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Perspectives on relativistic electron-positron pair plasmas for laboratory astrophysical experiments using intense laser-plasma interactions

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Physics of Plasmas

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Perspectives on relativistic electron-positron pair plasma experiments of astrophysical relevance using high-power lasers

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The study of relativistic electron-positron pair plasmas is both of fundamental physics interest and important to understand the processes that shape the magnetic field dynamics, particle acceleration, and radiation emission in high-energy astrophysical environments. Although it is highly desirable to study relativistic pair plasmas in the laboratory, their generation and control constitutes a critical challenge. Significant experimental and theoretical progress has been made over recent years to explore the use of intense lasers to produce dense relativistic pair plasma in the laboratory and study the basic collective plasma processes associated with these systems. Important challenges remain in terms of improving the number of pairs, system size, and control over the charge neutrality required to establish laboratory platforms that can expand our understanding of relativistic pair plasma and help validate underlying models in conditions relevant to high-energy astrophysical phenomena. We highlight recent progress in this field, discuss the main challenges, and the exciting prospects for studying relativistic pair plasmas and astrophysics relevant instabilities in the laboratory in the near future.

I. INTRODUCTION

Relativistic electron-positron (e^-e^+) pair plasmas are abundant in high-energy astrophysical systems, such as those associated with neutron star and black hole environments^{1–8}. The interactions of γ -photons with each other and with strong magnetic fields — which exceed the quantum critical field $B_c = 4.4 \times 10^{13}$ G in some systems^{9,10} — lead to prolific pair creation via electromagnetic cascades^{4,11–16}. These pair plasmas are relativistically hot (with temperature $T_{\pm} > \text{MeV}$) and can be accelerated to high speeds (with Lorentz factors reaching up to $\gamma_{\pm} \sim 10^4$) in the relativistic winds or jets associated with these compact astrophysical objects^{4,17}. Important examples are pulsar magnetospheres^{14,18–20}, relativistic jets from active galactic nuclei (AGN)^{21–24}, and gamma-ray bursts (GRB)^{7,25}, all believed to be associated with relativistic pair plasmas. Collective plasma processes, such as streaming instabilities^{26–28}, magnetic reconnection^{29–31}, collisionless shocks^{32,33}, and turbulence^{34,35} shape the magnetic field dynamics, energy partition, and radiation emission in these systems. The plasma behavior in such extreme, relativistic, and often radiative, environments can depart significantly from that of traditional non-relativistic plasmas studied in the laboratory and in space. Despite significant advances in theoretical and numerical studies of relativistic pair plasmas, our understanding of the plasma dynamics at these exotic, but rather important, regimes is still limited.

The fundamental interest and astrophysical importance of relativistic pair plasmas has motivated efforts to produce and study them in the laboratory^{36–40}. While

the full range of conditions associated with compact astrophysical objects is unattainable in terrestrial laboratories, there is significant value in the development of experimental platforms that would enable studies of the basic collective processes associated with pair plasmas in a controlled environment. Such experiments can offer a unique avenue for testing theoretical and numerical models, and developing a deeper understanding of the plasma physics that shapes high-energy astrophysical systems.

Advances in high-power lasers are enabling the generation of e^-e^+ beams in high atomic number (high-Z) metal targets, using either direct irradiation of the target by an intense laser pulse^{38,41–44} or by a relativistic electron beam produced by laser wakefield acceleration (LWFA)^{40,45–48}. In the last two decades significant progress has been made in controlling and characterizing pair production with lasers. Experiments using direct laser irradiation of a gold target have now produced $\sim 10^{12}$ relativistic pairs⁴² and experiments based on LWFA have reached pair beam densities of $\sim 10^{15} \text{ cm}^{-3}$ ⁴⁰. There is now a better understanding of how the number of pairs and their density scales with laser energy, and how to control the pair beam duration, divergence, energy, and charge neutrality by tuning both laser and target parameters.

At the same time, the continued increase in laser intensity is starting to open new avenues to explore pair production in ultra-strong fields that can exceed the quantum critical (or Schwinger) electric field $E_c = 1.3 \times 10^{16} \text{ V/m}$ ⁴⁹ leading to prolific pair production in vacuum. Under such conditions, the photon mean free path to one-photon pair decay can become small and lead to the onset of a quantum electrodynamic (QED) cascade with high multiplicity⁵⁰. This is a tantalizing prospect that would enable the generation of very dense relativistic pair plasmas in the laboratory and enable controlled studies of the interplay between strong-field QED and collective plasma

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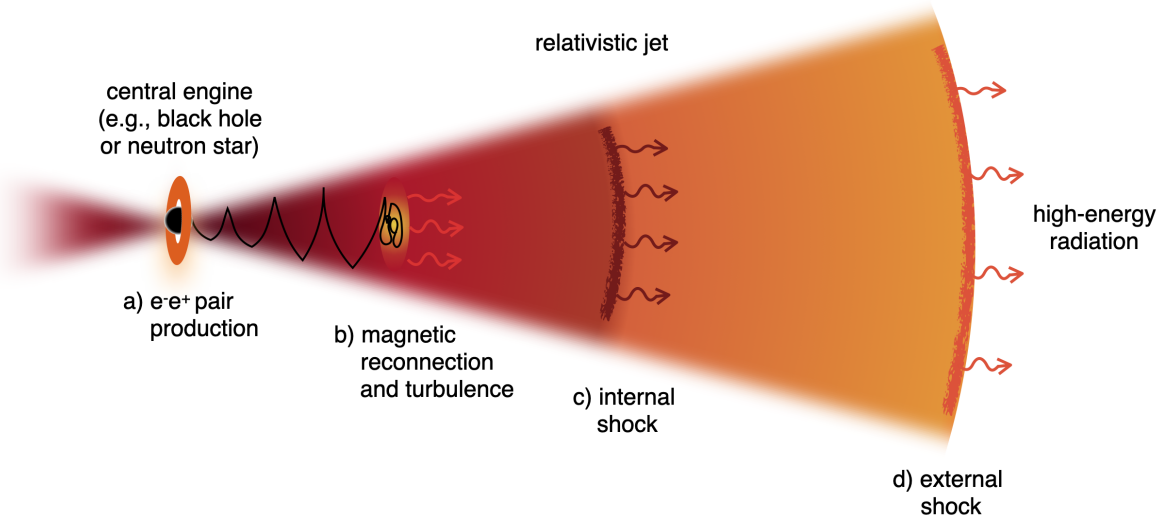


FIG. 1. Schematic representation of the prevalence of relativistic pair plasmas at different scales and physical regimes associated with high-energy sources from compact astrophysical objects. Copious pair production occurs via QED cascades near compact objects (a), such as black holes and neutron stars, and give rise to pair-dominated relativistic plasma jets that emanate from these objects. Pair plasma processes associated with relativistic instabilities, magnetic reconnection, turbulence, and collisionless shocks shape high-energy emission in these extreme environments (b-d).

processes^{50–54}.

In this paper, we discuss the current status of relativistic pair production with intense lasers and give our perspective on future developments and opportunities for experimental laboratory studies of relativistic pair plasmas and their relevance to astrophysical systems. We note that other schemes not involving powerful lasers have been proposed, and are being explored, for the generation of pair plasmas. These include trapping of positrons from radioactive sources³⁷, nuclear reactors^{39,55–57}, and particle accelerators^{36,58,59}. While these schemes also hold promise for the generation of pair beams and plasmas they will not be discussed in this paper, which is focused on laser-based configurations.

This paper is organized as follows. In Section II, we start with a general discussion of the astrophysical and fundamental plasma physics motivation to study relativistic pair plasmas and the requirements for laboratory experiments to access the basic processes associated with these plasmas. We review the main mechanisms for pair production in experiments with intense lasers in Section III. In Section IV, we discuss the current status of relativistic pair generation and characterization using intense lasers. In Section V, we provide our perspectives for future laboratory studies of relativistic pair plasmas based on the current status and expected advances. Finally, in Section VI, we present our conclusions.

II. RELATIVISTIC ELECTRON-POSITRON PLASMAS

A. Astrophysical motivation

In the past decade, extraordinary discoveries associated with extreme astrophysical plasmas have excited scientists and the public alike — from the first images of the plasma orbiting a black hole^{60,61} to the high-energy cosmic rays and radiation produced by relativistic jets and gamma-ray bursts^{62,63} to fast radio bursts from galactic neutron stars⁶⁴. It has long been recognized that the plasmas at the core of these extreme environments are relativistic and often electron-positron pair dominated^{1–4}. Pair-driven plasma processes shape the dynamics and energy partition in these systems over a wide range of scales and conditions — from highly magnetized regions near the compact objects to the interaction of very dilute relativistic pair beams with the intergalactic medium at 100 Mpc distances — in ways which are not well understood. This is schematically illustrated in Figure 1.

Relativistic pair plasmas can be produced around neutron stars and black holes by interactions of γ -ray photons with each other or with strong magnetic fields in the magnetospheres of these compact objects (Fig. 1a). For example, particles accelerated near the neutron star surface emit energetic γ -rays that propagate across a magnetic field of near quantum critical strength ($B \sim B_c$) and decay into an e^-e^+ pair. The freshly produced pairs undergo acceleration and also emit γ -rays, triggering an avalanche of pair production^{4,11–16}. Newly born

pairs start screening the accelerating electric field, thus preventing further particle acceleration. Similar electromagnetic (EM) cascades occur near the event horizon of supermassive black holes. These EM cascades fill the magnetospheres of compact objects with pair plasma and might comprise a significant part of the observed flux of CR high-energy positrons. They are expected to fill relativistic jets launched by compact objects with pair plasma¹⁷. The pair collective plasma motions in the discharge process can excite coherent EM waves that provide critical observational signatures of these extreme environments⁶⁵. The most intriguing class of neutron stars are magnetars, whose magnetic field strength can reach $\sim 10^{15}$ G^{9,10}. This field strength significantly exceeds the QED critical field B_c . Above this value, fascinating QED phenomena arise, such as photon splitting due to nonlinear QED vacuum birefringence^{66,67}. The equivalent Schwinger critical electric field E_c is capable to transfer the electron rest-mass energy, $m_e c^2$, over the reduced Compton wavelength, λ_c , giving rise to prolific pair production in vacuum, a phenomena that is exponentially suppressed at lower field strength $N_{\pm} \propto e^{-E_c/E}$ ^{49,68}. Understanding pair-plasma generation in these extreme fields and the interplay between QED and collective plasma processes is a frontier topic in plasma physics, with important implications to the understanding of the radiative signatures of compact astrophysical objects⁵².

A common observational feature of high-energy astrophysical plasmas is the broad non-thermal radiation spectrum, which is thought to be produced by energetic particles accelerated at relativistic shocks, turbulence, or during magnetic reconnection (or by a combination of these). In the highly magnetized regions of relativistic jets and winds, it is thought that magnetic reconnection and turbulence (Fig. 1b), which may be triggered by large-scale magnetohydrodynamic (MHD) plasma instabilities^{69–72}, can be responsible for the efficient conversion of the magnetic energy into high-energy non-thermal particles and radiation^{29,34,71,73,74}. In lower magnetization regions, radiation mediated shocks^{33,75} and internal collisionless shocks^{76,77}, both of which are shaped by pair-plasma instabilities, will further drive gamma-ray emission (Fig. 1c). Photon-photon induced cascades will also load the upstream region of external shocks in GRBs with relativistic pairs^{78,79} potentially impacting their magnetic field amplification via streaming instabilities^{28,80,81}, particle acceleration^{32,82}, and afterglow emission in GRBs^{83,84} (Fig. 1d). In all of these cases relativistic pair plasma processes have an important impact in particle acceleration and radiation emission.

Even at very large ($> \text{Mpc}$) distances from the central engine, very high-energy gamma-rays produce highly relativistic and extremely dilute pair flows. It has been proposed that pair-driven plasma instabilities can lead to significant energy loss of the pairs on time scales faster than inverse Compton scattering and potentially explain the absence of enhanced GeV emission that would be expected from inverse Compton cascades in TeV blazar

jets^{85,86}. This would also have important implications for current constraints on the intergalactic magnetic fields⁸⁷. While the growth rates associated with plasma micro-instabilities are indeed very fast^{88,89}, the nonlinear phase of the instabilities for high Lorentz factors and extremely low density ratios between the pair beam and ambient plasma are not well understood^{28,90,91}.

The ability to produce relativistic pair plasmas in the laboratory and study the basic processes and instabilities (in particular their nonlinear stages) that control energy partition in the plasma over a wide range of conditions, including different magnetizations, pair Lorentz factors, and radiative regimes would be highly valuable. This would provide a unique opportunity to advance our understanding of these exotic plasma regimes and benchmark current theoretical models and numerical simulations of the role these plasma processes play in astrophysical environments.

