MULTIPACTING SUPPRESSION MODELING FOR HALF WAVE RESONATOR AND RF COUPLER *

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Abstract

In prototype cryomodule test of Facility of Rare Isotope Beam (FRIB) β=0.53 half-wave-resonators (HWRs) severe multipacting barriers, prevented RF measurement at the full field specified. The multipacting could not be removed by several hours of RF conditioning. To better understand and to eliminate multipacting, physics models and CST simulations have been developed for both cavity and RF coupler. The simulations have good agreement with the multipacting discovered in coupler and cavity testing. Proposed cavity and coupler geometric optimizations are discussed in this paper.

INTRODUCTION

While the multipacting can be categorized by different physics features, the 1st order multipacting with electrons bouncing between two points is significantly stronger than other kinds of multipacting. First order two point multipacting is related primarily to the geometric structures. During the prototype cryomodule test with the final cavity coupler, multipacting barriers which did not show up or that could be easily conditioned in the vertical test prevented us from reaching full gradient. RF conditioning had very little effect. Since the only significant change from the successful vertical test was the coupler, we attributed these new barriers to the change of geometry in the coupler region. The fact that MP could be suppressed by magnetic field around the coupler confirmed our hypothesis. We developed physics models to help simplify the coupler geometry optimization to eliminate MP. Simulations done with CST [1] reassured the physics models. In this paper, Section 1 gives the physics model and CST simulation results of FRIB β=0.53 HWR 1st generation prototype; Section 2 discusses the physics model and optimization scheme for the RF coupler.

MULTIPACTING IN HWR

Multipacting Conditions in the HWR

From CST simulation, multipacting in the HWR cavity mainly locates at the short plate as shown in Figure 1 (green semi-circle). The two-point, 1st order multipacting can thus be described with a cyclotron model, as shown in Figure 2.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661

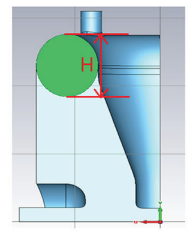

Figure 1: 1/8 structure of FRIB β=0.53 cavity, the short plate is marked as green semi-circle, which is the conjunction between cavity inner and outer conductor.

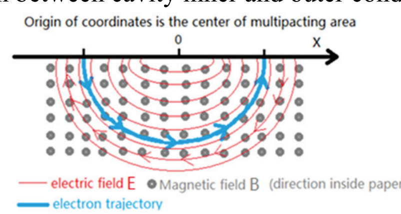

Figure 2: Physics picture of two point 1st order multipacting at a short plate. The flat is the infinitesimal approximation of the semi-circle short plate.

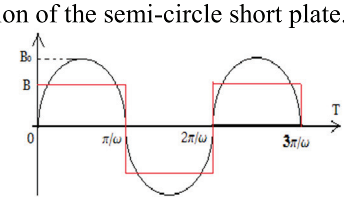

Figure 3: Assumption of B field (red line) as an approximation of the real field B_0.

The magnitude of B is assumed to be $1/\sqrt{2}$ of B_0 to simplify the analytical model, as the red step function shown in Figure 3. Electric field has the same assumption.

According to this cyclotron model, conditions of two-point 1st order multipacting are:

$$E_0(-x) = -E_0(x) \quad (1)$$

$$T = T_{rf} = \frac{2\pi}{\omega} \quad (2)$$

$$W_1 < K_{impact} < W_2 \quad (3)$$

B_0 and E_0 are the magnetic and electric field amplitudes on the plate surface, ω is the cavity's circular frequency, T is the cyclotron period of electron and T_{rf} is the RF period, [W_1, W_2] is the region of impact energy corresponding to SEY>1.

To further interpret Eq. (3) of K_{impact} in terms of electric and magnetic field, we obtain:

$$r \approx \frac{\sqrt{K_{impact} m}}{B_0 e} \quad (4)$$

$$K_{impact} = \frac{mE_0^2\pi^2}{B_0^2} \quad (5)$$

Therefore, Equation (3) for the two point 1st order multipacting condition becomes:

$$\frac{1}{\pi}\sqrt{\frac{W_1}{m}} < \frac{E_0}{B_0} < \frac{1}{\pi}\sqrt{\frac{W_2}{m}} \quad (6)$$

The conditions for two-point multipacting at half wave cavity must satisfy Eq. (1) and Eq. (6), while an additional condition can be deduced from:

$$B_0 = \sqrt{2}A\frac{m\omega}{e} \quad (7)$$

where m and e are electron mass and charge, A is the correction coefficient for the real field. The surface magnetic field is a fixed value of ~23 mT from CST simulation.

