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Devaux, M (CEA-ifu) *et al*

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M. Devaux, F. Debray, J. Fleiter, P. Fazilleau, T. Lécrevisse, C. Pes, J-M. Rey, J-M Rifflet, M. Sorbi, A. Stenvall, P. Tixador, G. Volpini

***Abstract*— Future accelerator magnets will need to reach higher field in the range of 20 T. This field level is very difficult to reach using only Low Temperature Superconductor materials whereas High Temperature Superconductors (HTS) provide interesting opportunities. High current densities and stress levels are needed to design such magnets. YBCO superconductor indeed carries large current densities under high magnetic field and provides good mechanical properties especially when produced using the IBAD approach. The HFM EUCARD program studies the design and the realization of an HTS insert of 6 T inside a Nb_3Sn dipole of 13T at 4.2 K. In the HTS insert, engineering current densities higher than 250 MA/m^2 under 19 T are required to fulfill the specifications. The stress level is also very severe. YBCO IBAD tapes theoretically meet these challenges from presented measurements. The insert protection is also a critical because HTS materials show low quench propagation velocities and the coupling with the Nb_3Sn magnet makes the problem even more challenging. The magnetic and mechanical designs of the HTS insert as well as some protection investigation ways will be presented.**

***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. Using high temperature superconductor (HTS) like YBaCuO (YBCO) or Bi-2212 in the magnets for future accelerators will be impossible to avoid. 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 [1-3], the stress level should be well controlled and new way of protection should be developed [4]. The objective of the study is to demonstrate the feasibility of a HTS magnet of 6 T in an aperture of 99 mm inserted in a Nb_3Sn dipole of 13 T. The design of this insert is mainly driven by the mechanical structure: an external tube of 3 mm with pads is used to maintain forces, as detailed on the seventh section. On the magnetic aspect, only the central field of 6 T is considered, the field quality is not taken into account for this first magnet.

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M. Devaux, P. Fazilleau, T. Lécrevisse, C. Pes, J-M. Rey and J-M. Rifflet are with the CEA-DSM-IRFU-SACM, France, melanie.devaux@cea.fr.
J. Fleiter is with CERN, Geneva, Switzerland.
F. Debray is with the Laboratoire National des Champs Magnétiques Intenses, LNCMI, CNRS/UJF/INSA/UPS 38042 Grenoble, France
M. Sorbi and G. Volpini are with INFN Sezione di Milano LASA, Milano, Italy.
A. Stenvall is with the Tampere University of Technology, Electromagnetics, P.O. Box 692, FIN-33101 Tampere, Finland.
P. Tixador is with the G2Elab/Institut Néel, CNRS/Grenoble-INP/UJF, 38042 Grenoble, France.

II. DESIGN CONSTRAINS

A. *Outsert in Nb_3Sn*

The HTS insert will be tested in the FRESCA 2 magnet done as task 7.3 of the EUCARD High Field Magnet project [5]. This Nb_3Sn magnet is designed as an accelerator like dipole, and will later on be used as a test station at CERN for superconducting cable developments. The long term use as a test station on one side and the very high cost of this 9 tons Nb_3Sn magnet on the other have imposed some constraints on the project:

- The insert has to be fully dismountable from the Nb_3Sn magnet, without the need of disassembling it.
- The insert should not transfer any load on the Nb_3Sn magnet during operation, therefore all the magnetic loads and deformations have to be self-supported by the insert.
- During the design process of the Nb_3Sn magnet, its inner bore has been fixed to 100 mm thus leading to defining the outer diameter of the HTS insert at 99 mm to allow its insertion.

B. *Design choices*

Several constraints needed in the design of a real accelerator magnet have not been considered in this design:

- The dipole insert will be made using block technique,
- All double pancakes are planar.
- The ends are designed as a half circle.
- The inner bore radius of the dipole field is 10 mm to leave a space for a Hall probe for the magnetic field measurement during testing.

III. HTS CHOICE

In order to reach the expected magnetic field of 6 T with an external diameter of 100 mm, the engineering current density over the winding needs to be around 250 A/mm² under 19 T.
For HTS two main options are possible: Bi-2212 or YBaCuO. We chose YBaCuO tapes to avoid the very critical final heat treatment required by Bi-2212.

