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PERSPECTIVE

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Collective coherent emission of electrons in strong laser fields and perspective for hard x-ray lasers

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ABSTRACT

Coherent motion of particles in a plasma can imprint itself on radiation. The recent advent of high-power lasers—allowing the nonlinear inverse Compton-scattering regime to be reached—has opened the possibility of looking at collective effects in laser–plasma interactions. Under certain conditions, the collective interaction of many electrons with a laser pulse can generate coherent radiation in the hard x-ray regime. This perspective paper explains the limitations under which such a regime might be attained.

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I. BACKGROUND

In the last few decades, the development of lasers has followed two distinct directions. In one of these directions, scientists have pushed the limit to reach multi-petawatt (10^{15} W) short laser pulses on the basis of chirped-pulse amplification;[1,2] in the other, efforts are under way to shorten the wavelength of the emitted radiation as much as possible.[3,4] In his 2003 Nobel Prize speech, Ginzburg identified the gamma-ray laser as one of the challenges of the 21st century.[5]

II. COLLECTIVE RADIATION EMISSION IN A STRONG LASER FIELD

One of the possible sources of high-frequency radiation is emission by electrons interacting with a strong optical laser pulse (nonlinear Compton scattering, NCS). For a single particle, the spectrum of this radiation is well known.[6,7] Naively, the radiation of N particles should simply be N times stronger. However, if the motion of the particles is strongly correlated, i.e., if the initial conditions for spatial location[8,9] and velocity[10] are close (meaning that the density of the particles is high and the temperature is low), then the radiated energy can be strongly enhanced due to coherency[8] (see Fig. 1).

Indeed, the energy of the emitted radiation in an external field at the classical limit is given by[6]

$$\frac{\mathrm{d}\mathcal{E}_k}{\mathrm{d}\mathbf{k}} = -\frac{j^\mu(k)\, j^\star_\mu(k)}{4\pi^2}, \tag{1}$$

where $\mathbf{k}$ is the radiation wave vector and j^μ is the Fourier transform of the current 4-vector. For two emitting particles,

$$|j^\mu|^2 = \underbrace{|j_1^\mu|^2 + |j_2^\mu|^2}_{\text{incoherent term}} + \underbrace{2\mathrm{Re}\left(j_1^\mu j_{\mu 2}^\star\right)}_{\text{interference term}}, \tag{2}$$

and under certain conditions, the interference term can be as large as the incoherent term, increasing the radiated power by a factor of 2. These conditions for the particles' initial displacement R were established in Ref. 8: R is inversely proportional to the emitted frequency ω, and it also depends on the particles' initial energy and the intensity of the laser.

For N particles, the number of incoherent terms scales as N, while the number of interference terms scales as N^2. This means that the coherent enhancement of radiation for a macroscopic number of particles can be huge. Since $R \sim 1/\omega$, the lower frequencies are enhanced more strongly than the higher frequencies; i.e., the shape

