# MAGNET DESIGN OPTIMIZATION FOR FUTURE HADRON COLLIDERS*

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*Abstract*

Fermilab in collaboration with other members of the US Magnet Development Program (MDP) is working on the development of accelerator magnets for future hadron colliders. A 4-layer, 15-T dipole with 60 mm aperture based on $Nb_3Sn$ Low Temperature Superconductor (LTS) has been fabricated and tested. It is an important milestone of demonstrating readiness of the LTS magnet technology for the next generation of hadron colliders. At the same time, design studies aimed at boosting the magnet performance even further with the help of High Temperature Superconductors (HTS) are under way. This paper introduces a novel magnet technology - Conductor On Molded Barrel (COMB) optimized for the HTS materials and discusses possible steps towards its demonstration.

## INTRODUCTION

There is a continued trend of increasing the magnetic field strength in the main bending and focusing magnets of circular colliders, including SPS, Tevatron, HERA, RHIC, and LHC [1]. While the machines also historically grew up in circumference, increasing the magnetic field strength remained a crucial way towards reaching higher beam energies. It is expected that the energy upgrade of the LHC to 25 TeV (HE-LHC) and the 100 TeV Future Circular Collider (FCC-hh) will need the nominal dipole field strength of 16 T, which requires the peak coil field of ~18 T to provide sufficient operating margins [2]-[3].

To demonstrate the feasibility of high field dipole magnets with accelerator field quality, Fermilab is engaged in an extensive magnet R&D [4] in collaboration with other members of the U.S. Magnet Development Program (MDP). The state of the art $Nb_3Sn$ cables being developed [5]-[6] will allow to improve the magnet performance and to reduce the cost. An essential part of the program is the 15 T $Nb_3Sn$ dipole demonstrator based on a 4-layer graded cos-theta coil with 60 mm single aperture and a ~600 mm diameter cold iron yoke [7]-[8].

In parallel, the magnet design studies are being conducted to explore the limits of the $Nb_3Sn$ accelerator magnet technology while pushing the nominal bore field over 16 T [9]. A preliminary analysis [10] indicated that such a goal can be achieved with the help of an internal Stress Management (SM), which can potentially enable the 16-18 T field range for the $Nb_3Sn$ magnets.

There is also an interest in increasing the nominal dipole field beyond 20 T [1] to reduce the machine circumference or to reach higher energy in existing tunnels. Such magnets can benefit from the high critical fields attainable in the HTS materials but will require an extensive R&D in the conductor development as well as unconventional magnet design approaches.

As a step in that direction, Fermilab is performing studies of the possible HTS coil designs and support structures, which can be tested as inserts in the available $Nb_3Sn$ magnets to demonstrate their viability for boosting the magnetic field in accelerator magnets. This paper reports the results of these studies and compares several options for the HTS coil development.

## HTS CONDUCTORS

Presently, RE-$Ba_2Cu_3O_{7-\delta}$ coated conductors (REBCO) and $Bi_2Sr_2CaCu_2Ox$ (Bi-2212), are among the most promising HTS materials available in long lengths that have demonstrated engineering current densities ($J_e$) of interest to high field magnets beyond $Nb_3Sn$.

REBCO is a highly anisotropic superconductor that is currently only available in tape form and does not require any heat treatment [11]. In addition, because the careful material selection for the deposition substrate (Stainless Steel or Hastelloy), REBCO tapes show remarkable mechanical properties [12]. However, due to the conductor geometry, cabling techniques developed for Low Temperature Superconducting (LTS) materials cannot be directly applied to REBCO conductors.

Several novel approaches to REBCO-based cables are being demonstrated including – among others - Twisted Stack Tapes (TST) [13], Roebel [14] and Conductor on Round Core (CORC®) [15]. Of benefit to CORC® cables are the efforts toward reduction of the substrate thickness, with the recently demonstrated value of 30 μm [16] and a room for further improvement. The thinner substrates will allow smaller Cu formers in CORC® cables, resulting in higher $J_e$, additional cable flexibility and current density retention at smaller bending radii.

