Preliminary design and multipacting simulation of a SRF quarter wave electron gun at Peking University *

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Abstract: Peking University is designing a new SRF gun that is composed of a quarter wave resonator (QWR) and an elliptical cavity. Compared to the elliptical cavity, the QWR is sufficiently compact at the same frequency and its electric field is quasi-DC. The RF parameters are determined by optimization of QWR cavity structure and the possible multipacting locations are analyzed by 2D MP simulation. The simulation results show that multipacting is not a critical issue for our optimized cavity structure.

Key words: QWR, multipacting, electron gun

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1 Introduction

The development of electron guns is widely believed to be a key requirement for future high average power free-electron lasers and energy recovery linacs. Superconducting RF (SRF) electron guns hold the promise of very bright beams for use in electron injectors. Up to now, most SRF guns have employed elliptical cavity or quarter-wave resonators [1, 2]. However, the quarter wave resonator (QWR) presents certain advantages over the standard elliptical type. QWRs can be made sufficiently compact at low RF frequencies (i.e. long wavelengths). The long wavelength allows us to produce long electron bunches that minimize space charge effects and enable high current. Because of these potential benefits, quarter-wave SRF electron gun projects have been developed by the Naval Postgraduate School (NPS) [3], the University of Wisconsin [4], and Brookhaven National Laboratory (BNL) [5]. Peking University is considering a new SRF injector that is composed of a quarter wave resonator gun and an elliptical booster cavity. The goal of the SRF gun is to deliver electron beams with energy of about 5 MeV, normalized transverse emittance of about 1 mm·mrad, and average current of 10 mA. The QWR cavity works at 325 MHz and the elliptical cavity, which adopts TESLA type, works at 1.3 GHz. In this paper, the preliminary design of the QWR gun is described and MP has been studied in detail to ensure that it does not limit the gun's performance.

2 325 MHz QWR gun cavity design

QWRs can be thought of as coaxial transmission lines that are shorted on one end and unterminated on the other end.

Cavity RF design work is performed by using Superfish [6] and CST Microwave Studio [7]. The cavity structure was optimized to pursue high cathode surface electric field and lower peak surface field ($B_{\rm pk}/E_{\rm acc}$, $E_{\rm pk}/E_{\rm acc}$) by adjusting the cavity geometry parameters.

Fastigiated inner conductor geometry is applied to have a low ratio of peak magnetic field to accelerating electric field ($H_{\rm pk}/E_{\rm acc}$). According to transmission line theory, the $H_{\rm pk}$ can be calculated as:

$$H_{\rm pk}=\frac{V_0}{2\pi a Z_0}. \tag{1}$$

Here $Z_0=60\ln(b/a)$, where b and a are the radius of outer and inner conductor respectively, V_0 is the voltage. Increasing the angle of the nosecone (α in Fig. 1) and decreasing the radius of inner conductor (a in Eq. (1)) are equivalent. $B_{\rm pk}/E_{\rm acc}$ versus different α is shown in Fig. 2. We can get a lower surface magnetic field by using a big angle α, but when the angle α is too large (the radius of outer conductor b is fixed) the short end of the cavity will be narrow, which can make cleaning difficult.

Rational design of the nosecone can decrease the peak surface electric field. We notice that the peak surface

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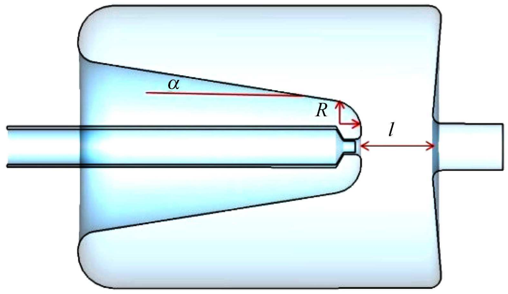

Fig. 1. Geometrical parameters under consideration for the optimization of the cavity: the radius of curvature of the nosecone at the inner surface (R), the angle of the nosecone (α), the length of the gap (l).

