Progress and Future of Shanghai Synchrotron Radiation Facility*

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Shanghai Synchrotron Radiation Facility (SSRF), a 3.5 GeV, 3.9 nm-rad synchrotron radiation light source, started its user operation in May 2009. By the end of 2015, SSRF has served more than 12000 users and produced major experimental results. The SSRF operation achieved a machine availability of >98% and mean time between failure (MTBF) > 80 hours. The electron orbit stability in the storage ring is kept within sub-micron levels. A proposal for SSRF Phase-II Project got approval in 2015. It consists of sixteen advanced beamlines, user experimental supports, beamline technique supports and machine upgrade. Free electron laser (FEL) technology is the next focus of SSRF. Shanghai Deep Ultraviolet Free-Electron Laser (SDUV-FEL), a test facility for new FEL principles, has been operated for 5 years and got a serial of important results. Shanghai X-ray Free-Electron Laser (SXFEL), a soft X-ray FEL test facility, started construction at the end of 2014. It will be commissioned in 2017.

1. Introduction

Shanghai Synchrotron Radiation Facility (SSRF), located at the Zhangjiang High-Tech Park in Shanghai, is a 3.5 GeV light source with emittance of 3.9 nm-rad and circumference of 432 m. It is comprised of a 150 MeV linac, a full energy booster, a storage ring and a set of beamlines, as well as the utility systems, as shown in Fig. 1. The construction and commissioning was completed and the design parameters were achieved at the beginning of 20091). SSRF has been opened to users from May 2009. 7 beamlines were constructed together with the accelerators in the Phase-I project and 6 beamlines were constructed during the operation period. There are 5 new beamlines under design and construction supported by the Follow-up Beamline Program and 16 beamlines proposed in the SSRF Phase-II Project. The accelerator upgrade is also planned in the phase-II project to extend the machine performance and accommodate more insertion devices. The proposal of SSRF phase-II project has got approval from the government in 2015 and the project is in feasibility study period now.

In the meantime, with the synchrotron radiation light source project, the free-electron laser (FEL) projects are also performed at SSRF. The Shanghai Deep Ultraviolet Free-Electron Laser (SDUV-FEL) source, based on a 160 MeV linac designed and constructed at the Jiading campus from 2000, and an undulator line constructed from 2008, is a test facility for new FEL principles and technologies2). A series of experiments, including the demonstration of echo-enabled harmonic generation (EEHG), cascading high-gain harmonic generation (HGHG) etc. have been successfully carried out in it. The Shanghai X-ray Free-Electron Laser (SXFEL) project, approved by the central government at the beginning of 2015, is under construction3). It consists of an 840 MeV linac, a two stage radiator sections and a FEL diagnostic beamline. The total length of this facility is about 300 m. It is located at the north of the Zhangjiang campus, just adjacent to the SSRF facility.

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shows the present view of the SXFEL building.

2. Shanghai Synchrotron Radiation Facility

2.1 Status of the SSRF Operation

As the main part of SSRF, the storage ring is composed of 20 double-bend lattice cells in 4-fold symmetry. There are sixteen 6.5 m long straight sections for accommodating insertion devices and four 12 m long straight sections, two of them will be used for insertion devices and two others are used for injection components and super conducting RF cavities, respectively. There are 140 beam position monitors (BPMs), 80 correctors and 60 air coils (corrector without iron core for fast correction) in the ring to measure and correct the beam orbit. A transverse feedback system with a bandwidth of 250 MHz is used to counteract the beam instabilities. The main parameters of the storage ring are shown in Table 1.

There are 7 beamlines constructed during the SSRF project and have been opened to users since May 2009. At the same time of the operation, 6 new beamlines construction are completed and opened to users in 2015, including 5 beamlines dedicated to protein sciences within the program of National Facility for Protein Sciences at Shanghai, and 1 soft X-ray beamline founded by user. The beamlines in operation are listed in Table 2.

With excellent performance, SSRF supplies annually beam time from 2000 hours in 2009 up to 5500 hours in 2015 to synchrotron radiation experiments and beamline developments. By the end of 2015, there are more than 27600 public users from 385 universities and institutes carrying out 7400 experiments at SSRF on more than 10 fields, including life science, material science, environmental, information, physics, chemistry etc. The users got major experimental results presented in more than 2500 publications, including about 49 papers published in Nature, Science and Cell. After several years of continuing upgrade and improvement, the SSRF operation achieved a machine availability of >98% and mean time between failure (MTBF) >80 hours in 2015. A typical daily operation status is shown as Fig. 3.

