TRAPPING OF THE PHERMEX BEAM IN A MIRROR FIELD*

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Abstract

An experiment is underway at Los Alamos National Laboratory to trap the 1-kA, 30-MeV PHERMEX beam in a magnetic mirror. The eventual aim is to accelerate the beam to 50 MeV by ramping up the magnetic field. Tangential injection of the beam through a soft iron nozzle is employed. Because the nozzle is placed within the magnetic mirror, energy must be extracted from the beam in one bounce time to prevent particles returning to the nozzle. A design to make the bounce time as long as possible is described, and two schemes to damp the axial motion are considered. Numerical simulations of the device show considerable axial spreading of the beam in one bounce time. Estimates are made of negative mass instability growth rates and the damping to be expected from the experimentally measured beam energy spread. Experimental results obtained to date are described.

Introduction

Compact electron ring accelerators have been studied as a low-cost and small-scale means of achieving high energies and substantial current densities.[1,2] Ring currents on the order of 100 A have been accelerated. To obtain higher current, either the injection energy has to be increased or some type of strong focusing has to be added to the system. Several schemes applying the latter approach are currently being investigated.[3] The former approach is the subject of an experiment being conducted at Los Alamos. The injector for the experiment is the upgraded PHERMEX beam generator.[4] This rf accelerator produces a train of up to ten 0.75-kA, 30-MeV beam pulses. The pulses are 3.3-ns long and spaced 20 ns apart. The object of the experiment is to trap and stack these pulses in a magnetic mirror, and then accelerate the ring to 50 MeV. Though similar in concept to one of the Astron experiments[5], the time between pulses is much shorter (20 ns vs Astron's 1 ms) and the injection energy is much higher (30 MeV vs Astron's 3-6 MeV). These differences are being exploited to increase the beam trapping efficiency in the Los Alamos experiment.

Magnetic Field Design

Figure 1 shows the relative geometry of the field coil and stainless steel chamber. The radial dimension of the chamber is determined by the pulse length of the individual 3.3-ns micropulses. For an electron velocity of approximately the speed of light and an injected radius of 0.16 m, an initial magnetic field of 0.6 T is required. The field is driven by a 250-kJ capacitor bank. The maximum field is determined by the volume enclosed by the field coils and is 1.8 T.

The first task in preparing for the experiment was to design a magnet that would allow the axial velocity of the ring, V_D, to be as small as possible. Keeping V_D small reduces the axial kinetic energy ($\propto V_D^2$) and increases the bounce period. A minimum initial axial velocity is required in order to miss the injector on the first revolution as shown in Fig. 1. Because the nozzle has a diameter of about 0.1 cm, and the circulation time for the beam is about 3.3 ns, this minimum velocity is about 1% of the speed of light (0.01 c). To optimize placement of the 12 field coils, a code was written to compute the magnetic field and predict the motion of the electron ring beam based on two constants of the motion--energy and canonical angular momentum. Because of the high energy, single particle equations adequately describe the motion. A design was empirically selected where the coil spacing was uniform in the center of the device and then decreased towards the ends as shown in Fig. 2. Note that the mirror region is smaller than one would deduce from the local value of B_z because the particle motion depends on the total flux within the orbit as well as on the local B_z. The predicted average axial velocity in this configuration was 0.02 c, yielding a bounce time of ~50 ns.

The chosen field design was used in a particle simulation of the device using the particle-in-cell (PIC) code IVORY. Particles were initialized in a 1-cm radius ring at the edge of the mirror and given an axial velocity of 0.01 c. A plot of particle positions after 50 ns is shown in Fig. 3. The ring has bounced off the other side of the mirror and some particles are almost back to the injector. Note that considerable axial spreading of the ring has occurred. This is because the discrete field coils produce a bumpy magnetic field. As the ring passes a coil (local "anti-mirror"), its average drift velocity decreases and it is axially defocused by the B_r field. Between coils (local mirror) the drift velocity increases, and the beam is axially focused. Thus, there is net defocusing because the ring spends most of its time in the defocusing regions.

