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Development of X-ray Free-Electron Lasers

(Invited Paper)

Zhentang Zhao (赵振堂), Dong Wang (王　东)

(*Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai* 201800, *China*)

E-mail: *zhaozt@sinap.ac.cn*

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Abstract This paper reviews the development of X-ray free-electron lasers (XFELs). With the unprecedented characteristics of flexible wavelength tunability, high brightness, ultrashort pulse duration, and fully transverse coherence, these accelerator-based X-ray light sources will open new fields in physics, chemistry, material, and life sciences. Based on the present status of XFELs in the worldwide context, the future directions are analyzed. A brief summary of the developments of free-electron lasers (FELs) in China is given.

Key words X-ray source; free-electron laser; self-amplified spontaneous emission; high-gain harmonic generation; echo-enabled harmonic generation

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1 Introduction

Light sources, as one of the most important tools to uncover the mystery of micro-cosmos, have never failed to revolutionize the understanding the matter and to create new science and technology. The discovery of X-ray and the inventions of synchrotron radiation and lasers, are among the greatest in the 20th century. The impacts of lasers and X-rays are proven by 10 Nobel Prizes based on lasers and 20 Noble Prizes on X-ray that have been awarded for related work[1~3].

Scientists have tried for a long time to obtain short wavelength lasers. With the conventional laser technology, it is found difficult to extend to the hard X-ray region. On the other hand, the free-electron laser (FEL), a device of high quality relativistic electron beam passing through undulator (specially designed periodic magnetic arrays), holds great promises as tunable, high power, and coherent sources for shot wavelength radiation. The successful commissioning and operation of the Linac Coherent Light Source (LCLS) hard X-ray FEL (XFEL) (0.15-nm wavelength) since April 2009, indicate the birth of X-ray laser and that the era of coherent X-ray science has arrived[4,5].

FEL has three different operation configurations: oscillator, seeded amplifier, and self-amplified spontaneous emission (SASE), and can be operated in the low- or high-gain regime. The high-gain FEL in the SASE configuration can generate multi gigawatt and femtosecond coherent X-ray pulses. With these unprecedented characteristics, FEL provides ideal probe for the ultrasmall and the ultrafast worlds.

This paper reviews the developments of the XFELs. In Section 2, historical remarks before the XFEL comes to reality are given, with the emphasis on the theoretical developments and proof-of-principle experimental demonstrations. The present status and the key technologies of XFELs and are reviewed in Section 3. Future directions to extend the capabilities and capacities of XFELs are examined in Section 4. FEL developments in China are summarized in Section 5, opportunities and possible challenges are briefly outlined. We conclude the paper with final remarks in Section 6.

2 Historical Remarks

The XFEL is ensured by several decades of continuous theoretical understandings, experimental demonstrations, and technological advances.

2.1 Theoretical Developments

The FEL was invented by Madey in the 1970s[6,7], however the story of FEL began much earlier. In the early 1950s, Motz invented the magnet configurations similar to wigglers[8,9]. During the 1960s, Phillips developed a device called Ubitron[10,11], which was considered as the low voltage FEL. In the 1970s, Madey realized that a laser-like amplifier could be possible by combining a high quality electron beam, a wiggler, and an input source or oscillator cavity mirrors; he also built up the theoretical framework with quantum mechanics theory.

Soon after the first operation of FEL, theoretical work grew very rapidly. Colson *et al*. first shows that a quantum mechanical description was not necessary, and that a classical description was enough[12]. The criteria for the validity of the classical approximation was also revisited and established by Schroeder *et al*.[13]. The existence of an exponential growth has been discovered by many researchers during this era of theoretical work[14,15], i.e. under the correct conditions, a collective instability could be created in the FEL. This instability is a form of self-organization of the combined system of electron beam, electromagnetic radiation, and the undulator magnet. This instability is called microbunching, and the FEL is said to be in the high-gain regime, since in the amplifier configuration, the energy can be magnified by a factor of $10^6 \sim 10^9$. It is soon thereafter found that the input source is not necessary and the FEL can amplify a portion of beam's spontaneous radiation, which is called SASE. The first full SASE FEL theory in the one-dimensional (1D) approximation was given in[16]. This theory described all of the FEL physics, including saturation power, undulator saturation length, etc., with an important FEL parameter ρ introduced. The extension to the three-dimensions was carried out, and the existence of gain guiding was shown[17].

