ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

SHANGHAI HARD X-RAY FEL FACILITY PROGRESS STATUS

Z. T. Zhao[1]†, H. Ding[2], B. Liu[1] on behalf of the SHINE Project Team[1,2,3]
[1]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China
[2]ShanghaiTech University, Shanghai, China
[3]Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai, China

Abstract

SHINE is a high repetition rate X-ray FEL facility under construction in Shanghai, China. The facility is based on an 8 GeV CW superconducting linac and plans to have 3 undulator lines and 10 experimental stations in phase-I, covering the photon energy range of 0.4–25 keV. Mass production of the components and installation of the machine are in course. User experiments are expected to start in 2027. This paper summarizes the proposed configuration and the status of R&D and production for the critical components and systems, discussing the key technologies. The current status of the project and the plans leading to the completion will be presented, outlining the major scientific goals of the facility.

INTRODUCTION

The Shanghai High Repetition Rate XFEL and Extreme Light Facility (SHINE) was proposed in response to the rapidly growing demands from Chinese science community on both high peak and high average brightness X-ray sources, and the plan to develop a photon science research facility complex, including synchrotron light source, X-ray free electron lasers and super-intense and ultrashort lasers, at the Zhangjiang high-tech park of Shanghai. This proposed project was officially launched by the central government of China in April 2017 [1].

SHINE is the largest major science and technology research infrastructure ever built in China to date. It consists of an 8 GeV CW linac using the advanced superconducting radio-frequency (SRF) technology, in phase-I three undulator lines, three following beamlines, and ten experimental end-stations, as well as a 100 PW super-intense and ultrashort laser. The SHINE facility will be installed in shafts and tunnels ~30 m underground, placed in north-south direction with total length of ~3.1 km, closely connected to the campuses of the Shanghai Synchrotron Radiation Facility, the Shanghai Advanced Research Institute and the ShanghaiTech University in the east, and the Shanghai maglev train line in the west. The whole project investment scale exceeds 10 billion CNY (~1.5B USD).

SHINE has constructed five shafts from north to south, one accelerator tunnel from shaft #1 to shaft #2, three parallel undulator tunnels from shaft #2 to shaft #3, and the following three beamline tunnels from shaft #3 to shaft #4 and to shaft #5, with each undulator tunnel capable to accommodate two undulator lines and each beamline tunnel capable to accommodate two beamlines. The three phase-I undulator lines will be placed in two undulator tunnels. The layout of the SHINE facility is shown in Fig. 1.

† zhaozt@sari.ac.cn

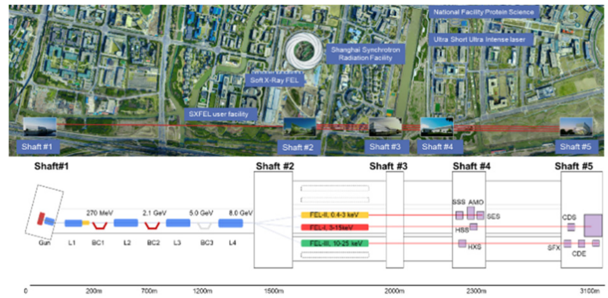

Figure 1: Layout of the SHINE facility.

The SHINE project started its civil construction in April 2018, and constructions of all shafts and tunnels were completed by the end of 2023. The utility facility at shaft #1 campus has been constructed and commissioned, it has been in routine operation for the SHINE linac sub-systems since March 2023. The rest utility facilities at other shaft campuses are either in installation or under commissioning, they will all be ready for SHINE within a year.

During the same period, the construction of the SRF technology infrastructures and R&Ds of key technologies and critical components, such as 1kW@2K helium cryoplant, SRF cavity surface processing infrastructures, vertical and horizontal test platforms, prototypes of SRF cryomodules (CM), VHF gun, undulators and so on, were carried out under the support of a Shanghai major science and technology project.

