MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

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Abstract

An essential part of a potential future muon collider is ionization cooling, which is required to reduce the emittance of the muon beam. A new scheme has recently been proposed which in simulations shows an improved performance in terms of cooling efficiency and transmitted muons. The lattice of this cooling channel consists of 12 stages, each of which requires different superconducting solenoids. The most challenging stage is the last one, where the solenoids are expected to deliver 15.1T in a bore of ~ 4.5 cm. This paper discusses the feasibility of the solenoids for the last stage of this lattice.

INTRODUCTION

A high luminosity Muon Collider requires a reduction of the six-dimensional volume by six orders of magnitude. A complete cooling scheme for a Muon Collider has been previously described [1]. This scheme uses separate 6D ionization cooling channels for the two signs of the particle charge. In each channel the emittance of a train of muon bunches is reduced until they can be injected into a bunch-merging system. The single muon bunches are then sent through a second 6D cooling channel where the transverse emittance is reduced as much as possible and the longitudinal emittance is cooled to a value below that needed for the collider. This paper focuses on the design of a 6D cooling channel for a single muon bunch after it exits the bunch merger system.

Table 1: Coil Dimensions

z1 (m)	dz (m)	r1 (m)	dr (m)	J (A/mm^2)
0.023	0.12	0.045	0.065	220
0.063	0.08	0.14	0.08	135
0.1	0.10	0.25	0.12	153
0.606	0.10	0.25	0.12	-153
0.663	0.08	0.14	0.08	-135
0.663	0.12	0.045	0.065	-220

Previous studies demonstrated that good cooling performance requires that the channel is tapered, that is the focusing field increases progressively. The 6D cooling channel after the merge will consist of eight stages, wherein the axial magnetic field increases from 2.6T at the first stage to 15T at the last stage.

In this paper we discuss the principle feasibility of the magnets for the last stage, which are the most challenging due to the high required magnetic field and the geometric constraints. The cell is described in the next section.

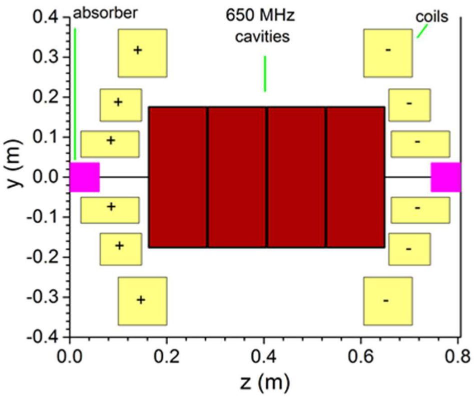

Figure 1: Schematic of Stage 8 cell.

STAGE 8 CELL

The dimensions of the coils required for the cell of the last cooling stage are summarized in table 1; Fig. 1 shows an overview of the cell.

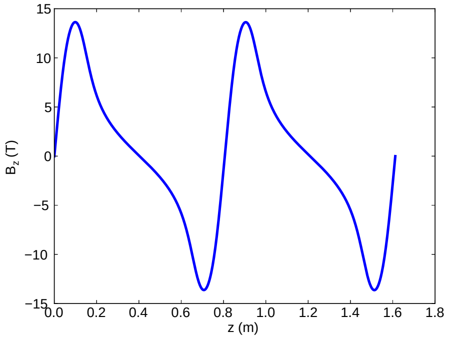

Figure 2: Stage 8: on-axis field.

As shown in the figure, the cell consists of six solenoids. The solenoids surround four RF cavities in the centre of the cell, which restore lost longitudinal momentum. At the beginning and end of the cell absorbers are required; at this position the longitudinal magnetic field changes direction (see Fig. 2).

SIMULATION DETAILS

To study the feasibility we employ the commercial software package COMSOL Multiphysics. The structural analysis is carried out in a coupled electromagnetic/structural

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* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

