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Design study of a L-band DC photocathode gun

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Abstract In this paper, we the design study of a L-band DC photocathode gun injector for the ERL (Energy Recovery Linac) test facility. The main parameters of the injector are energy of 2.3 MeV, a bunch length of 2 ps, and a normalized emittance of 2.1 mm·mrad.

Key words ERL, DC gun, photocathode

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1 Introduction

The next-generation light source based on ERL (Energy Recovery Linac) technology provides an evolutionary path for X-ray science, because the ERL generates coherent X-rays and femtosecond X-rays which are difficult to obtain in the existing storage rings[1]. When the divergence of an electron beam is smaller than the intrinsic divergence of an X-ray, a large part of undulator radiation becomes coherent, and this criterion is called the “diffraction limit” and is given by $\varepsilon < \lambda/4\pi$, where ε is the geometrical rms emittance and λ is the X-ray wavelength. In order to satisfy the diffraction limit for 1 Å X-rays, the emittance should be less than 8 pm·rad, which corresponds to the normalized rms emittance of ~0.1 mm·mrad at 5 GeV. The average current of an ERL light source should be as large as 100 mA to obtain X-rays of flux comparable to the 3rd-generation light sources. Thus, the requirements of an electron gun for a future ERL light source are an average current of 100 mA and a normalized rms emittance of 0.1 mm·mrad. A DC photocathode gun[2] is the leading choice in the high average current electron beam sources for ERL. The injector will be based on a DC gun with a laser driven negative affinity photocathode. The SRF cavity will be used to boost the energy of the beam to the energy where the space charge effects are significantly reduced.

The aim of ERL is ambitious, but the path to ERL is still long. There are many issues to be resolved. It is necessary to build a test facility to prove the principle. In North China, there is a preliminary proposal[3] for an ERL test facility which is used for THz radiation, and some key technologies will be investigated. One of these technologies is the high average current electron gun. In this paper, we provide the design of the L-band DC photocathode gun for the proposed ERL test facility.

2 Basic setup

The basic setup of the L-band DC photocathode gun injector is shown in Fig. 1. The system consists of the DC gun, the focusing solenoid and the boost L-band superconducting buncher cavity. The DC gun and the SC buncher are arranged separately. This setup is more flexible than the DC-SRF[4] setup and is favourable to the focusing element. The negative high voltage is added to the cathode. The total length

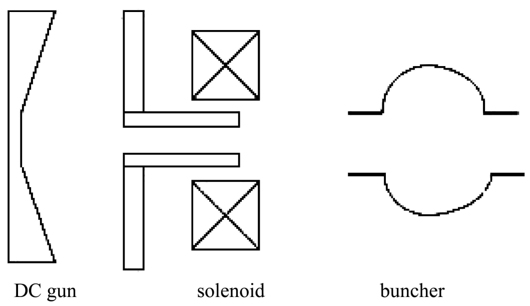

Fig. 1. Scheme of the DC phototcathode gun injector.

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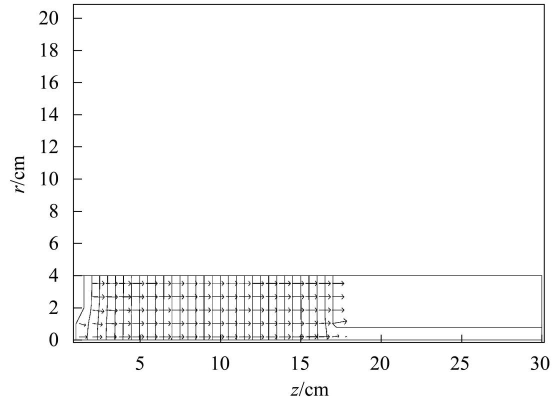

Fig. 2. The electric field of DC the gun.

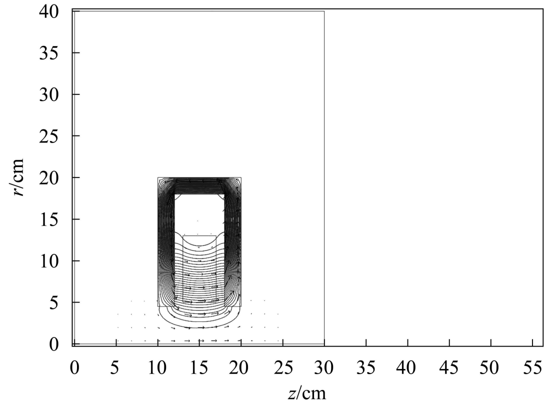

Fig. 3. The magnetic field of the focusing solenoid.

