# 50 TESLA SUPERCONDUCTING SOLENOID FOR FAST MUON COOLING RING*

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*Abstract*

A conceptual design is presented for the 50 Tesla superconducting solenoids that are required for an optimized fast cooling ring in current designs for multi-TeV muon colliders. The solenoid utilizes high-performance multi-filament Bi-2212/Ag round strand.

The conductor is a cable-in-conduit consisting of six such strands cabled around a thin-wall spring tube then drawn within an outer sheath. The spring tube and the sheath are made from high-strength superalloy Inconel. The solenoid coil comprises 5 concentric shells supported independently in the conventional manner. Each shell consists of a winding of the structured cable, impregnated in the voids between cables but empty inside so that the spring tubes decouple stress so that it cannot strain-degrade the fragile strands, and a high-E stress shell.

An expansion bladder is located between the winding and the stress shell. It is pressurized and then frozen to provide hydraulic compressive preload to each shell. These provisions makes it possible to accommodate ~10 T field contribution from each shell without degradation, and to distribute refrigeration so that heat is removed throughout the volume of the windings.

## INTRODUCTION

A key challenge in the design of TeV muon colliders [1] is the requirement to cool the 6-dimensional phase space of muons produced from a target by a factor $10^6$ in a rest-frame time that is a modest fraction of the 2.2 μs muon lifetime. In the past two years several designs have been developed that may be capable of this performance [2,3,4,5]. A technology challenge that is common to most of these designs is the use of high-field solenoids to produce a helical motion of the muon beam in succession with ionization loss in high-pressure hydrogen gas and re-acceleration in rf structures. There are two specifications for the solenoids used in this manner:

- 1 m long, 2 cm bore radius, 50 T field;
- 1 m long, 20 cm bore radius, 35 T field.

Since the solenoids must operate continuously, and a significant number of them will be required, they must be superconducting magnets. No one has ever built a solenoid with either specification.

Recent developments with Bi-2212 superconducting wire have achieved impressive performance. Two firms (Oxford Superconducting Technology and Showa Electric Wire) have attained current densities of ~400 A/mm$^2$ overall at high field strength (Figure 1a, Figure 2). Bi-2212 surpasses $Nb_3Sn$ whenever B >16 T at conductor.

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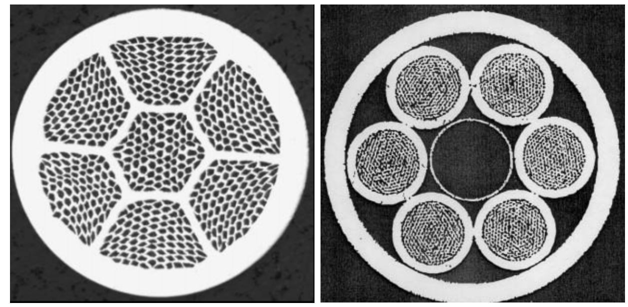

Figure 1: Bi-2212 strand and cable: a) Current high-performance Bi-2212 strand from OST; b) structured cable made using earlier strand.

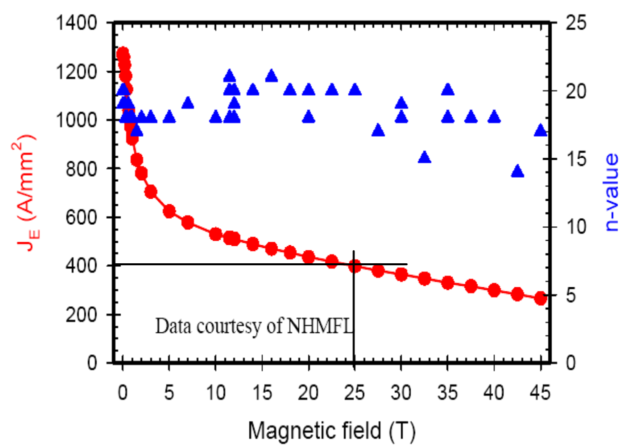


Figure 2: Measured performance of OST strand.

Several groups have suggested solenoid designs for muon cooling using either Bi-2212 or YBCO [6,7,8,9]. Most designs are predicated upon the use of tape conductor. There is significant experience with solenoidal insert windings using HTS tapes, but they typically produce a few T field differential in a background field of ~4-6 T. The Lorentz stresses for a sequence of shells capable of 35-50 T field exceed those in any HTS coils yet made.

The Texas A&M group has developed a structured cable (Figure 1b) that makes it possible to use round-wire Bi-2212 conductor with stress management integrated throughout the winding [10]. In the present work we model two solenoids using this structured cable that are could provide the performance required for 6-D muon cooling ring designs.