B. Basic plasma physics motivation

Pair plasmas represent a paradigm for the study of basic plasma science, and many open questions exist regarding these unique systems³⁶. A central research topic in plasma physics is instability^{27,92–95}. Of primary importance to many of these physical systems are the so-called streaming instabilities, which arise in plasmas hosting interpenetrating flows — a common configuration in high-energy astrophysical and laboratory plasma environments. Relativistic pair-driven streaming instabilities develop when the relative velocity between the pair plasma flows and the ambient medium approaches the speed of light and constitute a long-standing problem in fundamental plasma physics, with direct and far-reaching consequences for high-energy astrophysical environments. These instabilities control the energy transfer between relativistic flows, fields, and particles in these environments^{27,28,32,90–93,96,97}. However, because the properties of these relativistic pair plasmas can depart significantly from those of traditional non-relativistic plasmas studied in the laboratory and in space, our understanding of the basic plasma processes in this frontier regime is still very limited. Important open problems include the competition between different instabilities, their saturation level, and nonlinear evolution, the impact of the ambient magnetization, and the coupling with radiative processes in strong-field environments.

In pair plasmas there is no separation between electron and positron kinetic scales and this has qualitative implications for the properties of the waves and instabilities that develop in these systems. A very important goal for the study of pair-driven plasma instabilities is thus to understand the long-term evolution of micro-instabilities, their role on the electromagnetic field dynamics, particle acceleration, and radiation emission, and how they influence (and are influenced by) the large-scale dynamics of

the system.

The study of basic kinetic collective plasma processes — instabilities, shocks, magnetic reconnection, turbulence — in relativistic, pair-dominated environments is thus very important to build a systematic knowledge base for the development of theoretical models and for the interpretation of high-energy astrophysical observations. Advances in spacecraft measurements, dedicated laboratory experiments, computational power and numerical tools, and analytical theory have led over the past decade to mature understanding of these basic processes in non-relativistic electron-ion plasmas. However, for relativistic, pair-dominated regimes this understanding is still scarce. The ability to produce and probe relativistic, pair-dominated plasmas in the laboratory represents a unique opportunity to better understand these processes and to help develop better analytical and numerical models.

Below we discuss some of the important requirements for experimental studies of collective processes in relativistic pair plasmas.

C. Requirements for laboratory studies

To enable the study of collective processes in relativistic pair plasmas, laboratory experiments need to meet a set of basic conditions.

Particle number and plasma size. The smallest plasma scale associated with the development of collective behavior in pair plasmas is the skin depth, c/ω_p , where c is the speed of light in vacuum, $\omega_p = [8\pi n_{\pm} e^2 / (\gamma_{\pm} m_e)]^{1/2}$ is the pair plasma frequency, $n_{\pm}$ is the pair density, $\gamma_{\pm}$ the Lorentz factor of the pairs, m_e is the electron mass, and e is the elementary charge. (Note that in a pair plasma the total plasma frequency is $\sqrt{2}$ times larger than the electron plasma frequency due to the contribution of the positrons.) Thus, in order to study collective behavior, the pair plasmas produced in the laboratory must have a size much larger than the skin depth. Considering a Gaussian plasma profile, with root-mean-square width $L_{\pm}$ in each direction, this condition can be written as $L_{\pm}(\mu\text{m}) \gg 38\{\gamma_{\pm}/[n_{\pm}(10^{16}\text{cm}^{-3})]\}^{1/2}$ or, equivalently, in terms of the required number pairs as

$$N_{\pm} \gg n_{\pm}^{-1/2} \left(\frac{\gamma_{\pm} m_e c^2}{4e^2} \right)^{3/2} \simeq 8.4 \times 10^{17} \frac{\gamma_{\pm}^{3/2}}{n_{\pm}^{1/2}}. \quad (1)$$

In order to minimize the number of pairs required to study collective behavior one should maximize the pair plasma density and produce relativistic pairs with low to moderate Lorentz factor ($\gamma_{\pm} \lesssim 10$). For example, for a relativistic pair plasma with density $n_{\pm} = 10^{14} \text{ cm}^{-3}$ and $\gamma_{\pm} = 10$, the number of pairs that needs to be produced is $N_{\pm} \gg 3 \times 10^{12}$.

In cases where we are not interested in studying a pure pair plasma, but instead the propagation of a relativistic pair plasma or flow on an ambient electron-ion plasma,

this criterion can be potentially relaxed as the smallest scale for collective processes to arise becomes the skin depth of the, typically denser, ambient plasma. In this case, the condition on the minimum number of pairs can be written as

$$N_{\pm} \gg \frac{n_{\pm}^{1/2}}{n_0^{3/2}} \left(\frac{m_e c^2}{2e^2} \right)^{3/2} \simeq 2.4 \times 10^{18} \frac{n_{\pm}^{1/2}}{n_0^{3/2}}, \quad (2)$$

where n_0 is the density of the ambient plasma. Based on this expression, it may be tempting to consider the use of very dense ambient plasmas, as that would significantly reduce the number of pairs that are needed. However, as we discuss below, when the time scale for the processes of interest and the beam divergence are taken into account, this changes significantly this condition.

Neutrality. To investigate the behavior of pure pair plasmas, these need to be quasi-neutral, meaning that the number of electrons and positrons produced should be comparable, i.e. $n_{e+}/(n_{e-} + n_{e+}) \sim 0.5$. While pair production schemes will typically lead to the same number of secondary electrons and positrons being produced, the primary source of energy for the pair production can be dominated by one of the species. As we discuss below, many laser-driven pair production schemes will first convert the laser energy into relativistic electrons and the latter will then generate the high-energy γ photons required for secondary pair production. Because of this, electrons are typically the primary source of energy and tend to dominate the resulting number of charged particles. Different pair production schemes will enable different levels of control over the resulting neutrality. We also note that it is of interest to explore the physics of mixed-species plasmas containing electrons, positrons, and ions both from a fundamental perspective and for its relevance to many astrophysical systems of interest, where the exact composition ratio of the different species is not well understood²³.

Energy. Given that pair production by high-energy photons intrinsically requires a minimum photon energy equal to the rest mass energy of the electron-positron pair (i.e. $> 1 \text{ MeV}$), the majority of the pairs produced are naturally relativistic. Thus, this enables the generation of relativistic pair plasmas or flows with $\gamma_{\pm} \gg 1$.

Duration. The plasmas need to be long-lived, meaning that the pair plasmas need to be maintained for a time that is much longer than the time-scale of the plasma processes to be studied. The shortest time scale that needs to be captured for the study of collective processes is typically the inverse of the plasma frequency, which requires a duration

$$\tau_{\pm} \gg \omega_p^{-1} \simeq 125 \left[\frac{\gamma_{\pm}}{n_{\pm}(10^{16}\text{cm}^{-3})} \right]^{1/2} \text{ fs}. \quad (3)$$

Depending on the specific process of interest longer times scales need to be considered, typically associated with the growth rate of different instabilities in pair plasmas or of processes of interest, such as shocks, magnetic

reconnection, or turbulence. For the case of relativistic pair beam-plasma instabilities, two fundamental micro-instabilities that are commonly evoked are the oblique⁸⁸ (electrostatic) and Weibel⁹⁸, or current-filamentation⁹⁹, (electromagnetic) instabilities, whose growth rates are

$$\Gamma_{\text{obl}} = \frac{3^{1/2}}{2^{4/3}} \left(\frac{1}{\gamma_{\pm}} \frac{n_{\pm}}{n_0} \right)^{1/3} \omega_p \quad (4)$$

and

$$\Gamma_W = \left(\frac{1}{\gamma_{\pm}} \frac{n_{\pm}}{n_0} \right)^{1/2} \omega_p. \quad (5)$$

The growth rates of these two instabilities are compared in Fig. 2.

Ultimately, the electron-positron annihilation time needs to exceed the time scales of interest. The annihilation time scale is $\tau_a \sim 1/(\pi r_e^2 c n_{\pm})^{100}$, where r_e is the electron classical radius. For $n_{\pm} \sim 10^{20} \text{ cm}^{-3}$, $\tau_a \sim \text{ms}$ which is far greater than the ps – ns typical laser-driven pair-plasma interaction time. Thus, annihilation is not expected to be an issue for the laser-driven pair-plasma studies considered in this paper.

Divergence. In studies of pair beam-plasma interactions driven by the interaction of a relativistic pair beam with an ambient electron-ion plasma, it is important to guarantee that the beam does not diverge significantly during the time scale of the processes of interest, τ^{101} . That is, it is important to guarantee that $\theta c \tau < L_{\pm}$, where θ is the beam divergence. In studies of pair-driven instabilities, the duration of the processes of interest is typically some multiple δ (typically ~ 10) of the inverse instability growth rate, i.e. $\tau = \delta/\Gamma$. This condition can further constrain the requirements in terms of beam density and number to study a given process. As an example, for studies of the Weibel instability, the number of pairs required for a given beam density and divergence can be written as

$$N_{\pm} \gg \frac{(\delta\theta)^3}{n_{\pm}^{1/2}} \left(\frac{\gamma_{\pm} m_e c^2}{2e^2} \right)^{3/2} \simeq 2.4 \times 10^{18} (\delta\theta)^3 \frac{\gamma_{\pm}^{3/2}}{n_{\pm}^{1/2}}. \quad (6)$$

We see that this condition no longer depends on the ambient plasma density and becomes similar to Eq. (1) when $\theta \sim 1/\delta$.

Magnetization. For studies of magnetized relativistic pair plasmas, an external magnetic field must be supplied with an energy density that exceeds the kinetic energy density of the plasma. This condition can be written in terms of the magnetization parameter $\sigma_B = B_0^2/(4\pi n_{\pm} \gamma_{\pm} m_e c^2) > 1$, which requires a magnetic field amplitude

$$B_0(\text{T}) > 32[\gamma_{\pm} n_{\pm} (10^{16} \text{ cm}^{-3})]^{1/2}. \quad (7)$$

As with the condition for the minimum pair number required to study collective behavior, reaching magnetized plasma conditions favors the use of low to moderate pair

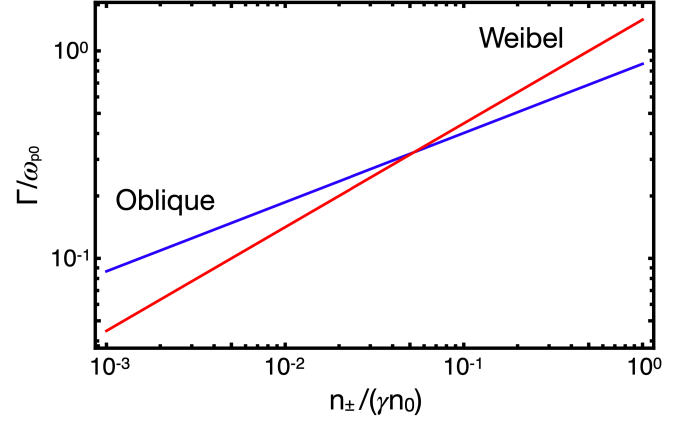


FIG. 2. Comparison of the growth rates (normalized to the ambient electron plasma frequency ω_{p0}) of the electrostatic oblique (blue) and electromagnetic Weibel (red) instabilities associated with the propagating of a relativistic pair beam of density $n_{\pm}$ and Lorentz factor $\gamma_{\pm}$ in a background electron-proton plasma of density n_0 .

Lorentz factors, but in this case it benefits from the generation of lower pair plasma density. For example, for $n_{\pm} = 10^{14} \text{ cm}^{-3}$ and $\gamma_{\pm} = 10$, the required magnetic field is $B_0(\text{T}) > 10 \text{ T}$, which can be readily produced on cm scales using pulse-power magnetic delivery devices^{102–105}.

III. PAIR PRODUCTION MECHANISMS BASED ON INTENSE LASER SOURCES

Production of an electron-positron pair requires a minimum energy of $2m_e c^2$. The energy source can be in the form of cosmic rays, fast electrons from earthly events like lightnings¹⁰⁶, charged particles from terrestrial accelerators^{59,107}, neutrons from nuclear reactors⁵⁵, or light from powerful lasers³⁸.

The generation of pairs with lasers typically involves a multi-step process, where first the laser field accelerates electrons to relativistic energies, the electrons then radiate high-energy γ photons, and finally the γ produce pairs via the interaction with the strong laser field itself, a nuclear field, or other photons.

In this section, we briefly describe the main pair production processes relevant to laser-driven experiments, comparing their likelihood (quantified in the cross-sections or pair production rates). We then discuss the range of laser intensities associated with the different regimes of pair production.

A. Pair production near atomic nuclei

Pair production near atomic nuclei is dominated by the so-called ‘Bethe-Heitler’ (BH) process¹⁰⁸, named after the two authors who first described the process in their seminal paper published in 1935. This is a two-step process, $e \rightarrow \gamma$ and $\gamma \rightarrow e^- + e^+$.

