Design studies on a 500 kV DC gun photo-injector for the BXERL test facility*

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Abstract: BXERL is a proposal for a test facility (Beijing X-ray Energy Recovery Linac), which requires its injector to provide an electron beam of 5 MeV, 77 pC/ bunch at a repetition rate of 130 MHz (average current of 10 mA). In this paper, we present the design of the injector, which consists of a 500 kV photocathode DC gun equipped with a GaAs cathode preparation device, a 1.3 GHz normal conducting RF buncher, two solenoids, and one cryomodule containing two 1.3 GHz 2-cell superconducting RF cavities as the energy booster. The detailed beam dynamics show that the injector can generate electron bunches with a RMS normalized emittance of 1.49 πmm·mrad, a bunch length of 0.67 mm, a beam energy of 5 MeV and an energy spread of 0.72%.

Key words: ERL, DC gun, photo-injector, buncher

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1 Introduction

The successful operation of the energy recovery Linac (ERL) at the Jefferson Laboratory of the USA [1], the JAERI institute of Japan [2] and the BINP institute of Russia [3] led to great research interest in developing ERLs for a series of applications, such as electron cooling [4], very high power free electron lasers, electron-ion colliders [5] and the production of high brightness, short pulse synchrotron radiation X-ray beams [6]. All of these applications require an electron beam with high average current and high brightness. The main features for an ERL facility are high average current, low beam emittance and short bunch length, which mostly depend on the injector beam performances.

In an ERL facility, the injector is not only the first component in the whole beamline, but also the first important device dominating the ERL performance. At present there are three different injector technologies that may potentially meet the ERL requirements [7–9]. They are the DC gun injector, the very high frequency (VHF) normal conducting RF gun injector and the superconducting RF gun injector. Each of these schemes assumes the use of a photocathode and a laser to generate the electron beam. They all have their advantages as well as some technical challenges. Up to now, all ERL facilities in operation have employed a DC gun injector. The accelerating field gradient in the DC gun is not high, limited by the field emission and the punch through the ceramic insulator. In order to reduce the emittance blowup due to the space charge effect in the DC gun, the pulse length of the driving laser should be several tens of picoseconds. A buncher is needed downstream of the gun to compress the bunch into several picoseconds for further accelerating in the energy booster. Two solenoids are used to keep the beam envelope in a reasonable size along the injector. One is upstream of the buncher and another one is downstream of the buncher. Therefore the standard setup of the ERL injectors is always as photocathode DC gun + solenoid + normal conducting RF buncher + solenoid + superconducting RF booster.

Lots of simulation work has been done on the injectors for different ERL facilities [10–12]. Considering the BXERL test facility, four criteria have to be satisfied when optimizing the injector design. In the following sections, we present the design of all injec-

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tor components first and then give the optimized beam dynamics results.

2 Injector design

The injector of the BXERL test facility includes a DC gun with a GaAs photocathode preparation device and a driving laser system, the solenoid 1, the 1.3 GHz normal conducting RF buncher, the solenoid 2 and two 1.3 GHz 2-cell superconducting RF cavities as the energy booster. The injector layout is shown in Fig. 1.

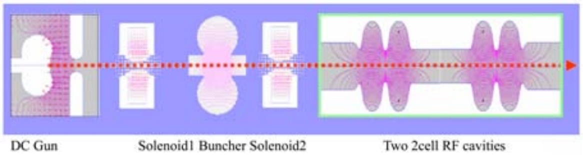

Fig. 1. The injector layout.

2.1 The DC gun

Figure 2 shows the structure of the DC gun and the field distribution along the z axis. The GaAs wafer is designed with a 12 mm diameter, which allows a laser with 6 mm diameter spot to be operated off-axis. A cathode electrode angle of 10° is chosen, so the electric field near the cathode can focus the beam at a constant size throughout the gun up to the first solenoid. There is no nose structure on the anode to avoid the field enhancement on the anode surface. The distance from the cathode to the anode is 12 cm. If the high voltage between the cathode ball and the anode is set to 500 kV, the maximum field gradient on the cathode surface is 5.48 MV/m and the maximum gradient along the z axis is 6.45 MV/m.

