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Towards laboratory produced relativistic electron-positron pair plasmas

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ABSTRACT: This paper reviews 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.

PACS: 52.38.Kd, 52.38.Ph. Keywords: positron, picosecond laser.

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 extraterrestrially 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 the laser prepulse interacting with the solid near the critical plasma density [19]. A large fraction of the absorbed laser energy goes into creating >MeV electrons. These MeV electrons are the power source of pair generation which 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 $\boldsymbol{e^- + Z \prod \gamma + e^- + Z}$**;** followed by $\boldsymbol{\gamma + Z \prod e^- + e^+ + Z}$, 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: $\boldsymbol{e^- + Z \prod 2e^- + e^+ + Z}$**.** 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} $\mathrm{Wcm^{-2}}$, 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 [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 (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.

Significant 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.

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 duration from 0.7-10ps at 1054 nm wavelength. With a focal spot of about 7-10 μm, the peak intensities of Titan laser reached as high as ~$1x10^{20}$ W/cm^2. A ns-long laser beam at 527 nm was available to fine-tune the pre-formed 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 in a time-integrated fashion. We measured up to $2x10^{10}$ 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, 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.

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 of 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 acceleration [41]. Furthermore, we found these relativistic positrons to be quasi-monoenergetic, and controllable via manipulating the laser and target parameters [42].

To transition relativistic electron and positron beams into a relativistic pair plasma, a few basic criteria need to be fulfilled. The pair density and temperature need to be such that there are a sufficient number of particles (>>1) inside the Debye sphere. The energy distribution of the plasma needs to be in the relativistic regime - this requires the temperature of the pairs to be great then 0.511 MeV. Finally, ideally, the plasma should process quasi-neutrality, although a single-component plasma, or non-neutral plasma can also be very useful and have been widely studied [15-17].

In the relativistic regime, the definition of Debye length is (in Gaussian cgs units) $\lambda_D=(\gamma^2 k_B T/(4\pi q^2 n))^{1/2}$ cm, where T is the plasma temperature, n the density, q the charge, k_B is Boltzmann's constant, and γ the relativistic scaling factor. Assuming a plasma with temperature of 1 MeV, density of 10^{14} cm^{-3}, and γ equal to 2, the Debye length is about 1 mm, and the number of particles inside the Debye sphere is about 10^{11}. Under these conditions there will be enough particles inside the Debye sphere. As explained below, we are approaching these conditions experimentally.

We have found unique characteristics of laser-produced positrons that may prove essential for creating relativistic pair plasmas in the laboratory. First, the laser-produced positrons are accelerated by the target sheath field to tens of MeV energies. This feature allows positrons to be created and accelerated to the relativistic regime in virtually one integrated process. Typical positron spectra for different targets and laser intensities are shown in Fig. 5 (from [42]). The high positron energies are due to acceleration by the sheath field at the rear of the target [42] which is established by the initial hot electrons escaping the target and the resulting electron cloud that then forms around the target. The existence of this field has been confirmed by proton and positive ion acceleration [41]. Since there are several orders of magnitude more electrons than positrons, the positrons play no role in the sheath formation. As the hot electrons that are responsible for the potential leave the target, it takes less than a few tens-of-femtoseconds to build up a MV/μm field on the rear target surface [43]. The majority of the positrons born inside the target pass through this sheath field as they leave the target, gaining energy equal to the electrostatic sheath potential.

The second characteristic that helps making a pair plasma is that the laser produced relativistic electrons and positrons form a jet behind the target [42]. For a finite number of pairs, the pair density is much higher in a jet than it would be if the pairs were isotropically distributed. The measured angular distributions of electrons and positrons from Titan experiments are shown in Fig. 5. The physics that determines the angular distribution of the fast electrons and positrons are different from that of the positrons. Fast electrons accelerated from the plasma in front of the target are directed primarily along the laser axis, driven by the **J**×**B** forces along the laser propagation direction as well as by the resonant and Brunel absorption mechanisms that drive electrons normal to the target. The positrons, which are created deep inside the target, by the > 1 MeV radiation from the energetic electrons, carry some of the forward momentum of the "parent" fast electrons forming an initially anisotropic distribution. Once outside the target, the positrons are further accelerated by the sheath electric field reshaping the positron distribution.

