Probing QED Cascades and Pair Plasmas in Laboratory Experiments LoI to Cosmic Frontier

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Extreme astrophysical environments like magnetars, neutron-star mergers, and core-collapse supernovae explosions exhibit super-critical magnetic fields. Experimental access to QED cascades and electron-positron pair plasmas in the QED regime will therefore boost our understanding of these objects, which are essential for the emerging field of multi-messenger astronomy. Here, we propose a collaboration between Fusion Energy Sciences (FES) and High Energy Physics (HEP) to initiate a seminal experimental research program on QED plasmas, enabled by a new paradigm of short, tightly focused electron beams.

I. INTRODUCTION AND MOTIVATION

The recent discovery [1–6] that magnetars [7, 8] — highly magnetized neutron stars — are progenitors of mysterious Fast Radio Bursts (FRBs) underscores the importance of understanding plasma physics and the associated coherent emission under extreme field conditions [9–13]. Neutron stars are by far the strongest magnets in the universe. They can have field strengths that significantly exceed the QED critical magnetic field $B \gtrsim B_{\rm cr} = m^2c^2/(\hbar e) \approx 4.4\times 10^{13}\,$G. Super-critical magnetic fields can also be produced during binary neutron-star mergers [14, 15] and core-collapse supernovae explosions [16, 17]. Understanding the basic physics of such extreme QED plasmas environments is therefore important for multi-messenger astronomy [18–22].

Even though super-critical magnetic fields are stable, energetic particles or photons will induce QED cascades when they enter such strong fields [8, 23]. During a QED cascade, i.e., a sequence of photon emission and pair production, the number of particles increases exponentially until an electron-positron pair plasma is formed. The resulting copious pair production populates the magnetosphere of compact objects [24, 25], changes the dynamics of magnetic reconnection and the resulting particle acceleration and radiation emission [26–29], and can also act collectively to emit coherent radiation. It is clear that the complex interplay between strong-field quantum and collective plasma processes plays an essential role in these extreme astrophysical environments [9–13]. This represents a new and largely unexplored "QED plasma regime" (see also separate LoI on associated theory questions [30]).

It has been pointed out by Bell & Kirk [31] that laser-matter interactions beyond intensity $I \gtrsim 10^{24}\,\mathrm{W/cm^2}$ are able to access the QED plasma regime, as the laser is able to accelerate electrons to relativistic energies which then probe the QED critical field in their rest frame [32–36] (this threshold assumes an optical laser). The prospect of studying a strong-field QED cascade and generating dense electron-positron plasmas in laboratory experiments is motivating strong investments in 100 PW-class laser systems like the one proposed in Rochester [37] and the one approved for construction in Shanghai [38] (see [39–41] for a more detailed overview). While this is an exciting possibility, it is important to note that it is highly non-trivial to cleanly focus 100 PW laser power, necessarily distributed among multiple beams, to a focal area of $10\,\mu\mathrm{m}^2$ in order to reach intensities $I \gtrsim 10^{24}\,\mathrm{W/cm^2}$. Solving this challenge will require substantial R&D beyond the current state-of-the-art [42, 43]. An alternative approach, advocated here, is to use lepton beams to enhance the interesting physical processes.

We propose here to probe supercritical electromagnetic fields and magnetar-type QED cascades first in electron-laser and later also in beam-beam collisions. This approach is complementary to laser-laser and laser-matter interactions. A facility which co-locates two disruptive technologies – multi-petawatt high-intensity laser and densely-compressed, ultra-relativistic electron beams – would enable world-wide unique scientific opportunities for HEDP and laboratory astrophysics [44].

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II. SEMINAL RESEARCH OPPORTUNITIES ENABLED BY BEAM-DRIVEN EXPERIMENTS

Beam-driven plasma experiments can provide an important new route to study the mechanisms by which strong-field QED cascades fill the magnetosphere of compact objects with an electron-positron pair plasma [23–25], and how strong-field QED processes will affect the collective behavior of the relativistic pair plasma [9]. As terrestrial electromagnetic fields will remain much below the QED critical field, at least in the mid-term future, the Lorentz boost of ultra-relativistic electrons (or positrons) is required to probe similar conditions as those encountered in supercritical astrophysical magnetic fields. This experimental scheme has been first applied in the famous SLAC Experiment 144 [45–47]. Upcoming LINAC-based experiments at DESY (LUXE [48]) and SLAC (E-320 at FACET II [49]) will provide further insights but will not reach the regime to produce a cascade with a high multiplicity. Studying strong-field QED is also a key part of the scientific program of all major all-optical high-intensity laser facilities [39], where electron beams can be produced via laser wakefield acceleration [50, 51]. However, LINAC beams currently offer significant advantages in terms of stability and reproducibility, which are critical for such experiments.

