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A HTS DIPOLE INSERT COIL CONSTRUCTED

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DELIVERABLE REPORT

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Abstract:

This report is the deliverable report 7.4.1 “A HTS dipole insert coil constructed“. The report has three parts: “Design report for the HTS dipole insert”, “One insert pancake prototype coil constructed with the setup for a high field test”, and “All insert components ordered”. The three report parts show that, although the insert construction will be only completed by end 2013, all elements are present for a successful completion and that, given the important investments done by the participants, there is a full commitment of all of them to finish the project

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Delivery Slip

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Executive Summary

Within HFM EuCARD program, the aim of task 4 is to design and manufacture a dipole insert made of HTS material generating 6 T inside a Nb_3Sn dipole creating 13 T at 4.2 K in a bore of 100 mm in diameter.

This work went through several steps:

- studies: insert design (magnetic and mechanical structures), conductor design (comparison of various HTS conductors, choice, final structure of the conductor), tooling and assembly, protection in case of quench of the insert alone and of the insert in the main dipole, adaptation of existing tests facilities for specific tests
- orders, realizations and delivery: the delivery of the YbaCuO conductor is expected in September 2013. Most of the parts for the cold mass have been delivered, all the parts for the winding machine and the adaptation of the test facility have been delivered
- test program: it included the characterization of various conductors, the realization and test of several pancake insert prototypes, the realization of one insert pancake prototype coil, ready to be tested in an external field , the realization of several setups to test the prototypes in an external field

Besides the design studies, lots of experimental developments were done during this project. Although the HTS dipole insert coil construction has some delay (this construction is now foreseen for the end of 2013), all elements are present for it successful completion. Moreover, the participants have agreed to go far beyond the initial goal of the task, and to test the dipole insert coil within the Nb_3Sn dipole once this one will have been tested.

PART I DESIGN REPORT FOR THE HTS DIPOLE INSERT

1. SUMMARY FOR PART I

Future accelerator magnets will need to reach fields in the 20 T range. Reaching such a magnetic field is a challenge only possible using High Temperature Superconducting materials. The limit with low T_c superconductors is about 16 T. The high current densities (200 MA/m^2) and stress levels (500 MPa) needed to satisfy the design criterion of such magnets make YBCO superconductor the most appropriate candidate especially the IBAD deposition technique with a strong Hastelloy® substrate. YBCO is in the form of very thin tape with anisotropic transport properties under magnetic field. A longitudinal field component (in the plane of the tape) does not reduce too much the critical current but the transverse component (perpendicular to the tape) rapidly reduces the critical current. This large anisotropy leads to a block coil design for the magnet.

The HFM EUCARD program is aimed to design and manufacture a dipole insert made of HTS material generating 6 T inside a Nb_3Sn dipole creating 13 T at 4.2 K in a bore of 100 mm in diameter.

In the HTS insert, engineering current densities of the order 250 MA/m^2 under 19 T are required to reach the performances in the available space all the more that no force should be transfered between the insert and the outsert. The stress level is very high due to the large values of field and current density. The insert consists of three flat double pancakes with different lengths. A magnetic core enhances the magnetic flux density and localizes the peak field in the straight sections and not in the coil heads. The insert operates in liquid helium as well.

A specific conductor has been designed and developed to fit some of the high energy magnet requirements. The core of this conductor is two YBCO tapes soldered face to face around a copper tape. Two CuBe tapes with electrical isolation on one side are in contact with the core conductor. CuBe shows high mechanical strength and a relatively low resistivity (protection). The yield strength reaches 600 MPa for the conductor. The core conductor has been successfully developed by SuperPower®. Two core conductors are further put in parallel and transposed between the two poles to enhance the operating current for protection issues. The insert current is 2.8 kA to reach 19 T in the central bore with 10.9 kA in the Nb_3Sn outsert. The I_c margin, with the present tape performance, is about 30 %.

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. However, the low inductance and magnetic energy of the insert (4 mH and 16 kJ) make the insert protection rather easy even with the CuBe shunts; the temperature rise should then be limited even with large threshold voltage values. Several dedicated numerical models, confirmed by some experiments, have been developed to study the protection.

The mechanical design of the HTS insert has been carefully studied to withstand the high mechanical forces and the required technological developments have been carried out to realize this compact dipole insert. The stress level reaches 600 MPa. The pancakes with the iron poles are inserted in several two steel wire-cut pads welded together by electron beam. The length of the pads is 100 mm. Two steel compression plates between the iron poles reinforce the structure in the magnetic field direction. The mechanical structure ends with a

3 mm thick and 100 mm long external tube in Nitronic® alloy such that the insert can self withstand its electro—magnetic forces and does not transfer any load to the outsert.

