ENGINEERING DESIGN OF HTS SOLENOIDS FOR THE 6D COOLING DEMONSTRATOR AND RF TEST FACILITY FOR THE MUON COLLIDER*

G. Scarantino[1,2†], D. Batia[3], M. Castoldi[2], L. Rossi[2,3], C. Santini[2], S. Sorti[2,3], M. Statera[2]
[1]University of Rome La Sapienza, Rome, Italy
[2]INFN-Milan, LASA laboratory, Milan, Italy
[3]University of Milan, Milan, Italy

Abstract

The 6D cooling section of a Muon Collider is essential to produce a high-brightness muon beam. To demonstrate the technological feasibility of this system, the IMCC has started a Muon Cooling Demonstrator programme. Within the programme, test stands integrating 3 GHz RF cavities and superconducting solenoids will be developed to test the RF breakdown limit in a 7 T background magnetic field. As key part of the programme, a cooling cell module based on the B5 cell type is currently under study, to validate at engineering scale the integration of a B5-like cooling cell. The magnets of the test stand and B5-like demonstrator are based on non-insulated high-temperature superconductors (HTS) operating at 20 K. The test stand consists of 250 mm bore split solenoid, generating 7 T field on-axis and gradient of nearly 70 T/m in alternate-polarity mode. It will serve as a proof of technology for the B5-like demonstrator, which consists of two pairs of split solenoids with 370 mm and 570 mm bores, designed to produce a precise magnetic field profile with on-axis field swing of ± 7.3 T, within a compact integration, subject to strong axial forces in the MN range. In this work, the engineering design of the solenoids of the B5-like demonstrator is presented along with the main design parameters of the RF test facility (RFMFTF v3.2). A focus is given to the technological solutions considered in the design, accounting for the compact magnet layout required for cooling cell integration.

INTRODUCTION

Muon colliders have recently gained renewed interest thanks to their potential to combine precision measurements typical of lepton colliders with the high center-of-mass energy reach of hadron colliders [1, 2]. Achieving the required luminosity requires strong emittance reduction in the 6D cooling section through the ionization cooling process [3, 4].

The rectilinear 6D cooling channel consists of two ~ 1 km strings (μ^+, μ^-), divided into 14 cell types (A1-A4, B1-B10), integrating superconducting solenoids, Lithium-Hydride (LiH) wedge absorbers and RF cavities [5]. To demonstrate the technological feasibility of the cooling section, the Muon Cooling Demonstrator programme was recently started, aiming at testing an array of B5-type cells [6]. Two key objectives are the demonstration of RF operation in a 7 T background field and the integration of magnets, absorbers and RF systems in a demonstrator module.

The challenges in the magnet design of the RF test facility and B5 demonstrator, are currently being addressed. These includes designing compact, high current density layouts needed for cooling cell integration, with associated forces in the MN range and high conductor stresses, targeting a 20 K, cryogen-free operation.

This contribution summarizes the design of the B5 demonstrator magnets and of the RF split-solenoid test facility. The proposed solution adopts metal-insulated HTS windings, combining the advantages of non-insulated coils with reduced charging times due to higher turn-to-turn resistance [7].

B5 COOLING CELL DEMONSTRATOR

The layout of the B5 demonstrator cell, illustrated in Fig. 1a, consists in two split-solenoid pairs surrounding a central RF cavity. Absorber wedges are placed at the maximum field gradient, with low-field dipole magnets for beam correction. The inter-cell cryostat layout simplifies assembly, redistributes mechanical loads and reduces cryogenic loads. Details on the engineering design of the B5 demonstrator cell are available in [8]. The solenoids of each pair are operated with opposite current polarity, generating a sinusoidal-shaped field along the beam axis, expressed in terms of longitudinal harmonics in Table 1.

