HIGH FIELD SOLENOID MAGNETS FOR MUON COOLING

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Abstract

Magnets made with high-temperature superconducting (HTS) coils operating at low temperatures have the potential to produce extremely high fields for use in accelerators and beam lines. The specific application of interest that we are proposing is to use a very high field (of the order of 50 Tesla) solenoid to provide a very small beta region for the final stages of cooling for a muon collider. With the commercial availability of HTS conductor based on BSCCO technology with high current carrying capacity at 4.2 K, very high field solenoid magnets should be possible. In this paper we will evaluate the technical issues associated with building this magnet. In particular we address how to mitigate the high Lorentz stresses associated with this high field magnet.

INTRODUCTION

Previous studies on the requirements of a muon collider have shown that substantial phase space reduction will be needed in order to achieve the desired luminosity [1, 2]. In order to achieve the luminosity of 7×10^{34} for a 3 TeV center of mass energy muon collider a 6D phase space reduction by 10^6 may be necessary. A number of muon cooling approaches have been investigated. A simulation of a cooling channel using helical dipole magnets for dispersion and gaseous H_2 as an absorber has shown a phase space reduction factor of 50,000 [3]. Further cooling can be achieved using parametric resonance ionization cooling (PIC) along with reverse emittance exchange [4]. 50 Tesla magnets can play a role providing cooling before entering the PIC cooling channel or as a final stage of muon cooling. This cooling stage could be an alternating solenoid lattice where a liquid H_2 absorber is placed in the center of a high field solenoid. The minimum emittance that can be achieved is that which occurs when the ionization cooling is balanced by heating from multiple scattering. This minimum transverse emittance is given by

$$\min \varepsilon_{xN} = \frac{\beta_\perp E_s^2}{2\beta_v mc^2 L_R \left|\frac{dE}{dz}\right|}$$

where β_v is the muon velocity, $\left|\frac{dE}{dz}\right|$ is the energy loss along the muon path and $\beta_\perp$, the transverse beta function, is given by $\beta_\perp = \frac{2p_z}{cB_z}$. The minimum emittance occurs where $\beta_\perp$ is minimum and the larger the field of the solenoid, the smaller the $\beta_\perp$ that can be achieved.

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This paper will examine how to achieve a solenoid magnet with a field 40-50T using high temperature superconductor that is currently available commercially. This is a concept study that is concerned with how to achieve the field while containing the Lorentz forces.

MAGNET DESCRIPTION

The choice of the physical dimensions is dictated by the muon cooling requirements. By design the muon kinetic energy entering the solenoid is ~60 MeV which determines that length of the solenoid should be 70 cm. The inner radius of the solenoid is determined by the minimum bending radius of the conductor, but it is consistent with the size of the liquid hydrogen absorber vessel needed for the muon beam.

Conductor Choice

HTS conductor was chosen over Nb_3Sn or NbTi superconductor because it can carry significant current in the presence of high fields. Fig 1 shows the critical current, J_c, as a function of field for NbTi, Nb_3Sn, and BSCCO 2212 wire [5]. For fields above 14 Tesla, the HTS wire has the greatest current carrying capability. In this study we are using BSCCO 2223 HTS tape from American Superconductor (ASC) [6] instead of the BSCCO 2212 wire, which has a larger current density, because the tape is currently available commercially with documented specifications and is available in a variety that is reinforced to be able to withstand high tensile strain.

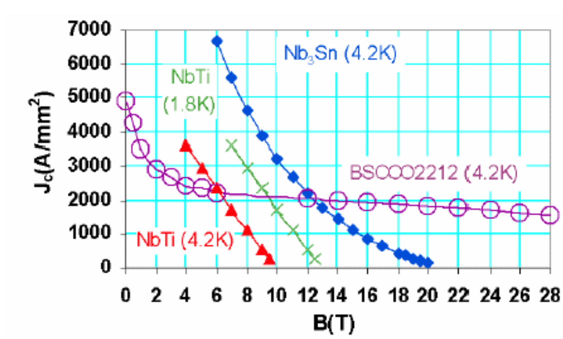

Fig 1: Critical current as a function of field for NbTi, Nb_3Sn and BSCCO 2212.