Although YBaCuO tapes show outstanding longitudinal field current capacity and mechanical properties (IBAD approach), all solutions available for high current cables are not fully mature yet, including the Roebel cable approach [6]. To a lesser extent YBCO large in field anisotropy poses some additional design challenges.

To get the highest possible current, we chose a 12 mm YBCO tape, the widest commercially available. To get high mechanical properties IBAD route (high strength hastelloy substrate) was selected with SuperPower as supplier.

IV. Insert Magnet Configuration

A. *Configuration and geometry*

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.

Taking in to account the 99 mm external diameter and the 12 mm height of the pancake (tape width), the insert consists of 6 pancakes (Fig. 1 and Table I). The mid plane pancakes are longer than the upper and lower ones in order to reduce the peak field problems at the edges. In order to enhance the magnetic flux density an iron pole has been considered.

Table II summarizes the magnetic data of the insert. The engineering current density is 246.3 A/mm^2 to reach the 6 T central field.

TABLE I Magnet Characteristics

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

TABLE II Magnetic Characteristics

Characteristics	Value
Central field (T)	6.09
Peak field (T)	5.87
Magnet inductance L per unit length (mH/m)in the central region	32.2
Stored magnetic energy per unit length (kJ/m)	46.5

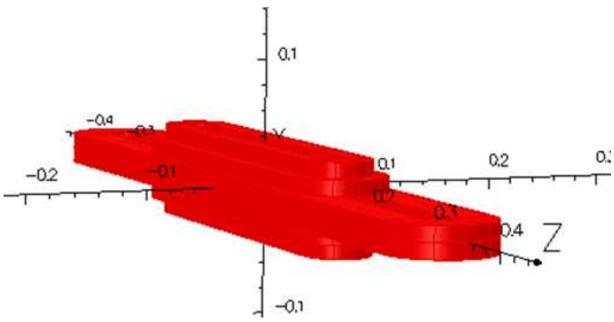

Fig. 1: View of the coil winding

B. *Magnetic field peak*

Since YBaCuO tapes show anisotropic behavior with respect to field orientation, the magnetic flux density should be determined both in amplitude but also in orientation. Both depend on the operation: the outer magnet increases the field amplitude but improves the field orientation.

The maximum field amplitude is located on the first turn of the first block in the middle of the straight section. In addition, the field along the straight section of the first turn of the first block and in the ends of the second block is close to the peak field. For example, in the ends of the second block, the value of the field is around 5.7 T.

C. *Perpendicular field contribution*

As transverse fields reduce the current density in HTS [1-3], its value is determined in the insert and its maximal field is compared to the local parallel one. The most critical field locations are summarized in Table III. The highest transverse field is found on the straight part of pancake 3. The transverse field contribution at the edges is less critical than in the straight parts. If the insert is tested in the dipole of 13 T, the maximal transverse field is equal of 2.9 T for a parallel field of 14.7 T.

TABLE III Most Critical Field Configuration on the Coil

Pancake number and Location	B_{tot} (T)	$B_{//}$ (T)	$B_{\perp}$ (T)
1 straight part	18.98	18.98	0
1 head	14.12	14	1.89
3 straight part	14.99	14.72	2.86

D. *Influence of the iron pole*

The iron pole (fig. 6) allows an increase of the central field of 10% from 5.46 T to 6.09 T for a same current density: It concentrates the field lines in the pole which limits the peak field on the coils and therefore generates a central field higher than the peak field on the conductor.

Maximal value of the transverse field without the iron pole equals 2.5 T. With iron pole it becomes 2.86 T. The iron pole is maintained in the final design due to its favorable contribution on the central field.

V. Conductor Definition

A. *Structure of the conductor*

The conductor has been thought to fulfill several requirements:

- High current capacity
- Allows Flexibility ine the winding
- YBaCuO layer close to the neutral axis to limit deformations in the coil ends
- Easy and low resistance connections
- Low AC losses to meet field quality specs.

The conductor for the insert is made by assembling two tapes. The two YBaCuO layers are not transposed and behave like a thick superconductor layer. The two tapes are soldered together face to face (closest YBaCuO layers) through a Cu tape of same thickness for the connection (see section V.B.). The soldering makes easy 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. 2. These Cu tapes are required for electrical stabilization and to facilitate quench protection but are not soldered to improve the flexibility of the conductor.

