GENERATION AND FOCUSING OF PULSED INTENSE ION BEAMS

MASTER

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ABSTRACT

Theoretical calculations suggest that an intense pulsed ~ 1 MeV proton beam can be used to simulate the characteristics of ~ 1 GeV heavy ion beam propagation in an inertial confinement fusion reactor chamber. Given the present availability of the former beams and the high projected cost for obtaining the latter ones, such experimental simulations appear appropriate. Work was undertaken under the cited contract to apply the technology of intense proton beams to this end. The first task was the development of a high brightness pulsed proton source which could produce a weakly convergent ~ 10 kA proton beam in a field free drift region. This was accomplished at ~ 250 keV, and preliminary beam propagation experiments were performed. It was concluded that a proper simulation experiment would require a higher voltage beam. An upgraded version of the existing generator, which would have produced a 30 kA beam at about 500 keV, and further propagation experiments were proposed as part of our unsuccessful renewal proposal dated October 15, 1979.

I. INTRODUCTION

The unimpeded propagation of high energy, heavy ion beams (HIB) from the final focusing lens to the target DT pellet in the reactor chamber is critical to their successful application as an inertial confinement fusion (ICF) driver.^{1,2} Theoretical calculations (see Sec. II) suggest that an intense pulsed ~ 1 MeV proton beam can be used to perform "scaled experiments" to investigate the characteristics of ~ 1 GeV HIB propagation in a reactor chamber. In particular, experimental verification or refutation of predictions that beam quality will not be degraded during propagation by specific instabilities if appropriate reactor chamber conditions are chosen can be obtained. Given the present availability of intense pulsed proton beams at up to a megampere³ and at energies of a few megavolts,⁴ and the high projected cost for HIB's suitable for ICF, such experimental information should be obtained as soon as possible because of its potential impact on HIB accelerator design and reactor system features (e.g.-number of beams, presence of gas or plasma in the reactor chamber, etc.).

Work was undertaken under this contract to apply intense pulsed proton beam technology to experimentally simulate the characteristics of HIB propagation in an ICF reactor chamber. The first step was to develop a weakly focused high brightness proton beam capable of investigating the predicted thresholds of particular instabilities that might be expected in HIB ICF. A diode with the necessary characteristics, called the "applied B_0 diode" was developed which produced ≤ 10 kA proton beams at ~ 250 keV. Preliminary beam propagation experiments were

performed in vacuum (10^{-4} torr) and in ~50 mtorr of neutral gas were performed. The diode and these experiments are discussed in Sec. III.

From the preliminary experiments and the theoretical work, it was concluded that a proper experimental simulation of HIB propagation requires a higher voltage beam. Thus, an upgraded version of our existing generator, which would have produced a 30 kA beam at about 500 keV, was included as part of our unsuccessful renewal proposal. A key propagation experiment would then have been to try to excite a two-stream instability and to observe its effect on beam emittance and the generation of forward current,^{4a} as seen in electron beam propagation experiments.⁵

Simulation of the filamentation instability is expected to require a higher voltage proton beam, such as that which the 2 MV LION accelerator presently being installed at Cornell is capable of producing.

In the remainder of this report, we discuss the theoretical basis of HIB simulation using proton beams (Sec. II), and the experimental progress achieved up to the time of termination of this contract (Sec. III).

II. THEORETICAL BASIS OF HIB SIMULATION

The principal instabilities that could afflict the beam are:

a) electrostatic two-stream instability, b) the filamentation instability, and c) resistive kink instability. We discuss below the consequences of these instabilities and how they could be simulated by proton beams.

A. Electrostatic Two-Stream Instability

The nonlinear effect of this instability is for the beam momentum to be imparted to the electrons of the ionized background gas through the coupling provided by the unstable wave spectrum. The electrons thus acquire a drift velocity and their contribution to the current may exceed the beam current. The net current could be reversed causing the unpinching or defocusing of the beam. Previous analysis^{4a} shows that the net current is given by

$$J = J_e + J_b \approx 28.4 \left(\frac{n_b}{n_e}\right)^{1/3} \left(\frac{A}{Z}\right)^{2/3} \frac{c^2}{\omega_p^2} \nabla^2 J_b, \quad (1)$$

where J_e, n_e and J_b, n_b are the electron and beam current and particle density, respectively, Z and A are the effective charge state and atomic mass number of the beam ion, ω_p is the electron plasma frequency.

