published) also indicate a charge transfer of about 0.5 electrons.

[11]C. S. Fadley and D. A. Shirley, J. Res. Nat. Bur. Stand., Sect. A. 74, 543 (1970).

[12]W. D. Grobman, R. A. Pollak, D. E. Eastman, E. T. Maas, Jr., and B. A. Scott, Phys. Rev. Lett. 32, 534 (1974); P. Nielsen, A. J. Epstein, and D. J. Sandman, Solid State Commun. 15, 53 (1974).

[13]P. Mengel, P. M. Grant, and B. H. Schechtman, to be published.

[14]We have become aware of an independent XPS study of $(SN)_x$ [L. Ley, Phys. Rev. Lett. 35, 1796 (1975) (this issue)]. Essentially our data are identical.

[15]D. E. Parry and J. M. Thomas, J. Phys. C: Solid State Phys. 8, L45 (1975).

[16]W. E. Rudge and P. M. Grant, Phys. Rev. Lett. 35, 1799 (1975).

[17]M. Boudeulle, Cryst. Struct. Commun. 4, 9 (1975), and Ph.D. thesis, Claude Bernard University, Lyon, 1974 (unpublished). We refer to this result as the Lyon structure.

[18]C. M. Mikulski, P. J. Russo, M. S. Saran, A. G. MacDiarmid, A. F. Garito, and A. J. Heeger, to be published (Penn structure).

Focused Intense Ion Beams Using Self-Pinched Relativistic Electron Beams

J. W. Poukey, J. R. Freeman, M. J. Clauser, and G. Yonas
Sandia Laboratories, Albuquerque, New Mexico 87115
(Received 18 October 1975)

A new two-dimensional diode simulation code is used to show the possibility of using hemispherical diodes to produce converging ion beams in the 1–10-MA range. The pinched electron flow enhances ion emission, while suppressing electron emission, allowing $I_i/I_e > 1$. Such focused ion beams are of considerable interest for use in ablatively driven implosions of fusion targets.

Ion currents of up to 10 kA have been produced in the reflex-triode work of Humphries, Lee, Sudan, and Condit.[1] It has been predicted by Creedon, Smith, Prono, and Bergstrom that a reflex triode with a fractional-range foil anode can produce still larger ion current densities.[2] However, substantial applied magnetic fields are required, and are not compatible with spherical implosions. Another method for generating large ion currents is to use a diode in which the electrons are insulated from the anode using an externally applied magnetic field in plane or cylindrical geometry.[3] The theory of both reflex triodes and magnetically insulated diodes has been discussed by Antonsen and Ott.[4] In this paper we discuss a third method for obtaining large ion currents which does not employ an external field, can be 50–75% efficient, and provides for spherical ion focusing. Previously we showed that the electric field of a pinching electron beam may itself be used to produce ion beams of hundreds of kiloamperes in cylindrically symmetric planar diodes.[5] The idea is that the electrons flow radially inward between the electrodes, displacing the equipotentials towards the anode (the largest displacement occurs at the axis of symmetry, as in the parapotential model[6]); the resulting higher electric field at the anode causes enhanced ion emission (assuming an ion source, i.e., anode plasma, is present). This shifting of equipotentials also causes reduced emission of electrons from the cathode, making it possible in some cases for the ion current to exceed the electron current (and thus using most of the input energy to accelerate ions, rather than electrons).

The problem in using ion beams from planar anodes for pellet implosion studies is that the ions form a rather parallel beam, whereas one would like a focused ion beam. Thus we have examined this problem in spherical geometry, and this paper will make plausible the possibility of producing reasonably well-focused ion beams (i.e., focused to dimensions < 1 cm) in the megampere regime.

For this study, a new particle simulation code was written, the spherical counterpart of the previously described cylindrical code.[5,7] The code is two-dimensional (r, θ with φ the symmetry coordinate), and both electrons and ions are treated self-consistently. The device consists of two identical hemispheres with the target at their center; the top half of such a hemisphere is shown in Fig. 1. The cathode is inside the anode so the ions move radially inwards. The electrons pinch to the axis of symmetry (at the pole of the hemisphere). A thin anode plasma is required to provide a source of ions, but plays no other role in the electron pinch. The case shown

