ELECTRO-MAGNETIC OPTIMIZATION AND ANALYSIS OF A QUARTER WAVE RESONATOR *

Z. Zheng[#, 1, 2], A. Facco[1, 3], Z. He[1, 2], Z. Liu[1], J. Wei[1], Y. Xu[1], Y. Zhang[1]
[1]Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824 USA
[2]Tsinghua University of Beijing, Beijing, 100084 China
[3]INFN - Laboratori Nazionali di Legnaro, Padova, Italy

Abstract

A β=0.085 quarter wave resonator (QWR) with resonant frequency=80.5 MHz is used in the Facility of Rare Isotope Beam (FRIB). Its baseline structure is designed to achieve the FRIB specifications with optimum cost to performance ratio. Electro-magnetic optimization is introduced in this paper to modify its internal geometry to reach instead maximum accelerating gradient, while preserving the original flange to flange length. Reduced peak magnetic field and increased shunt impedance are well achieved in the optimization while keeping the same stored energy. The maximum accelerating voltage is raised accordingly. Multipacting and steering are also analyzed for the optimized cavity. This resonator could be used in the ReA linac at MSU and in all applications where the maximum accelerating voltage should be achieved in a limited space, or where the accelerator cost is mainly driven by the resonator gradient.

INTRODUCTION

The baseline structure of FRIB QWR cavity is designed to achieve its goal with optimum cost to performance ratio. By further optimizing the baseline cavity, we aimed at a cavity design (that we nicknamed "race car") which provides significantly more accelerating gradient (E_a) still being affordable in cost, like an economy car in the auto world. The optimization is achieved mainly by reducing the peak magnetic field B_p and increasing the cavity shunt impedance R_{sh}. Lower B_p can speed up the “car” to higher cavity gradient, and increased R_{sh} allows keeping power consumption low, like saving “gasoline” for the “car”. With high gradient, low-β resonators like this “race car” design, compact accelerators which can reach several MeV per nucleon in a limited space can be built for different applications. In this paper, section 1 introduces the method and procedure of the electromagnetic optimization. Section 2 discusses multipacting and beam steering issues before and after the optimization.

ELECTRO-MAGNETIC OPTIMIZATION

The main goal of the optimization is reducing the peak magnetic field (B_p) and increasing shunt impedance (R_{sh}/Q) while keeping good values for the stored energy, the peak electric field (E_p) and the geometric factor ($R_s \times Q$). To achieve the “economy” concept, we should limit rising of the cavity cost as little as possible. Thus, we maintained the radius of cavity outer conductor and optimized the cavity inner part.

Performance of FRIB QWR

Before cavity optimization, simulation was performed to get the parameters of FRIB QWR with MWS [1]. Table 1 shows the simulation results (effective length=βλ).

Table 1: Cavity Parameters of FRIB QWR

Parameter	Value	Units
Frequency	80.50	MHz
E_p/E_a	5.9	Abs.
B_p/E_a	12.6	mT/(MV/m)
R_{sh}/Q	452	Ω
$R_s \times Q$	22.3	Ω

In superconducting low-β resonators, the highest reported surface peak fields before quench are approximately 80 MV/m and 150 mT in cw mode. So there is a tradeoff between E_p and B_p that should be taken into account when designing a cavity, and B_p/E_p~1.8 should be nearly an optimum. For the FRIB β=0.085 QWR, B_p/E_p=2.14 which means the cavity can be expected to quench at high accelerating gradient due to B_p. To raise the maximum achievable gradient to this cavity, the most effective method is reducing its B_p.

Procedures of Optimization

First step:

The peak magnetic field of FRIB QWR is located at the inner conductor near the short plate (Fig. 1). To reduce the B_p/E_p, we optimized the structure of inner conductor by scanning two geometric parameters (R_1 and L_1 in Fig.2).

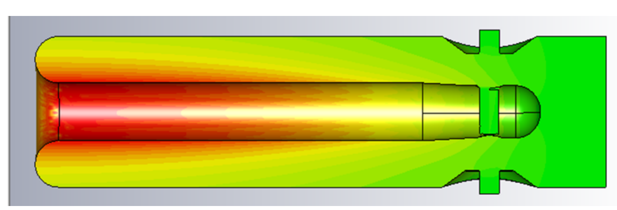

Figure 1: Magnetic field distribution of the FRIB QWR. Red means B_p. Cavity stored energy is normalized at 1J.

*Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661
#zhengw@frib.msu.edu

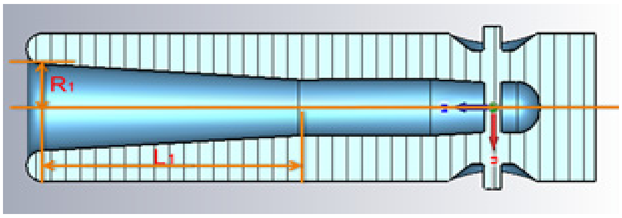

Figure 2: Diagram of the first step optimization.

