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CONCEPTUAL DESIGN OF THE HTS SPLIT COIL TEST FACILITY FOR THE MUON COLLIDER COOLING SECTION*

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Abstract

The cooling section of the Muon Collider requires a number of solenoidal coils of various diameters (0.05-2 m) and fields (2-40 T). An unusual feature of the cooling section is that the RF cavities operates under the large magnetic fields and field gradients generated by the focusing elements. Here we present the design of a test facility based on split coils, wound with HTS, to study the performance of RF cavities under magnetic field. The main characteristics are: 320 mm free room temperature bore, uniform 7 T field along 300 mm on axis, coils energized with parallel or antiparallel field: this last configuration provides a gradient field of about 40 T/m. The use of HTS in form of REBCO tape enables magnet operation at 20 K and cooling via solid conduction by cryocoolers. This facility will be a first prototype of the cooling cell magnets that are being designed in cryogen-free layout at 20 K for energy saving and will allow to anticipate system integration concepts. The conceptual design of the facility is almost frozen, and the engineering design is under way. If we get financial support by 2025, we can commission the facility in 2027.

INTRODUCTION

A test facility for radiofrequency cavities was recently proposed to test the breakdown limit of the cavities under high magnetic fields (7 T) in a configuration relevant for the Muon Collider design study carried out by the International Muon Collider Collaboration (IMCC) [1]. A test facility layout has been proposed and studied by the LASA laboratory (jointly managed by INFN and University of Milan) in Milan, Italy, which is currently finalizing the design and applying for a grant to proceed with its construction, commissioning and testing.

The construction of a test facility will be an important push toward the definition of a baseline technology for the 6D cooling cells of the Muon Collider, serving as a proof of concept of the cooling cells design, besides being a key tool for RF cavities testing.

In this work, the conceptual design of the HTS split coil test facility is presented and results of the magnetic and mechanical analyses and coil margin studies are reported. The thermal analysis during coil ramp up transient, a critical phase because of heat dissipation in the coil, has determined the charging time and the cooling configuration.

HTS TEST FACILITY: LAYOUT

The basic structure of the test facility consists in a split coil based on non-insulated HTS conductors winding (Fig. 1). A 12 mm wide and 0.067 mm thick REBCO tape is used for the design of the winding of the two cylindrical coils.

Two possible operative modes of the test facility are considered: same current polarity in both coils or opposite polarity. In the first mode, a 7 T field at the center of the coil axis is generated, with a field homogeneity better than 3.0% in a 300 mm axial length; with opposite polarities, a field gradient of 40 T/m, nearly constant along the length is generated, with zero field in the center. The apparatus operates at 20K in a cryogen-free configuration: Cryomech AL230 cryocoolers are considered for the design [2].

The structural support and cooling of the coils is provided by the 316LN steel vacuum vessel. The cold heads are integrated into the supports, connected to the coils at 20 K. The 60 K thermal shield is integrated with the HTS current leads and copper busbars, see Fig. 1 for a schematic view. The structure will then be anchored on a ground support platform.

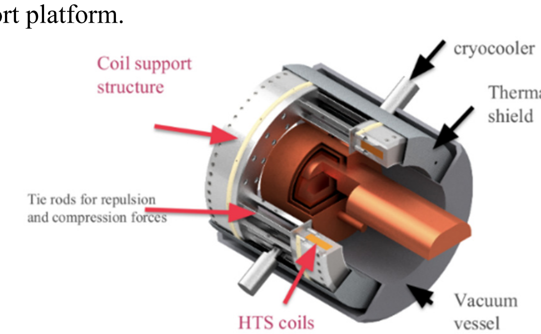

Figure 1: HTS split coil (schematic) in its cryostat.

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The coil structure is composed of a stack of six pancakes of 680 turns enclosed in two coaxial copper rings and interleaved with layers of copper, steel and polyimide insulating material (Fig. 2). The Cu layers are used as additional stabilizer and for cooling, being connected to the cold heads of the cryocoolers. The steel and polyimide layers are anticipated to be present in the coil stack but were not taken into account in this design phase.

