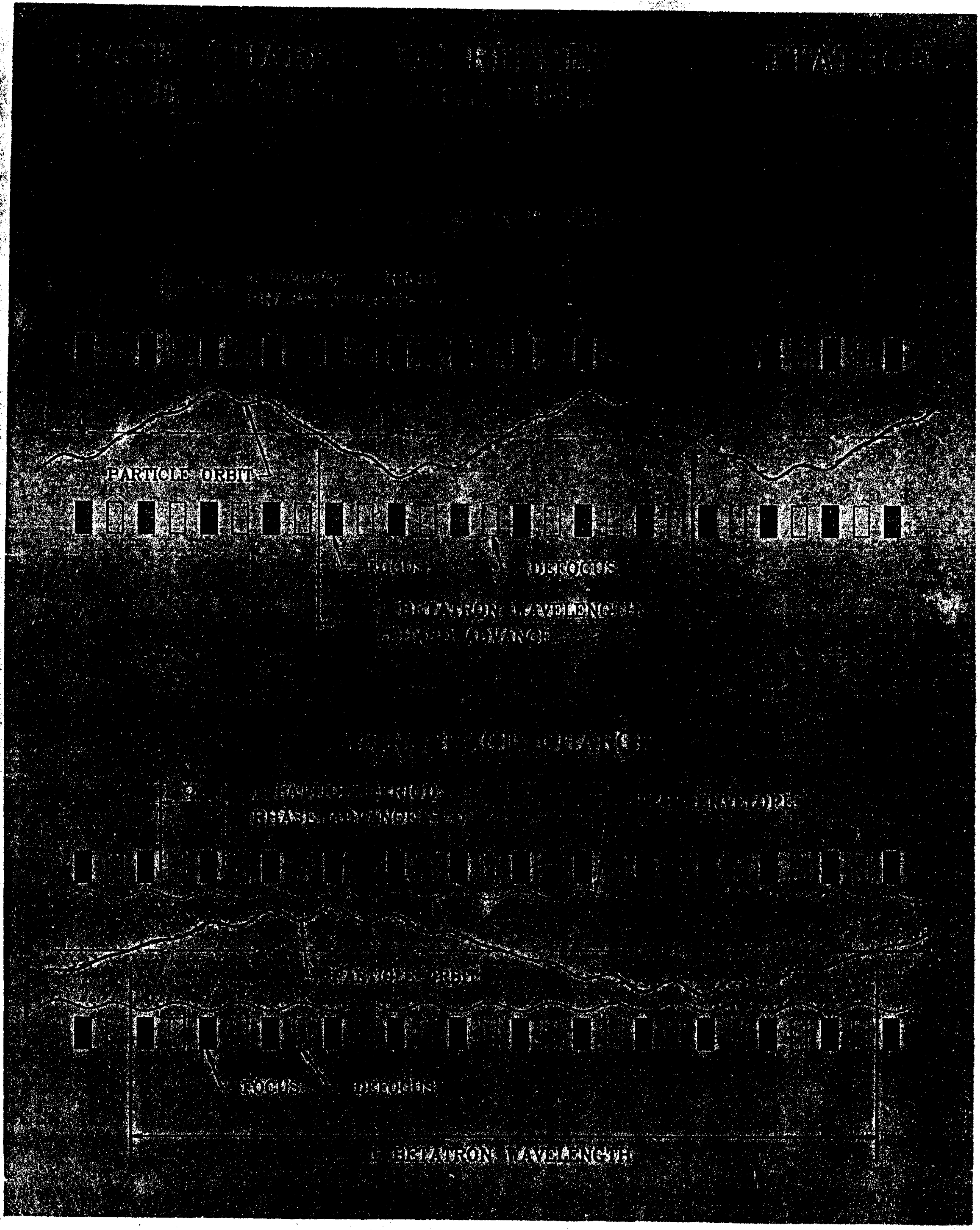
- Systems assessment studies by industry/national laboratories for induction linac drivers show attractive cost-of-electricity (50 mills/kWhr) for a 1 GWe plant


788- 10359

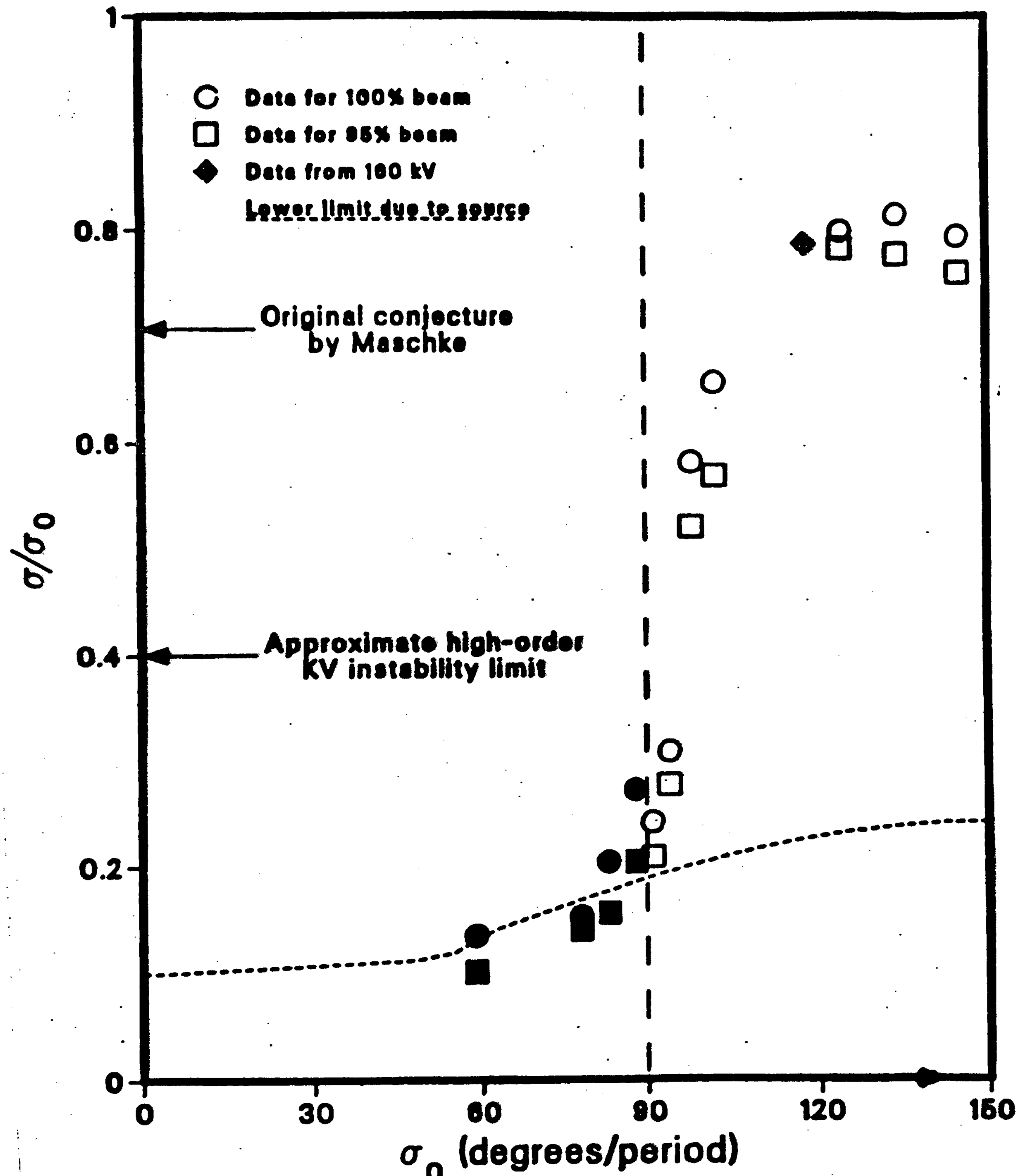


BBC8311-10597



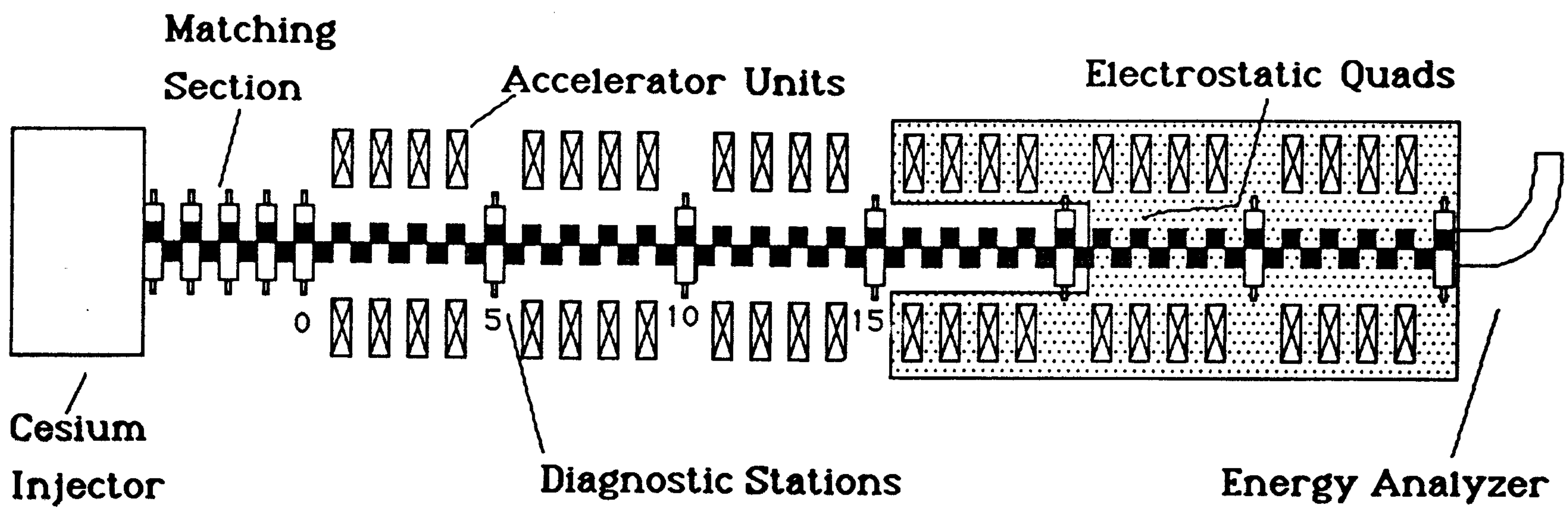


BBC867-5457

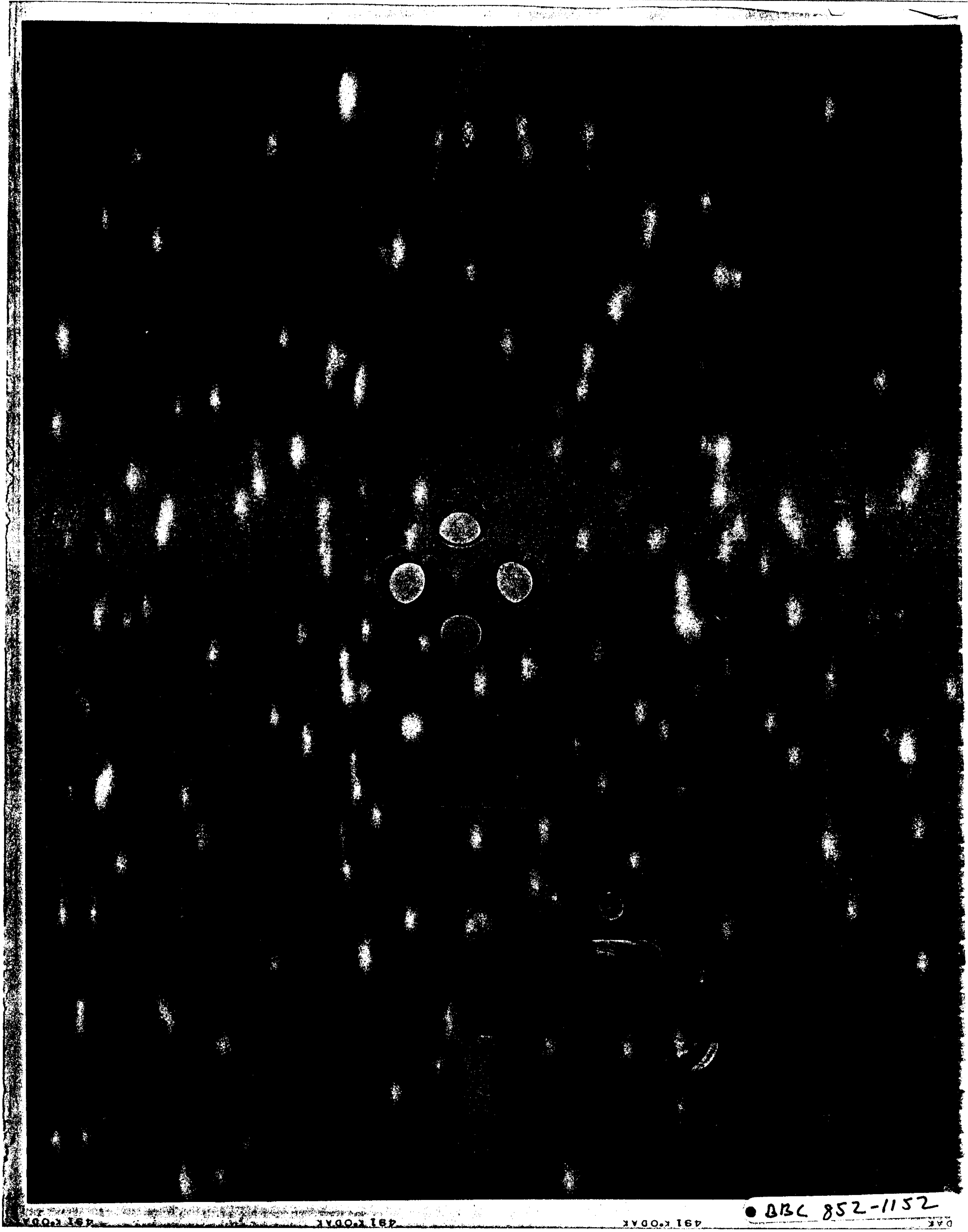

Data for 100% beam
Data for 95% beam
Data from 160 kV
Lower limit due to source
Original conjecture by Maschke
Approximate high-order KV instability limit
σ/σ0
σ0 (degrees/period)
0
0.2
0.4
0.6
0.8
1
0
30
60
90
120
150