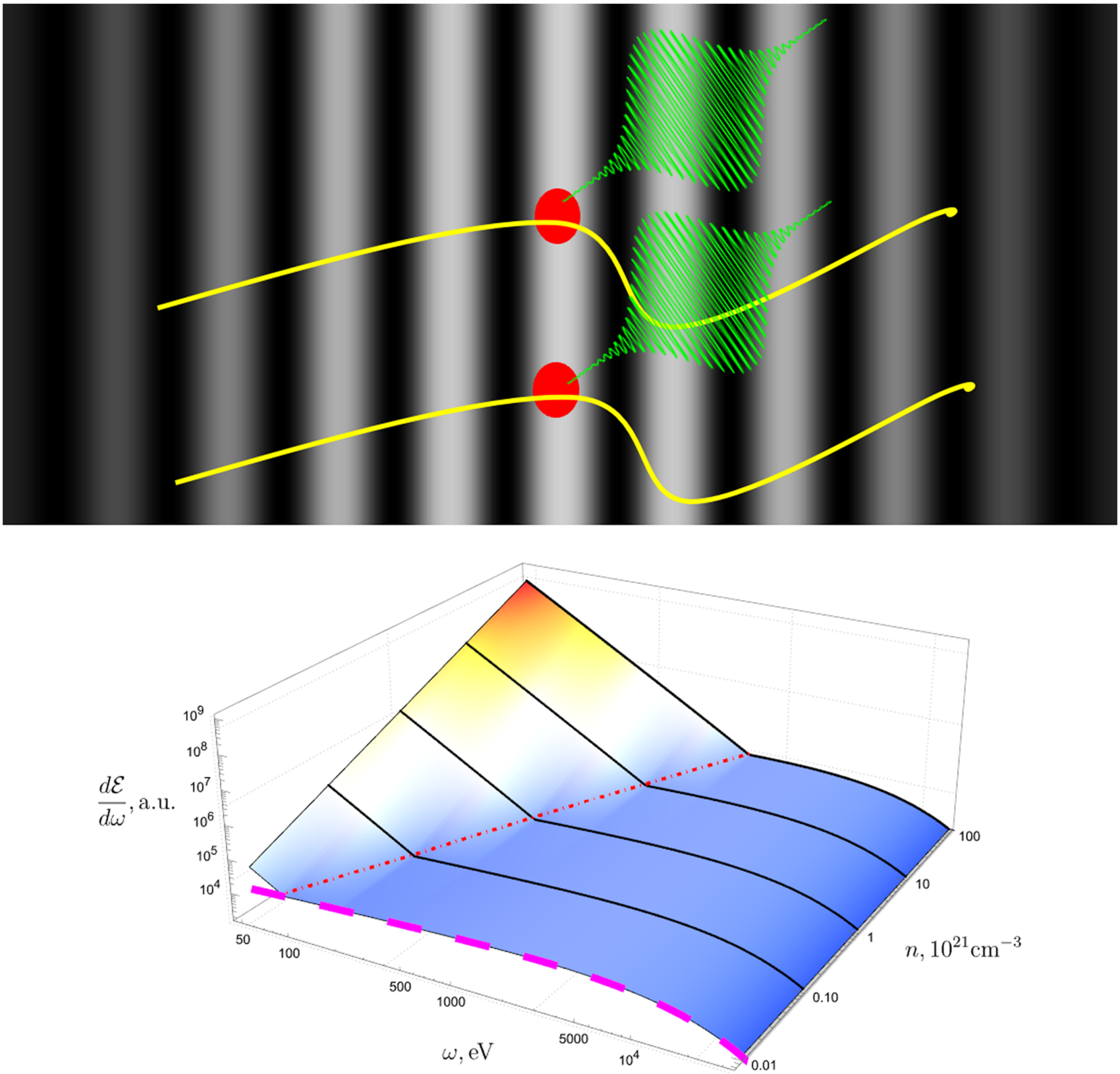

FIG. 1. Top: two electrons that are close to one another in a phase space and interact with a laser can radiate coherently. Bottom: spectrum of a large number (N) of electrons colliding with a laser pulse for various densities of electron bunch. Dashed magenta curve: spectrum without accounting for coherency (N times the single-particle spectrum). The dot-dashed red curve shows the dependence of the highest coherently enhanced frequency on the density. The surface combines coherent (to the left of the dashed red curve) and incoherent (to the right) spectra. Laser intensity 10^{19} W/cm^2, electron energy 50 MeV.

of the radiation spectrum (with respect to the single-particle spectrum) is substantially modified by the coherency (see Fig. 1). Note that since the average distance between the particles is defined by the density n, the spectrum is very sensitive to the density. This is revealed in two particular ways: first, the enhancement factor for each frequency is proportional to the density; second, the maximum frequency ω_{coh}, which is enhanced due to coherency, scales as $\omega_{\text{coh}} \sim n^{1/3}$.

It is worth noting that despite "higher" frequencies being unaffected by coherency, the threshold ω_{coh} of coherently enhanced "low" frequencies can be quite high—up to tens (and in some conditions even hundreds) of keV, depending on the laser intensity and

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the particles' initial energy.[8] In particular, for a 50-MeV electron beam with a density of 10^{22} cm^{-3} and a laser intensity of 10^{19} W/cm^2, the coherency threshold exceeds 1 keV (see Fig. 1), while a 10-keV coherency threshold is provided by an energy of 200 MeV and a solid density of 10^{23} cm^{-3}.[8]

