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SCLF: AN 8-GEV CW SCRF LINAC-BASED X-RAY FEL FACILITY IN SHANGHAI

Z.Y. Zhu[1], Z.T. Zhao[2†], D. Wang[2], Z. Liu[1], R.X. Li[3], L.X. Yin[2] and Z.H. Yang[2] for the SCLF Team
[1]ShanghaiTech University, Shanghai 201210, China
[2]Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China
[3]Shanghai Institute of Optics and Fine Mechanics, CAS, Shanghai 201800, China

Abstract

The Shanghai Coherent Light Facility (SCLF) is a newly proposed high repetition-rate X-ray FEL facility, based on an 8-GeV CW superconducting RF linac. It will be located at Zhangjiang High-tech Park, close to the SSRF campus in Shanghai, at the depth of ~38m underground and with a total length of 3.1 km. Using 3 phase-I undulator lines, the SCLF aims at generating X-rays between 0.4 and 25 keV at rates up to 1MHz. This paper describes the design concepts of this hard X-ray user facility.

INTRODUCTION

We are currently witnessing a rapid progress in X-ray free electron laser (XFEL) development across the globe, among which the superconducting RF (SCRF) linac based high-repetition-rate XFELs are leading ones. European XFEL [1] achieved its first lasing in early May 2017, and started operational phase in early July 2017. The LCLS-II [2] construction is now under way, and is scheduled to become operational in 2020. An energy upgrade proposal to LCLS-II, the LCLS-II-HE project, has also been initiated [3]. Considering this international context, and in response to the rapidly growing demands from Chinese science community on the high peak and high average brightness X-ray sources, and the needs from Zhangjiang Comprehensive National Science Center in Shanghai, a high repetition-rate XFEL, the Shanghai Coherent Light Facility (SCLF), was proposed.

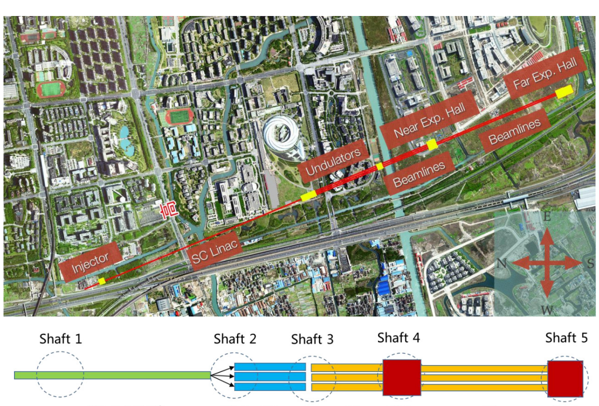

Figure 1: Aerial view of the SCLF project.

This proposal was officially approved by the central government of China in April 2017. The SCLF is an X-ray FEL facility based on an 8 GeV continuous-wave (CW) SCRF linac. As shown in Fig. 1, it will be located at the Zhangjiang High-tech Park of Shanghai Pudong, closely connected to the campuses of the Shanghai Synchrotron Radiation Facility, the Shanghai Advanced Research Institute and the ShanghaiTech University. The SCLF major facility will be installed in the tunnels at the depth of ~38m underground and with a maximum length of 3.1 km.

The SCLF will have five shafts, one accelerator tunnel and three parallel undulator tunnels and the following three beamline tunnels, with each undulator tunnel capable to accommodate two undulator lines. In its initial phase, the SCLF consists of an 8 GeV CW SCRF linac, three undulator lines, three following FEL beamlines, and ten experimental end-stations. The end-stations are distributed in the near experimental hall (NEH) in Shaft 4 and the far experimental hall (FEH) in Shaft 5. The initial three undulator lines will be located in two undulator tunnels. Using these three undulator lines, the SCLF aims at generating brilliant X-rays between 0.4 and 25 keV at pulse repetition rates up to 1 MHz.

The proposed SCLF project is planned to start its civil construction within one year immediately after its preliminary design report is approved by the central government. The whole SCLF project is expected to be completed in 7 years, and then the user experiments can start right after the completion of the beamline and experimental station commissioning.

MACHINE LAYOUT AND MAIN PARAMETERS

Figure 2 shows the layout of the SCLF. The SCLF accelerator complex comprises the following two parts: a photo-injector which generates a bright electron beam with repetition rate up to 1 MHz and accelerates it to ~100 MeV; The main SCRF linear accelerator, where the electron beam is accelerated to about 8 GeV and longitudinally compressed to about 1.5 kA with two compressors working at energies of 270MeV and 2.1GeV respectively.