2. INTRODUCTION

EuCARD program has as primary goal to develop instruments and technologies for future accelerators [1]. High temperature superconductors (HTS) like YBaCuO (YBCO) are an attractive option for the magnets of future accelerators [2]. They permit 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 an 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.

This report is completed by two other reports, one about the conductor definition and protection studies [7] and the other about mechanical analysis [8].

3. HTS MATERIALS

In the EuCARD proposal only Bi-2212 round wire was considered but YBCO (Y-123) coated conductors have made outstanding advances since the submission of EuCARD and they offer extremely interesting perspectives for very high field magnets. Table 1 summarizes the main advantages and disadvantages of Bi-2212 and YBCO.

Bi-2212 ($Bi_2Sr_2CaCu_2O_{8-x}$) shows a conventional structure (Figure 1) with superconducting (SC) filaments in a matrix, which should be silver or silver alloy (no reaction with Bi and oxygen permeability). YBCO ($YBa_2Cu_2O_{7-x}$) or more generally ReBCO where Re is a rare earth presents a completely new architecture with a stack of different layers above a metallic substrate (Figure 1), the YBCO layer being only a very small part (1-2 µm) of the conductor. The IBAD (Ion-Beam Assisted Deposition) suits particularly for high field magnets due to its Hastelloy® non magnetic substrate, which leads to a high mechanical strength.

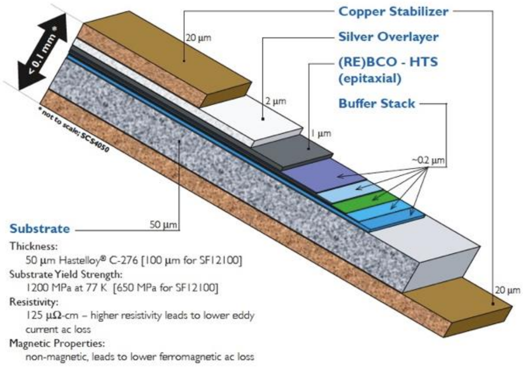

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Figure 1: The two HTS conductors (Bi-2212 on the left and YBCO on the right).

	Bi-2212 round wire	YBCO coated conductor
++	Round conductor (Ø = 0.8 mm) High current cable (Rutherford) Bending radius	Certainly material of the future Performances (J_c and stress (IBAD route))
-	Mechanical performances Limited lengths without defects Niche application material	Thin tape (4 x 0,1 mm^2) Lengths
--	Heat treatments	High current cables difficult

Table 1: HTS material comparison.

Figure 2 shows the engineering current densities for Bi-2212 (in red) and YBCO (in blue, for both longitudinal and transverse field directions) coated conductors at 4.2 K. The red square for Bi-2212 shows recent advances [9]. This figure shows the very high performance of YBCO in longitudinal fields but its large sensitivity to a transverse component [10]. Special care should be brought to it in the magnet design.

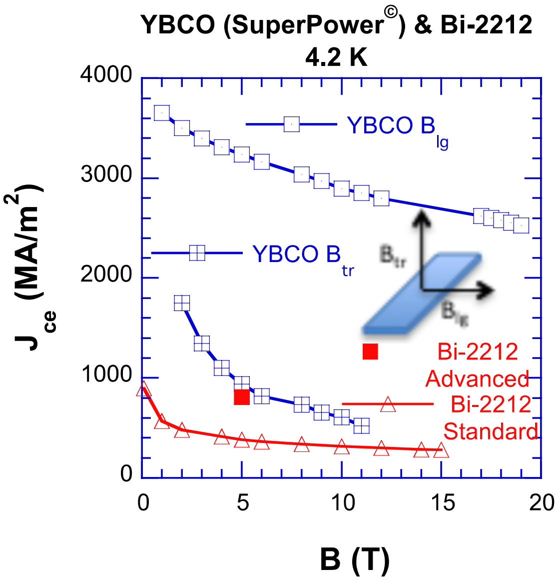


Figure 2: Engineering critical current density characteristics at 4.2 K for Bi-2212 and YBCO (the red square for Bi-2212 shows recent advances [9].

Bi-2212 is perhaps still a little bit more advanced from industrial point of view compared to YBCO coated conductors. The production lengths are for example longer (1.6 km) but OST (most advanced company) guarantees high performances only on a reduced length, typically 100 m. Some hectometres are also the today production length for YBCO.

Due to the Ag / AgMg matrix of the Bi-2212 wires, their intrinsic mechanical performances are limited ($\sigma_c \approx 100\,MPa$). But some solutions may be brought to solve this problem: reinforcement in the form of stainless steel for example.

