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DESIGN OF A LIGHT-ION-BEAM DRIVER FOR THE LABORATORY MICROFUSION FACILITY*

K. R. Prestwich, J. J. Ramirez, R. W. Stinnett, D. L. Johnson, C. L. Olson, M. J. Clauser, T. A. Mehlhorn, M. P. Desjarlais, G. O. Allshouse, J. P. Corley, D. L. Hanson, M. E. Cuneo, P. F. McKay, J. W. Poukey, S. E. Rosenthal, S. A. Slutz, J. P. Quintenz, D. L. Cook, and J. P. VanDevender

Sandia National Laboratories, Albuquerque, New Mexico USA

R. Peterson, R. Engelstad, and J. W. Powers

University of Wisconsin, Madison, Wisconsin USA

Abstract. The U.S. Department of Energy has initiated planning for a Laboratory Microfusion Facility (LMF) as part of the national Inertial Confinement Fusion (ICF) program. This next major ICF facility is expected to produce a 1000-megajoule thermonuclear yield with greater than 10-megajoules of input energy to the target. As part of this initiative, we have defined a light-ion-beam LMF concept and are pursuing research on critical design issues. Details of this light-ion-beam LMF driver concept are presented together with initial results from an LMF research program aimed at a technology validation experiment on Hermes III.

I. INTRODUCTION

The Laboratory Microfusion Facility (LMF) is being designed to provide the DOE fusion community a facility to study high gain ICF targets with yields in the 200-MJ to 1000-MJ range. To satisfy this need, it is necessary to deliver >10 MJ of energy to an ICF target with the ability to vary the magnitude and the pulse shape of the deposited energy as a function of time. It is also desirable for the facility to be capable of handling 500 high energy experiments per year with a planned operating lifetime >12 years.

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The light-ion beam LMF driver will consist of multiple accelerators that can be fired sequentially to provide the desired energy, pulse-shape variability and energy deposition uniformity.[1] As presently conceived, thirty-six lithium-ion beams will be delivered to the target, as indicated in Fig. 1. The thirty-six accelerators will consist of twelve Hermes-III-sized modules that produce a 40-ns ion beam with energy ramping from 18 to 20 MeV and current from 0.46 MA to 0.72 MA, and twenty-four high-energy accelerators that will deliver a 40-ns ion-beam pulse with energy ramping from 26 MeV to 32 MeV and current from 0.8 MA to 1.2 MA. Each beam will bunch during the 4.0-m drift to the target, decreasing the pulse duration to 15 ns. These high power beams will deposit either 310 kJ or 700 kJ of energy in a 2-cm diameter target. Pulse shaping can be varied by sequentially firing the modules.

Each beam will be generated by an accelerator module similar in design to Hermes III, a 22-MV, 730-kA, 40-ns electron beam generator that successfully came on line in April 1988.[2,3] Each accelerator will power an extraction ion diode similar to the one tested at the 1-MV level on MITE and produced ion beams with greater than 70% efficiency.[4] A cross-section of the extraction ion diode is shown in Fig. 2. It produces an annular ion beam that is transported ballistically and focused onto the target, as shown in Fig. 3. During transport, a gas background provides charge and current neutralization. The diode and a 30-cm-long, solenoidal-focusing lens located 1.5 m from the target act as an achromatic-focusing system. The distance from the focusing lens to the target is determined by the beam microdivergence. The diode beam microdivergence must be less than or equal to 6 mrad to achieve the desired focusing efficiency with the solenoidal lens centered at 1.65 m. The required beam divergence scales inversely with this distance.

The extraction ion diode is shown in Fig. 2. There are several constraints on the diode geometry and performance that determine the operating parameters.

(a) Liouville's Theorem leads to the relation, $R_{diode}\,\theta_{micro} \leq R_{target}\,\theta_{incident}$, that gives a maximum diode radius of approximately 16 cm.

(b) In order to achieve the correct applied magnetic field profile, the inner and outer radii of the diode should satisfy $R_o/R_i \leq 2.0$. Taken with (a), this results in an anode emitting area of 600 cm^2.

(c) The ratio of the anode-cathode gap to anode emissionlength, $d/(R_o - R_i)$ must be small to reduce edge effects on the source and in the accelerating gap. We will assume a limit of 0.5, for a maximum gap of 4 cm. This is consistent with present experiments.

