IMPROVED RF DESIGN FOR AN 805 MHZ PILLBOX CAVITY FOR THE US MUCOOL PROGRAM*

Zenghai Li, Lixin Ge, Chris Adolphsen, SLAC, Menlo Park, CA 94025, USA
Derun Li, Daniel Bowring, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

Abstract

Normal conducting RF cavities are required to operate at high gradient in the presence of strong magnetic fields in muon ionization cooling channels of a Muon Collider. An 805 MHz pillbox cavity at Fermilab MTA has shown significant degradation in gradient performance and damage in the high RF field regions when it was operated in magnetic fields up to 4 Tesla. These effects are believed to be related to the dark current and/or multipacting activities in the presence of the external magnetic field. To improve the performance of the cavity, a new RF cavity with significantly lower surface field enhancement outside the nominal beam region was designed, and will be built and tested in the near future. Numerical analyses of multipacting and dark current were performed using the 3D parallel code Track3P for both the original and improved cavity profiles in order to gain more insight into the gradient effects under strong external magnetic fields. In this paper, we will present the improved RF design and the dark current and multipacting analyses for the 805 MHz cavity.

INTRODUCTION

High gradient normal conducting RF cavities with frequencies from 200 MHz to 800 MHz will be used in muon ionization cooling channels for a neutrino factory or a muon collider. These cavities need to be operated under strong external magnetic fields. In experimental studies using an 805 MHz pillbox cavity at Fermilab MTA, significant degradation in gradient performance and damage in the high RF field regions occurred during operation in magnetic fields up to 4 Tesla [1,2,3]. Achievable accelerating gradients decreased as a function of external magnetic field and strong x-rays and dark currents were observed associated with cavity surface damage as shown in Fig 1. These effects are believed to be related to the dark current and/or multipacting activities in the presence of the external magnetic field. Therefore the experimental RF program is currently focused on attaining a more fundamental understanding of RF breakdown and surface damage in the presence of strong magnetic fields. The 805 MHz cavity under investigation has a pillbox geometry and was the first such cavity to be tested. The initial plan is to build and test a similar cavity with significantly lower peak surface fields outside the beam region to see if these changes improve performance. Also, fabrication techniques pioneered at SLAC will be used that have yielded high gradient structures (> 100 MV/m). In this paper, we present the modified design and multipacting analyses of both the original and new designs to better understand potential impacts they may have on performance.

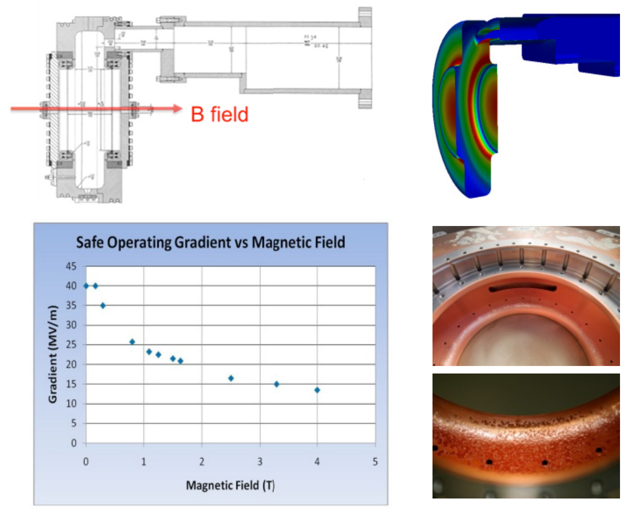

Figure 1. Original cavity design and gradient degradation and damage after operation in high external magnetic fields.

DESIGN IMPROVEMENTS

The field enhancements are localized around the coupling slot area and the disk opening aperture area (where a Be window is mounted). In the new design, the changes marked with red circles in Fig. 2 were made to minimize the peak surface field.

The first improvement was the modification of the disk aperture rounding from a circular profile to an elliptical profile. The minor axis of the elliptical profile is along the beam direction and is 11.4 mm, the same as the rounding radius of the original design. The major axis is in the radial direction and is elongated to 21 mm from 11.4 mm. With this modification, a 40% surface field reduction was achieved in this area.

