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6 Develop And Perform Experiments For High Intensity Charged Particle Beams

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"Develop and Perform Experiments For High Intensity Charged Particle Beams"

Summary of Work

The work performed and completed under this contract comprised an evaluation of ion transport methods and a preliminary ion transport experiment, including:

A. Operation of NRL GAMBLE I facility in positive polarity for ion beam generation.

B. Design and development of ion diodes appropriate to the GAMBLE I accelerator.

C. Application of appropriate diagnostics for determining ion yield of diodes and realization of a ballistic ion focus at the target plane.

D. Design and development of an ion transport feasibility experiment for GAMBLE I. and

E. Perform preliminary evaluation of ion transport mechanisms and efficiency.

F. Identify appropriate directions for continuing research.

G. Reporting on work performed at scientific meetings.

I. Introduction

Successful inertial confinement fusion, based on intense light ion beams, requires that methods be developed to efficiently generate, focus and transport such beams to a pellet. Present pellet designs call for diameters of approximately 1 cm while typical standoff distances for fusion reactor designs are several meters. The experiments discussed herein are designed to generate an intense ion flux by means of a pinch-reflex diode, to quickly bring the ions to a focus of approximately pellet dimensions near the diode, and then to attempt to propagate the focused beam, without significant expansion, over a trial standoff distance.

II. Work Performed

A. Operation of GAMBLE I Facility in Positive Polarity

To facilitate extraction of proton (or deuteron) beams from the diode, the GAMBLE I accelerator was converted to positive (reversed) polarity. Although the electrical design of the machine is optimized for negative polarity operation, the initial conservative design of the device permits positive polarity operation without major modifications. Typically, a 60 nsec pulse of 150 kA at 600 kV is obtained with 5.4 kJ of energy delivered to the diode. A variety of diode geometries were tested during the contract; time did not permit optimization of diode geometry to maximize total delivered ion energy.

B. Design and Development of Ion Diodes Appropriate to the GAMBLE I Accelerator

Figure 1 summarizes the various diode designs used in this work. These designs were geometrically scaled from diodes previously used on the NRL GAMBLE II machine. Diode operation of these scaled designs is, unfortunately, not well understood, and remains to be experimentally determined. Aluminum cathodes of ~7 cm^2 and ~30 cm^2 area were used in flat geometry. The degree of cathode "hollowness" was varied by means of metallic screens which were inserted in the cathode. Various anode foils were studied, as indicated on the figure. A 3 mm dia. aluminum button, 5 mm in length, was mounted in the center of the anode backing plate to help centralize the electron pinch. The backing plate for flat geometry was made of aluminum with a replaceable insert which was removed after each shot to examine the rear surface spall from the electron beam. Only the 30 cm^2 cathode was used in the 12 cm radius of curvature spherical geometry and the curved anode backing plate was made of stainless steel. For both flat and spherical geometry the anode foil was supported above the anode backing plate with a 5 mm thick lucite ring.

C. Determination of Diode Ion Yield and Realization of a Ballistic Focus at the Target Plane

The ion yields of the various diodes discussed above were diagnosed primarily by means of nuclear activation of carbon and boron nitride. By noting the time that the corrected diode voltage signal exceeded a particular activation threshold on effective ion current was computed. The time resolved ion current was monitored by means of Humphries' probes. Similarly, the radial distribution of ion current was determined. With spherical geometry diodes, witness plates were placed near the expected focus. Also, metallic apertures were used to determine the fraction of the total ion current passing through the aperture, i.e., the efficiency of focusing.

The principal results of the diode study are, in summary, that up to 7 kA and 30 kA of ion current were obtained respectively from the flat 7 cm^2 and 30 cm^2 cathodes. When identical diodes were used in curved geometry, a ballistic focus was achieved at the expense of total ion current, which dropped to 9 kA. Approximately 2/3 of the 9 kA ion current could be detected behind a 2 cm^2 aperture. A concomitant observation is that large oscillations appeared in the corrected diode voltage signal (actually in the dB/dt correction voltage) almost exclusively in the curved geometry. This made determination of ion current from activation difficult since the time above activation threshold could not be noted unambiguously. Present speculation is that these fluctuations may be associated with relaxation oscillations within the diode which may somehow be enhanced in the curved geometry.

