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<p>20. ABSTRACT (Continue on reverse side if necessary and identify by block number)</p> <p>There is presently great interest in using light ion beams to drive thermonuclear pellets. Terrawatt-level ion beams have been efficiently produced using conventional pulsed power generators at Sandia Laboratory with magnetically-insulated ion diodes and at the Naval Research Laboratory with pinch-reflex ion diodes. Both laboratories have recently focused ion beams to pellet dimensions. This paper reviews recent advances made at NRL in the area of ion production with pinch-reflex diodes, and in the areas of beam focusing and transport. In addition, modular generator and beam requirements for pellet ignition systems are reviewed and compared with the latest experimental results. These results include the following: (1) production of > 100 100 kJ proton and deuteron beams with peak ion powers approaching 2 TW on the PITHON generator in collaboration with Physics International (Continues)</p>		

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NRL Memorandum Report 4387

NRL Light Ion Beam Research for Inertial Confinement Fusion

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18. Supplementary Notes (Continued)

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20. Abstract (Continued)

Co., (2) focusing of 0.5 TW deuteron beams produced on the NRL Gamble II generator to current densities of about 300 kA/cm², and (3) efficient transport of 100 kA level ion beams over 1 meter distances using Z-discharge plasma channels.

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NRL LIGHT ION BEAM RESEARCH FOR INERTIAL CONFINEMENT FUSION

1. INTRODUCTION

The use of light ion beams (protons, deuterons, etc.) for inertial confinement fusion has been seriously pursued following the theoretical prediction¹⁻³ and the experimental documentation⁴, that small-area diodes ($\sim 100 \text{ cm}^2$) can be used to generate ion beams efficiently at the megavolt-megampere level. Soon after this, results of ballistic beam focusing experiments were presented⁵ and a technique for transporting ions in a plasma Z-discharge was introduced⁶. Recently, terrawatt-level ion beams with focused ion current densities in excess of 100 kA/cm^2 have been produced using water-dielectric transmission-line generators at Sandia Laboratories (SANDIA) with magnetically-insulated ion diodes⁷ and at the Naval Research Laboratory (NRL) with pinch-reflex ion diodes⁸.

Target designs for light ion beams⁹ call for delivery of about 2 MJ to an $\sim 1 \text{ cm}$ diameter pellet in an $\sim 10 \text{ ns}$ time scale in order to achieve high-gain thermonuclear ignition. Present pulsed power technology provides up to 10 TW single generator modules from which up to 300 kJ of ions can be extracted in 50-100 ns. Thus, a large number of modules and the means to transport energy from these modules onto the pellet are needed. Additionally, compression of the pulse to the pellet-implosion time-scale is required.

Two different approaches addressing these problem areas have emerged. An approach researched by SANDIA¹⁰ involves pulsed-power techniques for shortening the accelerating-voltage pulse, and self-magnetically insulated flow of electromagnetic energy in vacuum transmission lines which terminate in small ion diodes close to the pellet. Packing of transmission lines near the target, coupling of diodes to the lines, and ion-beam focusability will be investigated with the 36 short pulse, 1 TW PBFA I modules now in construction at SANDIA. For pellet ignition, this approach will require on the order of 100 modules.

A second approach, researched by NRL, involves the extraction and focusing of beams from self-insulated pinch-reflex ion diodes, coupled with transport of these focused beams in $\sim 1 \text{ cm}$ diameter Z-discharge transport channels. Pulse compression during transport to the pellet-implosion time-scale is achieved by increasing the accelerating voltage with time. These techniques are appropriate for modules operating up to the 10 TW level with a 50-100 ns pulse duration. The number of modules required for this approach is on the order of 10.

In the present report, major results of a combined experimental and theoretical study of the second approach are reviewed with concentration on recent advances made at NRL in the area of ion production using pinch-reflex diodes, and in the areas of beam focusing and transport.

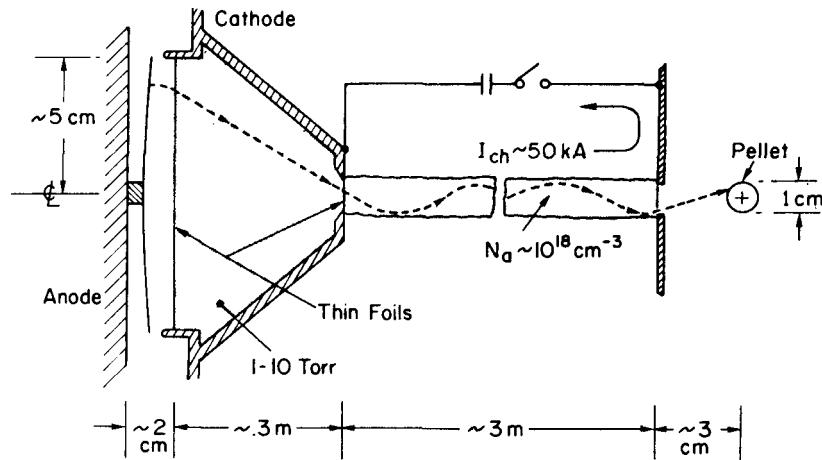


Fig. 1. Conceptual schematic of NRL Light-Ion Inertial Confinement Fusion Approach.

A conceptual schematic of the NRL approach is shown in Fig. 1. The diode and transport system together with the pulsed power generator (not shown) is one module of a multi-module pellet-ignition system. A pinch-reflex ion diode (~ 10 cm in diameter) produces the ions and properly aims them towards the transport system entrance aperture. The ion beam then free streams in a gas-filled chamber towards an ~ 1 cm diameter focus. The gas in the drift region allows the ion beam to be highly charge- and current-neutralized. Inside the channel, the ions are confined radially by the azimuthal magnetic field produced by the discharge of an external capacitor bank. The ~ 50 kA current in the channel is sufficient to provide radial confinement for ions entering the channel with transverse velocities below about 15% of their axial velocity. The plasma density in the channel must be sufficiently high to provide inertial resistance to channel expansion forces during beam transit and sufficiently low to prevent excessive energy loss of the beam during transport. Beam power multiplication of about a factor-of-five is achieved during transport to the pellet by ramping the accelerator voltage in time. Beams emerging from the channel propagate the last few centimeters to the pellet with low divergence because of the small transverse velocity. Several ion beams can then be overlapped onto the pellet.

The second section of this paper discusses ion production in pinch-reflex ion diodes including recent experiments¹¹ in collaboration with Physics International Co. on the PITHON generator. In these experiments, greater than 100 kJ of protons and deuterons were produced with peak ion powers approaching 2 TW. In Sec. 3, the self-focusing of ion beams with planar diode geometries is reviewed

and ion focusing experiments with curved geometries are reviewed in Sec. 4. In these experiments, 0.5 TW deuteron beams produced on the NRL Gamble II generator were focused to current densities of about 300 kA/cm^2 . In Sec. 5, the numerical simulation of pinch-reflex ion diodes is discussed. Theoretical work on ion orbits in the transport channel is reviewed in Sec. 6, and in Sec. 7 results of recent transport experiments are discussed. In these experiments, high current ion beams have been efficiently transported 1 meter distances using Z-discharge plasma channels. The MHD response of the channel induced by beam passage is then considered in Sec. 8. In Sec. 9, bunching of ion beams in transport channels is briefly discussed. Finally, the results of this research are used to determine a range of system parameters which are appropriate for driving high-gain pellets with proton or deuteron beams.

2. ION PRODUCTION

Self-pinched electron flow and laminar ion flow in a large-aspect-ratio electron-beam diode are conceptually illustrated in Fig. 2. After an initial phase leading to self-pinched flow¹², the electrons primarily originate from the edge of the cathode and flow under the dominant influence of the self-magnetic fields towards the diode axis ending up in a tight pinch at the center of the anode plane. The ions, which are primarily protons originating from the desorbed gases making up the anode plasma, are only slightly bent

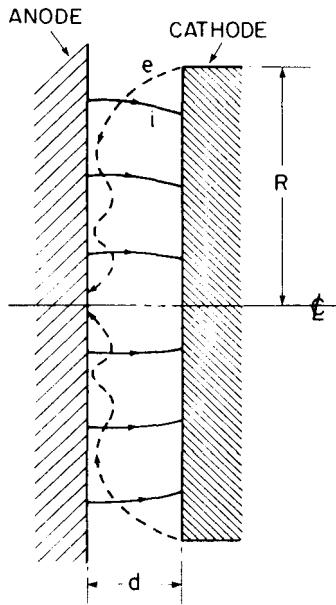


Fig. 2. Conceptual schematic of electron and ion flow in large-aspect-ratio ($R \gg d$) vacuum diode.

by the diode's self-magnetic fields due to their heavier mass. Thus ions flow in almost straight lines toward the cathode as they accelerate up to the diode voltage. The enhanced ion currents come about because of the additional electron space charge in the diode caused by the large electron path length (R) relative to the ion path length (d). For the simple diode configuration shown in Fig. 2 analytical theory predicts¹ and numerical simulation confirms¹³ an ion to electron current ratio of

$$\frac{I_i}{I_e} > \frac{R}{d} \left(\frac{eV}{2m_i c^2} \right)^{\frac{1}{2}}$$

where R is the diode radius, d is the anode-cathode gap spacing, V is the diode voltage and m_i is the ion mass.

