# Geometry dependent multipacting of a superconducting quarter-wave resonator at PKU *

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**Abstract:** A superconducting quarter-wave resonator (QWR) of frequency=162.5 MHz and $\beta$=0.085 ($\beta=v/c$) has been designed at Peking University. The multipacting (MP) simulation and analysis for the QWR with CST Particle Studio has been performed. The simulation results reveal that there is no sign of MP with its normal operating accelerating gradients in the range of 6–8 MV/m. The accelerating gradient range that may incur MP is from about 1.4 to 3.2 MV/m, and the places where MP may be encountered are mainly located at the top part of the QWR. So the effect of different top geometries on MP has also been studied in depth. Our results show that an inward convex round roof is better than other round roofs, and plane roofs have an advantage over round roofs on the suppression of MP in general. While considering the optimization of its electromagnetic (EM) design, our initial designed model is also acceptable.

**Key words:** MP, accelerating gradient range, geometry, growth rate

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## 1 Introduction

Multipacting (MP) is a resonant discharge process in which an electron avalanche builds up via secondary emission driven by a radio-frequency (RF) field [1]. When the MP effect occurs, these multiplied electrons can cause several severe problems, such as deteriorating the vacuum, absorbing incident power, and preventing the increase of accelerating gradient, leading to quenching the cavity and even damaging RF devices. The MP effect is an inevitable issue when we design a superconducting RF cavity, especially for low $\beta$ superconducting cavities, used for heavy ion acceleration, such as quarter-wave resonators (QWRs), half-wave resonators (HWRs), or spoke resonators.

A superconducting QWR of frequency=162.5 MHz and $\beta$=0.085 to accelerate high current proton beam has been designed [2]. Its electromagnetic (EM) design and optimization have been completed [3]. The current paper focuses on the MP study of the QWR with the code CST Particle Studio [4]. First, the initial QWR model will be checked. The accelerating gradient range and the location, where MP may occur, are investigated. Then, we change the shapes of the QWR where MP may occur, and explore the effect of different geometries on MP. The following sections will present more details.

## 2 The model setup

The QWR model is based on the optimized results of its EM design [3]. Its normal operating accelerating gradient range is from 6 to 8 MV/m. The model consists of two parts, the inner component being a vacuum chamber and the outer component being a 2.8 mm cavity wall made of niobium after 300 ℃ bake (Fig. 1.(a)). The vacuum part is used for calculating the EM field and the trajectories of the electrons, while the cavity wall is the area generating initial electrons and the boundary of the electron motion.

A module of CST Particle Studio can compute the EM field distribution in an eigenmode solver, as well as import external EM field files from CST Microwave Studio [4]. We choose the latter method to calculate the EM field distribution, which is more powerful and efficient. The "vacuum" model was imported first into CST Microwave Studio for field calculation. The EM field

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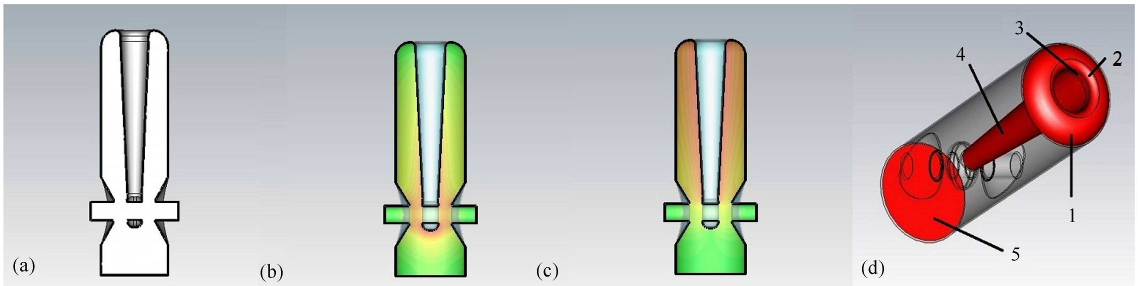


Fig. 1. The QWR model for MP simulation. (a) Prototype; (b) electric distribution; (c) magnetic distribution; and (d) the five regions to be checked.

distribution (Fig. 1.(b) and (c)) is simpler relative to a spoke cavity due to its high axial symmetry in geometric construction. There are five regions considered to be the potential areas of MP (Fig. 1.(d)).