## STRUCTURED CABLE USING BI-2212 ROUND WIRE

A composite cable has been developed for use in wind-and-react fabrication of Bi-2212 windings. It incor-

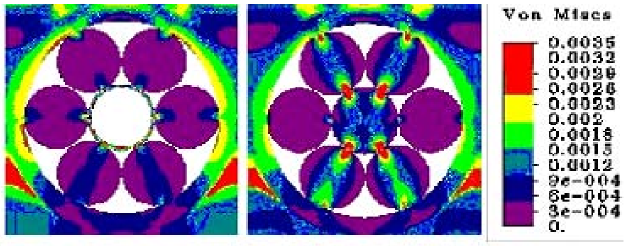


Figure 3: Von Mises strain in structured cable loaded vertically with 100 MPa: a) hollow spring tube in center; b) solid strand in center.

porates several novel features that together may make it feasible to solve some practical problems which have so far inhibited the use of HTS superconductors in practical high-field windings.

To make the armored spring-core cable, a multi-strand cable of Bi-2212 strands is spiral-wound around a *spring core*. The spring core is a thin-wall tube made from high-strength Inconel X750 super-alloy. The spring core provides control of mechanical stress within the fragile HTS strands of the cable. The spring-core cable is then encased within an *armor sheath*, constructed of high-strength metal (typically Inconel 718) The armor sheath is drawn down upon the cable to just preload the strands against the spring core. Samples of the structured cable have been built and tested, using 0.8 mm diameter strands in an overall 3 mm diameter sheath.

Each winding would be fabricated from a single length of structured cable, wound on with interlayer insulating fabric and also with a high-modulus round wire that partially fills the void space between cables. After the winding is wound and reacted to form the superconducting phase, it would be epoxy-impregnated so that the voids between adjacent cable elements would be filled but NOT the spaces among the round strands inside each cable.

The structured cable serves three purposes. First, the armor shell and spring core provide *stress management.* External mechanical stress from preload forces and from Lorentz forces is bypassed through the armor shell. To the degree that the shell deflects slightly under external loading, the spring core cushions the strands within so that very little strain can be produced on the fragile HTS strands.

Second, the hollow spring core is perforated by a pattern of laser-drilled holes, so that it can be used as a conduit for gasses during the high-temperature reaction heat treatment that is used to form the superconducting phase. The cable thus facilitates the possibility of using isothermal melt processing by which the heat treatment can be done at a lower reaction temperature. It also may make it possible to achieve a negative-feedback control on the critical partial-melt stage of the heat treat.

Third, the hollow spring core can be used again in the completed winding as a conduit for closed-circuit refrigeration, bathing the entire winding volume in cryogen.

We have performed a finite-element stress analysis of the cable in an impregnated winding under stress loading for three cases: a) the armored cable with the spring tube in the center; b) the armored cable with a seventh strand in the center; c) conventional coil wound from individual strands and epoxy impregnated. In each case we assumed that the winding was loaded with a vertical stress $S_0 = 100$ MPa, typical in a winding with $\Delta B \sim 10$ T. Figure 3 shows the von Mises strain distribution for the first two cases. In the conventional coil case (not shown), the strands experienced a four-fold stress concentration at each location where a strand on one layer passed over a strand on the last layer; the maximum strain exceeded the $2\text{x}10^{-3}$ degradation limit throughout the strand cross-section. Note that the small strain concentrations in the strands of Figure 3a are localized in the surface ~10% of each strand; as seen in Figure 1a that region is occupied by dispersion-hardened Ag with no superconducting cores, so no degradation of current transport should occur. Thus the structured cable with spring core reduces maximum strand strain by a factor >2, opening the way to use in high-field windings.

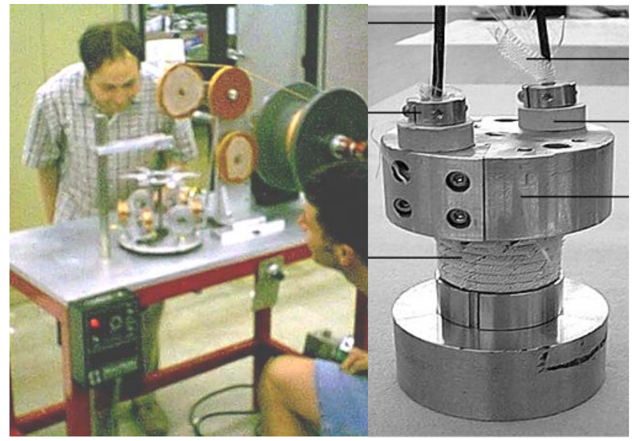

Figure 4: Fabrication and testing of structured cable: a) 6-on-1 cabling of strands onto spring tube; b) test fixture with 2.5 cm diameter winding of structured cable.

Short lengths of structured cable have been fabricated (Figure 4a) and tested in windings of 2.5 cm diameter. Note that the armor sheath of the (3 mm diameter) cable deforms to an oval when it is wound so tightly. This ovaling, however, simply deforms the inner spring tube, leaving the strands inside without any damage. The maximum strand current (10 μV/cm criterion) was measured for bare wire samples, straight cable samples, and the test windings. No degradation was observed from cabling, from heat treatment in the cable geometry, or from winding into test windings. This result validates the structured cable as a viable basis for high-field coil development.

