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DESIGN AND STATUS OF SHINE INJECTOR

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Abstract

Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE) is an x-ray FEL facility, consisting of an 8 GeV CW superconducting linac and 3 FEL undulator lines. These lines span a broad spectral range, extending from 0.4 to 25 keV. Photoinjector using VHF gun is one of the key parts of the facility. In this paper, the layout of the injector and some beam dynamics optimization results are presented. Additionally, we provide an update on the injector's current status and present some commissioning results of the electron gun section.

INTRODUCTION

Low emittance electron beam is of great importance for FEL generation, especially for hard X-ray lasing. Thus photo-injector is routinely used to provide low emittance, high brightness electron beam in worldwide FEL facilities [1, 2]. In order to produce high average power X-ray laser, the SHINE injector is required to achieve electron beam generation at a repetition rate of 1 MHz. According to the requirement of electron beam quality for SHINE (hard X-ray free electron facility), a 100 pC electron beam with emittance less than 0.5 mm-mrad is necessary at the entrance of SHINE undulator, and the transverse emittance from the photo-injector is at least 0.4 mm-mrad [3]. The main electron beam parameters are summarized in Table 1.

Table 1: Electron Beam Parameters of Injector

Parameter	Value	Unit
Energy	100	MeV
Charge	100	pC
Beam length (RMS)	~1	mm
Normalized slice emittance (RMS, 95%)	0.4	μm
Repetition rate (Max)	1	MHz

LAYOUT OF SHINE INJECTOR

The injector mainly performs electron beam generation, transport, transverse emittance compensation, electron beam longitudinal compression and acceleration, which consists of a VHF NCRF gun, a buncher, a single 9-cell cavity accelerating module, an 8-cavity accelerating module, three solenoids, a laser heater and three beam diagnostic sections.

The CW VHF gun stimulated by the APEX gun design is developed by Tsinghua university with a shorter acceleration gap (3 cm) and a different resonant frequency (217 MHz) [4-7]. The energy of the electron bunch is 0.85 MeV at the exit of the gun corresponding to a 30 MV/m cathode field. The solenoids located along the beamline are used to control the beam envelope and emittance compensation. The normal conducting 1.3 GHz buncher is used to compress the bunch length. An improved TESLA type double-feed single 9-cell accelerating cavity downstream of the second solenoid not only boost the beam energy to ~10 MeV, but also allows an optimized drift space for further emittance compensation before the standard 8-cavity module. With a double feed design, the influence of the coupler kick on the beam quality is mitigated. Then an 8-cavity cryomodule is used to boost the beam energy to ~100 MeV. The laser heater system downstream of the 8-cavity cryomodule generates an uncorrelated energy spread in the electron beam to sup-press the micro-bunching instabilities. The beam switchyard consists of a 50 Hz pulse-stealing kicker, a septum magnet and several dipole magnets.

In the SHINE injector, three beam diagnostic sections are designed as shown in Fig. 1, which can be used to optimize the injector in steps and monitor the beam parameters in CW operation mode. Moreover, combined with three beam diagnostic sections along the beamline, it allows the continual measurement of different beam parameters and feedback loop.

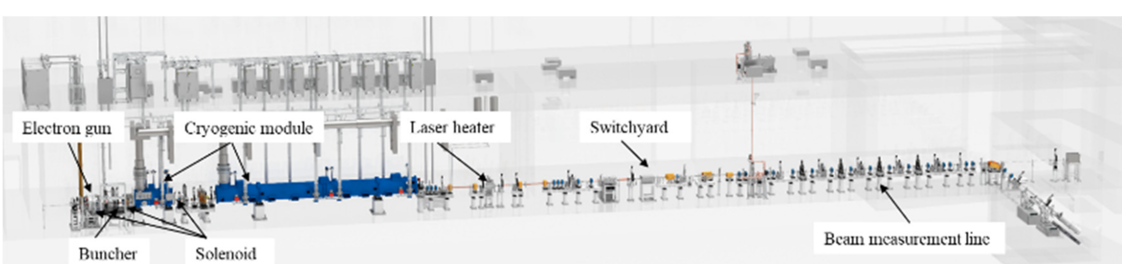

Figure 1: SHINE injector layout.

