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PHYSICS DESIGN AND DYNAMIC SIMULATION OF A C-BAND PHOTOCATHODE ELECTRON GUN FOR UEM*

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Abstract

For discovering structure at atomic scale and getting more details of chemical material and biological tissue, an ultrafast electron microscopy (UEM) has been developed and applied in plenty of subjects and studies. This paper described a C-band photocathode electron gun which will be working at 5712 MHz to produce ultrashort electron beams with better dynamic parameters. The RF gun is using coaxial coupler to decrease the size of the gun and keep better symmetry of the field in the photocathode gun so that the beam emittance and energy spread can be reduce a lot. The photocathode rf gun will be an important part of the ultrafast electron microscopy (UEM). Using CST MWS and superfish code to simulate design the gun. After dynamic simulation, the beam parameters as the following: Energy is of 3MeV, Normal emittance of 0.12mm-mrad in both direction, energy spread is of 5.8×10^{-4}, which are better enough for an UEM.

INTRODUCTION

The electron microscope is a kind of useful experimental instrument for observing structure of chemical material and biological tissue and studying the composition of them at small length scale. The electron gun, which provides electron beams with high energy to probe materials, is the most important part in electron microscope and also determines the quality of projective images [1, 2]. Photocathode gun, field-emission gun and thermal emission gun are the most common kinds used in electron microscopes as the electron source. Photocathode gun, which could provide electron beams with much higher energy and better dynamic properties, is suitable for ultrafast electron microscope (UEM).

The UEM, which differs from the traditional electron microscope, uses ultrafast electron beams with higher energy from hundreds of keV to several MeV level as a probe to discover molecule structure. Besides, the ultrafast electron beams with short pulse of femtosecond level, could also be used to observe the dynamic process with high temporal resolution.

Due to breakdown limit, electron gun using direct current could only accelerate electrons to hundreds of keV, which would cause the expansion of dimension due to space charge effect [3-5]. Thus, radio frequency gun (RF gun) is chosen to be used to get electron beams with higher energy of MeV. With RF gun, the electron beams will be accelerated rapidly to near realistic speed, which will decrease space charge effect.

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A solenoid magnet is used at the downstream of accelerating cavity to focus the electron beams and compensate the emittance of the electron beams so that the dynamic parameters of the exit beam of the photocathode gun will be improving. With emittance compensation, the emittance of both x and y plane would be decreased to the desired value [6].

In this research, CST Microwave Studio is used to simulate the 1.6-cell C-band gun cavity and optimize the structure of coaxial coupler. With smaller radius due to coaxial coupling, the solenoid could produce stronger magnetic field and will compensate the emittance much better. The magnetic field of solenoid is simulated and optimized to keep the dimension of electron beams and compensate emittance by using Parmela code. The dynamic parameters after optimization are calculated at the exit of the photocathode gun.

PHYSICS DESIGN OF THE PHOTOCATHODE

The photocathode gun consists of two parts: 1.6-cell accelerating cavity and waveguide coupler. The 1.6-cell cavity is designed and simulated by superfish code and CST MWS. Radius and shape of iris and length of cells are mainly optimized to get higher shunt impedance and cavity radius of half-cell and full-cell is adjusted to tune the frequency to working frequency of 5712 MHz. The result of 2D pi-mode field is calculated in superfish and the electric field along z-axis is showed in Fig. 1, which is used to accelerate electron beams.

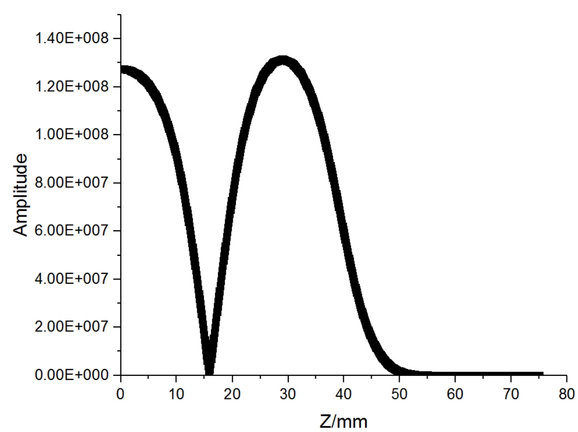

Figure 1: Ez of pi-mode along axis.

The coaxial coupler is adopted in this C-band gun to keep symmetry of field and decrease the radius of gun cavity to save space for solenoid in order to compensate emittance better. The coaxial coupler connects two rectangular waveguides and a coaxial transmission line.

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Main microwave parameters are listed in Table 1. The shape design uses LCLS gun as reference [7]. The full model is built and simulated using time domain solver in CST. The pi-mode electric field has been simulated and S11 curve is calculated and showed in Fig. 2. This curve has two resonance peaks at 5700 MHz and 5712 MHz, which represents the 0-mode and the pi-mode.