SASE FEL opened up new possibilities. It permits operation in spectral regime where conventional lasers are not available since an input source is not needed. Furthermore, SASE FEL can be operated where good mirrors are unavailable and allows for operation in extremely high peak power. The use of SASE principle to produce infrared (IR) radiation was first proposed by Kondratenko and Saldin in the 1980s[18], and in 1985, Murphy and Pellegrini proposed to use SASE FEL to generate soft X-rays[19].

However, SASE starts from the shot noise of electron beam. It is shown that temporal SASE FEL consists of a series of the spikes of random intensity separated by the FEL coherence length[20]. This effect makes the total FEL intensity fluctuate from pulse to pulse.

Another line of development to reach short wavelength on FELs has been based on harmonics. Based on previous work by Bonifacio *et al*.[21~23], the high-gain harmonic generation (HGHG) principle was developed by Yu *et al*. as an alternative approach[24]. Starting with the energy modulation in the modulator by laser-beam interaction, a dispersive section converts the energy modulation into a density modulation with rich harmonic contents. The radiator, which is tuned at the harmonic of seed laser, can produce a strong coherent harmonic radiation. Taking advantages of the seed laser, the HGHG offers the great advantages of a reduced line width thus full longitudinal coherence and better shot-to-shot stability. By staging this modulator-dispersive section-radiator HGHG unit, FEL in the X-ray regime can be obtained, which is called cascaded HGHG[25].

Recently, the echo-enabled harmonic generation (EEHG) FEL scheme was proposed by Stupakov *et al*.[26,27]. It holds great promises to generate much higher harmonics (several tens to hundred) of seed laser with much higher bunching factor and much better harmonic selectivity.

2.2 Experimental Demonstrations

Madey *et al*. built the first low-gain FEL amplifier and oscillator at 12 μm in the 1970s[28,29]. These initial FELs were followed over the years by many others operating from microwave to IR, visible (VIS) and near ultraviolet (UV) spectral regions, with electrostatic accelerators, radio frequency (RF) linear accelerators (Linac), and storage rings.

In order to push to shorter wavelengths, where conventional lasers and good mirrors are not available, high gain FELs, SASE, and HGHG are adopted. To experimentally verify the theory, a number of demonstration experiments have been carried out, as shown in Table 1.

Initial experimental high gain results were obtained in the microwave and IR wavelength regions[30,31]. The first detailed measurement of SASE intensity growth and its fluctuation was made in the IR spectral region by a University of California, Los Angeles (UCLA) Kurchatov group, where the exponential growth over 4 gain length was demonstrated[32]. In the same year, gain of 3×10^5 was obtained by a UCLA-Kurchatov-Los Alamos National Lab (LANL) Stanford Synchroton Radiation Lightsource (SSRL) group[33], where the electron beam microbunching was also directly measured using coherent transition radiation[34]. Other laboratories, like LANL and Brookhaven National Laboratory

(BNL), also carried out SASE demonstration experiments in the VIS and IR spectral regions.

In 2000 and 2001, three SASE FELs, low-energy undulator test line (LEUTL) in Argonne National Laboratory (ANL)[35,36], VIS to IR SASE amplifier (VISA) in BNL[37], and TESLA test facility (TTF) in Deutsches Elektronen Synchrotron (DESY)[38~41], reached saturation with gain larger than 10^7. The shortest wavelength achieved is 92 nm at TTF.

The HGHG principle is first experimentally demonstrated in the accelerator test facility (ATF) at BNL[42]. The seed laser at the wavelength of 10.6 μm produced saturated amplified FEL output at its 2nd harmonic. The experimental demonstration in the UV was carried out in the Source Development Laboratory (SDL) at BNL. An 800-nm seed from a Ti∶sapphire laser has been used to produce saturated amplified radiation at the 266-nm third harmonic[43].

Table 1 Parameters of early demonstration experiments

Machine	UCLA	LANL	LEUTL	TTF	VISA	DUV FEL
Wavelength / μm	16	15.3	0.385	0.095	0.84	0.266
Energy /MeV	1.32	17	255	250	71	177
Energy spread / %	0.14	0.33	0.4	0.06	0.1	0.15
Emittance / μm	10	7	8.5	6	2.3	5
Peak current /A	83	250	630	1300	250	300
Undulator period /cm	1.5	2	3.3	2.73	1.8	3.9
Time of Lasing	1997	1998	2000	2001	2001	2002

DUV: deep UV

3 XFEL and Its Present Status

Due to the lack of high reflectivity mirrors and input seed source of short wavelength, up to now, SASE FEL is the only proven approach to X-ray spectral region.

