CONF-800707--8

PROGRESS TOWARD FUSION WITH LIGHT IONS* IAEA-CN-38/P-3

ABSTRACT

New results in target design, beam generation and transport, and pulse power technology have led to a program shift stressing light ion-driven inertial confinement fusion. According to present estimates, a gain ten fusion pellet will require at least one megajoule and ~ 100 TW power input. Progress in ion sources has resulted in beam power density of ~ 1 TW/cm^2, a factor of ten increase over the last year,[1] and cylindrical implosion experiments have been performed. Other experiments have demonstrated the ability to transport ion and electron beams with high efficiency and have confirmed numerical predictions on the properties of beam transport channels converging at a target.[2-6] These developments together with improvements in pulse power technology allow us to project that the 72 beam, 100 TW Particle Beam Fusion Accelerator, PBFA-II will attain target output energy equal to stored energy in the accelerator.

INTRODUCTION

The light ion program at Sandia National Laboratories has the goal of utilizing efficient low-cost pulse-power to demonstrate proof-of-principle for inertial confinement fusion (ICF). Similar technology can be adapted for repetitive operation.[7] and the beams can be transported through a chamber containing sufficient gas to protect the wall.[8] Thus, the long-term potential for useful ICF energy production is expected to develop in a direct and logical manner. The Sandia ICF program developed initially from successes in electron beam pinch efforts. The superiority of ion beams for ICF ignition has long been recognized, but only recently have ion sources appeared with sufficient intensity to inspire confidence in this approach. Target experiments with ion sources are now beginning. In this paper results of these recent intense beam experiments are given, along with the plan for extending these results to higher power levels.

TARGET CONSIDERATIONS

To ignite an ICF Target, it will be necessary to deposit a few x 10^7 J/g in the outer layers during ~ 10 ns. Ion beams with atomic number 1-6 and energy 1-16 MeV can accomplish this without enhancement over normal stopping power. (Electron beam ICF requires such enhancement.)[9] With ions, no bremsstrahlung or hot electron component will preheat the thermonuclear fuel or pusher and thereby degrade target performance. Substantial deviations (factors of two or more) from the conventional stopping power are predicted for ions interacting with heated matter.[10] These effects do not reduce target efficiency but must be included in design, and corrected models for stopping power have been incorporated in a

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routine for inclusion in hydrocodes.[11] It is instructive to examine the gain curve shown in Fig. 1. Because light-ion drivers are very efficient, targets with gain 30 are expected to place the gain-efficiency product in the range 10 needed to satisfy economic constraints on reactors. For such gain, a few megajoules of ion energy on target will be required and yields will be in the 100 MJ range. A reactor operating at 3-5 hz would produce 100 MW electric; its relatively small size would be very attractive for introducing ICF technology to the commercial sector.[12]

BEAM GENERATION - PRESENT ACCELERATORS

Several ion diode options are under study for application on Sandia accelerators.[13] All options, except one, use magnetic fields... either self-generated by diode current flow or with externally excited coils... to suppress electron flow while allowing ions to be accelerated freely. Work at Sandia National Laboratories and Cornell University[14] has concentrated largely on diodes employing external magnetic fields, while work at the Naval Research Laboratory has been primarily with self-excited diodes.[15]

A schematic of the radial diode employed on the Sandia PROTO I and PROTO II[16] accelerators is shown in Figure 2; this device operates in the following manner. A magnetic field is established by pulsed coils. The risetime is selected so that field fully penetrates the stainless steel cathode structures, but only slightly penetrates the anode, and its value (typically 1-2T) is chosen so that electrons emitted at the edge of the cathode cannot reach the anode. When the power pulse (typically 1 MV, 500 kA for PROTO I; 2 MV, 4 MA for PROTO II) is applied, plasma layers form on the intense field regions of the cathode. Electrons from these plasma layers drift in axial and azimuthal directions to form a circulating electron cloud which constitutes a virtual cathode. The effective anode-cathode gap is smaller than the physical anode-cathode gap by an amount equal to the average electron radius in the field. The electric field stress upon the anode surface results in a surface breakdown along imbedded insulating hydrocarbon areas.[17] Ions (predominately protons in current experiments) from the anode-breakdown plasma are accelerated inward radially by the virtual cathode. One can obtain current density several times greater than would be calculated with classical Child-Langmuir theory. Note that if the applied magnetic flux is totally excluded from both the anode structure and anode plasma, then canonical momentum considerations show that there is no defocusing from the applied field.