Bi-2212, on the other hand, is produced as a multifilamentary round wire, which is a big advantage over REBCO, as it allows for the manufacturing of widely used Rutherford type cables. However, reaching the state of the art $J_e$ requires an overpressure, high temperature reaction in the oxygen environment with a temperature window of a few degrees [17], which creates additional constraints in the magnet fabrication process. While the magnetization is easily controllable due to the multifilamentary nature of the conductor, from a mechanical viewpoint, given its brittle ceramic composition in a soft Ag alloy matrix, Bi-2212 is considerably less forgiving than REBCO [18].

Each HTS conductor comes with its own unique set of strengths and weaknesses which makes the choice between the them far from obvious. The present studies focus mainly on the application of REBCO CORC® cables to the magnet design, but considerations for both conductors are included throughout the text.

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
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## COMB MAGNET TECHNOLOGY

The magnet technology based on flat cables with large aspect ratios was used in every superconducting collider built starting from Tevatron. It is ideal for NbTi and $Nb_3Sn$ materials that can be readily formed into the Rutherford cables and wound as self-supporting coils of the Roman arch geometry. Using of the HTS conductors, especially in the round form, however, requires an additional support structure to hold the turns in the correct position as well as to reduce the stresses on the conductors for the strain-sensitive materials, like Bi-2212. Canted-Cosine-Theta (CCT) magnet technology introduced in 2014 [19] offers the individual cable support, which is well suited for round conductors. Since then it was used in magnets designed at several institutions [20]-[21].

The proposed Conductor On Molded Barrel (COMB) magnet technology takes a different approach, which combines the individual conductor support inherent to CCT with the traditional cosine-theta coil geometry. In its simpler, single-COMB implementation, it is equivalent to the CCT geometry in case of the canted angle approaching zero (i.e. conductors being parallel to the magnet axis). It is useful for applications that require single-layer coils with individual support of every turn, however, the unique benefits of this technology become fully realized in the double-COMB design.

The double-COMB support structure designed to fit into the bore of Fermilab's 15 T dipole magnet is shown in Fig.1 along with a mockup coil built to demonstrate the manufacturability. As can be seen from the picture, one solid structural part holds two layers of the cable, which eliminates the disconnected parts that must fit together with a high precision as well as the layer-to-layer interface that can be a source of magnet training. For the reference, the 15 T dipole has 23 separate parts per half-coil (excluding the poles, which can be made as solid pieces), which makes the coil winding very labor intensive. Also, misaligned parts can case local cable stress concentrations and a degraded magnet performance.

Another benefit of the double-COMB design is that there is no splice in between the layers, which is especially important for HTS. The two-layer coil is wound from a single cable piece, as demonstrated in Fig. 1, which requires pulling about half of it through the transition hole in the COMB structure prior to the coil winding. Similarly to the traditional cosine-theta coils, the conductors are parallel to the magnet axis in the straight section while the ends are very compact, which maximizes the useful field region and the integral strength. Also, the magnet is assembled from half-coils (for a dipole), which are easy to fit with extra internal or external HTS or LTS coils. The prestress is controlled by midplane and azimuthal shims.

Even though the present focus is on the dipoles, this technology can be easily adopted for magnets with any number of poles. It may find application in magnets, which experience large radiation heat depositions (e.g. IR quadrupoles) that can benefit from the high critical temperature of HTS or in stand-alone correctors operating at intermediate temperatures.

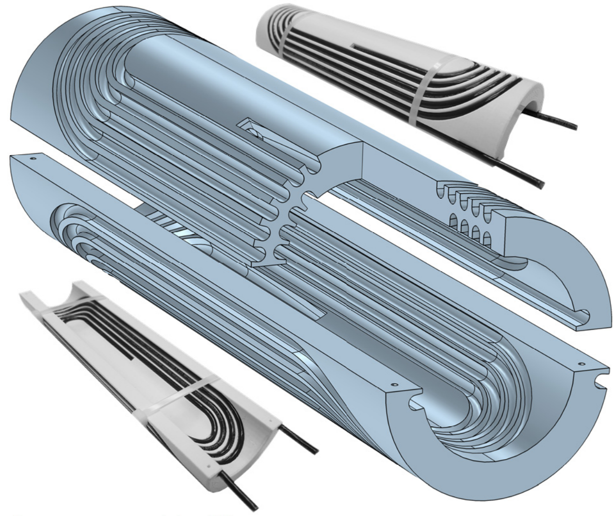

Figure 1: Double-COMB support structure (center) and the mock-up coil (top and bottom).