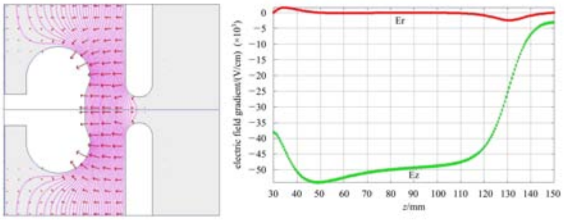

Fig. 2. The DC gun and the electric field along the z axis.

2.2 The buncher

Figure 3 shows the designed buncher and the RF field along the z axis. It is a 1.3 GHz normal conducting RF cavity. In order to reduce the required RF power, it is optimized to a high quantum factor. Table 1 summarizes the main parameters. In the following simulation, we set the maximum field gradient along the z axis to 5 MV/m. The required CW RF power is then about 15 kW. Taking account of the 10 mA beam energy gain of 230 kV in the buncher, 2.3 kW are needed. The total RF power for the buncher is about 17.3 kW.

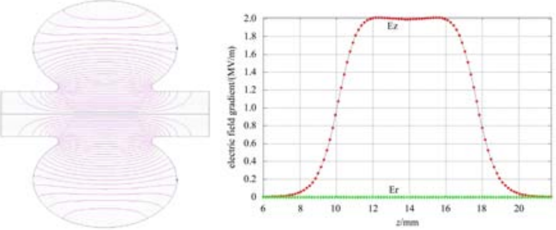

Fig. 3. The normal conducting RF buncher and the electric field along the z axis.

Table 1.

Standard room-temperature copper	
Frequency	1300.01884 MHz
Q	25411.5
Shunt impedance	67.288 MΩ/m
Rs*Q	239.038Ω
Z^*T^*T	40.382 MΩ/m
r/Q	250.921 Ω
Peak-to-average ratio $E_{\max}/E_0$	4.5576

2.3 The solenoid

Figure 4 shows the solenoid and its magnetic field along the z axis. The two solenoids in the injector have the same structure. The effective length is 10 cm.

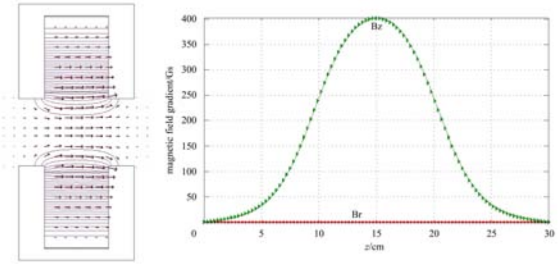

Fig. 4. The solenoid and the magnetic field along the z axis.

2.4 The 2-cell superconducting RF cavity[1)]

We plan to employ two 2-cell super conducting standing wave RF cavities in one cryomodule to accelerate the electron beam to 5 MeV. These are TESLA type cavities, shown in Fig. 5. All the parameters are given in Table 2. In order to extract the high order modes and damp them, the diameter of the beam tube between the two cells amounts to 70 mm, and that of the beam tube at one side is chosen to be 108 mm. The whole layout of the two 2-cell cavities, including the couplers and the dampers, is shown in Fig. 6.

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1) J. Y. Zhai et al., IHEP internal report on the BXERL test facility(in Chinese)

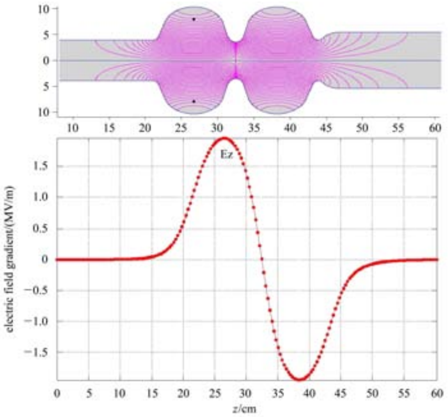

Fig. 5. The 2-cell superconducting RF cavity and the RF field along the z axis.

