# A Compact High-Average Current Photo-Injector[*]

ZHU Feng[1)]　　QUAN Sheng-Wen　　XU Wen-Can　　HAO Jian-Kui　　LIU Zhen-Chao

ZHAO Kui　　CHEN Jia-Er

(MOE Key Laboratory of Heavy Ion Physics, Institute of Heavy Ion Physics, Peking University, Beijing 100871, China)

**Abstract**　Based on the experimental results of the complex DC-SC photocathode injector (DC gun and 1+1/2cell superconducting cavity) at Peking University, an improved injector design is proposed. The new injector can provide high average current electron beams with bunch charge of 100 pc, cw operation, low transverse emittance and short bunch length. The optimization of the DC gun and superconducting cavity of the upgraded injector, structure design of the injector are presented in this paper.

**Key words**　photo-injector, superconducting cavity, DC gun

## 1　Feasibility of DC-SC complex photo-injector

DC photo-injector and SRF photo-injector are the two injectors which can provide high average current electron beams. But both of them also have their own disadvantages. DC photo-injector normally produces long bunch length electron beam, and it needs a buncher before the beams goes into the accelerator. So the scale of the whole injector is very large. SRF photo-injector needs to solve the compatibility of the photocathode and the superconducting cavity. The concept of combining of these two photo-injectors was first proposed by Peking University in 2001[1]. This is a compact electron gun, which integrates a pierce DC gun and a superconducting cavity. The photocathode is placed on the cathode of the pierce structure, and the pierce anode is on the entrance of the superconducting cavity. With this design, the compatibility problem between the superconduting cavity and the photocathode is solved because the photocathode is taken outside of the superconducting cavity. The DC gun can provide electron beams with high repetition rate. The conical wall and the high gradient of

the superconducting cavity focus and accelerate the electron beams further and thus high quality electron beam can be got.

To study the feasibility of the complex injector, Peking University manufactured a prototype injector including a DC gun and a 1.3GHz $1\frac{1}{2}$ cell superconducting cavity in 2002. After two years' commissioning and testing, this injector can successfully provide and accelerate electron beams[2]. Because the 2.0K system is not ready, the beam loading test was done at 4.4K. To avoid thermal quench, the injector was run at long pulse mode. The width of the macro pulse is 3.5ms. The repetition rate of the laser is 81.25MHz. The DC voltage is 40kV. The electron beam was successfully accelerated by the superconducting cavity. The accelerating gradient reached 6MV/m at the $Q_0 \approx 10^8$. The maximum energy gain was 1.1MeV at 4.4K. The prototype injector has confirmed the feasibility of the DC-SC integrating design.

## 2　Upgrade of DC-SC photo-injector

Based on the experimental results of the prototype injector and the need of Peking University energy re-

covery linac free electron laser (PKU-ERL-FEL), we need to upgrade the injector. PKU-ERL-FEL is a facility to provide users with IR FEL. The bunch charge is 60pC, repetition rate is 26MHz and the average current is about 1mA. POSSION, SUPERFISH, PARMELA, ASTRA and ANSYS programs are used to do simulations. Simulation results show that the new injector can provide electron beams with low emittance and short bunch length.
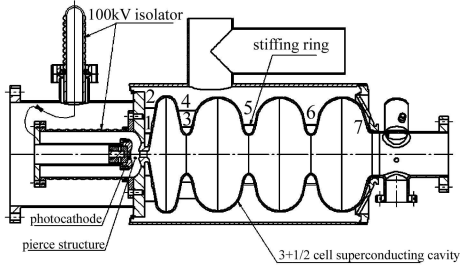


Fig. 1. Main parts of the upgraded photocathode injector.

The main parts of the upgraded injector consists of a 100kV DC gun and a $3\frac{1}{2}$ cell superconducting cavity. Fig. 1 shows the main parts of the injector. Beam dynamic simulation is done by PARMELA program. To get low emittance and small beam size, we add a solenoid with magnetic field of 850Gs. The solenoid is 50cm after the cavity (just behind the cryostat). The bunch shape has transverse uniform distribution and the beam transverse size is 3mm. The energy in the injector is relatively low. Therefore, the linear space charge effect dominates the transverse emittance increase. Such emittance increase can be compensated just by one solenoid[3]. Table 1 gives the initialized information and the simulation results of the injector. From Table 1, we can see that the new injector can provide electron beam with 100pC, high repetition rate, 5MeV energy, bunch length of 5.6ps and transverse emittance of 1.2mm·mrad, which satisfies the need of PKU-ERL-FEL.

The upgraded photo-injector is compact (about 1.5 meters long), practical and also allows continuous wave operation. It is a good injector for high average power PKU-ERL-FEL. Besides, by adding a bunch compressor and an undulator, it can also be a high average power THz source. The wavelength of the THz is about 300μm.

