# STUDIES OF THE HIGH-FIELD SECTION FOR A MUON HELICAL COOLING CHANNEL*

M. L. Lopes#, V.S. Kashikhin, A.V. Zlobin, Fermilab, Batavia, IL 60510, U.S.A.
R. Johnson, S. Kahn, Muons, Inc., Batavia, IL 60510, U.S.A.

*Abstract*

This paper presents the results of design studies of a high field section of a helical cooling channel proposed for the 6D muon beam cooling. The results include the magnet aperture limitations, the tunability of field components, the field correction, the superconductor choice and the magnet operation margin.

## INTRODUCTION

Helical cooling channels (HCC) based on a magnet system with and a pressurized gas absorber in the aperture has been proposed to achieve the high efficiency of 6D muon beam cooling [1-2]. The magnet system superimposes solenoid, helical dipole and gradient fields. To provide the total phase space reduction of muon beams on the level of $10^5$-$10^6$, the cooling channel was divided into several sections. To reduce the equilibrium emittance each consequent section has a smaller aperture and stronger magnetic fields.

In this paper, we focus on the design of the last high-field section of the HCC. The results of magnetic analysis and the considerations on superconductor choice for the high field section are presented as well as the limits of the system tunability in terms of the geometry main parameters. A straight correction solenoid for field and operation margin adjustment is used and its parameters are also discussed. The justification and target parameters for pursuing the improvements of the High Temperature Superconductor (HTS) for the high-field helical solenoid are also presented.

## SUPERCONDUCTOR CHOICE

The reference geometrical and magnetic parameters for the four sections of a HCC are summarized in Table 1 [2].

Table 1: Parameters for Each Section of the HCC

| Parameter | Unit | Section | | | |
|---|---|---|---|---|---|
| | | 1st | 2nd | 3rd | 4th |
| Section length | m | 50 | 40 | 30 | 40 |
| Helix period | m | 1.00 | 0.80 | 0.60 | 0.40 |
| Orbit radius | m | 0.159 | 0.127 | 0.095 | 0.064 |
| Solenoidal field, $B_z$ | T | -6.95 | -8.69 | -11.6 | -17.3 |
| Helical dipole, $B_t$ | T | 1.62 | 2.03 | 2.71 | 4.06 |
| Helical gradient, $G$ | T/m | -0.7 | -1.1 | -2.0 | -4.5 |

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#mllopes@fnal.gov

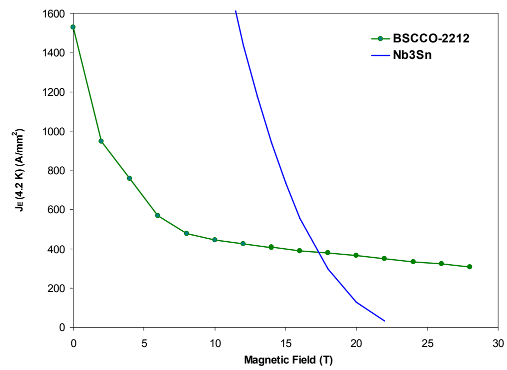


Figure 1: $J_E$ vs. B for $Nb_3Sn$ and Bi-2212 wires.

The maximum field in the coil of high-field helical solenoid (HS) with the nominal field components, shown in Table 1, reaches 21 T or higher for the coil aperture of 100 mm or larger. To provide a reliable magnet operation at the nominal parameters a HS should be designed with some operation margin, which could compensate for the quench performance degradation with respect to the design values and reduce the impact of coil training. The optimal value of operation margin for high-field helical solenoids is unknown at the present time and needs to be determined experimentally. Based on the experience with similar magnet systems, it could be 20-50% or even larger. To provide such a large operation margin the maximum design field for the high-field helical solenoid has to be at least 25-30 T.

