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[5]B. C. Barish *et al.*, California Institute of Technology Report No. CALT 68-611 (to be published); particle fractions were measured in separate runs at lower incident proton intensities using a differential Cherenkov counter. Background levels in the differential curve (from π, μ, and e) were explicitly measured by additional counters in coincidence.

[6]B. C. Barish *et al.*, California Institute of Technology Report No. CALT 68-605 (to be published).

[7]We have calculated the correction factors using antiquark contents $\alpha = 0.093$ ($E < 100$ GeV) and $\alpha = 0.186$ ($E > 100$ GeV) obtained from our measured values of $\langle y\rangle_{\bar{\nu}}$ and σ_0/σ_{tot}; B. C. Barish *et al.*, California Institute of Technology Report No. CALT 68-606 (to be published).

[8]A comparison of $\int F_2^{\nu}(x)\,dx$ with $\int F_2^{eD}(x)\,dx$ at similar four-momentum transfers ($Q^2 \sim 5$ GeV^2) yields a measure of $\langle e_q^2\rangle$, the mean-squared charge of the constituents. Our value of $\int F_2^{\nu}(x)\,dx$ agrees with that expected for scattering from fractionally charged constituents, given the present errors on the eD measurement. See H. Dedan *et al.*, Nucl. Phys. B85, 269 (1975).

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Production of Field-Reversing Electron Rings by Ring Stacking

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In the relativistic-electron-coil–Christa experiment two separate, strong E layers ae are generated from a single beam pulse, and then combined by moving one of the layers along the tank axis. The "stacking" of two layers with about half of the field-reversal strength each leads to the generation of single E layers with field-reversal strength.

According to Christofilos's Astron[1] and the related ion ring compressor[2] schemes, a fusion plasma is to be confined with the aid of a strong, field-reversing ring of high-energy ions which, as Christofilos expected, would be created and maintained by combining or "stacking" of a sequence of weaker rings. While such ring stacking certainly could provide a number of interesting design options for a reactor, experimental and theoretical indications for its feasibility unfortunately have appeared quite poor so far. In electron-ring experiments performed to simulate such ion rings, field reversal for times of up to 220 μsec has been achieved so far in three relativistic-electron-coil experiments (RECE)[3-5] by using single-pulse injection of kiloampere electron beams. In the Livermore Astron[6] experiment aimed at creating field-reversing rings by stacking of a multipulse sequence, rings with up to 40% field reversal were obtained by single-pulse injection.[7] Unfortunately, in spite of an extensive effort, ring stacking was only successful for the maintenance of rings with a strength of up to 20% of axial field reversal, and stacking with stronger rings failed. In addition, these results were supported by two theoretical analyses[8,9] which predicted considerable difficulty in achieving field reversal by stacking of charge-neutralized rings.

In contrast to these previous results, this Letter presents the first experimental evidence of successful stacking of strong rings in the RECE-Christa device, including the generation of field-reversing rings by stacking two rings of approximately half-reversal strength.

These results were achieved as part of a series of experiments aimed at extending the previous collisionally limited field-reversal times. For this purpose, electron rings formed in a high-density transient gas fill near the injector are to be transported, by means of pulsed magnetic fields, to a lower-density region downstream. In the course of the respective preparations, it has proved possible to trap two rings, one near the injector and one downstream, on a single shot of the machine. This afforded the opportunity to study ring stacking by transporting the upstream ring and combining it with the downstream one, and it is the results of these latter experiments that are reported in the following.

The experimental configuration shown in Fig. 1 is a modified version of the RECE-Christa apparatus used earlier.[5] In brief, an intense electron beam (2.5 MeV, 30 kA, 80 nsec) is injected,

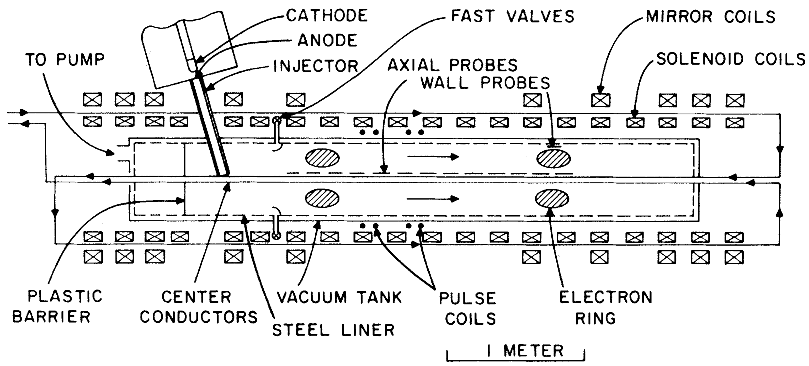

FIG. 1. Schematic of modified RECE-Christa apparatus.

