PROGRESS IN THE SDUV-FEL AND DEVELOPMENT OF X-RAY FELS IN SHANGHAI

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Abstract

As the solid development steps towards constructing a hard X-Ray FEL in China, the SDUV-FEL was integrated at SINAP to test the FEL key technologies, and the Shanghai Soft X-ray FEL test facility (SXFEL) was proposed and will be constructed to generate 9nm FEL radiation with two-stage cascaded HGHG scheme. Recently a design study on a compact hard X-ray FEL was initiated aiming at constructing this XFEL facility within the SSRF campus. In this paper, the progress in SDUV-FEL, including the recent results of SASE, HGHG and EEHG experiments, is presented and the preliminary design of the SXFEL test facility and the design consideration of a compact X-Ray FEL based on a C-band linac are described.

INTRODUCTION

Shanghai Deep Ultraviolet Free Electron Laser (SDUV-FEL) is an integrated multi-purpose test bed for FEL principles. A number of FEL experiments have been carried out soon after the linac performance optimization, among which the self-amplified spontaneous emission (SASE) in the ultraviolet spectral region was first observed in later 2009, seeded FEL began in early 2010 and first echo signal from echo-enabled harmonic generation (EEHG) observed in May 2010. High harmonic demonstration of EEHG is under way.

Design studies of the Shanghai Soft X-ray FEL test facility (SXFEL), aiming at generating intense SASE radiation in the water window and fully coherent radiation with wavelength of 9nm with cascaded HGHG scheme, has finished. The SXFEL project is now in the progress of approval. A design study of the compact hard X-ray FEL project, well suited for being located in the Shanghai Synchrotron Radiation Facility (SSRF) campus, has launched.

SDUV-FEL

SDUV-FEL is a collaborating effort between Shanghai Institute of Applied Physics, National Synchrotron Radiation Laboratory in Hefei, and Tsinghua University and Institute of High Energy Physics in Beijing, jointly funded by Chinese Academy of Sciences, Ministry of Science and Technology of China, and Chinese Natural Science Foundation. SDUV-FEL was started as a high gain harmonic generation (HGHG) test facility in 2002 [1, 2].

As shown in Figure 1, the SDUV-FEL linac is composed of a low emittance photocathode injector, five 3-meter long S-band main linac sections, one bunch compressor (BC). The main parameters of the linac performance are listed in Table 1. The real view inside tunnel is shown in Figure 2.

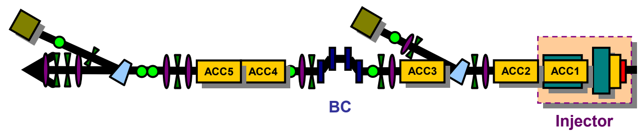

Figure 1: SDUV-FEL linac layout.

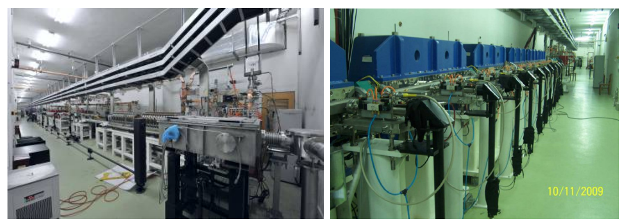

Figure 2: Inside the SDUV-FEL tunnel (left: linac part; right: undulator part).

Table 1: Main parameters of SDUV-FEL linac

Beam energy	100-150MeV
Energy spread (Projected)	<0.03%
Normalized emittance	4~5mm.mrad
Bunch charge	100~300pC
Bunch length (rms)	2~8ps
Seed laser wavelength	1047nm
Seed laser pulse length (FWHM)	8ps
Seed laser power	0~15MW

In late 2008, the proof-of-principle demonstration experiment of EEHG principle at SDUV-FEL was proposed [3, 4]. The hardware additions and modification were soon contracted and fabricated. In early 2010, the EEHG is ready to begin experiments, as shown in Figure 3.

