DESIGN AND EXPERIMENT OF A COMPACT C-BAND PHOTOCATHODE RF GUN FOR UED *

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Abstract

A compact C-band photocathode RF gun for the MeV UED facility is developed in Tsinghua University, which is designed to work at the frequency of 5.712GHz. This paper presents the physics and RF structure design, and beam dynamics optimization of this C-band RF gun. Some new structure design will be adopted in this gun, including the optimized cavity length and elliptical iris, which is helpful to achieve shorter bunch length, lower energy spread, lower emittance and larger mode separation. This paper likewise presents experimental cold test results of this C-band RF gun.

INTRODUCTION

The development of compact high brightness injectors for ultra-low emittance and ultra-short electron bunches has become the new research tools in materials, biology, chemistry science, and many other fields. Several advanced compact user facilities are developed in China, and some new techniques for superconducting RF, innovative structures for particle production and acceleration and beam diagnosis have been studied and utilized. In order to meet the requirements of these compact structures, and considering the advantages of higher gradient, the C-band structure is being widely studied recently. For example, a C-band (5712 MHz) high gradient traveling-wave accelerating structure has been designed and developed at Shanghai Institute of Applied Physics[1]. Comparing with the traditional S-band RF gun, the C-band RF gun has several advantages such as lower input power, smaller size, higher accelerating field, and better compression. Ultra-fast electron diffraction (UED) has been a powerful tool for micro-structure dynamics studies[2][3]. The MeV UED requires ultra-short electron bunches, which can be achieved by the better compression property of C-band RF guns. In addition, for obtaining the same electron beam energy as in S-band RF guns, the higher gradient of C-band RF guns can decrease the space charge effects.

This C-band RF injector is designed to work at the frequency of 5.712GHz[4]. The design of a 1.45 cell C-band gun based on the BNL-style S-band RF gun has been carried out, including physics, beam dynamics design and the mechanical structure design. The cell length has been adjusted through simulation for ultra-short bunch and lower energy chirp[5]. The elliptical iris replaces the original circular rounding shape and the helicoflex is removed in order to decrease breakdown rate 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.

The manufacture of the C-band RF gun, including the machining, brazing, cold test and tuning has been finished. The RF parameters after cold test are: π mode frequency is 5712.03 MHz, 0 mode frequency 5668.09 MHz, Q_0 of π mode 8374, the coupling factor 1.09, the field balance 1.02, and the mode separation 43.94 MHz, respectively, which match the parameters in RF design.

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

The RF structure design and simulation are done by Superfish(2D) and Omega3P(3D). The main microwave parameters of the C-band RF gun are listed in Table 1, and the 3-dimensional model and pi-mode field are shown in Fig. 1 and Fig. 2. The operation frequency is designed at 5712MHz. The mode separation increases to 42.7MHz by using the optimized elliptical iris instead of the rounding shape, while the maximum surface field at the iris decreases [6].

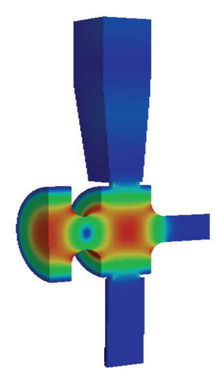

Figure 1: 3-dimensional model and pi-mode field of C-band photocathode RF gun.

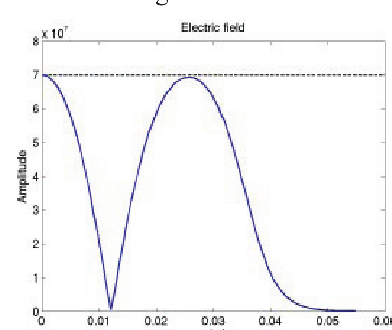

Figure 2: Ez of C-band RF gun along z-axis.

