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J. von der Linden,1,2,a) G. Fiksel,3 J. Peebles,4 M. R. Edwards,1 L. Willingale,3 A. Link,1 D. Mastrosimone,5 and Hui Chen1

AFFILIATIONS
1Lawrence Livermore National Laboratory, Livermore, California 94550, USA
2Division E4, Max Planck Institute for Plasma Physics, 17491 Greifswald and 85748 Garching, Germany
3The Gérard Mourou Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109, USA
4Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

a)Author to whom correspondence should be addressed: jens.von.der.linden@ipp.mpg.de

ABSTRACT
Creating a magnetized relativistic pair plasma in the laboratory would enable the exploration of unique plasma physics relevant to some of the most energetic events in the universe. As a step toward a laboratory pair plasma, we have demonstrated an effective confinement of multi-MeV electrons inside a pulsed-power-driven 13 T magnetic mirror field with a mirror ratio of 2.6. The confinement is diagnosed by measuring the axial and radial losses with magnetic spectrometers. The loss spectra are consistent with \( \frac{1}{2} \): \( 5 \) MeV electrons confined in the mirror for \( \sim 1 \) ns. With a source of \( 10^{12} \) electron-positron pairs at comparable energies, this magnetic mirror would confine a relativistic pair plasma with Lorentz factor \( \gamma \sim 6 \) and magnetization \( \sigma \sim 40 \).

Physics of Plasmas

I. INTRODUCTION
Pair plasma of positrons and electrons behaves drastically different from electron-ion plasmas due to their unity mass ratio. The unity mass ratio alters the waves and unstable modes in a pair plasma. Compared to electron-proton plasma, electron-positron plasma can achieve relativistic and magnetized conditions relevant to energetic astrophysical phenomena with less kinetic energy (1/1000) and weaker magnetic field (1/30).

Relativistic plasmas are found in energetic astrophysical systems abundant in antimatter, such as supernova remnants, gamma-ray bursts, and active galactic nuclei. The jets of active galactic nuclei and the magnetospheres of pulsars contain magnetically dominated plasma, where particles may be energized through relativistic magnetic reconnection and kink instabilities. In all these systems, intense non-thermal radiation is thought to result from collisionless shocks formed by magnetic field amplification or generation in Weibel-like instabilities. These Weibel-like instabilities are electromagnetic instabilities in plasmas with momentum anisotropy. Electromagnetic instabilities generally dominate over electrostatic modes (e.g., the two-stream instability) when the plasma has relativistic energies. Which electromagnetic instability dominates the mode spectrum has been the subject of recent theoretical work investigating the effects of ratio of thermal to directed momentum, magnetization, and mass ratio. The unity mass ratio of electron-positron plasma is predicted to lead to faster growth rates than in electron–proton plasma.

Although laboratory electron-positron plasma reduces the particle energy and magnetic field needed to achieve these relativistic and magnetically dominated regimes, the difficulty in producing a large number of positrons and in containing them for long lifetimes has so far precluded their use. In recent decades, much progress has been made in producing reliable positron sources. Positrons with energies of tens to hundreds of eV can be harnessed with continuous fluxes of \( 10^{9} \) s \(^{-1} \) through the capture of fission neutrons and moderation in \( \sim 10 \) ps laser-target interactions that can then be used in producing large numbers of multi-MeV positrons, up to a \( 10^{12} \). This favors laser-matter interactions as source for relativistic pair plasma experiments.
A plasma is relativistic when the Lorentz factor is $\gamma > 2$, i.e., the kinetic energy of particles exceeds their rest mass, 511 keV, for electrons and positrons. To study electromagnetic instabilities with these relativistic pairs, it is necessary for the plasma to be dense enough to attenuate electromagnetic waves. This means that the scale length of the plasma must be larger than the skin depth,

$$\lambda_s = c / \sqrt{\mu_0 n \epsilon_0 m_e}, \quad (1)$$

where $c$ is the speed of light, $n$ is the number density of electrons and positrons as both respond quickly to perturbations, $\epsilon_0$ is the elementary charge, $m_e$ is the electron (and positron) mass, and $\epsilon_0$ is the permittivity of free space. In addition, the lifetime of the plasma needs to be greater than the instability growth rate $\tau$, which is related to the inverse of the plasma frequency ($\tau \propto 1/\omega_p$). This can be achieved in either beams of pairs dense enough to result in instability growth during the time of flight or in less dense magnetically confined pairs.