Using these constraints together with an assumed diode current and pulse length, it is possible to define a basic diode configuration and to identify several research issues that must be addressed for the LMF. Because lower impedance diodes will minimize the extrapolation from previous diode experiments, we chose an ion current of 1.2 MA per module and a pulse length of 40 ns (FWHM). This requires the driver to be capable of delivering approximately 1.4 MA to a matched load if the ion current efficiency and impedance coupling efficiency of the diode are 90% and 95% respectively. The resulting driver module parameters, assuming a driver voltage of 32 MV, are 27 Ω, 38 TW, 1.5 MJ. Our goal is to achieve 95% energy efficiency due to ion source species purity.

At 32 MV with an anode-cathode gap of 4 cm, the peak-current density will be 2 kA/cm^2, that provides the 1.2-MA current from the 600 cm^2 anode area. The critical insulating flux in the anode-cathode gap is $V = B_{crit}\, d$, where B_{crit} is the applied field in Tesla, d is the anode-cathode gap in cm, and V is the anode voltage in MV. For $V = 32$ MV, $d = 4$ cm, and assuming that the diode will operate according to diode theory in the saturated mode ($V = 0.52\, V_{crit}$), the applied field needed is $B_{crit}/0.52 = 5.1$ Tesla.

The diode (which acts as a self-field lens) and the solenoidal lens form a "two-lens" system, and the parameters are chosen to make it achromatic.[5] For a diode with initial operating characteristics at voltage V_o and current I_o, we consider small changes from V_o, I_o as

$$V/V_o = 1 + \alpha \qquad (\alpha << 1) \tag{1}$$

$$I/I_o = (V/V_o)^k \qquad (k \approx 2.2) \; . \tag{2}$$

This I, V relationship is consistent with recent advances in diode theory.[6,7] As in Fig. 4, we consider an annular beam with outer radius r_o and inner radius r_{in}. The self field bending angle in the diode θ_d at t = o is coupled accurately with the diode shape to provide a beam parallel to the diode axis. Then as the voltage increases above V_o, the beam will focus inward with a bending angle $\Delta\theta_d$ given by

$$\Delta\theta_d = (I_o d/cr_o)[2\ Z_d\ e/(AV_oM_pc^2)]^{1/2}(k - 1/2)\ \alpha \tag{3}$$

$$\cdot(r_o/r)(r^2 - r_{in}^2)/(r_o^2 - r_{in}^2) \; ,$$

where d is the distance over which the beam self field bends the beam trajectories, Z_d is the ion charge state in the diode, A is the ion atomic number, and M is the proton rest mass. On leaving the diode, the beam drifts a distance L to the solenoid lens. The trajectory bending angle at the solenoid, θ_1, is given by

$$\theta_1 = \left[(Z_1^2\ B_Z^2\ r_o Le)/(8AZ_d V_o M_p c^2)\right](1 - \alpha)(r/r_o) \; . \tag{4}$$

By choosing

$$(I_o d/cr_o)\ [2\ Z_d e\ /\ (A\ V_o\ M_p\ c^2)]^{1/2}\ (k - 1/2) =$$

$$\left[Z_1^2\ B_Z^2\ r_o Le/(8AZ_d V_o M_p c^2)\right] \; , \tag{5}$$

the system is achromatic to lowest order in α. The radial miss distance at the target location a distance F past the lens is then given by

$$\Delta r = r_o \alpha^2 (L/F) \quad . \tag{6}$$

Energy loss and beam loss mechanisms for the "two-lens" system include: (1) E & B fields due to inadequate charge and current neutralization, (2) $d\varepsilon/dx$ (stopping power), (3) scattering, (4) E_z driving return current, and (5) instabilities (e.g., filamentation and ion-electron, two-stream instability). The gas pressure must be chosen high enough to provide good neutralization and a high plasma conductivity: this will minimize the effects of (1), (4), and (5). On the other hand, the gas pressure must be chosen low enough to minimize losses due to (2) and (3). From analytic and code calculations, we conclude that 1 Torr of helium will satisfy these constraints.

For 1-Torr helium, the x rays from the thermonuclear explosion are transported to the experiment chamber wall with negligible absorption in the gas. A radiation shield will protect the structural wall, but calculations with the Conrad code indicate that with a 1-gigajoule pellet yield, about 1 kg of material is vaporized and removed from this shield, resulting in a shock overpressure of 75 GPa.[8] This overpressure must be reduced to 0.2 GPa at the structural wall for an acceptable long-life chamber design. Several techniques to reduce this overpressure are being evaluated. If the overpressure can be reduced, preliminary assessment of the response of the wall to the overpressure, and wall fatigue analysis, indicate a 1.5-m-radius chamber should be feasible.

