Development of a Bi2212 Dipole Insert at Fermilab

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***Abstract*— A goal of the U.S. Magnet Development Program (US-MDP) is high-field magnets for accelerators with magnetic fields larger than 15 T, i.e., above the limits of Nb_3Sn accelerator magnets. Composite round wires and Rutherford cables made of high temperature superconductor Bi2212 may achieve this goal. Bi2212 is sensitive to transverse stresses and strains, and this requires stress management in the coil design. A stress management approach was developed at Fermilab for high-field large-aperture Nb_3Sn accelerator magnets. Now it is being applied to high-field dipole insert coils based on Bi2212 Rutherford cable. This paper describes the insert coil design and main parameters, including the superconducting wire and cable. The coil will be installed inside a 60-mm bore Nb_3Sn dipole outsert coil and cold iron yoke. The Bi2212 coil will be tested individually and in series with the Nb_3Sn outsert coil. The expected Bi2212 insert test parameters are reported and discussed.**

***Index Terms*— Bi2212 strand; Rutherford cable; dipole insert coil; mechanical design; dipole structure**

I. INTRODUCTION

ADVANCEMENT of composite $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi2212) wires and Rutherford cables, allows considering them for high-field accelerator magnets with hybrid coils made of Bi2212 and Nb_3Sn superconductors. In the United States this effort is being conducted by the U.S. Magnet Development Program (US-MDP) [1]. The Fermilab part of the program is focused on shell-type dipole coils with stress control elements [2].

The initial design of Bi2212 insert dipole coils developed at Fermilab used a double-layer coil with small bore and outer diameter (OD) suitable for installation inside 60 mm bore Nb_3Sn dipole coils [3], [4]. This design made use of a Rutherford cable with Bi2212 strands. The Bi2212 insert turns were wound into a special structure that ensured appropriate turn location and limited the maximum level of strain and stress in the brittle Bi2212 cable throughout magnet assembly and operation. After winding at Fermilab, the coil was expected to be heat-treated at NHMFL in Oxygen under a gas pressure of 50 bar to create Bi2212 stoichiometry. Then it was intended to be sent back to Fermilab for potting with epoxy, instrumentation, assembly within the Nb_3Sn outsert coil and iron yoke, and finally testing.

Several double-layer coils were designed, and plastic parts for them were fabricated using Additive Manufacturing (AM) technology. Practice winding of critical turns using Cu, Nb_3Sn and Bi2212 cables, and winding of the whole two-layer practice coils revealed mechanical stability problems with Bi2212 cable winding around the narrow pole and midplane turns in the inner layer. As a consequence, the coil aperture was increased, and the coil design was changed to single layer.

This paper summarizes the possibilities and limitations of the double-layer coils and introduces the single-layer coil design with larger aperture. The single-layer coil was optimized for better field quality and equipped with a new coil support structure. The 3D structure of the coil ends, and the coil winding scheme are described, and the coil test configurations and target parameters are presented and discussed.

II. WIRE AND CABLE

The insert coils under development at Fermilab use a Rutherford cable with rectangular cross-section made at LBNL of Bi2212 composite wire produced by Bruker OST LLC. The cable cross-section is shown in Fig. 1 and its main parameters are reported in Table I. Since the coil turns are placed inside a metallic structure, the Bi2212 cable is insulated with thick multilayer Mullite insulation.

Fig. 1. Bi2212 Rutherford cable cross-section [4].

TABLE I
BI2212 STRAND AND CABLE PARAMETERS

Parameter	Value
Strand diameter before/after reaction [mm]	0.8/0.778
Strand twist pitch [mm]	25
Number of strands in cable	17
Cable width [mm]	7.8
Cable thickness [mm]	1.44
Cable transposition pitch [mm]	58
Cable piece length [m]	~15

III. DOUBLE-LAYER INSERT COILS

The cross-sections of the two first versions of the double-layer coils [2], [3] are shown in Fig. 2. The bore of these coils is limited by the width of the cable used and by an inner diameter of 60 mm of the Nb_3Sn outsert coil. The aperture was increased from 17 mm in v.1 to 19 mm in v.2 by using a single structure for both layers in v.2 instead of two separate structures for each layer in v.1.

