FREE-ELECTRON LASERS DRIVEN BY LASER-PLASMA ACCELERATORS USING DECOMPRESSION OR DISPERSION*

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Abstract

Laser-plasma accelerators (LPAs) are a compact source of fs electron beams with kA peak current and low (submicron) transverse emittance. Presently, the energy spread (percent-level) hinders the free-electron laser (FEL) application. Given experimentally-demonstrated LPA electron beam parameters, we discuss methods of beam phase space manipulation after the LPA to achieve FEL lasing. Decompression is examined as a solution to reduce the slice energy spread. Beam dispersion, coupled to a transverse gradient undulator (TGU), is also discussed as a path to enable LPA-driven FELs. Using a TGU has several advantages, including maintaining the ultrashort LPA bunch length and radiation wavelength stabilization.

INTRODUCTION

Laser-plasma accelerators (LPAs) have the ability to generate ultra-high accelerating gradients, several orders of magnitude larger than conventional RF accelerators. Laser-plasma acceleration is realized by using a high-intensity laser to ponderomotively drive a large plasma wave (or wakefield) in an underdense plasma [1]. The plasma wave has relativistic phase velocity, and can support large electric fields in the direction of the laser propagation. When the laser pulse is approximately resonant (pulse duration on the order of the plasma period) and the laser intensity is relativistic, with normalized laser vector potential $a = eA/m_ec^2 \sim 1$, the size of the accelerating field supported by the plasma is on the order of $E_0 = m_ec\omega_p/e$, or $E_0[\text{V/m}] \simeq 96\sqrt{n_0[\text{cm}^{-3}]}$, where $\omega_p = k_pc = (4\pi n_0e^2/m_e)^{1/2}$ is the electron plasma frequency, n_0 is the ambient electron number density, m_e and e are the electronic mass and charge, respectively, and c is the speed of light in vacuum. For example, an accelerating gradient of $\sim$100 GV/m is achieved operating at a plasma density of $n_0 \sim 10^{18}$ cm^{-3}. Owing to these ultra-high accelerating gradients, LPAs are actively being researched as ultra-compact sources of energetic electron beams for a variety of applications. Electron beams up to $\sim$1 GeV have been experimentally demonstrated using high-intensity lasers interacting in centimeter-scale plasmas [2]. These LPA electron beams contain tens of pC of charge, percent-level relative energy spread, and have ultra-low normalized transverse emittances $\epsilon_n \sim$0.1 mm rad [3, 4]. In addition to extremely large accelerating gradients, plasma-based accelerators intrinsically produce ultra-short (fs) electron bunches with bunch lengths that are a fraction of the plasma wavelength [5, 6]. Because of the short beam durations, LPAs are sources of high peak current beams ($\sim$1–10 kA), and, hence, it is natural to consider LPA electron beams as drivers for a compact free-electron laser (FEL) producing high-peak brightness radiation [7–14]. LPA electron beams have been coupled into magnetostatic undulators to produce spontaneous radiation in the visible [15] and soft-x-ray [16] wavelengths.

Presently, the FEL application is hindered by the relatively large energy spread (few percent) of the LPA electron beam. LPA research has focused on methods to provide detailed control of the injection of background plasma electrons into the plasma wave, thereby controlling the LPA beam phase space characteristics and to improve the shot-to-shot stability and tunability of the beam parameters [17–19]. Although LPA beam phase space properties continue to improve, application of FEL beams may be accomplished using present experimentally-demonstrated LPA electron beam properties. In this paper we discuss post-LPA beam phase-space manipulation (i.e., beam decompression [11, 13] or dispersion [14]) to enable lasing of the LPA-driven FEL.

BEAM MANIPULATION FOR GAIN LENGTH REDUCTION

The fundamental resonant wavelength emitted in the FEL is $\lambda = \lambda_u(1 + K^2/2)/2\gamma^2$, where λ_u is the undulator wavelength and K is the undulator strength parameter. The ideal (with diffraction, energy spread, space charge, and emittance effects neglected) gain length (e-folding length of the fundamental radiation power) is [20]

$$L_{g0} = \lambda_u/(4\pi\sqrt{3}\rho), \tag{1}$$

where ρ is the FEL parameter

$$\rho = \frac{1}{4\gamma}\left[\frac{I}{I_\text{A}}\left(\frac{K[JJ]\lambda_u}{\pi\sigma_x}\right)^2\right]^{1/3}, \tag{2}$$

with σ_x the average rms beam transverse size (assuming a round beam $\sigma_x = \sigma_y$), I the peak beam current, $I_A = m_ec^3/e \approx 17$ kA is the Alfvén current, $[JJ] = [J_0(\chi) - J_1(\chi)]$ (planar undulator), $\chi = K^2(4 + 2K^2)^{-1}$, and J_m are Bessel functions.

