HTS Dipole Insert Developments

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***Abstract*—Future accelerator magnets will need to reach a magnetic field in the 20 T range. Reaching such a magnetic field is a challenge only reachable using high temperature superconductor (HTS) material. The high current densities and stress levels needed to satisfy the design criterion of such magnets make YBaCuO superconductor the most appropriate candidate especially when produced using the IBAD route. The HFM EUCARD program is aimed at designing and manufacturing a dipole insert made of HTS material generating 6 T inside a Nb_3Sn dipole of 13 T at 4.2 K. In the HTS insert, engineering current densities higher than 250 MA/m^2 under 19 T are required to reach the performances. The stress level is consequently very high. The insert protection is also a critical issue as HTS shows low quench propagation velocity. The coupling with the Nb_3Sn dipole makes the problem even more difficult. The magnetic and mechanical designs of the HTS insert will be presented as well as the technological developments underway to realize this compact dipole insert.**

***Index Terms*—High field magnet, high temperature superconductor, YBaCuO.**

I. Introduction

EUCARD PROGRAM has as primary goal to develop instruments and technologies for future accelerators [1]. High temperature superconductors (HTS) like YBaCuO (YBCO) are a non-negligible option for the magnets of future accelerators [2]. It permits to reach the very high field required thanks to their outstanding in field current capacities. In order to produce these kinds of magnets, the orientation of the field with respect to the HTS tape should be studied with caution [3], innovative protection scheme is needed [4], [5] and some technological developments are needed to withstand the high stress level. The objective of the study is to build a HTS magnet producing 6 T in an aperture of 99 mm inserted in a Nb_3Sn dipole of 13 T [6]. The design and the realization of this insert are mainly driven by the control of the stresses in all parts of the magnet. The magnetic aspect only considers a central field of 6 T, the field quality is not taken into account for this first magnet.

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TABLE I
Magnet Characteristics

Coil number and Location	Number of turns	Length (mm), heads included
1-1' mid plane	73	700
2-2' medium	61	350
3-3' external	35	326

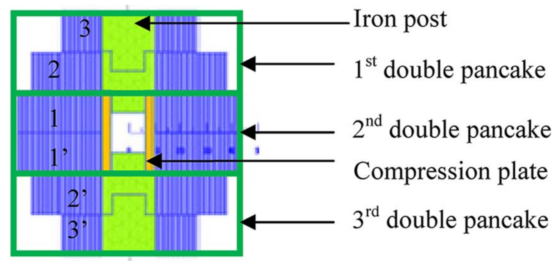

Fig. 1. Structure of the insert in 2D: three double-pancakes, iron post, and compression plates.

II. Insert Magnet Configuration

A. Configuration and Geometry

The outsert in Nb_3Sn imposes some constrains on the HTS insert presented in [7]. The block type configuration suits very well the YBaCuO tape geometry, both for the winding and the magnetic field orientation mainly in the favorable longitudinal direction [7], [8].

Taking in to account the 99 mm external diameter, the 10 mm internal radius and the 12 mm height of the pancake (tape width), the insert consists of 6 coils: one central double-pancake of 73 turns and two external double-pancakes. The external double-pancake has 61 turns on the first coil and 35 turns on the second one (Table I and Fig. 1).

The insert is studied to be located in the straight section of the Nb_3Sn outsert. That is why the central double-pancakes have the same length of the straight part of the outsert: 700 mm. It is longer than the external double-pancakes in order to reduce the peak field problems at the edges. Layer jumps are installed in the straight parts of the pancakes, each of the twinned conductors having his layer jump in one straight length. Therefore

TABLE II
INFLUENCE OF THE IRON POST

	B0 (T)	B_{peak} (T)	B_{peak} heads (T)	$B\perp_{peak}$ straight section (T)/B at this place	$B\perp_{peak}$ heads (T)/B at this place
No post	5.5	6	6	2.5/3.11	2.05/3.15
Post	6.1	5.8	5.8	2.7/3.2	1.5/3.1

