Summary – Internal Review Magnets Cooling Options for the Muon Collider

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The study presented at the internal review is an overview of cooling options for collider-type magnets, using a combined approach to the overall optimization of cryogenic infrastructures considering both sustainable magnet design and the optimization of the infrastructure considering all temperature levels involved in the collider ring. The focus has so far been directed towards collider magnets which, due to the heat loads that need to be extracted and to the sheer number of magnets, constitute an important part of the cryogenic effort of the whole Muon Collider complex.

For the collider arc magnets (i.e. series production, multiple units), several drivers have been identified. Those are:

- Energy consumption;
- Cryogenic availability;
- Choice of conductor;
- Local heat extraction;
- Distribution losses;
- Reduced complexity.

From the 2021 Snowmass report, the estimated electrical power to operate the Muon Collider is 300 MW. A tentative target of 10% of that power (30 MW) is taken for the cryogenic operation of the whole complex, with 25 MW allocated to the collider ring. This means that for a 10 TeV, 10 km ring, the electrical power consumption of the cryogenic infrastructure should remain below 2.5 kW per meter. The overall number of cryoplants needed to provide the necessary cryogenic environment should be limited as much as possible, since the number of cryoplants increases the cost of the cooling infrastructure but also negatively impacts the combined availability of the collider ring.

The heat load deposited on the absorber inside the magnet aperture due to muon decay is substantial (500 W/m), and as such must be extracted at the highest practical temperature level. Current proposals include water cooling at room temperature and CO_2 cooling at 250 K; an in-depth review of the base assumptions is needed, especially where it concerns the risks associated with each technology.

The choice of conductor will be the decisive factor in determining the operating temperature of the magnets and the allowable temperature gradient established along an arc cell. Local heat extraction at the cold mass level will become more demanding as the heat load increases, making the coil design more complex. As a tentative objective, based on our experience with thermal assessment of fully impregnated coil blocks, the heat load to the cold mass, including both beam-induced and static heat loads, should remain below 10 W/m.

The above drivers become further constrained by the need for reduced complexity in the cryogenic layout, which in turn depends on the nature and temperature range of the adopted cooling scheme. The number of temperature levels (cold mass, absorber, thermal shield, heat intercept, current leads) should be minimized. Additionally, the overall fluid inventory must be limited, therefore limiting the dependence on market availability and also reducing associated safety concerns.

Due to the necessity of very short (~ 30 cm) field-free regions between magnets in the arcs, the number of fluid connections (and aforementioned temperature levels) should be simplified in as much as possible to allow for such short interconnect regions to be implemented.

Lastly, the distribution losses constitute an important constraint to the design of the cryogenic layout. The sector and arc cell lengths will effectively be determined by the allowable pressure heads for each of the cooling circuits, which will in turn depend on the choice of fluid and cooling scheme.

Considering the various constraints imposed by the main drivers, which combine both sustainability and technical requirements, a few guidelines could be drafted: the heat load deposited at the absorber level shall be lifted at or above 250 K; the heat load to the coil shall remain below 10 W/m, and the cold mass shall be cooled at a base temperature of 4.5 K or above; and the overall electrical power consumption of the cryogenic system for the collider magnets shall not exceed 2.5 kW/m. For the heat load to the coil to remain at or below 10 W/m, a heat intercept (thermal shield) between the absorber and the coil is compulsory.

Along with the above guidelines, a few points that need attention were identified. Namely, the supporting structure that holds the absorber inside the cold bore contributes with an excessive amount to the coil heat load when compared to the unavoidable beam-induced loads. As such, efforts should be put into the design of optimized supports for the muon collider absorber. A preliminary cross-section of the coil and absorber should be outlined as it would allow to better estimate parameters for the cooling scheme layout.

Options for both LTS (around 5 K) and HTS (10+ K) collider rings exist and are promising, but need R&D to explore the limits of two-phase flow and supercritical cooling in confined geometries. In the case of magnets operating at around 20 K, solutions using two-phase H_2 cooling need both an in-depth safety assessment and demonstration, along with a change of mindset.

A detailed study of cooling schemes must follow once some base decisions have been taken regarding conductor choice and heat loads to coil, while considering the guidelines outlined by the main drivers and addressing the points identified above that need dedicated studies.