T. Godlove, V. Granatstein, K. R. Chu, R. Gullikson, and F. Firk. This work was partially supported by the National Science Foundation.

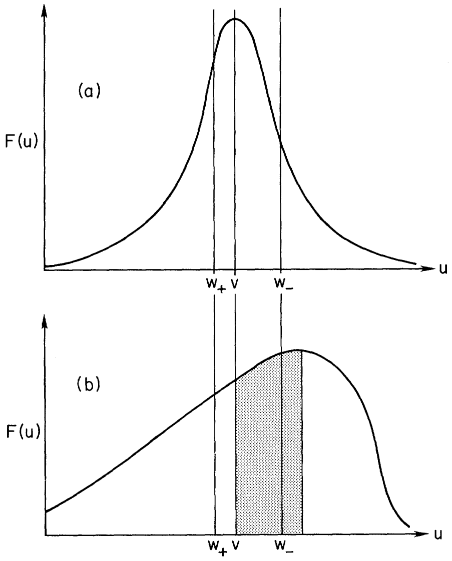

FIG. 1. Axial momentum distributions. In (a) a symmetric distribution is shown which is stable against spatial amplification for both the fast and slow space-charge waves, since $F'(w_+) > 0$ and $F'(w_-) < 0$. In (b) an asymmetric distribution similar to that furnished by a linac is shown which can support amplification for the fast wave, when w_- is in the shaded region where $F'(w_-) > 0$.

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[1] L. R. Elias *et al.*, Phys. Rev. Lett. 36, 717 (1976).

[2] D. A. G. Deacon *et al.*, Phys. Rev. Lett. 38, 892 (1977).

[3] H. Motz, J. Appl. Phys. 22, 527 (1951).

[4] H. Motz *et al.*, J. Appl. Phys. 24, 826 (1953).

[5] R. M. Phillips, IRE Trans. Electron Devices 3, 231 (1960).

[6] J. M. J. Madey, J. Appl. Phys. 42, 1906 (1971).

[7] V. P. Sukhatme and P. A. Wolff, J. Appl. Phys. 44, 2331 (1973).

[8] W. B.Colson, Phys. Lett. 59A, 187 (1976).

[9] F. A. Hopf *et al.*, Opt. Commun. 18, 413 (1976).

[10] F. A. Hopf *et al.*, Phys. Rev. Lett. 37, 1342 (1976).

[11] V. L. Granatstein and P. Sprangle, IEEE Trans. Microwave Theory Tech. 25, 545 (1977).

[12] T. Kwan, J. M. Dawson, and A. T. Lin, Phys. Fluids 20, 581 (1977).

[13] Ira B. Bernstein, Phys. Fluids 18, 320 (1975).

Trapping of Cusp-Injected, Nonneutral, Electron Rings with Resistive Walls and Static Mirror Coils

D. W. Hudgings, R. A. Meger, C. D. Striffler, W. W. Destler, H. Kim,
M. Reiser, and M. J. Rhee
*Electrical Engineering Department and Department of Physics and Astronomy, University of Maryland,
College Park, Maryland 20742*

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A hollow, rotating 2.3-MeV electron beam, moving with axial velocity of ~0.25c after injection through a magnetic-field cusp, is slowed down and trapped in a small magnetic mirror well by interaction with a 30–60-Ω/square resistive wall. The trapped-electron ring containing ~10^{12} particles performs a damped oscillation about the well minimum and settles down into an equilibrium state.

The electron-ring accelerator (ERA) concept, first proposed by Veksler *et al.*,[1] uses the electrostatic potential well of a high-density, relativistic electron ring for collective acceleration of positive ions. Experiments in progress at several laboratories[2–4] employ a pulsed magnetic mirror field with azimuthal beam injection to obtain a compressed electron ring. In the ERA experiment at the University of Maryland,[5–6] on the other hand, the ring is being formed with the aid of a static, cusped magnetic field. The cusp transforms a long hollow electron beam into a short rotating cylindrical electron layer (E layer) which propagates in the axial direction at a fraction of the speed of light. The length and velocity of the E layer depend on the pulse shape of the injected electron beam and the axial magnetic field, B. As B is increased, the axial velocity is reduced until a cutoff value, B_c, is reached where all particles are reflected in the cusp region. Experimentally, it is found that reproducible beams are obtained only when B is somewhat less than B_c such that the axial velocity of the E layer downstream from the cusp transition is in the range of $0.2c$ to $0.3c$.