nearly perpendicular to an axial magnetic mirror field of about 500 G, into a 4-m-long × 60-cm-diam vacuum vessel. In addition to the axial magnetic field a toroidal magnetic field, about twice the axial field at the injection radius, is produced by a set of axial conductors at the center of the machine. In the present experiments, the thick copper liner ($L/R \simeq 15$ msec) used previously has been replaced by a thin stainless-steel cloth liner ($L/R \simeq 10$ μsec) which provides a flux-conserving boundary during injection but still has a sufficiently short magnetic-field-penetration time to allow external pulsed coils to be used. In addition, the transient image currents produced in the liner help to limit the axial transport velocity of the rings. The two pulse coils, one upstream (referred to as upstream coil) and one at the middle of the tank (referred to as downstream coil), are driven by independent capacitor banks and produce a 5–10% field change. The respective current wave forms are shown in Fig. 2. To aid the ring transport, a 2.5%/m field gradient is produced by additional coils, not shown in Fig. 1.

The time evolution of the axial magnetic-field profile is shown in Fig. 2. At the time of injection ($t = 0$), the upstream pulse coil decreases the applied magnetic field while the downstream coil reenforces it, producing a short mirror trap near the injector in addition to the weaker mirror trap downstream. At 24 μsec when both driving currents are passing through zero, a steady field gradient results in the vicinity of the earlier minimum. To enhance this gradient, the downstream coil is permitted to swing negative, producing a new field minimum farther downstream ($t = 50$ μsec). At 76 μsec, this field minimum again has disappeared leaving only the steady field gradient connecting to the downstream well. Thereafter, this gradient is increased further, reaching its maximum at 96 μsec.

Two gas fillings are used, a uniform fill of from 20 to 300 mTorr of hydrogen and a transient fill produced by all four gas valves (having a total output of 150 atm cm^3) placed upstream. The flow from these valves is stagnated against a plastic barrier located upstream of the injector producing an enhanced density of a few hundred milliTorr of hydrogen in this region, at the time of injection. For diagnostic purposes, additional magnetic field probes spanning the length of machine have been placed on axis.

The ring-transport phase of these experiments will be the subject of a separate paper and thus will not be described in detail. In general the upstream rings were transported a distance over 10 times their radius. Figure 3 displays a set of

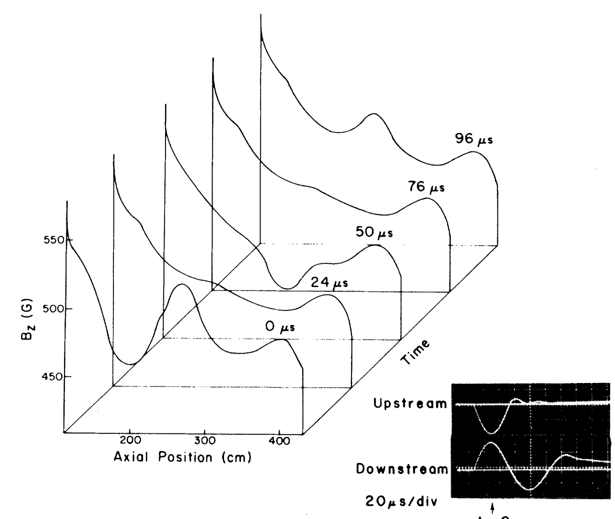

FIG. 2. Magnetic-field profile at different times, and pulse driving current wave forms. Injector position is 115 cm, upstream and downstream pulse coil positions are 202 and 269 cm, respectively.

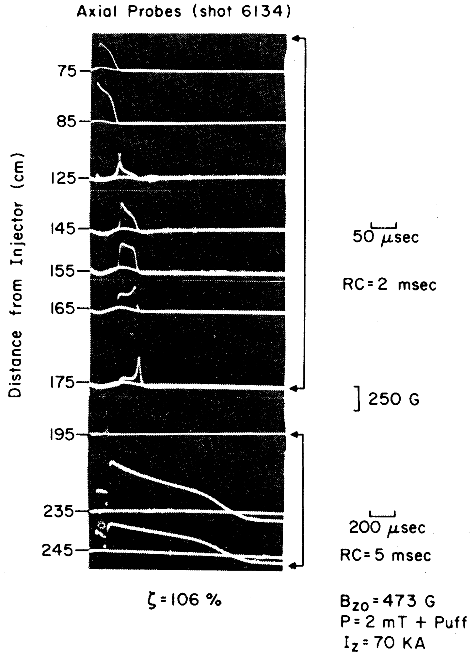

FIG. 3. Oscilloscope recordings, from a set of on-axis probes, showing ring translation and stacking to field reversal.

