BXERL photo-injector based on a 217 MHz normal conducting RF gun*

LIU Sheng-Guang(刘圣广)[1;1)] HUANG Tong-Ming(黄彤明)[2] XU Jin-Qiang(徐金强)[2]

[1] Key Laboratory for Laser Plasmas (Ministry of Education), Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China

[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: The Beijing X-ray Energy Recovery Linac (BXERL) test facility is proposed in Institute of High Physics (IHEP). In this proposal, the main linac requires the injector to provide an electron beam with 5 MeV energy and 10 mA average current. An injector based on DC gun technology is the first candidate electron source for BXERL. However, the field emission in the DC gun cavity makes it much more difficult to increase the high voltage to more than 500 kV. Another technology based on a 217 MHz normal conducting RF gun is proposed as the backup injector for this test facility. We have designed this RF gun with 2D SUPERFISH code and 3D MICROWAVE STUDIO code. In this paper, we present the optimized design of the gun cavity, the gun RF parameters and the set-up of the whole injector system. The detailed beam dynamics have been done and the simulation results show that the injector can generate electron bunches with RMS normalized emittance 1.0 πmm·mrad, bunch length 0.77 mm, beam energy 5.0 MeV and energy spread 0.60%.

Key words: ERL, normal conducting RF gun, photo-injector, CW mode

PACS: 29.25.Bx, 29.27.Ac, 29.20.Ba **DOI:** 10.1088/1674-1137/35/9/015

1 Introduction

The Energy Recovery Linac (ERL) is an advanced accelerator technology, which potentially has advantages of the linac accelerator and the storage ring accelerator. The beam quality of the electron bunches from ERL can be almost the same as that from the linac accelerator and the average current from ERL can be almost the same as that from the storage ring accelerator. Of course, there are lots of technical challenges on ERL presently, especially on the electron source and the superconducting Linac. With the operation of 3 ERL test facilities [1–3] in the world, this advanced accelerator technology has been demonstrated successfully and then more and more research interest and efforts have been aroused on developing ERLs for many scientific applications [4–6]. All these applications require an electron beam with low emittance, high average current and high peak current, which depends on the injector performance mostly.

The Beijing X-ray Energy Recovery Linac (BXERL) test facility is proposed in IHEP [7]. On this machine, we will demonstrate ERL technology and SASE-FEL technology simultaneously [8]. BXERL requires the injector to provide an electron beam with 5 MeV energy, 10 mA average current and the normalized emittance less than 2 πmm·mrad for the main linac.

Generally, three different injector technologies have been taken into account to satisfy the ERL requirements [9–11]. 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. These technologies have their advantages as well as some technical challenges. The three ERL test facilities in operation have employed the DC gun injectors. The accelerating voltages of those DC guns are less than 500 kV, which is limited by the field emission and the punch through of the ceramic insulator. From

Received 21 June 2010, Revised 6 May 2011

* Supported by Creative Research Foundation of Institute of High Energy Physics (H85453G0U2) and Key Project of Chinese National Programs for Fundamental Research and Development (2008CB817700)

1) E-mail: liushg28@hotmail.com

simulation results [12, 13], the voltage is not high enough for generating the high brightness electron beam for the main linac. The VHF guns with resonant frequency less than 300 MHz are able to accelerate the electron beam to high energy of more than 500 kV, even to 800 kV and can potentially operate in CW mode. Moreover, one RF period of this gun is long enough to a several-ten ps laser pulse, so the beam dynamic in this VHF RF gun is similar to that in the DC gun. In order to reduce the emittance blow-up due to the space charge effect in the gun, the pulse length of the driving laser should be adjusted to several ten picoseconds. A buncher is needed downstream of the gun to compress the bunch into several picoseconds for further acceleration in the energy booster. Two solenoids are used to compensate the beam emittance and to keep the beam envelope in a reasonable size along the injector.

In Section 2, we design the 217 MHz gun with 2D and 3D simulation codes and present the optimized gun parameters. The whole setup of the injector system and the detailed beam dynamics results are presented in Section 3. Some conclusions are given in the last section.

2 217 MHz gun design

A 1300 MHz RF buncher and two 2-cell 1300 MHz superconducting RF energy booster will be used in this injector system. Downstream of the injector, the main linac will employ 1300 MHz superconducting RF cavities. Considering the synchronization issue, we choose the resonant frequency of the gun to one sixth of the resonant frequency 1300 MHz, which is 217 MHz. On the other hand, the driving laser at 217 MHz repetition rate is available commercially. If there is one bunch in each RF bucket of the gun, the bunch charge should be 46 pC, corresponding to a 10 mA average current electron beam. In the following beam dynamics, all simulations are for the electron bunch of 46 pC.