We inferred the temperatures of the electrons and positrons from the experimental data [42]. For example, for the case of Omega EP data shown in Fig. 3, the longitudinal temperature is about 4 MeV for positrons and 7 MeV for electrons, and transverse temperature is about 2 MeV for positrons and 3 MeV for electrons. Furthermore, given the divergence angle, and the laser spot size, we can estimate the density of the electrons and positrons. For the duration of 10 picoseconds (laser duration), these relativistic electrons and positrons occupy a volume of $\sim 3\times 10^{-3}$ cm^3, from which a positron density of $\sim 10^{13}/cm^3$ and electron density of $\sim 10^{15}/cm^3$ are inferred. These temperature and density parameters are close to those needed to fulfill the criteria of *sufficient number of relativistic particles (>>1) in a Debye sphere*.

The non-neutral, relativistic, pair jet described above is transient in nature. Although it may be sufficient to study some dynamics of plasma interaction, in for example, the process of creating collisionless shocks [12-14], it is often desirable to have a stationary plasma where instabilities unique to the electron-positron plasma may be observed [44]. Myatt *et al.* [45] studied the possibility of using a mirror confinement for the pair plasma confinement. If realized, it would be a great advance in this field.

It is clear that we are making progress towards producing quasi-neutral electron-positron jets. A couple of methods, described in the next may be used to realize a quasi-neutral pair plasma.

THE PATH TOWARDS AN ELECTRON-POSITRON PLASMA

To achieve quasi-neutrality, the densities of electrons and positrons need to be about equal in the volume of their co-existence. At the present, the electron density is about three orders of magnitude higher than the positron density. One straightforward approach to get close to charge neutrality would be to keep the same yield but reduce the volume of the positron beam. Given that positrons experience the target sheath field [42] like protons, one may use similar methods of focusing protons [19, 46] on focusing positrons to increase the positron density.

Secondly, the existing experimental data show that the positron yield is generally proportional to the laser energy; thus increasing the laser energy may result in a larger pair density. Figure 6 shows the data obtained at the Titan laser and Omega EP as a function of laser energy up to 0.8 kJ. Scaling of the data suggests that the number of positrons could approach that of the electrons for laser energies of about 5 kJ, which may allow the generation of a pure, quasi-neutral electron-positron pair plasma. This is a very exciting possibility, and we will perform experiments and simulations to further understand the physics behind such scaling. The Omega EP laser facility has recently made available higher laser energies, up to 1.5 kJ per beam. We plan to do additional experiments at Omega EP using higher laser energies. We might be able to reach the "charge neutral pair plasma" threshold of about 5 kJ with the NIF ARC laser that is under development [47].

In summary, our recent experimental work suggests that in the near future relativistic pair plasmas will be made on Earth using powerful short pulse lasers. Once achieved, it will open many new areas of research, particularly in laboratory astrophysics research. Figure 7 shows existing antimatter plasmas at various temperatures and densities. Laser-generated antimatter plasmas may offer the first opportunity to approach the parameter space of many astrophysical events.

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FIGURE CAPTIONS

Figure 1: (from [33]) Electron and positron spectra showing the number of positrons measured coming from rear of the target, at an angle of 30 degrees to normal. Higher numbers of positrons are expected at smaller angles.

Figure 2: Positron spectra from Au and Cu targets. The absence of a positron signal from the Cu target is due to its lower atomic number since positron yield scales as Z^4.

Figure 3: Positron spectrum measured on the OMEGA EP laser system.

Figure 4 (From [39]): Positron energy distributions for six laser shots labeled A through F. The target and laser conditions are listed. Shots A-E were from the Titan laser and Shot F from the OMEGA EP laser. All spectra were obtained with the EPPS normal to the back of target.

Figure 5 (From [39]): Normalized total positron number ejected from the back of targets at various angles for 1-mm-thick, 6.4-mm-diameter targets irradiated by a 1-ps, 130-J laser (Shot B in Fig. 4). The data (red dots with error bars) are fit (black) with a Gaussian function. The result for the electrons is shown in the inset which includes both EPPS data (red squares) and data from radiochromic film (green dots). It was not possible to measure positrons for angles between –60º and –20º due to the laser beam layout.

Figure 6: The experimental scaling of detected electron and positron yield with laser energy. The green region is the LLNL Titan laser and blue is OMEGA EP. Linear extrapolation suggests that an equal number of electrons and positrons may be achieved at laser energy around 5 kJ, well within the capability of NIF ARC laser.

