The Promise of Self-Pinched Beam Propagation to Light Ion Fusion Reactors

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FUSION TECHNOLOGY INSTITUTE

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1. Introduction

Light Ion Fusion (LIF) is an approach to electrical power production that uses intense beams of low atomic number ions to drive inertial fusion targets to ignition. Perhaps the most difficult and least understood aspect of LIF is the transport of the beam from high voltage diodes to the target. Two transport schemes have been considered in two previous reactor designs: LIBRA [1] used pre-formed plasma channels, and LIBRA-LiTE [2] used neutralized ballistic ion transport with focusing lens magnets. A new conceptual design, LIBRA-S, would use self-pinched transport.

The purpose of this report is to quantify some of the potential advantages of self-pinched propagation by comparing LIBRA-S with LIBRA-LiTE and LIBRA. The details of the LIBRA-S design have not been worked out, so we have projected from our experience with LIBRA and LIBRA-LiTE. We have compared the three designs on the basis on overall parameters, including cost.

We begin by discussing the three transport schemes. Then we discuss the LIBRA reactor designs and compare them. We conclude by remarking on the potential advantages of self-pinched transport in light ion fusion reactors.

2. Ion Beam Propagation Schemes

Channel transport is depicted in Fig. 1. In this scheme, plasma discharges are formed in the target chamber fill gas along paths between ion diodes and targets with pre-ionizing lasers. One or more discharge current paths must be pre-ionized to complete the discharge circuits. Discharge currents flow from anodes at the entrance of the channels near the focus of the diodes, to a point near the target where the beams begin to overlap, through these current return paths, to cathodes. The current is mostly due to electrons that are flowing the direction opposed to the current flow. The discharge current should not heat the target, so the current return path must intersect the channels near before they reach the target. The discharge current creates azimuthal magnetic fields that confine the beam ions to a channel. In this manner, ions can be transported over a long distance even if the beam microdivergence is large. Microdivergence only plays a role in determining the spot size at which ions from the diode are focused onto the entrance to the channel and expansion of the beam as it leaves the channel in the overlap region. Propagation in plasma channels has been demonstrated experimentally [3] and has been studied theoretically [4]. Plasma channel transport has the advantages that