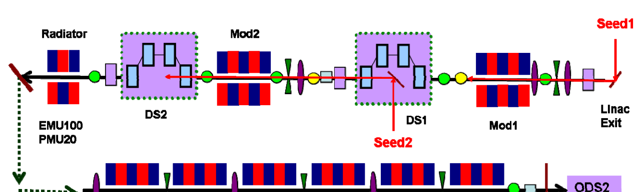

Figure 3: Layout of the FEL experiment area (seed: seed laser; Mod1: EMU type modulator; Mod2: PMU type modulator with movable gap; DS1 and DS2: dispersive sections; Radiator: small radiators with only a few periods; ODS: optical diagnostic systems).

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FEL EXPERIMENTS AT SDUV-FEL

Milestones

Soon after the photo-injector and linac commissioning and performance optimization (as shown in Table 1), FEL experiments began in September 2009. Some major milestones are achieved as follows:

- 2009.04-08: Linac commissioning/optimization
- 2009.09-12: SASE experiments
- 2010.01-03: Seeded FEL installations
- 2010.05: Seeded FEL experiments started
- 2010.05.17: First HGHG signal
- 2010.05.23: First echo signal, double peaks [5]
- 2010.07-08: Installation for high harmonic EEHG

SASE Results

In the end of 2009 since September, SASE experiments were carried out. The transverse profiles of the electron beam and SASE light from the OTR target at the end of the 9-meter-long radiator are shown in Figure 4. Gain of SASE amplification large than 10^4 is observed. The exponential growth of SASE intensity along the undulator is shown in Figure 5.

For more detailed diagnostics setups and SASE results, including the spectrum and simulation interpretations, refer our two companion papers [6, 7].

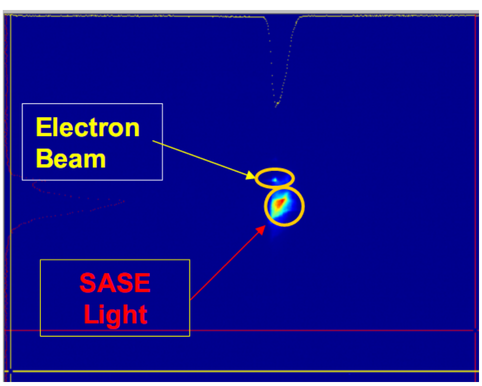

Figure 4: Transverse profiles of electron beam and SASE light measured by OTR.

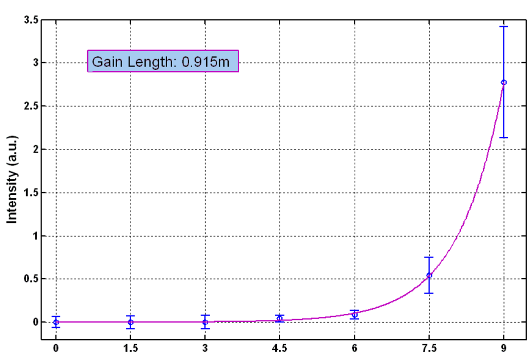

Figure 5: Exponential growth of SASE radiation intensity along undulator length (blue circles with error bars are experimental data and purple curve is the numerical fitting).

HGHG

Seeded FEL experiments began in May 2009. The first step is the overlap of the electron beam and laser beam in the modulator to achieve sufficient interaction.

The diagnostics setup of transverse and longitudinal overlap of laser-electron beam is shown in Figure 6. The transverse overlap is achieved with alignment of electron beam and laser beam with OTR screens at both ends of modulator undulator.

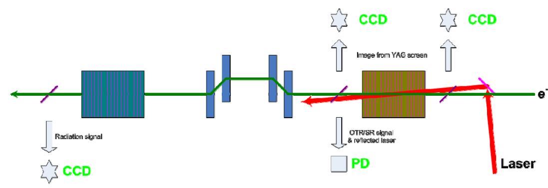

Figure 6: Diagnostics setup for electron-laser beam overlap.