Extensive calculations of the BH pair production cross-section have been performed over many decades and the results are summarized in the review papers by Motz, Olsen and Koch (1969)¹⁰⁹ and by Hubbell, Gimm and Overbo (1980)¹¹⁰. More recently, pair production using lasers has been estimated by, for example, Gryaznykh *et al.*¹¹¹, Nakashima and Takabe¹¹² and Myatt *et al.*¹¹³. While the precise cross-sections include Coulomb and screening corrections, its first order Born-approximation scales with the target material in each of the two steps as $\sigma_{e \rightarrow \gamma} \propto \alpha(r_e Z)^2$ and $\sigma_{\gamma \rightarrow e^- e^+} \propto \alpha(r_e Z)^2$, where $\alpha = 1/137$ is the fine structure constant and Z is the atomic number of the material. The BH process has a strong dependence in the target Z and its cross section for pair production, without screening, is¹¹⁴

$$\sigma_{\text{BH}} = \frac{28}{9} \alpha Z^2 r_e^2 \left[\ln \left(\frac{2\epsilon_\gamma}{m_e c^2} \right) - \frac{109}{42} - f(Z) \right], \quad (8)$$

where ϵ_γ is the photon energy and $f(Z) = (\alpha Z)^2 \sum_{i=1}^{\infty} [i(i^2 + \alpha^2 Z^2)]^{-1}$. Experimentally, due to the high efficiency in the laser energy conversion to relativistic electrons which then produce the MeV high-energy γ photons via bremsstrahlung, significant pair production has been achieved by this process using a dense high- Z target. For example, using ps-duration laser pulses with intensities about 10^{19} W/cm² and gold targets ($Z = 79$), up to $\sim 10^{12}$ pairs have been produced⁴².

We note that although pair production can also occur in the Coulomb field of electrons, the corresponding cross-section scales as $\sigma_{\gamma \rightarrow e^- e^+} \propto \alpha(r_e)^2 Z$, which is at least an order of magnitude smaller for high- Z targets, and therefore this process typically does not play an important role.

Near the nuclei of a solid target, pair production can also happen by electrons interacting with virtual photons, in what is called the Trident process, $e^- \rightarrow e^- + e^- + e^+$. The cross-section for the Trident process at electron energy ϵ_e greater than MeV^{111,113,115} is

$$\sigma_{\text{T}} = \frac{28\pi(\alpha r_e Z)^2}{27} \log^3(\epsilon_e/mc^2) \quad (9)$$

This process represents a less dominant mechanism in laser-driven pair production when compared to the BH process if the target thickness is more than ≈ 20 μm ¹¹² for which the electron- γ conversion efficiency via bremsstrahlung is high¹¹¹.

B. Pair production by photon-photon collisions

The interaction of two high-energy photons can lead to pair production via the linear Breit-Wheeler (BW) process¹¹⁶, $\gamma + \gamma' \rightarrow e^- + e^+$. This is the first-order perturbative QED process in photon-photon interactions. The product of the two photon energies needs to exceed 0.25 MeV^2 for pair production, requiring an MeV γ source. The effective cross section for pair production is

$$\sigma_{\text{BW}} = \frac{\pi}{2} r_e^2 (1 - \beta^2) \left[-2\beta(2 - \beta^2) + (3 - \beta^4) \ln \left(\frac{1 + \beta}{1 - \beta} \right) \right] \quad (10)$$

where $\beta = \sqrt{1 - 1/s}$ and $s = \epsilon_{\gamma 1} \epsilon_{\gamma 2} (1 - \cos\phi)/(2m_e^2 c^4)$, with $\epsilon_{\gamma 1}, \epsilon_{\gamma 2}$ the energy of the colliding photons and ϕ the collision angle.

This mechanism is characterized by a very weak probability, making it difficult to produce a large number of pairs. Recent experiments at the Relativistic Heavy Ion Collider produced $\gtrsim 6 \times 10^3$ pairs via linear BW¹⁰⁷. Using high-power lasers, different experimental configurations have been suggested in the last few years to study this process. The main idea is that a high-intensity laser is used to produce a collimated γ -ray source via bremsstrahlung or Compton scattering and this γ -ray source then collides with either a similar γ -ray beam ($\gamma - \gamma$ collider configuration)^{117–119} or with a bath of X-rays produced by multiple high-power lasers in a gold hohlraum¹²⁰. Theoretical and numerical calculations predict that the number of pairs that would be produced using state-of-the-art laser systems is $10^5 - 10^7$ ¹¹⁷, which is relatively low for pair plasma studies, but could enable the first experimental demonstration of this fundamental process.

C. Pair production in strong laser field

Finally, pair production can also be obtained from the interaction of high-energy photons with a strong laser field via the nonlinear Breit-Wheeler (NBW), or multi-photon, process $\gamma + n\gamma' \rightarrow e^- + e^+$ ¹²¹. This process was first observed experimentally at the Stanford Linear Accelerator Center (SLAC) in the collision of a 46.6 GeV electron beam with a TW laser pulse¹²². Pair production involved a two-step process. First low energy photons from the laser ($\hbar\omega \sim 2.35 \text{ eV}$) are Compton scattered by the electron beam to produce $\sim 30 \text{ GeV}$ photons. Then pair production is achieved by the collision of the high-energy photons with multiple low-energy photons from the laser. Quantum mechanical calculations of pair production in strong fields are usually carried out within the framework of a bound state formalism, i.e., the Furry representation¹²³. The transition probabilities in this case are most commonly given in terms of pair

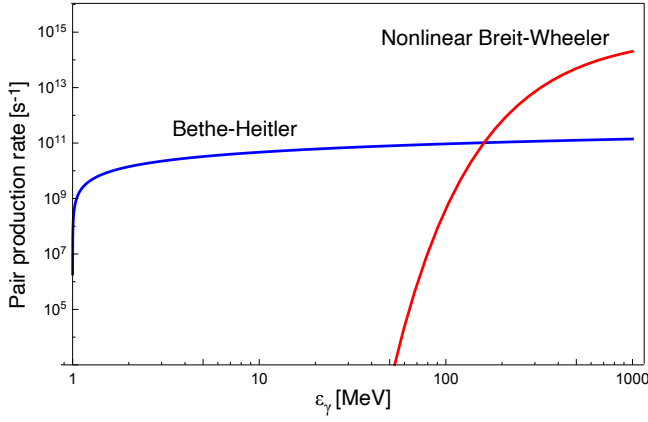


FIG. 3. Comparison of the electron-positron pair production rates for the interaction of a photon of energy ϵ_γ with 1) a gold target via the BH process (blue) and 2) a laser pulse with intensity of 5×10^{22} W/cm² (red).

production rates. The pair production rate is¹²⁴

$$\Gamma_{\text{NBW}} \sim \alpha \frac{c}{\lambda_c} \frac{m_e c^2}{\epsilon_\gamma} \frac{K_{1/3}^2 \left(\frac{2}{3\chi} \right)}{\chi} \quad (11)$$

where $\chi \simeq \epsilon_\gamma / (m_e c^2) E_l / E_S$ is the quantum field strength experienced by a photon of energy ϵ_γ counter-propagating with a laser with electric field E_l and K_n is the modified Bessel function of the second kind. For low χ (field strengths smaller than the Schwinger critical field), pair production is exponentially suppressed as $\propto \exp[-2/(3\chi)]$. Due to this suppression only ~ 100 pairs have been observed over 10,000 shots in the E-144 experiment at SLAC¹²². However, with currently laser systems it will be possible to reach $\chi \gtrsim 1$ and obtain high pair production rates. The E-320 experiment at SLAC¹²⁵ and the LUXE experiment at DESY¹²⁶ are currently pursuing this possibility with laser systems of 10s TW. In the near future such studies could be extended to very high laser intensities $I > 10^{22}$ W/cm² now available.

Figure 3 compares the pair production rates for the two dominant processes associated with the interaction of a high-energy photon with 1) a gold target via the BH process and 2) a laser with intensity of 5×10^{22} W/cm². The actual total number of pairs produced is dependent on the total number of high-energy photons and the duration of the interaction. Needless to say that only the interacting particles with energies above the pair creation threshold contribute. For laboratory studies, although highly relativistic electron beams can be driven by conventional accelerators as in earlier and more recent experiments^{127,128}, there is now also significant interest in driving them using more compact high power laser systems as discussed in the following section.

D. Dominant Pair Production Processes at Various Laser Intensities

The high-energy electrons and/or photons required for the different pair production processes discussed above can be provided by lasers when the focal brightness (commonly called laser intensity, which is used hereafter) is large enough. The electrons oscillating in the electromagnetic field of a laser acquire $\gamma v_{\text{osc}}/c = a_0$, where $\gamma = [1 - (v_{\text{osc}}/c)^2]^{-1/2}$ is the Lorentz factor of the electrons oscillating with quiver velocity v_{osc} and $a_0 \sim 8.55 \times 10^{-10} [I(\text{W/cm}^2) \lambda_0^2(\mu\text{m})]^{1/2}$ is the normalized vector potential of the laser. For example, for laser intensities $I \lambda^2 > 10^{18}$ W/cm² μm^2 , $a_0 > 1$ and it is possible to accelerate electrons to velocities near the speed of light. Above such laser intensities, the electron energy gain can significantly exceed MeV allowing the generation of the high-energy photons needed to produce electron-positron pairs and for significant energy conversion efficiencies to be reached between the laser and electron-positron pairs.

Broadly speaking, three main regimes can be identified when describing the dominant laser-driven pair production mechanisms according to the laser intensity, as shown in Fig. 4 for a typical 1 μm laser wavelength.

In regime (1), for laser intensity $10^{18} < I < 5 \times 10^{22}$ W/cm², pair production is expected to be dominated by the BH process, where the pairs are produced near the nuclear field by above threshold photons that are produced by laser accelerated electrons. We estimate this upper intensity limit by considering a photon energy $\epsilon_\gamma \sim \epsilon_e \sim a_0 m_e c^2$. By comparing the maximum pair-production rate of the different processes outlined above, we find that the BH process is dominant for $a_0 < 150$ (see Fig. 3), corresponding to a threshold laser intensity $I \sim 5 \times 10^{22}$ W/cm².

In regime (2), for laser intensity $5 \times 10^{22} \leq I < 10^{24}$ W/cm², pair production through NBW is expected to be dominant. The upper intensity limit is simply used to separate regimes below and above the threshold for QED cascades driven by NBW, which is roughly when $\chi \simeq 5 \times 10^{-6} \gamma a_0$ exceeds unity.

Above this threshold the probability of pair production by NBW in the strong laser field rises steeply. The mean free paths for γ emission and pair production become very short. Emitted pairs are accelerated in the laser field and emit more γ photons, which quickly decay into pairs, giving rise to a QED pair cascade. It is predicted that at $I \sim 10^{24}$ W/cm² the number of secondary pairs becomes comparable to the number of primary particles⁵⁰ and for $I > 10^{24}$ W/cm² the number of pairs can significantly exceed the number of seed particles, potentially enabling the generation of very dense relativistic pair plasmas^{129,130}.

Regime (3), for laser intensities $I > 10^{24}$ W/cm², is dominated by QED cascades.

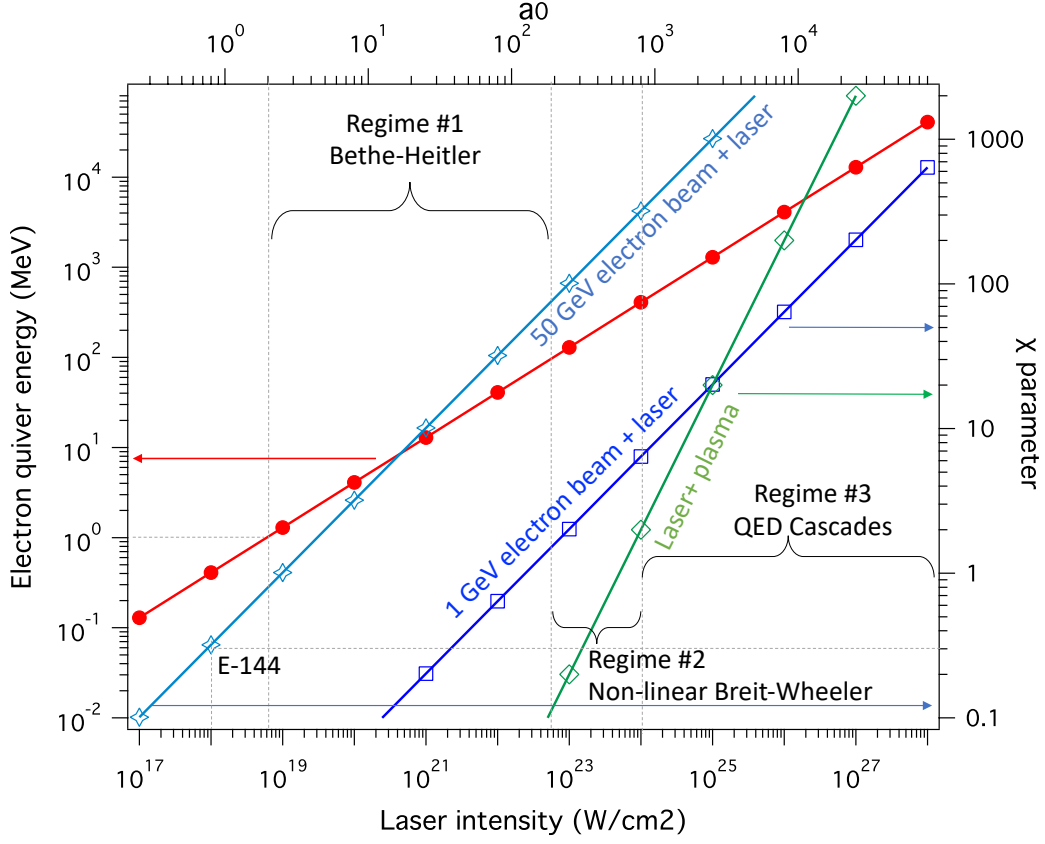


FIG. 4. Regimes of electron-positron pair production as a function of laser intensity (bottom axis) or, equivalently, normalized laser vector potential for $1 \mu\text{m}$ laser wavelength (upper axis). The electron quiver energy in the laser field is indicated in red. The quantum parameter $\chi = \gamma E_L / E_S$ is illustrated for the cases of a laser interacting with (light blue) a 50 GeV electron beam (including SLAC’s E-144 experiments), (darker blue) a 1 GeV electron beam, and (green) a plasma. The three dominate pair production regimes are marked.

