INSERT COIL TEST FOR HEP HIGH FIELD MAGNETS USING YBa$_2$Cu$_3$O$_{7-\delta}$ COATED CONDUCTOR TAPES

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ABSTRACT

The final beam cooling stages of a Muon Collider may require DC solenoid magnets with magnetic fields of 30-50 T. In this paper we present progress in insert coil development using commercially available YBa$_2$Cu$_3$O$_{7-\delta}$ Coated Conductor. Technological aspects covered in the development, including coil geometry, insulation, manufacturing process and testing are summarized and discussed. Test results of double pancake coils operated in liquid nitrogen and liquid helium are presented and compared with the performance of YBa$_2$Cu$_3$O$_{7-\delta}$ tape short samples.

KEYWORDS: Superconducting magnets, High Field Solenoids, YBCO, anisotropy.

INTRODUCTION

The final stage of cooling [1-5] of a Muon Collider requires solenoids generating magnetic fields in the range of 30-50 T. High temperature superconductors may be used for the manufacturing of such magnets, since state-of-the-art low temperature superconductors - such as Nb$_3$Sn - show critical fields well below the levels required by the conceptual designs of the new machine. When it comes to high field applications, YBCO has very interesting electrical and mechanical properties [6], does not need reaction, but shows highly anisotropic behavior with respect with field orientation, which needs to be accounted for in magnet design. YBCO comes only in tapes with rectangular cross section, which suits well the application in solenoid configurations. In the following all the aspects from insert coil manufacturing to short sample estimation and test results are described.
COILS GEOMETRY AND WINDING PROCESS

The YBCO tape used for this work has been manufactured by SuperPower and insulated with a thin spiral wrapped kapton layer. Each insert coil has been wound in a double pancake configuration using about 27.8 meters of tape, resulting in a total of 216 turns per coil. An external diameter of 62 mm has been chosen mainly due to limitations in the cold bore of the outsert magnets whereas the internal diameter has been fixed to 19 mm, according to the bending tests described in [7]. Some margin over the critical bending diameter of 11 mm has been accounted for in order to provide enough room for the coil winding support and the insertion of an axial Hall probe. The winding procedure has been specifically designed to avoid any electrical joint between two single pancake coils on the inner diameter as shown in FIGURE 1. This approach reduces the number of splices in the coil, eliminating the need for a splice on the inner diameter, which poses some manufacturing challenges and is subjected to limited cooling conditions during coil operation.

Half of the needed material needs to be spooled on a temporary support as shown in FIGURE 2 so that the winding of the actual coil can be performed using the same piece length for both half coils. A special stainless steel winding kernel has been machined with a shallow spiral support to accommodate the innermost turn of the coil. Even on an internal diameter of 19 mm, the level of hard bending in the tape due to the spiral groove is not believed to induce any performance degradation.
SINGLE COIL

In order to provide feedback to coil manufacturing, a double pancake coil was dry-wound, mounted on a test rig, supported with several turns of SS tape wound on top of the last insulated turn and tested in liquid nitrogen and liquid helium.

Liquid Nitrogen Test

Given the self-field conditions and the highly anisotropic behavior of the tape, the coil performance is limited by the field components perpendicular to the ab plane of the tape. In FIGURE 3 the typical in-field behavior of the YBCO tape at 77 K is shown together with the load line associated to the self-field operation. A critical current of about 40 A was estimated, resulting in a peak radial field of about 180 mT as shown in FIGURE 3.

![FIGURE 3](image.png)

FIGURE 3. (a) Radial Field load line at 77 K. (b) Radial Field distribution at the edge of the coil.

The coil was instrumented with a single pair of voltage taps monitoring the whole length of the coil and mounted on the test rig for testing. FIGURE 4 shows the VI curve for the coil confirming voltage development at the expected level of 40 A. The tape used for this unit winding had a nominal average short sample critical current at 77K, self-field of 113 A. The coil was cycled several time from 77 K to room temperature and tested again for I_c to check for possible degradation due to thermal shock. No degradation has been registered for the coil even after several cycles as shown in FIGURE 4.

![FIGURE 4](image.png)

FIGURE 4. VI curves of double pancake unit from different thermal cycles in liquid nitrogen.
Liquid Helium Test

Following the test in liquid nitrogen, the coil was cooled down to liquid helium in a vessel equipped with a hybrid Nb$_3$Sn/NbTi magnet providing up to 14T in a 77 mm cold bore. In order to estimate the performance of the coil, the distribution of the background magnetic field was simulated together with the additional field provided by the insert. With this information the critical current parameterization shown in [7] was used to estimate 498 A as short sample limit for this magnet, corresponding to a limiting field angle of about 8.8 degrees with respect to the ab plane of the tape, a peak central field of 17 T and a peak field on the conductor of 18.2 T in a 13.5 T background field as shown in FIGURE 4.