Since the double-COMB structure has a continuous cable channel of complicated topology spanning both inner and outer surfaces of the barrel, it is not well suited for CNC machining. It could, quite well, be unmanufacturable several decades ago, however, nowadays it can be readily produced by additive manufacturing (i.e. 3D printing) using the Direct Metal Laser Sintering (DMLS) or another material deposition process – hence the word "molded" in its name. In case of a long magnet, the central part can also be extruded or stamped to minimize fabrication time and cost and only the ends 3D printed.

## DOUBLE-COMB COIL PARAMETERS

To assess the magnet performance with the HTS inserts, a magnetic analysis was performed for four configurations shown in Fig. 2. The designs were based on the CORC® W5 cable [15] with the average reported $J_e$ of 365 A/mm$^2$ at 20 T and 4.2 K that was parameterized in the relevant range of the fields and temperatures according to [22]. In case A), the insert was designed to fit into the 60 mm bore of the Fermilab's 15 T dipole, and in case B) into the 123 mm bore formed by the outer coils of that magnet. The figure also shows the field distribution in the stand-alone HTS coil tests with and without the iron yoke.

The larger coil with 100 mm clear bore is envisioned as the first step in the technology demonstration based on the current generation of CORC® cables due to the large minimum cable bending diameter of 51 mm. The smaller insert coil with 40 mm clear bore and the minimum bending diameter of 18 mm can be made when more flexible cables based on the next generation of thinner REBCO tapes become available or from the Bi-2212 conductor.

Performances of the HTS coils are summarized in Tables 1 and 2 at different conditions. The maximum bore fields approach 13-18 T at 1.9 K for the two HTS coils powered to 100% of the Short Sample Limit (SSL) independently of the LTS magnet (with an extra pair of current leads and a power supply). When powered in series, the maximum bore fields of 8.4-11.5 T at 1.9 K are limited by the HTS performance.

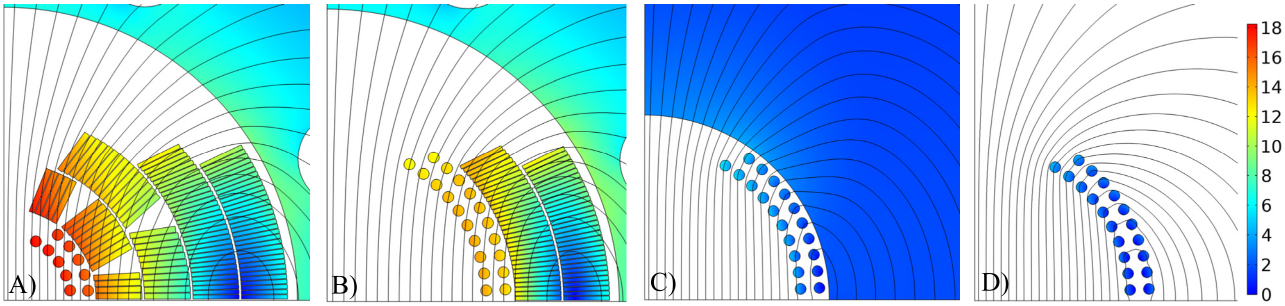


Figure 2: HTS insert fields (T) in 15 T dipole (A), in outer coils only (B) and stand-alone with/without iron yoke (C-D).