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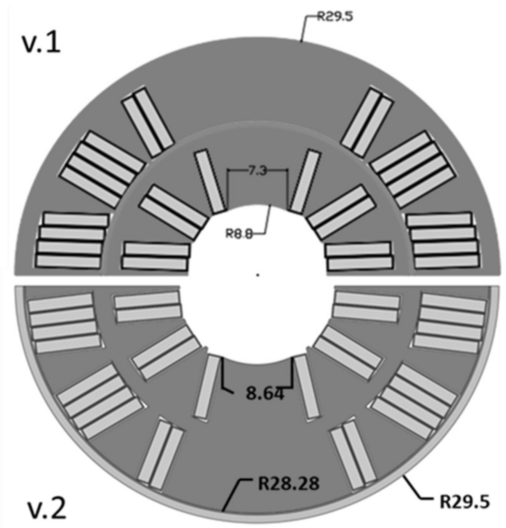

Fig. 2. Cross-sections of double-layer coils with 17 mm (top) and 19 mm (bottom) bore and different coil support structures.

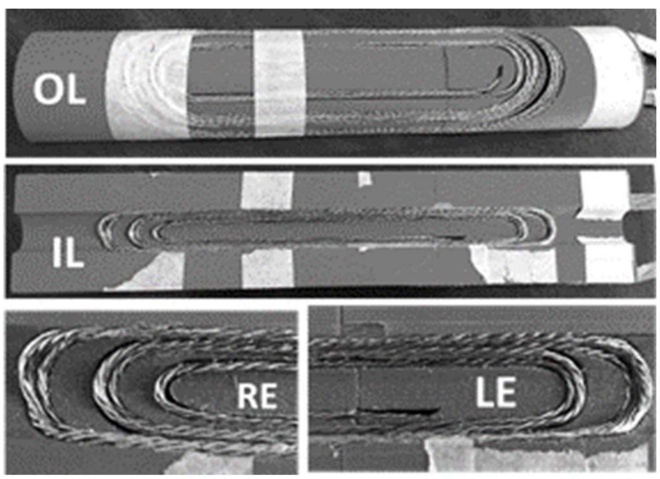

Fig. 3. Practice winding of double-layer coil into plastic structure.

The double-layer coils could produce a B_{max} in the bore of up to 4-6 T. The actual field value is controlled by the J_c of state-of-the-art Bi2212 wires. Both coil designs provided good field area in the aperture of ~10 mm in diameter. The plan for the first double-layer Bi2212 coil was to test it in a dipole mirror configuration inside a 60-mm Nb_3Sn coil [3]. For this configuration, the mechanical analysis has shown [3] that the maximum stress in the coil would be within the acceptable limits both for the Bi2212 turns (σ_{max}< 105 MPa) and for the coil structure, which would be made of Inconel 718 (σ_{max}< 700 MPa).

A critical parameter for coil winding is the width of the coil pole. Although it was increased from 7.3 mm in v.1 to 8.6 mm in v.2 it was still too small for winding 1.44 mm thick Bi2212 cable. Several plastic models of the straight section and the whole coil structure were made via AM technology. These models were used to study and practice winding of the coil end turns and the inter-layer jump.

Practice winding with Cu and Nb_3Sn cables of similar size as well as with actual Bi2212 cable has shown that preserving the cable mechanical stability during winding by pushing cable into grooves is challenging, especially for the inner layer due to the limited space for cable axial rotation by 180 degrees and small bending radiuses. In Fig. 3 this can be seen for a double-layer practice coil wound into a plastic structure. The winding of the inner-layer was tested both from inside and outside whereas the outer-layer was wound from outside. In addition, winding tests showed that bending the actual Bi2212 cable around the small inner pole may cause Bi2212 strand breakage in a cable of this size. Based on these studies the design was changed to a single-layer coil. The work on cable design and parameters as well as on structure and winding of double-layer coils continues.

