Muon Collider ESPPU Evaluation - Magnets

The Muon Collider poses extraordinary challenges to magnet technology, and meeting them will benefit not only the most efficient accelerator at the energy frontier, but also several other fields of science and societal applications. Through the integrated study and conceptual design activities of the last years we have identified the following grand challenges that have driven magnet R&D activities:

- Steady state superconducting solenoids for
    - Target, decay and capture channel
    - 6D cooling channel
    - Final cooling channel
- Fast pulsed normal conducting magnet systems, including the power converter and management, for the rapid cycled synchrotrons
- Steady state superconducting accelerator magnets, dipoles, quadrupoles and combined functions, for the rapid cycled synchrotrons and collider arc and interaction region.

The sections below describe the main achievements of the work performed in the period since the last Strategy Upgrade, in 2021.

Target, decay and capture channel solenoid (L. Bottura, C. Accettura, B. Bordini, A. Kolehmainen, A. Portone, P. Testoni, J. Lorenzo Gomez)

The solenoids that host the target and capture channel, where the muon beam is produced, pose the first grand challenge. The magnetic field profile along the axis of the channel has a shape derived from studies of optimal generation and capture, with peak field of 20 T on the target, and a decay to approximately 1.5 T at the exit of the channel, over a total length of approximately 18 m. The characteristic length of the field change is about 2.5 m, i.e. much larger than the gyration radius of the muons in the field so that the beam expands adiabatically in the channel. Such field profile can be generated

The interaction of the proton beam with the target produces a considerable amount of radiation, which needs heavy shielding to avoid heating and damaging the materials of the superconducting coils of the target solenoid. A free bore of at least 1.2 m is necessary to host the nuclear shield. Such large bore dimension result in high stored magnetic energy, which in turn affects magnet protection, and electromagnetic forces.

We have developed a fully superconducting solution for the 2 MW target variant, based on a HTS cable inspired by recent developments in the field of magnetically confined thermonuclear fusion. Field levels of 20 T are at the upper limit of performance for small bore Nb3Sn, and arguably out of reach for LTS with the bore dimension required. More important, the choice of HTS gives the possibility to set an operating point at a temperature higher than liquid helium. This brings the benefit of increased cryogenic efficiency, reduced wall-plug power consumption, and reduced helium inventory. We have set a reference an operating temperature in the range of 20 K, which has an efficiency advantage of a factor 5 with respect to cooling at liquid helium, 4.5 K.

The solution reached is shown in the schematic view of Fig. M1, contrasted to the design proposed by US-MAP [ref]. Thanks to the choice of HTS operated at high cryogenic temperature the stored energy is reduced by a factor three from the US-MAP value of 3 GJ to about 1 GJ of the present design, and the cold mass is similarly reduced by a factor two from the US-MAP value of 200 tons to about 100 tons of the present design. This has significant impact on system cost. In addition the elimination of the resistive insert in the US-MAP proposal, and operation at 20 K, yield to an estimated wall-plug power consumption below 1 MW, to be compared to the estimated 12 MW of the US-MAP proposal.