Table 2.

Type of accelerating structure	Standing wave
Accelerating mode	TM010, π mode
Fundamental frequency	1301.000 MHz
Design gradient	20 MV/m
Quality factor	1×10^{10}
Active length	0.2292 m
Number of cells	2
Geometry factor (G)	274.5 Ω
R/Q	214.2 Ω
$G\times R/Q$	58776 Ω^2
$E_{\rm peak}/E_{\rm acc}$	2.02
$B_{\rm peak}/E_{\rm acc}$	4.2 mT/(MV/m)

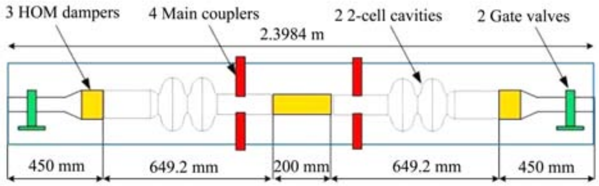

Fig. 6. The two 2-cell RF cavities in one cyromodule including the couplers and dampers.

3 Beam dynamics

The following simulation is constrained by the four criteria listed below:

(1) Make the transverse emittance as small as possible.

(2) Make the bunch length as short as possible.

(3) Make the energy spread as small as possible.

(4) Make the whole system compact in space.

Because the field gradient in this gun is low, the space charge is the dominating effect which worsens the beam quality of a 77 pC bunch. It is better to set the laser pulse longer and give it a bigger size in the transverse direction. On the other hand, a too long laser pulse would bring heavy pressure on the buncher downstream and a big laser spot will increase the thermal emittance. The optimized parameters for the simulation are finally as follows. The laser RMS beam size is 1.2 mm, flat-top longitudinally, where the flat part is 20 ps long，the rise and down time are all 2 ps. In the photoemission process, the GaAs cathode is illumined by a 532 nm laser. Photoelectrons have an initial kinetic energy of 0.2 eV. The thermal emittance due to the initial energy has been taken into account in the following simulation results.

The main function of the two solenoids in the injector system is to focus the electron beam at a reasonable size into the buncher and the energy booster. A minor emittance compensation effect can be made by them also. In the buncher we choose a suitable RF phase for the bunch injection, at which a good velocity compression can be achieved. Fig. 7 shows the RMS bunch length and the beam energy at the position 2 meters away from the cathode VS the injection phase. The phase for the minimum bunch length is 50° off from the phase for the maximum energy gain. In the simulation, we set the maximum field gradient along the z axis to 5 MV/m. The beam gains 213 keV energy from the bunch. The normal conducting RF cavity can operate in CW mode. Thermal loads from ohmic losses on the cavity can be extracted by the cooling water system. The two 2-cell superconducting RF cavities accelerate the beam from 0.713 MeV to 5 MeV. The maximum field gradient is set to 20 MV/m.

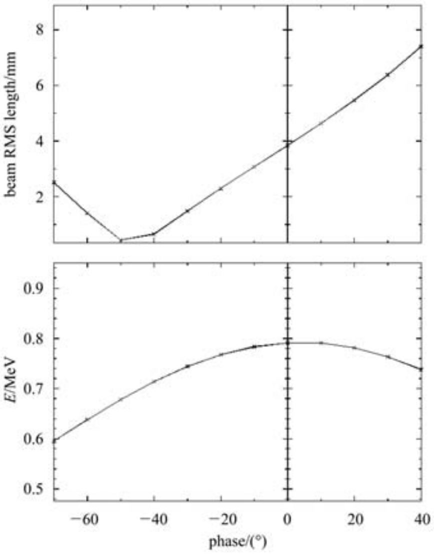

Fig. 7. The bunch length and the energy Vs the RF phase in the buncher.

