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DARK CURRENT STUDIES FOR A SW C-BAND ELECTRON GUN WITH A DEFLECTOR

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Abstract

To generate the very high brightness beams in light sources, injectors based on radiofrequency photo-guns with very high peak electric fields on the cathode are used. However, this very high surface electric field on the surface of a radio frequency cavity leads to the generation of dark current due to the field emission effect which can damage the instrumentation and radio-activate components. Consequently, it is important to reduce the emission of these electrons and evaluate the subsequent transportation. In this paper, the deflector has been innovatively positioned at the exit of the gun so as to reduce the dark current as much as possible. The dark current emission and spectrum of the dark current of the C-band electron gun have been evaluated by Particle-In-Cell simulations. The dark current before the accelerating sections has been captured and observed both with and without the deflector.

INTRODUCTION

The emission of dark current in electron gun is mainly due to the field emission process triggered by the high surface electric field on the photocathode surface or near the irises inside the electron gun [1]. There are studies show that the source of dark current is mostly distributed at the groove on the edge of the cathode plug, and a small part comes from the iris or coupling port. Moreover, the roughness of the cathode surface will further aggravate the emission of dark current. At present, the well-known Fowler-Nordheim formula is generally used to characterize the relationship between dark current intensity and applied electric field [2, 3]:

$$J = A\frac{\beta E}{\phi} exp(\frac{B}{\sqrt{\phi}}) exp(-C\frac{\phi^{\frac{3}{2}}}{\beta E}), \quad (1)$$

where J is the emission current density, ϕ is the work function of the emission surface, E is the electric field gradient, β is the field enhancement coefficient, and A, B and C are all known constants [4]. For the suppression method of dark current, we can reduce the field emission by improving the surface characteristics of the cathode material, like using better and reasonable surface processing technology and cleaning technology. And the collimator can be placed downstream of the electron gun to isolate the dark current. At present, new methods of dark current suppression are explored with great effort. In this paper, a new dark current suppression scheme using the deflector structure is proposed, and the corresponding simulation work is shown in the following sections.

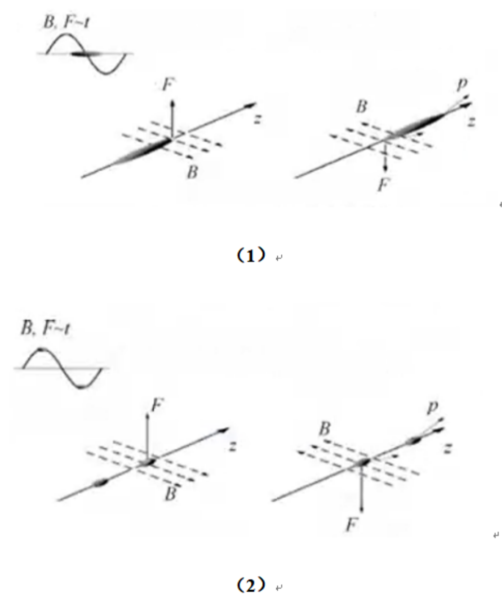

Figure 1: (1) Diagram of the force on the bunch at zero phase. (2) Diagram of the force on the bunch at 90 phase.

At first, the working principle of the deflector structure will be briefly introduced in Fig. 1. When microwave power is fed into the deflector, a harmonic time-varying transverse deflecting field can be generated inside the cavity, which can be used to change the direction of particle motion. This structure has a wide range of applications in the accelerator field. For a single electron beam, when it passes through the deflection cavity, the effect on the beam is different with the change of phase. When the bunch is short enough and the bunch is in a zero-crossing phase, the electrons at the head and tail of the bunch will receive Lorentz forces in opposite directions, and the transverse position will not be deflected significantly. Based on this effect, the main beam bunches of concern can be placed in this constant phase by adjusting the phase parameters, while other dark currents can be approximated as DC emission sources. After passing through the deflector structure, the field emission electrons in other phases will receive transverse deflection force and deflect in two directions according to the phase. Combining the necessary devices and simulations, the suppression of dark current in electron gun with deflector structures can be verified in Fig. 2.

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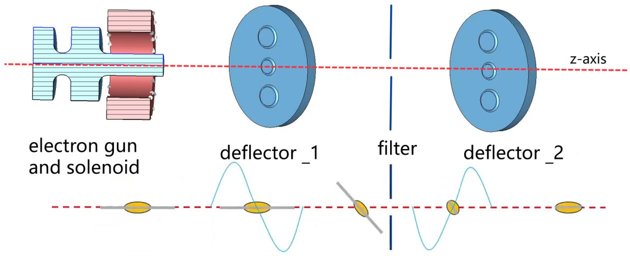

Figure 2: Dark current suppression diagram.

