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

http://fti.neep.wisc.edu

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Light Ion Beam Driven Inertial Confinement Fusion:
Requirements and Achievements

*H. Bluhm, G. Keßler, R.R. Peterson**
Forschungszentrum Karlsruhe
Institut für Neutronenphysik und Reaktortechnik
P.O.Box 3640, D-76021 Karlsruhe

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

Abstract. In this paper we compare the requirements for a light ion beam driven inertial confinement fusion reactor with the present achievements in pulsed power technology, ion diode performance, beam transport and target physics. The largest technological gap exists in beam quality and repetition rate capability of high power ion diodes. Beam quality can very likely be improved to a level sufficient for driving a single shot ignition facility, if the potential of two-stage acceleration is used. Present schemes for repetition rate ion diodes allow either too low power densities or create too large beam divergence. On the other hand repetitively operating pulsed power generators meeting the requirements for an ICF reactor driver can be built with present technology. Also a rather mature target concept has been developed for indirect drive with light ion beams.

INTRODUCTION

The use of light ions to implode DT filled targets in future commercial fusion reactors has been studied for over more than 10 years. The first self consistent light ion driven power plant design LIBRA was published by the University of Wisconsin (UWM), Sandia National Laboratories (SNL) and the Nuclear Research Center Karlsruhe (KfK) in 1989 [1]. The specific issues to be solved for any light ion beam driven ICF power plant are related to the repetitive operation of the high voltage pulse generator and the ion source, to the production of high quality beams and to their transport to the target. Although the reaction chamber and the targets driven by a light ion beam also have their peculiarities, these seem to be at least not more demanding than for any other driver option.

So far the LIBRA reactor studies have been restricted to detailed investigations of the generator, the beam transport, and the reaction chamber issues. They did not address the very difficult problem of high quality repetitive beam production to any depth. The physical and technical foundations of this challenging problem must be solved first in a separate experimental and theoretical research and development program. Such programs are underway at Sandia National Laboratories, Cornell University, NRL Washington, ILE Osaka, and at the Research Center Karlsruhe.

Meanwhile three versions of the LIBRA reactor study have appeared that mainly differ from each other by their schemes for beam transport. They considered

- preconditioning of beam channels by laser beam and pulsed direct current [1]
- ballistic transport and final focussing of the ions with robust solenoidal magnetic lenses (LIBRA-LITE) [2]
- self propagating ion beams in a self pinched mode (LIBRA-SP) [3]

From a reaction chamber design point of view the self propagating beam would be preferable. In this paper we attempt to compare the present status of R&D results with the key design parameters of the conceptual reactor design studies.

LIBRA-SP CONCEPTUAL DESIGN

The LIBRA-SP conceptual reactor design study of UWM-SNL-KfK is a 1000 MWe Inertial Confinement Fusion Reactor which utilizes 30 MeV Li+ ion beams propagating in a self-pinched mode from the ion diodes to the targets [3]. There are 24 Li+-ion beams transporting 7.2 MJ onto the target. These modules are fired in a two-step sequence to provide the desired power pulse shape. Out of these 24 beams 12 are operated in a prepulse mode delivering 1.2 MJ and 12 beams hit the target with 6 MJ in the main pulse. The prepulses have a half width of 40 ns whereas the main pulses are bunched with a pulse width of 40 ns at the diodes and 20 ns at the target. The pulses overlap at the target to impact it with 300 TW peak power. The main beam parameters are listed in Table I.

