STUDY AND DESIGN OF THIN WINDOWS FOR THE MUON COLLIDER DEMONSTRATOR RF CAVITY*

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Abstract

One of the essential features of the normally conducting RF cavities proposed for the Muon Collider is the presence of thin windows that cover the irises of the cavities. This feature addresses the need to increase the on-axis accelerating fields of the cavities and simplify their design. This paper summarizes the work done to date, both in terms of materials and geometric conformations, and in terms of experimental design, to create these structures that meet the requirements described above while also being compatible with the specific characteristics of a real cavity.

INTRODUCTION

In normal-conducting radio-frequency (RF) cavities, thin foils (about 100 μm) - known as windows - are placed over the beam irises to electromagnetically close the cavity. This design choice is primarily used in muon ionization cooling channels, where traditional open-iris cavities would suffer from significantly reduced shunt impedance due to the large beam apertures required, and keeps the ratio of the peak surface electric field to the accelerating field on-axis near unity; on the other hand, the use of thin foils poses two detuning effects: one due to foil thermal expansion (induced by RF currents) and one due to mechanical deformation induced by Lorentz force [1].

FOIL DESIGN

Two main foil geometries are used to reduce deformation: pre-stressed flat foil and pre-curved foils, intentionally curved so that thermal expansion occurs in a predictable direction, making frequency shifts easier to compensate.

The material proposed so far for windows manufacturing is Beryllium (Be), due to its unique combination of properties:

- Low Atomic Number (Low-Z): Minimizes beam scattering and energy loss.
- Thermal Conductivity (200 W/m/°C): essential for dissipating heat generated by induced RF currents.
- Elastic module (300 GPa) and Yield strength (500 MPa) allows it to withstand high electromagnetic forces.

Nevertheless, Beryllium poses very strict safety requirements, currently impossible to be satisfied in case of internal production at INFN and (currently) only 3 producers in the world can produce this kind of thin windows. An alternative material as the alloy Albemet has not been considered due to the same problems in supply and safety requirements.

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Due to these considerations, INFN proposed to the whole MC collaboration to evaluate Aluminium as an alternative, at least for the first tests for the demonstrator: it is a common material, easier and safer to machine than Beryllium, with similar thermal properties, but a worse mechanical behaviour. Since elastic module is about 70 GPa and Yield strength 100 MPa, one can expect larger deformation in aluminium foils. The low Z number keeps a reduced contribution in beam scattering and energy loss.

MUON COLLIDER COOLING CHANNEL DESIGN

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.

The strong magnetic fields generated by the superconducting solenoids rule out the use of high-gradient superconducting RF cavities. Depending on the stage of the cooling process, RF systems operating at frequencies around 704 MHz and capable of sustaining peak gradients on the order of 30 MV/m are required.

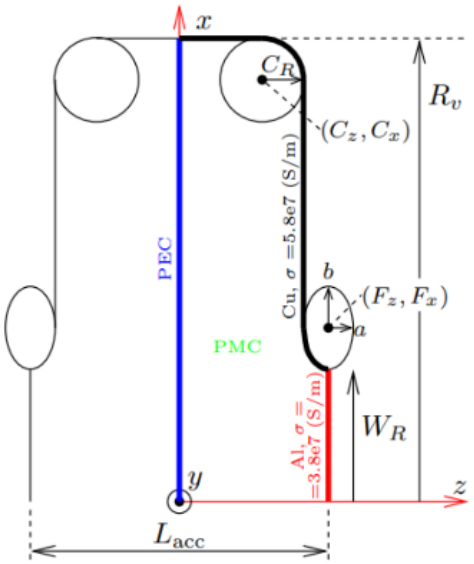


Figure 1: Geometrical model of the cooling cell.

A viable approach is therefore to employ normal-conducting copper cavities with open beam irises closed by thin conductive foils, which enhance the shunt impedance

while still allowing muons to pass through due to their high penetration capability.

Figure 1 illustrates the geometrical model of the flat-top cavity, with its defining parameters set as follows: $L_{acc} = 187.8$ mm, $R_v = 164.85$ mm, $W_r = 60$ mm, $a = 5$ mm, $b = 11$ mm, $C_r = 12$ mm.

Electromagnetic design parameters are the following: $J_{in} = 9.95$ J, $TTF = 0.645$, $E_0 = 15.50$ 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.

E.M. BEHAVIOUR OF THE CAVITY

Due to the large transverse emittance of the muon beam, RF cavities require wide apertures (up to 12 cm in diameter), which significantly reduce shunt impedance in conventional open structures. To mitigate this effect, larger cavities (up to 16 cm diameter) with thin (50–200 μm) windows have been investigated to allow beam transmission while limiting scattering, see Fig. 2. This configuration improves shunt impedance and helps align peak surface fields while keeping on-axis accelerating field. The baseline studies are performed at 704 MHz, considering both beryllium and aluminium as possible window materials.

