TW X-RAY FREE ELECTRON LASER OPTIMIZATION BY TRANSVERSE PULSE SHAPING*

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Abstract

We study the dependence of the peak power of a 1.5 Å TW, tapered X-ray free-electron laser on the transverse electron density distribution. Multidimensional optimization schemes for TW hard X-Ray free electron lasers are applied to the cases of transversely uniform and parabolic electron beam distributions and compared to a Gaussian distribution. The optimizations are performed for a 200 m undulator using the fully 3-dimensional FEL particle code GENESIS. The study shows that the flatter transverse electron distributions enhance optical guiding in the tapered section of the undulator and increase the maximum radiation power from a maximum of 1.56 TW for a transversely Gaussian beam to 2.26 TW for the parabolic case and 2.63 TW for the uniform case.

INTRODUCTION

Radiation produced by Self Amplified Spontaneous Emission X-ray Free Electron Lasers (SASE X-FELs) [1] has been used to probe matter at the fastest timescales (fs) and the smallest dimensions (Å). LCLS and SACLA, the world's most powerful existing X-FELs deliver diffraction limited X-ray pulses of a few to a hundred femtoseconds in the energy range of 0.25 to 10 keV with peak power at saturation of 20-30 GW and a line-width on the order of 10^{-3} [2]. Pushing the capabilites of XFELs to TW peak power levels will have a great impact on future scientific endeavours, particularly in the fields of coherent X-ray diffraction imaging and nonlinear science. It is well known that the peak power of an FEL can be increased by tapering the undulator magnetic field to match the electron energy loss while preserving the synchronism condition [3]. The LCLS for example currently boosts its output power by a factor 2-3 using a limited taper capacity $\Delta K/K \sim 0.8\%$. For a SASE FEL this gain is limited due to the spiky nature of the radiation [4]. In a seeded or self-seeded FEL however, recent work has shown that a more flexible taper capacity can lead to much larger output powers, reaching levels of one TW or larger [5,6]. The analytic models developed in previous studies to obtain the optimal tapering profile have included three dimensional effects but only considered electron beams with Gaussian transverse density profile. In this work we examine the effect of using transversely parabolic and transversely uniform electron distributions in a tapered hard X-ray FEL with LCLS-II like parameters. The results are compared to the Gaussian beam case in both single frequency and time dependent simulations using the GENESIS code [7].

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Table 1: GENESIS Simulation Parameters

Parameter Name	Parameter Value
Beam energy E_0	13.64 GeV
Beam peak current I_{pk}	4000 A
Normalized emittances $\epsilon_{x,n}/\epsilon_{y,n}$	0.3/0.3 μ m rad
Peak radiation power input P_{in}	5 MW
Undulator period λ_w	32 mm
Normalised undulator parameter a_w	2.3832
Radiation wavelength λ_r	1.5 Å
FEL parameter ρ	7.361 $\times 10^{-4}$

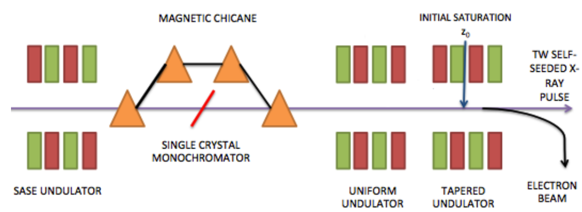

Figure 1: Schematic representation of a tapered X-ray FEL using a self-seeding monochromator and an optimised tapered section.

TAPERING OPTIMIZATION

Transverse Pulse Shaping in a Tapered FEL

In recent work [5] it has been pointed out that diffraction and refraction have an important impact on the peak power of TW X-FELs. Starting from conservation of energy and applying the same assumptions as in Ref. [5] we can write the radiation power as a function of the longitudinal position in the undulator:

$$P(z) = \frac{\pi r_s(z)^2 a_{s0}(z)^2}{4Z_0}\left(\frac{k_s m_e c^2}{e}\right)^2, \quad (1)$$

