PRELIMINARY ENGINEERING DESIGN OF THE COOLING CELL FOR THE MUON COLLIDER COOLING DEMONSTRATOR[*]

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Abstract

The rectilinear 6D cooling channel is a key element of the Muon Collider baseline, enabling the large emittance reduction required before acceleration. The Muon Collider Cooling Demonstrator aims to validate, at engineering scale and in relevant conditions, the integration of a single B5-like cooling cell. This paper presents the preliminary design of the Cooling Cell, developed within the MuCol and IMCC collaborations, and based on a high-field HTS solenoid pair, a low-Z absorber, and a 3-cell 704-MHz normal-conducting RF structure. A key point of the design effort is the introduction of the Inter-Cell Cryostat, a compact architecture that closes the magnetic forces inside the cold mass while decoupling the RF and absorber assemblies at room temperature. This solution enables a feasible mechanical integration, compliant with lattice length constraints, and provides sufficient space for waveguides and diagnostics. However, it requires a remote-handling connection between each cell. The final cell layout incorporates the MAG2.4 HTS solenoids operating at 20 K, an updated RF cavity with thin Al foils, a LiH absorber module, cryogenic and thermal-shield structures, and pillow-seal vacuum interfaces designed for remote-handling assembly. The configuration that we present is a step toward demonstrating the feasibility of the cooling channel of the Muon Collider.

INTRODUCTION

The Muon Collider (MC) baseline cooling concept relies on repeated passage through low-Z absorbers, followed by re-acceleration in RF cavities to restore only the longitudinal momentum, in the presence of alternating solenoidal focusing and dipole fields [1-3].

The rectilinear cooling channel is composed of repeated cells approximately 1 m long, each one integrating a high-field superconducting magnet system, a high-gradient normal-conducting RF cavity, and a low-Z absorber. The cooling cell combines several technologies operating close to their present limits: large bore HTS magnets with peak fields approaching 14 T on the conductor, RF cavities operating at gradients near 30 MV/m in strong magnetic fields, thin metallic windows, compact cryogenic systems, and highly constrained mechanical interfaces [4].

The Muon Collider Cooling Demonstrator has been conceived to address this challenge by proving that a representative cooling cell can be constructed, assembled, cooled down, energized, and operated safely with all major subsystems integrated at full engineering scale. The demonstrator, developed within the MuCol and IMCC collaborations, focuses on a B5-like cooling cell, derived from the baseline B5 cell of the MC cooling section [5, 6].

COOLING CELL ARCHITECTURE

The reference cooling cell is based on three principal subsystems: (i) a pair of high-temperature superconducting solenoids generating the required focusing, (ii) a 704 MHz three-cell normal-conducting copper RF cavity, and (iii) a liquid hydrogen (baseline for MC) or lithium hydride (considered for the demonstrator) absorber located in the beam pipe between RF structures. Additional systems include a low field dipole to generate dispersion over the absorber, vacuum vessels, thermal shields, cryocoolers, support structures, instrumentation, and remote-handling interfaces.

The design follows the one-meter lattice period adopted in the beam dynamics model [7]. This geometric constraint is particularly demanding because the RF cavity, absorber, and magnet system must coexist within a very limited longitudinal space while preserving access for RF waveguides, vacuum pumping, diagnostics, cryogenic services, and alignment systems.

A major breakthrough in the integration effort was the introduction of the Inter-Cell Cryostat. In this architecture (see Fig. 1) the superconducting coils and their mechanical support form a compact self-contained cold mass located between adjacent room-temperature RF structures. The large axial magnetic forces generated by the coils are reacted internally within the cryostat, rather than through the RF cavity or beam-pipe assemblies. This substantially simplifies the integration and allows the RF system and absorber to be supported independently at room temperature.

The Inter-Cell Cryostat offers several advantages. First, it decouples the magnetic and RF systems, enabling parallel development and testing. Second, it provides the radial space required for the RF power coupler and associated waveguide. Third, it reduces thermal bridges between warm and cold components. Finally, it permits modular assembly of the cooling channel from repeated standardized

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units. The main drawback of this approach is that the vacuum connection between the absorber beam pipe and the RF cavity is located in a region with restricted access between adjacent cryostats, thus requiring a dedicated remote-handling connection based on a custom pillow seal, discussed in Section on Integration.

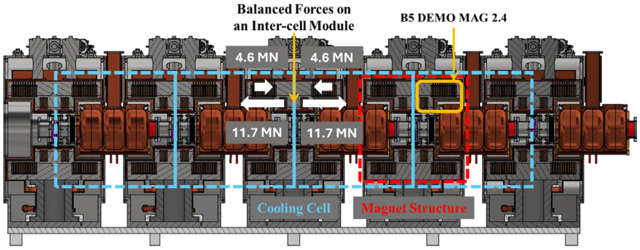

Figure 1: a five inter-cell module array (four full cooling cell structures plus two halves at beginning and end of array). The Inter-Cell Cryo-Magnet structure (red dashed line) is decoupled from cooling cell units (blue dashed line).

