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The excitation cross section to the intermediate level and the ionization cross section from it were estimated from the measurement of the laser power dependence of the photoion currents. The details of the derivations and the results will be published in the near future.

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# Magnetic field reversal induced by an intense rotating electron beam in an initially neutral gas[a)]

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We find field reversals up to four times the initial field and changes in the magnetic field on the axis of symmetry of 6 kG when a rotating electron beam is injected through a cusp into an initially neutral gas. The change in magnetic field on the axis was found to be independent of the magnetic field. This is shown to be consistent with measurements that the cusp transmission coefficient times the ratio of the azimuthal velocity ($V_\theta$) to the axial velocity ($V_z$) is independent of magnetic field.

PACS numbers: 52.55.Ke, 52.40.Mj, 52.50.Dg

The idea of using electron-ring currents to produce stable reverse-field mirror configurations was initiated by Christofilos.[1] Such configurations have been produced experimentally with intense electron-beam generators.[2] The lifetime of the field reversing rings has been extended to more than 100 $\mu$sec.[3] The braking of a rotating beam and plasma response have received consierable theoretical attention.[4–8] Magnetic field reversals of 2.2 with changes in the magnetic field up to 1.8 kG were observed long after the lifetime of the beam.[9]

It has been pointed out that these induced currents produce a plasma—magnetic-field geometry similar to a reversed-field $\theta$ pinch, and this may be a suitable method for producing an initial plasma in an imploding metallic linear fusion device.[10] We report field reversals up to four times the initial field and changes in the magnetic field on the axis of symmetry of 6 kG.

The experimental apparatus is shown in Fig. 1 and has been described elsewhere.[11] The electron-beam generator was operated in the range 1–1.4 MeV peak diode voltage and 50–90 kA diode current. The half-width of the current pulse was 50 nsec. The hollow cathode is made from graphite and has a 7-cm outer diameter with a 5-cm inner diameter. Rotation is imparted to the beam as it passes through a cusp magnetic field.[12] The center of the cusp is 10 cm from the anode and has a width of 8 cm (FWHM) at a radius of 3 cm. The rotation imparted to the beam can be observed from the damage on a Lucite rod placed in the path of the beam. The average value of the azimuthal and axial vel velocity components have been measured by this method.[11] Measurements of beam electrons are made by placing 0.63-mm tungsten wires in the beam path and looking at the x rays emitted with collimated x-ray pin diodes. The beam is injected into an initially neutral hydrogen gas in the 50–500-mTorr range. The response of the beam-generated plasma can be inferred, in part, by magnetic probes.

The magnetic probes are shielded from electrostatic noise by a quartz tube with a slotted silver coating. The magnetic probes are calibrated by measuring the field in the center of a 3 cm-i.d. by 50-cm-long single-turn solenoid, driven by a 20-A 200-nsec pulse. The calculated and measured sensitivity agree within 15%. The output of the probe is integrated with a 10-$\mu$sec integrator. The integrator is calibrated by putting a square pulse of known voltage and duration into the integrator and measuring the peak value. In addition we can get an additional check on the calibration by measuring the time for the peak to decay to $1/e$ of its value.

Figures 2(a) and 2(b) are oscilloscope traces of the change in the axial component ($B_z$) of the magnetic field.

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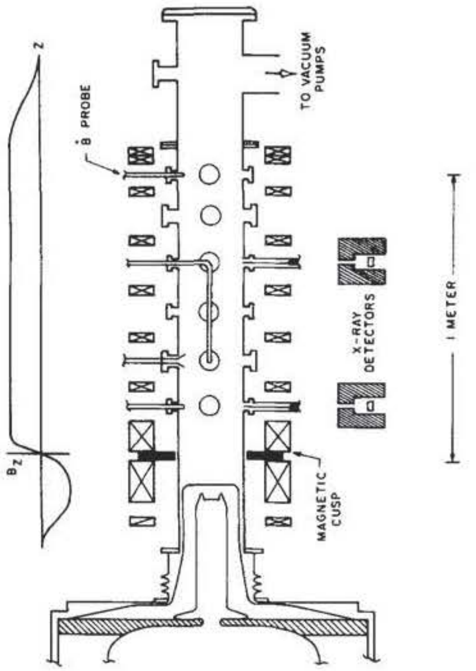

FIG. 1. Experimental apparatus. The stainless-steel drift chamber has a 19-cm inside diameter. The magnetic probe on the axis has a diameter of 1 cm. The anode is a 0.025-mm Ti foil.