IV. Single-layer Insert Coil Designs and Parameters

A. 2D Coil Design and Parameters

The enhanced Bi2212 insert uses a single-layer shell-type coil wound into a metallic structure. The coil structure ensures the design turn positions and provides turn stress management throughout fabrication and operation. As for the double-layer coils, the single-layer coil is to be placed and tested inside 60-mm bore Nb_3Sn dipole coils [5]. This determines an insert coil OD of 59 mm, providing a radial gap of 0.5 mm for the Bi2212-Nb_3Sn inter-coil insulation and instrumentation such as voltage taps and strain gauges.

The single-layer coil cross-section was optimized using the *ROXIE* code [6] inside the iron yoke with an inner diameter of 100 mm and constant magnetic permeability of 1000. Fig. 4 shows the final coil cross-section with the calculated field quality dB/B in the bore and the B field distribution in the coil turns at a current of 8 kA. Table II summarizes the main coil parameters. The good field quality area (the dark area in the bore in Fig. 4), where relative field variations dB/B with respect to the main dipole component B are less than $3 \cdot 10^{-4}$, is practically circular with a diameter close to 16 mm.

Table II
Parameters of Bi2212 insert with optimized coil

Parameter	Value
Number of layers/blocks/turns	1/4/8
Coil ID/OD [mm]	40/58
Coil B_{max}/I [T/kA]	0.284
Minimal pole width [mm]	19
Coil B_o/I [T/kA]	0.254
B_{max}/B_o	1.12

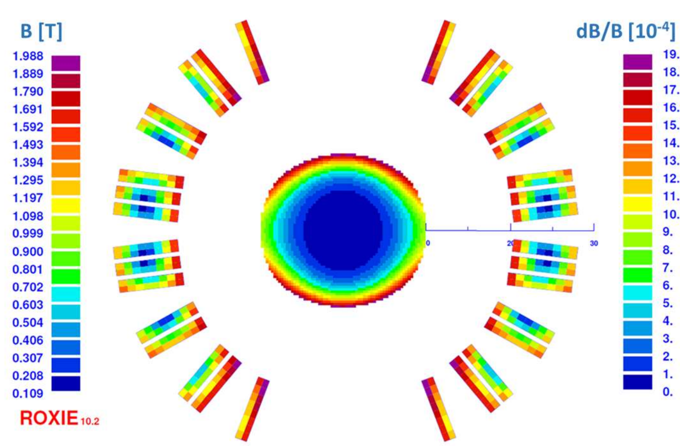

Fig. 4. The optimized single-layer coil cross-section with the field quality diagram in the bore and the field distribution in the coil turns at 8 kA current.

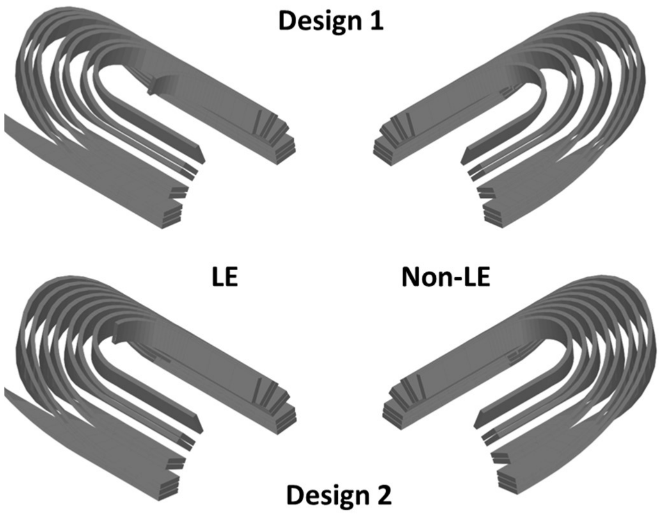

Fig. 5. Two designs of lead end (LE) and non-LE of the single-layer insert coil.

