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DESIGN OF A ROTATIONALLY SYMMETRIC S-BAND PHOTOCATHODE RF GUN*

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Abstract

The photocathode RF gun is one of the most critical components for high quality electron beam sources. The asymmetric multi-pole field contributes to the transverse emittance growth and degrades the beam quality. In order to overcome the problem, we propose a novel rotationally symmetric 1.6 cell RF gun to construct the symmetric field in this paper. The concrete proposal is that a coaxial cell with a symmetrical distribution of four grooves is concatenated to the first 0.6 cell at the photocathode end to form a new resonant cell (NRC) to mantain the symmetric multi-pole field in 1.6 cell. Our simulations indicate that 3D multi-pole fields of NRC are with the perfect symmetry. After that, the profile of the RF gun is optimized to improve the shunt impedance and mode separation and make the surface peak electric field at the photocathode end. Our simulations demonstrate promising outlook of using coaxial cell for photocathode RF guns with various applications.

INTRODUCTION

In many laboratories, the photocathode RF gun has been developed as the injector for linac based free electron lasers, ultrafast electron diffraction facilities, coherent terahertz radiation sources, and X or γ-ray Compton scattering facilities. In such guns, an electron beam is typically generated when the drive laser strikes the photocathode surface, and accelerated to relativistic energy to elmimate the space charge effect by an RF field. Thus, the RF field property is crucial for RF guns to work.

The Panofsky-Wenzel theorem [1] is a general theorem pertaining to the transverse deflection of particles by an RF field. According to the theorem, an undesirable characteristic that contributes to the transverse emittance growth is the presence of the asymmetric multi-pole field introduced by an input power side coupling slot in the RF gun. It is particularly detrimental to low emittance beam at low beam energy, especially in the injector for light sources. It has been demonstrated an emittance contribution of more than 1 π mm mrad for a conventional asymmetric input coupler. Thus, many methods, such as single feed with vacuum port, dual feed with racetrack coupler cell, four ports, coaxial coupling and so on, have been proposed to eliminate the RF field asymmetry. In view of the above mentioned facts, two major design philosophies are incorporated into the RF gun: symmetric field to decrease the multi-pole field contribution to the transverse emittance and high gradient RF field to suppress the space charge effect at low beam energy.

In the spirit of the idea, we propose a novel rotationally symmetric RF gun with curved surfaces of cylindrical cells in this paper. A coaxial cell with a symmetrical distribution of four grooves is concatenated to the first 0.6 cell at the photocathode end to form a new resonant cell (NRC) in which the TEM mode and TM_{010} mode do coexist.

DESIGN OF RF GUN

Figure 1 shows the cross section of the proposed rotationally symmetric RF gun with curved surfaces of cells which is based on LCLS gun operating at 2856 MHz, but the full cell is a rotationally symmetric shape rather than a racetrack shape [2]. It consists of a coaxial cell, a 0.6 cell and a full cell. Multi-pole field analysis and structure optimization are performed in the following.

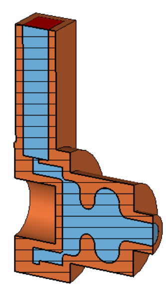

Figure 1: Cross section of the proposed rotationally symmetric RF gun.

Multi-Pole Field Analysis

In this section, we analysis the multi-pole field of the NRC and NRC without four grooves (NRCFG), where one groove of the NRC is the RF power coupling port.

According to Maxwell's equations, it is clear that the symmetric multi-pole field is in the 1.6 cell. The 3D multi-pole field distribution is simulated by the CST Microwave Studio code. The isolines located at the photocathode inner surface are depicted for 3D multi-pole electric field distributions including the monopole, dipole and quadrupole field for NRC and NRCFG as shown in Fig. 2. Meanwhile, we illustrate multi-pole electric field distributions along the radius 2 mm center circle which is located at the photocathode inner surface. It is straightforward to compare the symmetry of multi-pole fields from the bottom row of Fig. 2. As a result, the multi-pole field of NRC is the same as NRCFG with the perfect symmetry.