Here, we focus on developing magnetic traps in order to study magnetized and relativistic pair plasma. A (relativistic) pair plasma is considered magnetically dominated when the magnetization factor—the ratio of magnetic energy density over particle energy density—exceeds unity,

$$\sigma = (B^2/\mu_0)/(n\gamma m_e c^2), \quad (2)$$

where $B$ is the magnetic field and $\mu_0$ is the permeability of free space. Magnetic configurations can trap pairs with magnetic mirroring effects. This has been successfully demonstrated with lower-energy positrons: a magnetic mirror—intrapsitrons has trapped eV positrons for >70 ms, the magnetic dipole field of a permanent magnet has trapped eV positrons for >1 s, and the dipole field of a levitating superconductor has trapped 100 keV positrons for 100 $\mu$s.

Here, we report on the design of a cm-sized magnetic mirror and on experiments showing the confinement of laser-generated ≤2.5 MeV electrons for a nanosecond in the 13 T mirror field.

**II. MIRROR DESIGN**

Inhomogeneous magnetic fields exert a force on pairs opposite to the field gradient, $F = -\mu \nabla B$, where $\mu = \gamma m_e u_\perp^2 / (2B)$ is the magnetic moment of the particle with perpendicular velocity $u_\perp$. A magnetic mirror traps charged particles between two maxima of the magnetic field. The pitch angle of the particle determines if it is trapped or escapes through the loss cone. Trapped particles complete three motions in a magnetic mirror: they gyrate around the magnetic field, trapped particles follow well-constrained paths. Strong sensitivity of the chaotic system to initial conditions makes the electron path dependent on the time step. The numerical calculations of the invariants of motion, energy, and canonical momentum exhibit sufficient conservation when the number of time steps exceeds $10^4$ per mean gyration period. Despite the chaotic path, the drift motion is axis encircling due to the conservation of the third invariant. As the magnetic flux is not conserved, the electron drift does not lie on a cylindrical surface but makes small displacements off the surface to compensate for the varying angular momentum, enclosing a surface of constant canonical vorticity.

The MIFEDS coils can be arranged, so that the mirror is centered at target chamber center (TCC) where a target is placed to generate pairs through laser-matter interaction. The trapping of electrons and positrons for\textsuperscript{22} showed that such trapped particles with non-conserved first and second adiabatic invariants follow chaotic paths. Strong sensitivity of the chaotic system to initial conditions makes the electron path dependent on the time step.
positrons in this mirror will depend on the pitch angles of perpendicular velocity to parallel velocity with which the particles are injected into the mirror. A previous characterization\(^3\) of electrons and positrons leaving a 1-mm Au target measured an angular distribution with full widths at half maximum (FWHM) of \(50^\circ \pm 10^\circ\) with the beam centered on the rear target normal direction. The divergence can be characterized in terms of the polar angle \(\theta\) with respect to the mirror axis (Fig. 2). For a target placed in the center of the mirror with the

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**FIG. 1.** Numerically integrated path of a 2.5 MeV electron launched with pitch angle 51° from the mirror center. The electron is lost after \(~-1\) ns. (a) View perpendicular to mirror axis shows gyro and bounce motion. (b) View along mirror axis shows drift. (c) Time evolution of the magnetic flux \(\Psi\), angular momentum \(\psi(rL/c_{me}/q_e)\), and their sum, the canonical vorticity flux.

**FIG. 2.** (a) Laser-target interaction generates electrons in mirror field generated by two MIFEDS coils (orange). Target (gold) is centered between coils. Two EPPS magnetic spectrometers measure axial and radial losses (dotted lines) separating electrons (yellow) and positrons (red). The electron divergence is characterized in terms of the polar angle \(\theta\) with respect to the mirror axis (dashed line) (not to scale). (b) Magnetic field along mirror axis, \(z = 0\) is the mirror center.
target normal perpendicular to the mirror axis, the angular distribution of particles would be centered along the target normal, at 90° to the mirror axis.

To evaluate the confinement properties of the MIFEDS mirror, we numerically integrate the paths of 10,000 electrons with a 2.5 MeV kinetic energy and launched with this angular divergence from the center of the mirror with COMSOL Multiphysics® using the fifth order Dormand-Prince method. Figure 3(a) shows the time evolution of the number of 2.5 MeV electrons in the 13 T mirror (blue). The e-folding time of the number of electrons is ~2 ns. The losses are due to axial outflows of electrons, including from initially trapped electrons that move non-adiabatically into the loss cone. As the mirror is a closed system, the phase space of electrons can be described with Liouville’s theorem, and all trapped electron paths, even chaotic ones, will eventually cross their origin, the target. Collisions with the target scatter the electrons, perhaps shifting their pitch angle into the loss cone. Even with the pessimistic assumption that all target collisions are losses, electrons produced with a 20 μm thick and 0.5 mm diameter target are still trapped for several bounces with e-folding time of 1 ns [Fig. 3(b)].