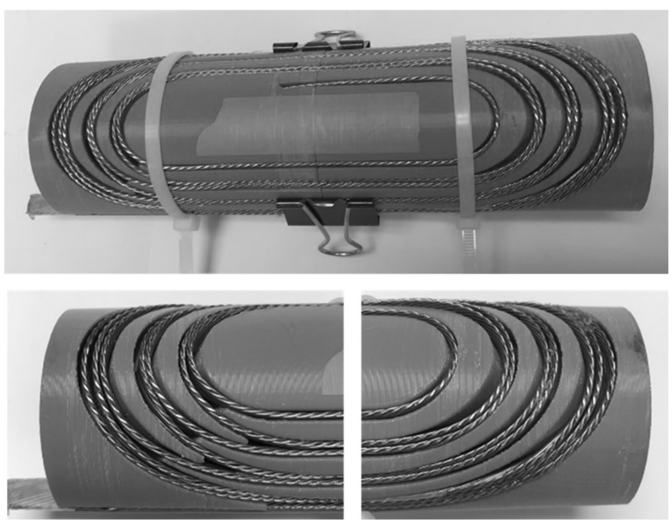

Fig. 6. Single-layer plastic half-coil (top) and practice half-coil LE (bottom left) and non-LE (bottom right) views. One can see the short inter-block cable transitions in the LE on the bottom left picture. The size of coil end blocks needs to be optimized to minimize the gaps between turns and structure.

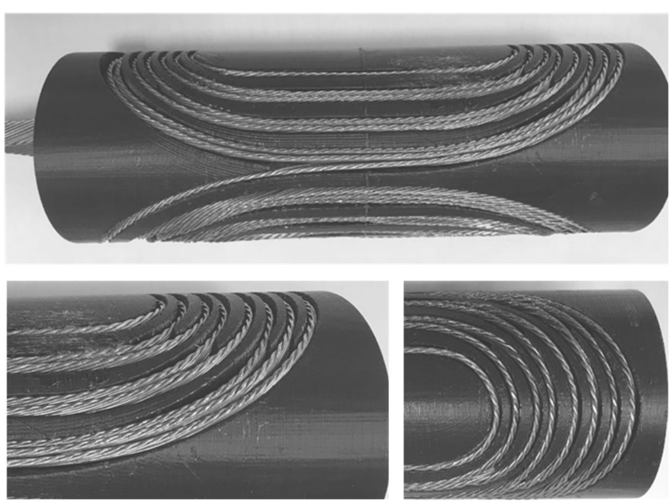

Fig. 7. Single-layer cylindrical dipole coil with a cable transition between the top and bottom half-coils (top) and non-LE site (bottom left) and top (bottom right) views of practice coil. The last block in the LE was fabricated without interturn spacers to test and compare two approaches to the coil end winding.

B. 3D Coil End Designs

The coil ends were designed using the 3D *ROXIE* code to optimize their length, produce coil blocks acceptable for winding the Bi2212 Rutherford cable, and minimize transitions between coil end blocks. Fig. 5 shows the 3D view of the two design versions of the single-layer coil ends. In Design 1 the end turns are grouped in blocks as in the coil straight section. In Design 2, to simplify winding, each end turn is placed in its separate grove. The inter-block transitions in Design 1 are short, i.e. inside one quadrant. The pole leads (not shown) in both designs are removed through the coil bore.

C. Practice Coil Winding

As in the case of double-layer coils, the single-layer plastic parts were produced using AM technology and practice winding was done to develop coil winding tooling and optimize the coil design and winding processes. Practice coil overall and coil end views of both coil designs of the single-layer coil are shown in Figs. 6 and 7. The coil with Design 1 ends was modeled using a traditional half-coil approach. The coil with Design 2 ends was modeled using a common cylindrical structure for both half-coils with the inter-coil cable transition placed in a special slot in the support structure (see Fig. 7, top). This approach minimizes the total length of cable leads and the number of lead splices. Both practice coils were successfully wound using a non-insulated Cu cable. The size of the coil end blocks will be further optimized for the real Bi2212 cable to minimize the gaps between turns and structure.

