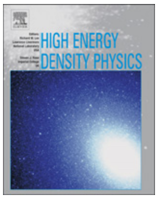
High Energy Density Physics xxx (2010) 1–4

Contents lists available at ScienceDirect

High Energy Density Physics

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



Intense laser pair creation and applications

Edison Liang

Q1 *Rice University, United States*

A R T I C L E I N F O

Article history:
Received 26 January 2010
Received in revised form
26 January 2010
Accepted 26 January 2010
Available online xxx

Keywords:
Relativistic pair production
Ultra-high intensity lasers

A B S T R A C T

We summarize recent results on pair creation using ultra-intense lasers and their potential applications to astrophysics and positronium physics.

1. Introduction

Relativistic electron–positron (e+e−) pair plasmas are believed to be ubiquitous in the high-energy universe, from the first few seconds of the Big Bang, to the winds of pulsars, jets of blazars and gamma-ray bursts (GRBs). The physics and manifestations of this exotic state of matter, however, have been relatively unexplored due to the lack of laboratory experiments. This situation is changing dramatically due to the advance of ultra-intense lasers that are capable of producing copious amount of multi-MeV e+e− pairs in the laboratory with densities exceeding 10^{16} cm^{-3} [1] and magnetic fields exceeding 10^9 G [2]. The creation of such exotic high energy density (HED) pair plasmas will undoubtedly open up entirely new frontiers in both laboratory astrophysics and basic plasma science. In this paper we briefly review the laser pair production processes and potential applications of laser-produced pair plasma.

2. The astrophysics context

Relativistic e+e− plasmas have been postulated as a major, perhaps the dominant, component of matter in pulsar magnetospheres, pulsar winds (PW), quasar jets and gamma-ray burst (GRB) outflows. While there is yet no direct observational evidence to confirm the presence of e+e− pairs (e.g. detection of 511 keV annihilation line), energetic and kinematic arguments strongly support the omnipresence of pair plasmas in the high-energy universe. Their dominance is also built into most popular theoretical models of these objects. For example, the dynamics and radiation output of pulsar wind and wind nebula are sensitive to pair loading. Similarly most GRB scenarios and many blazar models invoke pairs in the outflows. Yet both the microphysics of e+e− plasma kinetics (particle energization, radiation mechanisms, shock structure) and macro-dynamics of e+e− MHD outflows have only been explored recently, as computational technology (relativistic MHD and Particle-in-Cell codes) and computer power have reached the necessary capability. However, even with the most advanced supercomputers and algorithms, such numerical simulations are limited to small physical scales, idealized geometries and initial conditions, far from the dynamic range needed to address many critical astrophysical questions. It is therefore extremely desirable to be able to study at least some aspects of relativistic pair plasmas in controlled laboratory experiments, to search for scalable properties and physical laws that may be applicable to astrophysics, and to calibrate the numerical codes.

Hence a central question is whether results from laboratory created pair plasmas can be scaled to the astrophysical realm. It turns out that in the relativistic collisionless pair-dominated regime, the microphysics is controlled by a small number of dimensionless parameters. These include $\langle\gamma\rangle$ or kT/mc^2, Ω_e/ω_{pe} and $\lambda\omega_{pe}/c$ where λ is the characteristic size scale of the plasma or magnetic field. PIC simulations confirm that systems of very different sizes, for which these parameters are identical, exhibit similar microphysical properties and behaviors. Hence laboratory created pair plasmas can serve as useful platforms to study the microphysics of astrophysical plasmas.

3. Recent experiments

Conventional methods of achieving a significant density of positrons in the laboratory rely on collecting and trapping

---

E-mail address: liang@spacibm.rice.edu

1574-1818/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.hedp.2010.01.012

Please cite this article in press as: E. Liang, Intense laser pair creation and applications, High Energy Density Phys. (2010), doi:10.1016/j.hedp.2010.01.012

