Eur. Phys. J. D (2023) 77:55
https://doi.org/10.1140/epjd/s10053-023-00617-5

THE EUROPEAN PHYSICAL JOURNAL D

Editorial

Introduction to the Topical Issue high field QED physics

Tong-Pu Yu[1,a], Francesco Pegoraro[2,3,b], Gianluca Sarri[4,c], and David A. Reis[5,d]

[1] Department of Physics, National University of Defense Technology, Changsha 410073, China
[2] Dipartimento di Fisica, Universita' di Pisa, Largo Pontecorvo 3, 56127 Pisa, Italy
[3] Istituto Nazionale di Ottica, CNR, Pisa, Italy
[4] School of Mathematics and Physics, The Queen's University of Belfast, Belfast BT7 1NN, UK
[5] Stanford PULSE Institute, SLAC National Accelerator Laboratory, Menlo Park, CA, USA

Published online 4 April 2023

The advent of high-power ultra-intense laser pulses opens up new frontiers across fields including relativistic nonlinear optics, high-field quantum electrodynamics (QED), high energy particle physics and laboratory astrophysics. In recent years, several high-power laser facilities, e.g., Vulcan, the ELI-pillars, SULF, SILEX-II, GIST, CORELS, just to cite a few, have successfully delivered petawatt (PW)-scale laser pulses, paving the way for extensive research in novel regimes. With such intense laser pulses, the interaction between laser and matter enters into a QED-dominated realm, where extremely rich nonlinear phenomena such as rapid acceleration of electrons and ions, copious electron–positron pair production, and ultra-brilliant gamma-ray emission are involved. These nonlinear QED processes become important when the electric field in the particle rest frame approaches the critical field for QED, i.e., the Schwinger field $E_\mathrm{s} = 1.3 \times 10^{18}\ \mathrm{Vm}^{-1}$.

In this context, *High Field QED Physics* refers to a wide range of topics, both within and beyond ultra-intense laser interaction with matter. Thus, it includes advances in high field QED experiments, ultra-intense laser-driven particle acceleration and secondary particle generation, as well as new algorithms and simulation techniques for nonlinear processes. These general topics were interpreted in the broadest sense, and this issue was open to everyone working in related fields, including those focused on ultra-intense lasers or high energy particle physics and laboratory astrophysics.

The primary motivation for this Topical Issue is that the nonlinear phenomena and multi-photon processes in high field QED have been seldom demonstrated in experiments, and many predictions remain to be confirmed and thoroughly tested. This requires smart schemes for QED probing experiments and high precision measurements along with improved fundamental theory and new simulation techniques for such highly complex systems. It has been also shown that the gamma-ray polarization and the particle spin also affect QED processes to some extent, and this has been extensively investigated in recent years. The rich nonlinear processes occurring during ultra-intense laser interactions with matter provide also unique opportunities for laboratory astrophysics, including gamma-ray bursts, pulsars magnetospheres, active galactic nuclei, and black-hole jets.

Initially proposed by Prof. T.P. Yu and Prof. F. Pegoraro in 2019, with the aim of showcasing the most recent developments and achievements obtained in the high field QED realm in recent years, this issue was also highly motivated by the ninth National High Energy Density Physics Conference in China to be held in 2020. Unfortunately, due to the outbreak of COVID-19 around the world towards the end of 2019, this special issue was affected and was postponed several times, before being finally launched at the end of 2021, with the conference held successfully face-to-face at the end of 2022 in Changsha, China. We received about 20 submissions covering a wide range of high field QED phenomena, which provide an updated perspective of some important developments achieved recently, as well as new directions for high field-based studies in these areas.

The eleven papers included in this Topical Issue address theoretical, numerical, and experimental problems of major interest for present day research in *High Field QED physics*, such as radiation reaction effects, electron–positron pair production, high energy gamma photon emission, high field QED experiments, and some important aspects of high field QED theory.