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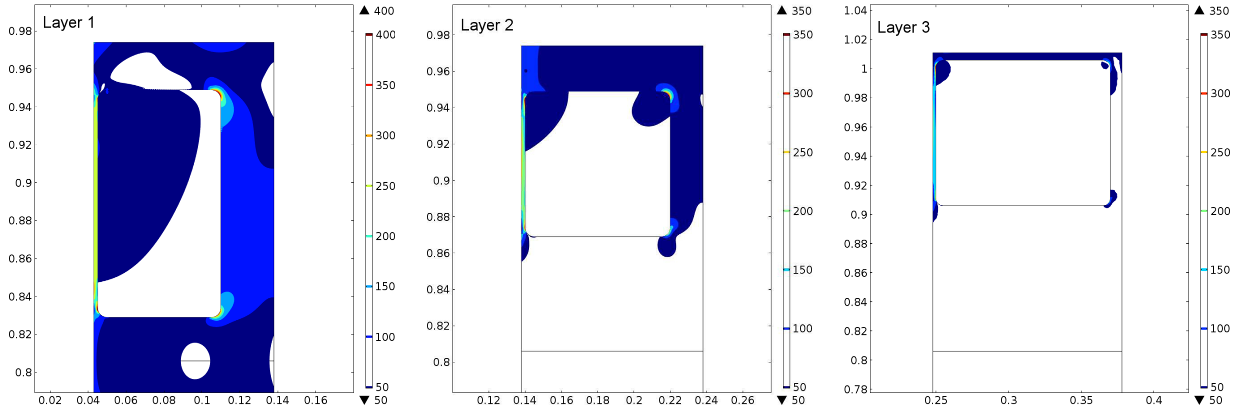

Figure 3: Von-Mises stress (in MPa, for σ > 50MPa) in the innermost (left figure), middle and outer former (right figure).

simulation, where the magnetic force is applied as a body load in the structural simulation. For the structural analysis contact elements are employed between the magnet and its support mandrel. In general linear elastic material properties are assumed, with the exception of Nb_3Sn which is modeled using an orthotropic material model. Thermal effects are not considered.

The critical surface of Nb_3Sn is modeled using the material model from [2]; the mechanical properties are taken from [3]. To evaluate the temperature margins we assume a wire from Oxford Superconducting Technology (internal tin Restack Rod Process) with a non-Cu fraction of 55%. The critical surface of NbTi is included using the fit from [4]; for the mechanical properties of the NbTi composite we use values from [5]. We assume a NbTi wire from OST with rectangular cross-section (Cu:Sc ratio 1.35:1). We assume volume packing factors of 50 and 70% for Nb_3Sn and NbTi coils, respectively. The support mandrels are assumed to be made of 316LN steel.

MECHANICAL ANALYSIS

An initial analysis showed that it is advisable to combine solenoids as shown in Fig. 4. It is envisaged that the complete assembly consists of three initially independent mandrels. The advantage of this is that within one of these mandrels the longitudinal forces cancel. The three independent mandrels can be combined to the larger assembly by welding or a bolted connection.

The inner coils are supported by a steel mandrel with an inner and outer radius of 43 and 138 mm, respectively. The IR and OR of the middle coils are 138 and 238 mm, and for the outer solenoids the IR and OR are 238 and 378 mm. In axial direction the inner and middle solenoids require an axial support of 25 mm and the outer solenoids of 5 mm on each side. Axial pre-stress of 75 MPa is applied in the simulation to reduce gaps in axial direction between former and coils to less than 50 µm.

Fig. 3 shows the von-Mises stress of the three formers. The simulation shows stress concentrations in the corners of the formers of about 500 MPa. The average von-Mises stress on the inside of the inner and middle former is about 250 MPa.

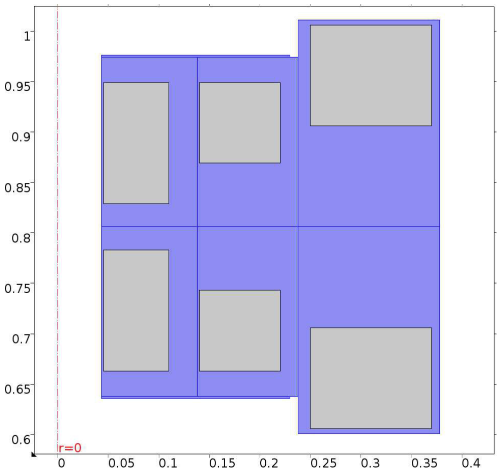

Figure 4: Geometry of the former.

The strain in the Nb_3Sn solenoids is about 0.27%, which is a concern as irreversible degradation of the superconductor can be expected. To lower the strain in the innermost solenoids wire tension of 30 MPa was applied. In combination with radial pre-stress (which in practise can be applied using a bladder as outlined in [6]) the strain can be reduced to 0.1% or less.