Multiple Beam Experiment

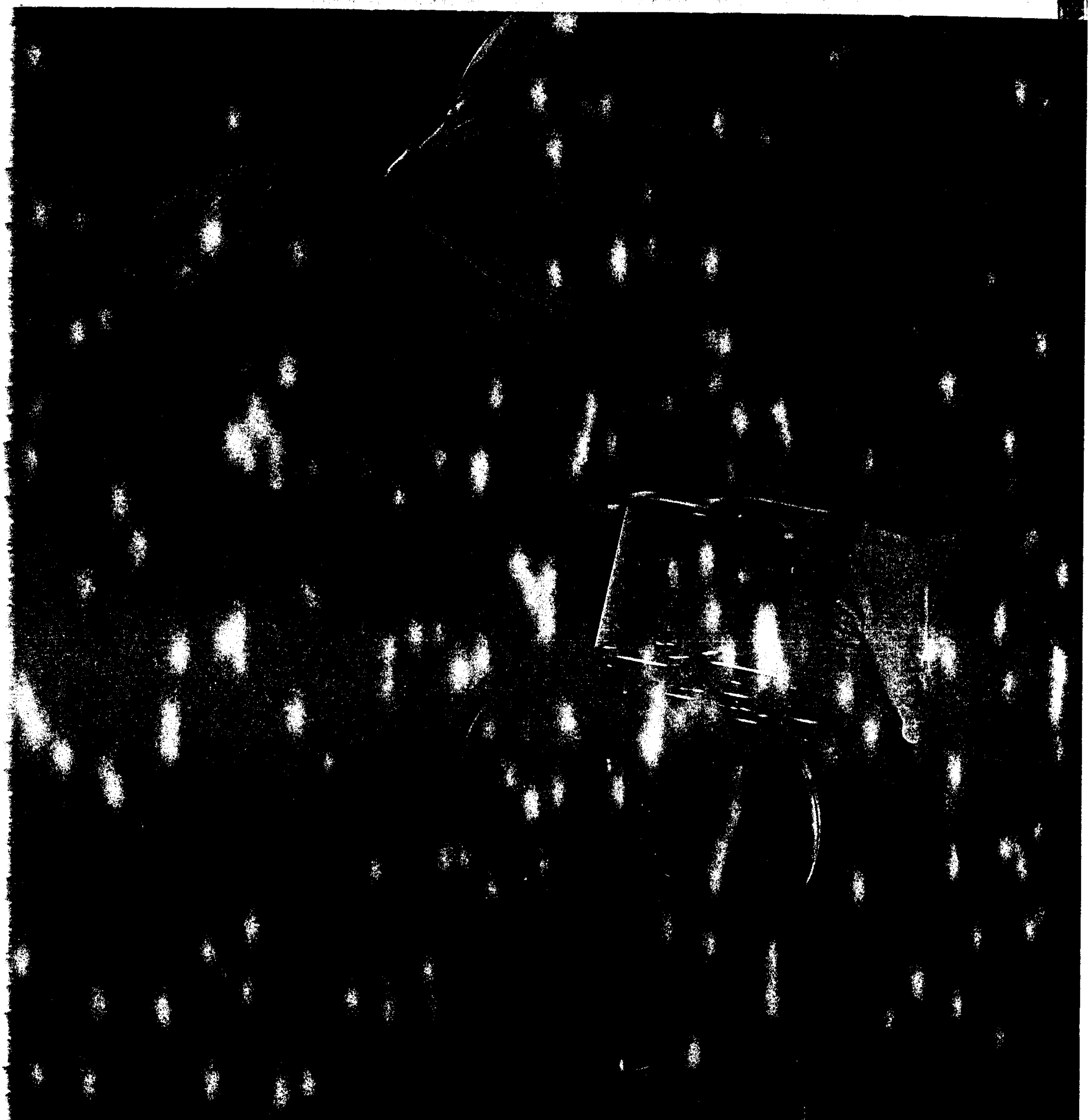
MBE-4



1/87



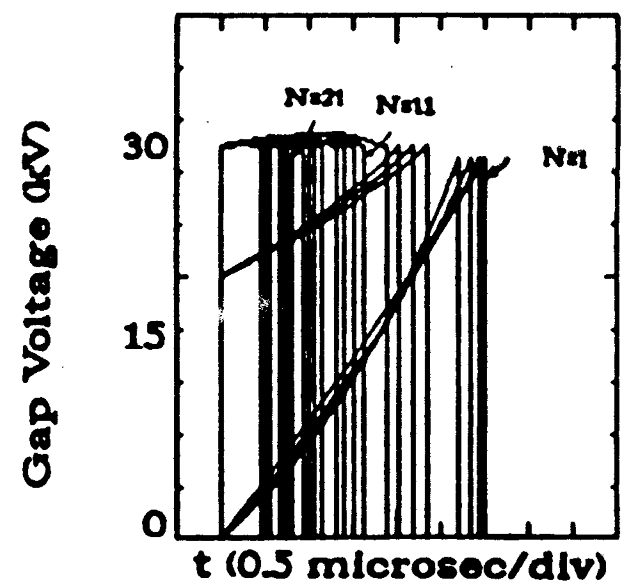
BBC 852-1152

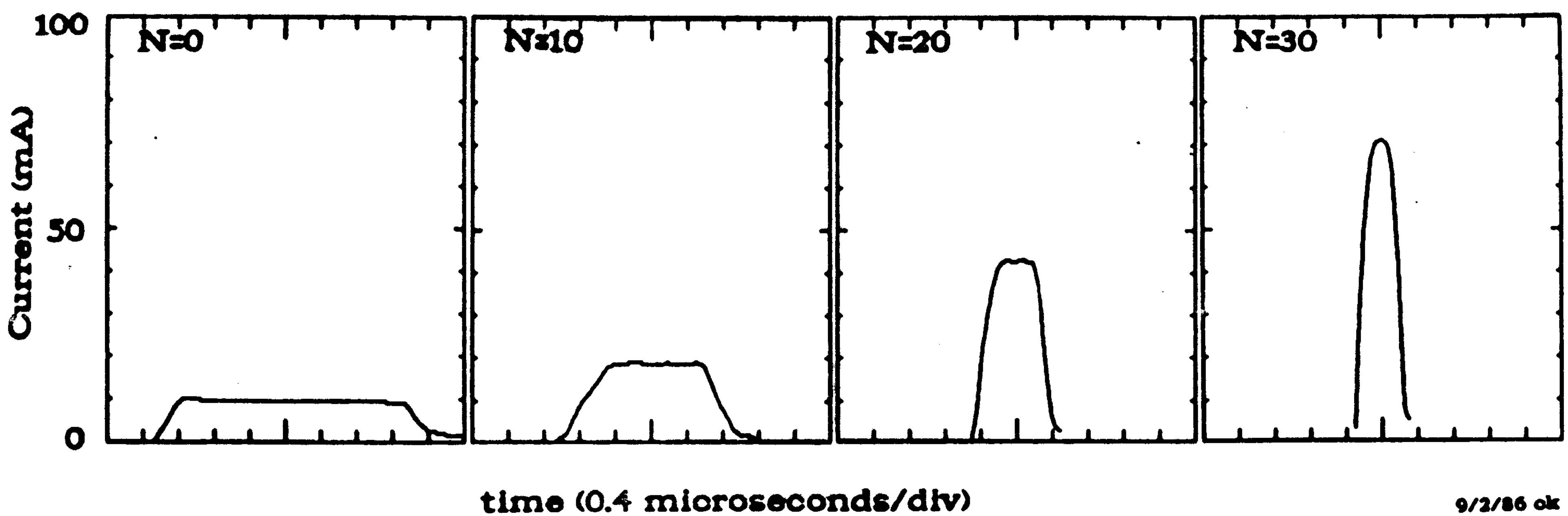


MBE-4

Current Amplification

($I \propto \beta^{2.5}$ Scenario)



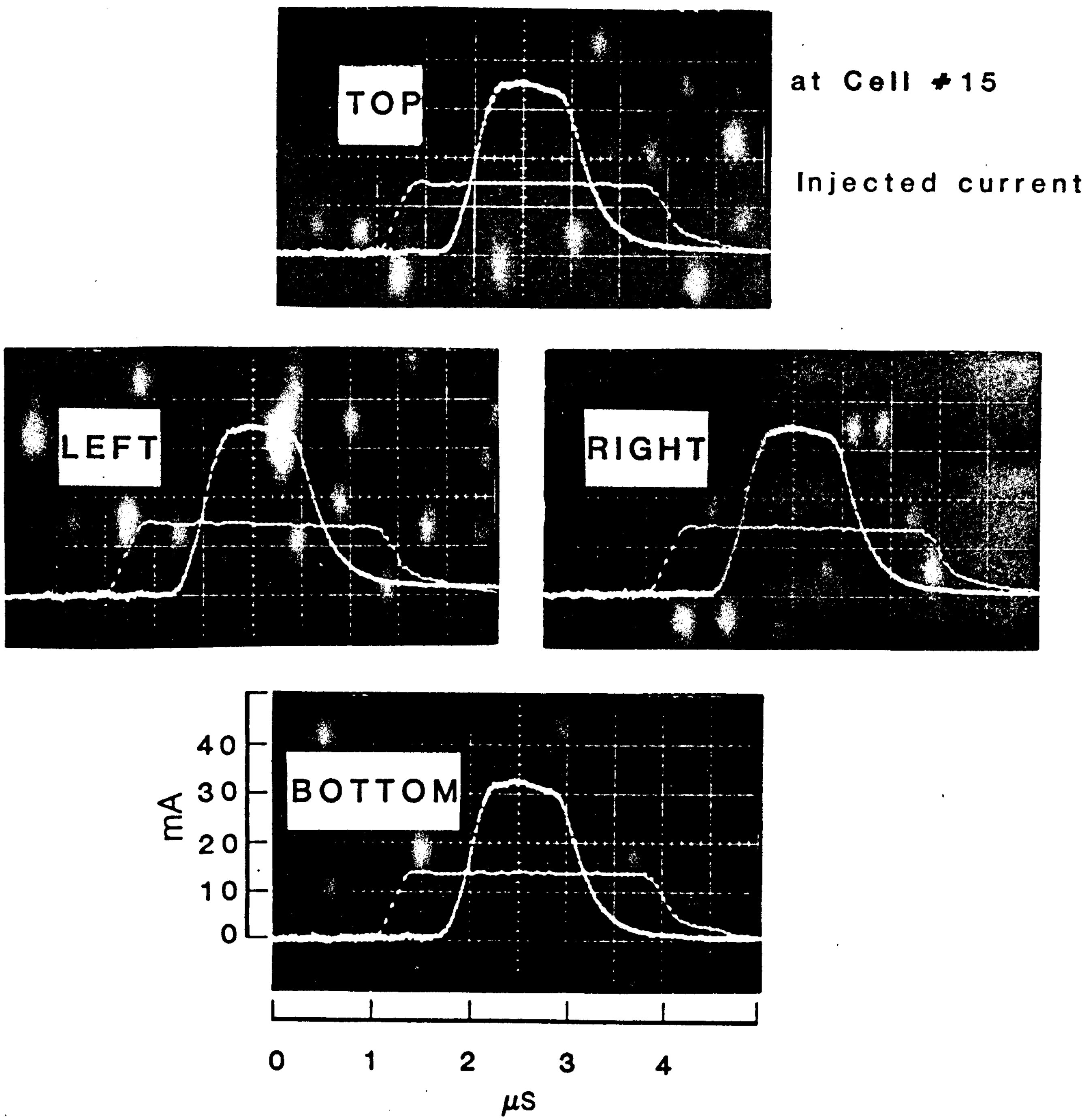


9/2/86 ok

MBE-4 Beam Currents

(at Cell #15)

Cesium Beams, 10-shot Overlay, 0.2 Hz

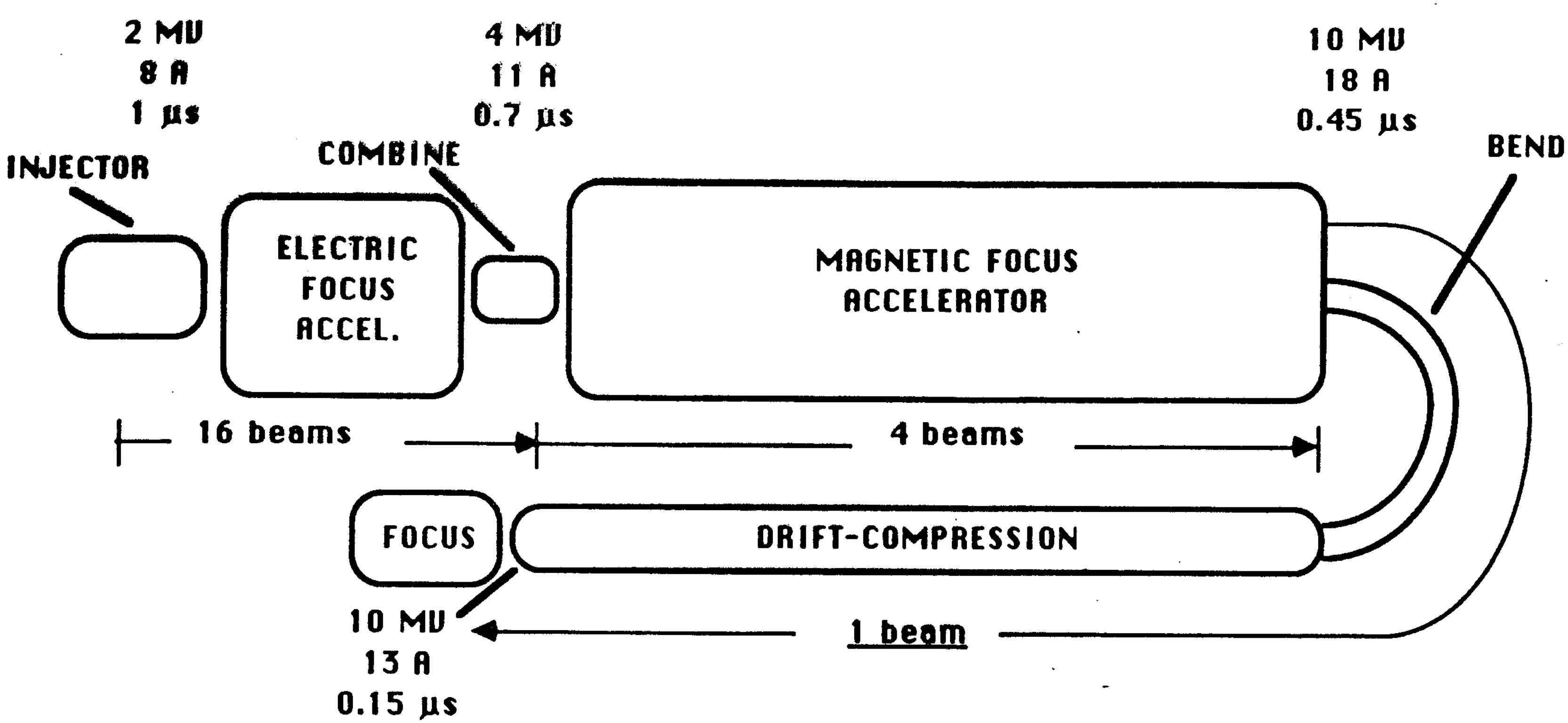


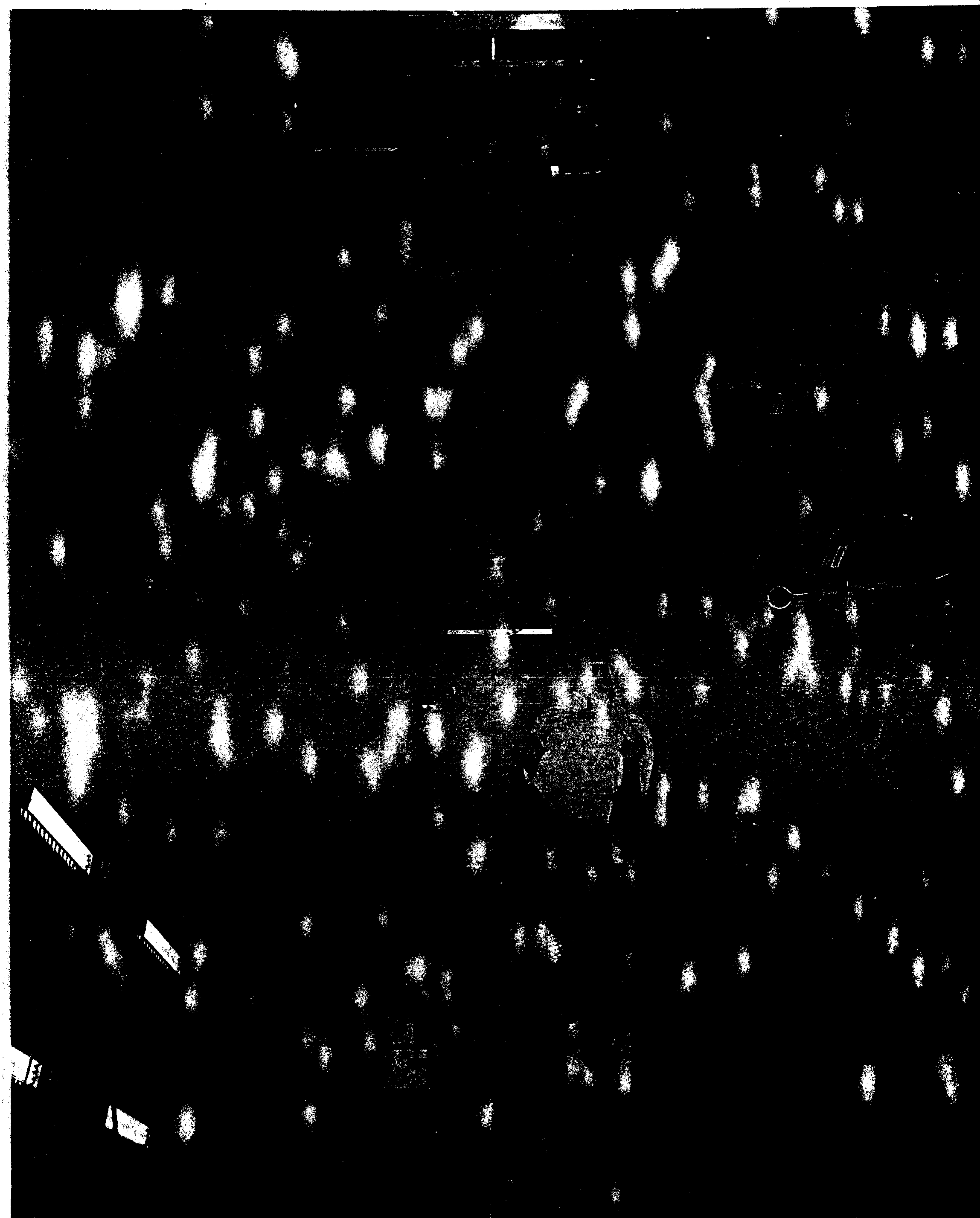
The Induction Linac Systems Experiment (ILSE) will address almost all the remaining driver issues

- Beam Combining or Merging
- Magnetic focusing in accelerators and transport
- Bending space-charge-dominated ion beams
- Drift-compression Physics
- Final Focus Physics
- Acceleration of higher charge state ions(?)