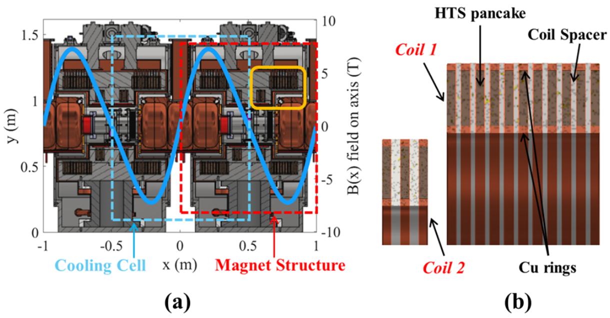


Figure 1: view of the B5 demonstrator cell and corresponding field along the beam axis (a). Magnet assembly (b).

B5 Demonstrator Magnets Layout

The nested coils of the split-solenoid pairs are identified as *Coil 1* type for the outermost coil and *Coil 2* type for the innermost one. The coil layout, reported in Fig. 1a,

* Partially funded by the European Union (EU). Views and opinions expressed are however those of the author only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them. Endorsed by the IMCC (International Muon Collider Collaboration).
† giuseppe.scarantino@mi.infn.it

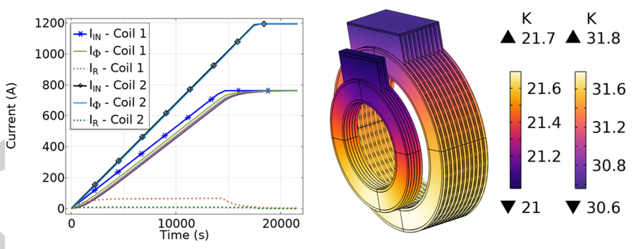
consists in a stack of eleven coil pancakes for *Coil 1* and three coil pancakes for *Coil 2*. The conductor layout consists of two 12 mm wide HTS tapes dry-wound with stainless-steel (SS) tape, 26 μm thick [9, 10]. Tape properties are based on industrial SuperOx REBCO conductors [11, 12]. The inter-turns surface contact resistance value has been assumed equal to 1 $m\Omega\ cm^2$ [7], [13]. The coils are operated at 20 K to reduce the cryogenic power consumption. The pancakes are stacked in a modular structure consisting in AISI 316-LN steel spacers, for mechanical support, Cu plates for conduction cooling, and thin G-10 layers for electrical insulation, to avoid axial shunts of the stacked pancakes. The pancakes are enclosed in two coaxial copper rings, soldered on the innermost and outermost conductor turns for electrical connection. External AISI 316-LN steel rings are fitted around the pancakes, providing radial pre-compression to the coil pancakes.

The coil configuration has been obtained from an optimization process, identifying the optimal configuration in terms of geometrical and engineering constraints. Details on the optimization process are available in [14].

Table 1 reports the main geometrical and design parameters resulted from the above mentioned electromagnetic design optimization. The axial positions refer to the coils marked in yellow in Fig. 1a.

Table 1: B5 Demo Magnets: Main Parameters

Parameter (Units)	**Coil 1**	**Coil 2**
B1, B2, B3 harmonics (T)	7.1, 1.02, 0.3	
Peak field on axis (T)	7.2	
Coil current (kA)	0.761	1.19
Number of turns (-)	485	456
Number of pancakes (-)	11	3
Coil radius (mm)	285	185
Coil axial position (mm)	646	556
SS spacers width (mm)	7.90	13.7
Axial force (MN)	-4.60	11.7
Current margin (%)	64	40
Mag. energy density (MJ/m^3)	152	147
Hotspot temperature (K)	142	144
Total HTS tape length (km)	43.3	7.60



(a) **(b)**

Figure 2: current evolution during charging (a). Temperature distribution at the end of *Coil 1* current ramp (b).

B5 Demonstrator Magnets: Thermal Design

The thermal design of the B5 demonstrator magnets has been evaluated via a coupled transient EM-thermal analysis, coupling an homogenized H-formulation with rotated anisotropic resistivity tensor to a transient 3D thermal model [15,16]. From a parametric analysis on the Cu cooling plates and the resulting thermal resistance network, the obtained layout, shown in Fig. 2b, presents ten Cu plates for *Coil 1* and two Cu plates for *Coil 2*, each connected to the cryocooler cold heads via interface Cu plates and Al thermal bridges.