Early experimental results¹⁴ with $R \approx 6$ cm and $d \approx 0.4$ cm giving $(I_i/I_e) \sim 1/2$ were in excellent agreement with this theory. These demonstrated 0.8 MeV proton currents of up to 200 kA. Using spherical section electrode structures, focused deuteron current densities of up to 70 kA/cm² were obtained¹⁵. These early results were obtained at 0.5 TW with the Gamble II generator operated for the first time in positive polarity. In positive-polarity operation, the cathode is mounted on the door of the generator so that ions accelerated through the diode potential can be injected into a drift tube region through a thin cathode transmission foil.

In the most recent positive polarity experiments⁸ on upgraded¹⁶ Gamble II at 1.5 TW, $\sim 60\%$ conversion efficiency from generator power to ion power was achieved using the refined diode design illustrated in Fig. 3. A thin CH₂ foil stretched across a dielectric ring is electrically connected to the positive electrode by a 1 cm-diameter rod on the diode axis. Plasma formation due to surface flashover causes the plastic foil to become a conductor early in the pulse and provides a source of ions. This geometry enhances ion emission by increasing the electron path length (and therefore lifetime) relative to that of ions by forcing the electrons to reflex through the thin foil as they pinch in radially. This reflexing is not due to spatial charge building up in the vacuum gap behind the foil because this is quickly neutralized by ions from the anode plasma. Rather, it is due to the azimuthal self-magnetic field caused by the return current flow through the center conductor. Thus, electron reflexing is magnetically induced behind the foil. In front of the foil, the electrons reflex in the self-consistent diode fields. The ions that are produced on the back of the anode foil do not carry diode current because the back plate is at anode potential. Results of the numerical simulation of this diode configuration will be presented in Sec. 5.

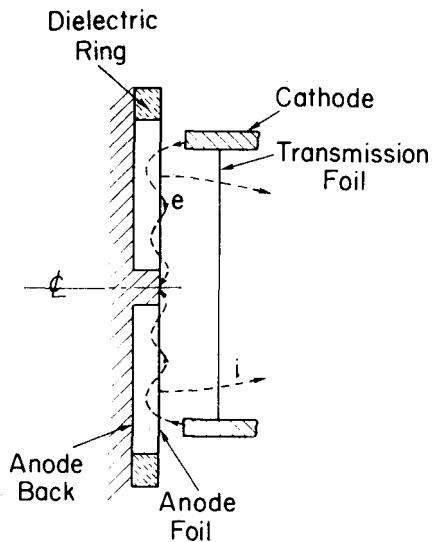


Fig. 3. Pinch-reflex diode schematic.

Typical diode electrical characteristics are shown in Fig. 4a for a 6 cm cathode radius, a 0.4 cm anode-cathode gap spacing, and a 0.5 cm vacuum gap behind the 0.01 cm CH_2 anode foil. Ion currents of 500 kA have been measured with 1 MA total diode currents. This corresponds to an average source ion current density of 5 kA/cm^2 . After passing through a phase associated with establishing the charged-particle flow illustrated in Fig. 3, the diode impedance remains well matched to the 1.5 ohm output impedance of the Gamble II generator. Closure of the anode-cathode gap due to electrode plasma motion usually occurs near the end of the electrical power pulse. The diode impedance can be adjusted by varying the cathode emitting area, the anode-cathode gap spacing, or the applied voltage. The natural voltage ramp which occurs demonstrates that accelerating voltages appropriate for ion bunching during transport to fusion pellets can be achieved with these generators. The net current signal (the current entering the cathode foil) is interpreted as the total ion current flowing in the anode-cathode gap. The location of the Rogowski coil used to make this measurement will be illustrated later in Fig. 6. On a few selected shots, the measured net current exceeded 700 kA at 1.3 MV out of 1.1 MA of total diode current. Carbon activation¹⁷ by proton beams indicates that greater than 50% of the net-current signal is due to protons. The interpretation of these results is limited by an unknown correction for deuteron activation. When the anode is coated with CD_2 , neutron time-of-flight measurements show that greater than 50% of the net current takes the form of deuterons. Up to 10^{12} neutrons have been measured on Gamble II. This data is consistent with ion

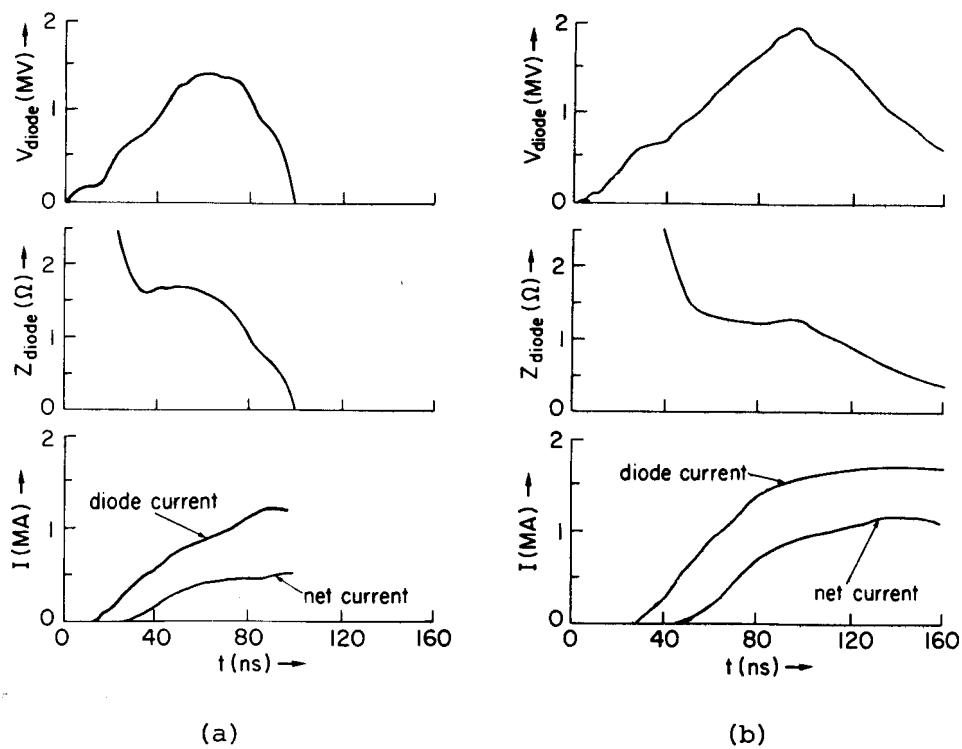


Fig. 4. Diode electrical characteristics for (a) Gamble II and (b) PITHON.

energies of at most 300 kV lower than the diode voltage of 1.3 MV. Several mechanisms are being investigated as a source of this loss.

In the most recent ion production experiments¹¹, a pinch-reflex ion diode, similar to that used on Gamble II (Fig. 3), was successfully operated at 3 TW on the Physics International PITHON generator. The main difference between the geometry used on Gamble II and that used on PITHON was that PITHON presently only operates in the normal negative polarity mode. Because the cathode was now at a 2 MV potential, this required special techniques to be able to both read out the ion current monitors and to fill the drift region behind the cathode with gas. Deuteron current measurements were made in the conventional manner by coating the anode foil with CD_2 and using both nuclear activation and time-of-flight neutron detectors to detect the neutrons produced from a (greater than one range thick) CD_2 target placed behind the cathode.

Typical diode electrical characteristics are shown in Fig. 4b for a 6 cm cathode radius, a 0.3 cm anode-cathode gap spacing, and a 0.5 cm vacuum gap behind the 0.01 cm CH_2 anode foil. Peak diode voltages of 2 MV at 1.5 MA diode current were obtained with flat impedance behavior even though the pulse length was almost twice as long as that on Gamble II. Ion currents of up to 1 MA were obtained

corresponding to peak ion powers approaching 2 TW. Over 100 kJ of ions were produced out of just over 200 kJ of electrical energy delivered to the diode. Impedance control and electrical reproducibility were excellent. When deuterons were produced, the neutron yield approached 10^{13} from the D-D and D-carbon reactions occurring in the CD_2 target.

As will be discussed in the last section, the voltage and ion currents produced on PITHON are in the range for a single module of a multi-module pellet ignition system. The long impedance lifetimes and high reproducibility associated with the ~ 1 cm gaps between the anode and cathode transmission foil indicates that programmed-voltage waveforms for beam bunching during transport can be employed. Focus perturbing effects associated with time varying B_θ fields in the diode region can be controlled for these ~ 1 cm diode gap by electrode shaping and naturally occurring gap closure as discussed in the next section.