In order to longitudinally overlap the electron beam with laser beam, the spontaneous undulator radiation from the electron beam passing through the modulator and the laser beam are sent to fast photodiode (PD, as shown in Figure 6). By looking at the signals on the oscilloscope triggered by BPM signal, the two signals can be synchronized. When laser path is adjusted long enough, two peaks will be detected by one PD, one for laser, the other for electron beam OTR/SR signal. Then we can adjust laser path and power to make two signals exactly at the same position. For a fast PD (2GHz) and high resolution oscilloscope (6GHz Bandwidth), the precision could be less than 30ps.

By fine tuning the delay line, the coherent undulator radiation (CUR) from the modulator2, which is tuned at the 2nd harmonic of seed laser, can be detected, as shown in Figure 7. In this way, the accurate synchronization less than 1ps can be achieved. The radiation intensity vs. laser delay with is 15ps (FWHM), which agrees with the laser measurement result. Auto-correlation measurement result of the drive laser is 12.3ps FWHM. It serves an indirect measurement of the electron bunch length.

For more details, refer the companion paper [8].

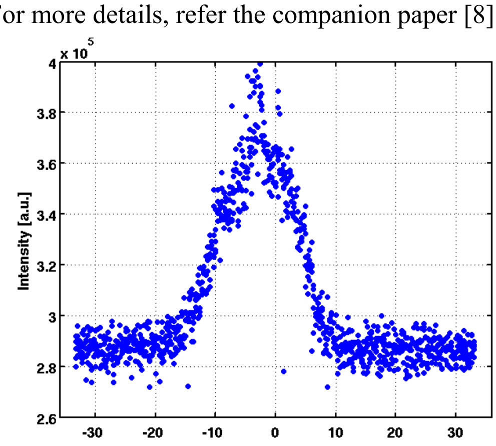

Figure 7: CUR intensity vs. laser delay.

After the well transverse and longitudinal overlap, we went on the HGHG studies with the same setup as Figure

6. Again the modulator 2 is tuned at the 2nd harmonic of the seed laser. By scanning the R_{56} of the dispersive section, it is the first time, to our knowledge, to observe directly the Bessel function like curve of HGHG bunching factor vs. R_{56}, as shown in Figure 8.

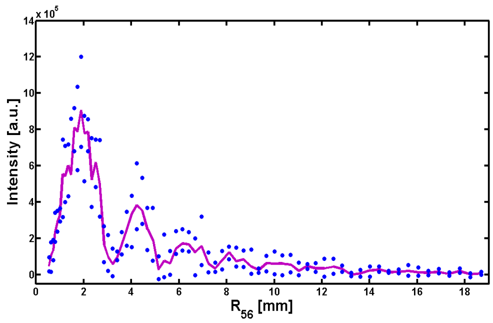

Figure 8: Bessel function like curve of HGHG bunching factor vs. R_{56}.

EEHG

Figure 9 and 10 show the tuning of the first and second stage of HGHG configuration.

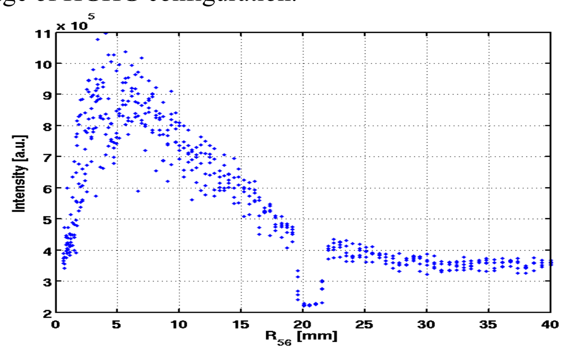

Figure 9: Intensity vs. R_{56} of the first stage of HGHG.

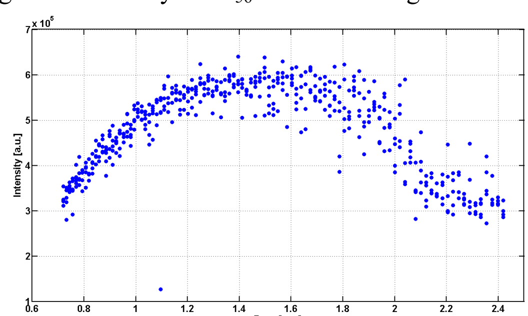

Figure 10: Intensity vs. R_{56} of the second stage of HGHG.

