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PHYSICAL DESIGN FOR EEHG BEAMLINES AT S^{3}FEL

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Abstract

The proposed Shenzhen Superconducting Soft X-Ray Free-electron Laser (S^{3}FEL) aims at generating FEL pulses from 1nm to 30nm. At phase-I, two undulator beamlines work at ehco-enable harmonic generation (EEHG) principle. The two undulators will cover the spectral ranges 2.3-15 nm (~ 83-539 eV) and 5-30 nm (~ 41-248 eV), respectively, when receiving electrons from 2.5 GeV superconducting linac. However, the generated FEL radiation is sensitive to various electron beam properties, e.g., its energy profile influenced by collective effects such as Coherent Synchroton Radiation (CSR), especially at high harmonics. To generate intense full coherent FEL radiation at ultra-short wavelength, a novel technique of EEHG cascaded harmonic lasing method is also considered. Physical design and FEL performance are described in this paper.

INTRODUCTION

The proposed Shenzhen Superconduction Soft X-Ray Free-electron Laser (S^{3}FEL) [1] is a high repetition rate FEL facility that consist of a 2.5 GeV CW superconducting linac and four initial undulator lines, which aims at generating X-rays between 40 eV and 1 keV at rates up to 1 MHz.

Two undulator beamlines (FEL-3 and FEL-4) work at echo-enable harmonic generation (EEHG) [2] principle which has the major advantage of full coherence, precisely arrival time control, uniform longitudinal profile and so on. The shortest wavelength is about 2.3 nm at a harmonic over one hundred. Since the various collective effects, the degrading of FEL performance becomes severer at such high harmonic number. One possible solution is adapting a novel technique called EEHG cascaded harmonic lasing method. This paper presents the detailed FEL simulation results for start-to-end electron beam coming from the superconducting linac.

FEL PERFORMANCE

The basic electron beam parameters after linac are listed in Tabel 1. The slice parameters of the start-to-end electron beam are shown in Fig. 1. The core of the bunch has relatively flat energy and current with normalized emittance of about 0.5 mm·mrad.

Table 1: Electron Beam Parameters

Parameter	Value	Unit
Beam energy	2.5	GeV
Slice energy spread	200	keV
Peak current	800	A
Charge	100	pC
Normalized emittance	0.5/0.5	mm·mrad

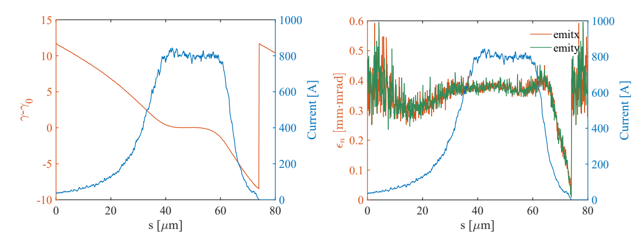

Figure 1: Beam energy (left), normalized emittance (right) and current (blue) of the electron beam.

The parameters of undulator beamlines and seed lasers are listed in Table 2. The FEL simulations are performed with electron beam after corresponding beam transport line and carried out by the time-dependent mode of GENESIS [3].

Table 2: Undulator Beamlines, Seed Lasers (SL) Parameters

Parameter	FEL-3	FEL-4
FEL wavelength [nm]	2.3-15	5-30
Undulator type	PMU	PMU+EPU
Undulator period [mm]	43	50
SL wavelength [nm]	266.7/240-267	266.7/240-267
SL pulse length [fs]	100	100
SL peak power [MW]	>200	>200
SL Rayleigh length [m]	1.0	1.0

FEL-3 (EEHG, 2.3–15 nm)

FEL-3 generates FEL radiation from 2.3 nm to 15 nm, covering the entire water window (2.3-4.4 nm).

