STRUCTURE DESIGN AND OPTIMIZATION OF A COMPACT C-BAND PHOTOCATHODE RF GUN *

Xiaohan Liu[#] ,Chuanxiang Tang
Department of Engineering Physics, Tsinghua University, Beijing 100084, P.R.China

Abstract

In this paper, we present the preliminary structure design and optimization of a C-band photocathode RF gun for a compact electron diffraction facility, which is designed to work at the frequency of 5.712GHz. A dual coupler and elliptical iris between the half-cell and full-cell will be adopted in this gun to achieve lower emittance and larger mode separation. A detailed comparison on the beam dynamics parameters of the optimized structure and traditional RF gun is performed. This paper likewise presents the 3-D simulation and analysis of this RF gun.

INTRODUCTION

High brightness injector is being actively developed in accelerator area. Ultra-short and ultra-low emittance electron bunches become the new research tools in biology, materials, chemistry science, and many other fields[1]. Several studies have shown that the photocathode RF gun can be utilized to generate high-energy ultra-fast electron beams. The C-band RF gun has several advantages over the traditional S-band RF gun, including smaller size, higher accelerating field, lower input power, and applicable in compact low energy facilities. Therefore, an C-band (5.712 GHz) RF gun is being developed for electron diffraction in Tsinghua Univercity[2].

For the requirement of low emittance beam bunch and high microwave field operation, some structure optimization of the C-band RF gun has been performed. Simulations of the three types structure indicate the difference in microwave parameters. The elliptical iris replace of rounding shape one and the helicoflex is removed in the optimized structure, in order to decrease the breakdown and dark current. The cell length has been scanned in beam dynamics simulation to obtain ultra-short bunch.

A dual coupler is designed in 3D EM simulation for this C-band RF gun to avoid field asymmetries. The RF power in a typical RF gun is fed through a waveguide connected to the full cell by a coupling slot. Previous studies reported that single feed coupler will cause field asymmetry which significantly deteriorates the transverse beam emittance[3]. The emittance growth can be suppressed by adopting the dual coupler for correcting the dipole field, while the quadruple field can be corrected by a race track interior shape for the full cell. The Z-coupling[4] hole is adopted to suppress breakdown in high power test by decreasing the heat temperature, while the vacuum will be improved in this case.

STRUCTURE COMPARISON AND OPTIMIZATION

We perform detailed simulations for comparing the main parameters of three different structures of C-band RF gun, as well as the sensitivity of microwave property for cell dimension. Type 1 is similar to the BNL design. Type 2 is optimized by a thin iris and a larger beam hole to increase the mode separation, but the iris is still a rounding shape. Helicoflex is removed in this type. Type 3 possess of a elliptical iris, while the mode separation is increased to 30MHz, and a dual coupler and a race track interior shape[5] for the full cell have been adopted. The compared parameters are shown in Table 1.

Table 1: Main Parameters Comparison

Type	Mode	Frequency /MHz	Mode sep. /MHz	Balance	Iris-r /cm	Iris-L /cm
1	π	5712.01	6.5817	1.00003	0.625	1.1025
	0	5705.43				
2	π	5712.02	26.7716	1.001	0.74	0.9525
	0	5685.25				
3	π	5712.00	30.1124	1.0005	0.7423	0.9522
	0	5681.89				

The sensitivity analyse on frequency of the π mode, field balance, and mode separation for cell dimension is performed (Figure 1). The microwave property of type 1 with the BNL design is instable and sensitive for the variety of full cell radius. The other two optimized structures have better stability. This stability will benefit the tuning process, and require lower machining techniques. Table 2 gives the quality factor of the π mode, shunt impedance, the calculated input power for building a 100MV/m accelerating field, and the normalized field at cathode and iris. Previous experiment on RF gun showed that there is serious breakdown at iris between the two cells. We normalize the field as the average along the longitudinal axis to one, and calculate the largest field at iris and the field at the cathode centre. For the rounding iris, the largest field at the iris is 98% of field at the cathode centre, and for the elliptical iris it is 88%, which is much lower.