In order to form a stationary electron ring which can be loaded with a small number of positive ions, the E layer must be slowed down and trapped. Several methods of stopping the beam have been investigated.[5,7-9] The interaction with a resistive wall[8] (which is an extension of the resistive-wire idea that Christofilos first applied in the Astron experiment[10]) was found to be the most promising scheme. In this Letter, we report the results of initial experiments in which electron rings containing $\sim 10^{12}$ particles with kinetic energy of 2.3 MeV were stopped by the resistive-wall interaction and trapped in a small static magnetic mirror. These results are relevant not only to electron-ring accelerators but to other E-layer and toroidal-beam experiments which are aimed at fusion applications.[11-13]

The basic features of the experiment are illustrated schematically in Fig. 1. A hollow electron beam pulse, with nominally 2.3-MeV kinetic energy, 30-kA peak current, and 30-nsec full width at half-maximum (FWHM) duration, is produced in a diode with a 12-cm-diam tantalum knife-edge cathode aligned coaxially with a slotted anode. An iron separates the diode magnetic field from the oppositely directed downstream field and produces a sharp cusp transition.[6] The axial magnetic field B versus distance z is shown in Fig. 1(b). After the cusp transition, the field is flat until $z = 50$ cm and then it falls off almost linearly. A small, 20-cm-diam mirror coil is located at $z = 100$ cm in the falloff region. It produces a peak field of up to 300 G (superimposed on the main field of 1500 G) and, together with the slope of the decreasing main field, provides a small well in which the electron ring can settle down after stopping by the resistive wall. Outside and coaxial to the E layer is a cylindrical tube with an inner diameter of 15 cm. This tube is either made of aluminum when a regular conducting boundary is desired, or of a glass-epoxy laminate with a resistive coating of 30–60 Ω/square on the inner surface to provide the resistive-wall effect. In addition to the outer wall, an 8.6-cm-diam "squirrel cage" inside the E layer is used in the experiment, as shown in Fig. 1(a). It consists of a series of axial conductors which allow axial image currents and electrostatic image charges but no azimuthal currents; this provides axial focusing for the electron ring.

A typical electron trajectory in the magnetic-field configuration of this experiment is depicted in Fig. 1(a). The azimuthal Lorentz force component in the cusp transition transforms the straight trajectory on the diode side into a helical orbit on the downstream side. The axial velocity v_z vs z of a typical particle in the case where resistive wall and mirror field are absent is shown by the dashed curve in Fig. 1(b). After slowing down from $\beta_z \approx 1$ to $\beta_z \approx 0.2$ in passing through the cusp, the electron's axial velocity increases again in the falloff region of the magnetic field.

To understand the resistive-wall effect, consider an idealized model of a filamentary electron ring with major radius R, moving axially in a uniform magnetic field and inside a thin coaxial boundary with radius $R + a$, thickness d, and surface resistivity ρ_s. Assume the ring contains N_e electrons with azimuthal velocity v_θ and axial velocity v_z. The magnetic and electric images induced in the wall by the moving ring produce forces which act back on the electrons and slow down the axial motion; the energy loss of the ring is dissipated as Joule heat in the wall. According to the theory, when $\rho_s < 100$ Ω/square, $a \ll R$, and $d \ll a$, the drag force due to the electric images can be neglected, and the force due to the magnetic interaction is given by the approximate expression[8] (MKS units)

$$F_z = -C(N_e/2\pi Ra)u/(1+u^2), \qquad (1)$$

where $C = e^2/4\pi\epsilon_0$, $u = 2\rho_s/Z_0\beta_z\gamma_z$, $\beta_z = v_z/c$, $\gamma_z = (1-\beta_z^2)^{-1/2}$, and $Z_0 = 120\pi$ Ω is the free-space impedance. The maximum of this force occurs when $\rho_s = 60\pi\beta_z\gamma_z$, and for our experiment one gets $\rho_s \approx 38$ Ω with $\beta_z = 0.2$. By exact numerical integration of the equations of motion that include the retarding force term (1) and the actual magnetic field with the small mirror bump, one gets the β_z vs z curve (solid line) shown in Fig. 1(b). This curve indicates that the ring is reflected at the mirror and then, because of the resistive-wall effect, performs a few damped oscillations until it settles down at the bottom of the magnetic mirror well.

Diagnostics used in the experiments include single-turn, passively integrated magnetic pickup loops located on axis and a 2-mm-diam NE-102 scintillating filament which intersects the E layer and is observed with a streak camera. A current monitor is located just downstream of the cusp region and measures the axial current entering the trapping region.