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The FEL requires the relative slice (i.e., over a a coherence length $L_c = \lambda L_{g0}/\lambda_u$) energy spread to be less than the FEL parameter $\sigma_\gamma/\gamma < \rho$. Satisfying this requirement has been a challenge for LPA-generated electron beams. The effect of energy spread on the FEL gain length can be estimated as [21]

$$L_g \approx L_{g0}\left(1+\Delta^2\right), \tag{3}$$

where $\Delta = \sigma_\gamma/(\gamma\rho)$. For typical LPA and FEL parameters, $\Delta > 1$, hindering the FEL application of these beams. Designing the magnetostatic undulator to be more compatible with large energy spread beams may be considered for a demonstration LPA-driven FEL experiment [13]. For an LPA-driven FEL operating in the extreme ultra-violet (or longer wavelength) regime, slippage in the FEL is also a dominant effect. Typically $L_b < \lambda/\rho$, where L_b/c is the electron bunch duration (∼fs).

The 6D brightness of the demonstrated LPA electron beams [11] is comparable to state-of-the-art conventional RF photo-cathode sources. This indicates that beam phase-space redistribution can be applied to achieve FEL lasing. There are several possible paths to realizing an FEL using experimentally-demonstrated LPA electron beams that rely on beam phase space manipulation of the beam following the LPA. One possibility is simple energy collimation of the beam (e.g., using a chicane and a slit) to reduce the energy spread (at the expense of beam current and FEL photons). Another possibility is to decompress the beam [11, 13, 22], thereby reducing the slice energy spread. A third possibility that has recently been proposed [14] is to produce a correlation between energy and transverse position of the beam electrons, and then to use a transverse gradient undulator (TGU) to satisfy the resonant condition for all energies. Although requiring a more complicated canted-pole undulator design, the use of a TGU has potentially a number of advantages, including maintaining the ultrashort LPA bunch length, removing wavelength fluctuations due to beam energy jitter, and higher saturated power (compared to decompression). A combination of decompression and dispersion, with a TGU, can also be considered to reduce the dispersion required to satisfying the resonance condition for all beam electrons in a TGU.

Gain Length Reduction using Decompression

Decompression (e.g., using a chicane) offers a possible path to realizing a soft-x-ray FEL driven by an LPA, with experimentally-demonstrated LPA beam parameters. The decompression will reduce the peak current, and, hence, the FEL parameter $\rho \propto I^{1/3}$. But, since the FEL parameter scales weakly with current, sufficient decompression will reduce the slice energy spread to $\lesssim \rho$, providing a path for FEL lasing.

Consider decompression of the beam by a factor $D > 1$, such that the bunch length increases to $L_{b,d} \approx DL_b$, and the instantaneous energy spread decreases to $\sigma_{\gamma,d} \approx \sigma_\gamma/D$, where the d-subscript indicates the value after decompression. Decompression can be achieved using a magnetic chicane with strength $R_{56} \approx DL_b/(\sigma_\gamma/\gamma)$. After decompression the peak current decreases $I_d \approx I/D$ and the FEL parameter is reduced $\rho_d \approx \rho D^{-1/3}$. The relative energy spread will be equal to the FEL parameter with a decompression factor $D = \Delta^{3/2}$. We will assume that the decompression lengthens the beam sufficiently such that the effect of slippage on the gain length may be neglected $L_{b,d} = DL_b \gg L_c$, then the (1D) gain length after decompression can be estimated from Eq. (3) as [11]