The most noticeable effect of variation of anode foil material was that the ion current appeared later in the diode voltage pulse when metallic anodes were used. This is probably a result of poor anode plasma turn-on (flashover being more difficult to initiate at the relatively low GAMBLE I voltages). The observation that the risetime of the ion current decreases for non-metallic anode foils tends to confirm this.

In general, the impedance behavior from shot-to-shot was not very reproducible. The reasons for this are not known at present but again, may be due to difficulties in rapidly forming uniform electrode plasmas. It should be emphasized that the diode ion yield experiments were not exhaustive, and that the basic diode physics needs to be understood more fully before additional transport work is attempted. This requires new diagnostics and diagnostic access to the diode itself.

D. Design and Development of an Ion Transport Feasibility Experiment for GAMBLE I

For efficient transport the ion beam should be electrically and magnetically neutralized. Neutralization is most easily accomplished by propagating the beam in a dilute plasma or neutral gas which is ionized by the beam front. Then an external magnetic field may be applied to guide the beam. One approach is to arrange the diode geometry so that the beam is strongly divergent. If the beam then travels through a region of constant axial magnetic field, ions diverging from the initial virtual focus will refocus periodically on axis. However, an unavoidable spread in the ion launching angle at a particular radius will broaden the focus in the plane perpendicular to the propagation direction. Also, the normal variation in diode voltage during the machine pulse will broaden the focus in the axial direction. These limitations, coupled with the necessity of using external magnets over the entire transport distance, convinced us to bypass the axial field transport scheme in favor of one relying on an azimuthal magnetic field.

A guiding azimuthal field can be created using several types of axial current conductors on the diode axis. For a uniform current distribution in an axial guiding "channel", ions will undergo simple harmonic oscillations about the guiding axis. The necessary current-carrying channel may be established by exploding a fine wire at reduced pressure, passing a current through a thick (non-exploding) wire or rod and relying on the beam front to ionize the background gas, or directly forming a long current-carrying plasma channel. These methods were investigated in this work and are discussed below.

Figure 2 is a schematic of the transport chamber. This hardware was mated to the previously optimized GAMBLE I diode. A 28μ f. (expandable to 56μ f.), 20 kV capacitor bank supplies current to the channel which is returned coaxially outside a dielectric drift tube. In this way the beam return current is forced to flow predominantly in the (relatively) low inductance beam channel. The 2 cm^2 entrance aperture is located 9 cm from the anode, somewhat inside the 12 cm geometric focus. A 2 μm thick kimfol window allows the diode and transport chamber to be differentailly pumped and the chamber backfilled to a desired pressure. A 78 percent transparent metal screen feeds current to the wire or rod and provides necessary mechanical support. Typically, the capacitor bank provides currents up to 30 kA, with a 10 μ sec quarter period, producing fields up to 6 kG 1 cm from the wire.

Since the physics of long exploding wires is not a well researched subject, considerable time was invested studying these channels. The plasma and wire light was observed with a framing camera looking through diagnostic parts in the transport chamber. The total current supplied to the channel was monitored with a Rogowski coil while the radial distribution of current was measured with an array of radially movable magnetic probes. Because the channel behavior is strikingly different for various background fill pressures, the results will be summarized for 4 pressure regimes.

a) Pressure range 10 T-760 T; here a fine wire (typically .05 mm dia.) undergoes an apparent explosion. Approximately 10μ sec before current flows in the wire discrete explosions are seen along the wire. These probably are whiskers exploding in the high radial electric field. Material expands radially from these locations at speeds of 1 mm/ sec. Finally, the wire flashes along its length and current begins to flow. A luminous core, surrounded by a more diffuse halo, is observed. The core expands to a maximum radius, which depends on bank energy and the wire mass, while the halo continues to expand. At 10-15 μ sec into the current pulse, sausage instabilities appear in the core, quickly followed by kink instabilities which rapidly destroy the channel. Jets of material are ejected from the minimum radius points of the kinks. Occasionally the center of the core is observed to darken late in the current pulse.

