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MULTIPACTING ANALYSIS OF HIGH-VELOCITY SUPERCONDUCTING SPOKE RESONANTORS*

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Abstract

Some of the advantages of superconducting spoke cavities are currently being investigated for the high-velocity regime. When determining a final, optimized geometry, one must consider the possible limiting effects multipacting could have on the cavity. We report on the results of analytical calculations and numerical simulations of multipacting electrons in superconducting spoke cavities and methods for reducing their impact.

INTRODUCTION

Superconducting multi-spoke cavities for frequencies of 325, 352, 500, and 700 MHz and velocities of β_0 = 0.82 and 1 have been designed and optimized [1, 2, 3] for a variety of possible applications. These applications include, but are not limited to, compact machines such as future light sources and high-energy proton or ion linacs. Here we focus on what regions of these resonators are most susceptible to multipacting events.

When the internal surface of a rf cavity is exposed to the high fields maintained in a superconducting cavity, electrons (known as primary electrons) can be emitted from the metal. The kinetic energy and trajectory of these electrons is determined by the electromagnetic fields, and in many cases, they will come in contact with another part of the surface with a certain amount of impact energy. If this energy falls within the secondary emission yield (SEY) range, then additional electrons, known as secondary electrons, will be ejected [4]. Figure 1 shows a generic SEY curve. The parameters E^{I}_{oc}, and E^{II}_{oc} are known as the crossover energies for which δ = 1. E_{om} marks the electron energy for which δ is maximum. These parameters can vary greatly between materials. Even for a given material, these parameters can vary widely based on both the bulk properties and surface condition.

For well prepared niobium cavities, the crossover energies are around 150 eV and 1050 eV, while E_{om} is around 375 eV [5]. We have presented preliminary results for crossover energies of 150 eV and 2000 eV previously [2]. When secondary electrons are in resonant trajectories, and each impact energy is in the range for which $\delta > 1$, then a cascade can occur generating excessive heat, thus leading to thermal breakdown. These regions are commonly called barriers, and they are classified as either "soft" or "hard." Soft barriers are those that can be conditioned through and thereby passed. It is believed conditioning occurs because multipacting electrons actually clean the surface to a point where the secondary emission yield is below unity [7]. Hard barriers are those which persist resulting in a limited achievable gradient and quenching.

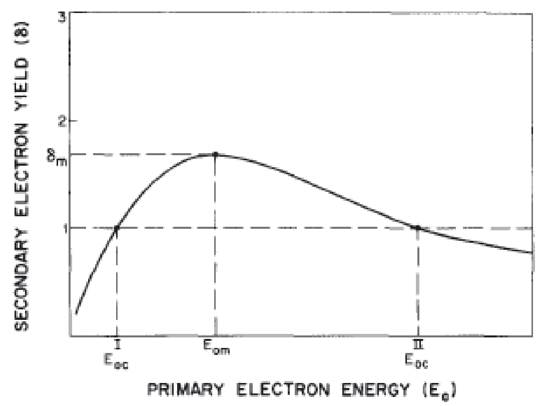

Figure 1: Definition of secondary-electron yield-curve parameters [6]

By improving the quality of the surface, the soft barriers on the gradient can be eliminated. On the other hand, hard barriers can only be overcome by changing the cavity geometry in such a way as to avoid resonant trajectories all together.

Multipacting is also characterized, most commonly, as either one-point or two-point. One-point multipacting occurs when the time of flight of the electron between two impacts is an integer number of rf cycles and that the electron's impact site is approximately the same as it's ejection site. This condition can be described in terms of the cyclotron and rf frequencies as [8],

$$\frac{f}{n} = \frac{eB}{2\pi m} \tag{1}$$

In the case of two-point multipacting, the time of flight is an odd number of half rf cycles and the impact site is not the same as the ejection site. The former condition can be described with the same parameters as (1) [9],

$$\frac{2f}{2n-1} = \frac{eB}{2\pi m} \tag{2}$$

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MULTIPACTING ANALYSIS

In order to analyze the multipacting conditions in our optimized multi-spoke cavities, the 3D parallel tracking code Track3P contained in the ACE3P code suite developed by SLAC was used [10]. The cavity was divided into three regions as seen in figure 2. The regions labeled 1 and 3 include the end caps, half of one spoke, and the outer conductor enclosing the end accelerating gaps. The region labeled 2 includes half of each spoke and the outer conductor enclosing the middle accelerating gap. Due to the symmetry, regions 1 and 3 give similar enough results that we will only discuss 1 and 2.