An important element in ion diode performance is the control of self-magnetic fields arising from the ion beam current. In the radial diode just described, axial pinches are produced and can either aid in attaining high current density on target, or cut off the diode current, depending upon the geometry and impedance. For example, for a diode with radius R >> d, the axial extent of the ion source, the maximum current that can be drawn before cut-off begins is $I_{lim} = 2.9(R/d)(AV/z)^{1/2}$, where A is the atomic number, z is the integer charge state, and I and V are in MA and MV. Although this limit is not approached for present parameters on PROTO I or PROTO II, the beams do undergo a series of pinches as they move inward radially. A single pinch would be located at the axis if $I = .72(d/R)(AV/z)^{1/2}$.[18] Current on both PROTO accelerators exceeds this condition, and as I varies, a series of pinches moves over the targets. Particle-in-cell computation of diodes agrees with experiment and with analytic envelope theory.[19] Experimental techniques used include filtered x-ray diode arrays, x-ray spectroscopy,[20] pin hole photography,[21] nuclear activation, and detection of prompt radiation from the reaction $^{19}F(p,\alpha\gamma)^{16}O$.[22] The latter technique is particularly useful for determining ion focusing and trajectories by allowing the proton beam to impinge upon fluorocarbon samples placed within the diode. Local proton current is inferred from the signal and the nuclear reaction cross-section which is a function of the diode voltage.

Other experiments have centered on "exploding-pusher" implosions utilizing aluminum foil cylindrical and conical diagnostic targets which are less than one range thick for megavolt protons. X-ray pin-hole camera and x-ray diode measurements were used to infer energy deposition profiles and the foil's dynamic response. Aluminum line radiation recorded by x-ray pin-hole imaging on film gives the beam profile on target, as shown in Fig. 3 by the faint ring; the intense centeral spot shows the high temperature spike formed when the radially imploding portion of the material stagnates near the axis. The PROTO I experiment has resulted in transfer of > 80% of the terminal power to the ion beam, and 1 TW/cm^2 has been deposited in the central region of a cone with 4 mm mean diameter. Hydrocode calculations using the ion deposition package [23] have been used to model these implosions. An example of such a calculation is included in Fig. 3. It is expected that during the next year PROTO II will be used to extend experiments to larger targets with power density > 1 TW/cm^2. PROTO II has produced ≈130 kJ of ions, and focusing experiments are in progress. A large-scale single diode patterned on this general design will be used on PBFA I, but for PBFA II individual diodes will be used with plasma transport channels.

BEAM GENERATION AND TRANSPORT FOR PBFA AND REACTORS

Future high power net-energy gain experiments will employ current-carrying plasma channels for ion transport through ~10 Torr of gas. To accomplish this requires: (1) beam with $\lesssim 15°$ half-angle, $\geq$ 1 TW/cm^2 power density at the focal point, and voltage programming to yield a bunching factor of ~3-5 at the target;

(ii) ionized channels about 1 cm in diameter and carrying $\gtrsim 50$ kA of pulsed plasma current to confine the ion beam.[24] Initially, thin wires have been used to guide the channel discharges,[25] but reactor applications will require a few joules of laser light to form preionized paths before firing the channel capacitor bank.[26-28]