The first two papers focus on QED physics in traditional accelerators. The first one is authored by Si and Huang [1], who proposed a potentially precise method for calculating the interaction cross section of electrons and microwave photons in a resonant cavity. It is shown

[a] e-mail: tongpu@nudt.edu.cn (corresponding author)
[b] e-mail: francesco.pegoraro@unipi.it
[c] e-mail: g.sarri@qub.ac.uk
[d] e-mail: dreis@stanford.edu

that with suitable corrections in the cross section formula of classical Compton scattering, the cross section of the linear or nonlinear microwave Compton scattering in the local space can be described accurately. This may provide a new way to generate electromagnetic wave sources with strong practical applications, e.g., terahertz waves, ultra-violet waves, and mid-infrared beams. The second paper was written by Musiienko, et al. [2], who proposed a potential barrier model by considering an additional current that can lead to high-gradient breakdowns in accelerating structures. A double potential barrier was proposed and used for calculations of the value of the field emission current density. It is shown that the field emission current increases more than 5 times for a constant value of the electric field strength when considering a non-ideal copper surface with the presence of nanoclusters on the surface of or nanoscale voids in the near-surface layer.

The contribution by Holtzapple, et al. [3] discusses a very important issue in *high field QED physics*, i.e., radiation reaction effects. Radiation reaction played a crucial role when Niels Bohr arrived at his postulates that became part of the foundation of quantum mechanics. In this article, the authors showed how, for ultra-relativistic electrons penetrating single crystals, the scenario, bizarre at first glance, can occur where the reaction force is many times greater than the interaction force between the electron and the crystal without which no radiation would appear.

The paper by Wen, et al. [4] considers the spinorial dynamics of relativistic electrons during ponderomotive scattering in intense laser pulses. They showed that with the evolution of electron spin, a helicity transfer from the transverse polarization to the longitudinal direction with a degree up to 10% can be realized around the reflection condition.

Filipovic and Pukhov investigate QED effects when high-intensity laser pulses graze the surface of a solid-state target by two-dimensional particle-in-cell simulations [5]. It is shown that the electrons extracted from the solid target collide with the counter-propagating laser, which can trigger several QED effects and lead to a QED cascade under a sufficiently high laser intensity. The results are interesting and important since the proposed target may yield many orders of magnitude more secondary particles and a QED cascade may become possible at lower laser intensities than in the seeded vacuum alone.

The paper contributed by Amat et al. [6], discusses the Schwinger pair production rate for some space-dependent fields via the worldline instanton formalism. It is found that under a given field the instanton paths with different values of the Keldysh parameter are exactly in the same plane and the normalized instanton actions are all bounded within the region from π to 2π.

Yang et al. [7] proposed a potentially enhanced terahertz radiation scheme by using the interaction of a linearly polarized laser pulse with a double-layer target consisting of a near-critical density plasma and an overdense density plasma. This clever scheme may provide theoretical and parametric guidance for the generation of high field terahertz waves based on irradiation of structured targets by a relativistic femtosecond laser.

The article authored by Hosak and Di Piazza [8] provides an approximated analytical solution of the Landau–Lifshitz equation in the presence of a virtually arbitrary electromagnetic field by making the assumption that the electron initial energy is the largest dynamical energy in the problem. They show that in a regime where radiation–reaction effects are a small correction of the Lorentz dynamics, the four-momentum of the electron can be determined perturbatively in the ultra-relativistic limit.

Plans for high field QED experiments using the PW laser dual beamlines at the Berkeley Lab Laser Accelerator (BELLA) are introduced by Turner et al. [9]. In this paper, the authors present a short overview of the upgraded BELLA PW facility with a high field QED experimental layout in which intense laser pulses collide with GeV-class laser-wakefield-accelerated electron beams. The presented simulation results showed that the potential experiments can allow for the study of laser-particle interactions from the classical to the SF-QED regime with a value of the nonlinear quantum parameter of up to 2. They also showed that these experiments will enable the study and production of GeV-class, mrad-divergence positron beams via the Breit–Wheeler process.

The paper authored by Gong et al. [10] reviews the computational approaches to examine the vacuum polarization density. Based on computational quantum field theory and solutions to the Dirac equation, the authors show how the vacuum polarization density induced by a strong external field can be calculated based on five independent methods. Especially, they discussed future challenges for each approach that might motivate new theoretical and computational studies.