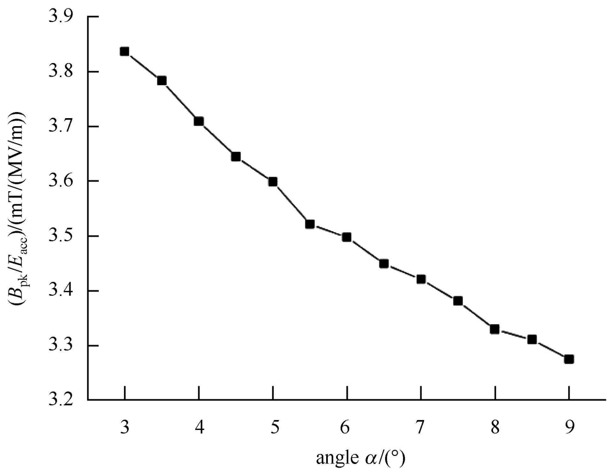

Fig. 2. $B_{\rm pk}/E_{\rm acc}$ versus different α.

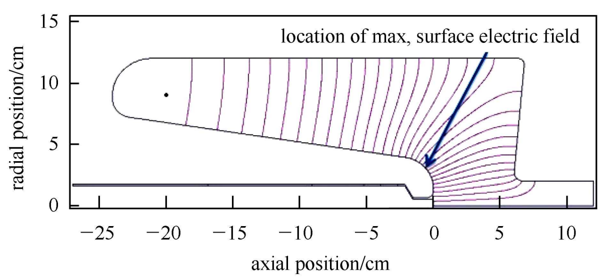

Fig. 3. (color online) Cavity geometry used in superfish calculations and location of peak surface electric field in the cavity.

electric field is located in the nosecone of the inner conductor surface (Fig. 3). The radius of curvature (R in Fig. 1) of the nosecone at the inner surface has an effect on the peak surface electric field. The $E_{\rm pk}/E_{\rm acc}$ versus different R is shown in Fig. 4.

The distance between cathode and exit aperture, or the gap length (l in Fig. 1), is an important parameter in this geometry. By decreasing the gap, the transit time factor and peak field at the cathode are both increased. This is good in terms of emittance preservation and minimization of the beam energy spread, but bad in terms of peak surface field, field emission, etc. In our design, the gap l is 6 cm, and the gradient $E_{\rm acc}$ is 20 MV/m. The energy gain from the gap is more than 1.0 MeV, which means that the β is close to 1.0.

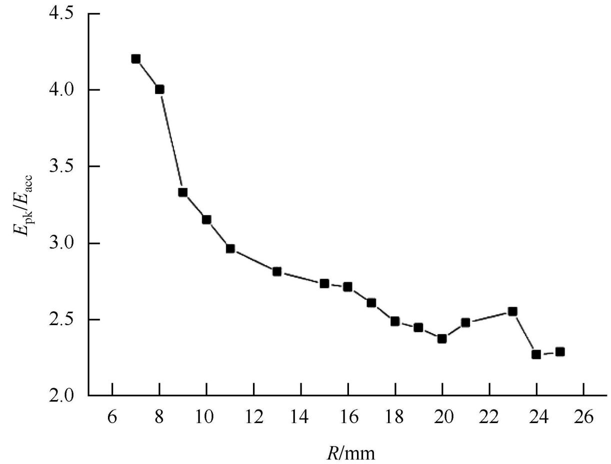

Fig. 4. $E_{\rm pk}/E_{\rm acc}$ versus different R.

The internal corners of the QWR cavity are supposed to be round, which is generally desired for ease of cleaning and to mitigate multipacting.

Just like the input coupler, the cantilevered cathode stalk becomes an RF transmission line, thereby allowing RF energy to flow down it. Any RF power pulled from the cavity decreases the cavity fields. The cathode stalk is a half wavelength design serving as a choke joint for the cathode. The diameter is variable along the stalk which provides a large reflection of RF power for its varied impedance along the stalk.

Figure 5 shows the accelerating electric field profile along the beam axis.

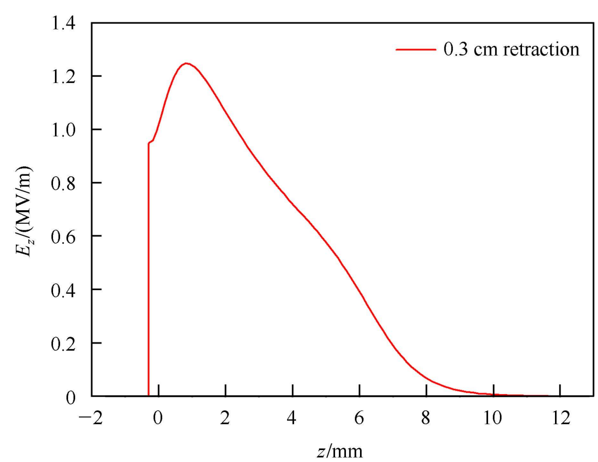

Fig. 5. (color online) Accelerating electric field profile along the beam axis.

