Progress Towards a Laser Produced Relativistic Electron-Positron Pair Plasma

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Abstract. A set of experiments has been performed exploring unique characteristics of pair jets and plasmas at several energetic short-pulse laser facilities including Titan at Livermore and OMEGA EP in Rochester, as well as the Osaka LFEX and AWE Orion lasers. New results are summarized, including positron beam emittance, scaling of pair production vs. laser energy, and initial results on the pair jet collimation using electromagnetic fields.

1. Introduction

Relativistic electron-positron pair plasmas and jets are believed to be abundant in many astrophysical objects and are invoked to explain energetic phenomena related to Gamma Ray Bursts, Active Galactic Nuclei, and Black Holes [1-9]. Making a relativistic electron-positron (antimatter) plasma in the laboratory that is astrophysical-relevant has been challenging due to the difficulties associated with producing high density of the pairs, the short lifetime of positrons, and their highly relativistic energies. As a result, the experimental platforms capable of simulating astrophysical conditions have so far been absent.

In the past few years, groundbreaking steps have been made using high-energy ultra-short laser pulses to make large numbers of positrons in a small volume [10]. It was found that laser-produced positrons have several characteristics that may prove essential for making a relativistic pair plasma.
The first is that intense lasers can make a very large number of positrons (10^{10} to 10^{12} per shot) in a short time (10 – 100 ps) [10]. This feature, in combination with the small volume (~mm^3) these positrons occupy, leads to a high density of positrons, even though only for a very short time. The second characteristic is that the target sheath field can accelerate these positrons to 10s of MeV, enabling positrons to be made and accelerated to the relativistic regime in one integrated process. The third characteristic is that MeV electrons and positrons produced from the laser-target interaction form overlapping jets behind the target, allowing much higher pair density to be achieved than it would be if the pairs were distributed isotropically.

Following these initial experiments that produced the high-flux jets of positrons with temperatures of MeV, we performed a new set of experiments focusing on understanding the physics of positron production, beam emittance of the jets, scaling with laser parameters and collimation. The new results show that the emittance of laser-produced positrons is 100 – 500 mm-mrad, comparable to that obtained at the Stanford Linear Collider [11]. The laser contrast was found to have a large effect on the positron yield [12]. The nonlinear scaling of positrons as a function of laser energy is evident when the laser energy is greater than 1000 J [13]. With plasma collimation, we hope to eventually use the multi-kilojoule, short-pulse laser systems worldwide, in combination with more advanced target designs, to create the first relativistic high-density pair plasmas in the laboratory - a completely novel system enabling detailed study of some of the most exotic and energetic systems in the universe [1-9].

2. Experiments and results

The new experiments were performed on the Titan and OMEGA EP lasers in the USA, as well as at the Osaka LFEX in Japan and AWE Orion laser in the UK. For the experiments discussed here, Titan produced 100-350 J in 1-10 ps, with 5-10 shots per day. At OMEGA EP, the laser energy was up to 1.3 kJ at pulse duration of 1-10 ps, with up to 14 shots a day. We used two beams of LFEX lasers at 1 ps, with up to 1.5 kJ per beam. One of the two ORION short pulse lasers was used with energy of 100-500 J in 0.5 ps. All experiment used lasers at fundamental frequency. The experiments were performed over a large range of laser parameters including the intensity (10^{18} – 10^{21} Watts/cm^2) and contrast (10^6 – 10^9). The data was grouped and compared under similar laser and target conditions.

2.1. Energy conversion

Using the LFEX laser at the Institute of Laser Engineering at Osaka University, we quantitatively investigated the production of high-energy particles and photons in the relativistic regime by observing electrons, positrons, x-rays, and photoneutrons simultaneously. The diagnostics for each observable were independently calibrated to determine the fraction of the laser energy converted to electrons, gammas and positrons [12]. The laser-to-electron conversion efficiencies are obtained from Laue diagnostic measurements of gold K\alpha and K\beta lines. The total gamma number and the energy transfer efficiency were inferred. The positron numbers and energies were measured directly using a magnetic spectrometer. The conversion efficiency from laser to electrons was 10-15%, laser to gammas (energy > 1 MeV) was ~ 0.2%, and laser to positrons ~ 0.002%. These measurements are consistent with the positron production occurring through Bethe-Heitler process [14], confirming our understanding of the laser pair generation physics.

