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STUDIES ON LPWA-BASED LIGHT SOURCES DRIVEN BY A TRANSVERSE GRADIENT UNDULATOR

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Abstract

The Accelerator Science Laboratory (ASL) is under development at the John Adams Institute in Oxford with the aim of fostering advanced accelerator concepts and applications. The option to install a Laser Plasma Wakefield Accelerator (LPWA) based light source driven by a transverse gradient undulator is being investigated. This report presents the accelerator physics, FEL studies and the performance expected from such a facility.

INTRODUCTION

Linac-based free electron lasers are of great interest because of their high brilliance, high peak power, short pulse length, and photon energy tunability. Ultrashort X-ray radiation pulses with fs-range duration have opened the path to ultrafast resolution measurements, with applications in many disciplines. Existing X-ray FEL such as FLASH [1] and LCLS [2], and many projects under development around the world are usually based on large scale facilities. Compact X-ray sources are needed for small-scale laboratories. The John Adams Institute (JAI) also proposes to establish an Accelerator Science Lab (ASL) dedicated for research and development of a compact light source [3]. The ASL will focus on Laser Plasma Wakefield Accelerator (LPWA) based FELs as one of its main goals.

LPWAs have the potential to provide accelerating gradient exceeding 100 GV/m, which allow a spectacular reduction of the scale and cost of a synchrotron radiation source. The generation of soft-X-ray undulator radiation with electron beams from laser-plasma accelerators based on gas-filled capillary discharge waveguide was demonstrated in both particle-in-cell simulations [4] and proof-of-concept experiments [5]. While the LPWA electron beams are generated with very small normalised emittance (~0.1 μm), their relative energy spread is usually large (~1%). This has adverse consequences on the feasibility of short-wavelength FEL driven by LPWAs, since the FEL requires the relative energy spread ($\sigma_\delta = \sigma_\gamma/\gamma_0$) to be lower than the FEL parameter ρ, usually 0.1% or less.

In order to investigate in full the beam dynamics of such accelerator facility and assess the expected radiation properties it is necessary to set up a complete S2E simulation from the laser exciting the plasma down to the laser radiation of the FEL. The present status in the assembly of such numerical engine is also reported.

TRANSVERSE GRADIENT UNDULATOR

Recently, Huang *et al.* have proposed the use of a transverse gradient undulator (TGU) to compensate the effects of energy spread on FEL performance in a FEL based on laser plasma accelerators [6]. The idea of the large energy spread compensation in TGU is based on the use of a dispersive section to transform the energy spread in longitudinal phase space into transversal displacement, followed by the TGU. The magnetic field of the TGU is obtained by canting the undulator poles as shown in Fig. 1.

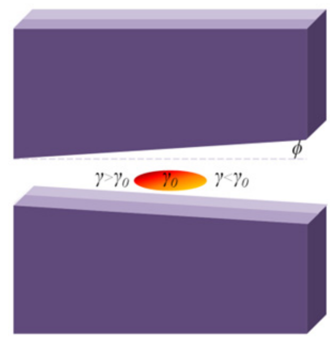

Figure 1: Transverse gradient undulator with magnetic poles canted by an angle of ϕ. The electrons with different energy see different magnetic field.

The variation of the undulator gap results in a transverse variation of the magnetic field and correspondingly of the undulator parameter K according to the relation $\Delta K = \alpha K_0 x$, where α is the gradient parameter which depends on the undulator canted angle ϕ, K_0 is the undulator strength parameter on the undulator axis and x is a transverse beam position from the axis. Electrons in different transverse positions experience different magnetic field strengths. With appropriate tuning of the dispersion function in the transfer line leading to the undulator, we can create a condition where all electrons with different energy satisfy the same FEL resonant wavelength

$$\lambda_r = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

where the average electron beam energy is $\gamma_0 mc^2$ and λ_u is the undulator period. The dispersion function η achieving this condition is given by

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

We considered an electron beam with 750 MeV energy, normalized emittance ε_{nx} = 0.1 mm-mrad, peak current I_p = 10 kA and beam size σ_x = 8.25 μm. Using a hybrid undulator with period λ_u = 1 cm and 1.5 mm gap which has undulator strength K = 1.4235 the FEL resonance wavelength is λ_r = 4.67 nm. The estimated FEL parameter is $\rho \approx 9\times10^{-3}$. The corresponding requirement in the energy spread would be $\sigma_\delta < 0.9\%$ which is smaller than what normally provided by LPWAs. Therefore we tested the effectiveness of a TGU in compensating the large energy spread. With a transverse gradient parameter α = 150 m^{-1}, the beam needs to have the dispersion η = 1.32 cm.