Table 1. RF parameters of the 325 MHz quarter wave electron gun.

parameter	value
frequency/MHz	325
Q_0	1.5e9
$(R/Q)/\Omega$	156
geometry factor/Ω	63.1
$(B_{pk}/E_{acc})/(\mathrm{mT}/(\mathrm{MV/m}))$	3.26
E_{pk}/E_{acc}	2.27
aperture/mm	40
maximum diameter/mm	240

At E_{acc}=1 MV/m and reference length 6 cm.

The RF parameters of the 325 MHz quarter wave electron gun are summarized in Table 1.

3 Multipacting simulation

Multipacting [8], a highly probable occurrence in most evacuated RF structures, is a low field electron

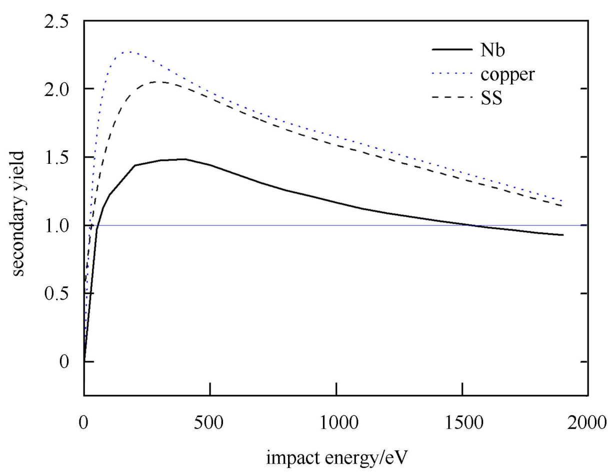

Fig. 6. (color online) Secondary electron yield for niobium, copper and stainless steel as a function of the electron impact energy in eV.

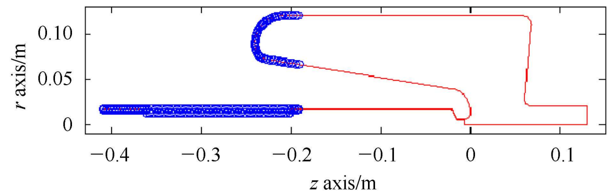

Fig. 7. (color online) Initial electron generation points from −41 cm to −19 cm, highlighted in blue.

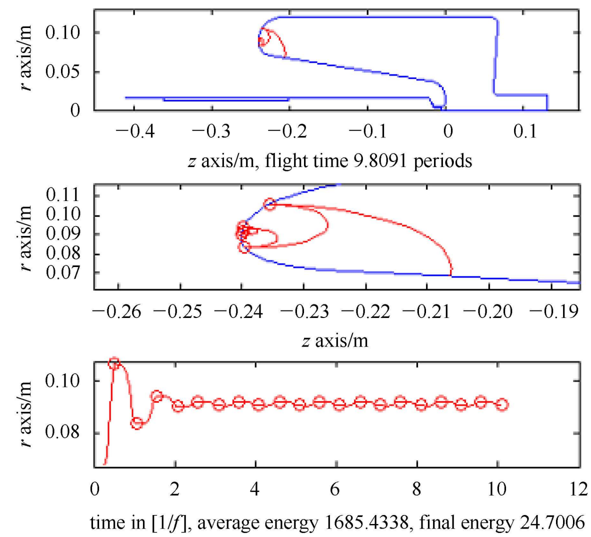

Fig. 8. (color online) The electron trajectory at 17.5 MV/m. The top figure represents the trajectory of the electron in (r, z) coordinates, the middle one is an expanded plot of a part of the top one, and the bottom plot illustrates the electron's trajectory in the (r, t) coordinates where t is the time in rf periods. The circles indicate the impacts on the walls of the cavity.