This mode is stabilized by a spread in the parallel beam velocity $\Delta v_{||}$ and by electron collisions ν_e . Thus, the growth rate Γ vanishes when (Singhaus criterion),

$$\Gamma = \omega_b \left(\frac{\omega_p}{2\nu_e}\right)^{1/2} - \omega_p \left(\frac{\Delta v_{||}}{v_b}\right) = 0, \quad (2)$$

where ω_b is the beam plasma frequency and $v_e \propto n_i Z_i^2 / T_e^{3/2}$, the subscript i refers to the background plasma ions, and T_e is the electron temperature. The background pressure necessary for stabilization is⁶

$$[p(\text{torr})]^{3/2} = 3.57 \times 10^{-12} \frac{Z_b^2 I_b (\text{amps}) T_e^{3/2} (\text{eV})}{\beta A \delta^2 a^2 (\text{cm}) Z_i^{5/2}}, \quad (3)$$

a is the beam radius $\beta = v_b/c$, $\delta = \Delta v_{||}/v_b$. For a beam with parameters given above $p \sim 1$ torr.

Consequently, the gas pressure for stabilizing proton beams as opposed to heavy ion beams for the same T_e , Z_i , a is given by

$$\frac{p_H}{p_p} = \left(\frac{Z_H}{A_H} \left(\frac{\delta_p}{\delta_H} \right)^2 \frac{\beta_p}{\beta_H} \frac{I_H}{I_p} \right)^{2/3}. \quad (4)$$

Subscripts H and p refers to heavy ion and proton, respectively. By requiring that $p_H \lesssim 5 p_p$ we observe that a 500 keV proton beam with $I_p \sim 30$ kA, $\delta_p \sim 4 \times 10^{-2}$ and $\beta_p = 0.03$ can simulate the two-stream stability threshold in gas of a highly stripped 20 GeV Uranium beam $Z_H \approx 70$, $A_H = 238$ $\delta_H \sim 10^{-2}$ with $I_H \lesssim 5$ kA.

B. Filamentation Instability

If the background pressure is increased to avoid the two-stream instability then because of the higher density and increased conductivity of the background plasma, the plasma return current magnetically neutralizes the beam almost completely. This condition would be ideal except for a tendency of the beam current to break up into filaments of transverse size λ

$$\frac{c^2 \tau}{4\pi\sigma} > \lambda^2 > \frac{\langle v_{\perp}^2 \rangle}{\beta^2 \omega_b^2}, \quad (5)$$

where σ is the plasma conductivity, τ is the beam pulse rise time, and $\langle v_{\perp}^2 \rangle$ is the perpendicular beam velocity spread. The growth rate Γ of this instability is

$$\Gamma = \beta \omega_b,$$

and according to Rosenbluth⁷ the number of e-folds in a beam converging on to the target is given by

$$N = \frac{1}{\Delta} f(\alpha \Delta), \quad (6)$$

where

$$\begin{aligned} f &= 6 && \text{for } \alpha \Delta \gg 1 \\ &= -\frac{\alpha \Delta}{2} \ln \alpha \Delta && \text{for } \alpha \Delta \ll 1 \end{aligned}$$

$$\Delta = \left(\frac{4\pi\alpha}{\tau} \right) \left(\frac{3\langle v_{\perp}^2 \rangle}{2\omega_b^2} \right); \quad \alpha = \omega_b R/c, \quad R \text{ is chamber radius. From the above it}$$

is clear that α is a measure of this instability and to compare a heavy ion beam and proton beam with respect to filamentation we have

$$\frac{\alpha_H}{\alpha_p} = \frac{Z_H}{A_H^{1/2}} \left(\frac{I_H}{I_p} \frac{\beta_p}{\beta_H} \right)^{1/2}. \quad (7)$$

Furthermore, for the same pulse rise time τ and background conductivity σ

$$\frac{\Delta_H}{\Delta_p} = \frac{\langle \theta_H^2 \rangle}{\langle \theta_p^2 \rangle} \frac{\alpha_p^2}{\alpha_H^2}, \quad (8)$$

and $\Delta < 1$ for instability. Let $\langle \theta_H^2 \rangle^{1/2} \approx 1$ mrad for a 5 cm dia. U beam, and $\langle \theta_p^2 \rangle^{1/2} \approx 2^\circ$ or 40 mrad. Then in order to make Δ_H and Δ_p comparable

$$I_p = I_H \frac{Z_H^2}{A_H} \frac{\beta_p}{\beta_H} \frac{\langle \theta_p^2 \rangle}{\langle \theta_H^2 \rangle}, \quad (9)$$

A 1 kA, 20 GeV, 5 mr-cm emittance U beam stripped to $Z \sim 70$ cm can be simulated so far as filamentation is concerned by a 2 MV, 200 kA, $\langle \theta^2 \rangle^{1/2} \sim 2^\circ$ proton beam provided the pulse rise time and the background plasma conductivities are comparable in both cases.