Channels for beam transport provide both current and space-charge neutralized beams, and trajectories are calculated by considering only the initial injection positions and velocities in the magnetic field of the channel. In long channels resistive voltage drops may result in some energy loss, but this is unimportant for multimegavolt ion beams. Monte-Carlo calculations show that trajectory changes caused by variation in charge state of ions interacting with the channel plasma will not be important.[29] Because electron beams have been readily available, the first multiple beam transport and combination experiment was performed with electrons; similar physics holds for ion beams. Six electron beams generated by PROTO II were introduced into radial channels converging toward a target.[30] Figure 4 shows that the experimental result matches theoretical predictions. 50 kJ of electron energy was efficiently transported over a .5 meter path to targets with diameter $\gtrsim 2.5$ cm. If ion beams had been available, a second theoretical curve shows that similarly efficient results could be obtained with smaller targets and higher power density. That similar physics holds for electron and ion transport has been established with single wall-guided channels at the Naval Research Laboratory[31] and with wire-guided free-standing channels at Sandia.[32] Recently, the creation of a 1.5 m channel in low-pressure NH_3 by preparing the discharge path with a CO_2 laser line has been demonstrated.[33] Plans are underway to transport an ~~ion~~ ion beam in such a channel.

Diodes suitable for injecting beams into channels include a modified version of the radial diode discussed above,[34] the pinch-reflex diode studied primarily at NRL,[35] and the Auto-Magnetic Plasma Filled Field Insulated Ion Diode (AMPFION).[36] The AMPFION approach utilizes a plasma gun ion supply, obtains its insulating magnetic field from the diode current itself flowing through spiral turns, has no magnetic field extending into the ion drift region, and produces a current-neutralized beam. In addition, the impedance characteristic associated with AMPFION produces a voltage wave-form which rises during the pulse to produce a bunched ion beam from a conventional pulse power source. The basic principles of AMPFION have been demonstrated, and work to improve the focal properties is in progress.

Ion diode research centers on improving the power density brightness factor JV/Θ^2, where J is the ion source current density, V is the accelerating potential, and is the divergence. The PROTO I diode has attained a power brightness ≈ 3 TW/cm^2-steradian at 1 MV and J = 5 kA/cm^2.) V must be within the range dictated by ion species and target design, and is 2-4 MV for proton beams. There is considerable impetus to develop higher voltage pulse-power sources. Larger anode-cathode gaps can be used at higher voltage, while maintaining a high value for J, reducing the effect of anode plasma perturbations (and hence Θ), and increasing impedance uniformity during the pulse. In addition, higher voltage beams are attended by lower self-fields at constant power, and more energetic or massive particles are less affected by magnetic fields, improving focusability. The power brightness is expected to scale approximately in proportion to $V^{2.5}$.

PULSE-POWER DEVELOPMENT

PBFA is modular in construction.[37] A 33 m diameter tank (Fig. 5) houses 36 oil-submerged Marx generators which store 4 MJ at a capacitor charge of 100 kV. The Marx section was completed during February 1980, and all 36 units have been triggered with a total spread of 20 ns. Pulse compression of the 1 μs Marx pulse takes place in an inner annular water tank. Because of its low cost, high dielectric constant, and favorable breakdown characteristics, deionized water is used for the dielectric pulse compression medium. The Marx energy is transferred to 36 coaxial water dielectric intermediate storage capacitors; upon command trigger, 36 pressurized SF_6-filled spark gap switches discharge energy from the intermediate capacitors into water-dielectric strip lines in 300 ns. Each strip line has five self-closing switches to form a 40 ns output pulse. This pulse is fed into a final strip line with a set of self-triggered switches for pulse sharpening and prepulse isolation, and then passes through a voltage-doubling tapered transmission line to the insulator stack, which separates water from vacuum. Because flashover properties of the vacuum surface limit the electric stress, the insulator cross-section must be quite large; this necessitates positioning these elements at a large radius. Low-loss power transport from the insulators to the diodes is accomplished with a separate self-magnetically insulated transmission line for each module. These lines transmit the 2 MV, 40 ns, 400 kA pulses along a line stressed to 2 MV/cm with virtually no loss, because self-magnetic fields prevent electrons (always present at these stresses) from crossing the interelectrode gap. Peak power transmission is nearly 100% efficient, and about 90% of the energy is transmitted. By paying careful attention to the electrodynamics of electron flow in the design of the injector region at the insulator, either polarity pulses can be efficiently transmitted.[38]