The oscilloscope trace in Fig. 2(c) shows the time dependence of the x-ray flux from beam electrons hitting the tungsten wire. More sensitive observations show the x-ray signal is less than 1% of the peak after about 100 nsec. However, the magnetic probe signals last 10 times longer than the x-ray pulse. This suggests that the magnetic probe signals are due to currents induced in the plasma rather than the beam electrons. Two characteristic time dependencies of the magnetic field on the axis of symmetry are observed. At a pressure of 100 mTorr of $H_2$ the signal remains relatively constant for about 1.5 $\mu$sec and then appears to decay exponentially as shown in Fig. 2(a). At higher pressures the change in the magnetic field decreases as shown in Fig. 2(b). Measurements with a 2-mm microwave interferometer show the plasma density decays to $10^{13}$ cm$^{-3}$ after 300 $\mu$sec at a pressure of 50 mTorr.

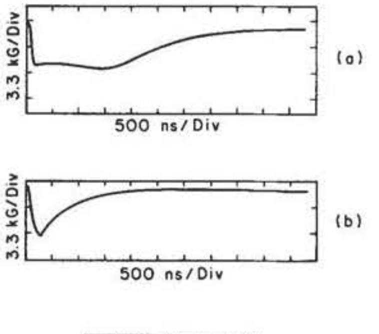

FIG. 2. Magnetic probe and x-ray measurements. Diode voltage and current were 1.4 MeV and 90 kA peak. The magnetic field was 1.6 kG. The pressure was 50 mTorr $H_2$ in (b) and 100 MTorr in (a) and (c). The magnetic probe was 26 cm from the cusp and the x-ray target 16 cm.

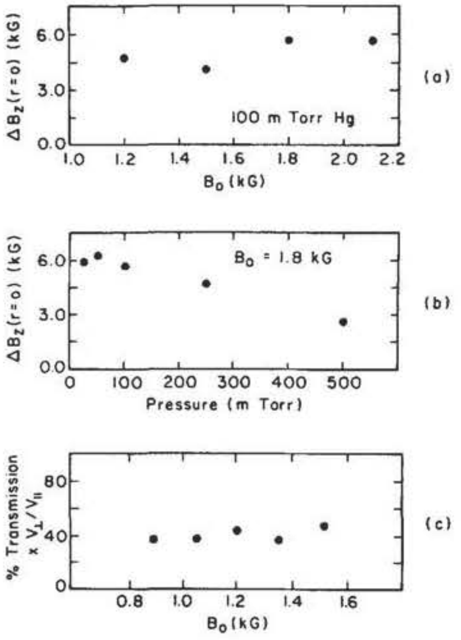

FIG. 3. Change of the magnetic field and product of transmission coefficient with perpendicular-to-parallel velocity ratio. The perpendicular velocity is in the azimuthal direction.

The peak of the change in the magnetic field is shown in Fig. 3(a). We find that the change in the magnetic field is almost independent of the initial value of the field. This is a surprising result. Since $V_\theta/V_z$ is an increasing function of the magnetic field,[11] this implies that the azimuthal current and the change in the magnetic field should be increasing functions of the magnetic field. This result suggests that the fraction of the beam passing through the cusp times the ratio of $V_\theta$ to $V_z$ is roughly a constant. This can be seen by relating the azimuthal current to the diode current. We have

$$I_D = n_b e V 2\pi a \Delta a, \tag{1}$$

where $n_b$ is the beam density, $e$ is the electronic charge, $V$ is the velocity of the beam leaving the anode, $a$ is the average radius of the beam, and $\Delta a$ is the width of the annular beam. After passing the cusp, from conservation of current, we have

$$n_b' V_z = \alpha n_b V, \tag{2}$$

where $n_b'$ is the beam density after the cusp, $V_z$ is the beam velocity after the cusp, and $\alpha$ is the transmission coefficient for the cusp. The azimuthal current is

$$I_\theta = n_b' e V_\theta \Delta a (1-f), \tag{3}$$

where $V_\theta$ is the azimuthal beam velocity and $f$ is the azimuthal current neutralization factor. We assume the induced plasma current at the end of the beam pulse is equal to the net current given by Eq. (3).