Figure 1 shows the critical surfaces (dependences of engineering current density $J_E$ vs. magnetic field B) for $Nb_3Sn$ and Bi-2212 strands at 4.2 K [3]. $Nb_3Sn$ and Bi-2212 represent low temperature superconductors (LTS) and high temperature superconductors (HTS) respectively and are being considered for using in high-field helical solenoids. As can be seen, the high magnetic field in the coil requires using HTS materials. However, due to the higher $J_E$ at the lower fields the $Nb_3Sn$ superconductor can be used in the coil sections with magnetic fields below 18 T, opening the possibility for a hybrid model.

## FIELD TUNING AND OPERATION MARGIN

Helical solenoid has to provide three nominal field components $B_z$, $B_t$ and $G$ in the required coil aperture for a given helix period and orbit radius (see Table 1).

Figure 2 shows the transverse field components $B_t$ and $G$ as well as the operation margin of helical solenoids with the nominal solenoidal field $B_z$=-17.3 T and the coil aperture of 100 mm as a function of the coil thickness. It was assumed that the coil was made of HTS (Bi-2212) cable with the coil packing factor of 0.3.

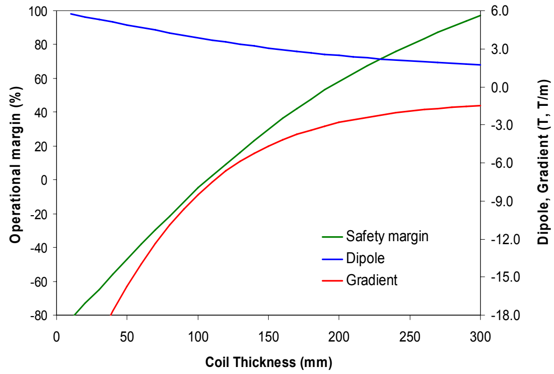


Figure 2: Operation margin, helical dipole and gradient field components vs. coil thickness.

One can see that the minimal coil thickness (operation margin is 0) is ~110 mm for the present current carrying capability of Bi-2212 strand. The helical dipole $B_t$ and gradient $G$ field components in this case are 3.5 T and -7.5 T/m respectively which are different than numbers in the Table 1. Nevertheless, the optimal $B_t/G$ ratio can be achieved at the coil thickness of ~200 mm, although the absolute values of $B_t$ and $G$ are approximately a factor of 2 smaller than the nominal values.

In order to achieve the absolute values of $B_t$ and $G$ in the HS with a 100 mm aperture, the current must be increased by 65%. However, the solenoidal field component $B_z$ in this case increases from the nominal value of -17.3 T to -28.5 T and the operation margin reduces to 0. Using the external straight solenoid (SS) with the reverse magnetic field of ~11 T allows reducing the solenoidal component $B_z$ in the HS aperture to its nominal value and provides the operation margin of ~12%. Further increase of the HS operation margin requires improving the current carrying capability of superconductor (Bi-2212 strand) with respect to the present level.

The $B_t/G$ ratio as a function of the HS coil thickness for four different coil apertures is plotted in Figure 3. The horizontal dashed line shows the nominal value of this ratio (see Table 1). One can see that it is practically impossible to provide the optimal $B_t/G$ ratio in high-field helical solenoids with the aperture smaller than 60 mm.

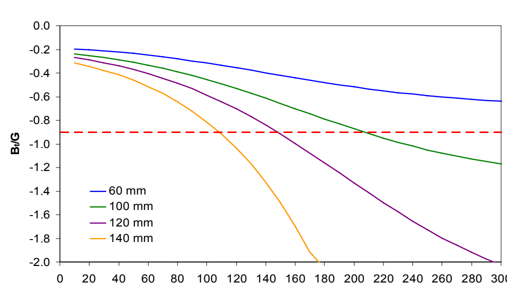


Figure 3: Helical dipole to gradient ratio vs. HS coil thickness for different coil apertures.