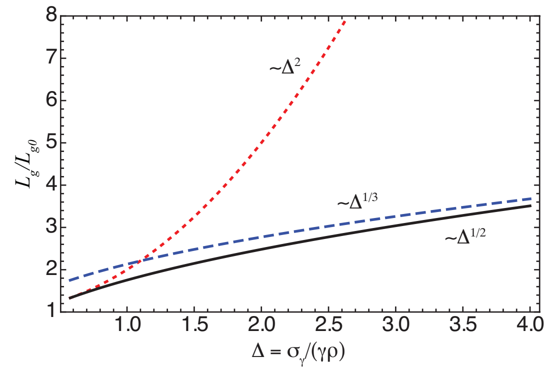

Figure 1: Normalized 1D gain length $L_g/L_{g0} = 4\pi\sqrt{3}\rho L_g/\lambda_u$ versus initial relative energy spread $\Delta = \sigma_\gamma/(\rho\gamma)$ (before beam phase space manipulation), without beam phase space manipulation (dotted red curve), with optimal decompression (solid black curve), with optimal beam dispersion coupled to a TGU with $\delta = \sigma_x/(\eta\rho) = 0.125$ (dashed blue curve).

$$L_g/L_{g0} \approx D^{1/3}\left(1 + D^{-4/3}\Delta^2\right). \tag{4}$$

Equation (4) indicates the gain length is minimized [11]

$$L_{g,\min}/L_{g0} = \frac{4}{3^{3/4}}\Delta^{1/2}, \tag{5}$$

for a decompression factor

$$D_0 = 3^{3/4}\Delta^{3/2} \tag{6}$$

At the optimal decompression factor the energy spread normalized to the FEL parameter is $\sigma_{\gamma,d}/(\gamma\rho_d) = D_0^{-2/3}\Delta = 3^{-1/2}$. Decompression is not advantageous for $\Delta \leq 3^{-1/2}$. With optimal decompression, the gain length grows as $L_{g,\min} \propto \Delta^{1/2}$ [compared to $L_g \propto \Delta^2$ without decompression for $\Delta > 1$]. Figure 1 shows the 1D gain length normalized to the ideal gain length versus normalized energy spread without decompression (dotted red curve) and with optimal compression (solid black curve).

The above analysis neglected diffraction and emittance effects. The gain length including these effects can also be minimized using decompression. Consider the gain length fitting formula obtained by Xie [23]: $L_g = L_{g0}[1 + \Lambda(\nu_d, \nu_\epsilon, \Delta)]$, where $\nu_d = L_{g0}\lambda/(4\pi\sigma_x^2)$ is the diffraction parameter and $\nu_\epsilon = 4\pi\epsilon_n k_\beta L_{g0}/(\gamma\lambda)$ is the emittance (angular spread) parameter, with k_β the betatron wavenumber. Decompression modifies the diffraction and emittance

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parameters such that $\nu_d \to D^{1/3}\nu_d$ and $\nu_\epsilon \to D^{1/3}\nu_\epsilon$. LPAs can generate electron beams with low normalized emittance on the order of $\epsilon_n \sim 0.1$ mm mrad, such that the effect of emittance on the power gain length can be neglected compared to the contributions from diffraction and energy spread for soft x-ray (and longer) wavelengths, i.e., $\nu_\epsilon \ll \nu_d < \Delta$ and $\Lambda(\nu_d, \nu_\epsilon, \Delta) \simeq \Lambda(\nu_d, 0, \Delta)$. Therefore the gain length after decompression $L_g = L_{g0}[1 + \Lambda(D^{1/3}\nu_d, D^{1/3}\nu_\epsilon, D^{-2/3}\Delta)]$ simplifies to

$$L_g/L_{g0} = D^{1/3}\Big(1 + D^{-4/3}\Delta^2 + 0.45\nu_d^{0.57}D^{0.19} + 9.8\nu_d^{0.95}\Delta^3 D^{-1.7}\Big). \quad (7)$$

Figure 2 shows the gain length Eq. (7) versus decompression D for $\nu_d = 0$ (i.e., 1D limit) and $\nu_d = 0.25$. Figure 3(a) shows the optimal decompression factor $D_{\rm opt}$ that minimizes the gain length Eq. (7). The minimum gain length with decompression $D_{\rm opt}$ is shown in Fig.3(b).

