FEASIBILITY OF A COMPACT X-RAY FREE-ELECTRON LASER OSCILLATOR BASED ON DIFFRACTION LIMITED STORAGE RING[*]

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Abstract

X-ray Free-Electron Laser Oscillators (XFELOs) utilize Bragg crystal-based x-ray cavities to generate high-brightness x-ray pulses with ultra-fine bandwidth. The successful realization of XFELOs would greatly benefit high-resolution photon-hungry experiments, such as nuclear resonant scattering and inelastic x-ray scattering. Existing XFELO proposals, constrained by either the electron beam repetition rate or limited single-pass gain in the undulator, typically require long undulators and long cavities. In this work, we investigate the feasibility of a compact XFELO design, utilizing the 6-meter straight sections of a Diffraction Limited Storage Ring (DLSR) and a cavity path length well below 100 meters. We show that sufficient single-pass gain can be achieved by optimizing the undulator and electron beam parameters. We present the projected performance of the proposed scheme based on the parameters of the High Energy Photon Source (HEPS) and discuss the practical challenges associated with its implementation.

INTRODUCTION

High-spectral-brightness is crucial for high-resolution experiments using synchrotron or free-electron laser-generated hard x-ray pulses. So far, the diffraction-limited storage ring (DLSR) [1] and the hard x-ray self-seeding (HXRSS) [2] represent the state-of-the-art sources generating the highest spectral density in circular and linear accelerators. Cavity-based x-ray free-electron lasers (CBXFELs) are attracting increasing interest for the possibility of pushing the spectral brightness one big step forward and enabling new frontiers in material sciences and x-ray quantum optics. The CBXFELs utilize high-reflectivity Bragg crystals as mirrors to form x-ray cavities, which can be categorized into x-ray free-electron laser oscillators (XFELOs) when the gain inside the cavity is low and x-ray regenerative amplification free-electron lasers (XRAFELs) when the gain is high. After more than 40 years of development, the CBXFEL was recently experimentally demonstrated [3] for the first time with a pulse-mode superconducting linac at DESY, opening a new era for the x-ray sciences.

Despite new projects established aiming at demonstrating CBXFELs among the high-repetition-rate XFEL facilities around the world [4–7], the idea of realizing CBXFELs using the storage ring electron beam is still limited to feasibility and performance studies [8–10]. The DLSR enabled ultra-low transverse emittance down to the diffraction limit, while its energy spread is still one order of magnitude higher than linac-based sources. A combination of a transverse gradient undulator (TGU) and a local vertical dispersion is proposed to compensate the energy spread. Another aspect is that the storage ring beam usually has a beam current of a few tens of Amperes, making it difficult to obtain sufficient gain in a typical straight section of only a few meters long in storage rings. A recent study of XFELO [10] using the PETRA-IV [11] long straight section required 30 meters of TGU and the cavity length of around 150 meters.

In this paper, we propose a more compact layout for realizing the XFELO using DLSR electron beams and present a preliminary feasibility study. In the following, we first introduce the proposed setup, then show the optimization of the small signal gain in a short TGU. Using parameters of the High Energy Photon Source (HEPS) [12], we show the projected performance obtained through numerical simulations. Finally, we discuss the challenges of actual implementation and discuss the road map for further development.

LAYOUT

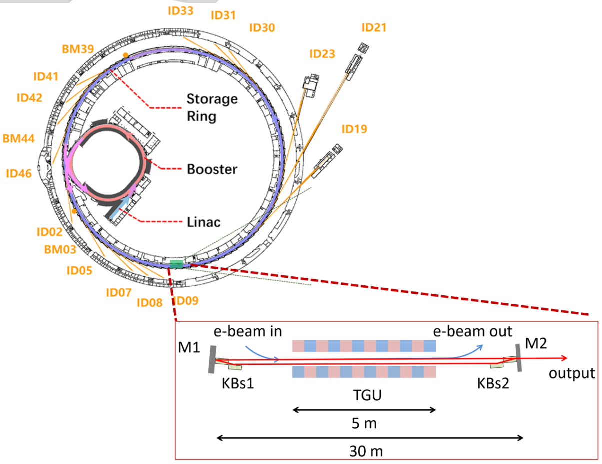

Figure 1: Schematic layout of the compact DLSR-XFELO.

Figure 1 gives the schematic layout of the proposed XFELO based on DLSR. The crystal cavity is composed of two high-reflectivity crystals with the working angles slightly off normal incidence. A closed loop is formed by adding two pairs of KB mirrors as retro-reflectors. The distance between the two crystals is about 30 meters, allowing the electron beam repetition rate of about 5 MHz. The forward and return optical paths are separated by a few millimeters.

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The downstream mirror is made thinner to allow a fraction of the total radiation inside the cavity to be outcoupled. The undulator is about 5 meters long and could be housed in a typical 6-meter-long straight section. Vertical dispersion is introduced and removed through modification of the nearby lattice. The advantage of the proposed compact layout is that it enables the possibility of validating the DLSR-XFELO concept with an existing fourth-generation light source like the Advanced Photon Source Upgrade (APS-U) [13] and the HEPS, without building a bypass line and significantly modifying the already tight accelerator hall.