With the ILSE results and progress in other inertial fusion programs, we hope to complete the HIFAR data base in the early 90's

Induction Linac Systems Experiment





A 5 MJ – 4 ms – Beam from a linac is 400 km long!

Compress it by a factor

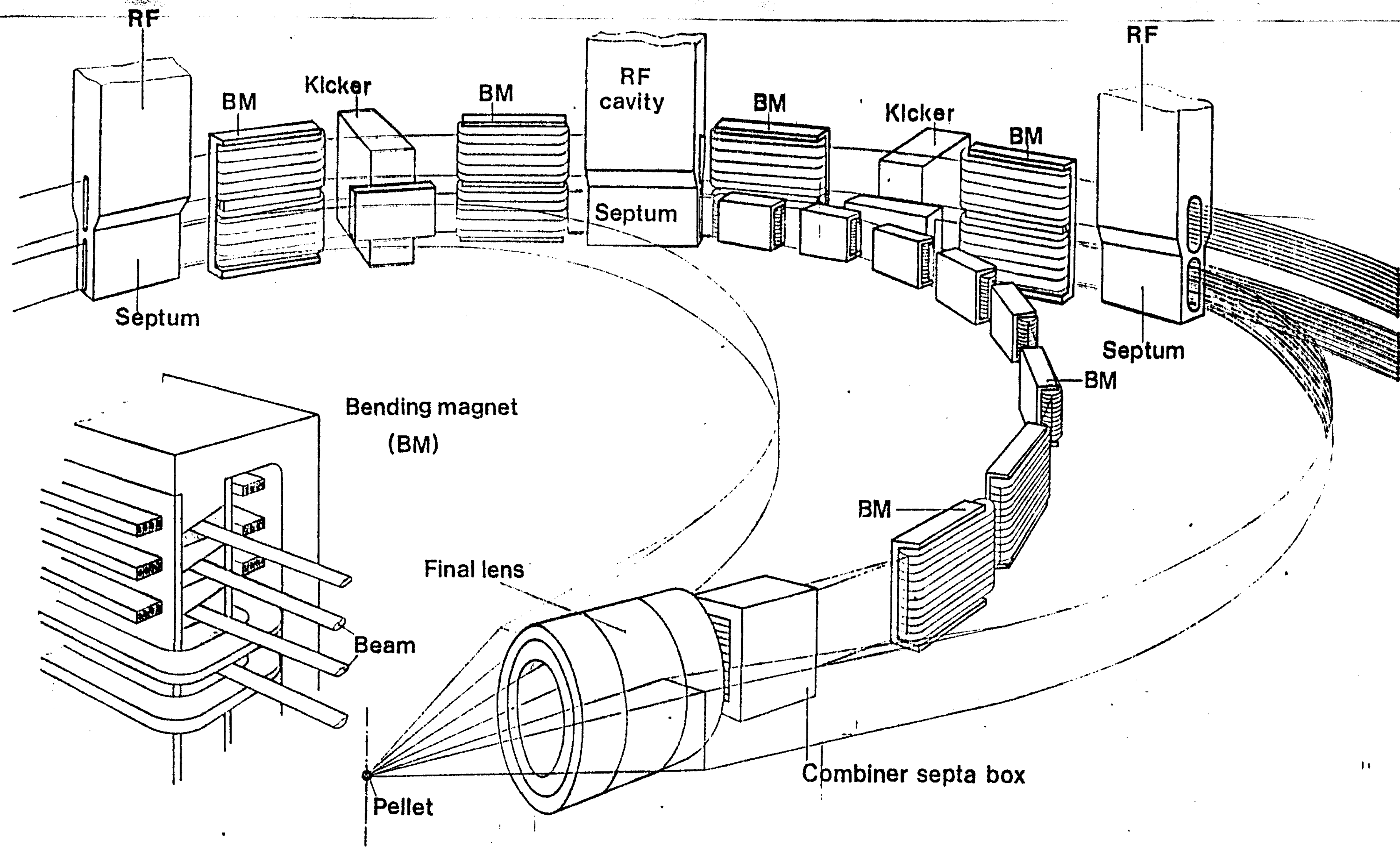
2×10^5!

=	100	transverse stacking
×	100	long. compression
×	20	beam lines

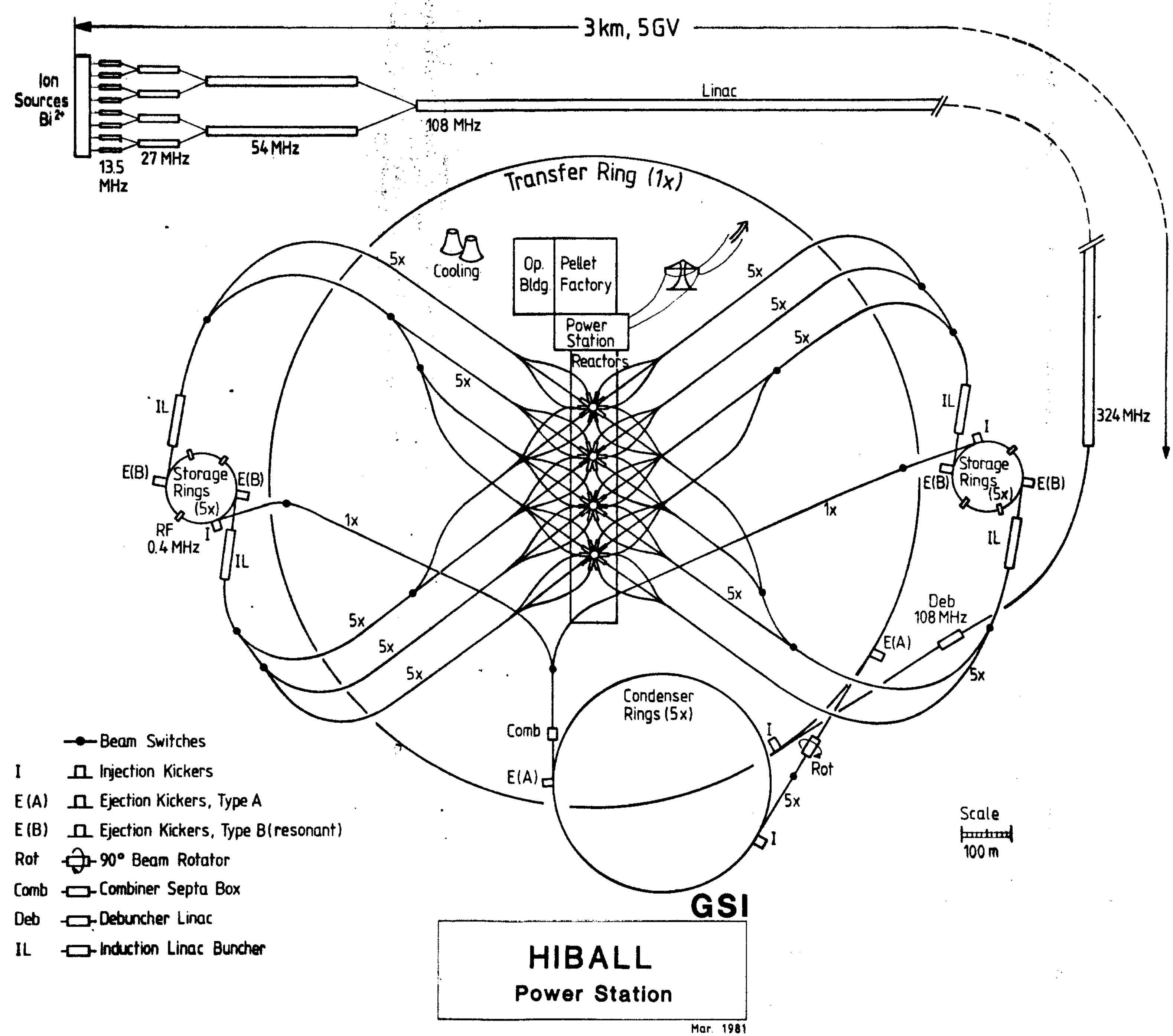
RF Linac Driver for Commercial HIB Fusion

Rolf W. Müller

GSI, Darmstadt, F.R. Germany



RF
Septum
BM
Kicker
BM
RF
cavity
Septum
BM
Kicker
BM
RF
Septum
BM
BM
Bending magnet
(BM)
Final lens
Beam
Pellet
Combiner septa box



3 km, 5 GV
Ion Sources Bi²⁺
13.5 MHz
27 MHz
54 MHz
108 MHz
Linac
324 MHz
Transfer Ring (1x)
Cooling
Op. Bldg.
Pellet Factory
Power Station
Reactors
5x
1x
IL
I
E(B)
E(A)
Storage Rings (5x)
RF 0.4 MHz
Deb 108 MHz
Rot
Comb
Condenser Rings (5x)
Scale
100 m
Beam Switches
I Injection Kickers
E (A) Ejection Kickers, Type A
E (B) Ejection Kickers, Type B (resonant)
Rot 90° Beam Rotator
Comb Combiner Septa Box
Deb Debuncher Linac
IL Induction Linac Buncher
GSI
HIBALL
Power Station
Mar. 1981

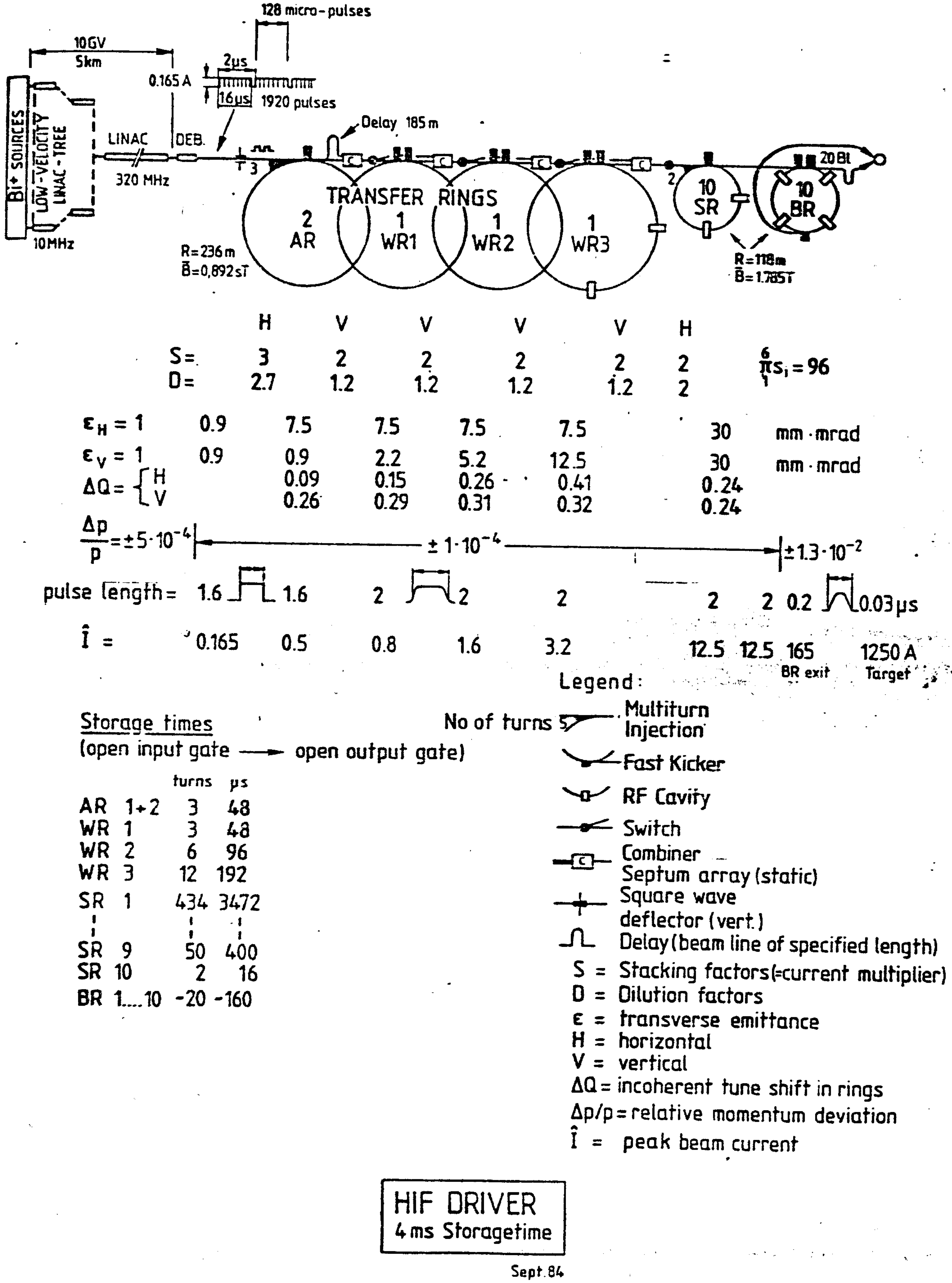


Fig. HIF driver, 4 ms storage time.