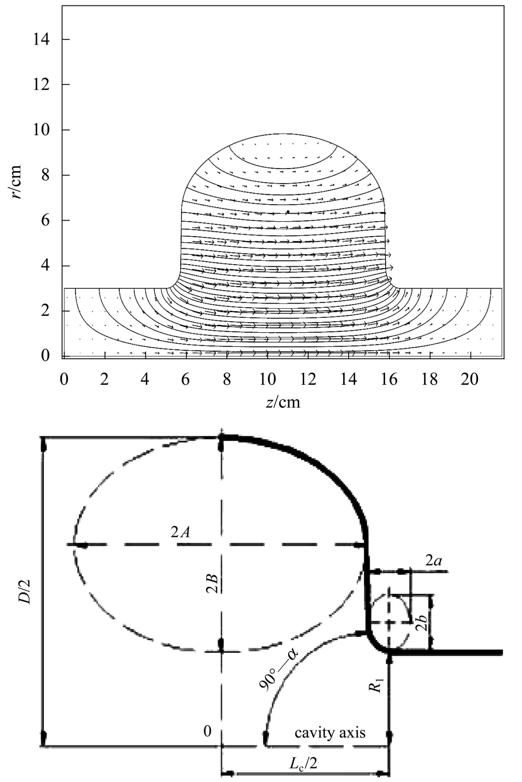

Fig. 4. The electric field of the L-band SC buncher cavity and the geometry of the cavity.

of the system is about 0.8 m. We use Superfish and Poisson[5] to simulate the DC gun, the focusing solenoid and the boost L-band superconducting buncher cavity, as shown in Fig. 2, Fig. 3 and Fig. 4, respectively . Tables 1, 2 and 3 summarize the parameters of the DC gun, the SC cavity and the laser system, respectively.

Table 1. The parameters of the DC gun.

GaAs wafer/mm	10
laser spot radius/mm	1
sloped focusing cathode/(°)	26.6
cathode anode distance/cm	16.2
beam charge/pC	77
the maximum axial electric field/(MV/m)	3.5
high voltage/kV	500
output beam bore radius/mm	8

Table 2. The parameters of the SC buncher.

cell length L_c/cm	11.4399
slope angle α/(°)	1
bore radius R_i/cm	2.9745
cavity diameter D/cm	19.4988
a/cm	0.7188
b/cm	0.8973
A/cm	4.9575
B/cm	3.4206
frequency/MHz	1300
quality factor	1.05×10^{10}
$(R/Q)/\Omega$	7.478

Table 3. The parameters of the laser system.

wavelength/nm	266
Rep. rate/MHz	130
pulse number/bunch	1
pulse energy/nJ	>18
laser radius(rms)/mm	1
rising time of pulse/ps	0.3
pulse length(rms)/ps	2.0
form of longitudinal pulse	uniform

The length of the solenoid is 20 cm, and the axial magnetic strength is 650 Gauss. The magnet shielding port can be installed on the side of the solenoid near the SC cavity buncher to shield the residual magnetic field, so the buncher is free of the stray magnetic field from the solenoid.

3 Beam dynamics result

We use Astra[6] to simulate the beam dynamics of the DC gun injector system. In the DC gun, the space charge limit current density is given by the Child-Langmuir law and estimated to be 2.33×10^8 A/m^2. In the simulation, the electron bunch charge is 77 pC, the corresponding current density ($\sim 10^7$ A/m^2) is far below the space charge limit current density, so no virtual cathode is formed inside the gun. GaAs is selected to be the cathode material. If the wavelength of the laser is 266 nm, the laser pulse energy will be 18 nJ (if the quantum efficiency (QE) of GaAs is about 2%) to produce the charge of 77 pC.

The beam dynamics in the DC gun is just that of the DC high voltage accelerator. In our simulation, we omit the initial energy spread and emittance of the electron beam. Due to the low energy, the space charge effect is strong. On the one hand, the bunch length quickly increases due to the longitudinal space charge force; on the other hand, the emittance dilutes due to the transverse space charge force. A solenoid is added to focus the beam. The beam dynamics in the buncher is that of the RF accelerator. The buncher compresses the beam while accelerating the beam to the final energy of 2.3 MeV.

