ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR12

CONCEPTUAL DESIGN OF AN 805 MHZ CAVITY WITH BERYLLIUM WINDOWS AND DISTRIBUTED COUPLING

T. Luo*, Lawrence Berkeley National Laboratory, Berkeley 94720, California, USA
D. Merenich, Northern Illinois University, DeKalb, Illinois 60115, USA

Abstract

For the future multi-TeV muon collider, ionization cooling is a critical step to achieve the required beam emittance for a proton-driven muon beam. Ionization cooling of intense muon beams requires the operation of high-gradient, normal-conducting RF structures in the presence of strong magnetic fields. The MAP modular cavity study at Fermilab has demonstrated the RF breakdown threshold at 13 MV/m for cooper surface and 50 MV/m for beryllium surface in a 3T solenoid B field. The MICE 201 MHz RF module has demonstrated several key engineering features for such type of cavity. Based on these previous studies, we carry out a conceptual design a new 805 MHz copper cavity with thin curved beryllium windows that is likely to achieve a gradient (without the transit time factor) of 27 MV/m. We also explore the distributed coupling for feeding the RF power to multiple cavities within the tight space in the superconducting solenoids. This cavity design study can be one option for the cavities in the muon collider demonstrator program to experimentally evaluate the 6D muon emittance cooling.

INTRODUCTION

Muon collider (MuC) is considered to be one of the most promising contenders for future particle physics discoveries in energy frontier, in terms of the footprint and cost. However, there are technical challenges for muon colliders to achieve the targeted luminosity with small emittance and high flux. Presently the most mature design of the muon source is based on proton spallation, pion decay and muon ionization cooling. In the ionization cooling process, the muon beam loses energy when passing through absorber materials and regains only the lost longitudinal energy from RF cavities which results a transverse emittance reduction. Due to the large divergence of the muon beam from the pion decay, a strong solenoidal magnetic field produced by superconducting (SC) magnets is required to confine the muon beam within the cooling channel.

The normal conducting radiofrequency (NCRF) cavities are essential components for muon capturing and ionization cooling. These cavities operate at hundreds of MHz in a multi-tesla B-field background from the surrounding SC solenoids. Achieving the high gradient in these cavities is critical for the ionization cooling rate and eventually the luminosity of the MuC. The major challenge for the MuC NCRF cavities is overcoming the RF breakdown and achieving high RF gradient in a strong B field at hundreds of MHz. Other important topics include the compact integration of the high power RF cavities with the SC solenoids in the cooling channel, the development of the high-peak-power short pulse length RF source at hundreds of MHz, the evaluation and mitigation of the higher-order-modes and the beam loading, etc.

The R&D in MAP and pre-MAP era has demonstrated the feasibility of achieving a 50 MV/m surface gradient in a 3T solenoid field, as well as some key engineering features for such cavities. Still, significant progress is needed to achieve or even surpass the current baseline design requirements. For the near term, one priority of NCRF R&D is to design and prototype a multi-cell fully operational RF cavity module for the proposed demonstrating cooling cell [1].

REVIEW OF THE PREVIOUS MUC NCRF CAVITY DEVELOPMENT

For the past decades, R&D efforts have been carried out mainly in two areas:

1. To understand the breakdown mechanism and the corresponding mitigation methods in a strong magnetic field.
2. To develop the cavity hardware and validate their performance.

In this short review section, we only look into the second area. Among the vacuum NCRF cavities developed for MuC, at least two cavities have demonstrated the required performance. Their R&Ds have enhanced our understanding and advanced the technical readiness for this type of NCRF cavities.

The first cavity is the 201 MHz RF module developed for Muon Ionization Cooling Experiment (MICE) [2]. It has achieved 10.3 MV/m in the fringe field of a 4T solenoid field. Although the gradient is moderate, this RF module is a complete operational unit demonstrating several key engineering features. One feature is the 0.38 mm thick Be window covering the cavity sidewalls. There are two main advantages of such a window:

1. Using low Z material such as Be to cover the high E field surface area can reduce the RF breakdown probability.
2. Covering the cavity sidewall can significantly increases the cavity shunt impedance.

Besides the Be window, other important experience that can be applied for future cavity develop include the surface polishing recipes, mechanical tuning mechanism, the vacuum protection scheme, etc.

The second cavity is the 805 MHz Muon Accelerator Program (MAP) modular cavity developed for studying the

* tluo@lbl.gov

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR12

breakdown process with impacts from the material type, production process, surface condition, etc. [3] It has achieved over 50 MV/m surface E field with Be sidewalls in the 3T SC magnet at Fermilab Mucool Test Area (MTA). In comparison, the copper surface can only achieve 13 MV/m in the same magnetic field. It shows the pathway to overcome the RF breakdown in a strong B field by implementing the breakdown-resilient material. Compared with the previous 805 MHz cavity, it moved the power coupling slot from the sidewall to the torus. This change significantly reduces the local E field and prevents the breakdown associated with the coupling slot, which was observed in the previous tests. It does increase the cavity's transverse size and makes it tricky to fit into the tight space of the SC magnet bore. As this cavity is only for the breakdown study, several engineering features are still lacking for a full operation in an ionization cooling channel.

