ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB145

COLD TEST OF A NOVEL S-BAND 1.6 CELL 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 cavity with a symmetrical distribution of four grooves is concatenated to the photocathode end of the traditional 0.6 cell cavity to form the novel 0.6 cell cavity. Through the detailed design study, 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. Considering the filling time, a coupling slot is designed to couple input power into the RF gun. The RF cavity is machined by numerical control machine tool, and the tuning and low power RF measurement are carried out. The experimental results are consistent with the simulation results.

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.

* Work supported by National Natural Science Foundation of China(Grant No. 11805199 and U1832135) and Fundamental Research Funds for the Central Universities (Grant No. WK2310000072)

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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.

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.

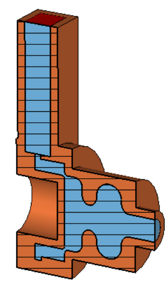

Figure 1: Cross section of the proposed rotationally symmetric RF gun.

OPTIMAL DESIGN OF RF GUN

Most of important characteristics of RF gun [3], 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. 2, 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.

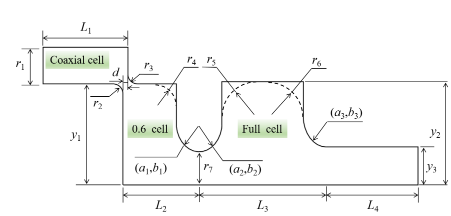

Figure 2: Cross section of the 1.6 cell RF gun (Solid line is the original gun; Dash line is the optimized gun).

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.

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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.

Table 1 presents the main microwave parameters of the optimal 1.6 cell cavity.

Table 1: Parameters of the 1.6 Cell After Optimization

Parameter	Vaule	Unit
f	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	

DESIGN OF COUPLER

The coupler is used to transmit RF power from power source to RF gun through input waveguide. In our scheme, the single coupling slot is utilized to connected with the input waveguide and the coaxial cell cavity as shown in Fig. 3. Furthermore, in order to reduce asymmetric RF field of the 1.6 cell cavity, the other three same grooves are uniformly distributed along the circumference at the end of the coaxial cell cavity.

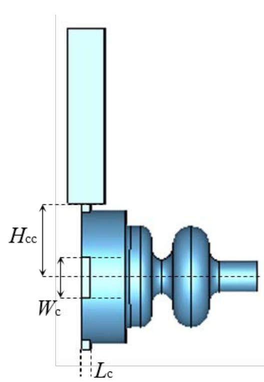

Figure 3: 3D schematic diagram of the RF gun with the coupler.

The design parameter of coupler mainly includes coupling coefficient, coupling state and resonant frequency of cavity. In the design of coupler, the coupling coefficient and coupling state are adjusted by changing the width W_c of coupling slot. And the resonant frequency of the cavity is adjusted by radii y_1 and y_3 of the cavity. The height H_{cc} from the center of the coaxial cell cavity to the bottom of the input waveguide and the length L_c of the coupling slot remains unchanged. The simulation and optimization of the coupler is performed using CST Microwave Studio frequency domain solver [4].

The coupling slot size of the cavity mainly affects the coupling coefficient and resonant frequency of the cavity, which are adjusted by the size of the coupling slot and the radius of the cavity, respectively. However, adjusting the radius of the cavity will affect the field balance inside the cavity. Therefore, the tuning of coupler is a complex, tedious and time-consuming work. At the same time, considering the feasibility of the tuning method in the machining process, we must simplify the number of geometric parameters of the structure in the process of simulation tuning. After comprehensive consideration, only the coupling slot width W_c, radii of the 0.6 cell cavity and the full cell cavity are used to tune the coupler.

For the photocathode RF gun, the coupling coefficient is a comprehensive parameter. Its theoretical design involves peak electirc field, power flow, filling time and so on. From the view of RF power flow, the matched coupling coefficient is to be 1. Nevertheless, to appropriately increase the coupling coefficient can be reduce the filling time of RF gun, the optimal coupling coefficient is designed to be 1.55 and the filling time is 0.68 µs.

After cut-and-dried simulation tuning, S_{11} parameter and Smith chart for 0 mode and π mode are shown in Figs. 4 and Fig. 5, respectively. Meanwhile, the mode separation 15.1 MHz, field balance and rotational symmetry of field distribution are the same as the result of the eigenmode. The cross section of the 3D electric field distribution is depicted in Fig. 6.

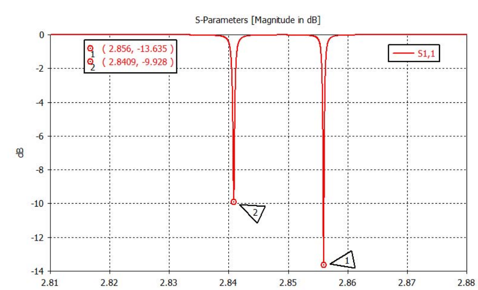

Figure 4: S_{11} parameter of 0 mode (2) and π mode (1).

LOW POWER RF MEASUREMENT

In order to measure the relevant microwave parameters of the cavity, we use CNC(Computer Numerical Control) machine tools to fabricate the cavity because of its elliptical surface, as shown in Fig. 7. Due to the influence of simulation error, machining error and measurement error, we adopt the residual machining method. In the process of machining, the cavity is tuned. By modifying the radii y_1 and y_3 of the cavity, the frequency and the field balance of π mode are

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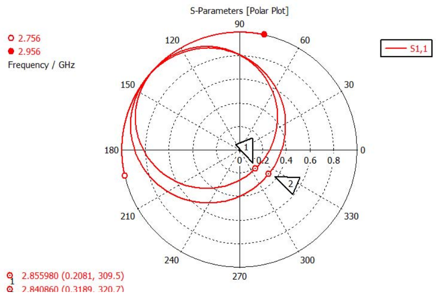

Figure 5: Smith chart of 0 mode (2) and π mode (1).