**FIGURE 4.** Magnetic field distribution at z=0; field, angle and Ic maps on HTS insert volumes.

The field distribution on the conductor and critical current estimation maps are shown in FIGURE 4, whereas the VI curve and the Hall probe readings are shown in FIGURE 5.

**FIGURE 5.** (a) VI curve of double pancake unit at 4.2 K in 13.5 T background field (b) Hall probe reading.
After the first test in helium, a total of 7 coils were wound following the same winding procedure previously described. Resistance at room temperature and inductance was measured on each coil right after winding and the values are in line with the estimated values as shown in FIGURE 6, therefore excluding any turn to turn short.

Single Coils Liquid Nitrogen Tests

Each double pancake coil was then separately mounted on the test rig and cooled down in liquid nitrogen.

The YBCO material used to wind the coils was delivered in three different spools, each one containing several 30 meters piece length, coming from different production runs. For each 30 meters piece length, average $I_c$ and minimum $I_c$ were reported by the manufacturer. Using the minimum $I_c(77K,0T)$ value reported on the datasheets and the curve in FIGURE 3 was scaled and used to estimate each coil critical current in nitrogen under self-field conditions. The results are shown in FIGURE 6, where the estimated coil critical current is plotted against the minimum short sample $I_c$ from each spool. Each coil was then separately tested for $I_c$. FIGURE 6 shows a summary of the results obtained using a $1\mu V/cm$ criterion. Coils from Spool 2 and 3 agrees closely with the predictions, whereas coils from Spool 1 show critical current values a few amps higher than the prediction, pointing to the fact that a separate measurement of anisotropy in nitrogen may
be needed for each single spool together with a measurement of how reproducible the anisotropic behavior is along the length of the conductor. FIGURE 7 shows the VI curves from all the coils. Each coil was tested more than once and cycled to room temperature with no performance degradation.

FIGURE 7. VI curve for each of the seven wounded coils measured independently in liquid nitrogen.

Multi Coil Nitrogen Test

After the preliminary tests, the best four performing coils were chosen and assembled together as shown in FIGURE 8. The best two performing coils were used as the two edges of the insert. The test rig has been designed to be modular so the top and bottom copper rings can easily slide up and down and fixed to accommodate different coil geometries. Further details on the design of the test setup can be found in [8].

FIGURE 8. Four YBCO double pancake coils assembled on the test rig before instrumentation.

The coils were bridged together on the outer diameter using 8 mm wider YBCO tape, cut from a 12 mm tape commercially available from SuperPower. Each coil was instrumented with a pair of voltage taps, each one monitoring roughly 28 meters of superconductor. The whole assembled coil was then supported by winding a 2 mm thick stainless steel support after applying ground insulation. This 4-coils pack was estimate to
carry about 32 A by evaluating the radial field distribution at the coil edge as shown in FIGURE 9.

![Radial Field Distribution](image)

**FIGURE 9.** (a) Typical $I_c$ versus radial field behavior of YBCO samples scaled on the minimum $I_c(77K,0T)$ measured from short samples of the weakest of the two edge coils (b) Radial Field distribution at the edge of the insert coil for a coil current of 32 A.

FIGURE 10 shows the voltage signals acquired from each of the 4 coils while ramping the current at a rate of 0.25A/s. The first coil to show voltage development is Coil 4, which is the weakest of the two edge coil, as expected, at the level of 32A evaluated using a criterion of 0.1 µV/cm. The quench is then seen in the two middle coils and finally in the top coil as well.

![Voltage Signals](image)

**FIGURE 10.** VI curves at 77 K for the four double pancakes assembled in the insert coil.

Helium Test

The same coil was then cooled down to liquid helium and tested in a background field of 14 T. The test showed a maximum coil current of 335 A, resulting in a peak central field of 21.2 T and a peak field of the conductor of about 21.6 T as shown in FIGURE 11. For this test the limiting factor was due to a poorly manufactured joint between two of the coils. The first coil to show voltage is not an edge coil, but one of the middle ones, resulting in 92% of the short sample limit for this magnet.

CONCLUSIONS

In this paper, the manufacture and test of YBCO double pancake coils have been described together with short sample estimation techniques. Test results for both liquid nitrogen and liquid helium temperatures have been presented and discussed.
FIGURE 11. (a) Magnetic field distribution at z=0 (b) VI curve for each of the four coil at 4.2 K, in a 14T background field (c) Magnetic field map of YBCO insert coil and outsert Nb$_3$Sn/NbTi coil.

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