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CATHODE STALK OPTIMIZATION FOR A 325 MHz SUPERCONDUCTING QWR ELECTRON GUN*

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Abstract

The structure of cathode stalk is very important for the performance of a superconducting QWR (Quarter Wave Resonator) electron gun. With improper design, RF power dissipation on the surface of cathode stalk and its surrounding tube can lead to a serious decrease of quality factor for superconducting QWR injector. We present here an optimized design of the cathode stalk for the 325 MHz superconducting QWR gun and special considerations are taken to minimize the power dissipation. The details of microwave simulation, beam dynamic simulation of the cavity with cathode stalks in different length, diameter and position are presented in this paper.

INTRODUCTION

An appropriate source is very important for the success of the proposed energy recovery linac (ERL) and high average power free-electron lasers (FELs). The superconducting radio frequency (SRF) electron guns offer great promise of very bright beams for use in electron injectors. QWR is compact at low RF frequency compared to elliptical cavity and its long wavelength allows to produce long electron bunches for which space charge effects can be minimized. Because of these potential benefits, projects of QWR electron gun have been developed at Naval Postgraduate School (NPS) [1], the University of Wisconsin [2] and Brookhaven National Laboratory (BNL) [3]. A 325MHz QWR electron gun has also been proposed at Peking University for obtaining higher beam current than the present DC-SRF gun.

One of the main problems of the SRF injectors is that a cathode inserted into the superconducting gun cavity causes worse performance of the SRF cavity. Usually we use a cantilevered stalk, not shorted directly to the cavity, to support the cathode in the desired position. This design has a singular flaw that the cathode stalk becomes an RF transmission line allowing RF energy to flow down it as a coaxial waveguide. As we know, any RF power pulled from the cavity degrades gun performance. This problem has been predicted in the Rossendorf gun [4] and Brookhaven SRF gun [5]. Both of them were designed to incorporate an RF choke to prevent the RF power flowing down the cathode stalk. The DC-SRF [6] gun in Peking University also offers an effective way to solve this problem, which combining a Pierce gun with a superconducting cavity. As to the QWR gun, its reentrant structure determines that a choke filter or a Pierce gun is not a good choice. So the design of the cathode stalk in QWRs is very important, the test in NPS shows that the quality factor of cavity with cathode stalk can be an order of magnitude smaller than that of the virgin cavity. We do some research on the design of the cathode stalk aiming to reduce the RF power dissipation on the cathode stalk on the basic of the 325MHz QWR electron gun.

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325 MHz QWR ELECTRON GUN

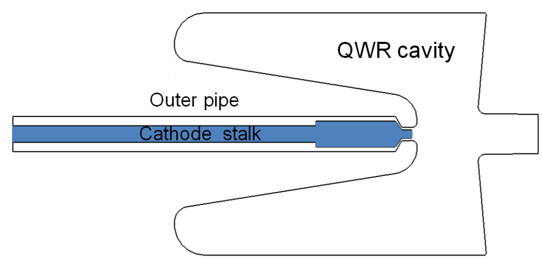

Figure 1: The schematic of 325MHz QWR cavity and the cantilevered cathode stalk.

The 325MHz QWR gun cavity design is given in reference [7], the simulation of the electromagnetic field of the QWR cavity was carried out with the Superfish code [8]. When the average accelerating electric field E_{acc}=20 MV/m, the stored energy of the cavity U=4.67 J and the cavity's intrinsic quality factor Q_0=1.536 $\times 10^9$ (T=4 K), the dissipated power in the cavity walls is given by

$$P_c = \frac{\omega_0 U}{Q_0} = 6.2\,\mathrm{W} \tag{1}$$

Here, we defined the RF power dissipation on the cathode surface and the outer pipe inner surface as P_d, that is

$$P_d = \frac{R_s}{2}\int_{A_1+A_2} H^2 da \tag{2}$$

Here, Rs is the surface resistance. We choose copper as the material of stalk because of its lower resistivity. A_1 and A_2 are the area of the cathode stalk surface and the area of the outer pipe inner surface, respectively. The QWR cavity and the cantilevered cathode stalk are shown in Figure 1.We define the quality factor which considering the RF power dissipation on the cathode surface and the surrounding tube inner surface as $Q_0^{'}$, which is defined as

$$Q_0^{'} = \frac{\omega_0 U}{P_c + P_d} \tag{3}$$

THE CATHODE STALK

Just like the input coupler, the cathode stalk and the outer pipe form a RF transmission line. We consider the case

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that the stalk and the outer pipe forming a simple coaxial waveguide. According to the transmission line impedance equation:

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \quad (4)$$

Here $Z_0 = \ln(b/a)$, here b and a are the radius of outer and inner conductor, respectively. Z_L is the load impedance, at the shorted circuited end Z_L=0 (at the end of the cathode stalk, the stalk is shorted to the outer pipe). Z_{in} is the input impedance seen looking from the cavity toward the load.