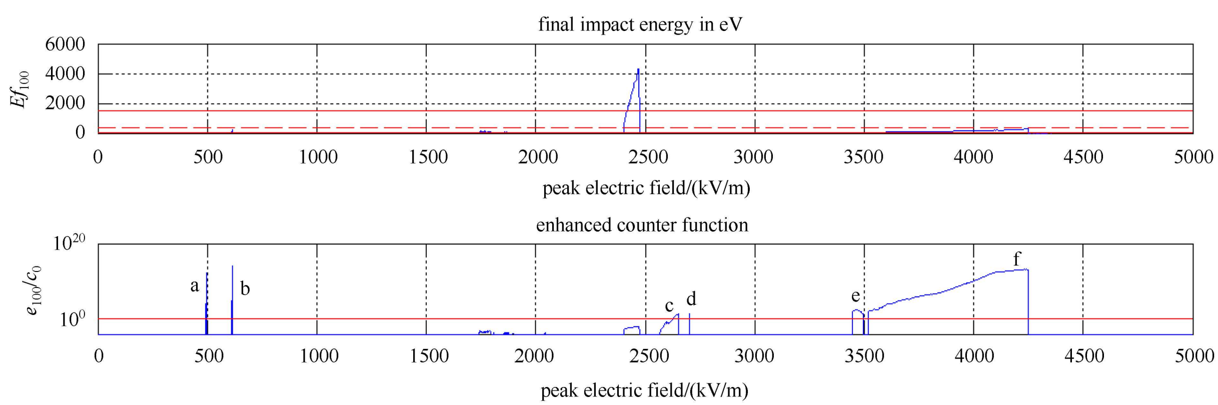

Fig. 9. (color online) The plot of final energy and enhanced counter function. Multipacting occurs at peak surface electric field 494–498, 612-614, 2568–2650, 2700–2704, 3426–3500 and 3520–4250 kV/m.