V. Single-layer Bi2212 Coil Parameters

A. Conductor Limit

The Bi2212 single-layer insert is to be tested in a dipole configuration using coils and magnet structure of the 11 T dipole MBHSP developed at Fermilab for the LHC upgrades [5]. Fig. 8 shows the dipole cross-section with the single-layer Bi2212 coil inside the 60-mm bore double-layer Nb_3Sn coil.

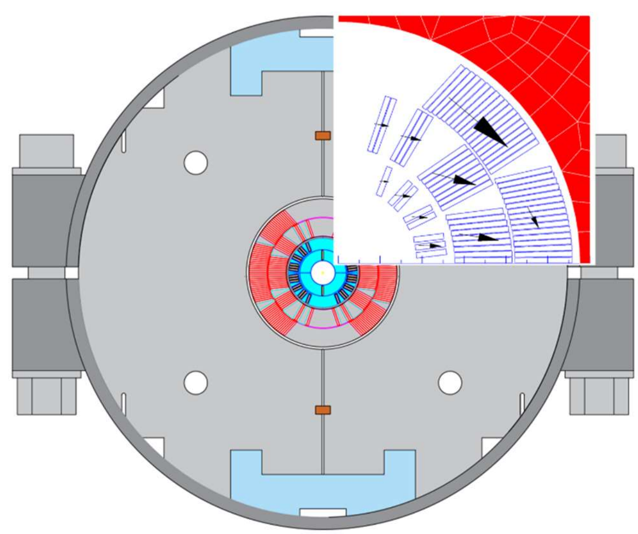

Fig. 8. Bi2212 dipole insert in the 11 T dipole coil [5]. The upper-right quadrant shows the Lorentz forces in the coil blocks.

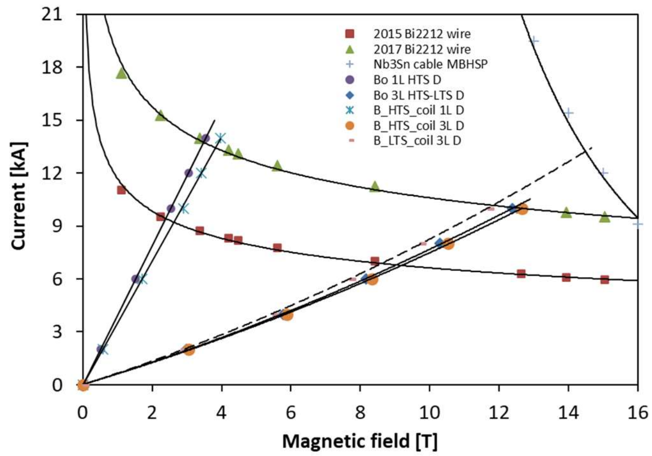

Fig. 9. $I_c(B)$ curves and *I-B* load lines of Bi2212 and Nb_3Sn coils in various test configurations.

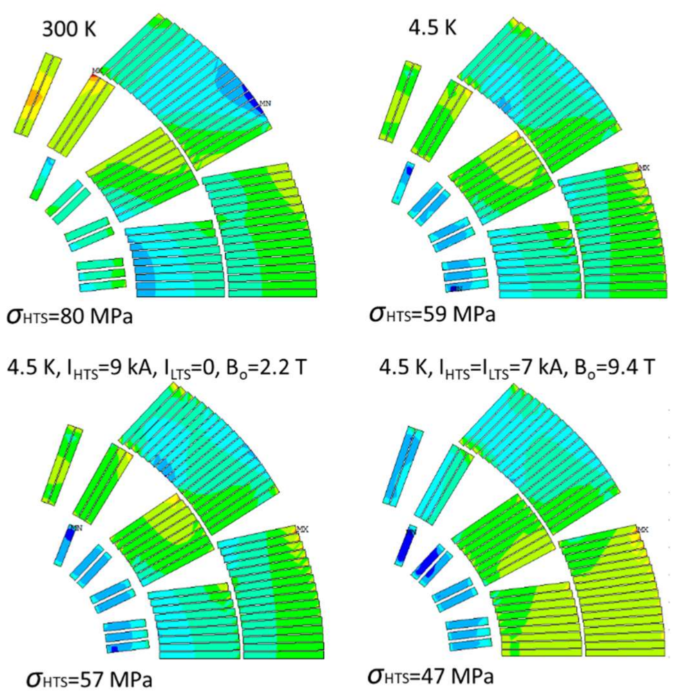

Fig. 10. Stress distributions in Bi2212 and Nb_3Sn coils after assembly and cool-down (top), at 9 kA for independent Bi2212 coil powering (bottom left) and at 7 kA for Bi2212 and Nb_3Sn coils powered in series (bottom right).