During early studies of the E-layer characteristics, rapid deterioration of the beam quality,

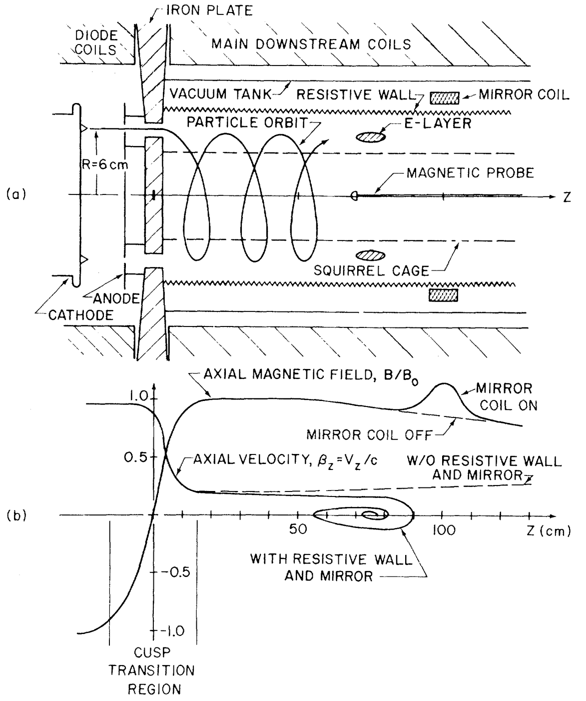

FIG. 1. (a) Schematic of experimental setup. (b) Axial magnetic field and axial particle velocity versus distance.

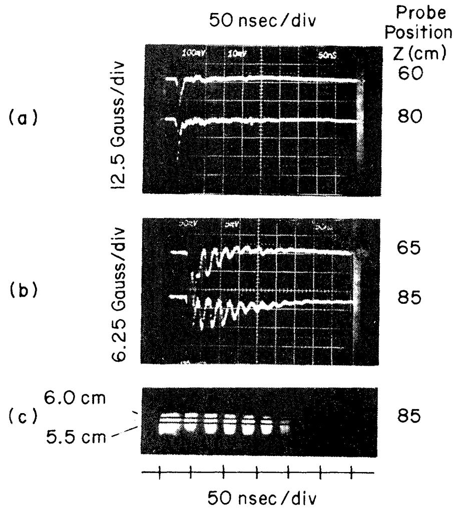

FIG. 2. (a) Oscilloscope traces of magnetic probe signals with no resistive wall and mirror. (b) Magnetic probe signals showing trapped ring when resistive wall and mirror are used. (c) Streak-camera picture of scintillating filament struck by trapped, oscillating electron ring. (The horizontal black lines in the picture are caused by fiducial marks on the scintillating rod.)

accompanied by production of several megawatts of microwave radiation, was observed.[14] This effect is attributed to the negative-mass instability and can be suppressed by passing the beam through a 6.3-mg/cm^2 foil in the anode plane.[6] However, the foil introduces an axial spreading of the beam. By lowering the injected beam current, it is possible to reduce significantly the effect of the instability and thus do experiments without the foil. Under these conditions, one obtains a beam pulse of 2 nsec FWHM and a $\leq$2-kA axial peak current just downstream of the cusp. This short E layer maintains a sharp beam front during its propagation over the 2-m experimental region. Use of the titanium foil, on the other hand, doubles the pulse width and decreases the peak density by a factor of 2.

Initially, the effects of the small mirror coil on the beam propagation inside an aluminum wall were studied, but no measurable trapping was observed in this case.[15] To provide an energy-loss mechanism for the E layer, the conducting wall is replaced by a resistive wall of 30–60 Ω/square. When the mirror coil is turned off and no scattering foil is used, we observe that the axial velocity of the E layer is reduced to $<0.1c$. When the mirror coil is turned on, trapping of the electron beam in the magnetic well is achieved. Figure 2 shows examples of shots without a foil which illustrate the observed effects. The upper two oscillograph pictures show the axial magnetic self-field of the moving E layer as measured by the two magnetic pickup loops located on axis at positions downstream from the cusp as indicated on the figure. The two traces in Fig. 2(a) represent the two probe signals when the beam propagates inside an aluminum conducting wall. The mirror coil has a peak field of 100 G in this case. As can be seen, no trapping occurs after the initial pulse has passed. Figure 2(b) shows the signals from the magnetic probes with the same mirror field when a resistive wall and a squirrel cage are present. In this case, the electron ring passes the first probe, reflects off the mirror, and then bounces back and forth with a 30-nsec period in the magnetic well. The amplitude of these oscillations damps out with an e-folding time of ~ 50 nsec when the integration constants of the probes (RC ~250 nsec) are taken into account. Observations with suitable magnetic probes over an extended time scale show that the ring remains trapped for several microseconds. Note that the two magnetic probes are axially displaced from the center of the mirror. Figure 2(c) represents a streak photograph of a scintillating filament placed in the beam above the downstream magnetic probe. The light from the streak picture shows the radial width (vertical line) versus time (horizontal line) of the ring beam as it passes several times through the scintillating filament. The picture agrees with the magnetic probe signals and proves that these signals are indeed from fast, relativistic electrons. The decrease of the mean ring radius that is apparent in the streak photographs may be attributed to the energy losses when the electrons pass through the filament.

