Trapping of High-Current Relativistic Electron Beams in a Magnetic Mirror Trap*

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500-keV, 10-kA electron beams are injected into a magnetic mirror trap of Astron geometry without wall resistors. When using H_2 and pressures of several hundred millitorr in the tank, we observe ring-shaped electron layers exhibiting field changes $\rho = \delta B/B_{\text{vac}}$ of up to 120% in the trap center and lifetimes of up to 20 μsec. With the exception of a fast final "dump" when the ρ of the layer has decreased to small values, we observe a smooth decay of the layer, roughly compatible with scattering of the fast electrons in the background gas.

As early as 1958, Christofilos[1] suggested confining a fusion plasma in an absolute-minimum-B configuration with closed field lines as it is created by trapping a sufficiently strong layer of relativistic electrons in a magnetic mirror. However, this idea has not yet been tested. The generation and stability of the relativistic electron layer are generally believed to be the major obstacles to this approach. In the well-known Astron experiment at Livermore, the injection of a well-collimated 6-MeV, 800-A beam leads to electron layers exhibiting axial field changes of up to 13% of the value needed to create a system of closed field lines.[2] This layer shows stable confinement for times of up to 50 msec. Using a separate approach, our group recently reported[3] the attainment of full field reversal by injecting very high-current beams of relativistic electrons directly between two mirrors. However, in that scheme, the presence of the injector within the trap region itself principally limited the confinement time of the electrons to a few hundred nanoseconds, and no indication concerning the stability of the layer could be obtained.

In the present paper, we wish to report first results of experiments in which similar high-current beams are injected into a magnetic mirror from outside the trap region. Using an arrangement similar to the Astron geometry, though without resistive structures, and background gas pressures of several hundred millitorr of H_2, electron layers exhibiting axial field changes of up to $\delta B/B_{\text{vac}} \lesssim 120\%$ are generated. Lifetimes of up to 20μsec are observed, roughly compatible with the scattering of the electrons in the hydrogen. Only when the layer strength has smoothly decreased to $\delta B/B_{\text{vac}} \simeq 15-20\%$ do we observe a faster loss of the electrons, similar to the "precessional dump" in the Livermore experiment. A dump level of this size appears compatible with the onset of the same instability for our field configuration.

In the new setup shown in Fig. 1, electron pulses of 10–30 kA, having energies of 400–600 keV and 80 nsec duration, are generated in the water-insulated pulse line QWIBLE, described elsewhere.[4] The beam is guided through a soft-iron–lined injector tube and injected into a new confinement tank (1.80 m long and 45 cm i.d.). To avoid bombardment and possible breakage of its glass wall by the energetic electrons, its inside is lined with 6-mm Lexan. Electrical conductivity at the wall is provided by a copper screen. Injection angle and radius can be varied

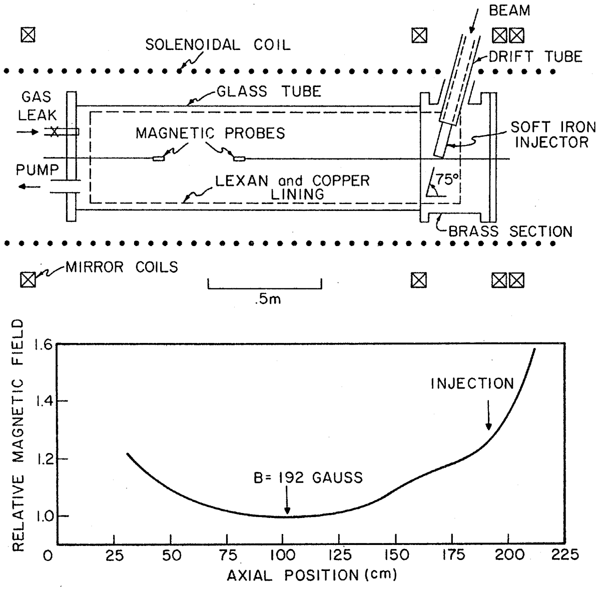

FIG. 1. Experimental arrangement and axial magnetic field distribution.

from 75 to 90 deg and 6 to 12 cm, respectively. A magnetic field of 100–500 G parallel to the tank axis is generated by a set of uniform windings and a number of movable mirror coils. All coils are energized in series from a crow-barred capacitor bank, providing a quarter-cycle rise time of 14 msec. To allow field penetration into the brass section, the beam injection is delayed 20–22 msec after the triggering of the capacitor bank. In the confinement tank, gas pressures from 0.01 to several torr are maintained. A thin Ti foil, 0.01 mm thick, at the end of the guide tube permits different gas pressures to be maintained in the guide tube and the tank.

