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Magnets for a Muon Collider

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Abstract. The renewed interest for a muon collider has motivated a thorough analysis of the accelerator technology required for this collider option at the energy frontier. Magnets, both normal and superconducting, are among the crucial technologies throughout the accelerator complex, from production, through acceleration and collision. In this paper we initiate a catalog of magnet specifications for a muon collider at 10 TeV center-of-mass. We take the wealth of work performed within the scope of the US-DOE Muon Accelerator Program as a starting point, update it with present demands for the increased energy reach, and focus on the magnet types and variants with the most demanding performance. These represent well the envelope of issues and challenges to be addressed by future design and development. We finally give a first and indicative selection of suitable magnet technology, taking into account both established practices as well as the perspective evolution in the field of accelerator magnets.

1. Introduction

A Muon Collider (MuC) has emerged in the past years as an instrument of great potential for high-energy physics [1]. It can offer collisions of point-like particles at very high energies, since muons can be accelerated in a ring without the severe limitation from synchrotron radiation experienced by electrons. Also, for center-of-mass energies in excess of about 1 TeV, a MuC can provide the most compact and power efficient route towards a high luminosity lepton collider. However, the need for high luminosity faces technical challenges arising from the short muon lifetime at rest (2.2 s) and the difficulty of producing bunched beams of muons with small emittance. Addressing these challenges requires the development of innovative concepts and demanding technologies in several fields of physics and engineering.

Such R&D work is the main objective of the International Muon Collider Collaboration (IMCC), initiated under the auspices of the Laboratory Directors Group (LDG) in response to the recommendation from the European Strategy Group [2]. The collaboration plans to develop a muon collider concept over the next five years, and formalize it in a pre-conceptual design report to be submitted to the next European Strategy exercise. More details on motivation, opportunities and plans can be found in Refs. [3, 4, 5].

Magnets, both normal and superconducting, have been identified as a crucial technology for all parts of a MuC complex [6]. The following paper provides a summary of the magnet demands, perceived challenges, technology options, and selected engineering tasks that encompass the magnet R&D required for the development of the MuC.



2. Magnet Needs and Challenges

The US Muon Accelerator Program (MAP) study [7, 8, 9] provides at present the most consistent baseline MuC concept, including an overview of the magnet requirements. The concept developed by MAP is shown in Fig. 1. While the study planned by the IMCC will evolve these configurations, the results of MAP already provide a broad envelope of the required magnet performance. We have hence taken MAP as the starting point to identify the main challenges and technology options, and rank priorities. The following sections present briefly the main functions of each block of the MuC schematic generated by MAP in Fig. 1, and the corresponding magnetic field demands, preferred magnet options, key challenges and overlap with existing fields and technologies.

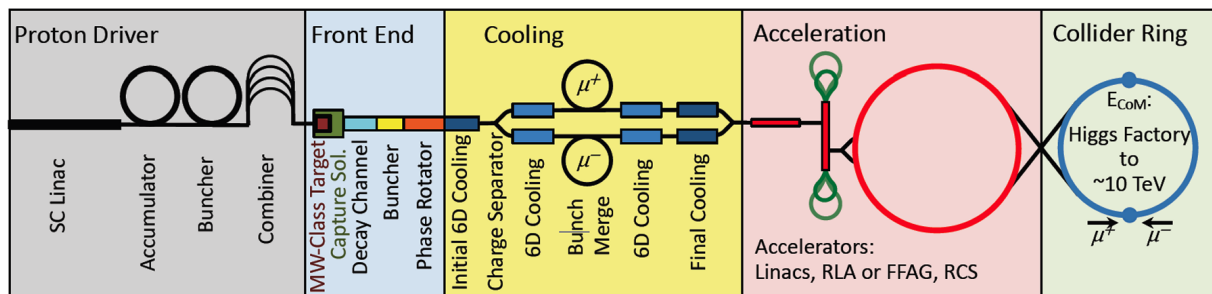


Figure 1. A block diagram of the key systems needed for the muon collider taken from the US MAP baseline [9].

2.1. Target and Capture

Muons are produced by the decay of pions that result from the collision of a short, high intensity proton pulse with a target. The pion production target is inserted in a steady-state, high field target solenoid, whose function is to capture the pions and guide them into a decay channel, where a combination of solenoids and RF cavities capture the muons in bunches.

The target solenoid requires a magnetic field of 20 T in a 150 mm bore diameter. The solution envisaged by MAP is a hybrid Superconducting (SC) and Normal Conducting (NC) magnet consisting of a large bore Low Temperature Superconducting (LTS) magnet (12 to 15 T, 2400 mm bore) and a resistive NC insert (8 to 5 T, 150 mm bore). The large bore of the LTS magnet is necessary to insert sizeable shielding to reduce both heat and radiation loads on the coil. Still, the heat loads on the SC coil are in the range of 5 kW, radiation dose in excess of 80 MGy, and a large number of Displacements-Per-Atom (DPA), around 10^{-2} .

