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PROGRESS IN THE DESIGN OF MAGNETS FOR A MUON COLLIDER *

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Abstract

Magnets have been identified as one of the critical technologies for a proton-driven Muon Collider. Within the scope of the International Muon Collider Collaboration we have progressed in the review of requirements, and the development of concepts towards the initial engineering of several of the most critical magnets identified from our previous work. In this paper we present an update of the accelerator magnet configuration for all the parts of the Muon Collider complex, from muon production to collision. We then give details on the specific technologies that have been selected as baseline. Overall, it is clear that a Muon Collider requires very significant innovation in accelerator magnet technology, mostly relying on the success of HTS magnet development. We include in our description a list of options and development staging steps intended to mitigate technical, cost and schedule risk.

INTRODUCTION

A Muon Collider (MuC) is an exciting candidate for a next generation energy physics machine. Above ~ 2 TeV, a muon collider is expected to be the most energy-efficient choice for exploration of the energy frontier [1], while maintaining a compact and potentially cost-effective footprint.

The two main challenges unique to a muon collider, the short muon lifetime and production of bright muon beams, translate into a unique set of demands for novel technologies. From the magnet perspective, this presents itself in various ways, including large-bore high-field solenoids, dipoles and quadrupoles, compact ultra-high-field solenoids, and very fast-ramping dipoles. The technological overlap with other fields of magnet science such as fusion is a strong motivator for present and future research and development.

Conceptual design activities within the scope of the International Muon Collider Collaboration (IMCC) and supported by the EU through the MuCol design study, have led to a baseline set for the main magnet performance parameters [2, 3]. These parameters are an evolution of previous studies, in particular the Muon Accelerator Program (MAP) [4, 5], extending the performance space by considering recent advances in magnet technology. In particular, work carried out so far has a strong focus on High Temperature Superconducting (HTS). The driving reasons for this are the higher field reaches possible, considerations of efficient cryogenic operation, and potentially limited future helium inventory.

A recent outcome of these IMCC studies are schedule and cost estimates for the magnet and powering systems of a reduced energy fast-track 3 TeV MuC and a 10 TeV MuC. Technically limited schedule estimates show that the former could be completed in 17 years while the latter in 26 years. The percentage cost contributions of the key magnets systems in both cases is shown in Fig. 1, and consider cost of materials, consumables, and labor. A realistic future aspirational cost reduction of the superconductor by a factor of 3 is assumed, and 20 kEUR/m for the labour based on LHC experience. This has set priorities going forward for cost optimization studies, and is discussed in next sections.

MAGNET REQUIREMENTS AND STUDIES

The following sections describe the key magnet systems for a MuC complex, namely the muon beam production (target, decay and capture channel), muon cooling (6D and final), acceleration and lastly collision.

Target and Capture

Muons are produced from the decay of pions generated from the collision of a short, high intensity proton pulse with a target. The target is placed within a steady-state, high field “target solenoid”, whose purpose is to capture and guide pions into a “decay and capture channel”, also embedded in solenoid magnets. The magnetic field profile is approximately 18 m with a peak of 20 T on the target and an adiabatic decay to roughly 2 T at the exit of the channel [6].

To achieve the field profile at the target, MAP considered a hybrid target solenoid configuration consisting of a normal conducting (NC) resistive insert (~ 5 T with a 150 mm bore) within a large bore Low Temperature Superconducting (LTS) magnet (approximately 15 T with a 2400 mm bore) [7, 8]. This hybrid concept remains a possibility and can be built based on known technology.

Following recent advancements in high-field large bore HTS magnets [9, 10], we have proposed an alternative design of the LTS outsert involving an HTS VIPER-like cable [11] operating at 20 K [12, 13]. The wider operating temperature range and margin of the HTS-based solution enable a reduced radiation shield thickness, and therefore smaller diameter SC coil of lower mass, operating cost, and possibly initial cost. The design thus far shows that the resistive insert magnet can be removed, reducing the magnet bore to a minimum of 1200 mm. Comparing the proposed HTS magnet design to the US MAP hybrid SC+NC design, the system’s

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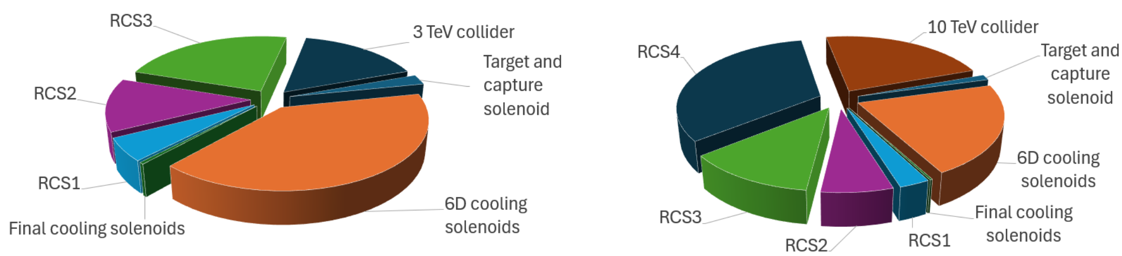

Figure 1: A cost comparison with percentrage contributions of key magnet technologies and powering systems required for a 3 TeV (left) and 10 TeV (right) muon collider.

stored energy is reduced from approximately 3 GJ to ~1 GJ, coil mass from about 200 tons to around 100 tons, and wall-plug power consumption from around 12 MW (dominated by the resistive insert), to approximately 1 MW.