ISBN 978-3-95450-122-9

Table 1: Main Microwave Parameters

Parameter	Pi-mode	0-mode
Frequency/MHz	5712.01	5669.31
Q_0	8663	7374
Q_{ext}	7079	14111
Mode sep./MHz	42.7	
Beta	1.09	
Field balance	1.01	

The mode separation increases to 42.7MHz 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 for the optimized elliptical iris type, the field at the iris reduces to 88.1% of that at the cathode, which helps suppress dark current. In addition, the 0-mode excitation can be suppressed successfully. The comparison on the 0-mode excitation of using the different iris shapes is shown in Table 3.

Table 2: Field comparison for different iris shapes

	Largest field at iris (MV/m)	Field at cathode (MV/m)
Rounding	1.770	1.792
LCLS elliptical type	1.687	1.854
Optimized elliptical type	1.672	1.891

Table 3: 0-mode excitation comparison for different iris shapes

	Rounding	LCLS elliptical type	Optimized elliptical type
Mode separation	6.5	30	42
Pi mode	100∠90°	100∠90°	100∠90°
0 mode	11.19∠-85。	2.24∠-89。	1.14∠-89。

SOLENOID DESIGN FOR EMITTANCE COMPENSATION

Conventional solenoid in S-band RF guns use 8 pancake coils[7]. If this type of solenoid is used for the 1.45-cell C-band RF gun, whose size reduces by more than a factor of 2 from S-band RF gun, its structure and dimensions of coils as well as the supporting structures will become too compact for practical mechanical fabrication. Therefore, we consider using a 4 pancake coil solenoid structure, as shown in Fig. 3. The longitudinal magnetic field distribution along the z-axis of such a solenoid is shown in Fig. 4. The design has been optimized to produce a better field uniformity at the flat top of the magnetic field shape.

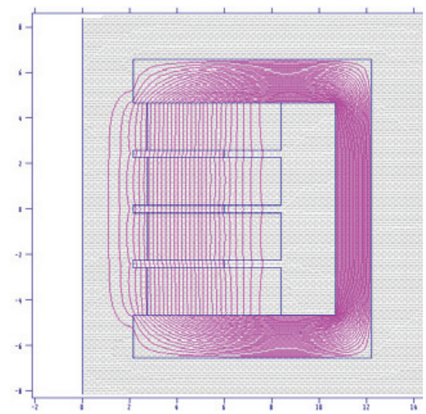

Figure 3: Poisson model of the 4 pancake solenoid coil.

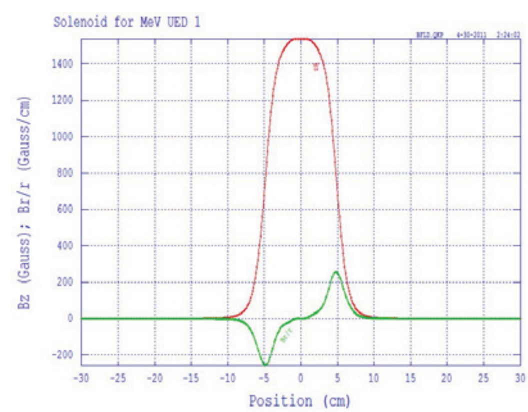

Figure 4: B_z distribution along the longitudinal z-axis.

Beam dynamics analysis has been performed for the beamline with the 4 pancake coil solenoid. According to the requirements of MeV UED facilities, it is desired that the bunch is focused at about 100cm in the longitudinal direction. The central solenoid field is scanned from 1400G to 2000G to obtain the minimum transverse emittance at that position. The dependence of the transverse emittance on Bz is shown in Fig. 5. It can be seen that the optimized central magnetic field is 1670G, for which we can obtain the minimum transverse emittance at around z =100cm.

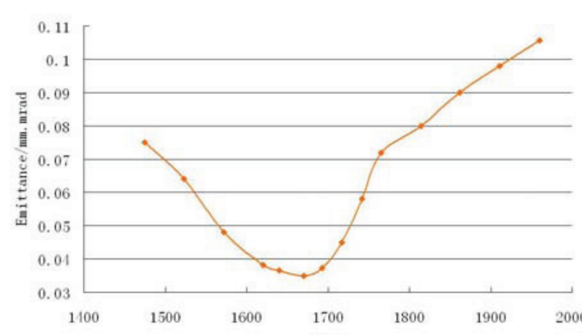

Figure 5: Transverse emittance versus Bz at z = 100cm.