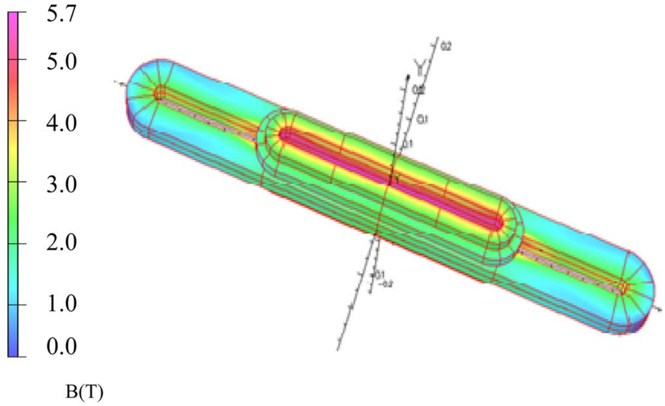

Fig. 2. Magnetic field in the insert.

the number of turns per pancake is odd despite the fact that the conductor is twinned (Table I).

B. Influence of the Iron Post

An iron post (Fig. 1) is placed in the center of the coils to improve the main field. Table II shows clearly the contribution of 10% of the post on the main field. The peak field is quite the same with or without the iron yoke. Its influence is studied carefully, especially the perpendicular field [6], [7] with a current density of 250 A/mm^2: maximal perpendicular field is studied on the straight section and on the heads without or with iron and evaluated to the field at this place. We see that without post, $B \perp max$ in the straight section represents 80% of the field without iron and 84% with iron. In the heads, $B \perp max$ represents only 48% of the field in the case with iron, against 65% in the case with iron. Hence we see the benefit of the iron in the heads. Influence of the perpendicular field on the current density is presented next paragraph.

C. Magnetic Field

As mentioned in Table II and Fig. 2, the insert has a central field of 6.1 T and a peak field of 5.9 T located on the first turn of the first block in the middle of the straight section. The inductance is 4 mH and the stored energy equals 16 kJ for a current density of 250 MA/m^2.

Influence of the perpendicular field on the current density has been detailed clearly in [7]: Jc versus B was plotted in the different critical points ($Bmax$ and $B \perp max$ in the straight section and the heads) for a 19 T background field. The most critical location was found to be in the straight section of coil 3. Locally due to the field orientation, the critical current is reduced to around 3550 A for an operating current of 2800 A: the margin in current is thus around 27%. By comparison where

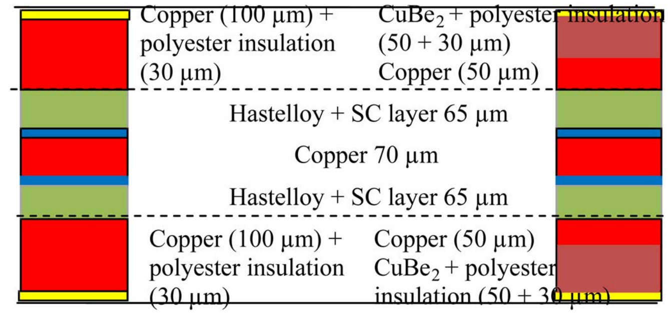

Fig. 3. Schematic cross-section of the conductor (a) with Cu alone or (b) with CuBe$_2$. In yellow the polyester insulation (30 μm in each case), in red, the copper, in purple the CuBe2, in brown the hastelloy, and in blue the superconductor. The dotted line indicates a contact between the three tapes.

there is no perpendicular field the margin is around 70%. It should be noted that this location is at the edge of a tape and that the opposite tape edge shows a far lower perpendicular field component, therefore the margin over the whole tape is greater than the calculated 27%.