First echo signal is observed soon after the two stage of the laser-beam interaction are well tuned, as shown in Figure 11, with double peaks observed from the direct EEHG induced microbunching, where the intensity is proportional to the square of bunching factor. It agrees well with the theoretical prediction.

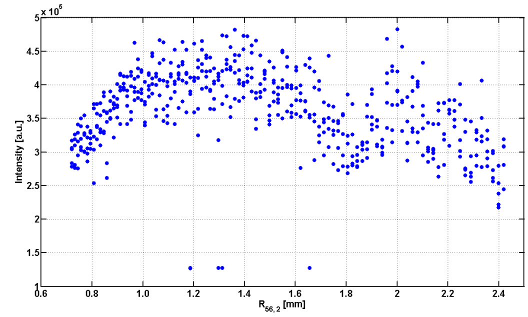

Figure 11: Intensity vs. $R_{56\text{-}2}$ of EEHG configuration.

In the EEHG setup, we set the $R_{56\text{-}1}$ to 13.6mm, where no coherent enhancement is seen, as shown in Figure 9. The spectrum of the EEHG spectrum from short radiator is shown in Figure 12. The 2nd harmonic is clearly observed.

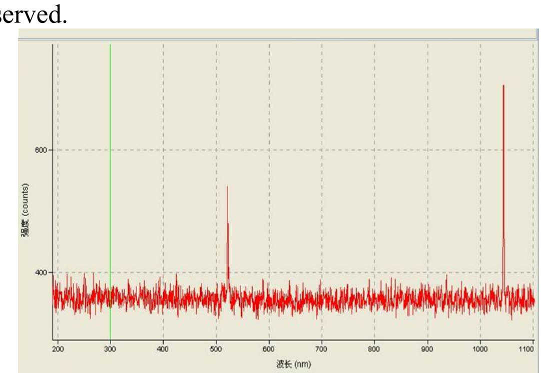

Figure 12: 2nd harmonic of the seed laser.

Future Plans

To further explore the advantages of EEHG scheme, experimental demonstration of high harmonic up to 7th~15th is underway. The VUV spectrometer has been tested and installed inside the tunnel, as shown in Figure 13. The comparison studies of high harmonic characterization are reported in a companion paper [9].

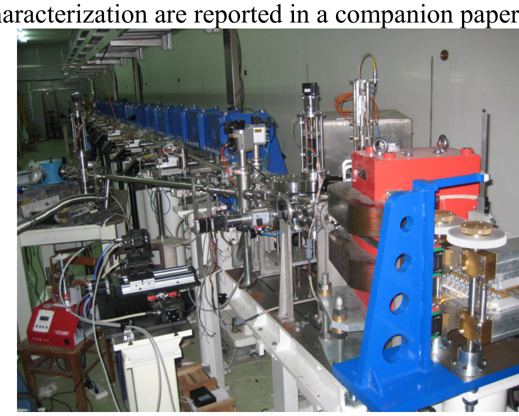

Figure 13: Experimental setup for the high harmonics EEHG demonstration.

PLANS FOR X-RAY FELS IN SHANGHAI

SINAP is planning for the future XFELs. SXFEL and compact hard X-ray FEL will be located in the SSRF campus as shown in Figure 14.

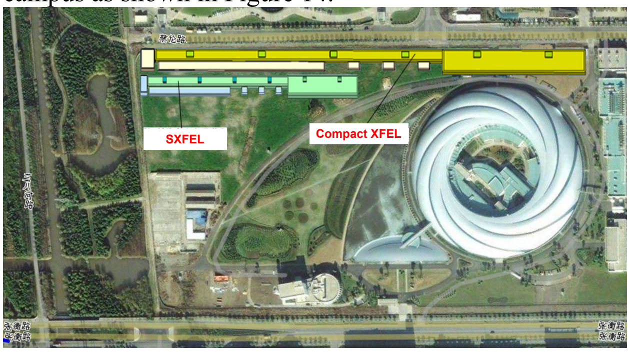

Figure 14: Layout of the Shanghai light source complex.