COLD TEST AND TUNING

Based on the RF structure and mechanical designs, the C-band RF gun has been fabricated from 3 cavity components: the cathode, half-cell and full-cell, as shown in Fig. 6. Fig. 7 shows the rf gun brazed from these components. Comparing with the size of pen, it is clearly shown that the C-band RF gun is very compact and small.

In contrast to the brazing techniques in conventional S-band RF guns, the cathode and the half-cell are brazed together, eliminating the use of helicoflex as in previous designs. This novel design helps avoid breakdown and produce better vacuum. The RF parameters after cold test and tuning are shown in Table 4.

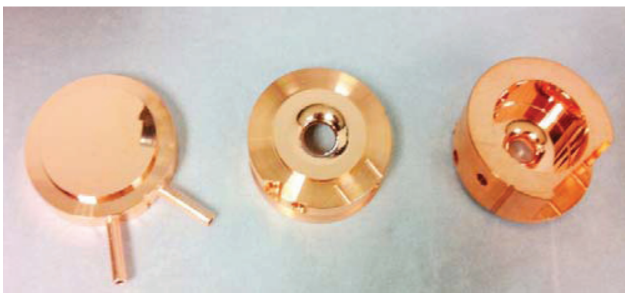

Figure 6: The 3 cavity components of the C-band RF gun: (Left) Cathode; (Middle) Half-cell; (Right) Full-cell.

Figure 7: RF gun after brazing from the 3 components.

Table 4: RF parameters after cold test and tuning

$f_{\pi mode}$ /MHz (23.5^{0}C，atm.)	$f_{\pi mode}$ / MHz (45^{0}C, vac.)	Q_0	Q_e
5712.68	5712.03	8374.245	7682.79
$f_{0 mode}$ /MHz (23.5^{0}C，atm.)	$f_{0 mode}$ / MHz (45^{0}C，vac.)	Q_0	Q_e
5668.74	5668.09	7474.403	12482.25
Mode Separation	Field Balance	β	
43.94MHz	1.02	1.09	

For 2-cell type RF guns, the mode separation between the π mode and 0 mode is related to the field balance in the half-cell and the full-cell. Fig. 8 shows the dependence of the field balance of simulation results and measured data on the mode separation. It can be seen that there is good agreement.

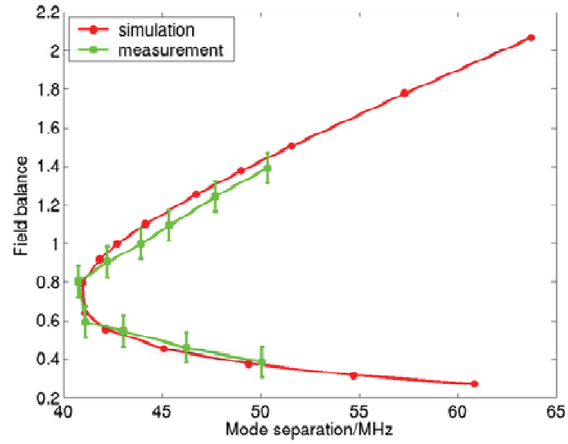

Figure 8: Dependence of field balance on mode separation（simulation in red and measurement green).

CONCLUSION

The detailed RF structure and mechanical designs for the C-band photocathode RF gun at frequency of 5712MHz is presented. The cell-length is optimized at 1.45 cell. The design of solenoid for the C-band RF gun and the beam dynamics optimization has been shown. The cold test and tuning has been finished, and the results match the designed RF parameters well. The high power experiments will be conducted in our future work.

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ISBN 978-3-95450-122-9