Compact laser-plasma-accelerator-driven free-electron laser using a transverse gradient undulator

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Abstract. Laser-plasma accelerators can produce a few GeV electron beams over a distance of a few cm. Such a beam typically has relatively low emittance, high peak current but a rather large energy spread and jitter. The large energy spread hinders the potential applications for coherent free-electron laser (FEL) radiation generation. We discuss a method to compensate the effects of beam energy spread by introducing a transverse variation of the undulator magnetic field. Such a transverse gradient undulator (TGU) together with a properly dispersed beam can greatly reduce the effects of electron energy spread and jitter on FEL performance. In this paper, we review the TGU concept, theory and discuss technical implementations. Using particle-in-cell simulations of a GeV laser-plasma accelerator and the FEL simulation code GENESIS that is modified to accommodate TGU, we show a soft x-ray FEL operating in the "water window" wavelengths can reach saturation with a undulator length of about 12 m.

Keywords: Free-Electron Laser, Laser Plasma Accelerator, Transverse Gradient Undulator
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INTRODUCTION

Laser-plasma accelerators (LPAs) have the ability to generate ultra-high accelerating gradients, several orders of magnitude larger than conventional RF accelerators. Owing to these ultra-high accelerating gradients, LPAs are actively being researched as compact sources of energetic beams for light source applications. Electron beams up to a few GeV have been experimentally demonstrated using high-intensity lasers interacting in centimeter-scale plasmas [1, 2]. These beams contain tens of pC of charge, few percent-level relative energy spread, and have ultra-low transverse emittances on the order of $\sim$0.1 mm rad. In addition to extremely large accelerating gradients, plasma-based accelerators intrinsically produce ultra-short (fs) electron bunches with bunch lengths that are a fraction of the plasma wavelength. Because of the short beam durations, LPAs are sources of high peak current beams ($\sim$1–10 kA), and, hence, it is natural to consider LPA electron beams as drivers for a free-electron laser (FEL) producing high-peak brightness radiation.

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. Although LPA beam phase space properties continue to improve, application of FEL beams may be accomplished using present experimentally demonstrated LPA electron beam properties. One method recently proposed to realize an LPA-driven FEL is to produce a correlation between beam energy and transverse position following the LPA, and then to use a transverse gradient undulator (TGU) to satisfy the resonant condition for all electron energies.

In this paper, we review the TGU concept, theory and discuss technical implementations. Using particle-in-cell simulations of a GeV laser-plasma accelerator and the FEL simulation code GENESIS that is modified to accommodate TGU, we show a soft x-ray FEL operating in the "water window" wavelengths can reach saturation with a undulator length of about 12 m.

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TRANSVERSE GRADIENT UNDULATOR

Concept

Transverse gradient undulator (TGU) has been proposed to reduce the sensitivity to electron energy variations for FEL oscillators [3] and recently for a high-gain FEL driven by a laser plasma accelerator [4, 5]. The idea is illustrated in Fig. 1. By canting the magnetic poles, one can generate a linear x dependence of the vertical undulator field so that

$$K(x) = K_0(1+\alpha x)\,. \tag{1}$$

Consider dispersing the electron beam horizontally according to its energy such that $\gamma(x) = \gamma_0(1+x/\eta)$. By choosing the dispersion function

$$\eta = \frac{2+K_0^2}{\alpha K_0^2} \tag{2}$$

and keeping it constant in the TGU [6], the change in electron's energy is now exactly compensated by the change in the magnetic field so that the resonant wavelength

$$\lambda_r = \frac{\lambda_u}{2\gamma(x)^2}\left(1+\frac{K(x)^2}{2}\right) \tag{3}$$

is independent of x as long as the dispersed beam size σ_x is not too large. This technique greatly reduces the sensitive of the FEL gain length dependence on the energy spread.