Soft X-ray FEL

The SXFEL was proposed by IHEP in 2006 to verify the cascaded HGHG scheme and command of key technologies for X-Ray FEL, and in 2007 it was decided to site this SXFEL in the SSRF campus. As shown in Figure 15, the proposed SXFEL aims at generating 9 nm FEL radiation based on a 270 nm seed laser using the two-stage cascaded HGHG scheme. In the first stage, the 6th harmonic of the seed laser is generated and will serve as the seed laser of the second stage. The nominal electron beam energy the linac is 840MeV, local energy spread is 0.1~0.15%, peak current is about 600A and the normalized emittance is 2mm-mrad. The main parameters of the SXFEL are summarized in Table 2. The SXFEL will be upgraded to a user facility. In order to extend to the "water window" region, the SXFEL is also designed with the capability to generate 4 nm SASE FEL with 1.3GeV electron beam based on the SLAC Energy Doubler (SLED) technique.

Table 2: Optimized parameters of SXFEL

Electron beam parameters:
Energy: 840 MeV, Peak Current: 600 A,
Energy spread: 0.1-0.15%,
Normalized emittance: 2mm.mrad,
Bunch length (rms): 1.6 ps

		HGHG			
		1st stage		2nd stage	
Seed laser	Power/MW	200		240	
	λ_s /nm	270		45	
Undulator		M*	R*	M	R
	λ_u /cm	5.8	3.8	3.8	2.6
	a_u	4.91	2.32	2.32	0.932
	L_u /m	1	6	1	14
Disperser	B_c /T	0.7		0.33	
	L_d /m	0.08		0.08	
FEL	λ /nm	45		9	
	P_{sat} /MW	710		420	

*M=Modulator, R=Radiator

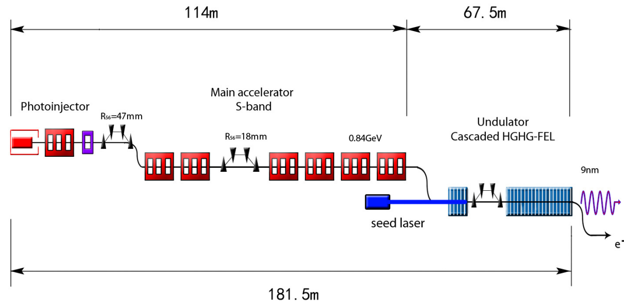

Figure 15: Layout of the SXFEL facility.

Hard X-ray FEL

A compact hard X-ray FEL facility is proposed based on self-amplified spontaneous emission (SASE) scheme to fit on the available space in the SSRF campus. It aims at generating 0.1nm coherent intense hard X-ray laser with the total facility length less than 600m [10]. The compact X-ray FEL facility consists of a low emittance S-band photo cathode injector, a high gradient C-band linear accelerator with two stages of magnetic bunch compressors and short period cryogenic permanent magnet undulator. Simulation results show that 0.1nm coherent hard X-ray FEL with peak power up to 10 GW can be obtained from a 70-m-long undulator when the slice emittance of the electron beam is lower than 0.4mm-mrad. The energy of the electron beam is 6.4GeV which is obtained in accelerator length of 230m with the 40MV/m C-band RF system.

C-band RF system R&Ds for the compact XFEL has been started since late 2009, aiming at building accelerating structures with constant gradient higher than 40MV/m. The preliminary results of an RF cold test of model structure have obtained [11].

CONCLUSIONS

A series of FEL experiments has been carried out in the SDUV-FEL test facility. First lasing of SASE at the wavelength of 385nm was achieved late 2009, with gain larger than 10^4. Seeded FEL experiments began in May 2010. For the first time the Bessel-function-like HGHG bunching factor vs. R_{56} was observed. Furthermore, first EEHG signal is observed in late this May, with the typical double peaks in the direct EEHG induced microbunching measurement evidently seen. As a next step, the high harmonic EEHG demonstration is underway.

Design studies on the SXFEL test facility and the compact hard X-ray FEL are being conducted. R&Ds of the key technologies for XFELs are underway in the meantime. The preliminary results of an RF cold test of the C-band model structure have obtained.

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