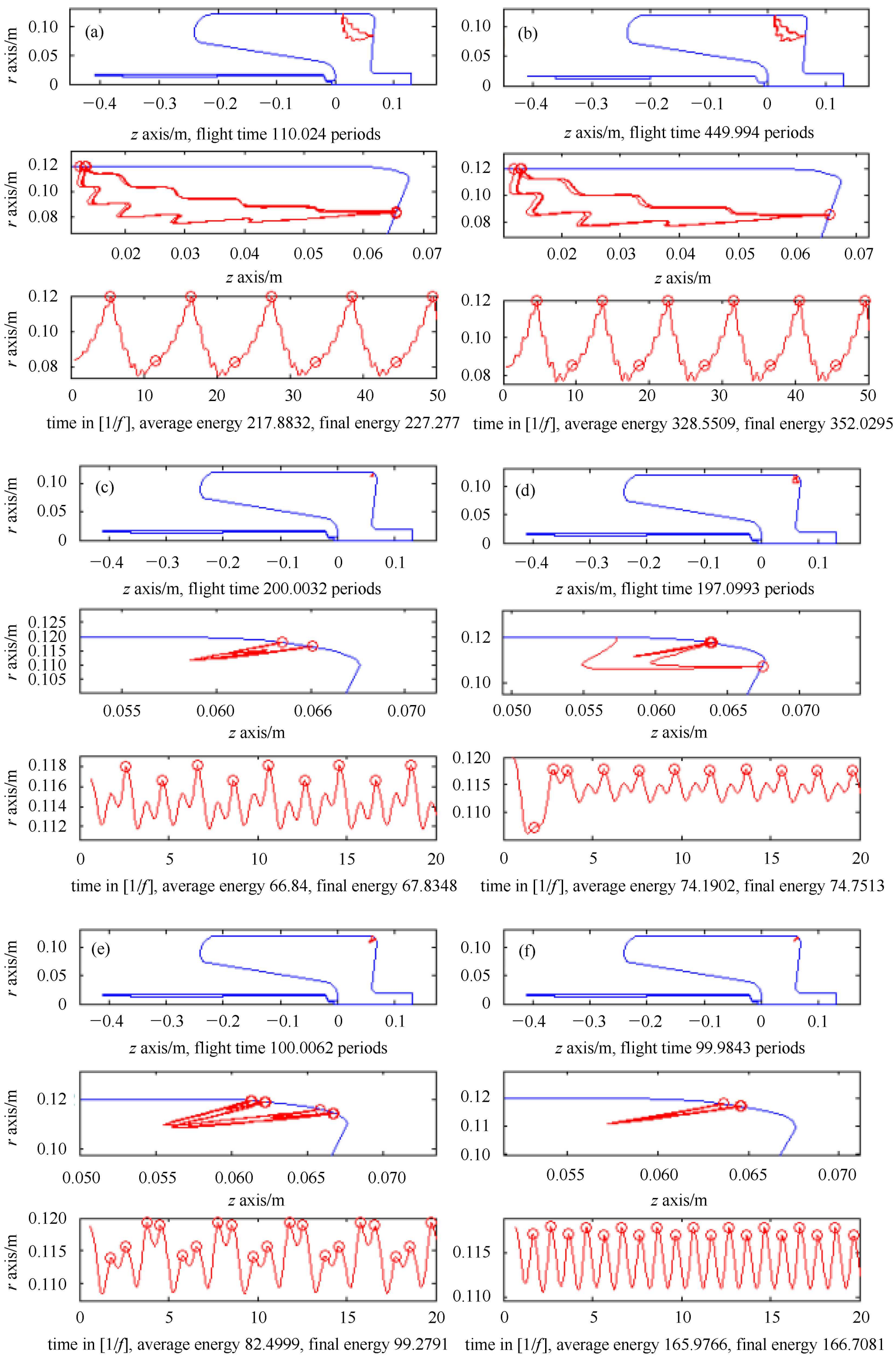

Fig. 10. (color online) 6 types of MP trajectories from Multipac results. (a) The fifth-order two point MP at peak surface electric fields 496 kV/m. (b) The forth-order two point MP at peak surface electric fields 612 kV/m. (c) The second-order two point MP at peak surface electric fields 2600 kV/m. (d) The second-order single point MP at peak surface electric fields 2700 kV/m. (e) The first-order four point MP at peak surface electric fields 3450 kV/m. (f) The first-order two point MP at peak surface electric fields 4000 kV/m.

avalanche phenomenon that is caused by resonant electron multiplication from secondary emissions. It occurs when free electrons, accelerated by the RF field, strike the surface of the cavity and release secondary electrons, which repeat the process, and this rapidly causes an electron avalanche. This electron discharge absorbs much of the power pumped into the system and prevents the structure from reaching its designed field. Furthermore, the impacts of the electrons on the cavity's wall raise its temperature, and may cause quench and breakdown of SRF guns.

MultiPac [9] is a simulation package for analyzing electron MP in axisymmetric RF structures and it is used for MP simulation of our QWR cavity. Code calculates enhanced counter function, $e_{\rm N}/C_0$, which denotes the ratio of the total number of secondary electrons after N impacts ($e_{\rm N}$) to the initial number of electrons (C_0). When the enhanced counter function is greater than 1 for 20 electron impacts, multipacting is possible (but yet to be verified) at that field level.

In Multipac we are able to assign different materials to different wall segments. The material of the cavity is Niobium, the stalk is copper and the out tube of the stalk is stainless steel (data from CST material library). Fig. 6 gives the secondary electron yield of these three materials.

The simulation was carried out with initial electron (seed electron) energy of 2 eV, a 5° rf phase interval, and a 2 kV/m electric field step. We scanned the cavity's peak surface electric field ($E_{\rm peak}$) from 0.0 MV/m to 60 MV/m which corresponding to the gap voltage range from 0.0 MV to 1.6 MV.

We are interested in the MP on the short end of the cavity (Fig. 7). After 25 impacts, the enhanced counter function for this part is only 1e-8 from 15 MV/m to 20 MV/m. The electron trajectory at 17.5 MV/m is shown in Fig. 8. After 100 impacts, the enhanced counter function is zero.

When N=100, the final impact energy and enhanced counter function of the whole cavity are shown in Fig. 9.