It is probable that this is a true wire explosion as no wire fragments remain after the shot and the current is predominantly within the small (~ 5 mm radius) channel. Therefore, the channel is likely composed mostly of high-Z material making it unsuitable for light ion transport due to the short stopping distances for these ions.

b) 2 T-10 T; here we observed a combination of a wire channel and a plasma discharge surrounding the wire. The radial expansion rate is increased to 3-4 mm/ sec. In general, it appeared that the wire guided the plasma channel to some extent, increasing stability somewhat. The current distribution was noticebly more diffuse. The difficulty here is that it is difficult to get sufficient current flowing in the channel before the radial expansion has allowed the channel to become too large. This is the pressure regime currently envisioned for transport of reactor level ion beams. The channel probably still has considerable high-Z content as the wire vaporizes.

c) .01 T-2 T; in this pressure range the wire apparently has little effect on the channel development. Frequently the wire is found unvaporized after the shot, although fragmented. The plasma breakdown channel is guided by the wire only early in the current pulse. Later the channel wanders off the drift tube axis and becomes unstable. The current profile becomes rather broad. This pressure regime is optimum for the GAMBLE I transport experiments.

d) less than .01 T; a pure vacuum wire explosion is produced here, which is again unsuitable for transport because of the instability of the channel and its high-Z composition.

E. Perform Preliminary Evaluation of Ion Transport Mechanisms and Efficiency

An initial evaluation of the transport efficiency was made using carbon activation targets located in the transport system. One target was located in a recess in the rear flange of the drift chamber. This was designed to be quickly removable for counting. Targets could also be placed immediately after the entrance aperture to monitor the injected current. When 1.5 mm dia. brass rods or wires .25 mm dia. or larger were used, other targets could be placed at various axial positions along the wire. This was possible since the larger conductors did not explode or melt and since the bank current was confined to the wire, the presence of the target did not interfere with channel development.

Two problems other than the poor total ion yield of the diode were immediately apparent. First, the jitter time of the marx generator in positive polarity was many tens of microseconds making proper synchronization of the transport system and the ion beam very difficult. This was not improved much by varying the switch pressure. Also, if the machine firing time was late, it was found that plasma from the transport chamber frequently reached the diode, resulting in a diode short. This could be supressed by adding a 2μ m kimfol foil inside the cathode, but this, of course, further reduced the energy of protons reaching the target and made activation measurements more suspect, since the mean proton energy was undoubtedly far below the 480 keV activation plateau.

The best transport observed was approximately 50 percent of the injected beam reaching the target at the end of the transport chamber. This was observed with an exploding wire guided plasma channel. Under similar conditions using a 1.5 mm dia. brass rod instead of the wire 40 percent transport was obtained. When a fine wire was used and a plasma channel formed but the background pressure was such that the channel was observed to kink and not be guided by the wire, transport dropped to 10 percent or less.

A crude estimate of the radial distribution of the transported beam was made using composite targets. One such arrangement is shown in Figure 3. The two targets were placed at the end of the transport chamber. The front target was 1.6 times the diameter of the entrance aperture while the rear target was 3 times the entrance aperture diameter. When 50 percent of the injected beam was observed to hit the front target, 30 percent of the beam hit the back target. This indicates that the beam has acquired more transverse energy than expected. This may occur because of the non-ideal entrance geometry, or because the transport field is not strong enough.

The same targets were also arranged as shown in Figure 4. Here the rear target is in the geometric shadow of the front target, i.e., no ion which enters the transport chamber has a line-of-sight path to the rear target. Ions striking the rear target must be deflected by the azimuthal field of the wire as shown. Fifteen percent of the ion flux to the front target was detected at the rear target.

F. Identify Appropriate Directions for Continuing Research

Two major technical problems apparent in this study need further work. The marx generator jitter time must be reduced to plus or minus a few microseconds. This may require more energy delivered to the switch trigger or triggering more of the marx column than is presently done. The ion yield of the diodes must be improved also. This will likely require more study of the diode mechanisms such as pinch formation and anode flashover. To do this diagnostic, access to the diode will be necessary.

In terms of further transport experiments, some attention should be given to the formation of pure plasma channels. Because some of the inefficiencies and technical complexity of injecting into a wire system are reduced, the plasma channel would appear to be more advantageous if it can be sufficiently stabilized. This was attempted by inserting a series of dielectric baffles and field enhancing apertures into the transport drift tube. The schematic of the insert is shown in Figure 5. While actual ion transport was not attempted, study of the channel showed some encouraging stabilizing effects, although it appeared that the stability was quite pressure sensitive. Another alternative would be a small bore drift tube where wall stabilization would be utilized.