The nonlinear development of the filamentation instability can be estimated by employing quasilinear theory from which we obtain the evolution of the averaged velocity distributions of the beam ions from the following equation

$$\frac{\partial}{\partial t} \langle f \rangle + \frac{q}{m} \langle E_z \rangle \frac{\partial}{\partial v_z} \langle f \rangle \quad (10)$$

$$= \frac{q^2}{m^2} \sum_k |E_k|^2 \left\{ \left(1 + \frac{kv_x}{\omega_k} \right) \frac{\partial}{\partial v_z} - \frac{kv_z}{\omega_k} \frac{\partial}{\partial v_x} \right\} \left\{ \frac{-1}{\omega_k} \frac{\partial}{\partial v_z} + \frac{ikv_z}{\omega_k(kv_x - \omega_k)} \frac{\partial}{\partial v_x} \right\} \langle f \rangle,$$

where

$$E_z = \frac{4\pi}{c} \frac{\partial}{\partial t} \int_0^r \frac{dr'}{r'} \int_0^{r'} dr'' r'' J; \quad J = J_c + J_b \text{ is the net current.}$$

By taking the v_x^2 moment of this equation for beam ions we obtain

$$\frac{d}{dt} \langle v_{\perp}^2 \rangle = - \frac{Z^2 e^2}{2m_b^2} \frac{v_b^2}{c^2} \sum_k \frac{1}{k^2 \langle v_{\perp}^2 \rangle} Z' \left(\frac{\omega_k}{k \langle v_{\perp}^2 \rangle^{1/2}} \right) \frac{d}{dt} |B_k|^2, \quad (11)$$

where $\omega_k = i\Gamma_k$, $\Gamma_k \approx \beta\omega_b$ for $k = 2\pi/\lambda$ and λ constrained by (5).

$B_k = (kc/\Omega_k)E_k$ is the filamentary magnetic field, $Z'(x)$ is the derivative of plasma dispersion function, $\langle v_{\perp}^2 \rangle$ is the transverse thermal spread or beam emittance. Thus, the instability increases the beam emittance dramatically.

By taking the v_z moment of (10) and neglecting the contribution from the RHS we obtain

$$\frac{\partial}{\partial t} J_b - \frac{\omega_b^2}{4\pi} E_z = - \frac{J_b Z^2 e^2}{2m_b^2} \sum_k \frac{1}{k^2 \langle v_{\perp}^2 \rangle} Z' \left(\frac{\omega_k}{k \langle v_{\perp}^2 \rangle^{1/2}} \right) \frac{d}{dt} |B_k|^2. \quad (12)$$

If the electron collision frequency $\nu_e \gg \Gamma_k$, the instability growth rate (which is probably valid for most of the beam path), the plasma electron current is given by

$$J_p = \frac{\omega_p^2}{4\pi v_e} E_z. \quad (13)$$

From (12) and (13) we conclude that the second term in (12) is of order ω_b^2/ω_p^2 and can be neglected, i.e., a negligible amount of beam energy goes to the plasma electrons. Thus

$$\frac{1}{J_b} \frac{\partial}{\partial t} J_b = - \frac{1}{v_b^2} \frac{\partial}{\partial t} \langle v_{\perp}^2 \rangle. \quad (14)$$

Since $\langle n_b \rangle$ is constant this merely states the conservation of the beam energy $v_b^2 + v_{\perp}^2$. Since the growth rate of the instability is faster than or comparable to beam betatron frequency the emittance is not conserved and the beam will suffer expansion.

C. Resistive Kink Instability

This instability will only occur when the pulse time is longer than the resistive decay time, i.e.,

$$\tau > (4\pi\sigma a^2/c^2)^{1/2}.$$

At high pressures the conductivity is large enough that this inequality is reversed and no danger from this mode exists.