FEL SIMULATION

Our study uses a beam generated from ELEGANT [7]. The beam is then imported to run a FEL simulation in GENESIS [8]. The TGU undulator is modelled in GENESIS by using appropriate normalized natural focussing parameters and undulator module offset [9]. We assume each magnetic pole canted by an angle ϕ = 0.15 rad, which has the transverse gradient α = 150 m$^{-1.}$ All beam and undulator parameters are listed in Table 1.

Table 1: Electron Beam Parameters in ELEGANT and Undulator Parameters in GENESIS

Parameter	Symbol	Value
Beam distribution		Flattop (long.) / Gaussian (trans.)
Beam energy	$\gamma_0 mc^2$	750 MeV
Norm. trans. emittance	ε_{nx}	0.1 mm-mrad
Peak current	I_0	10 kA
Bunch duration	T	5 fs
Energy spread (RMS)	σ_δ	1%
Undulator type		Hybrid
Undulator period	λ_u	1 cm
gap	g	1.5 mm
Undulator parameter	K_0	1.42
Transverse gradient	α	150 m^{-1}
Horizontal dispersion	η	1.32 cm
Resonance wavelength	λ_r	4.67 nm

Figure 2 shows the average power of a self-amplified spontaneous emission (SASE) FEL from a normal undulator (green) and transverse gradient undulator (blue). As can be seen in Fig. 2, the saturation power for the TGU is higher than the power for the normal undulator by over an order of magnitude, and the FEL power for the TGU tends to reach saturation faster than for the normal undulator. This indicates that the TGU can reduce the gain length. In terms of single-shot spectrum, the spectrum for the TGU is cleaner than for the normal undulator as shown in Fig. 3.

These simulations show that as significant emission can be obtained also in higher order harmonics as illustrated in Fig. 4, where the 3rd and 5th harmonics achieve saturation at roughly a factor 10^2 and $\sim 10^3$ below the power of the fundamental, respectively.

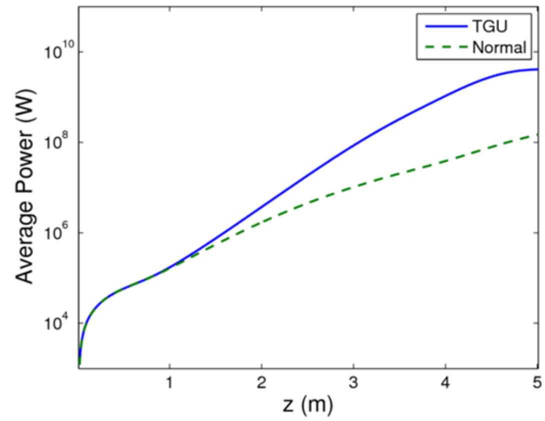

Figure 2: Average FEL power from the electron beam with dispersion of 1.32 cm for a normal undulator (green) and for a TGU (blue).

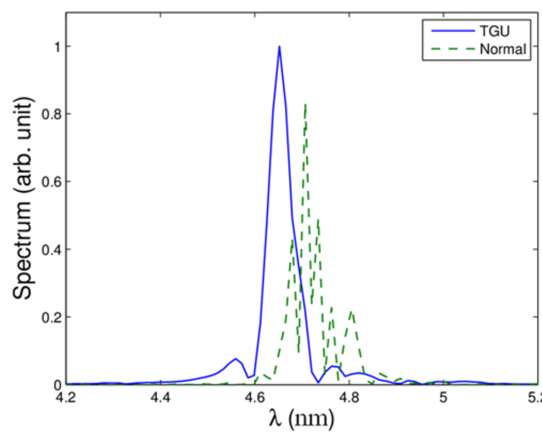

Figure 3: Power spectra at 5 m of SASE FEL for a normal undulator (green) and for a TGU (blue).

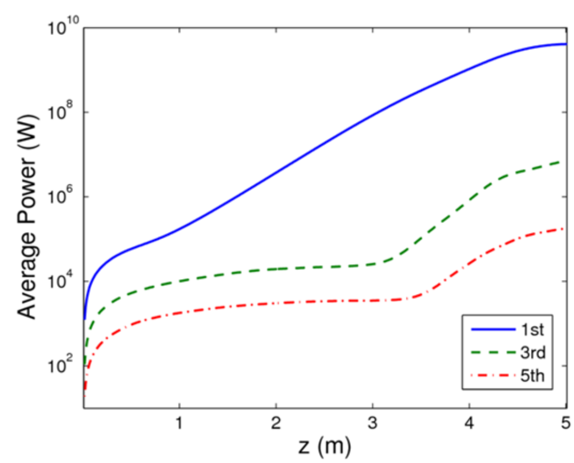

Figure 4: Average FEL power of fundamental and harmonics radiation for a TGU.