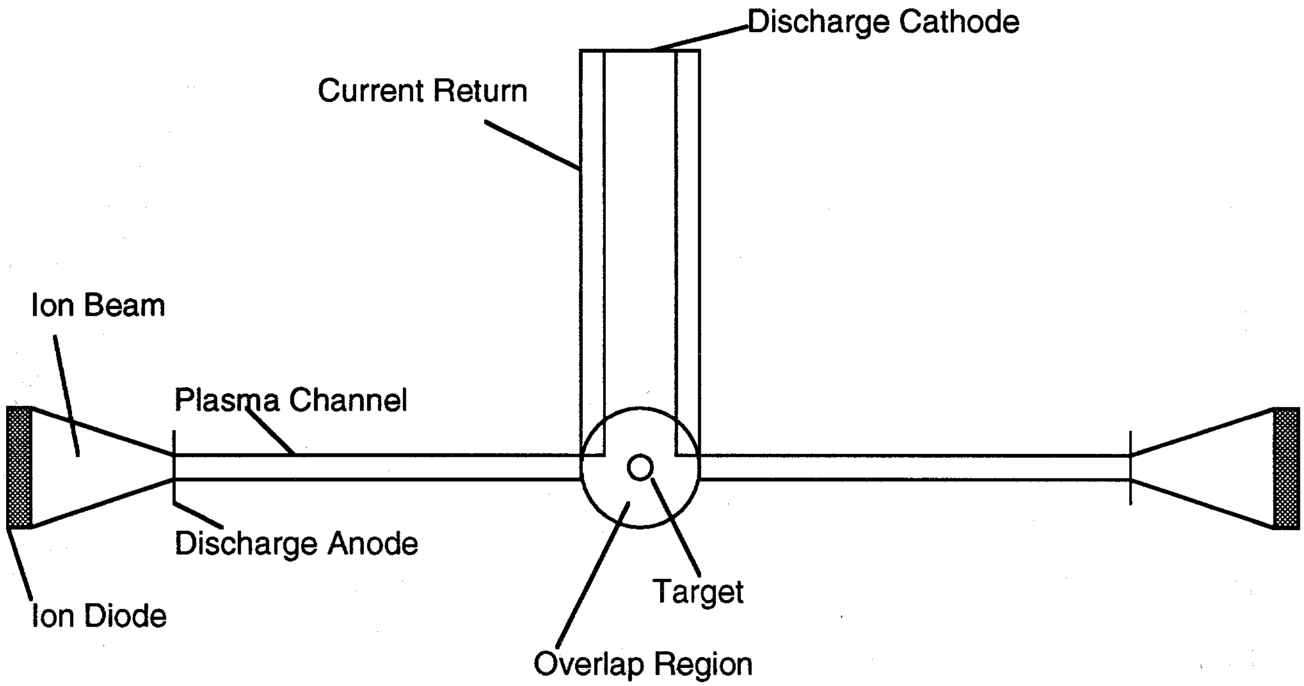

Figure 1. Plasma channel transport.

ions are confined to channels over a long distance, no structures are required close to the target, and the channels are formed in dense enough gases to protect the target chamber from the direct effects of the target explosions. The disadvantages of the plasma channel approach are that a large discharge voltage is require to form the channels fast enough to avoid MHD instabilities, that the radial size of the channels has a minimum set by channel physics, and that inductive effects limit the beam transport efficiency. In the LIBRA design, the discharge voltage is so high that solenoidal magnets are placed around the channels when they pass through the target chamber wall and blanket to slow the breakdown to these structures. The outstanding issues for channel transport include an understanding of this magnetic insulation approach, the behavior of the overlap region, beam ion energy loss in the channels, trapping of the ion beams from the diodes into the channel entrances, and mechanisms such as radiation transport that are responsible for the plasma channel radius. Also, all of the issues affecting ballistic neutralized transport play a role in the transport between the diode and the entrances of the channels.

Ballistic neutralized transport uses solenoidal focusing lens magnets to direct the beams onto the targets. Ballistic neutralized transport is depicted in Fig. 2. In this scheme, the beam ions drift from the ion diodes to the focusing lens magnets in a neutralized beam. The size of the diodes, the transport length and the divergence of the beam determine the bore of the magnets. In the magnets, the ion directions are

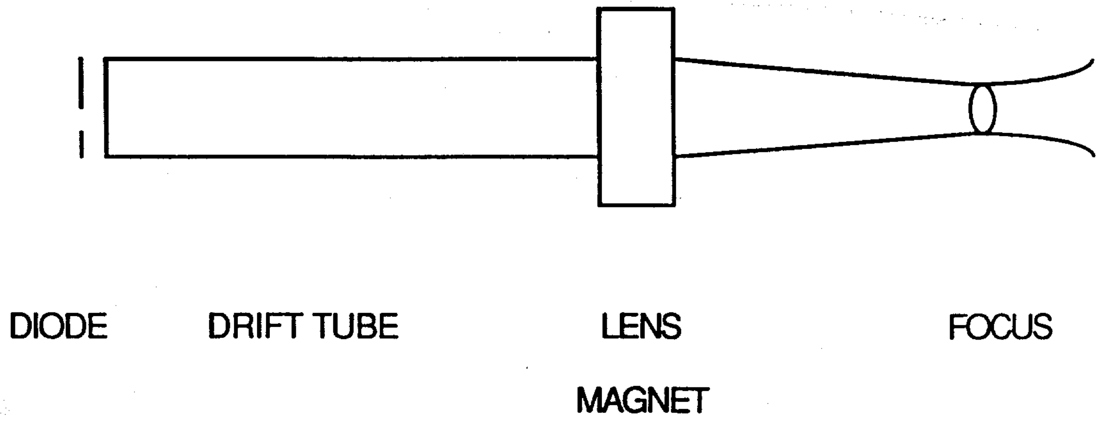

Figure 2. Ballistic neutralized transport.