MAGNET AND CRYOGENIC DESIGN

The baseline magnet configuration, denoted MAG 2.4, consists of pairs of concentric HTS-solenoids. Each solenoid is composed of two coils, a smaller one at lower radius and a larger one at higher radius. Both coils are wound with REBCO tape and targeting 20 K operation [8, 9], following the technology and procedures developed for the RFMFTF program [9-11]. The concentric coils are operated independently with currents around 1 kA, peak field on conductor reaches approximately 14 T with a stored energy in one cooling cell of about 12 MJ [9].

The coils, placed on each side with respect to the center of the cell, experience substantial and opposing axial forces in the ten MN range. At nominal operating conditions, the net axial force on each coil is approximately 7.1 MN (difference between 11.7 and 4.6 MN in opposite directions, see Fig. 1), in opposite direction so the total force is zero, if properly supported by the internal mechanical structure of the inter-cell cryostat. Finite-element analyses confirm that the resulting hoop, radial, and von Mises stresses remain within the allowable limits of the conductor stack and structural materials [9].

Protection studies indicate adequate temperature margin during operation and show that current unbalance during quench can generate at most about 1 MN of net force. [4]. Further work is underway to refine quench analyses and to quantify force redistribution during transient conditions.

The cryogenic design is based on conduction cooling using cryocoolers, avoiding the need for a liquid-helium distribution system in the demonstrator [12]. Four cryocoolers are foreseen per cell, connected to the cold mass through high-conductivity thermal links. Static heat loads on the coils are estimated to be about 20 W, while radiation to the thermal shield contributes approximately 63 W [9]. Gravity supports add approximately 15 W to the 60 K stage.

Thermal analyses predict a peak charging power loss of about 127 W and a maximum temperature increase at the end of the magnet ramp-up transient of approximately 32 K and 22 K in the two coils. The total charging time is estimated at about 6 h. The cooldown from 77 K to 20 K is expected to require approximately 15 h [9].

Support structures are optimized to balance mechanical stiffness and thermal performance. GFRP tension members with intermediate thermal intercepts can reduce the heat leak to the 20 K stage below 1 W while maintaining sufficient capacity for longitudinal load (around 1.2 MN axial force).

RF CAVITY AND ABSORBERS

The cooling channel requires high-gradient RF cavities to restore the longitudinal momentum lost by the muons in the absorber. Because of the strong magnetic fields, normal-conducting copper cavity, operating at 704 MHz (or 352 MHz in certain cells), have been adopted as the baseline. For the integration of the demonstrator cell, the RF structure consists of three coupled cells approaching 30 MV/m of electric field. The large beam emittance requires an aperture in the cavities that can reach up to 160 mm in diameter; for the demonstrator, a 120 mm aperture has been selected as a practical compromise. To reduce the shunt impedance, the cell irises are closed with thin metallic foils through which the muon beam passes with minimal scattering.

Procurement, cost, and stringent safety requirements for machining and handling of beryllium (the ideal material for performance) have motivated the proposal to use aluminum alloys for the first demonstrator prototypes. Alloys such as 6061-T6 and 6082-T6 provide a practical compromise between mechanical strength, thermal conductivity, and industrial availability.

Detailed thermo-mechanical analyses have been performed for foil thicknesses between 50 and 200 µm, window radii up to 80 mm, and gradients up to 40 MV/m [13]. The studies include RF heating, thermal deformation, Lorentz-force loading, and modal analyses. Curved foils provide the most favorable behavior by increasing stiffness and limiting displacement. Mechanical resonance frequencies are comfortably above the pulse repetition rate, although transient effects and damping require further study.

In light of the findings of these studies, the present baseline uses pre-curved aluminum-alloy windows mounted by mechanical compression, to facilitate rapid prototyping and replacement of damaged foils. The cavity incorporates six external cooling circuits, standard vacuum flanges, RF probes, and a specially designed compact waveguide flange to fit within the restricted envelope imposed by the magnet cryostat, see Fig. 2.

The mechanical design of the cavity is available, and prototypes of the most technologically complex components are currently being developed. This applies in particular to the windows discussed above.

The lithium hydride absorber is housed in a dedicated beam-pipe module supported independently from the cryostat. Adjustable supports permit alignment along the beam axis and replacement during maintenance. By separating the absorber and RF structures from the magnet cold mass, assembly and servicing procedures are significantly simplified and testing of single components will allow to intercept issues and defects at early stage during fabrication and preassembly.

