STUDY AND DESIGN OF A 3-CELL 704 MHz STRUCTURE FOR THE MUON COLLIDER DEMONSTRATOR RF CAVITY*

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Abstract

The Muon Cooling Complex is a crucial component of the future high-energy Muon Collider, where the ionization cooling technique is employed to reduce muon beam emittance by several orders of magnitude. The proposed cooling scheme requires cooperation in the same geometric section of static magnetic fields and radiofrequency electric fields of extremely high values. This feature represents a challenge in accelerator designs from the technological point of view. In this paper we present the solution developed for the Muon Collider demonstrator proposal and related to a 3-cell normal conducting RF structure. The electromagnetic simulation studies and detailed mechanical design are discussed.

INTRODUCTION

The muon collider has been proposed as a promising option for advancing the frontiers of particle physics [1]. Achieving high luminosity requires high beam brightness.

The International Muon Collider Collaboration (IMCC) has proposed a muon ionization cooling demonstrator to prove the six-dimensional emittance reduction across multiple cooling cell [2]. The preliminary design incorporates absorbers to reduce the beam momentum and high-gradient copper (Cu) RF accelerating cavities to restore its longitudinal momentum. The muon-cooling system so far generally described comprises a sequence of high-field superconducting solenoids to yield a tight focus at the absorber, with additional dipole coils on each solenoid to deliver sufficient dispersion.

Depending on the cooling stage considered, high-gradient RF cavities operating at frequencies of the order of hundreds of MHz and providing accelerating gradients of 30 MV/m are required. In the past significant efforts have been dedicated to the design of such RF cavities [3], exemplified by the construction and testing of an 805 MHz cavity for a future Muon Collider factory at Fermilab. This paper will outline the specific basic requirements underlying work carried out over the past three years.

RF CAVITIES REQUIREMENTS

High-gradient RF cavities are a key component of muon cooling channels in the design of a muon collider. A typical ionization cooling channel includes low-Z material absorbers, where muons lose energy, followed by high-gradient accelerating structures used to restore the longitudinal energy. The system is complemented by alternating superconducting solenoids that provide transverse confinement of the muon beam along the channel.

Strong magnetic fields from superconducting solenoids prevent the use of high-gradient superconducting RF cavities. Instead, normal-conducting copper cavities with open irises sealed by thin conductive foils are proposed to improve shunt impedance while allowing muon passage. RF systems near 704 MHz with peak gradients around 30 MV/m are expected throughout different cooling stages.

Most of the parameters being used for simulations of the entire cooling section are at the edge or beyond the present state-of-the-art, therefore required careful evaluation of the feasibility of the corresponding technological solution.

The large transverse emittance of the muon beams, with beam diameters up to 12 cm, requires RF cavities with large apertures. Such a large bore leads to a low shunt impedance in conventional open beam-pipe structures. Considering the aspects discussed above, a suitable solution may be to use conventional copper cavities with beam iris covered by thin conducting foils. This approach increases the cavity shunt impedance by exploiting the penetration capability of muon beams while keeping the maximum surface field comparable to the on-axis accelerating field.

Stringent beam dynamics requirements for electromagnetic field intensity in cavities limited performance at relevant frequencies due to breakdowns. Strong magnetic fields further complicated construction. As a result, laboratory test systems were set up to assess how different materials and surface treatments respond under specific operating conditions.

At LASA, a test system is ready for characterization of samples made of different materials treated according to different surface preparation procedures. The samples are excited by pulsed electric fields of the order of 50 MV/m and immersed in a static magnetic field up to 1.2 T.

RF CAVITY FREQUENCIES AND SHAPE

The reference frequency adopted for the study of the first RF cavity has been 704 MHz. This leads to cavity dimensions that represent a compromise between the required iris aperture, at least 120 mm in diameter, and the maximum allowable size of a cavity compatible with the bore of a strong superconducting solenoid. Figure 1 reports a description of the adopted geometry, while Fig. 2 illustrates the main electromagnetic features.

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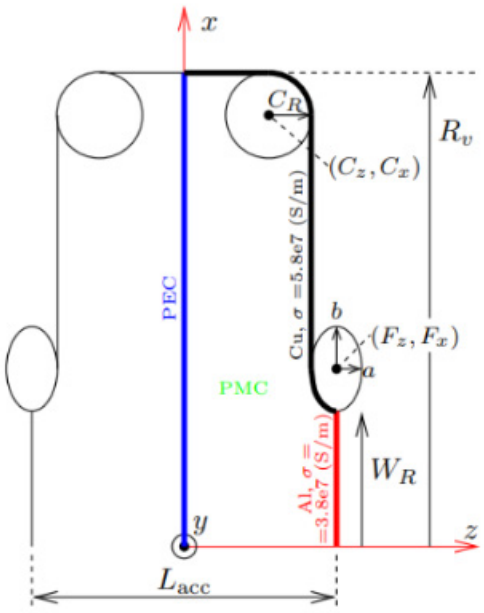


