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INJECTOR PHYSICS DESIGN AT SHINE

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Abstract

SHINE high brightness injector is one of the key components of the x-ray FEL facility. It consists of a NC photocathode gun, a buncher, three solenoids, two accelerator cryomodule to boost the beam over 100 MeV. In addition, a laser heater, the pulse extraction system and several beam measurement section are included in the injector. In this paper, we describe the injector physics design including the beam performance, beam diagnosis and beam feedback.

INTRODUCTION

Shanghai HIgh repetitioN rate XFEL and Extreme light facility (SHINE) is an x-ray FEL facility based on an 8 GeV CW superconducting linac and 3 FEL undulator lines covering the spectral ranges 0.4-25 keV. It will be located at the Zhangjiang High-tech Park, close to the Shanghai Synchrotron Radiation Facility (SSRF) campus and the ShanghaiTech University. The short wavelength radiation requires the high quality electron beam provided by the high brightness injector, which is one of the key components of the x-ray FEL facility.

Great successes have been achieved with normal conducting, low repetition rate injectors, such as the ones of the LCLS [1] and the Pal-FEL, or PITZ [2] of the FLASH and the Euro-FEL. However, the low repetition rate guns cannot be operated at MHz repetition rate. In order to obtain a high average power free electron laser, a high brightness CW injector is required. At SHINE, an APEX-type normal conducting RF gun (VHF gun) [3] is the main candidate for the CW injector.

The CW injector is the beginning part of the x-ray free electron laser facility, which can produce specified electron beams for the main accelerator. The beam dynamics process in injector including produce of electron beam, beam transmission, transverse emittance compensation, beam compression, acceleration, and so on is the key to the performance of the whole FEL facility. Table 1 summarizes the electron beam parameters of the SHINE injector.

Table 1: The Electron Beam Parameters of Injector

Parameter	Nom. value
Energy	100 MeV
Charge/bunch	100 pC
Beam length (RMS)	1 mm
Peak current	12 A
Normalized slice emittance (RMS, 95%)	0.4 um

Figure 1 illustrates the layout of the SHINE injector, including a normal conducting RF photocathode gun, a normal conducting RF buncher, three movable solenoids, a single 9-cell cavity [4] accelerating unit, an eight 9-cell cavities accelerating unit, a laser heater, the pulse extraction system, the deflecting cavity, magnets and beam measurement and the injector laser system consist of a photocathode drive laser system and a heating laser system. Moreover, the injector also includes photocathode system, solid RF power amplifier system, vacuum system, mechanical system, electron diagnostics system, control system, power supply system and etc.

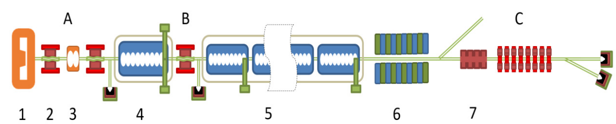

Figure 1: The layout of injector.

The 162.5 MHz VHF gun (more details in chapter 4.4.1) and the 1.3 GHz buncher (chapter 4.4.3) are the normal conducting while the single 9-cell cavity and the eight 9-cell cavities accelerating unit are superconducting (chapter 4.2). The energy of the electron bunch is 0.75 MeV at the exit of the gun. The 1.3 GHz buncher is used to compress the bunch about 3 times from about 30 ps to about 10 ps (FWHM), with the peak current of about 10 A after the buncher. The movable solenoids located along the beamline are used to compensate the transverse space charge effect, aiming to achieve lower emittance. The laser heater system downstream of the 8-cavity cryomodule generates an uncorrelated energy spread in the electron beam to suppress the micro-bunching instabilities.

BEAM DYNAMIC OPTIMIZATION

In this kind of injector, the bunch length and the transverse emittance of the electron beam are both affected by the accelerating components and the focusing components. Manual or semiautomatic scanning of these parameters cannot work in the optimization. The multi-objective and multivariate optimization algorithm combined with beam dynamics calculation software has been used. In the calculation, the 3D electric magnetic field results of these components are used and imported to the beam dynamics calculation software.

