Snowmass 2020 Letter of Interest: A Bright Beam-Filamentation Driven Gamma-ray Source

F. Fiuza[a], S. Gessner, M. Hogan, A. Marinelli, B. O'Shea, V. Yakimenko
SLAC National Accelerator Laboratory, Menlo Park, CA 94025,
USA

K. Marsh, W. Mori, C. Joshi
University of California Los Angeles, CA 90095 USA

S. Corde
LOA, ENSTA Paris, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris,
91762 Palaiseau, France

M. Litos, J. Cary
University of Colorado Boulder, Department of Physics,
Center for Integrated Plasma Studies, Boulder, CO 80309,
USA

N. Vafaei-Najafabadi
Stony Brook University, Department of Physics and Astronomy, Stony Brook,
NY 11794, USA

L. Gremillet, X. Davoine
CEA, DAM, DIF, 91297 Arpajon, France and Université Paris-Saclay, CEA,
LMCE, 91680 Bruyères-le-Châtel, France

M. Tamburini, C. H. Keitel
Max-Planck-Institut fur Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg,
Germany

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[a] fiuza@slac.stanford.edu

High-energy radiation sources have an extraordinary impact in society, from scientific research to medicine and industry. Synchrotron and free-electron-laser facilities based on multi-GeV electron beams can produce bright X-ray sources with 1-100s keV, which over the last decades have transformed our ability to probe the structure of matter at sub-nanometer scale with a strong impact on condensed matter physics, materials science, chemistry, and biology[1]. The extension of the photon energy of bright light sources beyond MeV has been a long sought-after goal, with important applications in areas such as nuclear and high-energy physics. However, the generation of high brilliance sources at very high-energies has been very challenging.

The importance of bright gamma-ray sources has stimulated several proposals for advanced radiation sources that exploit different mechanisms, from Compton scattering[2,3] to beamstrahlung[4,5]. In particular, the Extreme Light Infrastructure (ELI) for Nuclear Physics[6] in Europe is pursuing the construction of a Compton-based facility expected to yield gamma-ray pulses with energies up to 20 MeV, peak brilliance of $10^{20} - 10^{23}$ photons s^{-1} mrad^{-2} mm^{-2} per 0.1% bandwidth, and an electron-to-photon energy conversion efficiency of a few %. More work is still needed to understand how it might be possible to reach more efficient, higher brilliance gamma-ray sources at high energies.

Recently[7], it has been shown theoretically that dense (nC, few μm size) multi-GeV electron beams can produce collimated gamma-ray pulses with peak brilliance above 10^{25} photons s^{-1} mrad^{-2} mm^{-2} per 0.1% bandwidth in the MeV to GeV range based on electromagnetic instabilities generated by dense relativistic electron beams in plasmas. As the beam propagates in the plasma, these instabilities will exponentially amplify self-generated electromagnetic fields. The violent acceleration experienced by the beam electrons in these strong fields leads to significant synchrotron emission. The resulting high-energy photon pulse has a duration comparable to that of the electron beam and is highly collimated. When the beam density is comparable to the background plasma density, the conversion efficiency between the electron beam and the high-energy photons can largely exceed 10 %.

Here, we propose that the viability of such a bright gamma-ray source could be explored based on accelerator facilities capable of delivering dense, highly relativistic electron beams, such as FACET-II at SLAC[8]. FACET-II is expected to deliver 10 GeV, 2 nC electron beams with a density that could range from 10^{18} cm^{-3} to 10^{21} cm^{-3}, allowing the study of gamma-ray emission for a wide range of beam and plasma densities taking advantage of both gas and solid density targets. A better understanding of how the beam-to-plasma density ratio and the nonlinear evolution of the electromagnetic instabilities impact the beam energy losses and radiation emission is critical to optimize the properties of the gamma-ray source. This research could drive the development of stable high-energy, high-density beams for a future light source facility that would also benefit designs for short bunch particle colliders for high-energy physics studies[4,9].

Beyond the importance of the development of novel high-brilliance, high-energy light sources, the proposed studies could also have a significant impact on our understanding of the fundamental physics that shapes some of the most fascinating astrophysical environments, such as gamma-ray bursts and blazars. Indeed, the plasma instabilities associated with this advanced light source concept are thought to mediate the amplification of magnetic fields, the slow down of highly-relativistic pair plasma flows, and the high-energy radiation emission in these extreme astrophysical settings[10,11]. The controlled study of these relativistic instabilities in the laboratory would provide a unique opportunity to understand better their nonlinear physics and the associated radiation emission processes in conditions relevant to extreme astrophysical environments. This is critical to benchmark theoretical and numerical models.

In summary, we argue that there are unique opportunities for a research program based on the interaction of dense, ultra-relativistic electron beams with plasma. This program would enable the study in the laboratory of the fundamental processes that control high-energy radiation emission in extreme astrophysical environments and would harness these same processes to develop high-energy light sources with unprecedented brilliance for applications in nuclear physics and high-energy physics research, medicine, and industry. The associated research and development of stable high-density beams would further benefit designs of high-energy colliders based on very short and intense electron bunches.

REFERENCES

[1] D. H. Bilderback, P. Elleaume, and E. Weckert, Journal of Physics B: Atomic, Molecular and Optical Physics **38**, S773 (2005).

[2] K. Ta Phuoc, S. Corde, C. Thaury, V. Malka, A. Tafzi, J. P. Goddet, R. C. Shah, S. Sebban, and A. Rousse, Nature Photonics **6**, 1749 (2012).

[3] M. Vranic, T. Grismayer, S. Meuren, R. A. Fonseca, and L. O. Silva, Physics of Plasmas **26**, 053103 (2019), https://doi.org/10.1063/1.5090992.

[4] 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, Phys. Rev. Lett. **122**, 190404 (2019).

[5] F. Del Gaudio, T. Grismayer, R. A. Fonseca, W. B. Mori, and L. O. Silva, Phys. Rev. Accel. Beams **22**, 023402 (2019).

[6] "Extreme light infrastructure - nuclear physics (eli-np)," `http://www.eli-np.ro/`.

[7] A. Benedetti, M. Tamburini, and C. H. Keitel, Nature Photonics **12**, 319 (2018).

[8] V. Yakimenko, L. Alsberg, E. Bong, G. Bouchard, C. Clarke, C. Emma, S. Green, C. Hast, M. J. Hogan, J. Seabury, N. Lipkowitz, B. O'Shea, D. Storey, G. White, and G. Yocky, Phys. Rev. Accel. Beams **22**, 101301 (2019).

[9] M. Peskin and V. Yakimenko, on behalf of the collaboration, *Particle colliders with ultra-short bunches*, LoI to Energy Frontier.

[10] M. V. Medvedev and A. Loeb, The Astrophysical Journal **526**, 697 (1999).

[11] A. E. Broderick, P. Chang, and C. Pfrommer, The Astrophysical Journal **752**, 22 (2012).