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TOWARD A FULL S2E SIMULATION OF THE LPWA FEL

In order to investigate the possibility for ASL to use a beam from LPWA as a FEL driver, we have started setting up a chain of simulations that generate the electron beam form the laser pulse in the plasma down to the transfer line and the undulator. Such a numerical approach mimics the corresponding analysis of high brightness linac driven FELs.

With this aim in mind we have started investigating the analysis on the self-injection electrons in the bubble regime with 2D-3D Particle in Cell (PIC) simulation EPOCH (Extendable PIC Open Collaboration) [10] developed by Collaborative Computational Plasma Physics (CCPP) consortium in the UK. The aim is that of extending the simulation engine to ELEGANT [7] and GENESIS [8]. We report here the preliminary result obtained with EPOCH.

When a very intense laser pulse propagates through plasma, the plasma electrons are completely pushed away from the laser pulse and oscillate to form wakefields travelling after the laser pulse [11]. With laser spot size matched to the plasma and appropriate pulse duration, an ion cavity or the bubble can be formed [12].

We referred parameters for self-guiding in the bubble regime from [12]. The parameters such as laser spot size, pulse duration, laser intensity and plasma intensity satisfy matching condition for stable laser propagation [13]. We used Hydrogen plasma with the density of $n_p = 2.0\times10^{18}$ cm^{-3} corresponding to the plasma wavelength of $\lambda_p = 23.6$ µm. For the driver laser, we used the laser with the wavelength of $\lambda_L = 800$ nm, the peak intensity of $I = 3.0\times10^{19}$ W/cm^2, Gaussian transverse profile with spot size $w_0 = 15$ µm, and Gaussian full-width half maximum (FWHM) pulse duration $\tau_L = 30$ fs. The simulation was done in a window of length 80 µm and width 80 µm. The resolution in longitudinal direction is 40 cells/λ_L and in transverse direction is 75 cells/λ_p or $k_L\Delta z = 0.16$ and $k_p\Delta y = 0.08$. The number of particle is 20 particles/cell.

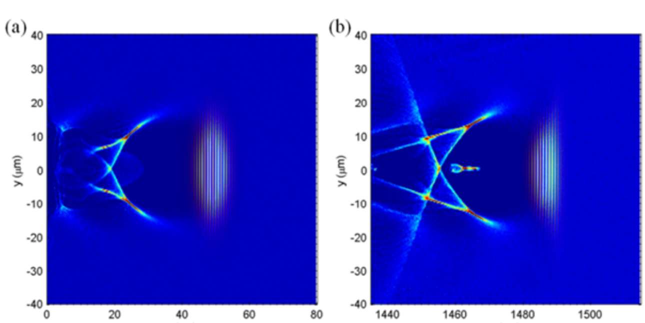

Figure 5: 2D electron density after laser propagating a distance of (a) $z = 60$ µm and (b) $z = 1.5$ mm.

From our 2D PIC simulations, the bubble has been excited by the laser that has propagated a distance about $z = 60$ µm as seen in Fig. 5(a). After that electrons have been injected into the bubble by the wakefield at the back. Figure 5(b) illustrates an example of self-injection after the laser propagating for about 1.5 mm. The longitudinal phase space of the trapped electrons is shown in Fig. 6. The bunch has average energy of 206 MeV and while the rms energy spread exceeds 10% it is clear that the there is a significant correlation with the longitudinal position in the bunch so that the slice energy spread is well below 1%. This bunch appears to be a promising candidate to drive a TGU FEL.

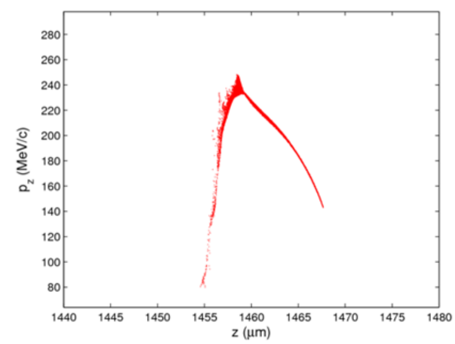

Figure 6: Longitudinal phase space of self-injected electrons inside the bubble after the laser beam has propagated 1.5 mm.

CONCLUSION

The LPWA based FEL light source was studied as an option for the ASL. We investigated the option of using a TGU to compensate the effect of large energy spread by dispersing the beam before entering the TGU. From the FEL study, the FEL power and gain length are improved over an order of magnitude by using the TGU instead of the normal undulator. Further optimization needs to be done to achieve higher FEL power and better quality of FEL radiation from the TGU.

We also began our investigation of the generation of the electron beam from the LPWA by performing 2D PIC simulations. Although the simulations are preliminary, they constitute a first step toward building a full S2E simulation of a LPWA driven TGU FEL. These studies are expected to inform the development of the ASL of the John Adams Institute at the University of Oxford.

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