COAXIAL COUPLER FOR X-BAND PHOTOCATHODE RF GUN*

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Abstract

The X-band photocathode RF gun can be utilized to generate electron beams with ultra-low emittance. In this paper, we present the design of a coaxial coupler for the X-band RF gun to avoid the emittance growth caused by field asymmetries. A detailed 3D simulation of the coupler is performed. The microwave circuit analysis is accomplished, and the relationship between the coupling factor and the coaxial coupler size is obtained. This paper likewise presents the beam dynamics parameters of the X-band RF gun with a coaxial coupler.

INTRODUCTION

Ultra-short and ultra-low emittance electron bunches are being actively developed as new research tools in biology, materials, chemistry science and in other fields. Several studies have shown that the photocathode RF gun can be utilized to generate high-energy ultra-fast electron beams for electron diffraction. Because of the high electric-field gradient, the space charge effects are greatly suppressed in the photocathode RF gun. The X-band RF gun has several advantages over the S-band RF gun [1], including a smaller size and the ease with which it obtains a higher accelerating field. Therefore, an X-band (9.300 GHz) RF gun is being developed [2].

A coaxial coupler is designed for this X-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 [3] reported that this side coupling to the full cell causes a field asymmetry which significantly deteriorates the transverse emittance [4]. The emittance growth can be suppressed by adopting the coaxial coupler, and the solenoid can be installed outside the full cell instead of at the gun exit to obtain better compensation of the emittance formation caused by the space charge effects.

The design of coupler structure plays an important rule in physics design of electron gun. A optimized coupler size is needed to achieve the critical coupling. In this paper, the 3D model of the coaxial coupler is presented. The method for calculating RF coupling between the waveguide ports and the RF gun with the coaxial coupler is described, and the scanned curve of the coupling factor for different coupler structures is shown. By comparing these results with those of microwave circuit analysis, we obtain the optimized structure of the coaxial coupler.

THE PRELIMINARY DESIGN

The preliminary designed structure of the X-band photocathode RF gun with a coaxial coupler is shown in Figure 1. The power is fed through the upper rectangle waveguide port, passed through both a coaxial-waveguide junction and a segment of the coaxial line, and then into the RF gun while the lower port is short circuited.

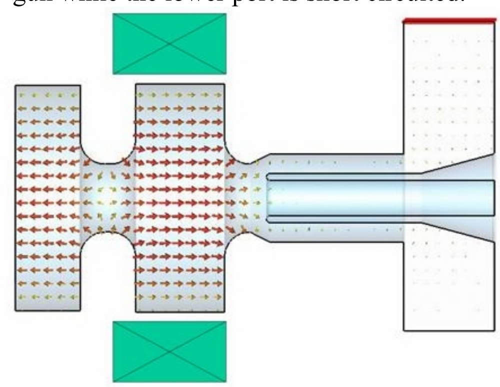

Figure 1: 3D model of the X-band RF gun with a coaxial coupler.

The 3D beam dynamics of the RF gun was simulated by PARMELA [5]. An increase of about 10% in emittance was obtained in an RF gun with a typical side coupling compared with a symmetric RF gun. The solenoid is installed outside the full cell, as shown in Figure 1, to obtain better compensation of the emittance formation caused by the space charge effects.

3D SIMULATION

The coupling factor was calculated by a transient analysis in a 3D EM simulation software[6]. 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:

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

We can get:

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

The decay portion of the curve became linear in logarithm scale, and we can obtain *Qe* from the slope of the curve. Q_0 is calculated for the specified gun structure. Taking into account that $\beta = Q_0/Qe$, the coupling factor can be calculated.

The relationship between the coupler size and the coupling factor is investigated by using the method above. Figure 2 gives the coupling curves for different lengths of the short waveguide opposite the power coupling hole (Fig. 2(a)) and the coaxial line (Fig. 2(b)) over a range of one wavelength. The curves show a periodic change, and the period is a half wavelength. In order to achieve critical coupling, a short waveguide of 33 mm and the coaxial

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line of 25.5 mm was chosen. Figure 3 shows the coupling curve and the emittance sensitivity for different beam apertures, and the optimized beam aperture of 2 mm is obtained.