Table 1 lists the important properties of this conductor used in the study. In addition ASC supplied the data on J_e at 4.2°K, which is shown in fig 2 as a scale factor to be multiplied by the current density at 77° K. The two curves show that the J_e is sensitive to the direction of the field with respect to tape orientation. It was necessary to make an extrapolation from these data to high field, which introduces some uncertainty in the calculations made. In this analysis we will assume that we are operating at 85% of the maximum critical current. Since development of improved HTS conductor is expected in the future, the choice of which conductor is most appropriate should be revisited.

Table 1: Properties of American Superconductor High Strength Plus Wire

Parameter	High Strength Plus Wire
Engineering Current Density, J_e	133 amp/mm^2
Thickness	0.27 mm
Width	4.2 mm
Maximum Tensile Strength	250 MPa
Maximum Tensile Strain	0.4 %
Minimum Bend Radius	19 mm
Maximum Length	400 m

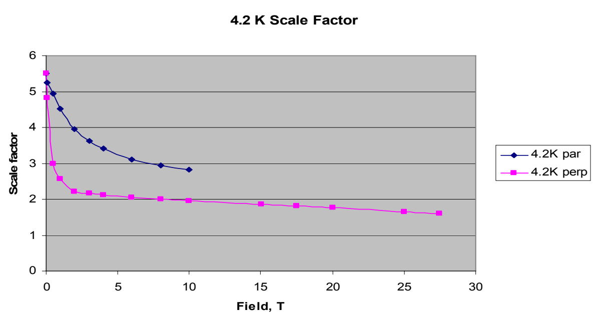

Fig 2: Scale factor to be multiplied by the 77°K current density for the American Superconductor HTS wire used. The blue (magenta) curve corresponds to the parallel (perpendicular) field orientation.

Mechanical Choices

Constraining the large Lorentz forces is the major design concern of very high field magnets. In this study we are proposing to mitigate the build-up of Lorentz forces by interleaving stainless steel tape under tension between the layers of the HTS tape. The interleaved stainless steel will prevent the HTS tape from exceeding its maximum tensile strain limit. We have examined cases with a fixed thickness stainless steel interleaving and with interleaving thickness varied to give the maximum allowable strain at each turn to minimize the amount of superconductor required.

Fig 3 shows strain vs. radius curves for a 40 Tesla solenoid with various thicknesses of stainless steel interleaving. The tensile strain is not maximum at the inner radius where the Lorentz stress is large. Since it comes from the hoop stress of the interleaving and conductor tape, it grows with radius giving a maximum value near the center of the magnet. This is advantageous since there is an additional contribution to the strain from the bend of the HTS tape at small radius. Figure 3 indicates that the smallest stainless steel interleaving thickness that keeps the conductor strain less than 0.4% is 5 mils. A 40 Tesla magnet constructed in this manner (case 1) would have an outer radius of 20 cm. Using this same approach for a 50 Tesla solenoid would require a 13 mil stainless steel interleaving which would significantly increase the outer radius of the magnet and consequently the amount of HTS needed.

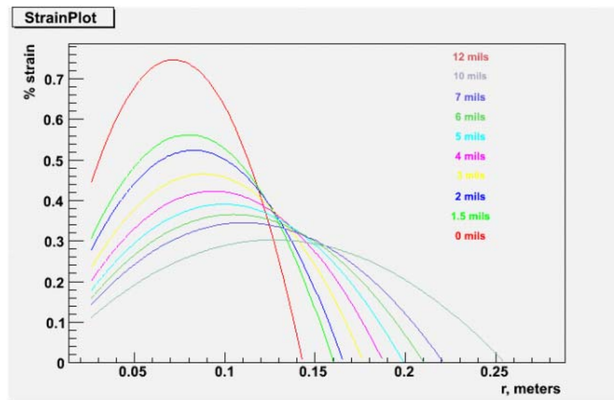

Fig 3: Tensile strain on the HTS conductor as a function of radial position for various thicknesses of stainless steel interleaving in a 40 Tesla solenoid.

The second approach is to vary the stainless steel interleaving thickness on each turn so as to have the largest current density such that the strain on the HTS tape does not exceed the maximum allowable tensile strain limit. The current density varies as a function of radius. This approach was applied to both a 40 Tesla (case 2) and a 50 Tesla (case 3) solenoid. The physical properties of these cases are listed in Table 2. The variable thickness model is more efficient in the use of the superconductor tape, however the magnet is under maximum strain throughout. In addition, by using separate power supplies, one can increase the current density as a function of radius since the solenoid field falls off with radius.

