Design study of a L-band photocathode RF injector

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Abstract In the proposal of the Beijing Advanced Light Source, a compact combination of XERL and XFEL using a common SC linac is being considered. In the meantime, an ERL-FEL test facility is being proposed and will be used for THz radiation. In this test facility, a L-band photocathode RF injector is needed. In this paper, we give the physical design of the L-band photocathode RF injector for the test facility.

Key words XFEL, RF gun, photocathode

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1 Introduction

Early in 2008, there was a proposal for one machine, two purposes [1]: using a common SC linac for XFEL and XERL simultaneously at IHEP. Since then, we have done a series of preliminary design studies on some topics [2–5]: DC/RF photoinjector, merger (merging three beams), big bore SC cavity, the interactions between FEL and ERL beams via SC accelerating structure, main linac lattice (using graded gradient focusing lattice [6]), etc. In the meantime, there was a proposal for an ERL-FEL test facility which is used for THz radiation [1] as shown in Fig. 1. This test facility will further prove the principle of ERL and the novel idea of the combination of the two hard X-ray light source candidates: ERL and XFEL (“one machine, two purposes”) using a common SC linac.

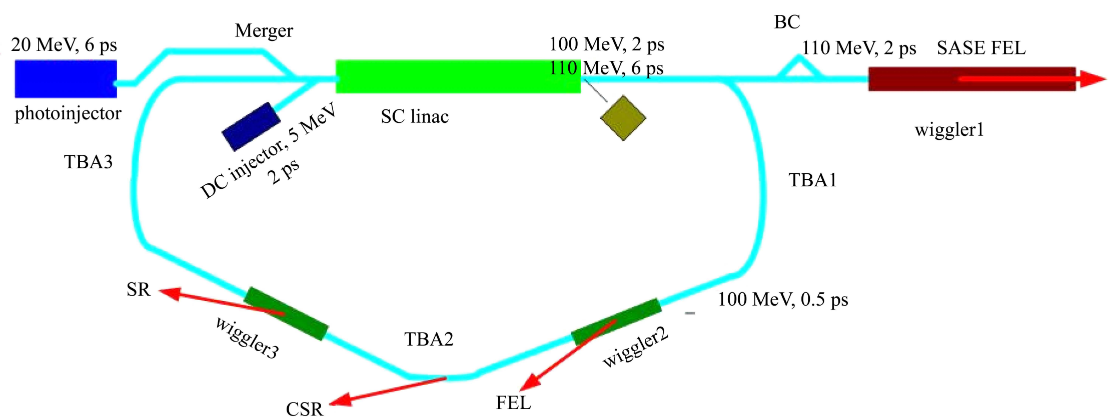

Fig. 1. Scheme of the ERL-FEL test facility.

In the test facility, there is a SASE FEL THz source driven by the 110 MeV electron beam which needs a 20 MeV L-band RF photoinjector whose main parameters are the pulse charge of 1 nC, the normalized emittance of 2 mm mrad, the energy spread of 0.2%, and the bunch length of 2 ps. In this paper, we report on the preliminary physical design of the needed L-band RF photoinjector.

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2 Basic setup of the system

The basic setup of the RF photocathode gun is shown in Fig. 2. It consists of a 1.5-cell L-band RF cavity, the solenoid, a focusing doublet and a L-band superconducting 9-cell cavity. We adopt the TESLA L-band 1.5-cell RF cavity [7], the main parameters of the cavity are summaried in Table 1. The RF gun cavity works in π mode. The field pattern is shown in Fig. 3 (calculated by Superfish).

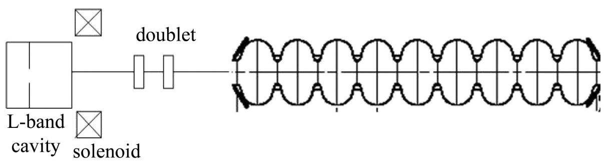

Fig. 2. Basic setup of the photocathode RF injector.