All the conditions described above have been verified by CST simulation, which is also an evidence of the domination of two-point 1st order multipacting.

Confirmation with TDCM Test

In the prototype cryomodule test of β=0.53 HWRs, multipacting is found when E_{acc} > 2.4 MV/m. As we process the cavity to suppress it, we can only ramp the peak electric field up to 15MV/m which corresponds to E_{acc} = 3.6MV/m as shown in Figure 4.

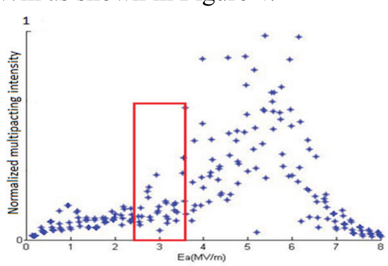

Figure 4: CST simulation of the cavity's multipacting in the cryomodule test. The red box marks the region of multipacting in the cryomodule test.

From CST simulation, the multipacting intensity grows significantly at about 3.6 MV/m, the same barrier as we observed in the cryomodule test. In the sense, CST model is reliable to predict experimental results.

The multipacting barrier was also observed in vertical testing of the HWR's. In the vertical tests, the multipacting barriers were easily conditioned. Most likely, the hard multipacting barriers in the coupler prevented efficient RF conditioning of the cavities and acted as a source of free electrons, eventually captured by MP in the cavity vacuum. Experimental results of the cavities and couplers installed in the test cryomodule are discussed in [4].

Optimization for FRIB HWR

Geometric modification on short plate is naturally the first choice. To keep cavity performance, we consider changing the height H of the circle as shown in Figure 1 for optimization.

Figure 5 gives the effect of H on multipacting intensity. As the current design is 52mm, we change H from 5mm to 82mm in the simulation. The CST simulation shows that two-point 1st order multipacting disappears at H = 5mm with only one-point 1st order multipacting left.

In the CST simulation, we also found that the two-point 1st order multipacting moves to the outer conductor while decreasing H. This phenomenon can be explained by the physics model of multipacting condition, where the area that satisfied Eq. (1) and Eq. (6) has been moved to outer conductor as H decreases. At the same time, the area is reduced. Finally, two-point 1st order multipacting disappears at H=5mm.

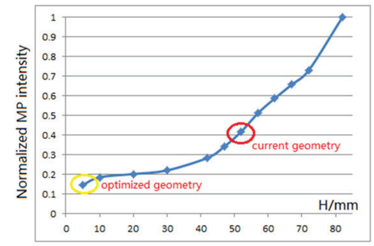

Figure 5: MP intensity versus H from CST simulations.

According to our analysis, the two-point 1st order multipacting can be suppressed by a flat short plate design (H=5mm). However, a flat plate is more sensitive to helium pressure fluctuation. If we make the plate thick, although the effect of helium pressure fluctuation becomes less, the cost increases a lot and thermal stability of the cavity is reduced. Moreover, this multipacting barrier is easily conditioned in the same cavities with the vertical test coupler. Due to such a trade-off and improvable test result, we currently prefer to condition the HWR to overcome multipacting. The solution is to remove MP from the coupler which is triggering the one in the cavity.

MULTIPACTING IN RF COUPLER

Physics Model for RF Coupler

Multipacting in RF coupler is caused by its coaxial structure, demonstrated by CST simulations. The coupler's multipacting locates at peak electric field region where magnetic force is very little. Assuming constant radial electric field, motion of electrons is

$$E_r = \frac{E_0 r_1}{r_2 - r_1}\ell n\frac{r_2}{r_1} \quad (8)$$

$$s(t) = \frac{eE_r}{\omega^2 m}(\omega t - \sin\omega t) \quad (9)$$

r_1 , r_2 is the inner and outer conductor radius, E_0 is electric field at inner conductor, e is electron charge, m is electron mass, ω is RF circular frequency, and $s(t)$ is the distance an electron travels.

Conditions for two-point multipacting thus become:

$$s(t = \frac{(2n-1)\pi}{\omega}) = r_2 - r_1 \Rightarrow E_0 r_1 = \frac{\omega^2(r_2-r_1)^2 m}{(2n-1)\pi e}(\ell n\frac{r_2}{r_1})^{-1} \quad (10)$$

$$W_1 \le \frac{2m\omega^2(r_2-r_1)^2}{(2n-1)^2\pi^2} \le W_2 \quad (11)$$

The RF power at which coupler has multipacting is

ISBN 978-3-95450-122-9

$$P_n = \frac{A\omega^4 (r_2 - r_1)^4 m^2}{(2n-1)^2 \pi \eta e^2} (\ell n(\frac{r_2}{r_1}))^{-1} \quad (12)$$

where n is the order of two-point multipacting, η is the wave impedance in vacuum (377Ω), A is 1 for traveling wave and 0.25 for standing wave (full reflection) from superposition theorem.

