26, 122 (1971).
[5]R. L. Morse and C. W. Nielson, Phys. Fluids 12, 2418 (1969).
[6]R. L. Morse, in *Methods in Computational Physics*, edited by B. Alder, S. Fernbach, and M. Rotenberg (Academic, New York, 1970), Vol. 9, p. 213.

Generation of Astron-Type E Layers Using Very High-Current Electron Beams*

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(Received 20 May 1971)

Reversal of the axial magnetic field in a magnetic-mirror trap is achieved by injection of a 30-kA, 0.34-MeV beam of electrons.

In 1958, Christofilos suggested[1] that stable confinement of a fusion plasma could be attained by injecting a cylindrical layer of highly relativistic electrons into a magnetic-mirror field. If this "E layer" is sufficiently strong to reverse the direction of the magnetic field on the cylinder axis, the magnetic field in the vicinity of the layer will constitute an absolute-minimum-B configuration with closed field lines. This suggestion led to the well-known Astron experiments which attempt to create such current layers by injection of a low-angular-divergence beam of relativistic electrons. After considerable technological developments, it has been found that single-pulse trapping of an 800-A, 6-MeV electron beam leads to E layers exhibiting axial-field changes of up to 13% and stable confinement of up to 12 msec.[2] However, to attain full field reversal, the stacking of a sequence of pulses appears necessary.

On the other hand, as a result of recent advances in high-voltage technology, pulsed electron beams of up to several hundred kiloamperes and several MeV are now available which may be used for single-pulse generation of strong E layers. The angular divergence of these beams exceeds that of the Astron beam; the influence of the angular divergence on injection may be balanced by the magnetic self-focusing of the beam.[3-5] When trapped, this increased perpendicular energy can be expected to result in a more stable E layer of larger useful volume.[6] In this paper, first results of some small-scale experiments are reported in which full field reversal was obtained for a short time period.

In these experiments, electron beams of 30–60 kA, having energies of 300–500 keV and a pulse duration of 50 nsec, were generated in the Cornell electron-beam facility.[7] As indicated in Fig. 1, these beams were guided through a soft-iron injector tube having 4 cm i.d., 1.10 m length, and 4 mm wall thickness. From this tube, the beam was injected into a Lucite tank, 25 cm in diameter and 1.80 m in length. Injection angle relative to the tank axis and injection radius could be varied from 75° to 90° and 6 to 10 cm, respectively. The tank was lined with a copper screen electrically connected to the injector and to a metal flange at the downstream end of the tank. Upstream, the tank was sealed with a transparent Lucite flange. A uniform magnetic field parallel to the tank axis was generated by coil windings (2 per in.) around the tank wall. In addition, movable field coils provided the capability for local field enhancements. The field energy was supplied by a capacitor bank having a quarter-cycle rise time of 3.4 msec. Gas pressures from 0.1 to several Torr were maintained in the tank.

For diagnostic purposes, open-shutter cameras viewed the tank from the side and through the Lucite flange at the upstream end. Fast changes of the axial magnetic field were measured by three magnetic pickup coils. Two of these coils could be moved along the tank axis entering from opposite ends, while the third could probe the field at various radial positions. Each probe consisted of an electrostatically shielded ten-turn loop of 0.007-in. copper wire wound on $\frac{1}{4}$-in. Lucite cylinders and placed in glass tubes having a $\frac{1}{2}$-in. o.d. Their output signals were fed through terminated 50-Ω cables, integrated by low-inductance, 10-μsec RC integraters, and finally displayed on scopes. The effectiveness of the electrostatic shielding and the general noise level were tested by placing all three probes in adjacent positions on axis. As expected, two identically wound axial probes showed signals of opposite

