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PHYSICAL DESIGN FOR SHENZHEN SUPERCONDUCTING SOFT X-RAY FREE-ELECTRON LASER (S^{3}FEL)

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Abstract

Shenzhen Superconducting Soft X-Ray Free-electron Laser (S^{3}FEL) is a newly proposed high repetition-rate X-ray FEL facility. It will be located at Guangming Science City in Shenzhen with a total length of 1.7 km. The electron beam is generated from a VHF photocathode gun and accelerated to 2.5 GeV through a superconducting RF linac. At initial phase, it is planned to build four undulator lines with two of them working at the principle of SASE and another two working at EEHG. S^{3}FEL aims at generating X-rays and EUV FELs between 1 and 30 nm at a rate up to 1 MHz to facilitate various scientific applications. This paper describes the physical design of S^{3}FEL.

INTRODUCTION

High repetition-rate free-electron lasers (FELs) have been the continuous pursuit of institutions and groups around the world due to the dramatic increase in average brightness and detection frequency. Free-electron laser in Hamburg (FLASH) [1] and European X-ray free-electron laser (XFEL) are now under operation at MHz in burst-mode [2, 3], while the linac coherent light source II (LCLS-II) [4], the Shanghai high repetition rate XFEL and extreme light facility (SHINE) [5] and MariX [6] are aiming to generate MHz FELs in continuous wave (CW) mode.

Shenzhen Superconducting Soft X-Ray Free-electron Laser (S^{3}FEL) is a newly proposed high repetition-rate X-ray FEL facility. The preliminary design report of the proposed S^{3}FEL project has been completed and submitted to the central government for approval. S^{3}FEL aims at generating X-rays and EUV FELs between 1 and 30 nm at a rate up to 1 MHz to facilitate various scientific applications, such as energy catalytic, quantum materials, atmospheric and interstellar science, biomedicine, atomic and molecular science.

The facility is planned to be built at Guangming Science City in Shenzhen with a total length of 1.7 km above ground. At the initial phase, it is planned to build one superconducting RF (SCRF) linac, four beam splitting sections, four undulator lines, four beamlines and fourteen end-stations. The main parameters of the electron beam and the radiation at S^{3}FEL are listed in Table 1.

Table 1: Main Parameters of S^{3}FEL

Parameters	Value
Beam energy	2.5 GeV
Slice energy spread	190 keV
Pulse charge	100 pC
Current	800 A
Emittance ϵ_x/ϵ_y	0.5/0.5 mm · mrad
Bunch length	50 fs (RMS)
Radiation wavelength	1-30 nm

MACHINE LAYOUT AND MAIN PARAMETERS

Figure 1 shows the schematic layout of the S^{3}FEL. The electron beam is generated from a VHF photocathode gun and accelerated to 2.5 GeV through a SCRF linac. Then it is distributed to four undulator lines for FEL radiation amplification through the beam splitting sections. There are two working modes of the radiation amplifier: self-amplified spontaneous emission (SASE) [7, 8], and echo-enabled harmonic generation (EEHG) [9, 10]. SASE lines and EEHG lines will produce FEL radiation with the shortest wavelength of 1 nm and 2.3 nm, respectively. Four beamlines, located downstream of the undulator lines, measure the pulse energy and the spectral properties of the radiation pulse online, and transport the radiation pulses to the fourteen end-stations.

Linac

The S^{3}FEL accelerator comprises the following two parts: a photo-injector which generates a bright electron beam with a repetition rate up to 1 MHz and accelerates it to 90 MeV; The main SCRF linear accelerator, where the electron beam is accelerated to 2.5 GeV and longitudinally compressed to 800 A with two compressors working at energies of 250 MeV and 1.2 GeV respectively.

This project adopts a dual photo-injector design, in which the first injector is in line with the main linear accelerator;

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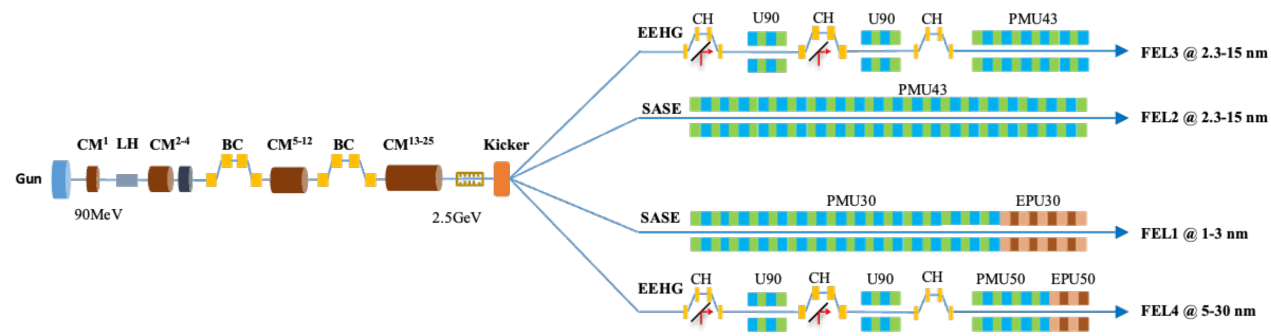

