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Generation and Propagation of an Intense Rotating Proton Beam

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An annular magnetically insulated diode in a cusplike magnetic field has been used to produce an ~6-kA, ~190-kV rotating proton beam. Diamagnetic signals and magnetically insulated Faraday cups indicate that (35±15)% of the beam traversed the cusp and reached the end of the system magnetic field 35 cm from the diode. Diamagnetism was in excess of 2% of the 8-kG applied field, and the beam was distinctly hollow with a 6-cm average radius.

The theoretically favorable plasma-confinement properties of field-reversed magnetic field configurations have led to many reactor proposals.[1-5] Such configurations have been experimentally realized (i) by the injection of relativistic electron beams[6] to form a reversed-field electron ring,[7] (ii) by plasma currents induced by relativistic-electron-beam injection,[8] and (iii) by reversed-field θ pinches.[9] However, synchrotron-radiation energy losses make a relativistic electron ring unsuitable for a fusion reactor. Indeed, Christofilos amended his original Astron concept[1] by replacing electrons with high-energy protons. Developments in intense-ion-beam[10-13] technology make it possible for a reversed-field ion ring to be produced by single-pulse injection.[2] This has led to two experimental programs[12,13] aimed at the injection and trapping of an ion ring in a mirror magnetic field.

In this Letter, we report experimental results on the production and propagation of a rotating beam of the type required for ion-ring formation. To summarize, an ion beam was produced with up to 40% efficiency using an annular magnetically insulating diode, and was caused to rotate by a cusplike magnetic field. Of the $\sim 4\times 10^{15}$ ions extracted from the diode, (35±15)% traversed the cusp, formed a rotating proton beam, and reached the end of the system magnetic field 35 cm from the diode. The (2–3)% diamagnetic signals (in an 8-kG applied field) are significantly larger than those previously reported.[14,11]

The apparatus used for the present experiments, including a detail of the diode region, is shown in Fig. 1. It is a cylindrically symmetric annular system, the anode surface of which is made coincident with a flux surface by properly positioning coils within the anode itself which are diamagnetic with respect to an externally applied field. The resultant magnetic field in the anode-cathode gap both inhibits the flow of electrons and imparts a rotational velocity to the protons as they cross the radial magnetic field lines both in and after the diode. For magnetic-insulation tests, the

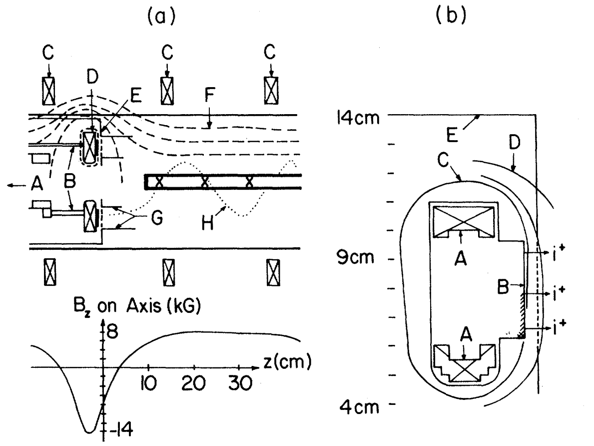

FIG. 1. (a) Schematic: A, connections to high voltage, with isolation inductor for connecting a capacitor bank to the anode coil; B, anode supports and anode coil feed; C, external coils; D, anode; E, cathode; F, magnetic field line; G, Mylar cylinders; H, typical particle orbit. Also shown is the total magnetic field at $r=0$. (b) Diode detail: A, anode coils; B, active anode surface; C, magnetic field lines; D, separatrix; and E, cathode.

anode is a metal surface connected to the high-voltage generator. For the proton-beam experiments, a 0.15-cm-thick, 185-cm^2 polyethylene annulus is mounted on the metal anode. The plastic has a 0.3-cm square array of 0.1-cm holes drilled in it to distort the surface electric fields sufficiently to produce a surface breakdown and a dense plasma on the anode. This plasma provides the protons which are accelerated across the anode-cathode gap to form the beam. The experiment was operated at a pressure of 10^{-4} Torr. The pulsed power generator used for these experiments was a 3.3-Ω, 250-keV, nominal 120-nsec pulse-forming line.