changed, directing the ions onto the target. While the ions are in the magnets, the beam may temporarily lose neutrality, possibly affecting the transport. Between the magnets and the target, the beam is once again neutralized. The focal spot size of the beam on the target is determined by the scattering that the beam endures in its transit between the magnet and the target, the distance between the magnet and the target, and the divergence of the beam as it leaves the magnet. Since the target requires a given beam intensity to ignite, reducing the focal spot size reduces the driver energy and the cost of the driver. But to get the spot size small, a small distance between the target and the magnets and a small beam microdivergence are required. The trade-off between microdivergence and magnet position is shown in Fig. 3 for a given focal spot radius for LIBRA-LiTE conditions [2]. The neutron damage rate in the magnets is also shown. With a typical neutron damage lifetime for steel being 150 dpa, one can see that the magnets will last 0.75 full power years. That the magnets are so close to the target that they must be replaced frequently is one of the disadvantages of ballistic neutralized transport. Another disadvantage is the low microdivergence, which might be hard to achieve. Also, the avoidance of excessive scattering requires that the target chamber fill gas is of such a low density that it can not protect the magnets and target chamber from target explosions. The advantage of ballistic transport is that it is most like the transport schemes that are used on current or near term experiments and, therefore, is probably the best understood. Understanding neutralization of the beam by the chamber gas and

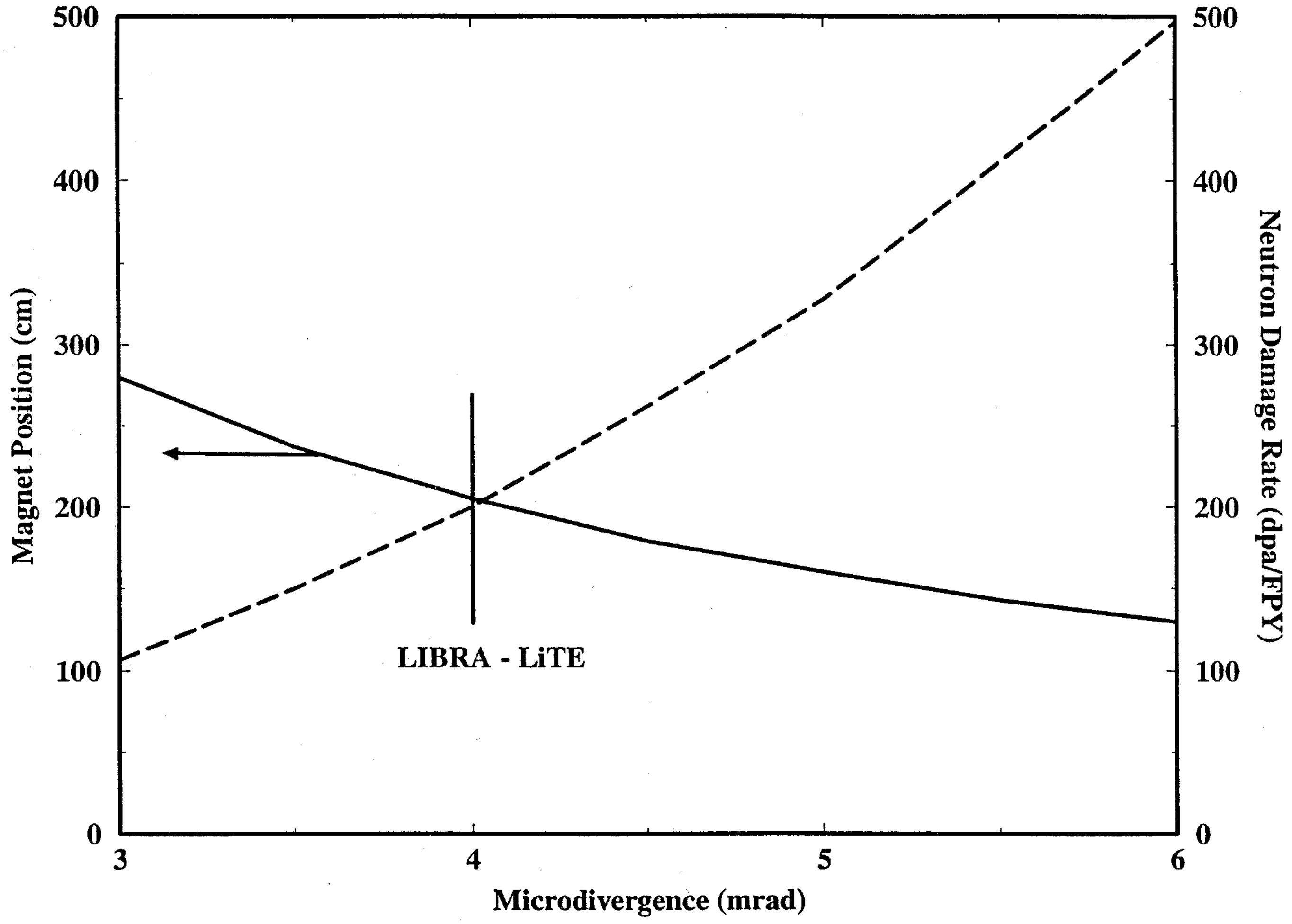

Figure 3. Magnet position and neutron damage rate in the magnets for LIBRA-LiTE conditions versus microdivergence leaving the diode.

the behavior of the beam in the magnets are two important physics issues that remain to be solved.