The evaluation of the coil charging transient, proved the feasibility of a six hours magnets charging, limiting the ramp in *Coil 1* to four hours to match the charging time in the two coil types due to their different inductance, assuming the same surface contact resistance in the two metal-insulated windings. The current ramp tuning limits the force unbalance between solenoids, avoiding excessive stresses on the magnets and their support structure .

Figure 2a reports the current ramp during charging. Considering cryocoolers of 50 W capacity at 20 K [17], connected to each solenoid, the peak temperatures at the end of charging are about 32 K for *Coil 1* and 22 K for *Coil 2*, remaining within conductor temperature margins, with a ~ 1 K uniformity within each pancake at the end of the transient.

Static heat loads have also been accounted, resulting from radiation power losses from the 60 K thermal shield and conduction terms from current leads and coil support structure. Thermal design parameters are summarized in Table 2. The main thermal design parameters are summarized in Table 2.

Table 2: B5 Demo Magnets: Thermal Design

Parameter (Units)	**Value**
Number of cryocoolers (-)	4
Rad. power on thermal shield (W)	63
Heat load on gravity supports (W)	15
Static heat load on coils (W)	20
Peak power on coils at charging (W)	127
Max temperature Coil 1 - Coil 2 (W)	32 – 22
Total charging time (hours)	6
Cooldown time: 77 K – 20 K (hours)	~ 15

B5 Demonstrator Magnets: Mechanics

Mechanical analyses have been performed on the B5 demonstrator magnets during charging transient and in nominal operative conditions. The model considers an homogenized coil structure at the pancake level, with smeared mechanical properties accounting for the anisotropic behaviour of the coil winding . Assuming frictional contact between the homogenized pancakes and the 316-LN steel spacers, maximum hoop stresses reach 207 MPa and 435 MPa in *Coil 1* and *Coil 2*, respectively, while peak positive radial stresses are 3.5 MPa and 8.0 MPa. The peak Von Mises stress in the 316-LN spacers is 560 MPa, located in *Coil 2*.

The reported stresses are below material limits for the REBCO conductors and 316-LN steel at 20 K, showing no criticalities in nominal operative conditions [18, 19]. Stress distributions of the B5 demonstrator magnets in steady-state operation are reported in Fig. 3.

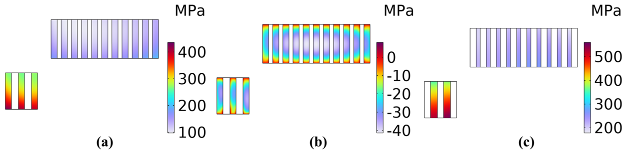


Figure 3: Hoop (a), radial (b) stress distribution on coils, Von Mises stress on coil spacers (c).

RF TEST FACILITY

A first step toward the construction of the B5 demonstrator magnets and system integration in a cooling cell, is the construction and testing of a split-solenoid facility for RF cavities, to assess the RF breakdown limit in a magnetic field in a configuration relevant for the B5 demonstrator cell. Compared to earlier 400 mm bore concepts [20, 21] for 1 GHz RF cavities, the updated *RFMFTF v3.2* design adopts a 250 mm bore with 170 mm free aperture for testing 3 GHz RF cavities.

The structure of the RF test facility, shown in Fig. 4a, differentiate from the the B5 demonstrator cell as the split-solenoid is here enclosed in a unified magnet structure to withstand the axial forces acting on coils. In the B5 demonstrator, due to the periodic cell structure, a more convenient solution is the inter-cell cryostat layout [8], visible in Fig. 1a.

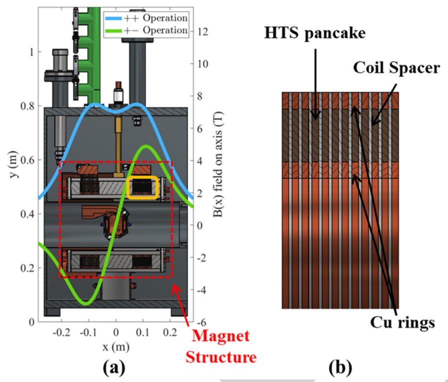


Figure 4: 3 GHz RF facility and axial field profiles in the two operation modes (a). Magnet *v3.2* assembly (b).