Recent advances in high-field large bore High Temperature Superconducting (HTS) magnets for fusion devices [10] suggest that the LTS outsert can now be built with HTS. The advantages of an HTS-based solution would be the reduction of the radiation shield thickness, profiting from the large temperature margin of HTS, leading to a smaller diameter SC coil, of lower mass and, possibly, cost. HTS also offers a wider operating temperature range than LTS, opening the possibility to operate at higher temperature than liquid helium, with lower operating costs. While a hybrid SC+NC magnet as originally planned in MAP can be built based on the extrapolation of known technology, an HTS SC+NC hybrid or full superconducting HTS, without the NC insert, could offer game changing advantages, but necessitates study and development.

The technology challenges of the target solenoid range from magnet engineering (field performance, mechanics, stored energy and protection), to infrastructure and operating cost (power and cooling), including the integration in a high-radiation environment. These challenges

and requirements broadly overlap with those of magnets for high-magnetic field science (e.g. user facilities based on hybrid SC+NC solenoids and all-SC solenoids), as well as magnets for fusion devices (e.g. the central solenoid magnets for a Tokamak [11]).

2.2. Cooling

The 6D cooling of the muon beam takes place in a km-long channel consisting of a tightly integrated sequence of absorbers (consisting of light elements such as hydrogen), solenoids, and Radio-Frequency (RF) cavities. Given the large number required (almost 3000), the solenoids of the cooling channel need to be as compact as practical. The final emittance of the muon beam is then reached in the final cooling stage. Its value is inversely proportional to the magnetic field of the final cooling solenoids. To achieve maximum cooling efficiency and minimum emittance there is hence a clear interest in steady-state solenoid fields at the upper end of the technology reach. A design study from MAP based on a 30 T final cooling solenoid demonstrated that an emittance of about 50 micron, roughly a factor of two greater than the transverse emittance goal (25 micron), can be achieved [12]. However, other analyses [13] show that fields in the range of 50 T improve the final emittance requirements and offer further gains in beam brightness.

The final cooling solenoids would hence aim at a magnetic field of 40 T (minimum) to 60 T (target) in a 50 mm bore. The available technology would be a hybrid SC+NC solenoid, for which a detailed design study of a 60 T hybrid magnet already exists [14]. This is however not viable for the amount of magnets required. Superconducting LTS+HTS solenoids, or even better, compact full-HTS solenoids would be superior in terms of magnet size and operating cost. For these reasons, we are concentrating effort on a conceptual design of a 40 T full-HTS solenoid using the novel concept of non-insulated windings.

The recognized challenges of this ultra-high field solenoid magnet are centered on forces and stresses, quench management, field stability (in the case of adopted non-insulated or partial-insulated winding technology), and the mechanical, cryo-cooling and powering integration of the LTS and HTS windings. This solenoid goes significantly beyond available technology, and will require considerable R&D and demonstration.

The magnetic field target, the bore dimension and challenges for the final cooling solenoid are shared with those of magnets for high-magnetic field science [15, 16], and ultra high-magnetic-field NMR and MRI technologies [17]. Additionally, an R&D on the final cooling solenoid would be highly synergic with the development of HTS high field magnets for High Energy Physics (e.g. HEP dipoles [18]) and light sources (e.g. superbends [19]).

2.3. Acceleration

Once captured and bunched, muons need to be accelerated rapidly to relativistic momentum to extend their laboratory lifetime. After an initial acceleration stage of a Linear Accelerator (LINAC) and Recirculating Linear Accelerators (RLA) a sequence will be used of Rapid-Cycled Synchrotrons (RCS) and Hybrid Cycled Synchrotrons (HCS). RCS and HCS based either on NC fast ramped magnets (RCS) or a combination of NC fast-ramping and static SC magnets (HCS) is the preferred option. In either case, fast-ramping magnets are required, and design concepts have already been presented to minimize power losses while giving a high field suitable for rapid acceleration of muons to TeV energies [20]. Fixed Field Alternating Gradients (FFAG) are considered as an alternative that does not require ramping.

The ramped magnets in the first HCS need to achieve a magnetic field sweep of the order of 3.6 T (± 1.8 T) within 0.4 ms (a rate of 9 kT/s) in a rectangular bore of 100 mm by 30 mm. A resistive solution appears as the only option for this specification. The last HCS would require 3.6 T over about 10 ms (a rate of 360 T/s). This lower magnetic field change rate lends support to HTS as a viable option, especially if the field swing could be extended. Recent R&D tests

have shown that a ramp rate of 300 T/s can be achieved with an HTS superferric magnet and modest AC loss [21], though the field swing is low compared to our requirements.