Figure 1 shows the gun structure and 18 geometry parameters. As the LBNL gun design [9], we use a nose structure to enhance the field gradient near the cathode surface. The accelerating gap is set to 4 cm. The other parameters have been optimized to increase the Q and shunt impedance of the cavity and to decrease the maximum power density. Table 1 shows these geometry parameters. Table 2 shows the optimized RF parameters. The 2D simulation results and 3D simulation results match each other very well. The quality factor of the optimized gun is about 30000 and the shunt impedance is about 5.96 MΩ. In order to guarantee the stability of the gun operation in a long term, we assume the gun operates at the high voltage of only 500 kV. In this case, the power loss on the cavity is about 42 kW, the total RF power needed is about 47 kW and the maximum field gradient in the gun is about 14 MV/m correspondingly. The gun cavity can be kept at a reasonable temperature with a normal cooling water system.

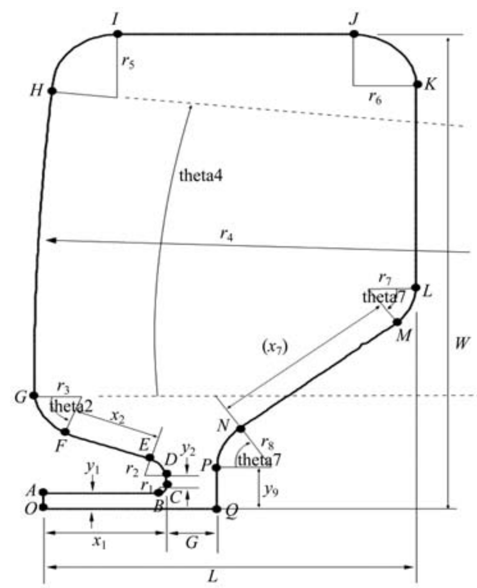

Fig. 1. The gun structure and parameters.

Table 1. Optimized geometry parameters.

	W	L	G	y_1	x_1	r_1	y_2	r_2	x_2	r_3	r_4	r_5	r_6	r_7	r_8	y_9
length/cm	32.1	30.3	4	1.5	3	0.5	1	2	2	3	300	5	5	5	4	2
	theta2	theta7														
angle/(°)	30	70														

Table 2. The optimized RF parameters.

simulation code	frequency/MHz	Q	P_total*/kW	Pd_max** /(W/cm^2)	R/Mohm	R/Q	stored energy/J	V_c/kV
superfish(2D)	216.49	29989	41.96	13.65	5.96	198.7	0.93	500
CST(3D)	216.64	30379	35.54	18.1	7.0	231.5	0.80	500

∗ Total power loss# ∗∗ Maximum power density

Figures 2 and 3 show the optimized RF gun in 2D and in 3D respectively. Fig. 4 shows the electric field distribution and Fig. 5 shows the magnetic field distribution in the gun. The gun is designed to generate an electron beam with 10 mA average current, so it will be operated in the CW mode. The candidate photo-cathode is GaAs, with high quantum effiency better than 1%, low initial kinetic energy driven by 532 nm laser. However, the cathode is so delicate that it survives only in the ultra-high vacuum better than 10^{-9}Pa. As Table 1 says, the cavity is relatively big. It is a challenging issue to achieve so good a vacuum in this cavity. 104 slots are designed on the cavity wall for vacuum extraction and 24 NEG pumps surround the RF cavity. These slots are designed to be big enough for gas extraction and small enough to guarantee that no considerable RF power leaks. Fig. 6 shows the electronic field near these slots. The RF power density outside the slot is 52.1 dB lower than that inside the slot. The RF cavity is made of perfect Cu and a stainless steel cavity is welded outside the Cu cavity to enhance the gun strength.

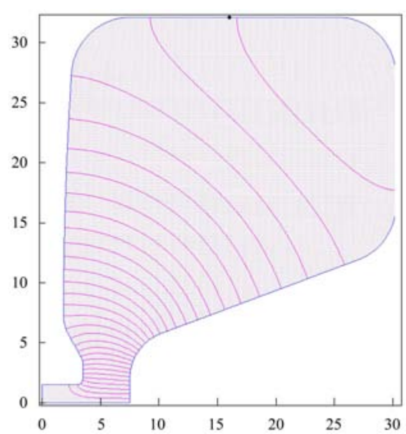

Fig. 2. The optimized gun in 2D.