Table 2: HS coil optimal thickness and operation margin, and SS nominal field for different HS apertures.

| HS Aperture (mm) | HS Optimal coil thickness (mm) | HS Operation margin (%) | SS Nominal field (T) |
|---|---|---|---|
| 100 | 200 | 12.9 | 11 |
| 120 | 150 | -1.4 | 8 |
| 140 | 110 | -17.4 | 6 |

The optimal $B_t/G$ ratio in high-field helical solenoids with larger apertures is achieved with thinner coils. Table 2 summarizes the optimal coils thickness and operation margin of HS with the external SS for the HS apertures of 100, 120 and 140 mm. The nominal field of the external straight solenoid, required to achieve the design value of $B_z$ in the HS aperture, is also shown in the last column of Table 2. The data in Table 2 show that the HS+SS magnet system with the optimal field components and larger apertures has insufficient operation margin due to the insufficient coil thickness.

To provide the large target operation margin with optimal coil size it imposes more demanding requirements on the superconductor current carrying capability. Figure 4 shows the operation margin of HS+SS magnet systems (with the nominal field components $B_z$, $B_t$ and $G$ as shown in table 1) as function of the superconductor (Bi-2212) engineering critical current density measured at 20 T and 4.2 K for the HS apertures of 100, 120 and 140 mm. As can be seen, to provide 30% operation margin of the high-field HS+SS magnet system it would require increasing the current carrying capability of Bi-2212 strand by 25, 50 and 100% (with respect to its present level) for the HS aperture of 100, 120 and 140 mm respectively.

## COIL OPTIMIZATION

The $J_E$ vs. B dependences for Bi-2212 and $Nb_3Sn$ superconductor, shown in Figure 1, suggest conductor grading to provide more optimal current density in the coil regions with lower magnetic field. Better performance at low fields and lower cost of $Nb_3Sn$ strands with respect to the HTS materials motivates also to use a hybrid design when HTS is used only in the coil regions with magnetic field above 17 T. Both approaches offer reduction of the magnet cost.

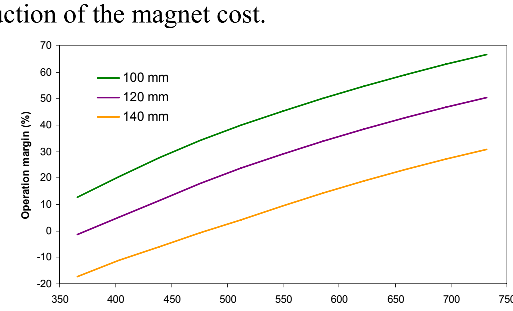


Figure 4: Operational margin as a function of superconductor (Bi-2212) engineering current density.

Table 3: Graded HTS HS Coil Characteristics

| Number of layers | Layer size (mm) 1st | 2nd | 3rd | 4th | Total size (mm) | *G* (T/m) | Op. margin (%) | SS field (T) |
|---|---|---|---|---|---|---|---|---|
| 1 | 200 | - | - | - | 200 | -4.65 | 12.9 | 11.2 |
| 2 | 50 | 130 | - | - | 180 | -4.63 | 14.0 | 9.6 |
| 3 | 50 | 40 | 80 | - | 170 | -4.57 | 13.8 | 9.1 |
| 4 | 50 | 40 | 30 | 30 | 150 | -5.16 | 11.5 | 7.1 |
| 4 | 50 | 40 | 30 | 20 | 140 | -5.50 | 9.6 | 6.2 |

However, the field requirements impose additional restrictions for hybrid coil design and conductor grading and they need to be taken into account. The coil optimization procedure in this case is iterative and thus less transparent than previously described procedure. It is illustrated below with some examples.

### *HTS Helical Solenoid with Coil Grading*

Table 3 summarizes results of Bi-2212 conductor grading in the HS with the coil aperture of 100 mm and external SS. The first row in Table 3 represents the reference HS coil without grading. In all cases solenoidal $B_z$ and helical dipole $B_t$ field components were tuned to the nominal values of -17.3 T and 4.06 T respectively. As can be seen, the 3-layer graded HS provides practically the nominal value of field gradient *G*, slightly larger operation margin and 23% smaller HTS coil volume. Moreover, coil grading allows substantial (~20%) reduction of the nominal field in the straight solenoid. Further reduction of coil volume by conductor grading detunes the field gradient and reduces the coil operation margin.