Due to its high cost and unfavourable irreversibility line, Bi-2212 will remain a material for niche applications whereas YBCO conductor will be widely used as soon it will show its ability to be produced in kilometre lengths at moderate price.

The main drawback of YBCO is the difficulty to make a high current cable with the elementary thin tapes. The most advanced solution is the Roebel cable (Figure 3) but it remains very expensive and it cannot be bent in all directions. We have proposed some solutions to increase the operating current for the HTS insert.

Figure 3: Roebel conductor for high currents with YBCO tapes.

The main issue with Bi-2212 is the heat treatment, which should be very accurate. The melting temperature plays a crucial part and should be within a window of one or two degrees to obtain the highest critical currents densities. These are required for the HTS insert. Due to the low bending radius in the coil ends of the insert, only the wind and react is possible for Bi-2212. This reaction of the insert after its winding was a too high risk to be considered for the project.

Moreover simple calculations show that engineering current densities above 200 MA/m^2 are required to produce 6 T in a 100 mm bore (internal diameter of the Nb_3Sn outer dipole). So the requirements for the HTS conductor are an engineering critical current density above 400 MA/m^2 under a field of 19 T and a critical stress higher than a few hundred MPa. These specifications definitely exclude the use of Bi-2212.

4. INSERT MAGNET CONFIGURATION

4.1. CONFIGURATION AND GEOMETRY

The Nb_3Sn outsert imposes some constrains on the HTS insert, presented in [6]. No mechanical load should be transferred between the two magnets so there is a gap of 0.5 mm between them. All the magnetic loads and deformations have to be self-supported by the insert. The insert should be fully dismountable from the outsert without disassembling it.

The block type configuration suits very well the YBCO tape geometry, both for the winding and the magnetic field orientation mainly in the favourable longitudinal direction (Figure 2).

Taking into account the 99 mm external available 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 2 and Figure 4).

The insert is designed to be located in the straight section of the Nb_3Sn outsert (700 mm). That is why the central double-pancakes have this length. The two external double-pancakes are reduced in length (Figure 5) in order to lower the peak field at the edges.

For this first HTS insert flat pancakes were considered. The realization of such a HTS insert already is a challenge and we did not want to add a supplementary issue with bent coil ends. Nevertheless bent coil end have been successfully realized with a single 4 mm wide tape [11].

The ground and inter-pancake isolation is performed by a 0.2 mm G10 foils between each coils.

Layer jumps are installed in the straight parts of the pancakes, each of the twinned conductors having its layer jump in one straight length. The length is sufficient not to reach the critical strain of the tape (0.6 %). Therefore the number of turns per pancake is odd despite the fact that the conductor is twinned (Table 2).

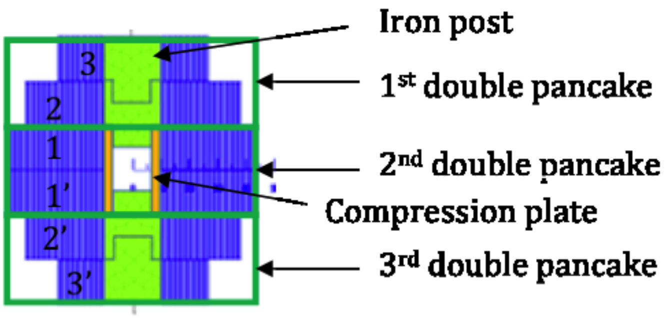


Figure 4: Cross section of the insert in 2D: the three double-pancakes, the iron post and the compression plates.

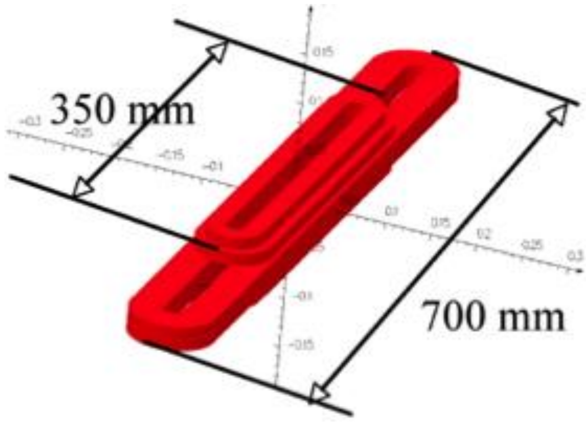


Figure 5: 3D view of the HTS insert with the different pancake lengths.

Coil number and location (Fig. 1)	Total number of turns	Length (mm) with heads
1-1' mid plane	73	700
2-2' medium	61	350
3-3' external	35	326

Table 2: Characteristics of the pancakes of the HTS insert.