IV. EXPERIMENTAL STUDIES OF PAIR PRODUCTION DRIVEN BY HIGH-POWER LASERS

The highest laser intensity currently achieved in the laboratory¹³¹ is $I = 1.1 \times 10^{23} \text{ W/cm}^2$. Such record intensities start to enable significant pair production by the BW process (regime 2 in Fig. 4). However, for the majority of currently available lasers, the operating intensities are in the range $I = 10^{18} - 10^{22} \text{ W/cm}^2$ (regime 1 in Fig. 4). At these intensities, as discussed above, hot electrons can be accelerated up to 10s MeV and the energy conversion efficiency from fast electrons to the above threshold ($> 1.02 \text{ MeV}$) bremsstrahlung photons can reach over 50% for thick targets¹¹³. Combined with the high cross-section for pair production in high-Z targets, the BH process underlines the primary pair-production process for current experiments using high-power lasers.

A. Experimental setup for laser-driven BH pair production

Two main experimental approaches have been used in laser experiments of pair production (illustrated in Fig. 5). One is the “Direct” approach, where the laser accelerates electrons and produces pairs on the same target, and the other is the “Indirect” approach, where the electrons are first accelerated by the laser in a gas target and these electrons then bombard a second, high-Z solid target to produce the pairs. Note that the “Indirect” approach follows the same process of positron generation used in electron-positron colliders where a high-Z target (tungsten, for example) is bombarded by GeV electrons from the accelerator¹²⁷. In experiments using either approach, the laser energy is first transferred to electrons then to bremsstrahlung photons and finally to pairs.

The electron source can be directly measured in the “Indirect” method while it can only be inferred in the “Direct” method as only electrons that escape the target are measured. Although in principle bremsstrahlung

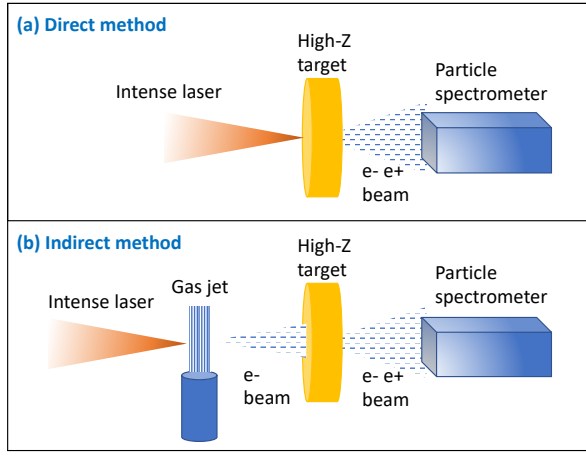


FIG. 5. Schematic experimental setups for (a) the “direct” laser pair production experiments and (b) “indirect” laser pair production experiments. Both setups requires high-Z targets for efficient BH pair processes. The required laser parameters are different too, which are listed in Table I.

photons are measurable, it is difficult to completely characterize their spectrum as the photons have large flux ($> 10^{20}$ ph/s) and a wide spectral range from 10 keV up to 100s MeV (with the upper limit being the maximum energy of the source electrons). The resulting pair number and energy distributions from experiments using both methods are directly observable using magnetic spectrometers^{132,133} at a given solid angle. The spectrometer generally uses either film-like static detectors such as image plates or scintillating materials coupled to photon detectors such as CCD.

B. State-of-the-art experimental results

A summary of representative state-of-art experimental results is given in Table I. As mentioned earlier, the direct measurements are on the electron and positron distributions. The number, density and other parameters are derived from the spectra together with the laser pulse parameters.

Generally speaking, the laser-driven electron source for pair production experiments can be described by a Maxwell-Boltzmann type distribution $f_e(\epsilon) \propto \exp(-\epsilon/T_e)$, where T_e is the electron temperature, and ϵ its energy. This distribution is typically a good approximation of the electron distribution from both the “Direct” approach and the “Indirect” approach when using processes like Self-modulated LWFA (SM-LWFA)^{142–144} or Direct-Laser-Acceleration^{145–147}. However, in some cases more complex expressions are needed, as for example in two-temperature distributions originating from different acceleration processes^{148,149}. For electron beams from LWFA, a mixture of a broader Maxwell-Boltzmann distribution and a narrower (quasi-monoenergetic) dis-

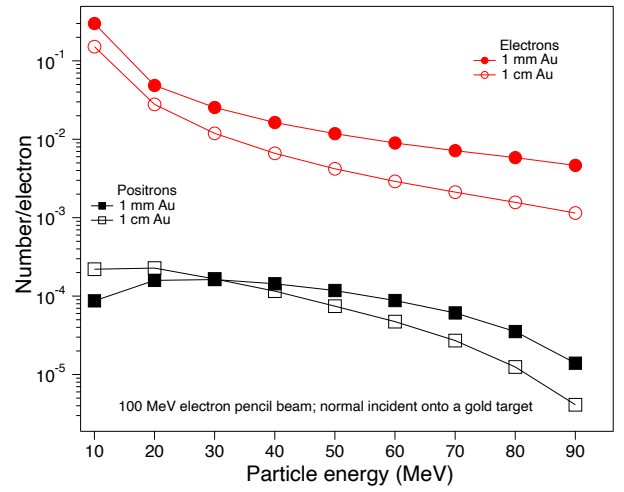


FIG. 6. The electron and positron spectra from a 100 MeV mono-energetic electrons incident on a gold target with 1 mm and 1 cm thickness, respectively.

tribution is often needed^{150–154}.

In experiments using the “Direct” approach, the resulting positron spectrum can also be well-described by a Maxwell-Boltzmann distribution in general but at a different temperature from that of the electrons³⁸. The positron spectrum from the “Indirect” approach can be more complex due to its multi-distribution source function. For example for a mono-energetic electron source, the “Indirect” approach produces positrons (and electrons) with non-Maxwell-Boltzmann distribution, as illustrated in Fig. 6.

Examples of experimentally measured electron and positron spectra are shown in Fig. 7 for both approaches: a) “Direct” approach using a 100 J laser at intensity of about 5×10^{19} W/cm² on a 1 mm thick gold target with broad electron spectrum between 1 and 50 MeV (upper red) and a positron distribution between 3 and 30 MeV (lower red); b) “Indirect” approach using a laser with about 14 J energy and a peak intensity of about 3×10^{19} W/cm² on 5 - 40 mm thick lead targets^{40,155}, with electron (upper blue) energy from 0.1 to 2 GeV and broad positron distribution (lower blue) measured from 200 MeV to 400 MeV.

An interesting difference in the positron distribution from the two approaches is the additional energy “boost” observed in the “Direct” approach. This near uniform energy shift of the positron energy distribution (e.g., Fig. 1 in reference¹³⁴) is due to the target normal sheath electric field¹⁴⁹ and is largely absent in the “Indirect” approach. This may be caused by the combination of relatively less strong sheath fields and the wider positron energy distributions leading to a less pronounced change in the positron energy distribution.

In the following, we will discuss the deduction of the pair numbers and densities in the experiments.

Positron number derivation. Experimentally, each en-

TABLE I. Results of laboratory experiments generating relativistic positrons using high power lasers ^a

Laser parameters	Target	N ₊	Duration (ps)	Emittance/Divergence	e ⁺ density (1/cm ³)	ratio(e ⁺ /e ⁻)	e ⁺ energy (MeV)	Laser system
"Direct" method								
100 J, 0.5 ps	0.1 mm Au	<5e7	0.5	-	-	-	3 - 9	Nova ⁴¹
300 J, 10 ps	1 mm Au	2e10	10	200 mm.mrad	1e13	<0.1	5 - 15	Titan ^{38,42,134}
1000 J, 10 ps	1 mm Au	6e11	10	250 mm.mrad	1e14	<0.1	10 - 20	Omega EP ^{42,134}
500 J, 1 ps	1 mm Au	5e11	1	-	1e14	<0.1	30	Orion ⁴²
800 J, 1-10 ps	1 mm Au	1e12	10	-	-	-	50	EP ¹³⁵
2000 J, 10 ps	1 mm Au	1e11	-	-	-	-	10	NIF ARC ¹³⁶
800 J, 10 ps	1 mm Au	1e11	10	250 mm.mrad	2e9	0.2	10-20	EP MIFEDS ^{137,138}
800 J, 1 ps	0.02 mm Au	1e10	1	-	1e9	1	13	EP MIFEDS ¹³⁹
100 J, 0.13 ps	2-6 mm Au/Pt	3e10	-	-	2e15	0.5	6-23	Texas PW ⁴³
100-200 J, 0.8 ps	1 mm Ta	3e9	-	-	-	-	-	XingGuang III ⁴⁴
"Indirect" method								
0.2 J, 0.13 ps	2 mm Pb	1e6	-	-	-	-	-	Atlas ^{45,140}
0.8 J, 0.03 ps	4.2 mm Ta	4e7	0.03	2.7 mrad	2e14	0.1	100	Hercules ⁴⁶
14 J, 0.04 ps	25 mm Pb	1e9	0.015	2-20 mrad	2e16	0.5	200	Astra-Gemini ⁴⁰
4 J, 0.045 ps	1 mm Pb	4e8	0.045	200 mrad	2e12	0.5	-	Shanghai ⁴⁸
10 J, 0.06 ps	3 mm Ta	-	-	-	-	-	-	Callisto ^{47,141}

^a The numbers quoted are representative and approximate. For exact values, please see individual reference.

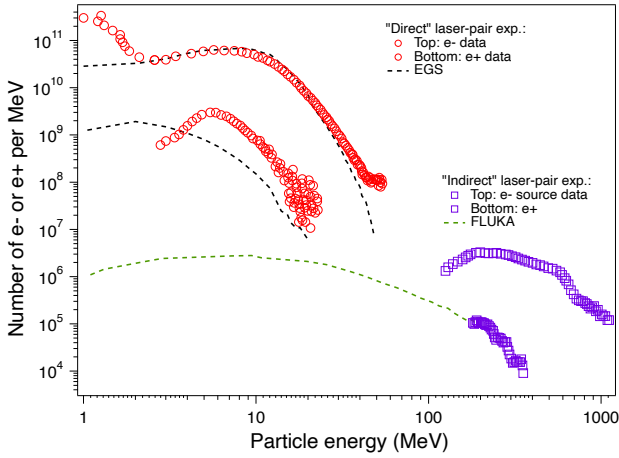


FIG. 7. Example electron and positron spectra measured experimentally (circle and square markers) and obtained from simulations for the "Direct" (upper-left group)³⁸ and "Indirect" (lower-right group)⁴⁰ approaches.

ergy spectrum of electrons or positrons $f(\epsilon, \theta)$ is measured at a given angle θ relative to the laser propagation (or target normal) direction. By integrating over the energy (ϵ) and angle (θ), one can calculate the total number of electrons (N_-) or positrons (N_+) as $N_{\pm} = \int \int f(\epsilon, \theta) d\epsilon d\theta$. This means that to infer the total pair yield from an experiment, both the energy and the angular distribution are needed. The energy distri-

butions are normally obtained by using magnetic spectrometers that can disperse the charged particles according to their kinetic energy and the angular distributions is either obtained experimentally^{43,134,137} by placing the magnetic spectrometer at various angles or obtained via calculations^{43,47,141,155,156}.

So far, the highest pair number reported per laser shot is about 10^{12} from the "Direct" method using 10 ps, 1 kJ laser pulse^{42,135}, and 10^9 from the "Indirect" method using 0.04 ps, 14 J laser pulse⁴⁰. The large difference in pair number from the two approaches is not surprising given the difference in laser energies used in the experiment: the maximum number of pairs produced is directly related to the number of laser accelerated MeV electrons, which, in turn, is proportional to the laser energy and intensity.