Table 1. Main parameters of L-band RF photocathode gun.

cathode	Cs_2Te
cathode radius	0.75 mm
QE	$>1\%$ at 270 nm
peak electric field	60 MV/m
energy	4 MeV
energy spread	$<1\%$ rms
RF frequency	1300 MHz
rep. rate	13 Hz
cell	1.5
cavity length	25 cm

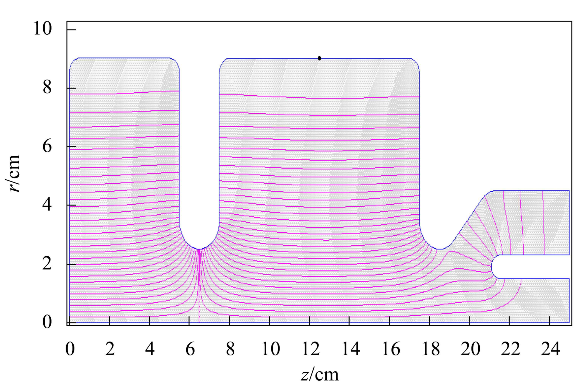

Fig. 3. Field pattern of π mode.

We have designed the L-band superconducting 9-cell cavity with the big bore of 4 cm , Table 2 summaries the main parameters of 9-cell cavity, which also works in π mode , as shown in Fig. 4 . The surface residual resistance affects the values of Q and R, and is set to 10 nΩ, the SC temperature is set to be 2 K in our calculation. The length of the tubes on the two sides of the cavity is 16 cm. Fig. 5 shows the typical standard parameter signals for SC half cell.

Table 2. Main parameters of 9-cell cavity.

working mode	π
half cell length L	11.54/2 cm
slope angle α	7 degree
bore radius R_i	4 cm
cavity radius D	10.699 cm
a	1.629 cm
b	2.606 cm
A	4.03 cm
B	3.224 cm
frequency	1300 MHz
quality factor	$\sim 1.0\times 10^{10}$
R/Q^*	920 Ohm

$*$ R/Q=voltage^2/(frequency$\times$stored energy).

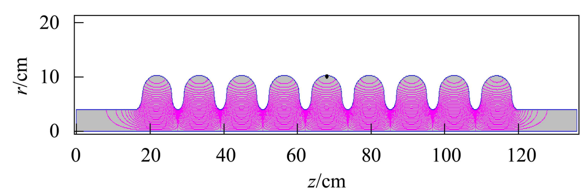

Fig. 4. Electric field of the 9-cell cavity.

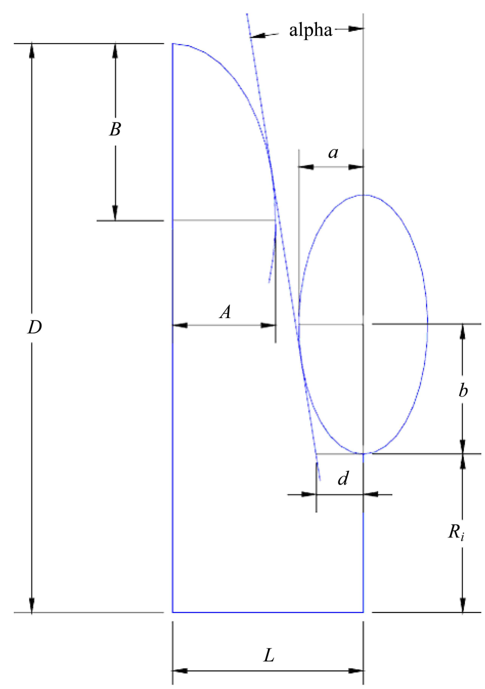

Fig. 5. Typical parameters of half SC cell.

Finally, we have also designed the focusing solenoid. The focusing field is shown in Fig. 6.

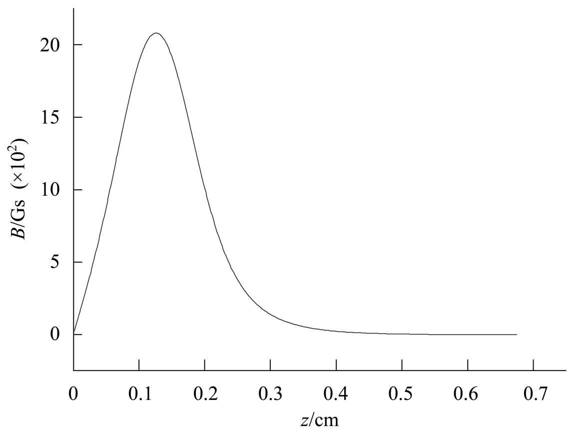

Fig. 6. The typical solenoid focusing field.

