SHANGHAI SOFT X-RAY FREE ELECTRON LASER TEST FACILITY

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Abstract

As a critical development step towards constructing a hard X-ray FEL in China, a soft X-ray FEL test facility (SXFEL) was proposed and will be constructed at the SSRF campus by a joint team of Shanghai Institute of Applied Physics and Tsinghua University. This test facility, based on an 840MeV electron linac, aims at generating 8.8nm FEL radiation with two-stage cascaded HGHG scheme. The project proposal was approved in February 2011 by central government, the construction is expected to start in early 2012. This paper describes the preliminary design of this soft X-ray test facility.

INTRODUCTION

The soft X-ray test facility based on the BEPC linac was proposed by C.N. Yang, L.H. Yu and S.Y. Chen in 2005. The main purpose of this test facility is to promote the FEL science development in China, including exploring the seeded X-ray FEL possibility by using two stages of cascading HGHG scheme [1-3] and making R&Ds on X-ray FEL related key technologies. After a series of discussions, considerations and comparisons organized by Chinese Academy of Sciences, it was decided to site this test facility in the campus of Shanghai Synchrotron Radiation Facility (SSRF). In the meantime, a conceptual design of this FEL test facility based on a new 840MeV linac and two-stage cascaded HGHG scheme was completed [4], which kept the potential to upgrade the energy to 1.3GeV by using SLED for generating SASE FEL at water window. In this way, it can be upgraded to a soft X-ray user facility in the near future.

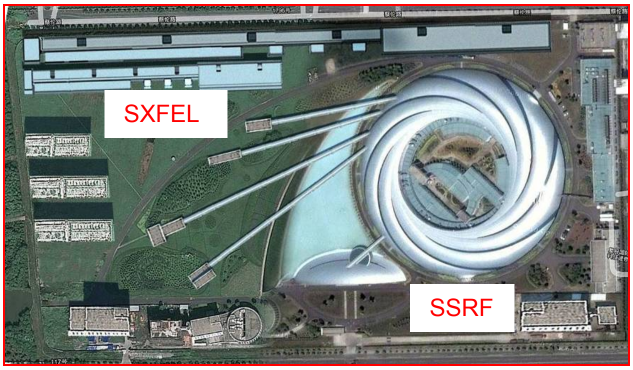

Figure 1: Layout of the SXFEL in the SSRF Campus

The test facility proposal report based on the conceptual design mentioned above was reviewed by a government entrusted organization, China International Engineering Consulting Corporation, and the SXFEL project proposal was approved by the State Reform and Development Commission in February 2011. It is followed by the SXFEL project feasibility study phase and the technical design phase before the formal start of the project construction, which is expected in early of 2012.

The SXFEL test facility will be designed and constructed under a close collaboration between Shanghai Institute of Applied Physics (SINAP) and Tsinghua University in Beijing. Tsinghua University is in charge of delivering the 130MeV photo cathode injector, and SINAP is responsible for the rest parts of facility development, including the facility integration, utility and building construction. The facility construction is expected to be completed before 2016, when a hard X-ray FEL user facility is expected to be launched.

THE SXFEL TEST FACILITY

The SXFEL test facility consists of a 130MeV photo cathode injector, a main linac accelerating the beam to an energy of 840MeV, an undulator section with two stages of HGHG scheme and a diagnostic beamline. Table 1 lists the main parameters of the SXFEL. The test facility converts the seeding laser at wave length of 265nm to the FEL at 44nm with the first stage HGHG and it is followed by the second HGHG stage to produce the 8.8nm soft X-ray FEL radiation.