From 2009 to 2011, SSRF was operated in decay mode. In each 12 hours, electron is injected into storage ring to a maximum current of 200 mA, and the stored beam current decayed from 200 mA to about 140 mA in 12 hours. The beam orbits drift about 10 μm in horizontal and 2 μm in vertical plane during the 12 hours operation period. Starting from 2012, after a serials of system upgrade and safety review, including the optimization of kickers parameters and tilt angle to decrease the injection disturbance on the stored beam, the machine protection system upgrade and the radiation safety interlock upgrade, the user top-up mode operation was commenced. With this operational mode, the beam orbit stability, the integrated photon flux and the flux constancy of experiments are greatly improved and increased. From 2012, the stored beam current was gradually increased from 200 mA to 250 mA. The filling pattern was modified from 500 continuous bunchs at beginning to 4 bunch-trains with uniform interval among them to avoid the beam instability in high current with small in-vacuum undulator (IVU) gaps. In top-up operation mode, slow

| No. | Beamline                     | Energy range (Source) |
|-----|------------------------------|------------------------|
| 1   | Macromolecular Crystallography | 5~18 keV (IVU25)       |
| 2   | XAFS                         | 3.9~23 keV (W80)       |
| 3   | X-ray Diffraction            | 4~22 keV (BM)          |
| 4   | X-ray Imaging                | 9~65 KeV (W140)        |
| 5   | Hard X-ray Micro-focus       | 5~20 keV (IVU25)       |
| 6   | SAXS                         | 4~22 keV (BM)          |
| 7   | Soft X-ray Spectromicroscopy | 0.2~2.2 keV (EPU100)   |
| 8   | Protein Macro-crystallography | 5~18 keV (IVU25)       |
| 9   | Protein Complex Crystallography | 7~15 keV (IVU20)      |
| 10  | High-throughput Protein Complex Crystallography | 5~20 keV (BM) |
| 11  | BioSAXS                      | 7~15 keV (IVU20)       |
| 12  | Infrared Spectroscopy and Imaging | 10~10000 cm⁻¹ (BM)     |
| 13  | Dreamline (soft X-ray beam line for ARPES and PEEM) | 20~2000 eV (DEPU)     |

Fig. 3 (Color Online) Daily operation status of SSRF.
orbit feedback (SOFB) and RF frequency feedback can keep the orbit stability within 2 μm and 1 μm in the horizontal and vertical planes, respectively. There are two orbit feedback systems, the slow orbit feedback and the fast orbit feedback (FOFB), operating simultaneously in the SSRF storage ring. They are designed to have cross-talk between them to avoid the power supply of air coil saturation. Sub-micron beam orbit stability can be achieved in both horizontal and vertical planes, which is shown in Fig. 4.

Accompanying with the new beamlines construction, more and more insertion devices (IDs) are introduced into the storage ring. It will result in the orbit distortion up to about 50 μm in peak value by the ID gap changing. The feedforwards of IDs help to reduce the orbit distortion to less than 5 μm in peak value. Figure 5 shows the current curve of the corrector located at both ends of the ID. For a few IDs, the feedforward for tune compensation is also adopted to reduce the tune shift during the gap changing.

2.2 SSRF Phase-II Project

SSRF Phase-II Project will pursuit sophisticated abilities in high resolutions on energy, momentum, time, space and single atom detection, as well as new opportunities through combination of different photon energy ranges. It consists of sixteen new advanced beamlines as shown in Table 3, user experimental supports, beamline technique supports and accelerator upgrade, aiming to improve substantially experimental research capabilities particularly for energy science, environment science, material science, life science, and earth science etc. The proposed beamlines will offer photons with much enriched energy options by filling the spectral gaps in the energy range of infrared (10 cm⁻¹~10000 cm⁻¹), tender X-ray (2~4 keV), super hard X-ray (70~300 keV) and γ-ray (0.4~20 MeV, 330~550 MeV). They provide more than sixty new synchrotron radiation experimental methods such as X-ray spectroscopy, X-ray diffraction/scattering, X-ray imaging, infrared and γ-ray to fulfill scientific requirements. These beamlines will assemble more than forty types of in-situ experimental environment and related devices, including low temperature (1.5~300 K), high temperature (300~2000 K), high pressure (300 GPa), pulsed strong magnetic field (20 T) and static strong magnetic field (10 T), electric field, pulsed laser (fs) and infrared laser heating (3000 K) etc., to satisfy scientific needs for real-time and dynamic studies. To be forged are the significant upgrading of the experimental capabilities in the following eight aspects: (1) higher spatial resolution (10 nm), (2) faster time resolution (100 ps), (3) higher energy resolution (meV), (4) higher chemical sensitivity (1 ppb) and single atom level detection capability, (5) multiple scale (nm~cm) structural analysis, (6) multiple level (100 ps~1000 s) dynamic analysis, (7) multiple elements ingredients in-