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The layout and β-function of 2.3nm@FEL-3 is shown in Fig. 2. Using the optimized EEHG parameters [4], the bunching at radiator entrance is nearly 6%. This is sufficient to achieve saturation of the FEL power at 2.3 GW already after 6 undulators, as show in Fig. 3. Figure. 3 also shows the FEL spot after radiator as well as the power profile and spectrum at saturation. The pulse duration is about 47 fs while the bandwidth of spectrum is close to 0.012 %. The transverse spot size is about 500 µm and the transverse divergence is 6.7 µrad at the end of the radiator.

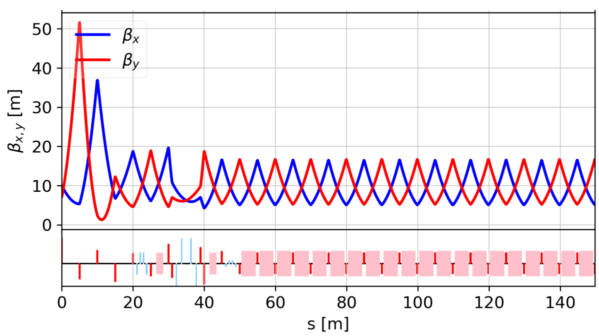

Figure 2: The layout of 2.3nm@FEL-3.

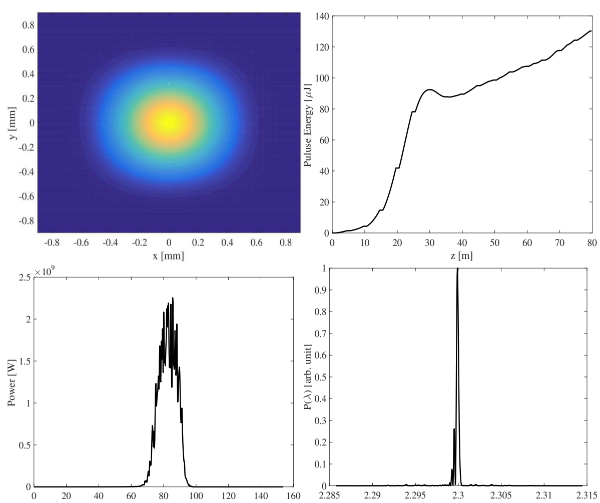

Figure 3: Simulation results of 2.3nm@FEL-3.

As for the 15 nm case at FEL-3, the saturation power is about 5.7 GW after 10 m of amplification. The pulse energy is around 360 µJ with a pulse duration of 60 fs. The bandwidth of spectrum is 0.057 %, indicating a nearly transform-limited pulse. The transverse spot size and divergence are about 1 mm and 45 µrad after the radiator.

FEL-4 (EEHG, 5–30 nm)

FEL-4 also operates in EEHG mode and generates FEL radiation between 5 nm and 30 nm, corresponding to a photon energy of 41-248 eV. It can provided fully coherent extreme ultraviolet (EUV) and X-ray beams with full wavelength and polarization tunability.

Figure 4 shows the layout and β-function of 5 nm@FEL-4. The maximum bunching factor is 10% at the entrance of undulator after optimization. The FEL pulse reaches saturation after 20 m of amplification, while pulse energy is nearly 226 µJ. The power profile and spectrum at saturation are also shown in Fig. 5. The pulse duration is about 55 fs with a spectrum bandwidth around 0.023 %. At the exit of the radiator, the transverse spot size and divergence are 760 µm and 12.4 µrad, respectively.

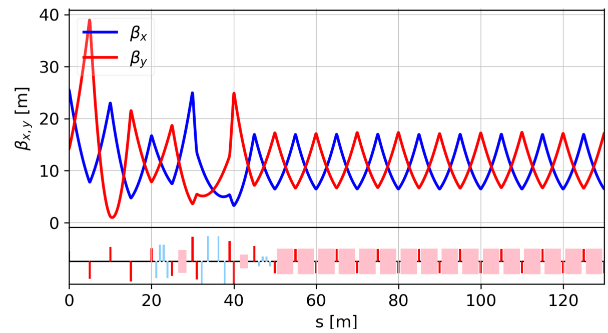

Figure 4: The layout of 5nm@FEL-4.