MAGNET DESIGN

The peak field on the conductor of the inner solenoids is 15.1T. The middle and outer solenoids have a peak field on the conductor of 7.12T and 6.77T, respectively. The inner two solenoids employ Nb_3Sn and the middle and outer solenoids NbTi.

The load lines for the solenoids are shown in Fig. 5 and 6. As shown, the Nb_3Sn solenoids operate at 91% of the load line at operational current. If the operating temperature is 1.9K this decreases to 85%. The middle and outer solenoids operate at 76% and 74% of the load line at 4.2K.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-WEPRI103

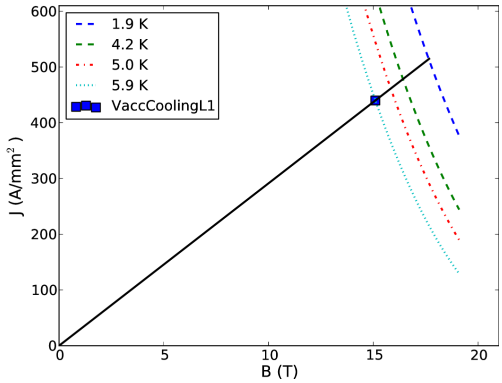

Figure 5: Load line Nb_3Sn coil.

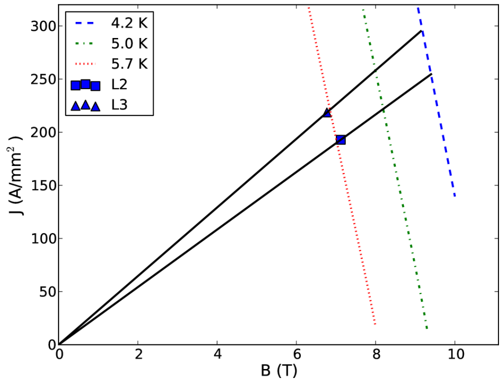

Figure 6: Load lines for outer NbTi coils.

DIPOLE FIELD

In the original lattice design the solenoids are tilted which results in a small dipole field which is required by beam dynamics. To generate the dipole field we opt for adding a separate dipole magnet instead, which allows to tune the dipole field.

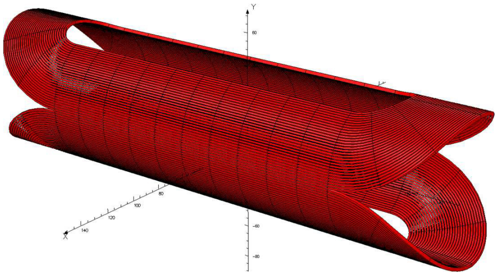

Figure 7: Dipole saddle coil.

The required dipole field is about 0.2T over a length of 0.3m. This dipole field can be generated by a saddle coil located on the inside of the solenoids (see Fig. 7). In azimuthal direction the turns cover about 120° on each side; the expected dipole field quality is about 1% (at 2/3 of the inner radius). The required current density is 220 A/mm^2. The inner and outer radii are 41 and 43 mm, respectively; the length of the dipole is 330 mm. The peak field on the wire is 0.5T (in a background field of 15T). At 4.2K the coil operates at 90% of the load line (83% at 1.9K).

MAGNETIC SHIELDING

It is assumed that up to seven magnet modules would be installed in one vacuum vessel, which would be about 7 m long. To reduce the stray magnetic field outside of the vacuum vessel the magnets can be shielded with a 0.1 m thick good quality soft-iron cylinder with an inner radius of 0.6 m. End discs with an opening of 0.2m in diameter for the beam are also required; these discs need to be 0.2m thick to avoid saturation. A finite element simulation shows that the stray magnetic field drops to less than 5 Gauss (0.5 mT) at a radial position of 2m. The iron shield will also reduce the risk of quench propagation between neighboring vacuum cells.

CONCLUSION

The solenoids discussed in this paper for a 6D cooling channel are challenging. The operating margins at 4.2K are too small for stable operation. Operation at 1.9K may be possible, even though it seems advisable to change the magnet specifications to allow for a margin of at least 20%.

The required dipole field can be generated by a saddle coil on the inside of the solenoids, which reduces the usable aperture by at least 10%. If this is not acceptable the solenoids need to be moved radially further outwards, which will impact their performance.

ACKNOWLEDGMENT

The authors acknowledge fruitful discussions with Soren Prestemon (LBL).

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