| Beamsline                          | Source                | Energy range         |
|------------------------------------|-----------------------|----------------------|
| Radioactive Material (BL13W)       | W                     | 5~35 keV             |
| E-line (combination of XES & XANES)| U+U                   | 130 eV~10 keV        |
| S²-line (combination of Nano-ARPES and Spin-ARPES (BL07U)| Twin EPU | 50~2000 eV |
| Time-resolved USAXS (BL10U1)       | U                     | 8~20 keV             |
| D-line ED-XAS Branch (BL10U2)      | U                     | 5~20 keV             |
| D-line IR Branch (BL10B)           | BM                    | 10~10000 cm⁻¹        |
| Ultra Hard X-ray Applications      | SCW                   | 30~150 keV           |
| Biosafety P2 Protein Crystallography (BL02U1) | U                 | 7~18 keV             |
| Hard X-ray Nanoprobe (BL13U)       | CPMU                  | 5~25 keV             |
| Shanghai Laser Electron Gamma Source (BL03ID) |                   | 0.4~20 MeV; 330~550 MeV |
| Laue Microdiffraction (BL135B)     | Super-B               | 7~30 keV             |
| 3D Nano Imaging (BL15B)            | BM                    | 5~14 keV             |
| Medium-energy Spectroscopy (BL16U1) | U                 | 2.1~16 keV           |
| Fast X-ray Imaging (BL16U2)        | CPMU                  | 8.7~30 keV           |
| Hard X-Ray Spectroscopy (BL11B)    | BM                    | 5~30 keV             |
| Membrane Protein Crystallography (BL20U1) | U               | 7~15 keV             |
| Surface Diffraction (BL20U2)       | CPMU                  | 4.8~28 keV           |
| X-ray Optics Test (BL09B)          | BM                    | 4~30 keV             |
situ analysis, (8) hazardous material study (bio-virus, radioactive materials etc). The layout of all the SSRF beamlines is shown in Fig. 6. Figure 7 shows the layout of the D-line (combination of ED-XAS beamline and IR beamline) design as example.

As a part of the phase-II project, the accelerator upgrade plan is user demand oriented. The major principle is to reconfigure and optimize the ring lattice, to provide more radiation resources and more operation modes. After intensive review, four systems have been proposed in phase-II: (1) Two double bend achromat (DBA) cells will be modified to superbend based lattice configuration. The magnetic field strength is 2.3 T for the bending magnet. It will increase the brightness of hard X-ray up to 40 keV and provide two 1.9 m straight sections for short IDs. (2) For the 12 m long straight section, a double waist design is adopted to get low beta-y for accommodating two IDs in it to avoid the beam lifetime decrease caused by small ID gap. The beta functions of the long straight section are shown as Fig. 8. After performance optimization, the storage ring emittance will keep unchanged. (3) In order to lengthen the bunch to reach high single bunch current, add the Landau damping to increase the threshold of beam instability, and decrease the impedance heat load to vacuum chamber, a superconducting third harmonic cavity will be added to the SSRF storage ring. The cavity will be operated in 1498.96 MHz at a temperature of 2 K and the voltage is 1.4~1.8 MV. Figure 9 shows the design of the Nb cavity. (4) A 650 W at 4.5 K liquid helium (LHe) cryogenic system will be constructed to supply the LHe to the cavity and to the superconducting IDs in phase-II project. This system will be combined with the existing LHe system in phase-I and be used as the back-up of the existing system. In addition, the beam diagnostic system, the control system and the interlock system will also be up-
graded to support the machine performance in phase-II project. New types of ID, including cryogenic permanent magnet undulator (CPMU), superconducting wiggler (SCW) and twin elliptically polarized undulator (EPU) will be developed to satisfy the requirements of new beamlines. The SSRF phase-II project is scheduled to complete in 2021.