The second improvement was to modify the rounding of the coupling slot. The rounding radius was increased from 3.2 mm to 9.0 mm on the cavity side, and from a sharp corner to a 7.5 mm radius on the waveguide side. Elliptical rounding was considered, however no significant improvement was found. With these large radii, the surface electric field is lowered by about 45% and the magnetic field by about 30%. In addition, the coupling slot in the new design was moved further outward (flush with the cavity outer radius) to achieve an even lower electric field. This change further reduced the surface electric and magnetic fields though not by a large amount. The major gain with this modification is that it

* Work supported by US DOE under contract number DE-AC02-05CH11231, and DE-AC02-76SF00515. Computations used computer resources at NERSC, LBNL.
[1]lizh@slac.stanford.edu

ISBN 978-3-95450-115-1

eliminated an area between the coupling slot and the cavity outer radius which could support significant multipacting as will be seen below.

The third significant modification was to replace the kidney shaped cutoff waveguide with a rectangular propagating waveguide. In the original design, the length of the kidney shaped section was used as a tuning parameter for the external coupling. The required coupling was obtained by trimming the length of this piece of waveguide. With modern simulation tools and machining technology, such tuning is no longer necessary. By replacing this waveguide with a propagating waveguide, the azimuthal opening of the coupling slot is dramatically reduced, which results in a significant reduction of the surface electric and magnetic fields. Combined with the larger rounding radii, the final electric field is lowered by a factor of 4 and the magnetic field is lowered by a factor of 2.5 around the slot area. The maximum electric field is now located on the window surface. These values were calculated for a flat window. With a curved Be window, the electric field is enhanced by up to 45% on the window. Table 1 summarizes the cavity and RF parameters of the original and the new designs for comparison.

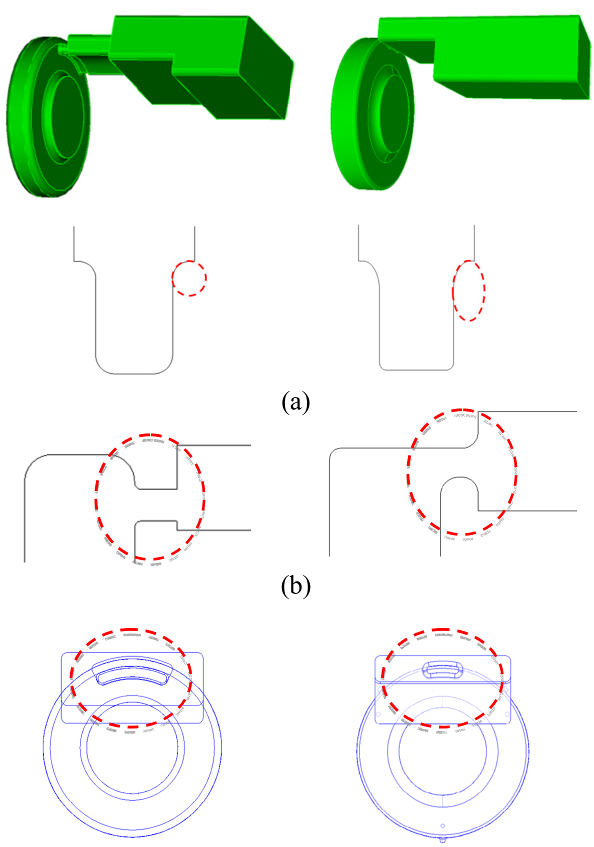

Figure 2. Cavity shape modifications to improve the surface fields. Left) original design; Right) new design. a) modified disk rounding profile; b) larger rounding around the coupling slot; and c) size of coupling slot significantly reduced after replacing the kidney cutoff waveguide with a propagating waveguide.