Table 2: Parameters describing the physical properties of the three cases examined.

Parameter	Case 1	Case 2	Case 3
Stainless Steel width	5 mil fixed	variable	variable
B_0 tesla	40	40	50
Inner Radius, mm	25	25	25
Outer Radius, mm	200	168	224
Conductor Length, km	60.0	46.7	59.9
Current, mega-amp-turns	23.56	23.20	29.73

MAGNETIC PROPERTIES

These three cases were modeled using the OPERA-2D finite element program [7]. It is assumed in these calculations that the solenoid is 70 cm long. Table 3 shows the magnetic properties from the analysis. Since these magnets have significant stored energy, a quench protection system will be necessary to dissipate the energy safely in case of an incident. As expected, the table also shows large radial forces which are mitigated locally so they do not accumulate. There are also compressive axial forces present from the radial fields at the ends of the magnet. Fig 4 shows the axial force density at the end of the magnet as a function of radius for the three cases. Fig 5 shows the axial force density along the magnet length for the radius where the force density is maximal. The allowable compressive strain that the HTS tape can tolerate is less than 0.15%. In the end region it may be necessary to reinforce the conductor against this compressive force. In the end region the HTS conductor can be wound as *pancakes* with stainless steel foil of appropriate thickness to prevent this compressive force buildup.

Table 3: Parameters describing the magnetic properties of the three cases examined.

Parameter	Case 1	Case 2	Case 3
Stainless Steel width	5 mil fixed	variable	variable
B_0, tesla	40	40	50
$\int B \cdot dl$, tesla-m	29.58	29.12	37.32
Stored Energy, mega joules	11.0	7.8	20.5
Total Radial Force, mega newtons	201	173	340
Axial End Force, mega newtons	-16.5	-11.9	-30.5

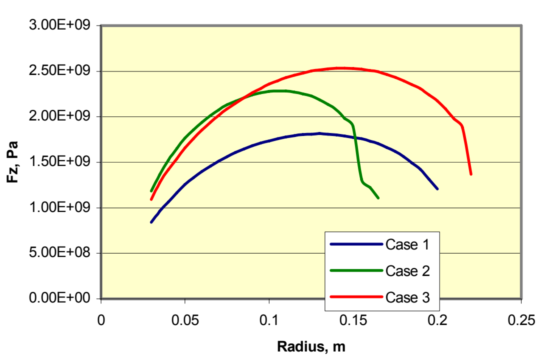

Fig 4: Axial force density along the radius at the end of the magnet for the three cases.

CONCLUSIONS

Very high field solenoid magnets up to 50 Tesla will play an important role in the final stages of cooling of muon beams for a muon collider. A 45 Tesla solenoid magnet using a Bitter magnet insert has been built at the NHFMF. It has the approximate specifications that would be needed for a muon collider. In this paper we have presented a concept for how a high field solenoid magnet could be build using HTS conductor at 4.2° K.

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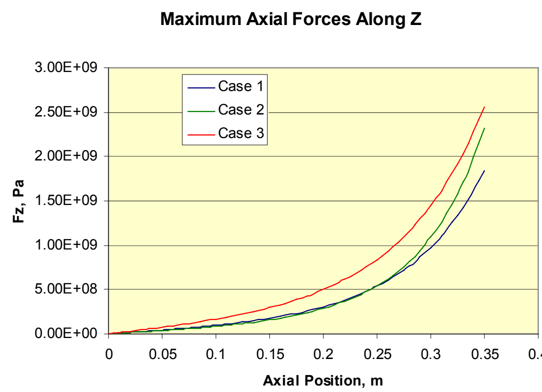

Fig 5: Axial force density along magnet length for each case at the radius where the force density is maximal.

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[6] American Superconductor specification sheet for HTS conductor, http://www.amsuper.com/products/htsWire/documents/WFS_HSP_1205_FINAL.pdf

[7] OPERA-2D is a finite-element suite of programs for electromagnetic design analysis. It is a product of Vector Fields, ltd.