Self-pinched propagation is a much less well-understood process than either channel or ballistic transport. A laser would likely be used to pre-ionize a path to guide the beam. The beam and chamber fill gas parameters would be chosen so that the beam is 90% to 95% current neutralized. The remaining beam current will form an azimuthal magnetic field that confines the beam. The advantages of this scheme are:

- no structures like magnets in the target chamber
- no large discharge voltages
- potentially high transport efficiencies.

For the purpose of this study, the transport efficiency is assumed to be 75%, 90% or 95%. The major physics issue for self-pinched transport is the neutralization of the beam. Both computer simulations and experiments are needed to resolve this issue.

3. The LIBRA Reactors

The three transport schemes have been incorporated in two completed reactor designs and one ongoing design. Parts of these designs not related to the transport are all based on the original LIBRA conceptual design, which used channel transport. The essential common features of the LIBRA designs are:

- **Pulsed Power**. The energy is supplied to the diodes by HERMES-III type pulsed power modules, one module for each diode. This technology uses a series of metglass induction cores to add the voltage from many water filled pulse shaping lines.
- **Target Performance**. The target yield, required beam symmetry, energy and power on target are provided by Sandia National Laboratories.
- **Target Explosion**. The spectra of target x rays, debris ions and neutrons are all scaled from work done at the University of Wisconsin for heavy ion fusion targets [5]. It has been assumed that the target emanations for light ion targets are the same as for heavy ion targets.
- **Target Chamber**. The target chamber design for all three concepts uses porous woven tubes coated and filled with liquid metal to protect the surface from target x rays and ions. The target chamber design for LIBRA is shown in Fig. 4 and for LIBRA-LiTE in Fig. 5, where one can see these INPORT tubes on the sides of the chambers.

There are differences between the designs brought on by the differences in transport methods. Because scattering is worse for high atomic number atoms, lithium is used in LIBRA-LiTE to coat and cool the INPORT tubes instead of $Pb_{83}Li_{17}$, which is used in LIBRA. Lithium is more reactive than is $Pb_{83}Li_{17}$, which makes LIBRA somewhat safer. $Pb_{83}Li_{17}$ allows the use of INPORT tubes made of SiC, which was thought to have high resistance to neutron damage. The use of $Pb_{83}Li_{17}$ and SiC limited the lithium coolant temperature to 500 C to avoid corrosion. This leads to a thermal efficiency for