Alternate beam transport schemes that use channels are also being investigated. Channel schemes allow higher pressures and a larger target chamber. In these schemes, the extraction ion diode is designed to focus the beam to the channel entrance that is located about 1 m from the diode. The beam is contained and guided along the path from this point to the target with a magnetic field from a current-carrying wire or discharge channel. Wall-confined, Z-discharges or free-standing discharges are both potential candidates. Results from analytic studies and previous experiments conclude that the diode microdivergence must also be about 6 mrad for these transport schemes.

The channel transport schemes allow chamber pressures as high as 100 Torr of nitrogen. This gas absorbs the x rays and debris from the thermonuclear explosion setting up a fireball that transfers energy to the structural wall on a much slower time scale. Studies indicate the 3-m radius chambers can handle 800-MJ explosions at a much higher rate that is required for LMF and have a thirty-year lifetime.[9] Additional analysis of this system was also carried out as part of the LIBRA Reactor Study.[10]

Research on positive polarity LMF MITLs has been initiated. When an MITL adder is designed to supply power to an extraction ion diode, the center electrode in the MITL is positive. Code calculations and analytic theory indicate that sheath electrons are constrained by many discreet equipotential lines, depending on where along the adder that they are emitted.[11,12,13] Those electrons emitted at the low voltage end of the accelerator are trapped near the anode, and those near the high voltage end are trapped near the cathode. The theory further indicates that this spatial distribution of electrons results in a much larger ratio of sheath to bound current than in ordinary MITL flow. The impact of this distribution of electrons on the ability to efficiently couple energy flowing from the MITL into an extraction ion diode is being assessed.

Initial positive polarity experiments on Hermes III indicated the MITL adder was functioning in a similar manner to the negative adder case.[1,14] The peak current was maintained throughout the system without substantial electron loss, and the peak output voltage of 18 MV was measured. The Hermes-III data and similar results on HELIA at ~3 MV are very encouraging with regard to the prospects of efficient positive polarity MITL adder operation, but the observed performance is not fully explained at this time. An initial set of experiments were performed on HELIA, where an extraction ion diode was powered by the output from HELIA, operating with a positive polarity MITL adder. Preliminary results indicate that the power delivered by the adder was efficiently coupled to the load. The observed diode behavior was very similar to that of other experiments where the diode was powered by a conventional MITL flow. In the HELIA experiments, enhanced ion-flow conditions were reached earlier in the pulse than was the case for previous ion-diode experiments. This behavior is important in order to efficiently couple energy into the diode load. MITL experiments will continue on SABRE, a 10-MV upgrade of HELIA and on Hermes III, and the results will be coupled with a thorough theoretical analysis to understand the sheath and bound current in the positive polarity MITL adder.

Although the extraction Applied-B ion diodes that are needed for LMF have many features in common with diodes developed on Proto I, Proto II, PBFA I, and PBFA II, they have some distinguishing features. The operating impedance of the LMF diode, 25-32 ohms, is much higher than that at which other high power diodes have been tested. The LMF diode voltage, 26-32 MV, is well beyond the existing experimental data base and will require the use of larger anode-cathode gaps and higher insulating magnetic fields than are presently used.

Initial experiments using an extraction Applied-B diode on HELIA at 3 MV, 16 Ω indicate that the diode can operate reasonably efficiently (>70%) with a rapid (<5 ns) transition to high ion current densities. This confirms other results on the MITE (SNL)[4] and LION (Cornell University Laboratory of Plasma Studies)[15] accelerators that indicate that extraction ion diodes can be efficient and perform according to the recently developed theory of Applied-B ion diodes.[6,7]