Table I. LIBRA-SP General Ion Beam Parameters

Parameter	Main Pulse	Pre-Pulse
Ion species	Li^+	Li^+
Ion energy [MeV]	30	30
Energy on Target [MJ]	6.0	1.2
Transport efficiency [%]	90	90
Number of beams	12	12
Pulse width at diodes [ns]	40	40
Pulse width at target [ns]	20	40
Total Diode current [MA]	5.56	1.11
Total current on target [MA]	10	1
Total power at diodes [TW]	167	33
Total power at target [TW]	330	30

The 24 Li+ ion beams are generated by Li+ ion diodes which are loaded by 24 driver modules. The driver modules are of the same technology as used in the electron accelerator Hermes III at Sandia National Laboratories [4]. This technology uses alternators and step up transformers in charging pulse lines to convert wall plug electrical power into 0.75 μs pulses

of 2.7 MV. The charging pulse lines then feed pulse forming lines that drive Metglas induction cells in 1.15 MV, 39 ns pulses. Each main module is made of 26 induction cells whereas each prepulse module is constructed with 18 induction cells. The driver modules are situated around the reactor chamber at two levels. Fig. 1 shows a cross sectional view of the reactor chamber with its beam lines aiming at the target.

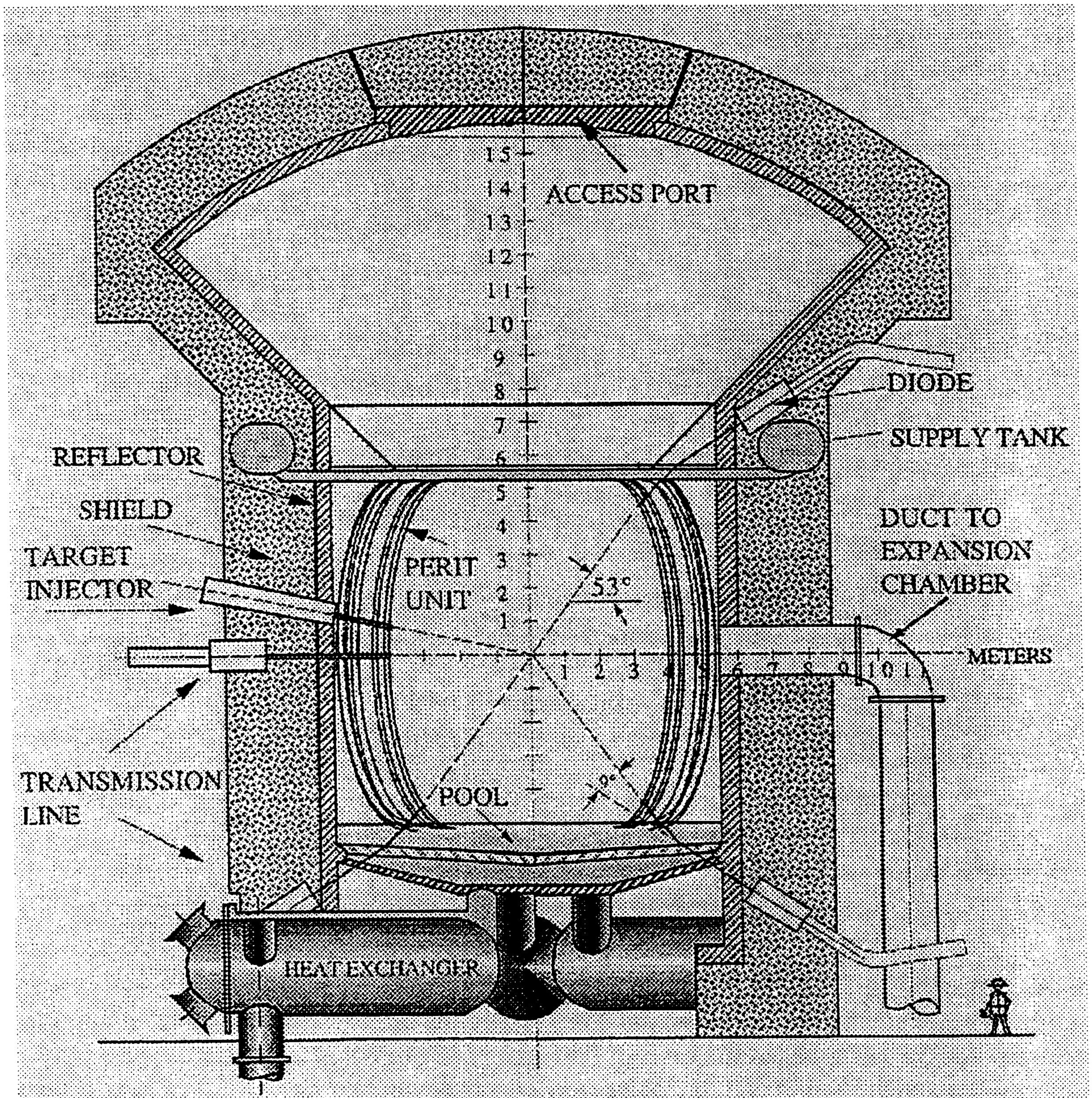

Figure 1. Cross-section of the Libra-SP target chamber

The reaction chamber is an upright steel cylinder (HT-9) of 5.7 m diameter and 13.6 m height which has an inverted conical roof extending an additional 9 m above the cylindrical position. The floor of the chamber consists of a perforated drain plate followed by a sump leading to the intermediate heat exchangers. The cylindrical wall of the reactor chamber is shielded by a bank of curved tubes which carry the PbLi coolant and breeder material. These coolant tubes have a system of spray fan nozzles (Perforated Rigid Tubes: PERIT) through which coolant flows and forms sheets of liquid metal in front of the main tubes. These sheets will mitigate the shock waves hitting the tubes and will shield the tube surfaces from the target X-rays.

The schematic picture of a possible 2-stage diode concept for LIBRA-SP is presented in Fig. 2. Three sets of magnets are shown, one on the anode side and two on the cathode side, each consisting of an inner and an outer ring coil. The annular ion beam passes through the ring shaped gap between the inner and outer coil on the cathode side. The focal length of the