3. ION FOCUSING IN PLANAR GEOMETRY

The processes believed to be important in ion focusing are schematically illustrated in Fig. 5. Ions traversing the vacuum gap are radially accelerated inward by the azimuthal magnetic field of the diode current flow. Particle-in-cell codes predict that the predominant electron flow in the diode is close to the anode surface where most of the potential drop across the diode takes place. Thus, the electron current contributes to the angular deflection of ions only for a small fraction of the vacuum space. The ions are radially

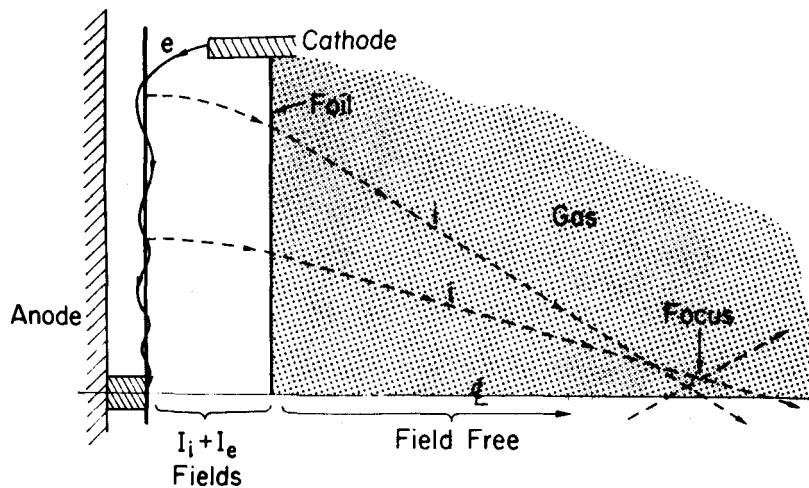


Fig. 5. Light ion focusing schematic.

accelerated primarily by their own current. If the ion current density were approximately uniform over the anode surface, then the resulting linear $B_\theta(r)$ would cause the ions to be pointed towards an approximately-common focus as they enter the cathode transmission foil. Scattering during passage through the 1.8 μm polycarbonate (KIMFOL) foil is about 20 mrad for 1 MeV protons. Beam induced breakdown of the low pressure gas filling the drift region to the right of the cathode foil allows beam current neutralization. The magnetic field acting on the ions is reduced by a factor of 50 by this neutralization. The ions have therefore nearly straight-line trajectories in this region and free stream towards the focus.

One major limitation to tight focusing is asymmetry in power and charged particle flow in the diode. This can be overcome by careful experimental design which results in well-centered electron pinches and centered symmetric ion focal spots. Another major limitation is the actual radial distribution of ion current which may direct ions emitted at different radii to different foci. In principle, for a given diode voltage and current, the shapes of the anode and cathode surfaces can be adjusted to correct for focus-perturbing effects of non-uniform ion current distributions. For instance, the launch angle can be changed by curving the anode surface. The radial deflection due to diode magnetic fields can also be changed by varying the axial position of the cathode foil as a function of radius. The anode-foil thickness can also be varied as a function of radius to vary the degree of electron reflexing and thus control the emitted ion current profile. A final major limitation to tight focusing is the time variation in the focusing magnetic fields which cause a change in focus location with time. This effect can be partially offset by the natural reduction of the anode-cathode (AK) gap due to electrode plasma motion. Thus, as the diode current increases, the increasing radial acceleration of the ions can be offset by the reduction of AK gap with time. In principle, both the initial AK gap spacing and the cathode foil material could be chosen to minimize this time variation effect.

Long focal lengths (i.e. large f-numbers) are achieved by magnetic self-focusing acting alone in a flat-anode geometry. This configuration is employed to inject ions into transport channels since larger-angle injection requires excessive transport-channel currents. Spherically-curved anodes in conjunction with self-magnetic forces are used to obtain shorter focal-lengths appropriate for target studies with the highest-focused current densities.

Three sets of focusing experiments in planar geometry were performed on Gamble II with electrical characteristics similar to those of Fig. 4a.

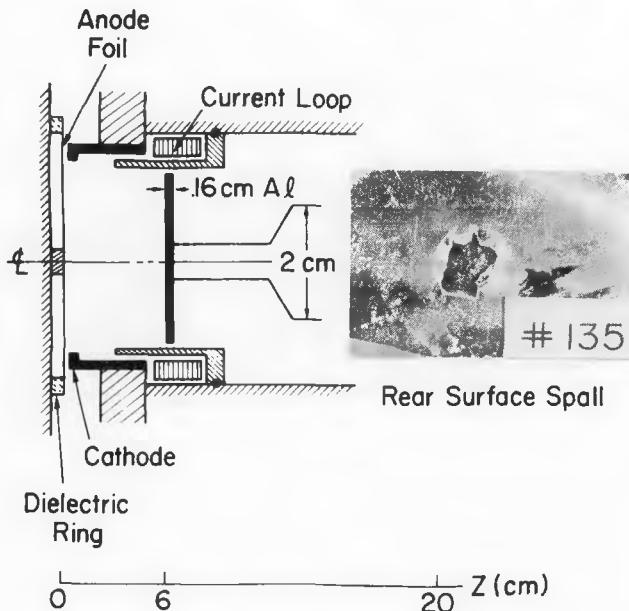


Fig. 6. Self-focusing in planar geometry with no cathode foil.

The first self-focusing experiments were performed with the planar diode geometry illustrated in Fig. 6 where a 0.01 cm thick CH_2 anode foil stretched across a dielectric ring was used with a 12 cm diameter hollow cathode without a cathode transmission foil. The ion beam was observed to self-focus 6 cm from the anode as indicated by the 1 cm^2 rear surface spall produced on a 0.16 cm thick aluminum witness plate. No spall was observed when the witness plate was placed a few centimeters to either side of this position. The focus location was in agreement with self-consistent analytical and numerical calculations for the self-focusing of a 500 kA, 1.3 MV proton beam. These calculations consist of solving ion orbit equations in the diode electromagnetic fields (determined from current and voltage measurements) and in the focusing/drift region magnetic fields (determined from net current measurements).

In the second set of self-focusing experiments, the 1.8 μm thick cathode foil was placed at 4 mm from the cathode face as shown in Fig. 7, and the drift tube was evacuated. A Rogowski coil in the evacuated drift tube measured a net current of about $\frac{1}{2}$ the total ion current. The ion self-focus, as determined from the rear surface spall of the witness plate, moved from 6 cm to about 12 cm from the anode plane, again consistent with the predicted location for this reduced net current in the drift section. The origin and nature of this net current has been discussed¹⁸.

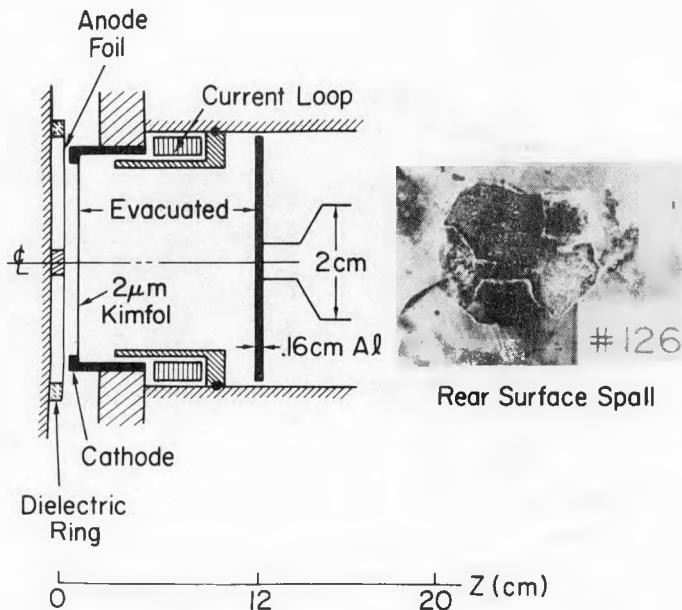


Fig. 7. Self-focusing in planar geometry with cathode foil and evacuated drift tube.