From Eqs. (1)–(3) and Ampere's law we have

$$\Delta B_z = \frac{4\pi}{c} I_\theta = \frac{2}{c} \frac{\alpha V_\theta I_D}{V_z a} (1-f). \qquad (4)$$

Hence if $\alpha V_\theta/V_z$ is a constant, then $\Delta B_z$ is independent of $B$.

We have measured the cusp transmission coefficient with a calorimeter and $V_\theta/V_z$ from the damage on Lucite rods.[11] The product of the two is plotted versus magnetic field in Fig. 3(c). We find $\alpha V_\theta/V_z \cong 0.4$ independent of the magnetic field. For $I_D = 90$ kA and $z = 3$ cm, Eq. (4) gives $\Delta B_z = 2.4$ kG $(1-f)$. However, the measured values are more than a factor of 2 greater than this even in the limiting case of no current neutralization (i.e., $f=0$). This implies a braking of the beam and an increase in $I_\theta$ after the cusp.

We have examined the axial dependence of $\Delta B_z$ with a series of magnetic probes along the axis. $\Delta B_z$ is a decreasing function of $z$ and becomes less than the initial field, at about 50 cm. Comparisons with calculations for stopping length[4,5,7] are difficult in beam-generated plasma. The plasma properties are changing rapidly during the beam pulse. Such rapid changes are outside the scope of the present theory.

The change in the magnetic field on axis versus pressure is plotted in Fig. 3(b). The current neutralization factor, $f$, increases with pressure, hence $\Delta B_z$ is a decreasing function of pressure.

In summary we find field reversals up to four times the initial field and changes in the magnetic field on the axis of symmetry of 6 kG when a rotating electron beam is injected into an initially neutral gas. The change in the magnetic field was found to be independent of the magnetic field. This has been shown to be consistent with measurements that the cusp transmission coefficient times the ratio of the azimuthal velocity is independent of magnetic field. We have inferred from the magnitude of $\Delta B_z$ that there is a braking of the beam, and an increase in $I_\theta$ due to a pile up of the beam after cusp.

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# Laser-driven shock wave inside a glass microballoon target

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A shock wave in fusion fuel filled in a glass microballoon target was directly observed. The shock speed and the width of the shock front were $5\times10^7$ cm/s and a few μm, respectively, which are in good agreement with the shock-tube theory.

PACS numbers: 52.50.Jm, 52.35.Tc

One of the important problems in laser fusion research is a behavior of a shock wave in fusion fuel. We have already investigated a laser-driven shock wave[1] propagating into a solid plane target by using an optical probing method, such as shadowgraphy, Schlieren method, and interferography. The existence of a protuberant shock wave driven by fast ions is also reported.[2] In this paper we present the observation of a shock wave inside a glass microballoon target and discuss the influence of the nonuniformity of the laser intensity distribution on the shock profile.

The one beam of the "Gekko II" glass laser system[3] was focused on a glass microballoon filled with 2 atm of $D_2$ gas. A high-speed shadowgraphy using SHG light of the main laser was used to observe the shock wave and the plasma. The spatial and temporal resolutions of the measuring system were better than 2 μm and 20 ps, respectively. We used large targets (140–150 μm in diameter and 1.5 μm in shell thickness) irradiated by the reduced laser intensity of $10^{15}$ W/cm$^2$, because the whole balloon was so rapidly ionized by the lateral thermal conduction that it became opaque to the probing light.

Figure 1 shows a series of the shadowgraphs taken at