where $a_{s0}(z) = |e|A_s(z)/\sqrt{2}mc^2$ is the on-axis normalized vector potential of the radiation field for a linearly polarised undulator, $r_s(z)$ is the radiation beam size, k_s is the radiation wavenumber and Z_0 is the free space impedance. We must now optimize the growth of the radiation field inside the undulator in order to maximize the output radiation power. As described first in Ref. [3], this can be achieved by an adiabatic decrease in the resonant energy $\gamma_r(z)mc^2$, which is defined by the now z dependent resonance condition:

$$\gamma_r^2(z) = \frac{k_w}{2k_s}\left(1 + a_w(z)^2\right), \quad (2)$$

where $k_w = 2\pi/\lambda_w$ is the undulator wavenumber and $a_w(z) = |e|B_w(z)/\sqrt{2}k_w mc^2$ is the normalized vector po-

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tential of the undulator field. The optimal taper profile can then be obtained by choosing a functional form for $a_w(z)$:

$$a_w(z) = a_w(z_0) \times [1 - c \times (z - z_0)^d], \tag{3}$$

where z_0 is the initial tapering location, and c and d are constants to be obtained through simulations that maximize the output radiation power. The quadrupole focusing gradient $K_q(z)$ is also similarly optimized (see Fig. 2). The importance of the transverse electron distribution becomes apparent when examining the FEL process post-saturation. After the exponential gain regime the FEL is dominated by refractive guiding of the radiation by the electron beam. For a bunched electron beam it has been shown that the guiding is described quantitatively by a refractive index proportional to the beam microbunching [8] $n \sim \left\langle e^{-i\Psi} \right\rangle$ where the average is over the beam electrons trapped in the ponderomotive potential and Ψ is the ponderomotive phase. It is thus important to maintain a sufficiently large microbunching throughout the tapered undulator as this increases the refractive index and boosts the coherent interaction between the electrons and the radiation [9].

In order to calculate the microbunching we follow Ref. [5] and first determine the fraction of trapped electrons trapped in the FEL bucket along the undulator:

$$F_t(z) = \frac{1}{N_e} \int_0^{r_{max}} F_t(r,z) f_0(r) 2\pi r dr, \tag{4}$$

where $f_0(r)$ is the transverse beam distribution and $F_t(r,z)$ is the *local* trapping fraction which is determined by the radially dependent maximum and minimum phases $\Psi(r,z)$ for which particles follow stable trajectories in phase space [3]. We make the resonant phase approximation, in which we assume the trapped electrons are uniformly distributed in the ponderomotive phase at each radial location r and their contribution to the microbunching is $\exp[-i\Psi_r(r,z)]$ and $\Psi_r(r,z)$ is the radially dependent resonant phase. Now the microbunching can be calculated simply by averaging the product $F_t(r,z) \exp[-i\Psi_r(r,z)]$ over the radial coordinate r. Examining Eq. 4 shows that by manipulating the transverse electron beam distribution it is possible to maximize the trapping fraction and consequently the microbunching throughout the tapered undulator. For the case of a transversely Gaussian electron distribution considered thus far, the electrons in the radial tail of the beam experience a smaller ponderomotive potential and thus can become detrapped from the FEL bucket. If however the electron distribution is flatter, as in the parabolic or uniform cases, it is possible to trap more electrons in the bucket, increasing the bunching factor throughout the undulator and thereby extracting more power. The following section examines these predictions using GENESIS simulations.

Simulation Results

The simulations are performed for a 200 m undulator with 3.4 m undulator sections, 1 m breaks and parameters similar to LCLS-II (see Table 1). After performing the multidimensional optimization, the taper profiles obtained for the three different transverse distributions are shown in Fig. 2. The corresponding evolution of the radiation field, power, electron beam microbunching and radiation size is illustrated in Fig. 3.

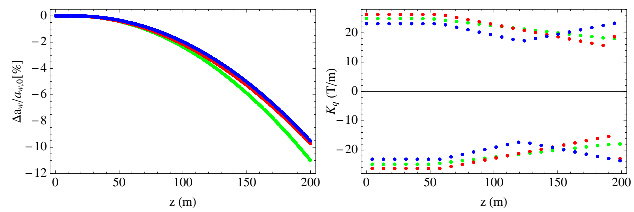

Figure 2: Optimal taper field and quadrupole focusing profile for the Gaussian (green), parabolic (red) and uniform (blue) transverse electron distributions obtained from multi-dimensional optimization using GENESIS single frequency simulations.