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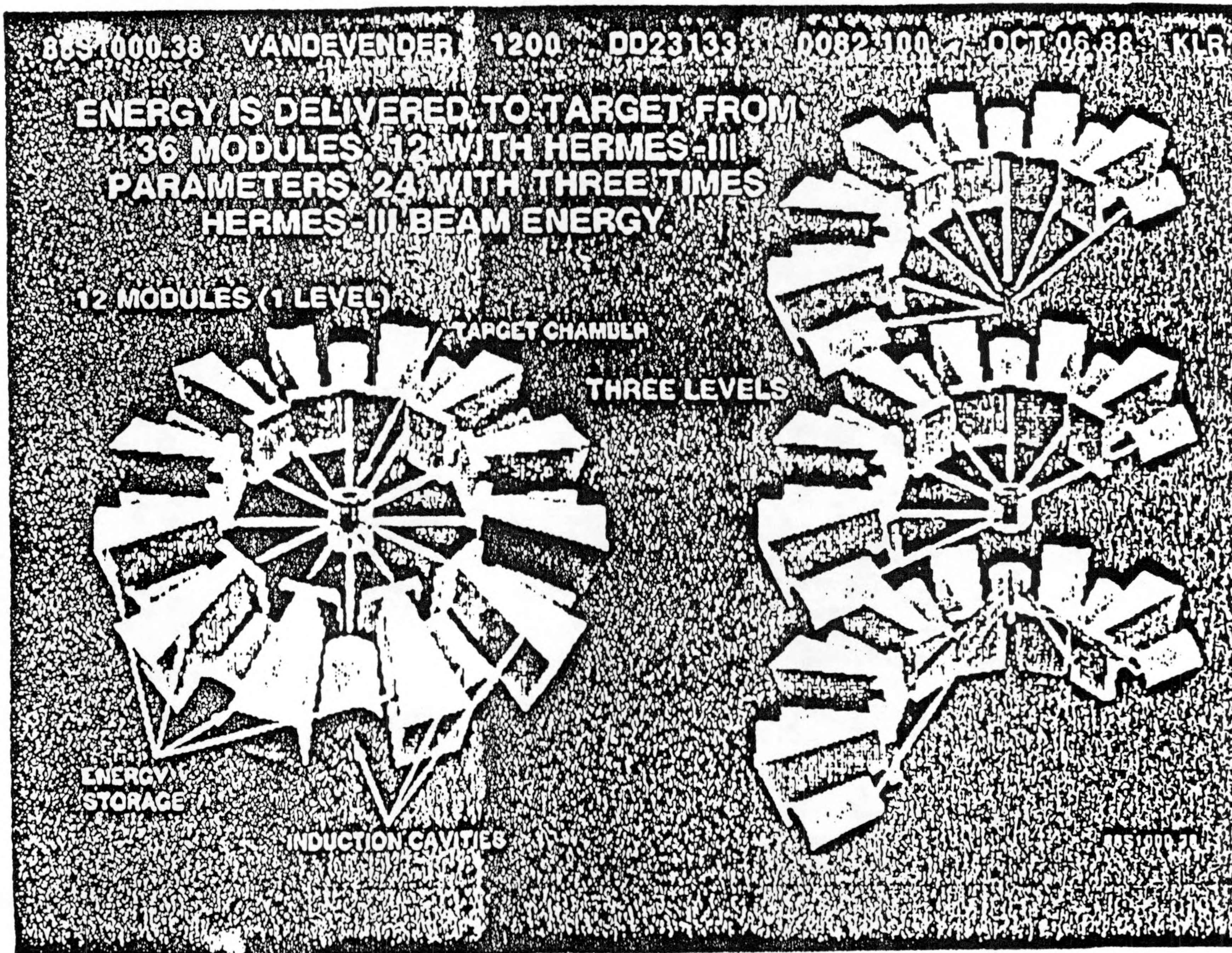
FIGURES

