Lorentz detuning and tuning system study of 3+1/2cell DC-SC photo-injector for PKU-FEL *

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Abstract A 3+1/2cell DC-SC photo-injector for PKU-FEL facility is under development，which is an upgrade design of the successful 1+1/2cell DC-SC photo-injector. The Lorentz detuning and tuning structure for the 3+1/2cell superconducting cavity is presented in this paper. The Lorentz force detuning coefficient is 1.2 Hz/(MV/m)^2 with double stiffening rings for the half cell and single stiffening rings between the adjacent TESLA cells. With the special stiffening structure, the 3+1/2cell whole cavity needs only one tuner. The influences of the tuning on frequency shift, field flatness and average gradient are discussed in this paper. The simulation results show that the stiffening rings' design is successful.

Key words 3+1/2cell DC-SC photo-injector, Lorentz detuning, tuning structure

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1 Introduction

After a successful proof-of-principle experiment on a 1.3 GHz, 1+1/2cell DC-SC photo-injector[1], a 3+1/2cell DC-SC prototype photo-injector for PKU-FEL has been under development since 2004. Up to now, both the physics and engineering designs of the injector are almost finished and some parts are being fabricated. The cryostat of the 3+1/2cell DC-SC injector consists of a DC pierce gun, a 3+1/2cell superconducting cavity, a He-vessel, a LN2 cooling thermal shield, a cold magnetic shield, as well as the main coupler and tuning system. The design parameters of the DC-SC injector are shown in Table 1. The injector will be operated in macro-pulse mode with 100 pC and 26 MHz pulse repetition. It would also allow CW operation if the liquid He supply is sufficient. The 3+1/2cell DC-SC injector will provide a final electron energy of 5 MeV and a bunch length of 5.6 ps, which could not only provide high quality electron beam for PKU-FEL, but also be a THz source with about 300 μm wavelength.

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

drive laser	
pulse length	8 ps
spot radius	3.0 mm
repetition rate	26 MHz
bunch shape	transverse uniform, longitude gaussian distribution
3+1/2 superconducting cavity	
accelerating gradient	13 MV/m
electron bunch	
charge/bunch	100 pC
energy	5.0 MeV
emittance (rms)	1.2 μm
longitudinal emittance (rms)	14 deg·keV
bunch length	5.6 ps
rms beam size	0.4 mm
energy spread	∼0.5%

2 DC gun and superconducting cavity

Figure 1 shows the design of the DC pierce gun and the superconducting cavity. The DC gun is a pierce structure with a 14 mm distance between two electrodes, which could be operated at 100 kV. The superconducting cavity consists of three full TESLA cells and a half cell. The design of half cell is the result of considering the RF-filed, beam dynamics numerical optimization, a better matching with the DC gun. The main parameters of the 3+1/2cell cavity calculated by SUPERFISH are listed in Table 2.

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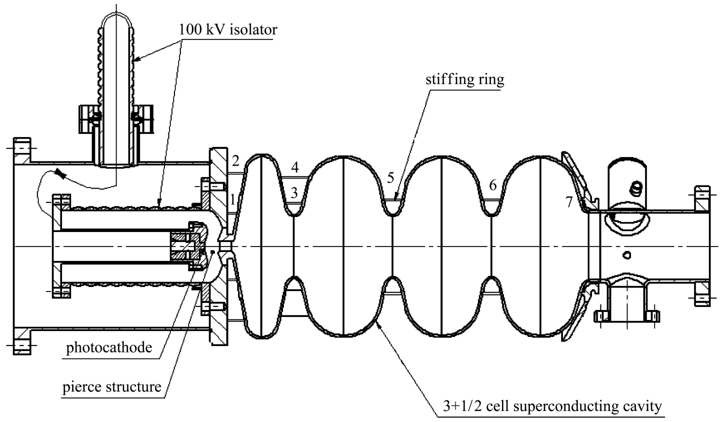

Fig. 1. The structure of the DC-SC gun.