CONCEPTUAL DESIGN OF AN 805 MHZ CAVITY FOR THE IONIZATION COOLING

In this design, we want to implement both the engineering features for an operational cavity demonstrated in MICE cavity and the breakdown mitigation practices learnt from MAP modular cavity. The goal is to achieve a high accelerating gradient with relatively low engineering risk based on what we have learnt from the previous R&D.

RF Design Of The Cavity Body

In the cavity body design, there are two major considerations:

1. Based on the modular cavity results, the upper limit of the E field is set at 50 MV/m on Be surface and 13 MV/m on Cu surface to prevent the RF breakdown in the SC magnet field.

2. Thin Be windows similar to MICE windows are implemented to cover both sidewalls.For this conceptual design we simply scale the MICE window to match the radius of the copper cell without detailed engineering considerations.

The windows are mounted to the Cu sidewall similar to the MICE window. A conceptual structure is shown in Fig. 1. The Be windows have to be thin to be transparent to the muon beam. For a thin window, a smaller size is preferred for better heat dissipation and mechanical robustness. But from the RF breakdown perspective, a larger window size is preferred as the Be surface has a much larger E field limit than the Cu surface, and the E field magnitude decreases along the radial direction. Thus the choice of the Be window size will be a balance between these two competing factors.

Without thorough exploration, we set Be window radius at 9.6 cm. With MICE Be window at a radius of 21 cm, we scale it uniformly in the radial direction with a factor of 0.46 to achieve 9.6 cm radius. The cavity radius is set at 142 mm to achieve the 805 MHz operation frequency.

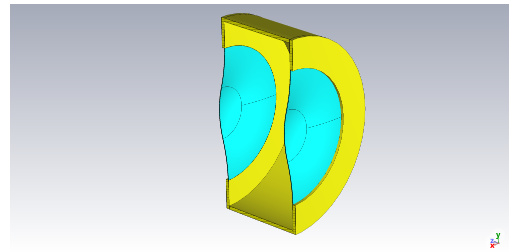

Figure 1: A conceptual structure of the proposed 805 MHz cavity. Yellow: Cu torus; Blue: Be windows

The cavity length is determined by maximizing the shunt impedance per unit length RT^2/L. If we ignore the Be window curvature, RT^2/L of a pillbox with flat Be windows on both sidewalls can be expressed analytically:

$$\frac{RT^2}{L} = \frac{T^2 \mu_0^2 c^2 L}{\pi (A+B)},$$

where

$$\begin{aligned} A &= R_{s1}[R_1^2 J_1^2(2.405) - R_2^2 J_1^2(\eta) + R_2^2 J_0(\eta) J_2(\eta) \\ &\quad + R_1 L J_1^2(2.405)], \\ B &= R_{s2}[R_2^2 J_1^2(\eta) - R_2^2 J_0(\eta) J_2(\eta)], \\ \eta &= 2.450 \frac{R_2}{R_1}, \end{aligned}$$

R_1 and R_2 are the radii of the Cu sidewall and the Be window, and R_{s1} and R_{s2} are the surface resistance of Cu and Be.

For a 200 MeV/c muon beam, and with room temperature conductivity $\sigma_{Cu} = 5.8 \times 10^7$ $\Omega^{-1} m^{-1}$ and $\sigma_{Be} = 1.8 \times 10^7$ $\Omega^{-1} m^{-1}$, we calculate RT^2/L for different cavity lengths with cavity radius fixed at 142mm and Be window radius varying from 70 mm to 100 mm, as shown in Fig. 2.

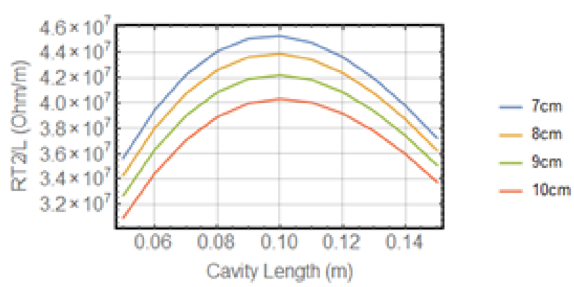

Figure 2: RT^2/L as a function of cavity length for different sizes of Be windows.

The plot shows for a given Be window size, there is an optimal length to achieve a maximum RT^2/L. For our choice of window size at 9.6 cm, we choose the length at 10 cm.

Now with the cavity geometry determined, we calculate its EM properties and power consumption with the numerical solver Omega3P [4]. The E field results are shown in Fig. 3.