The fabrication of the first pieces and batch manufactures of the SHINE components were almost performed at the same time, once after their R&Ds met the corresponding specifications. Then the installation of the SHINE injector started in April 2023 from its VHF gun. The single-cavity cryomodule i1CM and eight-cavity cryomodule i8CM are under installation now, aiming to complete the installation and start the beam commissioning of the injector in July 2024, and then the installation of the linac section L1 before the first magnetic compressor within another half year.

FACILITY OVERVIEW

Based on the demands from various research frontiers and considering state-of-the-art accelerator-based light source technologies, the overall scope of the SHINE facility is defined:

(1) The photon energy range is 0.4-25 keV, covering the soft X-ray (below 1keV), tender X-ray (around 2-5 keV) and the hard X-ray region (up to 25 keV), and retaining the

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

possibility to further extend the photon energy range and improve the FEL performance through electron beam energy manipulation and advanced FEL configurations.

(2) The maximum bunch repetition rate can reach 1 MHz, which can be used by multiple undulator lines simultaneously through switchyard. The repetition rate of a single beam line is arbitrarily adjustable according to experimental requirements, and the average brightness reaches the best performance level that it ever achieved.

(3) A group of tunnels to accommodate five or more undulator lines and ten or more beamlines, including an ultra-long beamline up to 1 km in length (from the light source point to the experimental station), and the ability to achieve advanced intersection of different photon energy X-rays.

(4) The capacity of the SHINE experimental hall can ultimately accommodate beyond 20 user experimental end-stations which will be equipped with various advanced experimental devices such as terahertz to ultraviolet lasers.

(5) The capabilities required for high demanding experiments are reserved, such as full coherence, femtosecond level ultrashort pulses, and polarization control. SHINE also keeps a few promising potentials, such as terawatt level peak power and attosecond level pulse length, etc.

Overall, the SHINE accelerator facility has a baseline energy of 8 GeV to provide photon energy of 0.4-25keV. In phase-I, 3 beamlines and 10 endstations were planned, with ultra-high peak brightness and average brightness, and femtosecond ultrafast pulses. At the same time, SHINE pursues ultra-high spatial resolution at the nanoscale and ultrafast time resolution at the femtosecond level.

According to the layout shown in Fig. 1, the main linac increases the energy of the beam generated by the injector from 100 MeV to 8 GeV, compresses the bunch length to tens of femtoseconds, and increases the peak current to over 1500 A, meeting the lasing requirements of X-ray free electron lasers. Compared to the copper linac based hard X-ray FELs, superconducting linear linac can effectively increase the bunch repetition rate of the electron beam, achieving ~10^6 pulses per second, greatly improving the average power of the electron beam and hence the output free electron laser, and supporting multiple experimental stations to conduct scientific experiments simultaneously.

Table 1: Main Parameters of the SHINE Facility

Parameters	Design/Typical Value
Beam Energy (GeV)	8
Bunch Charge (pC)	100
Repetition Rate (MHz)	0-1
Slice Emittance (mm·mrad)	0.45
Peak Current (A)	~1500
FEL-I Photon Energy (keV)	3.0-15.0
FEL-I Photons (0.1%BW)	>10^{11}@12.4 keV
FEL-II Photon Energy (keV)	0.4-3.0
FEL-II Photons (0.1%BW)	>10^{12}@1.24 keV
FEL-III Photon Energy (keV)	10.0-25.0
FEL-III Photons (0.1%BW)	>10^{10}@15.0 keV

To cover the photon energy range of 0.4-25 keV, the undulator lines select different types of permanent magnet undulators and superconducting undulators. Multiple FEL operation schemes such as self-amplified spontaneous emission (SASE), self-seeding, and external seeding are used to generate high brightness X-ray free electron lasers. Table 1 presents the main accelerator and FELs performance of the facility.