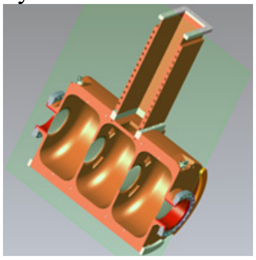

Figure 2: pictorial view of a section of the 3 coupled cells with the removable waveguide.

INTEGRATION

For practical construction and testing, the cooling cells are grouped into modules mounted on a common support girder. The reference demonstrator module contains five cooling cells and has an overall length of approximately 5 m and a mass of roughly 25 t. This modular approach provides a realistic representation of a section of the full cooling channel while remaining compatible with handling and test-facility constraints.

In a periodic channel, the axial magnetic forces are nearly self-balanced. The situation is fundamentally different at the ends of an isolated module, where the absence of neighboring cells leads to significant residual end loads of approximately 4.8 to 5.0 MN.

This issue affects not only the demonstrator but also the beginning and end of each cooling section and any transition between stages in the full collider. The present strategy is to withstand this 4.8 MN load when cold testing a single module, by means of a dedicated cold-to-warm transition, of 1 m length and high -still acceptable- cryogenic heat load. Meanwhile we are investigating mitigation approaches to strongly reduce the net axial force in the transition regions of the MC cooling section and of the demonstrator. Matching concepts to optimize transition between different cell types or between beam delivery and start of the cooling (for the demonstrator) are currently under study. A possible solution uses two matching solenoids followed by a regular B5 module. Another solution employs one matching solenoid and a modified B5 cell with tailored current settings. Both solutions reduce the unbalanced forces while providing a smooth transition of the optical functions.

The support girder carries both the room-temperature assemblies and the cryostat interfaces. Several concepts have been evaluated, including stainless steel and composite load paths with 60 K thermal intercepts. Structural analyses confirm acceptable stresses and deformations under static loads and electromagnetic forces, including quench conditions, thanks to a suitable support "foot" design, see Fig. 3.

The Inter-Cell Cryostat introduces a challenging connection between adjacent warm beam-vacuum assemblies. Because this region is inaccessible after installation, the connection must be tolerant to alignment errors and operable by remote handling. The baseline solution is a custom pillow-seal vacuum interface [14] shown in Fig. 3. The seal consists of a compliant metallic element compressed between mating flanges, with elastomer O-rings, providing reliable vacuum tightness even in the presence of modest positioning errors.

Prototype development of the pillow seal and representative assembly mock-ups are planned to validate leak tightness, mechanical robustness, and compatibility with remote installation procedures.

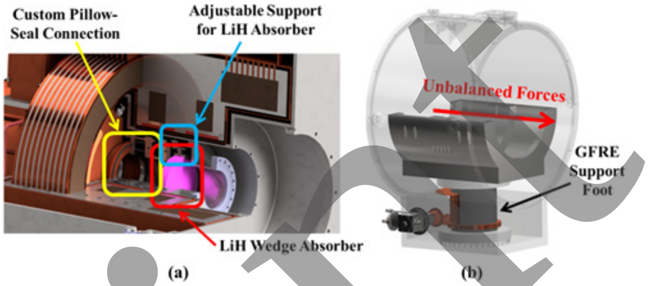

Figure 3: pillow-seal system and beam pipe connection elements (a). Inter-cell cryostat view with GFRE support foot (b).

CONCLUSIONS AND NEXT STEPS

A solution for integrating the cooling cells in the standard lattice of the rectilinear cooling has been developed, based on the innovative Inter-Cell Cryostat approach. The most important remaining challenge is the design of start/end structures capable of withstanding residual forces under both steady-state and fault conditions.

On the RF side, priorities are the fabrication and testing of aluminum windows, validation of the compression-based attachment system, and experimental assessment of thermal and mechanical behavior under high RF fields. For the mechanical integration, remote-handling mock-ups will be used to verify assembly tolerances and procedures.

A coherent preliminary engineering design has been established for the Muon Collider Cooling Demonstrator. The design integrates HTS magnets, a 704 MHz high-gradient RF cavity, a lithium hydride absorber, conduction cryogenics, and remote-handling interfaces within the strict geometric constraints of a one-meter cooling lattice.

By closing magnetic forces within the cold mass and decoupling the RF and absorber systems at room temperature, it transforms a conceptually attractive beam-dynamics cell into a realistic engineering configuration.

Although the treatment of start/end forces remains an important open issue, practical mitigation strategies have been identified and are under active development. The next key step is the construction of the RFMFTF prototype, which will provide essential validation of the HTS magnet technology and cryogenic design. This should be followed by the construction of either a full-scale or reduced-scale integrated cooling cell assembly, including magnets, RF cavities, and remote-handling interfaces, to experimentally validate the concept.

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