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

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*Abstract*

This paper describes the conceptual design and parameters of a short model of a high-field helical solenoid for muon beam cooling. Structural materials choices, fabrication techniques and first test results are discussed.

## INTRODUCTION

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

The strength of the magnetic field in the HCC high-field section suggests using High Temperature Superconductors (HTS) for the innermost coil layers [3]. Furthermore, due to the limited space available for the RF cavities, which have to operate at temperatures above 30 K, there will be little room for thermal insulation and support of the RF system inside the coil. The use of HTS solves these problems by allowing the coil and the RF system to be operated at the same optimal temperature ~30 K. Therefore, the development of both a conceptual and engineering design of a high-field helical solenoid based on HTS technology is a key step towards the realization of an HCC.

This paper describes the conceptual design and parameters of a short HTS model of a helical solenoid, structural materials choices, fabrication techniques and first test results.

## HTS CONDUCTOR CHOICE

Fig. 1 shows the dependences of engineering current density $J_E$ vs. transverse magnetic field B at 4.2 K [4] for two practical HTS conductors: BSCCO-2212 round wire and YBCO tape. Since YBCO tape has a strong anisotropy with respect to the field orientation, the YBCO data are presented for both parallel (//) and perpendicular (⊥) field orientations. Due to the fact that the helical solenoid has quite strong transverse field components, the $J_E$-B dependence in the perpendicular field will determine the superconductor limit of the coil. In this sense, BSCCO wire and YBCO tape have comparable properties.

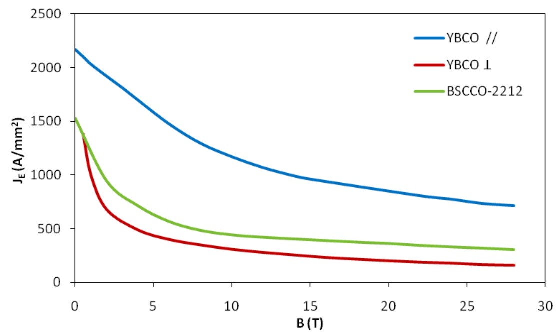


Figure 1: $J_E$ vs. B for BSCCO wire and YBCO tape.

BSCCO-2212 wire before the final heat treatment can be formed into multistrand round or flat cables [5] which then need to be reacted in Oxygen following a very strict heat treatment cycle. The peak temperature ~890°C needs to be well controlled (within 0.5°C for ~12 minutes) [6]. This process is presently hard to achieve making it difficult to guarantee $I_c$ magnitude and homogeneity, especially for a large volume of superconductor. Additionally, BSCCO wires are very sensitive to the longitudinal and transverse strain and stress; this imposes additional requirements for the conductor support structures [7].

In contrast to BSCCO, YBCO tapes do not require the final reaction, are flexible in the easy-bend direction, and show very promising mechanical capabilities [8]. Also, YBCO presently offers better $I_c$ performance at T>30 K with respect to BSCCO-2212 wires [9]. The problem of making multi-strand cable based on YBCO tapes can be solved using the ROEBEL cable design [10]. Taking into account the aforementioned considerations, YBCO tape was selected as the baseline conductor for the HCC high-field section model.

## SHORT MODEL PARAMETERS

The target design parameters of the high-field section of helical solenoid for HCC are shown in Table 1.

Table 1: Parameters of High-Field Helical Solenoid.

| Parameter | Unit | Value |
|---|---|---|
| Helix period | m | 0.40 |
| Orbit radius | m | 0.064 |
| Solenoidal field, $B_z$ | T | -17.3 |
| Helical dipole, $B_t$ | T | 4.06 |
| Helical gradient, $dB_t/dr$ | T/m | -4.5 |
| Maximum field in the coil | T | 21.0 |
| Coil ID | m | 0.10 |
| Coil OD | m | 0.50 |
| Coil length | m | 0.017 |
| Number of coil per period | | 24 |

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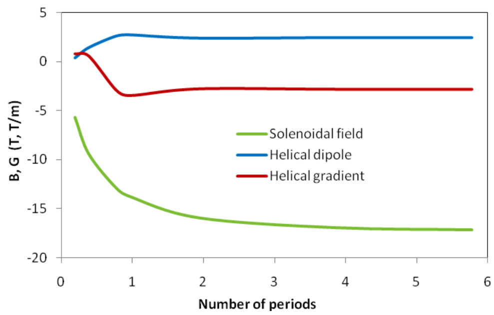


Figure 2: Field components vs. the number of periods.