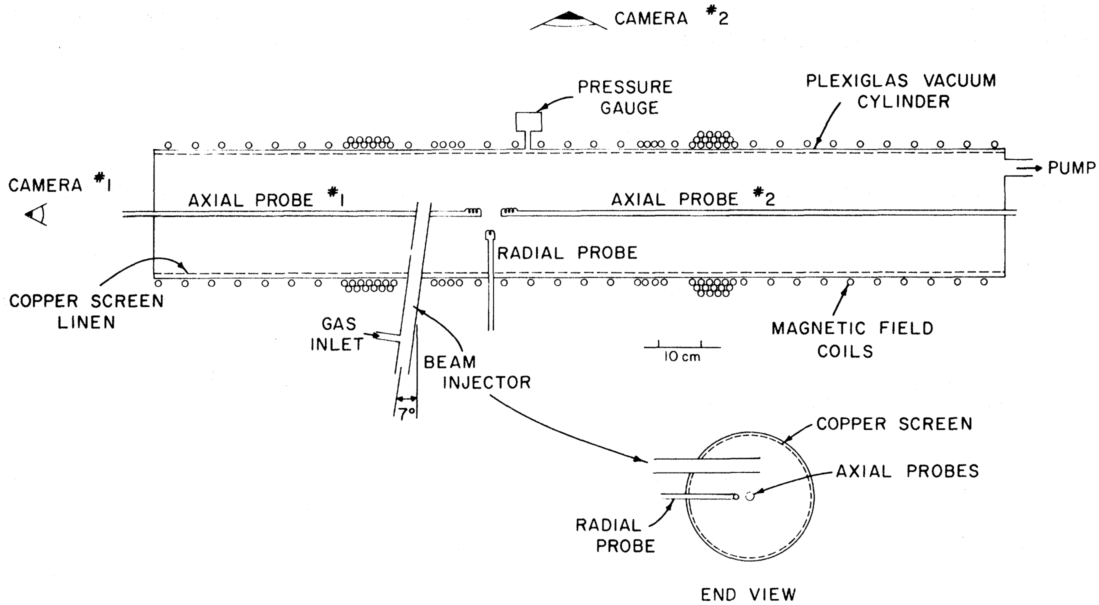

FIG. 1. Experimental arrangement.

polarity, otherwise identical within 10%. The radial probe exhibited the expected signal amplitude and polarity depending upon orientation. Also, other polarities and calibrations were carefully tested.

Experiments were performed for a number of combinations of pressure, injection currents, beam energies, injection angles, and applied magnetic-field strengths and configurations. As in our earlier beam experiments, good propagation was found for pressures above 150 mTorr with improving reproducibility at higher pressures.

Using a uniform magnetic field, the beam was observed to propagate along a spiral path down the tank, pitch and diameter being in rough agreement with injection angle and corresponding single-electron Larmor radius. When a single mirror of sufficient strength was applied along the path, reflection of the beam was observed. Since the mirror was short, a mirror ratio of almost 2, i.e., far above the adiabatic threshold, had to be applied to produce this reflection. Insertion of a second mirror on the upstream end resulted in a similar reduction of the number of electrons escaping to the upstream flange. An example of the camera recordings taken when two mirrors were used is shown in Fig. 2. The end camera clearly showed the ring of light produced by the beam. The side camera showed the cigar-shaped region of light. The dark vertical strips were produced by the field coils. The mirror peaks were located just outside either end of the region of light.

Magnetic-field changes on axis were measured about 20 cm downstream from the injector. As to be expected, the observed field changes were all directed opposite to the applied field. Under otherwise comparable conditions, the beam-produced field increased from 30% of the applied field for the uniform configuration to 40–50% with a single mirror to 100–140% in the double-

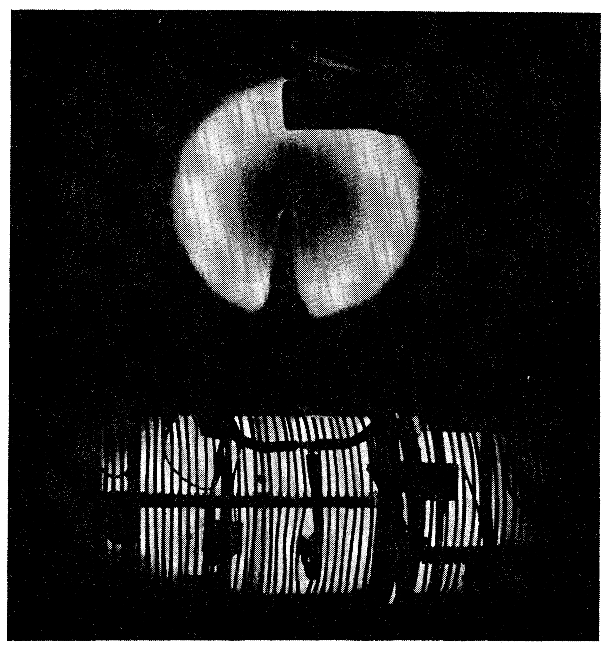

FIG. 2. Optical recordings of E layer (top: axially; bottom: from side).