4.2. INFLUENCE OF THE IRON YOKE – INSERT ALONE

An iron yoke (Figure 4) is placed in the centre of the coils to improve the main field. Table 3 shows clearly the contribution of 10 % of the iron core on the main field. The peak field slightly increases as well with the iron yoke but is located in the straight part whereas it would be located in the head without an iron pole.

Its influence has been carefully studied, especially in relation with the perpendicular field with a current density of 250 A/mm^2. The maximal perpendicular field is studied on the straight sections and on the heads without or with iron. The iron yoke increases the transverse component ($B_{tr\ max}$) in the straight sections but reduces it in the coil heads. Hence we see the benefit of the iron yoke in the ends. Figure 6 shows the magnetic flux distribution of the insert alone.

This study concerns the insert alone, the maximum field constraints should be studied with the outsert in the final configuration (see paragraph 6.).

	B_o (T)	B_{peak} (T)	$B_{tr\ max}$ (T) (straight part)	$B_{tr\ max}$ (T)/ (coil head)
No iron yoke	5.5	5.6	2.5	2.05
With iron yoke	6.1	5.9	2.7	1.63

Table 3: Contributions of the central iron yoke (250 MA/m^2), insert alone.

As mentioned in Table 3, 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 (Figure 6).

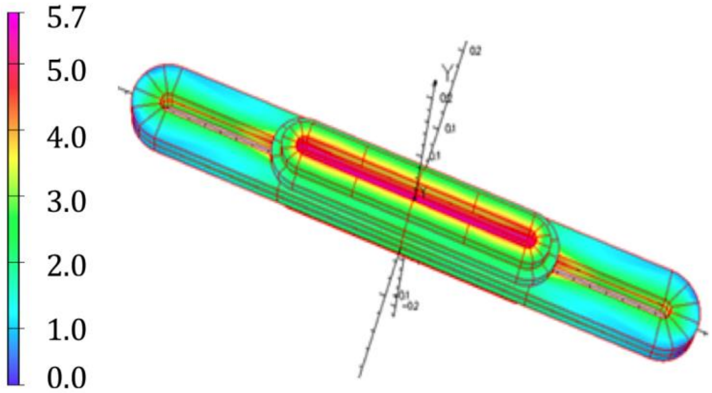


Figure 6: Magnetic flux density distribution in the insert (B field in Tesla)

The stored energy equals 16 kJ for a current density of 250 MA/m^2.

5. CONDUCTOR DEFINITION

The HTS conductor has been designed to fulfil several requirements:

- Potential current redistribution between the two tapes due to a lower local I_c
- High current capacity (protection issue)
- Easy to wind
- YBCO layer close to the neutral axis to limit stress in the coil ends
- Low resistance connections
- Mechanical resistance over 500 MPa

The insert conductor is composed of a 12 mm wide YBCO core conductor and two shunt tapes around (Figure 7).

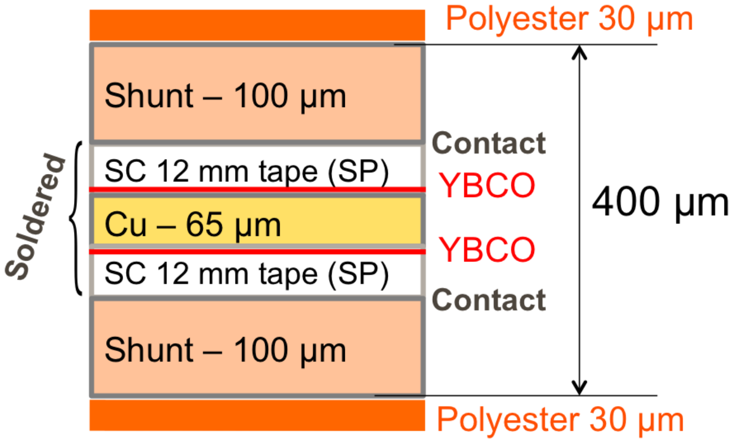


Figure 7: HTS insert conductor.

5.1. CORE CONDUCTOR

The core conductor for the insert is made by soldering two tapes through a copper tape (Figure 8). The two tapes are soldered together face to face (closest position of the YBCO layers for minimum bending radius and AC losses) through a Cu tape of the same thickness (70 µm) for the connections or the splices. With this configuration it is easy to make splices in the core conductor: the central copper tape is locally removed and replaced by an YBCO tape such that the active layers are face to face.

The soldering eases the current redistribution between the two tapes. The tape thickness is about 70 µm taking into account the Cu deposition above the Ag shunt for the soldering and a substrate of 50 µm.