## STRESS-MANAGED SOLENOIDS FOR MUON COOLING REQUIREMENTS

The structured cable was used as the starting point for preparing multi-shell designs for high-field solenoids. The coil was structured in independent shells in the fashion that is usual with high-field solenoids. The division of shells was chosen to limit Lorentz stress in each shell to ~120 MPa.


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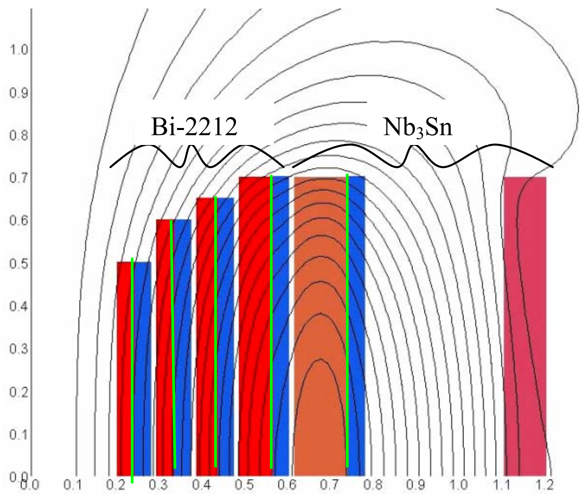


Figure 5: 35 T solenoid, 20 cm bore radius, with reverse winding: structured-cable windings (tan); stress shells (blue); expansion bladders (green). Dimensions in m.

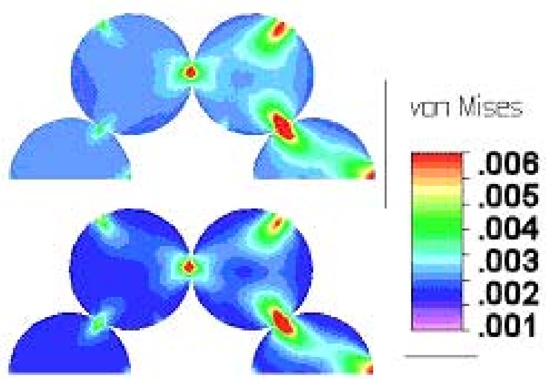


Figure 6: Von Mises strain distribution in inner shell at full field: a) innermost turn; b) outermost turn.

A new development was employed to manage stress within each shell, which has emerged from our development of high-field dipoles [11]. An outer stainless-steel stress shell is placed on each vacuum-impregnated winding, and an expansion bladder is located between the winding and the stress shell. The bladder consists of two thin stainless-steel shells, welded at top and bottom to form a hermetic bladder. After final assembly of each shell, it is heated to ~100 C, the bladder is evacuated and pumped full of molten Wood's metal, and the molten metal is pressurized to ~60 MPa (half the maximum Lorentz load on each of the innermost shells). The shell is then cooled to freeze the metal filling and freeze in the hydraulic preload. In this way we can favorably preset the stress-strain curve and thereby double the allowable working load of each shell.

The innermost four shells are made using Bi-2212 superconductor because their field exceeds the ~16 T working limit for $Nb_3Sn$. The outer shell and the reverse-field shell are made using $Nb_3Sn$ superconducting cable (the NHMFL cable-in-conduit might be the best choice for those windings). The stress and strain distribution within the preloaded shells has been simulated in finite-element analysis. Figure 6 shows the von Mises strain in the innermost and outermost cable layers in the inner shell at full field. Note that the pattern of strain should be just within the allowable limits for Bi-2212, and *the pattern of strain is the same on both cables* - a result of the bypass of the accumulating Lorentz stress through the armor sheaths and reinforced impregnation. Note that the (large) axial compression on the ends is supported the same way.

Table 1 summarizes the main parameters of the two solenoid designs. Both solenoids have 5 shells, and in each case the outermost shell is a reverse-field winding to kill long-range fringe field. The temperature indicated is that which would equilibrate if all stored energy were converted to heat the cold mass. Remarkably the two designs are very comparable in all main properties. Both appear to be well-optimized goals for magnet development.

Table 1: Main parameters of two solenoids

| | | | |
|---|---|---|---|
| Central field | 35 | 50 | T |
| Bore radius | 20 | 2 | cm |
| Overall diam. | 2.2 | 2.2 | m |
| Stored energy | 437 | 353 | MJ |
| Inductance | 373 | 509 | H |
| $J_E$ @ full field | 325 | 250 | A/mm$^2$ |
| Field @ 3 m | 40 | 50 | mT |
| Cold mass: Bi-2212<br>$Nb_3Sn$<br>SS shells | 2.6<br>2.4<br>7.2 | 2.9<br>3.0<br>5.6 | tons |
| $T_{max}$ in quench | 220 | 200 | K |

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