The final self-focusing experiments were performed with the cathode foil 2.8 cm from the anode and with the drift tube region behind the foil filled with 2 Torr of air. The large separation between the anode and the cathode foil insured that negligible electron current flowed from the cathode foil to the anode. This experiment is illustrated in Fig. 8. The cathode foil was bowed by the air pressure in the drift tube. The Rogowski coil surrounding the cathode foil support structure monitored the total current flowing into the cathode foil. The second Rogowski coil in the drift tube read less than 2% of the current read by the first for drift tube pressures between 0.2 to 3 Torr. With gas in the drift section, an aluminum witness plate placed at the 20 cm predicted focus location showed a 3 cm diameter rear surface spall. Computer analysis predicting ion orbits indicates that the 2-3 cm diameter focus spot size is consistent with axial motion of the best-focus location due to the time variation of diode current and voltage. That is, although the current and voltage values may be appropriate for tight focusing at peak power, the beam is under-focused early and over-focused late in time. No spall occurred a few centimeters to either side of this position and moving the cathode foil moved the focus location as predicted. It is important to note that damage patterns associated with focusing in the neutralizing gas backgrounds of this last set of experiments were typically well centered and symmetrical, whereas, focal spots obtained in vacuum display azimuthal irregularities and beam filamentation. Aluminum

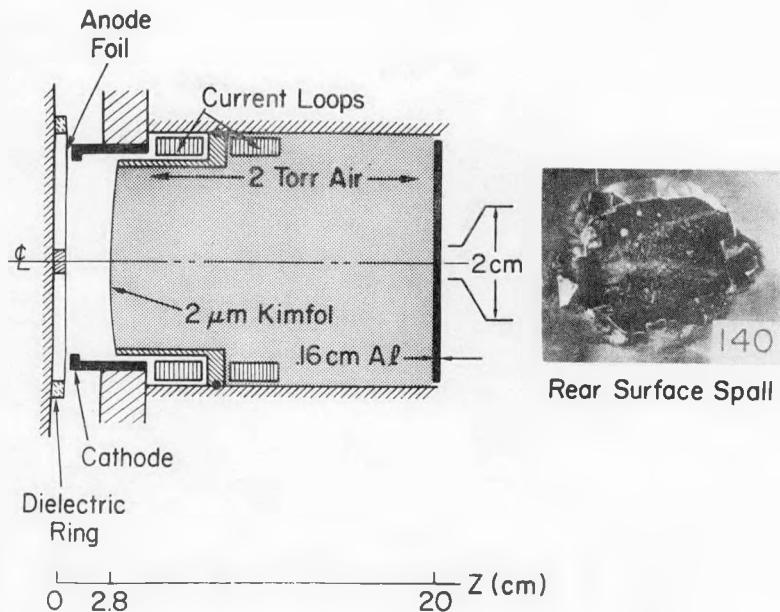


Fig. 8. Self-focusing in planar geometry with cathode foil and gas in drift tube.

K_{α} x-ray pinhole photographs⁷ showed a peak current density of about 50 kA/cm².

4. ION FOCUSING IN CURVED GEOMETRY

In order to achieve high ion current densities for beam target experiments, a 0.025 cm thick spherical-section plastic anode foil with a 12.7 cm radius of curvature was used. As shown in Fig. 9, the same cathode geometry previously shown was employed except for the closer proximity of the thin cathode transmission foil to the cathode surface. In this short-focal-length geometry, the ion launching angle dominates over the magnetic deflection in the diode. Focal spot broadening due to radial and temporal field effects is thus minimized. Aluminum witness plates placed at the best focus location exhibit smaller area spall patterns (1-1.5 cm diameter) than in flat geometry with gas. When the anode was coated with CD_2 , the observed focus was close to the geometric focus because of the small magnetic deflection of deuterons. By using small CD_2 targets and measuring neutrons from D-D and D-carbon reactions with activation counters and time-of-flight detectors, peak deuteron current densities of about 300 kA/cm² over 0.5-1 cm² were inferred. Typical neutron yields were a fraction of 10^{12} neutrons.

Important new experimental results for focusing are provided by a pinhole shadowbox diagnostic shown in Fig. 10. Small ion

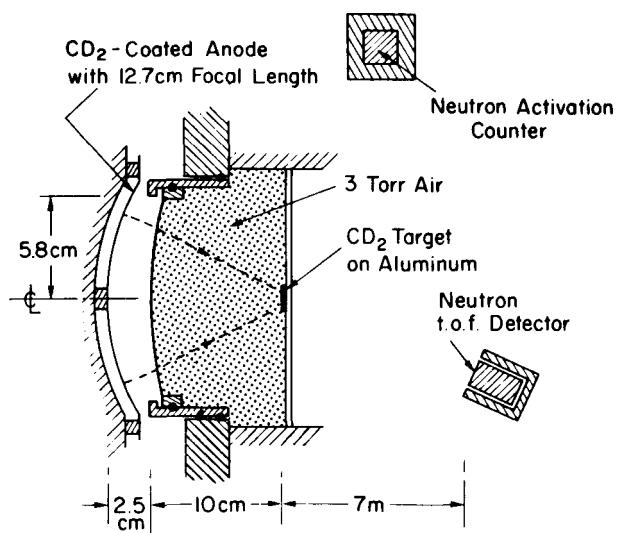


Fig. 9. Geometric focus experiments.

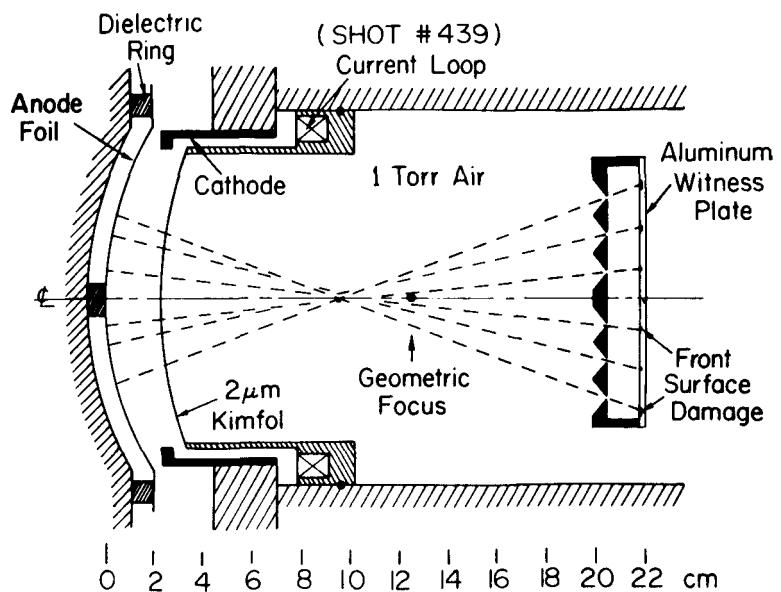


Fig. 10. Ion pinhole shadowbox.

beamlets are produced by masking off all of the beam drifting in the neutralizing background except for that portion emerging through 1 mm diameter holes placed along two diameters at right angles. Damage patterns produced on a aluminum witness plate 1 cm behind the pinhole array (shown as solid spots in the figure) allows one to determine ballistic orbits for ions entering pinholes at various radii. When the shadowbox is placed further from the diode than the center of the ion focus, these orbits can be projected from the damage spots back through the pinhole to the focus. These are shown as dashed lines in the figure. In this manner, the best focus location and the radial dependence of ion deflection angle can be determined. Additionally, the radial extent (typically a few millimeters) of each damage pattern reflects the time-variation of deflection angle due to time-varying diode fields. The preliminary Gamble II results with protons demonstrate that radial deflections of damage patterns (shown in Figure 10) are consistent with the measured focus location. Diode deflection angles were found to be roughly proportional to radius. Also, the significantly smaller observed azimuthal extent of damage compared with the radial extent of damage suggests that with proper aspheric anode and cathode shapes, focusing of ion beams to areas very much less than the present 1-3 cm² should be possible.

5. NUMERICAL SIMULATION OF PINCH-REFLEX ION DIODES

Numerical simulations of electron and ion flow in pinch-reflex diodes were conducted for the configuration shown in Fig. 11 using the NRL DIODE2D simulation code.¹⁹ The initial equipotential lines are also shown in the figure. The diode dimensions modeled in the simulation had an R/d=20 aspect-ratio where r=6.8 cm was the outer radius of the hollow cathode and d=0.32 cm was the separation of the cathode face from the anode foil. The thickness of the cathode shank was 0.8 cm and the scattering foil was assumed to be 125 μ m thick polyethylene. The distance between the reflexing foil and the solid anode was 0.29 cm. This space was assumed to be filled with ions which charge neutralize the reflexing electrons, making it unnecessary to solve for the electrostatic fields in that region. The distance from the reflexing foil back to the ion transmission foil inside the hollow cathode was 0.7 cm. These new simulations were carried out on a finer 64x40 mesh rather than the 32x40 mesh used in previously reported results.²⁰ The simulations also assumed azimuthal symmetry and were done in (R,Z) geometry with a time step of 0.25 psec.