G. Reporting on Work Performed at Scientific Meetings

A paper "Light-Ion Transport Experiments" by F. Sandel, et al, was presented at the 1978 IEEE Conference on Plasma Science, Monterey, California, in May, 1978. The published abstract is attached. A paper "Generation, Focussing and Transport of Intense Light-Ion Beams from Pinched Beam Diodes for Pellet Fusion," with F. Sandel as a co-author will be presented and published in the Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, August, 1978. The abstract is attached.

LIGHT-ION TRANSPORT EXPERIMENTS*

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For inertial confinement fusion using light ion beams to be a viable concept, transport of an intense light ion beam must be demonstrated.[1] Experiments have begun at the Naval Research Laboratory to investigate transport over moderate (~ 50 cm) distances using a variety of methods. The beam source for these experiments is the NRL Gamble I accelerator (750 kV, 250 kA) operated in positive polarity. Ballistic focusing[2] in the diode is used (thin hollow cathode and hemispherical anode) to produce a proton or deuteron beam of ~ 1 cm diameter.

The ion beam will be injected into a dielectric drift tube through a thin foil. A suitable hydrogen background pressure will be maintained in the drift tube to minimize scattering while allowing sufficient plasma formation for beam neutralization.[3] For the initial experiments, a fine wire will be exploded on the axis of the drift tube using a small capacitor bank discharged 10 μs before beam injection. The return path for the current (~ 100 kA) in the resulting plasma guiding channel is through a symmetric array of brass rods outside the lucite drift tube. An alternative transport scheme is to simply locate a current-carrying rod (~ 1 mm dia.) on the drift tube axis. Beam neutralization then relies on surface breakdown along the rod and beam-front ionization.

Another transport mechanism to be investigated is reflexive focusing, where an initially diverging beam is brought to a distant focus by means of an axial magnetic field, although this technique appears to be theoretically less promising than the azimuthal magnetic field approach.

Progress to date in these experiments is reported. Additionally, the difficult problem of diagnosis of intense charge and current neutralized beams is discussed. Finally, it should be noted that, due to the rather low drift velocity of the ions and the temporal nature of the accelerating voltage in Gamble I and similar devices, ion bunching[4] may be a factor in these transport experiments. Relevant observations will be reported.

* Work supported by the U. S. Department of Energy.

† JAYCOR, Inc., Alexandria, Va. 22304.

†† Science Applications, Inc., McLean, Va. 22101.

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[4] Shyke A. Goldstein, et al., these proceedings.

GENERATION, FOCUSSING AND TRANSPORT OF INTENSE LIGHT-ION BEAMS FROM PINCHED BEAM DIODES FOR PELLET FUSION*

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It has been demonstrated[1] that proton beams can be efficiently extracted from low impedance (~ 1 Ω) relativistic electron beam generators operated in the pinched-beam mode and that such beams are well suited to drive thermonuclear pellets[2]. These light-ion beams offer several advantages for pellet fusion. They can be ballistically focussed[3] for concentrating the beam down to pellet dimensions. The 10^{14} W power required for pellet fusion can be generated from reasonable (~ 1 Ω) impedance generators (10 MA at 10 MV for protons). They have energy deposition characteristics well suited to efficient pellet designs. Additionally, unlike either laser- or electron-beam drivers, the ion-beam energy is delivered to the target in a known fashion independent of any plasma-dynamic or electromagnetic effects which are difficult to determine theoretically. Finally, because of the natural voltage variation in diodes, the ion beam can be bunched during propagation in a plasma channel. More than an order of magnitude power multiplication may be achieved after propagation of a few meters. Thus, present long pulse diodes (~ 100 ns) may be used to generate short, intense ion pulses on target, significantly reducing the required generator power.

Before light ions can be seriously considered for fusion-reactor applications, a number of important technical capabilities must be demonstrated. These are the abilities to: (1) scale beam power to the 100 TW level, (2) focus the beam to pellet dimensions, and (3) propagate the beam over a few meters to demonstrate standoff between accelerator and pellet and the ability to bunch. Here, new experimental and theoretical research will be presented which indicates that the first two achievements can be accomplished and that techniques for attaining the third ability exist.