Short sample limits of the single-layer insert coil were estimated for the present cable with both a value of strand critical current I_c of 460 A (2015 Bi2212 wire) and of 630 A for more advanced 2017 Bi2212 wires. Fig. 9 shows the $I_c(B)$ curves and load lines of Bi2212 and Nb_3Sn dipole coils. The calculated field limit of the first individually powered single-layer Bi2212 dipole coil with 2015 strand is 2.7 T. It is achieved at the coil maximum current of 9 kA. In the three-layer hybrid dipole the field and current limits are 9.5 T and 6.5 kA respectively.

With Bi2212 wires produced after 2017, based on Fig. 9, the maximum field of the individually powered single-layer Bi2212 dipole coil increases to 3.8 T at ~14 kA. In the three-layer hybrid dipole with the Bi2212 and Nb_3Sn coils connected in series, the magnet maximum field and coil current will increase to 12.5 T and ~10 kA respectively.

B. *Mechanical Analysis*

The results of mechanical analyses performed using ANSYS for the described dipole configurations are shown in Fig. 8. The stress distribution and the maximum stress level were calculated in the Bi2212 and Nb_3Sn coil turns and the Bi2212 coil structure made of Inconel 718, and in the main elements of the dipole structure shown in Fig. 8, including iron yoke, aluminum clamps, stainless steel bolted skin and bolts using the material properties in [3]. The calculations were performed at room temperature after magnet assembly (Fig. 10, top left), after magnet cool down to liquid Helium temperatures at zero (Fig. 10, top right) and at a current of 9 kA only in the Bi2212 coil (Fig. 10, bottom left) and at current of 7 kA in both Bi2212 and Nb_3Sn coils powered in series (Fig. 10, bottom right).

The calculated maximum stress in the Bi2212 turns inside the Inconel 718 structure is 80 MPa. It is attained at room temperature after magnet assembly. At all the other conditions the maximum stress in the Bi2212 coil is less than 60 MPa. Since the Nb_3Sn outsert coil will operate in magnetic fields up to 9-10 T, its maximum stress is also low, i.e., less than 130 MPa at all conditions. The maximum stresses in the support structure of the Bi2212 coil and other elements of the magnet support structure are relatively low, lower than in the double-layer coil designs [3].

VI. Conclusion

Fermilab, in the framework of the US-MDP, is developing an insert dipole coil based on Bi2212 Rutherford cable and Stress Management Coil Structure. Several designs of small-bore double-layer and single-layer Bi2212 insert coils and coil structures were generated and studied. The maximum field in the double-layer inserts can reach 4-6 T and in the single-layer insert up to 3-4 T. The maximum field is limited by the space available for the Bi2212 insert coil inside the 60-mm bore outsert and by the present performance of Bi2212 wires and Rutherford cables. The maximum stresses in both Bi2212 coil options, including the coil support structure, are within the acceptable limits for the Bi2212 cable and for a support structure made of Inconel 718.

Winding of double-layer practice coils with several cross-section iterations using plastic parts and dummy cables revealed mechanical stability problems and even risk of strand damage in Bi2212 cable. It was therefore decided to proceed with a larger-bore single-layer coil. A single-layer insert coil with two end design versions, as well as the basic technological solutions, were developed and successfully tested using plastic coil structures and practice Cu cable. The final coil design was selected and will be studied experimentally on a series of short coils in a dipole configuration with Nb_3Sn 11 T outsert coils. Tests of the first Bi2212 coil in this dipole configuration are planned for the second part of 2023.

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