Table 1: Parameters of the Optimized 2.6-cell RF Gun

condition	Room	Cryogenic
Working mode (MHz)	5693.51	5712
Q_0	11473	52621
Ez, cathode (MV/m)	200	200
E_{max} /E_{acc}	88.59%	
Peak RF power (MW)	17.244	3.761
Max S_c (W/μm^2)	4.837	
RF pulse length (μs)	2	2
Maximum RF pulse heating(K)	19.98	4.85

THE NEW CRYOGENIC C-BAND GUN

In order to further improve the accelerating gradient of the electron gun in the existing injector, a new cryogenic C-band RF electron gun is designed recently in SXFEL and is expected to be used in the subsequent upgrade of the free electron laser device. In this design, the cathode gradient of the gun was set to 200 MV/m under cryogenic state (40 K) to get electron bunches with lower emittance, which means the surface field may be quite high to induce RF breakdown. To reduce the breakdown rate, the aperture of irises on the C-band RF gun have been optimized and the structure of the cathode cell has been specially designed to accommodate the z-coupling ports.

Using dual feed power coupling scheme and race-track design on the cathode cell, the multipole field components can be reduced. In the beam dynamics of the photo injector, the solenoids has been designed to wrap around the gun to obtain high-brightness beams at the injector exit. The parameters of the cryogenic gun are summarized in Table 1. To reduce the dark current from this cryogenic injector, deflector structure has been considered to surpress the field emission electrons. Considering that the 2.6-cell electron gun model in this paper requires both main solenoid and compensation solenoid to compensate the emittance, there are too many variables to be considered, so the model is simplified: the S-band 1.6-cell electron gun model is used for preliminary simulation exploration in this section.

RESULTS OF SIMULATION

Main Bunch Tracking

The 3D CST Particle-in-cell solver can be used to evaluate the electron emission process at the cathode, the propagation process along the electron gun structure, and the energy spectrum of electron bunches at the gun exit (see Fig. 3). Preparation work is required before the simulation of dark current emission and tracking. Firstly, the basic electron gun model needs to be established and its electromagnetic field distribution at 2856 MHz needs to be obtained by using the eigenmode solver. Then, the solenoid wrapped outside the electron gun is modeled. In this simulation, the solenoid coil is set to 1000 turns, the current is defined as 2 A, and the static magnetic field from it is calculated. Similarly, the model of a single S-band deflecting cavity is established, and the electromagnetic field in it is simulated. Then, the electromagnetic fields above are imported into the 3D CST Particle-in-cell solver.

After the import of fields, the weight coefficient, position and phase information of each field need to be set and adjusted. Here the position, size and phase of the deflection cavity need to be adjusted. In addition, a surface particle source with radius R = 1 mm is preliminarily set. In theory, the emission of the dark current is spread throughout the plane where the cathode is located, so a simplified model was used here to observe more obvious movements.

By tracking the electron beam of the 10 ps Gauss model, the motion of the main bunch was simulated. The distance from the electron gun exit to the center of the deflector was adjusted to be an integer multiple of the wavelength, and fine-tuning was made to control the arrival phase of the electron beam.

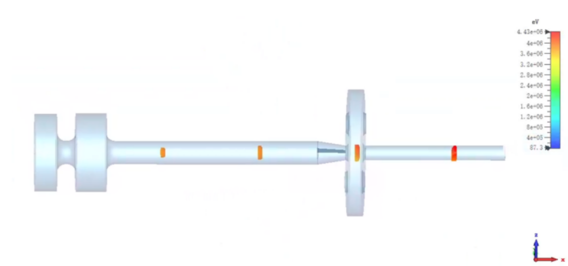

Figure 3: Main bunch tracking with the deflector.

It can be seen from the tracking results that after adjusting the phase parameters of each cavity, only the head and tail of the main bunches are subjected to opposite Lorenc magnetic force, but the transverse position is basically unchanged. As shown in the Fig. 4, only the distribution of the lower half of the bunch is shown to observe the change of orientation. The orientation of the main bunch at the cathode can be regarded as the z-axis direction. Under the focusing effect of the solenoid, the orientation of the bunch is deflected at a certain angle before entering the deflector; however, after the bunch leaves the deflector , the orientation gradually returns to the z-axial direction and changes in the opposite direction. Due to the shorter bunch length, the transverse position center of the whole bunch does not shift greatly. As far as the result is concerned, the theoretical expectation has been preliminarily reached. Then the dark current emission process will be further simulated and analyzed.