Positron density derivation. To further infer the pair density ($n_{\pm}$), the volume over which the pairs are created is needed. Inside the dense target, where positrons are produced, it is not currently possible to measure their volume directly. Positron characterization is typically done outside the target, but direct measurements using existing diagnostic techniques (such as interferometry or shadowgraphy) can also be challenging due to the relatively low pair density ($< 10^{16} \text{ cm}^{-3}$), long optical depth and short duration ($< \text{ns}$). Instead, the volume is often estimated as a frustum, as illustrated in Fig. 8: (a) the smaller base of the frustum is the source's transverse size; (b) the "slant height" is the pair spatial length, given as the product of pair beam duration and the pair velocity, and (c) the frustum's larger base is given by the pair's an-

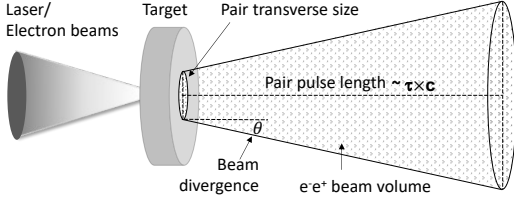


FIG. 8. Illustration of how the volume of laser-produced pairs is calculated behind the target where its properties are measured.

gular divergence together with (a) and (b). The accuracy of pair volume derivation is dependent on the accuracy of the measurement of (a), (b) and (c), or their estimates based on the physics processes that dominate them:

(a) *Positron source transverse size.* The positron source size can be measured using standard techniques such as “Pepper-pot” in 2D, or “knife-edge” in 1D. These techniques rely on the penumbra of the particles from the edge of the hole (in “Pepper-pot”) or edge (in “Knife-edge”). Although used in MeV positrons from “Direct” method¹³⁷, they are not applicable to high energy (100s MeV) positrons where the source sizes are either calculated or assumed as a point source.

(b) *Positron beam duration.* The pair beam duration which is a convolution of electron source duration, the BH pair production rate, and transport time in the target. While the electron source duration can be approximated as the laser pulse duration due to the fact that electrons are accelerated directly in the laser field, this is not necessarily the case for positrons. The positron beam duration can be affected by small-angle scattering in the dense target. For example, calculations for a 1.5 mm thick gold target show that for 10 MeV positrons the increase in beam duration due to scattering is about 190 fs⁴⁷. This would be larger for thicker targets, and therefore should be taken into account into the pair density evaluation¹⁴¹. In short, the increase of the positron beam duration over the laser pulse duration due to the transport is negligible for the “Direct” method using multi-ps lasers¹³⁴, but it can be comparable to that of the laser pulse length for much shorter laser pulse duration (10s fs) used for the “Indirect” approach and therefore needs to be considered^{47,141} in positron volume evaluation.

(c) *Positron angular divergence.* The positrons originating from the BH process have a spatial distribution that depends on the source of electrons and the target material and thickness. The pair angular distribution can be measured as part of beam emittance characterization¹³⁷. Divergence measurements based on the “Direct” method show that the sheath electric field at the target rear surface can reduce the angular divergence of positrons substantially^{137,157}. In cases where the divergence is not measured, it is common to estimate it based on Monte-Carlo simulations, although their accuracy depends on the physics included. For example,

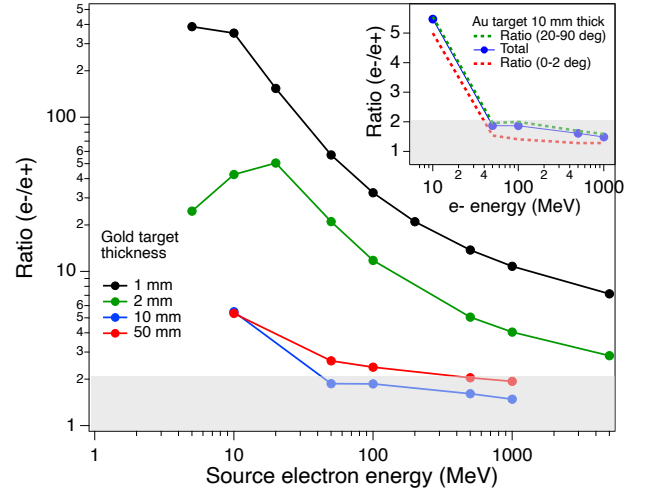


FIG. 9. Calculated electron/positron charge ratio for BH pair process for electrons with energies from 5 MeV to 1 GeV on a gold target for four different thicknesses. The inset shows the charge ratio for the particles within 2° and 20° to 90° collecting angles, together with that from all angles. The shaded region in both the figure and inset represents 50% to 100% charge neutrality.

straggling from small-angle deflections has been shown to have a significant effect^{47,141}. In addition, electromagnetic fields produced in the plasma can further affect the positron angular distribution¹⁵⁷, although these are not included in the Monte-Carlo simulations.

Insofar, the reported maximum pair densities outside the target range from $n_{\pm} = 10^9 - 10^{14} \text{ cm}^{-3}$ with^{138,139} and without^{43,134} magnetic collimation for the “Direct” method using 100 - 1000 J lasers, and $n_{\pm} = 10^{14} - 10^{16} \text{ cm}^{-3}$ for the “Indirect” method based on laser wakefield accelerated electrons^{40,155,158}.

We note that the maximum pair density can quickly drop with distance from the target, depending on the pair divergence. This can affect the pair plasma behavior or the instabilities produced by the interaction of the pair jet with an ambient plasma (as discussed in §IIC) and as such must be considered carefully in experimental studies.

Charge neutrality. It is important to have control over the charge neutrality of the electron-positron beams produced both for studies of pair-driven instabilities in a background plasma or pair plasma studies. The level of charge neutrality of the electron-positron pair beams can be calculated^{43,155,159} based on the individual electron and positron densities, which are estimated separately using the same method as described above.

While the number of electrons and positrons produced via the pair production mechanisms discussed above, including the BH (or Trident) process, is symmetric, the presence of the primary electrons will lead to an excess of negative charges in the resulting pair beams. Dif-

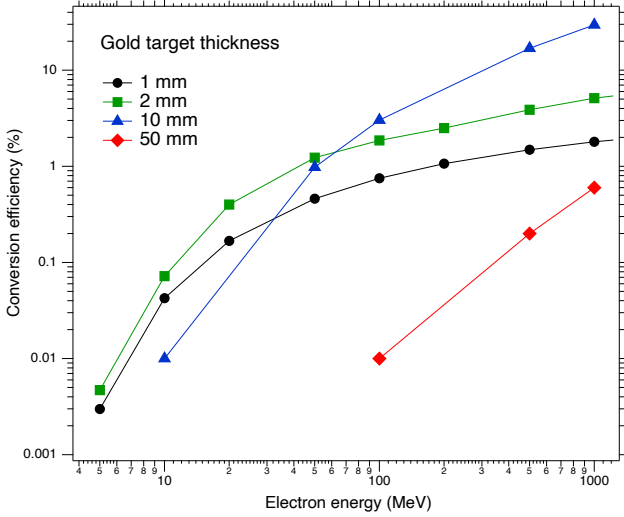


FIG. 10. The energy conversion efficiency from source electrons to positrons for four target thickness as a function of source electron energy.

ferent strategies are being explored to control the level of charge neutrality. One possibility is to use thicker targets than can range out the majority of the primary electrons^{40,43,59}. This is illustrated in the calculated data in Fig. 9. The ratio of total number of electrons and positrons outside the back of the target is calculated for four different thicknesses of a gold target at a range of pencil-type electron beams. A better than 50% charge neutrality can be achieved for thick targets (10 mm and 50 mm) when using primary electron energies above 100 MeV. For a small (e.g., 2°) collecting angle relative to the target normal direction, the electron and positron ratio can reach about 80% – 90%, as shown in the inset figure. We note that while using a thicker target to improve the charge neutrality can be advantageous at high electron energy (> 100 MeV), at lower energies an important drawback is the reduced conversion efficiency. This is shown in Fig. 10.

A promising possibility for improving the charge neutrality with a lower energy electron source is to apply an external axial magnetic field that is designed to collimate only a narrow energy band of the electrons and positrons, resulting in a quasi-charge neutral electron-positron jet^{138,139}. As discussed earlier, by using an externally applied magnetic field to the target, one should be able to remove the excess electrons from the pair beams and effectively achieve the charge neutrality without compromising the positron yield. For example, experiments have shown that the ratio of positrons to electrons in the pair beam increased from 0.01 without magnetic lens to 0.3¹³⁸ and 1¹³⁹ with the lens applied.

C. Positron yield scaling for laser-pair production via BH process

The positron yield is related to the target density ρ , photon distribution n_γ and the BH cross-section σ_{BH} and the optical depth of the photon in the target l as follows:

$$Y \propto \int n_i N_\gamma(\epsilon) \sigma_{BH}(\epsilon) <\rho l> d\epsilon \quad (12)$$

The integral is over all photon energies above the pair creation threshold and the average of ρl is over all the photon-target integration angle. $N_\gamma(\epsilon)$ is the bremsstrahlung distribution in the target:

$$N_\gamma \propto \int n_i n_e(\epsilon) \sigma(\epsilon)_{e \rightarrow \gamma} d\epsilon \quad (13)$$

To project the pair yield (Y) for near future lasers, we now discuss the relationship between the BH pair production, the source electron temperature, and the target material without going into the detailed derivations, which have been discussed elsewhere¹¹³. The pair yield is strongly dependent of the target Z ($Y \propto Z^4$) as each of the cross-sections of the two-step process are proportional to $Z^{211-113}$. The pair yield further depends on the laser intensity via the source electron distribution $n_e(E)$ produced by the laser and target plasma interactions. As will be discussed separately for the “Direct” and “Indirect” methods, the primary electron source ultimately determines the pair yield.

In the “Direct” pair production configuration, the dependence of primary electron source distribution $f_e(\epsilon)$ on the driving laser intensity has been studied for many years for applications such as electron fast-ignition and secondary source (gamma, proton and ion as well as neutron) generations. Basically, depending on the laser and target parameters, scalings such as “ponderomotive”¹⁴⁹ and “Pukhov-scaling”¹⁴⁵ have been used to describe the MeV electron-distribution for laser-solid interactions: T_e (MeV) $\approx (0.5 - 1.5) \times [I(10^{18} \text{ W/cm}^2) \lambda_0^2(\mu\text{m})]^{1/2145,149,157}$. Together with the electron re-circulation in the target, this leads to a quadratic scaling of the positron yield with the laser energy $N_\pm \propto \epsilon_{laser}^2$, as demonstrated experimentally and shown in Fig. 11. This scaling was supported by analytical analysis and by particle-in-cell simulations^{42,157}.

Recently, a higher electron temperature scaling (“super-ponderomotive”) was found for multi-ps KJ laser-plasma interactions: T_e (MeV) $\approx 5[I(10^{18} \text{ W/cm}^2) \lambda_0^2(\mu\text{m})]^{1/2160,161}$. Although the scaling of this long-pulse regime is more favorable for the pair yield¹³⁶, current multi-ps lasers (such as NIF ARC¹⁶²) operate at relatively low laser intensity ($I \approx 10^{18} \text{ W/cm}^2$) for which the expected pair yield is lower than that obtained at sub-ps lasers operating at higher laser intensities ($I > 5 \times 10^{19} \text{ W/cm}^2$).

In the “Indirect” pair production configuration, primarily electrons at typically produced by laser wakefield

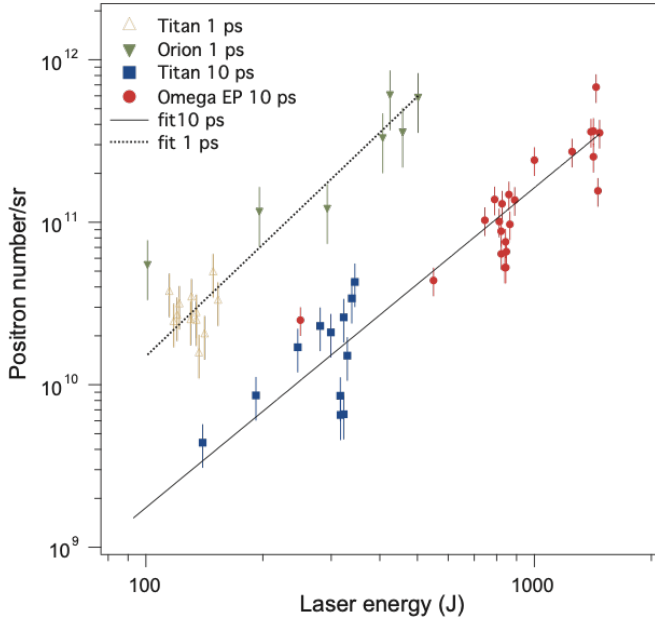


FIG. 11. The experimental scaling of positron numbers to the laser energies from Omega EP as well as Titan and Orion laser. Positron yield scales approximately the laser energy squared (From Chen et al., PRL, 2015).

acceleration. The laser converts its energy into a plasma wake with some efficiency over a dephasing length and then the electrons absorb the wake energy with a separate efficiency. The electron scaling is more complex because the acceleration mechanisms differ for different experimental setup for a wide range of laser intensities (10^{18-20} W/cm² and plasma target with density from under to over critical density. Like that in laser-solid interactions, the laser interaction with low density plasmas have been studied extensively for applications such as advanced accelerator concepts and low-emittance photon sources. These applications requires different electron distributions than that needed for pair plasma applications. As discussed in section, §II B to produce large enough relativistic pair plasmas (in skin depth units) for studying the underlying collective processes we want to maximize $N_{\pm}/\gamma_{\pm}$. This is naturally proportional to the charge and inversely proportional to the energy of the primary electron beam. So we are interested in maximizing charge without significantly increasing electron energy. The scaling of beam charge and electron distribution with laser energy depends on the specific regime of LWFA considered.