III. EXPERIMENTAL PROGRESS TOWARD HIB SIMULATION USING PROTONS

A. Technology Summary

The technological basis for the simulation of heavy ion beam propagation in a reactor chamber using an intense proton beam is the pulsed power technology which has been developed over the past 15 years. This technology has been used to produce intense electron beams of up to nearly 10^{13} W for ~100 ns in several laboratories.⁸ More recently^{3,9,10} it has been used to produce intense ion beams of up to 10^{12} W. This section briefly describes ion beam generation techniques, emphasizing the method used in the ion beam research at Cornell.

According to the Child-Langmuir formula for space charge limited flow in a vacuum acceleration gap, or diode, the current density, j , of a species of particle having charge q and mass m is given by

$$j = \frac{4\epsilon_0}{9} \sqrt{\frac{2q}{m}} \frac{V^{3/2}}{d^2} \text{ (mks units),} \quad (15)$$

where V is the applied diode voltage and d is the diode gap spacing.¹¹ Thus, unless one can suppress electron flow, the electron current density will be at 42 times the ion current density, assuming the cathode and anode of the diode can supply as many electrons and ions, respectively, as the formula allows. In other words, without electron flow suppression, a diode will be at best $2\frac{1}{2}\%$ efficient in production of protons. Three techniques are commonly used to accomplish this electron current reduction:

- 1) In the pinched beam diode, the self-magnetic field of the electron

beam in the diode causes the electrons to pinch to the diode axis.

This increases the electron pathlength in the diode by a factor of $\sim R/d$, where R is the cathode radius, while ions launched from the anode are nearly unaffected. This technique and its derivatives are studied principally at the Naval Research Laboratory¹² and Sandia Laboratories.¹³

2) In the reflex triode, originally developed at Cornell,¹⁴ and its derivatives,¹⁵ the electron lifetime in the diode is increased by allowing the electrons to pass through a highly transparent, or thin foil, anode as they move back and forth between two cathodes (usually one real and one virtual). The principal proponents of this technique are now at NRL.^{15,16}

3) In the magnetically insulated diode, electrons are prevented from crossing the diode gap by the application of an external magnetic field transverse to the electric field in the diode. This technique was also originally developed at Cornell,¹⁷ and is now used both at Cornell¹⁸⁻²³ and at Sandia.²⁴

It is the technology of the magnetically insulated diode that is involved in this proposal.

Since the detailed operation of magnetically insulated diodes are now well documented in the literature,²⁵ we do not repeat it here.

Appendix A, Sec. II, contains a review of the principal operational features of such diodes. Their use is indicated for the production of ion beams because of three attractive features. Firstly, the ratio of extracted proton current to total diode current can be $\sim 50\%$ for pulses of ~ 100 nsec or longer for a well designed diode. Secondly, their

reproducibility is good. Finally, at the power levels of $\leq 10^{11}$ W used in our laboratory (and appropriate for this proposal), electrode survival for many tens, or even hundreds of pulses with minimal maintenance allows intense ion beam experiments to be performed with a reasonable data collection rate. Furthermore, the ion current density can be higher than that predicted by Eq. (15), as it can be in the other two ion diodes, apparently as a result of electrons partially reducing the ion space charge fields in the diode gap.

Several different magnetically insulated diode configurations have been developed and tested at Cornell University during the last few years. These include two cylindrical diodes,¹⁷⁻¹⁹ a "planar" diode,²⁰ a spherical diode,²¹ and an annular ring diode.²² The operational characteristics, and some results obtained using these diodes are included in Appendix A. The most recently developed diode, called the B_0 diode, is particularly appropriate for heavy ion beam propagation simulation experiments. Therefore, we next describe its mechanical and operational characteristics in some detail. This will be followed by a presentation of experimental results using the present version of the B_0 diode. It will be seen that the beam we are now producing is capable of being used to begin a part of the heavy ion beam simulation experiments. However, the HIB simulation experiments will perform better at higher generator voltage than we presently have. Therefore, an upgraded version of our present generator has been designed, and components have been purchased. Further details on the advantages of the upgraded generator and its expected characteristics are presented at the end of this section.