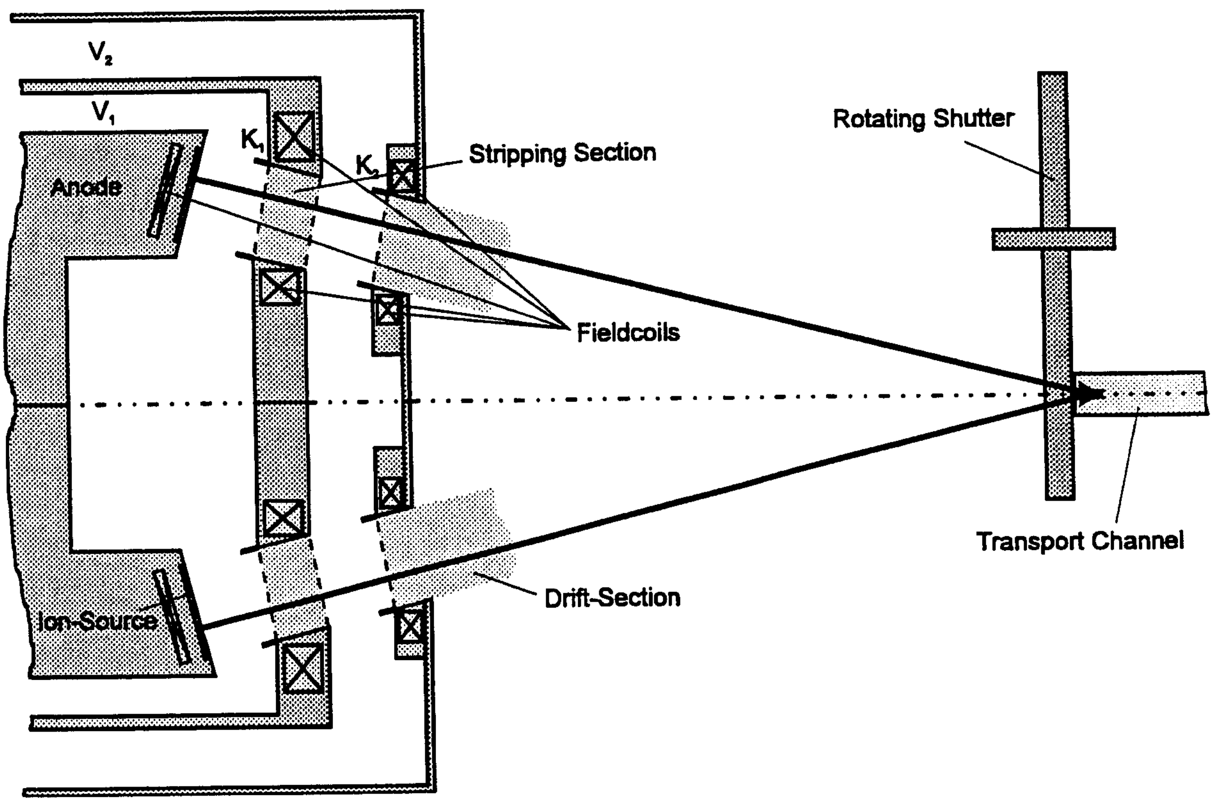

Figure 2. Schematic presentation of a possible two-stage diode design for LIBRA-SP

diode is given by the shape of the anode, the external magnetic fields acting upon the ions and by the degree of neutralization of the ion beam. The outer radius of the anode is an important parameter for the self pinched transport of the beam. The inner radius must be large enough to contain the magnetic field coils, the power feeds and the cooling channels. Rotating shutters between the 2 stage diode and the atmosphere of the reactor chamber separate the different vacuum conditions of the diodes and of the reactor chamber. It is assumed that the beams will propagate in a straight line without any pre-ionizing by a laser. The beam lines must therefore be aimed precisely at the targets.

The spherical target which is based on the target design for the Laboratory Microfusion Facility [5] is shown in Fig. 3. The peak beam power on target is 330 TW in a pulse width of

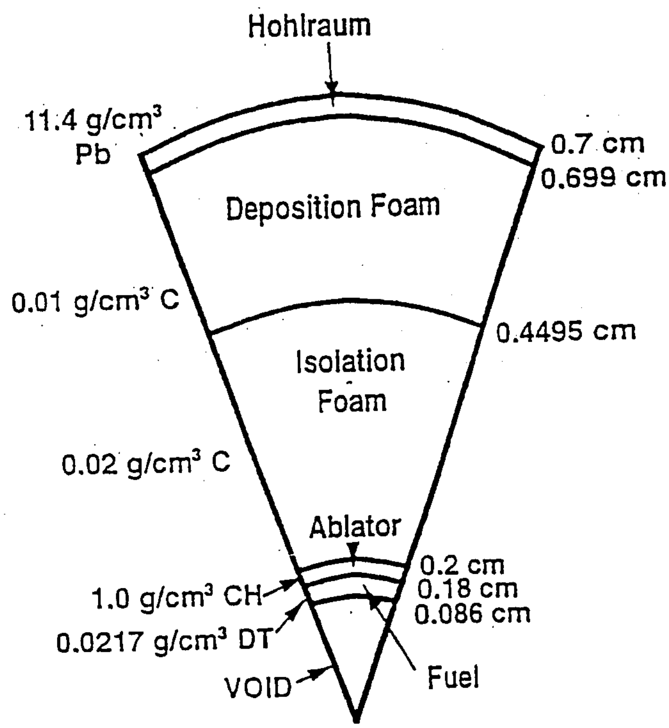

Figure 3. *Schematic of initial target configuration for LIBRA-SP*

20 ns. Internal pulse shaping of the X-ray flux on the inner DT-capsule is expected to lead to a gain of about 80, thus producing a total yield of 560 MJ, at a frequency of about 4 Hz. Some target data are given in Table II.