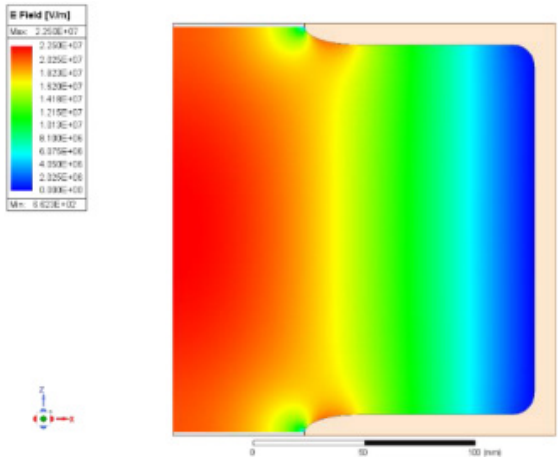
Figure 1: Geometrical model of the single cavity: L_{acc}=187.8 mm; R_v=164.5 mm; W_R=60 mm; a=5 mm; b=11 mm; C_r= 12 mm.

The choice of the RF cavity to be integrated depends on several key parameters, including the RF frequency, the required real estate gradient compared to the achievable peak surface field, the cell-to-cell coupling scheme, and the available space for ancillary systems such as tuners, power couplers, and cooling lines, all of which must be compatible with the tight constraints imposed by the cryomagnetic system.

Additional critical considerations include the required cavity breakdown rate and associated mitigation strategies in the presence of strong magnetic fields and gradients, as well as the choice of materials and surface treatments for the cavity walls, together with the availability of suitable RF power sources. Many of the parameters adopted in the cooling section simulations are at, or even beyond, the current state of the art, thus requiring careful assessment of the technological feasibility. A detailed description of the work conducted on the RF windows can be found in [4]. The first results from these studies have shown that curved shape foils with a thickness of 150 microns may be suitable to withstand the stresses due to thermal expansion and Lorentz forces, maintaining a total deformation compatible with the maximum frequency shift allowable.

During pulsed beam operation, RF-induced currents flowing through the foils lead to localized heating of the material. The resulting temperature increase causes thermal expansion, which may deform the foil geometry and consequently alter the resonant frequency of the cavity, producing a detuning effect. A similar phenomenon arises from the Lorentz forces generated by the electromagnetic fields: the associated radiation pressure acts on the foils, inducing mechanical deformation that further contributes to frequency shifts. Figure 3a illustrates the distribution of the radiation pressure, while Figure 3b reports the temperature map obtained for a 150 µm thick aluminium window.

To quantify the influence of these deformations on cavity behavior, full-wave electromagnetic simulations were carried out using a sector model of the cavity.

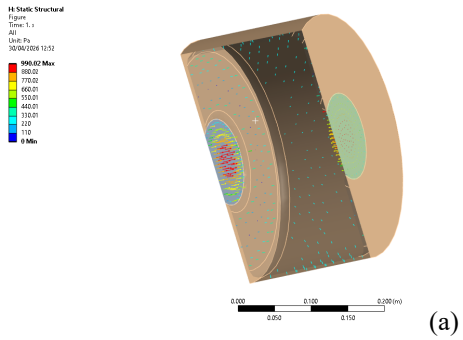


(a)

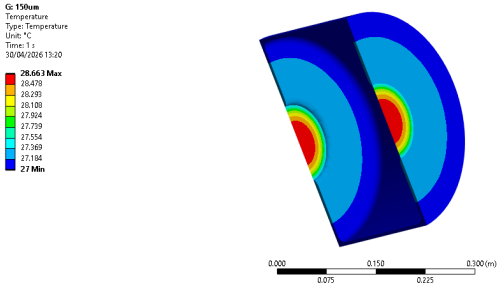
Parameter	Value	Unit
J_{in}	9.95	J
TTF	0.645	
E_0	22.50	MV/m
E_{acc}	14.51	MV/m
E_{max}/E_{acc}	1.42	
Q	35176	
r_{eff}	5.94	MΩ
R/Q	168.78	Ω
P_{diss}	1.25	MW

(b)

Figure 2: (a) Electric field profile on a transversal section of the RF cavity; (b) Electromagnetic design parameters.



(a)

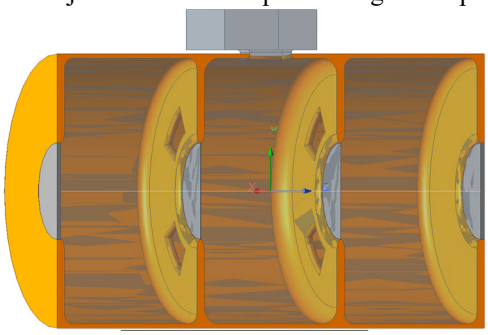


(b)

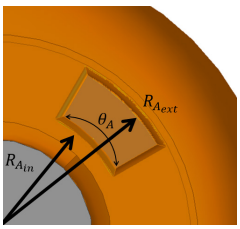
Figure 3: (a) Radiation pressure distribution and (b) temperature profile for a 150 µm Al window.