In order to induce a beam-driven QED cascade with a high multiplicity, the boosted rest-frame electric field E^* has to be significantly higher than the critical one, i.e., $\chi = E^*/E_{\rm cr} \gg 1$ has to be reached [$E_{\rm cr} = m^2c^3/(\hbar e) \approx 1.3 \times 10^{18}\,{\rm V/m}$]. By colliding a 30 GeV electron beam with $3 - 10$ PW laser pulses the QED critical field can be exceeded by $\chi \approx 35 - 65$ [44]. Assuming that in addition the initial electron beam density is high, a quasi-neutral electron-positron pair plasma with critical density can be produced [52]. This implies that the QED plasma regime is entered, where a non-trivial interplay between strong-field quantum and collective plasma effects takes place and can be studied. Co-location of a high-intensity laser with an ultra-dense and highly relativistic electron beam thus enables seminal research opportunities, which has also been pointed out in various recent community reports [53, 54].

QED cascades can also be induced and studied in lepton beam-beam collisions taking advantage of the strong fields — comparable to multi-PW lasers — associated with highly compressed beams [55] (see separate LoI on beam physics [56]). Already at the 10 GeV-scale QED cascades with multiplicities $\mu \sim 10$ can be induced in electron-positron collisions at moderate disruption parameters $D \sim 1 - 5$, where the beams are strongly compressed and the magnetic field is amplified [57]. Extremely large values of χ, and thus QED cascades with very high multiplicities $\mu \gtrsim 10^2$, are obtainable in electron-electron collisions at the 125 GeV-scale [55, 58]. This would provide a unique opportunity to develop the first precision understanding of strong-field QED processes and their interplay with collective processes in extremely relativistic and dense pair plasmas, thereby laying the experimental and theoretical foundations for applications to extreme astrophysical phenomena. In fact, such a configuration also offers unique advantages for future energy-frontier discovery-regime colliders, as described in a separate LoI [59].

III. SUMMARY AND CONCLUSION

Multi-beam facilities such as the co-location of a multi-PW optical laser with a highly compressed 30 GeV electron beam [44, 53, 54] and a 2×125 GeV electron-electron collider with dense bunches [55] could provide experimental access to QED plasmas. Such facilities would enable seminal research opportunities in the realm of laboratory astrophysics, as they could probe plasma conditions otherwise only encountered in extreme astrophysical environments. Accessing the fully non-perturbative strong-field QED regime provides access to a plethora of qualitatively new phenomena like QED cascades with large multiplicity, relativistic pair plasmas, and the interplay between strong-field quantum and collective plasma effects. Studying these phenomena in laboratory experiments will boost our understanding of some of the most intriguing astrophysical phenomena.

References

[1] M. Tavani *et al.*, "An X-Ray Burst from a Magnetar Enlightening the Mechanism of Fast Radio Bursts," (2020), arXiv:2005.12164.

[2] L. Lin *et al.*, "Stringent upper limits on pulsed radio emission during an active bursting phase of the Galactic magnetar SGRJ1935+2154," (2020), arXiv:2005.11479.

[3] A. Ridnaia *et al.*, "A peculiar hard X-ray counterpart of a Galactic fast radio burst," (2020), arXiv:2005.11178.

[4] C. K. Li *et al.*, "Identification of a non-thermal X-ray burst with the Galactic magnetar SGR 1935+2154 and a fast radio burst with Insight-HXMT," (2020), arXiv:2005.11071.

[5] C. D. Bochenek *et al.*, "A fast radio burst associated with a Galactic magnetar," (2020), arXiv:2005.10828.

[6] The CHIME/FRB Collaboration, "A bright millisecond-duration radio burst from a Galactic magnetar," (2020), arXiv:2005.10324.

[7] V. M. Kaspi and A. M. Beloborodov, "Magnetars," Annu. Rev. Astron. Astrophys. **55**, 261–301 (2017).

[8] B. Cerutti and A. M. Beloborodov, "Electrodynamics of Pulsar Magnetospheres," Space Sci. Rev. **207**, 111–136 (2017).