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BEAM DYNAMICS OPTIMIZAITON OF INJECTOR

Due to the large number of optimization variables and complex beam dynamics, the beam dynamics optimization of SHINE injector relies on a multi-objective optimization algorithm, which is capable of evaluating trade-offs between competing objectives. The bunch length and the transverse emittance of the electron beam are the main optimization objectives. The layout used in MOGA is presented in Fig. 2, which includes a dual-mode VHF electron gun, three solenoids, a single 9-cell cavity cryomodule, and a standard cryomodule. The thermal emittance of photocathode used in MOGA is 1.0 mm-mrad/mm.

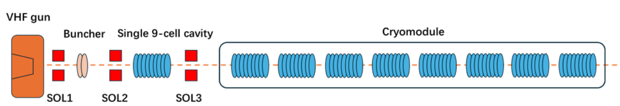

Figure 2: Configuration of injector used in MOGA.

Figure 3 presents the typical optimization results of MOGA. The electric field gradient at cathode is 25 MV/m, considering the risk of dark current with a higher launching field. The longitudinal profile of laser used in MOGA is flat-top, which can be obtained by pulse stacking technology. The optimal working point needs to be chosen from the Pareto front solutions. Since the SHINE requires the bunch peak current is about 10 A, the corresponding point at the bunch length of 1 mm is selected as the work point. The beam parameters at the work point are shown in Table 2. It is worth noting that beam dynamics studies of the injector with longitudinal Gaussian laser and different beam charge (20, 50, 100, 300 pC) are also carried out.

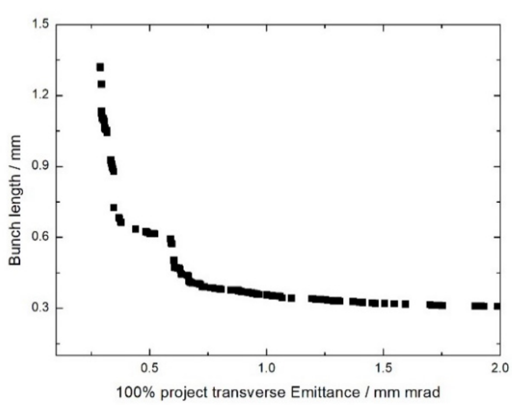

Figure 3: Pareto front of SHINE injector optimized by MOGA.

COMMISSIONING OF THE ELECTRON GUN SECTION

The installation of the electron gun section of SHINE injector has been completed in August 2023. RF conditioning and commissioning were carried out from September to December. It is planned to complete the installation and carry out the commissioning of the whole injector in 2024.

Table 2: Beam Parameters of the Injector Optimized by MOGA

Parameter	Value	Unit
Energy	127	MeV
Charge	100	pC
Beam length (RMS)	1.0	mm
Normalized projected emittance (RMS, 95%)	0.24	µm

Figure 4 presents the 3D diagram of the electron gun section, which includes VHF NCRF gun, 1.3 GHz NCRF buncher, two solenoids, collimator, YAG screen, BPM, spectrometer dipole, beam dump, etc. In this phase, the RF conditioning of the VHF gun and buncher was completed, their performance was measured and evaluated. The performance of driving laser and photocathode was also evaluated. The dark current measurement and scraping experiment were performed. BBA of laser, gun, and solenoid was carried out.

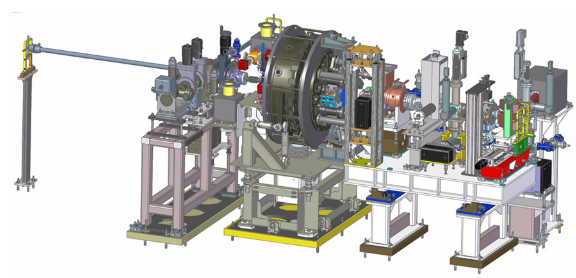

Figure 4: 3D diagram of the electron gun section of SHINE injector.