## 3 The MP simulation

The secondary emission model used in CST Particle Studio is based on the Furman probabilistic model [5]. The particle sources provide the primary electrons uniformly distributed over the 5 regions. Their energies are set to be uniformly distributed from 0 to 4 eV and their initial emission angles are set to be randomly distributed from 0 ° to 180 ° . The number of primary electrons per region ranges from 4000 to 5000. For each region, since all the primary electrons are launched simultaneously during the same RF period, we need to check different initial phases and find the most noteworthy phase of MP.

Two conditions have to be fulfilled to give rise to MP. One is a secondary emission yield greater than 1, which is mainly determined by use of a proper material, surface treatment, appropriate incident energy and incident angle of the primary electron. The other one is the relatively stable trajectory, which is mainly affected by the initial phase of primary electrons, appropriate EM field distribution and appropriate EM field intensity. However, for a given cavity and fabrication material, there are only two factors mainly influencing MP: the initial phase of primary electrons and the EM field intensity.

For Region 1, we set the $E_{\rm acc}$=2 MV/m ($E_{\rm acc}=V_{\rm acc}/L_{\rm eff}$) and scan different initial phases from 0° to 360° and find out the most noteworthy initial phase, 120° (Fig. 2). Then we fix the initial phase at 120° and change the value of $E_{\rm acc}$, checking if there exists MP under different EM field intensities. MP can be found in the accelerating gradient range from 1 to 3 MV/m, while there is no MP in the accelerating gradient range from 4 to 10 MV/m. A more detailed gradient scan shows that the accelerating gradient range where MP may occur is from about 1.4 to 3 MV/m and at $E_{\rm acc}\approx$2 MV/m, MP is manifested dramatically.

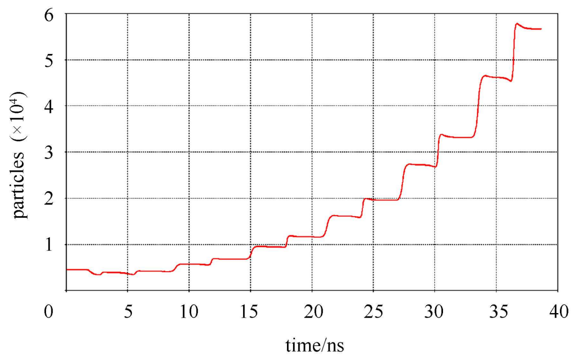


Fig. 2. (color online) The particle number versus time curve.

For Region 2 and 3, the same methods are adopted and the results are similar except that the noteworthy initial phases change. The accelerating gradient range where MP may occur is from about 1.4 to 3.2 MV/m. For Region 4, MP between the inner conductor and the outer wall can be spotted only when accelerating gradient drops to 0.1 MV/m. For Region 5, the results show that it is, actually, very difficult to form stable trajectories at the bottom of the QWR. The electrons' trajectories may incur weak MP when the accelerating gradient is below 1 MV/m. In short, the most sensitive place where MP may incur is located at the top part of the QWR.

## 4 Further study

In order to have a better understanding of the effect that geometries of the top part have on MP, we compare another three QWRs with different round roofs and four QWRs with different plane roofs to our initial designed model (Fig. 3). Their geometrical parameters are listed in Table 1. The differences on the top part will cause some changes in the resonant frequency, which is compensated by adjusting their cavity heights.