Table II. LIBRA-SP Target and Ion Beam Parameters

Total absorbed beam energy	7.2 MJ
Peak beam power (main + prepulse)	330 TW
Hohlraum radius	0.7 cm
Target gai	82
Fusion energy Yield	560 MJ
Peak beam intensity	54 TW/cm^2

STATUS OF R&D RESULTS

In the second part of this paper we analyze the present status of light ion beam reactors and compare it with the actual state of the art in driver technology, diode technology as well as experimental and theoretical results for target physics.

Driver Modules

The LIBRA-SP accelerator modules are based on the same successful technology used for the HERMES III and SABRE accelerators in Sandia, and for the KALIF-HELIA-facility at Karlsruhe as well.

This technology couples a self-magnetically insulated transmission line (MITL) with the induction linac technology. By this technique the voltage pulses from separate inductively insulated pulseforming lines are added on a coaxial vacuum line. The outer conductor of this line is formed by the inner bore of induction cells filled with laminated ferromagnetic cores. The central conductor of this line extends along the entire length of all induction cells. The voltage pulses reach the vacuum line through annular feed gaps between the cells. They propagate down the line and superpose to a pulse whose amplitude is proportional to the number of cells. This pulse can be coupled into single or two-stage ion diodes and converted into an intense ion beam.

To extract an ion beam from the accelerator the inner conductor of the vacuum line must be operated in positive polarity. In this configuration the magnetically insulated electron flow in the line is rather complex. Nevertheless experimental experience on HERMES III and Sabre has shown that the magnetically insulated voltage adder can operate with efficiencies of more than 80% [6].

In Table III the main data of a LIBRA driver module are compared to those of existing machines like HERMES III and KALIF-HELIA. It is evident that both, the electrical power and the pulse energy of HERMES III are similar to those of the main pulse beam lines of LIBRA-SP, while the electrical parameters of KALIF-HELIA are in the same class as those of the prepulse beam lines.

Table III. Comparison of LIBRA-SP driver Modules with Hermes III and KALIF-HELIA

Parameter	LIBRA-SP		Hermes III	KALIF-HELIA
	Prepulse	Main pulse		
Voltage at diodes [MV]	30	30	22	6
Number of 1 MV cavities	30	30	20	6
Current at diodes [kA]	93	463	730	400
Electrical power (1 beam) [TW]	2.8	14	16	2.4
Pulse width at diode [ns]	40	40	26	50
Polarity	+	+	- (+)	+
Energy into diode [kJ]	120	500	400	100
Type of diode	two-stage Li^+	two-stage Li^+	one-stage electron	one-stage and two-stage H^+ and Li^+

The successfull operation of the RHEPP facility [7], which is based on the same technology, has demonstrated that repetitive operation of pulsed power generators can be achieved with high voltage alternators, step-up transformers and pulse compression with magnetic saturable core switches in the charging circuit. A necessary prerequisite for long lifetime repetitive operation is to eliminate all spark gap switches in the machine by magnetic - or some other type of nonwearing-switches (semiconductor switches). This also has the advantage to increase the efficiency of the generator from typically 40-50% with spark gaps to more than 80% with magnetic switches.

Summarizing, high power pulse generators with 3-4 Hz repetition rate complying with the requirements for ICF-driver modules can be built with present day technology.

Extraction Ion Diodes

The conclusion of the last paragraph cannot be drawn for ion beam production. With respect to ICF reactor applications the main issue is to develop a technology that allows repetitive diode operation together with sufficiently small beam divergence. Presently both requirements are attacked independently. Although this may be reasonable for a single shot ignition facility and for other industrial applications of ion beams, a unified approach is necessary for an ICF reactor ion diode.