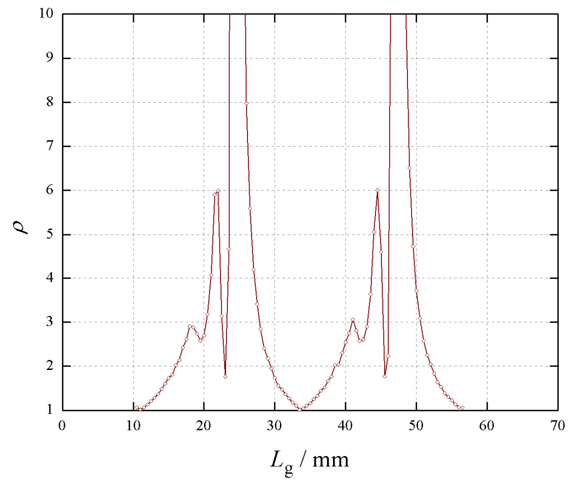

Figure 2(a): Coupling with respect to the length of the short waveguide opposite the power coupling hole.

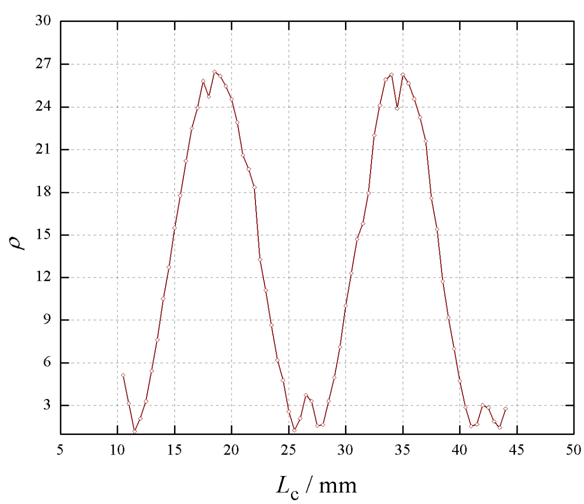

Figure 2(b): Coupling with respect to the length of coaxial line.

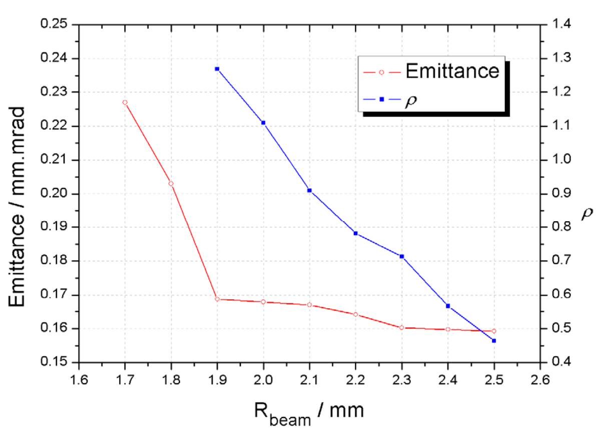

Figure 3: Coupling curve and emittance sensitivity with respect to beam aperture.

MICROWAVE CIRCUIT ANALYSIS

Preliminary microwave circuit analysis of the coaxial coupler was carried out. The equivalent circuit model was established and the transmission line theory was utilized to analyse the relationship between the coupler size and the microwave parameters [7]. The theoretical analysis was compared with the simulation results to determine the optimal size of the coupler.

For a three-port structure, the matrix of the S-parameter is:

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}.$$

As $[Z]=\frac{[I]+[S]}{[I]-[S]}$, the matrix of the characteristic impedance is:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix}.$$

For a three-port structure, shown in Figure 4, ports 1 and 2 are the rectangular waveguides and port 3 is the coaxial line. Port 1 was used to feed the power and port 2 was short circuited. The equivalent circuit model is shown as Figure 5.

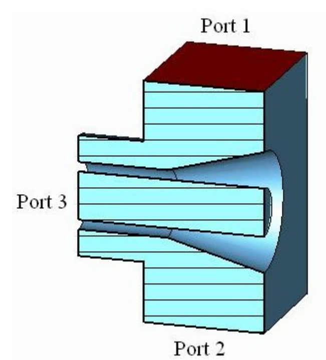

Figure 4: Three-port structure, in which ports 1 and 2 are rectangular waveguides and port 3 is coaxial line.