As a numerical example, consider an LPA-generated 0.5 GeV, 5 fs (FWHM), 10 pC electron beam, with 3% (rms) relative energy spread and 0.1 mm mrad transverse normalized emittance, coupled ($\sigma_x \simeq 20$ μm) to the THUNDER undulator (2.18 cm period and $K = 1.85$) [24] at LBNL. The fundamental wavelength is $\lambda = 31$ nm, $\rho = 0.015$, $L_{g0} = 6.5$ cm, $\Delta = 2$, $\nu_d = 0.25$, and $\nu_\epsilon = 4 \times 10^{-4}$. Decompressing by a factor of $D_{\rm opt} \simeq 13$, reduces the gain length to $L_g/L_{g0} \simeq 4.1$ (or $L_g = 0.27$ m).

With optimal decompression the output power, for fixed undulator length L_u, is greatly increased in the exponential gain regime $P \propto \exp[L_u/L_g(D_{\rm opt})] \gg \exp[L_u/L_g(1)]$. Operating the LPA-driven FEL in SASE mode, decompression increases the radiation pulse duration and reduces the temporal coherence. With decompression the number of temporal modes increases as $\sim D^{2/3}L_b/L_c$. Although decompression can reduce the gain length, allowing saturation to be reached for shorter undulators, the radiation power at saturation will be reduced owing to the reduced peak beam current $P_{{\rm sat},d} \sim \rho P_{\rm beam} D^{-4/3}$.

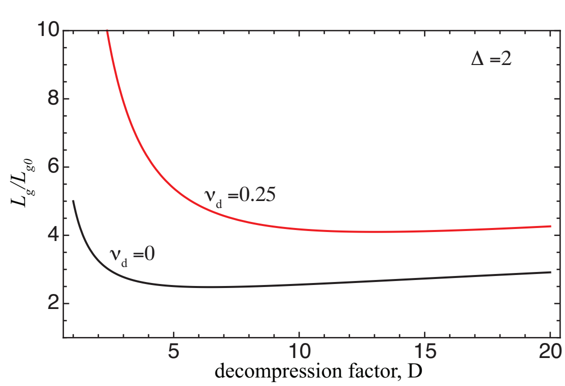

Figure 2: Normalized gain length L_g/L_{g0}, Eq. (7), versus decompression D for $\Delta = 2$ and $\nu_d = 0$ (black curve) and 0.25 (red curve).

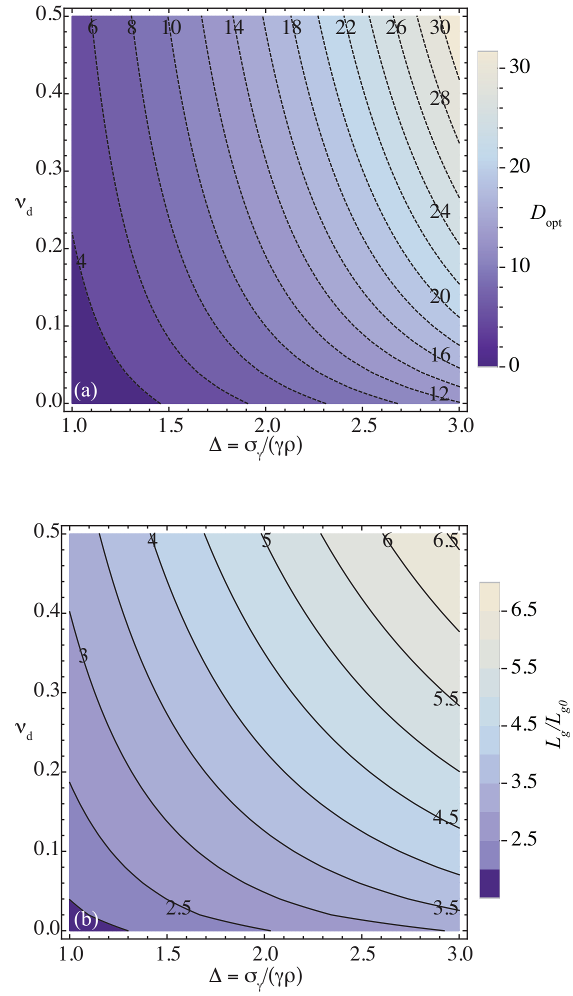

Figure 3: (a) Optimal decompression factor $D_{\rm opt}$ that minimizes the gain length Eq. (7). (b) Minimum gain length with decompression $D_{\rm opt}$.