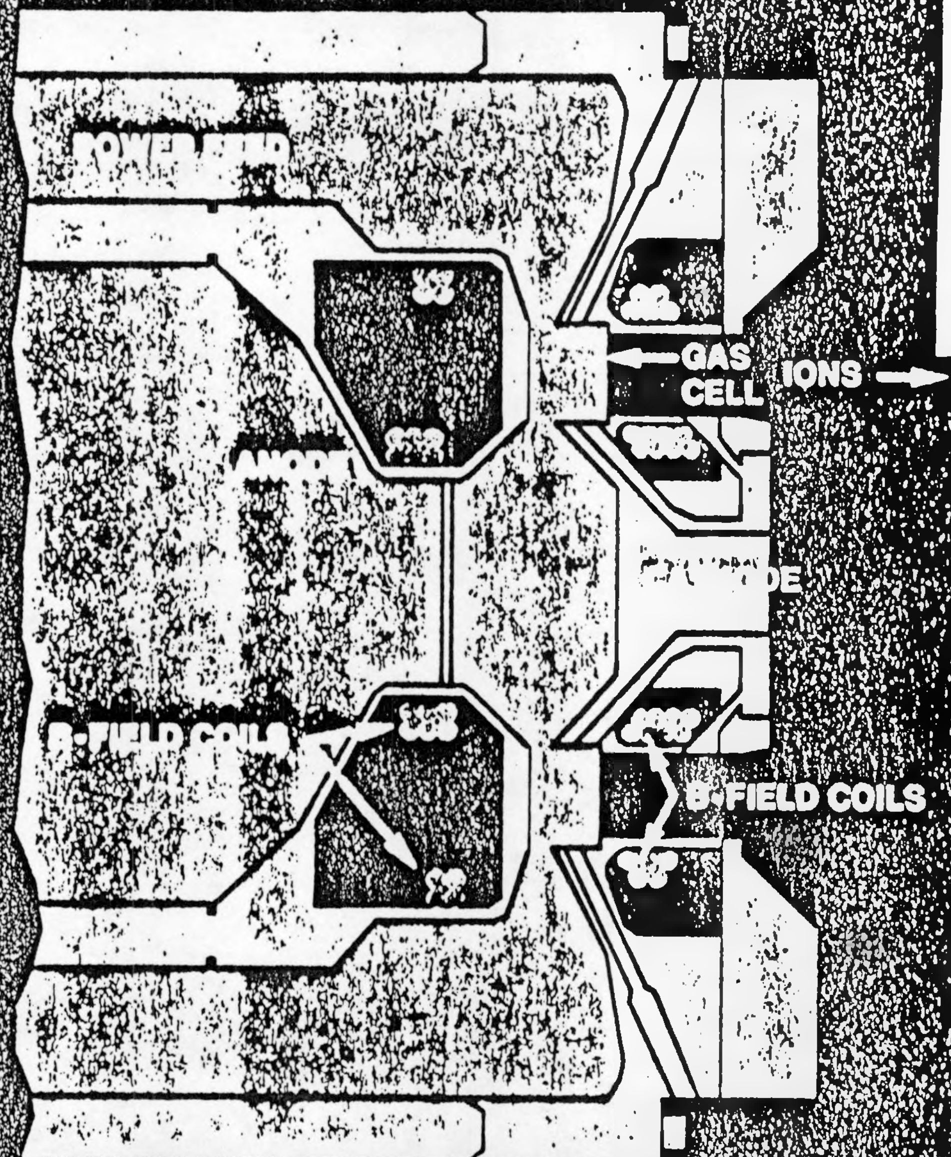
Fig 1



LIME LIGHT Ion Beam Driver

FIG 1

EXTRACTION APPLIED B DIODE



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(7)

