Focusing of Intense Ion Beams from Pinched-Beam Diodes

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Geometric focusing of proton and deuteron beams extracted from pinched-beam diodes to current densities above 70 kA/cm^2 is demonstrated by a variety of experimental techniques. Time-dependent computer simulations of the electron and ion flow show good agreement with experiment.

When self-pinched electron flow is generated in high-voltage, large-aspect-ratio diodes, a large fraction of the total current is carried by the ions. This high efficiency was first predicted theoretically[1,2] and subsequently confirmed experimentally.[3-6] Efficiencies above 50% and time-averaged proton currents up to 400 kA at 0.8 MV have been measured.[6] Since no external magnetic fields exist and electrons from the cathode follow the ions, geometric focusing of the ion flow may be achieved by contouring the diode geometry.[1,7] The same idea also motivated numerical simulation of spherical diodes[7] and they indicated the efficient generation and focusing of intense ion beams. Diode theory predicts that the total current is nearly proportional to voltage and the ratio of ion to electron current[1] is given by

$$I_i/I_e > 0.5(L/D)v_i/c\,, \qquad (1)$$

where L is the electron path length in the diode ($\sim\frac{1}{2}\pi R$ for a hemisphere), D is the ion path length, v_i/c is the ion velocity relative to the speed of light *in vacuo*. Equation (1) implies a favorable scaling for higher-voltage generators since ratios of unity have already been achieved[6] at the 1-MV level. Light-ion beams allow the ultization of high-gain thermonuclear pellets with low-beam-power and large-focusing-area requirements.[8] Extending experimental and theoretical results at 1 to 10 MV generator, assuming a constant 1-Ω operation, it is predicted that the ion-beam power density will exceed 10^{14} W/cm^2. High-gain pellets may thus be ignited with light-ion beams generated and focused from pinched-beam diodes using the specific techniques described in this paper.

Preliminary ion-focusing experiments have been conducted by two groups.[9,10] The results were encouraging since it was found that electron beams do pinch in spherical diodes and focused deuteron-current densities above 20 kA/cm^2 were inferred from the "tea-strainer" (cathode) and "oil-can" (anode) experiments.[9] Recently,[6] larger ion currents were obtained using shallow spherical-dish anodes with longer focal lengths mounted on the positive-polarity Naval Research Laboratory Gamble II generator operated at 0.7–1.2 MV, 0.5–0.75 MA, and 50-ns pulse full width of half-maximum. The diodes used had either solid anodes [Fig. 1(a)] or thin-foil anodes [Fig. 1(b)]. The electron flow starts from an azimuthally symmetric hollow cathode and pinches towards the anode center in the form of a collapsing hollow ring[11] that generates a plasma on the anode surface. Ions are then accelerated by the diode voltage into the drift tube. The anode surface was a section of a sphere having a 12.7-cm radius of curvature. Focusing of proton and deuteron beams from solid anodes [Fig. 1(a)] was first observed via visible-light photography of subrange foils, placed at different axial positions from the anode apex, in order to locate the focus of

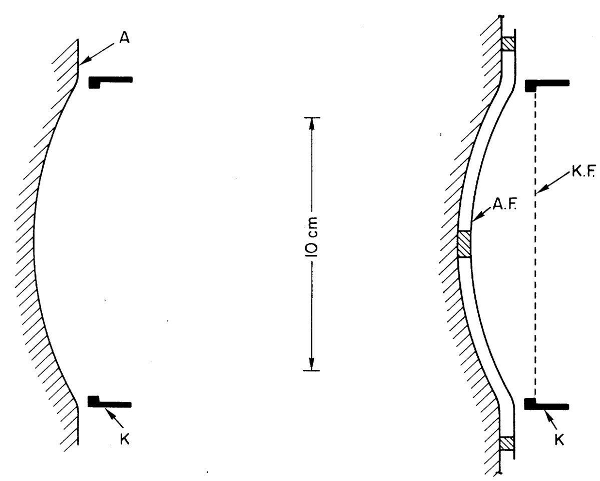

FIG. 1. Diode geometry using (a) thick and (b) thin spherical-shaped anodes and very hollow cathodes. The thin (25 mg/cm^2) plastic anode is attached to the central anode conductor and is supported mechanically by a nonconducting ring. A thin cathode foil [position "K.F." in (b)] of 2 μm polycarbonate provides electrons to flow with the focused-ion flow.

the ion beam.