The Length of the Stalk

According to Eq. 2, when the stalk length $l = \lambda/2$, the input impedance $Z_{in} = 0$, and when the stalk length $l = \lambda/4$ or $l = 3\lambda/4$,the input impedance $Z_{in} = \infty$, it means that all incident power is reflected. However, we noticed that when $l = \lambda/4$ or $l = 3\lambda/4$, the coaxial waveguide structure is similar to quarter wave resonator, and more power was stored in the coaxial waveguide to form a resonator, which can lead to more RF power dissipation.

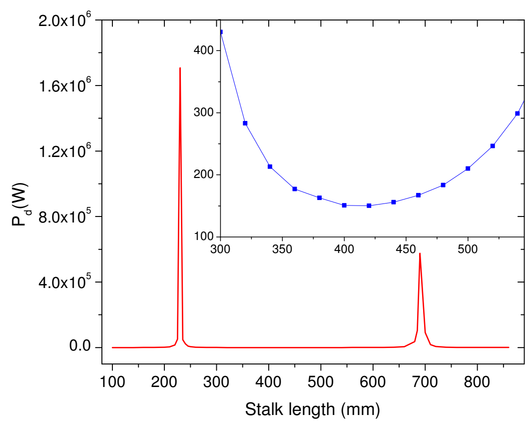

Figure 2: The magnitude of the power dissipation versus stalk length.

The magnitude of the power dissipation versus stalk length is plotted in Figure 2, and in our simulation: a= 5 mm, b= 6.5 mm, E_{acc}= 20.0 MV/m, the position of the cathode is Δz= 0.0 mm (seen in Figure 3).

We can see that when the stalk length $l = \lambda/4$ (230mm)or $l = 3\lambda/4$ (690mm) the power dissipation has the maximum. Actually, the coaxial waveguide forms a resonator cavity in this case. As expected, around the half wavelength the power dissipation has the minimum.

Position of the Cathode

The position of the cathode affects the fields on the cathode. RF focusing is achieved by pulling the cathode out of the cavity behind the back wall plane [9]. The field distribution is given in Figure 3 by pulling the cathode stem out of the cavity with distance Δz behind the inner conductor back wall plane. The electric fields components along the symmetry axis are show in Figure 4. The fields were calculated using the Superfish code, and the length of the cathode stalk is 400 mm.

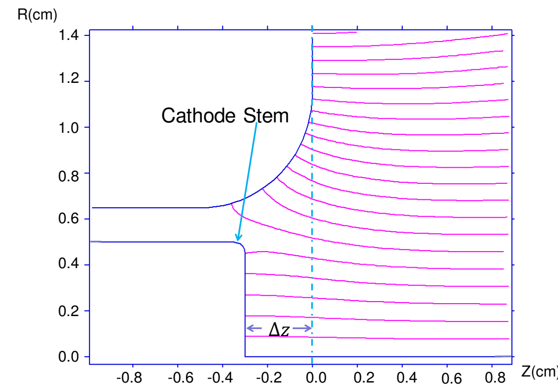

Figure 3: Close view of the field pattern near the cathode for the 32MHz QWR cavity.

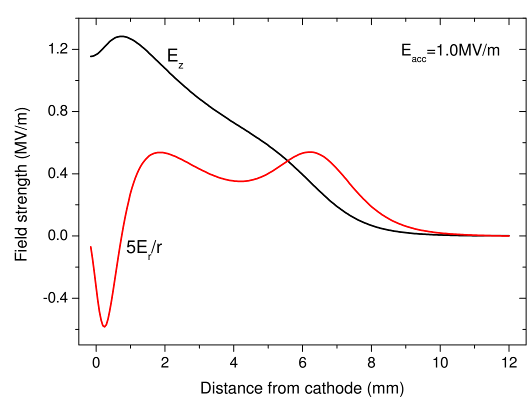

Figure 4: Simulated longitudinal and radial electric fields along the gun axis.

At cathode, where the energy of emitted electrons is low, the electric field has a radial focusing component E_r, which can be used to focus the beam and compensate for the space charge effect. At the same time, we notice that the P_d and electric field on the cathode (the accelerating component E_z) decrease when the cathode is pulled out of the cavity deeper into the surrounding tube. Figure 5 presents the electric field on cathode and P_d versus cathode position.

Actually, both large accelerating component E_z and radial focusing field E_r are needed at the cathode. An optimum Δz is depends on initial beam parameters. Figure 6 shows that the optimum Δz is affected by different initial beam parameters. We can see that, when the bunch charge is 50 pC, $\Delta z \approx$1.0 mm is an optimum for minimum transverse emittance, and when the bunch charge is 1.0 nC the optimum $\Delta z \approx$ 4.0 mm.The simulation condition: bunch radius σ_r=2.0 mm, bunch length σ_t=3.0 ps, E_{acc}=20.0 MV/m.