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

cavity frequency/MHz	quality factor Q_0 at 2K	E_{peak}/E_{acc}	B_{peak}/E_{acc}	geometry fator/Ω	$R/Q/\Omega$	external Q_{ext}
1301.7	1.43×10^{10}	2.13	5.03	241.6	417.9	1×10^7

3 Lorentz force detuning and cavity stiffening

Since the injector will be operated in pulse-mode and the high external Q_{ext} situation of the 3+1/2cell cavity, Lorentz detuning is a very important issue. The frequency error caused by Lorentz detuning would be more than 500 Hz without any cavity stiffening, as the injector is operated at 13 MV/m. So, it is necessary to make cavity rigid with proper stiffing rings. The principle is to dispose a fixed point in the cavity wall in order to balance the electric and magnetic forces of the detuning.

Lorentz force is the result of the electromagnetic field in a cavity interacting with the RF wall current. The resulting pressure acting on the cavity wall is[2]

$$p=\frac{1}{4}(\mu_0H^2-\varepsilon_0E^2)\,. \tag{1}$$

A small deformation of the cavity shape results in a shift of the cavity resonant frequency according to Slater's rule[3]

$$\frac{\Delta f}{f_0}=\frac{1}{4}\frac{\int_{\Delta V}(\mu_0H^2-\varepsilon_0E^2)\mathrm{d}V}{W}\,, \tag{2}$$

where

$$W=\frac{1}{4}\int_{\Delta V}(\mu_0H^2+\varepsilon_0E^2)\mathrm{d}V \tag{3}$$

is the stored energy and f_0 is the resonant frequency of the unperturbed cavity.

The frequency shift is proportional to the square of the accelerating field, which is described as

$$\Delta f=-KE_{acc}^2\,, \tag{4}$$

here E_{acc} is the cavity accelerating gradient. K is the Lorentz force coefficient, which strongly depends on the cavity wall's rigidity. The stiffening structure is to reduce K as less as possible.

To simplify the tuning system and with the consideration of mechanical space, we tune the whole 3+1/2cell cavity with only one tuner, which means we have to optimize the stiffing ring well. Employing the code ANSYS with formula (1)—(4), we get the minimum Lorentz force coefficient K to be 1.2 Hz/(MV/m)^2, when double stiffening rings are welded to each side of the half cell and one stiffening ring is welded between the adjacent TESLA cells as seen in Fig. 1. Table 3 shows the locations of each stiffening rings. This means the frequency error is 202.8 Hz due to Lorentz force at a gradient of 13 MV/m.

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

stiffening ring	position (around from the cavity axis)/mm
the half cell to LHe vessel	38
half cell to LHe vessel	85
half cell to TESLA cell	50
half cell to TESLA cell	80
adjacent of TESLA cell	53.5

4 Simulation of the tuning system

For the 3+1/2cell cavity, a frequency tuning is necessary during operation. To simply the tuning system, we employ only one tuner to tune the whole 3+1/2cell cavity. However, there is a DC gun adjacent to the half cell, the tuning should not destroy the pierce gun structure and change the distance between the cathode and the anode. We make the 20 mm thickness of the anode and 4 mm thickness of the beam pipe in order to stiffen the pierce gun.

ANSYS and Poisson SUPERFISH were combined to simulate the effect of tuning on the cavity frequency and the field flatness. Either side of the cavity was fixed, pressing or stretching the other side of the cavity. The range of pressing and stretching is 0.4 mm, which is enough for our situation. The tuning displacements lead to frequency shift Δf, as shown in Fig. 2. It demonstrates that the frequency shift is still linear to the displacement even tuning the whole 3+1/2cell cavity with only one tuner. And tuning either side of the cavity is the same to the frequency shift, which is very important for the cryomodule integration.