Decompression will reduce the slice energy spread, but will also generate a chirped energy distribution. The energy chirp on the beam may be characterized by the relative energy chirp over a coherence length normalized to the FEL parameter,

$$\hat{\mu} = \frac{L_c}{\rho\gamma}\frac{d\gamma}{cdt}. \quad (8)$$

After decompression,

$$\hat{\mu}_d \simeq D^{-1/3}\left(\Delta L_c/L_b\right). \quad (9)$$

The energy chirp will influence the gain length if $\hat{\mu}_d \sim (\sigma_{\gamma,d}/\gamma\rho_d) = D^{-4/3}\Delta$. Hence, the chirp may be neglected for sufficiently long bunches before decompression, $L_b/L_c \gg D$. A tapered undulator may be considered to mitigate the effects of the beam chirp due to decompression [13]. The radiation temporal coherence may also be improved and the pulse duration reduced by using a tapered undulator to operate the SASE FEL in a single spike mode.

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Gain Length reduction using Dispersion with a Transverse Gradient Undulator

Smith et al. [25] originally proposed a transverse gradient undulator (TGU) to reduce the sensitivity to electron energy variations for FEL oscillators. By canting the undulator poles a linear dependence on the (vertical) undulator field $K(x) = K_0(1 + \alpha x)$ can be achieved, where α is determined by the cant angle of the TGU. Consider using a dispersive element to generate a correlation between energy and transverse (horizontal) position $\gamma(x) = \gamma_0(1 + x/\eta)$. The resonance condition $\lambda = \lambda_u[1 + K(x)^2/2]/2\gamma(x)^2$ can now be satisfied for all electrons with the optimal dispersion [25, 26]

$$\eta = \frac{2 + K^2}{\alpha K^2}. \tag{10}$$

The TGU concept has been discussed to improve the spontaneous undulator radiation spectrum using a superconducting undulator [27]. TGUs have also recently been considered for a storage ring FEL [28].

Use of a TGU for an LPA-driven FEL in the high-gain regime was analyzed by Huang et al. [14]. The effect of the dispersion in the horizontal plane is to reduce the beam current and the FEL parameter. Following dispersion the horizontal size increases to $(\sigma_x^2 + \eta^2\sigma_\gamma^2/\gamma^2)^{1/2}$, and the FEL parameter is reduced, $\rho[1 + (\eta\sigma_\gamma/\gamma\sigma_x)^2]^{-1/6}$. Typically $\eta\sigma_\gamma/\gamma \gg \sigma_y$ and the dispersion creates a flat beam with a large aspect ratio. The horizontal beam size will introduce an effective energy spread in the TGU owing to the gradient in undulator field,

$$(\sigma_\gamma/\gamma)_{\text{eff}} = \frac{K^2}{2 + K^2}\alpha\sigma_x = \sigma_x/\eta. \tag{11}$$

For sufficiently small emittance, $\sigma_x = (\epsilon_n/k_\beta\gamma)^{1/2} \ll \eta\rho$, this energy spread may be neglected. Using Eq. (3), the gain length using optimal dispersion Eq. (10) coupled to a TGU is [14]

$$\frac{L_g}{L_{g0}} \approx \left[1 + \frac{\Delta^2}{\delta^2}\right]^{1/6} \left\{1 + \delta^2 \left[1 + \frac{\Delta^2}{\delta^2}\right]^{1/3}\right\}, \tag{12}$$

where $\delta = \sigma_x/(\eta\rho)$. Although the beam current is reduced by the dispersion, considerable improvement in the FEL performance is achieved. For $\Delta \gtrsim 1$ and $\delta \ll 1$ (i.e., $\sigma_\gamma/\gamma \gtrsim \rho \gg \sigma_x/\eta$),

$$\frac{L_g}{L_{g0}} \approx \left(\frac{\Delta}{\delta}\right)^{1/3} = \left(\frac{\eta\sigma_\gamma}{\sigma_x\gamma}\right)^{1/3}. \tag{13}$$

As indicated by Eq. (13), the gain length using a TGU with optimized dispersion has the favorable scaling $L_g \propto \Delta^{1/3}$, compared to $L_g \propto \Delta^2$ without using a TGU or decompression, and $L_g \propto \Delta^{1/2}$ with optimal decompression. Figure 1 shows the normalized gain length using a TGU with optimal dispersion versus normalized energy spread with $\delta = 0.125$ (dashed blue curve).