The photo-injector is based on the VHF photocathode gun similar to that developed at LBNL [4]. On the basis of LCLS-II experience, the design draws heavily to produce a 10ps (FWHM) long pulse with 100 pC bunch charge and a RMS normalized transverse emittance of 0.4 mm-mrad at 90-120 MeV. The bunch repetition rate is designed up to 1 MHz during the operation. The SCLF injector includes a 216 MHz photocathode VHF gun, a 1.3 GHz buncher, a 1.3 GHz single 9-cell cavity cryomodule, a 1.3 GHz eight 9-cell cavities standard cryomodule, a laser heater, and the beam diagnostics. A laser heater system is employed to

† zhaozt@sinap.ac.cn

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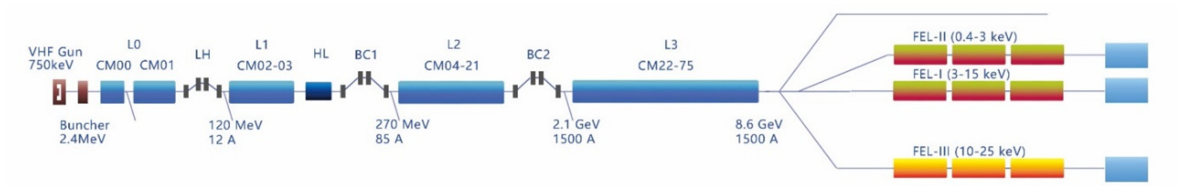

Figure 2: Machine layout of the SCLF.

suppress the micro-bunching instability and control the RMS deviation and the distribution shape of sliced beam energy spread by choosing the laser spot and the peak power. Moreover, the injector also includes photocathode system, drive laser system, solid state RF power sources, power supplies, vacuum and mechanic support systems.

The function of the SCRF linear accelerator system is to accelerate the 10 ps long electron bunch exiting the photo-injector to 8 GeV and to compress the beam to its final duration and peak current. Depending on the FEL lasing requirements, an electron bunch length of 70 fs (FWHM) and a peak current of 1.5 kA or higher can be provided with 100 pC of charge. The horizontal and vertical normalized emittances at the end of the linac should not exceed 0.4 mm-mrad to achieve the desired photon throughput.

At the exit of the photo-injector, the ~100 MeV electrons enter the L1 linac section (2 cryomodules) where they are accelerated to 326 MeV. Off-crest acceleration creates the correlated energy spread along the bunch needed to compress it in the first compressor BC1. Two 3.9 GHz SCRF cryomodules tuned at the 3rd harmonic of 1.3 GHz are placed right before the first bunch compressor BC1. The function of the harmonic cavities is to provide cubic corrections of the correlated momentum distribution along the bunch in presence of the photo-injector and the magnetic compressors non-linearity.

The L2 linac section (18 cryomodules) is located between the first and second bunch compressor, which accelerates the electron beam from 270 MeV to 2.1 GeV. They also provide the residual energy chirp needed for the second compressor BC2. After BC2 the beam is accelerated to its final 8 GeV energy in the L3 linac section (54 cryomodules). The baseline parameters for the cavity unloaded quality factor Q_0 and the CW accelerating gradient of the standard cryomodule are 2.7×10^{10} and 16 MV/m respectively.

As shown in Fig. 2, the beam distribution system (BDS) starts from the end of linac tunnel, passes through the Shaft 2 and ends in the undulator tunnels. The first three undulator lines, referred to as the FEL-I, FEL-II and FEL-III, will be installed in two of the three undulator tunnels. The FEL-I will deliver X-rays with photon energies from 3 keV to 15 keV; The FEL-II will cover the photon energy range of 0.4-3 keV; And the FEL-III will cover the photon energy range of 10-25 keV.

All the undulators of SCLF have been chosen to be variable gap one. The wavelength can be tuned by changing the undulator gap at constant electron beam energy. The FEL-I and FEL-II lines are based on out vacuum planar, hybrid permanent magnets type undulators. The magnetic lengths of the individual undulator are 5.0 m (26 mm undulator period) for the FEL-I and 4.0 m (68 mm undulator period) for the FEL-II, respectively. FEL-III undulator is designed to be superconducting undulator with period of 16mm to cover 10-25 keV photon energy range with the 8 GeV electron beam energy. Cavity beam position monitors, quadrupoles, correctors and quadrupole movers are installed between the undulator segments to monitor and correct the electron trajectory.

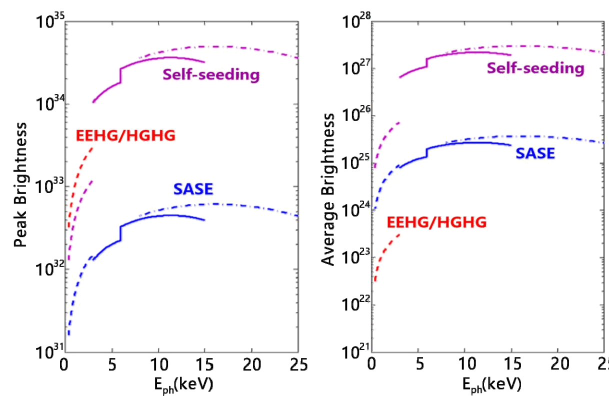

Figure 3: Peak and average brightness of the SCLF in units of photons/mm^2/mrad^2/s/0.1%BW. The repetition rate of the external seeding and self-seeding is assumed to be 10 kHz and 1 MHz in the calculation.

At the hard X-ray wavelength, the FEL process requires the straightness of the electron trajectory in the undulators to stay within 1 μm (RMS value over the undulator length). This requirement is beyond the state-of-the-art of present surveying techniques, a beam based alignment [5] procedure will be required to achieve the desired performance.