The focused-proton-beam size was studied by placing 1.5-mm-thick aluminum targets in the focal region. The real-surface spall was generated over an area of 1 cm^2 on the target placed at the best focus (about 9 cm from the anode apex). Very little or no spall was observed when the target was displaced 4 cm on either side of the focus. Preliminary results of measuring the heating of subrange foils placed at the focus are also consistent with a focal area of 1 cm^2 since viewing larger areas of the foils did not increase the signal of soft-x-ray detectors.

Absolute measurements of the time-average radial profiles of the ion current density were obtained by three independent techniques: carbon activation by protons,[12] and neutron production from $(CH_2)_n$ or $(CD_2)_n$ targets for deuteron beams.[3] All of these techniques, however, give only the average current of the ion pulse. No technique has yet been found reliable enough to give the time dependence of the ion current.

The measurements of the proton current density were made by placing a plate with a circular hole (1.2 cm diam) at different axial positions. A second carbon plate with a 33% transparent screen was placed behind the first as a target for the diverging proton beam. Carbon activation[4,12] gave a direct measure of the protons at energies above 475 keV. The time history of the diode voltage was used to find the pulse length (~40 ns) of ions with energy above this voltage. The current density varied (due to voltage variations between different experiments) between 22 and 32 kA/cm^2 at 8.5 cm from the apex. Using larger holes and counting the activation of the first carbon plate at different radii resulted in the radial-profile histogram of the proton current density at the focus (Fig. 2). These results are to be contrasted with those shown using flat anodes. Using deuteron beams, it was found that the focal distance shifted to 10 cm from the anode apex and the current density reduced to about 18 kA/cm^2.

The structure of the focus in the r-z plane was investigated theoretically using our numerical simulation code. In the simulations, a hypothetical diode which closely approximated the real experiment near peak voltage was modeled. The electron and ion orbits were calculated using a computer code similar to others,[2] but containing a fully time-dependent emission law for both the electrons and ions. The big hole in the cathode was represented by a region free of electron emission, the voltage was taken to be 750 kV, and a value $L/D = 20$ was used to account for cathode plasma motion.[11] Results have shown large-amplitude oscillations (50%) of the ion current while the ion directions varied only by two degrees. By assuming ballistic ion orbits outside the diode for an anode with a radius of curvature of 12.5 cm, the axial variation of the radial current-density profiles of the protons (Fig. 3) was determined. The general features of the computed focal structure are in agreement with experi-

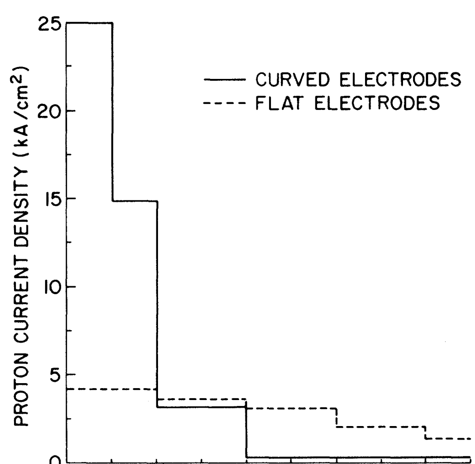

FIG. 2. Radial-profile histograms of the proton current density for flat (dotted line) and solid spherical (solid line) anodes at a distance of 8.4 cm.