GAIN OPTIMIZATION

Reducing the undulator length to only a few meters places more demanding requirements for the electron beam and undulator parameters. The electron beam key parameters, such as emittance and beam current, are bounded by the storage ring lattice and collective dynamics. The undulator parameters are bounded by the technology available at present. To maximize the gain in a short TGU undulator, we established a single-objective genetic algorithm optimization to find the best parameter space using the small-signal gain formula given in Refs. [9, 10]. In the optimization, we fixed the beam current to 200 A, undulator length to 5 m, beam energy to 6 GeV, and energy spread to 0.3 %. An upper limit of 160 m^{-1} is set for the TGU gradient parameter α. The optimized variables are the beam Twiss parameters, the Rayleigh length, detune, vertical dispersion, and coupling coefficients of the ring.

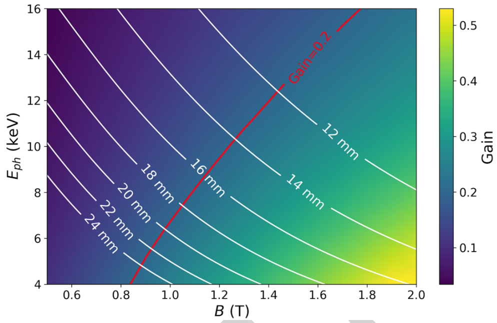

Figure 2: Global optimization results for various photon energies under different undulator settings.

Figure 2 gives the optimized gain results for various photon energies under different undulator periods. It is clear that for a fixed photon energy, a smaller undulator period, i.e., more periods in the fixed undulator length, is preferable for gain improvement. However, a smaller period results in a larger magnetic field, which is limited by the available undulator technology. In the following, we choose the undulator period to be 15 mm, which is capable of producing about 1.4 T using the Cryogenic Permanent Magnet Undulator (CPMU) technology. Suppose a gain of 0.2 is required for the oscillator to cover cavity losses and out-coupled radiation, the chosen undulator setting can cover radiation up to 8.5 keV. The optimized parameter space using the analytical formula is verified with the FEL simulation code Genesis [14] in steady-state mode, where vertical dispersion is introduced to the distribution using a transform matrix before the interaction and removed afterwards. It is also found that Genesis gives a higher gain than estimated from the analytical formula.

SIMULATION SETUP

Simulating the DLSR-XFELO system is particularly challenging as it involves simulation of the FEL process, Bragg reflection, field propagation, and electron dynamics in the storage ring. In this study, we use a simulation framework built upon standard simulation codes like Genesis in time-dependent mode [14] for FEL simulation, Bright [15] for Bragg reflection, Ocelot [16] for field propagation, and in-house one-turn map ring tracking code without collective effects. The particle information exchange between Genesis and the ring dynamics code is realized via sampling the Genesis dumped distribution with the recorded current profile. The FEL slippage effect is neglected in this study, mainly because the slippage length in a five-meter-long undulator for hard x-ray is much smaller than the delay caused by the complex reflectivity of the crystal. We have also assumed perfect synchronization between the beam and the returned x-ray pulse at the undulator.

The simulation parameters for the compact DLSR-XFELO system are listed in Table 1. Here, the beam parameters are derived from the HEPS, while the beam current and bunch charge are increased from the nominal parameters. Consequently, the energy spread is also increased to reflect the effect of collective instabilities at a short bunch length. Figure 3 shows the reflectivity and transmissivity for diamond (4,2,2) reflection at near normal incidence. A total of 13 % loss is imposed on the Bright dumped field distribution to model extra cavity losses and the out-coupled radiation.

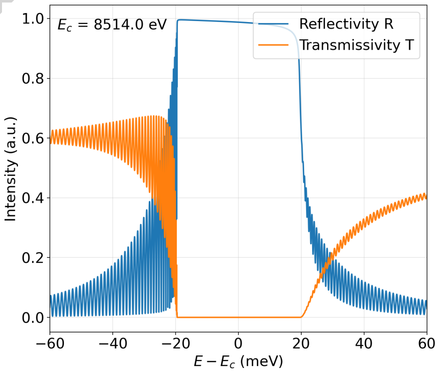

Figure 3: Reflectivity and transmissivity for the C422 reflection at 8.51 keV.