A detailed analysis was carried out for the most difficult solenoid (highest current, field, and energy) [12], concluding the present design sound and promising. We have advanced into engineering designs of magnet assembly supports and main mechanical structures, including integration with the target and tunnel.

Cooling

Muons exiting the target, decay and capture channel have a large spatial and energy spread, and thus must be cooled in six dimensions of the beam phase space (position and momentum) to reach values suitable for a collider. This 6D “beam cooling” process occurs over a long (~ 1 km) sequence of tightly integrated absorbers (consisting of light elements such as hydrogen), alternating polarity solenoids, and RF cavities. The final emittance of the muon beam is inversely proportional to the strength of the final solenoids, motivating the design of these to be very high field.

The MAP design study provided a baseline of 2954 solenoids over an entire 6D cooling chain which could produce the desired on-axis field profile [14], but were un-optimized from an engineering standpoint. The 18 unique solenoid types in this chain exhibit a diverse range of parameters, from small-bore to large-bore (90 mm to 1.5 m) and modest field to high field on-axis (2.6 T to 13.6 T). Mechanical analyses [2] show substantial stresses (large hoop and tensile radial stress), forces (37 MN axial force), and quench management challenges (energy densities up to 130 MJ/m^3 of a single coil).

The large number of 6D cooling solenoids pose a unique challenge in terms of integration, engineering and cost. As shown in Fig. 1, these solenoids based on the MAP configuration are identified as the largest contributor to the magnet and powering cost of a 3 TeV MuC, and a still substantial contribution in a 10 TeV MuC. Significant development has thus gone into a numerical optimization routine. Given a constrained space and desired field profile plus some error, solenoid geometries can be readily found and optimized around stress (upper limit of 300 MPa average hoop stress and little to no tensile radial stress), stored magnetic energy density (upper limit of 150 MJ/m^3 / coil), and cost. Results so far are very promising, showing potential to reduce the total volume of conductor by an order of magnitude, and significantly reduce the stored magnetic energy density and stresses. This work is an ongoing iteration with beam physics to constrain new optics configurations, in parallel to detailed engineering analysis for a planned demonstrator of an integrated cooling cell.

For the final cooling solenoids, the MAP scheme consisted of 17 solenoids with a bore field up to 30 T, resulting in a beam emittance of about 50 µm, roughly a factor of two greater than the transverse emittance goal (25 µm)[14, 15]. To improve upon these results, we are considering a Not/Metal-Insulated HTS solenoid design with the potential to reach and exceed 40 T, a clear bore of 50 mm, a magnet length of 500 mm, and compact enough in size (180 mm outer diameter) to reduce overall footprint, mass, and cost [16]. The solenoid is designed as a stack of soft-soldered pancakes, with a high operating current density target, 650 A/mm^2. Two critical parameters were identified in the conceptual design phase, the stress state and the transverse resistance. In the first, a radial pre-compression from a rigid external ring ensures no radial tensile stress under any operating condition. For the latter, the objective is to achieve protection through a low transverse resistance (potentially with mechanisms to actively trigger a quench), while still enabling a full ramp in less than six hours and maintaining field stability.

Developing a magnet of this class will require significant R&D. We have initiated this process by procuring HTS tapes for various testing and demonstrators. Despite their complexity, these solenoids are the smallest contribution to cost of the magnet and powering systems (see Fig. 1).

Acceleration

To extend their lifetime in the laboratory reference frame, the muons must be accelerated rapidly to relativistic momentum. The acceleration begins with an initial linear accelerator and sequence of re-circulating linear accelerators followed by a sequence of rapid-cycling synchrotron (RCS) and hybrid cycling synchrotrons (HCS) [17, 18]. The HCS design results in a more compact accelerator compared to an equivalent RCS.

In the current IMCC configuration, the RCS employs fast-ramped normal conducting (NC) magnets, sweeping from injection to extraction field levels 0.36 T to 1.8 T within

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0.35 ms (equating to a rate of 4 kT/s). In the HCS's, static superconducting (SC) magnets establish a field offset of 10 T (or assumed 16 T in the final HCS), while NC fast-ramping dipoles sweep from -1.8 T to 1.8 T in time intervals ranging from 6.37 ms to 1.1 ms (equating to a rate up to 3.3 kT/s). All dipole magnets, NC and SC, have a rectangular nominal aperture of 30 mm (vertical) x 100 mm (horizontal).

