White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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Oral	
Poster	
Either Oral or Poster	
Will not attend	

Title:	RELATIVISTIC PAIR PLASMA JET CREATION AND INTERACTION USING SHORT-PULSE LASERS
Corresponding Author:	Hui Chen
• Institution:	Lawrence Livermore National Laboratory
• email:	chen33@llnl.gov
Co-Authors:	F. Fiuza (SLAC), D. D. Meyerhofer (U. Rochester)

**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

Relativistic electron-positron pair plasmas exist in many astrophysical objects and are important to explain energetic phenomena related to Gamma Ray Bursts (GRBs), Active Galactic Nuclei (AGN), and black holes (BHs) [Fermi 1949, Bell 1978, Blandford 1978-1987, Meszaros 2002, Wardle 1998, Spitkovsky 2005-2011, Weidenspointner 2008]. Experimental platforms capable of producing relativistic pairs plasmas could have a great impact in our understanding of the basic plasma physics behind these astrophysical objects. However, this effort presents important challenges associated with producing a high density of pairs, the short lifetime of positrons, and their highly relativistic energies.

The advent of new, more powerful lasers, is opening new possibilities to create relativistic electron-positron pair jets and plasmas in the laboratory. It is an important challenge to understand how to use high-power lasers to create such extreme relativistic plasmas that display conditions relevant for the study of astrophysical environments and how to control and diagnose these pair plasmas. We have made substantial progress in these areas in the last few years. The success of this research can significantly impact the high energy density plasma physics and plasma astrophysics fields. It will also play an important role in a range of antimatter science and applications such as accelerator technology and new plasma diagnostics.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Electron-positron jets are generated using ultra-intense lasers, as follows: when an intense laser illuminates a solid target, the laser electric and magnetic fields (via the JxB force) interact with free electrons in a coronal plasma that is generated via the laser prepulse interacting with the solid near the critical plasma density. The majority of the absorbed laser energy goes into creating >MeV electrons. These MeV electrons are the power source of pair generation. Two relevant positron production processes are the Bethe-Heitler (BH) process [Heitler 1954] (which dominates for thick high-Z targets, positron generation, [Chen PRL 2009] and the Trident process [Heitler 1954, Gryaznykh 1998 and Nakashima 2002] which is more important for thin targets (less than 30 microns for solid gold, [Liang 1998]). In the BH process, the laser produced hot electrons make high energy bremsstrahlung photons that produce electron-positron pairs upon interacting with the nuclei, while in the Trident process the hot electrons produce pairs by directly interacting with the nuclei (Fig. 1a). This is in contrast to the direct Breit-Wheeler process of pair creation, which requires ultraintense lasers beyond the current capability.

We have shown experimentally that jets of mega-electron-volt (MeV) positrons and electrons can be made in a small volume (< 3 mm^3) using high-energy ultra-short lasers interacting with solid, high-Z targets [Chen PRL09, 10, HEDP 2011]. 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) [Chen PRL 2009]. 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 sheath field created on the rear surface of the target can accelerate these positrons to 10s of MeV [Chen PRL 2010], enabling positrons to be made and accelerated to the relativistic regime in an integrated process (Fig. 1b). 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. In addition, the emittance of laser-produced positrons has been measured to be 100 – 500 mm-mrad, comparable to that obtained at the Stanford Linear Collider [Chen POP 2013]. Table 1 summarizes the parameters presently achieved in pair jet experiments in the context of values desired for astrophysically relevant experiments. While jets of sufficient temperature and duration have been produced, present experiments have not yet produced sufficiently dense beam of positrons to achieve a near-unity ratio between the densities of electrons and positrons. The primary goal for future research is to increase the positron density, establishing a viable experimental platform for using laser-produced pair jets in astrophysical applications (Fig. 3).

Creating pair jets that would allow the experimental study of astrophysically relevant processes, such as magnetic field generation, amplification, and annihilation in pair plasmas will require about an order of magnitude larger laser energy than is currently available [Chen POP 2015]. Such a laser would produce about 100 times more positrons and 10 times more electrons than current facilities (Fig 2a), and these higher yields would be comparable to those needed for laboratory astrophysics experiments (Fig.2b). In fact, a new generation of intense high energy lasers, including NIF ARC [Crane 2010], Gekko LFEX [Shiraga 2011] and LMJ PETAL [Batani 2014], are being constructed to deliver about 10 kJ at 1-10 ps pulse durations. These are expected to be available for experiments in the next few years.