This configuration has been chosen among several options:
- Soldered tapes face to face without Cu tape in the middle
- Tapes with soldered through two Cu tapes in contact.

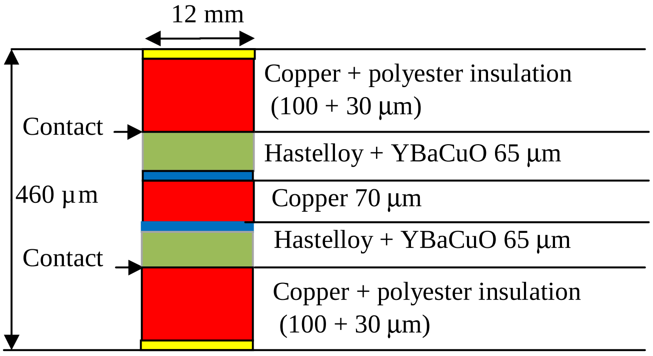

Fig. 2: Schematic cross section of the conductor.

B. Internal junction

Production of long lengths of superconducting ribbons of high properties is still a challenge. Therefore internal junction within the winding has to be possible. The internal junction between conductors is done by locally replacing the Cu tape between the superconducting tapes with a short length of YBCO tape. The SC ribbons are soldered face to face to ensure a very low contact resistance.

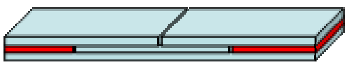

Fig. 3: Internal junctions. In black the location of the Cu tape used to do the junctions.

C. Copper stabilizer

The central copper shunt between the SC layers is not sufficient to provide protection. Therefore two copper layers are placed apart the central conductor containing the superconducting material. These layers are not tinned to the central part to avoid increasing the bending stiffness for winding. Their thickness of 100 µm has been determined in order to allow the insert energy to be dumped while keeping the hot spot temperature lower than 250 K.

D. Operating current and safety margin

The operating current needed in the conductor to reach the 19 T magnetic field is around 1400 A, or 700 A per SC tape.

The strong anisotropy of the superconducting tape makes the analysis of the critical field location with respect to superconducting material properties more difficult than with low temperature isotropic superconductors. The critical current has to be determined versus the field orientation for each critical location. Fig 4 shows the load lines [7] for each of the critical locations in the winding described in Table III, and the corresponding critical current lines established considering the local field orientation. From this graph it can be established that the most critical location is in the straight length of the outer pancake. 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 around 27%. 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%.

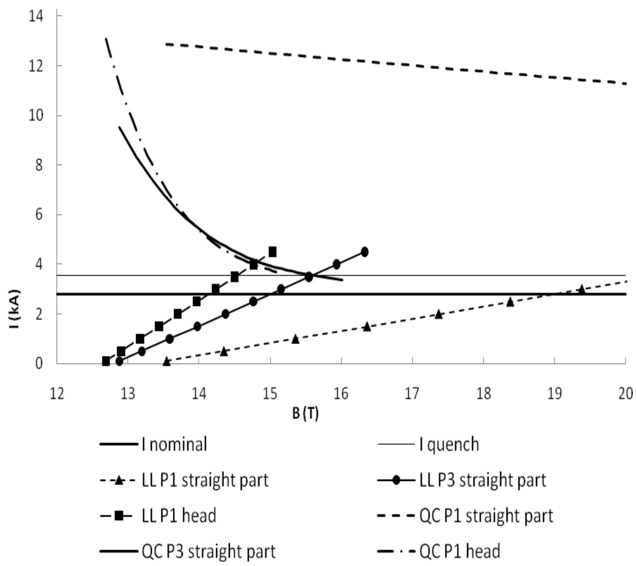

Fig 4: Load lines (LL) for the different most critical points of the winding (as described in Table III) and their corresponding quench current (QC) lines. The nominal operating current of the magnet and the quench current are figures as horizontal lines.

VI. Coil Winding

A. Pancake definition

The number of turns for the mid-plane pancake, medium pancake and external pancake are respectively 73, 71 and 35. In order to increase the operating current and reduce the time constant to dump the stored energy, the conductor is co-winded in pairs.

B. External connections and conductor transposition

The twinned conductor requires equilibrating the inductance to make sure the same current flows through each of the two conductors. This is done by inverting the inner/outer position of each conductor of the twinned pair at each central and external connection of the pancakes, as sketched on Fig. 5.