According to the FEL scaling laws[44], the gain of SASE FEL depends strongly the radiation wavelength and on the electron beam brightness, i.e., as the radiation wavelength decreases the electron beam density must greatly increase. For the hard XFELs, like LCLS, the beam emittance should match the photon emittance, which could be expressed as $\lambda/4\pi$. With the technically feasible undulators and cost effective accelerators, an electron beam with a normalized emittance lower than 1 um-rad is primarily required. The peak current and relative energy spread are set to about a few kiloampere and 10^{-4} to get reasonable saturation length and laser power. With a normal compression ratio of about 10^2, the beam charge should be about 100 pC. These parameters set very stringent requirement on every subsystem.

The invention of the photo-cathode RF gun and the emittance compensation method[45] has great impact on the development of XFELs. At the same time, the experience on linear colliders has demonstrated that electron beam quality can be preserved during acceleration and bunch compression. Meanwhile the undulator technology developments have greatly improved during the process of the third generation synchrotron radiation light sources.

Thanks to the above mentioned technological advances, the XFEL becomes feasible. And an XFEL facility usually consists of a high brightness

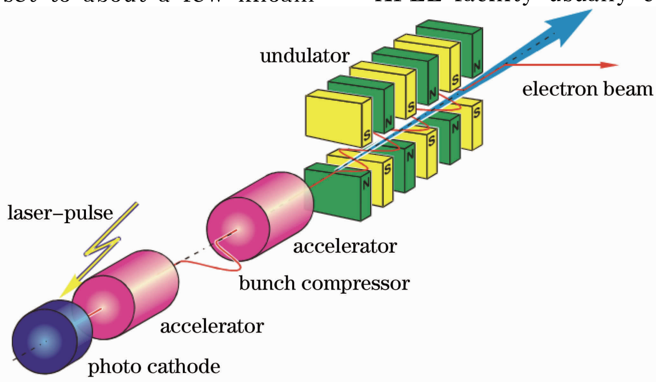

Fig.1 Typical layout of single pass XFEL

injector, a high performance linac including bunch compressors, an undulator, X-ray beamlines, and experimental stations, as shown in Fig. 1[46].

A geographical distribution of major XFELs around the world is briefly shown in Fig. 2.

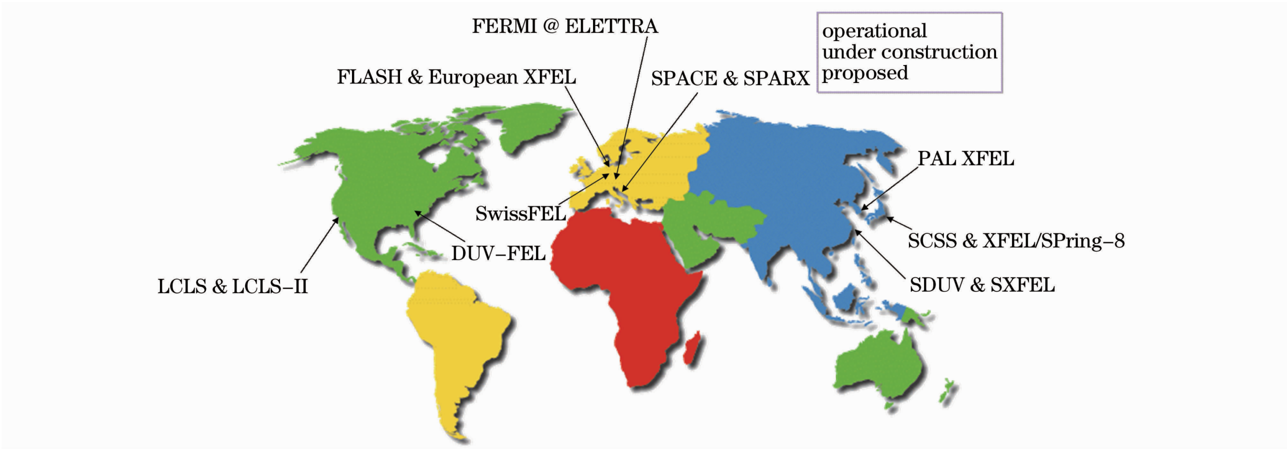

Fig. 2　XFELs worldwide

The Free Electron Laser Source at Hamburg (FLASH) at DESY is the world's first soft XFEL[47,48], whose shortest wavelength has reached recently down to 4.45 nm[49]. It is also the first soft X-ray user facility, demonstrating as a reliable machine and having generated significant science results[50]. The steady improvements are shown in Fig. 3[51].