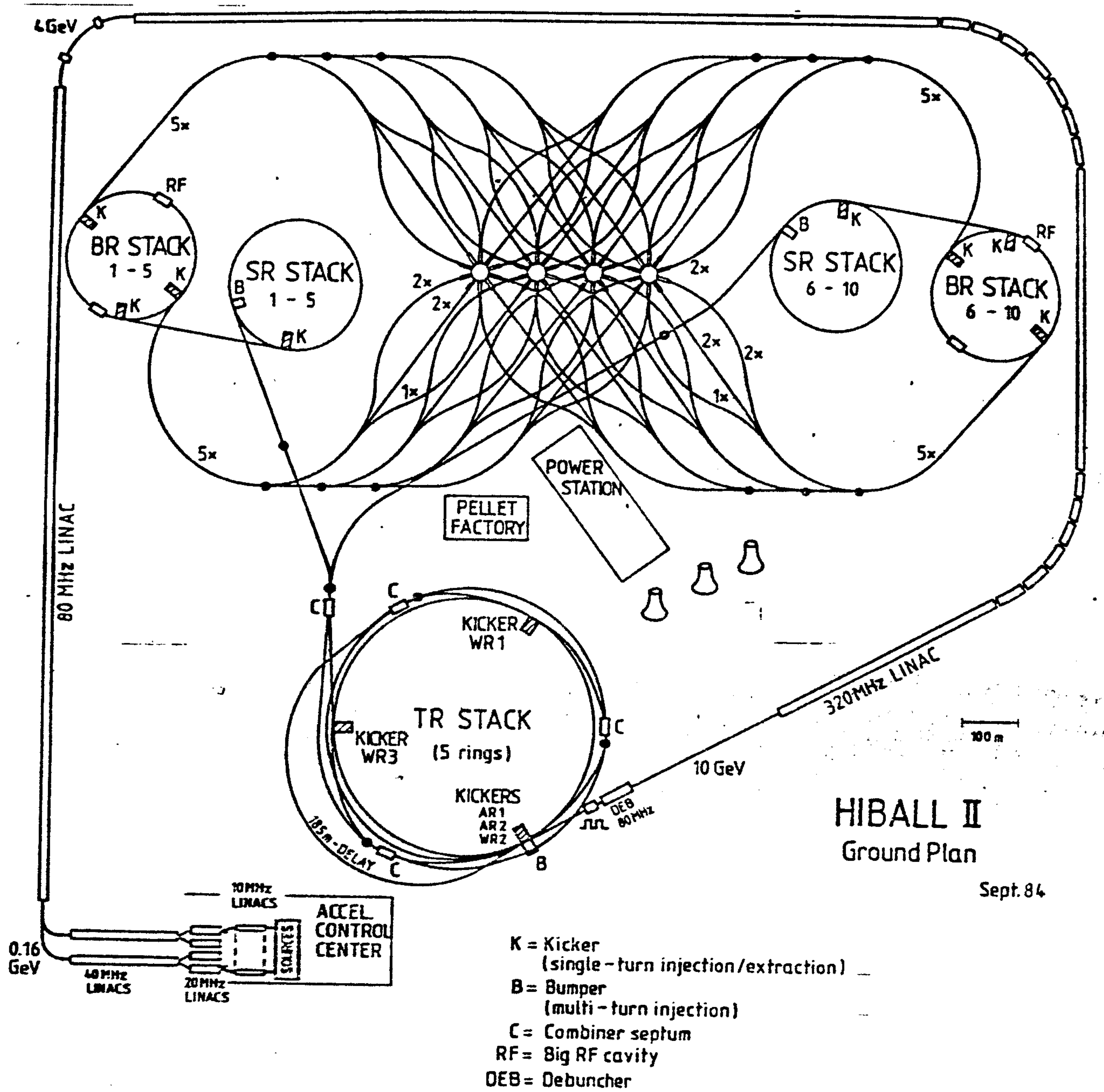
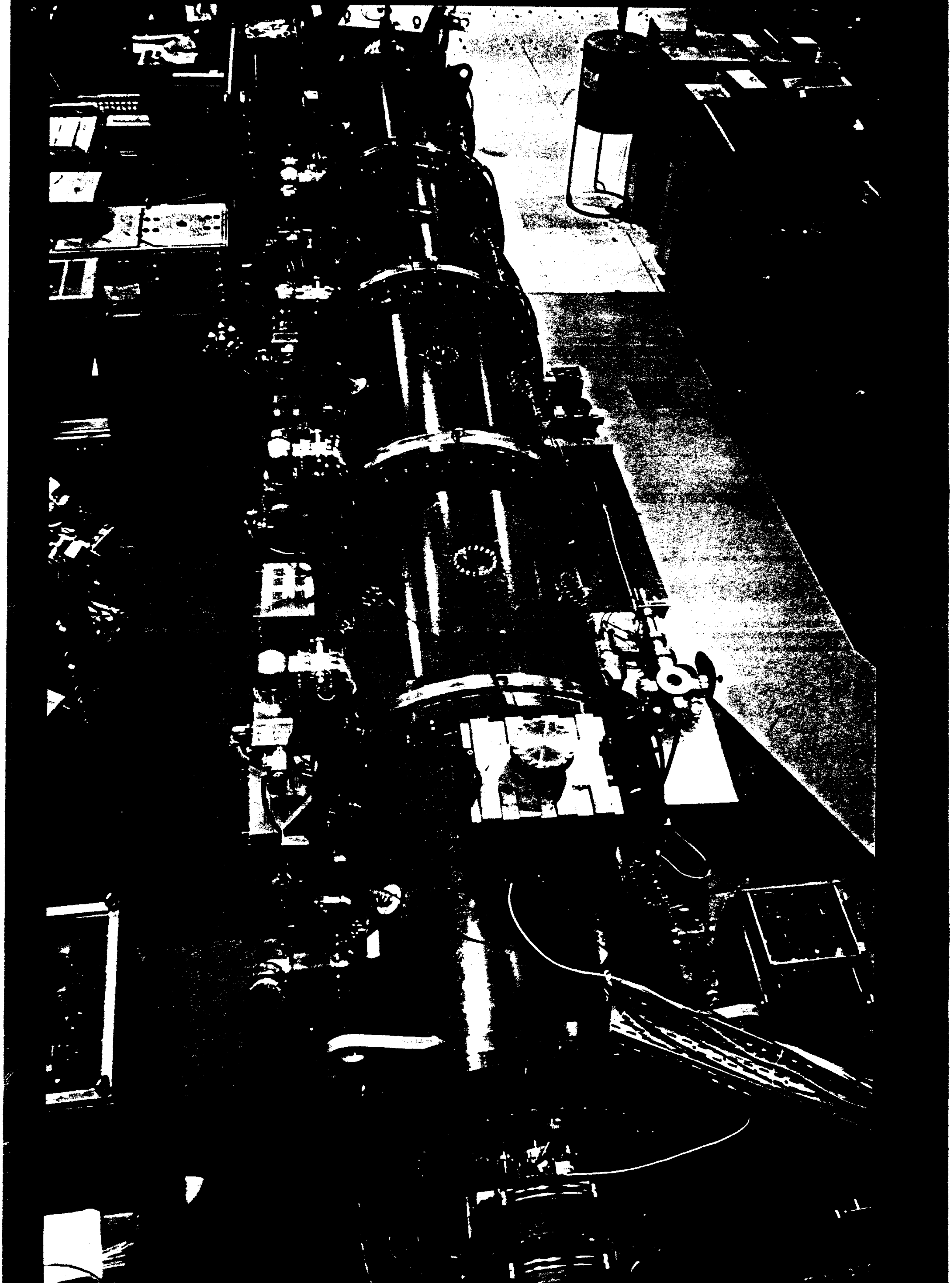


Fig. . HIBALL-II ground plan.



GSI-Kc 428/21

R. Arnold, J. Meyer-ter-Vehn 1986

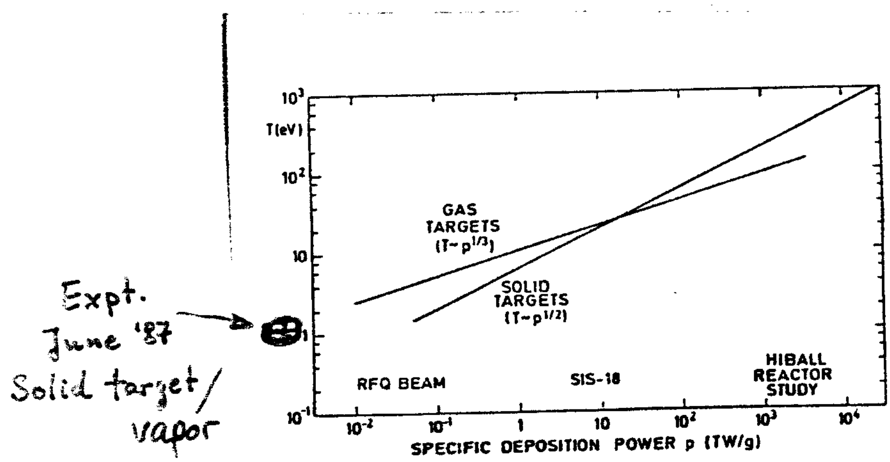


Fig. 1: Maximum T for given P.

June 28 – 30 1988
Darmstadt
HIF

July 4 – 7, 1988
Karlsruhe
Beams

Critical Issues of Accelerators For Commercial HIB Fusion

Edward P. Lee

Lawrence Berkeley Laboratory

Third Inertial Confinement Fusion Systems and Applications Colloquium

University of Wisconson

November 9, 1987

Types of Issues

- "Show Stoppers" — None So Far
- Beam Physics Not Fully Understood When Current Limits Are Pushed
- Control of Beam Quality at Acceptable Cost
- Developement of Special Components
- Cost Reduction of Components
- Strategy for R+D → Reactor

"Heavy Ion" Today Means

$$\frac{\text{Mass Number}}{\text{Charge State}} \gtrsim 50$$

$$\beta_{final} \approx .2 - .4$$

<u>Examples</u>

10 GeV U^{238}	$\gamma = 1 - 5$
5 GeV Cs	$\gamma = 1 - 2$
1.5 GeV A	$\gamma = 1$

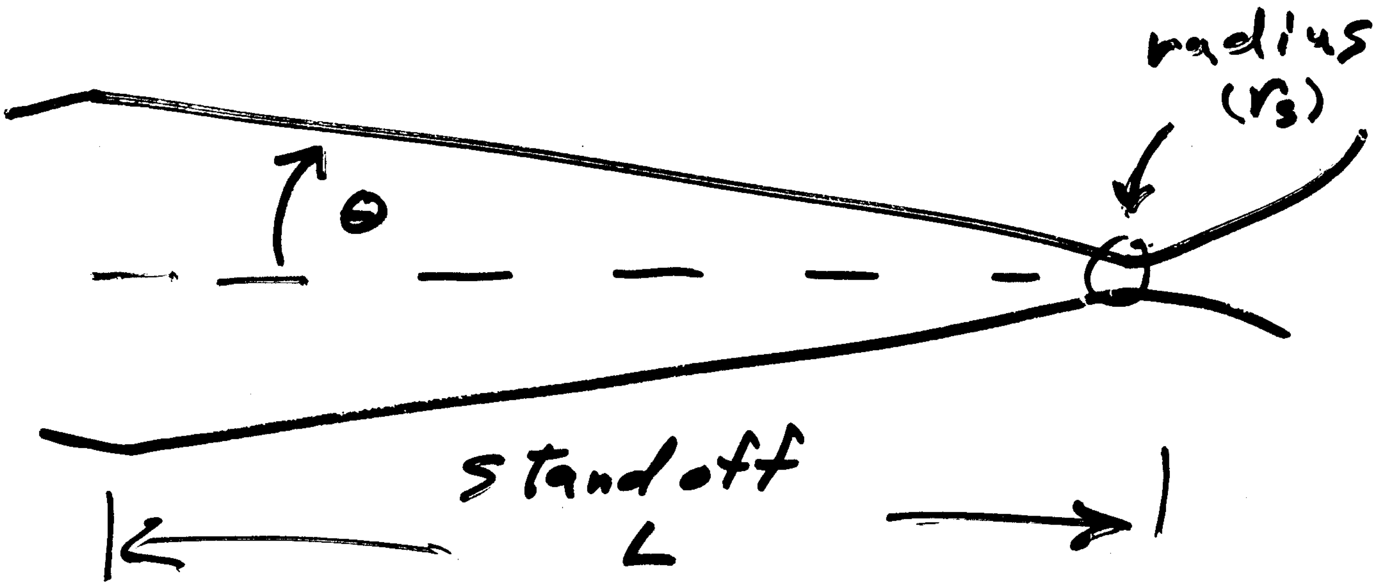
Space Charge Limits May Be Tested At Low velocity with Any Convenient Ion

10 MeV C^+	ILSE
1 MeV Cs^+	MBE
100 MeV Na^+	HTE

Spot Size on Pellet Defines Limits on Beam Quality

Emittance $= \epsilon =$ radius $\times$ angle spread

Fractional Momentum Spread $= \frac{\Delta P}{P}$



$$r_s^2 = \frac{\epsilon^2}{\theta^2} + 64\theta^2 L^2 \left(\frac{\Delta P}{P}\right)^2 + \text{jitter}$$

$$+ \text{aberration effects} + \text{space charge effects}$$

Optimum value of θ for Minimum spot Size (r_s) :

$$\theta = \left(\frac{\epsilon}{8 L \, \Delta P/P_0} \right)^{1/2}$$

$$r_s = 4 \left(\epsilon L \, \Delta P/P_0 \right)^{1/2}$$

Take "Typical" Values
$$\begin{cases} L = 10 \text{ m} \\ \epsilon = 3 \times 10^{-5} \text{ m-r} \\ \frac{\Delta P}{P_0} = \pm .001 \end{cases}$$

θ = .019 radians (ok)

r_s = .0022 m (ok)

Space Charge and Jitter May Play A Role So We Should Try For Lower Values of ϵ and $\Delta P/P_0$

Adiabatic Invariants :

$$\epsilon_n^t = \beta\gamma\,\epsilon \quad \text{(Normalized Emittance)}$$

$$\epsilon_n^l = \beta\gamma\left(\frac{\Delta P}{P_0}\right)\cdot \text{Pulse Length}$$

Issue of Control :

Can ϵ_n^t and ϵ_n^l be kept sufficiently small during acceleration & beam handling operations.

Number of Gaps and Magnets / beam $\sim 10^4$

Neutralization In Reactor Chamber

Pellet Charge up — Negligible —
(V ≲ 1 MV)

Plasma Conduction
Discharge by Light Ions
Beam Neutralized
Other Mechanisms

Beam Sufficiently Neutralized
— Probably ok —

Neutralization Fraction ≈ .9 { Good enough for A/q ≳ 50

Spot Position Controlled
— Unknown At Present —
Role of Gas Stripping Unclear
LLNL To Study This Year

Gas In Final Focus Beam Lines

Beam Ions Must Not Strip
Before Leaving Final Lens

$\sigma_s \approx 3 \times 10^{-17}\ cm^2$ $\left(\begin{matrix} 10\ GeV \\ U^{238}\ on\ Li \end{matrix}\right)$

l_s = stripping length $= \dfrac{1}{n_g \sigma_s} \approx \dfrac{1\ cm}{P_{Torr}}$

$l_s > 300\ m$ Desired in the Final Lens

$P_{Torr} < 3 \times 10^{-5}$ Required

Reactor Pressure $\sim 10^{-2} - 10^{-3}$ Torr

- Handle Gas with Fast Shutters (~2 ms) & Pumping
- Design Study Needed

Final Compression

The Pulse Is Reduced To ~10 ns By Drift Compression

$$\text{Tail Velocity} = v_0 + \Delta v$$

$$\text{Head Velocity} = v_0 - \Delta v$$

$$\text{Drift Distance} = \frac{\text{Initial Pulse Length}}{2\,\Delta v / v_0}$$

$$\approx \frac{20\text{ m}}{.05} = 400\text{ m}$$

Space Charge Stops Compression

Issue: Does Momentum Spread Remain Small? ($\Delta P / P_0 \lesssim 10^{-3}$)

- LLNL Simulations Encouraging
- ILSE Experiment Planned

Bends Before Final Focus

- Bends Cannot Be Avoided
- Bends Are Unpleasant:

  Chromatic Effects
  Aberations

- Space Charge Effects Are Known To Be Important — But There is No Complete Theory For Space Charge In A Bend.

- Image Charges Alter the Dynamics In a Known Way — Compensate as Needed
- Compression Is Simultaneous with Bending

ILSE Experiment Planned

More Theory/Simulation Needed

Beam Combiner

- Predicted Emittance Growth $\approx \times 4$ If Beams Are Very Close

- It Is Difficult To Fit In The Bends And Quads – Due To Closeness of Beams

- Downstream Beam May Be Poorly Matched

This Is A Major Feature of ILSE

Much Simulation and Design At Present

Source / Injector

Wish List:

I ~ 1 Ampere / Beam

V ~ 2 MV (?)

ϵ_n ~ Few × 10^{-7} m-r

N_{Beam} ~ 32 - 128

Single Charge State

Multiply Ionized as Desired

Negligible Losses

~30 μs Pulse Length

Long Life, etc.

Issue — Do it <u>all</u> <u>at</u> <u>once</u>

HIFSA

HEAVY-ION FUSION SYSTEMS ASSESSMENT

PROJECT TEAM

University of California
- Los Alamos National Laboratory
- Lawrence Berkeley Laboratory
- Lawrence Livermore National Laboratory

McDonnell Douglas Astronautics Company

Stanford Linear Accelerator Center

University of Wisconsin

POLAROID
C62? ?327 P

POLAROID
B617 9326 C

UPDATE OF HIFSA IMPLICATIONS FOR HEAVY-ION FUSION

Donald J. Dudziak
and
William B. Herrmannsfeldt

3rd ICF COLLOQUIUM

MADISON, WISCONSIN
9-11 NOVEMBER 1987

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C628 9327 P

PRESENTATION

- Project goals and guidelines
- Brief review of system technologies and options matrix
- Emphasis on systems trades, COE, sensitivity
- Comment on R&D requirements to achieve promising systems

POLAROID

HIFSA PROJECT GOALS

- Assess present *HIF* technologies
- Stimulate innovative system and component concepts
- Investigate numerous systems options
- Explore promising regions of parameter space and determine sensitivities
- Identify several promising configurations for further study and R&D assessment

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HIFSA PROJECT GUIDELINES

- Consider only induction linac drivers
- Consider only electric power applications
- Use a few "developed" reactor concepts covering pulse energy/rep rate range
- Collate target physics data into usable form for systems studies
- Examine a few key technology issues in depth (e.g., ion charge state, cavity clearing, beam transport)
- Develop system models for
  - accelerator (LIACEP)
  - final beam transport and focus
  - target manufacturing costs
- Do *not* pursue a point design

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MAJOR TECHNOLOGIES
and
SYSTEMS OPTIONS

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INDUCTION LINAC

- Incorporate detailed LINAC design cost and performance model from LBL

- Accelerator design based on derivatives of single-charge/single-pass model

- Include technology and physics options such as:
  - Multiple charge state ions
  - Transport at tune depressions as low as 8 - 10°
  - Explore multiple pulse designs
  - Beam combining at low energies and splitting at high energies

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ACCELERATOR MODEL

- Based on >500 Discrete **LIACEP** Data Points
- Input Variables:
  - Repetition Rate (5, 10, 15, 20 Hz)
  - Ion Mass (130, 160, 190, 210 amu)
  - Ion Energy (5, 10, 15, 20 GeV)
  - Beam Energy (1, 2, 3, 5, 10 MJ)
  - Emittance (15, 30 μrad-m)
  - Number of Beams (4, 8, 16)
  - Charge State (1+, 3+)
- Calculated Parameters:
  - Accelerator Efficiency (%)
  - Accelerator Length (km)
  - Accelerator Cost

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BEAM TRANSPORT MODEL

- GIVEN:
  - Cavity radius
  - Pole tip field
  - Ion mass
  - Gain curve parameter, γ
  - Target model spot size restrictions
  - Miscellaneous beam parameters

- DETERMINE FINAL TRANSPORT PARAMETERS:
  - Size
  - Length (beamline and final focus)
  - Number of beamlets
  - Cavity clearing limits on rep rate
  - Cost