The time evolution of the electron and ion flow in the diode is shown in Fig. 12 for a simulation done at 1.5 MV. The positions of the electrons and ions are shown in (R,Z) configuration space at four different times. Early in time (step 500), the electrons (one in 10 is plotted on the figure) had transited the diode and

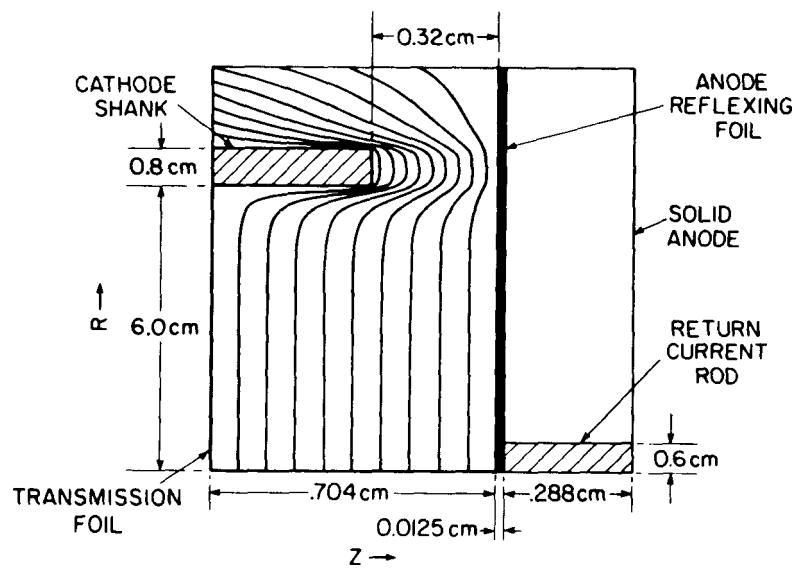


Fig. 11. Configuration used for pinch-reflex diode simulation showing equipotential lines due to applied voltage.

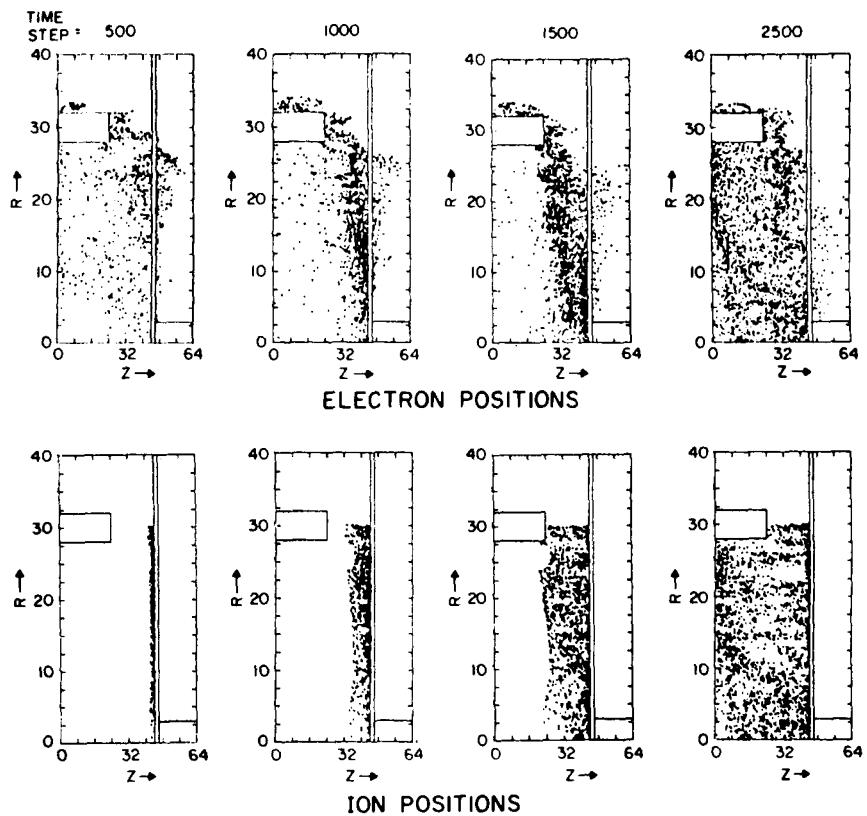


Fig. 12. Time history of the electron and ion positions in the diode.

reflexed several times through the foil. The ions had not yet crossed the diode gap and were clumped along the anode foil. By time step 1000, the electrons had established the pinched flow along the diode side of the reflexing foil. At step 1500, the pinched electron flow was well established and the electrons filled the diode gap. However, electrons did not flow along the foil except at low radii because of the tendency for electrons to follow ions at large radii to provide space charge neutralization. At step 2500, all the ions had now crossed the gap and a quasi-steady state was established. The flow pattern shown at step 2500 persisted for the remainder of the run which was taken to step 4000.

In the quasi-steady state the equipotential lines are piled up near the anode foil so that most of the potential drop occurs over a distance much less than the 0.32 cm gap between the cathode face and the anode foil. This justifies the assumption of Sec. 3 that the ion bending between the anode and cathode foil is primarily due to the self-magnetic field of the ions. The current density profile of the ions arriving at the cathode transmission foil is shown in Fig. 13. This current profile, which is the result of averaging the arriving ion current for 500 time steps, shows a $1/R$ dependence as predicted by analytic theory² for planar diodes. The simulation for this case assumed that ion emission occurred along the reflexing foil up to a radius of 6.4 cm. In this case, the net ion current was 590 kA and the electron current 330 kA. In order to determine if the average ion current density could be increased by suppressing ion emission at large radii, a case where emission was allowed only up to a radius of 3.0 cm was also

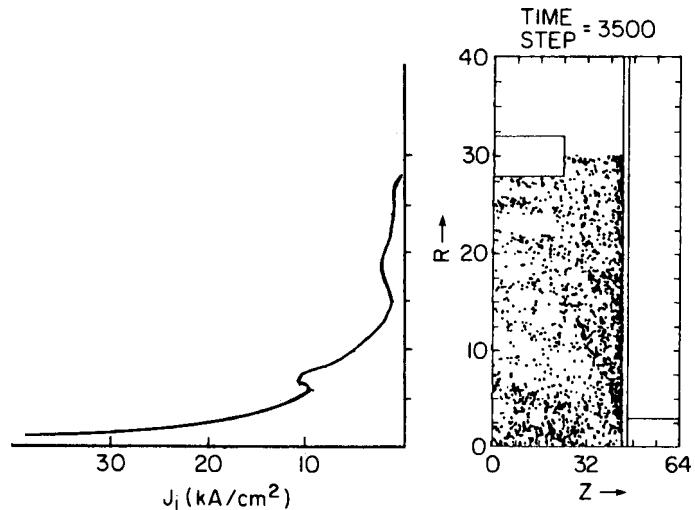


Fig. 13. Ion current density profile at the cathode and ion positions in the quasi-steady state.

simulated. In this case, the total diode current remained close to 900 kA and the total ion current decreased by about a factor of 2.

The simulation results are in reasonable agreement with the NRL experimental data with respect to total ion and electron currents. The geometry was different enough so that it is difficult to make a more quantitative statement. The transmission foil is further removed from the cathode face in the present Gamble II experiments than in the simulation and this may affect the diode behavior. Further simulations that are closer to the actual experimental configurations are being conducted so that a more direct comparison with experiments can be made.

6. ION ORBITS IN Z-DISCHARGE CHANNELS

As shown in Fig. 14, ions enter the discharge channel with a range of injection angles up to θ_M determined by the anode radius and distance to the focus. The externally-applied current flowing through the channel must be sufficient to confine ions with maximum transverse kinetic energy, that is, ions which enter the channel with the maximum injection angle at the maximum injection radius, r_s . The required discharge current can be determined from conservation of ion energy and P_z conical momentum

$$v_r^2 + v_z^2 = v_0^2 ; \quad v_z = v_0 \cos\theta + \frac{q}{m} \int_{r_0}^r B_\theta(r') dr' ,$$

where $\frac{1}{2}mv_0^2$ is the energy of an ion with charge q , θ is the injection angle and r_0 is the injection radius. In order for the magnetic

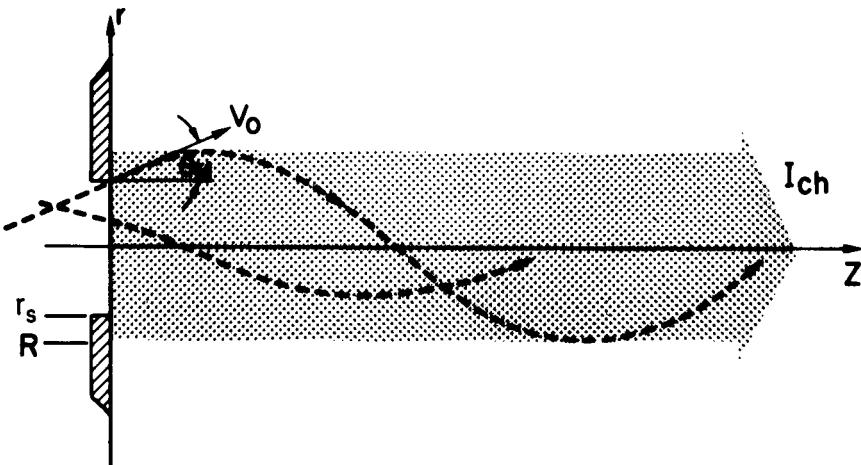


Fig. 14. Ion orbits in a z-discharge channel.

field to be just sufficient to confine a maximum-transverse-energy ion to the channel radius (R), V_r must vanish when $r = R$ for initial conditions $\theta = \theta_M$ and $r_o = r_s$. Substituting into the previous equation, results in the expression

$$q \int_{r_s}^R B_\theta dr = m V_o (1 - \cos \theta_M) . \quad (1)$$

Defining an ideal channel as one carrying a uniform discharge current so that $B_\theta \sim r$ when $r \leq R$, Eq. (1) takes the form

$$I_{ch} (A) = \frac{10^{-3} V_o (1 - \cos \theta_M)}{1 - (r_s/R)^2} \quad (2)$$

for protons where I_{ch} is in amperes when V_o is in cm/s. This result indicates that megampere discharge currents are required to confine ions injected with large angles. Protons of 5 MeV with $\theta_M = 0.2$ radians require about 120 kA for confinement within the channel when $r_s/R = 2/3$.