### *Hybrid Helical Solenoid*

Using the $Nb_3Sn$ superconductor in coil outer layers makes the current density grading even more efficient (see Figure 1). However, due to the different fabrication procedures used for HTS and LTS coils (Bi-2212 and $Nb_3Sn$ in particular), they have to be wound and processed separately and then assembled together. A radial gap is required in order to insert the HTS helical solenoid into the $Nb_3Sn$ one. This gap not only reduces the efficiency and increases the overall size of the magnet but also increases the peak field in the $Nb_3Sn$ coil, reducing its operation margin (see Figure 5).

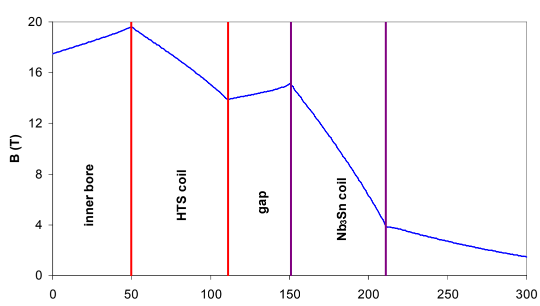


Figure 5: Maximum field in HS coil cross-section as function of the radial direction. No correction coil.

Table 4: Hybrid HS Coil Characteristics

| Layers thickness (mm) HTS | $Nb_3Sn$ | Normalized coil volume[1] HTS | Total | *G* (T/m) | Margin (%) HTS | $Nb_3Sn$ | SS field (T) |
|---|---|---|---|---|---|---|---|
| 200 | 0 | 1.00 | 1.00 | -4.65 | 12.9 | - | 11.2 |
| 110 | 20 | 0.39 | 0.53 | -4.63 | 11.2 | 18.9 | 11.9 |
| 100 | 30 | 0.33 | 0.54 | -4.55 | 10.8 | 18.3 | 12.0 |
| 70 | 70 | 0.20 | 0.65 | -4.13 | 7.7 | 9.3 | 13.5 |
| 60 | 90 | 0.16 | 0.75 | -3.92 | 5.3 | 6.8 | 14.6 |
| 50 | 110 | 0.13 | 0.84 | -3.59 | 2.6 | 3.1 | 16.0 |

[1] the HTS coil volume and the total volume of HTS and $Nb_3Sn$ coils normalized by the coil volume without grading

The minimal gap needed for assembly is equal to the longitudinal coil thickness. In this simulation it was 15.4 mm which includes also the longitudinal coil support structure. The radial gap was increased to 40 mm to account for the radial mechanical support and some extra clearance. The results of coil and field optimization for a hybrid HS with an external SS are summarized in Table 4 (it was considered the coil aperture of 100 mm). The first row represents the reference HS made of HTS. In all cases $B_z$=-17.3 T and $B_t$=4.06 T as in Table 1. As one can see, the HTS-$Nb_3Sn$ hybrid HS provided practically the nominal value of field gradient *G* and the HTS coil volume reduction by a factor of 3 and the total coil volume reduction by a factor of 2. However, in this case the operation margin reduces by 16% and the nominal field of the straight solenoid increases by 7%.

## CONCLUSIONS

Field tuning in the high-field section of HS requires optimal coil thickness and external straight compensation solenoid. The high operation field and operation margin requirements suggest using HTS materials such as Bi-2212 in high-field section of HCC. However, better performance at low fields and lower cost of $Nb_3Sn$ strands with respect to HTS materials motivates using a hybrid design and conductor grading. Those approaches allow reducing the HTS coil volume. The optimization process of hybrid or graded HS coils includes field tuning as an important condition. To provide the target operation margin for HS with optimal coil size the improvement of the HTS current carrying capability is needed.

## REFERENCES

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