3 Beam dynamics result

We use ASTRA [8] to simulate the beam dynamics of the above RF photocathode injector system. The initial charge of the bunch from the cathode is 1 nC. The quantum efficiency of Cs_2Te is bigger than 1%. So the laser pulse energy is about 0.46 μJ. The simulation takes into account the space charge effect.

The thermal emittance from the photocathode can be estimated as [9]

$$\varepsilon_{\text{th}} = \frac{r_{\text{c}}}{2}\sqrt{\frac{k\cdot T_{\text{e}}}{m\cdot c^2}},$$

where r_{c} is the cathode radius, m is the electron rest mass, k is the Boltzmann constant, and T_{e} is the cathode temperature. In our case, the cathode radius is 0.75 mm, and the typical thermal emittance is estimated to be 0.3–0.4 mm·mrad. We take into account the thermal emittance in the simulation.

The peak magnetic field of the compensation solenoid is about 1600 Gauss. The length of the quadrupole of the doublet is 5 cm, and the focusing gradient is 0.3 T/m. The solenoid field and the doublet focusing gradient are optimized to make the rms envelope and the normalized emittance small. According to Serafini's envelope theory of the photoinjector [10], the laminar regime extends to an energy γ as

$$\gamma = \sqrt{\frac{2}{3}}\cdot\frac{I_{\text{p}}}{I_{\text{A}}\cdot\varepsilon_{\text{th}}\cdot\gamma'},$$

where I_{p} is the peak current, I_{A} is the Alfven current, and ε_{th} is the emittance induced by thermal cathode. The energy will be over 100 MeV using the above formula for our case and is too high for our test facility. So we just use the solenoid to compensate the emittanec induced by the space charge effect. Further, we don't use solenoid for the SC linac. Instead, we use a doublet to match the gun beam into the SC linac booster.

The final parameters of the photorinjector are the energy of 20 MeV, the energy spread of about 0.1%, the bunch length of 2 ps and the normalized emittance of 1.9 mm·mrad (horizontal) , 1.7 mm·mrad (vertical). In the simulation, the laser parameters we used are listed in Table 3. Figs. 7, 8, 9, and 10 show the normalized emittance, the beam envelope, the output transverse phase space and the output longitudinal phase space with the energy spectrum respectively.

Table 3. Main laser parameters.

wavelength	270 nm
laser radius	0.75 mm
Rep. rate	13 Hz
pulse energy	0.46 μJ
pulse length	2 ps (rms)
rise time	0.3 ps
form of longitudinal pulse	uniform

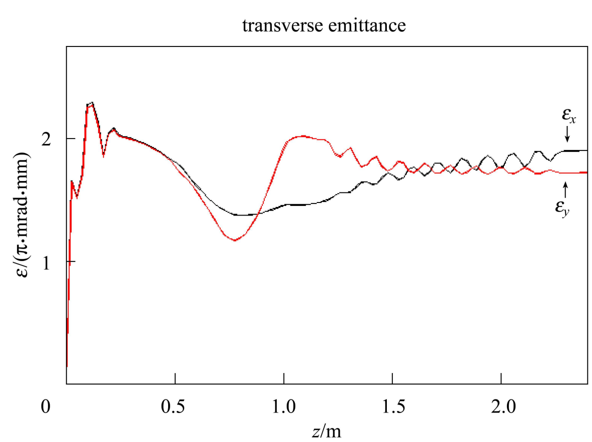

Fig. 7. Normalized emittance evolution along the distance.