We first consider the blowout regime of nonlinear LWFA, where the laser is matched to the blowout radius and the pulse length is a fraction of it, as derived by Lu *et al.*¹⁵⁰. The accelerated beam charge scales with $(E_L a_0)^{1/3}$ and the matched laser duration scales with $(E_L/a_0^2)^{1/3}$, where E_L is the laser energy. In order to maximize the beam charge, we would like to maximize a_0 , but this can also put significant constraints on the required laser du-

ration. In order to understand the optimal scaling for the duration currently envisioned for near future high-intensity laser systems, we consider a laser duration of 20 fs, which seems a reasonable lower limit.

For fixed laser duration, the matched spot size is also fixed, and we have that a_0 scales with $E_L^{1/2}$. This yields a beam charge scaling with $E_L^{1/2}$. For this fixed laser duration, the accelerated electron beam energy would also be fixed, meaning that $N_{\pm}/\gamma_{\pm}$ would also scale with $E_L^{1/2}$. For current 1-10 J laser systems, the produced beam charge at this laser duration is $\sim 0.1 - 1$ nC. For future laser systems, such as the recently proposed EP-OPAL, with 1 kJ, 20 fs, it could be possible to produce a 400 MeV electron beam with a maximum charge of ~ 10 nC.

The nonlinear bubble regime⁷ can potentially lead to the injection of more charge than the blowout regime. However, in the case of the bubble regime, both the charge and the electron beam energy scale with $E_L^{1/2}$. Therefore, in this regime higher energy lasers do not bring a significant advantage in terms of the $N_{\pm}/\gamma_{\pm}$ scaling.

The linear LWFA regime, in particular the SM-LWFA regime, can be more advantageous in terms of producing very high charge by using a laser pulse that is considerably longer than the plasma wake wavelength¹⁴²⁻¹⁴⁴. In this case, the electron beam spectrum will have a large energy spread in contrast with the nearly mono-energetic spectrum associated with the blowout and bubble regimes of LWFA. While the characterization of the energy conversion efficiency between the laser and the beam in SM-LWFA has not been thoroughly established, it seems reasonable to consider values of $\sim 10\%$ based on recent studies¹⁶³ that have demonstrated 11% conversion efficiency in the generation of about 200 MeV, $0.7 \mu\text{C}$, electron beams using the kJ-class OMEGA EP laser. For 10 kJ-class laser systems, such as the NIF-ARC, this would potentially enable the generation of 10 μC electron beams with similar energy.

Finally, we note that other schemes for electron acceleration are under investigation. In particular, recent experiments using such Direct-Laser-Acceleration^{145,146} demonstrated the generation of $\approx 0.2 \mu\text{C}$ electron beams¹⁴⁷. While this beam charge is slightly lower than that obtained from SM-LWFA under similar laser conditions, this could also be a promising source for electron-positron generation that should continue to be explored in the future.

V. PROSPECTS FOR FUTURE EXPERIMENTAL DEVELOPMENTS AND PROGRAMS

The number and density of pairs produced by previous experiments is still below the requirements to produce a large enough pair plasma that supports collective behavior, as we will discuss in more detail in §V E. How-

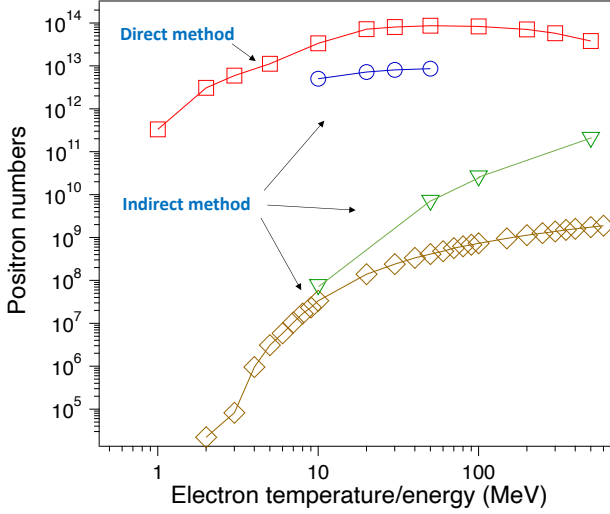


FIG. 12. Number of positrons expected from BH process from near term lasers on a 1 mm gold target using the “Direct” method (red squares) or the “Indirect” method based on either SM-LWFA (blue circles) or LWFA (gold diamonds); Estimates for the “Indirect” method based on LWFA for a 10 mm gold target (green upside down triangles) are also shown.

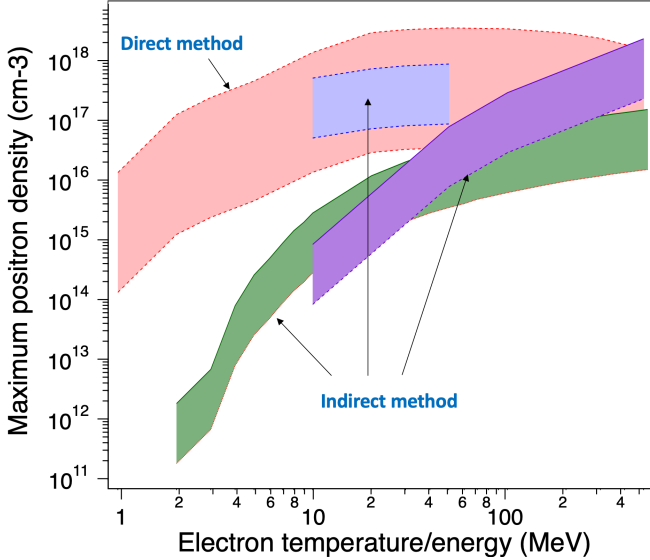


FIG. 13. Positron density range achievable from near term lasers using “Direct method” and a 1 mm gold target (red shade); using SM-LWFA electrons via “Indirect method” on a 1 mm gold target (blue shade); using LWFA electrons on a 1 mm gold target (green shade); and a 10 mm gold target (purple shade).

ever, this situation is expected to change over the coming years. As the energy and power of lasers increases, it is expected that not only will the number and density of pairs produced by the BH process significantly increase but also it will become possible to access different regimes

of pair production associated with higher laser intensities. In this section, we will first estimate the pair beam parameters that could be produced with these near future laser systems and discuss their application to laboratory relativistic pair plasma studies, and then we will discuss some of the pair plasma studies that are accessible with these parameters. Finally we will comment on the diagnostic development needed for the experiments.

A. Improving Bethe-Heitler pair production number, density, and charge neutrality

Laser energy, pulse duration, and intensity. For clarity and simplicity, we consider as relevant laser parameters for the BH pair-production regime laser energy of up to 10 kJ, pulse duration between 10 fs to 10 ps, and maximum laser intensity of 5×10^{22} W/cm², which corresponds to the transition to the BW dominated pair regime. For laser intensities below this threshold the electron temperature is less than 500 MeV assuming an optimal super-ponderomotive coupling of 5 times the ponderomotive electron temperature.

For the pair generation target, we considered a 1 mm thick gold slab target in most cases although the results of using thicker (up to 10 mm) target are discussed too. The goal is to provide a baseline picture for the discussion. The pair yield can be affected by the details of the target, such as target material and transverse size or shape. Please see references^{47,113,157} for a more detailed discussion of how the pair yield depends on the target and laser parameters.

Primary electron distributions: Depending on the scheme of pair-production considered, we assume the source electron distribution to be either 1) Maxwell-Boltzmann or 2) quasi mono-energetic. For the “direct” method based on laser-solid target interactions, we assume a 30% energy coupling efficiency between the laser and electrons based on previous experimental results¹⁵⁷. We note that higher coupling factors, up to 90%, are possible if an under-critical density plasma is present at the laser-target interface^{161,164}. In the case of the “indirect” method based on SM-LWFA we assumed a 10% energy conversion based on previous studies¹⁶³. Finally, for the “indirect” method based on LWFA we assume a quasi-monoenergetic electron distribution with a maximum 10 nC charge as discussed in §IV C.

Pair pulse length: For simplicity we consider a pulse duration of 10 ps for the electron source produced by laser pulses with similar duration in both “Direct” and “Indirect” method based on SF-LWFA. This consideration is based on the fact this is currently the longest pulse duration for relativistic laser intensities and one for which there is a large number of experimental results¹⁵⁷. For the “Indirect” method based on LWFA we consider a pulse duration of 0.01 – 0.1 ps for the quasi mono-energetic source.

Pair number: for electron sources with Maxwell-

Boltzmann distribution, the number of pairs produced as a function of input electron temperature has been well documented analytically and found to agree with experiments^{42,113,157}. Based on previous studies, we assume that the fraction of pairs that escape the solid target is $\sim 10\%$ of the total number of pairs created¹⁵⁷. In Figure 12 we show the estimated pair yield as function of electron temperature from 1 – 500 MeV for a 10 kJ laser and 1 mm thick gold target. Under such conditions, the predicted maximum positron yield is $N_{\pm} = 10^{14}$. This is about two orders of magnitude higher than the current maximum positron yields achieved with kJ class lasers⁴².

For the “Indirect” pair production approach based on the SM-LWFA scheme, we estimate a maximum positron yield of $N_{\pm} = 10^{13}$ for the same 10 kJ laser system and 1 mm thick gold target. For the LWFA scheme we estimate the pair yield based on a monoenergetic electron beam interacting with either a 1 mm or 10 mm thick gold target.

A maximum positron yield of $N_{\pm} = 10^{11}$ could be achieved from a 10 nC electron beam driven by a kJ laser. This is about three orders of magnitude higher than the maximum currently achieved yield based on LWFA⁴⁰.

These estimates are based on the current understanding of the scaling of the different schemes. We note that the exact yields can depend on the details of the laser-target parameters, including target material⁴⁷, size⁴³, and shape¹³⁵.

Pair angular distribution: the angular spread of the pair beam depends on the laser energy and target conditions. For the “Direct” method, we consider a range of $10 - 40^\circ$ full width at half maximum (FWHM) angular spread based on previous measurements^{38,137,157}. For the “Indirect” methods, previous studies show divergence angles varying from a few mrad up to rad depending on the positron energy^{46,47,158,165}. We considered a range of $10 - 100$ mrad in our estimates.

Pair density: based on the previous discussion for the different pair parameters, we can estimate the pair density. The key to derive pair density is to estimate their volume, which can be described as frustum with the source size for smaller areas. The height is the pair length (duration) and pair source divergence determines the shape of the frustum.

The resulting pair density is shown in Fig. 13. For the “Direct” pair production method, the range of densities estimated are shown in the red band. The upper and lower bounds represent the ranges covered by laser pulse duration of 1 – 10 ps and positron divergence angle of $10 - 40^\circ$ (FWHM).

For the “Indirect” laser pair production using monoenergetic electrons based on LWFA, the green and purple bands represent the range of pulse duration (10 – 100 fs) and positron divergence (10 – 100 mrad) considered for either a 1 mm (green) or 10 mm (purple) thick gold target. For pair production based on SM-LWFA the estimated pair density is shown in the blue band for a range of pulse durations between 1 and 10 ps, a positron divergence of

10 mrad, and a 1 mm thick gold target.

B. Pair-production from laser-solid interactions at $5 \times 10^{22} \text{ W/cm}^2 < I < 10^{24} \text{ W/cm}^2$

Up now experimental studies have been limited to the laser intensity regime $I < 5 \times 10^{22} \text{ W/cm}^2$ and the dominant pair production mechanism has been BH. Exciting recent developments in laser systems promise to open a new window for pair production studies at higher intensities in the near future like that achieved on Ref.¹³¹. This has motivated important theoretical and numerical studies of pair production at ultrahigh intensities^{51,166–172}. While there is no experimental data yet for this regime, we shall discuss the current understanding of the properties of pair beams and plasmas that could be produced based on theoretical arguments and existing numerical studies.

In the interaction of an ultraintense laser with a solid target, while the target is overdense, the reflected laser light will create strong-field conditions in the counter-propagating laser field region that can lead to significant gamma-ray emission by Compton scattering of laser-accelerated electrons and pair production^{51,166,171}. The condition that the plasma remains relativistically overdense, limits the laser intensity to $\sim 10^{24} \text{ W/cm}^2$ for typical high- Z solid targets, such as Al. In this regime, pair production can be achieved via two main processes: BH and BW.