Analytical and computational techniques have been used to determine the effects of various forms of nonideal channel behavior on ion confinement and beam bunching.²¹ Axial electric fields associated with plasma currents and expansion disrupt confinement and reduce beam power multiplication due to bunching only if large enough to strongly slow the beam during transport. Radially non-uniform net currents develop as the beam passes through the background because of beam-induced MHD expansion of the channel. The effects of the resulting B_θ fields on beam confinement are discussed in Sec. 8. Channels which taper to smaller radius as they approach the pellet were investigated as a means of increasing the beam current density. A WKB-like analysis for the ion motion shows that only a small improvement in current density due to radial beam compression can be achieved before disruption of axial compression by bunching. Both analytic and numerical calculations were performed to determine ion confinement in a channel with a large amplitude $m = 0$ sausage instability. Fig. 15 shows one result of this work. The channel B_θ was modeled as $\sim r$ inside the channel radius $R(z)$, and $\sim 1/r$ outside. With every change in axial location $\Delta z = \lambda$, the value of R changed abruptly and randomly to simulate the non-linear development of the instability. A large number of ion orbits were numerically determined for a range of injection angles up to θ_M and injection radii up to r_s . The figure shows a cross-section of beam ion density at various axial locations along the channel. The case shown corresponds to $r_s = 0.4$ cm, $R = 0.6$ cm, $E_i = 5$ MeV, $\theta_M = 0.2$ radians, $I_{ch} = 120$ kA, $\lambda = 3.8$ cm, $\Delta R_{rms}/\bar{R} = 1$. This high

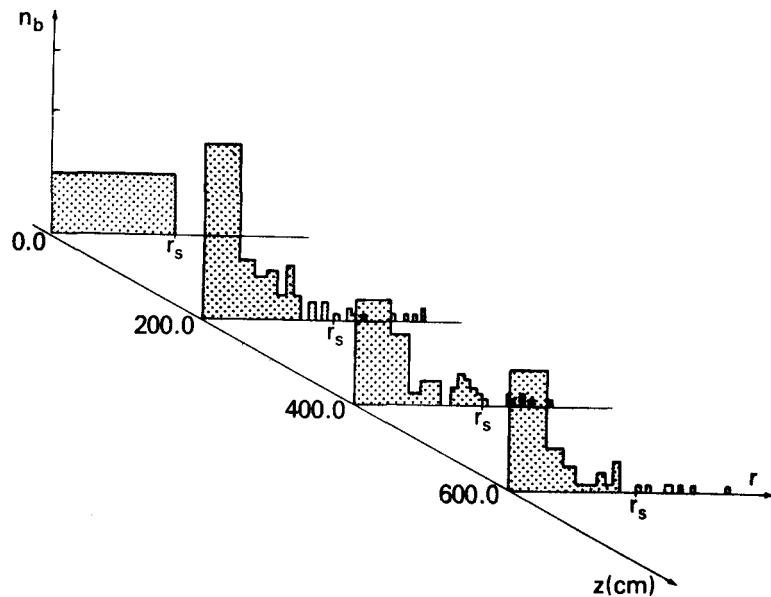


Fig. 15. Beam density profile at various axial locations along a sausage unstable channel.

degree of fluctuation is required for radial loss of half the beam ions after transporting 6 m. When ΔR_{rms} is decreased by about a factor of 2, only about 9% of the beam is lost at 6 m. Good radial confinement is predicted for all cases in which the axial wave length of the instability is much smaller than the betatron wavelength of the ion in the channel. Electrostatic and electromagnetic microinstabilities driven by the relative streaming between the beam ions and the channel plasma have been discussed previously.²²

7. ION TRANSPORT EXPERIMENTS

Figure 16 illustrates the experimental configuration for transport experiments on Gamble II. The planar, pinch-reflex diode configuration shown previously in Fig. 8 was used to bring a 0.5 MA, 1.4 MV proton beam to a narrow-angle focus ($\sim 50 \text{ kA/cm}^2$) 20-30 cm downstream from the diode. The transport section consisted of a copper pipe containing an insulating ceramic liner filled to the 0.2-2 Torr air background pressure of the focusing-drift section. The inside diameter of the ceramic liner defines the diameter of the wall-stabilized discharge. A discharge channel diameter of 4.5 cm was employed. The discharge current was provided by a 20 kV, 10 kJ capacitor bank. The current rose to about 50 kA in 15 μs after which time the ion beam was injected into the channel. This current satisfies Eq. (2) for the injection angles employed in the experiment. Measurements of transport efficiency were provided by diagnosis of 6 MeV gamma rays produced by the interaction of beam protons with fluorine²³. Collimated scintillator-

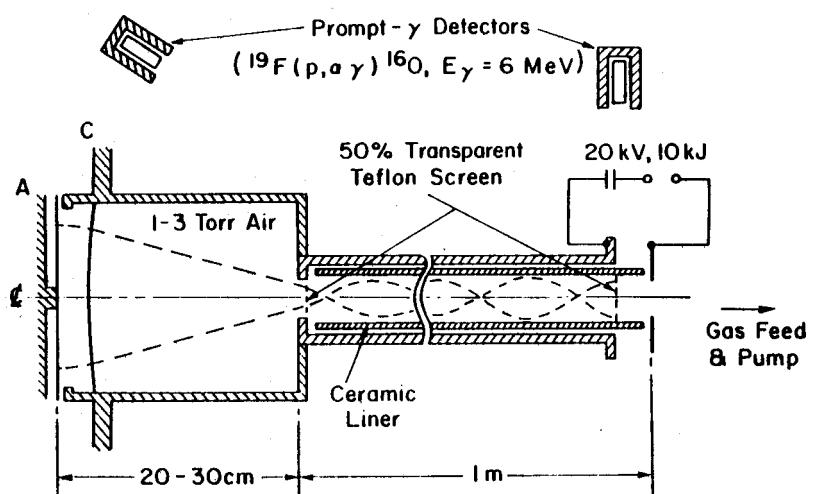


Fig. 16. Ion transport experiment schematic.

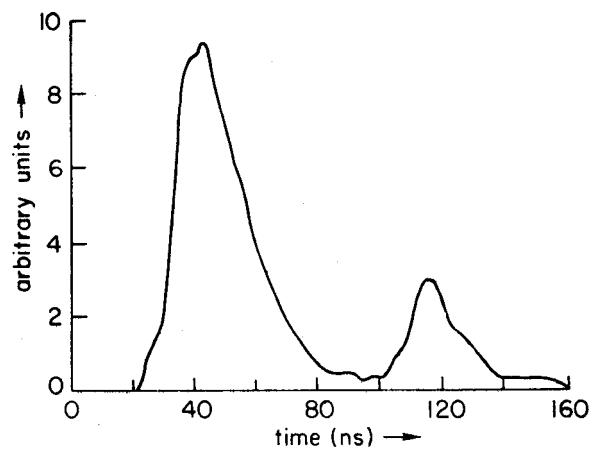


Fig. 17. Prompt- γ signal from two 50% transparent teflon targets placed on meter apart in the channel.

photomultiplier detectors were used to detect the gamma rays produced in 50% transparent teflon screens placed at the entrance and exit apertures of the transport system.

The signal shown in Fig. 17 was obtained with a single detector placed about 4 m from both screens and behind about 0.5 m of concrete. Signals from the two screens are separated by the ion time-of-flight through the 1 m discharge channel. Because the teflon screens are 50% transparent, the second signal must be multiplied by a factor of 2 in order for comparison with the signal from the entrance aperture. Since the gamma-ray production cross-section is a strong function of the proton energy, the transport efficiency could not be immediately inferred from the ratio of signals associated with the two screens. Assuming no ion energy loss during transport, experimental results indicated a lower limit of 50% transport efficiency. If an energy loss of 200 kV is assumed, which is consistent with the relative timing between the prompt- γ signals shown in Fig. 17, then the particle transport efficiency in the channel is about 80%. A more concrete example of the ability to transport ion beams is provided by witness plates at the exit aperture. Aluminum plates 0.16 cm thick exhibited rear surface spalls with widths less than the channel diameter. Null experiments, measurements without channel current, did not show evidence of ion transport.

