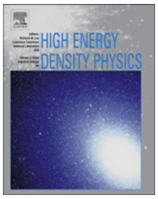
High Energy Density Physics 7 (2011) 225–229

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp



Towards laboratory produced relativistic electron–positron pair plasmas

Hui Chen[a,*], D.D Meyerhofer[b], S.C. Wilks[a], R. Cauble[a], F. Dollar[c], K. Falk[d], G. Gregori[d], A. Hazi[a], E.I. Moses[a], C.D. Murphy[d], J. Myatt[b], J. Park[a], J. Seely[e], R. Shepherd[a], A. Spitkovsky[f], C. Stoeckl[b], C.I. Szabo[e], R. Tommasini[a], C. Zulick[c], P. Beiersdorfer[a]

[a] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*
[b] *LLE, University of Rochester, Rochester, NY 14623, USA*
[c] *University of Michigan, Ann Arbor, MI 48109, USA*
[d] *University of Oxford, Oxford, UK*
[e] *Naval Research Laboratory, Washington, DC 20375, USA*
[f] *Princeton University, Princeton, NJ 08544, USA*

ARTICLE INFO

Article history:
Received 7 May 2011
Accepted 7 May 2011
Available online 13 May 2011

Keywords:
Positron
Picosecond laser

ABSTRACT

We review recent experimental results on the path to producing electron–positron pair plasmas using lasers. Relativistic pair-plasmas and jets are believed to exist in many astrophysical objects and are often invoked to explain energetic phenomena related to Gamma Ray Bursts and Black Holes. On earth, positrons from radioactive isotopes or accelerators are used extensively at low energies (sub-MeV) in areas related to surface science positron emission tomography and basic antimatter science. Experimental platforms capable of producing the high-temperature pair-plasma and high-flux jets required to simulate astrophysical positron conditions have so far been absent. In the past few years, we performed extensive experiments generating positrons with intense lasers where we found that relativistic electron and positron jets are produced by irradiating a solid gold target with an intense picosecond laser pulse. The positron temperatures in directions parallel and transverse to the beam both exceeded 0.5 MeV, and the density of electrons and positrons in these jets are of order 10^{16} cm^{-3} and 10^{13} cm^{-3}, respectively. With the increasing performance of high-energy ultra-short laser pulses, we expect that a high-density, up to 10^{18} cm^{-3}, relativistic pair-plasma is achievable, a novel regime of laboratory-produced hot dense matter.

1. Introduction

It is generally believed that electrons and their anti-particles, positrons, were created, along with other fundamental particles and anti-particles, in equal portions at the beginning of universe. While at present the observable universe is mostly made of particles (matter) instead of anti-particles, relativistic electron–positron pair plasmas are believed to exist extra -terrestrially in a wide range of astrophysical phenomena, including some of the most energetic events, such as out-spills of Black Holes, Active Galactic Nuclei, Gamma-ray Bursts and Pulsar Wind Nebulae [1–14]. Relativistic pair plasma interactions are hypothesized to play important roles in interpreting the energy mechanisms driving the magnetic field and radiation from these objects [5–14].

At low temperature, single-component positron plasmas, and non-neutral electron–positron plasmas have been studied extensively [15–17] in the laboratory, for example using the Penning-Malmberg traps. In the relativistic regime, a charge - neutral pair plasma has not yet been made at laboratory. “If and when we can produce them 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.” [18] With the increasing performance of powerful short pulse lasers, the creation of a relativistic pair plasma may soon be realized in the laboratory.

Electron–positron plasmas are generated using ultra-intense lasers as follows: When an intense laser impinges on a solid target, the laser electric and magnetic fields, via the $\mathbf{J} \times \mathbf{B}$ force, interact with free electrons in the coronal plasma that is generated by a laser prepulse interacting with the solid near the critical plasma density [19] A large fraction of the absorbed laser energy goe s into creating

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[*] Corresponding author.
E-mail address: chen33@llnl.gov (H. Chen).

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doi:10.1016/j.hedp.2011.05.006

electrons at energies greater than an MeV. These MeV electrons are the power source of pair generation that can take place via the Bethe-Heitler (BH) process [20] or the Trident process [20–22]. The BH process is a two-step process: first $e^- + Z \rightarrow \gamma + e^- + Z$; followed by $\gamma + Z \rightarrow e^- + e^+ + Z$, where γ is a bremsstrahlung photon and $\boldsymbol{Z}$ represents an atomic nucleus. That is, laser-produced hot electrons make high-energy bremsstrahlung photons that, in turn, produce electron–positron pairs upon interacting with the nuclei. In the Trident process, hot electrons produce pairs by directly interacting with the nuclei: $e^- + Z \rightarrow 2e^- + e^+ + Z$. It has been shown that BH process dominates for thick high-Z targets [22,23], while the Trident process plays a more important role for thin targets [22,24]. These positron-producing processes are in contrast to the direct process of pair creation by an ultra-intense laser, which creates pairs by the vacuum polarization caused by the strong electric field of the laser [25]. The threshold laser intensity for the direct process, which is also known as the Schwinger limit, is about 10^{28} Wcm^{-2}, which is beyond the capability of current laser technology, but has been observed in intense laser interactions with a 50 GeV electron beam [26].