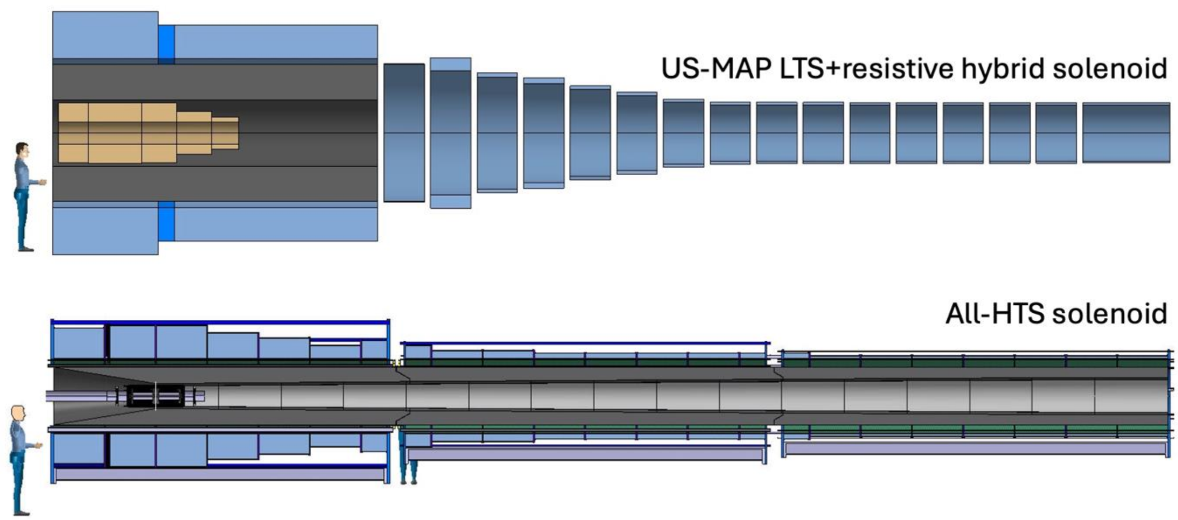

Figure M1. Comparison (to scale) of the solenoid coils of the target, decay and capture channel of a Muon Collider, as produced by the MAP study (top) [ref] and resulting from the optimization of an all-HTS solution (bottom) [ref]

The design developed has progressed significantly in terms of magnet engineering, and we have reached the stage of initial engineering details on:

- conductor design and performance, including cooling, operating margin, quench detection and protection analysis;
- mechanical analysis, down to the level of the HTS tapes in the conductor;
- coil manufacturing, including winding technology, joints and terminations, and impregnation;
- mechanical structures, supports and screens, cryostat and integration with thermal screen and target.

The level of detail reached can be appreciated by sample views of the conductor, winding and 3D coil model shown in Figs. M2 and M3. While challenging, we could find valid engineering solutions for all above aspects, and we can be reasonably confident to proceed further with this baseline.

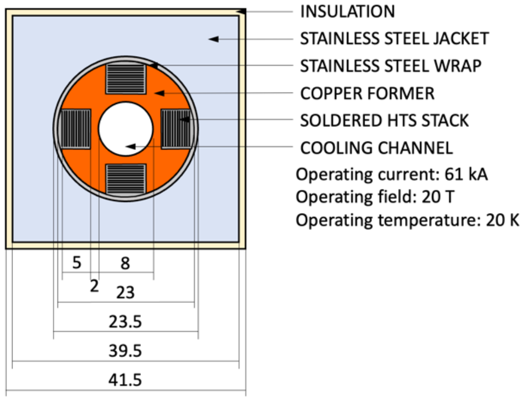

Figure M2. Schematic view of one of the possible conductor configurations planned for the solenoid coils of the target, decay and capture channel (left) [ref], with an image of a mock-up produced on real size (right) showing the HTS tapes, central copper former and jacket.

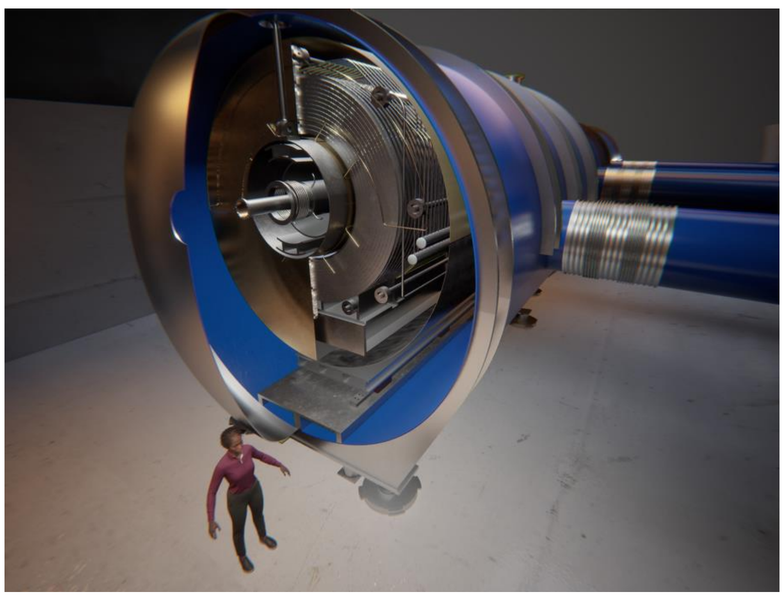

Figure M3. Rendering of the magnet system for the target, decay and capture channel integrated in the cryostat, showing details of the winding, joints, cooling channels, thermal screen and supports