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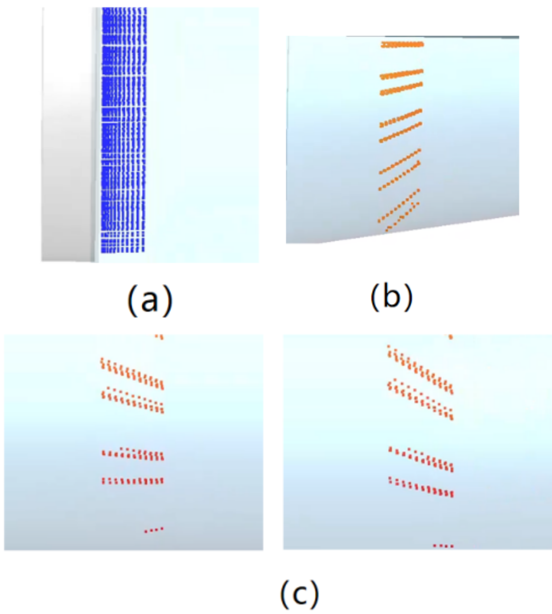

Figure 4: (a) bunch at the cathode, (b) bunch before entering the deflector, (c) bunch after leaving the deflector.

Dark Current Tracking

By changing the electron emission source to a DC emission model, the dark current emitted from the cathode can be simulated [5]. Here, we also refer to the above method and keep the field parameters unchanged during the simulation for the main bunch. The transmission of dark current with and without deflecting field is simulated respectively, as shown in the Fig. 5.

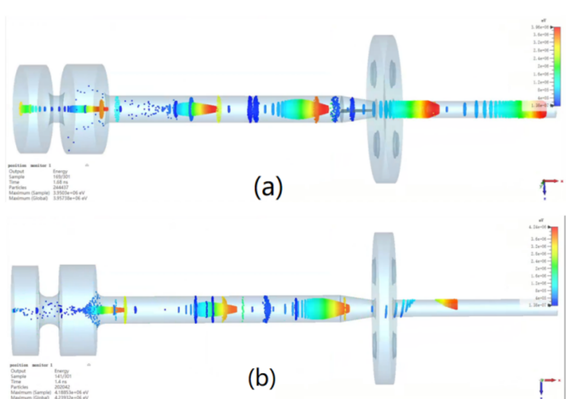

Figure 5: Dark current tracking with(a) and without(b) deflecting field.

At this time, it can be obviously observed that the dark current can reach the model exit easily if there is no deflecting field. However, when there is a deflecting field, a part of the dark current will receive a big force in the transverse direction, thus deviating from the axial direction and losing on the beam pipe wall.

In addition, the number of electrons that can reach exit can be observed by a monitor to evaluate the suppression effect of this scheme. As shown in the Fig. 6, it can be observed that under the effect of the deflector, the number of electrons captured at the exit decreases to a certain extent, which may be due to the problem of phase matching. With the increase of emission time, the isolating effect gradually weakens. Only at the first peak of dark current emission, the ideal inhibition ability is shown. Therefore, it is still necessary to further optimize the model, find its stable working state, and conduct a quantitative evaluation of its inhibition ability. When the ideal isolating effect is achieved, same simulations work will be done in the C-band injector.

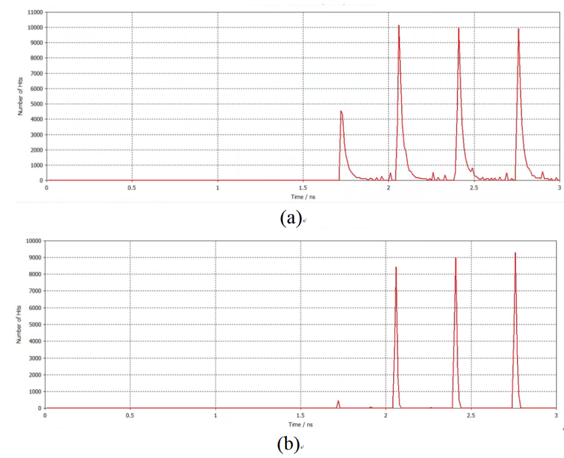

Figure 6: (a) Dark current at the exit without deflecting field, (b) Dark current at the exit with deflecting field.

CONCLUSION

In this paper, a new scheme for suppressing dark current by using deflector structure is explored. Dark current is an unavoidable problem in electron gun, and its existence will cause bad effects on the stability and quality of electron beam. Therefore, the suppression of dark current is of great significance for improving the performance of electron beam. Through the preliminary simulation work, we verified the effectiveness of the deflector structure in dark current suppression, and initially obtained two heoretical verification models, but it is still necessary to constantly improve the model to enhance the credibility and quantitatively evaluate the suppression effect, so as to provide theoretical support for the subsequent experimental verification.

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