3. Free Electron Laser Facility

Free electron laser facility is the fourth-generation light source that delivers extremely high intensity, tunable, ultrashort and coherent light pulses over a broad wavelength. The free electron laser facility and related technologies are the next focus in SSRF.

3.1 SDUV-FEL

SDUV-FEL is an integrated multi-purpose test platform for FEL principles and technologies. It is a collaboration project among Shanghai Institute of Applied Physics (SINAP), University of Science and Technology of China (USTC), Institute of High Energy Physics (IHEP) and Tsinghua University (THU). The SDUV-FEL project was started as a 262 nm self-amplified spontaneous emission (SASE)/88 nm HGHG FEL test setup in 2000. The linac is mainly composed of a low emittance photocathode injector, five 3 m long S-band accelerating structures and one bunch compressor. The basic undulator line hardware were installed in 2008, including six 1.5 m long planar undulators with period length of 25 mm and fixed gap of 10 mm. Figure 10 shows the basic layout of SDUV-FEL. With minor modification, it is well suited for a variety of seeded FEL schemes: EEHG, cascaded HGHG, coherent harmonic generation (CHG), etc.

The FEL experiments have been performed since 2009. Some major milestones that are achieved are as follows: (1) in the end of 2009, SASE experiments were carried out and the SASE light at the end of the 9 m long undulator were obtained from the optical transition radiation (OTR) target. (2) Seeded FEL experiments began in May 2010. After well transverse and longitudinal overlap between the electron beam and the laser beam, the HGHG signal was obtained soon and the HGHG saturation was achieved at the end of 2010. (3) The first lasing of a free electron laser with an EEHG scheme was observed at the 3\textsuperscript{rd} harmonic of the seed with a gain of close to 100,000 over spontaneous radiation in 2011\textsuperscript{b} and the 10\textsuperscript{th} harmonic, shown as Fig. 11, was obtained in 2013. Besides these, a series of achievements, including a widely-tunable HGHG, cascaded HGHG and the polarization control via crossed-planar undulators are demonstrated in the following years\textsuperscript{5,6}. Presently, the experiments are still ongoing in the SDUV-FEL facility. SDUV-FEL will be closed when SXFEL starts operation in 2017.

3.2 SXFEL

The main purpose of the SXFEL test facility is to promote the development of FEL science in China, which includes exploring the possibility of seeded X-ray FEL by using two stages of cascaded HGHG and conducting R&D on X-ray FEL related key technologies. The layout of SXFEL is schematically shown in Fig. 12. The conceptual design of SXFEL is based on an 840 MeV linac and two-stage cascaded HGHG scheme, which keep the potential to upgrade the energy to 1.6 GeV by adding more C-band RF accelerating structures for generating SASE FEL in the “water window” region. With the EEHG successfully demonstrated, a new cascaded EEHG-HGHG mode was proposed on SXFEL as an alternative, promising operation scheme.

The SXFEL test facility consists of a 130 MeV photocathode injector, an 840 MeV main linac, an undulator system and a diagnostic beamline. Table 4 lists the main parameters of SXFEL.

The accelerator is based on S-band and C-band linac technologies, and it is designed toward a compact linac with the high performance photo cathode RF gun and C-band high gradient RF accelerating structures. The main linac is comprised of three linac sections (L1, L2,
Table 4  Main parameters of SXFEL.

| Linac               |                                               |
|--------------------|------------------------------------------------|
| Electron energy    | 840 MeV                                       |
| Energy spread (rms)| ≤ 0.1%                                        |
| Normalized emittance (rms)| ≤ 1.5 mm・mrad                              |
| Bunch length (FWHM)| ≤ 1.0 ps                                      |
| Beam charge        | 0.5 nC                                        |
| Peak current at undulator | ≥ 500 A                                    |
| Pulse repetition rate | 10 Hz                                         |

| Undulator Stage-1  |                                               |
|--------------------|------------------------------------------------|
| Seed laser wavelength | 264 nm                                    |
| FEL output wavelength | 44 nm                                    |
| Modulator undulator period | 80 mm                                    |
| Modulator undulator K value | 5.81                                     |
| Radiator undulator period | 40 mm                                    |
| Radiator undulator K value | 2.22                                     |
| Radiator undulator section length | 3 m                                      |