We recognize that a magnet system of this field and dimension remains nonetheless a very challenging realization, depending on the success of a new technology, HTS, not yet deployed on large scale. This is why, as part of the next study phase, we propose to design, build and test a Target Solenoid Model Coil (TSMC) that shall demonstrate HTS force-flow cooled magnet technology at relevant scale. The optimal TSMC configuration is presently under study, balancing performance in relevant conditions vs. affordable cost. A suitable configuration for the TSMC is shown in Fig. M4, a solenoid with a 1 m inner bore diameter, 2 m outer diameter and 1.2 m height. Preliminary targets chosen to map closely the operation of the coils of the target, decay and capture channel, are:

- Bore field of 20 T at 20 K operating temperature;
- Electromagnetic pressure J B R in excess of 500 MPa;
- Stored energy in excess of 100 MJ;
- Operating voltage of 2.5 kV;

Achieving above on a magnet of this size will give sufficient confidence in the realization of the full magnet system. The proposal is expanded further later, as well as in a companion detailed proposal [ref].

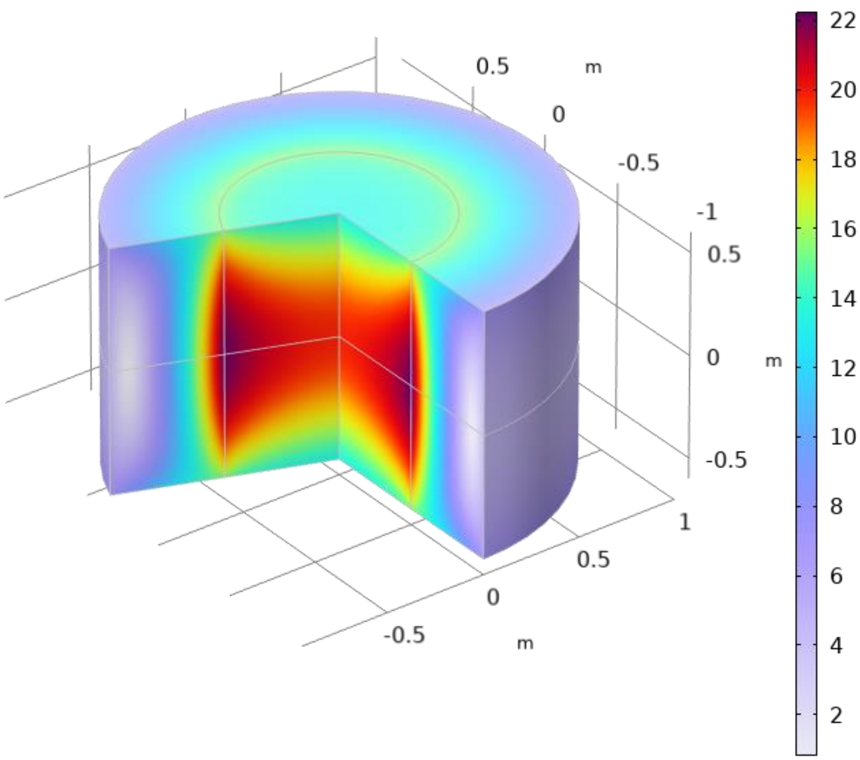

Figure M4. Configuration selected as initial baseline for the design of a Target Solenoid Model Coil and corresponding field map in nominal operating conditions.

4 MW option. NOTE: not a simple scale-up, devise new magnet configuration: hybrid ? Add considerations on the concept for such a change

Identify challenges for this magnet system (bullet points)

6D cooling channel solenoids (S. Fabbri, M. Statera, G. Scarantino, et al.)

The 6D "beam cooling" process occurs over a ~ 1 km long sequence of tightly integrated absorbers, alternating polarity solenoids, and RF cavities. The US-MAP design study provided a baseline of 2954 solenoids over one entire 6D cooling chain which could produce the desired on-axis field profile. We performed an analysis on these solenoids, considering them operating individually and within their respective lattice. The results are reported in Table MI. We found substantial stresses (large hoop and tensile radial stress), forces (37 MN axial force), and quench management challenges (energy densities up to 91 MJ/m^3 in a single coil). This motivated the development of solenoid design rules implementing engineering limits on operating margin, stress and stored energy density to be integrated already at the stage of the beam optics design, as well as the development of a numerical optimization tool which can improve the solenoid configuration given a desired field profile.