In more recent transport experiments a smaller 1.6 cm diameter channel was used with a much faster risetime (0.5 μ s) capacitor bank than previously employed. Preliminary results indicate that proton beams with current densities of several tens of kA/cm^2 were efficiently transported over 1 m distances. Unlike the large diameter channel transport experiments, shots were taken with the ion beam injected into the channel while the channel plasma was still radially imploding. On these shots, the shapes and relative timing of the input and output prompt- γ signals suggest that the protons may have gained rather than lost energy in the channel. This observation would be consistent with recent theoretical predictions²⁴ that the transported ion beam could gain energy from the fields associated with a radially imploding Z-pinch plasma. This phenomenon is presently under investigation.

8. RESPONSE OF THE CHANNEL TO BEAM TRANSIT

As the focused ion beam transits the transport channel, it heats the background plasma by collisional deposition and induces plasma-electron return currents which resistively heat the plasma. Since the electromagnetic fields induced by the beam can vary substantially from those assumed to confine the beam ions, it is important to determine how the self-consistent fields alter beam confinement and energy loss during transport. To answer these

questions, a 1-D radial, time-dependent MHD code has been developed²⁵. The code solves the usual conservation equations for particle number, momentum and energy. The $\vec{V} \times \vec{B}$ and $\vec{V} \times \vec{E}$ Maxwell's relations, and electron transport equations (using classical coefficients for electrical and thermal conduction) close the set of equations. The beam is specified by its current density in space and time and the particle energy as a function of time. Collisional beam deposition and plasma-electron return-current heating are included as is bremsstrahlung radiation cooling. Development of radial profiles in time for background density, electron and ion temperature, azimuthal magnetic field and radial velocity are shown in Fig. 18 for a 50 kA discharge in deuterium carrying 600 kA of 5 MeV protons in a 50 ns pulse. Since the plasma is initially at rest, no radial velocity profile is shown in Fig. 18a. The initial temperature distribution is thus determined by an equilibrium pressure balance condition. Once the beam enters the channel, the plasma pressure and $\vec{j} \times \vec{B}$ forces acting on the plasma push material out of the channel interior and pile it up against the steep density gradient at the channel edge. The initial magnetic field profile corresponds to uniform current density arising from the long times and the low conductivities associated with channel creation. Once the beam heats the channel (Fig. 18b), the conductivity rises quickly and magnetic field lines become frozen in the plasma. The magnetic field is then convected out of the center of the channel along with the plasma flow.

A primary criterion for maintenance of beam confinement is suggested by Eq. (1) and is given by the integral extended from r_0 to R . If the value of the integral is reduced, ions injected with large r_0 or θ_0 can reach the high density edge of the channel and be lost. For low beam current cases, the plasma channel response to the beam is sufficiently gentle not to disrupt confinement. However, in the high-current cases, ions with larger transverse energy are lost.

The evolution of the confinement integral with time does not depend sensitively on the ion energy. This behavior can be understood qualitatively by examining the plasma equation of motion.

$$\rho \frac{dv_r}{dt} = - \frac{\partial p}{\partial r} - j_z B_\theta \approx j_b B_\theta \quad (3)$$

The final expression on the right hand side of Eq. (3) results from the dominance of the $j \times B$ term over the pressure term and good beam current neutralization. For a maximum allowed acceleration given by $2R/\tau^2$, where τ is the beam duration, Eq. (3) yields

$$I_b I_{ch} < 300 \rho R^4 / \tau^2 \quad (4)$$

for maintenance of beam confinement. In Eq. (4), the currents are

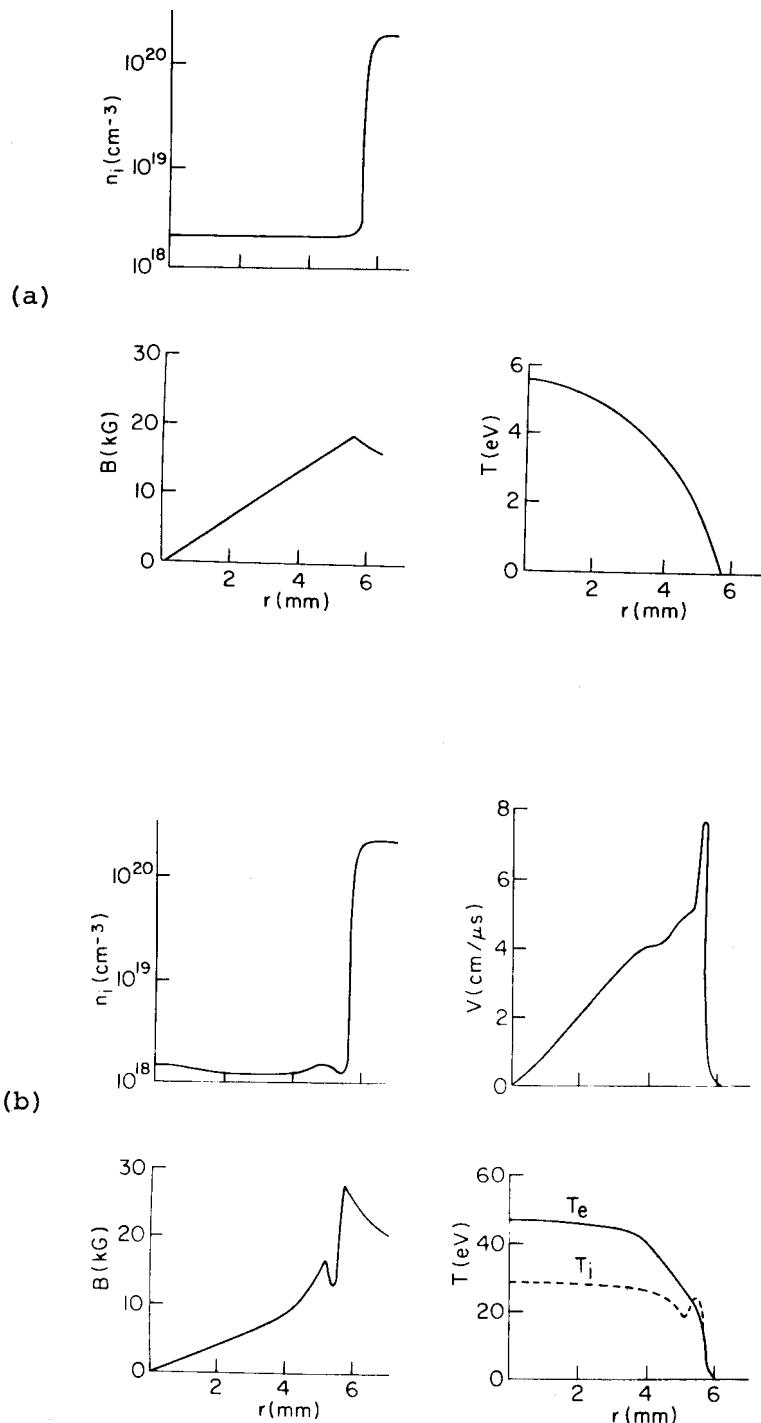


Fig. 18. Initial (a) and final (b) radial profiles in time for background plasma density, azimuthal magnetic field, electron and ion temperature ($T_i = T_e$ initially), and radial plasma velocity ($V=0$ initially).

in amperes and the terms of the right-hand-side are in cgs units. This condition is in qualitative agreement with the results of the MHD code. Because of the greater primary beam deposition, lower-voltage ion beams require lower background density. Thus, the maximum allowed value of $I_b I_{ch}$ is reduced with lower ion voltage. This indicates that less power can be transported in channels carrying lower-voltage ions unless the channel current can be significantly reduced. However, the channel current is determined primarily by the spread of injection angles and θ_M is unlikely to be reduced for less-stiff lower-energy ions. Additionally, Eq. (4) is easier to satisfy with the beam in the bunched state since $I_b T$ remains constant as T is reduced. If a final focusing stage after transport can be employed²⁶, then the beam can be transported with a radius larger than the pellet size. In this case the constraints of Eq. (4) can be considerably relaxed because of the strong R^4 dependence.

A second important consideration for beam transport channels is the total energy loss suffered by the beam during transport. The energy loss consists of both that due to primary deposition and that due to slowing in the electric field produced by return currents and plasma expansion. For the example considered in Fig. 18, the 5 MV protons lose about 200 kV/m. This energy loss could be reduced or possibly turned into an energy gain²⁴ if the channel plasma during beam injection is imploding with a velocity of $\sim 10^7$ cm/sec using a 100 kA channel current.

9. BEAM BUNCHING DURING TRANSPORT

Since the time of flight of the ions through the channel to the pellet usually exceeds the beam pulse duration, applying an accelerating voltage ramp at the diode can result in power multiplication (PM) by beam bunching²⁷. Since the pulsed-power technology employed results in ion emission times of 50-100 ns and the desired irradiation time on the pellet is about 20 ns, as much as a factor-of-5 bunching is desirable. For purely axial motion, ions accelerated by the ideal voltage waveform

$$\Phi(t) = \frac{\Phi_0}{(1-t/t_a)^2} ; 0 \leq t \leq t_a < t_a \quad (5)$$

all arrive at the target at the same time t_a . In reality, errors in voltage shape, $\delta\Phi$, and the spread in ion injection angles contribute to a spread in arrival times, δt_a , thus limiting the degree of power multiplication to a factor $\tau/\delta t_a$. For a desired PM factor of 5, analysis indicates that $\delta\Phi/\Phi \leq 0.15$ and $\theta_M \leq 0.3$ radians are sufficient for parameters of interest.