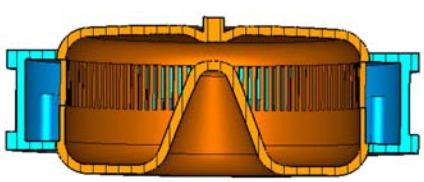

Fig. 3. The mechanical structure of the RF gun in 3D (color figure online).

For any frequency choice there are always RF power levels that excite potentially dangerous multipactoring resonances. It is a necessary step to find the RF power levels, at which the multipactoring occurs in the gun cavity. An analysis of the phenomenon for our VHF structure has been performed by using Fishpact codes, shown in Fig. 7. The peak field region from 12.5 to 28 MV/m does not show multipactoring resonances, in particular at the field of 14 MV/m corresponding to our nominal gap voltage of 500 kV. From these results, we can see that it is possible to operate the gun at 750 kV accelerating voltage in the future.

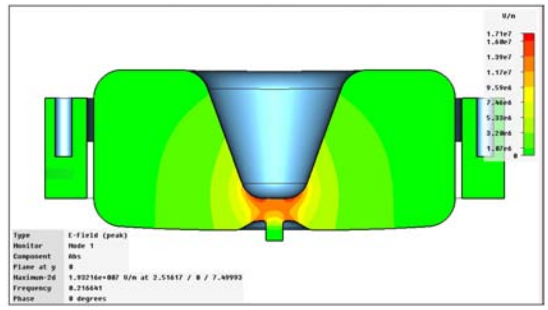

Fig. 4. The electric field distribution in the gun (color figure online).

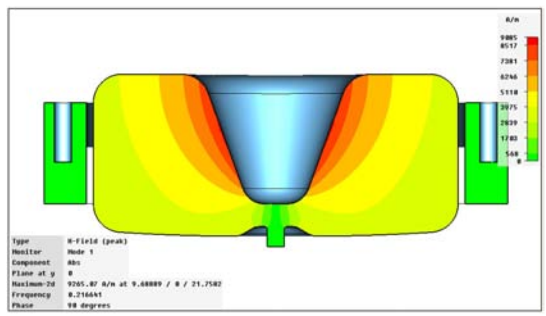

Fig. 5. The magnetic field distribution in the gun (color figure online).

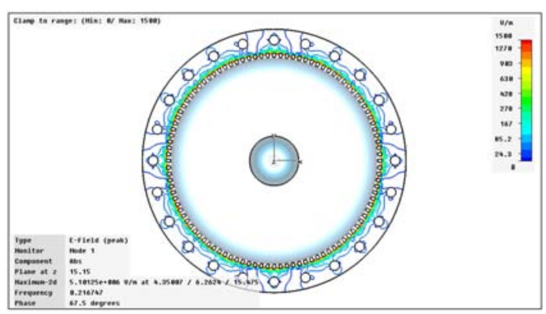

Fig. 6. The electric field distribution near the pump slots (color figure online).

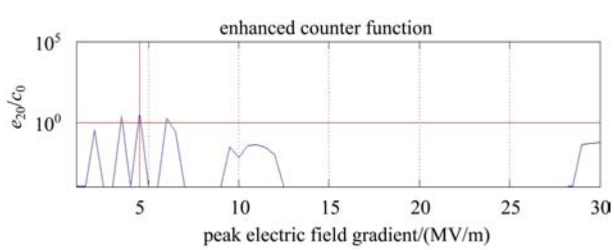

Fig. 7. Multipactoring modes versus peak field gradient for the gun.

3 Beam dynamics for the injector

Figure 8 shows the layout of the injector, which consists of one 217 MHz RF gun, two solenoids, one RF buncher at 1300 MHz and two 2-cell 1300 MHz superconducting RF cavities as the energy booster. Figs. 10 and Fig. 11 show the electric field and magnetic field of the injector components, from which you can find their positions away from the cathode. The total length from the cathode to the cyromodule exit is less than 3.0 m.

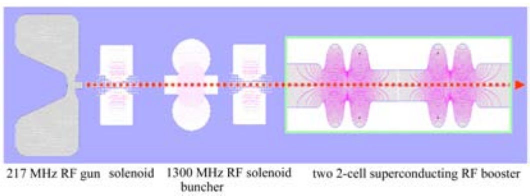

Fig. 8. The injector based on the 217 MHz RF gun.