Cell	EMag	eMag	Coil	JE	Bpeak	σHoop	σRadial
	(MJ)	(MJ/m^3)		(A/mm^2)	(T)	(MPa)	(MPa)
A1	5.4	20.5	A1-1	63.25	4.1	34	-5/0
A2	15.3	75.8	A2-1	126.6	9.5	137	-28/0
A3	7.2	72.8	A3-1	165	9.4	138	-29/0
A4	8.4	91.5	A4-1	195	11.6	196	-49/0
B1	44.5	55.9	B1-1	69.8	6.9	95	-14/0
B2	24.1	61.8	B2-1	90	8.4	114	-20/0
B3	29.8	88.1	B3-1	123	11.2	173	-37/0
B4	24.1	42.4	B4-1	94	9.2	231	0/20
			B4-2	70.3	7.8	66	-24/0
B5	12	86.3	B5-1	157	13.9	336	0/21
			B5-2	168	12.3	159	-55/0
B6	8.2	68.3	B6-1	185	14.2	314	-1/22
			B6-2	155.1	10.3	118	-43/0
B7	5.6	58.6	B7-1	198	14.2	244	-1/21
			B7-2	155	10.1	118	-37/0
B8	1.4	20.3	B8-1	220	15.1	255	-3/22
			B8-2	135	6.2	110	-2/5
			B8-3	153	6.2	41	-23/0

Table MI. Result of the analysis of the solenoids of the 6D cooling channel designed by US-MAP.

Describe the engineering design guidelines and limits provided for the beam optics studies.

The design rules are presently used by the IMCC to iterate and improve upon the configuration originated by US-MAP.

Show an example of A-B plots for solenoids.

Report and comment in Tab. MII the first evaluation of present baseline cooling optics from IMCC (NOTE: quote that this is work in progress).

Table MII. Result of the analysis of the solenoids of the present baseline for the 6D cooling channel.

Solenoid design applied to the RFMFTF and demonstrator (watch for overlaps with demonstrator activities).

Identify challenges for this magnet system (bullet points)

Final cooling solenoids (B. Bordini, C. Accettura, A. Dudarev, et al.)

Among the solenoids in the cooling channel, the final cooling solenoids are most challenging in terms of field performance, with a target of 40 T or higher. The bore dimension is relatively small, 50 mm, which makes them an ideal development vehicle to implement new technology such as non-insulated windings, and probe performance limits. We have proposed a conceptual design at the early stage of the study [ref]. The solenoid concept is based on soldered single pancakes, stacked with stress-management plates, and joined electrically. The coil is pre-compressed radially by a solid mechanical structure, supporting the electro-magnetic loads, and necessary to avoid tensile stress in the coil at nominal operating conditions.

We have started the development of engineering solutions for the realization. Fig. M2 shows the initial results of the engineering design, the 46 identical modular pancakes and three pairs of thicker single pancakes at both ends of the solenoid.

Figure M2. Cross-section of the 40 T solenoid.

Describe further the design (ASC 2024 paper)

- Engineering
- Mechanics
- Quench protection
- Magnetization and current distribution

The engineering studies are complemented by an intense campaign of electrical, mechanical and thermal measurements, necessary to establish the thermo-physical and mechanical properties of single tapes and stacks of tapes.

We have procured over 10 km of 4-mm-wide tape from three different companies: Faraday Factory Japan, Fujikura, and Shanghai Superconductor Technology. The goal is to begin producing smaller coils in the initial phase of technological development to manage costs effectively. We have initiated the characterization of the superconducting properties of the procured tape through critical current measurements at 4.2 K in a background magnetic field, oriented perpendicular to the transport current direction and the wide face of the tape, with fields up to 19 T. These measurements were conducted at the University of Geneva. Fig. M3 shows the results of the first sample measured which are outstanding, with an engineering current density exceeding 2 kA/mm2 at 16 T.

Figure M3. Critical current measurements (triangles) at 4.2 K of a procured ReBCO tape (B // c-axis).