Parameter	Current experimental range	Desired for astrophysics relevant experiments
$T_{//}$	0.5–4 MeV	~MeV
$T_{\perp}$	0.2–1 MeV	~MeV
n_{e+}	**$\sim 10^{11-13}$ cm^{-3}**	$>10^{14-16}$ cm^{-3}
n_{e-}	$\sim 10^{12-15}$ cm^{-3}	$>10^{14-16}$ cm^{-3}
τ_{jet}	5–20 ps	>10 ps

Table 1. Parameters of laser produced electron-positron jets relative to those needed for laboratory astrophysics experiments. The principal shortfall is highlighted in bold. [from Chen et al., POP (2015)]

Secondly, magnetic collimation of the relativistic pair jets is needed to increase the density in a larger volume. At present, although very high positron and electron densities are achieved near the back of the target, in the absence of collimation the pair density rapidly declines as the jet propagates away from the target. To maintain the high pair density achieved over a longer propagation distance (larger volume), it is important to pursue the development of magnetic fields to collimate and focus the pair jets. The effectiveness of magnetic collimation has been demonstrated [Chen POP 2014] in experiments at Omega EP, in which a relativistic pair jet with ~15 MeV peak energy was collimated using magnetic fields from an external, pulsed Helmholtz-type coil. Further experiment techniques are needed to collimate higher energy pairs that would need magnetic field strengths higher than 10's of Tesla. Options for achieving this include laser-produced magnetic fields.

Lastly, we need to develop techniques for relativistic pair plasma confinement. While unconfined dense pair jets are expected to be very useful for laboratory astrophysics (to initiate instability growth through jet-jet, or jet-plasma interactions), it is important to have the pair plasma confined for studies of phenomena that take longer than 10's of ps to develop, such as magnetic reconnection. To capture and confine relativistic pair jets, the magnetic "mirror" geometry [Wesson 2011], established over decades of magnetic confinement fusion research, may be used. Relative to conditions in magnetic fusion plasmas, as well as low temperature/energy single component positron plasmas, the key features of confined relativistic pair plasmas are very short time scales (sub nano-second), relativistic energies (> MeV) and densities up to 2 orders of magnitude greater than in conventional magnetically confined fusion plasmas. However, with the rapid development of transient high magnetic field generators using lasers and pulsed-power devices, mirror-confined relativistic pair plasmas may be realized in the laboratory in the near future.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

Studying electron-positron pair plasma is one of the most fundamental yet challenging topic: *"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."* The success of this project will greatly impact the high energy density plasma physics, as stated in a recent review report: *"Because of the unity mass ratio, pair plasmas behave differently from electron-ion plasmas in many respects. It is extremely desirable to study pair plasmas in the laboratory, both for the fundamental physics and for astrophysical applications"* [ReNew Report, 2010].

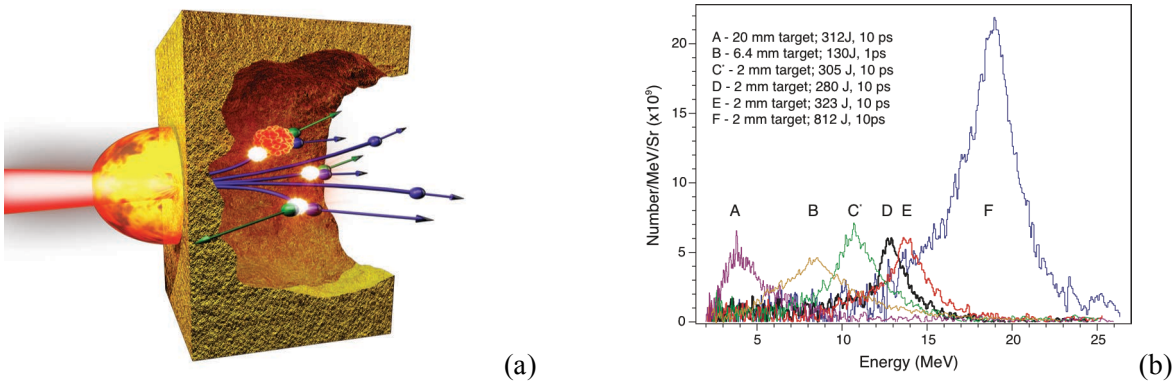

Figure 1: (a) Illustration of relativistic pair generation using short pulse lasers and gold target; and (b) sample energy spectra of positrons from various experiment [Chen PRL2010].