PBFA II will occupy the same tank as PBFA I. The number of Marx generator modules will be increased to 72, and the rating of each Marx module will be nearly doubled by using higher energy density capacitors. PBFA II will store 15 MJ and deliver ≈ 4 MJ to the diodes. Similar pulse forming circuits will be employed, but a close-coupled water strip-line transformer will be inserted between the pulse network and the water-vacuum interface to increase the voltage. It now appears feasible to rejoin vacuum-insulated lines at a common load.[39] If success is achieved, options for either high or low impedance loads for PBFA will be possible. PBFA I will be completed on schedule during July 1980, and pulse-power experiments will be carried out until January 1981. Diode and target experiments will be carried out until mid 1983, when the upgrading to PBFA II will commence. During 1986-87, PBFA II will provide 100 TW and 1 MJ of ions to ICF targets which are expected to provide energy output equal to energy stored in the capcitor bank, i.e., net energy gain.

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FIGURE CAPTIONS

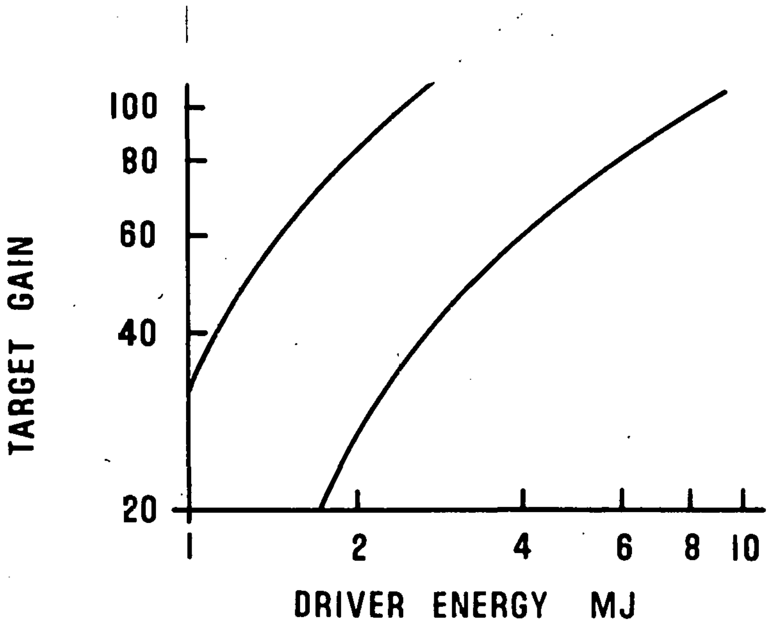
1. Expected gain-energy relationship for various fusion target calculations falls between the two curves. (After R. Bangerter, Lawrence Livermore Laboratories).

2. Schematic Diagram showing essential features of the radial ion diodes used with Proto I and Proto II.

3. Hydrocode calculation (shown in half-plane) of ion-driven conical foil target less than one range thick to peak ion voltage, 45 ns after irradition. At this time the voltage is low and, as shown, ions no longer fully penetrate the foil. Also shown is the time integrated pinhole picture of a similar target.

4. Results of six-electron-beam tranport experiment showing data points taken with thermoluminescent detectors and a pinhole x-ray camera. The solid curve is the theoretical result for electron beams, and the dotted line shows the expected improvement for ion beams.