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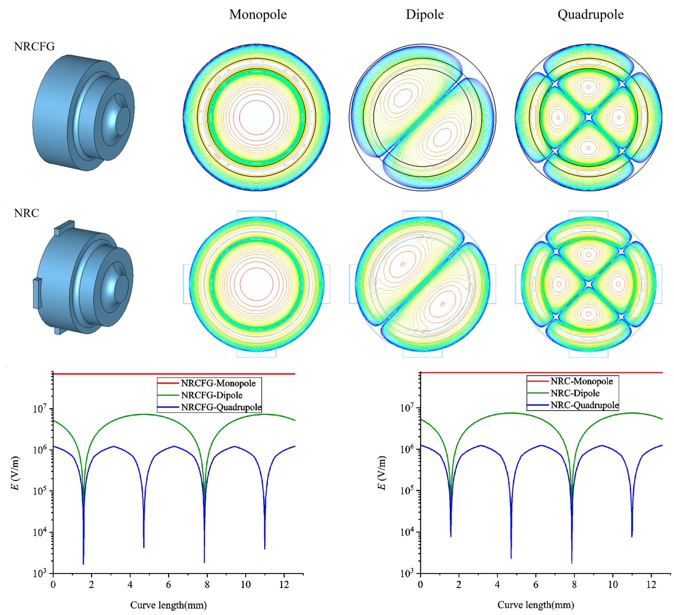

Figure 2: Multi-pole electric field distributions for NRC and NRCFG.

Optimization

Most of important characteristics of RF gun, such as shunt impedance Z_s, quality factor Q, mode separation Δf, field balance E_{1p}/E_{2p}, surface peak electric field E_p and so on, are strongly dependent on the 1.6 cell which is defined by 21 independent parameters under optimization as shown in Fig. 3, where E_{1p} and E_{2p} are the maximum electric field of the 0.6 cell and the full cell along the longitudinal axis, respectively.

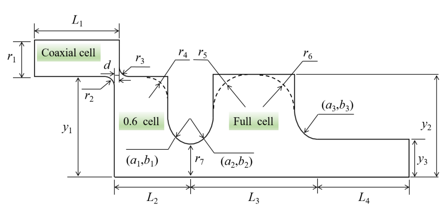

Figure 3: Cross section of the 1.6 cell RF gun. (Solid line is the original gun; Dash line is the optimized gun.)

So the 1.6 cell must be carefully optimized in the first stage. The optimization of the gun primarily aims to maximize the shunt impedance Z_s, maintain the mode separation Δf and the ratio E_p/E_a at a proper value, ensure the field balance $E_{1p}/E_{2p} = 1$ and make the surface peak electric field E_p at the photocathode inner surface center.

Firstly, the definition of the shunt impedance per length of the accelerating structure Z_s is

$$Z_s = \frac{2\left[\int_0^L E_z(z)\mathrm{d}z\right]^2}{R_s L \int\limits_s \left|\vec{H}\right|^2 \mathrm{d}s} \tag{1}$$

where L is the length along the longitudinal axis, R_s is the surface resistance, E_z is the distribution of the electric field along the center axis and $\vec{H}$ is the magnetic field distribution on the inner surface of cells. It is straightforward to increase the integral of the electric field distribution along the axis and decrease the magnetic field $\vec{H}$ or the area S of the inner surface of cells to improve the shunt impedance. The method's essential is to reduce an ohmic loss because of wall current along the metal inner surface. In order to improve the shunt impedance, we adopt the curved surface of cells to decrease the area of the inner surface.

Secondly, the mode separation is the frequency difference between π mode and 0 mode. According to the report of C. Limborg et al. [3], the larger mode separation may be associated with lower beam emittance, reduced sensitivity to timing adjustments and operated stability at both low and high average power. Therefore, we will increase the mode separation as soon as possible. At the same time, the field balance will also be maintained.

Thirdly, the breakdown phenomenon of an accelerating structure is found to exhibit a strong dependence of the maximum electric field on the surface. Meanwhile, the high gradient RF field is utilized to suppress the space charge effect for low beam energy. So it needs to make the surface peak electric field at the photocathode end to avoid RF breakdown at other places. The surface peak electric field E_p can be calculated from some parameters of RF gun, as follows:

$$E_p = R_{\mathrm{ratio}} E_a = 2E_a \frac{\sqrt{\beta_c}}{1+\beta_c}\sqrt{\frac{P_{\mathrm{fwd}} Z_s}{L_g}} \tag{2}$$

where P_{fwd} is the input power, Z_s is the shunt impedance per length, L_g is the effective length of the RF gun, β_c is the coupling coefficient, R_{ratio} is a constant for a specific gun, and E_a is the average electric along the longitudinal axis. In our design, we assume that the input power P_{fwd} is 10 MW, the coupling coefficient β is around 2, the shunt impedance

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per length Z_s is about 50 MΩ/m, and the R_{ratio} is about 2. Thus, the photocathode inner surface electric field is around 120 MV/m.