CAVITY TRANSPORT

- Determine allowable repetition rates as a function of:
  - Target Yield
  - Background Pressure
  - Cavity Size
  - Fluid Temperature
- Identify stable transport at pressure 10^{-2} - 10^{-1} torr
- Study cavity leakage into final transport lines
- Incorporate alogrithms for different types of reactor cavities

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CAVITY MODELING

Parameter	Limiting Values: Mag.-Prot. Wall	Liq. Wall	Gran. Wall	Wetted Wall
Rep Rate, Hz	20	2	10	10
Wall Life	f(radius, fusion power)	Life of Plant	Life of Plant	f(radius, fusion power)
Irradiation Scheme	All	SS,DS	SS,DS	All
Number of Beams	Any	Any	38	Any

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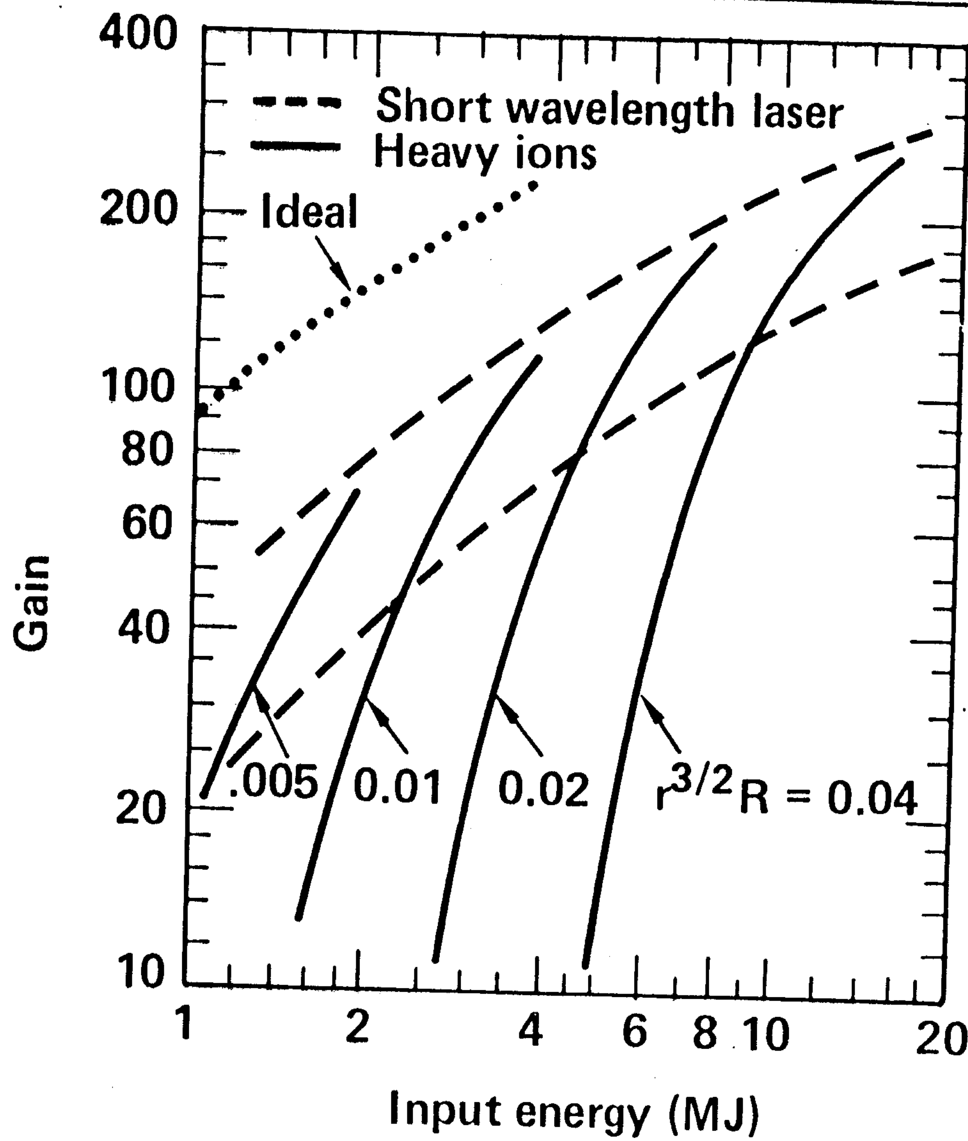
TARGET MODELING

Target Type	Irradiation Scheme: Single-Sided	Double-Sided	Sym. Planar	4 π Symmetric
Single Shell[a]	•	•		
Double Shell	•	•		
Symmetric			•	•

[a]Includes single shell/range multiplied and single shell/gain multiplied (advanced) concepts.

HIFSA **Los Alamos**

Target gain as a function of input energy for single-shell targets



50-60-0381-0589

TARGET MANUFACTURING COST MODEL

SIMPLE METHODOLOGY BASED ON TARGET SUBSTRUCTURES

- Direct-Drive Targets
  - Generic fuel capsules for single-shell and double-shell targets
  - Generic outer fuel capsule for double-shell targets
  - Generic driver-beam absorption structure

- Indirect-Drive Targets
  - Generic fuel capsules
  - Generic radiation case and driver-beam absorption

- DELPHI Process with Ad Hoc Panel of Experts
  - Many scientific and engineering disciplines represented
  - Repeated sessions to achieve consensus
  - Capital, O&M, and materials reference costs
  - Scaling with target yield and production rate

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A BEAM OF HEAVY IONS CAN BE TRANSPORTED THROUGH A FUSION REACTOR CAVITY

- A detailed analysis has demonstrated that the beam can be delivered to the target even when streaming instabilities are present

- High background gas density ($\lesssim 10^{16}$ cm^{-3}) tolerable
  - High allowed liquid lithium temperature (~550°C)
  - High pulse repetition rate (~10 Hz)
  - High allowed beam injection charge state (+4)
  - Low required beam voltage (~4 GeV)

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SYSTEMS

TRADEOFFS & SENSITIVITIES

HIFSA

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DATABASE PARAMETER VARIATIONS

Net Electric Power (MW)	500, 1000, 1500
Cavity Types	Magnetically-Protected Wall
	Liquid Wall
	Granular Wall
	Wetted Wall
Target Types	SS, SSRM, DS, SYM
Gain Multiplier	Off/On (SS Target Only)
Irradiation Schemes[a]	1-Sided
	2-Sided
	Symmetric-Planar
	4π Symmetric
	Double-Pulse, Double-Sided

[a]Not all irradiation schemes apply to all targets.

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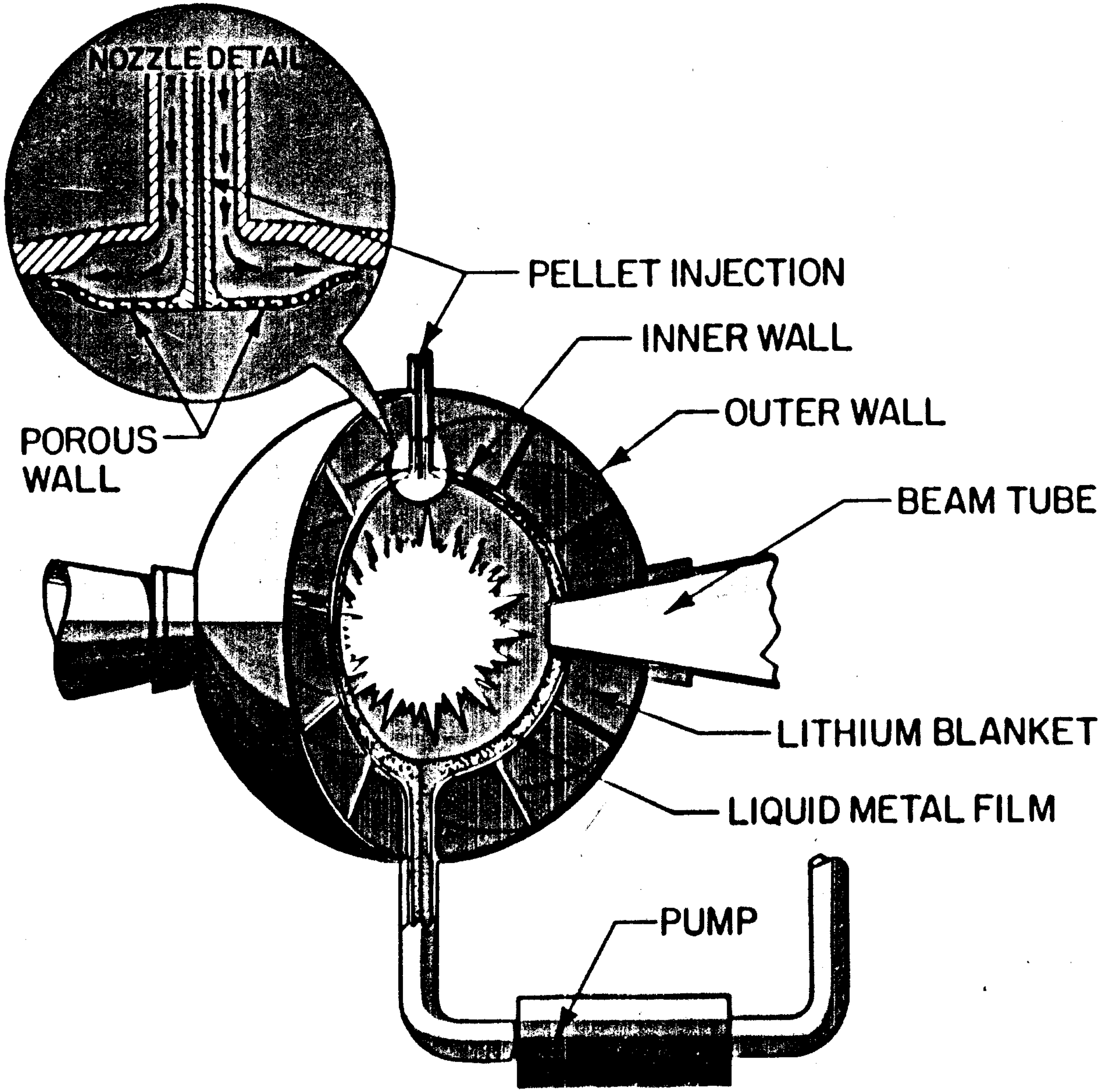
DATABASE PARAMETER VARIATIONS (Cont.)

Gamma	0.01, 0.02, 0.03, 0.04 (0.075, 0.15, 0.225, 0.3 For Sym. Target)
No. of Accelerator Beams	4, 8, 16
Ion Mass (amu)	130, 200
Repetition Rates (Hz)	1 (2) 19 (Mag.-Prot. Wall) 1 (0.2) 2 (Liquid Wall) 1 (2) 9 (Granular Wall) 1 (2) 9 (Wetted Wall)

LOS ALAMOS WETTED-WALL ICF REACTOR CONCEPT



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COSTING METHODS

	MCF	NEDB
Inflation (%)	5	6
Escalation (%)	5	6
Construction Time (y)	5	8
Fixed Charge Rate	0.100	0.083
Availability	0.75	0.75

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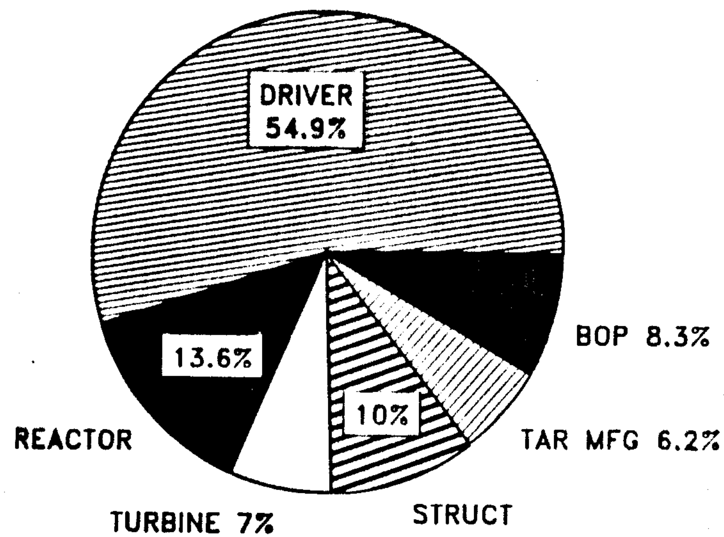
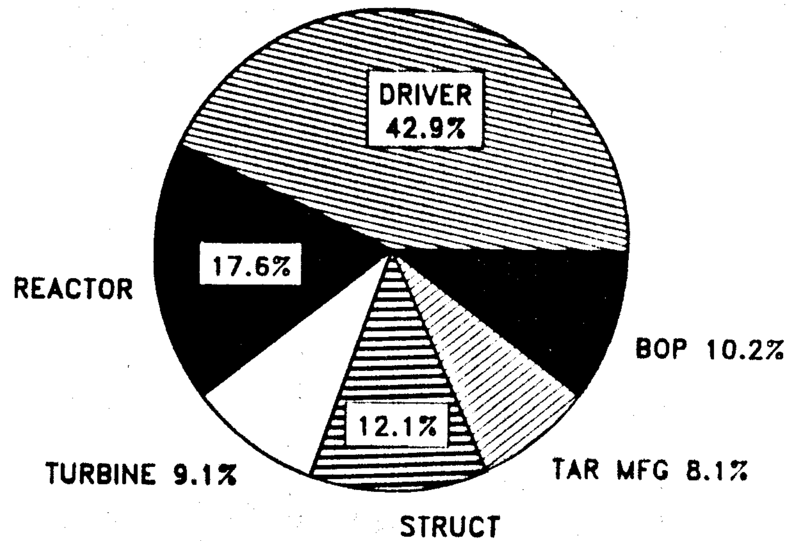
COMPARISON OF +1 TO +3 DRIVER

WET WALL; 1000 MWe; 1 Cav; SS Targ; 2S Irrad; 16 Beams
+1 vs +3; Mass 130; RR 5 Hz; Gam 0.03



+1 IONS
(75.2 Mills/kWh)



+3 IONS
(58.8 Mills/kWh)

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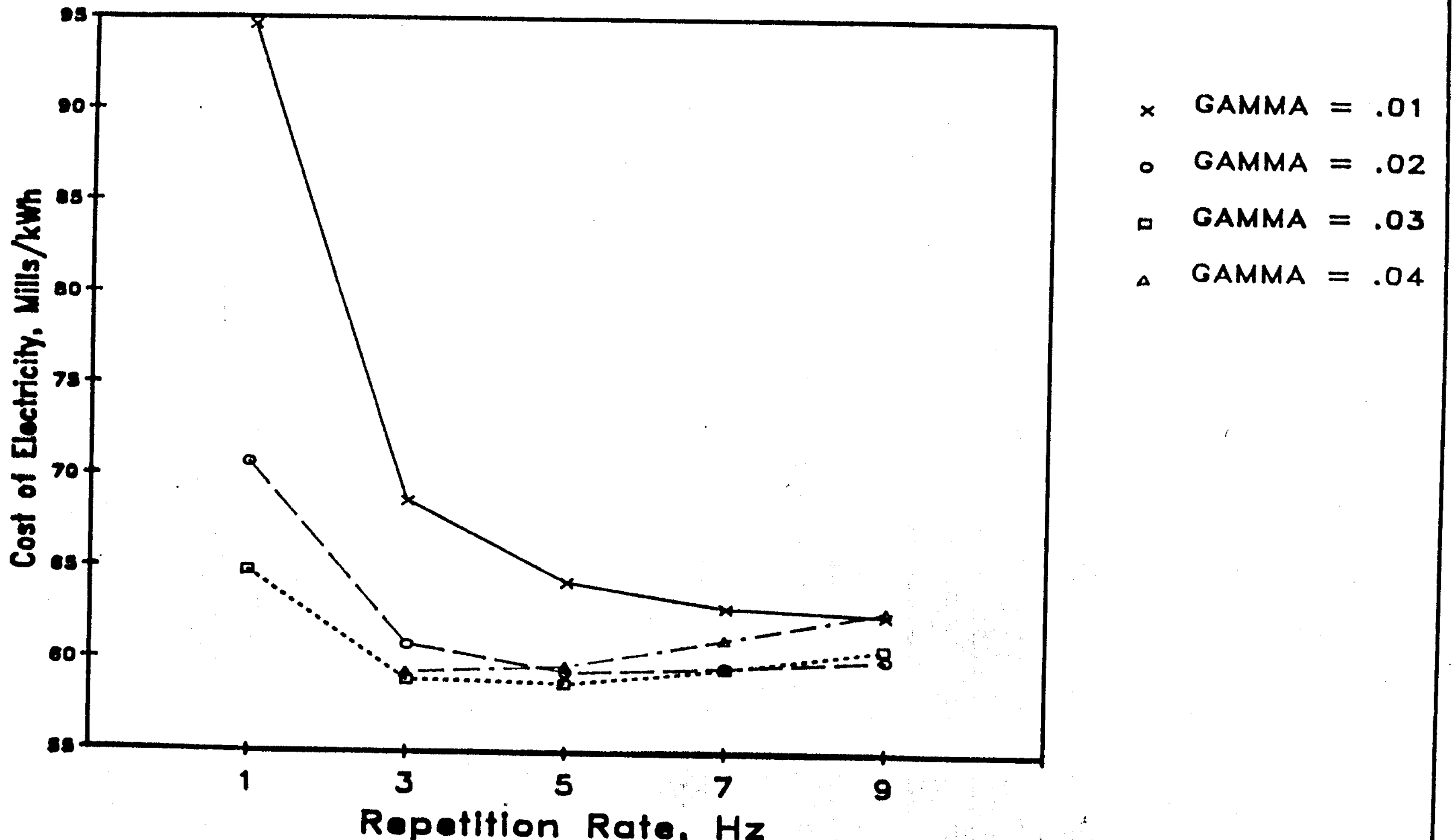
COE vs REPETITION RATE