[9] A. Philippov, A. Timokhin, and A. Spitkovsky, "Origin of Pulsar Radio Emission," Phys. Rev. Lett. **124**, 245101 (2020).

[10] P. Zhang, S. S. Bulanov, D. Seipt, A. V. Arefiev, and A. G. R. Thomas, "Relativistic plasma physics in supercritical fields," Phys. Plasmas **27**, 050601 (2020).

[11] D. Uzdensky, M. Begelman, A. Beloborodov, R. Blandford, S. Boldyrev, B. Cerutti, F. Fiuza, D. Giannios, T. Grismayer, M. Kunz, N. Loureiro, M. Lyutikov, M. Medvedev, M. Petropoulou, A. Philippov, *et al.*, "Extreme Plasma Astrophysics," (2019), arXiv:1903.05328.

[12] D. B. Melrose and R. Yuen, "Pulsar electrodynamics: an unsolved problem," J. Plasma Phys. **82**, 635820202 (2016).

[13] D. A. Uzdensky and S. Rightley, "Plasma physics of extreme astrophysical environments," Rep. Prog. Phys. **77**, 036902 (2014).

[14] F. R. N. Schneider, S. T. Ohlmann, P. Podsiadlowski, F. K. Röpke, S. A. Balbus, R. Pakmor, and V. Springel, "Stellar mergers as the origin of magnetic massive stars," Nature **574**, 211–214 (2019).

[15] Y. Q. Xue *et al.*, "A magnetar-powered X-ray transient as the aftermath of a binary neutron-star merger," Nature **568**, 198–201 (2019).

[16] P. Mösta, C. D. Ott, D. Radice, L. F. Roberts, E. Schnetter, and R. Haas, "A large-scale dynamo and magnetoturbulence in rapidly rotating core-collapse supernovae," Nature **528**, 376–379 (2015).

[17] S. Akiyama, J. C. Wheeler, D. L. Meier, and I. Lichtenstadt, "The Magnetorotational Instability in Core-Collapse Supernova Explosions," Astrophys. J. **584**, 954–970 (2003).

[18] M. Wang, S. Ai, Z. Li, N. Xing, H. Gao, and B. Zhang, "Testing the Hypothesis of a Compact-binary-coalescence Origin of Fast Radio Bursts Using a Multimessenger Approach," Astrophys. J. **891**, L39 (2020).

[19] B. P. Abbott *et al.*, "GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$," Astrophys. J. **892**, L3 (2020).

[20] LIGO Scientific Collaboration and Virgo Collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral," Phys. Rev. Lett. **119**, 161101 (2017).

[21] C. Palenzuela, L. Lehner, M. Ponce, S. L. Liebling, M. Anderson, D. Neilsen, and P. Motl, "Electromagnetic and Gravitational Outputs from Binary-Neutron-Star Coalescence," Phys. Rev. Lett. **111**, 061105 (2013).

[22] M. Anderson, E. W. Hirschmann, L. Lehner, S. L. Liebling, P. M. Motl, D. Neilsen, C. Palenzuela, and J. E. Tohline, "Magnetized Neutron-Star Mergers and Gravitational-Wave Signals," Phys. Rev. Lett. **100**, 191101 (2008).

[23] Z. Medin and D. Lai, "Pair cascades in the magnetospheres of strongly magnetized neutron stars," Mon. Not. R. Astron. Soc. **406**, 1379–1404 (2010).

[24] A. Y. Chen, F. Cruz, and A. Spitkovsky, "Filling the Magnetospheres of Weak Pulsars," Astrophys. J. **889**, 69 (2020).

[25] A. N. Timokhin and A. K. Harding, "On the Maximum Pair Multiplicity of Pulsar Cascades," Astrophys. J. **871**, 12 (2019).

[26] K. M. Schoeffler, T. Grismayer, D. Uzdensky, R. A. Fonseca, and L. O. Silva, "Bright Gamma-Ray Flares Powered by Magnetic Reconnection in QED-strength Magnetic Fields," Astrophys. J. **870**, 49 (2019).

[27] H. Hakobyan, A. Philippov, and A. Spitkovsky, "Effects of Synchrotron Cooling and Pair Production on Collisionless Relativistic Reconnection," Astrophys. J. **877**, 53 (2019).

[28] G. R. Werner, A. A. Philippov, and D. A. Uzdensky, "Particle acceleration in relativistic magnetic reconnection with strong inverse-Compton cooling in pair plasmas," Mon. Not. R. Astron. Soc. Lett. **482**, L60–L64 (2019).