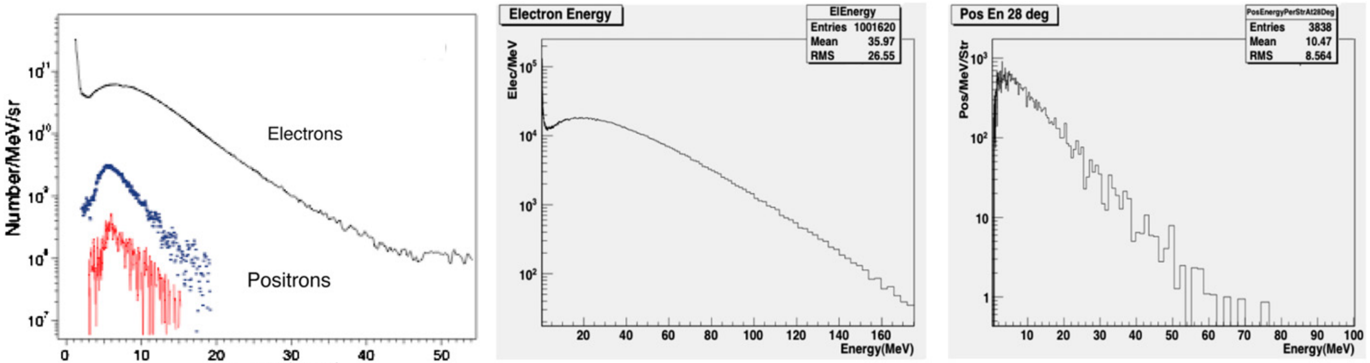


Fig. 1. GEANT4 simulated spectra of emergent electrons (middle) and positrons (right, Ref. [10]) agree qualitatively with Titan laser-produced electrons and positrons (left, from Ref. [1]).

radioactive decay or accelerator-produced e+ in magnetic traps. However, Coulomb repulsion limits the density one can achieve with such traps. Also since such trapped e+ are cold, they annihilate rapidly when encountering any e− so it is difficult to produce e+e− plasmas of any significant density. However, recent advances in ultra-intense lasers changed the landscape. Lasers with intensity $> I_c = 2\times10^{18}$ W cm^{-2} couple most of its energy to target electrons with a characteristic temperature of kT/mc^2 ~ $\lambda I^{1/2}$ when λ is wavelength measured in microns and I is measured in units of I_c. Hence for laser intensities $>10^{19}$ W cm^{-2}, easily achievable with modern short pulse lasers, most of the laser energy can be converted into relativistic electrons above the pair production threshold. When such electrons collide with high-Z target ions such as Au or Pt, they pair-produce via the Trident and Bethe–Heitler [3] processes. Estimates by several groups using laser intensity $\geq10^{20}$ W cm^{-2} irradiating Au targets suggest that in-situ pair density $\geq10^{18}$ cm^{-3} may be achievable [4,5]. The first PW laser experiment producing significant numbers of pairs was performed by Cowan et al. [6], though the pair yield was rather low ($\sim10^{-4}$/hot electron). Liang [7] proposed much higher pair density may be achievable in principle using double-sided irradiation. Other proposals involve using circularly polarized lasers, pre-compressing the high-Z target, and using the laser wakefield acceleration mechanism [8] to make MeV electrons in a gas jet before converting them into pairs via separate high-Z target [9]. A major milestone was achieved recently by Chen et al. [1] using the Titan laser at LLNL irradiating thick (~mm's) gold foils. They found pair yields up to several percents which increase with thickness according to the Bethe–Heitler formula. This suggests that with more powerful lasers (NIF-ARC) the maximum pair yield may exceed $\sim10^{12}$ e+/kJ of laser energy and the in-target pair density may exceed $\sim10^{18}$ cm^{-3}.

In order for the emergent pair cloud to constitute a “plasma” it should be much larger than the skin depth. For a pair cloud size ~100’s of microns, this requires an initial pair density $n > 10^{17}$ cm^{-3}. We note that for laser intensities exceeding 10^{30} W cm^{-2}, pairs can be produced directly by vacuum breakdown. However, that kind of laser intensity is not yet available in the near future. In addition to creating pairs, intense laser–target interactions also produce ultra-strong fields that can exceed 10^9 G [2]. The relation between strong field generation and pair creation has not yet been studied, but it is conceivable that some created pairs will be imbedded in strong fields. Once strongly magnetized pair plasmas are created in the laboratory, they can be used to study many aspects of major astrophysics problems, from collisionless shocks to GRB jets, as well as many basic plasma physics questions. Each astrophysical problem will likely require a different experimental setup and a different set of diagnostics.

4. GEANT4 simulations

To model the Titan experiments [1], we have simulated the pair production processes in thick gold targets using the CERN code GEANT4 [10]. These Monte Carlo simulations gave excellent agreements with observed positron data for targets up to 1 mm, see Fig. 1. However, for targets much thicker than 1 mm, GEANT4 predicts emergent positron to electron ratios higher than those observed in Titan results. This discrepancy is likely due to low energy physics of electron and positron attenuation and secondary electron productions missing in the code, and remains to be resolved.