In the case on BH pair production, previous numerical studies considered a $\sim 100 \text{ J}$ laser with $I \sim 10^{23} \text{ W/cm}^2$, $\tau = 25 \text{ fs}$ interacting with a solid-density $50 \mu\text{m}$ thick gold target¹⁷¹. It was shown that 10^{13} pairs, with a density of $\sim 3 \times 10^{19} \text{ cm}^{-3}$ and an average energy of 6 MeV can be produced, which would enable the study of collective effects in relativistic pair plasmas.

In the case of BW, it was shown that a 300 J, 10 PW, 30 fs laser can produce $N_{\pm} = 10^{1051,166}$. This is a negligible fraction of the number of particles of the target in the same volume. (Inside the target, the resulting plasma is not pair dominated.) However, as the relativistic electron-positron pairs escape from the rear side they form a pair dominated jet with density $\sim 10^{20} \text{ cm}^{-3}$. The pairs have an average energy of 200 MeV per particle, which can be of interest to studying relativistic pair-driven instability from the propagation of this jet in an ambient electron-proton plasma.

C. QED cascades induced by laser-laser interactions at $I > 10^{24} \text{ W/cm}^2$

In the interaction of ultra-intense counter-streaming laser-pulses it is possible to accelerate and trap a population of seed electrons that can initiate a QED pair cascade. Electrons accelerated in the laser field will emit high-energy photons that will decay in e^-e^+ pairs. It

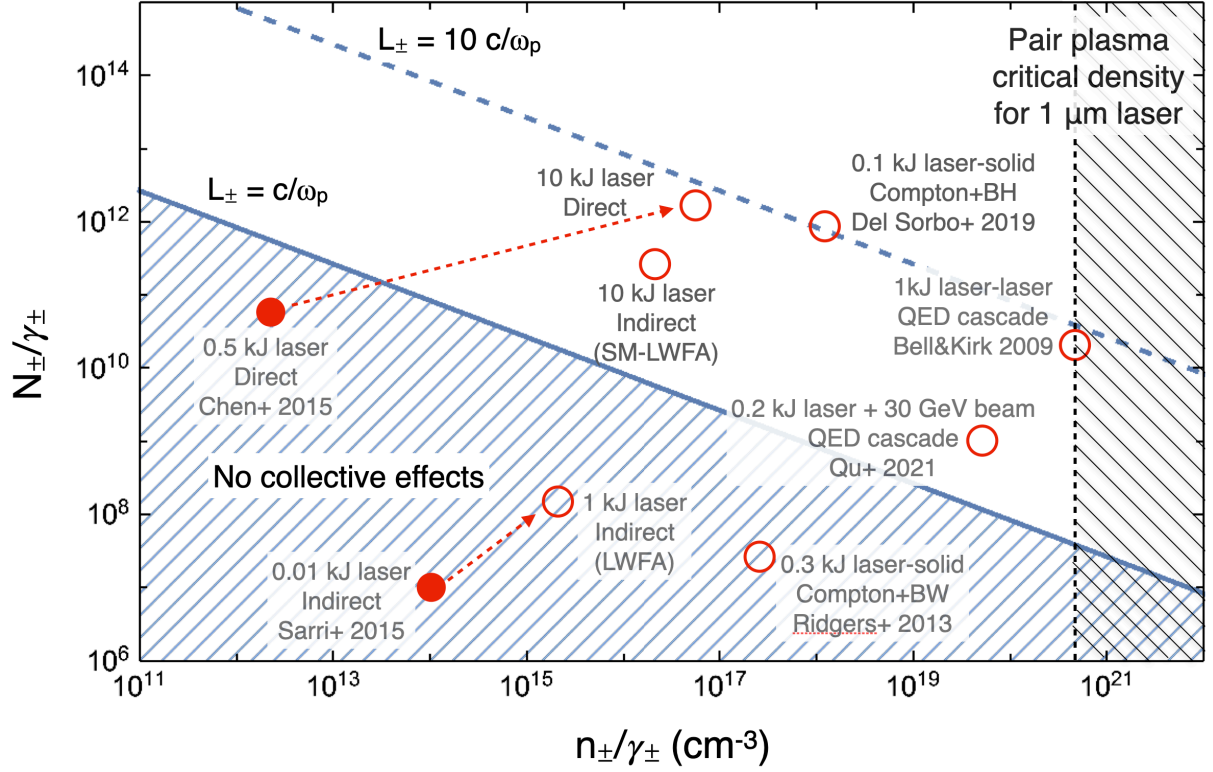


FIG. 14. Prospects for the experimental study of collective effects in relativistic pair plasmas. Electron-positron number and density of relativistic pair plasmas obtained in recent laser experiments (filled circles) and projected for future experiments (open circles) based on existing scalings and numerical simulations. Shaded blue region indicates parameter space where the pair plasma size ($L_{\pm}$) is smaller than a relativistic skin depth for which no collective plasma effects are expected. Shaded black region indicates the relativistic pair plasma critical density above which a laser with 1 μm wavelength cannot propagate in the pair plasma and will be reflected.

was predicted that the threshold laser intensity for the development of a QED cascade is $I \sim 10^{24} \text{ W/cm}^2$ ⁵⁰. This exciting prospect has motivated a large number of theoretical and numerical studies^{50,129,130,173–182}.

During the cascade the laser will be fully depleted with its energy going into high-energy photons and e^-e^+ pairs. As shown by Bell and Kirk⁵⁰, above this threshold intensity the number of photons and pairs, as well as their energies is in rough equipartition (see figure 1 of Ref.⁵⁰). This enables a simple estimate of the total number of pairs produced from energy conservation:

$$\epsilon_L = \epsilon_{\gamma} N_{\gamma} + \epsilon_{\pm} N_{\pm} \approx 2\epsilon_{\pm} N_{\pm}, \quad (14)$$

where ϵ_L is the laser energy and $\epsilon_{\pm}$ is the average electron/positron energy. At an intensity of 10^{24} W/cm^2 the average energy per pair produced is $\sim 100 \text{ MeV}$ (50 MeV per particle). This indicates that the total

number of pairs produced per Joule of laser energy is $N_{\pm}/\epsilon_L \approx 3 \times 10^{10}/\text{J}$. It is interesting to note that as the laser intensity is increased above this threshold the energy per pair also increases, which leads to a lower number of pairs produced for a fixed laser energy. Thus, in order to maximize the number of pairs produced the laser intensity should not significantly exceed this threshold. The density of pairs is given by the volume over which the pairs are produced. For a typical laser wavelength of 1 μm , the smallest volume is $\sim 1 \mu\text{m}^3$, corresponding to a maximum pair plasma density per Joule of laser energy of $n_{\pm}/\epsilon_L \approx 3 \times 10^{22} \text{ cm}^{-3}/\text{J}$. Interestingly, for a pair plasma with $\gamma_{\pm} \sim 100$ this value is close to the density at which the pair plasma becomes (relativistically) opaque to the laser, which is the maximum pair density that is produced by the cascade. This maximum density is given by

$$n_{\pm, \text{max}} = 5.6 \times 10^{20} \gamma_{\pm}. \quad (15)$$

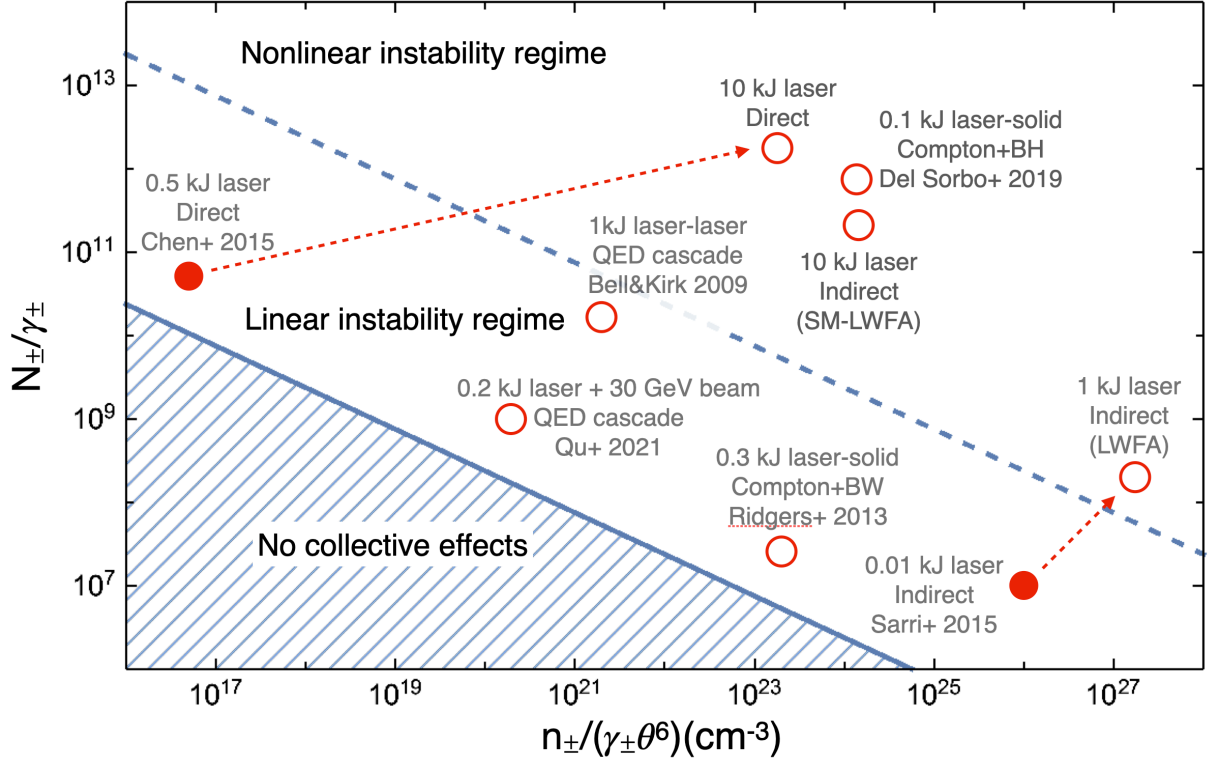


FIG. 15. Prospects for the experimental study of collective effects and instabilities in the interaction of relativistic pair beams with ambient electron-ion plasmas. Electron-positron number, density, and divergence of relativistic pair plasma beam obtained in recent laser experiments (filled circles) and projected for future experiments (open circles) based on existing scalings and numerical simulations. Shaded blue region indicates parameter space where the pair plasma size ($L_{\pm}$) is smaller than the skin depth of the background plasma. Solid and dashed blue curves illustrate the onset of linear and nonlinear regimes for the Weibel, or current-filamentation, instability.

Above this density the laser light would be reflected and pair production would cease. This will thus also limit the maximum number of pairs that can be produced by the laser-laser induced QED cascade, which can be written as

$$N_{\pm,\text{max}}/\epsilon_L = n_{\pm,\text{max}}c/I_L = 1.7 \times 10^9/J. \quad (16)$$

For two counter-streaming lasers with 1 kJ each, such as the L4 laser at ELI¹⁸³, a maximum number $N_{\pm,\text{max}} = 3.4 \times 10^{12}$ pairs could be produced. This is roughly an order of magnitude larger than the largest number of pairs currently produced using the BH process at similar laser energy⁴².

The electrons and positrons produced during the cascade will be heated in the transverse direction by the laser fields, leading to comparable pair transverse and longitudinal momenta. Thus the divergence angle of the resulting pair plasma is $\theta = \tan^{-1}(p_{\perp}/p_{\parallel}) \sim 45^\circ$ and the

pair density will drop due to plasma expansion following the cascade.

We note that these laser-laser cascades need to be seeded and that in order reach saturation of the QED cascade within the pulse interaction it will be important to start already with a large number of electrons. This could be achieved for example by having the two lasers focused on a μm -scale liquid hydrogen jet with density $\sim 5 \times 10^{22} \text{ cm}^{-3}$ ¹⁸⁴. For a laser intensity $I > 10^{24} \text{ W/cm}^2$ the plasma will be relativistically transparent. However, it will be important to address the role of plasma effects on the laser focusing and in establishing an optimal QED cascade¹⁸⁰. This, as well as the control of the initial seed plasma density profile, could be achieved by using a thinner (sub μm) liquid jet that is pre-expanded by the laser pre-pulse (or by a separate laser)¹⁸⁵. Additionally, the production of dense pair plasma from QED cascades will also require precise transverse alignment of the laser

beams and adjustment between the laser duration and transverse spot size¹⁸⁶.

D. QED cascades induced by laser-electron-beam interactions

The interaction of high-energy electron beams and intense lasers can also lead to prolific pair production^{54,187–191}. The electron beams can be produced either by conventional accelerators, as in the SLAC E-144 experiment¹²², or by an intense laser. Recent numerical studies have shown that by colliding a GeV electron beam with a laser of intensity $I \gtrsim 5 \times 10^{23} \text{ W/cm}^2$ it is possible to convert a significant fraction ($\gtrsim 10\%$) of the number of primary electrons into pairs¹⁹⁰. For typical electron beams with nC charge, the resulting number of pairs $N_{\pm} \simeq 10^9$ could still be relatively small for collective pair plasma studies. However, at higher electron energies, as $\chi \gg 1$ the number of pairs could increase significantly via the onset of QED cascades, as shown recently^{54,191}.