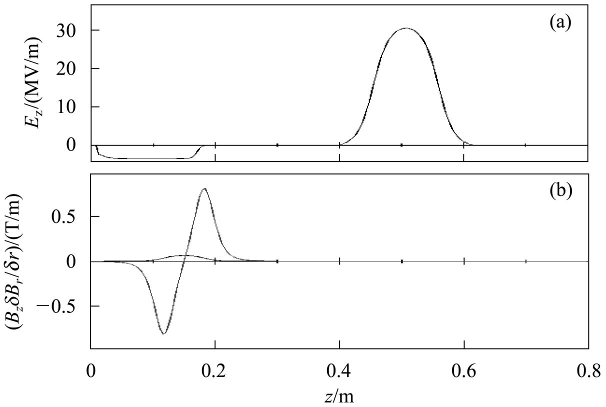

Fig. 5. The electric field (a) and the solenoid magnetic field (b).

The maximum magnetic strength of the solenoid is set to be 650 Gauss, and the maximum electric field strength of the buncher cavity is set to be 30 MV/m. Fig. 5 shows the longitudinal profile of the DC field and RF field in the gun and the buncher cavity, respectively. The phase motion in the buncher is strong and the bunch is compressed. Fig. 6 shows the evolution of the beam size, the transverse emittance and the rms bunch length along the distance. The final parameters of our system are an energy of 2.3 MeV, a bunch length of 2 ps, and a normalized emittance of 2.1 mm·mrad.

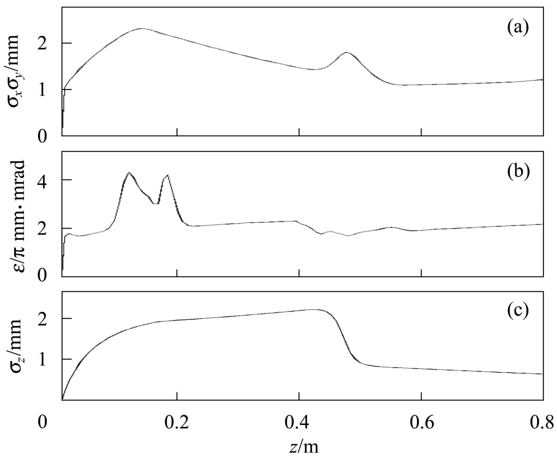

Fig. 6. The evolution of the beam size (a), the transverse emittance (b) and the bunch length (c).

4 Photo-cathode life-time consideration

The QE of the GaAs photocathode within the DC high voltage photoemission electron guns degrades primarily as a result of the ion back bombardment[6] where the residual gas between the cathode-anode gap is ionized by the extracted electron beam and back-accelerated toward the photocathode with sufficient kinetic energy damaging the photocathode surface. In addition, the ions produced in a beam line behind the anode and trapped within the beam can also be back-accelerated toward the photocathode and damage the cathode. The numerical example shows that the flux of trapped ions can significantly exceed the flux of ions produced at the anode-cathode gap[7]. The rate of QE degradation depends strongly on the rate of ion production which is a function of the vacuum condition within the gun and beam line. The following measures to cure the ion back bombard problem and prolong the cathode life-time are considered in this gun design:

1) To establish a very good base vacuum (say $10^{-11} \sim 10^{-12}$ torr (1 torr = 1.33322×10^2 Pa)) in the gun chamber and the beam line, by employing the fine heating bake out of gas from the chamber and the beam line, using highly effective non-evaporable getters (NEG) and ion pumps with high resolution (say <50 pA) power supplies.

2) To make a larger laser spot size when ion damage is distributed over a larger area. In our setup, the laser spot size is 1 mm, and the current density is relatively smaller.

3) To employ a positive potential barrier of a few volts at the end of the accelerating gap of the gun

(i. e, at anode) to eliminate the flux of trapped ions.

5 Conclusion

We have given the preliminary design of the DC photocathode gun injector for ERL. The main parameters of the injector are an energy of 2.3 MeV, a bunch length of 2 ps, and a normalized emittance of 2.1 mm·mrad. These parameters can be optimized further. Some measures to cure the problem of ion back bombardment on the cathode are preliminarily considered.

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