5. Scaling of positron yield and e+/e− ratio

With increasing laser energies we expect the positron yield to increase. Fig. 2 shows the current projections of the positron yield for TPW, Omega-EP and NIF. Preliminary Omega-EP results [11]

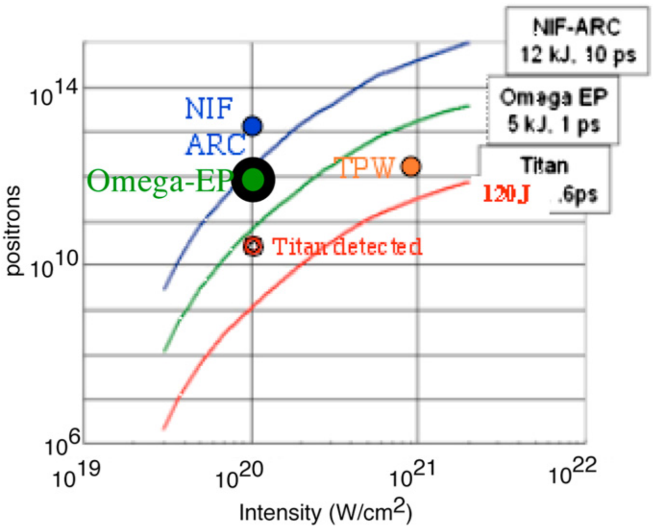


Fig. 2. Positrons generated by various high intensity lasers. Revised scaling of positron yield per laser pulse for TPW, Omega-EP and NIF-ARC based on Titan results. The Titan data suggest that NIF-ARC can exceed positron productions of 10^{13}. The curves were based on previous results before Titan experiments.

Please cite this article in press as: E. Liang, Intense laser pair creation and applications, High Energy Density Phys. (2010), doi:10.1016/j.hedp.2010.01.012

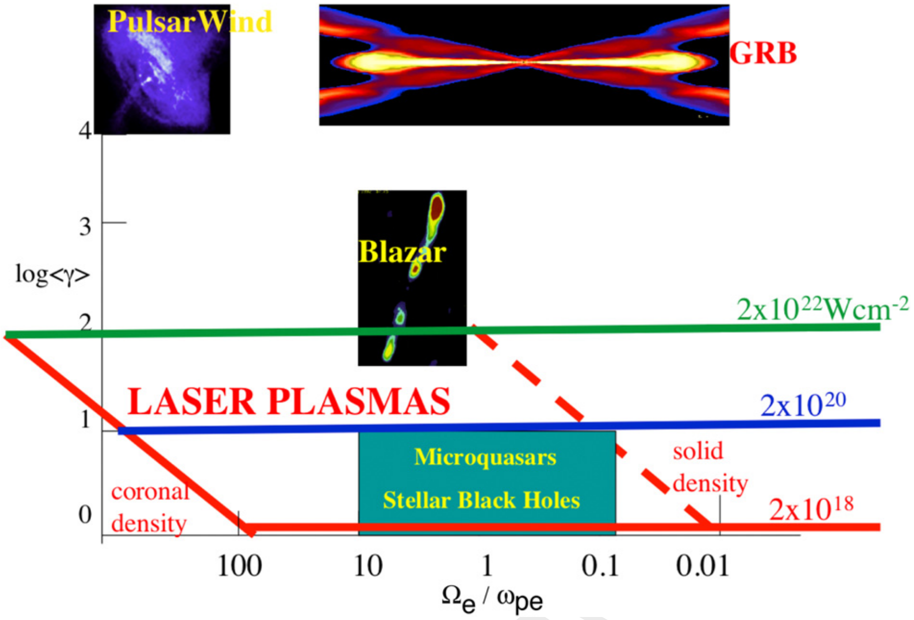


Fig. 3. Phase space of laser-produced pair plasmas overlap with those of many astrophysics regimes. γ = internal Lorentz factor. Ω_e = electron gyrofrequency. ω_{pe} = electron plasma frequency.

seem to support these scaling relations. If this scaling holds up, then we expect NIF-ARC beams to easily exceed 10^{13} pairs per pulse and a peak pair density of 10^{18} cm^{-3}. These results are interesting for both astrophysical applications and the creation of dense positronium gas.

Fig. 1 shows that in the Titan experiments, the maximum emergent e+/e− ratio is only a few percent. Such plasmas are far from being pair dominated. To simulate many astrophysical phenomena, it is desirable to achieve much higher e+/e− ratio. One can first try to magnetically separate the e− from e+ and then re-inject a small fraction of the e− to form a pair plasma.

But such processes take time and dilute the pair density. Recent GEANT4 simulations [10] suggest that for targets thicker than ~8 mm (however the pair yield/kJ peaks around 5 mm), the emergent e+/e− ratio may exceed 80% due to the fact that the incident and secondary electrons are more heavily attenuated than the positrons which are created by bremsstrahlung gamma-rays closer to the back surface. Moreover, the emergent e+ and e− have different time profiles and spectra. Hence almost pure MeV pair plasmas may in principle be created from very thick targets with time and energy selection. Such results remain to be confirmed with experiments.