Figure 7: The densities and temperatures from laboratory antimatter (electron-positron) plasmas and some astrophysical objects. The temperature in the relativistic case refers to the bulk lorenzt factor of the plasma.

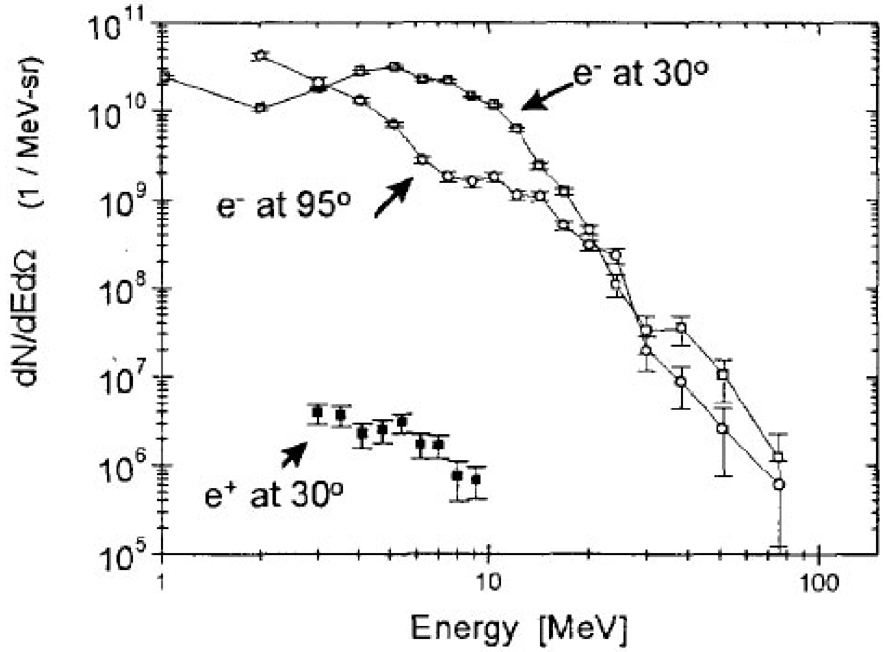


Figure 1

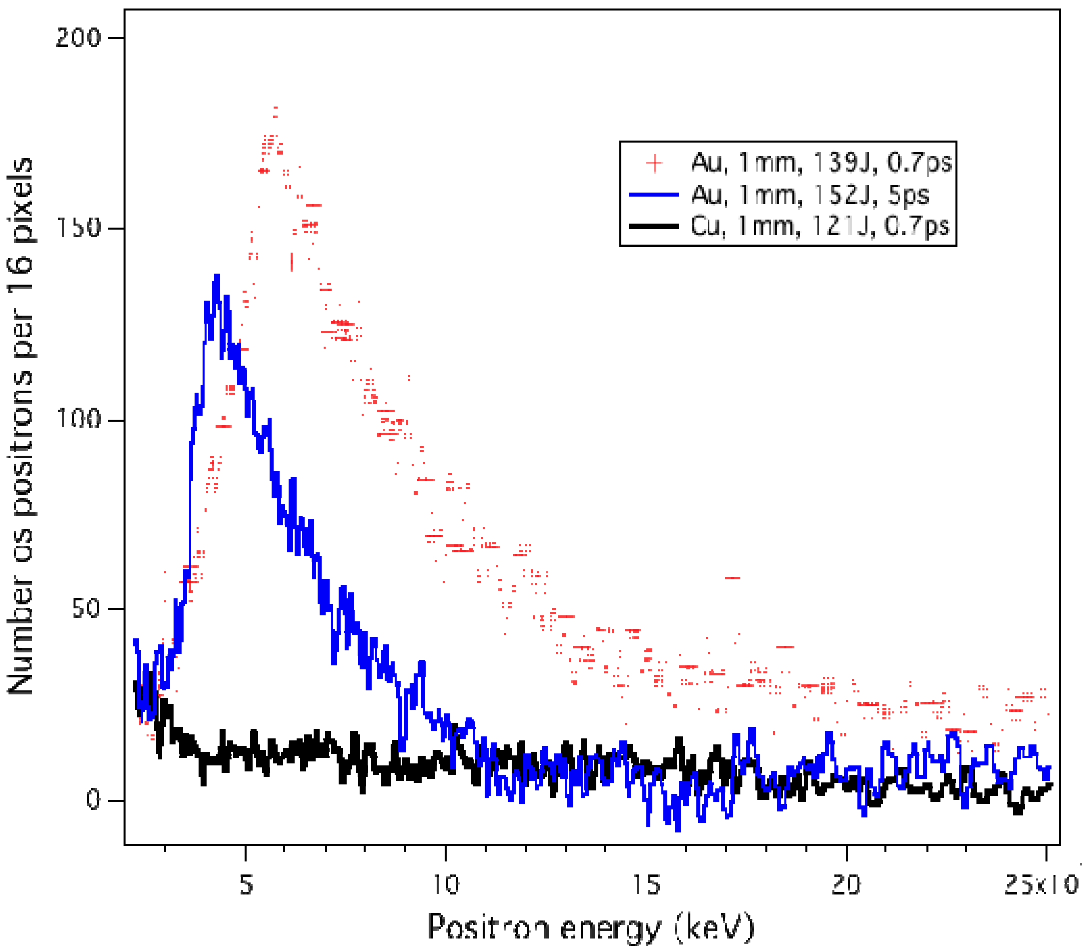