Table 1. Simulation results of the upgraded DC-SC photocathode injector.

| Drive laser | |
|---|---|
| pulse length | 8ps |
| spot radius | 3.0mm |
| repetition rate | 26MHz |
| bunch shape | transverse uniform, longitude Gaussian distribution |
| $3\frac{1}{2}$ superconducting cavity | |
| accelerating gradient | 13MV/m |
| electron bunch | |
| charge/bunch | 100pc |
| energy | 5.0MeV |
| emittance/rms | 1.2μm |
| longitudinal emittance/rms | 14deg·keV |
| bunch length | 5.6ps |
| rms beam size | 0.4mm |
| energy spread | ∼0.5% |

## 3 Integrated structure design of the injector

### 3.1 Geometry parameters of the pierce gun and the superconducting cavity

The optimization of the main parts determines the performance of the injector. Fig. 2 is the schematic of the pierce structure. The angles of the cathode and anode are 16° and 21°, separately. The operation high voltage is 90kV. The distance between both electrodes is 14mm. The gradient at the cathode is 5MV/m, the peak surface electric field is 12MV/m.
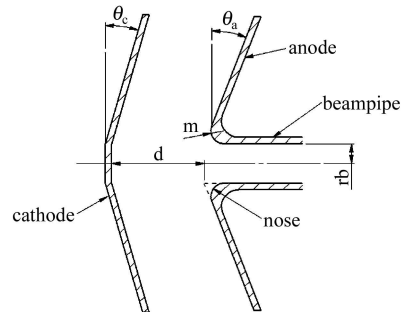


Fig. 2. Schematic of the pierce structure.

Three cells of the $3\frac{1}{2}$ cell superconducting cavity adopt TESLA midcup and endcup[4]. So the optimization emphasis of the cavity is put on the first

half cell (see in Fig. 3). There is a small beam tube between the DC gun and the superconducting cavity. In order to control the emittance increase, the length of the small tube is as short as possible. To avoid the fields from the superconducting cavity going inside the DC gun, the shortest length of the tube is 17mm when the radius of the tube is 6mm. With a conical wall, the first half cell has a negative value of the radial field near the entrance of the cavity and focuses the electron beam after the DC structure when the energy is only 90keV. Fig. 4 shows the fields near the axis of the cavity in the first half cell. The angle of the conical wall is 10°, which gives a low emittance and also helps to rinse the cavity.
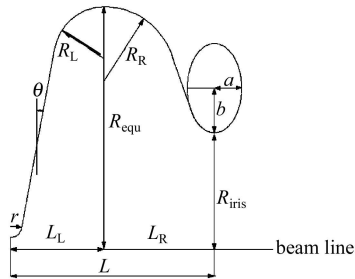


Fig. 3. Shape of the first half cell of the super-conducting cavity.
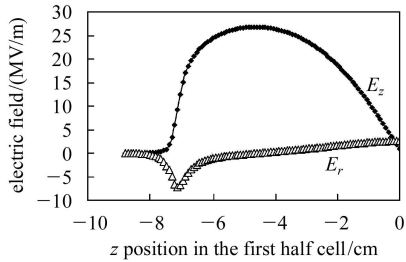


Fig. 4. RF fields near the axis of the first half cell (Fields are normalized to the accelerating gradient of 20MV/m).

Table 2 lists the geometry parameters of the first half cell of the superconducting cavity. Table 3 gives the RF simulation results of the 3+1/2 cell cavity.

Table 2. Geometry parameters of the first half cell cavity of the injector (dimensions are in mm).

| $r$ | $L_L$ | $L_R$ | $R_{equ}$ | $R_L$ | $R_R$ | $a$ | $b$ |
|---|---|---|---|---|---|---|---|
| 3 | 35.189 | 37.715 | 105.3 | 17.14 | 17.14 | 12 | 20 |

Table 3. RF parameters of the 3+1/2 cell cavity.

| $F$/MHz | $E_p/E_{acc}$ | $B_p/E_{acc}/$ (mT/(MV/m)) | $R/Q/\Omega$ | $Q(@2K)$ |
|---|---|---|---|---|
| 1301.38 | 2.12 | 4.95 | 418 | $1.4\times10^{10}$ |

## 3.2 Mechanical design

The $1\frac{1}{2}$ prototype injector is designed to test the feasibility of DC-SC complex photo-injector. There is neither tuning system, nor 2K transfer line. The new injector is the real one to provide high quality electron beam to PKU-ERL-FEL. It has much improvement and modification, especially in the mechanical design.

### 3.2.1 Alignment

In the test injector, the pierce gun and the superconducting cavity are separate.It is very difficult to adjust the center of the cathode and the axis of the cavity in a good alignment. This problem can be solved by the central flange between the pierce gun and the superconducting cavity in the new design (see Fig. 1).