Figure 8 shows the optimized simulation results. The curves (a) and (b) show the field distribution and the positions of all components, the total length from the cathode to the cyromodule exit is only 3.2 m;

(c) is the normalized emittance, 1.49 mm·mrad at the end of the injector; (d) is the curve of the RMS bunch length, 0.67 mm; (e) is the curve of the energy spread, 35.90 keV, 0.72%; (f) shows the accelerating process, 5 MeV in the end; and curve (g) shows the beam size along the injector.

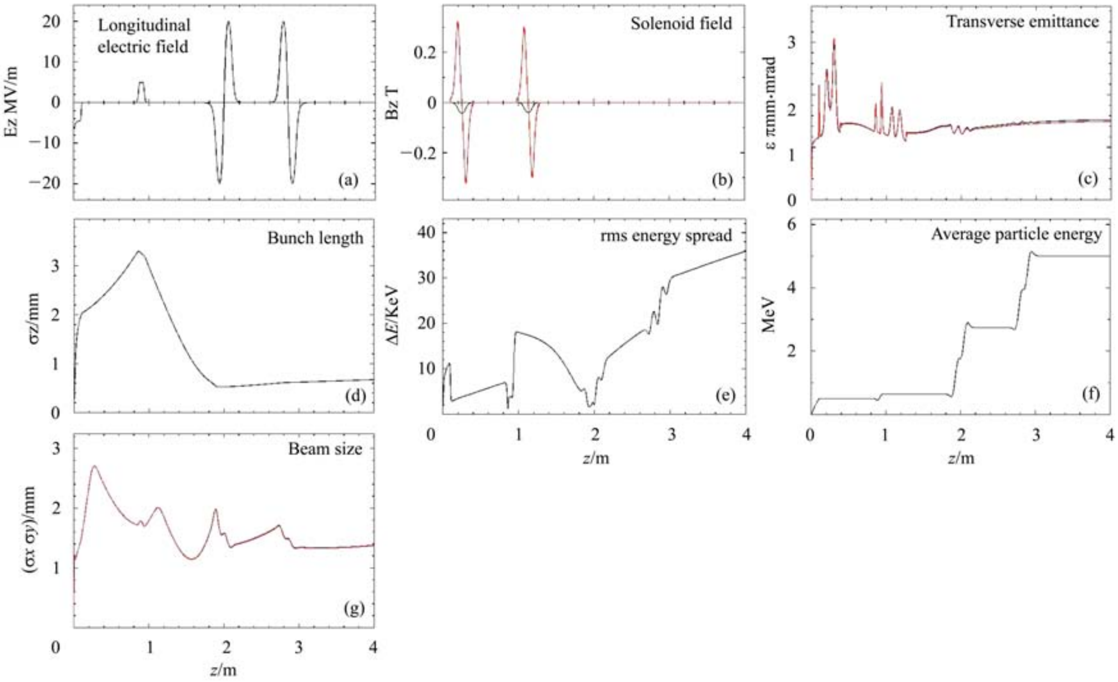

Fig. 8. The beam dynamic results.

4 Conclusions

The BXERL test facility plans to employ a photocathode DC gun injector, including one 500 kV DC gun, two solenoids, a normal conducting RF buncher and two 2-cell superconducting RF cavities in one cyromodule. All these components were optimized with the SUPERFISH and POISSION codes. We optimized the beam line setup of the injector with the code ASTRA. The optimized simulation results are good enough to satisfy the requirements for the BXERL test facility. The RMS normalized emittance is 1.49 πmm·mrad, the RMS bunch length is 0.67 mm, the beam energy is 5.0 MeV，the RMS energy spread is 0.72% and the injector is compact enough with an extension of 3.2 m from the cathode to the exit of the cyromodule.

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