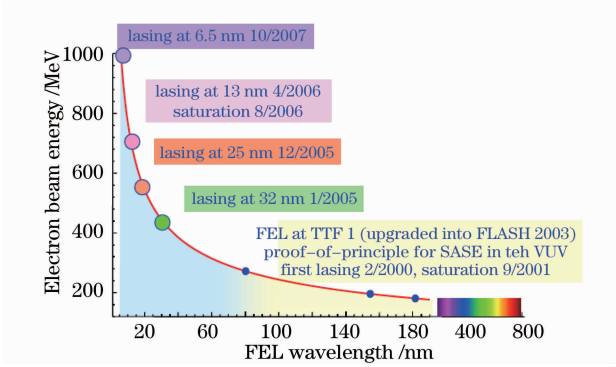

Fig. 3　FLASH FEL: from UV to soft X-ray

The successful commissioning and operation of the LCLS[4,5,52] has demonstrated that the hard XFEL has come of age. The machine layout and first lasing results are shown in Fig. 4 and Fig. 5[52].

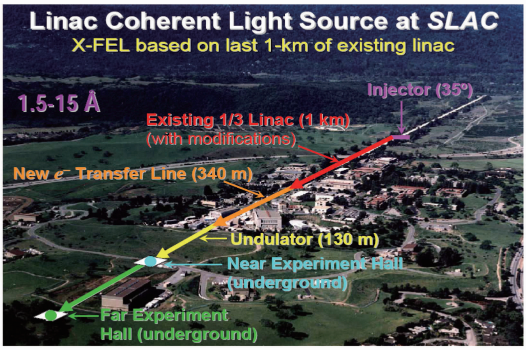

Fig. 4　The first hard XFEL: LCLS

The XFEL/SPring-8 project, funded in 2006, aiming at generating intense 0.1-nm coherent X-ray light, is now under construction[53]. The first lasing is expected in summer 2011. XFEL/SPring-8 is based on the compact concepts, which has been tested with the SPring-8 compact SASE source test accelerator (SCSS-TA)[54,55]. The SCSS-TA itself is also serving as a unique user facility in the extreme UV (EUV) spectral region. The European XFEL has been officially launched at the end of 2009, and is schedule to be open to user in 2014[56]. The Paul Sherrer Institute in Switzerland is also planning for a hard XFEL[57], SwissFEL by 2012. It is designed to cover the wavelength range of 0.1～7 nm in the first phase and with the possibility to extend to 0.08～30 nm in the future. As a national facility compared with the European XFEL, the compactness concept is also adopted. The technical developments are on the way: the first beam from the SwissFEL injector test facility has been accelerates

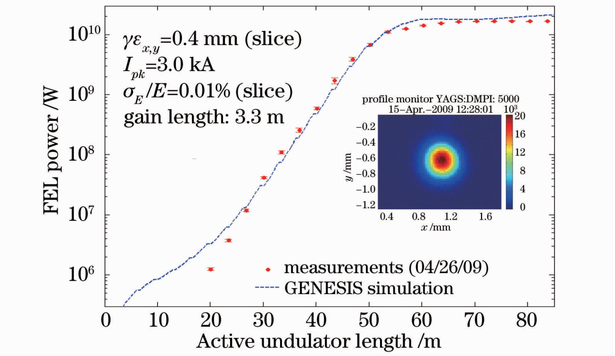

Fig. 5　Exponential growth and X-ray spot of LCLS XFEL

to 5 MeV. A 10-GeV accelerator based 0.1-nm FEL project is under design studies in the Pohang Accelerator Laboratory (PAL)[58]. A brief parameter comparison of these hard XFELs is given in Table 2.

Table 2 Parameters of worldwide hard XFEL projects

	LCLS	XFEL/SPring-8	European XFEL	SwissFEL	PAL XFEL	Shanghai XFEL
Wavelength /nm	0.15	0.1	0.1	0.1	0.1	0.1
Peak brighness* /10^{33}		1	5	0.3	0.76	1
Energy /GeV	13.6	8	17.5	5.8	10	6.4
Emittance / μm	0.43	0.8	<1.4	0.43	0.5	0.4
Charge /nC	0.25	0.3	1	10～200	0.2	0.2
Peak current /kA	3	3	5	2.7	>3	3
Pulse length [1σ, fs]	20～30	20～200	100	1～20	<50	～20
P_{sat}/GW		20	20	2 (effective)	12	10
L_{sat}/m	60			<50	<60	50
Rep rate /Hz	60	60	10 (3000/pulse)	100	60	60
Facility length /m	2000	700	3400	705	900	580
Start of operation	2009	2011	2014	2016	2018	2020