6. Astrophysical applications

Density pair jets created in the laboratory can be used to study a variety of astrophysical phenomena, from pulsar wind nebula (PWN) to gamma-ray bursts. Perhaps the most exotic astrophysics application is the study of pair-equilibrium thermal plasmas, which supposedly has a fundamental temperature limit first derived by Bisnovati-Kogan, Zeldovich and Sunyaev [12] of ~20 mc^2 for a non-magnetized e-proton plasma. To achieve such hot thermal pair-equilibrium states, the pairs must be confined for times longer than pair creation and annihilation times as well as thermalization times. In the laboratory this means the laser pair production must continue for a long time and the created pairs must be confined. One way to achieve this may be to use multiple ARC beams staggered over time. The feasibility of such experiments is currently under investigation. Fig. 3 shows the phase space of sample astrophysical phenomena versus phase space of laser-produced pair plasmas.

7. Application to dense positronium physics

The advantage of laser created positron source over conventional positron source from radioactivity and accelerators is the high beam current due to the pico-second duration pulse. Provided that we can manage to cool the MeV positrons sufficiently rapidly, it may be possible to create ultra-high density slow positron source, which in turn leads to high density positronium (Ps) formation. The ultimate application of such high density, cool Ps is to form a Bose–Einstein condensate (BEC) of Ps [13,14], which has revolutionary applications to both fundamental physics, such as tests of QED and probing the vacuum, and to antimatter technology, such as the gamma-ray annihilation laser (GRASAR) [13,14]. We note that the critical density for a BEC of Ps at cryogenic temperature is only 5×10^{17} cm^{-3} (Fig. 4), well within reach of future laser pair production using NIF. Hence NIF-ARC is a very promising first facility that may have the capability to make a BEC of Ps and GRASAR.

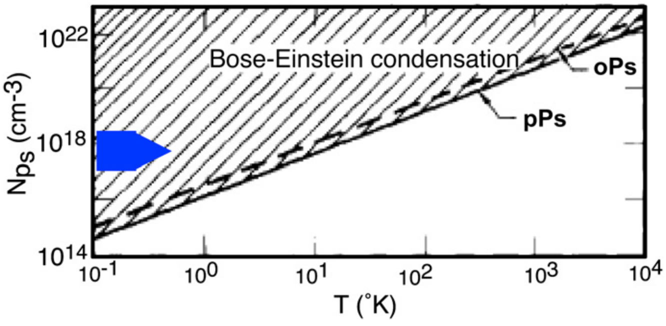


Fig. 4. Solid curve denotes the Bose–Einstein critical density as a function of temperature for pPs. Dashed curve denotes that of oPs. Bold arrow indicates critical density at cryogenic temperatures.

Please cite this article in press as: E. Liang, Intense laser pair creation and applications, High Energy Density Phys. (2010), doi:10.1016/j.hedp.2010.01.012

References

[1] H. Chen, et al., Phys. Rev. Lett. 102 (2009) 105001.
[2] M. Tatarakis, et al., Nature 415 (2002) 280.
[3] W. Heitler, Quantum Theory of Radiation, Oxford, United Kingdom, 1954.
[4] E. Liang, S. Wilks, M. Tabak, Phys. Rev. Lett. 81 (1998) 4887.
[5] K. Nakashima, H. Takabe, Phys. Plasmas 9 (2002) 1505.
[6] T. Cowan, et al., Laser Part. Beams 17 (1999) 773.
[7] E. Liang, in: M. Lontano, G. Mourou, O. Svelto, T. Tajima (Eds.), AIP Conference Proceedings No. 611, AIP, New York, 2002, 369 pp.
[8] T. Tajima, J.H. Dawson, Phys. Rev. Lett. 43 (1979) 267.
[9] C. Gahn, et al., Phys. Plasmas 9 (2002) 987.
[10] A. Henderson et al., in preparation.
[11] H. Chen et al., Nature, submitted for publication. **Q2**
[12] G.S. Bisnovati-Kogan, et al., Sov. Astron. 15 (1971) 17.
[13] E. Liang, C. Dermer, Opt. Commun. 65 (1988) 419.
[14] D. Cassidy, A. Mills, Phys. Status Solidi A 4 (2007) 3419.

Please cite this article in press as: E. Liang, Intense laser pair creation and applications, High Energy Density Phys. (2010), doi:10.1016/j.hedp.2010.01.012