Table 1: A-B HTS Insert Performance at 4.5/1.9 K

| Test mode | Param. at SSL | Insert coil ID, mm | |
|---|---|---|---|
| | | 40 | 100 |
| HTS+LTS powered in series | $B_1$, T | 10.39/11.52 | 7.69/8.43 |
| | $B_p$, T | 10.91/12.11 | 8.63/9.48 |
| | I, kA | 5.96/6.72 | 7.09/7.95 |
| HTS+LTS powered separately | $B_1$, T | 16.15/17.77 | 11.82/12.93 |
| | $B_p$, T | 16.56/18.25 | 13.46/14.73 |
| | $I_{HTS}$, kA | 4.37/5.07 | 5.10/5.87 |
| | $I_{LTS}$, kA | 10.99/12.17 | 14.38/15.86 |

Table 2: C-D HTS Coil Performance at 77/4.5/1.9 K

| Test mode | Param. at SSL | Value |
|---|---|---|
| With iron yoke (OD = 400 mm) | $B_1$, T | 0.80 / 4.06 / 4.40 |
| | $B_p$, T | 1.06 / 5.27 / 5.73 |
| | I, kA | 1.92 / 10.19 / 11.22 |
| No iron yoke | $B_1$, T | 0.55 / 2.74 / 2.98 |
| | $B_p$, T | 0.85 / 4.22 / 4.60 |
| | I, kA | 2.42 / 11.96 / 13.02 |

While the bore fields are considerably smaller than in the case of independent powering, the forces on the HTS conductors are only 12% lower because of the increased current at lower fields, which makes this case is just as useful for evaluating the COMB structure performance. This mode can be realized with a single pair of leads and a power supply, but the quench protection of the HTS insert will require a careful consideration to avoid damaging it by the large energy stored in the LTS magnet.

In the stand-alone tests, the HTS coils can first be tested at the liquid nitrogen temperature to 0.5-0.8 T bore fields and then to 3-4.4 T bore fields at 1.9 K, depending on the presence of the iron yoke. While they do not reveal the full HTS performance, these can still be useful intermediate tests for demonstrating the COMB technology.

The structural analysis was performed for the worst case in terms of the total forces and stresses in the HTS coil, which corresponds to independent powering of design B) at 1.9 K. The following assumptions were used: the gap in the iron yoke closes during the cool-down and remains closed under all conditions (i.e. the shell/clamp system is strong enough to make it happen); there is a free sliding contact between HTS-LTS coils, LTS coil and the iron yoke as well as between the cables and the pole blocks in that coil; the coils are prestresses by means of the radial and azimuthal shims during the assembly at the room temperature to the level that all conductors stay in contact with the adjacent parts up to the maximum load; the COMB structure is made of 316L stainless steel.

The equivalent (von Mises) stresses in the coils and the support structure are shown in Fig. 3 after the cool-down and at the maximum current quoted in Table 1. After the cool-down, the stress is relatively uniform and on a level of 90-100 MPa in the HTS and the LTS coils. At the maximum current, the stress distribution changes with the bias towards the midplane and the peak stress reaches 160 MPa in the LTS coil (which is acceptable for $Nb_3Sn$ conductor). However, the peak stress in the HTS coil goes only slightly up to 110 MPa, which indicates the SM benefits of the COMB structure. This level of stress is low enough even for the strain-sensitive Bi-2212 [18], while the REBCO-based cables can tolerate stresses up to 170 MPa [15] without critical current degradation. The peak stress in the structure is only 143 MPa, which is ~1/2 of the yield stress for 316L stainless steel.

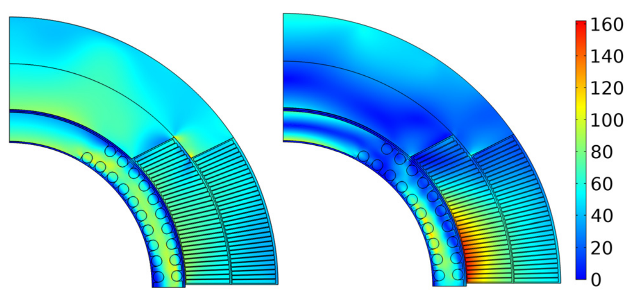


Figure 3: Equivalent stresses in the coils (MPa) after cool-down to 1.9 K (left) and at the maximum current (right).

## CONCLUSION

Design studies aimed at boosting the magnet performance for future hadron colliders are under way. The proposed COMB magnet technology offers unique benefits for reaching higher fields using the state of the art HTS materials. It is well suited for short models with a quick turn-around, while can also be easily scaled up for longer production magnets. Testing the first models stand-alone at 1.9 – 77 K is a valuable part of the technology demonstration, which can later be used as inserts in the LTS magnets to reach higher fields.

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