For diagnostic purposes, an open-shutter camera views the tank through the downstream Lucite flange. Two magnetic probes, as described in Ref. 3, using 100-μsec RC integration, measure fast changes of the magnetic field along the tank axis. In addition, a fast liquid-scintillator–photomultiplier combination is used to detect high-energy x rays coming from the confinement tank. To avoid saturation of the multiplier during injection, the detector is heavily shielded towards the injection region and "sees" only about $\frac{2}{3}$ of the downstream part of the glass section.

In the first set of experiments, we used the axial magnetic field distribution shown in Fig. 1. Hydrogen pressures of 0.7 and 2 Torr were maintained in the tank and the transfer tube, respectively. Typical beam parameters were 500 keV and 10–20 kA. The magnetic probes were located on axis at the trap center and 30 cm downstream thereof. The injection angle was 75 deg.

Typical recordings of these conditions are shown in Fig. 2. The camera generally indicates a round, though often slightly eccentric, ring pattern. With sizable shot-to-shot variations in amplitude, the magnetic probes usually exhibit a sharp spike at the beginning with decay times of of 0.1–1 μsec. Thereafter, the center probe signal decreases much slower and roughly linearly from a level corresponding to $(0.3-0.5)B_{\text{vac}}$ until it reaches a level of $(0.15-0.2)B_{\text{vac}}$. At this point, which generally occurs 5–12 μsec after injection, depending on the initial signal size, a faster "dump" terminates the signal. The slope of the linear-signal portion reproduces quite well from shot to shot and increases with increasing tank pressure. The downstream probe, after a similar initial spike, generally shows a smaller signal which remains almost constant to a final cutoff which always occurs in coincidence with that of the first probe. The x-ray detector shows an even more pronounced initial spike having a decay time of 100–200 nsec. Additional recordings identify this spike as the tail end of a large x-ray burst occurring during injection for about 150 nsec and about 10 times higher than visible on the trace of Fig. 2. After about 1 μsec, the signal becomes rather flat until a final spike appears, again in coincidence with the cutoff in the magnetic-probe signals.

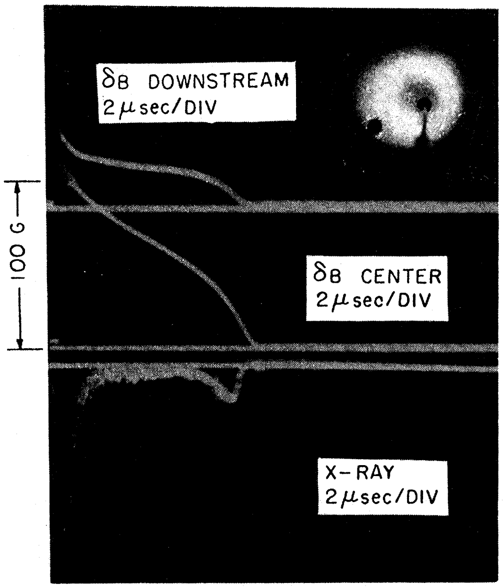

FIG. 2. Typical set of recordings during first series of experiments including axial photograph, magnetic-probe traces, and x-ray signal. (Tank pressure, 700-mTorr H_2; magnetic field, as in Fig. 1.)

To test the origin and significance of these signals, a number of experiments were performed. First, in a series of ten shots, the downstream mirror coil was switched on and off, alternately. With the mirror on, signals of the type mentioned earlier were recorded. Without this mirror, only the initial sharp spike remained in the x-ray and magnetic-probe traces, exhibiting decay times of a few hundred nanoseconds. With and without the mirror, the height of the x-ray spike remained roughly the same; the size of the spike in the magnetic-probe signals generally was slightly smaller without the mirror. In a similar series of experiments with the downstream coil energized, a Lucite strip (2 cm wide and 25 cm long in radial direction) was moved into the trapping region. In this case, the signals were identical to the above case with the coil off. These results agree with the expectation that the fast electrons are lost very rapidly if either the mirror is open or the Lucite strip is in place, and the magnetic-probe signals indicate a rapid decay of remaining plasma currents.