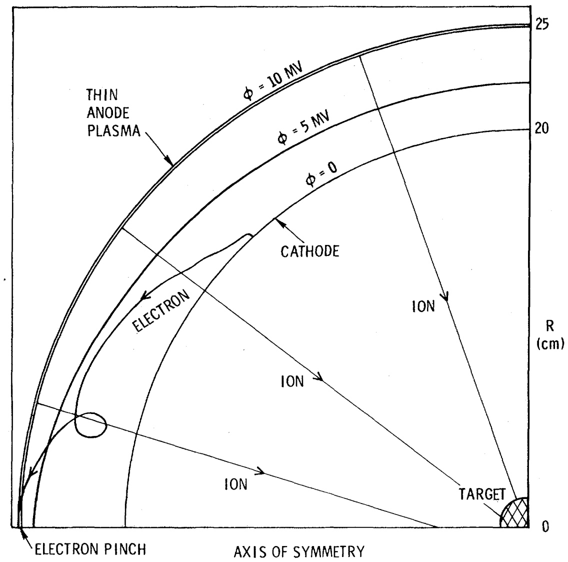

FIG. 1. Code solution for 10-MV hemispherical diode. Ion current is 0.5 MA, all the electron current of 0.7 MA pinches to the axis of symmetry.

in Fig. 1 is a 10-MV diode with cathode radius $R = 20$ cm, anode radius $R_A = 25$ cm. The computed currents (hemisphere only) were $I_e = 700$ kA, $I_i = 530$ kA. The equipotential shifting effect is indicated by the 5-MV equipotential; this causes the ion current density j_i to be largest near the electron pinch region (θ near 0). In fact, $\frac{2}{3}$ of the ions are inside $\theta < 45°$ (solid angle 0.6π) so that the device could be built from a number of spherical sectors with several power feed points.

The shifting of the equipotentials also explains why the ions will not focus exactly to a point at the sphere center. The electric field has an E_θ component, which causes the ions to cross the axis of symmetry before reaching the sphere center. (We are assuming the ions drag an equal number of electrons with them through the cathode so that the ion trajectories for $r < R$ are straight lines, and we are neglecting ion angular momentum effects due to anode-plasma temperature or scattering in the cathode.) Although most of the ions will still hit a reasonably sized target so that the spherical diode itself may be viable, we speculate that there is an optimum shape for the electrodes (perhaps different for cathode and anode), somewhere between plane (ions never cross symmetry axis) and spherical (ions cross too soon). Questions of focusing efficiency, deposition symmetry, and the angle of ion incidence on target remain to be answered for such a diode.

Next we turn to the question of how the currents I_e and I_i scale with voltage V and radii R and R_A. If we repeat the case of Fig. 1 but with $R = 8$ cm, $R_A = 10$ cm, or with $R = 4$ cm, $R_A = 5$ cm, we find the same currents $I_e = 700$ kA, $I_i = 530$ kA in all three cases. (Here "same" means within 10 kA.) This suggests that the currents depend only on $R/d = (R_A/R - 1)^{-1}$ (=4 for these runs) and not on R and R_A separately. To check this, the cases $R = 9$ cm, $R_A = 10$ cm and $R = 36$ cm, $R_A = 40$ cm ($R/d = 9$) were run at 10 MV and in both cases $I_e = 1.0$ MA, $I_j = 1.6$ MA was obtained. Thus we conclude that the currents depend only on V and R/d. This is not too surprising, since it agrees with the result found by Langmuir for nonrelativistic electron diodes.[8]

The form of $I_{e,i}(V, R/d)$ is not known. Both I_e and I_i increase with V; if in the $R/d = 9$ case above, we change V from 10 to 20 MV, we find $I_e = 1.6$ MA, $I_i = 4.7$ MA (55% of the ions in $\theta < 45°$). For cylindrical diodes, Goldstein has suggested that $I_i/I_e \propto R/d$.[9] For the 10 MV cases above, we have $dI_i/RI_e = 0.18$ for $R/d = 9$, $dI_i/RI_e = 0.19$ for $R/d = 4$. We tentatively conclude $I_i/I_e = f(V)R/d$, where the function f increases with V (somewhat slower than linearly, apparently).

The ion currents calculated for these cases represent an enhancement over the ordinary one-dimensional space-charge-limited ion currents[8] by a factor of from 2 to 3. (The electron currents are much reduced, of course.) The important thing is not so much the enhancement of I_i, but rather the fact that I_i/I_e can be made greater than 1; in the 20 MV, $R/d = 9$ case mentioned above, $\frac{3}{4}$ of the power will be put into the ions (in contrast to the $2\frac{1}{2}$% which would result for a nonrelativistic planar one-dimensional diode). The average ion current density on a 1-cm target would be ~ 1 MA/cm^2 for this case.