More specifically, our experimental results may be stated as follows: (a) From the magnetic probe signals, one can estimate that the number of trapped electrons in a typical shot is $\sim 10^{12}$. No attempt has been made yet to optimize the trapping process by systematic variation of experimental parameters. (b) The trapped-electron rings perform coherent, damped axial oscillations. The damping time τ_D of the amplitudes decreases as the number N_e of electrons in the ring increases. The experimental values for the axial frequency ω_z and damping time τ_D are in good agreement with the theoretical calculations. (c) Magnetic probe signals show that the trapped-electron ring lasts for several microseconds which is sufficient for future ion-loading experiments. (d) The major radius R and the minor cross section of the trapped-electron ring have not been precisely determined yet. From the streak photographs, one infers that R is between 5 and 6 cm while $\Delta R \lesssim 1$ cm. The axial width Δz is significantly less than the 20-cm separation of the magnetic probes. (e) The shots without scattering foils are accompanied by microwave production similar to the radiation reported previously[14] but of lower intensity. There appears to be no different in the radiated power between experiments where the beam is trapped and those without trapping. This indicates that the radiation is produced primarily by the initial injected beam when the intensity is considerably above the threshold for the negative-mass instability. The relatively long lifetime of the trapped ring also supports this interpretation. (f) Experiments were also performed with a 2.2-mg/cm^2 aluminum foil and a 6.3-mg/cm^2 titanium foil placed behind the anode. Trapping was observed with the aluminum foil, but no trapping occurred when the titanium foil was used. Reproducibility with the aluminum foil is, however, not as good as in the experiments without foil.

In conclusion, these results have demonstrated that cusp-injected, short E layers moving axially at velocities of $0.2c$ to $0.3c$ can be slowed down and trapped in a static magnetic mirror well by the interaction with a resistive wall. The absence of trapping with the titanium foil indicates that the resistive-wall effect is strongly dependent on the particle density distribution. For successful trapping, a sharply bunched, coherently moving beam front is required, as is expected theoretically.

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[1] V. I. Veksler *et al.*, in Proceedings of the Sixth International Conference on High Energy Accelerators, Cambridge, Massachusetts, 1967 (unpublished).

[2] L. S. Barabash *et al.*, IEEE Trans. Nucl. Sci. 22, 1988 (1975).

[3] U. Schumacher, C. Andelfinger, and M. Ulrich, Phys. Lett. 51A, 367 (1975).

[4] S. Kawasaki, N. Kobayashi, Y. Kubota, and A. Miyahara, IEEE Trans. Nucl. Sci. 22, 992 (1975).

[5] M. Reiser, IEEE Trans. Nucl. Sci. 20, 310 (1973).

[6] W. W. Destler, D. W. Hudgings, H. Kim, M. Reiser, M.-J. Rhee, C. D. Striffler, and G. T. Zorn, IEEE Trans. Nucl. Sci. 24, 1656 (1977).

[7] J. G. Kalnins, H. Kim, and J. G. Linhart, IEEE Trans. Nucl. Sci. 20, 324 (1973).

[8] P. Merkel, Part. Accel. 8, 21 (1977).

[9] U. Schumacher, I. Hofmann, P. Merkel, and M. Reiser, Part. Accel. 7, 245 (1976).

[10] B. W. Stallard and T. J. Fessenden, Phys. Fluids 17, 575 (1974).

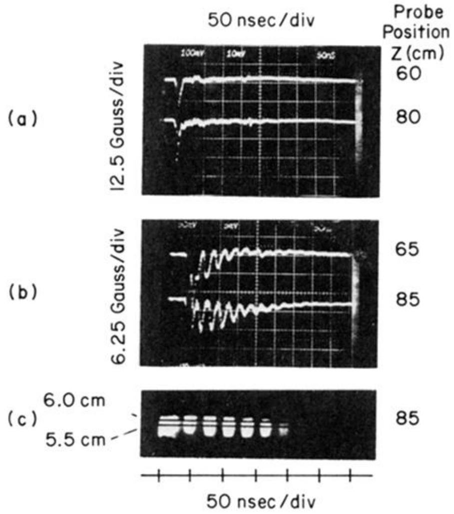
[11] H. A. Davis, R. A. Meger, and H. H. Fleischmann, Phys. Rev. Lett. 37, 542 (1976).

[12] R. N. Sudan and E. Ott, Phys. Rev. Lett. 33, 355 (1975).

[13] S. J. Marsh, A. T. Drobot, J. Golden, and C. A. Kapetanakos, Phys. Rev. Lett. 39, 705 (1977).

[14] W. W. Destler, D. W. Hudgings, M. J. Rhee, S. Kawasaki, and V. L. Granatstein, J. Appl. Phys. 48, 3291 (1977).

[15] R. A. Meger, D. W. Hudgings, and M. J. Rhee, in Proceedings of the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology, Cornell University, October 1977 (to be published).



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