Extraction of Axial Energy

Two schemes to slow the axial drift of the ring are under consideration. The first involves using a resistive wall and the second relies on a pulsed electric field. The resistive wall method was used in the Astron experiment[6] to damp axial velocities of about 0.1 c. For the Los Alamos experiment, a graphite-wall drift tube is being constructed. (Initial experiments are proceeding in a stainless steel drift tube.) A simple model of the energy loss yields the order-of-magnitude result,

$$W_\sigma = RI^2L\left(\frac{\mu_o\pi^2}{4\sigma V_D h^3}\right)^{1/2} \quad \text{(mks units)} \qquad (1)$$

where R is the beam major radius, I is the beam current, σ is the wall conductivity, h is the distance from the beam to the wall, and L is the axial distance of beam drift. As shown in Ref. [7], this energy derives from the axial motion rather than the azimuthal motion and so helps to trap the beam. The kinetic energy in the particles is $W_p = 1/2\ \gamma N m V_D^2$, where N is the total number of electrons, m is the electron mass, and γ is the relativistic factor. Substituting the numbers for the Los Alamos experiment ($I = 1$ kA, $\gamma = 60$, $L = 44$ cm, $h = 4$ cm, $\sigma = 10^5$ siemens/m, $V_D = 0.02$ c), we find $W_\sigma/W_p \approx 1.8$ during a single bounce. This is an encouraging result, although probably an overestimate. The axial spreading of the ring has not been taken into account in the analysis.

*Work performed under the auspices of the U.S. Department of Energy by Los Alamos National Laboratory under W-7405-ENG-36.

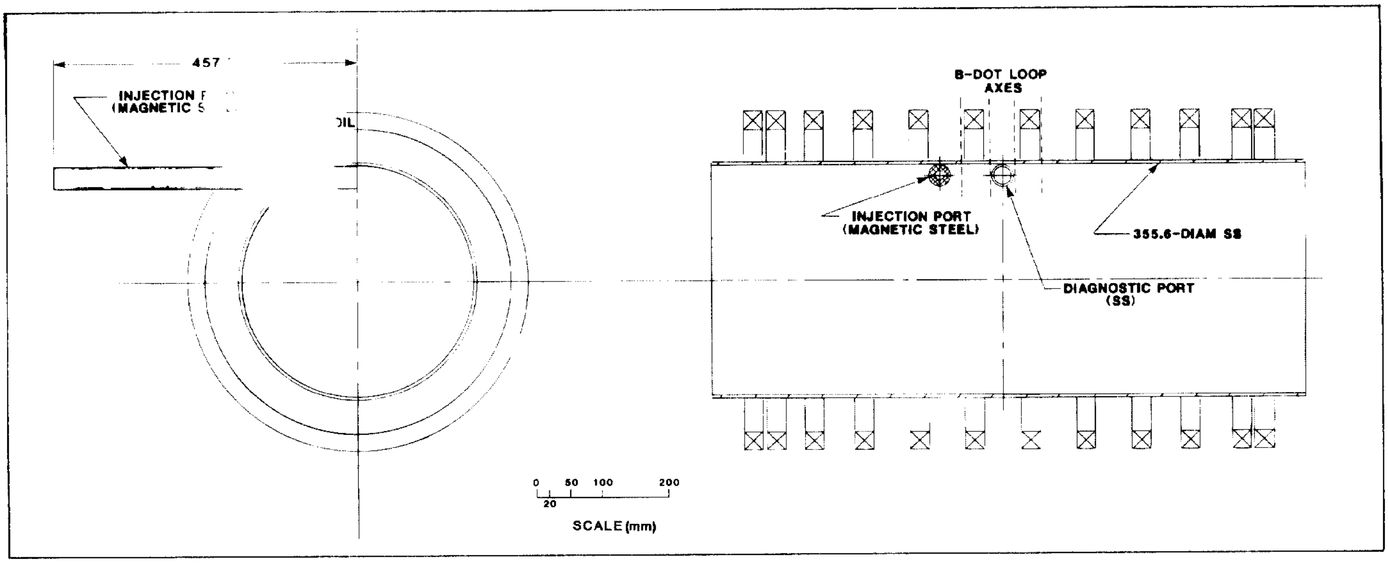

Fig. 1. Schematic of the pulse field assembly.