In an additional series of shots, tank fillings of 800-mTorr H_2 were compared with fillings of 400-mTorr H_2 plus 40-MTorr Kr. The two fillings are roughly equivalent with respect to ionization processes and the scattering of slow electrons. However, fast electrons are scattered faster by about a factor of 10 in the second case. As expected, with the Kr in, the signal duration decreases sharply to 1–2 μsec. From separate attenuation measurements, it was concluded that the major part of the x-ray signal was due to x rays having energies larger than 50 keV.

From these experiments, it appears that fast electrons were trapped between the mirrors, generating an electron layer of considerable strength. Assuming that these layers were positioned around the tank center, a layer length of 30–50 cm is indicated by the difference between the two magnetic-probe signals. From this and the layer diameter of 30 cm apparent in the photograph, we estimate that a few percent of the electrons entering the tank were trapped. This agrees with the x-ray detector signals which indicate that 90% of the total time-integrated intensity was contained within the initial spike and about 10% in the longer tail associated with the layer.

In a separate set of experiments, it was found that layer strength and lifetime increased when lower tank pressures and lower upstream mirror ratios were used. For 400 mTorr of H_2 in the tank, a slightly smaller mirror ratio upstream, and $B_{\text{vac}} = 185$ G in the tank center, the magnetic probe at the tank center indicated field changes of up to 230 G and lifetimes of around 20 μsec. An example for these conditions is shown in Fig. 3.

According to our magnetic-probe signals, the decay of these layers generally is smooth over most of their lifetime and does not give any indications of gross instabilities, even for the strongest layers. This smooth decay appears almost linear as predicted by Humphries[5] for the collisional decay of a self-compressed electron layer. The measured decay times are reasonably compatible with this explanation: The mean scattering angle of 500-keV electrons in 1 Torr of H_2 reaches 30 deg after about 5 μsec. The different time dependences of both probe signals also is consistent with the lengthening of the self-compressed layer during its decay.

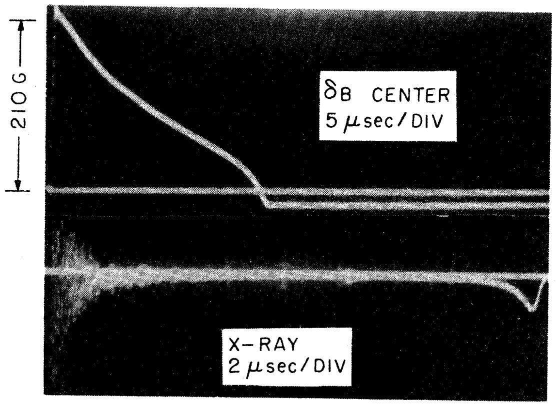

FIG. 3. Recordings for field-reversed layer using 400-mTorr H_2, $B_{\text{center}} = 185$ G, and upstream mirror ratio at injector position reduced to about 1.2.

Independent of the initial layer strength, the final "dump" of the layer appears quite regularly when the axial field changes have decreased to 15–20% of the external field. A preliminary analysis[6] of the "precessional dump" first observed at Livermore[7] under the conditions existing in our experiment indicates that a dump level of this size may be compatible with the onset of this instability.

We would like to thank our theorist colleagues R. N. Sudan and R. V. E. Lovelace for many very stimulating and vivid discussions, N. C. Christofilos, P. B. Weiss, and W. Condit for preparing and lending to us the x-ray detector, and the laboratory staff connected with the construction of the experiment for their excellent work and effort.

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†On leave from Lawrence Livermore Laboratory, Livermore, Calif.