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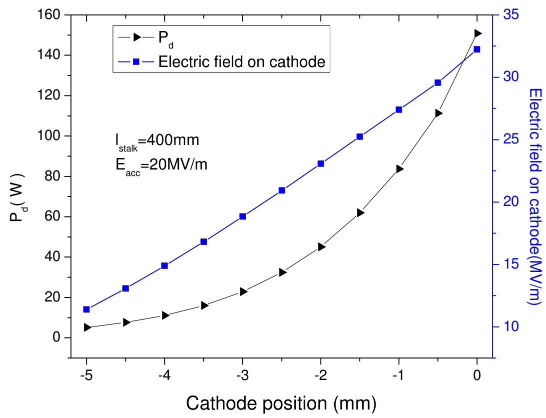

Figure 5: Electric field on cathode and P_d versus cathode position.

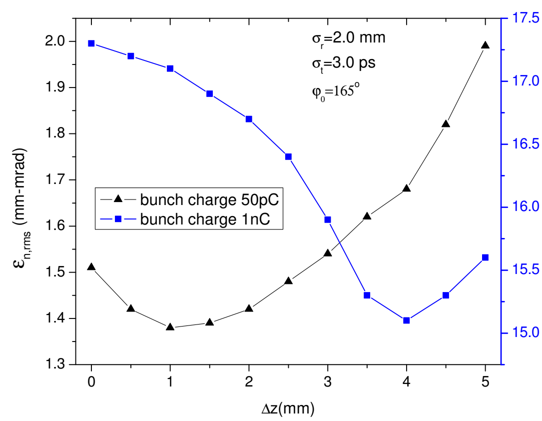

Figure 6: The optimum Δz for best transverse emittance is affected by different beam parameters.

The Variation of Stalk Diameter

RF power dissipation on the surface of the stalk as well as the outer pipe, i.e. P_d, is attributed to the RF power being coupled onto the cathode stalk. The more power coupled onto the cathode stalk the more RF power dissipated. If we want to decrease the RF power dissipation we have to decrease the power coupled into the stalk. As we known in microwave engineering, the voltage reflecting coefficient, Γ:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{5}$$

Table 1: The RF Power Dissipation of Different Kinds of Stalk Structure

Structure type	P_d / P_c	Q_0'
Simple coaxial line	7.27	1.86×10^8
Once diameter change	3.17	3.68×10^8
Twice diameter change	1.08	7.38×10^8

When the load is mismatched, the presence of a reflected wave leads to power reflection. If we change the impedance along the stalk, there is more power reflected into cavity and the RF power coupled on the stalk decreases. The characteristic impedance of the coaxial line is defined as $Z_0 = \ln(b/a)$, we can change the stalk diameter to have various impedance. Three kinds of stalk structure were simulated, seen in Figure 7 (l_{stalk}=400 mm, Δz=2.0 mm). The calculation result of P_d is list in Table 1. We can see that P_d for stalk with changing diameters significantly reduced.

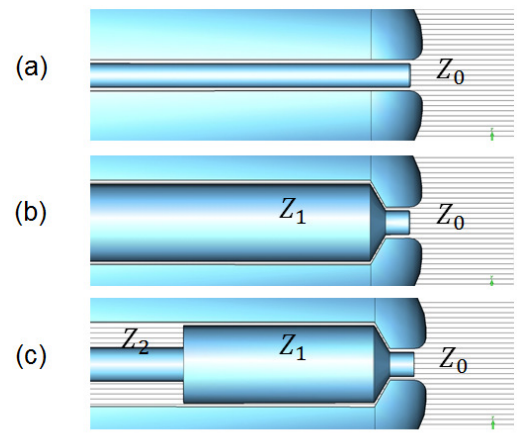

Figure 7: (a) The simple coaxial line structure. (b)The coaxial line structure with once diameter changing. (c)The coaxial line structure with twice diameter changing.

Active Cooling

Proper cooling method can reduce R_s since $P_d \propto R_s$ according to Eq. 2, LN2 can satisfy the cooling requirement in our case.

The copper's electrical conductivity used in calculation is σ_{293K}=5.8×10^7 S/m and σ_{77K}=2.0×10^7 S/m [10].

The power dissipation at different temperature has the following relation:

$$\frac{P_{d,77K}}{P_{d,293K}} = \frac{R_{s,77K}}{R_{s,293K}} = \sqrt{\frac{\sigma_{293K}}{\sigma_{77K}}} = \frac{1}{1.85} \tag{6}$$

We found that the $P_{d,77K}$ nearly a factor of two smaller than $P_{d,293K}$, and in this case, the $Q_0' \approx 1.0 \times 10^9$.

CONCLUSION

In this paper we try many ways to reduce the RF power dissipation P_d. The simulation result shows that P_d can be significantly reduced by choosing a half wavelength cathode stalk. When the cathode tip retracted behind the back wall plane, the RF power loss P_d also decreases. Meanwhile, the radial focusing component used to compensate for the space charge can be achieved. The RF power can also be reduced by changing the diameter of stalk for variable impedance and employing active cooling. Finally, quality factor for the injector with cathode stalk can be on the same order as the virgin cavity.

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