The primary challenge of the NC ramping dipoles lies in finding an optimal integrated design for the magnets and power converters, which can manage the multi-GW power necessary for pulsing while maintaining precise control of the field ramp shape and homogeneity, and minimizing capital and operational expenditures. The second challenge is mitigating the losses originating from components exposed to field changes (iron hysteresis, eddy currents, etc.). Concerning power converters, series/parallel arrangements of power cell units operate predominantly on resonance principles, where energy stored in capacitors is discharged onto magnets to create an acceleration profile.

The two main cost drivers in the powering configurations are the capacitor-based energy storage and the active power converters necessary for controlling ramp linearity and reproducibility. Optimization of this system has been crucial, reducing the initial estimated cost of the capacitors by nearly an order of magnitude, with them now contributing to roughly 2% of the total magnet and powering systems cost.

An optimization procedure was carried out to minimize the power required for pulsing and total losses while maintaining the required field quality during a ramp [19]. Various coil configurations, iron cross-sections, materials, and current densities were considered. The power required for pulsing is directly proportional to the magnetic energy stored in the ramped magnets, and a minimum achievable stored energy was found to be 5.4 kJ/m. The best compromise between stored energy, losses, and field quality was found to be achieved with "H" and "Hourglass" shaped iron cores [19]. These configurations will be used in further studies.

For the SC dipoles, rejecting the cos-theta coil geometry due to its inefficiency for a rectangular aperture, our conceptual design focuses on flat racetrack coils which appear feasible to achieve a target field of around 10 T. With HTS, this could operate at temperatures significantly above liquid helium (10 to 20 K), offering gains in efficiency. We are currently progressing with a numerical optimization routine that minimizes cost while maintaining a certain field quality.

Collision

The final stage of the muon accelerator complex is the collider ring, where two counter-rotating bunched beams of positive and negative muons collide. To maximize the collisions of stored muon beams in their limited lifetime, the arc dipoles should be at their highest possible field to enable to smallest collider ring circumference [20]. At the same time, a large aperture is fundamental to allocate a radiation shield, which protects the superconductor from the heat load (500 W/m) and radiation dose due to muon decay products and triggered cascades [21, 22].

Assumptions in the present study of the 10 TeV collider optics include a steady-state magnetic field up to 16 T within a 160 mm aperture by the main arc magnets. To minimize straight sections and address effects from the high neutrino flux, these arc magnets are assumed to serve combined functions (e.g., dipole/quadrupole and dipole/sextupole) [20], with dipole fields in the range of 10 T and gradients of the order of 300 T/m. While these field requirements combined with aperture constraints are part of an initial assessment, they currently exceed practical limits and will necessitate iteration. As for the interaction region (IR) quadrupole magnets, the assumption from optics studies is a peak field of 20 T, also associated with large apertures, up to 300 mm.

Analytical evaluations of the dipoles, quadrupole, and combined function magnets performances are ongoing assuming a maximum magnet cost of 400 kEU/m [21] and operating margin, peak stress, and hot spot-temperature upper limits according to the considered superconductor. These evaluations are summarised into A-B (aperture (A) versus bore field (B)) design charts for various operating points, including Nb-Ti at 1.9 K, Nb_3Sn at 4.5 K, and REBCO at either 4.5 K or 20 K.

For the 10 TeV collider arc magnets, Nb-Ti at 1.9 K cannot reach high field and is sub-optimal due to a low operating margin (considering the substantial energy deposition), cryoplant efficiency, and energy consumption concerns. Nb_3Sn at 4.5 K, being limited by peak stress and operating margin, provides feasible solutions only up to 14 T, which can be considered for a 3 TeV MuC (~ 11 T, 150 mm aperture). Analysis of ReBCO shows that it is mainly limited by the balance between total cost of super conductor and quench protection. Assuming a realistic cost projection reduction by a factor of 3, two possible configurations for Not/Metal-insulated ReBCO operating at 20 K can be 16 T, 100 mm or 14 T, 140 mm. Recent analyses of the quadrupoles show that lowering the operating temperature can offer gains at higher gradients. This is important for the IR and arc quadrupoles, with assumed gradients above 300 T/m.

CONCLUSION

The next step in the future of high energy physics will be a machine with potentially higher field magnets that should consider energy efficiency, economics/cost and limited helium inventory. A muon collider profiting from HTS technology development could be the most efficient and sustainable machine for the physics reach available [23].

It is clear that a MuC will require significant research and innovation to develop the required magnet technologies. However, an exciting step can be a 3 TeV fast-track machine, which by leveraging existing or near-demonstration technologies could realise the magnets in a 17 year technically limited schedule as compared to 26 years in the 10 TeV case. In both energy ranges considered, we have identified the key cost contributors, setting prioritization for optimization studies going forward.

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