Gain-guided X-ray free-electron laser oscillator

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X-ray free-electron laser (FEL) facilities around the world (see [1][5]) generating X-ray pulses with peak brightness approximately 10 orders of magnitude higher than synchrotron radiation have enabled a broad scope of scientific investigations in fields such as biology; chemistry; material science; and atomic, molecular, and optical physics [6]. All cited hard X-ray FELs use self-amplified spontaneous emission (SASE) [7] as their lasing mode. SASE starts with the initial electron beam shot noise and results in radiation with excellent spatial but rather poor temporal coherence. The spectral brightness of SASE can be improved by using advanced self-seeding technology in the X-ray regime [8, 9]. However, large shot-to-shot fluctuations in self-seeding (~50% r.m.s.) still limit the applications of X-ray FELs.

The basic schematic diagram is shown in Fig. 1. For illustration, two parallel Bragg crystals are employed to form a symmetry X-ray resonator. The scheme might be implemented directly or with a more complex four-mirror cavity, enhancing wavelength tunability [25]. The crystal thickness is adjusted to efficiently couple out X-ray power from the downstream mirror as well as maintain sufficient round trip reflectivity. The high repetition rate electron bunches match with the circulating X-ray pulse and supply sufficient gain to overcome the roundtrip loss. Spontaneous radiation from leading electron bunches inside the undulators starts the XFELO, and a portion of this signal is reflected back and amplified by interactions with a later fresh electron beam. The entire

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system functions at a low gain regime where the single pass gain remains constant and the intra-cavity X-ray power experiences exponential growth. In the saturation regime, however, the strong electromagnetic field results in electron beam over-modulation and FEL gain degradation. When the energy coupled outside cavity is exactly compensated by the FEL single-pass gain (i.e. the zero net round trip gain), XFELO reaches equilibrium and de-
number of undulator periods $N_u$, making the XFELO efficiency:

$$\eta = K_1 \left( \frac{w_1}{\sqrt{2} \sigma_e} \right)^2 \frac{1}{N_u}$$  \hspace{1cm} (5)$$

where $K_1$ is a coefficient. According to Ref. [31, 32], the FEL small signal gain is proportional to the square of the number of undulator periods multiplied by the electron density, which is inversely proportional to the transverse electron beam area for a given bunch charge, i.e.,

$$RG_c = K_2 \frac{N_u^2}{\sigma_e^2}$$  \hspace{1cm} (6)$$

where $K_2$ is the coefficient. Through Eqs. (3), (5), and (6), the efficiency ratio between gain-guided and conventional XFELO is seen to be:

$$\epsilon = \frac{\eta_{\text{gg}}}{\eta_{\text{normal}}} = \frac{w_1^3}{2w_2\sigma_e^2}$$  \hspace{1cm} (7)$$

where the radiation radius of the traditional XFELO with external focusing elements is assumed to equal the transverse electron bunch size for the maximizing coupling factor ($w_1 = \sqrt{2} \sigma_e$). For simplicity, we further assume the X-ray waist is at the exit of the undulator, where the X-ray radius becomes minimum ($w_1 = w_0$) and spot size parameter $w_2$ is given by:

$$w_2 = w_0 \sqrt{1 + \left( \frac{L_c}{z_R} \right)^2}$$  \hspace{1cm} (8)$$

where the Rayleigh length is $z_R = \pi w_0^2 / \lambda$.

Combining the previous equations, the ratio of efficiency can be solved as a function of electron beam transverse size, as shown in Fig. 2. In this letter, an XFELO at 14.3 keV photon with a round trip length $L_c = 300$ m resonator is considered. Efficiency increases as the electron beam size increases, reaching a maximum value of 77% at $\sigma_e = 43 \mu$m. Low charge density decreases efficiency at large electron beam sizes. Additionally, $w_2/w_1$ decreases as the transverse electron beam size increases, as did the required product $RG_c$. The relatively larger required FEL gain $G_c$ might resemble RAFEL [33]. However, the round trip net gain $G$ remained at the level of a low gain oscillator due to X-ray diffraction. This letter concentrates on the X-ray transverse profile evolution and explores the possibility of a self-focusing XFELO scheme instead of trying to focus X-rays with external elements. The proposed scheme provides a moderate gain at the transverse X-ray center and controls the transverse mode of the X-ray via cavity configuration, thus benefiting from the high stability of a small XFELO gain.