In the soft X-ray spectral regime, there is a growing interest in high performance FEL facilities. From FEL mechanism point of view, the soft X-ray machine may work at various modes (SASE or seeded) with very high quality radiations. Due to the rapidly increasing demand for ultra-bright and ultra-short soft X-ray worldwide, it tends to build dedicated user facilities other than to share the beam time of hard X-ray machines. A Brief parameter comparison of these soft XFELs is given in Table 3. Italy's FERMI@ELETTRA[59] is the first of its kind. It adopted the HGHG scheme to produce fully coherent light at up to 4nm wavelength. Encouraged with the great success of LCLS, the Critical Decision O (CDO) of LCLS-II project has been granted by the DOE[60], Lawrence Berkeley National Laboratory (LBNL) proposed a CW type high repetition rate FEL concepts[61], which is also followed by several other projects like New Light Source (NLS) in UK[62], WiFEL proposal under the collaboration between Wisconsin University in Madson and MIT[63].

Table 3 Parameters of worldwide soft XFEL projects

	FLASH	FERMI@ELETTRA	SPARX	LCLS II	SXFEL	MAX IV	LBNL NGLS
Wavelength /nm	6	5	0.6	1.5～6	3 (9)	1	1
Energy /GeV	1.0	1.2	2.4	3～7	1.3 (0.84)	3.4	2.5
Rep rate /(Hz/pulse)	5	50	100	120	10	200	1×10^5

4 Future Directions

With the of nearly 35 years of continuous advances in FEL physics, high quality beam generation and preservation during acceleration and compression and a number of experimental demonstrations in a broad wavelength ranges from IR to UV are recently carried out by FLASH in the soft X-ray and LCLS in the hard X-ray regions, FELs are now coming to the spotlight as the premier light sources, with the capabilities to enable unprecedented scientific researches, as summarized in previous Sections.

Nevertheless, the full potential of FELs still needs more explorations and further upgrade[64,65]. In this Section, these opportunities are briefly examined and the challenges are figured out.

4.1 Temporal Coherence Improvements

The intrinsic noise of the SASE radiation and thus poor temporal coherence and shot-to-shot fluctuation can be overcome with a number of approaches:

1) Self-seeding: the self-seeding approach[66] requires two undulators: the SASE light from the first undulator is spectrally filtered with an X-ray monochromator and amplified in the second undulator. In principle, self-seeding can be operated in any wavelength and has the advantage of maintaining the full tunability of the FEL source. The main difficulty lies in the transport and matching of the electron and laser beams, and the corporate social responsibility effect on beam quality degradation in the dispersive section between the two undulators.

To get around the technical difficulties, the two-bunch self-seeding scheme is proposed recently independently by Geloni *et al*. at DESY[67] and Ding *et al*. at Southwest Louisiana AIDS Council (SLAC)[68].

2) HGHG and EEHG: Seeded FELs, especially HGHG and recently proposed EEHG, offer several advantages with respect to SASE in terms of stability and coherence length. Several schemes aimed at the generation of radiation at short wavelength combining the injection of an external seed and exploiting the harmonic generation process have been proposed.

Cascaded HGHG with fresh bunch technique[25] and high-order harmonic generation (HHG) seeded HGHG schemes[69~72] are under active research and development (R&D) worldwide to extend to the X-ray spectral region. The noise issue will be the major difficulty to be answered theoretically and experimentally.

EEHG, a newly proposed FEL concept, holds great promise of generating coherent radiation with very high harmonics and very nice harmonic number selectivity. Currently the proof-of-principle experiments are undergoing at shear wave dispersion ultrasound vibrometry (SDUV) FEL in Shanghai Institute of Applied Physics[73] and Next Linear Collider Test Accelerator (NLCTA) at SLAC[74,75].

3) Single spike operation: It is predicted in 1D case, that if the length of electron beam is shorter than the 2π times coherence length, the SASE FEL is shaped in one single spike[20,76]. This operation mode has been experimentally demonstrated at LCLS in the X-ray spectral region[77]. The challenges lie in the stringent requirements on RF phase stability posed by the strong compression and the diagnostics difficulties in this extremely low charge.