Figure 1: Schematic layout of the S^{3}FEL.

the second injector is parallel to the main linear accelerator as a backup beam supply device. The VHF photocathode gun produces an electron beam with a charge of 100 pC, an energy of 750 kV, and a bunch length of about 20 ps at a repetition rate of 1 MHz. After that, the electron beam transmits the solenoid, buncher and a 1.3 GHz 8-cavities standard cryomodule (CM1) for further compression and acceleration. The electron beam at the exit of CM1 reaches 90 MeV with a peak current of 9 A and beam length of 4.5 ps. The normalized slice emittance is not greater than 0.5 mm·mrad. A laser heater system is used to suppress the micro-bunching instability caused by beam noise and current intensity fluctuations.

The main SCRF linear accelerator system comprises twenty-four 1.3 GHz 8-cavity cryomodules, two 3.9 GHz 8-cavity cryomodules and two bunch compressors. Twenty-four 1.3 GHz cryomodules are distributed in 3 accelerating sections, L1 (CM2-4), L2 (CM5-12) and L3 (CM13-25). Two 3.9 GHz cryomodules are placed right after the L1 to provide cubic corrections of the correlated momentum distribution along the bunch. Three-stage acceleration sections accelerate the electron beam to 250 MeV, 1.2 GeV and 2.5 GeV, respectively. The two compression sections are respectively located after the first two acceleration sections. Lattice functions of the SCRF linac are shown in Figure 2.

The function of the SCRF linac is to accelerate the electron beam from 90 MeV to 2.5 GeV, compress the RMS bunch length from 4.5 ps to 50 fs, and increase the peak current of the electron beam from 9 A to 800 A. To satisfy FEL lasing requirements, it is necessary to ensure that the current intensity distribution is close to the flat-top distribution, and the slice energy distribution is less than 0.02%. The horizontal and vertical normalized emittances at the end of the linac should not exceed 0.5 mm·mrad.

Linac to Undulators

A beam distribution system (BDS) lies downstream of the transport line after the linac, distributing the beam to four downstream undulator lines while maintaining the quality of the electron beam. BDS should has the characteristics of precision, speed and stability. To realize this, BDS adopts a vertical fast kicker combined with a horizontal lamberson septum magnet to achieve bunch-by-bunch separation of the

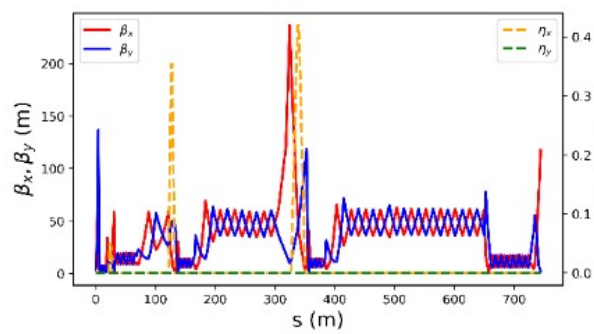

Figure 2: Lattice functions of the SCRF linac.

1 MHz electron beam. BDS is designed to be a dual-DBA dogleg structure, which consists of two symmetrical double-bend-achromat (DBA) and a matching section in between. The phase advance between the two DBAs is set as π to mitigate the emittance growth caused by the CSR effect. The total deflection angle of the dog-leg is not larger than 3° and the total length is about 250 m. A start-to-end tracking from the linac end throughout the BDS is performed by the code Elegant [11]. Phase space and current distribution of the electron beam at exit of BDS are shown in Figure 3.

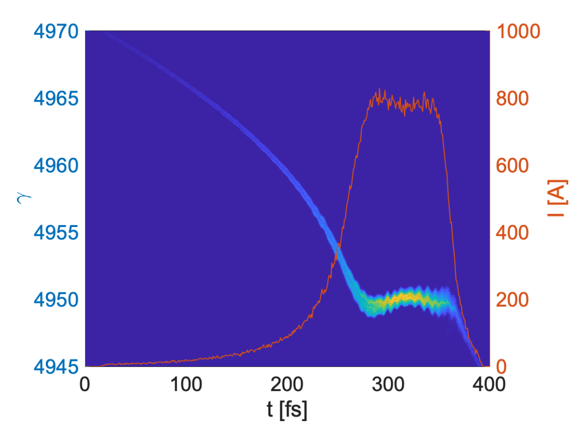

Figure 3: Phase space and current distribution of the electron beam at exit of BDS.