EM field accuracy is a very important issue to obtain good simulation results. A tetrahedral mesh is adopted to calculate their EM fields. Tetrahedral mesh division is based on finite element analysis, which can get very good precision with much fewer mesh cells, compared

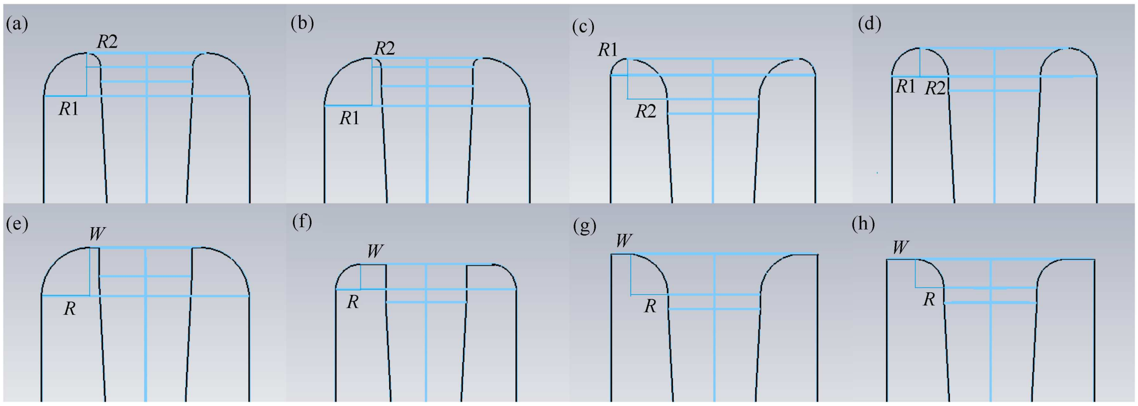


Fig. 3. The cross sections of different roofs of QWRs. (a) Initial designed roof; (b) inward convex round roof; (c) outward convex round roof; (d) symmetrical round roof; (e) inward plane roof 1; (f) inward plane roof 2; (g) outward plane roof 1; and (h) outward plane roof 2. $R1$ is the curvature radius of the outer blend edge of the round roof, and $R2$ is the curvature radius of the inner blend edge of the round roof. $R$ is the curvature radius of the plane roof, $W$ is the width of the plane roof.

Table 1. Geometrical parameters of different roofs.

| model | initial designed roof | inward convex round roof | outward convex round roof | symmetrical round roof |
|---|---|---|---|---|
| $R1$/mm | 35.5 | 39.5 | 13.5 | 23.5 |
| $R2$/mm | 11.5 | 7.5 | 33.5 | 23.5 |

| model | inward plane roof 1 | inward plane roof 2 | outward plane roof 1 | outward plane roof 2 |
|---|---|---|---|---|
| $W$/mm | 7.5 | 23.5 | 13.5 | 23.5 |
| $R$/mm | 39.5 | 23.5 | 33.5 | 23.5 |