[29] D. A. Uzdensky, "Magnetic Reconnection in Extreme Astrophysical Environments," Space Sci. Rev. **160**, 45–71 (2011).

[30] Sebastian Meuren and Gerald Dunne on behalf of the collaboration, "Theory Frontier LoI: Understanding the Fully Non-Perturbative Strong-Field Regime of QED," (2020).

[31] A. R. Bell and J. G. Kirk, "Possibility of Prolific Pair Production with High-Power Lasers," Phys. Rev. Lett. **101**, 200403 (2008).

[32] A. Gonoskov, A. Bashinov, S. Bastrakov, E. Efimenko, A. Ilderton, A. Kim, M. Marklund, I. Meyerov, A. Muraviev, and A. Sergeev, "Ultrabright GeV Photon Source via Controlled Electromagnetic Cascades in Laser-Dipole Waves," Phys. Rev. X **7**, 041003 (2017).

[33] T. Grismayer, M. Vranic, J. L. Martins, R. A. Fonseca, and L. O. Silva, "Seeded QED cascades in counterpropagating laser pulses," Phys. Rev. E **95**, 023210 (2017).

[34] M. Tamburini, A. D. Piazza, and C. H. Keitel, "Laser-pulse-shape control of seeded QED cascades," Sci. Rep. **7**, 5694 (2017).

[35] S. S. Bulanov, C. B. Schroeder, E. Esarey, and W. P. Leemans, "Electromagnetic cascade in high-energy electron, positron, and photon interactions with intense laser pulses," Phys. Rev. A **87**, 062110 (2013).

[36] C. P. Ridgers, C. S. Brady, R. Duclous, J. G. Kirk, K. Bennett, T. D. Arber, A. P. L. Robinson, and A. R. Bell, "Dense Electron-Positron Plasmas and Ultraintense γ rays from Laser-Irradiated Solids," Phys. Rev. Lett. **108**, 165006 (2012).

[37] J. Bromage, S. W. Bahk, I. A. Begishev, C. Dorrer, M. J. Guardalben, B. N. Hoffman, J. B. Oliver, R. G. Roides, E. M. Schiesser, M. J. Shoup III, M. Spilatro, B. Webb, D. Weiner, and J. D. Zuegel, "Technology development for ultraintense all-OPCPA systems," High Power Laser Science and Engineering **7** (2019), 10.1017/hpl.2018.64.

[38] E. Cartlidge, "The light fantastic," Science **359**, 382–385 (2018).

[39] I. C. E. Turcu, B. Shen, D. Neely, G. Sarri, K. A. Tanaka, P. McKenna, S. P. D. Mangles, T. P. Yu, W. Luo, X. L. Zhu, and Y. Yin, "Quantum electrodynamics experiments with colliding petawatt laser pulses," High Power Laser Science and Engineering **7** (2019), 10.1017/hpl.2018.66.

[40] C. N. Danson, C. Haefner, J. Bromage, T. Butcher, J. F. Chanteloup, E. A. Chowdhury, A. Galvanauskas, L. A. Gizzi, J. Hein, D. I. Hillier, N. W. Hopps, Y. Kato, E. A. Khazanov, R. Kodama, G. Korn, *et al.*, "Petawatt and exawatt class lasers worldwide," High Power Laser Science and Engineering **7**, e54 (2019).

[41] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, "Extremely high-intensity laser interactions with fundamental quantum systems," Rev. Mod. Phys. **84**, 1177–1228 (2012).

[42] C. P. J. Barty, "The Nexawatt: A Strategy for Exawatt Peak Power Lasers Based on NIF and NIF-like Beam Lines," J. Phys.: Conf. Ser. **717**, 012086 (2016).

[43] I. Gonoskov, A. Aiello, S. Heugel, and G. Leuchs, "Dipole pulse theory: Maximizing the field amplitude from 4π focused laser pulses," Phys. Rev. A **86**, 053836 (2012).

[44] S. Meuren, P. H. Bucksbaum, N. J. Fisch, F. Fiúza, S. Glenzer, M. J. Hogan, K. Qu, D. A. Reis, G. White, and V. Yakimenko, "On Seminal HEDP Research Opportunities Enabled by Colocating Multi-Petawatt Laser with High-Density Electron Beams," (2020), arXiv:2002.10051.