Table 4 gathers the main parameter of the YBCO core conductor.

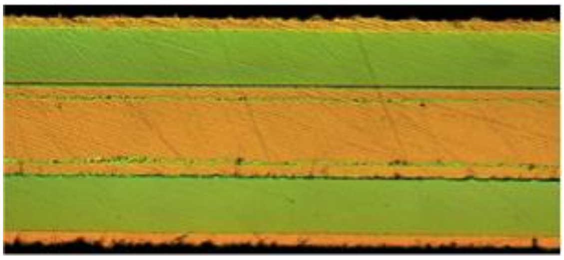


Figure 8: YBCO core conductor for the HTS insert (SuperPower®).

Supplier	SuperPower®
Width	12.1 mm
Thickness	0.215 mm
Substrate	Hasteloy® - 2 x 50 µm
Minimum I_c (77 K, 0 T)	750 A
Silver / Copper	2 µm / 7 µm

Table 4: YBCO core conductor specification.

In this design the two tapes are not transposed and the current distribution will not be balanced between the two tapes. Furthermore since the two YBCO layers are fully coupled, the thickness to be considered for AC losses (field quality) should be the total thickness (67 µm) and not the thickness of one YBCO layer (1 µm).

5.2. CURRENT INCREASE

Using this core conductor, the rated current will be 1.4 kA (700 A per SC tape) in the operating condition. This current is too low for protection issue, not for this very small insert, but for future inserts. In order to increase the current two such conductors will be wound in parallel to get an operational current of 2.8 kA.

To have a balanced current distribution between the two conductors, they are transposed between the two poles (Figure 9).

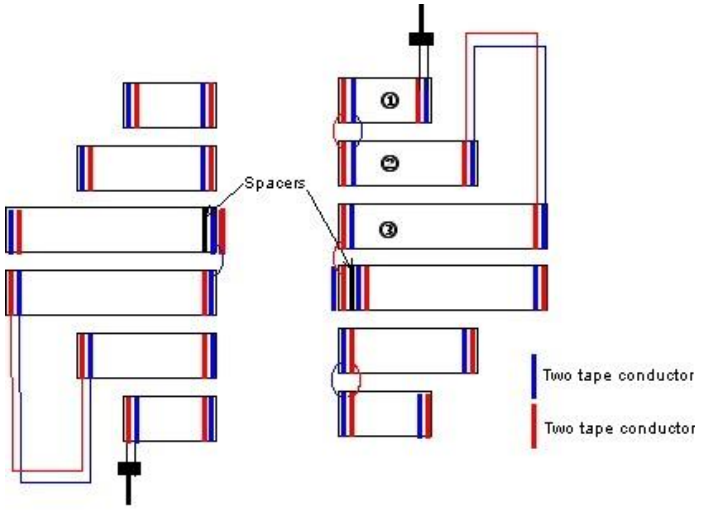


Figure 9: Connections of the two conductors transposed between the two poles.

5.3. SHUNT TAPES

Two extra CuBe shunts are placed in contact with the two YBCO tapes as shown inFigure 7. These shunt tapes are not soldered to improve the flexibility of the conductor but should be in good electrical and thermal contact for protection.

The shunt tape must fulfil contradictory requirements:

- high mechanical properties to withstand the stresses in the insert,
- low electrical resistivity to limit the temperature rise in case of a quench.

Unfortunately, copper tapes cannot hold the stress levels in the winding under a field of 19 T. Reinforcement of the stabilizer is therefore required. To withstand the stress levels in the insert, a CuBe shunt has been chosen. This Cu alloy (Table 5) shows, especially after heat treatment, very high mechanical properties (higher than Hastelloy®) whereas its electrical resistivity is rather low, especially when compared to Hastelloy® (1.25 µΩm). All these properties have been measured for these CuBe tapes.

CuBe	Without heat treatment Unannealed		With heat treatment Annealed	
	300 K	77 K	300 K	77 K
ρ (10^{-8} Ωm)	8.7	6.9	6.8	5.4
σ_{lim} (MPa)	660	880	1240	1480

Table 5: CuBe properties with and without heat treatment at 300 K and 77 K

The Young modulus of the conductor has been estimated using the mixture law of multi-materials for all the components of the conductor. It is equal to 150 GPa.