Considering the demand of the low photon energy below 0.4 keV from the experimental station and the need of some advanced FEL operation schemes, a low-energy bypass line for transporting beam with an energy of ~5 GeV will be added. The beam from the bypass line will be transported into the FEL-II undulator line, covering the photon energy range of 0.2-1.4 keV. With the low-energy bypass line, the SHINE facility can realize better FEL performance with external seeding schemes, more flexible operation of FEL-1, FEL-II and FEL-III lines simultaneously, and earlier FEL lasing and operation for the commissioning of beamlines and end-stations. This also makes the facility possible for parallel installation and commissioning.

INJECTOR AND MAIN LINAC

The SHINE linac comprises a high brightness injector and 4 sections of main linac as well as up to three magnetic bunch compressors. The injector consists of a ~1 MeV electron source, a single-cavity SRF module (i1CM), an eight-cavity SRF module (i8CM), a laser heater, a beam switchyard, and a beam diagnostic section. The electron source is based on a 216 MHz normal conducting VHF gun, which is developed by Tsinghua University [2]. The i1CM and i8CM have symmetric coupler configurations to eliminate emittance growth from coupler kicks. The electron source was installed and commissioned in 2023, as shown in Fig. 2, and the two injector cryomodules were installed this year. The injector is under integration, and is expected to start beam commissioning at the end of July this year.

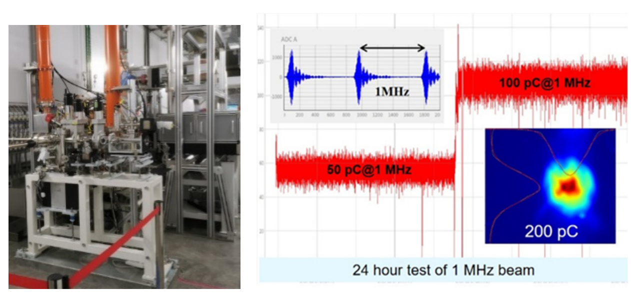

Figure 2: The SHINE VHF gun (left) and its 24-hour beam test at 1 MHz bunch repetition rate (right).

To meet the requirements of X-ray FEL performance, the 8 GeV SHINE linac needs to provide high brightness electron beam at up to 1 MHz bunch repetition rate, with normalized beam emittance of < 0.5 μm at nominal bunch charge of 100 pC and peak current over 1500 A [3].

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

At the exit of the injector, the beam energy is ~100 MeV, the bunch length is 1 mm and the peak current is about 10 A. In the main linac, the beam will be further accelerated to 8 GeV in four acceleration sections (L1, L2, L3 and L4) which consist of seventy-five 1.3 GHz SRF cryomodules. To obtain the required peak current, the bunch current will be compressed to over 1500 A by two or three bunch compression sections (BC1, BC2 and BC3). Two 3.9 GHz SRF cryomodules are used before BC1 as linearizer. The layout of the SHINE linac is shown in Fig. 3.

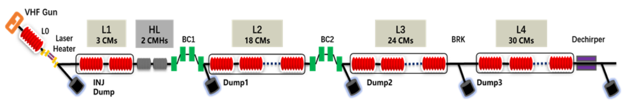

Figure 3: Layout of the SHINE linac.

Considering soft X-ray FEL lasing with relatively low beam energy, a design to extract the electron beam from the BREAK section between L3 and L4 was made. With the help of the bypass line, the beam up to 5 GeV can be delivered into FEL-II undulator line.

To enable more advanced operation schemes at FEL-II driven through the bypass line, and to ensure baseline design remain unaffected of FEL-II driven by the main linac, a three-stage magnetic compression scheme was designed. The bypass line is used for operating with longer bunch lengths, typically around 100 fs, with a peak current of approximately 800 A. While the main linac line operates with shorter bunch lengths, usually around 30 fs, with a peak current of about 1500 A. To accommodate these requirements, the bunch after BC2 is around 100 fs long, which can then be directly transferred to the FEL-II undulator using the bypass line. The remaining bunches can be further compressed to 30 fs with BC3, ensuring that bunches in main undulator lines remain unaffected downstream.