With the metal anode, diode perveance ($I/V^{3/2}$, where I and V are diode current and voltage) was reduced by a factor of 60 as the insulating magnetic field was increased from 0 to 7.5 kG. The accelerating gap spacing was 5.0 ± 0.25 mm, and the diode voltage and current were 290 kV and 8–9 kA at 7.5 kG, 1.8 times the critical field for magnetic insulation.[12] Anode damage and x-ray pinhole photography showed that the remaining electron current was along two paths. Firstly, although the electron drift surfaces were closed around the anode annulus [see Fig. 1(a)], they did connect electrically stressed areas of the cathode to the four 1-cm-diam rods which connect the back of the anode to the generator. Secondly, some of the electrons on those drift surfaces drift across magnetic field lines and strike the anode surface near the inner edge.

When the polyethylene anode surface was used, an ion beam was accelerated axially through the 65%-transparent stainless-steel cathode. The gap spacing and the insulating magnetic field were as above. The perveance increased by a factor of ~6, only partly due to the proton beam as additional electron flow was produced by the presence of the ion beam.

The radial distribution of the extracted ion current density was found to be highly nonuniform using four magnetically insulated, 0.002-cm^2-aperture Faraday cups located 0.6 cm from the cathode and at the radial positions 8.9, 8.3, 7.3, and 6.6 cm. The *time-averaged* extracted current densities at these positions, averaged over four azimuthal positions and several shots per position, were 10, 15, 70, and 60 A/cm^2. Peaks were typically double these values. These are to be compared with an expected (space-charge–limited flow) average proton current density of 9 A/cm^2 after correcting for cathode transparency. Evidently this enhancement is a result of the electrons near the inner edge of the anode as observed during the magnetic-insulation tests. These measured averaged current densities were corroborated by calorimetry; the radial dependence was verified by damange on "witness targets." A total ion current of 12 ± 3 kA was estimated out of a total diode current of typically 28 kA at a voltage of 160 kV, a 40% ion production efficiency. The *average* ion current was 6 times the proton space-charge–limited–flow value given the initial diode geometry.

The diode parameters during the beam-propagation studies were a 5.75-cm diode gap and a 6.1-kG insulating field. For these tests, the system was highly reproducible but less efficient in ion production. Farraday cup and calorimetric measurements of the extracted ion beam indicated about 6 kA average current at 190 kV, or ~4 $\times 10^{15}$ ions per pulse, a factor of about 4 times the space-charge–limited–flow proton current. Typical diode voltage and current wave forms are shown in Fig. 2(a).

It was anticipated that the production of a rotating proton beam would require provisions for prompt and complete charge neutralization of the beam as it traversed the cusp. With only the vacuum chamber walls to provide the electrons (presumably after proton bombardment), magnetic pickup loops on axis 13, 23, and 33 cm

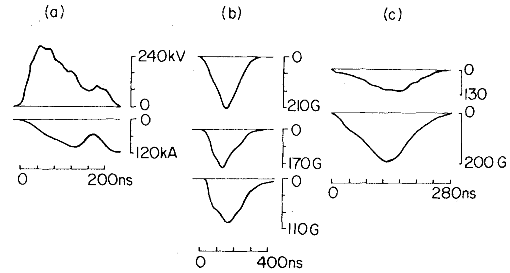

FIG. 2 (a) Diode voltage and current for propagation experiments. (b) Diamagnetic signals at 13, 23, and 33 cm. (c) Upper trace: The Faraday-cup signal at 1.5-cm radius, with no bias voltage, 15 cm downstream. The vertical scale is in A/cm^2 of electron current. Lower trace: the diamagnetic signal at 13 cm on the same shot.

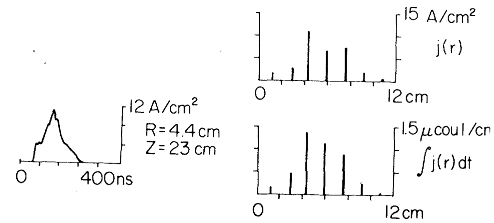

FIG. 3. A typical oscillograph of the azimuthal proton current density obtained from a magnetically insulated Faraday cup shown together with histograms of $j_{\text{peak}}(r)$ and $\int j(r)\,dt$ obtained using eight such Faraday cups 23 cm downstream, with Mylar cylinders in place.

downstream from the diode showed peak diamagnetic signals of 270, 130, and 65 G, respectively. The applied field in this region was about 8 kG. However, thermofax-paper witness targets showed that the proton beam expanded to the axis and to the vacuum chamber walls within the first 10 cm of propagation.