integrated magnetic pulse signals from an array of probes located on axis. Since these probes sense the pulsed coil fields as well as the rings' fields the pulse coil banks have been discharged to produce baselines. The probe signals at 85 and 235 cm from the injector show that two rings are simultaneously trapped. Translation of the upstream ring from its original position to the downstream coil at 155 cm (at 50 μsec) is evident from the probe traces spanning the range from 75 to 155 cm. After remaining close to this position, for about 35 μsec, thr ring moves farther downstream as registered on the probe at 175 cm. The signals from probes at 235 and 245 cm show the 68% (as measured at 85 cm) upstream ring and the 44% downstream ring coalesce to produce a field-reversed ring ($\delta B/B_{z0}$ = 106%). (The brief decrease in the downstream probe signal just before coalescence is due to the magnetic attraction of the rings before merging.) The present, although not yet very detailed, probe data do not indicate any sizable axial ring lengthening in the stacking process. The subsequent ring decay does not indicate any instabilities and is roughly consistent with a collisional decay in the background gas which ranges from 20 to 100 mT, over the first 900 μsec, plus the background of from 1 to 2 mTorr of unknown composition.

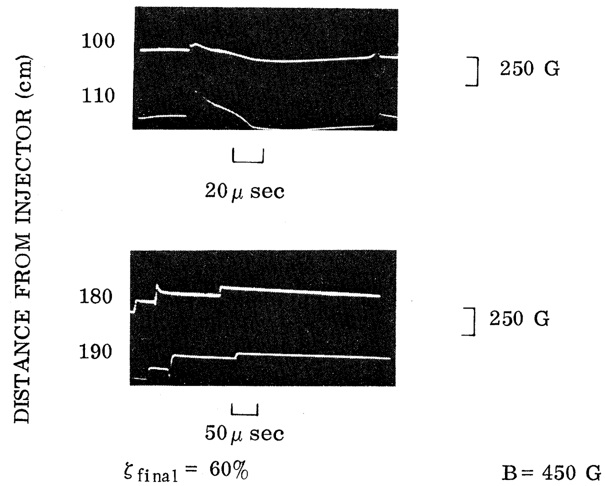

FIG. 4. Oscilloscope recordings, from a set of on-axis probes, showing the stacking of three relatively weak rings.

The decay acceleration after 900 μsec appears to be caused by a rapid influx of gas from the transient gas fill.

Figure 4 shows a similar stacking of weaker rings during the course of earlier experiments in which similar pulse coils were placed inside the original copper liner. Here, three rings combined to produce a final ring having $\delta B/B_z = 60\%$. (In this case significant strength loss in the moving ring occurs due to the reduction of the radial space by the internally positioned pulsed coils.) It is important to note that the small third pulse stacked well onto the already quite strong ring produced by the first two pulses.

Only conjectures can be offered at this point concerning the reasons for the success of our experiments *vis-à-vis* the earlier-mentioned experimental and theoretical results. The most significant differences between the Livermore experiment and our own probably are both a much clearer separation of the fast-electron trapping and the ring stacking process (sometimes called "superstacking"), and possibly a shorter initial ring length in our experiment. The resistive time scales of the background plasma appear comparable in both experiments. The effective wall-penetration time, varying in our experiment between 10 μsec for the mesh liner to effectively zero (with no separate resistive structure inside) for the copper liner (with the resistive wall structure at Livermore in between), appears less important. Also, the ratio of toroidal to axial field is lighter by about a factor of 2 in our case.

A comparison with the mentioned theoretical results of Berk and Pearlstein,[8] and of Byers *et al.*[9] proves even more difficult and ambiguous at this time. Berk and Pearlstein only treat the very idealized case of a radially thin, axially short, weak incoming pulse interacting with a radially thin, axially very long, trapped layer in a one-dimensional model. In particular, they have not included any induced plasma currents and their resistive decay, nor any toroidal magnetic field. All of these assumptions constitute a very poor approximation to the existing experiments. Similar objections apply to a comparison with results of Byers *et al.* They also do not include any plasma conductivity and present only a very limited analysis of trapping and stacking in the presence of a strong toroidal field. Also, the stacking results shown by them only concern rather weak layers.

Finally, the authors would like to thank again Dr. W. C. Condit of Lawrence Livermore Laboratory for supplying and additional help with the fast gas valves, and J. Milks for his excellent technical support in the course of the experiments. This work was supported by the U. S. Energy Research and Development Administration under Contract No. EY-76-S-02-2319.*000.