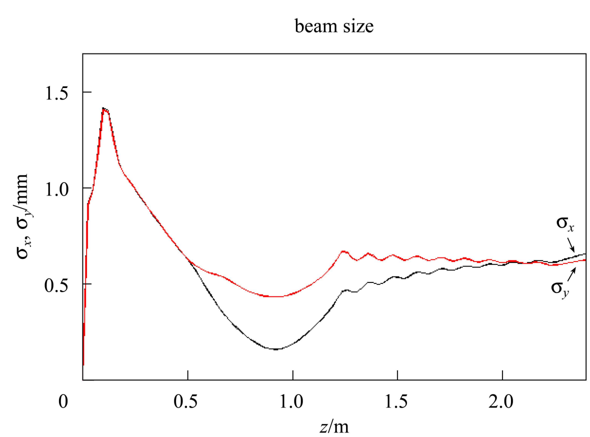

Fig. 8. Rms beam envelope along the distance.

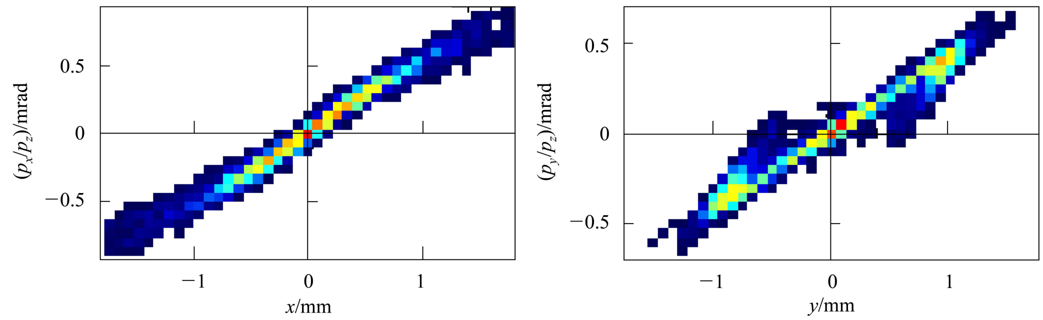

Fig. 9. Output transverse phase space (horizontal and vertical).

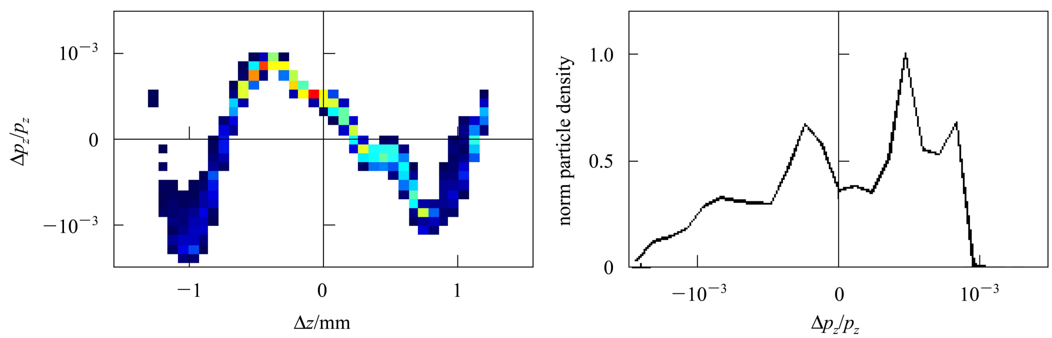

Fig. 10. Output longitudinal phase space and the energy spectra.

Table 4 summaries the main parameters of the L-band photoinjector.

Table 4. Main parameters of the RF injector.

pulse charge	1 nC
energy	20 MeV
normalized emittance	<2 mm·mrad
energy spread	$<0.1\%$ rms
RF frequency	1300 MHz
Rep. rate	13 Hz
total length	2.4 m

4 Discussion

In this paper, we report on the preliminary design of the L-band photoinjector. Due to the low energy limit, we don't use Serafini's envelope theory of the photoinjector for two compensation points completely. Instead, we use a doublet to do the beam match between the gun and the booster linac. The final parameters of the designed photoinjector satisfy the requirement of the proposed ERL-FEL test facility. Finally, we just do the extensive calculations to optimize the parameters simply. [11] gives an optimization method algorithm based on parallel computer.

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