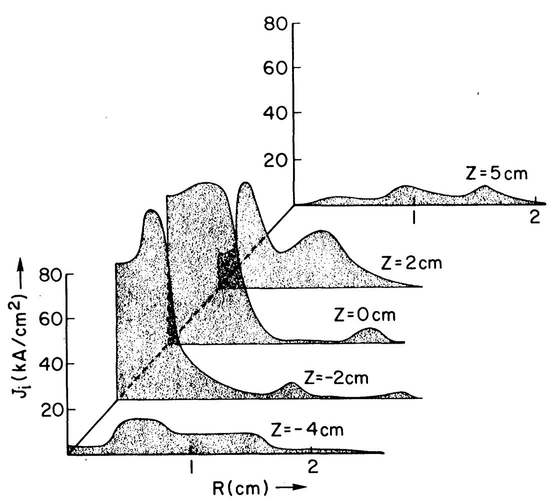

FIG. 3. Proton current-density profiles as computed by a two-dimensional, time-dependent diode simulation code. Results were extrapolated from flat to curved solid-anode geometry ($Z = 0$ is the center of the sphere with 12.7-cm radius of curvature).

ment. The shift in the axial position of peak ion current density (computed at 11 cm but observed at 8.5 cm from anode) is, however, unexplained. As will be shown below, self-magnetic-field effects in the drift tube are the probable cause of this effect.

The results of our numerical simulations show that a large fraction of the electron current is lost at large radii without enhancing the ion current. The solid anode has therefore been replaced in more recent experiments by a thin spherical anode foil attached to the solid anode by a small central conductor [Fig. 1(b)]. Electrons undergo a self-magnetic, pinch-reflex flow that increases the ion current. A new diode code that includes energy loss by the electrons in the foil has shown that the ion current is twice that predicted by Eq. (1). In addition, fluctuations in the diode are lower by an order of magnitude when compared to the ion current fluctuations for solid anodes.

The results of the pinch-reflex experiments with deuterons show that well-centered electron beam pinches are formed and that the ion current densities are enhanced. In the new geometry, net currents in the drift tube (where the pressure always equaled the diode pressure of 0.5 μm) were measured by a current shunt between the cathode and the target at the focus. Net currents of ~200 kA were recorded when hollow cathodes [no foil at position marked "K.F." (cathode foil) in Fig. 1(b)] were used. Placing a foil of 2-μm Kimfol (polycarbonate) in the cathode plane [position K.F. in Fig. 1(b)] reduced the net currents to ~90 kA while not reducing the total deuteron currents. The current density of the deuteron beams as a function of the axial distance from the anode is shown in Fig. 4. High current densities (~70 kA/cm^2) were observed using the cathode foil. These densities were derived from the neutron flux (about 10^{11} neutrons total) generated by 135-kA deuteron beam impinging on a 1.9-cm^2, $(CD_2)_n$ target. About 175 kA of deuteron current was measured on a 100-cm^2 target. Thus, about 75% of the deuteron current was focused. In the case of the hollow cathode with no Kimfol, also shown in Fig. 4, the quality of the focus was poor while the total current was about the same. It is believed that the high self-fields due to the large net currents when no Kimfol was used affected the ion orbits, giving a poor focus. When the Kimfol is present the bending of the ion orbits is primarily due to the self-magnetic field in the diode. The effect of this bending was computed