Figure 5 presents the dark current results of the gun. It indicates that the dark current increases exponentially with the increase of the voltage of the electron gun. In order to reduce the risk of dark current, the VHF electron gun operate with about 750 kV. And a collimator with holes of different sizes is placed downstream of the laser box to reduce the dark current transported to superconducting accelerating cavities.

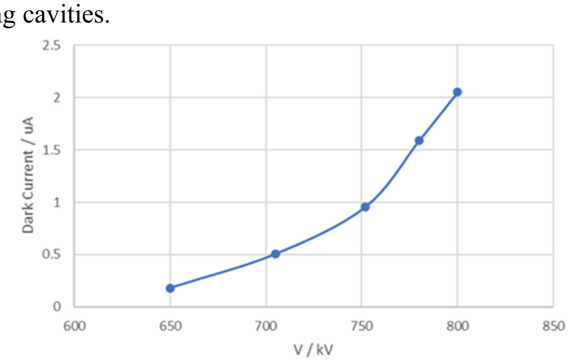

Figure 5: Dark current vs voltage of the gun.

The testing results indicate that the dark current can be reduced to be less than 400 nA before entering the single 9-cell cavity cryomodule. Figure 6 presents the dark current emission imaging. It shows that the dark current is emitted mainly from the area near the cathode on the nose cone of the electron gun.

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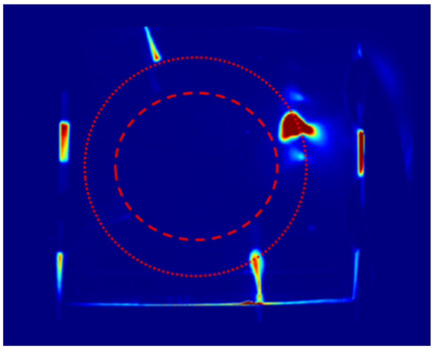

Figure 6: Dark current emission imaging.

Figure 7 presents the relationship between the beam energy of the buncher phase. It indicates that voltage of the buncher is larger than 200 kV, reaching the physical target.

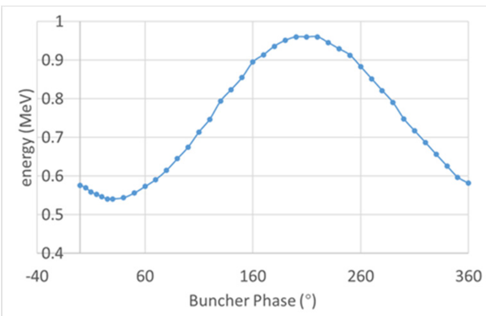

Figure 7: Energy vs phase of the gun and buncher.

The photocathode material used in SHINE injector is Cs2Te. The quantum efficiency of the photocathode can reach 8 %, meeting the application requirements. During this commissioning, the electron gun section achieved generation and operation of 1 MHz, 100 pC electron beam. Figure 8 presents the historical data recording of operating charge, beam vacuum and repetition rate.

CONCLUSION

In this paper, we briefly introduce the physical layout of SHINE injector and the study of beam dynamics optimizations. The installation and commissioning of the electron gun section was completed in 2023. Some results of commissioning are presented.

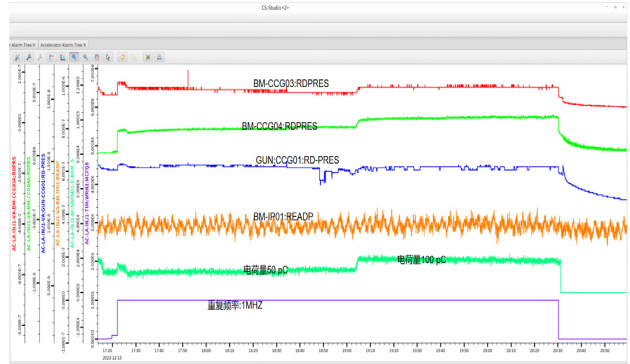

Figure 8: 1 MHz, 100 pC electron beam commissioning.

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