ION DIODE – TARGET CHAMBER AREA

Fig 4
Ion Diode –
target chamber
area drawing

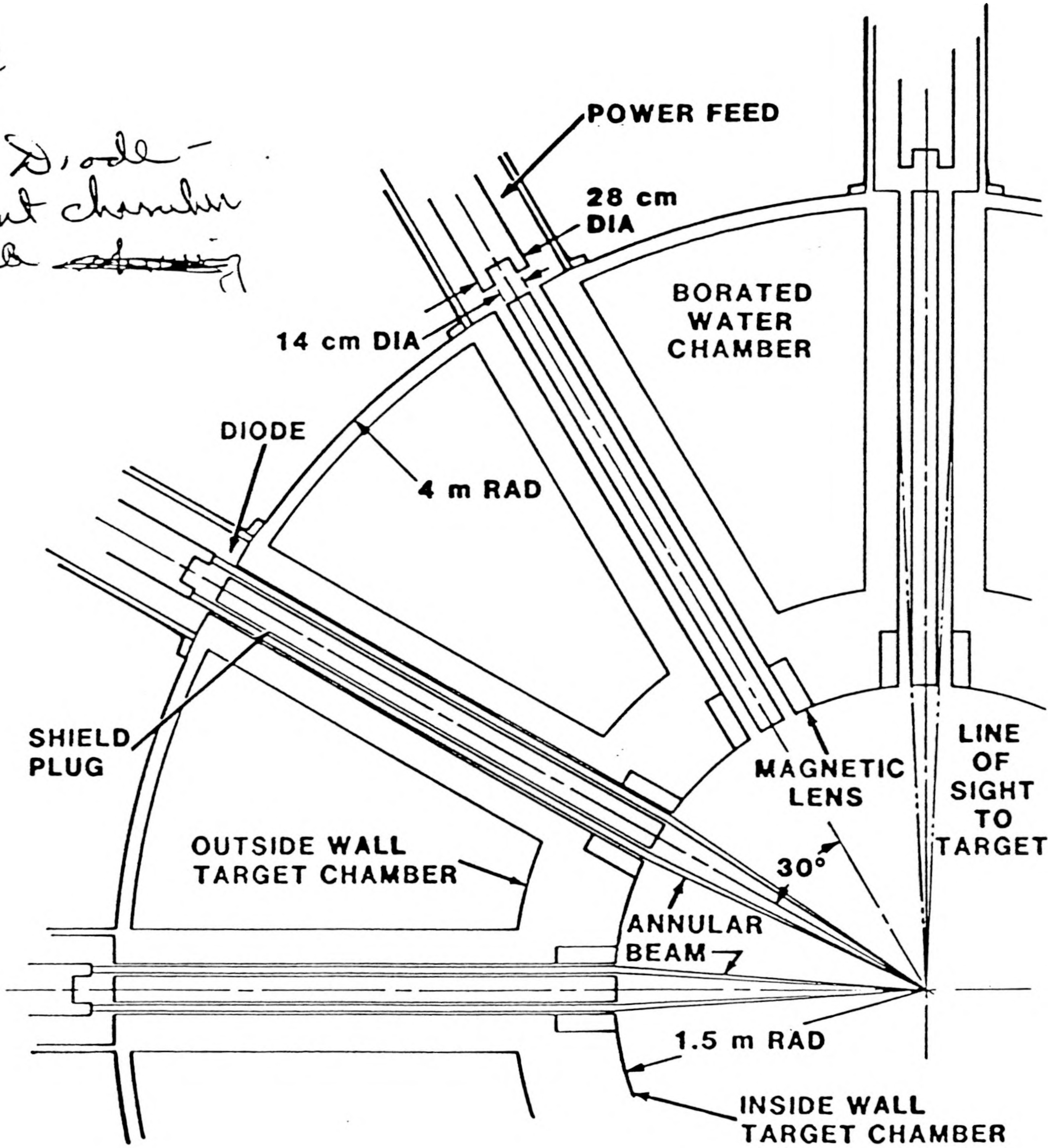

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FIG (3)

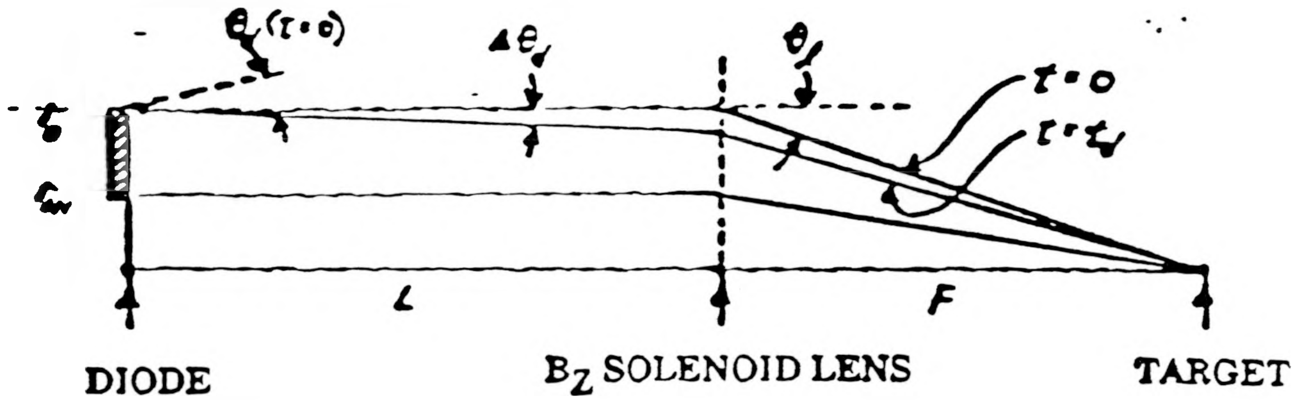

Fig. 8. Achromatic magnetic lens system.

(2)

FIG. (4)