The optimized parameters chosen are: R1=90 mm (the original value is 52 mm), L1=450 mm (As a reference: total length of the cavity is 1041 mm). After the first step, Bp/Ep is reduced significantly. But shunt impedance is lowered and cavity frequency is increased.

Second step:

We reduced the radius of inner conductor (R2 in Fig. 3) to increase shunt impedance and increased L2 to tune the resonant frequency back to 80.5 MHz. Optimization from scanning four parameters (R1, R2, L1 and L2) and the optimized parameters are chosen: R1=80 mm, R2=30 mm (the original value is 52 mm), L1=793 mm, L2=951 mm (the original value is 821 mm; cavity length extends 130 mm).

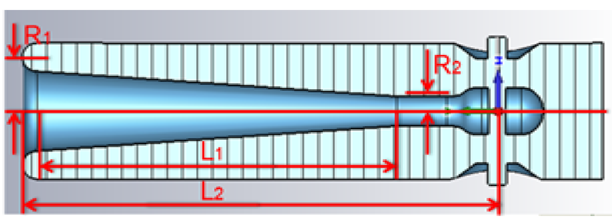

Figure 3: Diagram of the second step optimization.

Third step:

We tried to reduce the peak electric field to further improve cavity performance. E_p was located in the region of the inner conductor (IC) drift tube (nicknamed "donut"), so we optimized its shape. We tried three kinds of donuts during the optimization (see Fig. 4). Because the simulation results reconfirmed that even with tapered IC the original donut has minimum E_p, we kept it.

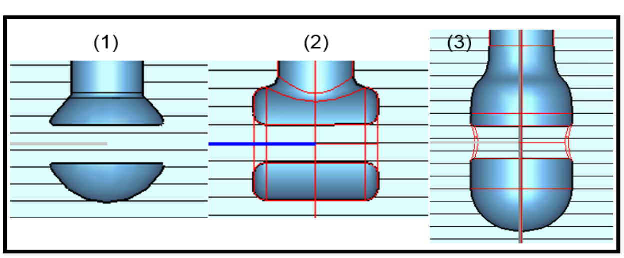

Figure 4: Three kinds of donuts in the third step optimization. (1) sphere donut, (2) cylindrical donut, (3) the original donut.

A final re-optimization was done by tuning all parameters together.

After these optimization steps, the cavity parameters resulted significantly modified regarding the maximum gradient capabilities, with rather limited rise of cost. We called this cavity design "race car" and its parameters are shown in Table 2 (effective length=βλ).

Table 2: Cavity Parameters of "race car"

Parameter	Value	Units
Frequency	80.48	MHz
E_p/E_a	5.8	Abs.
B_p/E_a	8.6	mT/(MV/m)
R_{sh}/Q	548	Ω
$R_s \times Q$	20.6	Ω

Comparing Table 2 with Table 1, the improvements from the FRIB QWR to the "race car" are as following: 1) peak magnetic field was reduced significantly; 2) shunt impedance was increased. We can see that B_p/E_p~1.5, significantly below 1.8. However, since staying at 1.8 would not reduce E_p anyhow, we decided to minimize B_p as much as allowed by our outer conductor diameter.

Thus, if we assume cavity will not quench below E_p=80 MV/m, the "race car" should provide a maximum accelerating gradient of 13.8MV/m if the effective length is defined as L_{eff}≡βλ=0.317 m, and 16.3 MV/m if L_{eff}≡D=0.27 m, where D is the real outer conductor diameter. If we assume – according to the ReA cavities test results – that operation at B_p=100 mT could be safely achieved, an acceleration of 3.7 MV in a cavity which is only 27 cm long might be feasible, if E_p=67 MV/m can be maintained as foreseen for elliptical cavities. This voltage until now for this range of beta was planned in operation only with cavities of considerably larger size.

MULTIPACTING AND BEAM STEERING

The "race car" design exceeds the expected FRIB cavity operation gradient, but some issues, such as multipacting and beam steering, needed to be studied carefully.

Multipacting Analysis

In the FRIB QWR, there are two types of multipacting: one is located at short plate [2], the other one is between inner and outer conductor (IC and OC). Both of them in clean cavities can be suppressed in a short time by RF conditioning during RF tests. For the "race car" cavity, the tapered IC may enhance multipacting near the short plate.

In Fig. 5, simulation of the FRIB QWR's multipacting was verified by the cavity vertical tests [3]. Thus, we can use simulations to predict multipacting of the "race car".

ISBN 978-3-95450-138-0

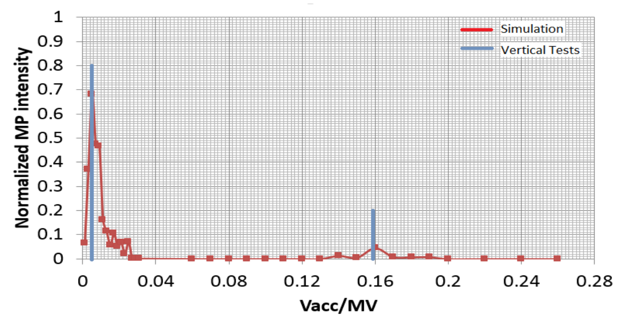

Figure 5: Multipacting barrier in simulation and vertical tests. In simulation, normalized MP intensity is proportion to the total number of secondary electrons in 10 RF cycles. In vertical tests, it is proportion to the frequency of multipacting (the number of multipacting processing tests over the total number of tests). The multipacting at lower accelerating gradient occurs between IC and OC while the higher one is on the short plate.