Fig. 2 shows the HS field components versus the number of solenoid periods. As can be seen, to reproduce all three of the field components the HS model needs to be 0.8-1.2 m long and consist of 2-3 periods. Taking into account the large HTS conductor volume in such a model, its high cost, as well as the complicated magnet design, it was considered prudent to build a scaled down version to validate the design and building procedure before proceeding to a magnet with the full design specifications. Thus, it was decided to limit the model axial size to a few (2-6) coil rings and reduce the ring width. The described short model addresses the magnet design and technology, and the conductor performance issues related to the helical solenoid based on YBCO tape.

The coil uses 12 mm wide 0.1 mm thick YBCO tape from SuperPower with a nominal $I_c(0T,77K)=320$ A. A 12.7 mm wide and 0.05 mm thick Kapton tape is used for turn-to-turn electrical insulation. Each coil has 100 mm inner diameter and consists of 50 turns, which is equivalent to a radial coil thickness of 7.6 mm. Table 2 shows the calculated parameters of the short models with 2, 4 and 6 coil rings. Note that the lower quench current in the case of two rings is due to the larger transverse field component in the coil because of short model length.

## COIL SUPPORT STRUCTURE

The support structure of high-field HS short model is based on double-pancake units with two coils shifted in the transverse direction. The coils are electrically connected with bridge splices on the matching coil inner surfaces. The unit leads are located on the outer coil surfaces. Fig. 3 shows the expanded view of the mechanical structure of the double pancake unit. The coil inner support rings have 100 mm outer diameter and are 10 mm thick. The flanges are 3 mm thick. The rings and flanges are made of the 304 stainless steel. Outside the coil is supported with 20 turns of a 0.1 mm thick stainless steel bandage.

Table 2: Short Helical Solenoid Model Parameters.

| Parameter | Unit | Number of rings | | |
|---|---|---|---|---|
| | | 2 | 4 | 6 |
| $I_{quench}$ | A | 1283 | 1321 | 1179 |
| $B_z$ | T | -1.4 | -2.6 | -2.9 |
| $B_t$ | T | 0.09 | 0.40 | 0.68 |
| $dB_t/dr$ | T/m | 1.1 | 1.7 | 0.3 |
| Stored energy | kJ | 0.95 | 2.80 | 3.70 |

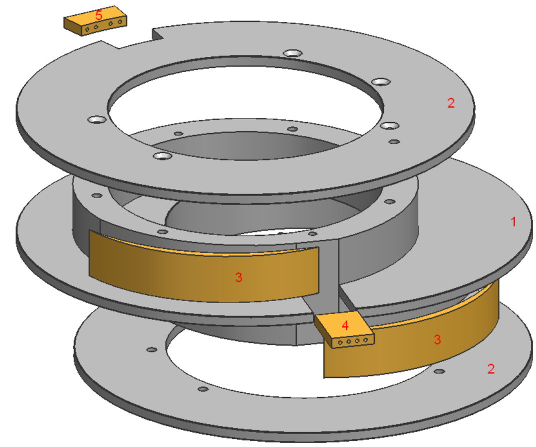


Figure 3: Expanded view of a double pancake unit: 1) inner support rings with flange; 2) side flanges; 3) spacer for the first turn and splice accommodation; 4) insert with holes for the inner splice cooling and support; 5) inserts for the outer splice support.

The ring surface is designed to accommodate the flat inner coil splice and part of the first turn, which is then covered with a special G-10 spacer to compensate for the cut from the circular ring. The slots in the flanges that allow the transitions (inner and outer splices) are supported with additional G-10 pieces.

The support side flanges are electrically insulated from the coil using 0.5 mm G-10 flanges. The support rings are insulated with 0.5 mm thick multilayer Kapton insulation. On the top of the last turn 0.2 mm multilayer Kapton is used as ground insulation.

A FEA based on ANSYS model was done to verify the level of stresses that the structure will be subjected due to the Lorentz forces at short sample limit at 4.5 K. The maximum stress in the support structure is 171 MPa which is acceptable for this short model.

Fig. 4 shows the assembled mechanical structure of double-pancake unit. The design of double-pancake units allows them to be connected in series with other units to form a longer helical solenoid. This is done by replacing the side flanges with ones (shown in dark gray in Fig. 4) that accommodates the splice between units. The modular structure of HS also allows the inclusion of gaps between the units to provide space for RF system and absorber technological feeds through [11]. The optimization of gap size, coil parameters, and support structure will be done as a next step of this work.

