simulation II leads to a greater loss of current, corresponding to a hard disruption, as compared with simulation I in which the plasma recovers after a comparatively small loss of current. Both cases show a strong negative voltage spike.

The role of the $m=1$ instability in these simulations is twofold. The first effect arises from the fact that the $m=1$ mode restrains q_0 from falling below a value around unity. This restraint on q_0 prevents the current from being carried close to the axis and enhances the destabilizing interaction of the current gradient with the $m=2$ island. The second effect is that already described; the growth of the $m=2$ island ultimately drives q_0 below unity, producing a continuing instability of the $m=1$ mode from which the plasma does not recover. If the $m=1$ mode is excluded the disruption does not occur.

Our conclusion is that it is possible to simulate a number of experimental observations on tokamak disruptions by including only the $m=1$ kink and the $m=2$ tearing mode. There are two phases in the disruption. In the first contact with the limiter—or an outer region of cold plasma—drives a strong $m=2$ tearing mode and in the second this growth can lead to the expulsion of the hot central plasma and a loss of plasma current. Hard or soft disruptions occur according to the intensity of the interaction with the limiter.

---

[1] B. B. Kadomtsev, Fiz. Plasmy 1, 710 (1975).

[2] A. F. Danilov, Yu. N. Dnestrovskii, D. P. Kostomarov, and A. M. Popov, Fiz. Plasmy 2, 167 (1976).

[3] A. Sykes and J. A. Wesson, Phys. Rev. Lett. 37, 140 (1976).

[4] B. V. Waddell, M. N. Rosenbluth, D. A. Monticello, and R. B. White, Nucl. Fusion 16, 528 (1976).

[5] F. Karger, H. Wobig, S. Corti, J. Gernhardt, O. Klüber, G. Lisitano, K. McCormick, D. Meisel, and S. Sesnic, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975).

[6] O. Klüber, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland, 1975* (European Physical Society, Geneva, 1975), Vol. 2, p. 50.

[7] B. Carreras, H. R. Hicks, J. A. Holmes, and B. V. Waddell, in Proceedings of the International Atomic Energy Agency Symposium on Current Disruption in Toroidal Devices, Garching, Germany, 1979 (to be published), paper A1.

[8] R. B. White, D. A. Monticello, and M. N. Rosenbluth, Phys. Rev. Lett. 39, 1618 (1977).

Transient Magnetic Field Reversal with a Rotating Proton Layer

C. A. Kapetanakos, J. Golden, J. A. Pasour, S. J. Marsh,[a] and R. A. Mahaffey[a]
Naval Research Laboratory, Washington, D. C. 20375

(Received 31 December 1979)

This paper reports on the transient field reversal of the applied magnetic field with a proton pulse. The 400–500-kA (peak), 50-nsec-duration, 1.7-MeV peak-energy hollow proton pulse containing about 8×10^{16} protons is generated by an inverse reflex tetrode. After passing through a magnetic cusp, the pulse propagates in a 1.5-kG uniform field B_0 with a self-generated magnetic field $\Delta B_z \simeq 1.25 B_0$.

PACS numbers: 52.55.-s, 52.40.Mj

Magnetic field configurations with closed field lines generated by energetic particles are very promising for confining plasmas for thermonuclear applications for the following reasons: (1) The closed magnetic field lines considerably enhance the plasma confinement time; (2) the gyrating particles of the ring serve as an internal energy source for heating the confined plasma; and (3) the β of the plasma can exceed unity[1] making possible a high-power-density, small-size thermonuclear reactor with significant economic benefits.

Initially, the effort was focused on the formation of relativistic electron layers.[2,3] However, reversed field configurations (RFC) that are generated by energetic electrons are not of interest for thermonuclear applications because of the synchrotron radiation losses from the fast moving electrons. To avoid the radiation losses Christofilos[4] proposed the replacement of electrons by ions having energies in the gigaelectronvolt range. In the Christofilos[1] scheme, as well as in a similar scheme proposed by McNally,[5] the ion beams are generated by conventional accelerators and have very low current ($\sim$1 mA). In this Letter we report on the first transient field reversal ever obtained with ions.[6,7] The protons are generated by a pulsed ion source that is powered by a high-voltage generator.

