Geometric focusing of an intense pulsed proton beam

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Using geometric focusing technique with a magnetically insulated diode, we have studied the focusing properties of an intense pulsed proton beam. Local divergence is found to have less effect on the focusing than deviation of ion trajectories from the ideal ones (aberration), which strongly affects the focusing. An annular distribution of the ion current density is found by ion-trajectory calculations to be a space-charge effect. The space-charge neutralization factor is estimated to be more than 99.9%.

Recently, considerable attention has been given in the literature to inertial-confinement fusion (ICF) by an intense pulsed light-ion beam (LIB).[1] LIB focusing[2–4] is one of the important themes to achieve ICF by LIB effectively. To estimate quantitatively the focusing ability of LIB, we here introduce the total divergence angle, $\theta=\tan^{-1}(r^*/f)$, where r^* is the focusing radius of LIB where half the total ion current is involved, and f is the focusing distance from the anode (see Fig. 1). Even with a magnetically-insulated diode (MID) that has been reported to have the smallest divergence in the ion diodes, θ has been found to be $>2°$.[3] We consider that the angle θ basically consists of three factors; local divergence angle (ϕ), deviation (δ) of the ion trajectories from the ideal ones (or aberration), and space-charge effects.[4] The local divergence originates from an effect due to the presence of knock pins, a temperature of the beam source, an inhomogeneity of magnetic field, or scattering processes. The aberration arises from the fact that the direction of beam acceleration is not exactly directed toward the focusing point, presumably due to an unevenness of the electrodes, an inhomogeneity of the anode plasma, etc. The divergence due to space charge is also important for the LIB focusing, particularly in the high-current relatively low-energy region. The LIB is almost space charge and current neutralized by electrons emitted from the cathode or a drift tube.[1] However, a small amount of space charge may play an important role for focusing. A quantitative determination of the space-charge neutralization factor (f_s) has not been done previously. In this paper, we wish to report the detailed focusing properties.

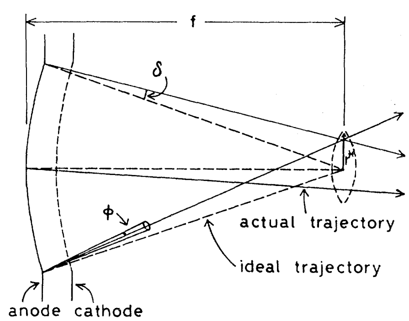

FIG. 1. Schematic of geometric focusing from spherically shaped MID, where θ [$=\tan^{-1}(r^*/f)$], ϕ, and δ are total divergence angle, local divergence angle, and deviation angle from ideal trajectory (or aberration), respectively.

The experiments were carried out in the Nagaoka ETIGO-I,[5–8] 15-kJ-LIB generator at the Technological University of Nagaoka. A spherically-shaped MID is utilized to study geometric focusing. The radii of curvatures of anode and cathode are 160 and 150 mm, respectively. The gap length of MID is 10 mm. As reported elsewhere, there appeared a voltage reflection due to an impedance mismatch between the pulse-forming line (PFL) and MID; the diode works at a relatively high impedance in the first phase (phase I), while the impedance decreases in the second phase (phase II) due to the presence of a residual anode-sheath plasma. The diode voltages are typically $V_d^{(\mathrm{I})}=550-630$ kV and $V_d^{(\mathrm{II})}=200-300$ kV at V_c (charging voltage of Marx generator) $=\pm 30$ kV, where the suffixes I and II refer to phases I and II, respectively. The pulse width of V_d is 80–100 nsec [full width at half maximum (FWHM)] in both phases. The diode currents are $I_d^{(\mathrm{I})}=27-34$ kA and $I_d^{(\mathrm{II})}=60-70$ kA. We have operated MID at $B/B_c \sim 3$ (phase I) and 4.3 (phase II), B and B_c being the transverse magnetic field strength and the critical magnetic field strength above which an electron flow is insulated, respectively.

Figure 2 shows the distribution of ion-current density (J_i) measured by a biased-ion collector (BIC). In phase I, as seen in Fig. 2(a), LIB is focused at the center around the geometric focusing point with a maximum value of $J_i^{(\mathrm{I})} \sim 3.2$ kA/cm^2. The focusing diameter (FWHM) is $d_f^{(\mathrm{I})} \sim 10$ mm. Moreover, we find $r^* \sim 16$ mm, which gives $\theta \sim 6°$. Contrary to