Cryomodules have been under developing for SHINE since 2017. A single-cavity cryomodule (i1CM) and an eight-cavity cryomodule (i8CM) for the injector, a standard eight-cavity cryomodule (CM01-ND, ND denotes N-doped cavities) for the main linac have been assembled and passed horizontal tests, all meet their specifications [4]. In the meantime, many components for the SHINE cryomodules have been developed:

(1) TESLA type 1.3-GHz 9-cell cavities are adopted at SHINE, which are provided by different suppliers since prototype development. High-Q recipes, including 3/60 N-doping and mid-T baking recipes have been studied and applied on the R&D cavities, resulting in high-Q and relatively high gradient performance, with averaged Q_0 higher than 3.0×10^{10} at the gradient range of 16-21 MV/m and the average maximum gradient larger than 25.0 MV/m in vertical test.

(2) The CW fundamental power coupler (FPC) for the SHINE cryomodule has been developed based on the TTF-III pulsed power coupler. To date, 30 FPCs have been manufactured and RF conditioned. All of them have passed the RF high power test, including CW operation at 14 kW for 6 hrs in TW mode and 7 kW for 12 hrs in SW mode.

(3) The coarse tuner was made as a double lever tuner. The fast tuner was realized by piezoelectric ceramic actuator acting directly on the cavity end flange. The fast-tuning resolution can reach 0.15 Hz, with a step size of 0.5 nm.

(4) The first two HOM absorber prototypes with silicon carbide and aluminium nitride material have been designed and fabricated. It has been verified by high power tests that the absorbed power could reach 100 W at 1.3 GHz.

(5) The SC magnet, consisting of quadrupole coils and correction coils, was developed and installed in the cryomodule. To date, four SC magnets have been integrated into SHINE cryomodules with qualified performance.

(6) The cold BPM has been developed and passed the ten-cycle cryogenic leak test, and a beam test under the warm section shows that the system has a resolution better than 50 μm@10pC.

The SHINE linac requires cryogenic cooling at 2 K for cavities, 5 K for cold interception, and 40 K for thermal shields, respectively. To ensure operation with ample margins, three helium cryoplants are employed, which are built in shaft #1 (two sets) and shaft #2 (one set) respectively. Each cryoplant is designed to deliver a cooling capacity of 4 kW at 2 K. As of now, the installation of all equipment associated with these cryoplants has been completed.

The SHINE cryogenics system consists of not only the cryoplant, but also the cryogenic distribution system that delivers the cryogen to the accelerators, and also the utility system to serve liquid nitrogen together with the helium management. The commissioning is underway for the first cryoplant, including the warm compressor station, a 4.5 K cold box, a 2 K cold box, and the intermediary cryogenic transfer line. The construction marked significant milestones with the first acquisition of liquid helium at the end of 2023 and the achievement of super-fluid helium in the beginning of 2024. Currently, the cryoplant provider and SHINE cryogenics team are optimizing the system towards achieving its nominal performance.

FEL LINES AND BEAM SWITCH YARD

The electron beam with beam energy up to 8 GeV and bunch repetition rate up to 1 MHz is used in phase-I to feed three individual undulator lines downstream, either simultaneously or separately. A beam switchyard section is used to efficiently separate the high repetition rate bunches, subsequently delivering the separated beam accurately to each undulator line [5].

There are three linac-to-undulator deflection branches (LTU-1/2/3) after the linac exit and a straight branch from the linac exit to the main dump in the middle of shaft #2 (LTD). For each LTU branch, a set of fast kicker magnets combining a DC Lambertson septum are used for fast beam separation. The kicker set consists of 8~10 kicker magnets with about 0.8 mrad total deflection angle in vertical direction. The rising edge and falling edge of the kicker magnet are far less than 1μs, which enables bunch-by-bunch beam