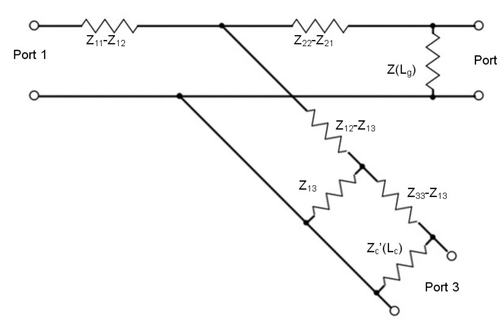

Figure 5: Equivalent circuit model for the three-ports structure.

In transmission line theory, the impedance at a distance Lg away from the short plant of port 2 is:

$$Z_{(Lg)} = \frac{Z_0 + jtg\beta L_g}{1 + jZ_0 tg\beta L_g},\ \beta = \frac{2\pi}{\lambda_g} = \frac{2\pi}{45.6\,mm}.$$

Port 3 is connected to the RF gun after a coaxial line with a length of Lc. The characteristic impedance Zc is determined by the structure, frequency and Q of the RF gun. The impedance at port 3, which is at a distance Lc away from the gun exit, is:

$$Z'_{c\,(Lc)} = \frac{Z_c + jtg\beta L_c}{1 + jZ_c tg\beta L_c},\ \beta = \frac{2\pi}{\lambda_c} = \frac{2\pi}{32.3\,mm}.$$

We can obtain the impedance of port 1 by:

$$Z = \frac{\left[Z_{12}(Z_{33} + Z'_{c(Lc)}) - Z_{13}^2\right] \times (Z_{11} - Z_{12} + Z_{(Lg)})}{(Z_{11} + Z_{(Lg)})(Z_{33} + Z'_{c(Lc)}) - Z_{13}^2} + Z_{11} - Z_{12}$$

As $\rho = \frac{|Z+1| + |Z-1|}{|Z+1| - |Z-1|}$, the standing wave ratio ρ is a function of the variables Lg and Lc. In this way we can determine the relationship between the coupler size and the coupling factor.

Figure 6 shows the relationship between ρ and the different lengths of the short waveguide port 2 from the equivalent circuit model and from the computer simulation. The results match well in the range of 25–40 mm, and the chosen length (33 mm) is in this range.

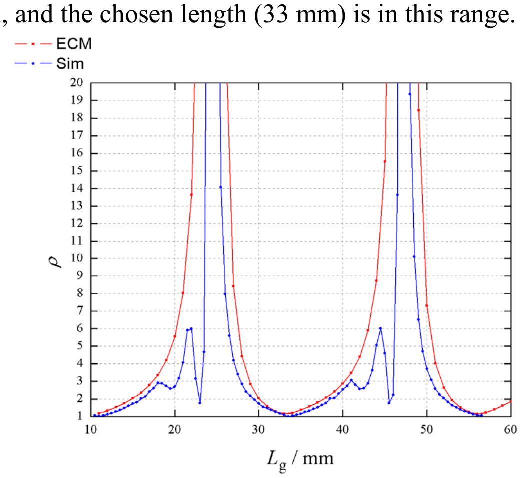

Figure 6: ρ for different lengths of the short waveguide for the equivalent circuit model analysis (red) and in 3D simulation (blue).

OPTIMIZED RESULT

Based on the results obtained from the circuit model and from the computer simulation, the optimized size of the coupler is shown in Table 1, as well as the 3D beam dynamics parameters. If critical coupling can be achieved less than 5.5 MW input RF power is needed for 100 MeV/m gradient on the axis.

Table 1: Optimized Parameters

Gun Parameters	
Freq. of π Mode (MHz)	9300.66
Q_0 of π Mode	7740
Beam Dynamics Parameters	
Bunch Charge (pC)	1
Bunch Radius (mm)	0.5
Injection Phase (Deg.)	10
Field at Cathode (MV/m)	100
Electron Energy (MeV)	1.18
RMS Bunch Length at Gun Exit (fs)	52.2
Normalized Emittance (mm.mrad)	0.16
Optimized Coupler Structure	
Coupling Factor	1.10
Length of Short Waveguide (mm)	33
Length of Coaxial Line (mm)	25.5
Beam Aperture (mm)	2

CONCLUSION

The detailed design of a coaxial coupler for the X-band photocathode RF gun is presented. The equivalent circuit analysis method for the coupler is summarised in this paper. Comparing the results of equivalent circuit analysis with the 3D simulation, the optimized size of the coaxial coupler is obtained. The beam dynamics parameters are acceptable, with ultra-low emittance and ultra-short bunch length, for ultra-fast electron diffraction.

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