RF Test Facility Magnets Layout

The split-solenoid configuration proposed for the 3 GHz RF test facility shares the same technological solutions of the B5 demonstrator magnets.

Each coil stack consists in twelve stacked pancakes, separated by a 2 mm AISI 316-LN steel spacers (Fig. 4b), with thin Cu layers in between for conduction cooling and G-10 sheets for electrical insulation.

The coils are wound with two 4 mm wide HTS tapes from Shanghai Superconductors Ltd. [22], and a 26 μm thick 316-LN steel tape. The metal-insulated winding layout is shared with the B5 demonstrator magnets, differentiating in terms of tape width and choice of tape manufacturer.

As key requirement of the RF test facility, the solenoids are designed to be operated with the same current polarity "++", or in opposite current polarity "+−" (Fig. 4a). In "++" mode, the solenoids generate a 7 T peak field with a uniformity below 3% in a 73 mm axial, 90.6 mm radial central region. In alternate polarity mode "+−", the solenoids generate a gradient field of 67.4 T/m, with a peak-to-peak distance of 220 mm. The two operational modes are required to characterize the RF breakdown in relevant operative conditions in view of the B5 demonstrator cell integration.

Table 3 summarizes the main design parameters of the split-solenoid for the RF test facility *v3.2*. The "++" operating mode is the most demanding due to the positive magnetic coupling between the two solenoids, leading to higher hoop stress and peak hotspot temperature during quench.

Table 3: RF Test Facility Magnet *v3.2*: Main Parameters

Parameter (Units)	**Value**
Coil current (A)	580
Number of turns (-)	201
Number of pancakes (-)	12
Coil radius (mm)	125
Coil axial position (mm)	62.5
SS spacers width (mm)	2
Axial force on coil (MN)	0.78
Current margin (%)	32
Mag. energy density (+−) (MJ/m^3)	190 (147)
Hotspot temperature (+−) (K)	167 (148)
Total HTS tape length (km)	8.35
Peak hoop stress (+−) (MPa)	579 (385)
Peak positive radial stress (+−) (MPa)	0.9
Peak Von Mises stress (spacers) (MPa)	130

CONCLUSION

The present work summarized the main design parameters of the B5 demonstrator magnets and split-solenoid for the RF test facility. The proposed metal-insulated HTS technology enables compact high-field solenoids with adequate thermal and mechanical margins at 20 K cryogen-free operation. Coupled EM-thermal analyses showed it is possible to power the B5 demonstrator magnets in six hours, providing a 50 W at 20 K conduction cooling via cryocoolers. Peak temperatures remains within conductor margins, and thanks to ramprate tuning in each solenoid pair, unbalanced forces acting on solenoids are prevented. Mechanical analyses showed peak stresses at nominal current are within material limits, with the possibility of reduction via radial pre-compression. The design of the split-solenoid for the RF test facility is progressing, serving as a proof of technology for the final B5 demonstrator cell. Future work will focus on quench protection aspects, validating the two designs in case of fault scenarios, and on prototype coils winding and testing to characterize the proposed metal-insulated windings.

REFERENCES

[1] J. P. Delahaye *et al.*, "Muon colliders", Jan. 2019, arXiv:1901.06150 [physics.acc-ph]. doi:10.48550/arXiv.1901.06150

[2] J. De Blas *et al.*, "The physics case of a 3 TeV muon collider stage", 2022, arXiv:2203.07261 [hep-ph]. doi:10.48550/arXiv.2203.07261

[3] D. Neuffer, "Introduction to muon cooling", *Nucl. Instrum. Methods Phys. Res. A*, vol. 532, pp. 26–31, Oct. 2004. doi:10.1016/j.nima.2004.06.051

[4] D. Stratakis and R. B. Palmer, "Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study", Phys. Rev. ST Accel. Beams, vol. 18, p. 031003, Mar. 2015. doi:10.1103/PhysRevSTAB.18.031003

[5] C. Accettura *et al.*, "The Muon Collider", Apr. 2025, arXiv:2504.21417 [physics.acc-ph]. doi:10.48550/arXiv.2504.21417

[6] R. Losito *et al.*, "Presentation of cooling cell conceptual design", Tech. Rep. 101094300, May 2024. doi:10.5281/zenodo.11402737.