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

separation with programmable arbitrary separation pattern. The kicked beam is delivered to the DC Lambertson septum with ~17 mm vertical offset and then deflected horizontally through a dog-leg deflection line with two identical double-bend achromatic cells. The optics of the horizontal dog-leg are designed to mitigate various collective effects in the beam deflection process, such as the emittance growth due to CSR effect and the micro-bunching instability. The total deflection angles of each LTU branch and the consequent horizontal offsets to the linac line are: 3.0° for 1.85 m of LTU-2, 3.6° for 8.95 m of LTU-3 and 2.0° for 1.45 m of LTU-1. After the horizontal dog-leg, the 17 mm vertical offset and the vertical dispersion are corrected by a small angle vertical dog-leg. Both the horizontal and vertical dispersion are closed at this point. The beam is then delivered to the entrance of the corresponding undulator line by a series of FODO cells with 45° phase advance.

In phase-I, three undulator lines have been designed to cover the photon energy range of 0.4 and 25 keV, including a soft X-ray FEL line (FEL-II) and two hard X-ray FEL lines (FEL-I & FEL-III), as shown in Fig. 4.

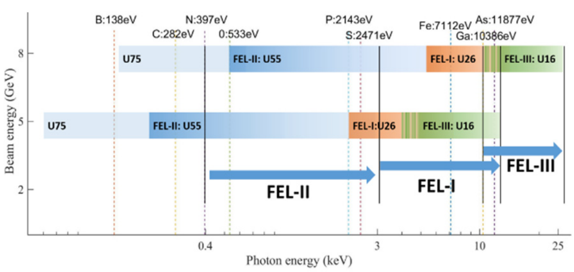

Figure 4: Photon energy coverage of three undulator lines.

The FEL-I is a hard X-ray line covering the photon energy from 3 to 15 keV. The basic FEL operation modes are SASE and self-seeding with horizontal polarization, in which the normal planar undulator is adopted with 26 mm undulator period, 1.05 T maximum magnetic peak field and 4 m segment length. The output FEL photon number is about 1×10^{10} to 5×10^{11} per pulse with pulse duration ~30 fs (FWHM) and up to 1 MHz repetition rate.

The FEL-II is a soft-to-tender X-ray line covering the photon energy from 0.4 to 3keV [6]. The baseline operation modes of FEL-II consist of SASE, self-seeding, external seeding and polarization control. The output FEL photon number is about 5×10^{11} to 7×10^{12} per pulse with pulse duration ~30 fs (FWHM) and up to 1 MHz repetition rate. According to the research requirements, the newly added bypass line will send a 5 GeV beam to FEL-II and generate the FEL pulse with photon energy as low as 0.2 keV. The bypass line can also be used for operation of EEHG towards higher harmonics, EEHG-HGHG cascades with fresh slice technology [7], and other advanced operating modes, such as large bandwidth, ultra-short pulse and two-color. Typically, the electron beam from the bypass line will have a bunch length of ~100 fs and a peak current of ~800 A, which is beneficial for EEHG-HGHG cascading mode in FEL-II.

The FEL-III is designed to cover the photon energy of 10-25 keV, in which the baselines are SASE and self-seeding. The output photon number is about 2×10^{9} to 8×10^{10} with FEL pulse duration of 30 fs and up to 0.1 MHz repetition rate. Due to the relatively high photon energy radiation and wide photon energy tuning range, the superconducting planar undulator (SCU, vertical) with 16 mm period, 1.583 T maximum magnetic peak field and 4 m segment length became the first option in the initial design, and a SCU prototype has been developed with achieved magnetic field at a 3 m long segment. The development turns out to be extremely challenging now, hence several optimization or alternative solutions have been or are being studied, e.g., enlarging the undulator period to 16.5 mm (decreasing magnetic peak field to 1.503 T), changing the 4 m segment to two 3 m pre-series modules.