3-CELL CAVITY STRUCTURE

The cell described above was used as the basic building block of a three-cell cavity designed to meet the requirements imposed by beam dynamics. Considerations primarily related to the limited space available due to the presence of solenoids in the cooling cell led to the proposal of a standing-wave structure, featuring a central power coupler with the adjacent cavities coupled through 4 coupling slots.

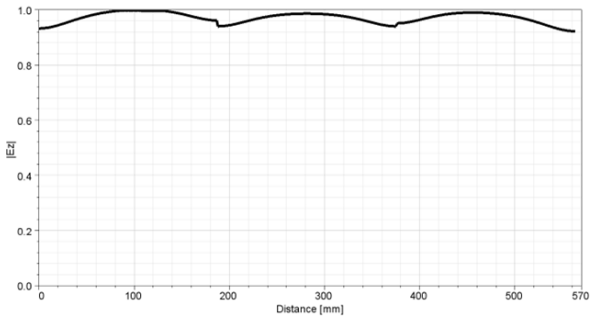


(a)



Par.	Value
$R_{A_{in}}$	85 mm
$R_{A_{ext}}$	113,5 mm
θ_A	15 mm
Fillet	4 mm

(b)



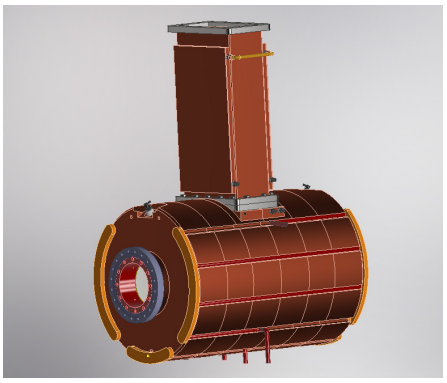
(c)

Figure 4: (a) Schematic view of the 3-cell RF structure. (b) coupling slots; R_{Ain}=85 mm, R_{Aext}=113.5 mm, Θ_A=15mm and (c) Electric field amplitude normalized for the π-mode.

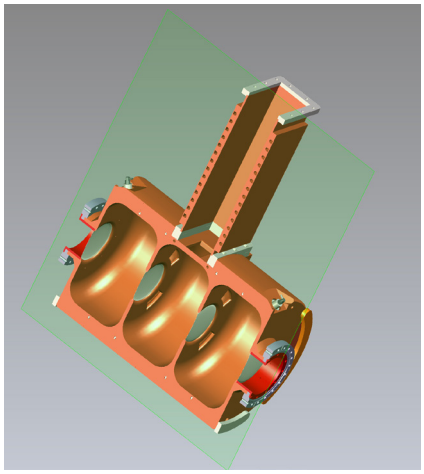
The mechanical design was developed based on the following key points:

- Machining by turning and milling (deep drawing is not feasible)
- Use of OHFC copper and steel for vacuum and RF connection flanges as well as for electric field probes
- Combination of brazing and sealing with aluminum O-rings and screws (allowing for the replacement of deteriorated foils)
- Design of a custom flange to secure the waveguide due to limited space. Similar constraints apply to the waveguide itself.
- Vacuum pumping through the waveguide (upstream of the separating ceramic)
- Automatic vacuum maintenance throughout the structure (provided that the ends are sealed with blind flanges)
- Cooling provided by 6 external circuits.

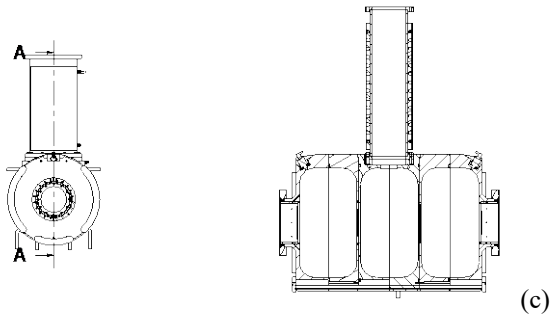
The 3D rendering and full mechanical design is shown in Fig. 5.



(a)



(b)



(c)

Figure 5: (a) and (b) pictorial 3D view of the proposed 3-cell 704 MHz cavity; (c) Related mechanical design.

CONCLUSION

A 3-cell RF cavity operating at 704 MHz, capable of producing an accelerating field of 22.5 MV/m along the axis with a power requirement of the order of 10 MW, has been designed in both its electromagnetic and mechanical details over the past three years and is ready for construction.

The cavity currently represents a concrete step toward the realization of the first module of a cooling cell.

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