WET WALL; 1000 MWe; 1 Cav; SS Targ; 2S Irrad; 16 Beams
+3 Ions; Mass 130; RR Var; Gam Var



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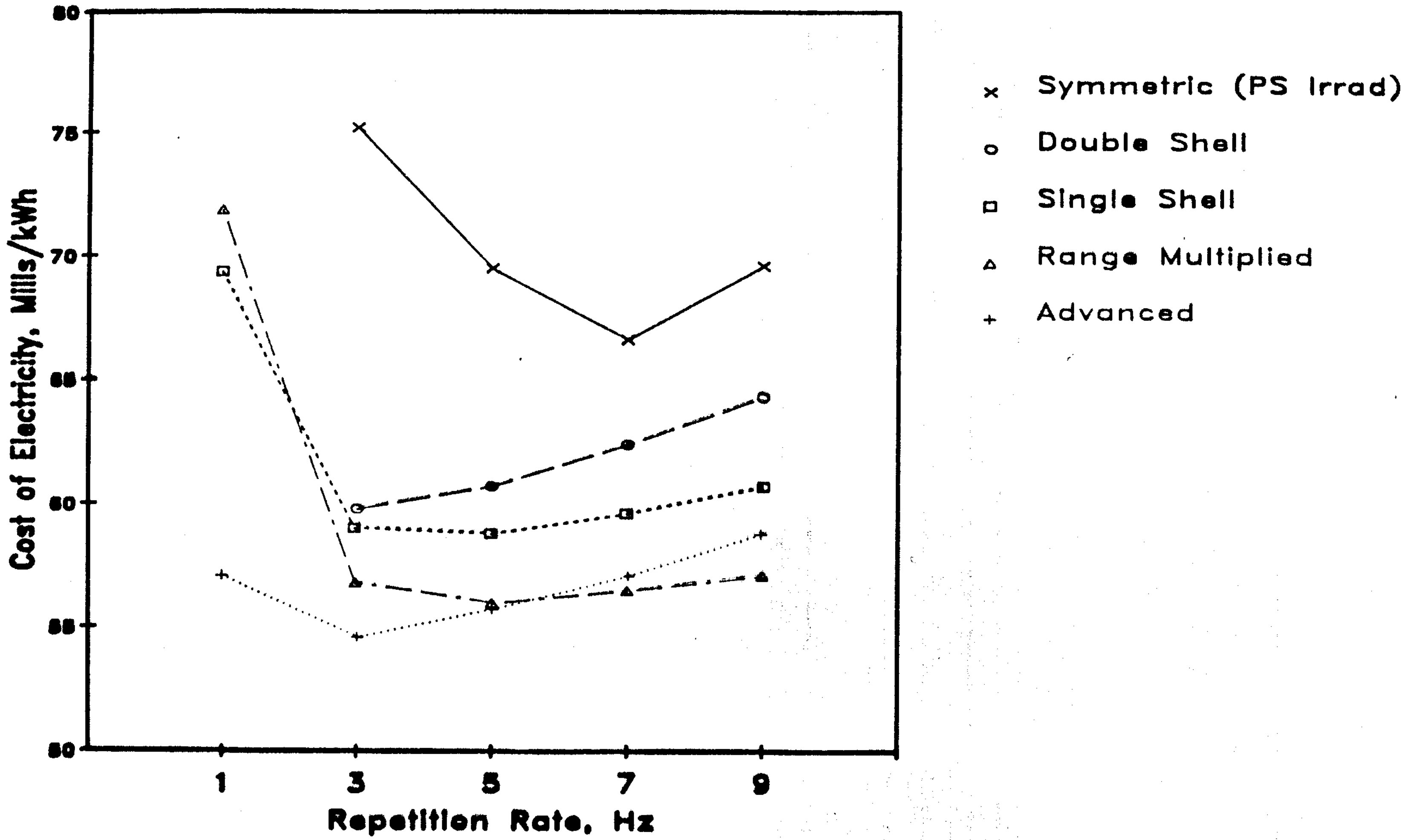
COMPARISON OF TARGETS

WET WALL; 1000 MWe; 1 Cav; Var Targ; 2S Irrad; 16 Beams +3 Ions; Mass 130; RR Var; Gam 0.03 (0.225 SYM)



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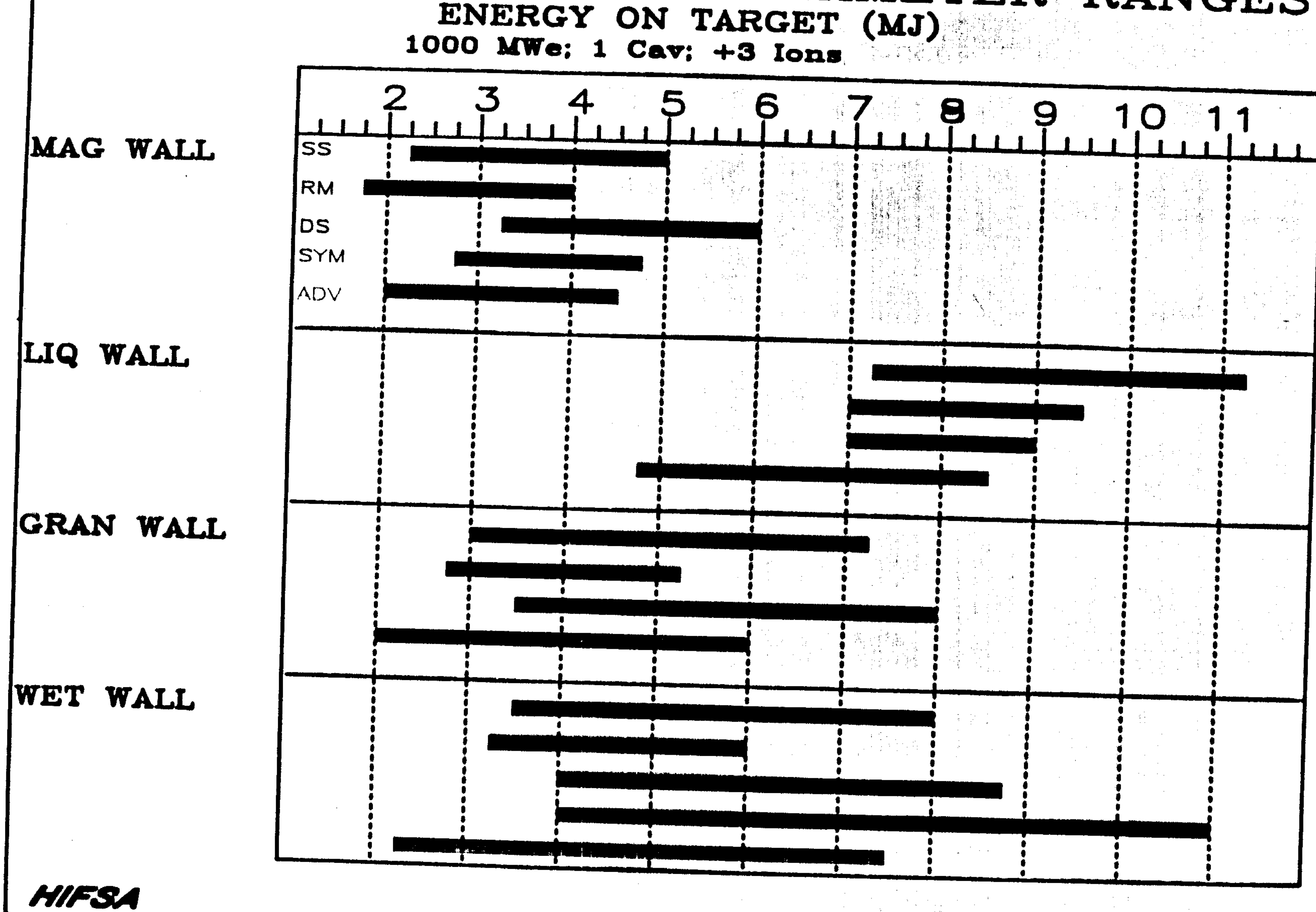
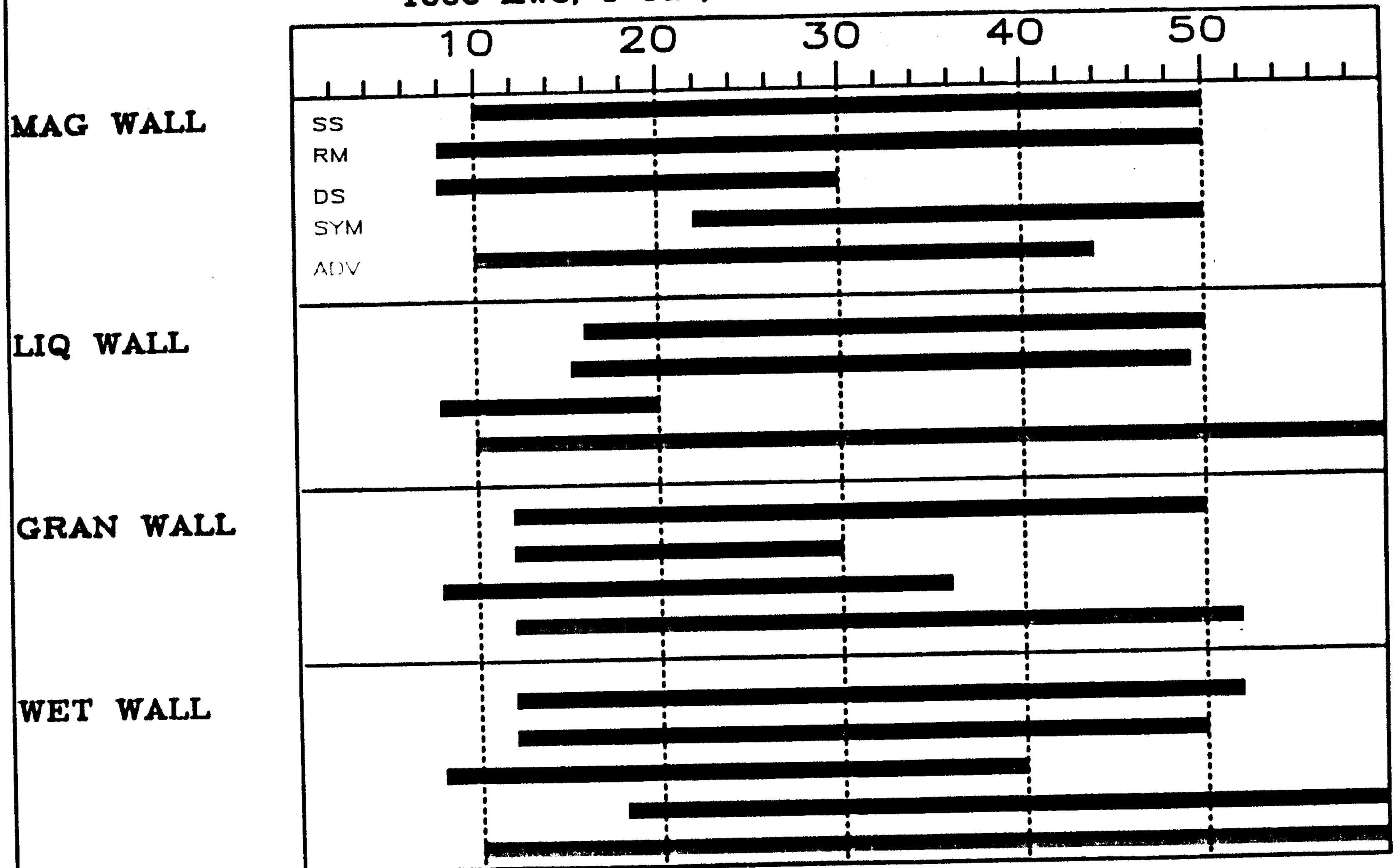
HIF NEAR–OPTIMUM PARAMETER RANGES



HIF NEAR–OPTIMUM PARAMETER RANGES

NUMBER OF BEAMS IN FINAL TRANSPORT

1000 MWe; 1 Cav; +3 Ions



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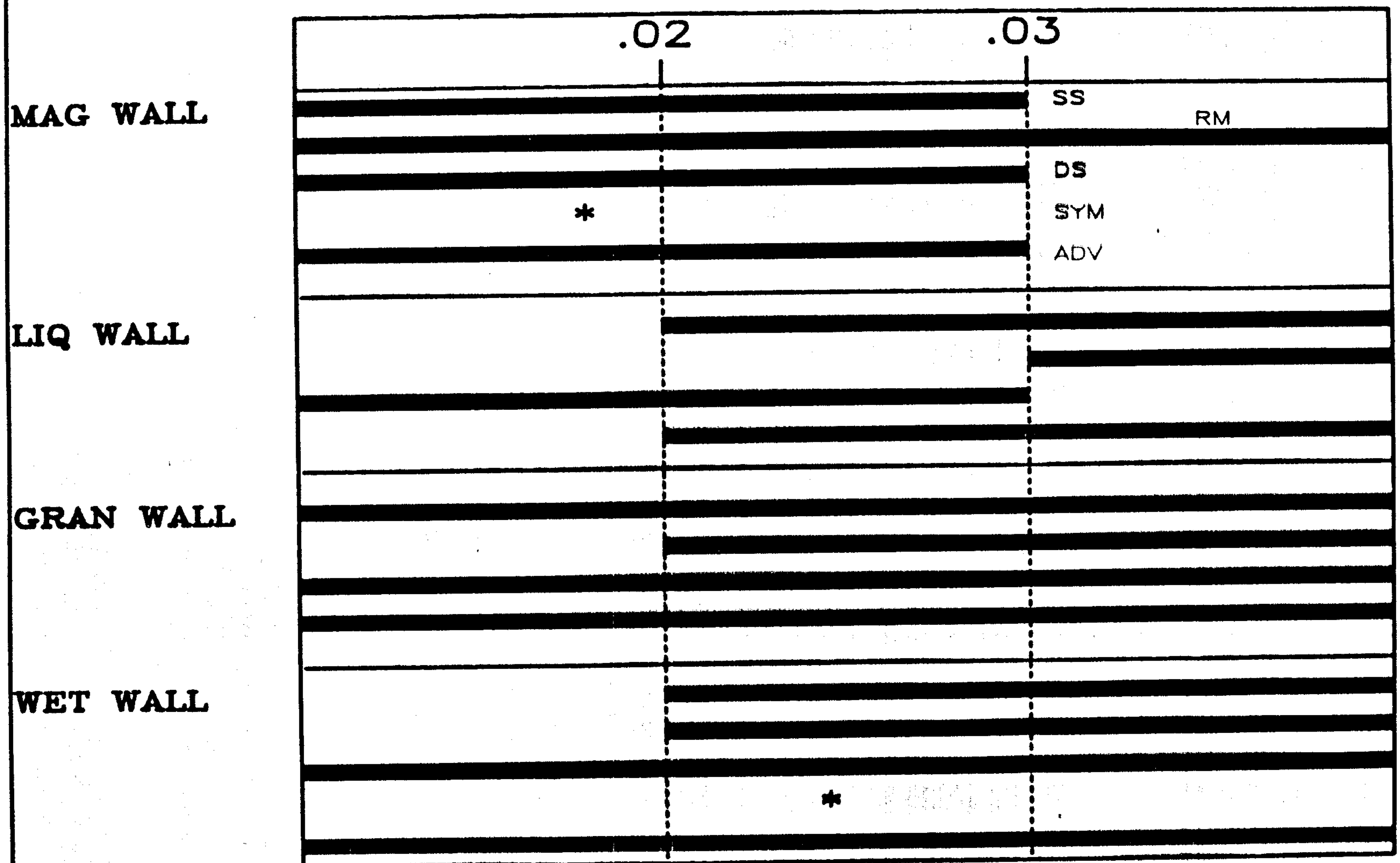
HIF NEAR–OPTIMUM PARAMETER RANGES