III. CONDUCTOR DEFINITION

A. Structure of the Conductor

The conductor has been thought to fulfill several requirements:

– High current capacity
– Flexibility in the winding
– YBaCuO layer close to the neutral axis to limit stress in the coil ends
– Low resistance connections
– Mechanical resistance over 400 MPa

The conductor for the insert is made by assembling two tapes. The two YBaCuO layers are not transposed and behave like a thick superconducting layer. The two tapes are soldered together face to face (closest YBaCuO layers) through a Cu tape of the same thickness for the connection. The soldering eases the current redistribution between the two tapes. The tape thickness is about 65 μm taking into account the Cu deposition above the Ag shunt for the soldering and a substrate of 50 μm. Two complementary copper tapes are placed in contact with the two YBCO tapes as shown on Fig. 3(a). The copper is required for electrical stabilization and to facilitate quench protection. These Cu tapes are not soldered to improve the flexibility of the conductor. Unfortunately pure copper tapes cannot hold the stress levels in the winding under 19 T. Reinforcement of the stabilizer is therefore required. The pure copper tape has been divided into two tapes, one of pure copper for its electrical properties and acting as a protection and one of $CuBe_2$ alloy for its mechanical properties close to the hastelloy substrate [9] and acting as a reinforcement [Fig. 3(b)].

In order to increase the operating current and reduce the time constant to dump the stored energy, the conductor is co-wound in pairs.

B. Characterization of $CuBe_2$

Different experiments have been done to determine the resistivity and mechanical properties of $CuBe_2$ (ultimate stress,

TABLE III
RESISTIVITY OF $CuBe_2$

	Resistivity at 77 K	Resistivity at 300 K
$CuBe_2$	$6.9.10^{-8}$	$8.7.10^{8}$
Annealed$CuBe_2$	$5.4.10^{-8}$	$6.8.10^{-8}$

TABLE IV
TENSILE TESTS ON $CuBe_2$ (77 AND 300 K)

	Ultimate stress (MPa)	Elastic stress (MPa)	Maximal elongation (%)
$CuBe_2$ (77 K)	910	750	30
Annealed $CuBe_2$ (77 K)	1530	1280	7
$CuBe_2$ (300 K)	685	570	16
Annealed $CuBe_2$ (300 K)	1250	950	3

elastic stress and maximal elongation) at 77 K and 300 K. Measurements were done with two different $CuBe_2$ tapes of 12 mm wide and 135 μm thickness: some have been annealed at 300°C during 3 hours contrary to the other ones. Table III shows the results of the resistivity of $CuBe_2$.(Table IV)

Tensile tests have been done thanks to Instron Calibration Lab 5500 R. The samples are fixed between two pads from a distance of 70 mm. The velocity of the stretching is 4 mm/s.

$CuBe_2$, annealed or not, confirms the good mechanical resistance of this material at 77 K. Protection calculations are underway to definitively choose one of the conductor or a solution between the two conductors: a compromise should be done as we will need $CuBe_2$ for mechanical reasons and Cu for protection.

C. Electrical Insulation of the Conductor

The turn to turn electrical insulation is a polyester tape of 30 μm applied on the external face of the $CuBe_2$. A ground and inter-pancake of 0.2 mm made of G10 foils is added between each coils to insulate them between them.

D. Protection

Protection of this insert and what happens in case of quench of the insert or the outsert is presented by E. Häro [5].

IV. MECHANICAL STRUCTURE

A preliminary magnetic design has been defined to determine forces in the structure. The configuration chosen is the worst case scenario i.e. with the Nb_3Sn field contribution of 13 T under a total field of 19 T. In this configuration, the maximum deformation must be inferior to 0.5 mm: the insert should transfer no load on the Nb_3Sn dipole. After evaluating forces on the blocks of the insert, we defined the structure and materials to support them and then we reorganized the coils position.

The structure presented in Fig. 4 is designed to maintain resulting forces on half of the coils equal to 7.36 MN/m in the horizontal direction and null on the vertical direction in the straight section. Forces on the heads are negligible compared to forces in the straight section. Von Mises stresses on the coils are evaluated to around 300 MPa with some peak stress at 400 MPa. Conductors with $CuBe_2$ are considered to support stresses up to 500 MPa and those with only Cu only 300 MPa. These results confirm the relevancy of adding $CuBe_2$ in conductors.