To optimize the gun, 21 independent parameters need be subject to the scanning with the SUPERFISH code, which is a very time consuming and mountain of work. To improve efficiency, a Python code has been developed to write an input file with different sets of parameters, invoke the SUPERFISH code, automatically post-process and output the results. Since the result is very plentiful, we only discuss the significant results after careful optimization as follows.

The radii of curvature r_4, r_5 and r_6 are optimized to improve the shunt impedance which is up to 48.1 MΩ/m.Table 1 presents the main microwave parameters of the 1.6 cell.

Table 1: Parameters of the 1.6 Cell After Optimization

Parameter	Vaule	unit
f_π	2856	MHz
f_0	2840.9	MHz
Δf	15.1	MHz
Q	15658	
Z_s	48.1	MΩ/m
r/Q	141.2	Ω
ZT^2	18.5	
E_p/E_a	1.94	
E_{1p}/E_{2p}	1	

The π mode electric field distribution of the optimal profile is shown in Fig. 4. The longitudinal electric field of the π mode and 0 mode are depicted in Fig. 5. The field balance E_{1p}/E_{2p} is 1.

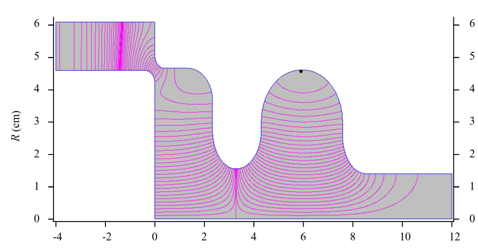

Figure 4: π mode electric field distribution of the RF gun after optimization (Unit: cm).

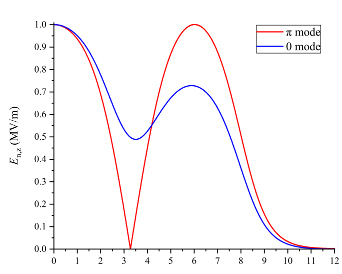

Figure 5: Longitudinal electric field of the π mode and 0 mode.

The mode separation varies with the iris radius r_7 as shown in Fig. 6. It is obvious that the mode separation is a monotone increasing function of iris radius r_7. In our design, the reasonable mode separation is 15.1 MHz.

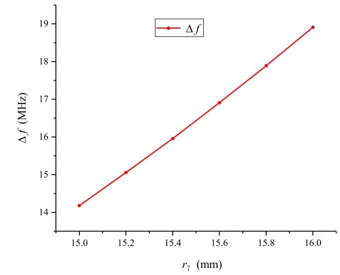

Figure 6: Mode separation vary with the iris diameter.

In order to make the surface peak electric field at the photocathode end, we utilize the elliptical shape in the iris of the RF gun. As a result, the normalized surface electric field along the inner cavity is depicted in Fig. 7. There are seven peak points of the surface electric field. It is obvious that the maximum peak point P1 of the surface electric field is located at the photocathode inner surface center.

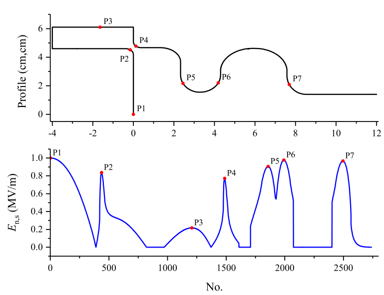

Figure 7: Surface electric field along the inner cavity.

CONCLUSION

In this paper, we discuss in detail a novel RF gun which is simulated for a symmetric RF field. With the coaxial cell connected to the 0.6 cell, multi-pole fields are the perfect symmetry and the solenoid could be placed at the optimum location for emittance compensation. The optimal results are that the shunt impedance is 48.1 MΩ/m, the mode separation is 15.1 MHz and the surface peak electric field is located at the photocathode inner surface center. Because of the rotational symmetry, the novel RF gun features in convenient machining, simple fabrication, low cost and profound applicability.

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