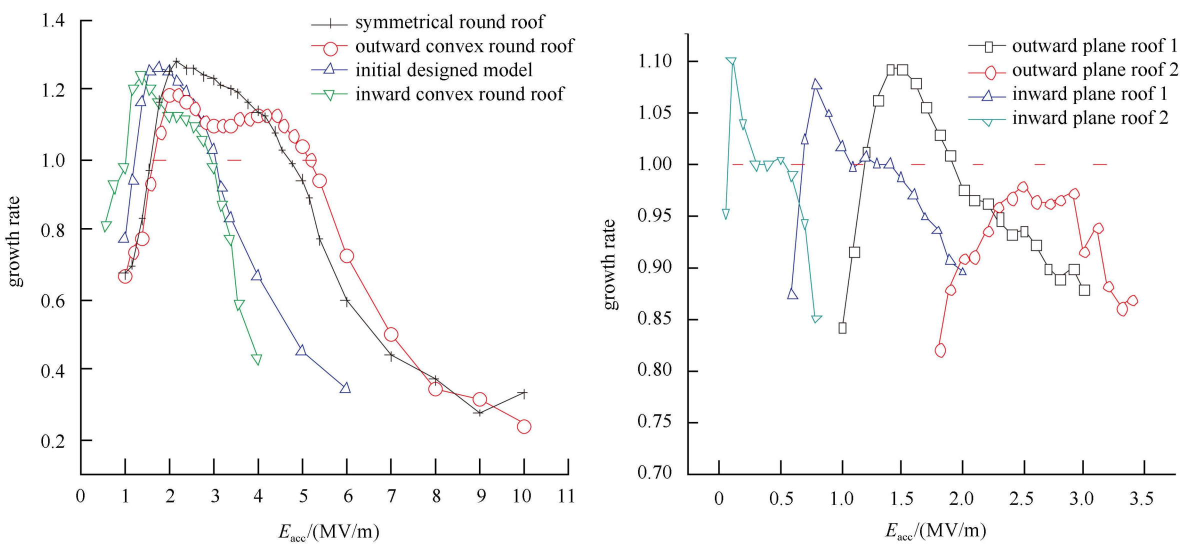


Fig. 4. Growth rate vs $E_{\rm acc}$ curves of different top geometry models.

with a hexahedral mesh. About 10 thousand tetrahedral mesh cells are set for EM field calculation. EM field files are separately imported into CST Particle Studio for MP simulation. In each case, we get an MP curve like Fig. 2 and export its plot data for further data analysis. By exponential curve fitting, we can get their growth rate at each accelerating gradient.

The left map is the result of round roofs and the right map is the result of plane roofs. The vertical axis is their growth rate, which means the average multiplication factor of each collision. That is to say, if one electron impacts on the cavity wall under a certain accelerating gradient, the growth rate refers to the number of electrons emitted from the surface of the wall in average. So, if the growth rate is above 1, there is MP, while if the growth rate is below 1, there is no MP.

For round roofs, relative to the symmetrical round roof and outward convex round roof, the inward convex round roof occupies a lower and narrower acceleration gradient range that may incur MP. When decreasing $R1$ and increasing $R2$, the corresponding acceleration gradient range moves leftward on the growth rate vs $E_{\rm acc}$ map, leaving its normal operating accelerating gradient range. As for the symmetrical roof and outward convex roof, their accelerating gradients that may incur MP start from about 1.6 MV/m and can reach up to 5 MV/m. MP may be a quite severe problem if designed in such a way.

For the plane roofs, MP may occur in three of them. There is no sign of MP for outward plane roof 2. As for the other three roofs, the corresponding accelerating gradient ranges that may incur MP are much lower and narrower than the round roofs. They are all below 2 MV/m and last less than 1 MV/m.

The reason for differences between the round roofs and the plane roofs can only be explained qualitatively now. For the round roofs, the specific locations of MP electrons are close to the connection point of the two filleted corners. The electrons are almost symmetrically distributed at the two sides of that point. It is easier for the electrons to satisfy the resonance condition on a surface with relatively symmetrical smooth transition. Nevertheless, for the plane roofs, the smooth transition is replaced by an abrupt right angle. The relatively asymmetrical roof in geometry makes it more difficult to satisfy the resonance condition. So the plane roofs can suppress MP more effectively than the round roofs for QWR.

## 5 Conclusion

In general, according to the simulation results, there is no sign of MP during the normal operating accelerating gradient range from 6 to 8 MV/m for this particular superconducting QWR. However, an MP trap may exist during the accelerating gradient range from about 1.4 to 3.2 MV/m. The places where MP may be encountered are mainly located at the top part of the QWR.

The effect of different top geometries on MP has also been studied in depth. The MP cases of several QWRs with different round roofs and plane roofs are compared. Simulation results reveal that inward convex round roof is better than other round roofs, and plane roofs have an advantage over round roofs on the suppression of MP in general. While considering the optimization of its EM design, our initial designed model is also acceptable. This study may provide a useful reference on the suppression of MP for the later QWR designs.

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