5. PBFA-I artist's conception cut-away.



TARGET GAIN
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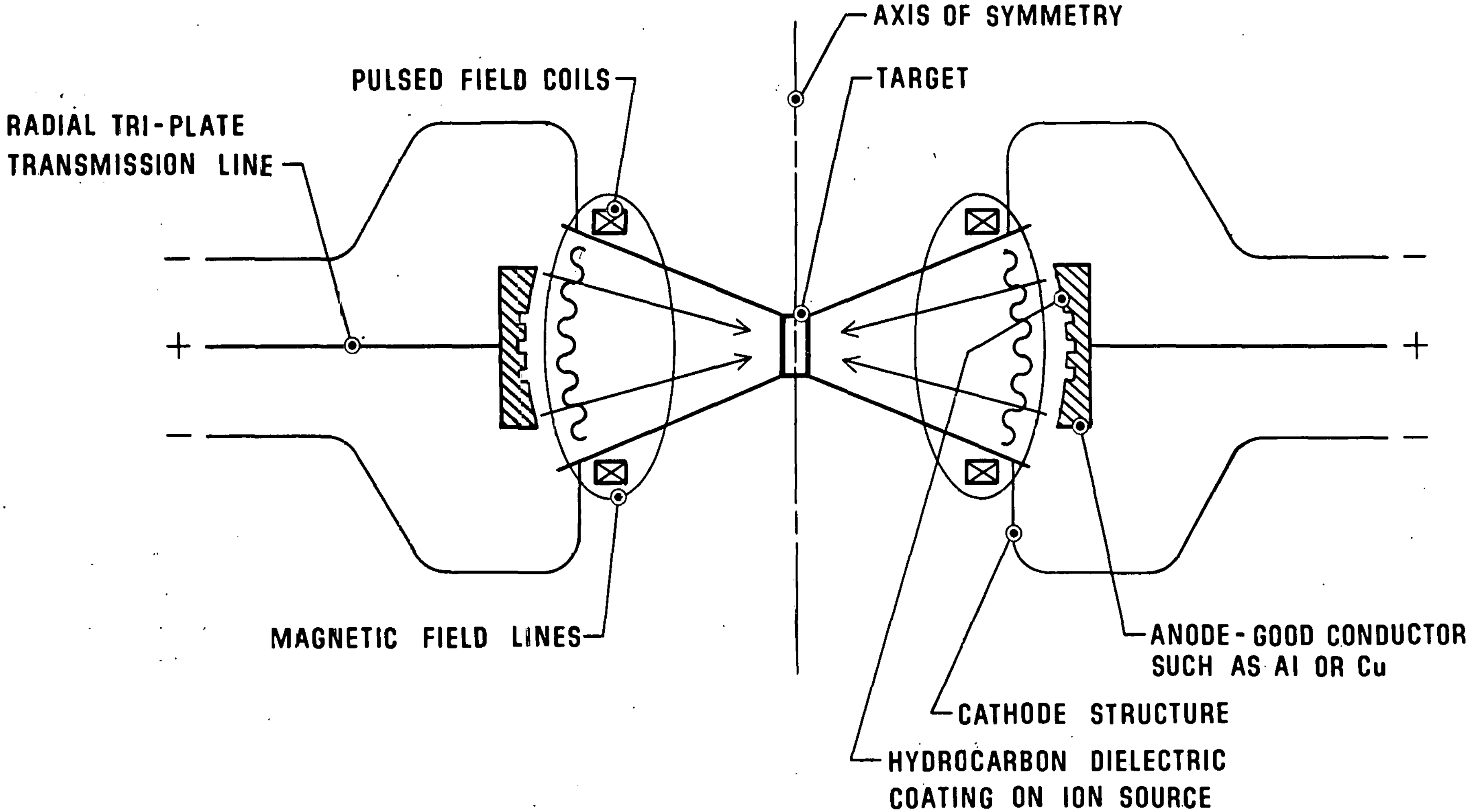
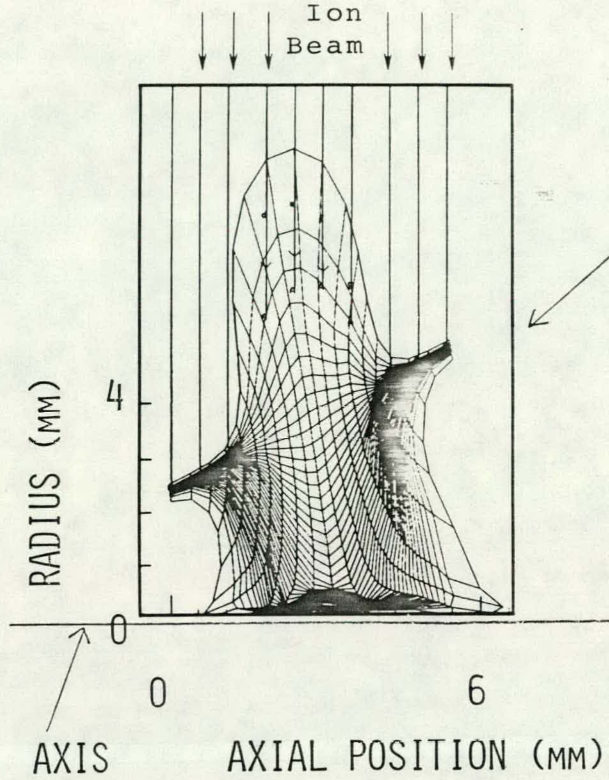
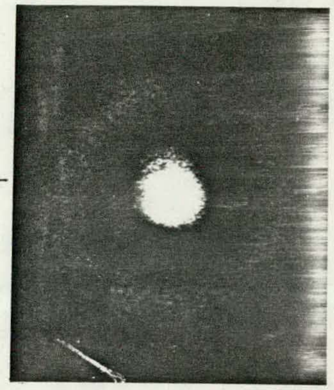
8
10
DRIVER ENERGY MJ