As a numerical example, the proposed gain-guided XFELO is simulated using the parameters of the Shanghai Coherent Light Facility (SCLF), the first hard X-ray FEL facility in China (currently under construction). The 1 MHz repetition rate, 8 GeV electron bunches with ultra-low 0.4 $\mu$m-rad normalized emittances delivered by the CW superconducting accelerator are suitable for XFELO operation. The bunch charge is 100 pC and peak current is 1 kA. As mentioned above, X-ray photon energy is set to 14.3 keV, equal to the Bragg energy of sapphire crystal mirrors at normal incidence to the (0 0 30) atomic planes. For a 0.01% slice relative energy spread electron beam, seven segments of the 5 m undulators with 26 mm period are used to provide sufficient FEL gain. A typical FODO lattice is employed to control the electron beam size. The three-dimensional simulation is conducted using a combination of GENESIS [34], OPC [35], and BRIGHT [36]. The simulation results of various electron beam sizes with carefully optimized mirror reflectivity for power maximization are shown in Fig. 2. As expected, the peak power efficiency first increases and then decreases as the transverse beam size increases, reaching its maximum $\epsilon = 82\%$ when $\sigma_e = 40\mu$m, agreeing well with the theoretical study. The faster simulated decline following optimum electron beam size might be due to the three-dimensional effects leading to deviations in FEL gain calculations in the model.

The simulation result details for maximum efficiency are shown in Figs. 3 and 4. The downstream crystal thickness is $d_2 = 70\mu$m, providing sufficient reflectivity ($R_2 = 95\%$), whereas the upstream mirror thickness is $d_1 = 40\mu$m with a reflectivity of $R_1 = 70\%$ for efficient output coupling. The additional loss is due to the cavity output coupling and Bragg crystal mirror bandwidth stop ($\sim 65\%$). The transverse radiation profile at the undulator exit, upstream mirror, and undulator entrance are shown in Fig. 3 (a), (b) and (c), respectively. Since no focusing elements exist, the propagation of X-rays inside the vacuum chamber leads to a beam size expansion of nearly a factor of 2 during one round trip. The overall loss is exactly compensated by the FEL gain $G_c = 28$.
in the XFELO saturation regime. The parameter $M^2$ is calculated to evaluate the X-ray transverse quality from the gain-guided XFELO. An $M^2$ value close to unity indicates the X-ray pulse from the gain-guided XFELO could be perfectly focused onto a small spot in the experimental station. The output pulse energy at different round trips is presented in Fig. 4 (a), starts from the shot noise and growing exponentially before reaching a stable value of 73.6 $\mu$J. Figure 4 (b) and (c) show the output X-ray temporal profile and spectrum, respectively. The output peak power is nearly 0.8 GW, meaning the peak power efficiency ratio between gain-guided (red solid line) and normal XFELO (green dashed line) is approximately 82%. The X-ray pulse duration is 75 fs (FWHM) with a bandwidth of 41 meV (FWHM), corresponding to a 0.75 time-bandwidth product (close to the value of the Fourier transform limit of a Gaussian pulse).

The robustness of gain-guided XFELOs is investigated in a further study. Due to the relatively large X-ray profile and partial overlap between electron beams and X-rays, the crystal tilt angular misalignment should be less than 50 nrad, much easier to achieve than the 10 nrad in a normal XFELO [25]. This large X-ray profile also relaxes the requirements for electron beam trajectories along the undulators; for instance, the required 18 $\mu$m (r.m.s.) beam orbit straightening can be established by beam-based alignment. When compared to normal XFELOs, the X-ray footprint on the crystal surface is approximately doubled, which is helpful for reducing crystal thermal loading. Additionally, these discussions and simulations indicate that gain-guided XFELO would enable X-ray output power adjusting by simply tuning the quadruple magnet strength inserted between the undulators instead of the changing mirror reflectivity mechanically.

This letter proposed a gain-guided XFELO eliminating external focusing elements and thus simplifying X-ray cavity configurations. A theoretical model based on Huygens-Fresnel paraxial wave propagation is used to describe the transverse mode evolution of X-ray pulses. The electron beam plays two roles in X-ray optics: gain media and “focusing element”. Taking advantage of the wave diffraction effect during propagation in the vacuum chamber, the X-ray power density at the center decreases and over-modulations of electron beams inside the undulator are mitigated, making the energy extraction efficiency of gain-guided XFELOs comparable to that of the conventional ones. With some reasonable assumptions, equations are obtained for predicting the requirements and expected performances of the proposed scheme. The feasibility of the proposal was verified through three-dimensional numerical simulations using SCLF parameters as an example. The typical results of the two-mirror symmetry cavity indicates that a gain-guided XFELO is capable of generating 73.6 $\mu$J, as large as 67.5% pulse energy of a normal configuration (128 $\mu$J). The output
peak power of 0.8 GW at 41 meV bandwidth are equivalent to that of conventional systems. Without inserting additional focusing elements, the proposed scheme holds several advantages over normal XFELO: avoidance of potential thermal loading effects, improved wavelength and peak power tuning, and enhanced system robustness. This proposal is expected to promote the future construction of XFELs.

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