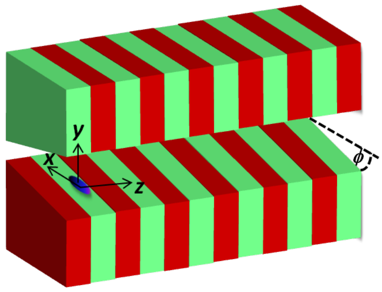

FIGURE 1. Transverse gradient undulator by canting the magnetic poles. Each pole is canted by an angle ϕ with respect to the xz plane. The higher energy electrons are dispersed to the higher field region (positive x) compared to the lower energy electrons to match the FEL resonant condition.

Theory

In a normal undulator, the gain length dependence on the (Gaussian) energy spread can be described by

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\left(1+\frac{\sigma_\delta^2}{\rho^2}\right)\,. \tag{4}$$

Hence when the relative energy spread σ_δ is greater than the FEL parameter ρ, the gain length is significantly increased. For a transverse gradient undulator, the beam is dispersed in the horizontal direction with an increased beam size. This reduces the beam density and the coupling to the radiation through the FEL parameter ρ. We can define an effective ρ for TGU as

$$\rho_T = \rho\left(\frac{\sigma_T}{\sigma_x}\right)^{-1/3}\,,\quad \sigma_T = \sqrt{\sigma_x^2+\eta^2\sigma_\delta^2}\,, \tag{5}$$

where η is the dispersion in the undulator and σ_x is the intrinsic beam size. This slight reduction in FEL efficiency is paid off because the gain length is insensitive to the intrinsic energy spread.

Because of the transverse field gradient, an intrinsic horizontal beam size will also induce an effective energy spread in a TGU as

$$\sigma_\delta{}^{eff} = \frac{K_0^2}{2+K_0^2}\frac{\sigma_K}{K_0} = \frac{K_0^2}{2+K_0^2}\alpha\sigma_x \,. \tag{6}$$

The intrinsic beam size is determined by the horizontal emittance ε_x and the beta function β. For a relatively short undulator of length L_u considered here for LPAs without external focusing, it is reasonable to take $\beta \approx L_u/2$, and hence $\sigma_x = \sqrt{\varepsilon_x L_u/2}$ in Eq. (6). The 1D gain length for a TGU equivalent to Eq. (4) is then [4]

$$L_g^T \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho_T}\left[1+\left(\frac{K_0^2}{2+K_0^2}\right)^2 \frac{\alpha^2\varepsilon_x L_u}{2\rho_T^2}\right] . \tag{7}$$

This equation can be rewritten as [7]

$$L_g^T \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\left[\left(\frac{\sigma_T}{\sigma_x}\right)^{1/3} + \frac{\sigma_\delta^2}{\rho^2}\left(\frac{\sigma_T}{\sigma_x}\right)^{-1}\right] . \tag{8}$$

Let us suppose that we can optimize the dispersion to minimize the gain length while Eq. (2) is satisfied. From Eq. (8), we have the optimal dispersion and gain length [7]

$$\eta \approx 2.28\sigma_x\sigma_\delta^{1/2}/\rho^{3/2} , \tag{9}$$

$$L_g^T \approx 1.75\frac{\lambda_u}{4\pi\sqrt{3}\rho}\left(\frac{\sigma_\delta}{\rho}\right)^{1/2} . \tag{10}$$

Compare this with Eq.(4), the effects of large energy spread is greatly reduced in a TGU.

A self-consistent theoretical analysis of a TGU-based, high-gain FEL which takes into account three-dimensional (3D) effects, including beam size variations along the undulator is presented in Ref. [8]. The calculated gain length compares favorably with simulations and also confirm the simple 1D theory for the optimum dispersion. Figure 2 shows such a comparison using 1-GeV, soft x-ray FEL parameters used in Ref. [4]. Since the beam cross section is highly asymmetric in a TGU, higher-order transverse modes can be developed for such an FEL. Their effects on transverse coherence are analyzed in Ref. [9].