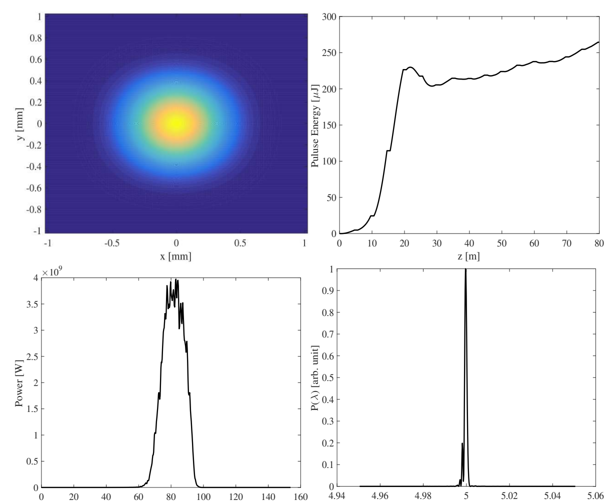

Figure 5: Simulation results of 5nm@FEL-4.

In the case of 30nm@FEL-4, the saturation peak power is about 6.0 GW after 2 undulators. The pulse energy at saturation is 348 µJ with a pulse duration of 57 fs. The FEL spectrum has a bandwidth of 0.112 % and the TBP is about 0.64. The transverse spot size and divergence are 1.3 mm and 70 µrad at the exit of radiator.

COLLECTIVE EFFECTS

Coherent Synchrotron Radiation (CSR)

The strong chicane needed in the first dispersion section makes the system vulnerable to the CSR effect. Besides increasing emittance and energy spread, CSR also imprints a long-wavelength energy modulation on the electron bunch. Such energy modulation will interfere with bunching process, which eventually leads to a loss of longitudinal coherence [5]. Taking 2.3nm@FEL-3 as an example, the simulation results have been illustrated in Fig. 6. The bunching factor decrease to 2.5% and the saturation length is slightly increased.

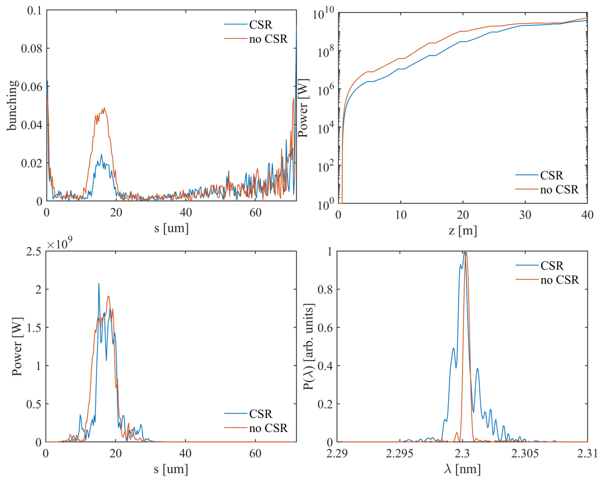

Figure 6: The influence of CSR on EEHG.

Incoherent Synchrotron Radiation (ISR)

Despite of the CSR, the ISR effect induced by the strong chicane will also smear the fine structure of the longitudinal phase space. The ISR quantum diffusion induced energy spread growth can be written as [6]

$$(\sigma_{\Delta E})_{ISR} = \left[\frac{7\hbar}{15mc} L r_c \gamma^4 k_\omega^3 K_\mu^2 F(K_\mu)\right]^{-1/2}, \quad (1)$$

where r_c is the classical radius of electron, k_ω and K_μ denote the undulator wave-number and the strength of undulator, respectively. $F(K_\mu) = 1.2K_\mu + 1/(1 + 1.33K_\mu + 0.4K_\mu^2)$. According to the parameters at S^{3}FEL, the ISR-induced quantum diffusion effect is calculated about 12.7 eV, which is much smaller than the spacing of adjacent energy bands (~70 keV) and therefor negligible.