[7] T. Lécrevisse *et al.*, "Metal-as-insulation HTS coils", *Supercond. Sci. Technol.*, vol. 35, p. 074004, May 2022. doi:10.1088/1361-6668/ac49a5.

[8] G. Scarantino *et al.*, "Preliminary Engineering Design of the Cooling Cell for the Muon Collider Cooling Demonstrator", presented at the IPAC'26, Deauville, France, May 2026, paper WEP1010, this conference.

[9] L. Rossi *et al.*, "Design and plan of a 10 T HTS energy saving dipole magnet for the Italian Facility IRIS," *IEEE Trans. Appl. Supercond*, vol. 34, no. 5, pp. 1–6, 2024. doi:10.1109/TASC.2024.3355357

[10] S. Sorti *et al.*, "Final Design and Production of a 10 T HTS Energy-Saving Dipole Magnet for the Italian Facility IRIS," *IEEE Trans. Appl. Supercond.*, vol. 36, no. 3, pp. 1–5, May 2026. doi:10.1109/TASC.2025.3628303

[11] SuperOx, "2G HTS wire specifications", https://www.superox.ru

[12] University of Victoria Wellington, Robinson HTS critical current database, SuperOx YBCO 2G HTS data, https://htsdb.wimbush.eu

[13] C. Genot *et al.*, "Experimental measurements of contact resistivity between superconducting HTS tapes with or without metallic co-wound tape", *Cryogenics*, 1vol. 32, p. 103691, Jun. 2023. doi:10.1016/j.cryogenics.2023.103691

[14] G. Scarantino *et al.*, "Design Optimization of the B5 Cooling Cell Demonstrator Solenoids for the Muon Collider,"*IEEE Trans. Appl. Supercond.*, vol. 36, no. 5, pp. 1–5, Aug. 2026. doi:10.1109/TASC.2026.3659069

[15] R. C. Mataira *et al.*, "Finite-element modelling of no-insulation HTS coils using rotated anisotropic resistivity," *Supercond. Sci. Technol.*, vol. 33, p. 08LT01, Jun. 2020. doi:10.1088/1361-6668/ab9688

[16] G. Scarantino *et al.*, "Electro-thermal and mechanical analysis of the HTS split coil test facility for the Muon Collider cooling section," *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, pp. 1–5, 2025. doi:10.1109/TASC.2024.3519293

[17] SHI Cryogenics Group, "SHI SRDK 500B2 technical specification sheet", https://shicryogenics.com/product/rdk-500b2-20k-cryocooler-series

[18] C. Zhou *et al.*, "Critical Current of Various REBCO Tapes Under Uniaxial Strain", *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, pp. 1-4, Jun. 2016. doi:10.1109/TASC.2016.2535202

[19] Shanshan Wu *et al.*, "Mechanical properties and microstructure evolution of cryogenic pre-strained 316LN stainless steel", *Cryogenics*, vol. 121, p. 103388, 2022. doi:10.1016/j.cryogenics.2021.103388

[20] M. Statera *et al.*, "Conceptual design of the HTS split coil test facility for the Muon Collider cooling section", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2575–2577. doi:10.18429/JACoW-IPAC2024-WEPR38

[21] G. Scarantino *et al.*, "Electro-thermal and mechanical analysis of the HTS split coil test facility for the Muon Collider cooling section", *IEEE Trans. Appl. Supercond.*, vol. 35, no. 5, pp. 1–5, 2025. doi:10.1109/TASC.2024.3519293

[22] Shanghai Superconducting Technologies Co., Ltd., "SST REBCO tape specifications", http://www.shscsc.com/HomeEN/CaseEN