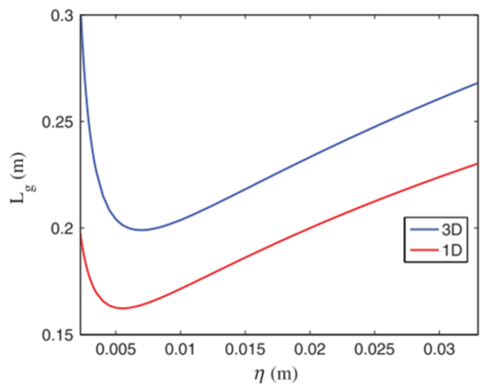

FIGURE 2. Frequency-optimized gain length as a function of dispersion for the LPA parameters (see Ref. [8] for more details). The data shown were derived using the parallel-beam theory (blue) and the 1D formula of Eq. (7) (red).

Technical implementation

Transverse gradient undulator should be relatively straightforward to implement. For hybrid undulators, if the magnetic pole face is canted with the full angle $2\phi \approx \Delta y/(\Delta x)$, then the gradient parameter is

$$\alpha = 2\phi\frac{1}{K_0}\frac{\partial K_0}{\partial y} = 2\phi\left(\frac{5.47}{\lambda_u} - 3.6\frac{g}{\lambda_u^2}\right) , \tag{11}$$

where the last step uses Halbach's formula [10] for hybrid undulators and g is the average full gap of the canted poles. A Hybrid TGU has been developed at Shanghai Institute of Applied Physics with $\lambda_u = 6$ cm and $\alpha = 50\ \mathrm{m}^{-1}$ [11]. TGU concept can be also implemented using a superconducting (SC) undulator [12]. The advantage of a superconducting undulator is the combination of smaller period, larger magnetic field and higher transverse gradient.

Due to the large divergence and energy spread of laser plasma beams, the transport and matching optics from the accelerator to the undulator is a major challenge. Recently, a rather compact beam transport system from a laser plasma accelerator to a TGU has been discussed in Ref. [13]. The transport system consists of dipoles and quadrupoles to match the beam's betatron functions and dispersion, and sexupoles for chromatic correction. The length of the total system is about 5 meters and can transport a beam with $\pm 1\%$ energy spread. The total momentum compaction of the transport system should be controlled as well to avoid strong bunch compression or decompression (in case the electron beam is strongly chirped).

NUMERICAL SIMULATIONS

In Ref. [4], we have shown the numerical simulations of a compact soft x-ray FEL example using a laser plasma beam with 1 GeV central energy and 1% rms energy spread. To reach the important "water window" wavelengths, we consider using the SC undulator described in Ref. [12] that also reaches very large transverse gradient $\alpha \approx 300\ \mathrm{m}^{-1}$. For a peak current $I_{pk} = 10$ kA and $\gamma\varepsilon = 0.1\ \mu$m, the TGU-based FEL reaches the saturation power of 1 GW in 5-m undulator length. We have also showed that the TGU improves the SASE power by about two orders of magnitude and the bandwidth by another order of magnitude over the normal undulator. The simulation did not take into account any energy-time correlation that always exists in a laser plasma accelerator. However, since the electron bunch is very short (< 10 fs fwhm), the soft x-ray FEL pulse slips through the entire electron bunch and is affected by the projected energy spread instead of time-sliced energy spread which can be much smaller than 1%.

To confirm this expectation and to use more realistic simulation parameters, we take a step towards start-to-end simulations by using the phase space distributions from particle-in-cell simulations of a laser plasma accelerator. Figure 3 shows the longitudinal phase space and the peak current of a 1.1 GeV beam obtained from a simulation performed with the particle-in-cell code INF&RNO [14], where we considered the interaction of a 2.7 J laser pulse (pulse length 20 fs, spot size 28 μm) with a 7 mm long gas-jet with a plasma density of $3 \times 10^{18}\ \mathrm{cm}^{-3}$. During propagation in the plasma the high-intensity laser pulse excites a bubble wake where electrons are self-injected [15]. Due to the relatively high bunch charge (120 pC) and very short bunch (9 fs FWHM), the normalized transverse emittance is 0.5μm, but the peak current reaches more than 15 kA at the tail of the bunch (see Fig. 3). The time-energy correlation is also highly nonlinear as shown in Fig. 3, with the projected rms energy spread on the order of 1%.