[45] C. Bamber, S. J. Boege, T. Koffas, T. Kotseroglou, A. C. Melissinos, D. D. Meyerhofer, D. A. Reis, W. Ragg, C. Bula, K. T. McDonald, E. J. Prebys, D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, *et al.*, "Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses," Phys. Rev. D **60**, 092004 (1999).

[46] D. L. Burke, R. C. Field, G. Horton-Smith, J. E. Spencer, D. Walz, S. C. Berridge, W. M. Bugg, K. Shmakov, A. W. Weidemann, C. Bula, K. T. McDonald, E. J. Prebys, C. Bamber, S. J. Boege, T. Koffas, *et al.*, "Positron Production in Multiphoton Light-by-Light Scattering," Phys. Rev. Lett. **79**, 1626 (1997).

[47] C. Bula, K. T. McDonald, E. J. Prebys, C. Bamber, S. Boege, T. Kotseroglou, A. C. Melissinos, D. D. Meyerhofer, W. Ragg, D. L. Burke, R. C. Field, G. Horton-Smith, A. C. Odian, J. E. Spencer, D. Walz, *et al.*, "Observation of Nonlinear Effects in Compton Scattering," Phys. Rev. Lett. **76**, 3116 (1996).

[48] H. Abramowicz, M. Altarelli, R. Aßmann, T. Behnke, Y. Benhammou, O. Borysov, M. Borysova, R. Brinkmann, F. Burkart, K. Büßer, O. Davidi, W. Decking, N. Elkina, H. Harsh, A. Hartin, *et al.*, "Letter of Intent for the LUXE Experiment," (2019), arXiv:1909.00860v1.

[49] S. Meuren on behalf of the FACET-II SFQED Collaboration, "Probing Strong-field QED at FACET-II, Experimental proposal (approved as E-320)," , unpublished (2018).

[50] J. M. Cole, K. T. Behm, E. Gerstmayr, T. G. Blackburn, J. C. Wood, C. D. Baird, M. J. Duff, C. Harvey, A. Ilderton, A. S. Joglekar, K. Krushelnick, S. Kuschel, M. Marklund, P. McKenna, C. D. Murphy, *et al.*, "Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam," Phys. Rev. X **8**, 011020 (2018).

[51] K. Poder, M. Tamburini, G. Sarri, A. Di Piazza, S. Kuschel, C. D. Baird, K. Behm, S. Bohlen, J. M. Cole, D. J. Corvan, M. Duff, E. Gerstmayr, C. H. Keitel, K. Krushelnick, S. P. D. Mangles, *et al.*, "Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser," Phys. Rev. X **8**, 031004 (2018).

[52] K. Qu, S. Meuren, and N. J. Fisch, "Observing Collective Plasma Effects in Beam-Driven QED Cascades via Laser Frequency Upconversion," (2020), arXiv:2001.02590.

[53] R. Falcone, F. Albert, F. Beg, S. Glenzer, T. Ditmire, T. Spinka, and J. Zuegel, "Workshop Report: Brightest Light Initiative," (2020), arXiv:2002.09712.

[54] S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, E. Scime, and W. Solomon, "A Community Plan for Fusion Energy and Discovery Plasma Sciences – Report of the 2019–2020 American Physical Society Division of Plasma Physics Community Planning Process," APS-DPP-CPP , 1–186 (2020).

[55] V. Yakimenko, S. Meuren, F. Del Gaudio, C. Baumann, A. Fedotov, F. Fiuza, T. Grismayer, M. J. Hogan, A. Pukhov, L. O. Silva, and G. White, "Prospect of Studying Nonperturbative QED with Beam-Beam Collisions," Phys. Rev. Lett. **122**, 190404 (2019).

[56] Vitaly Yakimenko and Glen White on behalf of the collaboration, "Accelerator frontier LoI: beam physics of extreme bunch compression," (2020).

[57] D. Del Sorbo *et al.*, "in preparation," (2020).

[58] F. Del Gaudio, T. Grismayer, R. A. Fonseca, W. B. Mori, and L. O. Silva, "Bright γ rays source and nonlinear Breit-Wheeler pairs in the collision of high density particle beams," Phys. Rev. Accel. Beams **22**, 023402 (2019).

[59] Glen White and Michael E. Peskin on behalf of the collaboration, "Short-Bunch Paradigm Laserless $\gamma\gamma$ Collider LoI: Energy Frontier," (2020).