A HIGH FIELD HTS SOLENOID FOR MUON COOLING*

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Abstract

The ability of high temperature superconducting (HTS) conductor to carry high currents at low temperatures makes feasible the development of very high field magnets for uses in accelerators and beam-lines. A specific application of a very high field solenoid is to provide a very small beta region for the final cooling stages for a muon collider. Since ionization cooling in a solenoid acts simultaneously on both transverse planes, any improvement in maximum field has a quadratic consequence in the reduction of the 6-dimensional (6D) beam emittance. This paper describes a conceptual design of a 45 Tesla solenoid based on Bi-2223 HTS tape, where the magnet will be operated at 4.2 K to take advantage of the high current carrying capacity at that temperature. In this design, an outer Nb_3Sn shell surrounds the HTS solenoid. This paper describes the technical issues associated with building this magnet. In particular it addresses how to mitigate the large Lorentz stresses associated with the high field magnet and how to design the magnet to reduce the compressive end forces. Also this paper discusses the important issue of how to protect this magnet if a quench should occur.

INTRODUCTION

In order to provide luminosity of the order of 10^{34} for a muon collider [1], a 6D phase space reduction of 10^6 may be necessary. A large fraction of the required cooling can be provided by either a cooling channel composed of helical dipole magnets to provide dispersion and H_2 as an absorber [2] or a solenoid cooling channel with absorber [3]. A simulation of the helical cooling channel has shown a 6D phase space reduction factor of 50,000. One approach to provide for the final stages of muon cooling is to use an alternating high-field solenoid lattice where liquid H_2 absorber is placed in the center of the high-field solenoids. The minimum transverse emittance is proportional to the beta function, which is inversely proportional to the magnetic field. This paper will examine how to achieve a 45 Tesla solenoid magnet using high temperature superconductor that is currently commercially available. This a conceptual study that is concerned with how to contain the large Lorentz force associated with the high field. This paper describes improvements to the previous conceptual design [4].

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MAGNET DESCRIPTION

The choice of the physical dimensions of the magnet is determined by the muon cooling requirements. The magnet is 1 m long, which provides a reasonably uniform field over the 70 cm long vessel, which contains the liquid hydrogen absorber needed for muon cooling. The inner radius of the solenoid is determined by the minimum bending radius of the HTS conductor, but it allows for the radial size of the liquid hydrogen absorber vessel, radiation shielding, and the necessary insulation.

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 as a function of field for NbTi, Nb_3Sn and Bi-2212 cable at 4.2 K [5]. For fields larger than 15 T, only the HTS wire has sufficient current carrying capacity. In this study we have chosen to use the Bi-2223 HTS conductor tape available from American Superconductor (ASC) instead of the Bi-2212 conductor shown in figure 1. The Bi-2223 conductor tape has an effective current density (J_E) of only 2/3 of that of Bi-2212 and is not isotropic with respect to its orientation in a magnetic field. However, the Bi-2223 conductor tape is currently available in a variety that is reinforced to be able to withstand high tensile strain and has documented specifications [6]. Also YBCO HTS conductor, which has the promising characteristics for the future, is becoming available commercially, but we do not yet have sufficient information to include YBCO in the study.

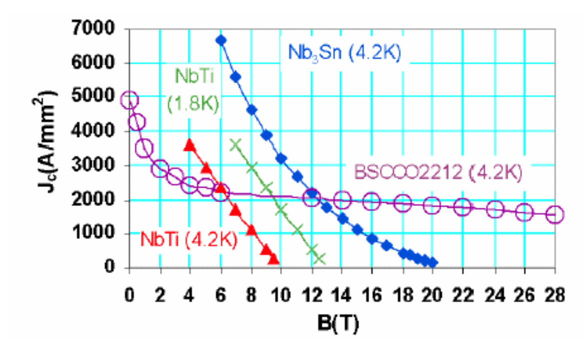

Figure 1: Critical current as a function of field for NbTi, Nb_3Sn and Bi-2212 conductors.