Au, 1mm, 139J, 0.7ps
Au, 1mm, 152J, 5ps
Cu, 1mm, 121J, 0.7ps
Number as positrons per 16 pixels
Positron energy (keV)
0
50
100
150
200
5
10
15
20
25x10³

Figure 2

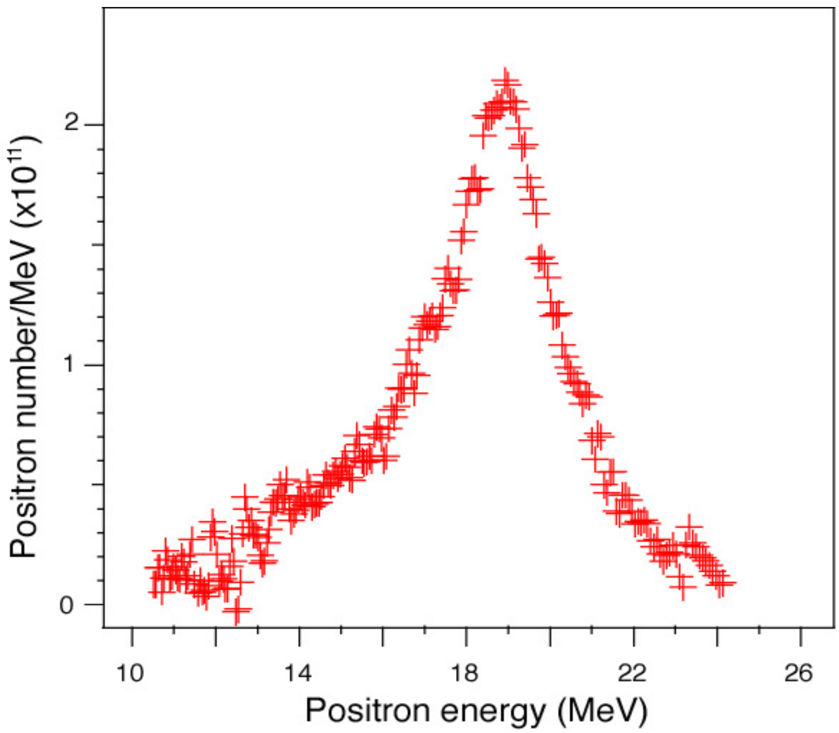

Positron number/MeV (x10^{11})
0
1
2
10
14
18
22
26
Positron energy (MeV)