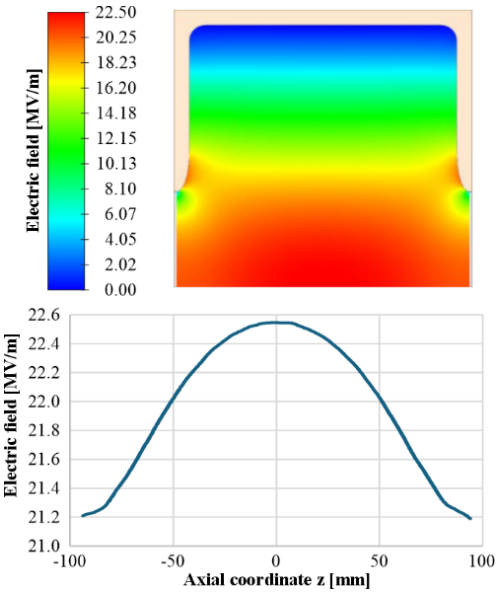


Figure 2: Electric field profile on a transversal section of the cavity (upper) and on beam axis (lower).

The inclusion of metallic windows at the cell irises simplifies the RF electromagnetic design, but it also introduces significant challenges in terms of mechanical engineering, the soldering or assembly process, and the ability to withstand RF-induced pressures and thermal stresses.

RF HEATING AND DETUNING ANALYSIS

Detuning due to thermal expansion and radiation pressure was evaluated through full-wave FEM simulations performed on a cavity sector model: first, EM simulations evaluate Lorentz forces and heat flux on the foil, then thermo-structural simulations evaluate the corresponding deformation and finally, back to EM analysis, the new frequency on deformed geometry was obtained. It was assumed E = 22,5 MV/m, D = 120 mm, while the foil thickness Δth is variable (positive values toward the inside of cavity).

Figure 3 shows the distribution of Lorentz force and temperature, while Table 1 shows the results in terms of loss of frequency.

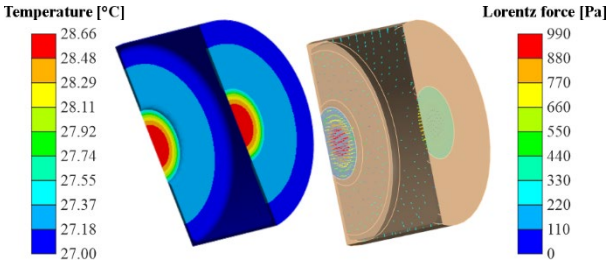


Figure 3: Distribution, for a 150 μm Al window, of temperature (right) and Lorentz force pressure (left).

Table 1: Detuning Due to Window Deformation

f (MHz)	Δth (mm)	Δf (kHz)
704.031	0	-
703.828	0.2	203
703.93	0.1	101
704.131	-0.1	-100
704.231	-0.2	-200

THERMO-MECHANICAL ANALYSYS FOR ALUMINUM FOILS

FEM analysis were performed to evaluate deformation and stress distribution on the foils; the analysis considers an axial symmetric geometry for the foil, applying first the thermal load (T = 300 K imposed at the outer diameter), then the Lorentz force (foil fixed at outer diameter) and finally both cases combined. Figure 4 summarises the described configuration, while Fig. 5 shows the distribution of radiation pressure and heat flux over foil radius. Base temperature, at which deformations are evaluated, is set to T = 20°C. It was produced a set of results, parametrized on foil material, diameter, thickness, geometry (flat or curved) and electric field.

Peak value over time for radiation pressure was assumed constant in the entire period of duty cycle. Figure 6 shows the results, in terms of displacement on beam axis, for the 3 load configurations already discussed: only thermal load, only mechanical load, both loads. Material is set as aluminium, radius 60 mm, accelerating field E_0 22.5 MV/m and foil thickness 150 μm.

In curved foils, thermal loads tend to accentuate the curvature of the foil outward from the cavity, while in flat foils produce buckling behaviours if no other forces are applied.



Figure 4: Loads and constraints applied for FEM analysis on curved foil.