Table 1 summarises the main geometric and operational parameters. In the following sections, the results of each detailed study are presented.

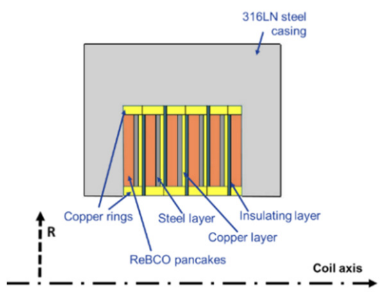

Figure 2: Section view of the coil stack with steel casing.

Table 1: List of Main Parameters from Preliminary Design

Parameter	Value
Coil inner diameter (free bore aperture) [mm]	400 (320)
Number of pancakes per coil (number of turns per pancake) [-]	6 (12)
Coil radial width (axial) [mm]	45.6 (72)
Coil winding method	Not insulated
Coils distance [mm]	200
Center field on axis – same polarity configuration	7
Field gradient on axis – reverse polarity operation [T/m]	40
Coil total inductance [H]	4.54
Energy stored in the coil [MJ]	6.4
Coil operational temperature [K]	20
Thermal shield temperature [K]	60
Cooling source	Cryocoolers

MAGNETIC DESIGN

The magnetic design of the HTS split coil was performed in COMSOL [3], considering two different coil operation modes:

- Same polarity (parallel field).
- Inverse polarity (antiparallel field).

The first is proposed for testing purposes, to test the breakdown limit of RF cavities, while the inverse polarity configuration is the actual operational mode of the Muon Collider cooling cells.

To reach the target central field of 7 T in the same polarity configuration, a current of 530 A is required, with a peak field in the coil below 16 T. The same current with opposite polarity generates a field gradient of 40 T/m along the coil axis. Figure 3 shows the magnetic flux density map on a cylindrical region of interest along the central axis, while the flux densities along the coil axis, are plotted in Fig. 4.

These are the results of a parametric optimization on the coil geometry [4]. Within this study, the coil margins were also assessed for the parallel field configuration. The results of the load line, current, temperature and energy margins are summarized in Table 2.

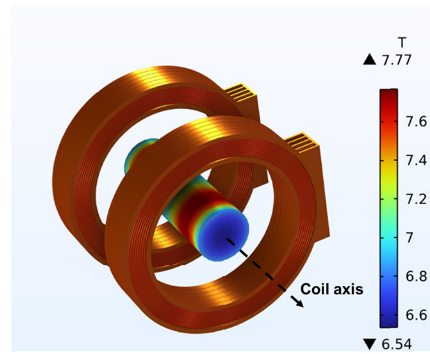

Figure 3: Magnetic flux density distribution on the central coil region (same polarity).

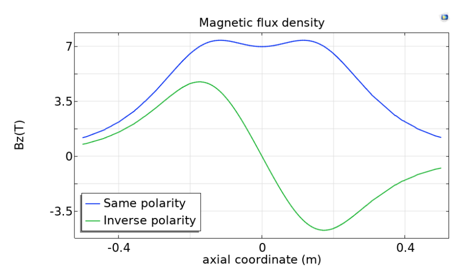

Figure 4: Field distributions along the coil axis.

Table 2: List of the Main Magnetic Design Parameters

Parameter	Value
Operational current [A]	530.3
Tape Eng. current density [A/mm^2]	621.8
Field uniformity: 300mm on axis [-]	< 3%
Minimum current margin [-]	40%
Load line margin [-]	44%
Minimum temperature margin [-]	15
Minimum energy margin [J/cm^3]	2.5

As typically observed in non-insulated HTS coils, the associated margins are large, which makes magnet protection in case of a quench more critical.