Figure 6 is the comparison between the widely known scaling law from E. Somersalo's paper [2] and Eq. (12).

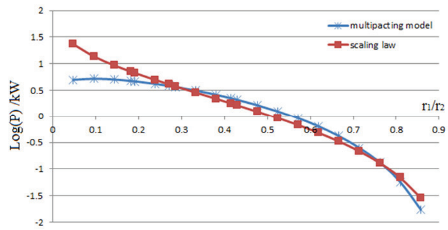

Figure 6: Comparison of the Eq. (12) results (blue line) and E. Somersalo's scaling law (red line) for two-point 1st order multipacting in the FRIB coupler, as we change the inner radius. Outer radius is 21mm.

In spite of our rough assumption for constant radial electric field, which should only valid with short gap between inner and outer conductor, the two lines have a rather good agreement and start having a larger discrepancy when r_1 is less than 4.

Confirmation with TDCM Test

Figure 7 shows the geometry of the FRIB HWR coupler, which is scaled from the SNS RF coupler. While the SNS coupler works at peak pulsed power 550 kW with little multipacting issue, the FRIB coupler must work at the power of 5kW CW, just at the multipacting barrier as shown in Figure 8. We define total secondary electrons in 8 RF cycles as multipacting strength. Density of primary electrons is identical for both couplers. As a result of CST simulation, the maximum multipacting of the SNS coupler is only 5% of FRIB's one. We compared CST simulation with TDCM test for the FRIB coupler, and they agree well as indicated in Figure 8.

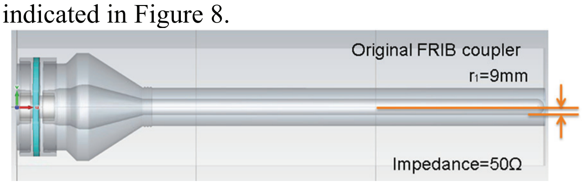

Figure 7: Geometry of FRIB coupler

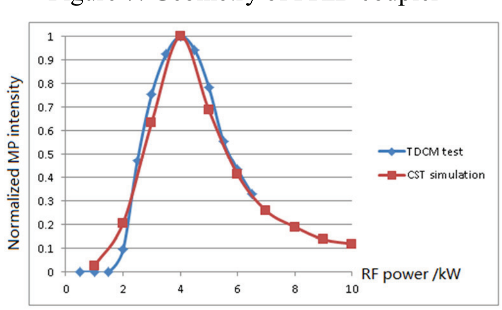

Figure 8: FRIB RF coupler's multipacting in cryomodule test and CST simulation. The peak electron intensity is normalized to 1.

Geometric Optimization of RF Coupler

Suggested by our analysis, there are two methods to suppress multipacting with geometric modification and two optimizations are proposed:

1) Reduce inner radius from 9mm to 6mm. The impedance will be changed from 50Ω to 75Ω though. Cavity design and CF flanges will be kept the same. RF power condition for two-point multipacting will shift to a higher point by 1.5 kW according to our model.

2) Enlarge outer radius to 31.4mm. Coupler impedance is also 75Ω. This change requires modification of the cavity at the port and a larger CF flanges. However, the RF power condition has been moved much higher - to about 18.2 kW.

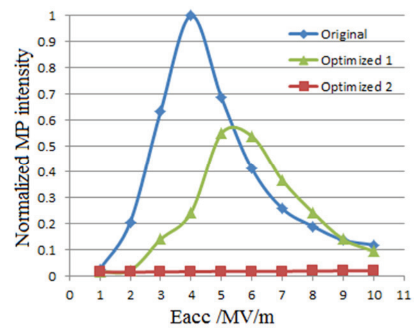

Figure 9: CST comparison of multipacting with the original coupler and two optimized designs. Green line corresponds to a smaller inner radius (6mm), while red line corresponds to a larger outer radius (31.4mm).

Figure 9 shows the comparison of multipacting intensity before and after the optimizations. Although we would prefer not to modify the cavity port, enlarging outer radius gives a much better mitigation of multipacting, and we are currently inclined to implement this modification.

CONCLUSION

In this paper, we verified CST simulations of multipacting with cryomodule test results for both HWR and RF coupler at FRIB. As the two-point 1st order multipacting dominates, we developed model and explained its physics for both HWR and RF coupler. Geometric optimizations have been proposed to mitigate multipacting, which are considered to be important changes and are under discussion and review.

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