The mechanical strength is given by a mixture law as well:

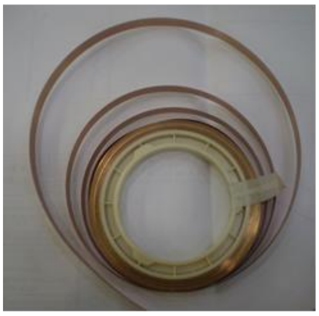
$$\sigma_{\max} = \sum \alpha_k \sigma_k \approx \alpha_{Hast}\,\sigma_{Hast} + \alpha_{CuBe}\,\sigma_{CuBE} = \frac{100}{460}1200 + \frac{e_{CuBe}}{460}\sigma_{CuBe} \quad [MPa]$$

$$\begin{cases} e_{CuBe} = 100\ \mu m \\ \sigma_{CuBe} = 1480\ MPa \end{cases} \qquad \sigma_{\max} \approx 580\ MPa$$

5.4. ELECTRICAL INSULATION OF THE CONDUCTOR

The turn-to-turn electrical insulation is a polyester tape of 30 µm thickness applied on the external face of the CuBe. A ground and inter-pancake insulation layer of 0.2 mm thickness, made of G10 foils, is added between each coil.

First trials to coat polyester on CuBe have successfully been achieved (Figure 10). The thickness of the insulation is 30 µm and the insulation withstands a voltage of 1000 V. With 2500 V, electric arcs appear. These values validate the insulation, as such a high voltage cannot appear during the discharge of the magnet (± 400 V).



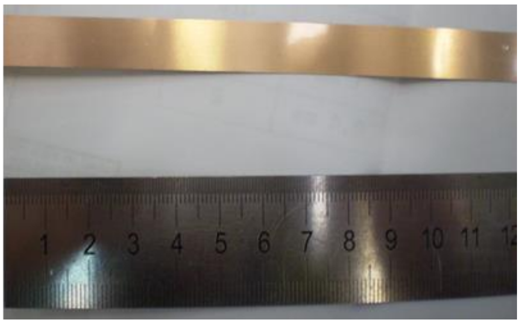


Figure 10: Polyester insulation of the shunt.

6. MAGNETIC STUDY WITH THE OUTSERT

With the conductor described before, the total current of the insert reaches 2.8 kA, so 1.4 kA in each core conductor.

Since the iron yoke of the insert increases the central magnetic field density produced by the two magnets together, we have reduced the current of the outsert to get 19 T as total central field. The iron poles increase the outsert central field from 13 T to 13.6 T at rated outsert current. The outsert current is then decreased to 10.9 kA (instead of the rated current of 11.7 kA), as the insert current has been kept to 2.8 kA, being the worst case for the insert. The other solution would have been indeed to keep the outsert current at 11.7 kA and to reduce the insert current to have a central field of 19 T. This solution increases the margins of HTS.

Figure 11 shows the magnetic flux density distribution with the two magnets in operation to produce 19 T in total.

The influence of the perpendicular field on the current density has been studied. J_c versus B was plotted in the different critical points (B_{max} and $B_{tr\ max}$ 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. Due to the field orientation, the overall critical current is reduced to around 3550 A for an operating current of 2800 A: the margin in current is thus around 27 %. If we look at the local magnetic field, the margin is still 14 %.

By comparing where there is no perpendicular field, the margin is around 70 %: the conductor operates mainly rather far from its critical value, which is not favourable for its protection (low propagation velocity).

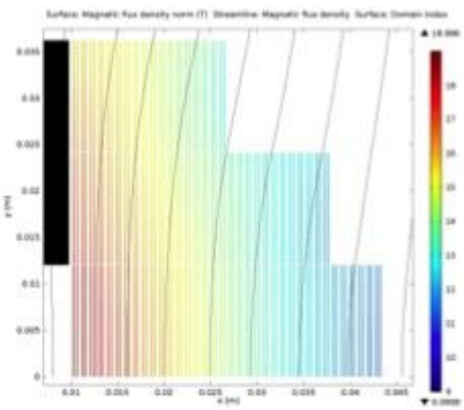


Figure 11: Magnetic flux distribution through the HTS insert with the outsert contribution (I_{Nb3Sn} 10.9 kA I_{HTS} = 2.8 kA).

7. PROTECTION

Different studies have been carried out to analyse the stability of the conductor and its protection as function of the shunt choice: pure Cu, pure CuBe and Cu/CuBe with various proportion.

The possibility to decrease the current of the insert rapidly to 0 A was studied by the means of circuit analysis. Two possible schemes were studied (Figure 12). First, the dump resistor value was selected such that the terminal voltage at 2800 A is 800 V (± 400 V). This means 0.28 Ω for the discharge resistance. Second, a variable dump resistor was considered in the protection. A gate-turn-off (GTO) thyristor circuit was analytically developed to adjust the resistance of the circuit in such a way that at lower currents, the resistance is increased to enhance the current damping.