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*Work supported by National Natural Science Foundation of China and National Basic Research Program of China (973 Program)

[#] liu-xh08@mails.tsinghua.edu.cn

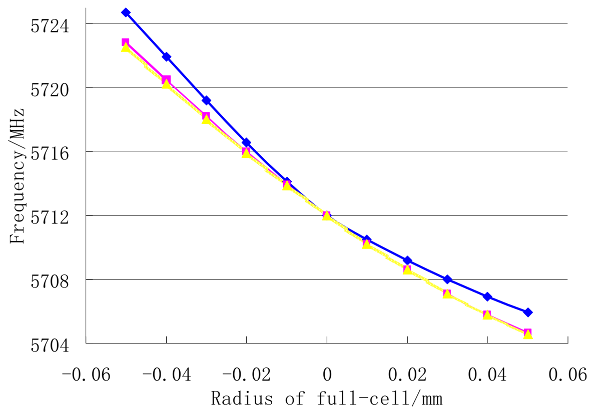

Figure 1(a): Sensitivity of the frequency for the radius variety of full cell on type 1 (blue), type 2 (pink) and type 3 (yellow), respectively.

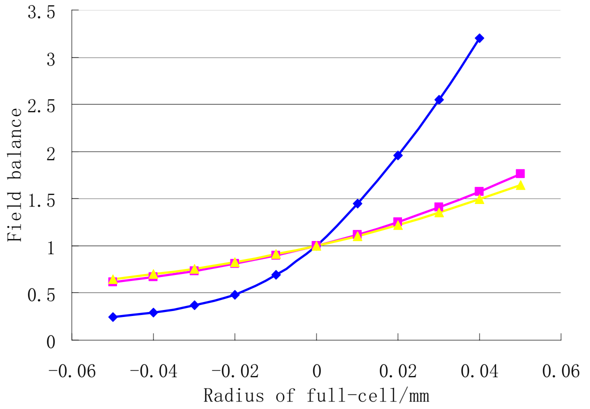

Figure 1(b): Sensitivity of the field balance for the radius variety of full cell on type 1 (blue), type 2 (pink) and type 3 (yellow), respectively.

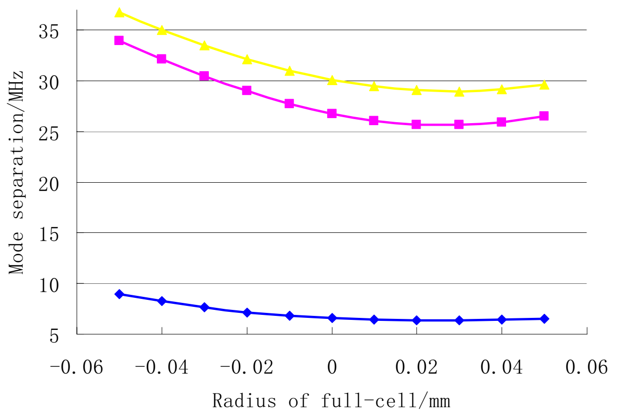

Figure 1(c): Sensitivity of the mode separation for the radius variety of full cell on type 1 (blue), type 2 (pink) and type 3 (yellow), respectively.

Table 2: Microwave Property Comparison

Type	1	2	3
Q_0	11247.7	11380.9	11768.1
$r / M\Omega$	3.103	2.767	1.877
P_0 / MW	1.386	1.643	2.941
Iris Field	1.770	1.769	1.687
Cathode Field	1.792	1.805	1.914

BEAM DYNAMICS OPTIMIZATION

As the advantage in microwave property of the type 3 structure showed above, it has more optimized dynamics parameters. The beam dynamics simulation with PARMELA of the C-band RF gun with this new structure has been performed (Table 3).

Table 3: Beam Dynamics Parameters

Input Parameters	
Bunch Charge (pC)	1
Bunch Radius (mm)	0.5
Injection Phase (Deg.)	10
Field at Cathode (MV/m)	100
Beam Dynamics Parameters	
Electron Energy (MeV)	2.35
RMS Bunch Length at Gun Exit (fs)	35.3
Normalized Emittance (mm.mrad)	0.181

For the requirement of the ultra-short beam bunch in our ultra-fast electron diffraction, this C-band RF gun should achieve more compression in bunch length. We scanned the length of the full cell, and observed beam dynamics result in different cases. The energy curves of the 1.6 cell and 1.5 cell for different injection phases are shown in Figure 2. By shortening the full cell length and increasing the accelerating gradient, we can see the energy chirp in a proper phase range (Figure 2(b)). Therefore, the head of the electron beam gain lower energy, while the tail of the electron beam arrive at the gun exit with higher energy. Consequently the tail electron will chase the head, and the beam can be further compressed.