B. The B_0 -Diode

Development of the applied B_0 diode was motivated by the need for a high brightness pulsed ion source which could efficiently produce a weakly converging ion beam in a field free drift region. Designed and built at Cornell in cooperation with S. Humphries, Jr., of Sandia Laboratories, Albuquerque, it is potentially applicable to two areas in inertial fusion research: 1) Injection into a current carrying plasma channel for transport to a pellet,²⁶ and 2) simulation of heavy ion beams propagating through the ambient medium in an inertial fusion reactor chamber. For light ion fusion application, a further requirement on the source is that it must be capable of being scaled up to the $\sim 10^{12}$ W/beam required by the Sandia program. For heavy ion beam simulation, however, a beam current of a few 10's of kA is all that is required, as discussed in Sec. II.

The applied B_0 diode, shown in Fig. 1, is similar in magnetic field geometry to the pinched electron beam ion diodes which have already proven to be useful in ion beam sources. However, it has the advantage that the current which produces the B_0 magnetic field is supplied by an external capacitor bank rather than by the very electron current which it is intended to inhibit. This means that the insulating field can be controlled independently of the diode parameters, and can be made extremely reproducible. Furthermore, according to the theoretical model of Lee and Goldstein,²⁷ the ratio of ion current I_i to electron current I_e in the pinched beam diode, shown schematically in Fig. 2, is given by

Fig. 1a: Cross-sectional diagram of the applied- B_0 diode. The path of the current for producing the externally applied B_0 is shown by arrows. The high current radial feed plate shown has four holes for the four anode stalks (two shown) to pass through. The cathode vane structure consists of sixty current carrying copper vanes which carry the current radially, but permit the structure to be highly transparent to the axially directed ion beam. The lucite interface is 38 cm in diameter, with the rest of the drawing to scale.

TO
OMNIPULSE
PULSE LINE

300 kV
3.3 Ω
80 ns

CATHODE VANE
STRUCTURE

I_θ

I_θ

LUCITE ANODE
SURFACE WITH
CU PINS

COAXIAL CABLES (8)
TO
88 μ f, 20 kV
CAPACITOR BANK

Fig. 1b. An artist's exploded view of the B_θ diode.

Fig. 2. Schematic diagram showing the operation of the pinched beam diode. R_1 is the cathode radius; R_2 is the inner limit of significant electron emission because of the electron space charge depression of the cathode field inside that radius; R_p is the electron pinch radius. Ion orbits are nearly straight lines, while electron orbits are greatly convoluted in the magnetic field of the combined currents.

$$\frac{I_i}{I_e} \geq \frac{R}{2d} \left(\frac{2 \text{ eV}}{m_i c^2} \right)^{1/2}. \quad (16)$$

This model, subsequently verified in particle simulation codes and later in experiments at NRL¹² and Sandia,¹³ predicts that I_i/I_e will be small except in very large aspect ratio diodes, namely, $\frac{R}{2d} \geq [(m_i c^2)/(2 \text{ eV})]^{1/2}$. Thus, for a 0.5 MeV proton diode, $[(m_i c^2)/(2 \text{ eV})]^{1/2}$ is about 60, giving I_i/I_e of only 0.16 for the typical values for R and d of 10 cm and 0.5 cm, respectively, used in our diodes. By using an externally supplied current on axis to add to the current produced by the generator, the same electron dynamics can be produced, without wasting generator power to produce all the necessary current on axis. The result is a predicted increase in I_i/I_e during the high voltage pulse. This has been demonstrated experimentally.

For purposes of heavy ion beam propagation simulation experiments, this diode has the advantage that the B_0 field which prevents electrons from crossing the diode gap also weakly focuses the ions. This will be evident in the results of the preliminary beam propagation experiments described in part C of this section.

The diode operation is as follows. A 14 kV, 88 μ F capacitor bank is connected through a switch and eight RG-8 coaxial cables to the radial feedplate shown in Fig. 1. Current from this bank flows radially inwards to an axial conductor, along that conductor, which is on the axis of an annular ion diode, and then radially outward through the cathode, which is a high transparency radial vane structure. Up to 200 kA of axial current has been achieved, producing up to a 16 kG B_0 .

magnetic field at the inner edge of the anode annulus 2.5 cm radius, and 5 kG at the outer edge, 7.6 cm radius (see Fig. 1). The diode voltage is provided by an Omnipulse generator,²⁸ typically operating at 250-300 kV with an 80 nsec pulse. The generator is fired when the applied magnetic field has reached its peak.