Table 1: Main Parameters of the SXFEL

Electron parameters	Beam energy 840MeV, peak current 600A, energy spread 0.1-0.15% Normalized emittance RMS 2mm-mrad, pulse length FWHM 1ps				
		1st stage		2nd stage	
Seed laser	Wavelength（nm）	265		44	
	Peak power（MW）	200		100	
	Pulse duration（fs）	~100		~100	
		Modulator	Radiator	Modulator	Radiator
Undulator parameters	Period length（cm）	5.8	3.8	3.8	2.5
	Magnetic gap（mm）	12	10.7	10.7	10.8
	Beta function（m）	4		4	
	aw0	4.87	2.30	2.30	0.95
	Undulator length（m）	1.0	6.0	1.0	18
Dispersive section	R_{56}（μm）	24		7	
FEL parameter	Wavelength（nm）	265	44	44	8.8
	Output peak power（MW）		≥100		≥100
	Pulse duration（fs）	~100		~100	
	Peak brilliance**			$\geq 1\times10^{29}$	

The SXFEL accelerator is based on S-band and C-band linac technologies, and it is designed towards a compact linac with the high performance photo cathode RF gun and high gradient accelerating structures. Figure 2 shows the layout of the SXFEL linac.

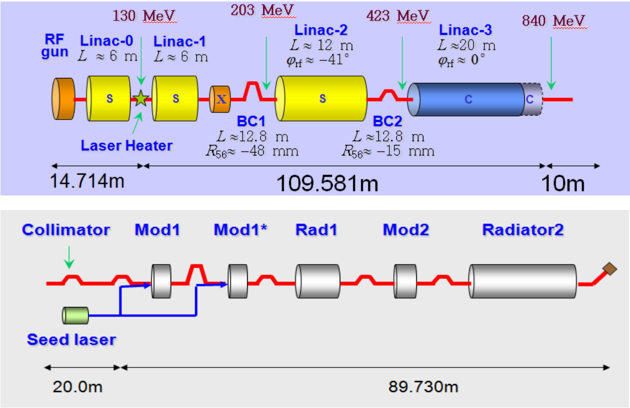

Figure 2: Layout of the SXFEL accelerator and undulator

As shown in Figure 3, SXFEL adopts the LCLS-type S-band photo-injector, which contains a photo-cathode RF gun, two accelerating structures and a laser heater. The pulse stacking technique is used to generate a flat top drive laser beam, which simplifies the temporary shape system. Two diagnostics stations are downstream the electron gun and the laser heater. A transverse deflecting cavity and a 2-cell FODO lattice are used to reconstruct the 6D phase space of the electron bunch.

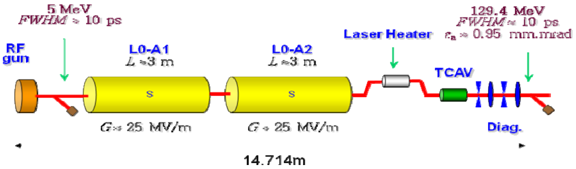

Figure 3: Layout of the SXFEL injector

By optimizing the laser spot size, the strength of the solenoids and the amplitude and phase of the gun and accelerating structures, the inject beam parameters are finalized, as shown in table 2. By reducing the bunch charge to 0.5nC, the normalized slice emittance reaches to sub-micron level. The operation parameter errors of photo-cathode gun, drive laser, solenoids and accelerating structures are examined, and all the beam parameters are controlled within the specifications.

Table 2: Main beam parameters of the SXFEL injector

Parameters	Value
Energy	130 MeV
Projected emittance (RMS)	0.95 mm.mrad
Central Slice emittance (RMS)	0.65 mm.mrad
Bunch length (FWHM)	9 ps
Projected energy spread (RMS)	0.14%