GAMMA (Rspot3/2 * RANGE)**

1000 MWe; 1 Cav; +3 Ions;



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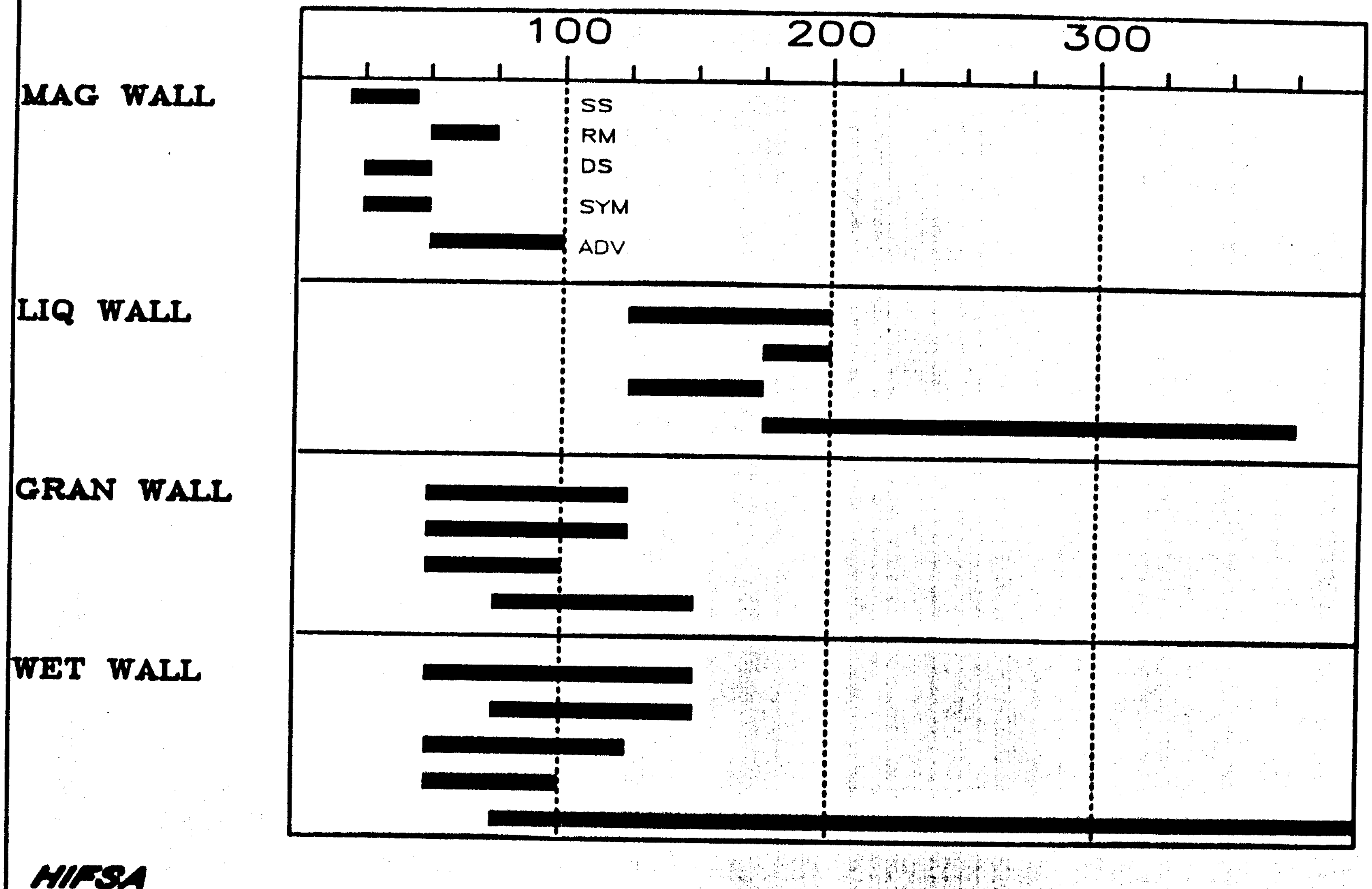
* gamma range for symmetric target is 0.225 – 0.300

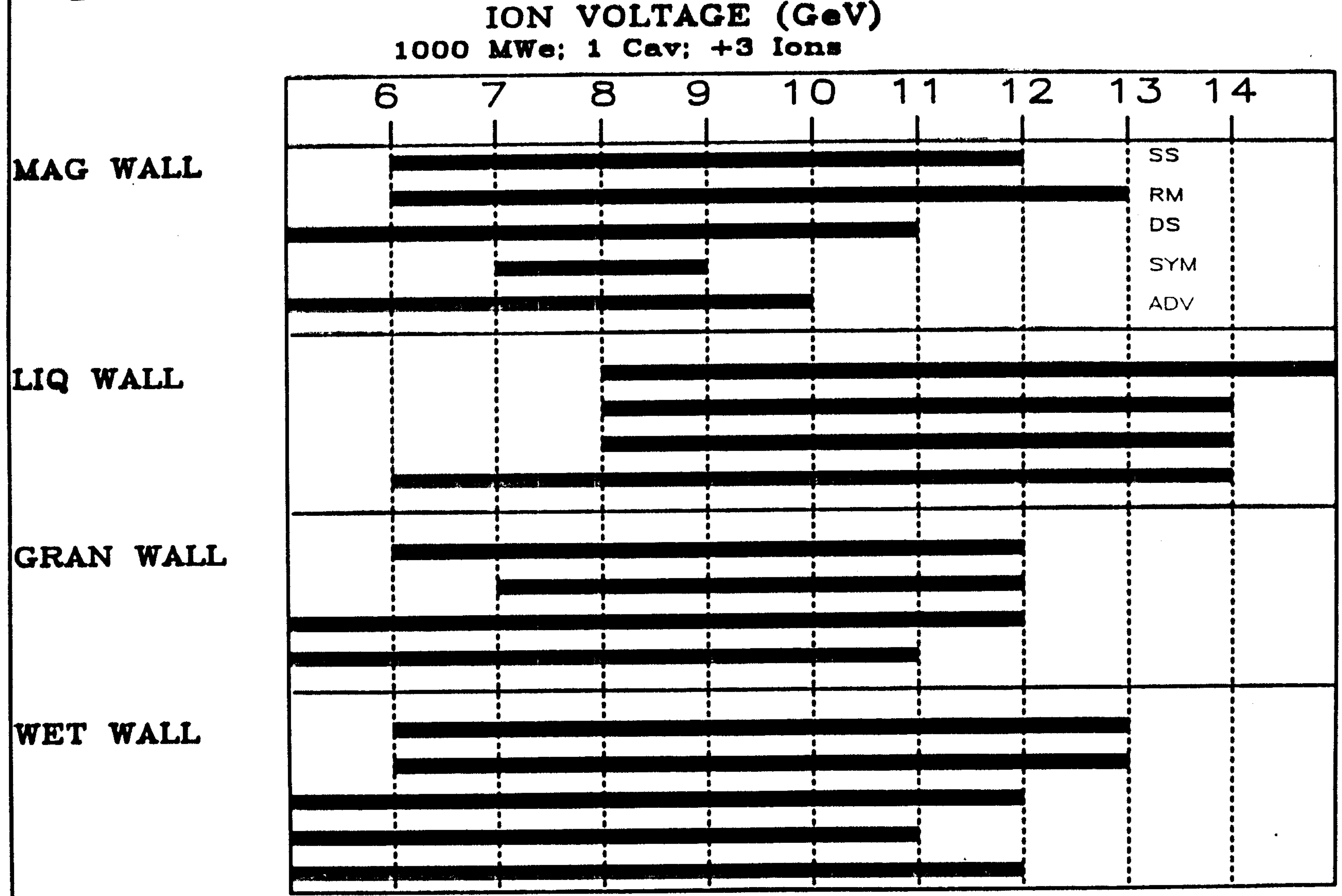
HIF NEAR—OPTIMUM PARAMETER RANGES

GAIN

1000 MWe; 1 Cav; +3 Ions



HIF NEAR–OPTIMUM PARAMTER RANGES



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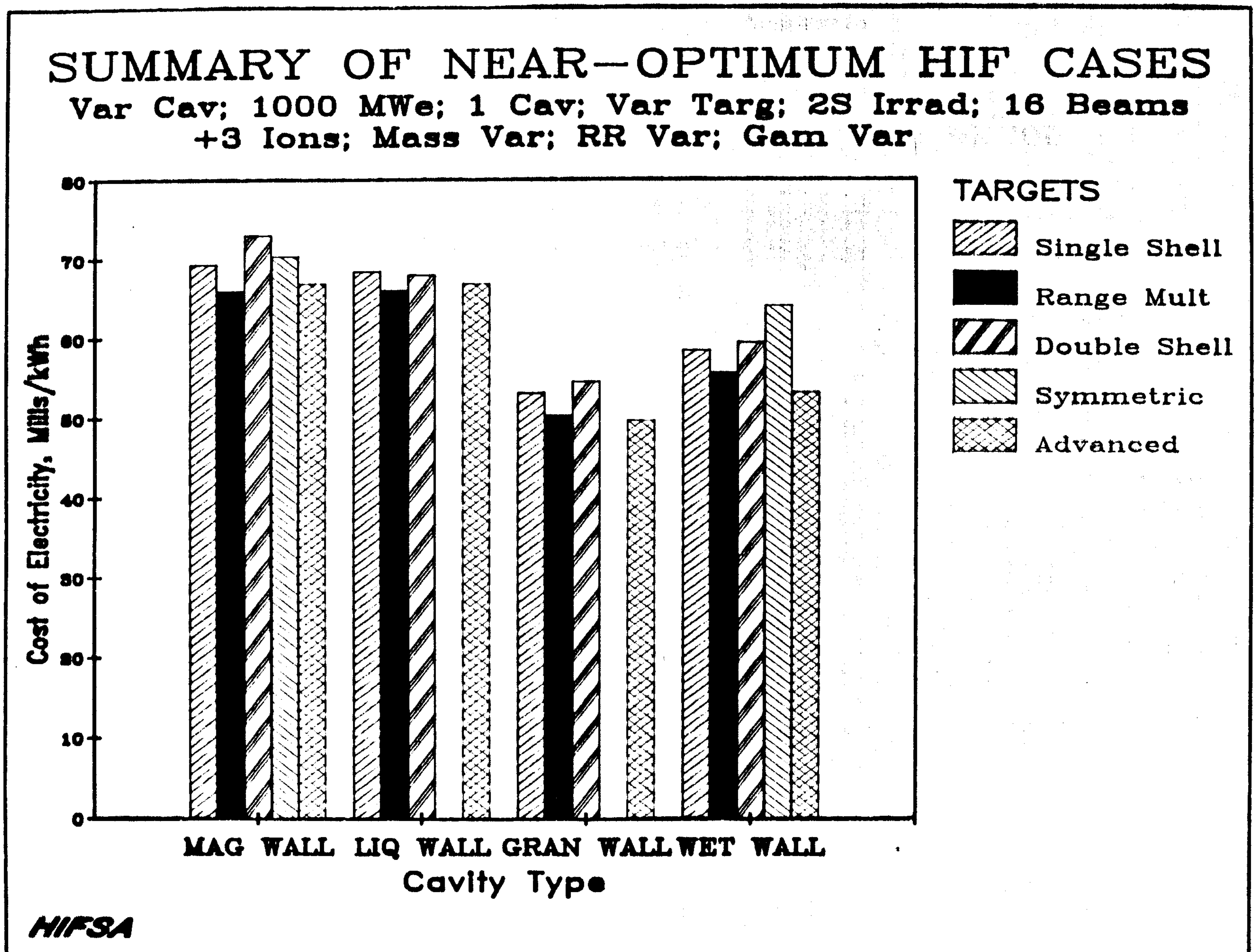
SUMMARY OF NEAR–OPTIMUM HIF CASES
Var Cav; 1000 MWe; 1 Cav; Var Targ; 2S Irrad; 16 Beams
+3 Ions; Mass Var; RR Var; Gam Var
Cost of Electricity, Mills/kWh
0
10
20
30
40
50
60
70
80
MAG WALL
LIQ WALL
GRAN WALL
WET WALL
Cavity Type
TARGETS
Single Shell
Range Mult
Double Shell
Symmetric
Advanced
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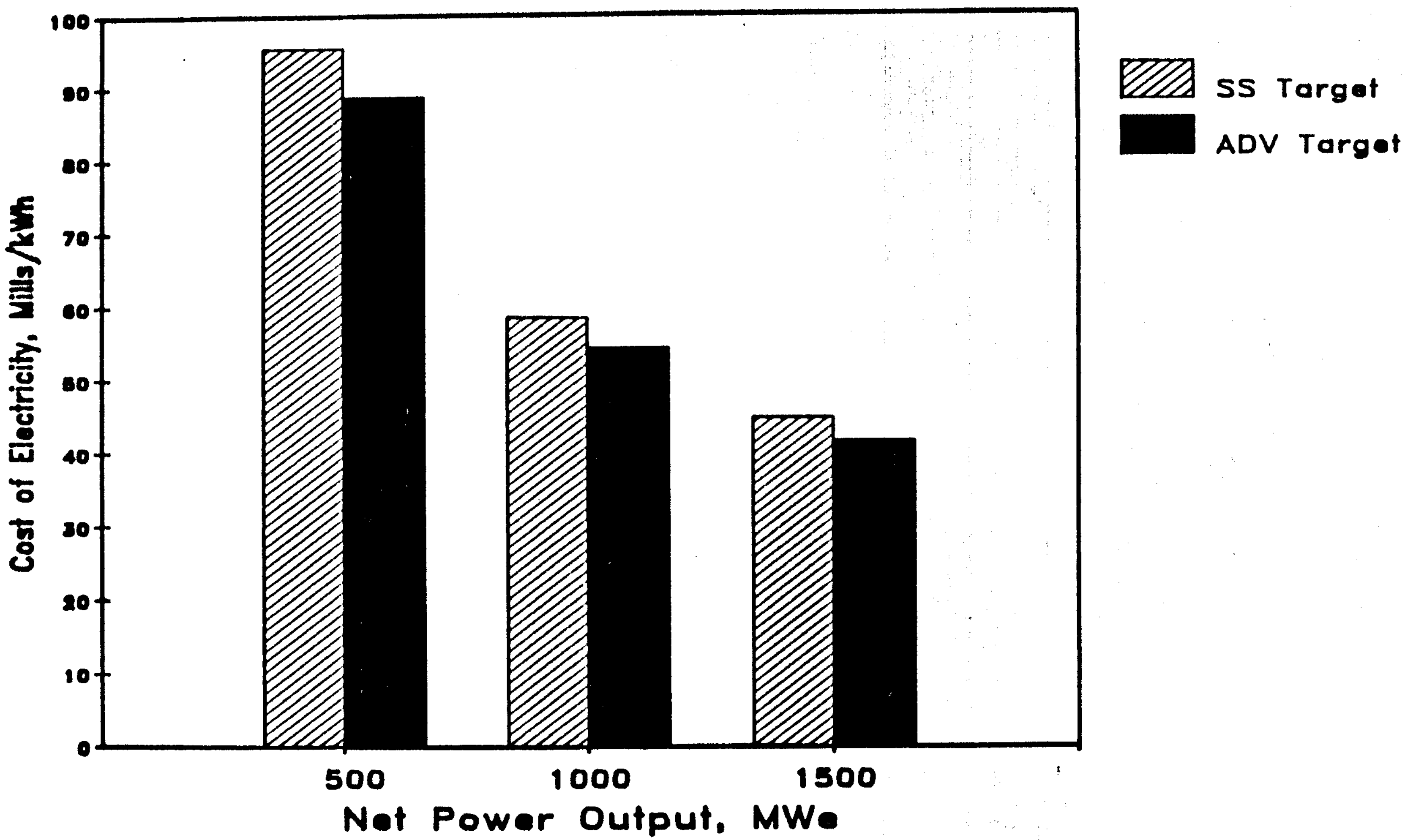
NEAR–OPTIMUM COE vs POWER LEVEL

WET WALL; Var Pwr; 1 Cav; Var Targ; 2S Irrad; 16 Beams +3 Ions; Mass 130; RR Var; Gam Var