The achievable acceleration is limited by the E field on the Cu surface, which should not exceed 13 MV/m. With

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR12

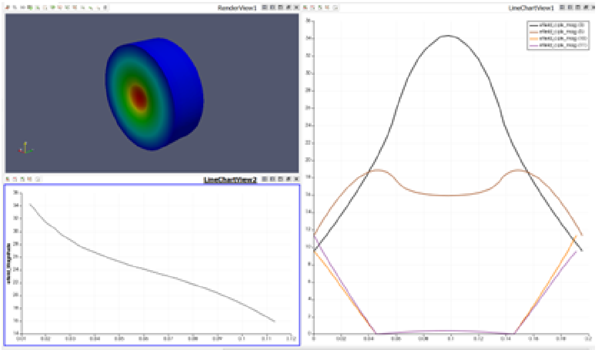

Figure 3: The E field in the cavity. Top left: the E field magnitude on the cavity surface, facing the curved-in window; bottom left: the E field across the cavity center, from curved-in window to curved-out window; Right: the E field on the surface in the middle plane, black: on the curved-in window, brown: on the curved-out window, orange and magenta: on the Cu torus.

this limit, the achievable gradient and corresponding power heating for this design are as shown in Table 1.

Table 1: Cavity Key Parameters

Average E gradient w/o transient factor (MV/m)	27.4
E max on the Cu surface (MV/m)	13.0
E max on the Be surface (MV/m)	39.1
r/Q (Ω) w/o transient factor	259
Q_0	21320
RF power (MW)	1.36

The achievable gradient, which is calculated as the total voltage divided by the cavity length, is 27.4 MV/m, comparable to the desired gradient for the rectilinear cooling channel. The maximum E field on the Be surface is 39.1 MV/m, well within its limit of 50 MV/m. The required RF power 1.36 MW is at a similar level of MAP modular cavity. Still being a preliminary study, further optimization and detailed design work will be carried out in the future.

Distributed Coupling For RF Power Feeding

Before the MAP modular cavity, the RF power was fed into the 805 MHz cavity from the coupling slot on the sidewall, resulting in the maximum surface E field located at the coupling slot. Significant surface damage around this area was observed during the high power testing. In MAP modular cavity, the RF power coupling slot was moved from cavity sidewall to the torus, and the E field at the coupling slot was reduced to below the E field along the center axis. No surface damage was observed at the coupling slot in the high power test in this cavity. We want to keep this ”power feeding from torus” practice for the new cavity design to raise the RF breakdown threshold, even if it means a slightly larger bore size of the SRF magnets.

Another consideration for this design is that since each cavity cell is covered by the beam windows, there is no beampipe aperture to couple the RF fields between the adjacent cell like a conventional LINAC. Thus each cell needs to be powered individually.

The distributed coupling [5] could be a particularly suitable power feeding scheme for the ionization cooling cavities: coupling from the torus and powering each cell individually. A conceptual illustration of a 4-cell RF module is shown in Fig. 4. A more detail design study will be carried out to verify the feasibility of this concept and achieve the proper coupling for each cell.

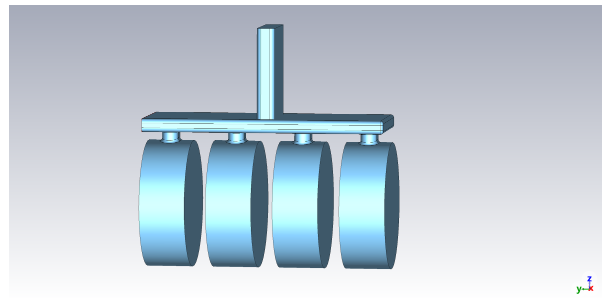

Figure 4: A conceptual vacuum model of the distributed coupling for a 4-cell cavity module

CONCLUSION

In this paper, we have presented a preliminary conceptual design of an 805 MHz Cu cavity with curved Be beam windows. This design utilizes the RF breakdown mitigation and the demonstrated engineering features learnt from the previous MICE and MAP cavity development. This conceptual design can potentially achieve an E field of 27 MV/m, limited by the maximum E field on the Cu surface. This gradient is comparable to the required value for the rectilinear cooling channel in a MuC. We have also explored to implement the distributed coupling for powering a multi-cell RF module. Still being at a preliminary stage, a more detailed RF study as well as the engineering design work will be carried out in the future. A cavity with similar concepts scaled to the right frequency could be an option for the proposed MuC ionization cooling demonstration.

ACKNOWLEDGEMENTS

This work is supported by Director of Science of the U.S. Department of Energy and the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory, under Contract No. DE-AC02-05CH11231. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231.

REFERENCES

[1] J. S. Berg *et al.*, “An engineering prototype of a late stage ionization cooling cell for a muon collider”, presented at the IPAC’24, Nashville, TN, USA, May 2024, paper WEPR34, this conference.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR12

[2] M. Leonova *et al.*, “MICE Cavity Installation and Commissioning/Operation at MTA”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 3342–3344. doi:10.18429/JACoW-IPAC2015-WEPTY032

[3] D. Bowring *et al.*, “Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration”, *Phys. Rev. Accel. Beams*, vol. 23, p. 072001-8, 2020.

[4] K. Ko *et al.*, “Advances in Parallel Electromagnetic Codes for Accelerator Science AND Development”, in *Proc. LINAC’10*, Tsukuba, Japan, Sep. 2010, paper FR101, pp. 1028–1032.

[5] S. Tantawi *et al.*, “Design and demonstration of a distributed-coupling linear accelerator structure”, *Phys. Rev. Accel. Beams*, vol. 23, p. 092001-11, 2020.