The insulation characteristics of the diode were studied as a function of magnetic field with a bare aluminum anode. Electron current was reduced by a factor of 15-20 from the electron Child-Langmuir current for the diode geometry used as B_0/B^* was raised to 1.65 (at the outer radius of the anode). Here $B^* = \frac{1.7 \times 10^{-3}}{d} \sqrt{\gamma^2 - 1}$ is the critical field for magnetic insulation of a diode with gap d . γ is the usual relativistic factor for the electrons. In this case, $d = 0.7$ cm and $\gamma = 1.5$, i.e., $\lesssim 275$ keV applied from anode to cathode. Motion of electrons emitted from the cathode consists of a radially inward $\underline{E} \times \underline{B}$ drift and a "grad B" drift across the gap (since $B_0 \propto \frac{1}{r}$).

Various plasma producing anodes were investigated for ion beam production in the B_0 diode: 1) velvet cloth about 0.15 mm thick, suggested by D. J. Johnson of Sandia and provided by S. Humphries; 2) 0.15 mm thick polyethylene with equally spaced 0.8 mm holes about 0.64 cm apart; and 3) a 0.6 cm thick lucite sheet with copper pins through it spaced 0.64 cm apart and cut off flush with both surfaces of the lucite. Among all of these the lucite anode seemed to work best. It is found to produce the most uniform ion beam (see Fig. 3), with nearly twice the total ion current of the other anodes. Its anode plasma ion source is believed to be initiated by field distortion induced

Fig. 3a. Ion current density versus radius for the lucite anode, measured 8 cm from the anode. Diode voltage was ~275 kV and external current was 140 kA. (See Fig. 3b for results using velvet.)

Fig. 3b. Ion current density versus radius for the velvet anode at the same location, and under the same diode voltage and external current conditions as Fig. 3a.

surface discharges at the lucite-copper pin boundaries when the high voltage pulse is applied, rather than by electron bombardment. We believe that the anode plasma uniformity is better with lucite (giving a more uniform ion beam) due to using 1/4" thick material. This makes more capacitive energy available to drive the initial surface breakdown.

C. Propagation of B_0 -Diode Proton Beams in Vacuum

Once ions are produced in the B_0 diode, they cross the cathode anode gap and pass through the vaned cathode structure into a field free vacuum drift region. The focusing property of the B_0 diode is due to each ion in the beam being deflected radially inward by the applied B_0 as it crosses the anode-cathode gap. Therefore, if the beam is charge and current neutralized as it propagates in the drift space, a focal region should be observed along the axis. This characteristic of a beam from the B_0 diode is shown in Fig. 4, which presents ion current density data obtained with biased ion collectors,²⁹ as a function of radius and axial position. These data were obtained using a lucite anode, a diode voltage of 250 kV, and an applied axis current of 150 kA. It is clear in Fig. 4 that the position of maximum current density on the axis occurs near $z = 20$ cm. The peak current achieved is in excess of 600 A/cm^2 . The current is nearly all protons as determined by time-of-flight and the use of 2μ mylar foil filters on the charge collectors. Note that the profile at 10 cm in Fig. 4 shows the current density to be higher near the inner edge of the anode. This is believed to be a result of the "grad B" drift of the electrons across the gap, which reduces the effective gap and cancels some of the ion space charge near the anode at smaller radii.

Fig. 4. Current density as a function of radius at several axial positions for the beam produced by the B_0 diode. The dashed line at $z = 20$ cm is calculated from single particle trajectories assuming the current density profile shown at $z = 0$ (100 A/cm^2 peak at $r = 2.5 \text{ cm}$).

The dashed curve shown at $z = 20$ cm in Fig. 4 is a computer calculated profile assuming the triangular current density profile shown (dashed) at $z = 0$ (100 A/cm^2 at $r = 2.5$ cm), and assuming there are fields acting on the protons only in the anode-cathode gap. The agreement at $z = 20$ cm indicates that the beam self-fields are having minimal effect on the proton propagation after the cathode. Such agreement is obtained for assumed beam divergence angles $\leq 2^\circ$. Other measurements suggest that the mean angle of divergence is $1-2^\circ$. Finally, we note that the presence of the focus in the propagating beam indicates that a high degree of charge and current neutralization is achieved. In fact, a magnetic probe at a radius of 10 cm showed no detectable net current. The necessary electrons are evidently produced by proton bombardment of the sides of the vanes in the cathode.