SIMULATION RESULTS

Figure 4 illustrates the in-cavity radiation power, pulse energy, electron beam vertical emittance, and energy spread at different passes. The radiation starts from noise and saturates after about 200 passes, with saturated in-cavity

Table 1: Simulation Parameters

Parameter	Symbol	Value	Unit
Electron beam			
Energy	E_b	6	GeV
Energy spread	σ_E/E	0.3	%
Natural emittance	$\varepsilon_{x,0}$	34	pm·rad
Coupling coeff.	κ_c	0.06	–
Bunch charge	Q	12	nC
Peak current	I_p	200	A
Repetition rate	f_{rep}	5.05	MHz
Undulator			
Period length	λ_u	15	mm
Total length	L_u	5	m
TGU alpha	α	133	m^{-1}
TGU dispersion	D	0.01	m
Maximum field	B_{max}	1.4	T
Cavity			
Cavity length	L_c	29.7	m
Photon energy	E_{ph}	8.51	keV
Reflection	–	C422	–
Waist size	w_0	12	µm
Cavity loss	L_{loss}	15	%
Coupling out	T_{out}	5	%

pulse energy of about 500 µJ. With 2 % out-coupling fraction, this corresponds to 10 µJ peak pulse energy in a macropulse that lasts about 70 passes. Assuming 50 ms for the beam to return to the equilibrium state, photon flux on the order of 1×10^{12} photons/s can be obtained. With its narrow spectrum of 50 meV, the spectral flux can reach 1×10^{11} photons/s/meV. Such capability is comparable to HXRSS performance at kHz repetition rate.

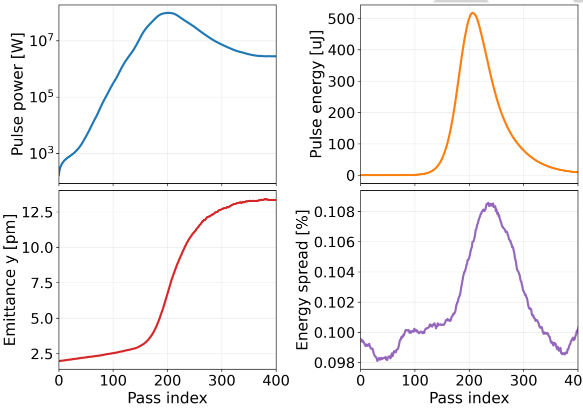

Figure 4: In-cavity radiation and electron beam properties at different passes.

Figure 5 gives the radiation and beam profile evolution at different passes. It is clear that the beam core saturates first, then the pulse profile experiences a broadening while the beam core power starts to decrease, with corresponding changes in the spectrum. The increase of vertical beam emittance dominates the saturation process. Figure 6 gives the transverse radiation profile at saturation, where a gaussian mode can be seen.

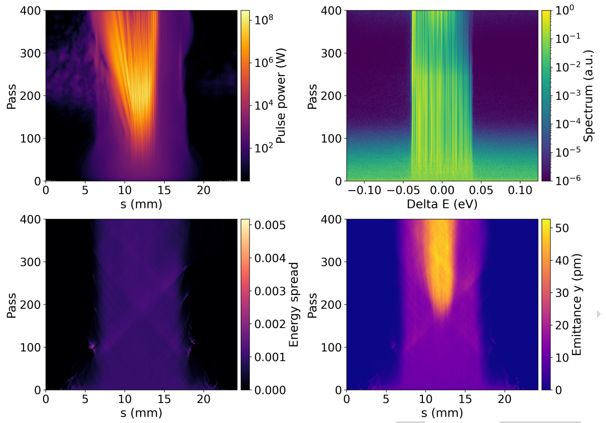

Figure 5: Profile of radiation power, radiation spectrum, beam energy spread, and beam emittance at different passes.

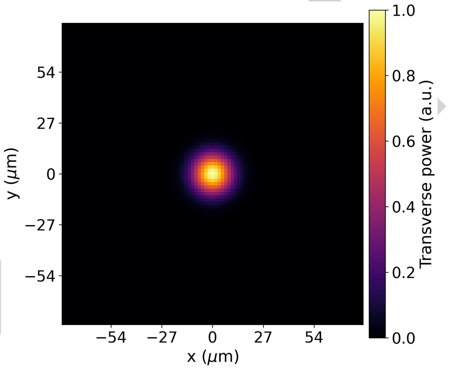

Figure 6: Transverse profile of the intra-cavity pulse at saturation

CONCLUSION

In this paper, we have studied the feasibility of realizing the low-gain XFELO in a regular straight section at diffraction-limited storage rings. To provide sufficient gain for the oscillator, parameters for the electron beam and undulator need to be further improved. On the one hand, a short-period, high-field undulator is necessary to provide more periods and maintain the resonant condition. On the other hand, the stored electron beam needs to have a much higher beam current than in typical operation. Due to the introduction of TGU, the saturation of the oscillator is dominated by the increased beam vertical emittance. Besides, unlike linac-based XFELOs, after saturation, radiation power decreases further due to diluted beam quality. Another macropulse will be generated once the beam is properly damped back to its equilibrium.

The proposed compact layout gives promising performance and holds the possibility to demonstrate at an existing DLSR, yet more systematic work needs to be done. These include more accurate modeling of the coupled behavior, storage ring dynamics at high current, as well as technologies in crystal cavity and undulator.

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