The lowest measured ion beam divergene from single stage diodes is around 17 mrad [8]. Until today two-stage diodes have mainly been operated on rather low power machines [9,10]. In these experiments values as low as 10 mrad have been found. For reactor applications less than 5 mrad are needed while 10 mrad maybe sufficient for an ignition facility. A prerequisite for divergence reduction is to identify the main sources, and to understand their origin and their dependence on important parameters like current density, voltage, magnetic field, ion mass etc. A large experimental and theoretical effort is presently underway in several laboratories to accomplish this task.

So far two main sources of beam divergence have been identified inside the diode accelerating gap: inhomogeneities and surface roughness of the anode plasma which delivers the ion beam and instabilities of the free electron sheath containing the virtual cathode. While the first source can be mitigated by improved anode plasma production it is not yet clear whether the most damaging electron sheath instabilities can be suppressed. Although reliable scaling laws are not yet available, it seems obvious that the effect of instabilities decreases with decreasing current density, and increasing voltage and ion mass. The advent of new high voltage accelerators like PBFA-X, KALIF-HELIA and Sabre shall accelerate the determination of the required scaling laws.

In addition it will become possible to investigate two-stage diodes on higher power machines. Two-stage diodes allow an independent control of voltage and current and much stiffer diode impedances are predicted. This kind of impedance behavior is necessary if beam bunching shall be utilized to increase the power density on target. However, the largest potential of two-stage diodes in reducing the beam divergence is probably given by post acceleration. 3-dimensional particle in cell code simulations have shown that the ion divergence scales with the injected current density [11,12]. If the current density is kept close to the value at which the formation of a virtual anode occurs only longitudinal velocity is added to the ions in the second stage and thus their divergence is reduced. Since the physics of the second acceleration stage is even more complex than that of the first, an experimental verification of the predicted results on high power machines seems necessary. Generally it appears desirable to increase the particle energy and mass of light ion driver beams.

Although the voltage adder technique may allow accelerating voltages of up to 60 MV single stage acceleration looks completely unrealistic at these voltages. It would require very large insulating magnetic fields, exceeding the yield strength of any coil material. If a two-stage scheme is used high particle energies are easier to realize. Utilizing charge stripping between the stages high particle energies can be achieved with much lower voltage pulses. E.g. connecting two 10 MV accelerating stages by a stripping cell 40 MeV $Li3^+$ ions can be produced.

Although a repetition rate capability is not necessary for a single shot ignition facility, it needs to be developed for a reactor diode. A good starting point for this development is the MAP-diode [13]. However, a strong increase in current density and a drastic reduction of beam divergence is necessary before this diode satisfies the requirements for a reactor driver. Therefore, other schemes should be considered.

Summarizing it is very likely that the big experimental and theoretical effort to understand the physics of the accelerating gap in high power ion diodes will lead to a beam divergence reduction compatible with the requirements for an ignition facility. Two-stage ion acceleration has an even larger potential to improve the beam quality. However, more experimental results from high power accelerators are needed. The development of ion diodes with repetition rate capabilities is still in its infancy. New schemes that do not sacrifice the beam quality have to be created.

Beam Transport

Several different transport schemes have been considered for light ion beam driven reactors. The most promising among these are ballistic transport combined with solenoidal focusing [2, 14] and self-pinched transport [3]. In the first scheme a background gas provides charge and current neutralization. The gas pressure must also be chosen to prevent excessive small angle scattering and energy loss and to avoid the occurence of filamentation instabilities. If 30-40 MeV $Li3^+$ ions are considered about 100 Pascal of helium gas pressure complies with these requirements. A disadvantage of this approach is that the solenoidal lens must still be rather close to the target and therefore, will be exposed to a large neutron and soft X-ray radiation flux.