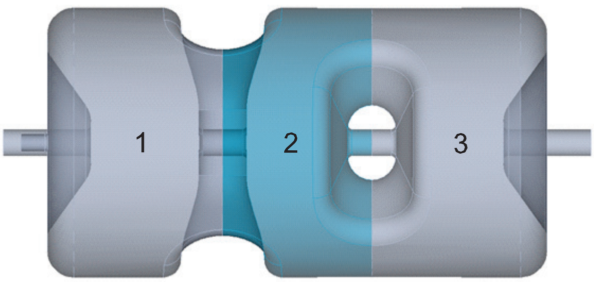

Figure 2: 325 MHz, β_0 = 0.82 cavity divided into three regions for multipacting analysis.

End cells

Figure 3 shows the resonant electrons surviving 50 rf cycles in region 1, along with their impact energies.

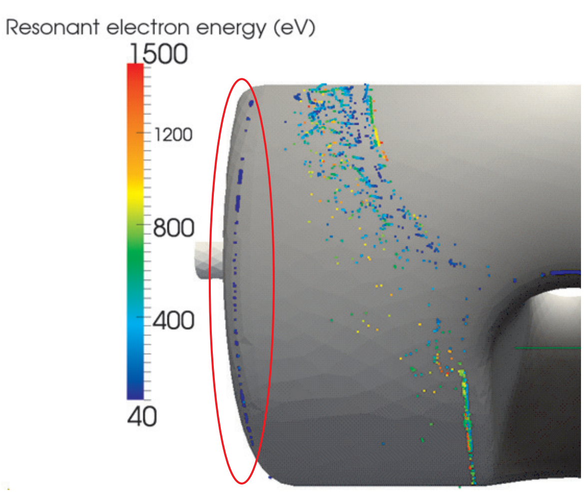

Figure 3: Resonant electrons and their impact energies surviving after 50 rf cycles as simulated by Track3P.

Figure 5 shows a plot of the resonant energies shown in figure 3. Upon inspection of figure 5, there are two observations to take note of. First, it appears that there are possible hard barriers between around 0.4 - 2 eV. Secondly, there are stable multipacting electrons at high field gradients. These electrons are found to be two-point, first order, and reside in the end cap area identified in figure 3. An example of these particle's trajectory is shown in figure 4.

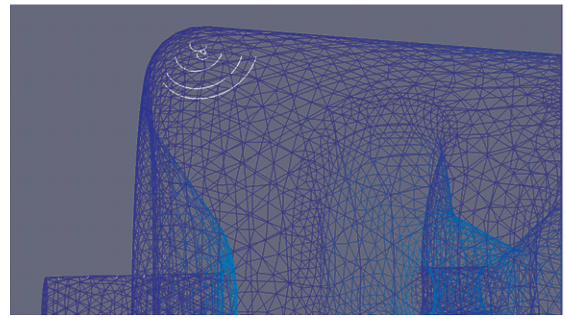

Figure 4: Two-point resonant electron trajectories in the end cap of the cavity.

The question of whether hard barriers exist has recently been tested on a similar cavity operating at 700 MHz, β_0 = 1. The cavity was designed and built in a collaboration between ODU and Niowave [3]. Multipacting analysis of that cavity showed a similar potential for hard barriers at low field gradients, but recent tests at 4.2 K have shown this not to be the case.

To address the question of soft barriers at high field gradient, the inset of figure 5 shows the multipacting electron energies present at 6 MV/m - 10 MV/m for this region of the end cap. The plots are for two different rounding radii at the outer edge, and the picture is of the end cap itself. A more subtle rounding (shown in black) has electrons with resonant impact energies of up to about 250 eV, although most fall below 150 eV. On the other hand, a larger rounding radius (shown in red), results in virtually all of the electron energies being below 100 eV.