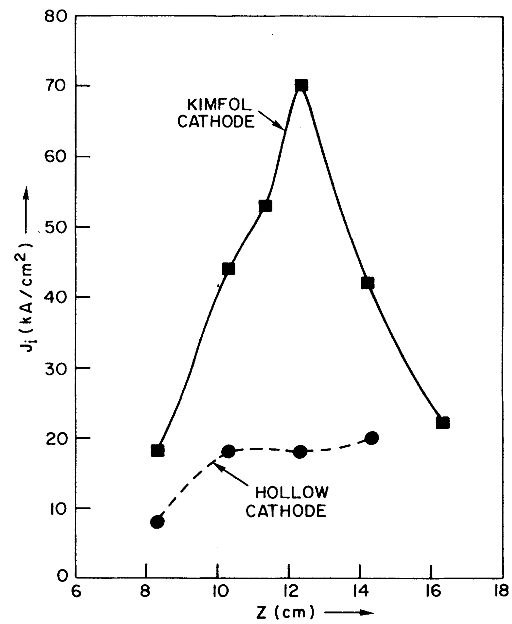

FIG. 4. Deuteron current density on diode axis as a function of axial distance from anode apex. The diode of Fig. 1(b) was used with (solid curve) and without (dashed curve) a 2-μm polycarbonate foil at position at "K.F." of Fig. 1(b). Systematic calibration errors may be ± 20% while relative errors between data points are due to shot-to-shot voltage variations and are ± 10%.

for the experimental parameters and the predicted deuteron current density of 90 kA/cm^2 at the ion focus is in good agreement with the observed current density of 70 kA/cm^2 (Fig. 4). Bending of the ion orbits in the diode may be reduced by smaller anode-cathode gaps and by using aspheric anodes while the net current in the drift tube may be decreased by filling it with plasma. An order-of-magnitude increase in ion current density may then be achieved. It should be noted that effects due to asymmetries in charge flow in the diode were probably masked in the present experiment, but will be investigated in future experiments.

In conclusion, using several diagnostic techniques it was demonstrated that diodes with shallow, spherical-dish anodes and very hollow cathodes have efficiently generated and focused intense proton and deuteron beams up to current densities of 70 kA/cm^2. Reasonable agreement between numerical simulation results and the experimental results was demonstrated. Insight into the factors which limit beam focal size has been gained and the use of future diodes in order to achieve 1-MA/cm^2 ion beams is anticipated.

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One-Dimensional Fluctuations and the Chain-Ordering Transformation in $Hg_{3-\delta}AsF_6$

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Neutron-scattering behavior and other properties of the mercury chains in $Hg_{3-\delta}AsF_6$ are calculated from a simple microscopic model. The independent chains satisfy a quantum sine-Gordon equation. The theory accounts for existing observations and makes a number of testable predictions about properties of the disordered phase, the nature of the phase transition, evolution of long-range order, and the excitation spectrum at low temperatures.

There is considerable interest in the mercury chain compound $Hg_{3-\delta}AsF_6$ which is known to have a number of rather unusual properties.[1,2] Structurally[1,3] it consists of a body-centered tetragonal (bct) lattice of AsF_6^- anions, through which pass two orthogonal arrays of nonintersecting linear chains of Hg cations, one parallel to $\vec{a}_T$, the other to $\vec{b}_T$. A neutron scattering investigation[4] has established or confirmed the following points:

(1) At room temperature and above, the scattering intensity consists of a series of uniform, thin sheets in reciprocal space, implying weak correlations between chains, but very long-range order within a chain. The spacing $2\pi/d$ between sheets corresponds to an interatomic separation $a_T=(3-\delta)d\approx 2.82d$ which is incommensurate with the basal spacing a_T of the AsF_6^- lattice.

(2) As the temperature T is lowered, modulation of the intensity within the first sheet grows, signifying an increasing short-range order between parallel chains in the separate arrays. At $T=T_c=120\,\mathrm{K}$, there is an apparently second-order transition to a phase which is different from that anticipated in the short-range order above T_c, reflecting, instead, interactions between a-axis and b-axis chains as discussed qualitatively by Hastings *et al.*[4]

(3) The diffuse sheets are the origin of inelastic-scattering surfaces with linear dispersion dependent only upon the component, Q, of momentum along the chains. That is, $\omega=\pm c|q|$, where $q=Q-Q_n$ and $Q_n=2\pi n/d$, suggesting one-dimensional phonon modes in the individual chains.[4]

We have formulated and analyzed a simple microscopic model system which treats exactly the