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Undulator Lines

At initial phase, it is planned to design four undulator lines referred to as the FEL1, FEL2, FEL3 and FEL4. FEL1 and FEL2 work at the principle of SASE and another two working at EEHG. SASE is the most common FEL operational mode and it can generate high-intensity, ultrashort light pulses with tunable wavelength form VUV to hard X-rays. Starting from noise, however, leads to the chaotic temporal profiles and noisy spectra. EEHG, which generally rely on the techniques of optical-scale precise manipulation of the electron beam phase space with external coherent lasers, is capable of generating laser-like X-ray pulses with Fourier transform limit, stability, repeatability and controllability.

The FEL1 will deliver X-rays with photon wavelength from 1 nm to 3 nm; both FEL2 and FEL3 will cover the photon wavelength from 2.3 nm to 15 nm; and FEL4 will cover the photon wavelength from 5 nm to 30 nm. All undulators of S^3FEL are selected as out-of-vacuum and variable gap type. The wavelength can be tuned by varying the undulator gap at constant electron beam energy. Two types of undulators are used here, namely permanent magnet undulator (PMU) and elliptically polarized undulator (EPU). EPUs are placed at the end of FEL1 and FEL4 to generate polarization-controlled radiation pulses [12]. The magnetic lengths of the individual undulator are 4.0 m. Quadrupoles and diagnostic components are installed between the undulator segments to monitor and correct the electron trajectory.

In the SASE lines, the maximum repetition rate of the FEL pulses can be 1 MHz; in the seeding lines, the maximum repetition rate is designed to be 1 kHz due to the power limitation of the seed laser. Lower peak power can be traded for higher repetition rate when the average power of the seed laser is constant. Direct-amplification enabled harmonic generation [13], which can reduce the peak power of the seed laser, is an alternative to generate higher repetition rate EEHG FELs. In order to make the radiation pulses generated by the EEHG continuously tunable, the wavelength of the second seed laser is continuously adjustable from 240 to 267 nm with the help of OPA technology. In FEL1, two long break sections are reserved for future upgrade of two-stage self-seeding [14]. In FEL3, the harmonic jump exceeds over 100 to achieve the shortest wavelength radiation. To prevent the degradation of FEL performance due to various collective effects, such as coherent synchrotron radiation (CSR) and intra-beam scattering (IBS), alternative methods such as EEHG cascade harmonic lasing [15] and harmonic optical klystron EEHG [16] are also prepared.

FEL Performances

FEL simulations are performed with the electron beam from BDS. Figure 4 shows the Genesis [17] simulation results of the SASE output at 1 nm, where grey lines indicate the computed results from the 101 shots while the red line shows the average value of all shots. The FEL pulse energy reaches 500 µJ at around 100 m with peak power of about 7 GW and the pulse length of about 70 fs (FWHM). At exit of the undulator, the FEL pulses has a transverse beam size of about 150 µm and a diffraction angle of 5.4 µrad.

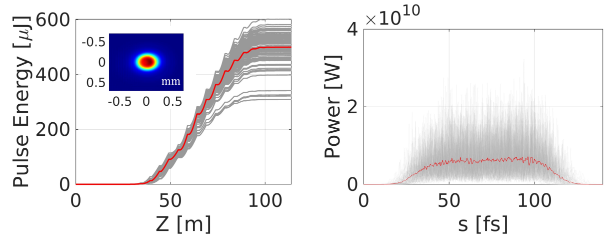

Figure 4: SASE radiation at 1 nm.

Simulations were also performed for other undulator lines and wavelengths. In summary, S^3FEL can generate FEL pulses with wavelengths from 1 to 30 nm, pulse lengths from 50 to 100 fs (FWHM), pulse energies from 0.1 to 1.6 mJ and bandwidths from 0.01% to about 1%.

SUMMARY

With the development of superconducting technology, the construction of megahertz-level repetition rate free electron lasers has become one of the most important development directions in the field of free electron lasers in the world. The proposed Shenzhen Superconducting Soft X-Ray Free-electron Laser aims at generating X-rays and EUV FELs between 1 and 30 nm at a rate up to 1 MHz. With high peak and high average brightness, the proposed facility would facilitate the development of cutting-edge scientific researches and promote the construction of a science center in the Guangdong-Hong Kong-Macao Greater Bay Area.

ACKNOWLEDGEMENTS

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