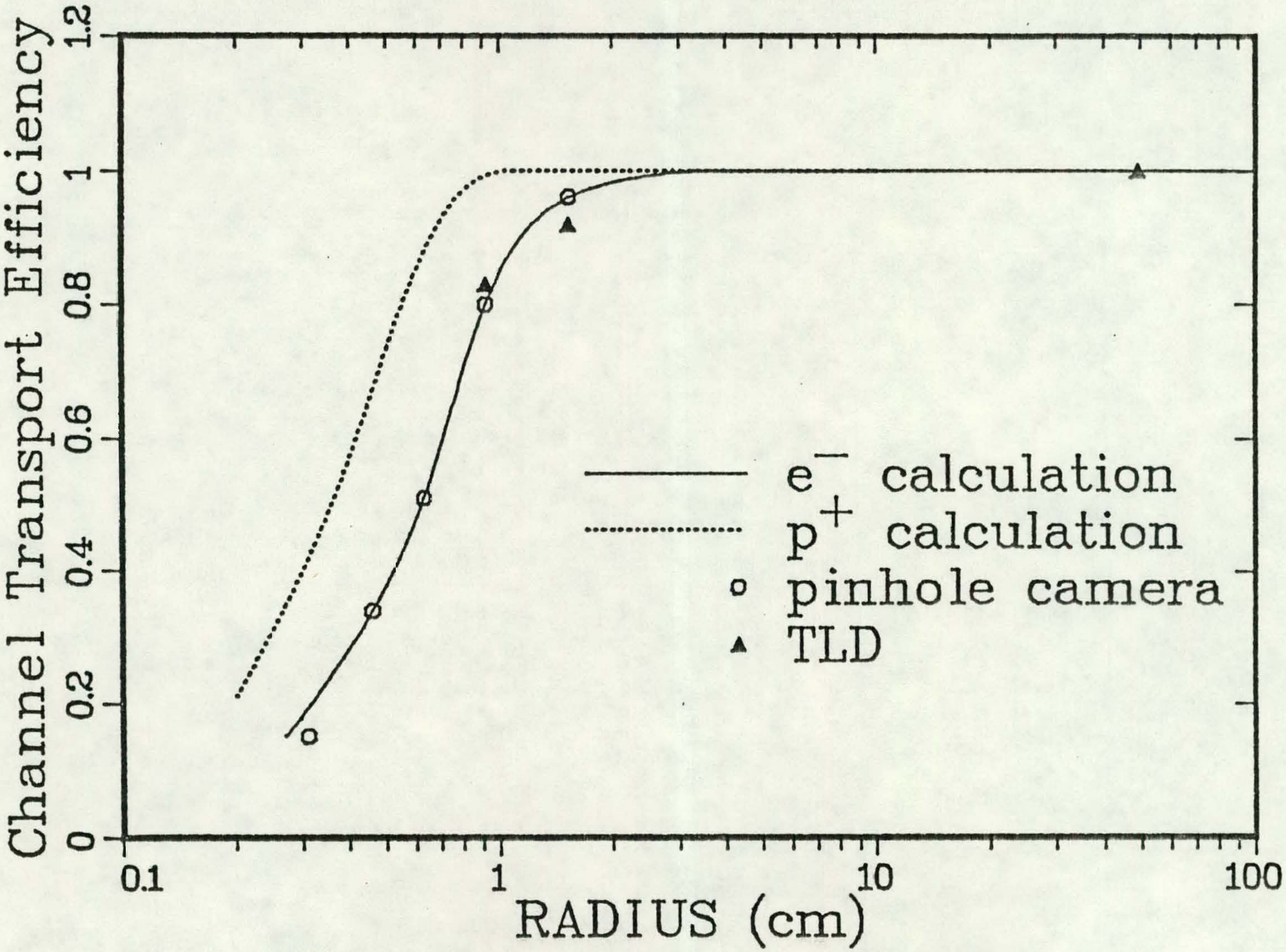

AXIS OF SYMMETRY
PULSED FIELD COILS
TARGET
RADIAL TRI-PLATE
TRANSMISSION LINE
MAGNETIC FIELD LINES
ANODE - GOOD CONDUCTOR
SUCH AS Al OR Cu
CATHODE STRUCTURE
HYDROCARBON DIELECTRIC
COATING ON ION SOURCE



INITIAL POSITION
OF FOIL

PIN HOLE PHOTO:
RING SHOWS ION DEPOSITION
CENTER SHOWS COMPRESSION





Channel Transport Efficiency