MECHANICAL DESIGN

A preliminary mechanical analysis of the coil and steel structure was developed considering the coils as homogeneous mediums with orthotropic properties, without considering the details of the coil stack. From the modelling of the unrestrained coil subjected to the electromagnetic (e.m.) force, exceeding values of the maximum hoop stress

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were found (~660 MPa). To reduce it, a 50 mm thick 316LN steel restraining cylinder was introduced to house the coil (Fig. 5), reducing the coil stress to 350 MPa and the corresponding deformation below the limiting value of 0.25%. Methods of prestress application on the coil are currently under consideration.

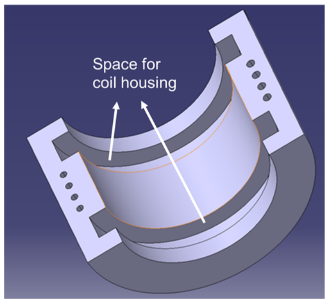

Figure 5: View of the restraining cylinder half shell.

The maximum stress values of the coil and steel structure are reported in Table 3.

Table 3: Mechanical Design Parameters

Parameter	Value
Coil maximum hoop stress [MPa]	350
Coil maximum axial stress [MPa]	220
316LN structure maximum axial stress [MPa]	300
316LN structure radial stress [MPa]	250

THERMAL DESIGN: MAGNET RAMP UP

The coil thermal analysis was performed during the magnet charging transient, being the most challenging operational conditions. The cooling configuration consists in two single stage cryocoolers connected to the coils via longitudinal copper plates. The maximum allowed coil temperature increase was set at 4 K. An equivalent network model was used to compute coil inductances and resistances to then estimate the power deposited during the transient. All material properties are considered temperature dependent.

The coil stack geometry and cryogenic interface were optimized to meet the target [5], leading to an estimated 20 hours charging time and a maximum temperature increase of 3.5 K for the same polarity configuration (Fig. 6).

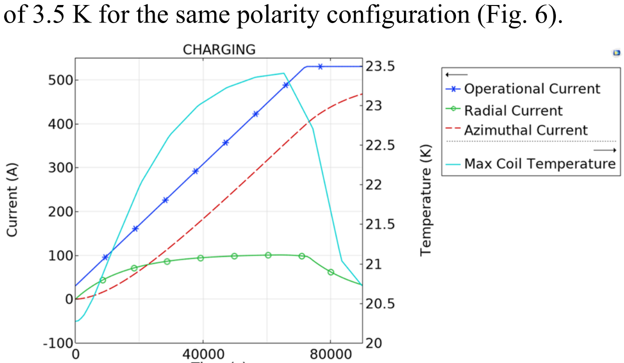

Figure 6: Time evolution of temperature and currents.

In Table 4, the results of the main thermal design parameters are reported. The static loads on the coil and on the thermal shield are obtained from analytical calculations.

Table 4: Main Thermal Design Parameters

Parameter	Value
Number of cryocoolers [-]	2
Radiation power on the thermal shield (on the coil from shield) [W]	32.6 (0.1)
Conduction power on the coil [W]	10
Coil radial resistance [Ω] (contact resistance [μΩcm²])	$5.12 \cdot 10^{-4}$ (30)
Peak power deposited in the coils during charge (inverse polarity) [W]	24.4 (16)
Maximum temperature increase (inverse polarity) [K]	3.5 (2.3)
Current ramp rate [A/s]	0.00736
Charging characteristic time [s]	8876
Total charging time [h]	20
Coil cooldown time: 77K-20K [h]	11

CONCLUSION

In this work the conceptual design of the HTS test facility for the Muon Collider cooling section is presented. The preliminary design can be currently considered almost frozen, and it is moving toward a more detailed engineering design which is well under way. The design described in this work do not show major criticalities for the mechanical design. However, the non-insulated concept, that is critical to cope with quench protection (the stored energy exceed 6 MJ) is still under test for coil of similar size. We hope to receive support for INFN and for an EU grant, in 2025, such as to commission the facility by 2027.

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