The position of maximum current density discussed in the last two paragraphs is not a real focus point where ions from all over the anode converge. Since the magnetic deflection inward is proportional to the B_θ -field, protons from outer regions converge further away from the diode than those from the inner region. Therefore, the point of maximum current at $z = 20$ cm is formed mostly by ions coming from the inner region of the anode. This has been demonstrated experimentally by covering the outer region of the cathode with a mylar annulus. With this result in mind, and a desire to increase the focal length of the propagating beam, we tested a diode with anode and cathode surfaces

curved in an appropriate way. In fact, the point of maximum current density was pushed out to 25-30 cm, with a current density of more than 550 A/cm^2 . (Anode-cathode gap was tapered from 10 mm outside to 7 mm inside.)

An improved (i.e., more cylindrically symmetric) version of the flat electrode diode has recently been tested. The extracted ion current has been increased from 6 kA to nearly 10 kA under similar conditions. Furthermore, the peak current density (near $z = 20 \text{ cm}$) has been increased to about 800 A/cm^2 . The 10 kA corresponds to a v/γ_p of $\sim 10^{-2}$, where $v = N_p (Z_p e)^2 / 4\pi\epsilon_0 m_p c^2$ is the number of protons ($Z_p = 1$) per classical proton radius of beam length and γ_p is the proton relativistic factor, equal to 1 here. Since instability growth rates scales as v/γ (see Sec. II) for the purposes of this report this beam is equivalent to a high energy heavy ion beam of particle current 10 kA with mass $200 m_p$ ions and twelve time ionized, or 1 kA and 40 times ionized. Therefore, this beam provides a reasonable simulation of such a heavy ion beam in a reactor chamber. This is adequate for two stream instability experiments (see Sec. II), but the simulation would be better at somewhat higher voltage and current as mentioned in the Introduction. Simulation of the filamentation instability will require the substantially higher voltage generator which is expected to be available during FY 1981 as part of another research program.

Finally, we note that the 10 kA of propagating beam current corresponds to nearly 20 kA of ion current in the diode (taking the cathode

transparency into account). Since the total diode current is 60 kA, the ratio of I_i/I_e is about 40%, a factor of 3 higher than predicted by the Lee Goldstein formula for the pinched beam diode without an externally supplied bias current on axis.

D. Propagation in Gases - Preliminary Experiments

We have performed some preliminary experiments on beam propagation in gases with our present generator system. Using a pulsed valve system, about 50 mtorr of nitrogen was puffed into a 10 cm region across the path of the ion beam at a distance of about 20 cm from the diode. Charge collectors, which were covered with thin aluminized mylar foil to avoid gas entering through their apertures, showed no appreciable change in current density. Thus, in the present pressure range, and in propagating about 10 cm of neutral gas, the beam does not show any deterioration in focal quality. This is consistent with the prediction of Sec. II.

REFERENCES

1. See, for example, Proc. Heavy Ion Fusion Workshop, R. C. Arnold, Ed., (1978)[Argonne National Laboratory Report ANL-79-4].
2. Robert Conn, University of Wisconsin, private communication (1979). See also, presentations by LLL to the Jason Review Committee on Ion Beam Driven Inertial Confinement Fusion, July, 1979.
3. Gerold Cooperstein, Naval Research Laboratory, private communication (1979).
4. G. W. Kuswa, S. Humphries, Jr., D. L. Johnson, R. J. Leeper, and J. R. Freeman, in Proc. 2nd Int. Top. Conf. on High Power Electron and Ion Beam Research and Technology, J. A. Nation and R. N. Sudan, Eds. (Ithaca, New York, 1977), Vol. I, p. 99.
- 4a. R. N. Sudan, Phys. Rev. Lett. 37, 1613 (1976).
5. See, for example, R. J. Briggs, J. C. Clark, T. J. Fessenden, R. R. E. Hester, and E. J. Lauer, Proc. 2nd Int. Top. Conf. on High Power Electron and Ion Beam Research and Technology, J. A. Nation and R. N. Sudan, Eds., (Ithaca, New York, 1977), Vol. I, p. 319.
6. See, for example, H. L. Buchanan, F. W. Chambers, E. P. Lee, S. S. Yu, R. J. Briggs, and M. N. Rosenbluth, Lawrence Livermore Laboratory Report UCRL-82586 (June 1979).
7. M. N. Rosenbluth, private communication.
8. See, for example, B. Bernstein and I. Smith, IEEE Trans. Nucl. Sci. NS-20, 294 (1973), and T. H. Martin, D. J. Johnson, and D. H. McDaniel, Proc. 2nd Int. Top. Conf. on High Power Electron and Ion Beam Research and Technology, J. A. Nation and R. N. Sudan, Eds., (Ithaca, New York, 1977), Vol. II, p. 807.