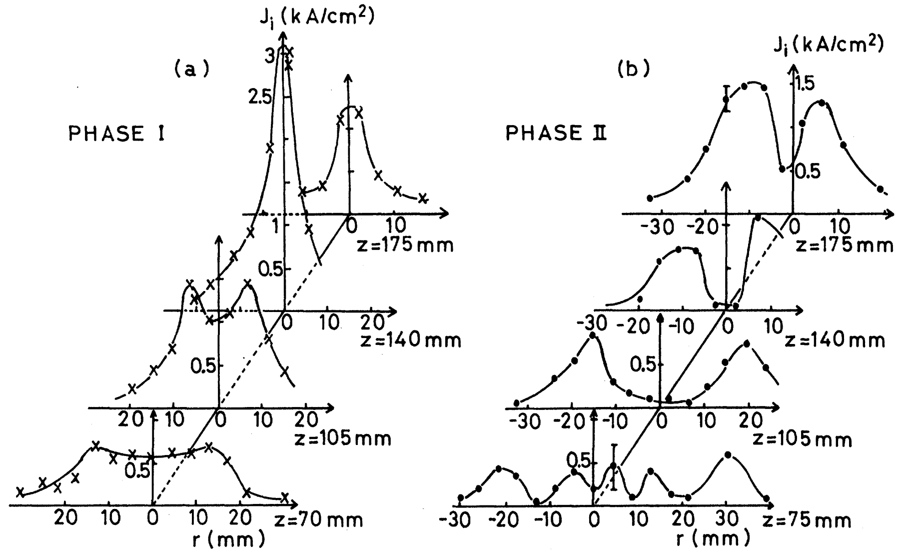

FIG. 2. Distribution of $J_i(r,z)$ in (a) phase I and (b) phase II.

phase I, no current is present at the central part in phase II, hence yielding an annular distribution [see Fig. 2(b)]. The focusing diameter (FWHM), $d_f^{(\mathrm{II})} \sim 30$ mm, is much larger than that in phase I. The maximum density is $J_i^{(\mathrm{II})} \sim 1.5$ kA/cm^2, which appears at 1.5–2 cm downstream from the geometric focusing point. An important fact is that in both phases we have found good focusing[8] in the case of small values of total ion current.[9] This gives possible evidence that the annular distribution seems to be due to a space-charge effect at relatively low-energy, large ion currents.

Now, we present some data measured by a shadow box.[8] A damage pattern has been obtained at a copper plate placed 10 mm downstream from the shadow plate, which has 45 holes (1.5-mm-diam each). Comparing the diameters of the holes and damages, we determine ϕ as well as the ion trajectories. If the shadow box is placed at 55 mm downstream from the anode, we have observed that the diameters of 27 in 30 damages are less than 1.8 mm. This gives $\phi \sim 1°$. Figure 3(a) shows ion trajectories in a plane parallel to the insulating magnetic field. The dashed lines represent ideal trajectories of ions. As a whole, the ions are seen to focus toward the geometric focusing point. However, ions in the outer region tend to be defocused. Figure 3(b) shows ion trajectories in a plane perpendicular to the insulating magnetic field. We see LIB tends to defocus upward, i.e., the same direction as the $\vec{E}\times\vec{B}$ drift. Using these data, we estimate the aberration angle and plot it in Fig. 3(c). Figure 3(c) indicates that there exists a relatively large deviation in the r direction ($\delta_r \sim 3°$), and that ions tend to deviate outward. In the θ direction, it is less ($\delta_\theta \sim 1.7°$), but is still larger than ϕ.

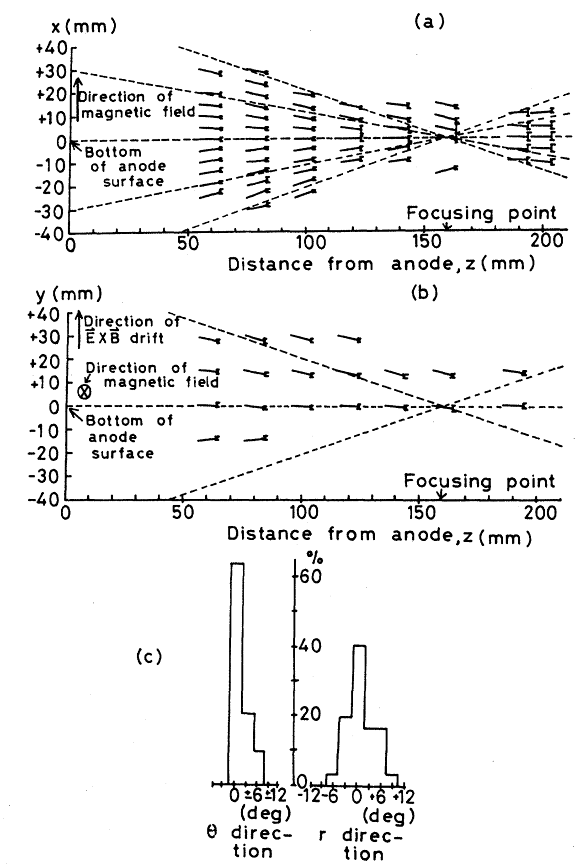

FIG. 3. Ion trajectories (phase I) in planes (a) parallel and (b) perpendicular to insulating magnetic field. (c) Deviation angle from ideal trajectories measured at 55 mm downstream from anode (phase I). Shadow-box measurements were carried out at $V_c = \pm 35$ kV.

