DESIGN AND BEAM DYNAMICS SIMULATION FOR THE PHOTOINJECTOR OF SHANGHAI SOFT X−RAY FREE ELECTRON LASER TEST FACILITY

W.H. Huang[#], H.J. Qian, Q. Du, Y.Ch. Du, Ch. X. Tang, L.X. Yan
Department of Engineering Physics, Tsinghua University, Beijing 100084, PR China

Abstract

The Shanghai soft X-ray free electron laser test facility (SXFEL) aims to radiate at 9 nm based on the cascaded high-gain harmonic-generation (HGHG) scheme. The photoinjector of SXFEL consists of Ti-sapphire driving laser system, S-band photocathode RF gun, booster linacs, laser heater, beam diagnostics and matching section. It will produce ~130 MeV electron beam in high charge regime (~0.5 nC) with a baseline transverse emittance of 1.5 mm-mrad. This paper will present basic designs and beam dynamics simulations of SXFEL photoinjector.

INTRODUCTION

The soft X-ray FEL test facility (SXFEL) was initiated by IHEP-Tsinghua group in 2005. It will verify the cascaded HGHG scheme and carry out the research on key technologies for X-Ray FEL. After in-depth discussion in Chinese community, it was decided to choose SSRF campus in Shanghai as the facility site and SINAP as the host institute for the SXFEL project in 2007 [1]. The SXFEL project proposal got official approval on Feb. 2011. It aims at generating 9 nm FEL radiation based on a 270 nm seed laser using the two-stage cascaded HGHG scheme. The SXFEL project will be carried out by a domestic collaboration. Tsinghua University will be responsible for the photoinjector of SXFEL.

The intensive design studies for SXFEL photoinjector are carried out in Tsinghua University. This paper will present preliminary designs and beam dynamics simulations of SXFEL photoinjector.

LAYOUT OF THE SXFEL PHOTOINJECTOR

The SXFEL aims to radiate at 9 nm with a 270 nm seed laser based on two-stage cascaded HGHG scheme. As shown in Fig. 1, the photoinjector of SXFEL consists of Ti-sapphire driving laser system, S-band photocathode RF gun, booster linacs, laser heater, beam diagnostics and matching section.

The SXFEL injector is required to produce a single bunch with nominal charge of 500pC at a repetition rate of 10 Hz. At exit of injector, the beam should be ~130 MeV and with a baseline transverse emittance of 1.5 mm-mrad. Table 1 summarize the beam requirements based on FEL physics.

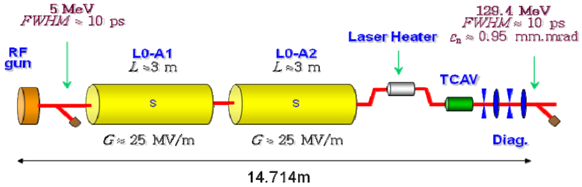

Figure 1: Layout of SXFEL photoinjector.

Table 1: Beam Requirements at Exit of SXFEL Injector

Parameters	Design value
Bunch charge	500pC
Energy	130MeV
Pulse length (FWHM)	10 ps
Normalized emittance (RMS)	<1.5 um
Rep. rate	1~10 Hz
Beam-RF timing jitter (RMS)	<250 fs

Photocathode RF Gun

Photocathode RF gun has been a well developed technology to provide electron beam with low transverse and longitudinal emittance, and BNL type RF gun has been studied at Tsinghua University since 2001. Based on our experience and latest gun developments from SLAC, PAL and KEK, a new prototype gun for the SXFEL project was designed and is under fabrication [2].

To reduce the RF breakdown possibility at high gradient, the old HELICOFLEX cathode seal was changed for a MATSUMOTO gasket, inserted tuners are removed for deformation tuners, and the profile of the disk iris was modified from circular to elliptical to reduce the surface field. Besides, RF pulse width reduction is also considered in the new gun operation to achieve high gradient, and lower dark current and RF pulsed heating, so mode separation of the new gun was increased from 3.3 MHz to 15.2 MHz to reduce the 0-mode excitation at Pi-mode frequency. To eliminate the multipole field contribution to beam emittance, a 4-hole scheme was used to suppress the quadrupole field, and the dimensions of the other three holes are specially tuned to minimize the dipole field. Besides structure modifications, copper is chosen as the main photocathode due to its robustness and low thermal emittance.

Laser System

The laser system for the SXFEL injector is required to deliver a UV pulse of 250 μJ to the photocathode assuming a QE of 10-5. A Ti:sapphire based amplifier

---

[#] huangwh@mail.tsinghua.edu.cn

system with third-harmonic generator will provide such laser pulse. The Ti:sapphire system includes Kerr-lens mode-locked oscillator, regenerative amplifier and multi-pass amplifier. The IR pulse from Ti:sapphire system is compressed and frequency-tripled, where more than 1.5 mJ UV pulse energy at 266 nm wavelength is produced. The temporal shaping of the UV pulse will be accomplished through the technique of pulses tacking by birefringent crystal of a-BBO serials, a Gaussian-to-flattened shaper made from aspheric lenses is used to reshape the natural transverse Gaussian profile into quasi flattened distribution. Then the shaped pulse is transported to the photocathode by imaging relay optics.

Electron Beamline

The SXFEL injector starts with a photocathode RF gun system, followed by two modified SLAC S-band linac sections, producing a single electron bunch at a 1~10 repetition rate with nominal energy of 130 MeV and 500 pC of bunch charge. The electron bunch is then sent through a laser heater to increase its slice energy spread which will help damp the microbunching instability in the magnetic bunch compressors. The laser heater consists of a 4-dipole chicane, a short undulator, and an IR laser (800 nm). After the laser heater, the electron bunch is matched to the main linac entrance by triplets.