Besides the engineering of such magnets, the primary challenge of an accelerator ring of the required dimension is that the stored energy is of the order of several tens of MJ. Powering at a high-pulse rate with good energy recovery efficiency between pulses will require mastery in the management of peak power in the range of tens of GW. Resonant circuits combined with energy storage systems seem to be the only viable solution, based on existing technology (e.g. capacitor banks), or alternatives such as superconducting magnetic energy storage and flux-pumps [22]. A high energy storage density and high quality factor are mandatory to limit foot-print, energy consumption, capital and operating cost.

The work required on magnets and powering for the accelerator stage has clear synergies with the design of RCS for nuclear and high energy physics machines [23, 24], as well as accelerator driven nuclear energy and radioactive waste disposal [25]. Power management at the projected level, in addition, is an R&D that goes beyond magnet science, where connections to the field of electrical engineering can be found.

2.4. Collision

The last stage of the muon accelerator complex is the collider ring that stores and collides the muon beams. The collider ring needs to have the smallest possible circumference to collide the stored muon beams as often as practically feasible and thus make the best use of their limited lifetime. At the same time, sufficient radiation shielding must be present to protect against the sizeable radiation and heat loads from muon decay and collisions. A heat load of 500 W/m originated by muon decay (electrons) and synchrotron radiation is reduced by shielding to below 5 W/m at the level of the coil, and radiation dose below 40 MGy [26]. To allow for a compact collider ring and maintain sufficient space for shielding, the ring and Interaction Region (IR) dipole and quadrupole magnets thus need to be high-field and large aperture [27].

The assumptions for the present study of the 10 TeV collider optics is that the main arc magnets generate a steady-state magnetic field up to 16 T in a 150 mm aperture. In order to reduce straight sections, and mitigate the effects from the high neutrino flux, the arc magnets are presently assumed to have combined functions (e.g. dipole+quadrupole and dipole+sextupole) [28]. The most recent optics requires dipole fields in the range of 10 T and gradients of 300 T/m. These field demands combined with the aperture constraints are presently the only initial evaluation exceeding practical limits of what is possible, and will require iteration. For the IR quadrupole magnets the assumption from the optics studies is of a peak field of 20 T, also associated with large apertures, up to 200 mm. The requirements for arc and IR magnets are marginally or above the reach of Nb₃Sn. The combination of high magnetic field and high heat flux may be resolved by devising the collider ring and IR magnets as hybrid LTS+HTS (or all-HTS), where the HTS may be operated at higher temperature, under the heat and radiation load. At higher energies, i.e. towards a 14 TeV option, the required field and gradient will need to increase, up to a peak field in the range of 20 (arc) to 25 (IR) T.

The challenges of collider and IR magnets stem principally from the high field and large aperture required, as well as the radiation and heat load. These challenges are broadly shared with the development of high-field magnets for a future hadron collider such as the FCC-hh, and in particular the need to manage stress in compact windings with high current density [29].

3. CONCLUSION

A muon collider promises great potential to deliver fundamental physics at the energy frontier. This has motivated the recent formation of the International Muon Collider Collaboration, which will evolve the original MAP design into a mature pre-conceptual design of the entire complex.

This paper has laid out the main magnet challenges that the IMCC will address, which are summarized below:

- **Target and pion capture:** A 1 m to 2 m bore superconducting (or hybrid) solenoid producing 20 T field and withstanding radiation heat load and dose from the target.
- **Muon cooling system to deliver orders of magnitude emittance reduction:** A channel of tightly integrated and high current density solenoids producing 4 T to 14 T on axis in a bore range of 100 mm to 1400 mm, RF cavities, and absorbers; A few ultra high-field solenoids with magnetic fields reaching beyond the current state of the art, more than 40 T in a bore of 50 mm.
- **Acceleration to TeV energies on the time-dilated muon lifetime scale:** Fast-ramping magnets to enable RCS capability, with field swings just short of 4 T on the ms timescale, while keeping efficient energy storage, power management, and ramp linearity control.
- **Collider ring to deliver collisions before muon decay:** high field combined function arc magnets with a 150 mm bore and peak field of 16 T; IR magnets with a bore up to 200 mm and peak field of 20 T, that can withstand large stresses and significant energy deposition and radiation dose from the muon beam decay and interaction debris.

To address these challenges, critical R&D efforts and suitable technology options based on existing and ongoing design studies have been identified. Research in these areas has synergies with many other fields in science, such as NMR and high magnetic field science, and can help drive technology which can be transformational for applications such as fusion.

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