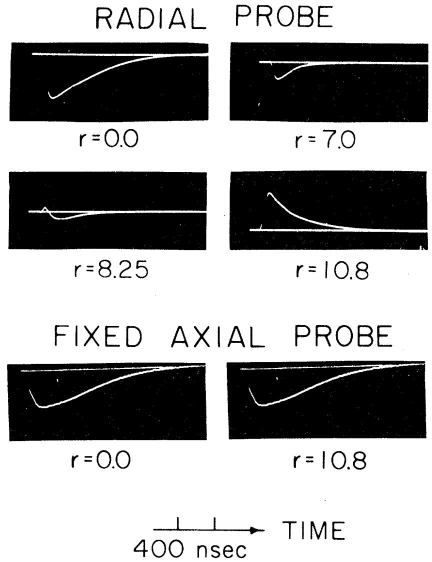

FIG. 3. Examples of magnetic probe traces.

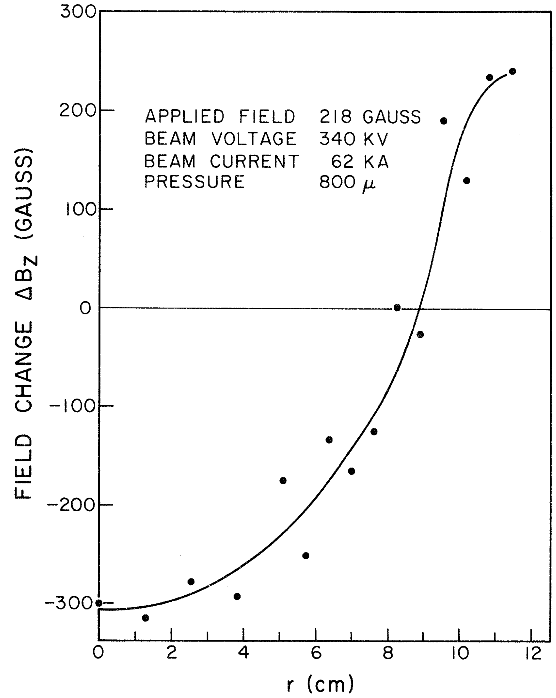

FIG. 4. Radial dependence of field changes ΔB_z.

mirror arrangement. In this latter configuration actual field reversal on axis and a minimum-B geometry were produced.

This double-mirror arrangement was investigated in more detail for a particular set of experimental parameters (beam energy $\approx$ 340 keV, beam current $\approx$ 60 kA, air pressure 800 mTorr). Radial and axial profiles of the magnetic-field changes were determined. For each measurement, one axial probe was kept at a fixed position and used as a reference while the other probes were moved in steps from shot to shot. Examples of the scope traces taken during the radial profile measurement are displayed in Fig. 3. During this sequence, axial-probe number 1 was kept fixed; signals from it are shown in the lowest row of this figure. The signals on the radial probe at various radial positions are shown in the upper two rows. For both probes, negative signals represent field changes opposite to the applied field. On axis, signals generally rose for about 90–120 nsec and then decayed with a half-time of 400–600 nsec. The rms scatter of their amplitude was somewhat less than 10%. The signals on the radial probe were negative on axis, becoming more positive with increasing radial position, changed sign at about 8 cm, and remained positive from this point to the copper screen. The corresponding plot of the radial dependence of the peak-field changes ΔB_z normalized to the corresponding signal observed on the fixed axial probe is shown in Fig. 4. From the slope of this curve, it can be seen that while some current existed for small radial position, most flowed in a strip a few centimeters wide centered around 9 cm. As to be expected, the total magnetic flux inside the copper screen was conserved.

The axial profile of the field changes along with the applied magnetic field is shown in Fig. 5. Around $z = 0$ the ΔB_z signal appeared relatively constant, reversing the total field from around + 200 to − 70 G. The ΔB_z signals increased