The main linac comprises 3 linac sections (L1 to L3), 2 bunch compressors BC1 at 204MeV and BC2 at 420MeV, the layout of the main linac is shown in Figure 4. In the initial design, the L3 also uses the S-band accelerating structure. But the jitter analysis shows a better result when using the C-band accelerating structure. Because C-band accelerating structure with a stronger longitudinal wake compensates the energy spread at a phase close to the crest, it reduces the jitter of the beam energy. Meanwhile, it is found that the beam parameters is not obviously depredated = due to the stronger transverse wake of the C-band structure from the simulation results. Another reason to adopt the C-band accelerating structure is its compactness for the future hard X-ray FEL user facility, which can be sited in the SSRF campus. There are two beam diagnostics sections downstream the BC1 and L3 respectively, combining with the transverse deflecting cavity and 2-cell FODO section to get the 6D phase space information after the bunch compression. BPMs and screens along the linac will be used to monitor the beam trajectory, beam transport and matching. Some non-destructive bunch length and bunch energy detectors will be installed at the BC1 and BC2 to feedback on the beam energy, peak current and arrival time jitter with the LLRF system.

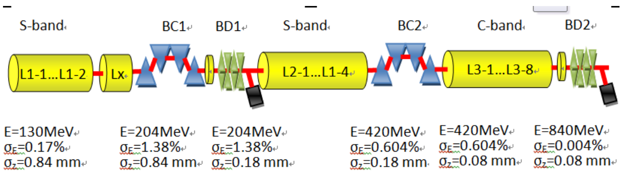

Figure 4: Layout of the SXFEL main linac

From the experience of LCLS, the emittance and stabilities of the electron beam benefit from the low charge operation. But for the cascaded HGHG operation, the fresh bunch must be implemented along the stages. The typical pulse length of the seed laser is about 100fs (FWHM). Considering the slippage of the two stages, and the 2σ jitter between the electron beam and the laser beam, the electron bunch length should not be less than 800fs (FWHM) with a jitter of 100fs between the electron beam and the laser beam. The requirement on peak current of this cascaded HGHG scheme is 600A, which turns out to require an electron bunch charge about 0.5nC. Comparing to 1nC charge operation in the initial design, this will relax the requirement on the laser system and the difficulty on the emittance preservation.

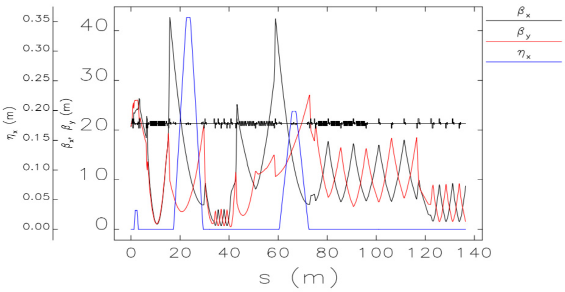

Figure 5: Twiss function along the main linac

The triplets and FODO lattice are employed for the accelerating sections, while two doublets are used for the chicane to minimize CSR effect by minimizing the horizontal beta function at the last bending magnet. The beam envelope matching between bunch compressors and accelerating sections is done by two doublets. At L3, space for four C-band sections is reserved for future energy upgrade. Two 2-cell FODO section with a phase advance of 2π are used for beam diagnostics. The twiss function along the main linac is shown in figure 5.

Simulation studies on the micro-bunching instability induced by CSR and LSC effects show that the energy modulation and current density modulation are quiet high. The laser heater is planned to be used to suppress this instability. The requirements on the laser power and heating effect are still under optimization study. Table 3 shows the final beam parameters at the exit of the SXFEL main linac.

Table 3: The main beam parameters of the SXFEL linac

Parameters	Value
Energy	840 MeV
Projected emittance x/y (RMS)	0.98/0.97 mm.mrad
Central slice emittance x/y (RMS)	0.64/0.64 mm.mrad
Bunch length (RMS)	0.26 ps
Projected energy spread (RMS)	0.06%

Longitudinal stability caused by the amplitude and phase error of the accelerating field and the magnetic field error of the bending magnets in chicanes has been studied and optimized. Requirements on the synchronization, the RF system and power supplies are defined. The study on the transverse beam stability due to the misalignment and magnet field error shows that the beam trajectory could be well controlled to a few tens of microns by global correction algorithm.

