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Preface to Special Topic: Relativistic Plasma in Supercritical Fields

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I. INTRODUCTION

A mini-conference on "Relativistic Plasma in Supercritical Fields" was held at the 2022 meeting of the American Physical Society Division of Plasma Physics in Spokane, Washington. The objective of this miniconference was to bring together researchers from several different physics communities to address the emerging frontier topic of plasma physics in the strongest electromagnetic fields, motivated by a surging interest in the physics of matter existing in extreme astrophysical objects and generated by highest power laser systems that are currently being constructed and proposed around the world. This Physics of Plasmas Special Topic comprises papers from this mini-conference.

The plasmas that exist in extreme astrophysical objects such as magnetars or surrounding black holes[1], or that are generated in the foci of the most intense lasers[2], cannot be described within the traditional plasma physics framework but must include relativistic effects (including general relativistic in the astrophysical context) and quantum electrodynamics (QED) emission processes to understand them properly. One of the predictions of QED is that in the presence of an electric field stronger than a critical field strength, a "breakdown" of the vacuum occurs, which results in the spontaneous creation of matter and antimatter in the form of electrons and positrons along with prolific high energy photon production[3–5]. While QED is probably one of the best verified theories so far at a single particle level[6,7], the new collective phenomena that arise when electrons, positrons, and photons are exposed to strong electromagnetic fields are not yet well understood[8–11].

Strong electromagnetic fields are those that approach or exceed the QED critical electric, $E_{cr} = m_e^2 c^3/|e|\hbar$, or magnetic, $B_{cr} = m_e^2 c^2/|e|\hbar$, field strengths, in which interactions become highly nonlinear. Here m_e and e are electron mass and charge respectively, c is the speed of light,and $\hbar$ is the Planck constant. In such fields, the prolific production of high energy photons, electrons and positrons can cause complex new plasma interactions with these fields, since photon emission modifies the particle kinetics and electron-positron pair production modifies the local charge density. Plasma under such conditions is only starting to be theoretically explored and experiments need to be designed for high-power laser systems. The physics of such plasmas in strong fields is relevant to early universe conditions[12], extreme astrophysical objects such as neutron star atmospheres[13] and black hole environments[14], and is critical to future high-intensity laser driven relativistic plasma physics[8–11].

II. MINICONFERENCE SUMMARY

The mini-conference on "Relativistic Plasma in Supercritical Fields" was held at the 64rd American Physical Society Division of Plasma Physics meeting held between October 17–21, 2022 in Spokane, Washington. Leading researchers from the extreme astrophysics, laser-plasma and strong-field quantum electrodynamics theory communities were invited to present their latest results, cross-cutting challenges and future prospects in three half-day sessions. The following is a summary of these presentations.

Session I: Facilities for Extreme Fields and Electron-Positron Pair Production

The on-going research on relativistic plasma in supercritical fields is driven by the increased availability of high power laser systems around the world (for recent summary see[10]). There are many PW- and multi PW-class facilities that are already operational, which will enable experimental exploration of plasma behavior in strong fields, including different scenarios of the electron-positron pair production.

An introductory talk giving an overview of the sessions by Alec Thomas of the University of Michigan kicked off the mini-conference. The first session was primarily about experiments and applications, starting with four talks on Laser Facilities for Extreme Field physics research. Stepan Bulanov from Lawrence Berkeley National Laboratory introduced the BELLA PW Laser Facility upgrades to enable high field physics research, with a new second beamline allowing two independently tunable laser pulses to be combined at variable energy ratios, with a combined peak pulse power of 1 PW for collision experiments. Tom Blackburn from the University of Gothenberg introduced the LUXE experiment to study non-perturbative QED in electron-laser and photon-laser collisions using a high-intensity optical laser pulse and 16.5 GeV electrons from the XFEL electron beam, as well as high-energy secondary photons. Ji Liangliang from Shanghai Institute of Optics and Fine Mechanics presented the 10 PW laser facility (SULF) and a proposed 100 PW laser station (SEL) for extreme field physics, which has the exciting prospect of being combined with the hard x-ray free electron laser facility (SHINE). Diagnosing such high intensities was addressed in the talk by Andrew Longman from Lawrence Livermore National Laboratory, which presented ponderomotive electron scattering from Nitrogen and Argon gas at pressures of 10^{-4} mBar to determine the peak laser intensity and focal spot characteristics.