Intra-Beam Scattering (IBS)

IBS describes multiple Coulomb scattering in the electron beam, which leads to an increasing in electron beamsize and energy spread. The IBS-induced energy spread growth can be expressed as [7]

$$(\sigma_{\Delta E})_{IBS} \simeq \left(2\pi^{3/2} \ln \Lambda r_c \frac{I}{I_A} \frac{1}{4\pi\sigma_x^3} \frac{\beta_x}{\gamma} s\right)^{1/2} E_0, \quad (2)$$

where I denotes the beam current, $I_A \approx 17kA$ is the Alfven current, σ_x and β_x denote transverse beamsize and transverse β-function, s is the distance along the beamline and $E_0 \approx 511$ keV is the static electron energy. $\ln \Lambda$ denotes Coulomb logarithm which calculted as

$$\ln \Lambda = \ln\left(\frac{\sqrt{2}}{6} \frac{\epsilon_N^3}{r_c \sigma_x^2} \left(\frac{I}{I_A}\right)^{-1/2} \gamma^{1/2}\right) - \ln\left(\frac{2\epsilon_N}{\eta\sigma_x}\right), \quad (3)$$

where ϵ_N denotes the electron beam normalized emittance.

The decreasing bunching factor can be estimated by $b_h = b_h^{(0)} e^{-l/L}$ [8], where l is the distance between the exit of the first dispresion section and the radiator entrance, $L = 2\sigma_E^2/Dm^2B_2^2$. According to the parameters at S^{3}FEL, the IBS-induced energy spread growth is about 9.8 keV. The bunching factor decrease to about 1.7 % which is still sufficient to suppress the electron beam shot noise and improving the temporal coherence of final FEL pulses.

EEHG CASCADED HARMONIC LASING

Although EEHG has the highest harmonic up-conversion efficiency, it's difficult to achieve lasing with a harmonic number up to 100 experimentally. Recently, a novel technique called EEHG cascaded harmonic lasing has been proposed [9]. With the parameters of S^{3}FEL, a start-to-end simulation result has been shown in Fig. 8. An intense, almost Fourier transform-limited pulse can be generated.

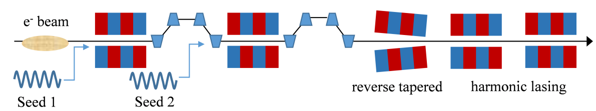

Figure 7: The layout of EEHG cascaded harmonic lasing.

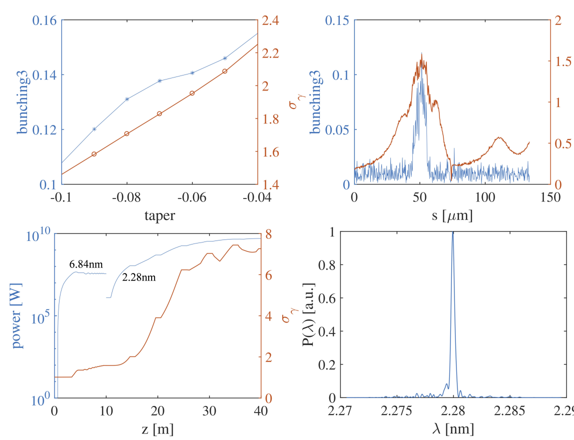

Figure 8: Simulation results of proposed scheme.

CONCLUSION

In this paper, the physical design and FEL performance of EEHG beamlines at a newly proposed FEL facility, S^{3}FEL, have been described. We also investigated the influence of various collective effects on the radiation at EEHG using theoretical analysis and numerical simulations. The design and optimization of EEHG cascaded harmonic lasing in the case of 2.3 nm@FEL-3 is preliminary studied.

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