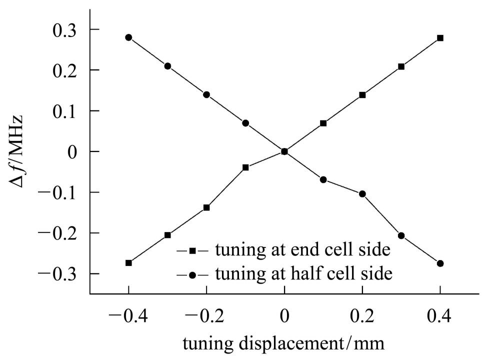

Fig. 2. The frequency shift Δf for tuning displacement.

Figure 3 shows the influence of tuning displacement on the field flatness of the cavity. The flatness of the cavity before tuning is about 3.4%. The flatness of the cavity would be better than 3.4% if detuning with some special displacements, as we don't do any change for the 3cell TESLA cells. However, the flatness is not much different than the one tuned on either side of the cavity.

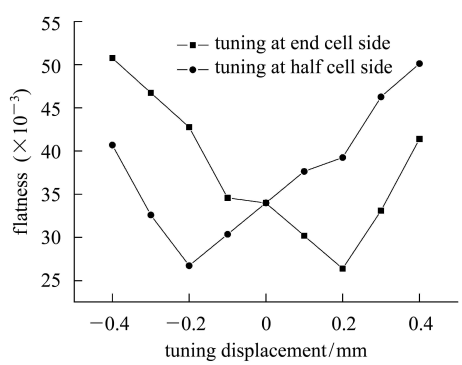

Fig. 3. The flatness for tuning displacement.

The E_{peak} for each cell influenced by the tuning are shown in Fig. 4. We can come to conclude that tuning at either side of the cavity will not affect the average gradient much and the E_{peak} of each cell.

For the cryomodule integration, we will tune the cavity on the half side, as shown in Fig. 5. The tuning system is similar to the ELBE's tuning system. The tuner mechanism consists of two levers, a spindle with partly left-hand thread and right-hand thread and two special bearings. The main parameters that should be considered include the tuning range, the high resolution, the linear operation and the life time. A prototype for experiment is being fabricated and will be completed in June 2007.

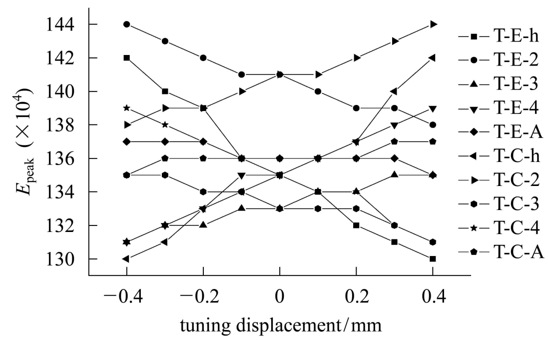

Fig. 4. The E_{peak} of each cell for tuning displacement.
T-E-h/2/3/4/A means the E_{peak} of the half cell/2d cell/3d cell/4th cell/Average when tuning is at the end cell side (the 4th cell). T-C-h/2/3/4 the peak E_{peak} of the half cell/2d cell/3d cell/4th cell/Average when tuning is at half cell side.

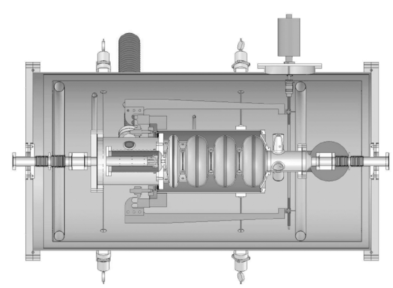

Fig. 5. Schematic injector layout.

5 Conclusion

The Lorentz detuning factor has been optimized to 1.2 Hz/(MV/m)^2, which can satisfy the mechanical and cost requirement for the 3+1/2cell cavity. The simulation results show that one tuner for 3.5cell superconducting injector is also qualified with double stiffening rings for the half cell and single stiffening rings between the adjacent TESLA cells. The tuner located on either side is reasonable. However, the cavity will be tuned at the cathode side with the consideration of mechanical space. And the thick anode and beam pipe are used to stiffen the pierce gun.

References

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