Moreover, according to Ref. 8, the ratio of the energy of the coherently enhanced radiation to that of the incoherent radiation (for initially slow particles and a relativistically intense laser $a_0 \gg 1$) is

$$\frac{\mathcal{E}_{\text{coh}}}{\mathcal{E}_{\text{incoh}}} \sim \frac{1}{64\pi^3}\frac{n\lambda_{\text{L}}^3}{a_0^2}, \qquad (3)$$

where $a_0 = eE_{\text{L}}\lambda_{\text{L}}/2\pi mc^2$ is the dimensionless laser amplitude (in which E_{L} and λ_{L} are the laser's electric-field amplitude and wavelength, $-e$ and m are the electron charge and mass, and c is the speed of light), meaning that the total energy of the coherent part of the spectrum can be much higher than that of the incoherent part. Indeed, for solid-density electrons and an optical laser pulse, the factor $n\lambda_{\text{L}}^3$ can be as high as 10^{11}, and for $a_0 \sim 10^2$ (corresponding to an intensity $I \sim 10^{22}$ W/cm^2), one obtains $\mathcal{E}_{\text{coh}}/\mathcal{E}_{\text{incoh}} \sim 10^4$.

III. CHALLENGES AND PROSPECTS

Although the creation of a "graser" (gamma-ray laser) is not imminent, it is clear that possibilities do exist for generating coherent hard x-rays using collective effects in plasmas when interacting with a short and ultra-intense laser pulses in the infrared regime. Optimization of the interaction process allows the coherent and incoherent contributions of the radiation generated by nonlinear inverse Compton scattering to be influenced; partial control of the coherency is thus possible.

Nevertheless, a number of important theoretical questions still remain, and these need to be addressed in subsequent refined research. First, the presented approach is purely classical, and for an accurate investigation of the emission at high frequencies, one has to develop a quantum approach with accounting for coherency. Second, the effect of the temperature of the particle ensemble should be taken into consideration. Third, when coherency is taken into account, the particles can radiate so strongly [see Eq. (3) and the discussion below] that even for a mildly relativistic bunch and a moderately intense laser ($I \gtrsim 10^{18}$ W/cm^2) this will modify their trajectories in the laser field (the radiation reaction effect[6]), which will in turn affect the radiation emission. Finally, for a detailed description of laser–electron-bunch collision—which is necessary for planning and interpretation of experiments—numerical simulations are required. Particle-in-cell simulations are very powerful tools for investigation of the interaction of a plasma with a short intense laser pulse. Developing an implementation of coherent photon emission in such simulations is a challenging but necessary step toward employing coherent NCS for the creation of a hard x-ray source.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

E. G. Gelfer: Conceptualization (equal); Formal analysis (lead); Investigation (lead); Methodology (lead); Writing – original draft (equal); Writing – review & editing (equal). **A. M. Fedotov**: Investigation (supporting); Methodology (supporting); Writing – review & editing (equal). **O. Klimo**: Investigation (supporting); Writing – review & editing (equal). **S. Weber**: Conceptualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available upon reasonable request from the authors.

REFERENCES

[1] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," Opt. Commun. **56**, 219 (1985).

[2] C. Danson *et al.*, "Petawatt and exawatt class lasers worldwide," High Power Laser Sci. Eng. **7**, e54 (2019).

[3] J. Hecht, *The History of the X-Ray Laser* (Optics Photonics News, 2008).

[4] G. Baldwin, J. Solem, and V. Gol'danskii, "Approaches to the development of gamma-ray lasers," Rev. Mod. Phys. **53**, 687 (1981).

[5] V. L. Ginzburg, "Nobel lecture: On superconductivity and superfluidity (what I have and have not managed to do) as well as on the 'physical minimum' at the beginning of the XXI century," Rev. Mod. Phys. **76**, 981 (2004).

[6] L. D. Landau and I. M. Lifshitz, *Theoretical Physics: The Classical Theory of Fields, Course of Theoretical Physics Series Vol. 2* (Pergamon Press, London, 1988).

[7] E. Esarey, S. K. Ride, and P. Sprangle, "Nonlinear Thomson scattering of intense laser pulses from beams and plasmas," Phys. Rev. E **48**, 3003–3021 (1993).

[8] E. Gelfer, A. Fedotov, O. Klimo, and S. Weber, "Coherent radiation of electrons in an intense laser pulse," arXiv:2306.16945 (2023).

[9] A. Gonoskov, S. Bastrakov, E. Efimenko, A. Ilderton, M. Marklund, I. Meyerov, A. Muraviev, A. Sergeev, I. Surmin, and E. Wallin, "Extended particle-in-cell schemes for physics in ultrastrong laser fields: Review and developments," Phys. Rev. E **92**, 023305 (2015).

[10] A. Angioi and A. Di Piazza, "Quantum limitation to the coherent emission of accelerated charges," Phys. Rev. Lett. **121**, 010402 (2018).

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