We can diagnose losses from the mirror with magnetic spectrometers placed outside the mirror. Figure 4 shows the trajectories of 10,000 electrons with energies 2, 3, 5, and 13 MeV in the mirror, without any collective effects. 2 MeV electrons are only lost axially and only for shallow launching angles with respect to the mirror axis, while at higher energies, electrons are also lost radially. At higher energies, an increasing portion of electrons is not trapped at all. Instead, they exit the mirror in less than one gyro-orbit. The trajectories of 3, 5, and 13 MeV electrons exhibit non-axisymmetry, as the electrons sweep a radial loss angle corresponding to the portion of the last gyro-orbit they complete before leaving the mirror field. There is also a gap in losses at polar angles intersecting the coils. That is, an electron cannot escape by penetrating the coil due to a strong field near the wire surface. Two orthogonal magnetic electron-positron-proton spectrometers (EPPS) can validate these calculated loss spectra. Ratios of the flux F of 10,000 simulated electrons launching from the target with no magnetic field applied and the magnetic field applied F(B = 13 T)/F(B = 0 T) and F(B = 9 T)/F(B = 0 T) quantify the effect of the magnetic mirror without requiring knowledge of the absolute electron numbers (Fig. 5). The magnetic field increases the number of ≤2.5 MeV electrons exiting the mirror radially (ratio < 1) and correspondingly increases the number exiting axially (ratio > 1). At higher energies, the effect of the magnetic field becomes negligible (ratio ~1); however, the ratios do not vary monotonically with energy.

III. EXPERIMENT SETUP

We conduct experiments at Omega EP to demonstrate the confinement properties of the high field mirror for relativistic electrons. This is because (1) the mirror trapping mechanism does not depend on the sign of charge, and (2) the energy of the positrons from laser-target interactions is 5–30 MeV, too high for currently achievable magnetic fields without additional methods to reduce the target-normal sheath acceleration (TNSA) of positrons. The target dimensions, 20 μm thick and 0.5 mm diameter, are optimized for electron production. The short 20 μm thickness of the target limits the production of positrons through the Bethe-Heitler process to levels just above the noise floor. The relativistic electrons are generated by the interaction of an Omega EP wavelength λ = 1054 nm, 10 ps FWHM pulse with the target. A background shot is taken with no applied magnetic field. The magnetic mirror field is applied for five shots: three with 13 T and two with 9 T at the coil center. The laser energy is 900 ± 20 J for the shot without magnetic field and the first shot with 13 T. However, after this first magnetized shot, MIFEDS debris and copper disposition on the laser optics limit the laser energy to 770 ± 40 J for all remaining shots. With 80% of the laser energy contained within a 16 ± 2 μm radius, the laser energies correspond to intensities of I = 9 ± 1 × 10^18 and I = 7 ± 1 × 10^18 W cm⁻², with a laser power contrast of about 10⁸–10⁹. At such laser conditions, the radially escaping spectrum (Fig. 6) fits a Maxwellian-like exponential with temperature T = 5.8 ± 1 MeV, close to the expected value according to Pukhov scaling. 4.7 MeV, and within