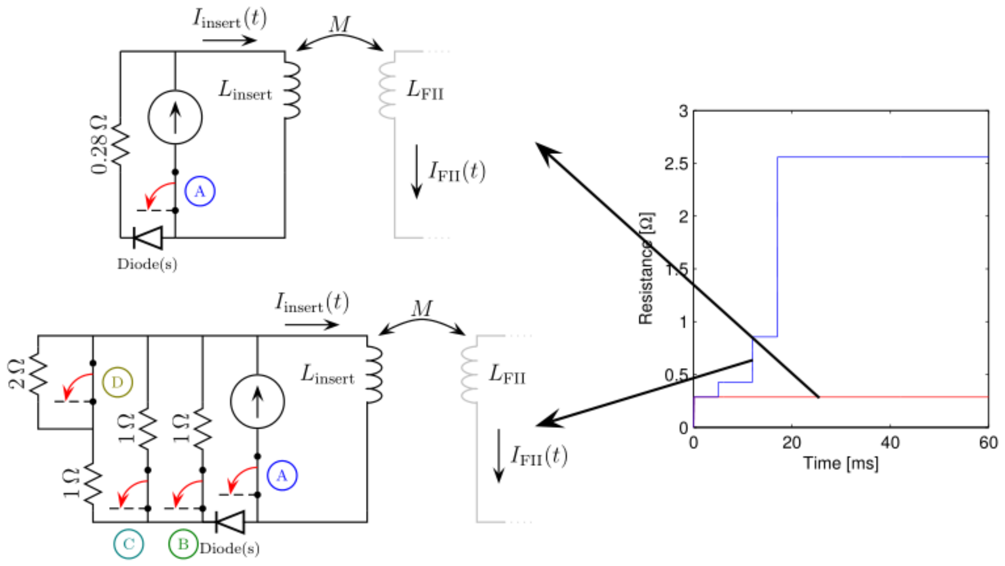


Figure 12: The two different circuits studied for the HTS magnet protection.

The insert discharges with the two possible methods are shown in Figure 13. As can be seen, with constant dump resistor, the insert can be discharged in 60 ms whereas with the GTO circuit, this time can be reduced to 20 ms. During the discharge the terminal voltage remains constantly below 800 V. The terminal voltage is not raised above 800 V during the subsequent steps in case of the GTO circuit, because in case of FRESCA-II quench, this would lead to an overvoltage (limit about 1000 V).

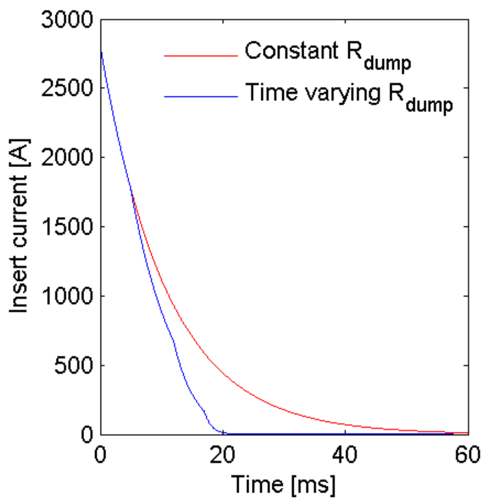


Figure 13: Current discharge for the two cases.

The low stored energy of the insert (about 16 kJ) allows a very fast discharge.

In case of an ousert quench, the high dump resistance of the insert protection circuit decreases the insert's current to a low value and thus protects the HTS coil. However, the effect of AC-losses has not been studied.

With a variable size dump resistor, the current can be decreased even faster (in about 20 ms compared to 50 ms), but this circuit should be studied in detail (including with experiments) before relying on it in this new magnet protection design.

In order to simulate the temperature evolution in the coil during a quench, a full scale finite element model of the coil was build and simulated with dedicated finite element method software (Figure 14).

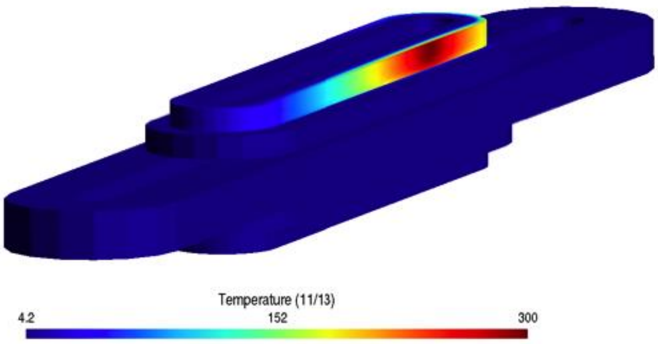


Figure 14: Temperature distribution in the coil, with mixed shunt, at the time instant when the maximum temperature has reached 300 K.