Each side of the main parts has three strings and the angle of each two strings is 120°. By measuring and changing the force of the strings, we can adjust the axis of the cavity to the beam line.

### 3.2.2 Lorentz force detuning

The bandwidth of the cavity is very narrow because the injector works at 2K and the external $Q$ value ($Q_e$) is $1\times10^7$. Without stiffing rings, the frequency shift caused by the Lorentz force detuning is higher than 500Hz when the cavity is operated at 13MV/m. The resonant frequency is hard to be found when the cavity is operated at pulsed mode. By adding stiffing rings to the cavity, we can reduce the Lorentz force detuning coefficient to 1.2Hz/(MV/m)². The position of the stiffing rings are shown in Fig. 1 and listed in Table 4. Under such condition, there is no problem with the RF control of the cavity.

Table 4. Position of the stiffing rings of the 3+1/2 cell cavity.

| stiffer ring | position (distance from the axis)/mm |
|---|---|
| 1 | 38 |
| 2 | 85 |
| 3 | 50 |
| 4 | 80 |
| 5, 6, 7 | 53.5 |

### 3.2.3 Tuning system

Another difficulty is tuning of the $3\frac{1}{2}$ cell superconducting cavity. Firstly, the pierce structure is connected to the cavity. The distance between the cathode and the anode should not be changed. At the meantime, the beam tube of the coupler side should be fixed. Secondly, the geometry of the first half cell is much different from the other three cells. It is not easy to keep the good flatness of the whole cavity while the cavity is tuned to the right frequency. To solve the first problem, we place a bellow between the outer wall of the helium vessel and the center flange. When the cavity is compressed or stretched, the whole DC part will move together with the cavity while the helium vessel is fixed. The tuning range of the cavity is about $\pm200$kHz. The corresponding longitudinal length change of the cavity is about $\pm0.3$mm.

For the second problem, we use only one tuner to tune the $3\frac{1}{2}$ cell cavity through optimizing the position and number of the stiffing rings. ANSYS and SUPERFISH programs are used to do the simulations. Without stiffing rings, the change of the field flatness of the $3+1/2$ cell cavity is larger than $7\%$ when the cavity is stretched or compressed 0.6mm. But with the stiffing rings listed in Table 4, the change of field flatness of the whole cavity is within $3\%$ when the cavity is compressed or stretched 0.6mm.

The calculation shows that the cavity can work well at low temperature with only one tuner. The design of the tuner is also finished.

### 3.3 Primary consideration of the cryomodule

Figure 5 shows the schematic of the integrated injector. Under vacuum condition, the heat load of the cryostat is mainly caused by thermal conductivity and thermal radiation. Through thermal simulation, we know that the thermal distribution of the DC part. The temperature of any point of the DC part is below 10K. Therefore, the DC part is not a heat source to the 2K system. Calculation gives that the heat load of the injector cryostat is about 8W.
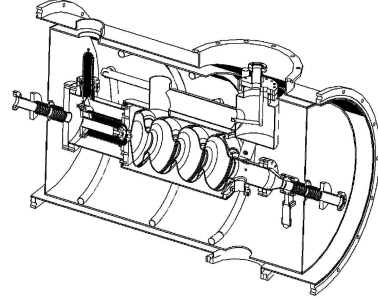


Fig. 5. Schematic of the cryomodule of the injector.

The cavity will be operated at 2K. The interface of the LHe port is connected to the 2K transfer line provided by Linde company.

## 4 Conclusion

The status of Peking University upgraded DC-SC photo-injector is discussed in this paper. This injector is a compact one and will provide high quality electron beams for PKU-ERL-FEL. It allows continuous wave operation or long pulsed mode operation with energy of 5MeV. The design of the cavity and DC pierce structure has been finished. The alignment of the cathode and the cavity can be solved in the new design. By optimizing the position and number of the stiffing rings, we can solve Lorentz force detuning and filed flatness problems of the $3\frac{1}{2}$ cell superconducting cavity. The cryogenic system has been considered.

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# 紧凑型高平均流强光阴极注入器[*]

朱凤[1)] 全胜文 徐文灿 郝建奎 刘振超 赵夔 陈佳洱

(北京大学重离子物理研究所 北京 100871)

**摘要** 根据北京大学1+1/2单元超导腔直流–超导(DC-SC)光阴极注入器的实验研究结果, 证明了这种新型光阴极注入器的可行性, 在此基础上对这种新型注入器进行了升级设计, 使之成为实用的紧凑型高平均流强的光阴极注入器, 为北京大学自由电子激光装置提供品质良好的电子束流. 给出了升级的3+1/2单元超导腔注入器的详细设计, 包括注入器核心结构的电磁场设计、束流动力学模拟、机械设计. 并对整个注入器的恒温器进行了初步设计.

**关键词** 光阴极注入器 超导腔 直流电子枪