A source of space-charge-neutralizing electrons was brought closer to the proton beam by placing Mylar cylinders just inside and just outside the beam inner and outer radii, as shown in Fig. 1. A surface flashover plasma due to the accumulated positive charge from proton bombardment was expected to provide the required space-charge neutralizing electrons in position to propagate *along* field lines with the rotating proton beam. Indeed, the diamagnetic signals at 23 and 33 cm increased to 185 and 100 G, respectively, as shown in Fig. 2(b). The 13-cm signal also shown in Fig. 2(b) decreased to 200 G, apparently because of the loss of some of the rotating protons to the 10-cm-long Mylar cylinder. Note that the 23-cm signal, in excess of 2% diamagnetism, is representative of the actual propagating beam since it is located a full beam diameter away from the cusp. Note also that while the 33-cm signal is smaller than that at 23 cm, it is also wider.

A quantitative profile of the rotating proton beam produced with the Mylar cylinders in place was obtained using eight Faraday cups oriented to measure azimuthal current density. They were located along a radius at intervals of 1.6 cm starting 1.3 cm off axis. Figure 3 shows a typical Faraday-cup signal and histograms of $j_{\max}(r)$ and $\int j(r)\,dt$ taken 23 cm downstream. The profile is seen to be distinctly hollow with a radius of about 6 cm. This information yields a lower bound of 1×10^{15} protons in the rotating beam at this point. Repeating this procedure at 33 cm yields 80% of the number of protons found at 23 cm, with the profile still hollow. Removing the Mylar cylinders gave a beam with 35% fewer protons and a relatively flat profile.

By time correlating the Faraday-cup signals with the diode voltage, the axial velocity of the proton beam was obtained. The increase in the width of the Faraday-cup signals with distance provided an estimate of the axial velocity spread. These numbers are 3×10^8 and 1×10^8 cm/sec, respectively, with the velocity corresponding to 200 keV being 6×10^8 cm/sec. Thus ~75% of the beam kinetic energy was converted to rotational energy by passage through the cusp. With use of proton beam speed, an estimate of the number of protons in the beam from the diamagnetic signals yielded upper bounds of 3×10^{15} and 2×10^{15} protons at 23 and 33 cm, respectively. A comparison of this estimate with the Faraday-cup results suggests that cross-field current neutralization of the proton beam by electrons is negligible. Averaging the Faraday-cup and diamagnetic signals estimates gives $(1.5\pm0.5)\times10^{15}$ protons reaching the end of the system magnetic field, out of a total of 4×10^{15} ions extracted from the diode. (Note that a polyethylene anode is expected to yield a proton/carbon current density ratio of ~6 based upon space-charge-limited-flow theory. However, the carbon ions do not contribute to the rotating-beam azimuthal current density or diamagnetic-signal measurements.)

Although the Mylar cylinders improved the strength and quality of the propagating beam, it was desired to determine if they completely suppressed the space-charge fields. If a positive space charge was left in the cusp region, high-energy electrons would be accelerated into it along field lines. Therefore, three Faraday cups were placed 15 cm downstream from the anode at radii of 3.5, 6, and 10 cm with their axes *along* the magnetic field. The inner two cups were on field lines which connected to the Mylar cylinders, while the outer one was not. With no bias on the cups, negative signals were observed on the inner two probes with temporal behavior similar to the diamagnetic signal at 13 cm [Fig. 2(c)]. The outermost probe gave only noise. Bias voltages of up to -500 V had littel effect on the signals, while a bias of -1000 V reduced the signal amplitudes on the inner two probes by about a factor of 2. Evidently, these electrons were accelerated along field lines from the outer Mylar cylinder through a positive space potential at the cusp to an average energy of ~1000 V at $z = 15$ cm. Such electrons run ahead of the protons, forming a negative space potential which decelerates them, as evidenced by nearly null signals on these probes using -800-V bias at 25- and 35-cm axial positions.

A proton ring may be trapped[12] by a resistive wall interaction which dissipates the axial energy of the beam. A resistive ring was placed around a rotating beam with $\leq 1\times 10^{15}$ protons. About 5 mJ out of an estimated axial energy of 3–5 J was dissipated by the resistor in agreement with expectations based upon the diamagnetic signals measured on axis. Since the fraction of the axial energy dissipated by resistive structures increases roughly linearly with both the number of protons and the structure length, this modest result bodes well for trapping experiments in which $>10^{16}$ protons are expected.

Conclusions for ion-ring–trapping experiments which may be drawn from this work are as follows: (1) Efficient magnetically insulated proton sources can be produced which operate at several times the space-charge–limited–flow current density, allowing lower voltage operation with smaller sources than previously expected; (2) intense proton beams may efficiently cross a magnetic cusp near the transmission cutoff, if a source of cold electrons is provided in the cusp; (3) cross-field current neutralization of high-energy protons by electrons is not significant; and (4) resistive wall trapping is not inhibited by plasma formation around the rotating beam.

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