4) Regenerative amplifier and XFEL oscillator: Regenerative amplifier FEL (RAFEL) has been demonstrated in the IR spectral region[78] and proposed for the vacuum UV FELs[79]. Huang *et al*. also proposed the RAFEL for hard X-rays[80], in which three Bragg crystals were used to form a ring resonator. It uses significantly shorter undulator but requires a uniform bunch train in space and energy. Later on, Kim *et al*.[81] proposed to generate next generation coherent X-ray sources of high average and peak brightness and narrow bandwidth with extremely low emittance electron beams of a multi-GeV electron recovery linac in combination with a low loss diamond crystal cavity.

4.2 Shorter Pulse

With the conventional laser technologies ultrashort extreme UV pulse down to less than 100 attosecond has be obtained[82]. These extremely short pulses can enable scientists to gain insight into and control of the motion of electrons on the atomic scales. This new field is called attoscience[83]. However, it appears difficult to generate intense radiation with wavelength down to 1 nm or shorter with this technique.

In order to extend the strength of attoscience, new light sources with higher performances, such as higher photon flux, higher photon energies, tunable wavelength, variable polarization, etc, are highly desirable. All these tasks can be addressed by the XFELs.

Recently years, there is a growing trend to generate attosecond X-ray pulse with FELs. These approaches[84~93] can be divided into several different categories, of which the main stream is through laser and beam manipulations. A brief comparison of these schemes is given in Table 4.

Table 4 Various short pulse schemes in FEL

	Emittance spoiler	Slicing wavelength	Slicing current	HC FEL seed	Energy chirp	Single spike
Pulse length /as	<1000	300	250	100	200	300
Photon per pulse	10^{10}	10^{8}	10^{9}	10^{6}	10^{10}	10^{8}
Contrast	Poor	Poor	Poor	Good	Good	Excellent
Rep rate	Linac	Laser	Laser	Laser	Laser	Linac
Synchronization	No	Yes	Yes	Yes	Yes	No
Stability	Poor	–	–	–	–	Poor
Diagnostics	OK	OK	OK	OK	OK	Difficult

4.3 Higher Repetition Rate

As shown in Table 2, most of the hard XFEL projects are based on the room temperature linacs, except the Eurepean XFEL. They are less expensive but can only operate at about 100-Hz repetition rate with high accelerating gradient. By considerably lowering the gradient about 10 kHz might be possible.

Increasing the repetition rate with the CW operation of a superconducting RF (SRF) linac is the most efficient way to reach higher average brightness and serve multi-users simultaneously[61]. However, at present, the cost of CW SRF linac is considerably higher than the room temperature one. Only when the cost can be minimized, the benefits offered by the SRF technology can be fully utilized.

4.4 Smaller and Cheaper

The total length of the LCLS project is around 2 km, and total cost is near 400 M $, not including the already existing accelerators. European XFEL is also huge and costly (3.4 km in length and around 1 billion Euros). It is a natural attempt to find the possibility of reducing the size of an XFEL machine to a reasonably modest scale without degrading the radiation quality. With the advances of low-emittance electron sources, short period in-vacuum undulator and high-gradient C-band or X-band accelerating structures, compact FELs have already become the main stream of hard XFEL design. A well known example is the SCSS-TA and later XFEL/SPring-8, which is expected to get 0.1-nm hard X-ray with the total facility length about 750 m. The SwissFEL, which is under design studies, is also aiming at generating hard XFEL with the facility length around 700 m. With the even higher gradient X-band accelerating structures, SLAC has proposed an XFEL program with total length around 500 m.

5 High-Gain FEL Developments in China

The FEL development in China started in the 1980s. During the 1980s and the 1990s, the Shanghai Institute of Optics and Fine Mechanics (SIOM), National Synchrotron Radiation Laboratory (NSRL) in Hefei, Institute of High Energy Physics (IHEP), Chinese Academy of Engineering Physics (CAEP), China Institute of Atomic Energy (CIAE), the Southwest Institute of Applied Electronics (SIAE), University of Electronic Science and Technology of China (UESTC), and Shanghai Institute of Applied Physics (SINAP) were working on FEL related projects, covering the spectral region from millimeter-wave to far-IR (FIR), IR to UV[94].

The Beijing FEL (BFEL) at IHEP is an IR FEL oscillator. It succeeded in lasing at 10.6 μm in May 1993[95,96] and was the first FEL lasing in Asia. BFEL became a user facility after saturation in 1994. The induction linac based FEL amplifier (SG-1 FEL) of CAEP achieved its first lasing at 34 GHz with power 10 MW in April 1993. First lasing of the CAEP FIR-FEL at the central wavelength of 115 μm was observed in March 2005[97], which indicated the birth of the first coherent terahertz (THz) source in China[98].