Five talks on Electron-Positron Pair Production then followed. Several talks discussed the optimization of pair-production for potential applications. Yutong He from the University of California, San Diego gave a talk on the formation of GeV-level collimated linear Breit-Wheeler positron beams using experimentally available laser pulses and targets. Alexander Macleod from ELI Beamlines discussed the prospects for all-optical nonlinear Breit-Wheeler pair production using 'gamma-flash' photons. Optimization of positron acceleration by multi-PW laser pulses in plasma channels was presented by Dominika Maslarova from the Czech Technical University in Prague. From a more fundamental perspective, the damping of particle states in the nonlinear Compton scattering and nonlinear Breit-Wheeler pair production processes was addressed by Tobias Podszus from Max Planck Institute for Nuclear Physics. Finally, Kaoru Sugimoto from Osaka University discussed how ultra-short petawatt laser light may self-organize as a photon-photon collider in a near critical over-dense plasma.

Session II: Extreme Astrophysics and Electron-Positron Pair Cascades

The study of astrophysical effects in the laboratory setting is one of the main applications of high power lasers. Expanding these studies to the regimes involving extreme field have attracted a lot of attention recently.

In this second session, talks from the extreme astrophysics and laser-plasma communities were brought together to highlight common problems. The session started with Thomas Grismayer from Instituto Superior Técnico presenting a simple kinetic model to predict the growth rate of electron-positron pair cascades with particular application to the polar caps of neutron stars. Maxim Lyutikov from Purdue University introduced a model of the generation of coherent radio emission in the magnetospheres of magnetars with nearly critical strength magnetic field, with applications to fast radio bursts. A general consideration of low-frequency waves and instabilities in QED-strong field plasmas from Mikhail Medvedev from University of Kansas showed that the general structure of plasma eigenmodes remains qualitatively the same but may see order one QED corrections. Kevin Schoeffler from Instituto Superior Técnico discussed limits on the compression of magnetic islands, a source of synchrotron radiation bursts in particle-in-cell simulations of strong-field 3D relativistic magnetic reconnection. An overview of radiative magnetic reconnection in strong magnetic fields in neutron star magnetospheres was given by Dmitri Uzdensky of the University of Colorado, Boulder.

The session continued with studies of electron-positron-gamma ray cascades, with presenter Kenan Qu from Princeton University showing that creation of QED plasma also induces strong coherent laser reflection at high reflection coefficient, which provides potential experimental signatures of QED plasma creation. Christopher Ridgers from the University of York discussed the progress made towards probing QED-plamas with current petawatt-class laser facilities. One feature of laser-solid density plasma interactions is the generation of extremely strong magnetic fields, for which Brandon Russell from the University of Michigan presented a new analytic scaling of the magnetic field strength with laser intensity, supported by simulations. Closing the session, Alec Griffith from Princeton University discussed laser frequency upshifts in QED cascades and detectability concerns.

Session III: Radiation reaction, gamma-ray production, lepton spin effects and vacuum physics

The study of the fundamental strong field quantum electrodynamics effects in plasma that will be enabled by high power laser facilities is one of the main directions of research. The radiation reaction effects, gamma-ray production, lepton spin effects, and vacuum physics were covered in the final session. The session started with Pablo Bilbao from Instituto Superior Técnico talking about radiation reaction cooling as a progenitor of kinetic instabilities and coherent radiation, in particular development of the cyclotron maser instability. Prokopis Hadjisolomou from ELI Beamlines presented studies of bright gamma-ray flashse in the λ^3 regime, in particular showing that radial laser polarization offers substantial advantages. Tae Moon Jeong from ELI Beamlines followed this up with a study of efficient generation of γ-photons from a solid target irradiated by 1-100 PW laser pulses.

Three talks on lepton spin effects in plasma commenced with Daniel Seipt from the Helmholtz Institute Jena described a new kinetic framework, in particular unifying classical precession and quantum emission processes and developing single particle equations-of-motion through momentum moments. Yan-Fei Li from Xi'an Jiaotong University presented a study on helicity transfer enabled by radiative transverse polarization, followed by spin rotation induced by the anomalous magnetic moment of the electron. Modeling of an experiment to characterize the polarization dependent nonlinear Breit-Wheeler was introduced in a talk by Qian Qian from the University of Michigan.

Physics of the vacuum was also of interest, with an experimental scenario for direct, precision measurement of the two coupling coefficients of the QED Lagrangian via photon-photon scattering being presented by Wendell Hill from the University of Maryland. Finally, to round off Session III and the mini-conference, Martin Jirka from ELI Beamlines discussed how an all-optical configuration in the λ^3 regime based on 10 PW-class lasers with a 50 GeV electron beam could be used to reach parameters where the framework of perturbative QED in strong external electromagnetic fields breaks down.