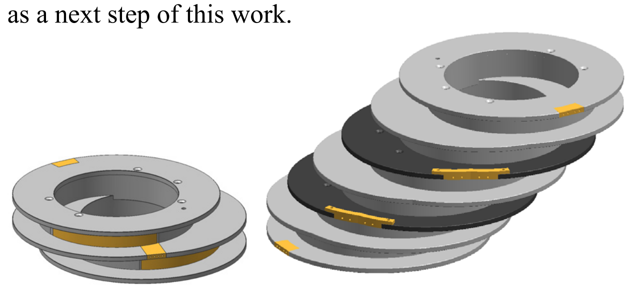

Figure 4: The double pancake unit (left) and three double-pancakes connected together (right). The dark grey flanges accommodate the splices between units.

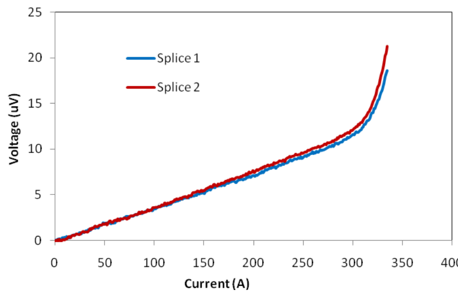


Figure 5: V-I curve at 77 K for each of the inner splices.

## MODEL FABRICATION

The described short model will address the issues of the magnet design, technology, and conductor performance. It is developed through several steps including computer modelling, prototyping, and procedure preparation.

The electrical connection of the two single coils is one of the critical elements that may limit the magnet performance. It is done by bridging the ends of two parallel spools of 12 mm YBCO tape with a short piece of YBCO tape. During the coil splicing, the tape temperature has to be carefully monitored not to exceed 250°C, to avoid conductor damage [12].

To optimize the splicing procedure, several splice samples were fabricated and tested in liquid Nitrogen. The splicing was made using Sn63%Pb37% (eutectic) solder which has a melting temperature of 183°C. The V-I curves for two splices are shown in Fig. 5. The measured splice resistance was less than 40 nΩ in both cases. No $I_c$ degradation due to the splicing process was found.

The YBCO and Kapton tapes are co-wound into the coil support structure described above. Around 40 m of the HTS tape is used to wind each double pancake coil. The tape is wound with a tension up to 45 N to achieve dense winding with high compaction factor. This tension limit is also low enough so as to avoid damaging the YBCO conductor.

To reduce the risk of damage of expensive HTS tape, check coil winding and assembly steps, and to optimize the coil instrumentation plan, the practice coils and a complete technological model were fabricated. They used the real support structure and final materials except the HTS tape which was substituted with SS and Cu tape. The practice coil side view is shown in Fig.6.

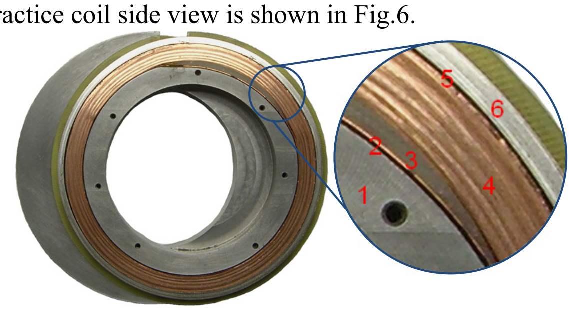


Figure 6: Double-pancake technological model: 1) inner support ring; 2) coil inner ground insulation; 3) spacer for the first turn; 4) coil; 5) coil outer ground insulation; 5) stainless steel bandage outer support.

## CONCLUSIONS

The final section of the HCC will use a helical solenoid based on HTS (YBCO) conductor to provide operation at high fields and at a temperature of ~30 K. The YBCO tape has certain advantages due to its excellent electrical and mechanical properties. A short helical solenoid model based on 12 mm YBCO tape was designed to study and address the design, technological and performance issues related to magnets based on YBCO conductor. The modular HS design concept based on double pancake coil units has been developed and studied using practice coils and a full technological model. The fabrication of the first real double pancake unit has started. The first single module test is planned in July and multi-module short model fabrication and test are scheduled for August-September 2010.

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