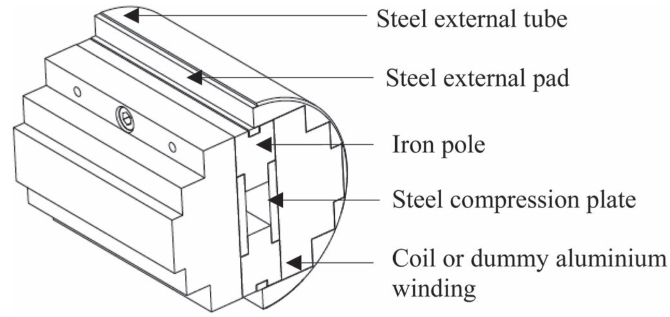

Fig. 4. Mechanical structure of the insert.

To maintain forces and to not load them on the Nb_3Sn dipole, no impregnation is envisaged on the coils due to the possible delamination of the conductors [11]. An efficient system of pads and tube is planned with the following purpose for each component:

– External pad: it is used to apply uniformly the load from the coil winding to the external tube. The Von Mises stresses on the pad can be up to 800 MPa on some critical points. The material used will probably be 304 stainless steel due to its high elastic limit [12].
– Compression plate: they reduce the oval shape induced by the magnetic loads by keeping the compression stiffness in the Y direction.
– Pole: they ensure the compression stiffness in the Y direction by applying load on the compression plates. The material is iron for its magnetic contribution
– External tube: it carries the resulting load and limits the deformation. Due to the magnetic forces it will become ovoid. The material will be Nitronic alloy high elastic limit. Its thickness is 3 mm optimized to have stresses around 500 MPa [7].

V. ASSEMBLY

The conductor will be in three ribbons: one Cu + $CuBe_2$ insulated, one SC + Cu + SC and then one Cu + $CuBe_2$ insulated. As we will wind in pairs, six ribbons will be wound together and maintained by contact (winding tension are enough to maintain them). Mid-plane pancakes will be wound together around the compression plates. Other coils will be wound as double-pancake around the iron post (separated in 2 parts, see Fig. 1) and piled on the first coils.

Then pads of 100 mm will be fitted in staggered rows of 50 mm all along the coils. They will be cut by electro erosion at LNCMI-Grenoble. A first test has been done successfully as presented in Fig. 5. Then they will be electron beam welded. Preliminary welding trials are underway at Cern.

The external tube will be assembled in 8 parts of 100 mm on the external pads. As the internal radius of the tube (93 mm)

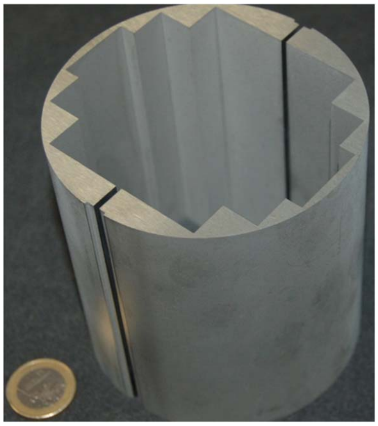

Fig. 5. First test of electro-erosion of a pad of 100 mm.

equals the external tube of the pads, we are currently study the assembly of the tube on the pads by thermal shrinkage. The solution plans to heat the tube with temperature over 500 K and to slide it over the pad. Moreover, the tube in seven parts is easier to assemble than a longer one.

The tube is then half-recovered with kapton to ensure the electric insulation between the insert and the Nb_3Sn dipole.

A mock up with a dummy aluminum winding is planned to validate all the steps of the presented assembly.

VI. Conclusion

The design for the HTS insert is now well advanced. New developments have been realized and validated. A pancake prototype will be built and tested in different field directions to confirm models and influence of perpendicular fields. Using these results, the insert will be realized and tested in the dipole FRESCA II [6] to reach a central field of 19 T in the test station.

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