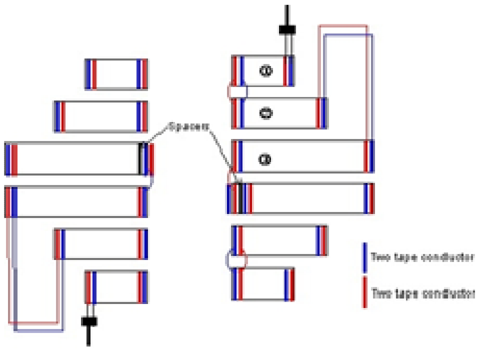

Fig. 5: Connections between the different pancakes.

C. *Layer jump definition*

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 the number of turns per pancake is odd despite the fact that the conductor is twinned.

D. *Electrical insulation*

The turn to turn electrical insulation is a polyester tape of 30 µm applied on the external face of the copper stabilizer. The copper strip is provided already insulated by the supplier. The ground and inter-pancake insulation is made of G10 plates of 0.2 mm thickness.

VII. 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. 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. 6, is designed to maintain resulting forces on half of the coils equal to Fx= 7.36 MN/m and Fy= 0 MN/m.

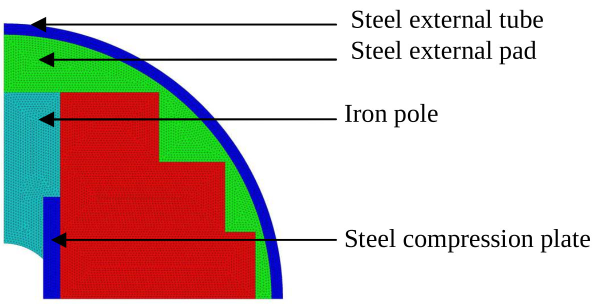

Fig. 6: Mechanical structure of the insert. For the model, contact has been considered between coils.

The purpose of each of the mechanical parts is the following:

- External pad: it is used to apply uniformly the load from the coil winding to the external tube. The material used will probably be 304 stainless steel due to its high elastic limit.
- 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 used has to have a high elastic limit.

The mechanical stresses in the external tube have been calculated for tube thickness 2, 3 and 4 millimeters. For each of these tube thicknesses the winding cross section has been calculated considering the minimum radial thickness of the external pads had to be 1 mm. For a current density over the winding of 250 A/mm² the stress evolution across the thickness of the tube has been calculated and is shown on Fig. 7 and summarized in Table IV.

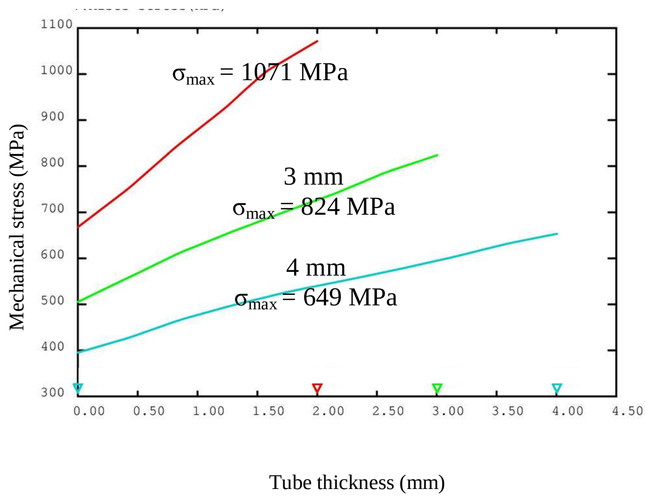

Fig. 7: The stress evolution across the thickness of the tube for 3 different tube thickness, 2, 3 and 4 mm.

TABLE IV: Stress Evolution in the External Tube for J_E = 250 A/mm²

Tube thickness (mm)	Coil winding cross section (mm²)	Maximum field on axis (T)	Maximum stress (MPa)
2	985.5	18.56	1071
3	942	18.4	824
4	893	18.21	649

Considering the external tube would be manufactured using 316 L stainless steel having an elastic limit of 980 MPa [8] at 4 K, the design is safe for the tube of 3 mm thickness. The average stress across the tube thickness being around 660 MPa, the operating stress is around two third of the elastic limit and peak stress lower than the elastic limit. As a consequence of these calculations the thickness of the external tube has been fixed to 3 mm.