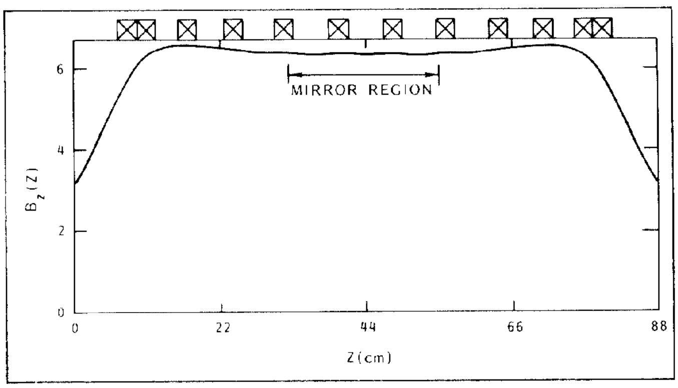

Fig. 2. Field coils.

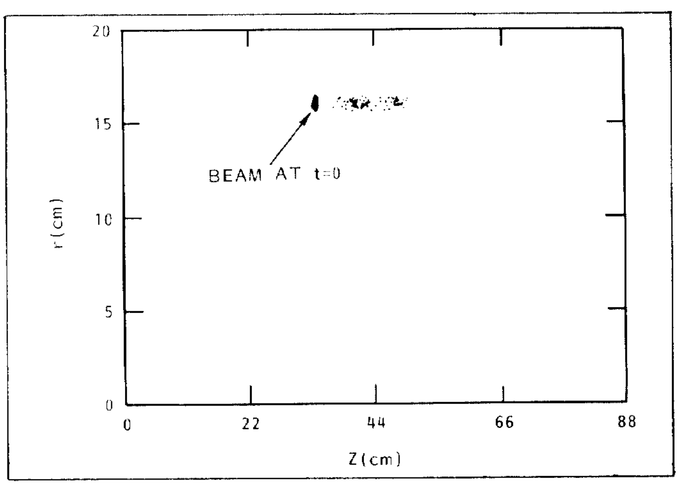

Fig. 3. Plot from IVORY.

The second scheme to slow the ring involves pulsing an axial electrode to negative potential. The potential must change on the time of one bounce (~50 ns) to extract energy. For a 30 MeV ring traveling at 0.02 c, the axial energy corresponds to a potential of 6 kV. Thus, very modest voltages are sufficient to cause trapping. A numerical simulation of this scheme is in progress.

Negative-Mass Instability

Beam disruption in previous electron ring experiments has been attributed in part to the negative mass instability.[6,7] This instability causes the beam to bunch azimuthally and spread out radially. Theory[8] predicts the following peak growth rate for a monoenergetic beam,

$$\Gamma = \frac{c}{h}\left[1.6\,\frac{\nu}{\gamma}\right]^{1/2} , \qquad (2)$$

where c is the speed of light, $\nu = I/I_A$, and I_A is the Alfven limiting current. For a single ring with 1 kA current, $\gamma = 60$, h = 4 cm, and R = 16 cm, the predicted e-folding time is 5 ns for modes in the vicinity of $\ell = 5$. An energy spread on the beam can stabilize the mode through Landau damping.[7,8] The required spread in this case is about 5-10%. Experimental measurements on the PHERMEX pulses show a spread of about 6%. Thus the instability, if present, should have a substantially smaller growth rate than given by Eq. (2) and will saturate at a lower level than would be the case for a monoenergetic beam.

Experimental Results

The pulsed field coil assembly is pictured in Fig. 4. The individual coils on each half of the assembly were connected in series with the two halves driven in parallel by the capacitor bank. The measured inductance of the half assemblies was 2.04 mH and the effective inductance of the full assembly was 1.11 mH. The measured resistance of the cables and the coils from the capacitor bank was 188 mΩ. Figure 5 is an electrical schematic of the capacitor bank and field coils. Figure 6 is an oscilloscope trace with voltage and magnetic field. The upper trace is the time dependent capacitor bank voltage, which is crowbarred by an ignitron just after the voltage is reversed. The lower trace is the time dependent magnetic field. It is 0.6 T for an initial capacitor bank voltage of 3.36 kV. The measurement was made just inside the chamber at the injection nozzle.

The assembly was located in the PHERMEX chamber. The drift tube in the PHERMEX chamber was disassembled just downstream of the steering lens. A 12.7-mm-diam collimator was placed in the drift tube and the beam was focused to a 5-mm-diam spot at an 0.5-mm-thick beryllium exit window using upstream solenoidal focusing lens. The emittance of the beam is dominated by multiple scattering in the window.