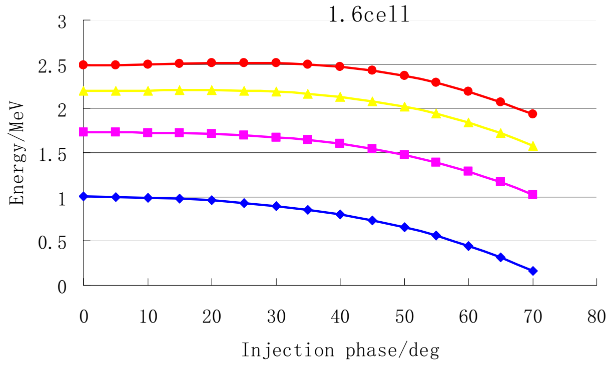

Figure 2(a): Energy curve for the 1.6 cell at accelerating gradient 80MV/m (red), 120MV/m(yellow), 150 MV/m(pink),and 170 MV/m(blue), respectively.

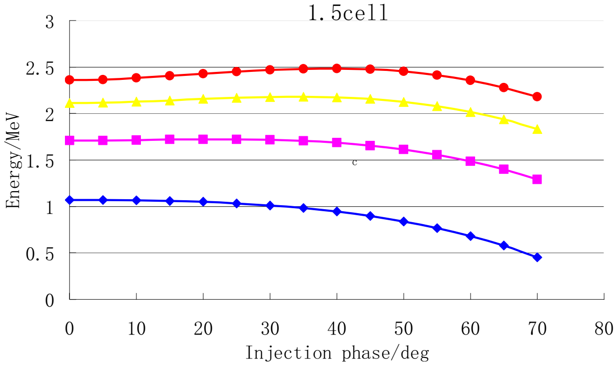

Figure 2(b): Energy curve for the 1.5 cell at accelerating gradient 80MV/m (red), 120MV/m(yellow), 150 MV/m(pink),and 170 MV/m(blue), respectively.

COUPLER DESIGN

A dual coupler with Z-coupling hole is designed in the 3D model (Figure 3) [6]. Comparing with the single feed coupler, the dual coupler will avoid field asymmetry which significantly deteriorates the transverse emittance. In addition, the dipole field can be corrected. The Z-coupling hole is adopted to suppress breakdown in high power test by decreasing the heat temperature, while the vacuum will be better than that of θ-coupling.

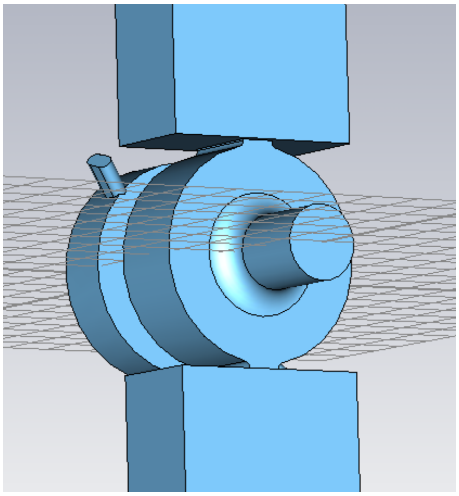

Figure 3: 3D model of the dual coupler with Z-coupling hole.

In order to obtain the critical coupling, we adjusted the Z-coupling hole, and calculated the coupling factor. A pulse signal was fed to the electron gun through the coupler, and the decay curve of the stored energy in the electron gun can be monitored as [7]:

$$W_t = W_0 e^{(-2\pi f t / Q_e)} .$$

We can thus obtain:

$$Q_e = -2\pi f t / \ln(W_t / W_0) .$$

The decay portion of the curve becomes linear in logarithm scale, and we can obtain Qe from the slope of the curve [8]. Q_0 is calculated for the specified gun structure. Taking into account that $\beta = Q_0/Qe$, after the dimension optimization, the width of the z-coupling hole is 6.6 mm, and the length is the same as that of the full-cell for the critical coupling.

CONCLUSION

The detailed structure design for the C-band photocathode RF gun is presented. The analysis and comparison on microwave parameters and beam dynamics results are summarised in this paper. Many new designs have been attempted in this new gun. The advantages have been confirmed by comparing with the traditional design. The optimized size of the iris, dimension of the dual coupler, and the cell length are obtained. The processing and experiment will be conducted in our future work.

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