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0.2
0.4
0.6
0.8
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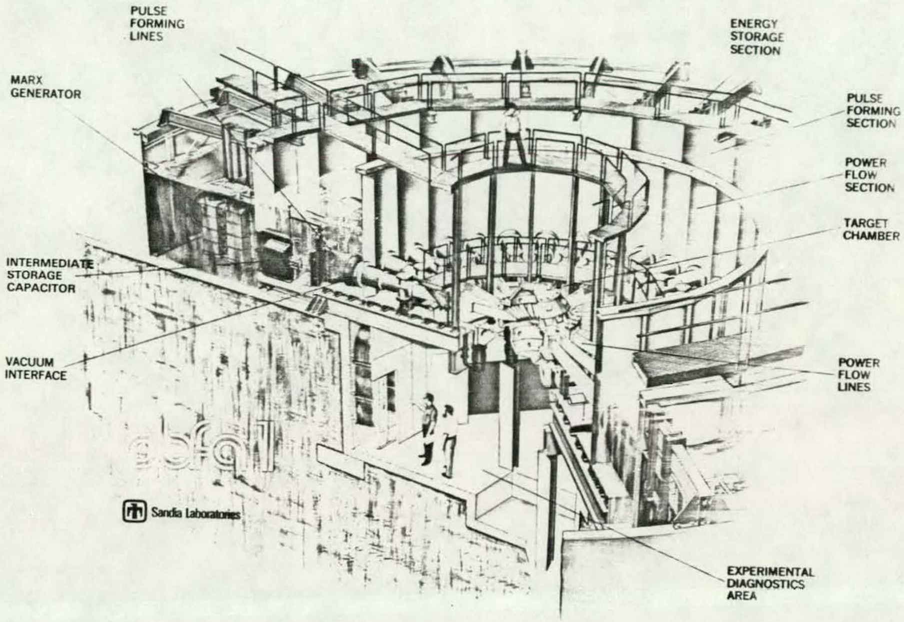
1.2
0.1
1
10
100
RADIUS (cm)
e⁻ calculation
p⁺ calculation
pinhole camera
TLD


PULSE FORMING LINES
ENERGY STORAGE SECTION
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VACUUM INTERFACE
POWER FLOW LINES
Sandia Laboratories
EXPERIMENTAL DIAGNOSTICS AREA