Magnetically Collimated Relativistic Charge-Neutral Electron–Positron Beams from High-Power Lasers

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Relativistic electron–positron pair plasmas are important objects for study in fundamental plasma physics; they have unique properties resulting from mass symmetry and are used to explain observations of multiple astrophysical phenomena, such as gamma-ray bursts, black holes, and active galactic nuclei.[1–7] The creation of dense, relativistic pair plasmas in the laboratory has remained elusive due to the short positron lifetime and difficulty in producing plasmas of high-enough density.[8] To create a useful pair plasma for laboratory astrophysics, three conditions must be satisfied: (1) high-energy (MeV) particles must be confined longer than the plasma time scale of interest; (2) the plasma dimensions must be significantly greater than the Debye length; and (3) the plasma must be charge neutral. To date, there are limited experiments that produce high-temperature pair plasmas and high-flux pair jets required to simulate astrophysical phenomena.[9,10]

One method to generate energetic positron–electron pairs relevant to laboratory astrophysics experiments is to use ultrashort high-intensity lasers. Previous experiments have produced jets of positrons and electrons with MeV energies in a small volume (<3 mm^3), with particle densities of about 10^{15} cm^{-3} and 10^{13} cm^{-3} at the source for electrons and positrons, respectively.[11,12] These positrons are generated through the Bethe–Heitler process, whereby bremsstrahlung γ rays from high-energy electrons decay into electrons and positrons. So far, of the three plasma conditions, the confinement condition (2) has been achieved experimentally using an imposed magnetic field,[12] and the neutrality condition (3) has been achieved in another experiment using a very thick, high-Z target to generate equal numbers of electrons and positrons with >5-MeV energy.[13] No previous experiment has produced a high-temperature, neutral pair-plasma beam; many experiments have produced jets with electron density exceeding the positron density by severalfold but have not confined or collimated them for long periods.

Magnetic focusing has provided a promising path toward satisfying the conditions of charge neutrality and MeV confinement. Indeed, previous experiments demonstrated the use of an externally imposed magnetic field to collimate electrons and positrons for measurement.[14,15] These experiments measured nearly 70× as many positrons on magnetized shots as unmagnetized shots due to collimation by the magnetic field. Ratios of electrons to positrons ranged from 10 to 3 for various shots during the experiment, but did not reach charge neutrality. This improvement suggests that externally imposed magnetic fields have great potential to collimate fully neutral pair plasmas. Here we report the measurement of a neutral, collimated electron–positron beam by utilizing recent upgrades to the pulsed-power system known as MIFEDS (magneto-inertial fusion electrical discharge system).[16] This represents a significant step toward generating charge-neutral electron–positron pair-plasma jets in the laboratory.

Five magnetized shots and one unmagnetized reference shot were carried out in the experiment on the OMEGA EP laser, which used 10-ps pulses with λ = 1054-nm light, focused on a 500-μm-diam, 20-μm-thick gold disk. The laser energy was 900±20 J (intensity = 9×10^{18} W/cm^2). It should be noted, however, that MIFEDS-related debris and copper deposition on laser optics caused an estimated loss of energy and intensity of 15% to 20% after the first magnetized shot, leading to on-target energies in the range of 770±40 J with an intensity of $7\pm1 \times 10^{18}$ W/cm^2. At these conditions, the positron yield can be estimated from Myatt *et al.*[17] Assuming a laser energy of about 800 J and a laser-to-electron conversion efficiency of 30%,[18] the expected positron yield is about

7.5×10^{10} in total, with a density of approximately 3×10^{10} positrons/sr since without collimation, the positrons diverge with an angle of 1 to 2 sr (Ref. 16). The combination of positron number and divergence results in a measurement that is barely above the detection threshold of the spectrometer.