THE SXFEL PERFORMANCE

The 1st stage of the cascaded HGHG is expected to generate 44nm radiation from the 265nm seed laser. The length of the seed laser pulse is about 100fs (rms) which is much shorter than the electron bunch length (1ps) after compression. So only part of the electron beam is modulated in the modulator and generates coherent radiation in the radiator of the 1st stage. This radiation will be shifted to a fresh part in the electron by a fresh bunch chicane and serves as the seed laser for the 2nd stage. A short undulator with the type of the radiator of the 1st stage is employed as the modulator and a small chicane is used as the dispersion section in the 2nd stage. Finally, the 8.8nm radiation will be generated by the fresh bunch in the radiator of the 2nd stage. The total harmonic number of the two stages of HGHG is 6×5.

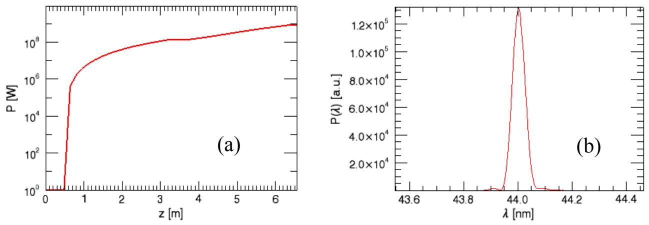

Figure 6: FEL performance of the 1st stage HGHG. (a) radiation power as a function of the radiator length; (b) spectrum of the radiation.

With the parameters shown in Table 1, the SXFEL performance was simulated with the time-dependent mode of GENESIS [5]. A 265nm laser pulse with longitudinal Gaussian profile, 200MW peak power and 100fs (rms) pulse length is used as the seed laser of the first stage. To obtain realistic simulation results, the whole electron beam was tracked through the first stage to the 2nd stage HGHG. The simulation results are illustrated in figure 6.

The 1st stage HGHG generates 44nm radiation pulse with the output peak power of about 500MW which is sufficient for the energy modulation in the 2nd stage. The radiation of the 1st stage is fully coherent and the length of the seed laser pulse is well maintained. This radiation was shifted by about 300fs by the fresh bunch chicane between two stages and interacts with the fresh part of the electron beam in the modulator of the 2nd stage. From figure 7(a), it is found that the 8.8 radiation saturates after about 15m of the radiator with a peak power of about 600MW. Figure 7(b) shows the spectrum of the output radiation.

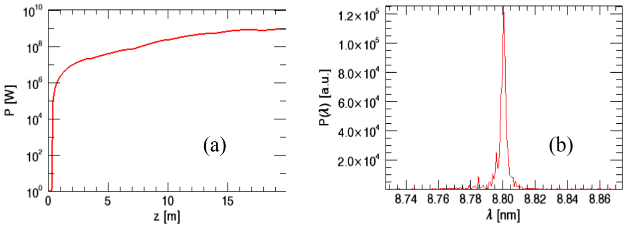

Figure 7: FEL performance of the 2nd stage HGHG. (a) Radiation power as a function of the radiator length; (b) Spectrum of the radiation.

FUTURE UPGRADE CONSIDERATION

The SXFEL is considered to be upgraded to a soft X-ray user facility with the radiation wavelength extended to the "water window" region by boosting the beam energy to 1.3GeV based on the SLED technique and more C-band accelerating structures. Two undulator lines, their associated beamlines and experimental stations are planned for future user experiments.

To further reduce the FEL radiation wavelength, the echo-enabled harmonic generation (EEHG) [6, 7] scheme has been considered. It allows the generation of more than 50th high harmonics with relatively small energy modulation and implies that the high power soft X-ray radiation can be generated directly from a UV seed laser by a single stage. A few of possible ways are considered for SXFEL, such as using the EEHG radiation to seed the HGHG, three stages of cascaded HGHG with harmonic number of 6×5×3 and using HHG as seed laser of EEHG.

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