Next, we calculate ion trajectories to obtain $J_i(r,z)$. Comparing the experimental and theoretical results of $J_i(r,z)$, we finally estimate f_s. As considered previously, the LIB focusing is affected by the effects of local divergence, aberration, and space charge. However, we neglect the first two effects and assume that the focusing is entirely determined by the space-charge effect. Such a procedure will give the minimum of f_s. The other assumptions are as follows: (1) The incident distribution of $J_i(r)$ is uniform over the anode surface. (2) All the beam particles are fired exactly toward the geometric focusing point. (3) The electric field produced by the space charge is only in the r direction. (4) The self-magnetic field is in the θ direction. (5) The beam consists of protons. (6) The beam energy is estimated by the peak value. (7) In axial symmetry, the electric and magnetic fields at a radius r are determined by the total charge and current involved inside r.

From these assumptions, we write the basic equation of motion as

$$\ddot{r} = \frac{eI}{2\pi\epsilon_0 m_p v_z r}\left[(1-f_s) - \left(\frac{v_z}{c}\right)^2 (1-f_c)\right] , \quad (1)$$

where I is the total ion current inside r, m_p is the proton mass, and v_z is the axial beam velocity. In Eq. (1), we have used $f_c = 0.8$, which is obtained by the comparison of BIC signals with and without bias voltage. Calculating Eq. (1) so that the focusing radius less than 5 mm is achieved, we finally estimate $f_s > 0.999$ in phase I.

Next, we consider the LIB focusing in phase II. Many numerical calculations have been carried out to predict ion trajectories, as seen in Fig. 4. In the case of $f_s = 0.9992$ that is constant in the r direction [see Fig. 4(a)], we have found the same diameter of the focused LIB as observed experimentally. However, it does not give an annular distribution. Now, we assume that the value of f_s changes radially, while

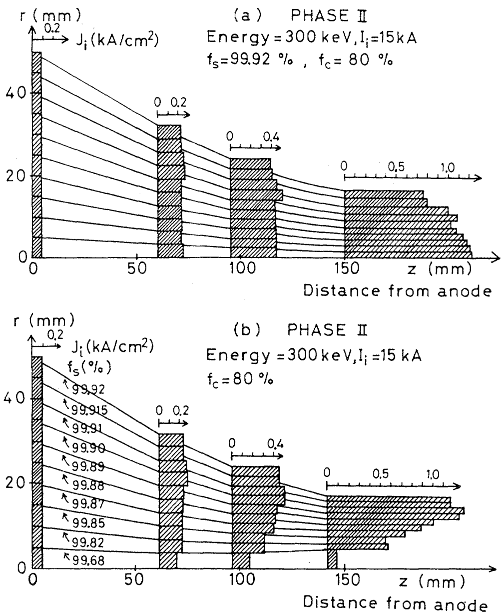

FIG. 4. Calculated trajectories of ions (solid lines) in (a) phase I and (b) phase II with ion-current density predicted (shaded area).

remaining $f_s = 0.9992$ at the outermost region as determined from Fig. 4(a). Figure 4(b) shows a typical result, where the central region is supposed to be less charge neutralized than the outer region; $f_s = 0.9992$ and 0.9968 at $r = 50$ and 5 mm, respectively. Comparing Figs. 2(b) and 4(b), we see that reasonable agreement is obtained, and that consequently the annular distribution of $J_i(r)$ in phase II can be due to a space-charge effect. Thus, we determine $f_s = 0.9992$ at the outermost region, hence the total charge neutrality. The central region appears to be less charge neutralized than the outer region. The presence of hot electrons[10] probably produced by beam-plasma interactions may correlate with such a phenomenon.

[1]S. Humphries, Jr., Nucl. Fusion 20, 1549 (1980); also, many references cited therein.

[2]J. Maenchen *et al.*, Phys. Fluids 22, 555 (1979).

[3]D. J. Johnson *et al.*, J. Appl. Phys. 50, 4524 (1979).

[4]Divergence angle of 1° has been reported by Cornell's group. Their estimate does not mean θ, but correspond to ϕ in our definition. See the following article: G. Cooperstein *et al.*, in *Proceedings of the 8th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1980), CN-38/P-2.

[5]K. Yatsui, in *Proceedings of the Japan-U.S. Workshop on Compact Toroid* (Osaka University, 1981), p. 105.

[6]K. Masugata *et al.*, Jpn. J. Appl. Phys. 20, L347 (1981).

[7]K. Yatsui *et al.*, in *Proceedings of the 4th International Topical Conference on High-Power Electron and Ion Beam Research and Technology* (Palaiseau, France, 1981), p. 27.

[8]K. Masugata *et al.*, Kakuyugo-Kenkyu 47, Suppl. 8, 100 (1982).

[9]Total ion current (I_i) may be estimated by $I_i = \int_0^{r=30\text{ mm}} 2\pi r\, dr$ by use of Fig. 2; for example, $I_i^{(\mathrm{I})} \sim 9$ kA and $I_i^{(\mathrm{II})} \sim 15$ kA at 140 mm downstream from the anode.

[10]K. Yatsui *et al.*, in *Proceedings of the 3rd European Conference on Controlled Fusion and Plasma Physics* (Utrecht, The Netherlands, 1969), p. 27; also, Phys. Lett. 39A, 425 (1972); also, J. Phys. Soc. Jpn. 33, 829 (1972).