As a numerical example consider a (superconducting) TGU with $\lambda_u = 0.01$, $K = 2$, and a transverse gradient $\alpha = 75\ \text{m}^{-1}$. Consider a 1 GeV, 15 kA LPA beam, with 1.5% (rms) relative energy spread and $\sigma_x = 15\ \mu$m before dispersion. The resonant FEL wavelength is 3.9 nm. Optimal dispersion requires $\eta = 2$ cm. The FEL parameter is $\rho = 0.006$, $\Delta = 2.5$, and $\delta = 0.125$. Neglecting diffraction effects, using a TGU with optimal dispersion reduces the gain length to $L_g/L_{g0} \simeq 3$.

Although requiring a more complicated canted-pole undulator design, the use of a transverse gradient undulator has potentially a number of advantages compared to decompression, including maintaining the ultrashort LPA bunch structure (i.e., generation of ultrashort radiation), removing wavelength fluctuations due to beam energy jitter (although energy jitter will translate to transverse position jitter), reduced bandwidth, improved temporal coherence, and, with wavelength stabilization, seeding is enabled. Note that use of a tapered undulator with a decompressed (energy chirped) beam can allow the SASE FEL to operate in a single spike mode, reducing the pulse duration, and improving the temporal coherence. The saturated power with optimal dispersion in the TGU will be $P_{\text{sat,TGU}} \sim \rho P_{\text{beam}}(\delta/\Delta)^{1/3}$ owing to the reduced beam current. Comparing the power at saturation in the TGU $P_{\text{sat,TGU}}$ to the power at saturation using optimal decompression $P_{\text{sat},d}$:

$$\frac{P_{\text{sat,TGU}}}{P_{\text{sat},d}} = D_0^{4/3}(\delta/\Delta)^{1/3} = 3\delta^{1/3}\Delta^{5/3}. \tag{14}$$

For typical LPA parameters with $\Delta > 1$, higher saturated power is achieved using a TGU.

There is no benefit from the combination of decompression and optimal dispersion in terms of reduced gain length. However, if the horizontal beam size after dispersion is limited $\sigma_x \leq \sigma_{x,m}$ (for example, due to technical constraints on the transverse field gradient of the undulator), then decompression may be considered before dispersion to reduce the slice energy spread such that $\eta\sigma_\gamma/(D\gamma) < \sigma_{x,m}$, resulting in a longer gain length.

One potential disadvantage of using a TGU is the loss of transverse coherence, owing to the excitation of multiple transverse modes in the flat beam with large aspect ratio $\eta\sigma_\gamma/\gamma \gg \sigma_y$ [14]. A 3D theory of TGU-based FELs operating in the high-gain regime can be found in Ref. [29]. Transverse coherence of the radiation can be improved by external seeding or self-seeding.

SUMMARY AND CONCLUSIONS

In this work we have described the use of beam-phase-space manipulation to reduce the FEL gain length and enable lasing of an LPA-driven FEL. Decompression was examined as a solution to reduce the slice energy spread. The optimal beam decompression was derived. Beam dispersion, coupled to a transverse gradient undulator (TGU), was also discussed as a path to enable LPA-driven FELs.

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A TGU-based LPA-driven FEL was compared to an LPA-driven FEL that uses decompression. Using a TGU has several advantages, including maintaining the ultrashort LPA bunch length, stabilization of wavelength fluctuations, enabling seeding, and higher saturated power. These beam-phase-space manipulation techniques, used after the LPA and before the undulator, allow FEL lasing for presently achievable LPA parameters.

In addition to compactness, an LPA-driven FEL may offer advantages over conventional light sources. For example, in addition to generating high-peak brightness LPA electron beams, a single laser system may drive multiple beamlines, producing ultra-short radiation over a broad range of wavelengths, from high-field THz to Thomson-scattered gamma rays [30], all intrinsically synchronized to the high-peak power drive laser. Such a compact, ultra-short, hyper-spectral source (along with laser-driven electron and ion beams) would provide unique opportunities for pump-probe experiments in ultra-fast science. Future LPA experiments using more energetic (tens of Joules), short-pulse, PW laser systems (e.g., BELLA [31]) will enable generation of 10 GeV electron beams in less than a meter of plasma, opening the possibility of a compact LPA-driven hard-x-ray FEL.

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