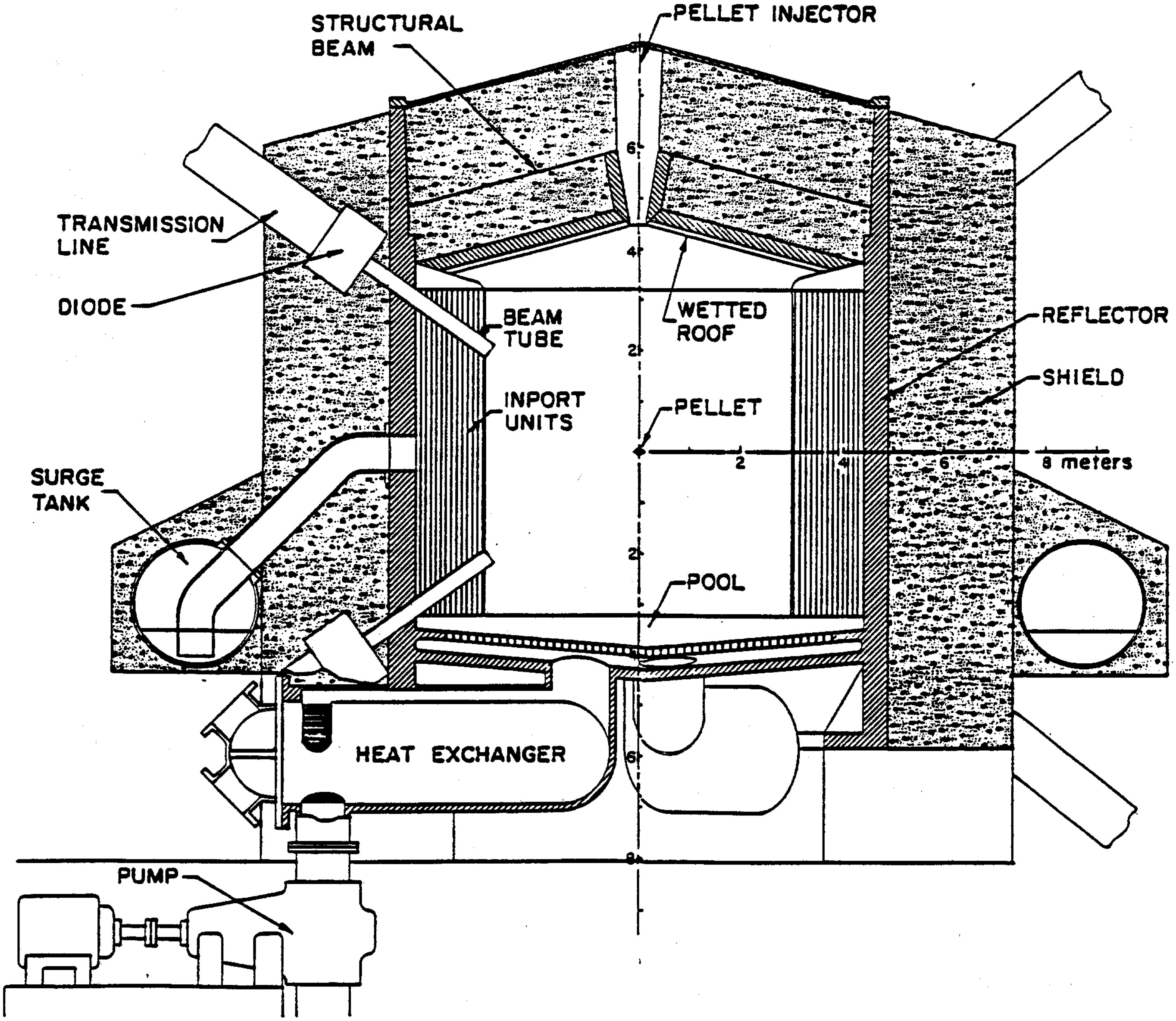

Figure 4. LIBRA target chamber.