The important characteristics of the Bi-2223 conductor used in this study are listed in Table 1. We would like to operate this magnet at 4.2 K to take advantage of the increased critical current density at that temperature. Figure 2 shows data for a scale factor to be multiplied by the J_E at 77 K to use for 4.2 K. The current carrying capacity for Bi-2223 tape is sensitive to its orientation with respect to the magnetic field. Fig 2 shows curves that correspond to the configurations that are parallel and perpendicular to the plane of the tape. It is necessary to make an extrapolation to high field since the data for Bi-2223 up to 45 T is not available. The Bi-2212 conductor has been measured up to 45 T [7] and the general shape of the distribution has been used in the extrapolation, however this does introduce some uncertainty in the calculations made. For this analysis we are operating at 85% of the maximum critical current, but we are planning to work close to the material strain limit. Since the development of improved HTS conductor is expected in the future, the choice of which superconductor 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 at 45 T
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

Mechanical Choices

Constraining the large Lorentz forces is a major concern in the design of this magnet. We are proposing to mitigate the build-up of Lorentz forces by interleaving stainless steel tape between the layers of HTS tape. The interleaved stainless steel will prevent the HTS tape from exceeding its maximum tensile strain limit. The thickness of the stainless steel interleaving is varied with radius so that the tensile stress on the HTS tape will be at the tensile strength limit. Having a uniform tensile strain on the HTS tape will prevent the radial stress from accumulating from layer to layer. The HTS tape is insulated with 25 µm kapton to prevent shorts from the large voltage drop between adjacent layers. The HTS part of the magnet is wound in three separate radial blocks with a 1 cm gap to provide for support and cooling services. In the end region of the magnet where the field is not oriented in the preferred direction for the conductor, one needs to lower the current density in the conductor. The Nb_3Sn outer magnet extends 25 cm beyond both ends of the HTS part to reduce the radial component of the field in the end region of the HTS. Figure 4 shows the geometry of half of the magnet. The outer radius of the HTS part of the magnet is 39 cm and outer radius of the whole magnet is 57 cm. The total length of the HTS conductor used in the magnet is estimated to be 137 km.

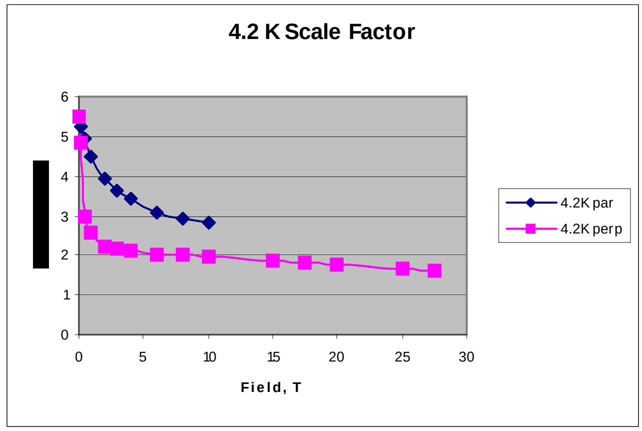

Fig 2: Scale factor to be multiplied by the 77°K current density for the American Superconductor HTS wire used. The blue (magenta) curve corresponds to the parallel (perpendicular) field orientation.

Figure 3 shows the thickness of stainless steel interleaving that is required to keep the tensile strain of the HTS conductor below the 0.4% strain limit. Although the Lorentz stress is largest at the inner radius of the magnet, the tensile strain is largest at about ¾ of the way in the magnet because tensile strength comes from the hoop stress, which grows linearly with radius.

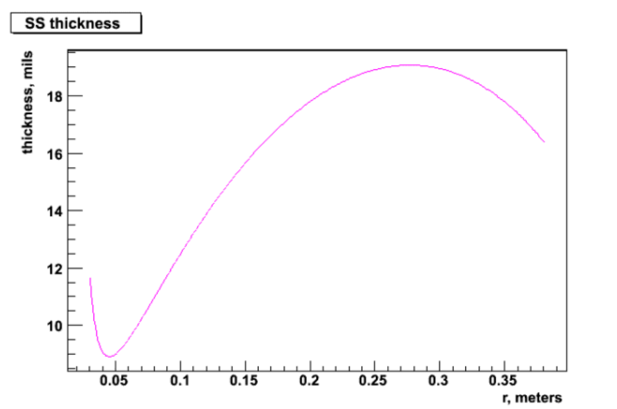

Figure 3: Thickness of stainless steel interleaving not to exceed the maximum allowable strain for a 45 T solenoid.