Table 1. Cavity and RF Parameter Comparison

Parameter (dimensions in mm)	Original	New - flat window	New - curved window
Slot height	15.2	13.5	13.5
Slot opening angle (deg)	53	22.2	22.9
Slot rounding 1	3.2	9	9
Slot rounding 2	0	7.5	7.5
Disk ellipticity (minor/major axes)	11.4 /11.4	11.4 /21	11.4 /21
E_{max} on slot-1	69.8	16.1	16.3
E_{max} on slot-2		8.40	8.93
E_{max} disk rounding	45.0	31.8	33.3
E_{max} on window	32.9	33.4	48.3/27.7
H_{max}	0.30	0.12	0.12
Qext	12899	15043	12662
Qo	16007	16761	16717
Coupling β	1.24	1.11	1.32

MP SIMULATION USING TRACK3P

Multipacting (MP) analyses were carried out using Track3P, which is 3D particle tracking code in an unstructured finite-element mesh [4,5]. In a typical MP simulation, electrons are launched from specific surfaces at different phases over a full RF period. The electrons follow the electromagnetic fields in the cavity and eventually hit a boundary, where secondary electrons are emitted with zero energy. The tracing of the electrons continues for a specified number of RF cycles, after which the MP trajectories are characterized in terms of order (number of RF cycles to return to the original site) and point (number of impact sites per MP cycle). MP involves particles with trajectories resonant with the RF. These particles will impact the surface at the same locations with constant energy in our simulation. Those trajectories with impact energies having a Secondary Emission Yield (SEY) greater than unity are considered MP events. The SEY curve in Fig 3 was used for this purpose.

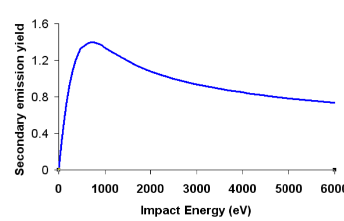

Figure 3. Secondary emission yield for copper.

MP SIMULATION RESULTS

The RF fields in the cavity were obtained using the parallel code S3P [6,7]. The fields in the cavity were established via waveguide excitation with proper wall impedances so that the fields in the waveguide have the correct standing wave ratio (coupling β = 1.3). A 3 T external magnetic field was applied parallel to the cavity axis. The flat window cavity surface field level was varied from 0.1 MV/m to 30 MV/m in intervals of 0.1 MV/m.

Initial particles were distributed on all cavity surfaces. 50 RF cycles were simulated at each field level. Regions that support resonant trajectories were then identified and further analysed. Fig. 3 shows the impact energies of all resonant trajectories versus field level. Fig. 4 shows the same quantities in four specific surface areas.

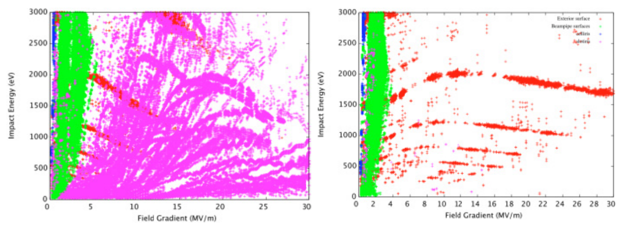

Figure 3. Impact energies of all resonant trajectories as a function of field level. Left) original design; Right) new flat window design.