Figure 3

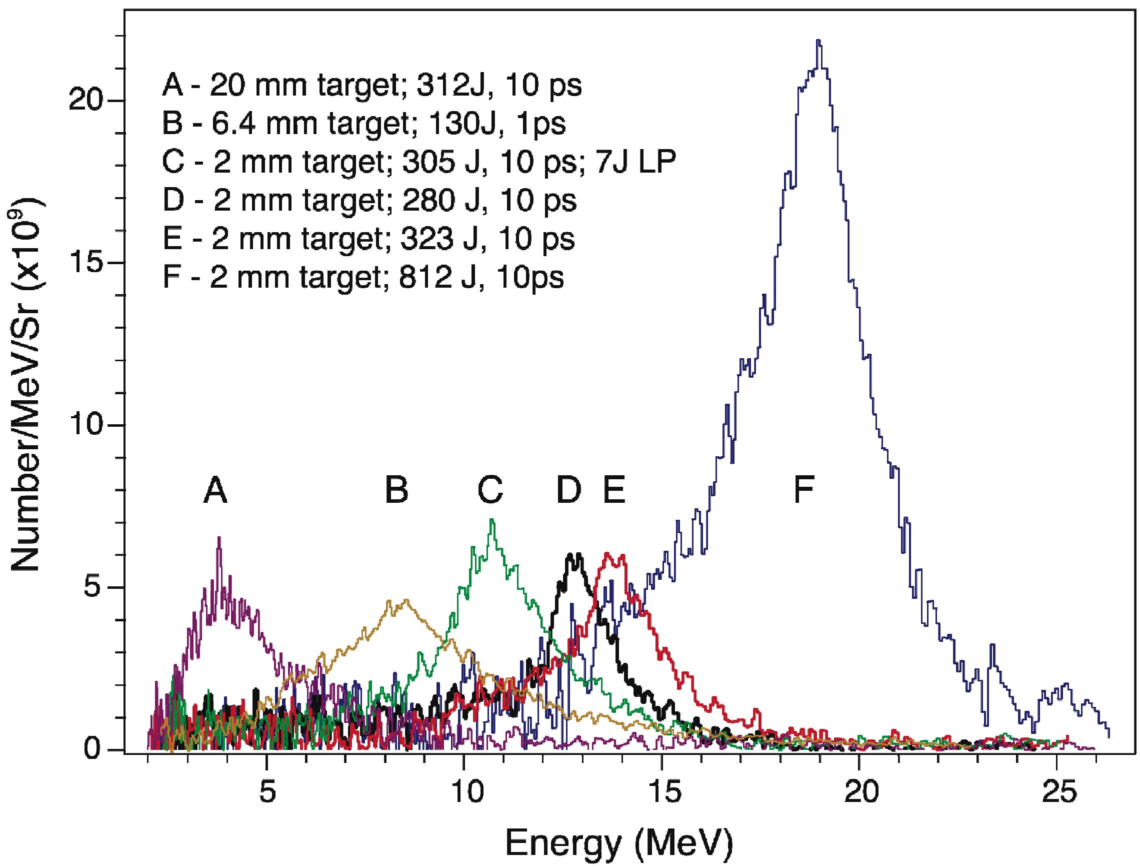