MAGNETIC PROPERTIES

A magnetic model of the solenoid was made using the OPERA-2D finite element program [8]. Figure 4 shows a contour plot of the magnitude of the field in the conductor regions. Also shown are the field contour lines, which indicate the direction of the field. Table 2 shows the magnetic properties of the magnet. The HTS inner magnet provides 2/3 of the 45 Tesla field seen in the aperture. This magnet has a considerable amount of stored energy, which would have to be removed in case a quench incident occurs. This is discussed in the next section. The total stored energy can be split between the HTS and Nb_3Sn parts of the magnet using $U = \pi\int r\, A\cdot J\, ds$ where J is the current density in the corresponding magnet

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region. The energy in each part is sensitive to the field of the other part.

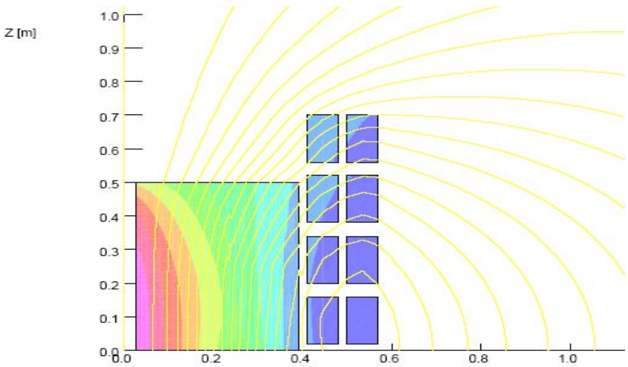

Figure 4: The contour plot of the hybrid magnet shows the modulus of the field through the coils. The yellow contour lines illustrate the field direction.

Table 2: Parameters describing the magnet properties

Parameter	Whole Magnet	HTS Magnet	Nb_3Sn Magnet
B_0, Tesla	45.9	30.0	15.9
$\int B \cdot dl$	59.7	32.0	26.7
Stored Energy, Mega-joule	182	57.7	124.6
Axial Force, Mega-newtons	-151	-42	-109
Total Radial Force, Mega-newtons	532	375	157

Since the radial forces are mitigated locally by the stainless steel interleaving, they do not accumulate. There are compressive axial forces present from the radial field components in the ends of the magnet. The axial forces do accumulate with a maximum force density at the center of the magnet. The HTS tape can only tolerate a limited compressive strain in this direction. It is important that the magnet be designed so that the axial forces are minimized. Extending the outer magnet beyond the ends of the inner magnet is intended to reduce these axial end forces.

QUENCH PROTECTION

There is a concern that a quench in a very high field HTS magnet could be self-destructive. First the quench propagation velocity in an HTS conductor has been measured to be about 4 cm/sec [9], which can be compared to the quench velocity in NbTi, which is about 1 m/sec. The quench velocity in HTS is slow at 4.2 K since it is far from critical temperature. The standard approach used with NbTi and Nb_3Sn of firing heaters to force the whole magnet to go normal will not work since the magnet is so far from the critical temperature. If a quench occurs the superconductor can heat up locally to a temperature that can damage it. Consequently the quench must be detected very quickly. Typically quench detection systems trigger at ~250 mV. If a quench could be detected with a system sensitive to 10-25 mV, the quench could be detected in 0.1 sec, which could limit the temperature rise to less than 200 K. In order to achieve this level of quench detection sensitivity it will be necessary to have a detection circuit on every other layer of conductor.

Because the stored energy in the inner HTS part and the outer Nb_3Sn part are comparable, one cannot assume that the outer magnet will stay superconducting as the inner magnet is brought down. The inner and outer magnets will have to be ramped down together at the same decay rate. The ramp down of the inner magnet was modeled using the QUENCH program [10]. If an external resistance of 8 ohms were attached to each of the 200 bi-layer quench circuits the ramp down time constant would be ~2.5 sec. The collection of these external resistances would have to handle the 60 MJ of energy. A similar system would be necessary for the outer magnet.

CONCLUSIONS

Very high field solenoid magnets up to 45 Tesla will have an important role in the final stages of cooling for a muon collider. In this paper, we present a conceptual design for such a high field magnet using HTS conductor that is available on the market.

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