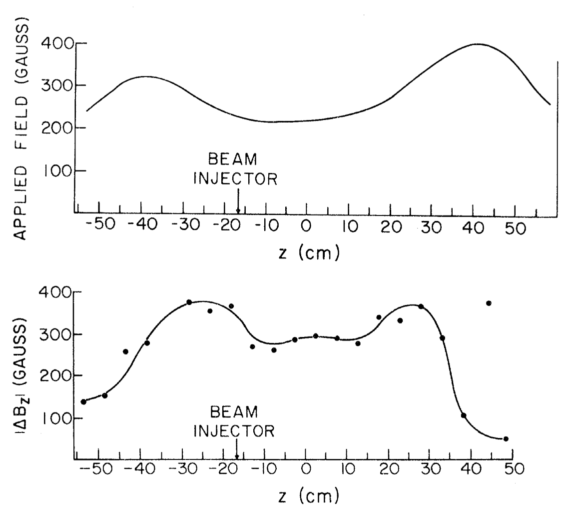

FIG. 5. Applied field B_0 and field changes $|\Delta B_z|$ on axis.

slightly at positions just inside the mirrors. At the mirror peaks the ΔB_z signal decreased substantially. However, as can be seen from the figure (and also from side photography), more complete confinement was provided by the large downstream mirror than by the weaker upstream one. Between the mirror peaks the time dependence of ΔB_z was essentially as shown in the traces of Fig. 3. Outside of the mirrors the ΔB_z signals were much shorter, lasting for only approximately 100 nsec. Therefore, leakage out the ends occurred for times short compared to the persistence of the ΔB_z signal between the mirrors.

Thus, in the double-mirror arrangement, a compact current sheet with closed field lines and a minimum-B geometry were created. A determination of the actual confinement time of the fast electrons is complicated by the possible existence of counterstreaming currents in the created plasma which may persist even after all fast electrons are lost. In the present experimental arrangement, relatively short fast-electron lifetimes are expected. At injection, the average pitch distance for the electron trajectories was only about 6 cm, compared with the injector diameter of 4.5 cm. Thus, the probability for the electrons to hit the injector or the surrounding highly perturbed field region was large and certainly limited the lifetime of the electrons to a few oscillations between the mirrors, each taking approximately 30 nsec. In addition, the lifetime may have been shortened by asymmetries in the applied fields resulting from imprecise positioning of the field coils and from stray fields. Investigations of these questions and experiments on beam trapping away from the injector are in progress.

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*Work supported by the U. S. Office of Naval Research.

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[1]N. C. Christofilos, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, Switzerland, 1958), p. 279.

[2]Lawrence Radiation Laboratory Report No. UCRL-50002-69 (unpublished).

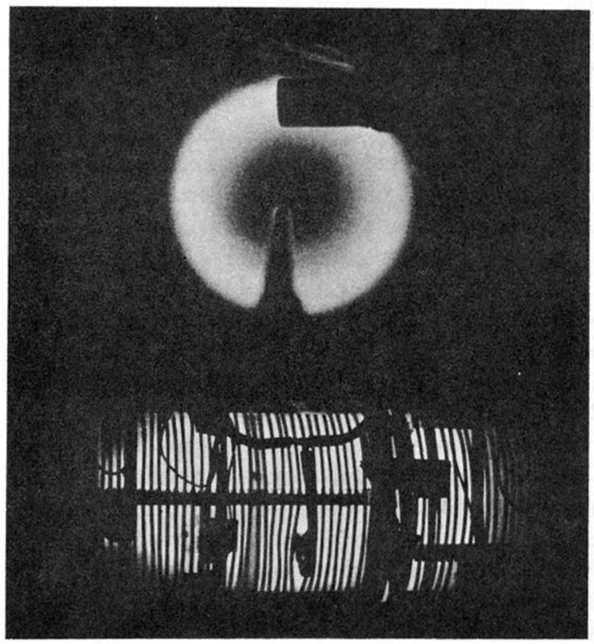
[3]S. E. Graybill and S. V. Nablo, Appl. Phys. Lett. 8, 18 (1966).

[4]G. Yonas and P. Spence, in *Record of the Tenth Symposium on Electron, Ion, and Laser Beam Technology,* edited by L. Marton (San Francisco Press, San Francisco, Calif., 1969), p. 143.

[5]M. L. Andrews, H. Davitian, H. H. Fleischmann, D. A. Hammer, J. A. Nation, and N. Rostoker, Appl. Phys. Lett. 16, 98 (1970).

[6]See Ref. 2, p. 15; T. K. Fowler, private communication.

[7]J. J. Clarke, M. Ury, M. L. Andrews, D. A. Hammer, and S. Linke, in *Record of the Tenth Symposium on Electron, Ion, and Laser Beam Technology,* edited by L. Marton (San Francisco Press, San Francisco, Calif., 1969), p. 117.



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