No transport apparatus in the reactor chamber is required for the self-pinched transport scheme. Since it would allow small holes in the chamber wall and thus easy protection of the diode hardware it is considered as the most preferable concept for high yield repetitive target ignition. Self-pinched transport requires a low pressure ±10 Pascal gas background in the chamber. A net electrical current

$$I_{net} = 0.5\left(\frac{R_o}{r_f}\right)^2 \Theta_m^2 I_A$$

is needed to trap the ion beam. (I_A = Alfve'n current, R_o = radius of the beam envelope, r_f = focal spot size, θ_m= beam microdivergence). The details of this transport scheme have not yet been studied adequately. The key issue is the gas breakdown process, which occurs at the head of the beam. If the breakdown process occurs too fast the net current frozen in the plasma may become too small to confine the beam. Theoretical modeling suggests that fast electrons with mean free path greater than the beam radius produce non-local breakdown effects which may influence the net current amplitude [15].

Summarizing, both transport schemes need further theoretical and experimental investigations. This is especially true for the self-pinched transport, where very little experimental work has been done.

Target Physics

The concept of the foam filled light ion driven hohlraum target shown in Fig. 3 is probably one of the most attractive target designs. It takes advantage from the proper range of 30 MeV Li-ions, which is large enough to penetrate the hohlraum wall, yet short enough to be completely stopped in the foam. This target concept avoids some of the nonsymmetry problems resulting from rather localized converters and therefore does not need any shims to smooth the radiation. In addition the foam filled hohlraum reduces the hydrodynamic inward motion of the hohlraum wall.

Conversion of light ion beam energy into a soft X-ray radiation field has been carried out with foam filled hohlraum capsules at specific power depositions around 1000 TW/g on PBFA II [16]. In these experiments hohlraum temperatures around 60 eV have been achieved and it has been shown that a transparent hohlraum fill was created. Also another basic LIF target concept has been investigated: Internal pulse shaping using shells of BeO and Be was demonstrated in laser driven hohlraums [16].

The target experiments on PBFA II with specific power depositions above 1000 TW/g allow to study the physics in the prepulse of an ignition target. Besides this several other issues of ICF targets can be studied at even lower power densities around 200 TW/g attainable on KALIF and comparable generators of the 1 TW class. Target layers have been accelerated to approximately 1/10 of the implosion velocity necessary to ignite a target [17]. We have started in our own laboratory to study the hydrodynamic stability of perturbed accelerated foil targets. In addition from these target experiments fundamental quantities of intense ion beam target interaction like specific energy loss, ion range, eos data, opacities, and soft X-ray conversion efficiency can be determined.

Summarizing, a very attractive target concept has been developed for LICF. Fundamentals of this target concept have been verified experimentally. The presently achieved power density in the focus of intense light ion beams is sufficient to study several quantities that are important for ICF.

CONCLUSIONS

We have compared the requirements for a light ion beam driven inertial confinement fusion reactor with the present achievements in pulsed power technology, ion diode performance, beam transport and target physics. It is obvious, that the largest technological gap still exists in the production of high quality (low divergence) intense ion beams. Therefore, a continued strong research effort is necessary to solve this issue. A large potential lies in the utilization of two-stage acceleration. Using this potential and improving our knowledge about the physics of the diode accelerating gap will very likely lead to beam qualities matching the requirements for an ignition facility. Besides beam quality, repetition rate capability is the next big issue of ion diode development. Although not necessary for a single shot ignition facility, new schemes should be investigated as early as possible. Here the main problem is not to loose beam quality in return.

After the diode issues the second largest needs for development are in the beam transport. Especially, the self-pinched propagation scheme requires further experimental and theoretical investigations.

In contrast to the diode and transport problems the achievements in driver technology and target design look very mature. Suitable pulse power generators with repetition rate capability (3-4 Hz) can be built based on available technology. In addition some ion beam-target interaction experiments with relevance to ICF targets can be carried out with presently achievable beam intensities.

The large research and development effort that is still needed to match the requirements for light ion beam driven ICF seems justified by two potential advantages of the light ion approach:

1. Its outstanding low costs and high efficiencies;
2. The prospect that this technique is likely to meet the requirements for a high gain ignition facility, which then could be built at affordable costs.

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