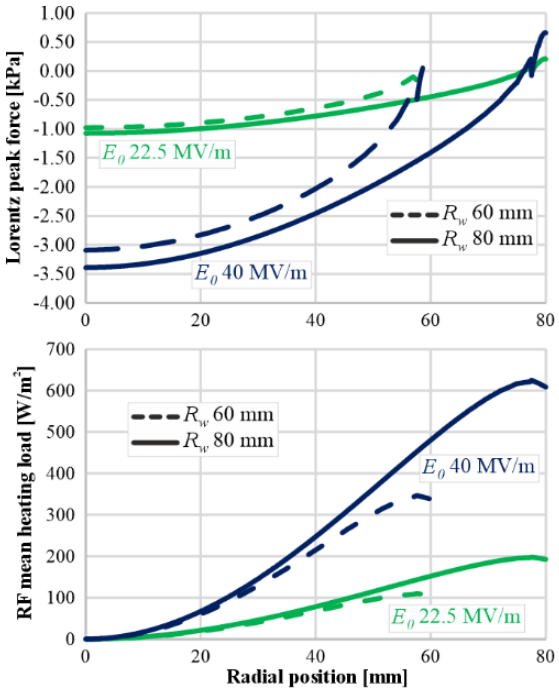


Figure 5: Radial distribution of Lorentz peak force (top) and mean RF heating load (bottom), for different values of accelerating field E_0 and maximum window radius R_w.

Displacement due to Lorentz force Counteract the effect of thermal loads for considered curved-out windows, while on flat geometries produce an unacceptable deformation (order of millimetres) at any considered thickness.

Maximum and minimum values for displacement over thickness are shown in Fig. 7. An increase in foil radius reduces the stiffness of the foil itself, thus producing large displacements. An increase of accelerating field produces mostly an higher Lorentz force, so it increases the contribution of negative displacements. Stress distribution over the section decreases with thickness and, at least for curved foils, only thickness higher than 150 µm are technically machinable. Unrealistic values for thick 50 µm (displacement of 90 mm) are removed from the graphs.

CONCLUSION

The analysis of the data presented above leads to the following conclusions: there is an acceptable limit for window deformation caused by the line width of the RF power generator's frequency (estimated at 400 kHz); assuming cavity aperture diameters greater than 120 mm is unrealistic; the use of aluminium with thicknesses between 100 and 150 µm serves as a reference in terms of maximum acceptable deformation (see section on maximum frequency deviation) when considering models with curved-shape foils. Electric field values around 22.5 MV/m are consistent with the above.

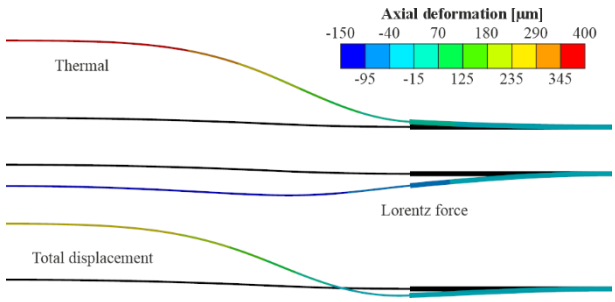


Figure 6: Axial displacement along the beam axis for thermal, Lorentz, and combined loads. Undeformed geometry is shown in black. Data refers to a 150 µm Al foil with $R_w = 60$ mm and $E_0 = 22.5$ MV/m.

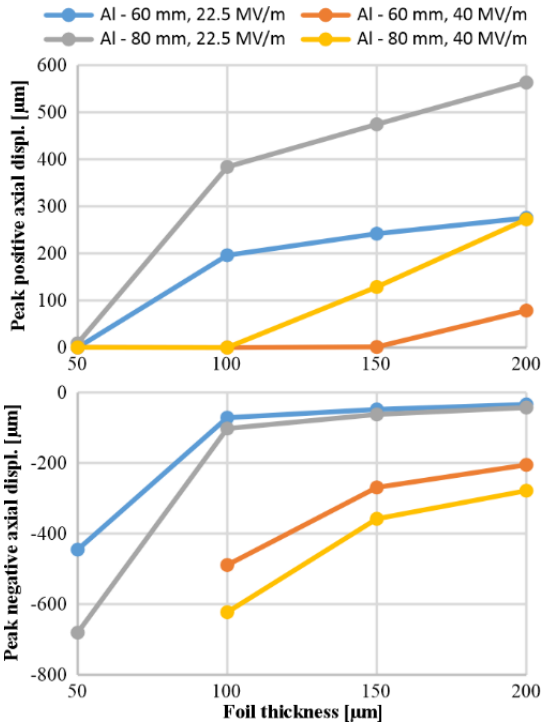


Figure 7: Peak axial displacement vs. foil thickness. The top plot displays positive values (outward from the cavity), while the bottom negative values (inward into the cavity).

REFERENCES

[1] Derun Li, "Design and fabrication of an 805 MHz RF cavity with Be windows for a RF high power testing for a Muon Cooling experiment", in *Proc. PAC'01,* Chicago, IL, USA, Jun. 2001, paper MPPH062, pp. 918-920.