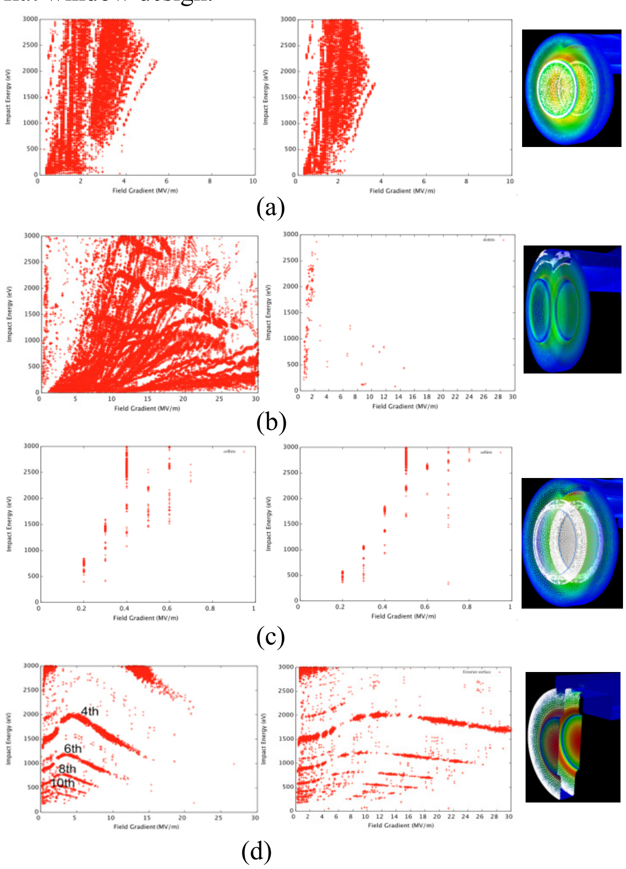

Figure 4. Impact energy of resonate particles vs field level in different regions. Left) original design; Right) new flat window design: a) the window area; b) coupling slot rounding area; c) the disk rounding area; d) the cavity outer wall.

MP on the Be window

Most of the MP particles are located in the corner between the rounded copper disk and the window surface. A strong MP band is seen in the voltage range from 0.2 MV/m to about 3 MV/m in the new design and 0.2 MV/m to about 4-MV/m in the original design (high impact energy resonances are not likely to multipact). The curved window has a similar MP band but is slightly narrower.

MP on the disk iris rounding

There are sparse resonances and most are of high impact energy. Multipacting is not expected to be significant in this area.

MP on the coupling slot region

There is multipacting at all field levels up to 30 MV/m in the original design. Most of these particles are located in the corner between the coupling slot and the cavity outer wall. In the new design, this area was eliminated, which resulted in a significant reduction in the number of resonant particles.

MP on the other surfaces

These are mostly higher order resonances where the particles are located largely in the corner of the cavity outer wall. The new design has similar impact energy bands, but the range of field levels is wider due to the smaller rounding radius. Because of the high order of these trajectories, they are not likely to produce a strong RF processing barrier.

SUMMARY

The new cavity design significantly reduces the peak surface fields around the coupling slot and the disk rounding areas. The highest electric field is on the Be window surface in the new design rather than on the copper surface. As a result, the effect of field emission dark currents should be significantly reduced in the coupling slot and disk rounding regions. Multipacting analysis indicated significant improvements in the new design in the coupling slot region. An engineering design of the new cavity is complete and it will hopefully be built in the near future.

REFERENCES

[1] Derun Li et. al., “Design and Fabrication of an 805 MHz RF Cavity with Be Windows for a High RF Power Test for a Muon Cooling Experiment,” Proc. PAC2001, Chicago, 2001.

[2] Derun Li et. al., “rf breakdown with external magnetic fields in 201 and 805 MHz cavities,” PRST-AB **12**, 031002, 2009.

[3] Alan Bross, “The Muon Accelerator Program “*High”*-Gradient Normal Conducting RF R&D,” US High Gradient Workshop, SLAC, Menlo Park, 2011.

[4] K. Ko et al, “Advances in Parallel Computing Codes for Accelerator Science and Development,” Proc. LINAC 2010, Tsukuba, Japan, 2010.

[5] L. Ge et al., "Multipacting Simulations of TTF-III Power Coupler Components," Proc. PAC07, Albuquerque, New Mexico

[6] Lie-Quan Lee et al, “Omega3P: A Parallel Finite-Element Eigenmode Analysis Code for Accelerator Cavities,” SLAC-PUB-13529, 2009.

[7] Z. Li et al., "Towards Simulation of Electromagnetic and Beam Physics at the Petascale," Proc. PAC07, Albuquerque, New Mexico.

ISBN 978-3-95450-115-1