The high gain FEL program in China began in 1998, when Shanghai Deep-UV (SDUV-FEL) project[99] was proposed under the collaboration of SINAP, IHEP, and NSRL. The main idea is to build an HGHG FEL test facility and R&Ds the key technologies.

In 2009, a multi-purpose FEL test facility based on a photo cathode RF gun and a 150-MeV linac was established at SINAP. It also includes driv and seed laser system, a magnetic compressor, an HGHG modulator and dispersi section, a modulat section, and a 9-m radiator undulator. Figure 6 shows the SDUV-FEL accelerator and radiator undulator, The SDUV-FEL design parameters are shown in Table 5.

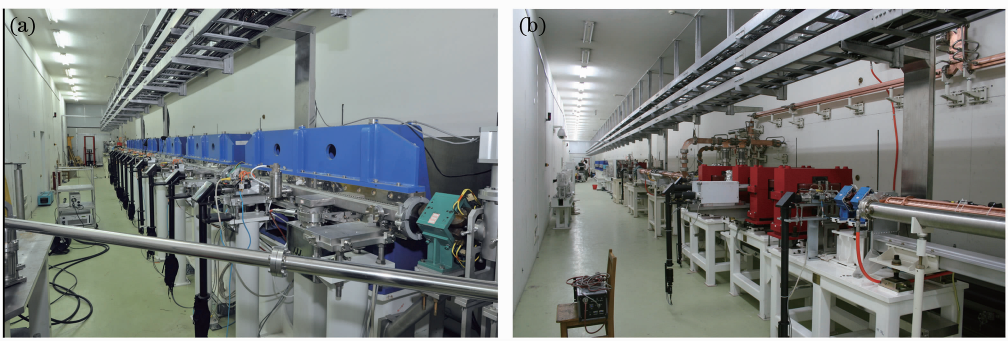

Fig.6 SDUV-FEL test facility. (a) FEL radiator, (b) accelerator

In 2009, for the first time in China, SASE experiments have been demonstrated. In 2010, seeded FEL experiments were successfully conducted with HGHG and EEHG configurations. For the first time EEHG is demonstrated experimentally and its characteristics are being systematically investigated. By now SDUV has become a world-class test-bed for the new FEL concepts and technologies.

Table 5 Main parameters of the SDUV-FEL

Parameter	Value
Beam energy /MeV	160
Normalized emittance /(mm · mrad)	5
Pulse length /ps	2～3
Seed laser wavelength /nm	1047
Seed laser energy / μJ	200
Modulator 1	6.5 cm × 10 (EMU)
DS 1 maximum R_{56} /mm	70
Modulator 2	5.0 cm × 10 (PMU)
DS 2 maximum R_{56} /mm	10
Radiator	6 × 2.5 cm × 60

The Shanghai soft XFEL test facility was proposed to verify the new FEL schemes and command the key technologies of short wavelength FEL. While it would pave the way to the hard XFEL facility, the Shanghai soft XFEL has the great potential to become the first soft XFEL user facility in China.

The Shanghai soft XFEL accelerator is composed of a photo cathode RF gun, an 840-MeV linac, 2 bunch compressors, as shown in Fig. 7. With the self-limited etch depth (SLED) technique, the electron beam energy can be upgraded to 1.3 GeV.

The Shanghai soft XFEL can be operated in SASE and cascaded HGHG modes. With the 1.3-GeV electron beam energy and SASE operation mode, the intense coherent FEL radiation at water window can be generated. With the 0.84-GeV electron beam and the fresh bunch based cascaded HGHG principle, as shown in Fig. 8, a transform limited FEL radiation at 9 nm can be produced. The main parameters are shown in Table 2.

The design study of the Shanghai hard XFEL project (Shanghai XFEL)[100] has been launched, aiming at generating high power, coherent hard X-ray source at 0.1 nm following the well-recognized compact concept.