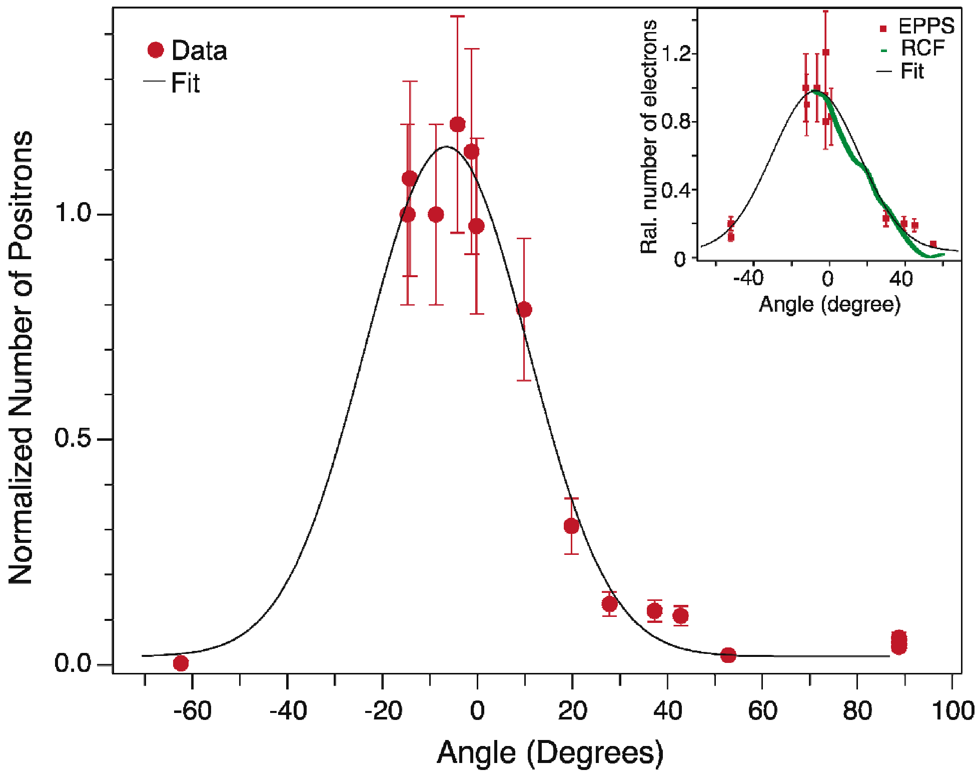
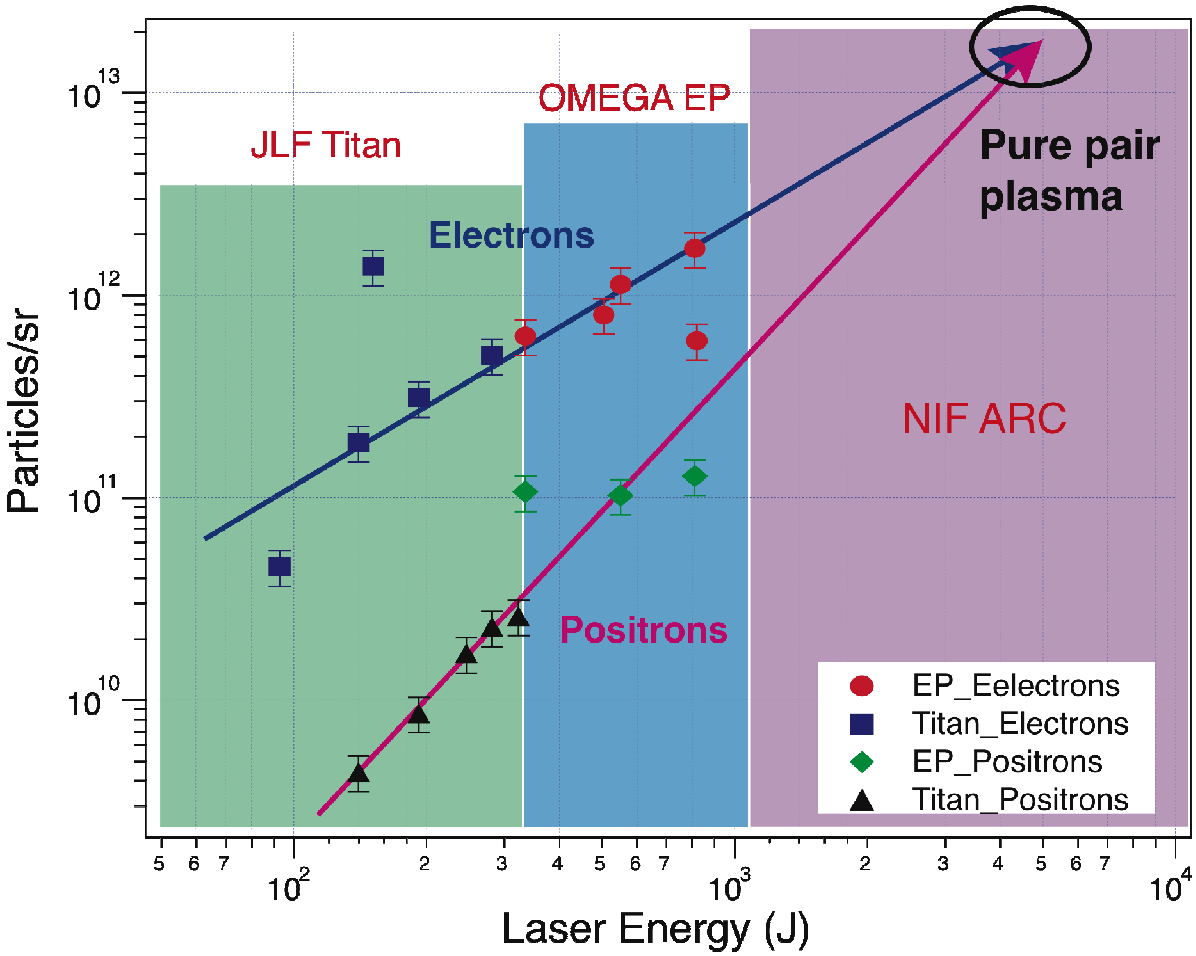