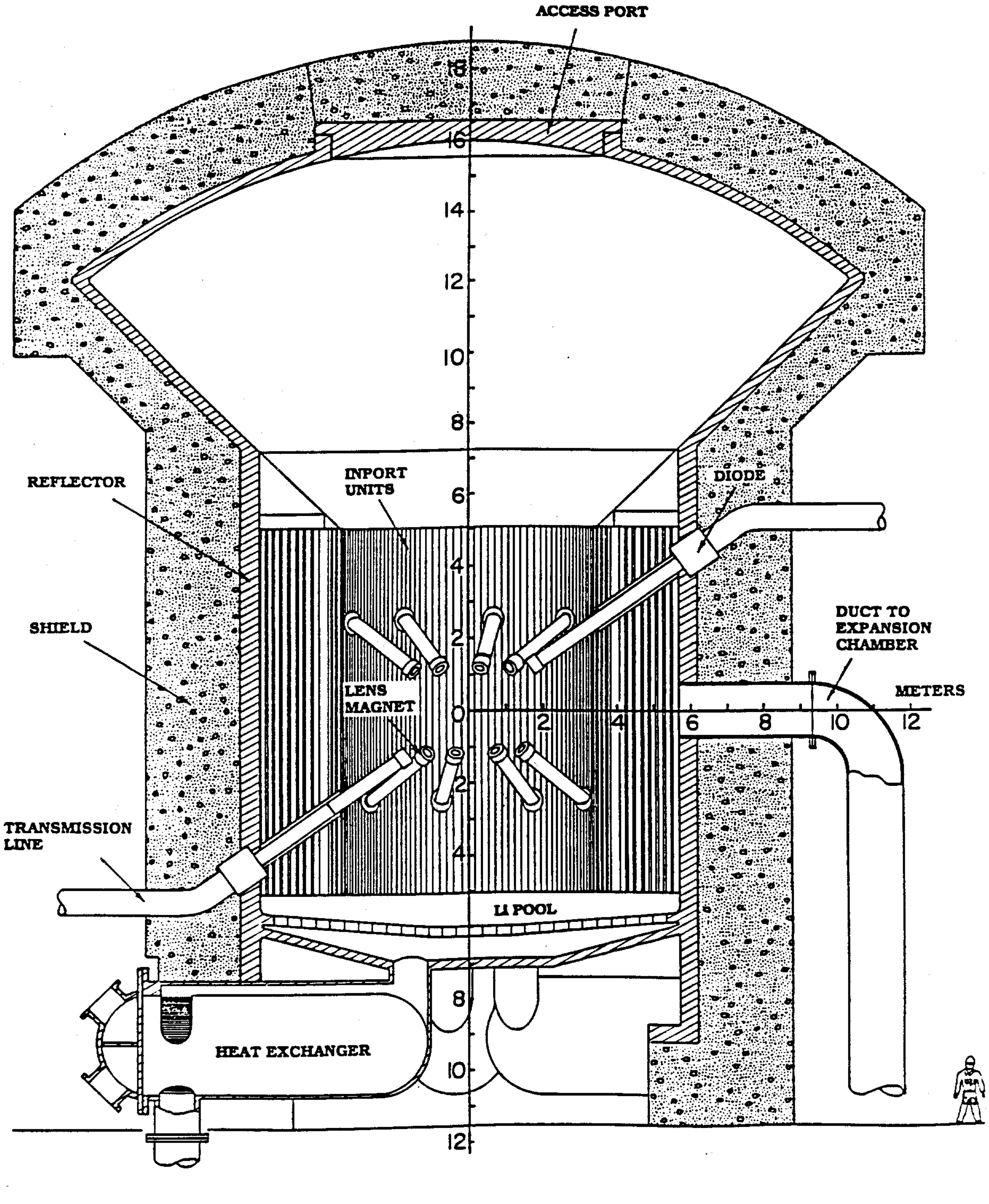

Figure 5. LIBRA-LiTE target chamber.

generating electricity for LIBRA of 38%, when the secondary coolant is helium. LIBRA-LiTE used INPORTs made of steel to avoid the rapid corrosion of SiC by lithium. This allowed a coolant temperature of 525 C and a thermal efficiency of 44% for a secondary coolant of $Pb_{83}Li_{17}$. In both LIBRA and LIBRA-LiTE the secondary coolants were chosen to reduce tritium permeation and improve safety. $Pb_{83}Li_{17}$ and lithium also lead to different neutron energy multiplications, with LIBRA having 1.28 and LIBRA-LiTE, 1.21. As seen from Figs. 4 and 5, LIBRA and LIBRA-LiTE have different roof designs. LIBRA-LiTE had the roof removed to a distance (16 m) where it will survive neutron, x-ray, and debris ion damage without any protection. The target chamber roof in LIBRA is protected by fabric panels coated and filled with $Pb_{83}Li_{17}$ and is much closer to the target. LIBRA and LIBRA-LiTE used single stage applied magnetic field extractor diodes, for which we have assumed an efficiency of conversion in beam energy of 80%.

The details of the reactor design for LIBRA-S, the version using self-pinched transport, have not been decided upon. In this report, we have assumed that the INPORTs in LIBRA-S are covered and filled with lithium and that LIBRA-S has the same thermal efficiency as LIBRA-LiTE. It would also have the same neutron energy multiplication as LIBRA-LiTE. The roof is as in LIBRA-LiTE. The diodes for LIBRA-S are two-stage applied magnetic field extractor diodes, for which we assume 90% efficiency. We have not currently designed the laser system that might be needed to guide the self-pinched beams and we have ignored the laser system in the power balance.