![Figure 3](https://example.com/figure3.png)
IV. RESULTS AND ANALYSIS

Two electron-positron-proton spectrometers (EPPS) are positioned to sample the electron losses parallel to the MIFEDS magnetic mirror axis and normal to the mirror axis, radial with respect to the mirror geometry (Fig. 2). Each EPPS accepts particles through a 0.95 × 0.96 mm² slit. The radial EPPS is 48 cm, and the axial EPPS is 57 cm from the center of the mirror, which is also the target chamber center. After each shot, the image plates from the two EPPS are scanned after 25 minutes and adjusted for fading with a factor of 0.67.
Two super-Gaussians are fitted to the background and signal on each image plate in order to remove the background and determine the projected slit width. Calibrations of the absolute dose and dispersion with measurements in the expected trapped particle energies, 3–15 MeV, provide absolute electron energy spectra. Without the magnetic field, the electrons exit mostly radially, normal to the target surface. The electron energy distribution is determined by the laser-plasma acceleration processes in the pre-formed plasma on the surface of the target. Refluxing of electrons in the target may broaden the energy distribution. The broad angular divergence of electrons leaving the target results in axial losses measured by the EPPS even when no magnetic field is applied. In shots with applied magnetic field, the radial electron loss spectra have three characteristic differences to the baseline no-magnetic-field shot (Fig. 6): (1) the radial EPPS measures a significantly lower number of electrons, (2) the energy spectrum has a steep drop at 3.7 MeV, and (3) followed by a steady increase until 18 MeV for the 13 T field. The energy of the broad peaks in the axial spectrum corresponds to the electron energy, for which the focal length is the coil-to-target distance 7.5 mm, i.e., the energy of electrons that should be collimated. The narrower spikes in the measured axial loss spectra below 5 MeV have been noted in magnetic focusing experiments and correspond to complicated trajectories of specific energy electrons, which focus and subsequently re-collimate upon exiting the coil. There is significant variation in the spectra between shots; this may be related to variation in the laser parameters, tilt off the mirror axis (3°–5°) in the construction of the coils, and shot-to-shot variation in the magnitude of the magnetic field. The radial spectra have a strong dependence on the magnetic field magnitude because of the large azimuthal rotation introduced by the field. Despite this variation, the characteristics described here are recognizable across all shots. To relate the measured losses to the calculated particle trajectories, we compare the numerical electron flux $F(B = 13 \, \text{T}) / F(B = 0 \, \text{T})$ from the calculated trajectories to the ratios of the measured spectra (Fig. 5). The simulated flux ratios are consistent with the characteristics observed in the measured fluxes: (1) the radial flux is significantly reduced and the axial flux is correspondingly enhanced, (2) the radial flux sharply drops off for energies above 3.7 MeV, and (3) followed by a steady increase until 18 MeV for the 13 T. The reduction in the radially lost electrons and corresponding increase in axially lost electrons.

![Graph](image-url)
agrees with the path integrations of trapped electrons lost along the axial loss cones.

As the mirror force is independent of the sign of the charge, this mirror should be able to confine positrons and electrons simultaneously. Positrons and electrons could be generated outside of the mirror with thicker targets optimized for positron production. The pairs could then be magnetically transported to the mirror with a solenoid acting as collimating lens. The lens would select particle energy, and if tilted also select charge,\(^1\) so that a unity charge ratio pair beam could be injected into the mirror. A thin foil placed inside the mirror could scatter the injected pairs out of the loss cone.\(^2\) The coils could also be arranged in a cusp configuration with a magnetic null at the center; this may simplify injection from an outside target as the magnetic null would allow pairs to transition non-adiabatically to trapped particles.\(^3\)

With 1 mm thick targets, up to \(10^{12}\) positrons have been produced.\(^7\) In the mirror described here, this would result in a density of \(n \sim 10^{12} \text{ cm}^{-3}\). The magnetization would be \(\sigma \sim 40, B = 5 \text{T}\) at the mirror center and confined energies of 2.5 MeV (\(\gamma \sim 6\)) in Eq. (2). This density \(n = 10^{12} \text{ cm}^{-3}\) and relativistic Lorentz factor \(\gamma = 6\) would correspond to skin depths of 0.9 cm [Eq. (1)], being on the same order as the coil diameter and separation, characteristics of the mirror geometry. As the Debye length approaches the skin depth in relativistic regimes, a pair plasma of these densities would approach the conditions for supporting electrostatic and electromagnetic instabilities.\(^\ast\)

V. CONCLUSION

We have trapped \(\lesssim 2.5\) MeV electrons for a nanosecond in a 13 T magnetic mirror field and, thereby, demonstrated that magnetic mirror coils driven by the existing MIFEDS power supplies can trap relativistic electrons and positrons. This can be achieved without the conservation of the magnetic moment and bounce invariant, resulting in chaotic but nonetheless trapped particle paths. Measurements of the axial and radial losses from the magnetic mirror are consistent with numerically calculated electron losses and confinement of \(\lesssim 2.5\) MeV electrons for several bounce periods. Future experiments could use a high yield positron source; the largest positron yield achieved with intense laser-matter interaction\(^17\) is \(10^{15}\). Trapping this yield in the mirror discussed here would produce a pair plasma approaching the plasma conditions for supporting electrostatic and electromagnetic instabilities. The pairs would be relativistic with \(\gamma \sim 6\) and magnetized with \(\sigma \sim 40\). Increases in the magnetic field could increase the energy of pairs that can be trapped. For example, the upgrade of the pulsed power supply at OMEGA from MIFEDS-2 to MIFEDS-3 will increase the stored electric energy from 200 J to 2 kJ, enabling higher currents and corresponding magnetic fields to be driven in the coils.\(^28\)

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The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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