First theorized in 1973 by Shearer et al. [27], the use of ultra-intense lasers to generate positrons has been studied through theory and modeling [27–32]. For example, Liang et al. in 1998 [24] proposed using an ultra-intense laser to create dense electron–positron plasmas by using a scheme of double illumination of thin targets to achieve a positron production rate of about 10^7/s. This scheme has not been realized experimentally due to the requirement for lasers to create the necessary conditions and the need for technology to measure these mechanisms. In 2005, Wilks et al. [30] presented a numerical study through insight gathered from PIC simulations, and postulated "that the electron–positron plasma leaves the creation region in dense jets, with relativistic energies". More recently, using analytical calculations that optimized target material and dimensions, Myatt et al. (2009) [32] reported that up to 10^{11} pairs could be produced from a kJ-class short-pulse laser, confirming that the production of a relativistic pair plasma is indeed possible given today's petawatt laser capabilities. Although efficiency estimates vary, approximately 10^{10} to 10^{11} positrons/kJ of laser energy are predicted, assuming various laser target conditions [22,30–32].

Experimentally, the ability of intense short laser pulses to create positrons in laser–solid interaction was first demonstrated on the Nova petawatt laser in 1999 by Cowan et al. [33] and later on a tabletop laser in 2000 by Gahn et al. [34], where small numbers of positrons were measured. An example of the Nova experimental result is shown in Fig. 1 from Ref. [33] for Au targets with thickness of 125 microns. In contrast, using gas-jets, which produced high energy electrons from a 2-mm-thick target, Gahn et al. were able to produce about 20–40 positrons/shot on a table-top laser by integrating over many shots. The maximum number detected was ~ 100 for a 4 MeV effective electron temperature, although a large number, i.e., 10^{11} positrons/kJ laser energy, was predicted [29] if one were to extrapolate Gahn's condition to a kJ laser energy. These previous experiments were performed about a decade ago, and were primarily limited by the laser availability and laser–solid interaction physics, which prevented the production of significant amount of positrons to make a pair plasma.

Much progress has been made in recent years. In this paper, we will review the recent experimental results, and then give perspectives on creating relativistic electron–positron pairs using intense short pulse lasers.

2. Recent experimental results

In recent years, we performed a series of experiments on the Titan laser at the Jupiter Laser Facility [35] at Lawrence Livermore National Laboratory. For the experiments described here, the Titan laser produced 100–400 J with pulse durations from 0.7 to 10ps at 1054 nm wavelength. With a focal spots on the order of 7–10 μm, the peak intensities reached as high as ~1 × 10^{20} W/cm^2. A ns-long laser pulse at 527 nm was available to fine-tune the preformed plasma condition on either side of the targets. We used two absolutely calibrated electron–positron–proton spectrometers [36,37] to measure, in a time-integrated fashion, the charged particles coming out of the target. We measured up to 2 × 10^{10} positrons [23] per steradian ejected out the back of ~mm thick gold targets. Fig. 2 shows positron spectra obtained from both Au and Cu targets. The lack of positron signal from Cu is due to the fact that in BH process, the positron yield varies as Z^4, where Z is the atomic number of the material. The signal from the low-Z targets helped to confirm the positron data and provided the background signal from other sources such as x-rays and gamma rays from the intense laser–target interactions.

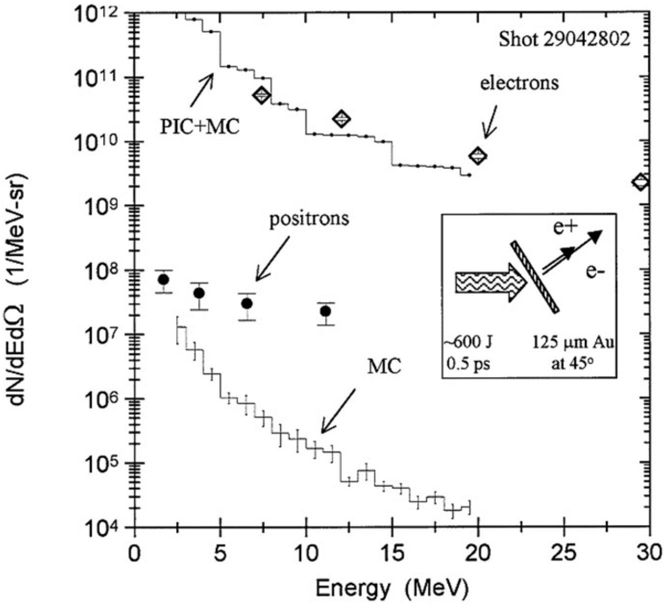

Fig. 1. (from Ref. [33]) Electron and positron spectra showing the number of positrons measured coming from rear of the target, at an angle of 30° to normal.

We found that the positrons were produced from an electron energy distribution that has 2-to-4- times higher electron temperature than predicted by ponderomotive scaling [23], a result from the laser interacting with an inhomogeneous low density preplasma. The contributing electron acceleration mechanisms are a combination of ponderomotive acceleration and self-phase modulated wakefield acceleration [30,38]. This experiment suggested positron densities inside the target to be ~ 10^{16} positrons/cm^3, among the highest created in the laboratory.

This initial success was followed by positron experiments on the Omega EP laser [39], performed by the collaborative team from LLNL and Laboratory for Laser Energetics (LLE). The Omega EP backlighter produced ~ 1 kJ in a 10-ps laser pulse that interacted with a 1-mm-thick Au target. Positrons emitted from the rear side of the target were measured with an electron–positron-proton magnetic spectrometer. A quasi-monoenergetic positron beam was observed with a maximum energy of ~ 18 MeV (Fig. 3) [40]. It is estimated that 10^{12} positrons were produced. The positron production rate during the laser shot appears to be the highest ever observed in the laboratory [40]. These data together with those obtained from Titan revealed the nature of positron acceleration to be the same as that of proton acceleration, namely sheath field