DEVELOPMENT OF A COMPACT C-BAND PHOTOCATHODE RF GUN*

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Abstract

A C-band photocathode RF gun for a compact electron diffraction facility is developed at Tsinghua University, which is designed to work at the frequency of 5.712GHz. This paper presents the physics and structure design of this C-band RF gun, and the comparison of beam dynamics of S-band and C-band photoinjectors. New design features will be adopted in this gun, including the optimized cavity length and elliptical iris, which are helpful to achieve better compression, lower emittance and larger mode separation.

INTRODUCTION

Ultra-fast electron diffraction (UED) has been a powerful tool for micro-structure dynamics studies. The previous keV UED system has some limitations on temporal resolution, which is caused by space charge effects of a low energy beam [1]. By increasing the electron energy from keV to MeV, the space charge effects are dramatically reduced. A compact MeV UED facility based on a C-band photocathode RF gun at Tsinghua University is under development. The C-band RF gun is utilized to generate ultra-short and ultra-low emittance electron bunches, which can match the requirements of MeV UED.

Comparing with the traditional S-band RF gun, the C-band RF gun has several advantages, including smaller size, higher accelerating field, lower input power, better compression and applicability in compact low energy facilities [2]. Detailed comparisons of beam dynamics for the S-band and C-band will be performed. The MeV UED requires ultra-short electron bunches, which can be achieved by the better compression property of C-band RF gun. In addition, space charge effects will affect the temporal resolution of the diffraction ring, and hence cause an offset of the diffraction ring peak. For obtaining the same electron beam energy as in S-band RF gun, the higher gradient of C-band RF gun is helpful to decrease the space charge effects [3].

This C-band RF gun is designed to work at the frequency of 5.712GHz. Optimizations on structure design and beam dynamics have been carried out. The cell length has been adjusted through simulation for ultra-short bunch and lower energy chirp [4]. The elliptical iris replaces the original circular rounding shape and the helicoflex is removed in the optimized structure, in order to decrease breakdown and dark current. The mechanical structure design likewise has adopted innovated features, including the inside rounding shape, the match and brazing of the cathode and the half-cell, and the non-inserted turner for both the half-cell and full-cell.

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

The main microwave parameters of the C-band photocathode RF gun are listed in Table 1, and the 3-dimensional model and pi-mode field are shown in Fig. 1. The operation frequency is designed at 5712MHz. The cell-length is optimized at 1.45 cell, which will be studied in detail for beam dynamics.

Table 1: Main Microwave Parameters

Parameter	Pi-mode	0-mode
Frequency/MHz	5712.01	5681.90
Q_0	10104	12387
$r/M\Omega$ /m	72.5	110.1
Mode sep./MHz	30.1	
Balance	1	

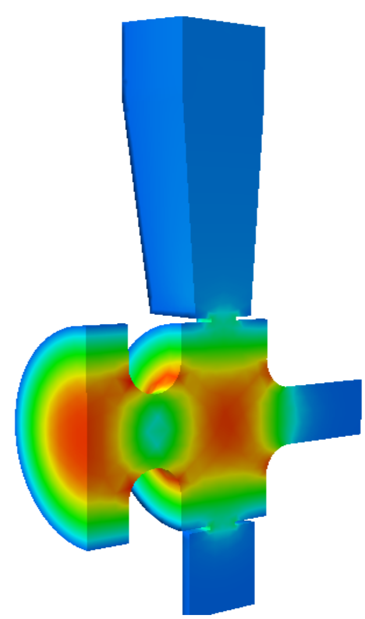

Figure 1: 3-dimensional model and pi-mode field of C-band photocathode RF gun

The mode separation increases to 30MHz by using the elliptical iris instead of the rounding shape, while the maximum surface field at the iris decreases. We calculated the normalized surface field inside the RF gun using a normalized average field at 1. From the results in Table 2, we can achieve that the field at the iris reduces to 88.1% of the field at the cathode, which helps suppress dark current.

In addition, the elliptical iris will help suppress the 0-mode excitation. When the pi-mode accelerating field is 100MV/m and phase is 180^0, the ideal 0-mode field is 0 at the phase of -90^0. Because of the bandwidths of both the pi-mode and 0-mode, when driving at the pi-mode frequency, the 0-mode would be excited, which will affect the beam quality [5]. The comparison on the 0-mode excitation of using the different iris shapes is shown in Table 2.

Table 2: Iris Optimization

Surface field		
Parameter	Rounding Iris	Elliptical iris
Normalized field at iris	1.770	1.687
Normalized field at cathode	1.792	1.914
Proportion	98.8%	88.1%
0-mode excitation		
Mode sep./MHz	6.5	30.1
Pi-mode/MV/m	100∠180°	100∠180°
0-mode/MV/m	11.19∠-85°	2.24∠-89°

We calculated the dipole and quadrupole fields in the full-cell caused by the coupler that feeds at the full-cell. The dipole field is 5.2e-3 and the quadrupole field is 1.33e-3 above the reference field at the radius of 5mm away from the center of the full-cell. The emittance growth caused by the multi-pole fields is estimated using the following formula [6]. The initial bunch length is chosen at 100fs.

$$\begin{aligned}\varepsilon_{n,y}^{110} &= \sqrt{<(p_{y,110} - <p_{y,110}>)^2><y^2> - <p_{y,110}y>^2} \\ &= a_1 \alpha L \cos\overline{\varphi_0}\,\sigma_y \sigma_\varphi \\ &\approx 0.01 mm.mrad\end{aligned}$$

This emittance growth is acceptable for the requirements of the electron diffraction facility. Further reduction of the dipole field can be achieved by enlarging the vacuum hole at the opposite side of the coupling hole.