9. M. Greenspan, S. Humphries, Jr., J. Maenchen, and R. N. Sudan, Phys. Rev. Lett. 39, 24 (1977).
10. D. J. Johnson, A. V. Farnsworth, J. P. Quintenz, R. J. Leeper, and E.J.T. Burns, Conf. Record, 1979 IEEE Conf. on Plasma Sci. (Montreal, Canada, 1979), p. 76.
11. C. D. Child, Phys. Rev. 32, 492 (1911); I. Langmuir, Phys. Rev. 2, 450 (1913).
12. S. J. Stephanakis, G. Cooperstein, Shyke A. Goldstein, D. Mosher, F. W. Aliphant, F. C. Sandel, and F. C. Young, Conf. Record, 1979 IEEE Conf. on Plasma Sci., (Montreal, Canada, 1979), p. 79.
13. G. Yonas and the Sandia Laboratories Particle Beam Fusion Group, Proc. 7th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, (Innsbruck, Austria, 1978), Vol. III, p. 125.
14. S. Humphries, Jr., J. J. Lee, and R. N. Sudan, Appl. Phys. Lett. 25, 20 (1974); J. Appl. Phys. 46, 187 (1975).
15. J. A. Pasour, R. A. Mahaffey, J. Golden, and C. A. Kapetanacos, Phys. Rev. Lett. 40, 448 (1978); R. A. Mahaffey, J. A. Pasour, J. Golden, and C. A. Kapetanacos, Appl. Phys. Lett. 32, 522 (1978).
16. J. A. Pasour, R. A. Mahaffey, J. Golden, and C. A. Kapetanacos, to be published (1979).
17. P. Dreike, C. Eichenberger, S. Humphries, Jr., and R. N. Sudan, J. Appl. Phys. 47, 85 (1976).
18. S. Humphries, Jr., R. N. Sudan, and L. Wiley, J. Appl. Phys. 47, 2382 (1976).
19. M. Greenspan, S. Humphries, Jr., J. Maenchen, and R. N. Sudan, Phys. Rev. Lett. 39, 24 (1977).

20. J. Maenchen, L. G. Wiley, S. Humphries, Jr., E. Peleg, R. N. Sudan, and D. A. Hammer, *Phys. Fluids* 22, 555 (1979).
21. M. Greenspan, D. A. Hammer, and R. N. Sudan, *J. Appl. Phys.* 50, 3031 (1979).
22. P. L. Dreike, D. A. Hammer, R. N. Sudan, and L. G. Wiley, *Phys. Rev. Lett.* 41, 1328 (1978).
23. P. L. Dreike et al., Proc. 2nd Int. Top. Conf. on High Power Electron and Ion Beam Research and Technology, J. A. Nation and R. N. Sudan, Eds., (Ithaca, New York, 1977), Vol. I, p. 37.
24. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, J. P. Quintenz, R. J. Leeper, E.J.T. Burns, and S. Humphries, Jr., *Phys. Rev. Lett.* 42, 610 (1979).
25. See, for example, Appendix A, which is published in Collective Methods of Acceleration, N. Rostoker and M. Reiser, Eds., (Harwood Academic Publishers, New York, 1979), p. 413; or Appendix C, published as Ref. 20.
26. See, for example, G. Yonas, *Scientific American* 239, p. 50 (Nov. 1978).
27. Shyke A. Goldstein and Roswell Lee, *Phys. Rev. Lett.* 35, 1079 (1975).
28. S. Humphries, Jr., *Laser Focus* 14, 57 (1978).
29. See, for example, C. Eichenberger, S. Humphries, J. Maenchen, and R. N. Sudan, *J. Appl. Phys.* 48, 1449 (1977).

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APPENDIX A
PROGRESS IN THE PRODUCTION OF INTENSE PROTON BEAMS
WITH MAGNETICALLY INSULATED DIODES

LPS 249