A schematic of the experiment that does not include the gate coil and the magnetic mirror[8] is shown in Fig. 1. The applied magnetic field that is used in the experiments described in this Letter consists of a short uniform region, a magnetic cusp, a 75-cm-long uniform field B_0, and a single magnetic mirror. The inverse reflex tetrode (IRT) ion source is located in the short uniform field and is powered by the upgraded Gamble II generator.[9] The low-inductance ion source has a 37-cm-long, 37-cm-o.d. cylindrical anode stalk. The 100-μm-thick, 18.5-cm-i.d. hollow polyethylene anode foil A is mounted on the front end of the anode stalk. The other end of the stalk is covered by a stainless steel plate. Electrically connected to the end plate is a movable stainless steel disk G. Electrons emitted from the grounded screen cathode K are accelerated toward the semitransparent anode, pass through it, and form a virtual cathode (VC) between A and G. Those electrons transmitted through the VC reach the grid G. The rest of the electrons oscillate between VC and K until they are absorbed by the anode. The protons are extracted out of the plasma that is formed from the plastic anode. When the applied voltage V_0 increases or remains constant, protons directed toward VC are unable to reach G or they reach it with zero velocity. Thus, these protons do not deplete the energy content of the system. However, most of those ions emitted toward K pass through the coarse screen and enter the cusp. Typically, the operating pressure in the system is below 0.7 mTorr.

For a limited range of relevant parameters tested (applied voltage, anode thickness, applied magnetic field), the IRT has the interesting feature that its impedance Z remains approximately constant during an appreciable fraction of the 80-nsec (full width at half maximum, FWHM) long pulse.[7] Since $Z \simeq$ const, the inductively corrected voltage follows the current and thus increases with time. Typically, in a high-voltage shot, after a fast initial rise the voltage increases from 0.6 to about 1.7-MV within 60 nsec. In addition, because $Z \simeq$ const, the ion source is coupled to the generator with high efficiency. Approximately 75 kJ of energy are extracted out of the generator, i.e., about 85% of the maximum energy delivered to a matched load. The peak power is approximately 1.4 TW.

The number of protons N_p at various axial positions is inferred[10] from the measured number of delayed γ rays emitted from the annihilation of positrons (β^+) that are produced in the resonant reaction $^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C$. The number of counts is corrected for the reaction $^{12}C(d,n)$-$^{13}N(\beta^+)^{13}C$ induced by the natural isotopic abundance of deuterium in polyethylene.[10] In our best shots N_p measured with the carbon target located 15 cm from the anode is between 7×10^{16} and 8

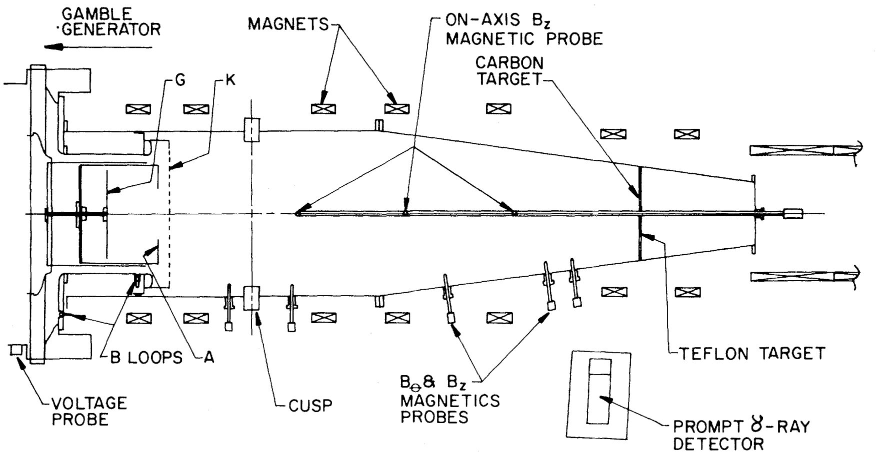

FIG. 1. Schematic of a section of the Naval Research Laboratory ion-ring experiment in which the series of experiments that are described in this report have been performed.

$\times 10^{16}$ per pulse. This number must be considered as a lower bound since protons with energy less than 470 keV do not activate the target and the number of counts is not corrected for target blowoff. For a triangular ion pulse of 50-nsec baseline duration the 8×10^{16} particles correspond to 500-kA peak proton current.