III. PAPERS IN THE SPECIAL TOPIC COLLECTION

Out of this mini-conference, eleven papers were published in this *Physics of Plasmas* Special Topic collection. These are summarized in the following:

- *"Pair production in an electron collision with a radially polarized laser pulse"*[15] explores electron–positron pair production in laser–electron collisions, revealing that radially polarized laser pulses are more efficient than linearly polarized ones due to their larger strong electromagnetic field area, offering insights into optimizing laser pulse characteristics for enhanced pair creation.

- *"Parametric study of the polarization dependence of nonlinear Breit–Wheeler pair creation process using two laser pulses"*[16] uses a new spin and polarization-dependent QED module within the OSIRIS 4.0 particle-in-cell code framework to demonstrate a two-pulse-pair production scheme and predicts a significant difference in pair production yield with the relative polarization of two linearly-polarized laser pulses.

- *'Radiation-dominated injection of positrons generated by the nonlinear Breit–Wheeler process into a plasma channel"*[17] studies the creation of positron-electron pairs resulting from the orthogonal collision of a relativistic electron beam with a multi-petawatt laser pulse, highlighting the critical role of radiation reaction and suggesting strategies for enhancing positron yield for injection into a channel for direct-laser acceleration.

- *"Plasma modes in QED super-strong magnetic fields of magnetars and laser plasmas"*[18] discusses nonlinear Maxwell's equations resulting from QED-induced vacuum polarization and magnetization, introduces a framework for studying linear modes and emphasizes the significance of charge-neutral electron–positron plasmas in supercritical magnetic fields.

- *"Ultrafast relativistic electron probing of extreme magnetic fields"*[19] explores the feasibility of utilizing laser-wakefield accelerated electrons as a probe to measure strong magnetic fields generated during ultra-intense laser–solid interactions, addressing theoretical considerations, challenges, and proposing a potential experimental setup to measure such fields.

- *"Simulations of laser-driven strong-field QED with Ptarmigan: Resolving wavelength-scale interference and γ-ray polarization"*[20] describes the locally monochromatic approximation (LMA) in the open-source Ptarmigan code, which enables accurate predictions of strong-field quantum electrodynamics (QED) interactions, achieving percent level accuracy across regimes in field strength and offering fine-grained control over physics parameters.

- *"Gamma-flash generation in multi-petawatt laser–matter interactions"*[21] provides a comprehesive review and comparison of various γ-flash schemes to guide experiments and addresses applications such as increased positron generation and nuclear activation due to photonuclear reactions.

- *"Kinetic theory for spin-polarized relativistic plasmas"*[22] develops kinetic equations for spin-polarized relativistic plasma incorporating leading order quantum effects and provides effective single-particle equations of motion, with potential generalization to a comprehensive description of a QED plasma involving electrons, positrons, and photons.

- *"Toward direct spatial and intensity characterization of ultra-high-intensity laser pulses using ponderomotive scattering of free electrons"*[23] introduces a technique employing ponderomotive electron scattering in ultra-low-density gases to directly measure laser characteristics, including spatial, spectral, and temporal features, presenting and validating three models through numerical simulations, for potential applications in high-power laser facilities.

- *"Kinematically boosted pairs from the nonlinear Breit–Wheeler process in small-angle laser collisions"*[24] studies nonperturbative photon-pair conversion in converging laser pulses, revealing a substantial yield enhancement at small convergence angles for photons with specific frequencies, offering a distinguishing feature for nonperturbatively produced pairs and providing insights for experimental strategies in high-energy astrophysics.

- *"Highly polarized positrons generated via few-PW lasers"*[25] uses a few-PW circularly polarized laser pulse as a femtosecond timescale method for generating ultra-relativistic polarized positrons with up to 90% polarization degree using a fully spin-resolved QED Monte Carlo method, demonstrating its potential for applications in fundamental physical studies, material processing, and high-energy experiments.

IV. CONCLUDING REMARKS

The mini-conference on *"Relativistic Plasma in Supercritical Fields"* provided an exploration of the emerging frontier in plasma physics at the extremes in electromagnetic fields. Presentations spanned a wide range of topics, from new facilities for strong fields, electron-positron pair production and cascades to the implications of these phenomena in extreme astrophysical environments and high-intensity laser-driven relativistic plasma physics. The presentations highlighted the critical role of strong electromagnetic fields in shaping new regimes of plasma physics, where traditional models fall short. The mini-conference not only facilitated the exchange of knowledge and ideas between experts from the extreme astrophysics, strong-field quantum electrodynamics theory and high intensity laser-plasma communities but also paved the way for future research directions. We hope this collection of papers inspires researchers to address the experimental and theoretical questions in this exciting new area of plasma physics.

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