Finally, the article by Zi et al. [11] demonstrates a new all-optical scheme for the generation of high-brightness GeV photons and high energy density electron–positron pairs. It is realized numerically by using two counter-propagating ultra-intense laser pulses interacting with a solid aluminium (Al) target. A series of particle-in-cell simulations indicated that these findings may provide a feasible scheme to produce high energy and high density pair plasmas for extensive scientific research and applications in the upcoming tens and 100 PW laser facilities.

High field physics areas now cover a wide range of fundamental physics investigations, and this Topical Issue provides an updated perspective of these developments, as well as new directions for high field-based studies in these areas. With the advent of the high power laser facilities as mentioned above, extensive research in the high field QED realm and associated new frontiers will attract an increasing attention in the near future.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: No data were produced in this work. All data

generated or analyzed during this study are included in this published article.]

References

1. M. Si, S. Chen, Y. Huang, M. Ruan, G. Tang, X. Lan, Y. Chen, X. Lou, The linear and nonlinear inverse Compton scattering between microwaves and electrons in a resonant cavity. Eur. Phys. J. D 76:63 (2022). https://doi.org/10.1140/epjd/s10053-022-00389-4
2. I.I. Musiienko, S.O. Lebedynskyi, R.I. Kholodov, Nanoclusters and nanoscale voids as possible sources of increasing dark current in high-gradient vacuum breakdown. Eur. Phys. J. D 76:63 (2022). https://doi.org/10.1140/epjd/s10053-022-00394-7
3. R. Holtzapple, C.F. Nielsen, A.H. Sørensen, U.I. Uggerhøj, CERN NA63, On the significance of radiation reaction. Eur. Phys. J. D 76:167 (2022). https://doi.org/10.1140/epjd/s10053-022-00496-2
4. M. Wen, L. Ding, W. Wu, Q. Li, C. Yu, L. Jin, Spinorial dynamics of relativistic electrons during ponderomotive scattering in intense laser pulses. Eur. Phys. J. D 76:168 (2022). https://doi.org/10.1140/epjd/s10053-022-00498-0
5. M. Filipovic, A. Pukhov, QED effects at grazing incidence on solid-state targets. Eur. Phys. J. D 76:167 (2022). https://doi.org/10.1140/epjd/s10053-022-00494-4
6. O. Amat, L.N. Hu, A. Sawut, M. Mohamedsedik, M.A. Bake, B.S. Xie, Schwinger pair production rate and time for some space-dependent fields via worldline instantons formalism. Eur. Phys. J. D 76:168 (2022). https://doi.org/10.1140/epjd/s10053-022-00519-y
7. G. Yang, W. Sun, F. Wan, X. Ban, Q. Liu, Z. Wang, X. Zhang, M. Ma, J. Zhang, B. Zhao, C. Lv, Terahertz radiation enhanced by a laser-irradiating on a double-layer target. Eur. Phys. J. D 76:189 (2022). https://doi.org/10.1140/epjd/s10053-022-00508-1
8. A. Hosak, A. Di Piazza, Approximated analytical solution of the Landau-Lifshitz equation in tightly focused laser beams in the ultrarelativistic limit. Eur. Phys. J. D 76:200 (2022). https://doi.org/10.1140/epjd/s10053-022-00531-2
9. M. Turner, S.S. Bulanov, C. Benedetti, A.J. Gonsalves, W.P. Leemans, K. Nakamura, J. Van Tilborg, C.B. Schroeder, C.G.R. Geddes, E. Esarey, Strong-field QED experiments using the BELLA PW laser dual beamlines. Eur. Phys. J. D 76:1 (2022). https://doi.org/10.1140/epjd/s10053-022-00535-y
10. C. Gong, Y.J. Li, T.T. Xi, Q. Su, R. Grobe, Computational approaches to examine the vacuum polarization density. Eur. Phys. J. D (2022). https://doi.org/10.1140/epjd/s10053-022-00586-1
11. M. Zi, Y.Y. Ma, X.H. Yang, G.B. Zhang, J.X. Liu, Y. Yuan, M. Peng, Y. Cui, S. Kawata, High-energy-density positron and γ-photon generation via two counter-propagating ultra-relativistic laser irradiating a solid target. Eur. Phys. J. D 77:41 (2022). https://doi.org/10.1140/epjd/s10053-023-00597-6