Proton- and deuteron-beam measurements have been made [4] using both flat and geometric-focussing geometries differing from previous solid anode geometries [1] in the following ways: (1) a thin-foil anode reflexing structure which extends beyond the cathode radius, (2) a controlled vacuum gap between foil anode and anode back-plate, and (3) the use of a small diameter return path which provides on-axis electrical continuity between foil and anode back-plate. In the new flat pinch-reflex geometry, the maximum inferred proton current from carbon activation [1] averaged .32 ± .1 MA corresponding to total proton yields of $(1.3 \pm .4) \times 10^{17}$ with ion pulse durations of 60-90 ns. These data indicate that nearly one half of the diode current can be routinely extracted as protons. This represents a nearly factor-of-two improvement in efficiency over that predicted by the Goldstein and Lee formula [5]. Thus, the efficiency originally predicted for 10^{14} W generators has already been achieved on Gamble II at .5 TW. Recent numerical simulation results suggest that this improvement can be traced to the use of the thin-foil anode structures which allow for electron reflexing in the anode plane.

In the new spherical-section thin-anode-foil focussing geometries, ion focussing was tested using CD_2-coated anodes and targets. These data demonstrate a three-fold improvement in focussed-deuteron current density over that attainable with earlier designs. Consistent with numerical simulation predictions, about 1/2 of the total deuteron number produced in the diode was observed to be focussed into a 1.9 cm^2 area implying 70 kA/cm^2 at a location 12 cm from the anode. Additional improvements in focussing may require aspheric anode configurations in order to compensate for magnetic deflection in the diode. An upper limit of 4^o beam divergence due to thermal, time varying-fields, or scattering effects can be associated with the deuteron focussing results. As will be discussed below, this figure is sufficient to allow focussing over several-meter distances. The most recent measurements have determined the importance of current neutralization to good focussing. The observed large net currents are not understood at this time although their reduction to safe levels can be achieved by low-density gas or plasma fill in the drift chamber.

After geometric focussing, the intense ion beam can be propagated in Z-pinch plasma channels in a manner similar to that already achieved with pinched electron beams [6]. The low emittance of the ions allow transport of tightly focussed beams. Return-current heating of the channel provides a high degree of current neutralization for fusion-level beams propagating in backgrounds of a few Torr. The current-carrying ($\sim 10^5$ A) plasma channel of small radius ($\sim \frac{1}{2}$ cm) is established a few microseconds before the short-focal-length geometrically-focussed ion beam is introduced. The interface between the vacuum diode and the plasma channel consists of a thin foil placed at the focal point of the ion beam. The oscillatory motion of the ions in the azimuthal magnetic field is harmonic for a uniform current distribution. The radial displacement of the ions is easily computed from the channel current and focussing geometry and can be less than 0.5 cm. The effects of self-consistent fields are now under investigation.

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‡‡ University of Maryland, College Park, Md.