The accessible SCLF photon brightness are plotted in Fig. 3 versus the photon energy accessible from the FEL-I, FEL-II and FEL-III. The main parameters of the SCLF project are summarized in Table 1.

Both the FEL-I and the FEL-III will run in the SASE mode, with self-seeding option [6, 7]. The high brightness SASE (HB-SASE) mode [8] will also be implemented in FEL-I. In FEL-II, several operation schemes will be made possible, e.g. SASE, self-seeding, cascaded EEHG [9, 10], and polarization control with EPUs as an afterburner.

In the initial phase, the SCLF project will provide three X-ray beam paths, one for each undulator line. These beam paths, shown schematically in Fig. 4, include the components necessary to filter, attenuate and collimate the X-ray beam. Ten experimental end-stations, distributed in the NEH and the FEH, covering the research fields of physics, chemistry, materials, life science, and extreme environment science, are planned.

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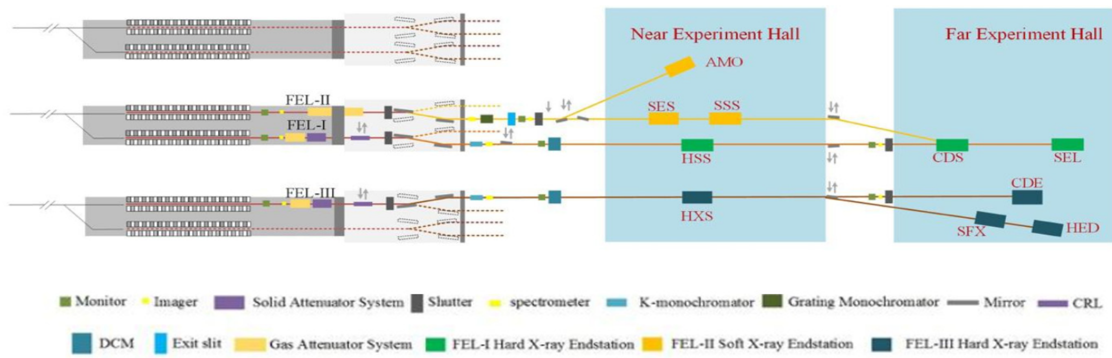

Figure 4: Initial FEL beamlines and the ten end-stations. AMO: atomic, molecular, and optical physics; CDE: Coherent Diffraction End-station; CDS: Coherent diffraction end-station for single particle and biomolecules; HED: High Energy Density science; HSS: Hard X-ray Scattering Spectrometer; HXS: Hard X-ray Spectroscopy; SEL: Station of Extreme Light; SES: Spectrometer for Electronic Structure; SFX: Serial Femtosecond Crystallography End-station; SSS: Soft X-ray Scattering Spectrometer.

Table 1: Main Parameters of the SCLF

Parameters	**Nominal**	**Objective**
Beam energy/GeV	8	4-8.5
Bunch charge/pC	100	10-300
Peak current/kA	1.5	0.5-3
Slice emittance/μm-rad	0.4	0.2-0.7
Max repetition rate/MHz	1	1
Beam power/MW	0.8	0-2.4
Photon energy/keV	0.4-25	0.4-25
Pulse length/fs	66	3-600
Peak brightness*	5×10^{32}	10^{31}-10^{33}
Average brightness*	5×10^{25}	10^{23}-10^{26}
Total facility length/km	3.1	3.1
Total tunnel length/km	5.7	5.7
Tunnel diameter/m	5.9	5.9
2K Cryogenic power/kW	12	12
RF power/MW	2.28	3.6

* Photons/μm^2/rad^2/s/0.1%BW

The SCLF scientific instruments will enable the probing of structural dynamics of materials, including the physical and chemical behaviours in biomaterials and condensed matters, in the fundamental length (~Å) and temporal (~fs) scales.

As shown in Fig. 4, a variety of advanced techniques are employed in the initial 10 end-stations, including Coherent Diffraction Imaging (CDI), time-resolved photoelectron spectroscopy/microscopy, ultrafast x-ray absorption/emission scattering spectroscopy, Serial Femtosecond Crystallography (SFX), etc. These ten end-stations in the first installation phase are decided as the results of the demanding from the wide scientific user communities. Among these 10 end-stations, the Station of Extreme Light (SEL), which combines the hard X-ray FEL with a 100 PW laser, is aimed at pioneering cutting-edge researches on strong field QED physics.

SUMMARY

The rapid development of new XFEL user facilities around world has opened up a new paradigm for X-ray sciences. The proposed Shanghai Coherent Light Facility is aimed to join this exclusive club as one of the most advanced user facilities by delivering fs-scale X-ray pulses from 0.4 keV to 25 keV, up to million pulses per second. The 8 GeV SCRF linac based SCLF will enable the probing of structural and functional properties of materials, including the physical and chemical behaviours in condensed matters and biomaterials, in the fundamental length (~Å) and temporal (~fs) scales. In addition, SCLF will work together with a 100PW laser facility to serve for a dedicated end-station for strong field QED physics.

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