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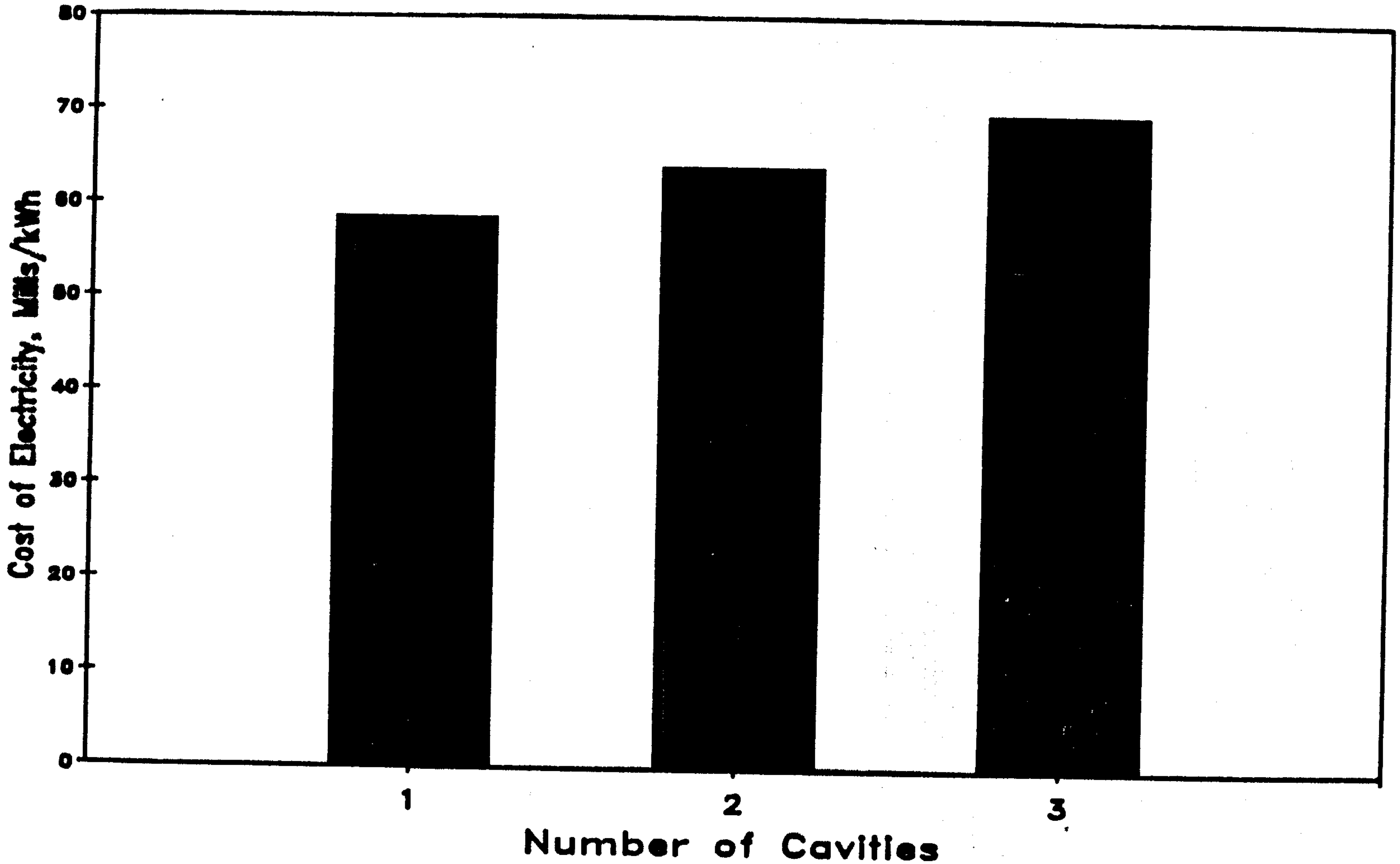
COE VS. NUMBER OF CAVITIES

WET WALL; 1000 MWe; 1,2,3 Cav; SS Targ; 2S Irrad; 16 Beams +3 Ions; Mass 130; RR 5 Hz; Gam 0.03



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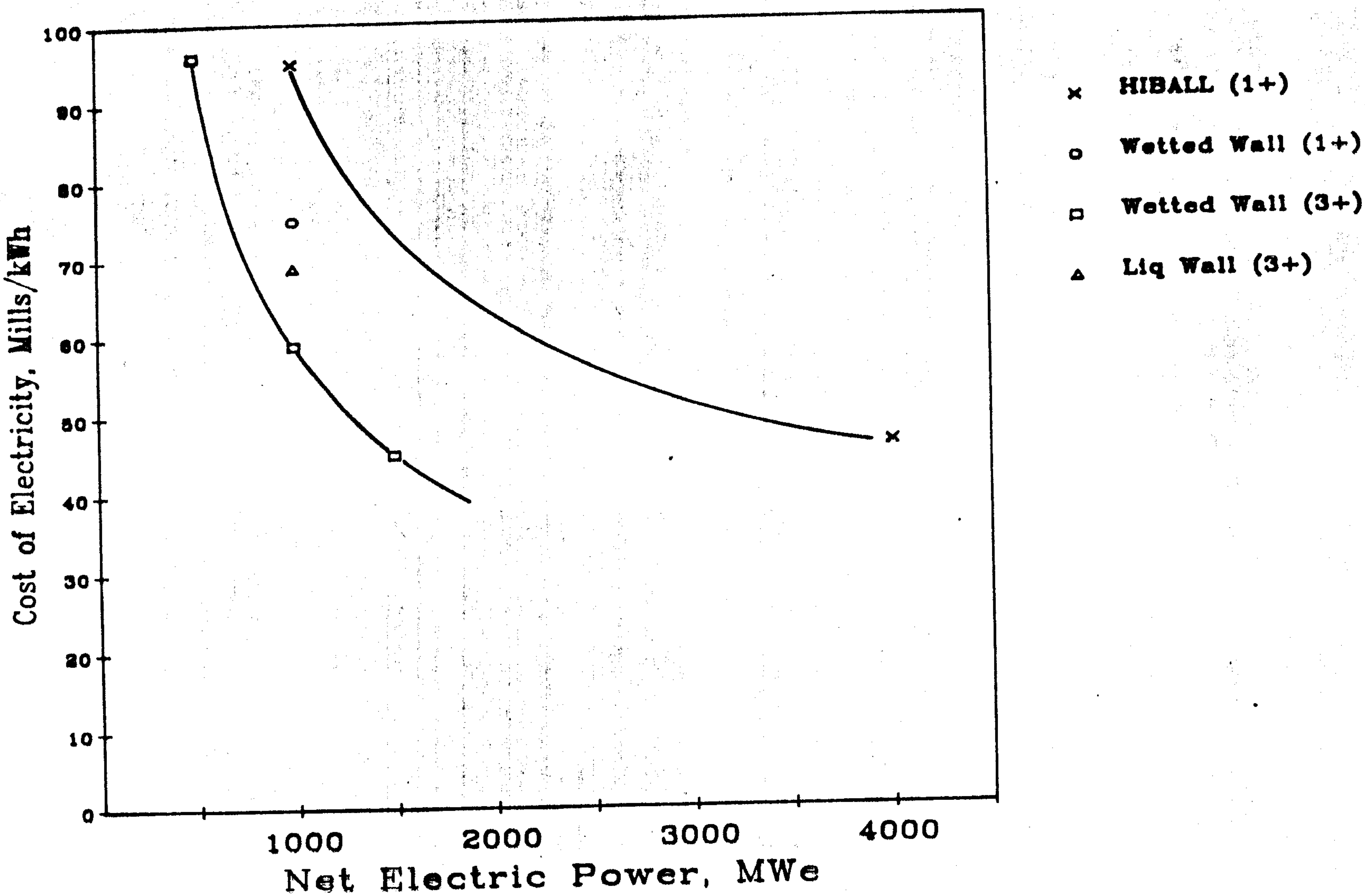
COE as a FUNCTION of PLANT SIZE



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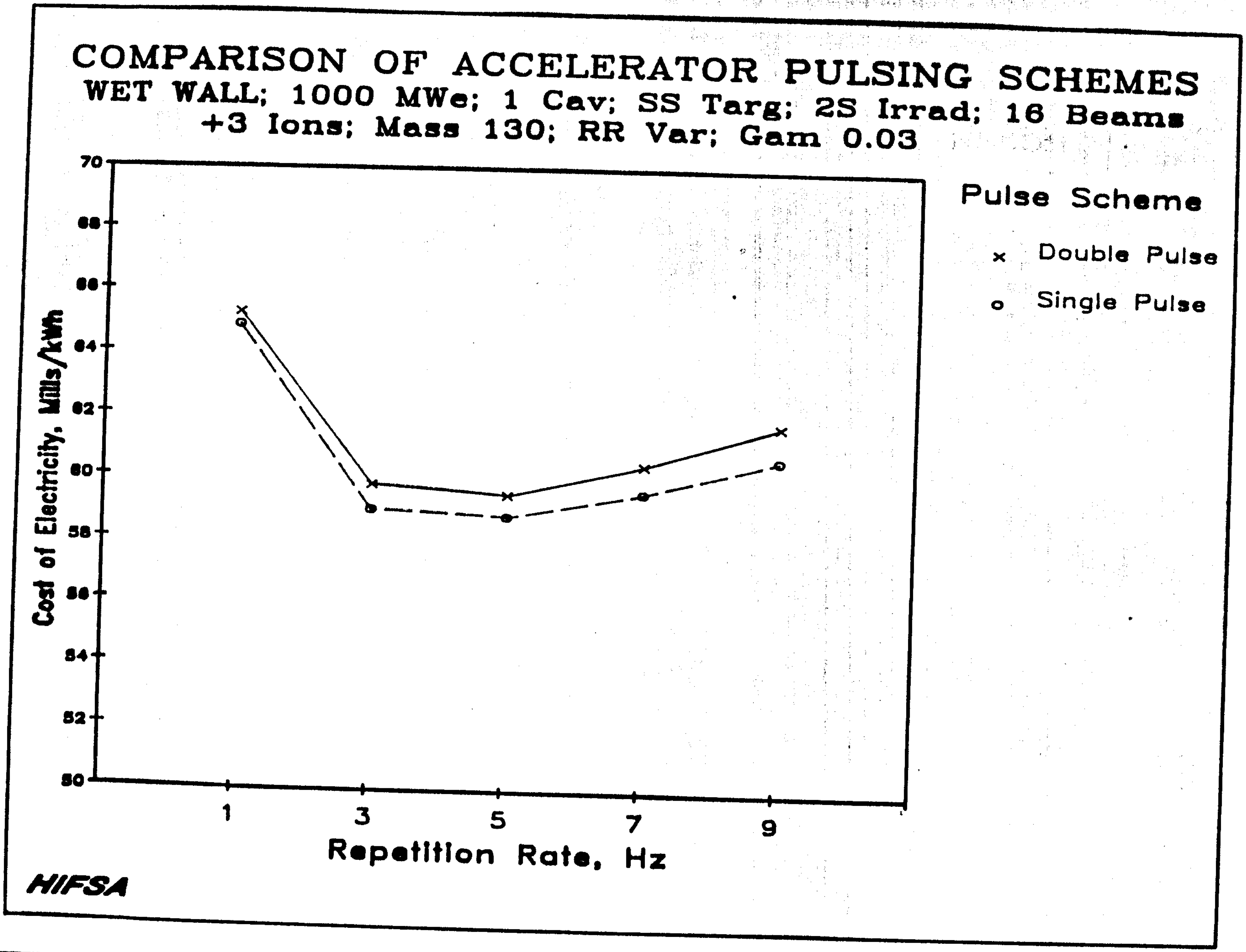

COMPARISON OF ACCELERATOR PULSING SCHEMES
WET WALL; 1000 MWe; 1 Cav; SS Targ; 2S Irrad; 16 Beams
+3 Ions; Mass 130; RR Var; Gam 0.03
Cost of Electricity, Mills/kWh
70
68
66
64
62
60
58
56
54
52
50
1
3
5
7
9
Repetition Rate, Hz
Pulse Scheme
× Double Pulse
o Single Pulse
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POLAROID
C628 9327 P

MAJOR R&D REQUIREMENTS

- Higher charge-state accelerator
  - Source development
  - Final focus and cavity transport
- Core and insulator development
- Beam merging at low-energy end
- Beam splitting at high-energy end
- Beam transport simulation and experiments
- Beam neutralization
- Longitudinal compression
- Pulse shaping

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POLAROID
C628 9327 P

SUMMARY

Innovative *HIF* technologies indentified

- Higher ion charge states
- Improved cores, insulation, etc.
- Cavity beam transport and cavity clearing analysis favorable
- Target gain data parameterized
- Target manufacturing costs estimated

Comprehensive systems model and systems code developed

Extensive, robust operating space with competitive *COE* identified

COST REDUCTION ANALYSIS FOR AN ICF HEAVY-ION ACCELERATOR

G. R. Thayer
J. R. Sims
M. D. Henke
D. B. Harris
D. J. Dudziak
N. R. Phillips (BDM Corp)

Los Alamos National Laboratory

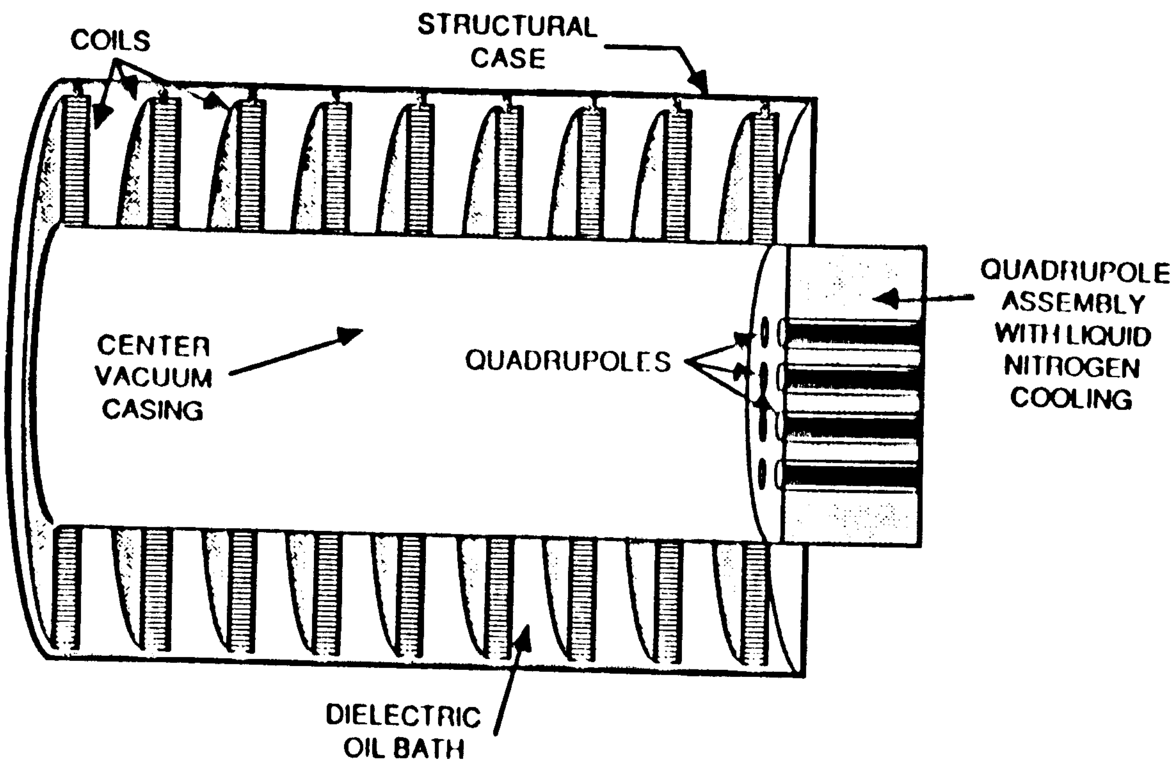
Project Steps

1. Use LIACEP to generate base case accelerator parameters and cost
2. Select a "representative" accelerator module for the study
3. Produce a design
4. Obtain independent cost estimates for major items in the module
5. Examine manufacturing techniques to lower costs
6. Investigate optimum module assembly strategy

COSTING BASIS

- Costs appropiate for the year 2025
- Assume 10th-of-a-kind facility
- Assume design will incorporate duplicate modules

MODULE GEOMETRY



OUR STUDY INDICATES MODULE COSTS ~20% LESS THAN LIACEP

- A conceptual design of an accelerator module has been completed.
- Some manufacturing methods that could produce these cost savings have been suggested.
- Independent cost estimates indicate that large scale manufacturing of components could result in costs lower than the estimates in LIACEP.

LIACEP CALCULATED COSTS

*Core	229 k$ → 109 k$
* Insulator cylinder	160 k$ → 112 k$
* Superconducting quads	131 k$ → 140 k$
Pulse electronics	123 k$
Vacuum, support & alignment, computer, beam management and control	26 k$
Magnet refrigerator, quadrupole structure, magnet power supply	105 k$
Conventional facilities	64 k$
TOTAL	838 k$