A - 20 mm target; 312J, 10 ps
B - 6.4 mm target; 130J, 1ps
C - 2 mm target; 305 J, 10 ps; 7J LP
D - 2 mm target; 280 J, 10 ps
E - 2 mm target; 323 J, 10 ps
F - 2 mm target; 812 J, 10ps
A
B
C
D
E
F
Number/MeV/Sr (x10^9)
Energy (MeV)
0
5
10
15
20
25

Figure 4



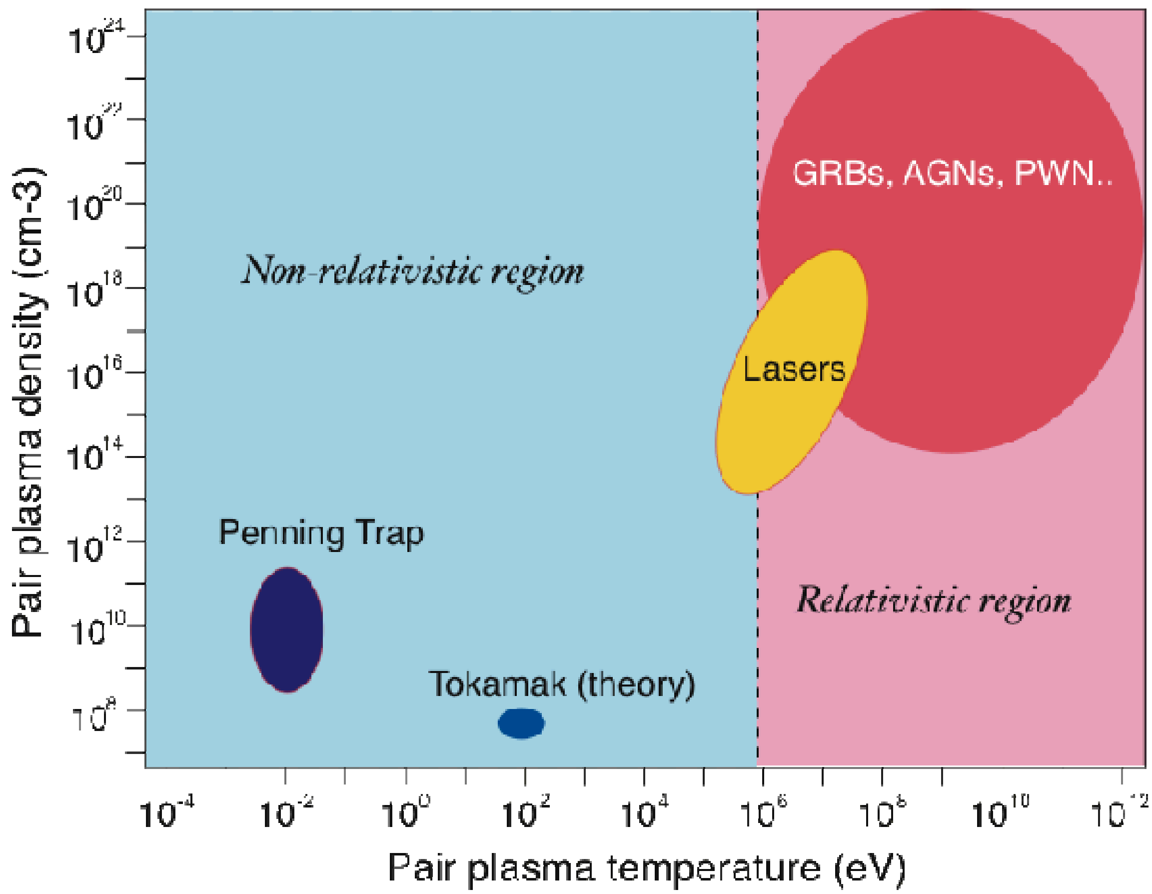
Data
Fit
Normalized Number of Positrons
1.0
0.5
0.0
-60
-40
-20
0
20
40
60
80
100
Angle (Degrees)
EPPS
RCF
Fit
Ral. number of electrons
1.2
0.8
0.4
0
-40
0
40
Angle (degree)

Figure 5



OMEGA EP
JLF Titan
Pure pair plasma
Electrons
NIF ARC
Positrons
EP_Eelectrons
Titan_Electrons
EP_Positrons
Titan_Positrons
Particles/sr
Laser Energy (J)

Figure 6



Pair plasma density (cm-3)
Pair plasma temperature (eV)
Non-relativistic region
Relativistic region
GRBs, AGNs, PWN..
Lasers
Penning Trap
Tokamak (theory)

Figure 7