Initial trapping experiments were performed in air. The range in air for 30-MeV electrons is 100 m. Therefore, the setup was adequate for examining trapping of a single micropulse for several turns. During the initial experiments to trap an electron ring a

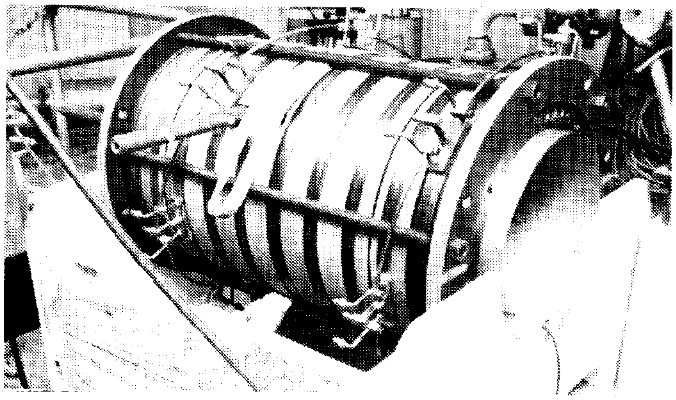

Fig. 4. Photograph of the magnetic field coil assembly.

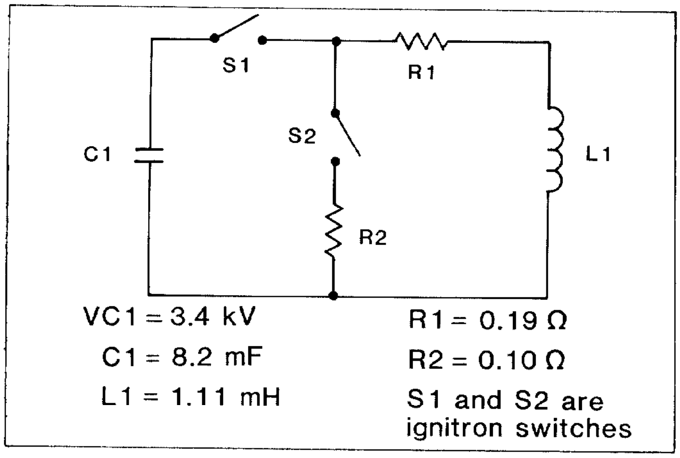

Fig. 5. Simplified electrical schematic with the capacitor bank and field coils.

problem was discovered. The stray fields from the pulsed magnet covered a sufficiently large length of the upstream drift tube that even though the field was small, the integral magnetic field over the drift tube length was large enough to prevent injection into the nozzle. After extensive upstream shielding and maximum steering, we were able to transport the beam into the chamber at the end of the experimental run.

Future experiments are planned to solve the magnetic shielding problem. At present there are two approaches. The first would simply use a combination of massive μ-metal and iron shielding around the drift tube or field coils. The second approach would involve decreasing the inductance of the coils, which increases the field rise time and lowers the mass of the shielding otherwise needed.

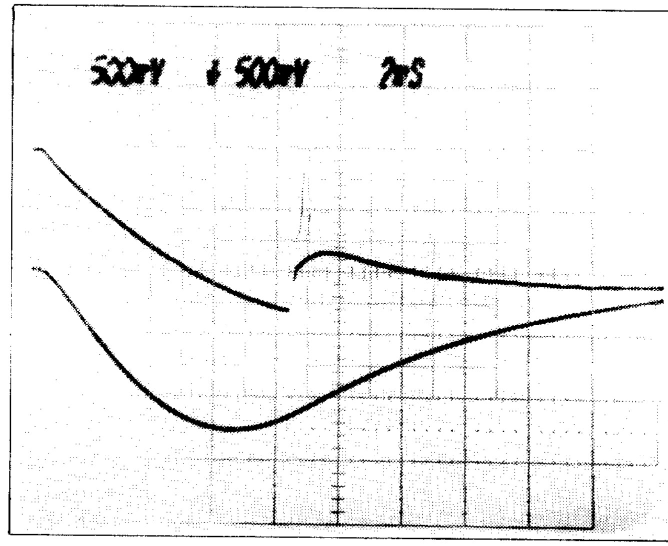

Fig. 6. Time dependent capacitor bank voltage and axial magnetic field oscilloscope traces.

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