The other important conclusion is the implication of the fact that I_i depends only on R/d and V. Since one usually works at fixed V, and since in practice the applied radial field V/d is usually restricted to a few megavolts per centimeter to avoid possible gap-closure problems, one can increase both I_i and I_i/I_e at the desired (fixed) V and d by simply increasing R. The 20 MV, $R/d = 9$ case ($I_i = 9$ MA for whole sphere, $I_i/I_e = 3$) with, say, $R = 72$ cm, $d = 8$ cm should, according to target calculations,[10] be of real interest for ion-beam fusion studies. This large R and d, in addition to giving a reasonable V/d, would allow the chamber to survive, and for a short-pulse machine would give an ion bunch, rather than a beam (since ion transit time to center is greater than ion creation time). As suggested by Winterberg,[3] the power delivered to the target might be enhanced by the time variation of the voltage.

The practical upper bound to R would be determined by the ion-beam transverse energy and by focusing requirements. Fusion-target calculations[10] indicate that the fusion energy produced in the target will exceed the beam energy when the target is irradiated with beam currents around 10 MA and proton energies of 10 MeV or greater. To obtain the high compression ratios calculated for these targets the uniformity of irradiation must be better than 5–10% over the surface of the target. As suggested earlier the tightness of the ion-beam focus and the uniformity of irradiation can be controlled by appropriately shaping the anode and cathode. However, the tightness of the focus is limited by such factors as scattering by the cathode and transverse (thermal) energy at the point of emission. The target calculations assumed that the ions were normally incident on the target surface, but 20 MeV protons can be incident as much as 30° away from the surface normal without greatly altering the behavior of the target. Thus the ion trajectories need only pass within half the target radius of the target center. For a $\frac{1}{4}$-cm-diam target, this would correspond to a transverse energy of 10 eV at $R = 72$ cm.

Goldstein and Guillory[11] have recently proposed another method of producing a focused ion beam using a self-pinched electron beam. Electrons from a cylindrical hollow cathode pass through a spherical anode mesh and create a space-charge well which accelerates ions radially inwards to a target. A plasma forms on the target surface and secondary electrons are emitted which make many passes through the anode mesh; these secondaries are an important feature of the device. The ion current can not exceed the current of the primary electron beam, and some of the ions will flow radially outwards. As we have seen, the device proposed in the present paper allows $I_i/I_e \gg 1$.

[1]S. Humphries, J. J. Lee, and R. N. Sudan, Appl. Phys. Lett. 25, 20 (1974), and J. Appl. Phys. 46, 187 (1975); S. Humphries, R. N. Sudan, and W. C. Condit, Appl. Phys. Lett. 26, 667 (1975).

[2]J. M. Creedon, I. D. Smith, and D. S. Prono, Phys. Rev. Lett. 35, 91 (1975); D. S. Prono, J. M. Creedon, I. Smith, and N. Bergstrom, J. Appl. Phys. 46, 3310 (1975).

[3]R. N. Sudan and R. V. Lovelace, Phys. Rev. Lett. 31, 1174 (1973); R. V. Lovelace and E. Ott, Phys. Fluids 17, 1263 (1974); K. D. Bergeron, to be published; F. Winterberg, *Physics of High Energy Density* (Academic, New York, 1971), p. 370; F. Winterberg, Nature (London) 251, 44 (1974).

[4]T. M. Antonsen, Jr., and E. Ott, Cornell University Report No. LPS 166, 1975 (unpublished).

[5]J. W. Poukey, Appl. Phys. Lett. 26, 145 (1975), and in Proceedings of The Thirteenth Symposium on Electron, Ion, and Photon Beam Technology, Colorado Springs, Colorado, May 1975 (to be published).

[6]J. M. Creedon, J. Appl. Phys. 46, 2946 (1975).

[7]J. W. Poukey, J. R. Freeman, and G. Yonas, J. Vac. Sci. Technol. 10, 954 (1973).

[8]I. Langmuir and K. B. Blodgett, Phys. Rev. 24, 49 (1924).

[9]Shyke A. Goldstein and R. Lee, Phys. Rev. Lett. 35, 1079 (1975).

[10]M. J. Clauser, Phys. Rev. Lett. 35, 848 (1975).

[11]Shyke A. Goldstein and J. Guillory, Phys. Rev. Lett. 35, 1160 (1975).