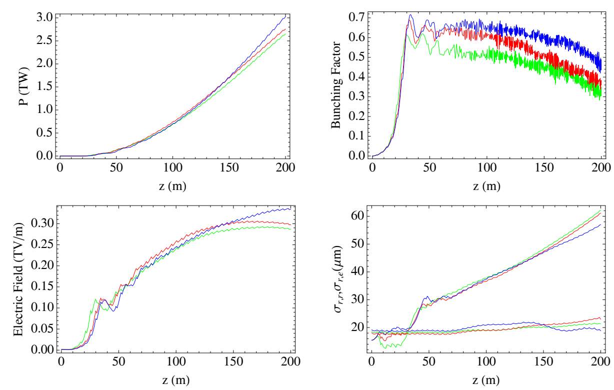

Figure 3: Comparison of time independent results for Gaussian (green), parabolic (red) and uniform (blue) transverse beam distributions at λ_r = 1.5 Å. X-ray pulse power, upper left and electric field, lower left, electron microbunching upper right, electron and radiation beam radii lower right.

The main result is an increase in the bunching factor for the parabolic and uniform distributions as compared to the Gaussian. This is indicative of a larger trapping fraction and consequently a greater output power. Such a discrepancy is however only marginally observed in single frequency simulations with the Gaussian beam achieving P_{max} = 2.65 TW compared to P_{max} = 2.76 TW for the parabolic case and P_{max} = 3.03 TW for the uniform case. Using the same optimal undulator parameters found via time independent simulations, we performed time dependent simulations of the three different transverse distributions for 6.4 fs bunch lengths. Analyzing the results shown in Fig. 4 we notice that the uniform and parabolic distributions exhibit a steady growth in output power, and a slow decrease in the bunching factor throughout the tapered undulator. On the other hand the transversely Gaussian beam suffers a signficant reduction in the bunching and power as well as an increased diffraction of the radiation. Furthermore, in the time dependent case the transversely Gaussian beam shows an early saturation of

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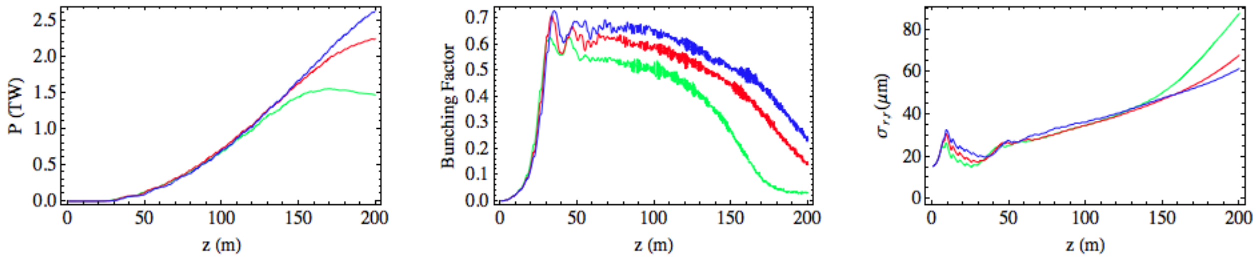

Figure 4: Power, bunching factor and radiation size as a function of longitudal distance for transversely Gaussian (green), parabolic (red) and uniform (blue) beams. The results are shown for a wavelength $\lambda_r = 1.5$ Å and bunch length of 16 fs. The optimized taper profiles are found in time independent simulations.

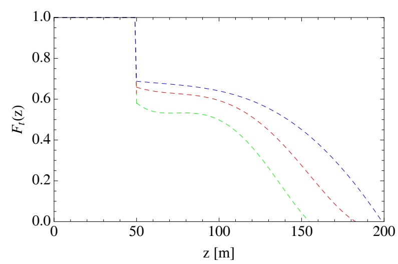

Figure 5: Evolution of the trapping function $F_t(z)$ for the Gaussian (green), parabolic (red) and uniform (blue) transverse electron distributions obtained from GENESIS single frequency (solid) and time dependent (dashed) simulations.