There are two beam diagnostic stations, one is right after the gun exit, consisting ICT, Faraday Cup, YAG profile monitor and low energy spectrometer, for characterizing the beam parameters from the gun. The other is after the linac sections for characterizing the beam slice emittance, bunch length, and slice energy spread, including triplets, deflecting cavity and dipole spectrometer. Besides, beam position monitors and beam phase cavities are also included in the beam line to help commission the photoinjector.

RF Systems

The SXFEL injector includes three klystrons. A 40 MW klystron powers the photocathode RF gun and the deflecting cavity, and two 80 MW klystrons power the two SLAC linacs. Due to the strict timing stability requirement as shown in Table 1, the RF power source is required to have a high voltage stability of 0.1% (RMS) and a phase stability of 0.2 deg (RMS). Besides, the low level RF is locked to the laser oscillator in a feedback loop to control the relative timing jitter between low level RF and laser.

BEAM DYNAMICS SIMULATION OF SXFEL PHOTOINJECOR

Initial Conditions

Due to high charge (500 pC) requirement and limited gradient (~100 MV/m) of the RF gun, the cathode UV laser spot size and pulse length start from 1mm radius and 10 ps (FWHM) to relax intense space charge effect. The transverse pulse shaping is done by πShaper to achieve quasi-uniform distribution [3], and then truncated by an aperture which is finally imaged onto the cathode. The longitudinal pulse is shaped into a quasi-flattop distribution by pulse stacking technique [4].

Optimized Parameters for SXFEL Injector

By doing both PARMELA and ASTRA simulations, the bunch emittance at linac exit is optimized to be below 1.5 mm-mrad. The optimized beamline parameters are shown in Table 2 and Fig. 2, and the bunch parameters at booster linac exit are shown in Table 3.

Table 2: SXFEL Photoinjector Design Parameters

Parameters	Design value
Charge	500 pC
Laser radius	1 mm
Laser pulse width (FWHM)	10 ps
Laser rising time (10% − 90%)	<3.6 ps
Thermal emittance	0.5 mm.mrad
Gun gradient	100 MV/m
Laser-RF phase	25 deg
Gun solenoid intensity	2067 Gs
Gun solenoid position	21 cm
Entrance of first linac	150 cm
Gradient of first linac	20 MV/m
Linac solenoid length	1.2 m
Gradient of second linac	22 MV/m

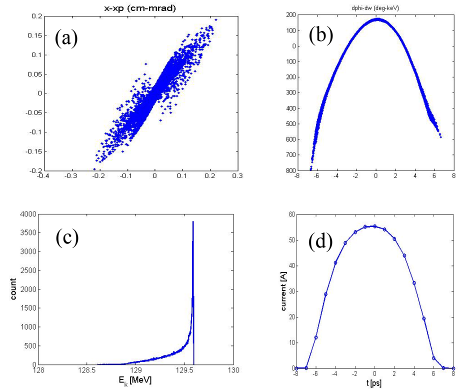

Figure 2: (a) transverse distribution (b) longitudinal distribution (c) peak current (d) energy spread at injector exit.

Table 3: Beam Parameters at Linac Exit

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%
Energy	130 MeV

Sensitivity Study

To achieve the required timing jitter of 250 fs at linac exit and to regulate the beam emittance within ±5% of the designed value, machine sensitivity study is done by doing parameters scan. Combining simulation results and current level of technology, the machine parameter stability requirement is shown in Table 4.

Table 4: Machine RMS Stability Requirement

Parameters	Value
UV energy	5%
Laser-RF phase	0.3 deg
RF power	0.2%

When machine stability is managed within the range listed in Table 4, simulations show beam emittance and its timing jitter relative to RF are well within the 5% and 250 fs requirements (Fig. 3).

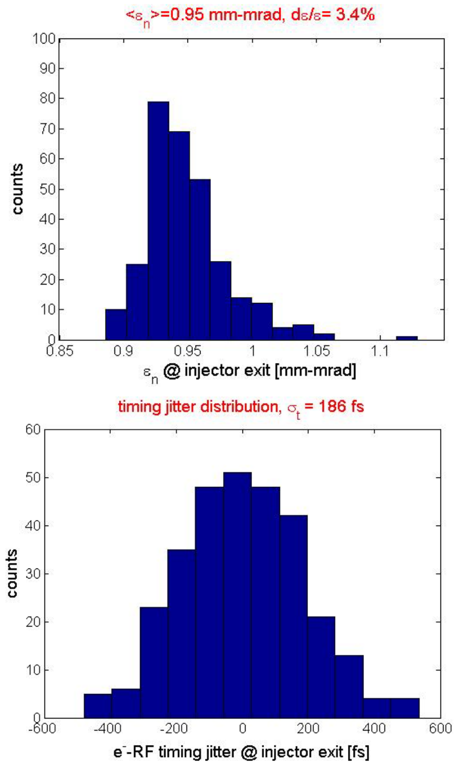

Figure 3: Electron beam stability performance with a machine stability listed in Table 4.

CONCLUSIONS

Preliminary design and simulations of the SXFEL injector have been presented in this paper, including brief introductions to main subsystems of the injector, beam dynamics simulations with nominal parameters, and machine sensitivity studies. Simulations show SXFEL injector beam qualities are well within the capabilities of current photoinjector technology.

REFERENCES

[1] Z.T. Zhao et al, FEL2010, 15(2010).
[2] H.J. Qian et al., these proceedings, THPB24.
[3] http://www.pishaper.com/
[4] L.X. Yan et al., Nucl. Instr. and Meth. A 637 (2011) S127-S129.