| Undulator Stage-2  |                                               |
|--------------------|------------------------------------------------|
| FEL output wavelength | 8.8 nm                                    |
| Modulator undulator period | 40 mm                                    |
| Modulator undulator K value | 2.22                                     |
| Radiator undulator period | 23.5 mm                                   |
| Radiator undulator K value | 1.43                                      |
| Radiator undulator section length | 3 m                                      |
| Vacuum chamber dimension | 6.0 mm × 15.0 mm                          |

Fig. 12 (Color Online) Schematic layout of SXFEL.

L3) and a single stage bunch compressor at beam energy of approximately 200 MeV. L1 consists of S-band structures, while L2 and L3 are composed by C-band structures. There is a space between L2 and L3 reserved for the second bunch compressor and more C-band structures for the future energy upgrade. The beam orbit stability have been studied and optimized. The jitter amplitude can be controlled within 10% of the beam size in rms at the exit of the linac. The C-band RF accelerating structure is one of the most critical components of the SXFEL facility7). The C-band structure is optimized to work at a 4π/5 mode with a round cell shape for obtaining high shunt impedance and low short-range wakefields. The total length of the structure is 1.8 m with the designed accelerating gradient of 40 MV/m. Prototype has been developed successfully. High power tests show that the average accelerating gradient of the prototype structure reaches 47 MV/m, and the breakdown rate is about 0.01% on average in over 24 hours at 42.7 MV/m gradient. The beam tests have also been successfully performed at the SDUV-FEL facility. The prototype of the 1.8 m C-band accelerating structure is shown in Fig. 13.

The final FEL output from SXFEL will be at 8.8 nm with peak power greater than 100 MW. As illustrated in Fig. 12, the two-stage undulator line is comprised of a seed laser system, stage-1 modulators and radiators, stage-2 modulator and radiators, as well as a couple of chicanes. The first stage HGHG/EEHG is expected to generate 44 nm radiation from the 265 nm seed laser. This radiation will be shifted to a “fresh” part of the electron beam by a fresh bunch chicane and serves as the seed laser for the second stage. The 8.8 nm radiation will be generated by the fresh bunch in the radiators of the

Fig. 13 (Color Online) The prototype of the C-bend accelerating structure.
second stage. The total harmonic conversion number of the two stages is $6 \times 5$ (264 nm $\rightarrow$ 44 nm, 44 nm $\rightarrow$ 8.8 nm). A prototype of 3 m long planar undulator with period length of 23.5 mm and maximum adjustable taper of 0.5 mm was developed. The requirement of undulator phase error is less than 5 degrees rms and the beam orbit straightness in the undulator is less than 5 $\mu$m rms. Many measurements have been performed on this prototype and the results show that the performance satisfies SXFEL’s requirements. Figure 14 shows the prototype undulator in magnetic field measurement bench.

Construction of the SXFEL building started in December 2014 and it is expected to be ready by March 2016. Presently, the components of SXFEL are in the mass production stage. Installation of the facility is planned to start in May 2016 when the building and the infrastructure are available, and will be finished by the end of 2016. The FEL commissioning is scheduled in early 2017.

The proposal about upgrading the SXFEL test facility to a soft X-ray user facility is under consideration. This would be accomplished by having the radiation wavelength extended to cover the “water window” region by boosting the electron beam energy to 1.6 GeV with more C-band accelerating structures and by making the FEL output saturation with more undulators in the second stage. Two EPUs would be added to realize full control of soft X-ray FEL polarization. The associated beamlines and experimental stations are also planned for future user experiments.

4. Summary

SSRF is in user operation with high reliability and stability. More machine studies will be carried out to optimize the performance. More than 20 new beamlines, supported by the Follow-up Beamline Program and the SSRF Phase-II Project, are under construction and design. The free electron laser is the next focus of SSRF. A series of achievements on new FEL principle and technology have been obtained based on the SDUV-FEL source. The SXFEL test facility with the output of 8.8 nm radiation is under construction and will be commissioned at the beginning of 2017. By adding more accelerating structures and undulators, the machine will be upgraded to a user facility with saturated 3 nm output wavelength.

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