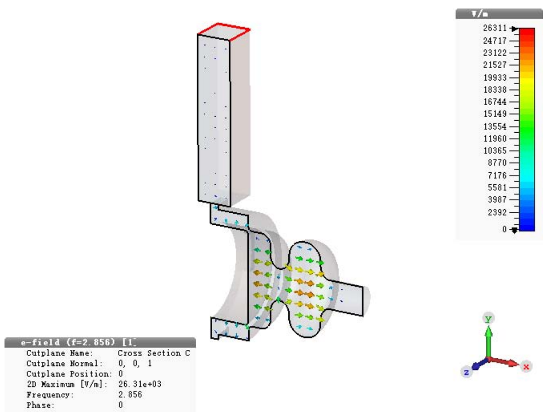

Figure 6: Cross section of the 3D electric field distribution.

adjusted. The coupling coefficient is tuned by modifying the width W_c of the coupling hole. We have measured the RF of low power in the cavity, including the work frequency, the mode separation, the distribution of π mode and 0 mode along the axial field, S11 parameter and the coupling coefficient. As a result, the work frequency of the π and 0 mode are 2855.616 MHz and 2840.400 MHz, respectively. The mode separation is 15.216 MHz. The electric field distribution curve along the axis of the cavity is measured by using the bead pull method. The filed distribution curve of the π and 0 mode are shown in Fig. 8. The measurement curve of S11 parameter is shown in Fig. 9. The experimental results are consistent with the simulation results.

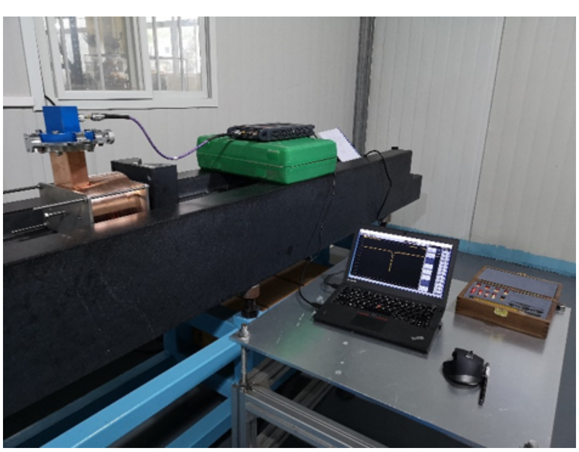

Figure 7: Cavity in Tuning.

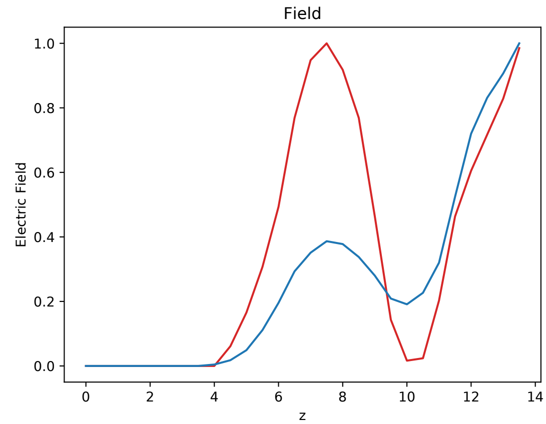

Figure 8: The filed distribution of the π and 0 mode.

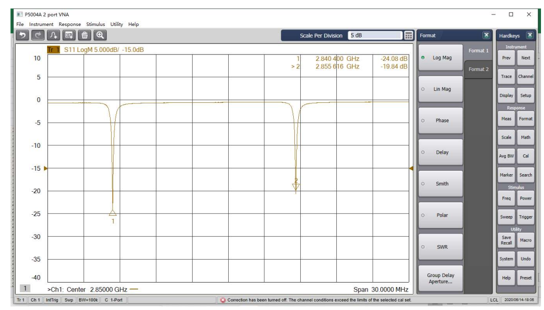

Figure 9: The measurement curve of S11 parameter.

CONCLUSION

The proposed idea of the novel 0.6 cell cavity for the photocathode RF gun is demonstrated and studied thoroughly, including cavity structure optimization, field distribution symmetry analysis, coupler tuning, machining, tuning and low power RF measurement. The low power measurement results are consistent with the simulation results.

ACKNOWLEDGEMENTS

The author sincerely thanks Yuanji Pei for constant encouragement and discussing. We appreciate the support from National Natural Science Foundation of China (Grant No. 11805199 and U1832135) and Fundamental Research Funds for the Central Universities (Grant No. WK2310000072).

REFERENCES

[1] W. K. H. Panofsky and W. A. Wenzel, "Some Considerations Concerning the Transverse Deflection of Charged Particles in Radio-Frequency Fields", *Review of Scientific Instruments*, vol. 27, no. 11, pp. 967–967, Nov. 1956. doi:10.1063/1.1715427

[2] D. H. Dowell *et al.*, "The Development of the Linac Coherent Light Source RF Gun", *ICFA Beam Dyn. Newslett.*, vol 46, pp. 162-192, Sep. 2008.

[3] C. Limborg-Deprey *et al.*, "RF Design of the LCLS Gun", SLAC National Accelerator Laboratory, Menlo Park, California, USA, Rep. LCLS-TN-05-3, Feb. 2005.

[4] CST-Computer Simulation Technology, https://www.3ds.com/products-services/simulia/products/cst-studio-suite