The radial profile of the beam is determined by individually counting small segments of a carbon target after it is activated by the beam. Figure 2 shows the radial profile of the proton beam 15 cm from the cathode, 20 cm upstream of the cusp. It is apparent that the thickness of the beam is appreciably greater than that of the anode foil. The observed "filling in" of the proton beam is due mainly to the qv_zB_θ pinching force that acts on the ions inside the anode-cathode gap. The azimuthal magnetic field B_θ is generated by the ion current and the net electron current in the gap. It is estimated from the equations of motion, neglecting the radial electric fields, that at the cathode the protons have a radial velocity $v_r = v\sin\varphi$, where v is the velocity corresponding to the applied voltage and

$$\sin\varphi \approx (d/\tau V_0)\int_0^d B_\theta dz . \qquad (1)$$

In Eq. (1) d is the A-K gap, τ is the ion transit time, and the integral is along the particle orbit. For $d = 2$ cm, $B_\theta = 10$ kG = const, $V_0 = 1$ MV, Eq. (1) gives $\varphi \approx 16°$.

The beam pulse shape is inferred from the prompt γ-ray flux emitted from the reaction ^{19}F$(p, \alpha\gamma)^{16}$O, when the proton beam strikes a Teflon target.[11]

The self-generated magnetic field ΔB_z is monitored with several fast, center-tapped magnetic probes. After integration, the signal from each half of the probe is fed to the differential amplifier of an oscilloscope. A three-coil probe is inserted from the downstream end of the system along the symmetry axis and monitors ΔB_z at 10, 60, and 110 cm from the cusp. Typical oscilloscope traces from this multiprobe are shown in Fig. 3. The second probe is located in the uniform external magnetic field and the peak of the diamagnetic signal is 1.25 times greater than B_0, i.e., the external field has been reversed. The peak of the third trace is lower than the peak of the second perhaps as a consequence of particle losses on the converging walls of the vacuum chamber. The low-level signal that precedes the main signal in the third trace is extraneous and does not change polarity when the external field is reversed.

It has been determined from the time delay between the signals of the B_{z2} and B_{z3} probes that in the uniform field the rotating layer propagates with an average axial velocity v_z of about 1.25 cm/nsec, when the peak V_0 is about 1.2 MV.

The macroscopic velocity of rotation v_θ of the ion pulse is inferred from the measured rotation of the image of a wedge-shaped notch introduced in the pulse by a mask and the known distance between the target and the mask. Typically, $v_\theta \simeq v_z/5$. Therefore, when the peak V_0 is about 1.2 MV, the energy associated with the azimuthal rotation is approximately 40 keV. The gyroradius of a proton with this energy in a 1.5-kG magnetic field is about 19 cm. This radius is further reduced because of the compression of the self-generated magnetic field by the wall of the vacuum chamber. From the duration of the prompt γ-ray pulse that is typically 25 nsec FWHM and

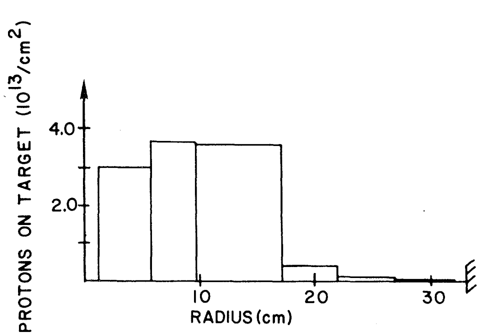

FIG. 2. The proton dose vs radius at 15 cm downstream from the cathode.

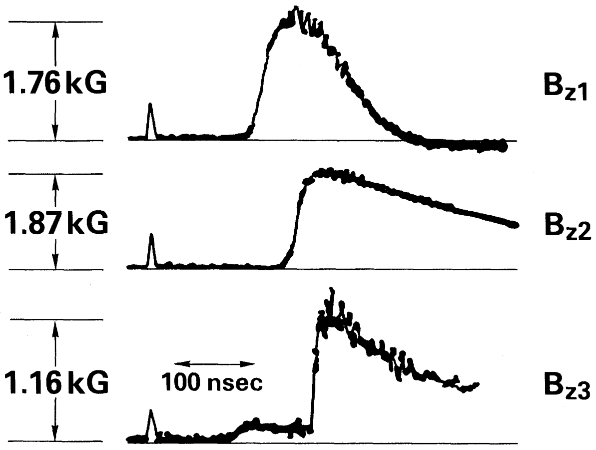

FIG. 3. Diamagnetic signals measured by on-axis probes at (upper) 10, (middle) 60, and (lower) 110 cm downstream from the cusp.

the measured v_z, it is estimated that the length of the ion pulse is about 31 cm when the peak V_0 is 1.2 MV. A similar conclusion can be reached from the temporal widths and the time delay of the signals of the B_z probes that are located near the wall of the chamber.