Table 1: Main Microwave Parameters

Pi-mode frequency	5712.02MHz
0-mode frequency	5699.82MHz
Mode separation	12.22MHz
Shunt impedance per meter	143.879 MΩ/m
Q factor	12084.4

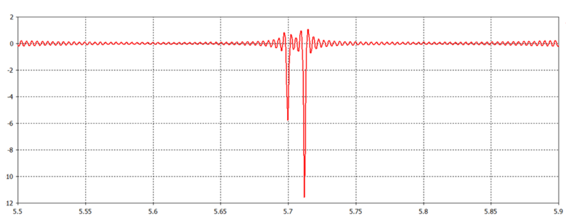

Figure 2: S11 curve of full model.

SIMULATION IN DYNAMIC PROCESS

Solenoid Design

A solenoid magnet is designed to prevent the expansion of beam size and emittance due to space charge effect [6]. The length of coaxial line needs to be extended by a wavelength of 52.48 mm in order to leave space for installing the solenoid. The pattern of the electric field in 2D model calculated in superfish is showed in Fig. 3.

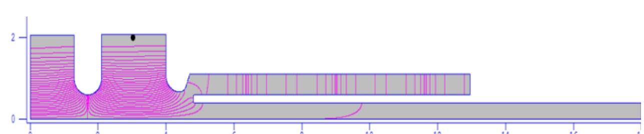

Figure 3: the electric field in 2D model after coaxial length extended.

In this paper, shape and magnetic field strength of the solenoid are mainly optimized. The initial shape of the solenoid and the magnetic field strength is presented in Fig. 4, from which we could find out that the length of magnet is too long and the maximum of the magnetic field is not high enough. To improve the maximum of the magnetic field and shorten the effective field length, the new solenoid shape is designed and simulated, the results of which are in Fig. 5. The maximum has been promoted by about 50% with the same ampere turns in simulation and the effective field length decrease, which could offers stronger focus strength.

Different values of maximum magnetic field have been simulated to determine the most suitable value of the magnet and the results are showed in Fig. 6. The range of scanning is from 2100 G to 3500 G, and from the results the value of 3100 G is enough to prevent the electron bunches from expansion.

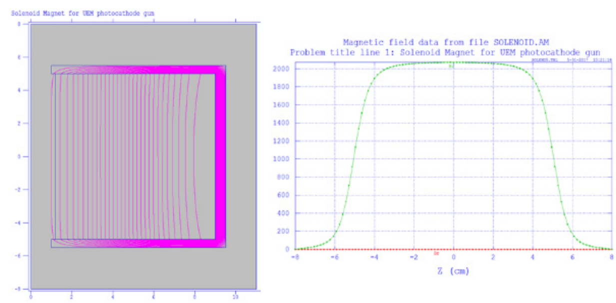

Figure 4: Initial solenoid shape and magnetic field.

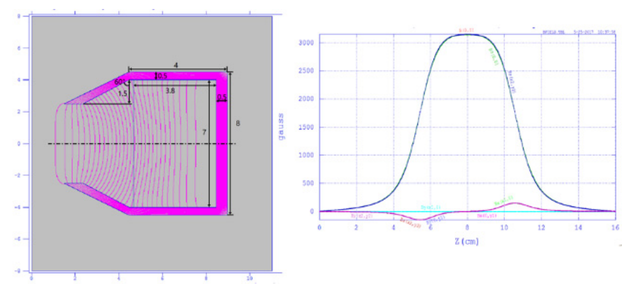

Figure 5: Optimized solenoid shape and magnetic field.

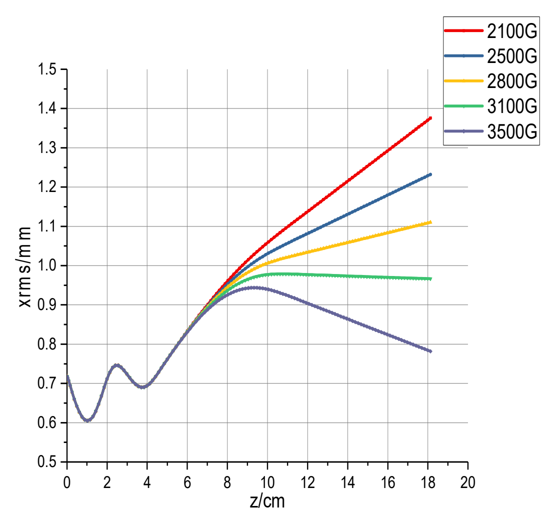

Figure 6: rms size in x-plane of the electron bunches in scanning different values of maximum of magnetic field.