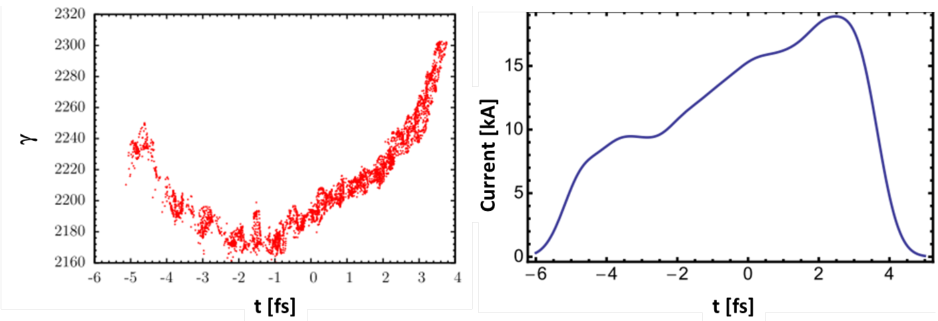

FIGURE 3. Simulated LPA beam longitudinal phase space (left) and current profile (right). Head of the bunch is to the left.

Our optimization for a "water" window soft x-ray FEL leads to a more conventional undulator of Hybrid type, with the period 1.5 cm and the average undulator parameter of 1.72. The Transverse gradient is 46 m^{-1} (Table. 1). The beam is focused to a waist in the middle of 12-m undulator, with the initial betatron functions 12.5 m and 4.3 m in x and y directions. The beam is dispersed in the horizontal direction according to the TGU resonant condition (i.e., Eq. (2) with $\eta \approx 3.4$ cm. GENESIS 1.3 [16] is modified to include the undulator transverse gradient effect. As in Fig. 4, GENESIS simulation shows that the 3.9-nm soft x-ray FEL reaches saturation in 12 to 13 meters of undulator length. The peak power is a few hundred MW, which is more than 2 orders of magnitude higher than a normal undulator of the same length. The output spectrum shows more than 3 orders of magnitude improvement over the normal undulator

TABLE 1. Parameters for a laser-plasma-accelerator-driven soft x-ray FEL using TGU. The longitudinal beam distribution is shown in Fig. 3.

Parameter	Symbol	Value	Unit
Beam energy	$\gamma_0 mc^2$	1.12	GeV
Projected rms energy spread	σ_δ	$\sim 1\%$	
Norm. transverse emittance	$\gamma_0 \varepsilon_{x,y}$	0.5	μm
TGU undulator period	λ_u	1.5	cm
TGU undulator parameter	K_0	1.72	
Transverse gradient	α	46	m^{-1}
Dispersion in TGU	η	3.4	cm
FEL wavelength	λ_r	3.9	nm

since the bandwidth of a TGU FEL is much narrower than the normal case as the large energy spread is compensated by the transverse gradient of the undulator.

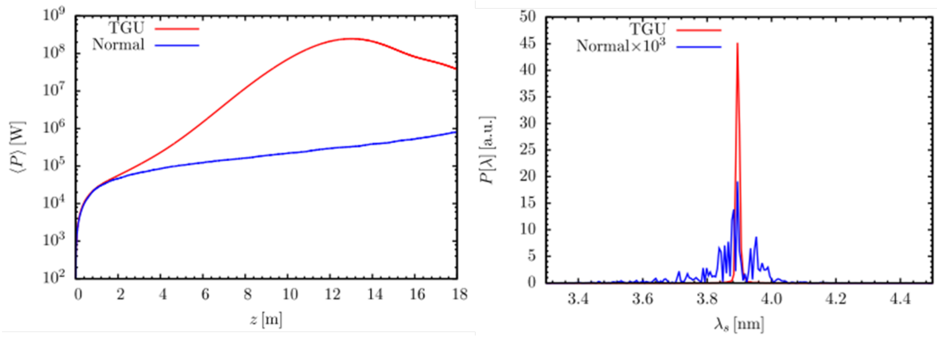

FIGURE 4. 3.9 nm SASE FEL power vs. undulator distance (left) and output spectrum (right).

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