BEAM DYNAMICS STUDIES AND COMPARISON

The beam dynamics is based on the requirements of the UED, which operates with the beam energy at ~2MeV, low charge at 0.1pC~1pC, ultra-short bunch length at ~100fs. The beam dynamics simulation is done with Parmela [7]. An accelerating field of 90MV/m is required to obtain 2MeV beam energy at the exit of the RF gun. We used the C-band gun model with different half-cell length from 1.65 cell to 1.45 cell, and compared their beam dynamics parameters, with the goal of operating at an optimized injection phase of 20~30deg.

Table 3: Beam Dynamics Parameters

Input Parameters	
Bunch Charge (pC)	1
Bunch Radius (mm)	0.5
Field at Cathode (MV/m)	90
Bunch length(fs)	100
Thermal emittance（mm.mrad/mm）	0.6
Injection Phase (Deg.)	Vary
Parameters after Optimization	
Cavity length	1.45 cell
Electron Energy (MeV)	2.06
RMS Bunch Length at Gun Exit (fs)	38.2
Normalized Emittance (mm.mrad)	0.167
Injection Phase (Deg.)	20
Energy spread	0.06%
Input power(MW)	1.61

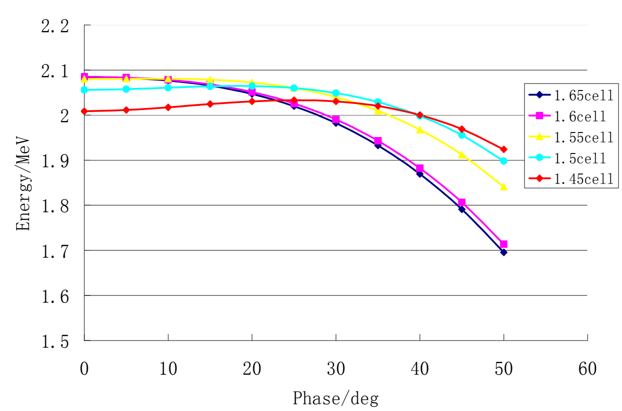

Figure 2(a): Beam energy for different half-cell length from 1.65 cell to 1.45 cell when varying injection phase.

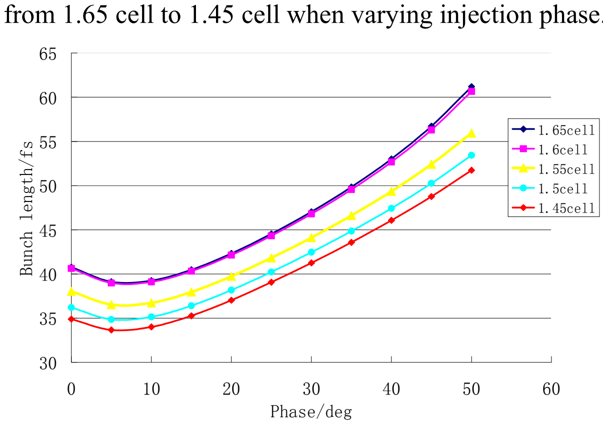

Figure 2(b): Bunch length for different half-cell length from 1.65 cell to 1.45 cell when varying injection phase.

It is shown in Fig. 2 (a) that the energy curve of the 1.45 cell become flatter in the phase range of 20~30deg, so it helps achieve smaller energy spread and remove the bad energy chirp which causes lengthening of the electron bunch. From Fig. 2 (b) we can see that the 1.45 cell RF gun help achieve better compression and shorter bunch length. The input parameters and main beam dynamics parameters after optimization are summarized in Table 3.

We compared the beam dynamics results of the S-band photocathode RF gun using the same initial beam parameters for the C-band RF gun. In order to obtain the same 2MeV energy electron beam, the field gradient of the S-band RF gun is fixed at 45MV/m. The comparison is shown in Table 4. It can be seen that the C-band RF gun has more than twice the bunch length compression than the S-band, and the energy spread of C-band is less than half of the S-band. Several factors contribute to the advantages of the C-band. The wavelength at the C-band is half of that at the S-band, therefore the same bunch length beam will spread over a wider phase range, which will generate a bigger energy chirp. In addition, the higher accelerating gradient of the C-band will also be beneficial for lower energy spread and shorter bunch length.

Table 4: Comparison of C-band and S-band RF gun

Parameter	C-band	S-band
Field at Cathode (MV/m)	90	45
Bunch Charge (pC)	1	
Bunch length(fs)	100	
Bunch Radius (mm)	0.5	
Electron Energy (MeV)	2.06	2.05
Bunch Length at Gun Exit (fs.rms)	38.2	67
Energy spread	0.06%	0.13%

MECHANICAL STRUCTURE DESIGN

The mechanical structure design has been done with some innovated features. Because of the smaller size of the C-band gun, the accuracy of machining becomes more important. To make sure that the pi-mode frequency is 5712MHz, two tuners at the full-cell as well as another two for the half-cell are utilized. Different from the traditional tuners, these four are designed to be non-inserted, which helps suppress breakdown [8]. Inside rounding shape is also utilized to reduce dark current and breakdown. Furthermore, the helicoflex is removed. Instead, the cathode and half-cell will be brazed together directly, which is helpful to achieve higher Q factor and better vacuum.

CONCLUSION

The detailed physics and structure design for the C-band photocathode RF gun at frequency of 5712MHz is presented. The cell-length is optimized at 1.45 cell. The comparison of beam dynamics parameters with S-band RF gun is summarised in this paper, in which the advantages of the C-band gun have been confirmed. Machining with innovated features has finished and processing is ongoing. Cold tests and high power experiments will be conducted in our future work.

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