In order to magnetize shots, field-generating coils were set up in a magnetic mirror configuration with wire loops 14 mm apart with an inner diameter of 10 mm. These produced a field of up to 13 T at the ends of the mirror and 5 T in the center near the source. For two of the five shots, the MIFEDS charge voltage was tuned to examine a lower field of approximately 4 T and 9 T at the center and edges, respectively. The energy distributions of electrons and positrons were measured with an electron–positron–proton spectrometer (EPPS), which was placed along the primary magnetic-field axis. The magnetic field axis and spectrometer collection region were aligned perpendicular to the laser and target axis.

Initial particle-tracing simulations, carried out with the multiphysics code COMSOL, show that when the field is imposed, particles with energy less than 2.5 MeV are completely confined radially. For higher-energy particles, those with a small initial pitch angle relative to the mirror field axis will be well focused and collimated by the magnetic field due to slight deflections. Particles of roughly 13 MeV from a point source 8 mm away from the coil would be collimated, given the coil radius and peak magnetic-field profile used on the experiment. For particles with energy higher or lower than this optimum energy, particles will be overfocused prior to reaching the spectrometer or not focused at all.

These simulation predictions were borne out in the experiment, which consisted of five magnetized shots (three at high field and two at low field) and one unmagnetized reference shot. In the no-field case, almost no positrons were measured above noise level (as expected) and electrons followed a single temperature spectrum across all energies of interest. When the field was applied, positrons of equal energy and number to the electrons were measured. The positron signal peaked at 13 MeV (Fig. 1), which matches the estimated best focus from the initial simulations. Two shots were also performed using a weaker, 9-T field, which decreased the peak energy of focused particles to 10 MeV, while still maintaining an even ratio between positrons and electrons. These collimated beams of pair particles were maintained over the 50-cm distance between the experiment and the spectrometer.

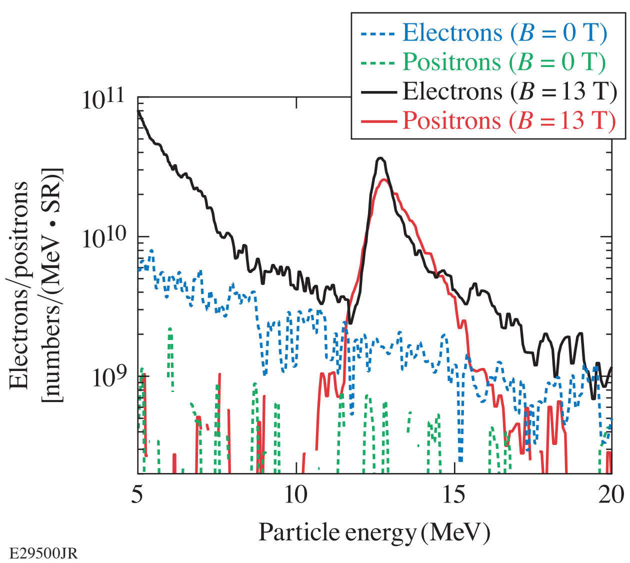

Figure 1
Electron and positron spectra measured using the field axis EPPS. With no field (dotted curves), only electrons characterized by a single slope temperature were measured along this direction. When the 13-T collimating field was applied, nearly identical quantities of electrons and positrons peaked at around 13-MeV energy were measured.

While these measurements of charge-neutral, focused electron–positron beams represent a step forward toward a true pair plasma, the densities are still insufficient for many astrophysics purposes. To effectively create scaled astrophysical shocks within the pair plasma, densities of at least 10^{13} cm^{-3} and energies of over 10 MeV are required. While our jet contains energies of 13 MeV and is collimated over a long distance (>50 cm), the density is considerably lower—roughly 2×10^{8} cm^{-3} based on the assumption that the particles are accelerated throughout the laser pulse. To increase density toward meeting the confined pair-plasma goals, future work will concentrate on increasing the density of the pair-plasma beam. Thicker gold or microstructured targets can be used in the future (similar to those used in other pair-plasma–generating experiments[14]), which will substantially increase the conversion to positrons. Further upgrades to MIFEDS will also be applied in order to increase the energy range for confined or collimated particles.

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