Accurate knowledge of the elastic-plastic properties, fracture toughness, and thermal expansion of ReBCO materials is crucial for precise stress analysis in superconducting magnet systems. To address this, we initiated a comprehensive measurement campaign to determine the thermomechanical properties of ReBCO tapes and stacks. The campaign includes both macro and micro mechanical characterizations. The macro-scale samples consist of individual tapes or stacks a few centimeters long [ref], while the micro-scale samples are micrometric pillars (micropillars) obtained through focused ion beam (FIB) milling of the individual layers of REBCO tapes [ref]. Additionally, nanoindentation measurements were performed [ref]. Although we are just at the beginning, this campaign has already yielded valuable results, including data on the thermal expansion properties of various REBCO tapes [ref], as well as insights into the elastic modulus, yield stress, plastic flow behavior, and fracture toughness of the different layers within the REBCO tapes [ref].

Figures with sample thermophysical and mechanical measurement results to date.

In parallel, we are starting the winding of single pancakes that match well the dimensions and properties of the final cooling solenoid design. These pancakes, tested singularly or stacked in small coils, will serve as the main R&D vehicle to develop and validate engineering solutions. We are exploring two approaches for soldering the coils: either after the winding is completed or during the winding process. For the latter, we have designed and manufactured a custom winding machine, which is currently being commissioned. Meanwhile, we have initiated a testing campaign to evaluate the quality of different soldering techniques on tape stacks and small pancakes. After soldering, the samples were analyzed using X-ray Computed Micro Tomography and micrographic techniques to assess the level of residual porosity. For the pancakes, critical current measurements were also performed. The results obtained so far are encouraging, demonstrating that it is possible to completely fill the gaps between the tapes when precompression is applied during soldering. Moreover, the critical current measurements indicated that the tapes can be soldered without degrading their superconducting properties.

Figures with pancake/stacks and tomography results

Outline the plan of manufacturing and testing, electrical and mechanical

Identify challenges for this magnet system (bullet points)

Accelerator magnets (F. Boattini, M. Breschi, S. Fabbri, A. Pampaloni, et al.)

The main dipole magnets of the rapid cycled synchrotrons, including the power converter and energy storage system, is one of the main challenges of the complex that accelerates the muon beams to collision energy. The specification of the resistive dipole magnets call for a magnetic field of 1.8 T in the 30 mm x 100 mm rectangular aperture, ramped with ms time scale, and homogeneity in the range of few 10^{-4}. We have chosen a solution relying on resistive magnets powered by quasi-resonant power converters and capacitor-based energy storage. This system allows to reach the desired combination of field, aperture and fast ramping, managing efficiently the reactive power.

Describe briefly the system: storage, powering and magnet. Refer to power converter chapter for details.

The magnet optimization work was driven by the need to limit the magnet stored energy, as this reduces the size of the energy storage and limits the reactive power required from the power converter during fast ramps. At the same time, the design options selected minimize the losses during electrodynamic transients in the copper coils and in the ferromagnetic yoke of the magnet, to reduce the active power drawn from the electrical network.

Three configurations were analyzed, namely the hourglass, the window-frame and the H-type magnet. The configurations analyzed are shown schematically in Fig. M4.