Undulators for FEL-I and FEL-II are now in batch manufacturing, based on their protypes developed over last 5 years. In FEL-I line, 42 planar undulators will be used. In FEL-II line, 32 planar undulators will be installed, in which 14 upstream undulators are coupled with two different period arrays. Downstream of the FEL-II line, four eliptic polarized undulators will be used to realize the regulation of output FEL polarization state in the form of "afterburner". The upstream 14 undulators of the FEL-II line adopt a lateral switching dual-period design, with magnet arrays switchable in x-direction between 55 mm period arrays and 75 mm period arrays. Combining transverse translation period-switching with phase shifting, the considerable magnetic force compensation is achieved [8]. The magnet materials for these undulators are made of Nd2FeB14, with a residual magnetic flux density of 1.26 T and coercivity value exceeding 2150 kA/m, while the poles material is made of cobalt-vanadium-iron. The undulators adopts 4 sets of independent motion systems to achieve a smooth taper or center-height adjustment.

The prototypes of U26 and dual-period U55&75 have been successfully developed in 2023. The achieved magnetic performance is listed in Table 3.

Table 3. Magnetic Performance of Undulator Prototypes

Parameters	U26	U55&U75
Location	FEL-I	FEL-II
Period length (mm)	26	55 / 75
Segment length (m)	4.0	4.0
Minimum/Max gap (mm)	7.4/200	10.4/200
Working effective field (T)	0.4-1.0	0.3-1.25/0.4-1.5
Phase error (°)	<6	<5
Trajectory straightness (μm)	< 1.0 @ 8GeV	< 1.0 @ 8GeV
First integral (Gs·cm)	<50	< 100
Second integral (Gs·cm^2)	<15000	< 30000

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

As the main operation scheme, self-seeding can generate quasi-fully coherent FEL pulse comparing to SASE, this scheme is also designed for all the three undulator lines, including grating and crystal based monochromatic schemes [9]. Developments of the two types of monochromators have been completed in 2022 and 2023 respectively, and the following online tests after overall system integration are still on going.

BEAMLINES AND END-STATIONS

In phase-I, the SHINE project needs to construct three X-ray beamlines, one for each undulator line, and 10 end-stations, as shown schematically in Fig. 5. These beamlines include the components necessary to filter, attenuate and collimate the X-ray beam. Ten experimental end-stations, distributed in the near experiment hall (NEH) and the far experimental hall (FEH), covering the research fields of physics, chemistry, materials, life science, and extreme environment science, are planned.

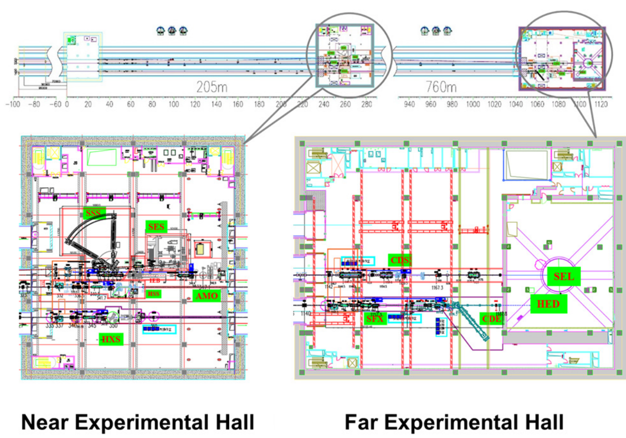

Figure 5: The SHINE initial beamlines and ten end-stations.

The SHINE 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. The phase-I end-stations include:

FEL-I
- HSS: Hard X-ray Scattering Spectrometer;
- CDS: Coherent Diffraction end-station for single molecules and particles;
- SEL: Station of Extreme Light.

FEL-II
- SSS: Soft X-ray Scattering and Spectrometer;
- SES: Spectrometer for Electronic Structure;
- CDE-IEB: Coherent Diffraction imaging Endstation-Imaging Endstation for Biomaterials;
- AMO: Atomic, Molecular, and Optical physics;

FEL-III
- HXS: Hard X-ray Spectroscopy;
- CDE-IEM: Coherent Diffraction imaging Endstation-Imaging Endstation for Materials;
- SFX: Serial Femtosecond Crystallography;
- HED: High Energy Density science.