Initial Phase Scan

To find out the range of initial phase of captured electron bunches, dynamic process of electron bunches emitting from the photocathode is simulated and different values of initial phase are scanned. The result that electron bunches with initial phase from 165 degree to 200 degree could be captured and accelerated in the C-band photocathode gun is presented in Fig. 7-9.

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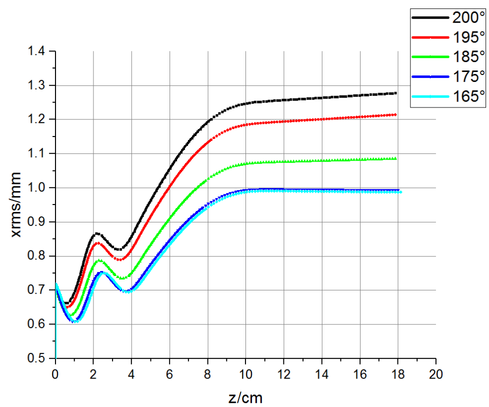

Figure 7: The change of rms size in x-plane.

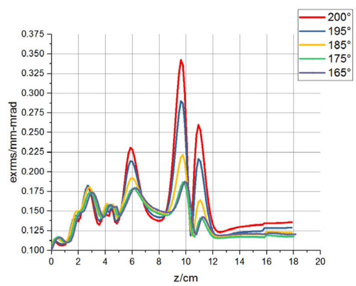

Figure 8: The change of rms emittance in x-plane.

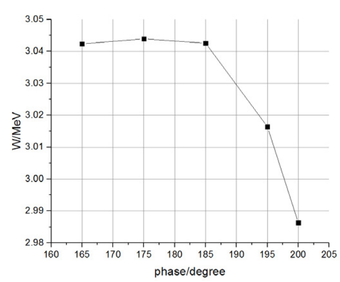

Figure 9: Energy of electron bunches at exit of electron gun with different initial phase.

Figure 7 shows the change of rms size and Fig. 8 shows the change of rms emittance in x-plane of electron bunches during dynamic process, which suggests that the initial phase from 165 degree to 175 degree are with best rms size and smallest emittance of 0.1 mm-mrad. Figure 9 suggests that electron bunches with initial phase from 165 degree to 185 degree gain energy of 3 MeV. Due to the results, the initial phase should be limited in the range of 165 degree to 175 degree to gain better properties of beams.

Simulation of Dynamic Parameters

Electron emitting from cathode would have external thermal emittance, which could not ignored in dynamic simulation [7]. Thermal emittance of electron bunches could be calculated using the relationship for uniform emission from a thermionic cathode of radius r_c and effective temperature T_e:

$$\varepsilon_{th} = \frac{r_c}{2}\sqrt{\frac{kT_e}{m_0 c^2}}$$

Table 2: Main Dynamic Parameters at the Exit of Gun

Rms size in x-plane	0.9874mm
Rms size in y-plane	0.9897mm
Emittance size in x-plane	0.1205mm-mrad
Emittance size in y-plane	0.1203mm-mrad
Energy gain	3.0423MeV
Energy spread	5.84e-04

In this condition, the thermal emittance is about 0.1 mm-mrad when r_c =0.1mm and T_e =300 K. The dynamic simulation results with thermal emittance are presented in Fig. 10, which shows the change of rms size and rms emittance of electron bunches.

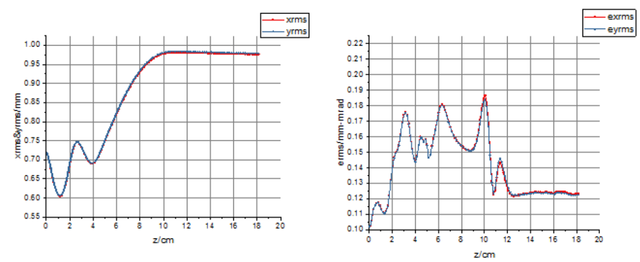

Figure 10: Rms size and emittance in x-plane and y-plane of electron bunches.

The main dynamic parameters of electron bunches at the downstream of the coaxial photocathode gun are listed in the Table 2. The final rms emittance in both x-plane and y-plane are 0.12 mm-mrad, which has been satisfied the gun requirement, and magnetic field produced by solenoid maintains the size of electron bunches bleow 1mm in both x-plane and y-plane. The electron bunches finally gain energy of 3 MeV with energy spread of 5.84e-04.

CONCLUSION

In this paper, we design a 1.6-cell C-band photocathode electron gun with coaxial coupler. After finishing the physical design, the solenoid magnet has been designed and dynamic process has been simulated using Parmela and dynamic parameters are calculated. Furthermore, after fabricating the model of gun, the electric field and shunt impedance would be measured.

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