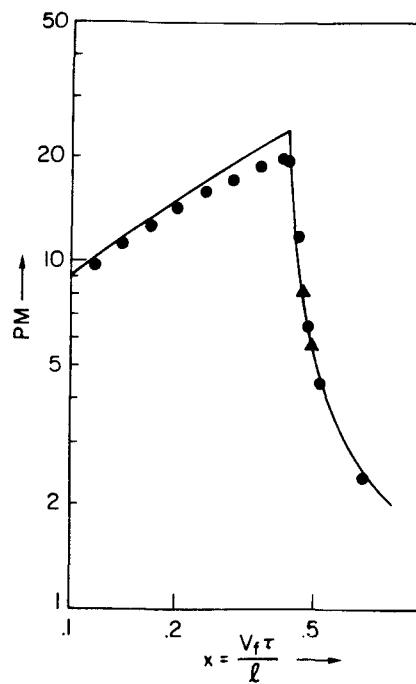


Fig. 19. Theoretically achievable power multiplication predicted by analytic modeling (solid curve) and macroparticle code.

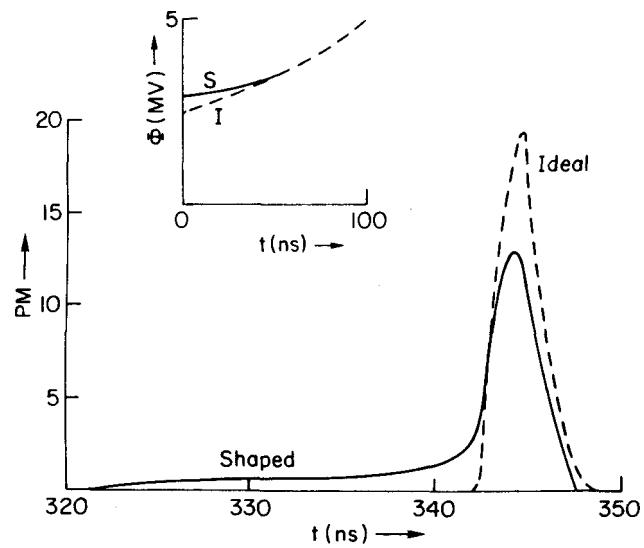


Fig. 20. Bunched pulse shaping.

Figure 19 compares analytic modeling of achievable power multiplication with a macroparticle code, where ℓ is the distance to the target and V_f is the ion speed at $t = T$. Below $x = 0.414$, PM is limited by the spread in injection angles $\theta_M = 0.2$ radians. Above this value, PM is determined by a maximum voltage ramp $\Phi_f/\Phi_0 = 2$ in order to control the energy spectrum of ions depositing in the pellet.

Figure 20 compares the time variation of power on target using two voltage waveforms and the parameter set $r_s = 0.4$, $R = 0.6$ cm, $\ell = 7.5$ m, $\theta_M = 0.2$ radians. Peak power multiplication is achieved by employing the ideal voltage. In that case, the power multiplication is limited by the dispersion in injection angles. When the accelerating voltage is higher than the ideal early in time, some ions arrive early on target. This results in a shaped foot which may be desirable for some inertial-confinement-fusion target configurations.

10. SYSTEM REQUIREMENTS FOR INERTIAL CONFINEMENT FUSION

Pulsed power, ion focusing, transport, bunching and beam-target interaction considerations can be combined in order to determine an acceptable set of system parameters for the ignition of a high-gain fusion pellet. High voltage beams are easily focused because of their relative insensitivity to time-varying magnetic fields in the diode. However, their long range in materials leads to inefficient energy coupling to fusion targets. Low voltage beams suffer from excessive energy loss in the transport channel and difficulty in focusing. For any voltage, channel hydrodynamic response calculations indicate difficulty in transporting ion beams much in excess of 1 MA without employing a final focusing stage. Thus, for a fixed power and energy requirement delivered to the target, MHD considerations establish a lower limit on the number of channels which can be used to transport ion beams to the target. An upper limit on the number of channels which can be used is set by considerations that include channel creation energy and beam overlap problems. These points are considered in Fig. 21 which defines an acceptable parameter range for a 2 MJ ion beam incident on a high-gain pellet. The SANDIA PBFA concept has design objectives in the lower right-hand corner of the window. Research at NRL concentrates primarily on parameters of the upper left. Table 1 summarizes an acceptable range of system parameters based on the considerations discussed above. Parameters based on two pellet requirements and two ion pulse durations are shown. The stored energy is an estimate of the total electrical energy stored in the Marx generators required to provide the total ion beam energy. The shorter-duration beams require higher powers in the diode but also require less bunching in order to achieve power on target. The focused power represents the total focused ion beam power for all the modules into the entrance of all the channels.

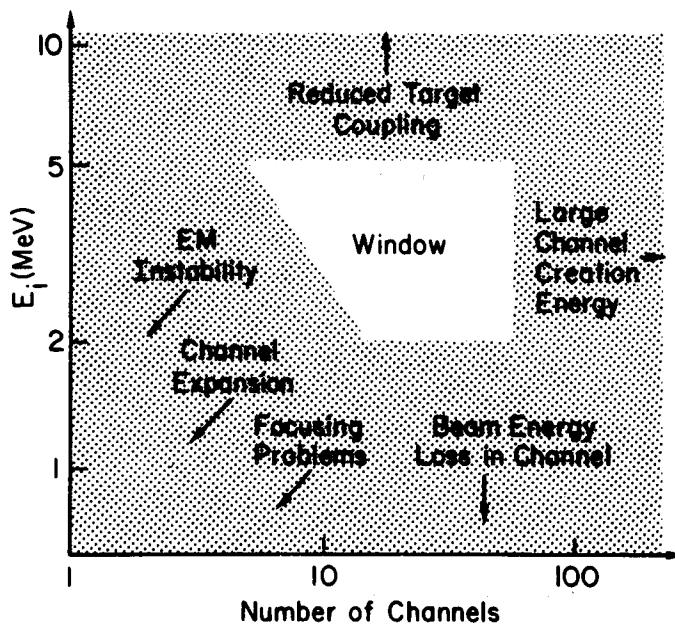


Fig. 21. Channel number considerations for protons in hydrogen.

Table I. Ignition System Parameter.

ENERGY ON PELLET (MJ)	3	2		
POWER ON PELLET (TW)	200	100		
STORED ENERGY (MJ)	24	16		
PULSE DURATION (ns)	100	50	100	50
FOCUSED POWER (TW)	35	70	23	45
POWER MULTIPLICATION	6	3	4.5	2
FOCUSED CURRENT (mA)				
5 MeV PEAK	7	14	4.5	9
2 MeV PEAK	18	35	12	23
MIN. BUNCHING LENGTH (m)				
5 MeV PROTONS	6	2.5	6	2
2 MeV DEUTERONS	3	1	2.5	0.8

Focused current represents the total current transported by all channels. Using 1 MA as the current which can be transported in any given channel, the focused current numbers represent an estimate of the minimum number of channels required to transport the total beam. The minimum channel length (i.e. stand-off distance) is arrived at by determining the smallest transport length which can achieve the desired degree of power multiplication (PM) using an accelerating voltage which varies by no more than a factor of 2. This bunching length may be estimated from²¹

$$\frac{V_f T}{l} = \frac{0.414}{1-1/PM}$$

The scaling of l with PM results from the fact that smaller lengths than necessary for optimal bunching are sufficient for moderate power multiplication factors.

Extension of these results to ion species other than $Z = 1$ requires further investigation of transport properties. Higher voltage beams can transport at lower beam current to achieve beam powers comparable to $Z = 1$. Channel currents are uncertain. From Eq. (1), I_{ch} is proportional to the larger values of m/q . However, it tends to be reduced by the smaller values of θ_M permitted by better focusing control.

In the near future scaling of present results will be attempted in the following areas. Diode behavior at the 3-5 TW level on PITHON will be studied in order to check ion beam efficiency and focusability. The physics of higher voltage (up to 10 MV) diodes operating at impedances up to 20 ohms will be studied on the Harry Diamond Laboratory Aurora generator.²⁸ Transport of ion beams will be performed in longer channels where beam bunching may be investigated. Larger diameter channels with a final focusing stage will be studied in order to achieve transport of higher current, longer duration ion beams. The effect of imploding plasma discharges on the energy of the transported ion beam will be investigated. These experiments will provide the MA/cm² level fluxes required for relevant ICF beam target studies.

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