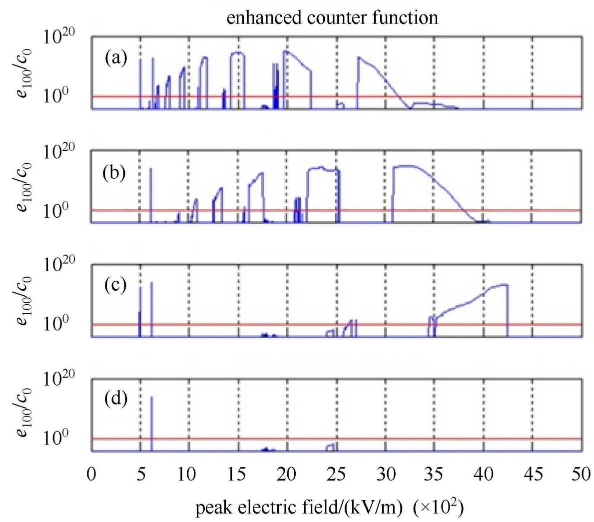

Fig. 11. (color online) Enhanced counter function plot for different radius of the corner in the open end of the cavity (a) R=30 mm. (b) R=20 mm. (c) R=5 mm. (d) R=2 mm.

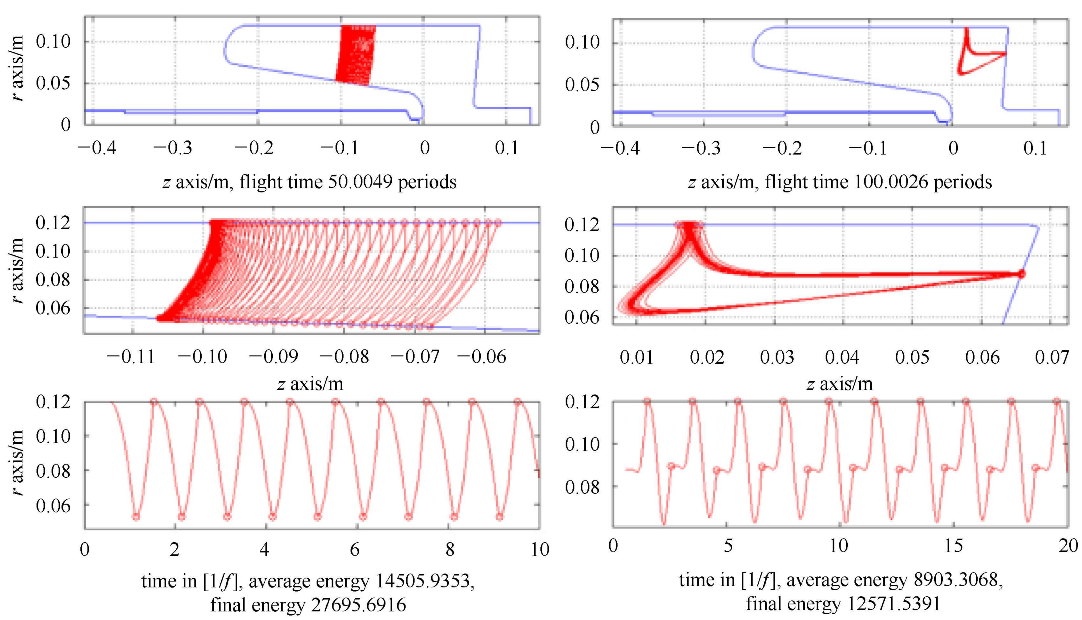

Fig. 12. (color online) The electron trajectories at peak surface electric fields 1750 kV/m (left) and 2400 kV/m (right).

No multipacting is found above 5 MV/m. The position whose enhanced counter function is bigger than 1 is located in the corner of the open end of the cavity. Different types of MP are shown in Fig. 10.

Hence, we must suppress the MP phenomenon in the 325 MHz QWR. The electron's stable resonant trajectory can be broken by changing the radius of the corner. Enhanced counter function plot for different radius of the corner in the open end of the cavity is shown in Fig. 11.

We noticed that most of the MP barriers disappear when the radius of the corner is 2 mm. There is only one MP barrier with the enhanced counter function is higher than 1. However, because the electric field is very low and the range is very narrow, this is not a critical issue. In Fig. 11(d), we can see there are two other field levels whose enhanced counter function are smaller than 0.01. The electron trajectories are shown in Fig. 12. The locations are between the inner conductor and the outer conductor, and in the corner of the open end of the cavity. They should not be a problem if good processing procedures are applied to the cavity.

4 Conclusion

We designed a QWR cavity for the SRF electron gun and it shows good RF properties. By careful design of the QWR cavity shape, MP can be suppressed, which is not a critical issue if the cavity has good surface treatment. Beam-dynamic simulation is ongoing for an injector design with a 2cell booster.

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