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Reflectivities of Hg-In Liquid Alloys from 0.31 to 9 eV

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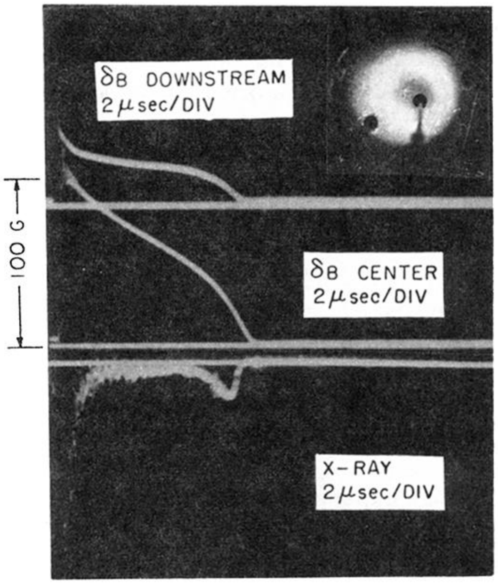
We have measured the reflectivity of liquid Hg-In alloys at near normal incidence from 0.14 to 4.0 μm. Our results deviate from the predictions of the Drude free-electron model. We attribute this to an unusual two-peaked density-of-states profile in liquid In and to concentration gradients of the components in a layer at the surface of the alloy.

Bloch and Rice[1] have concluded that the apparent contradictions resulting from the respective interpretations of the reflectance[1-3] and ellipsometric[3-5] measurements of the optical properties of liquid Hg can be resolved by assuming that the conductivity near the surface of the metal passes through a maximum before it levels off to its bulk value. If analogous surface-conductivity profiles exist for other pure liquid metals then it may not be possible to obtain the bulk values of $\sigma(\omega)$, the frequency-dependent conductivity, from the ellipsometric data. We believe that an additional surface effect, which can mask the influence of the bulk properties on both reflectance and ellipsometric results, will appear in liquid-metal alloys. An elementary thermodynamic analysis[6] shows that a solute which raises the surface tension of a mixture will have a smaller concentration in the vicinity of the surface than in the bulk. Thus, at the surface of such a liquid alloy there is a region in which the composition is different from that of the bulk. If the thickness of this surface-concentration region is an appreciable fraction of the penetration depth of the incident electromagnetic radiation, we expect that the reflectance will be affected at short wavelengths. Because of the larger penetration depth, at longer wavelengths the reflectances will be much more representative of the bulk electronic structure of the sample. In this Letter we report reflectances of liquid mercury-indium alloys which we believe exhibit the effects of a surface-concentration region.

After accounting for the effects of surface structure on the reflectance spectrum, it is possible to deduce some of the properties of the energy level distribution of the electrons in the bulk liquid. In the following we report the appearance of unexpected resonances in the bulk electronic spectrum of Hg-In alloys. We discuss the surface properties after a consideration of the bulk properties of the alloys.

We have measured the near-normal-incidence reflectances of a series of liquid Hg-In alloys containing up to 41.3 at.% In over the wavelength range 6000 to 40 000 Å, and of alloys containing up to 50.8 at.% In over the wavelength range 1400 to 5900 Å (from 8.8 to 2.2 eV). The reflectances were measured relative to that of pure liquid Hg using modifications of techniques described previously.[4,7] A MgF_2-alloy interface and top-surface reflection was used in the ultraviolet and visible; the precision in this region is ± 2%. A sapphire-alloy interface and bottom-surface reflection was used in the long-wavelength region (0.6 to 4.0 μm); the precision of these measurements is ± 0.2% (see Figs. 1 and 2).

One striking characteristic of the data displayed is the consistent drop below the expected Drude free-electron reflectivity for $\lambda < 1.0$ μm. Qualitatively, this agrees with the previous work of Schulz.[8] Just as striking, however, is the increase over the expected Drude reflectivity for $\lambda > 2.0$ μm for the alloys containing 30.0 and 41.3 at.% In. Recalling the comments of the first paragraph, we believe that the reflectivities at 4.00 μm, where the classical penetration depth is about 350 Å, are a much better measure of the bulk properties than are the shorter-wavelength reflectivities.



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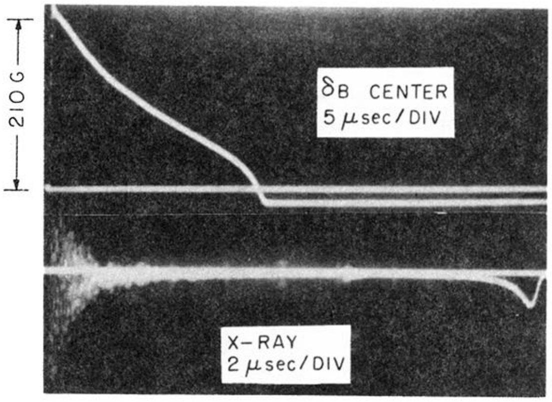

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