A variety of advanced experimental 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.

The design parameters of beamlines are frozen, technical and engineering design of FEL-I/II/III and 3 end-stations (include AMO, SES and CDS) have been done, The engineering design for 5 endstations (include SSS, HSS, HXS, SFX and CDE) are almost completed. FEL-II has highest priority, and now the first experiments and science cases for the FEL-II endstations are in preparation.

Among these 10 end-stations, the Station of Extreme Light (SEL), which combines the hard X-ray FEL with a 100 PW laser, aims at pioneering cutting-edge researches on strong field QED physics.

SUMMARY AND OUTLOOK

The 8 GeV SRF linac based SHINE facility is aiming to join the exclusive XFEL club as one of the most advanced FEL user facilities by delivering fs-scale X-ray pulses from 0.4 keV to 25 keV, up to million pulses per second, serving the scientific research frontiers on physical science, materials science, energy and environmental science and life science. In addition, the SEL station of SHINE will combine a 100 PW laser with XFEL for strong field QED physics research.

The design and construction of the SHINE facility is in good progress, while the project is still facing challenges in key technologies, schedule and budgets. R&Ds of key technologies for this project have been made since 2017 and are still ongoing, while mass production of key components started successively according to the schedule. The civil engineering and utility constructions are proceeded in good shape, providing timely the conditions for facility equipment installation and systems commissioning. The injector installation started in April 2023, aiming to achieve 100 MeV beam in the coming summer of 2024. Great efforts have been made to develop cryomodules, undulators and other crucial components for SHINE, and encouraging progresses have been achieved. With the help of a bypass line, first lasing of the FEL-II line at the end of 2025 seems possible, but really challenging.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUZN1

REFERENCES

[1] Z. Y. Zhu *et al*., "SCLF: An 8-GeV CW SCRF Linac-based X-ray FEL facility in Shanghai", in *Proc. FEL2017*, Santa Fe, USA, 2017, pp. 182-184. doi:10.18429/JACoW-FEL2017-MOP055

[2] L. Zheng *et al*., "Design, fabrication, and beam commissioning of a 216.667 MHz continuous-wave photocathode very-high-frequency electron gun." *Phys. Rev. Accel. Beams* 26, 10 (2023): 103402. doi:10.1103/PhysRevAccelBeams.26.103402

[3] D. Gu *et al*., "Physics Design and Beam Dynamics Optimization of the SHINE Accelerator", in P*roc. FLS2023*, Luzern, Switzerland, 2023, pp.174-176. doi:10.18429/JACoW-FLS2023-WE4P13

[4] J. F. Chen *et.al*., "Cryomodules development for SHINE project", presented at IPAC'24, Nashville, USA, May 2024, paper WEPS42, this conference.

[5] S. Chen *et al*., "Design of the Beam Distribution System of SHINE", in *Proc. FLS2023*, Luzern, Switzerland, 2023, pp. 87-90. doi:10.18429/JACoW-FLS2023-TU4P07

[6] T. Liu *et al*., "Status and future of the soft X-ray free-electron laser beamline at the SHINE", *Front. Phys*. 11:1172368, 2023. doi:10.3389/fphy.2023.1172368

[7] C. Feng *et al*., "Coherent and ultrashort soft x-ray pulses from echo-enabled harmonic cascade free-electron lasers", *Optica*, 2022:46606. doi:10.1364/OPTICA.466064

[8] S. Zhou *et al*., "The Magnetic Design of a Double-Period Undulator Based on Magnetic Force Compensation Technology", *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 5, 2024. doi:10.1109/TASC.2023.3346838

[9] T. Liu *et al*., "Optimization for the Two-Stage Hard X-Ray Self-Seeding Scheme the SCLF", in *Proc. IPAC'18*, Vancouver BC, Canada, 2018, pp.4460-4463. doi:10.18429/JACoW-IPAC2018-THPMK070