4. Comparison of Three LIBRA Reactor Concepts

We have compared LIBRA, LIBRA-LiTE, and three versions of LIBRA-S on the basis of the basic parameters, efficiencies and cost. The comparison is shown in Table 1. LIBRA-L is short for LIBRA-LiTE and S-1, S-2, and S-3 are the three versions of LIBRA-S. The propagation schemes are denoted as C (channel), B (ballistic), and S-P (self-pinched). The direct driver cost is scaled from LIBRA-LiTE on the basis of energy supplied to the diodes and repetition rate:

$$\text{Driver Direct Cost} = (357 + (4.49\,\text{RR}))(\text{E}_{\text{on diodes}}/8.33)^{0.8} \tag{1}$$

The non-driver portion of the total direct cost is scaled from LIBRA-LiTE on the basis of thermal power. The total direct cost is

$$\text{Total Direct Cost} = \text{Driver Direct Cost} + (0.4729\,\text{Thermal Power})\,. \tag{2}$$

These costs are in millions of 1993 dollars, $E_{\text{on diodes}}$ is the pulsed power energy into the diodes in MJ, and the thermal power is in MW. RR is the rep rate in Hz. The unit direct cost is the total direct cost divided by the net electrical power.

5. Conclusions

The comparison in Table 1 shows that LIBRA-S should have significant cost advantages over LIBRA and LIBRA-LiTE. The increased transport efficiency and diode efficiency and the removal of magnet power have resulted in a much smaller recirculating power fraction for all three versions of LIBRA-S. There is only a small increase in the recirculating power fraction of LIBRA-S as the transport efficiency changes from 95% to 70%. There are much lower driver energies and driver costs for the LIBRA-S designs, which are related to the recirculating power fraction. Finally, the unit direct costs for LIBRA-S are much lower than for LIBRA and LIBRA-LiTE. Once again, there is only a small change in the unit direct cost as the transport efficiency is reduced from 95% to 70%.

Therefore, the combination of a two-stage diode and self-pinched transport can lead to a significant improvement in the design of light ion beam reactors. Multi-stage diodes are currently being studied experimentally [6], and have been shown to have good efficiency. Self-pinched propagation is not well studied, and is therefore still speculative. This study shows that the potential exists that self-pinched propagation will lead to better light ion beam reactor designs.

Acknowledgement

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Table 1. Comparison of LIBRA Power Plants

Parameter	Units	LIBRA	LIBRA-L	S-1	S-2	S-3
Net electrical power	MWe	331	978	1077	1073	1058
Ion beam transport		C	B	S-P	S-P	S-P
Number of beams		18	30	30	30	30
Energy on target	MJ	4	6	6	6	6
Target gain		80	100	100	100	100
Target yield	MJ	320	600	600	600	600
Rep rate	Hz	3	3.9	3.9	3.9	3.9
Fusion power	MW	960	2340	2340	2340	2340
Fusion neutron power	MW	653	1591	1591	1591	1591
Energy multiplication		1.28	1.21	1.21	1.21	1.21
Total neutron power	MW	836	1927	1927	1927	1927
X-ray and ion power	MW	286	697	697	697	697
Gamma power	MW	2.78	6.79	6.79	6.79	6.79
Recirc. power	MW	37	89	13.5	13.5	13.5
Thermal power	MW	1162	2720	2646	2646	2646
Thermal efficiency	%	38	44	44	44	44
Gross electric power	MWe	442	1197	1164	1164	1164
Driver efficiency	%	49	38	38	38	38
Prime energy storage	MJ	17.0	33.2	18.7	19.7	23.6
Diode stages		1	1	2	2	2
Diode efficiency	%	80	80	90	90	90
Energy into diode	MJ	8.3	12.5	7.0	7.4	8.9
Transport efficiency	%	60	60	95	90	75
Energy into beam	MJ	6.7	10.0	6.32	6.7	8.0
Net driver efficiency	%	23.5	18.0	32.1	30.5	25.4
Gain·net driver efficiency		18.8	18.0	32.1	30.5	25.4
Net efficiency	%	8.9	7.9	14.2	13.4	11.2
Gain·efficiency		7.2	7.9	14.2	13.4	11.2
Driver power	MWe	51.0	129.7	72.8	76.8	92.2
Magnet power	MWe	27	75	0	0	0
Aux. power	MWe	32	13.5	13.5	13.5	13.5
Recirc. power fraction	%	24.9	18.2	7.4	7.8	9.1
Direct driver cost	M$ (1993)	370	518	326	341	394
Total direct cost	M$ (1993)	920	1804	1577	1591	1645
Unit direct cost	$/We (1993)	2.78	1.84	1.46	1.48	1.55

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