Comment on “Free-Electron Laser and Laser Electron Acceleration Based on the Megagauss Magnetic Fields in Laser-Produced Plasmas”

In a recent Letter, Loeb and Eliezer\(^1\) suggest that the magnetic fields generated in laser-produced plasmas could be used as a wiggler for an x-ray free-electron laser (FEL) or for an inverse FEL accelerator. As an example they point out that 10-Å radiation could be amplified by a 150-MeV electron beam passing through magnetic fields with periodicity of 100 μm and strength of 1 MG. However, beam-plasma interactions can adversely affect any plasma-based FEL scheme. Here we comment on fundamental limitations to FEL gain resulting from the wake fields produced in the plasma by the electron beam. The optimized small-signal gain of an FEL is well known to scale as\(^2\)

\[
g \approx 2 \times 10^{-3} \left[ a_w^2 / (1 + a_w^2) \right] N^2 l / \gamma,
\]

where \(a_w = eA / mc^2\) is the normalized magnetic field factor.

\[
F_r = -e (E_r - B_\theta) = \left[ -8\pi n_b e^2 r / (k_p a)^2 \right] \left[ 1 - \cos k_p (z - ct) \right] \Theta(t - z/c),
\]

\[
F_z = -eE_z = (-4\pi n_b e^2 / k_p) \sin k_p (z - ct) \Theta(t - z/c),
\]

where \(z\) is the distance behind the leading edge of the beam, \(r\) is radial position, \(\Theta\) is the step function, and \(k_p = \omega_p / c\).

The longitudinal force directly gives rise to energy spread. For the present parameters, this retarding force varies from zero at the head to 40 MeV/cm at \(z = 0.1 \mu m\) \((k_p z = 0.2)\). Thus the beam will develop an energy spread of 40 MeV \((\approx 25\%)\) over the length of the FEL. We find that for any conceivable FEL parameters, the use of a simple uniform electron beam in a plasma will lead to unacceptable energy spread for FEL action in the x-ray region.

Although a precisely placed precursor beam can be used to produce a canceling wake and eliminate the longitudinal force, the radial force will remain. This gives rise to betatron oscillations of wavelength \(\beta = 2\pi (\gamma mc^2 r / F_r)^{1/2} = 1 \text{ mm}\) and angular divergence \(\Delta \theta = 2\pi r / \beta \approx 2\pi \text{ mrad}\). This is more than an order of magnitude too large for FEL action at the specified wavelength.

Finally, we point out that fine-scale magnetic field structure may exist in the plasma which cannot be resolved by Faraday rotation experiments. This gives rise to additional perpendicular velocity kicks to the electrons lowering their parallel velocity and altering the resonance condition. Although lasing action may not be possible in the scheme of Loeb and Eliezer, the strong \(a_w\) would enable significant spontaneous radiation of γ rays by the e beam of a compact gigaelectron-volt storage ring.

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\(^2\)See, for example, W. B. Colson and A. M. Sessler, Annu. Rev. Nucl. Part. Sci. 35, 25–54 (1985), and references therein.
\(^3\)For example, the beam length \(L\) will be shorter than an e-folding length of the plasma two-stream instability if
\(L \approx \gamma (n_b / n_0)^{-1/2} c / \omega_p\), where \(n_b\) is the beam density, \(n_0\) is the plasma density, and \(\omega_p\) is the plasma frequency.
\(^4\)P. Chen, Stanford Linear Accelerator Center Report No. SLAC-PUB-3823 (to be published).