Using this retaining tube the radial deformation on the mid-plane is 0.35 mm. This deformation is lower than the 0.5 mm radial gap between the HTS insert and the Nb_3Sn magnet, so the design constraint stating that no mechanical load transfer had to be allowed between the insert and the outsert is fulfilled.

More critical is the stress in the external pads as it reaches the elastic limit of 304 L stainless steel in the angles at the edges of the conductor blocks. Calculations in elastoplastic conditions are underway to address the risk associated with this overstress.

The von Mises stresses over the coil winding reaches locally 400 MPa, the average value being lower than 200 MPa. The average shear stress over the winding is around 50 MPa.

VIII. PROTECTION

A preliminary protection study has been performed assuming different quench scenarios, which include the HTS insert alone during the test, or inserted in the FRESCA 2 magnet with the electromagnetic coupling between the two magnets. A coupling coefficient of 0.9 has been assumed between FRESCA II and the insert. This assumption appears conservative because it allows large energy transfer from one magnet to the other during the discharge, and it gives a mutual inductance of 44.4 mH (the mutual inductance variation for iron saturation has been neglected).

The Lubell formula [9] has been used to evaluate the critical temperature T_c, with the following values for the ultimate critical temperature and critical magnetic field: T_{c0}=44 K, B_0=36.39 T. The generating temperature T_g is then linearly scaled between T_c and 4.2 K, with respect to the operating current. The quench study has been performed with the code QLASA [10], where the quench velocities are calculated with the analytical Wilson's formula.

Assuming a dumping resistance of 0.590 ohm (corresponding to a maximum voltage of 800 V for the insert), a threshold voltage for the quench detection system of 10 mV and a delay time of 50 ms for the opening of the power supply switch, the hot spot temperature reaches about 160 K when the insert is tested alone.

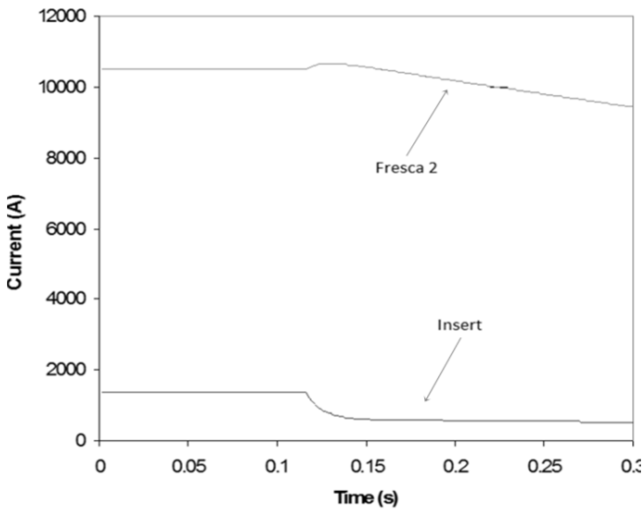

Fig. 8: Simulation of the current decay of the Insert and FRESCA 2 magnets, in case of quench of the insert with a triggered fast discharge for FRESCA 2.

In case of test of the insert inside the FRESCA 2 magnet, a quench of one of the two magnets would produce a dangerous increase of current for the other magnet. For this reason the protection scheme is to induce a fast discharge of both magnets in case of quench detection. Fig. 8 represents the simulation of a current decay in case of a quench of the insert, with a fast discharge for the FRESCA 2 magnet too. At the initial time of the fast discharge some extra current is induced into the FRESCA 2 dipole, which reaches 10650 A (i.e. 150 A above the nominal value). Later, the discharge time of the Fresca magnet dominates the current decay of the insert, which goes to zero slowly, with a constant time τ = 1.28 s. There is some energy transferred from Fresca dipole to the insert, and the hot spot temperature reaches about 300 K.

IX. CONCLUSION

The design for the HTS insert has been studied and established for all the critical aspects as mechanical structure, operating point and protection. Winding, junctions and connection choices will be confirmed thanks to a prototype tested under a field of 20 T. Using these results, the insert will be realized and tested in the dipole FRESCA II [5] to reach a central field of 19 T in the test station.

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