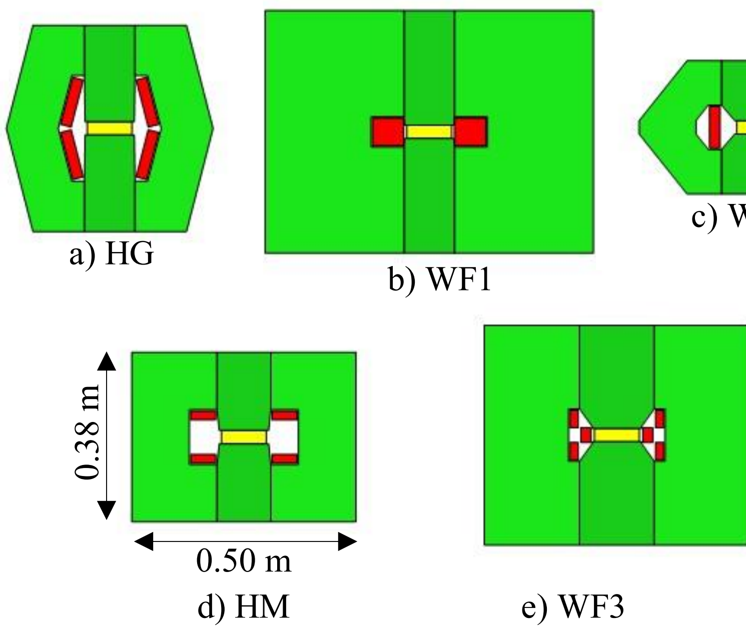

Figure M4. Summary of the optimized geometries (the figures are in scale): a) Hourglass HG, J = 10 A/mm2, Emagn = 5.71 kJ/m; b) Window-frame WF#1, J = 10 A/mm2, Emagn = 5.37 kJ/m; c) Window-frame WF#1M, J = 20 A/mm2, Emagn = 6.05 kJ/m; d) H-type HM, J = 20 A/mm2, Emagn = 5.74 kJ/m; e) Window-frame WF#3, J = 20 A/mm2, Emagn = 5.36 kJ/m.

Although all configurations reach the prescribed magnetic field in the air gap, none of them is optimal for all requirements (magnetic energy, losses, field homogeneity). The minimum energy found is around 5.4 kJ/m, which is reached with several design options. The configurations which exhibit the lowest energy are: WF1 (5.38 kJ/m) at 10 A/mm2 and WF3 (5.36 kJ/m) at 20 A/mm2. The configuration exhibiting the lowest losses is the hourglass magnet. The configuration exhibiting the best field homogeneity is the window frame magnet with 1 coil.

The best compromise between energy, losses and manufacturing simplicity leads to the choice of a H-type magnet. Further analyses are devoted to optimizing the copper losses, the field homogeneity in the air gap and to assess whether the activation of the cobalt in the Supermendur material is acceptable in this accelerator.

Describe the analytical model of the dipole magnet based on reluctances, as used in the system optimization

Details on loss evaluation and 3D design

Summary of quadrupole design

In parallel to the work on the normal-conducting pulsed magnets, we are progressing with the design of the superconducting magnets of the hybrid cycled synchrotrons. These magnets provide a field offset, and allow using the full field swing of the normal conducting magnets, from negative to positive field values, effectively making the synchrotrons shorter. The work has focused on HTS dipoles generating a 10 T steady state field in a rectangular aperture identical to that of the resistive dipole magnets, i.e. 30 mm x 100 mm.

Following initial conceptual studies, the configuration presently studied in detail is shown in Fig. M5.

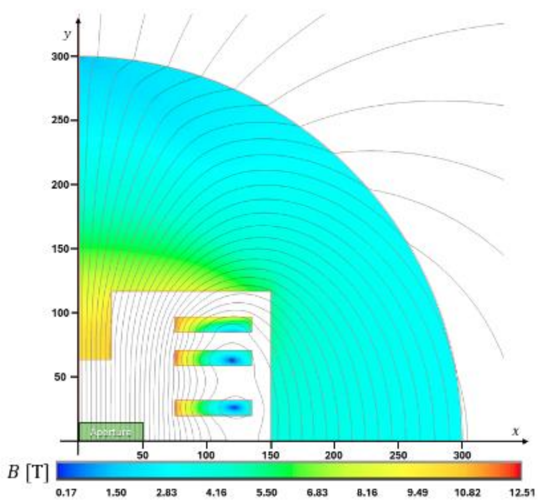

Figure M5. Conceptual design of a 10 T HTS, 30 mm x 100 mm aperture dipole for the hybrid cycled synchrotrons.

Describe the design of the 10 T dipole

Mention pulsed HTS dipoles as an option for the last RCS

Identify challenges for this magnet system (bullet points)

Collider magnets (B. Caiffi, S. Mariotto, et al.)