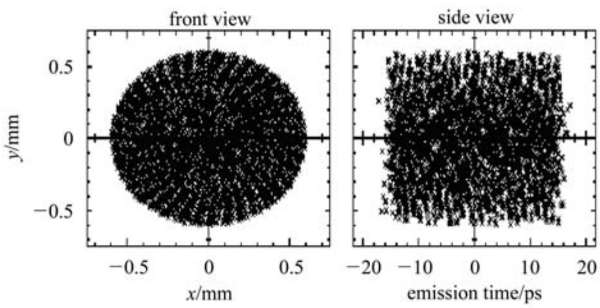

Fig. 9. The transverse and longitudinal distribution of the driving laser pulse.

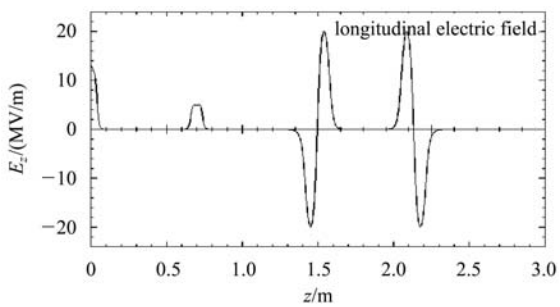

Fig. 10. The electric field of the accelerating structures and positions.

The gun frequency is 217 MHz and one RF period is about 4615 ps. One pulse of the driving laser with several ten ps covers several degree of RF phase only. Therefore the beam dynamics in this gun are almost the same as that in the DC gun. As noted above, the field gradient in this gun is not high for CW operation mode, so the space charge is the most important effect to worsen the beam quality of a 46 pC bunch. It is better to set the laser pulse longer and in a bigger size in the transverse direction. On the other hand, too long a laser pulse would bring heavy pressure on the buncher downstream and a big laser spot will increase the thermal emittance. The optimized and comprise parameters for simulation are as follows: the laser RMS beam size is 0.3 mm and it is in the flat-top shape longitudinally, the flat part is 30 ps long, the rise and down time are all 2 ps, as Fig. 9 shows. In the photoemission process, the GaAs cathode is illumined by 532 nm laser. The kinetic energy of the photoelectrons is assumed to be 0.2 eV. The thermal emittance due to the initial energy has been taken into account in the following simulation results.

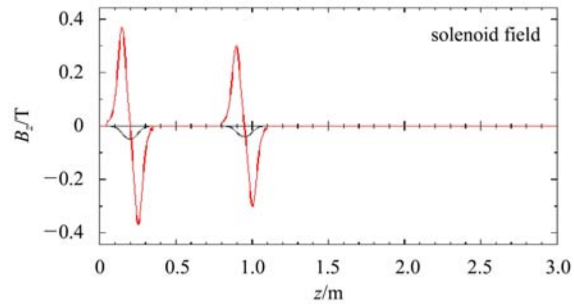

Fig. 11. The magnetic field of the solenoids and positions.

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 little bit of emittance compensation effect can also be made by them. In the buncher, we choose a suitable RF phase for the bunch injection, at which good velocity compression can be achieved. The phase for the minimum bunch length is 50° away from the phase for the maximum energy gain. In the simulation, we set the maximum field gradient along z axis to 5 MV/m. The beam gains 275 keV energy from the bunch. Thermal loads from ohmic losses on the cavity can be extracted by the cooling water system. The normal conducting RF cavity can operate in the CW mode. The two 2-cell superconducting RF cavities accelerate the beam from 0.775 MeV to 5 MeV. The maximum field gradient is set to 20 MV/m.

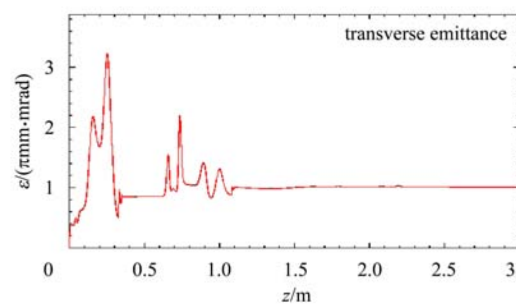

Fig. 12. The normalized emittance along the beam line.

Figures 12–16 show the optimized simulation results. At the end of the injector, the normalized emittance is 1.0 πmm·mrad, the RMS bunch length is 0.77 mm, the beam energy is 5 MeV and the RMS energy spread is 30 keV, the relative energy spread is only 0.6% and the beam size is kept less than 2 mm along the whole injector.