The high-energy electron beam enables a strong boost of the laser field strength experienced by electrons in their rest frame $\chi \sim 0.8\epsilon_b(\text{GeV})[I(10^{22}\text{W/cm}^2)]^{1/2}$. For electron beams from current linear accelerators with $\epsilon_b \gtrsim 10$ GeV and currently available laser intensities, it is possible to reach $\chi \gg 1$, opening an interesting route for the study of QED cascades and associated pair plasmas. In this scheme, the electron beam also provides the dense seeding population for the cascade, with $n_{\pm} \simeq \chi n_b$. For highly compressed electrons beams, such as those being explored at the FACET-II facility at SLAC¹⁹², beam densities $n_b \gtrsim 10^{20} \text{ cm}^{-3}$ could be produced in the near future, enabling the generation of pair plasmas with densities potentially approaching the relativistic critical density. The energy of the resulting pair is primarily dictated by the laser intensity with $\gamma_{\pm} \simeq a_0$, and similarly to the laser-laser cascades its divergence angle is $\theta \sim 45^\circ$.

Recent 3D PIC simulations of the head-on collision of a 3 PW laser pulse (50 fs duration, $2.5 \mu\text{m}$ waist, $3 \times 10^{22} \text{ Wcm}^{-2}$ intensity) with a 30 GeV, 1 nC, $4 \times 10^{20} \text{ cm}^{-3}$ electron beam indeed showed the possibility to produce a pair plasma with $N_{\pm} \sim 10^{11}$, $n_{\pm} \sim 5 \times 10^{21} \text{ cm}^{-3}$, $\gamma_{\pm} \sim 100$, and $\theta \sim 45^\circ$. As discussed in Ref.¹⁹¹, such a configuration would open the possibility for the study of collective effects associated with the dense relativistic pair plasmas.

As in the case of laser-laser configurations, the production of dense pair plasma from laser-electron-beam QED cascades will also require precise transverse alignment and adjustment of the duration between the laser pulse and the electron beam.

E. Future laser-driven pair-plasma studies

The scalings for pair production with high-power lasers discussed for the different regimes are summarized in Figs. 14 and 15. We can see in Fig. 14 that while the number and density of pairs produced by previous experiments is still below the requirements to produce a large enough pair plasma that supports collective behavior, the availability of high-intensity kJ-class lasers is expected to enable the generation of pair plasmas with a size of up to $10c/\omega_p$ via different approaches. For 10 kJ, multi-ns lasers such as NIF-ARC¹⁶² and PETAL¹⁹³ that are now becoming available, both the “Direct” method and the “Indirect” SM-LWFA regime could enable the generation of the required pair plasmas with densities $n_{\pm} = 10^{16} - 10^{18} \text{ cm}^{-3}$ via the BH process. In parallel, upcoming short pulse ($\lesssim 30$ fs), ultra-intense lasers, such as the ones becoming available at ELI¹⁸³, APOLLON¹⁹⁴, OMEGA-MTW/OPAL^{195,196} and Michigan-ZEUS¹⁹⁷, offer exciting opportunities to explore different regimes.

For example, at 0.1 kJ and 10^{23} W/cm^2 , relativistic pair plasma jets with density $\sim 10^{19} \text{ cm}^{-3}$ could be produced via BH in the laser interaction with high-Z solid targets¹⁷¹. In the collision between two kJ, 10^{24} W/cm^2 lasers, or between a 0.2 kJ, $3 \times 10^{22} \text{ W/cm}^2$ laser and a 30 GeV electron beam, QED cascades can be produced in the laboratory giving rise to the generation of relativistic and ultradense pair plasmas. This is a tantalizing prospect, where under the action of strong fields, the coupling of QED processes and collective plasma effects becomes important in the pair plasma dynamics. This constitutes a new strong-field QED-plasma regime that is largely unexplored and is relevant to the understanding of the dynamics and radiative signatures of compact astrophysical objects^{4,13–16,30,31}, such as the environments of black hole and neutron stars — in particular, magnetars^{9,10}.

In Fig. 15 we observe that the relativistic pair beams currently generated in high-Z targets via the BH process (either based on the “Direct” or “Indirect” method) can already enable the study of pair-driven plasma instabilities associated with the propagation of these beams in an ambient electron-ion plasma. As an example, we consider the case of the relativistic Weibel, or current-filamentation, instability, which growth rate, in the cold limit, is given by Eq. (5) and shown in Fig. 2. The pair number, density, and beam divergence produced in previous experiments (see Table I) puts current studies already in the linear regime¹⁹⁸. However, based on the experimental and simulation results, and associated scalings discussed in this section, we see that near future experiments could probe the saturation and nonlinear dynamics of these type of plasma instabilities, where we have assumed that the saturation time corresponds to 10 e-foldings of the instability ($\delta = 10$) in Eq. (6).

Considering the propagation of a pair beam on a cold and denser background electron-ion plasma, the mag-

netic field produced by the Weibel instability at saturation (via magnetic trapping^{91,199}) has amplitude $B(T) \simeq 6.4n_{\pm}(10^{16}\text{cm}^{-3})/[n_0(10^{18}\text{cm}^{-3})]^{1/2}$ and the magnetic wavelength $\lambda(\mu\text{m}) \simeq 33.4/[n_0(10^{18}\text{cm}^{-3})]^{1/2}$, where we have considered the most unstable mode $k_{\text{max}} = \omega_{p0}/c$ with ω_{p0} the background plasma frequency. See Ref.⁹¹ for a detailed discussion of the dependence of the field structure on the beam and plasma parameters. If $n_{\pm}/n_0 \ll 1$, the resulting background density modulation will be very small, $\delta n/n_0 \ll 1$. But in future studies using high-energy lasers the pair beam density can be comparable to the background density. For a pair beam of $n_{\pm} \sim n_0 \sim 10^{18}\text{cm}^{-3}$ the resulting B-field has $B \simeq 640$ T and the background plasma electron density will develop strong modulations $\delta n/n_0 \sim 1$.

Finally, we comment on the possibility of future experiments probing highly magnetized pair plasma regimes with $\sigma_B \geq 1$. Given the dependence $B_0(T) \propto \sqrt{\gamma_{\pm} n_{\pm}}$ from Eq. (7), magnetized studies favor the use of moderate-intensity ($I \gtrsim 10^{19}$ W/cm²) ps laser drivers producing moderate pair energy $\gamma_{\pm} \gtrsim 10$ and densities $n_{\pm} \sim 10^{16} - 10^{18}\text{cm}^{-3}$. For such conditions the required external magnetic field is $B_0 = 10^2 - 10^3$ T. While challenging, recent advances in both pulsed-power and laser-driven magnetic delivery devices could produce the required magnetic field strengths over mm-cm scales. Current experiments have demonstrated the capability of producing 10-60 T magnetic fields using pulsed power systems^{102,103,105} and 10s to 100s of T using laser driven capacitor coils²⁰⁰⁻²⁰². Moreover, new experimental schemes have been proposed to produce $\approx$ kT field using the spinning angular momentum of intense lasers²⁰³.

F. Diagnostics for the laboratory pair plasma experiments

Future laboratory experimental studies of relativistic pair plasmas, be it from basic plasma modes to instabilities, particle acceleration, or radiative processes, will require advanced diagnostics to observe the signatures of the relevant plasma processes including particle energy distributions, plasma density, magnetic field, and emitted radiation. This will require advances in current instruments in terms of sensitivity, precision, coverage, and better spatial and temporal resolving power, which we summarize below.

Pair energy distribution: For example, to measure a 10% change in the energy distribution of electrons, positrons or ions as a result of pair plasma driven instabilities or shocks^{32,204-206}, one needs the particle energy spectrometer to measure with similar accuracy both the particle numbers as well as its energy. Although both the dispersion^{132,207} and dose¹³³ have achieved better than 10% accuracy, the noise/background of the measurement will need to be counted for the needed overall measurement accuracy. At the present, the detection threshold for electrons is about $5 - 10 \times 10^7$ (sr MeV)⁻¹¹⁵⁹ for high power laser experiments. Obviously, if the pair

numbers are smaller, improvements must be made in the background reduction in order to reach lower detection threshold. This can be done through experimental and diagnostic hardware design. For example, in addition to selecting the detectors with higher sensitivities to pairs but not to background photons, one can also increase the signal-to-noise ratio by adding shielding and reducing the secondary radiation from the spectrometer housing onto the detectors.

Electromagnetic fields: Another importance signature from the pair plasma interactions discussed above are the generation of magnetic fields (few to 100s of Tesla with modulations on scales of few to 10s of μm). Because of its prominence in high power laser-plasma interactions, diagnostics for electromagnetic fields have been studied extensively with techniques including charged particle deflection²⁰⁸⁻²¹¹, Faraday rotation of the polarized light⁷ and atomic spectroscopy^{212,213}. While the atomic spectroscopy is still being developed experimentally, and Faraday rotation technique is not applicable for pure pair plasma, the short pulse driven charged-particle radiography technique^{210,214,215} has been developed for over a decade and it is widely used and remains to be a powerful electromagnetic field diagnostics. This is due to its high sensitivity, and μm spatial and sub-ps temporal resolving capabilities. Recent developments in high energy density plasma studies have established methods for extracting path integrated 2-dimensional data, distinguishing between electric and magnetic fields, and interpreting complex field structures^{208,216-220}. Riding along the continuing diagnostic development, it is expected that charged-particle radiography will play an important role in the measurement of electromagnetic field from the pair plasma experiments.

Plasma density: As to the density modulations from the pair plasma interactions, which is estimated to be of the order of 10% - 100% of background plasma densities of 10^{16} to 10^{20}cm^{-3} with spatial size of $1 - 10\mu\text{m}$, the measurement techniques will strongly depend on the density level.

For a small volume $\leq 100\mu\text{m}^3$, low density $\leq 10^{18}\text{cm}^{-3}$ pair plasma, either refractive index or scattering based density measurement techniques, such as interferometry, reflectometry or coherent and incoherent scattering¹⁰⁴, would have difficulties obtain sufficient signals over background. At higher density ($\geq 10^{19}\text{cm}^{-3}$), either optical interferometry, shadowgraphy, or optical to X-ray Thompson scattering could be used^{104,221}. Although not yet demonstrated, fluorescent spectroscopy might be of use to inform the local plasma density if tracer elements are used as dopant in the interaction regions.

High-energy radiation: Finally, the measurement of MeV to GeV radiation signatures of the above mentioned pair plasma processes will be challenging too. Conventional single-counting, pulse-height based solid detectors are likely to have "pile-up" issues due to the high photon flux that is typical to the radiation source produced in

short pulse, high power laser experiment. To use such technique would require a large array ($\geq 1000 \times 1000$) of sensors to obtain sufficient statistics in single-counting mode. Low efficiencies in both photon dispersion techniques based on Bragg reflection/transmission and in detection due to the low scattering and stopping cross-section of the photons in materials also need to be considered. Moreover, MeV - GeV photons from the laser- or beam-plasma interaction contribute as a background in the measurements.

Despite these difficulties, and due to its broad application in high energy physics and high power laser driven high energy density physics experiments, a large effort has been dedicated to improved MeV-GeV radiation diagnostics. This includes, step-filters^{222,223}, scintillating arrays²²⁴, magnetic electron spectrometers that detect electrons from forward Compton scattering of MeV photons²²⁵⁻²²⁷, gas Cherenkov detectors^{228,229}, or nuclear activation excited by MeV gammas²³⁰. All of these works will benefit future pair plasma experiments.

Given the recent developments in diagnostics and new techniques now being proposed that may be applicable in the near future, we are optimistic that the diagnostics needed can be fielded in experiments to observe the signatures of the pair plasma interaction processes. This, of course, will require careful evaluation of the different signatures of the processes of interest and ensuring the necessary data quality and quantity due to the challenges discussed above.

VI. SUMMARY

We have discussed the current status of laser-driven generation of relativistic electron-positron pairs and progress towards the study of basic pair plasma processes of relevance to high-energy astrophysical systems. Based on current experimental and numerical studies and the understanding of the scaling of pair production using different laser-driven configurations, we presented our perspectives for future experimental studies in this exciting frontier topic. In particular, we discussed the possibility of producing relativistic pair plasmas and study their collective modes over a wide range of conditions, from different degrees of magnetization to the QED-plasma regime, where the interplay between quantum and collective processes becomes important. We have also addressed the prospects for studying streaming instabilities associated with the propagation of relativistic pair beams on ambient electron-proton plasmas. This is a fast developing field, motivated by exciting observational discoveries, theoretical and computational developments, and technological advances in light sources and diagnostics that are pushing the limits of our understanding of relativistic pair plasmas.

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AUTHOR DECLARATIONS

The authors have no conflicts to disclose.

AUTHOR CONTRIBUTIONS

Both authors contributed equally to this work.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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