The magnets in the collider are the final grand challenge that we have identified. Besides the difficulty in the magnet technology, muon beams require optics solutions that are far from standard practice, and integrating the specifications from beam optics poses an additional challenge. In order to provide quick feedbacks to the beam dynamics, cryogenics and energy deposition study requirements, an analytic evaluation of the maximum field or gradient as a function of the magnet aperture was performed (see [ref] and [ref]). The sector coil approximation was assumed and all the most important constraints were included in the calculation, namely:

- Margin on the load line. A temperature margin of 2 K was assumed for NbTi, while 2.5 K was considered for Nb3Sn and ReBCO. While in the case of Nb3Sn the margin is required to ensure stable operation and limit training, in the case of ReBCO we would expect that such margin would be largely more than what is needed. However, considering that we plan to design for operation in gas, we have kept the same margin to accommodate for temperature fluctuations that may come from the cryogenic system.
- Feasibility of the protection system. 40 ms delay between the quench and the firing of the protection system were assumed and a maximum hot spot temperature at the end of the discharge of 350 K for NbTi and Nb3Sn and 200 K for ReBCO were set, as explained in details in [ref].
- Mechanics: the average stress on the midplane was estimated analytically considering only the E.M. forces as explained in [ref] and the limit was set to 100 MPa, 150 MPa and 400 MPa respectively for NbTi, Nb3Sn and ReBCO.
- Cost: the target budget was set to 400 kEur/m for the arc magnets, more than twice the limit set for the FCC project [ref], and 800 kEUR/m for the IR magnets.

The result of this analysis are “A-B” plots of maximum aperture for a given field, and “A-G” plots of maximum aperture for a given gradient, satisfying all requirements above. We report in Figs. M6 (A-B and A-G plots for Nb3Sn operated at 4.5 K, 400 kEUR/m cost limit), Fig. M7 (A-B plots for REBCO dipoles operated at 4.5 K, 10 K and 20 K, 400 kEUR/m cost limit) and Fig. M8 (A-G plots for REBCO quadrupoles operated at 4.5 K, 10 K and 20 K, 800 kEUR/m cost limit).

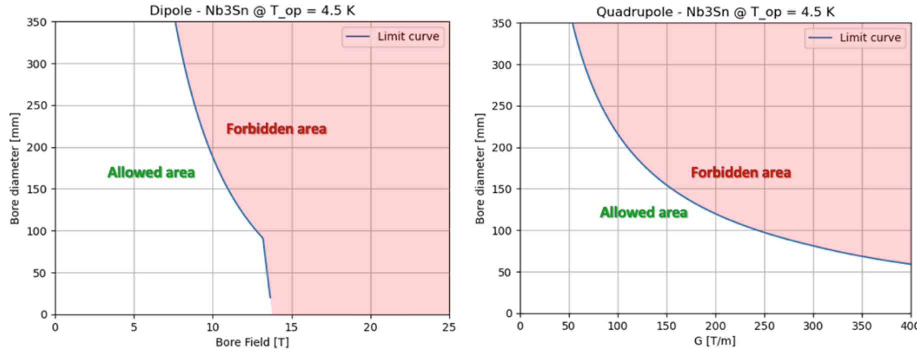

Figure M6. A-B plot for dipoles and A-G plot for quadrupoles built with Nb3Sn and operated at 4.5 K.

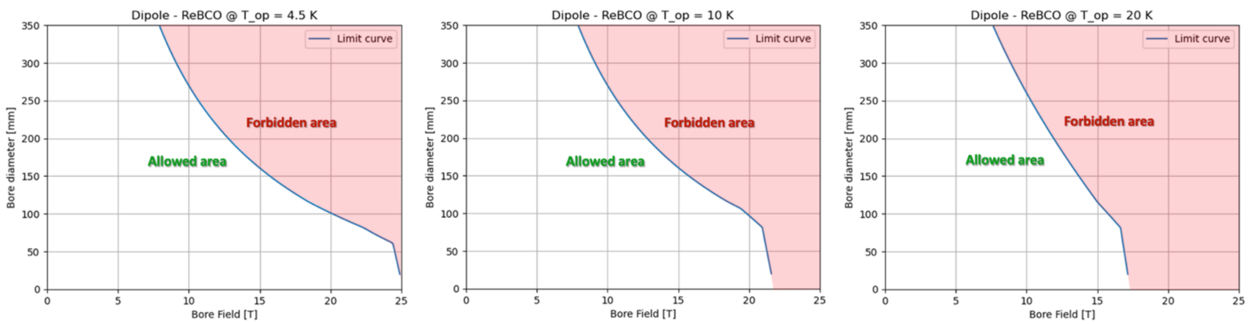

Figure M7. A-B plot for dipoles built with REBCO and operated at 4.5 K, 10 K and 20 K.