Figure 2 shows the multi-objective optimization results of the injector under 100pC and 200pC modes, respectively. It indicates that the emittance increases obviously with the increase of the bunch charge even with

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the same bunch length. Multi-objective optimization results usually generate Pareto front. All the points in this line are optimal point, meaning impossible to get the results located in the lower left of this line.

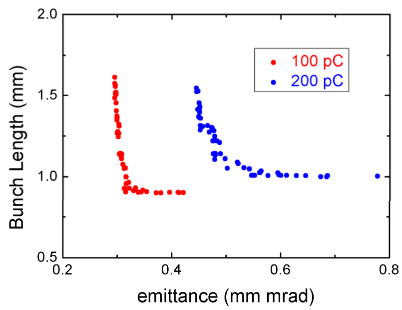

Figure 2: Multi-objective optimization results of the injector.

As the results given by multi-objective optimization are usually the minimum values meeting the specified conditions. The optimal solutions need to be chosen according to the practical situation. For both 100 pC and 200 pC, selecting the lower emittance usually means the sacrifice of the bunch length. In our design, we select the normalized transverse emittance of 0.3 mm mrad and the bunch length of 1.1 mm. Figures 3, 4 and 5 show the beam dynamics optimization results at the exit of the 8-cavity cryomodule. Table 2 shows the design parameters of optimization. From the results, one can see that the slice emittance along the beam is about 0.25 mm mrad, which will be very important for the FEL performance. The peak current of the beam at the exit of the injector is about 10 A. The current distribution is not Gaussian-like, which may cause potential difficulties on the further bunch compression process in the linac. This is probably due to the strong space charge effect in the gun and the nonlinear compression in the buncher.

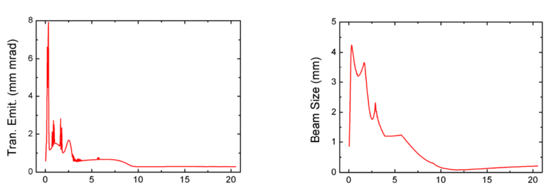

Figure 3: Electron beam parameters changes along the injector (100 pC).

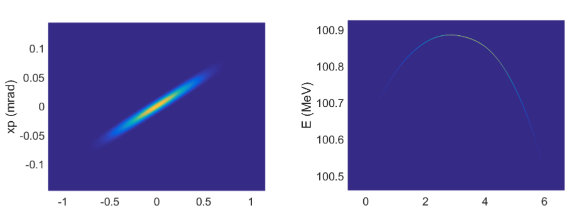

Figure 4: The longitudinal phase distribution of the electron beam at the injector exit.

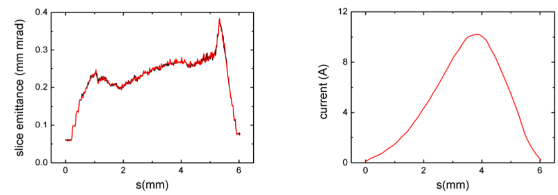

Figure 5: Slice parameters of the electron beam at injector exit.

Table 2: The Design Parameters of Optimization for Injector

Parameter	Value
Energy	100 MeV
Charge/bunch	100 pC
Bunch length (RMS)	1.1 mm
Peck current	11 A
Normalized slice emittance (RMS, 95%)	0.2~0.28 um

THE LASER HEATER SYSTEM

As shown in Figure 6, the laser heater system is located downstream of the 8 cavities accelerating units (cryomodule). The laser heater system consists of a 50 cm long, 5 cm period undulator located at the center of a small bunch compression chicane, aiming to increase the slice energy spread to suppress the micro-bunching instability including LSC, CSR and wakefield [5].

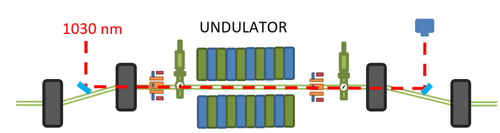

Figure 6: Layout of the SHINE laser heater system.