We simulated multipacting for both the FRIB QWR and the "race car", and compared them in Fig. 6. As a result, taper did enhance multipacting on the short plate. The multipacting barrier on short plate of the "race car" is shifted to a higher gradient and becomes wider. But the overall multipacting intensity doesn't increase much (maximum value increases from 0.7 to 1 in Fig. 6). Thus, the "race car" design might need more time than the FRIB one for RF conditioning to suppress multipacting.

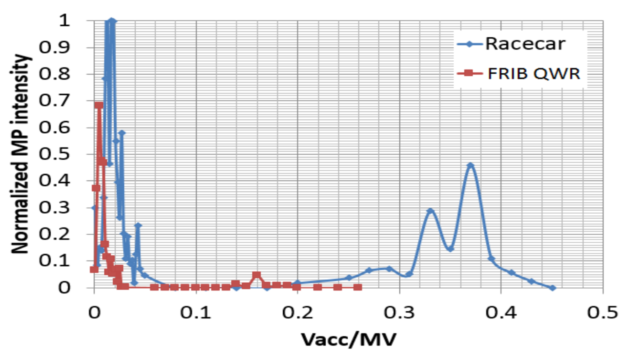

Figure 6: Multipacting comparison between FRIB QWR and "race car" by simulations. Normalized MP intensity is proportion to total number of secondary electrons in 10 RF cycles.

Beam Steering Analysis

In the FRIB QWR, beam steering can be corrected by offsetting the cavity down 1.5 mm [4]. Since in the "race car" radius of the inner conductor curvature is reduced from 52 mm to 30 mm above the beam axis, the vertical electric field distribution (E_y) is changed (see Fig. 7) and so the beam steering. Comparing with the FRIB QWR, the steering becomes weaker for $\beta<0.085$ but larger for $\beta>0.085$ (see Fig. 8). The disadvantage is that the previous correction method with the "race car" is not as good as with the FRIB cavity, although looking acceptable. Beam port shaping for better correction can be considered if necessary.

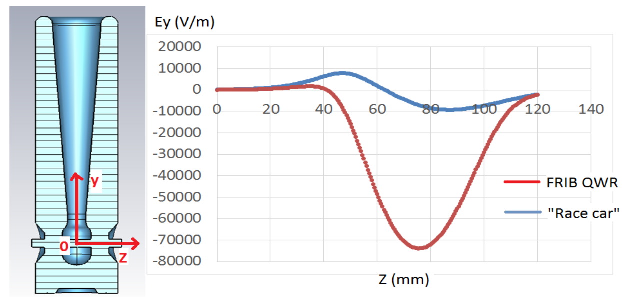

Figure 7: Ey comparison between the FRIB QWR and the "race car" cavity.

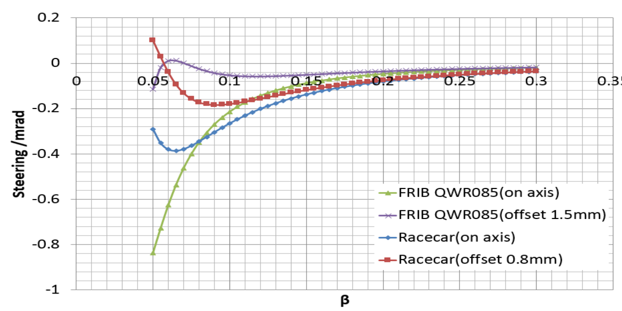

Figure 8: Steering and the correction comparison between the FRIB QWR and the "race car". By offsetting cavity down 1.5 mm we will have a minimum steering for the FRIB QWR, while for the "race car", the required correction will be 0.8 mm.

CONCLUSION

By simultaneously reducing peak magnetic field and increasing shunt impedance, the FRIB β=0.085 QWR geometry was optimized for maximum acceleration gradient without increasing the cavity longitudinal dimensions but only the vertical length by about 130mm. The cost increase for this new geometry appears to be rather affordable. This resonator type might benefit the ReA linac at MSU and other applications where maximum acceleration must be achieved in a limited space. Both multipacting and beam steering issues have been thoroughly studied with simulations. The construction of a prototype is planned for next year.

REFERENCES

[1] http://www.cst.com/
[2] Z. Zheng, "Multipacting suppression modeling for Half Wave Resonator and RF coupler", proceeding of Linac2012, Tel-Aviv, Israel.
[3] J. Popielarski, "Multipacting in FRIB prototype cavities", internal report.
[4] A. Facco, "Beam steering correction in FRIB quarter-wave resonators", proceedings of IPAC2012, New Orleans, Louisiana, USA.