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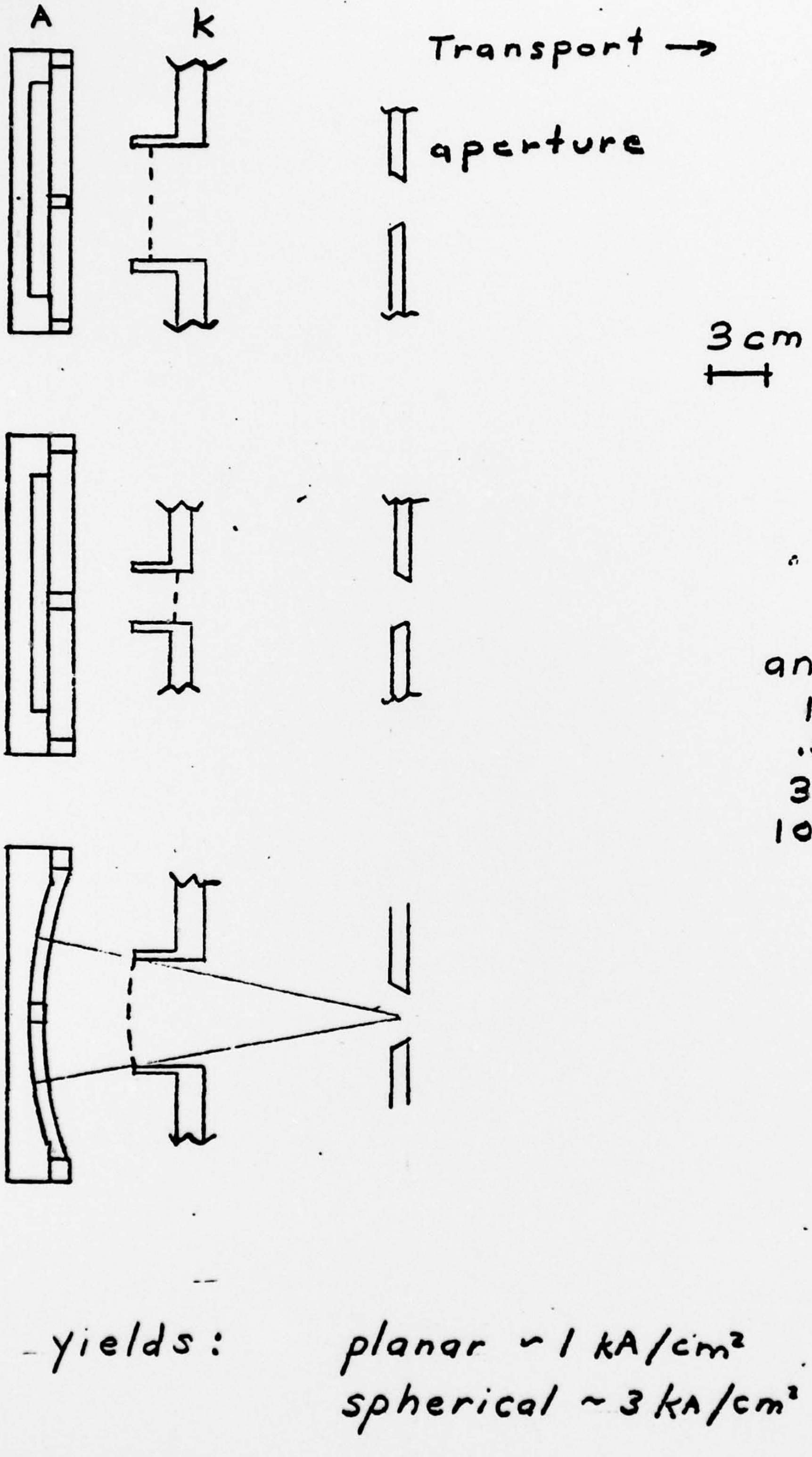
Figure 1