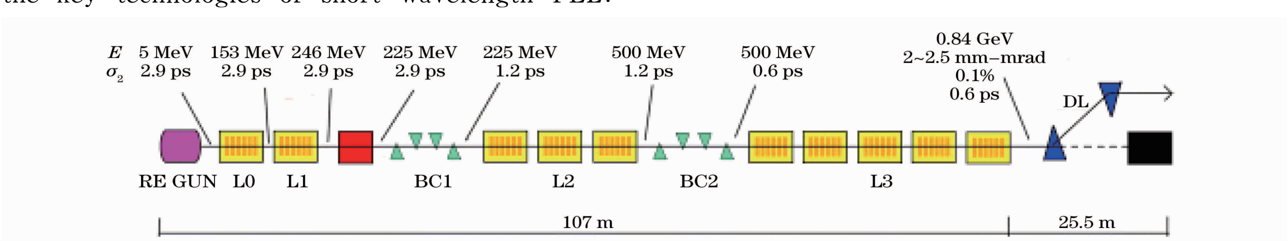

Fig. 7 Layout of Shanghai soft XFEL accelerator

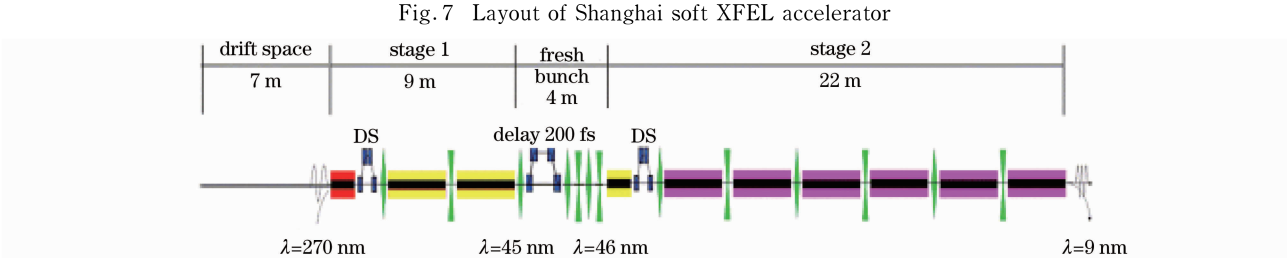

Fig. 8 HGHG scheme of Shanghai soft XFEL

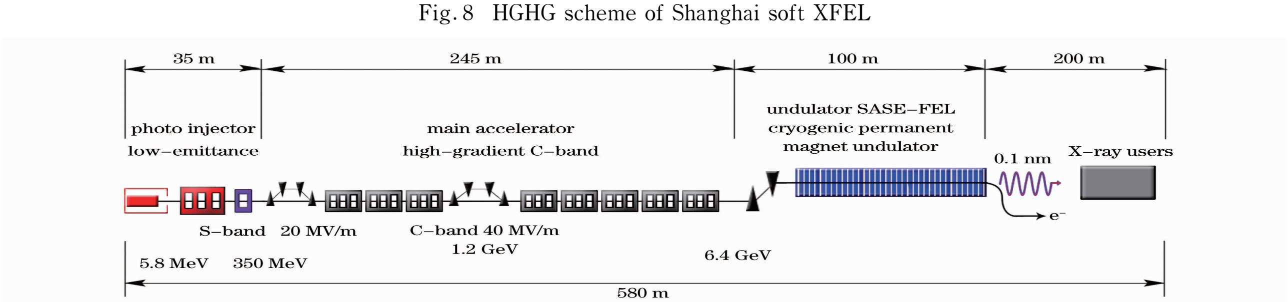

Fig. 9 Layout of Shanghai hard XFEL

The key elements of the Shanghai hard XFEL design are high brightness photo cathode injector, C-band based high gradient accelerators, 2 stages of high performance bunch compressors and the high precision cryogenic in-vacuum undulators. The schematic layout is shown in Fig. 9. The total length of the Shanghai hard XFEL project is 580 m. The main parameters are shown in Table 3.

6 Conclusions

The XFEL integrated particle accelerator and laser physics and technology on a state of the art level, in this sense both FEL and lasers share the same theoretical basis and can benefits from each other.

With its performance higher than expected, LCLS opens the era of hard XFEL, it will be closely followed by SCSS and European XFEL in 2011 and 2014 respectively, and by SwissFEL and PAL-XFEL before 2020. In the meantime many soft XFEL facilities, FLASH, FERMI, LCLS-II, MAX-IV-FEL, and NGLS, are under rapid development in various stages. Ultra-short pulse down to a few femtoseconds to even attoseconds long, seeding and many other innovative schemes may possibly extend further high capabilities for scientists to perform frontier research in brand new fields.

The development of Chinese XFEL is in a critical phase. Based on accumulated technical experience at SDUV-FEL, Chinese XFEL is being developed by exploring the innovative schemes and new technologies. The construction of Shanghai soft XFEL will extend a possibility of choosing scheme and lay a solid technical foundation for the development of Chinese hard XFEL facility.

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