At this point, it is necessary to examine if the observed diamagnetic signal of the pulse is consistent with the observed approximate dimensions, velocity, and N_p. The azimuthal current (uniform current density) required to generate a 1.8-kG magnetic field at the center of a coil of length $2L = 30$ cm, inner radius $a_1 = 5$ cm, and outer radius $a_2 = 15$ cm is 52 kA, i.e., about $\frac{1}{5}$ of the average proton current of the ion source and in agreement with the radio $v_\theta/v_z = \frac{1}{5}$ and the measured N_p.

Additional insight is gained by considering a long, rigidly rotating ion layer. It can be shown[7] that the number of protons per unit length required for field reversal is $N_l \geq (q^2/mc^2)^{-1} = 0.65 \times 10^{16}$ cm^{-1}. Therefore, most of the protons of the pulse must be concentrated within a 10-cm axial length in order to have a field reversal factor $\eta \simeq 120\%$. However, it should be emphasized that the rigid-rotor model overestimates N_p required for field reversal because the azimuthal current density J_θ in this model peaks at the outer edge of the beam. In contrast, the experimental J_θ peaks near the inner edge of the beam.

Computer similation of the experiment with use of the measured voltage and total current and the assumption that the current efficiency of the IRT is 30% show that $\Delta B_z/B_0 \simeq 1.44$ at 60 cm after the cusp (position of B_{z2} probe).

The slow decay of signals of the B_{z2} and B_{z3} probes (Fig. 3) is probably associated with the plasma formed on the surface of the long probes. This is supported by the observation that the decay of signals of small B_z probes that are inserted radially is substantially faster than that of the long multiprobe. Although the plasma formed on the housing of the magnetic probe can explain the slow decay of the probe signals, it cannot account for an appreciable fraction of the observed diamagnetism.[7] In addition, the experimental evidence indicates[7] that there is not an appreciable number of electrons that have axial velocity and total energy comparable to that of the protons. Therefore, it is very doubtful that fast electrons are contributing to ΔB_z.

In contrast to axial fields, the aximuthal field of the layer appears to be almost zero before the cusp and very small in the uniform field region. Typically, the field B_θ at 3 cm from the vacuum chamber wall and 77 cm beyond the midplane of the cusp is less than 100 G.

The achievement of transient field reversal with a rotating proton layer is an important step toward the objective of our program which is the formation of a trapped, field-reversed ion ring. Presently, our effort is concentrated on reducing the "filling in" of the hollow beam by suitable reshaping of the anode and cathode electrodes. This will make possible the operation of the system in higher magnetic fields, thus achieving higher velocity ratios v_θ/v_z without appreciable losses at the cusp. Higher values of the ratio v_θ/v_z will make feasible the use of the originally proposed magnetic field configuration.[8]

We are grateful to A. E. Robson for very helpful discussions and to R. Covington for his technical assistance. This work was supported in part by the U. S. Department of Energy and the U. S. Office of Naval Research.

---

[a] Permanent address: Sachs/Freeman Associates, Inc., Bladensburg, Md. 20710.

[1] R. F. Post, UCRL Report No. UCRL-81586, 1978 (unpublished).

[2] N. C. Christofilos, in *Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, New York, 1959), Vol. 32, p. 279.

[3] T. J. Bzura *et al.*, Phys. Rev. Lett. 256 (1972).

[4] N. C. Christofilos, U. S. Patent No. 3 664 921 (1972).

[5] J. Rand McNally, Jr., ORNL Report No. TM-4965, 1975 (unpublished).

[6] C. A. Kapetanakos *et al.*, in Proceedings of the Third International Topical Conference on High Power Electron and Ion Beam Research and Technology, Novosibirsk, USSR, 3-6 July, 1979 (to be published).

[7] C. A. Kapetanakos *et al.*, National Research Laboratory Memorandum Report No. 4135 (unpublished).

[8] C. A. Kapetanakos *et al.*, in *Proceedings of the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology, Ithaca, New York, 1977,* edited by J. A. Nateon and R. N. Sudan (Cornell Univ., Ithaca, 1977), Vol. 1, p. 435.

[9] R. Boller *et al.*, in *Proceedings of the Second International Pulsed Power Conference, Lubbock, Texas, 1979,* edited by A. H. Guenther and M. Kristiansen (IEEE, New York, 1979), p. 205.

[10] F. C. Young, J. Golden, and C. A. Kapetanakos, Rev. Sci. Instrum. 48, 432 (1977).

[11] J. Golden *et al.*, Rev. Sci. Instrum. Methods 49, 1384 (1978).