The parameters of the heating laser are listed in Table 3 Energy modulation is introduced as the electron beam transporting through the undulator, interacted with the 1030 nm heating laser. The laser-induced energy modulation will be smeared by the following temporal washing effect provided by the chicane. The slice energy spread is increased to about 5 keV after the laser heater system, considering the micro-bunching instability gain in the linac (more details in chapter 3.3). Actually, the slice energy spread could be increased up to 20 keV, aiming to suppress the FEL performance if necessary. The laser spot size in the undulator should be adjusted equally to the beam size as a laser heater with a matched laser spot effectively suppresses the instability and does not change the slice energy spread. Actually, the laser spot size is usually 50% larger than the beam size for the resistance of the transverse jitters of both the heating laser and the electron beam.

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Table 3: The Parameters of the Heating Laser

Parameter	Nom. value
Operating wavelength	1030 nm
Pulse repetition rate	0-1 MHz
Peak power in the undulator	1.5 MW
Laser pulse energy in the undulator	15 μJ
Pulse length (Gaussian)	10-20 ps
Power instability (rms)	1 %
Pointing instability (rms)	10 μm
Transverse beam size at the cathode	0.3 mm
Timing jitter relative to RF (rms)	100 fs
Maximum intensity variation (peak)	15 %
Rayleigh length	110 cm
Laser average power	50 W

BEAM DISTRIBUTION SYSTEM AND FEEDBACK LOOP

The beam distribution system downstream of the laser heater system consists of the kicker-lambertson system and the DBA section. The layout of the beam distribution system is given in Figure 7. The kicker-lambertson system is used to steal the beam to the third beam measurement section at the frequency of 50 Hz (the cold component), providing the continuously measurement of the beam parameters and the feedback loop. The DBA section transport the beam to the linac at the frequency up to 1 MHz (the warm component). The beam energy and the bunch length are measured by the beam position monitor (BPM) and the bunch length monitor (BLM) at the frequency up to 1 MHz, supporting the fast energy feedback and the machine protection system (MPS).

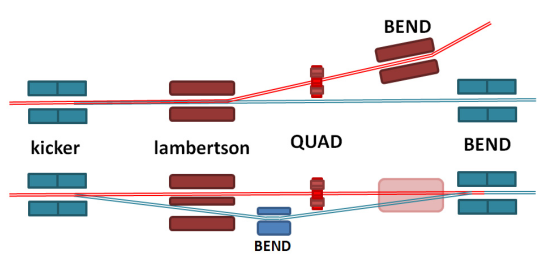

Figure 7: The layout of the beam distribution system.

At the same time, we would like to introduce the feedback loop of the SHINE injector, and the results are shown in Figure 8. The bunch charge measured by ICT or BPM contributes to the bunch charge feedback loop by tuning the driving laser. The transverse deflecting cavity combined with the analytical magnet in the third beam measurement section can provide the arrival time, bunch length and the slice energy spread, which help to finish the arrival timing feedback, the bunch length feedback (tuning the buncher) and the heating laser feedback (tuning the heating laser). The beam energy and the project energy spread measured by the analytical magnet can be referred to tuning the module, forming the energy feedback loop. Moreover, the orbit feedback is necessary in three beam measurement sections. All those feedback loops help to provide the more stable electron beam.

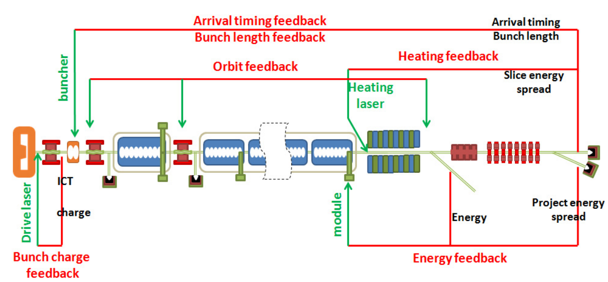

Figure 8: The layout of the injector feedback system.

CONCLUSIONS

In this paper, we presented the SHINE injector physics design including the layout, the parameter optimization, the laser heater system, the beam distribution system and the feedback loop system.

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