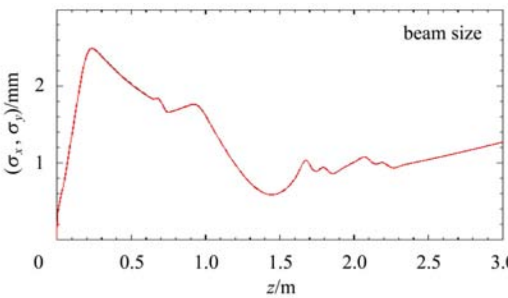

Fig. 13. The RMS beam size along the beam line.

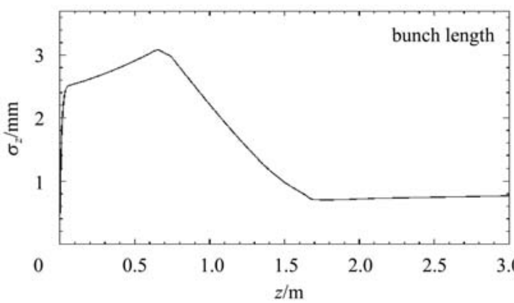

Fig. 14. The RMS bunch length along the beam line.

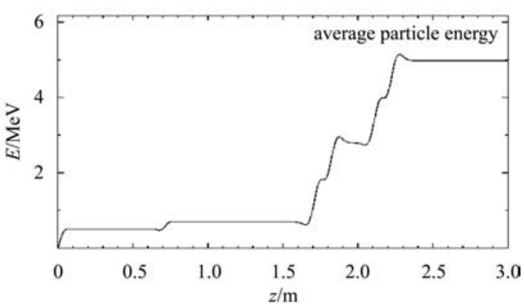

Fig. 15. The beam energy along the beam line.

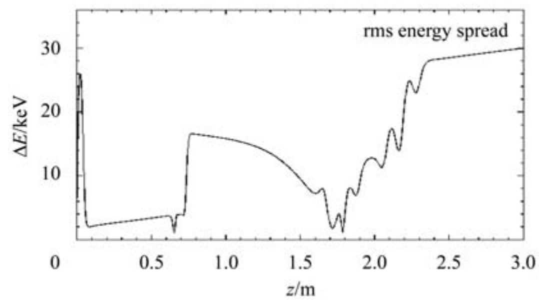

Fig. 16. The RMS energy spread along the beam line.

4 Conclusions

The photo-injector based on a 217 MHz normal conducting RF gun has been designed as the backup technology for BXERL test facility, which includes one normal conducting RF gun at 217 MHz, two solenoids, a normal conducting RF buncher at 1300 MHz and two 2-cell super conducting RF cavities at 1300 MHz in one cyromodule. The RF gun is optimized with 2D SUPERFISH and 3D MICROWAVE STUDIO codes. The injector setup and detailed beam dynamics have been done with ASTRA code. The optimized simulation results are good enough to satisfy the requirement of the BXERL test facility. The RMS normalized emittance is 1.0 πmm·mrad, the RMS bunch length is 0.77 mm, the beam energy is 5.0 MeV, the RMS energy spread is 0.6% and the injector is only 3.0 meters long from the cathode to the exit of the cyromodule.

We wish to thank WANG Shu-Hong, WANG Guang-Wei and Hou Mi for their valuable suggestions and discussions.

References

1 Neil G R et al. Phys. Rev. Lett., 2000, **84**: 662
2 Hajima R et al. First Demonstration of Energy-Recovery Operation in the JAERI Supper Conducting Linac for a High-Power Free-Electron Laser. http://www.aps.anl.gov/News/Conferences/2002/fel2002/talks/MO-O-09.pdf
3 Antokhin E A et al. NIM A, 2004, **528**: 15–18
4 Ben-Zvi I. The ERL High-Energy Cooler for RHIC, Proc. of EPAC06
5 Derbenev Y S et al. In Proceedings of the 2004 European Particle Accelerator Conference, Lucerne, 893–895
6 Gruner S M et al. Rev. Sci. Instrum., 2002, **73**: 1402
7 WANG Shu-Hong et al. IHEP Internal Report on the BXERL Test Facility (in Chinese)
8 CHEN Sen-Yu, WANG Shu-Hong, ZHU Xiong-Wei. Chinese Physics C (HEP & NP), 2010, **34**: 112–114
9 Baptiste K et al. NIM A, 2009, **599**: 9–14
10 Teichert et al. FZD SRF Gun Development and Testing, Energy Recovery Linac Workshop ERL'09, 08.-12.06.2009, Ithaca, USA
11 Ben-Zvi I et al. NIM A, 2006, **557**: 337–344
12 Hajima R et al. NIM A, 2006, **557**: 103–105
13 Bazarov I V et al. Phys. Rev. ST Accel. Beams, 2005, **8**: 034202