GAMBLE I ION DIODES

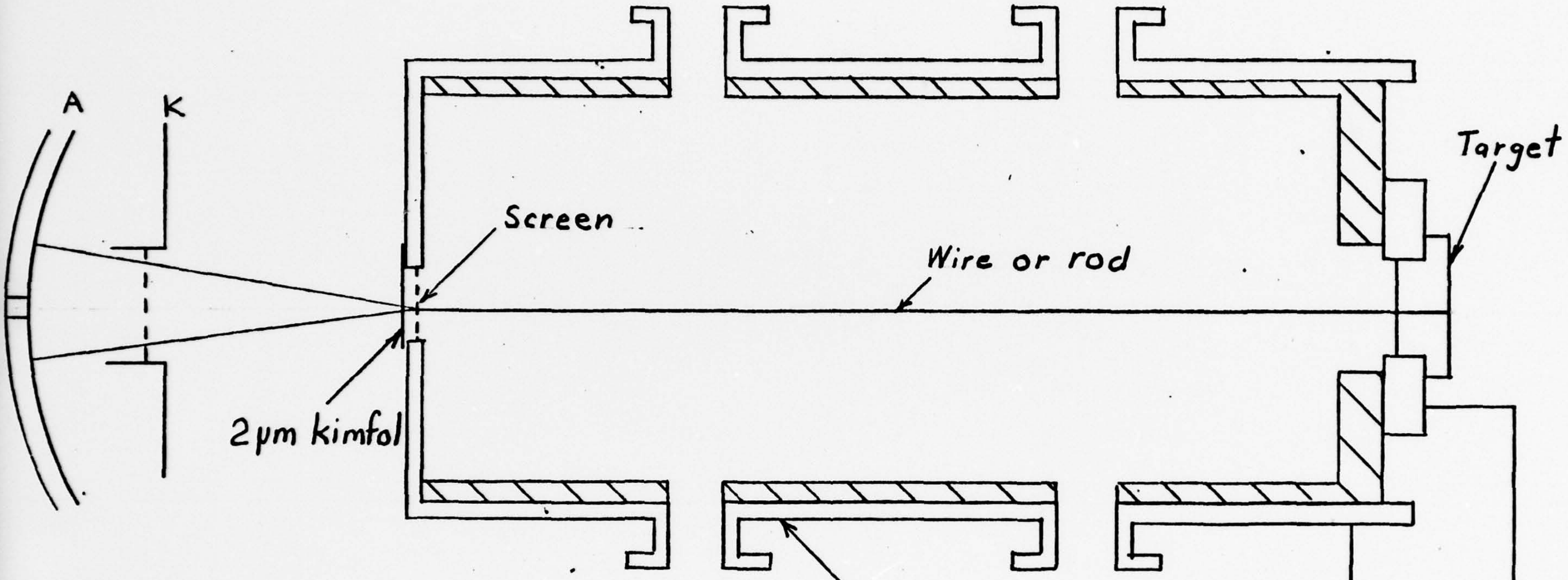


anode foils:
1 mil Al
.5 mil poly.
3 mil mylar
10 mil PVA

yields: planar ~ 1 kA/cm²
spherical ~ 3 kA/cm²

focusing: 2/3 through 2 cm² aperture

ION TRANSPORT EXPERIMENT

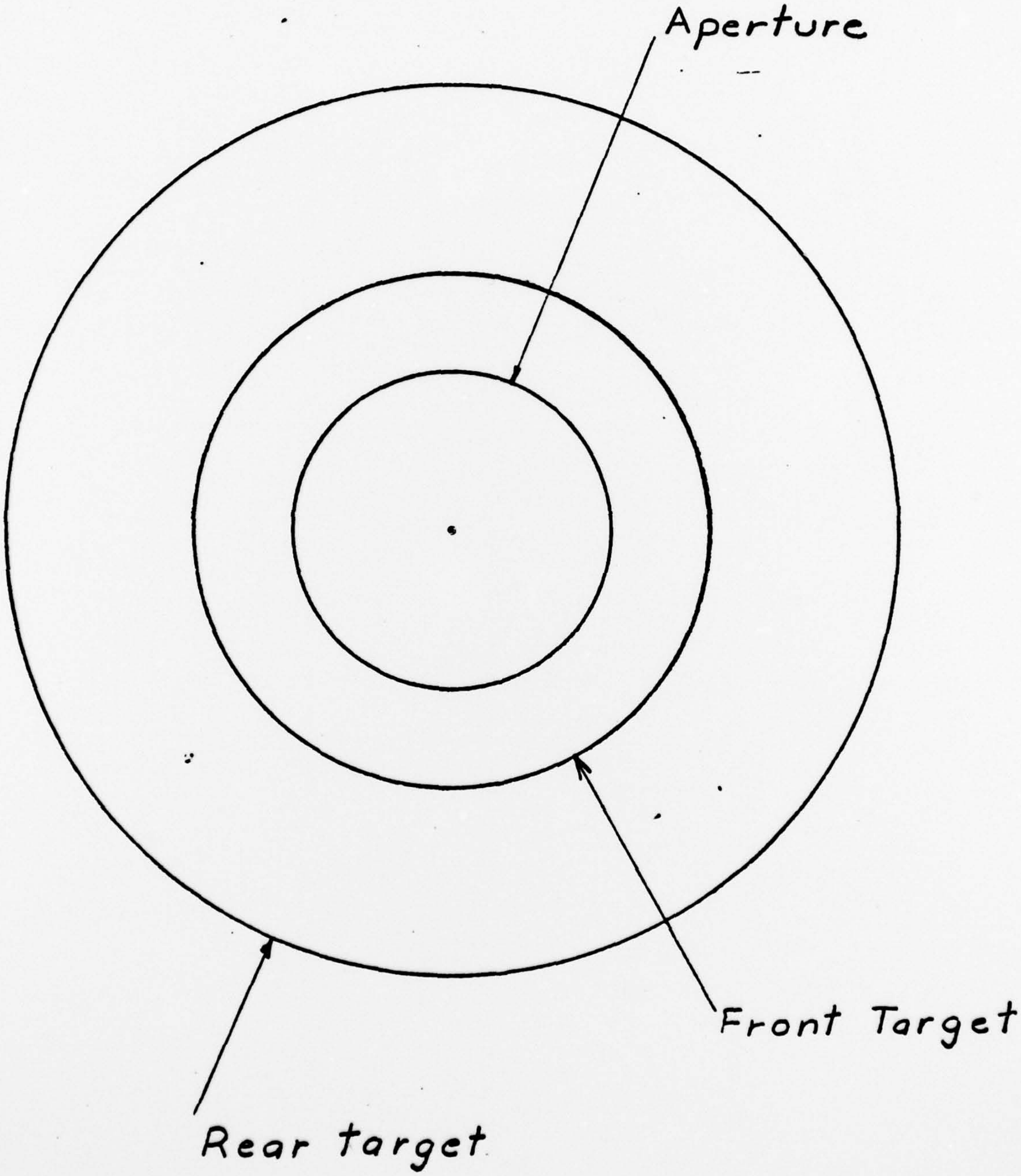


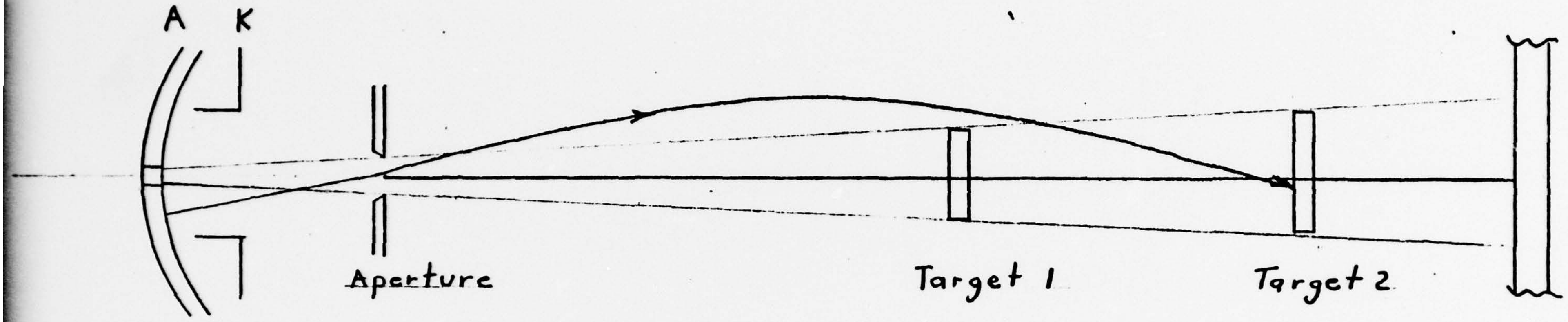
Diagnostics:
- C activation
- BN activation
- Humphries probe array
- Channel current
- X-ray pinhole camera
- PIN diodes
- Framing and still cameras

Figure
2

Figure 3

RADIAL DISTRIBUTION





Figure
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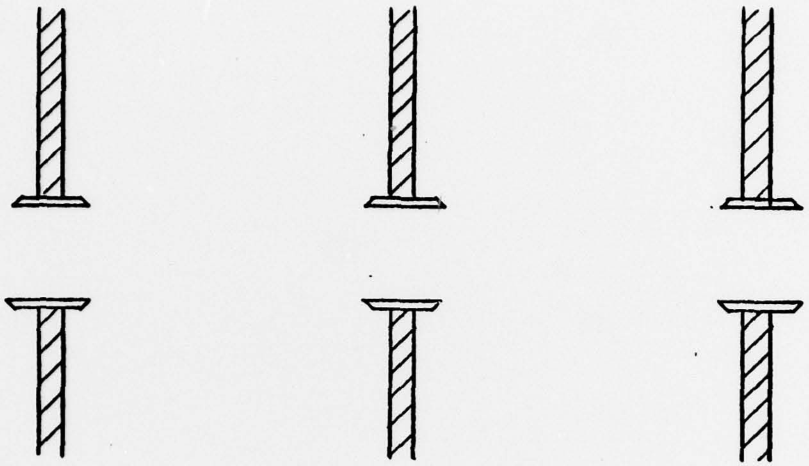

Figure
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