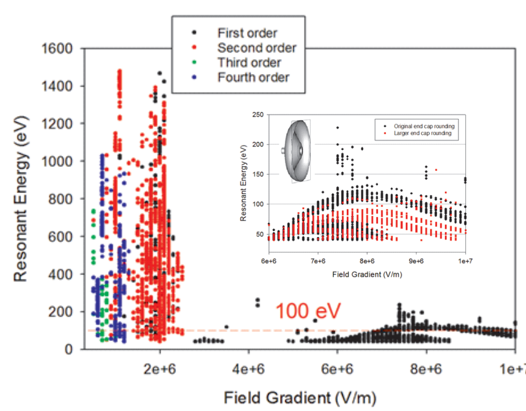

Figure 5: Resonant electron impact energy in region 1 for gradients up to 10 MV/m. The inset shows the impact energies for stable multipacting electrons for two different end cap outer rounding radii.

Center cell

The main regions of stable multipacting electron trajectories in the center accelerating gap are shown in figure 6. The low energy electrons (dark blue in color) are, as in the end caps, the ones that are still present even at high gradients. The energy of these electrons is shown in figure 7, and is similar, but slightly less than that of their counterparts at the end caps. These are also two-point, first order electrons which get trapped in the curvature where the spoke base meets the cylindrical outer conductor. As such, varying the curvature in this region can effect the electron's trajectory and impact energy. The inset of figure 7 is an example of this. For a smaller rounding radius (shown in black), there are a number of resonant electrons with energies between 100 and 120 eV for a field gradient of 7-9 MV/m. By increasing the rounding radius (shown in red), the maximum impact energy is now below 100 eV.

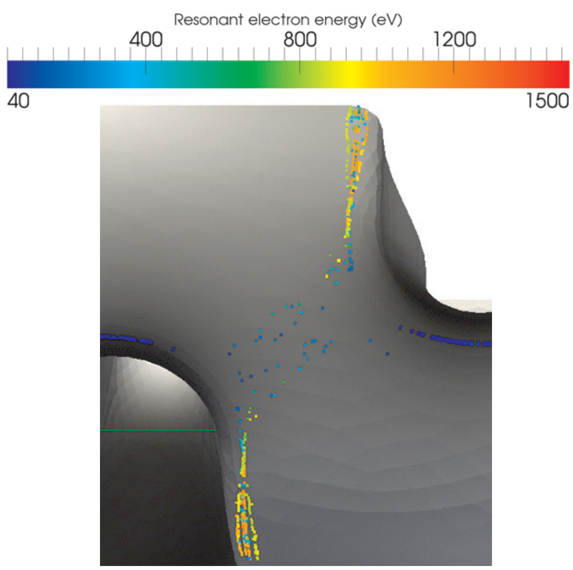

Figure 6: Resonant electrons and their impact energies surviving after 50 rf cycles as simulated by Track3P.

CONCLUSION

Multipacting simulations for multi-spoke cavities show that there is a potential for hard barriers at low field gradients and stable multipactors at high field gradients. However, recent prototype tests of an ODU designed, Niowave fabricated two-spoke cavity operating at 700 MHz has shown that these potential barriers should be able to be processed through.

Additionally, the soft barriers present at high gradients can be minimized by slightly altering the geometry in specific areas of the cavity. Both the end cap and spoke base rounding radius can be increased to a point where the stable, two-point, first order multipactors in these regions are likely to be conditioned away. Experiments at high gradients will have to be done in the future to verify this.

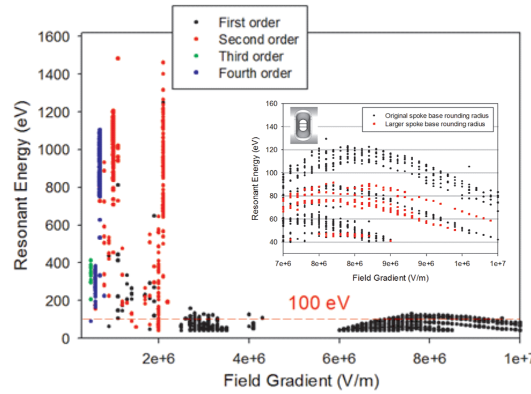

Figure 7: Resonant electron impact energy in region 2 for gradients up to 10 MV/m. The inset shows the impact energies for stable multipacting electrons for two different rounding radii where the spoke base meets the outer conductor.

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