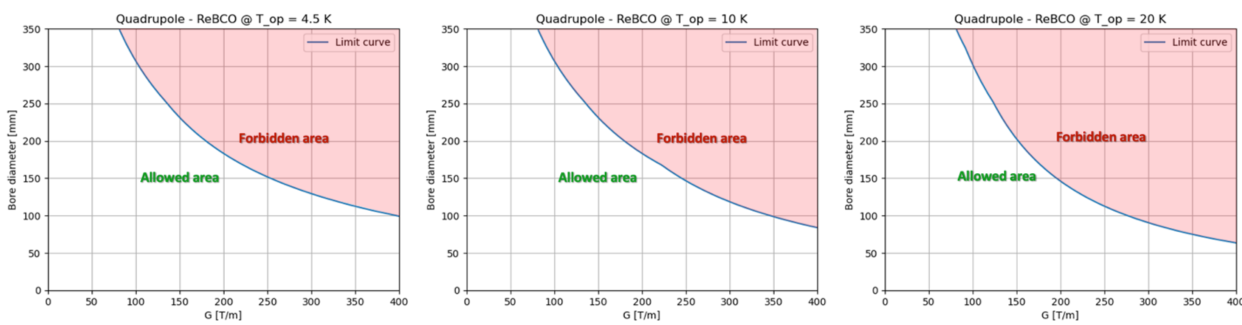

Figure M8. A-G plot for quadrupoles built with REBCO and operated at 4.5 K, 10 K and 20 K.

The above performance limits are intended as guideline for the choice of parameters combination. Being purely analytical, they are powerful scaling and scoping tools, but cannot substitute for actual design which may require additional margins to cope with actual geometric and material constraints.

We recall that the magnet aperture in the collider arc is 158 mm for cold mass at 4.5 K and 138 mm for a cold mass at 20 K. Using the above plots we see that a dipole built with Nb3Sn, with an aperture of 158 mm, operated at 4.5 K, can reach fields of the order of 11 T. The same evaluation of a dipole built with REBCO, with an aperture of 138 mm, operated at 20 K, can reach fields of 14 T. We have hence set these as magnet performance targets representative of the challenges and pushing the limit of present technology. We note at this point that these magnet performance targets imply coil dimensions that are significantly larger than what has been done in HL-LHC, and what is planned for FCC. Typically, the stored energy is a factor three to four larger.

Add further comments on magnet cross section, and the fact that for a 10 km machine we can afford more material in the magnet (higher cost per unit length).

Add evaluation for NbTi.

Work has started to advance in the magnet design of the HTS dipole. Two options are considered, blocks and cos-theta. Figure M9 shows the cross sections of the most promising candidate configurations. Both satisfy the design objectives of margin and stress, though for both many issues such as coil winding technology, ends, joints, magnetization and loss, field quality need to be addressed in detail

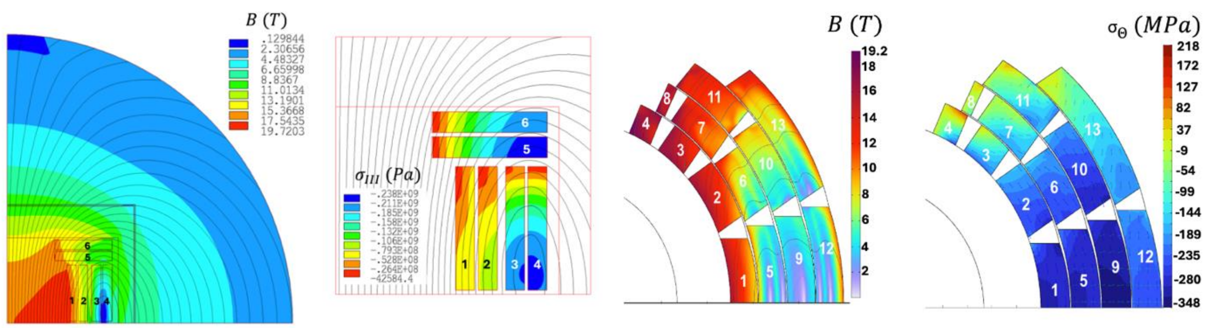

Figure M9. Design of the cross section of HTS dipoles.

Develop further on magnet design

Identify challenges for this magnet system (bullet points)