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Anomalous Fast-Particle Losses from Strong Electron Rings in Quadrupole-Stabilized Mirror Fields

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Experiments on strong E layers trapped in a magnetic mirror field, B_0, indicate anomalous fast-particle losses when quadrupole Ioffe field components, B_Q, are added. These losses include both loss bursts at critical field-reversal levels $\delta \equiv \delta B/B_0$ of $\sim 25\%$ and $\sim 50\%$ (independent of B_Q and gas pressure) and enhanced steady-state losses between and above these levels. The anomalous loss rate normalized to the normal collisional loss rate is independent of the background pressure, but roughly proportional to B_Q with no evident threshold.

Field-reversing rings of high-energy ions trapped in a magnetic mirror field have been proposed as a means of confinement and heating of fusion plasmas in Christofilos's Astron and some other related schemes.[1,2] If this is to be accomplished, stabilization of the dissipative precessional mode[3] of these rings will be needed. In earlier experiments[4,5] with electron rings, stability was obtained either by image currents in metallic wall liners or by the application of toroidal, B_θ, magnetic fields. Unfortunately, image-current stabilization becomes ineffective in an actual reactor as a result of field penetration during the required long ring lifetimes, and the stabilization by toroidal fields, although potentially necessary, would require the presence of a conductor through the ring axis with all its technological and economic penalties. Therefore, we previously investigated a stabilization of the precessional mode in the relativistic-electron-coil experiment (RECE)-Berta device by external quadrupole Ioffe fields, B_Q. As expected theoretically, the precessional mode was stabilized for relatively weak rings both with[6] and without[7] conducting

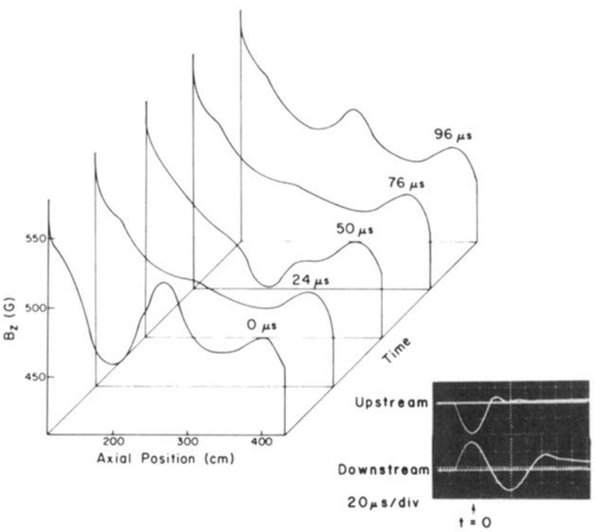


FIG. 2. Magnetic-field profile at different times, and pulse driving current wave forms. Injector position is 115 cm, upstream and downstream pulse coil positions are 202 and 269 cm, respectively.

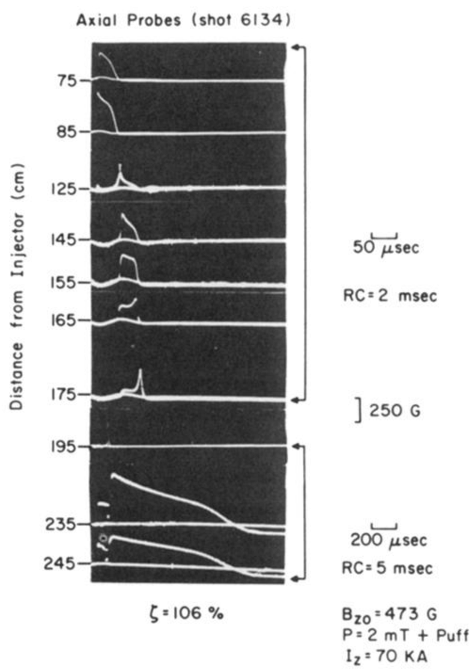
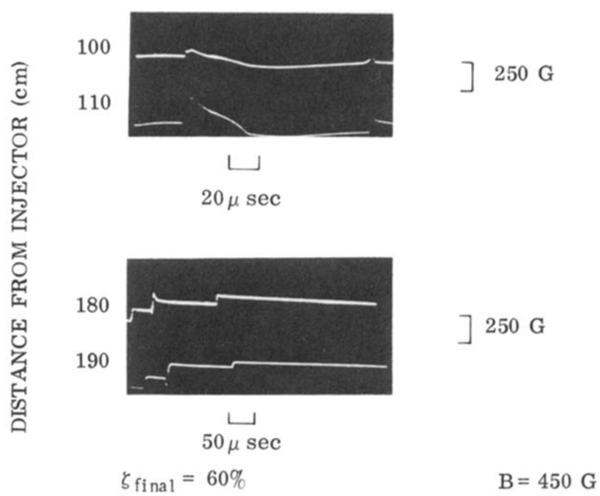


FIG. 3. Oscilloscope recordings, from a set of on-axis probes, showing ring translation and stacking to field reversal.



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