2.2. Positron beam emittance

We performed the first measurements of the emittance of intense laser-produced positron beams on the Titan and OMEGA EP lasers [11]. Emittance is a basic parameter that describes the quality of particle beams and can be derived through measurements of beam divergence and source size. We measured these two parameters for different positron energies under various laser conditions. The divergence angle (full-width at half-maximum) was found to be 20 ± 6 degrees for laser energy of ~300 J at 10 ps (the positrons distribution was peaked at ~12 MeV); ~ 22 degrees for ~850 J, at 10 ps pulse duration, where the peak of the positron energy distribution shifted to ~18 MeV due to the higher laser energy. We found that both the positron beam divergence and source size varied as a function of positron
beam energy at the peak of its distribution. The source size varied between 800 and 400 µm for peak energies between 6.5 MeV and 16 MeV, respectively.

In summary, the laser-produced positrons have a geometric emittance between 100 - 500 mm-mrad, comparable to the positron sources used at existing accelerators. With $10^{10}$-$10^{12}$ positrons per bunch, this low-emittance beam, which is quasi-monoenergetic in the energy range of 5 – 20 MeV, may be useful as an alternative positron source for future accelerators.

2.3. Scaling

Preliminary experimental results from OMEGA EP show that the positron yield as a function of laser energy is not linear (Fig. 1) [13]. This is surprising, since, assuming that the fraction of absorbed laser energy is constant, one would expect the positron yield to be linearly proportional to the laser energy. Our result indicates that another physics parameter becomes important when the laser energy is higher than about 1 kJ. For example, simulations have shown that the electron reflux factor and the enhancement of the hot electron temperature appear to play a less important role at intensities in the range $10^{18} - 10^{19}$ W/cm², but can no longer be ignored when it is higher than $10^{19}$ W/cm², corresponding to laser energies higher than 1000 J.

2.4. Initial pair jet collimation by external magnetic fields

The ultimate goal is to confine the particles to make a relativistic charge-neutral electron-positron pair plasma. If successfully confined, the electron-positron plasma would offer a novel system to enable a detailed study of some of the most exotic and energetic systems in the universe. We performed initial experiments on the OMEGA EP laser system (at ~1 kJ over 10 ps), which were designed to collimate the positron jets produced in high intensity laser-plasma interactions. The targets were of 1-mm-thick gold. Previous experiments by this team have shown that quasi-monoenergetic relativistic positron jets with a beam divergence of 30° were formed during high-intensity interactions with thick gold targets [10]. The current experiments were designed to collimate the positron jet with an external magnetic lens. Using the recently developed magnetized-inertial fusion electrical delivery system (MIFEDS) [15], strong collimation of both positrons and electrons were observed. This results in a “near-pencil” beam with an equivalent beam divergence angle of 5°. The charge imbalance was reduced from ~100 (no collimation) to ~ 2.5 (with collimation), a significant step towards making a charge neutral electron-positron pair plasma in the laboratory. A jet of positrons and electrons was emitted from the rear side of the target. Between the target and the detector, MIFEDS coils produced peak magnetic field of about 7 Tesla.

Fig. 1: Number of positrons as a function of laser energy. Data shown are taken from two experiments (blue dots and green squares. The lines are drawn as guides. As a whole, the data cannot be well fit with a linear function.

Fig. 2: Raw image of positron data from three shots. One shot (top image) had no MIFEDS coil and the other two (middle and bottom images) with the coil at different location. The positron distribution peaked at ~13 MeV. The signal from the collimated beam is 30-40 times higher.
The collimated beams were measured with a magnetic electron-positron spectrometer. Without the external magnetic field, the peak densities are about $10^{13}$ and $10^{15}$ cm$^{-3}$ for positrons and electrons, respectively [10]. With the external B-field applied, a factor of $\sim 40$ increase in the peak positron signal was observed (Fig. 2).

3. Future plans
Building upon the progress as described in this paper, our next step is to attempt trapping the particles in order to create a pair plasma. This will be a very challenging task as the particle energies are relativistic and the particle flux is orders-of-magnitudes higher than that obtained from conventional sources such as radioactive isotopes. However, this is an important scientific topic that needs to be addressed as highlighted in the recently published report on “Basic Research Needs for High Energy Density Laboratory Physics” by the US Department of Energy [17]: “if and when we can produce them (relativistic pair plasma) in the laboratory, we would expect novel dynamics and matter-antimatter elementary thermal processes. The extreme electromagnetic fields and particle energies now accessible approach the edge of understood physics, with the forces acting on electrons exceeding past experimental and even theoretical considerations, including gravity.”

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