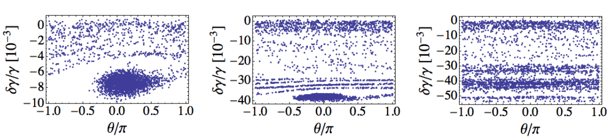

Figure 6: Longitudinal phase space evolution for a 6.4 fs bunch with Gaussian transverse electron distribution obtained from GENESIS time dependent simulations. The data is shown from left to right at z = 50, 120, 180 meters.

the power, a result previously reported in Ref. [5]. For the three different distributions the trapping fraction is displayed in Fig. 5 and the corresponding longitudinal phase space evolution for the Gaussian beam is shown in Fig. 6. The data shows significant detrapping for the Gaussian case after $z =$ 120 m which is consistent with the growth in the radiation size due to reduction in guiding observed in Fig. 4. The parabolic and uniform distributions maintain an improved trapping and guiding and this sustains the growth in output power allowing them both to reach over 2 TW of power at $z = 200$ m. Using the optimized taper profiles for each electron distribution the extraction efficiency reaches values between $\eta = 2.75\%$ and $\eta = 4.83\%$, an order of magnitude improvement compared to state of the art X-FELs such as the LCLS.

CONCLUSION

We evaluated the effect of changing the transverse electron distribution in an optimized tapered free electron laser. The performaces of FELs with transverse Gaussian, parabolic or uniform beam distributions are compared. The tapering profile as well as the quadrupole focusing is optimized to yield the maximum output power following the method described in Ref. [5]. Optimizations were performed for a 200-m long undulator with break sections using the three dimensional particle code GENESIS. Time independent results show that the effect of changing the transverse beam distribution is mostly marginal, yielding similar growth in the radiation power for the transversely Gaussian, parabolic and uniform distributions. This is not the case when multifrequency effects are taken into account in time dependent simulations, where the transverse distribution has an important impact on the FEL process affecting the trapping fraction and consequently the maximum output power. For a resonant wavelength of $\lambda_r = 1.5$ Å and a bunch length of 6.4 fs the maximal power increased from $P_{max} = 1.56$ TW for the Gaussian beam, to $P_{max} = 2.26$ TW for a parabolic beam and $P_{max} = 2.63$ TW for a uniform beam. An argument based on the reduction in the trapping fraction has been considered to explain this discrepancy in maximal power output. For all three transverse distributions, using the optimized taper profiles, the extraction efficiency is between $\eta = 2.8 - 4.8\%$, a factor of 20-40 improvement on current state of the art X-FEL facilities.

The study shows that transverse pulse shaping is an effective way to improve the performance and increase the output power of a tapered X-ray free electron laser. In light of the promising results found in this study we propose to investigate methods to transversely shape the electron beam distributions, like shaping the laser pulse on the FEL injector photocathode, using suitable masks inside the beamliine or introducing nonlinear elements in the electron beam transport line.

REFERENCES

[1] R. Bonifacio, C. Pellegrini, L. Narducci, Optics Communications, vol. 50, no. 6, p. 373, 1984

[2] C. Pellegrini, N. A. Part Accel. Conf. Proceedings, California, 2013

[3] N.M. Kroll, P.L. Morton, M. Rosenbluth, IEEE Journal of Quantum Electronics , vol. 17, p. 1436, 1981

ISBN 978-3-95450-133-5

[4] W.M. Fawley, Z. Huang, K.-J. Kim, N.A. Vinokurov, Nucl. Instrum. Meth., vol. 483, p. 537, 2002

[5] Y. Jiao, et. al., Phys. Rev. ST. AB., vol. 15, p. 050704, 2012

[6] W. Fawley, et. al., FEL 2011 Conference Proceedings, p. 050704, 2011

[7] S. Reiche, Nucl. Instrum. Meth., vol. 429, p. 243, 1999

[8] E.T. Scharlemann, A.M. Sessler, J.S. Wurtele, Phys. Rev. Lett., vol. 54, p. 1925, 1985

[9] D. Prosnitz, A. Szoke, V.K. Neil, Phys. Rev. A, vol. 24, p. 1436, 1981

ISBN 978-3-95450-133-5