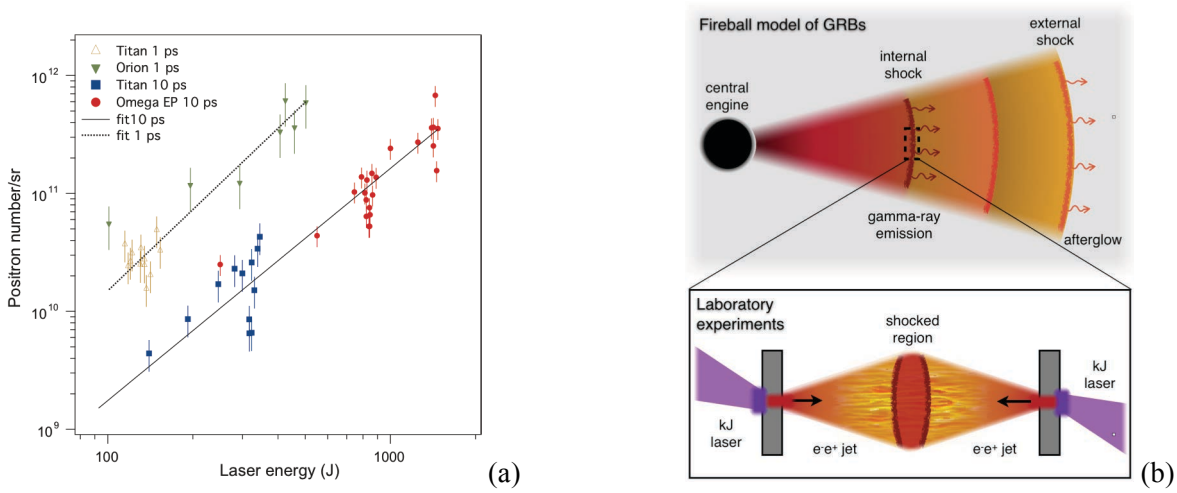

Figure 2: (a) Positron yield scales as the square of laser energy [Chen PRL2015]. (b) Laboratory colliding pair jets could mimic the physics processes in fireball model of gamma-ray bursts.

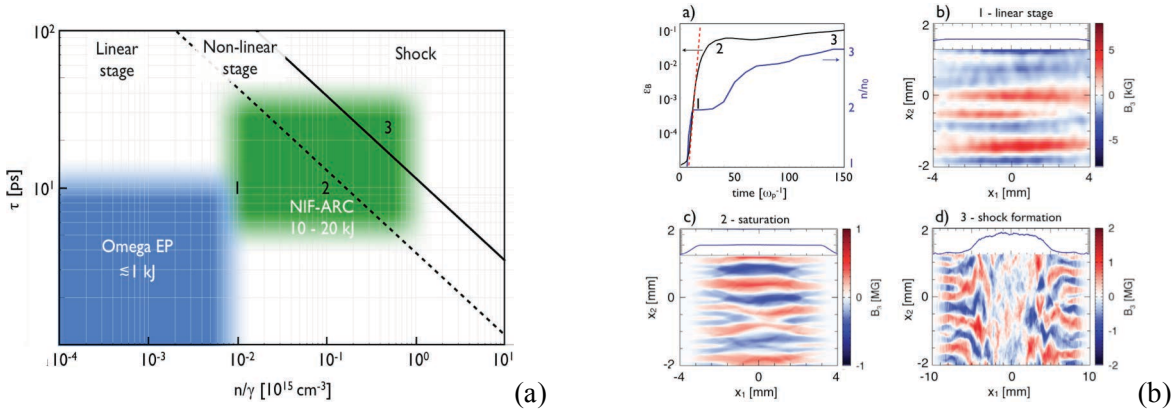

Figure 3: (a) Counter-streaming relativistic pair plasmas using 1-20 kJ lasers can access three stages of magnetic field evolution and shock formations found from PIC simulation (b) [Chen&Fiuza PRL 2015].

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