Coils with two types of cables were studied, in the first one the shunt consisted of only CuBe and in the second one 50 % of the shunt was Cu and 50 % was CuBe. The latter is called mixed shunt case in the following. Quench was initiated by assuming that a 7 mm (for the CuBe shunt case) and 13 mm (for the mixed shunt case) long conductor part, with a cross-section area of 12 x 0.40 mm^2 (uninsulated), has a reduced critical current to 0 A, while the coil operates at 2800 A. The conclusions of these studies are:

- Quench can be detected below 70 K for the CuBe only shunt cable, even with a very high detection threshold voltage (100 mV). Due to the low inductance of the coil, a quench is a safe event. However, if the tape has very inhomogeneous properties, an abrupt quench can develop during loading, even at low currents, and then quench may not be detected. It is very difficult to predict this kind of behaviour beforehand or to develop a reliable simulation model for that case.
- The temperature time derivative is really high, with constant current, 400 K is reached in 390 ms in case of cable with CuBe shunt and in 850 ms in case of mixed shunt cable.
- A very pessimistic hot spot temperature in case of CuBe only shunt would be 157 K. This results from the time to reach 100 mV added with a delay time of 50 ms and decay time of 60 ms (from circuit simulations). All the time the heat is generated according to the constant current of 2800 A.
- It is unclear how high hot spot temperatures can be tolerated in an YBCO coil and when does the delamination of the conductor really occur. It is expected that a lot of information will be gained from the tests of the magnet.

8. MECHANICAL STRUCTURE

The magnetic design has been analyzed 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 less than 0.5 mm: the insert should not transfer any 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 coil positions.

The structure presented in Figure 15 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 500 MPa.

Conductors with CuBe are considered to support stresses up to 500 MPa confirming the relevance of CuBe shunts for the conductors.

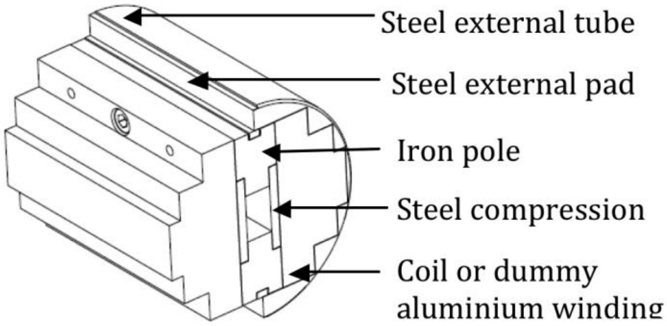


Figure 15: Mechanical structure of the insert.

Although the forces must be maintained and no load must be transmitted to the Nb_3Sn dipole, no impregnation is envisaged on the coils to avoid possible delamination of the conductors [12]. An efficient system of pads and tube is foreseen 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 [13].
- 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 with a high elastic limit. Its thickness is 3 mm, optimized to limit stresses to around 500 MPa.

9. ASSEMBLY

The conductor will be in three tapes: one CuBe insulated, one YBCO+Cu+YBCO and then one CuBe insulated. As we will wind in pairs, six tapes will be wound together and maintained by contact pressure. Mid-plane pancakes will be wound together around the compression plates. Other coils will be wound as double-pancake around the iron pole (separated in 2 parts, see Figure 4) 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 Figure 16. Then they will be electron beam welded. Preliminary welding trials have been done at CERN. Figure 17 shows the full penetration of the weld, which ends with a heel.

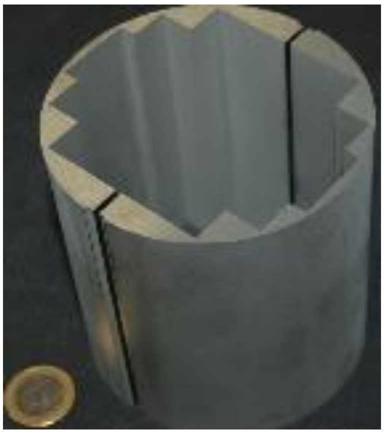


Figure 16: First tests of wire cutting of a pad of 100 mm at LNCMI.

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) equals the external tube of the pads, we are currently studying the assembly of the tube on the pads by thermal shrinkage. The foreseen solution is to heat the tube to a temperature of over 500 K and to slide it over the pad. Moreover, the tube devided into seven parts is easier to assemble than with one long tube.

The tube is then recovered with Kapton® (two half lapped layers) to ensure the electric insulation between the insert and the Nb_3Sn dipole.

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

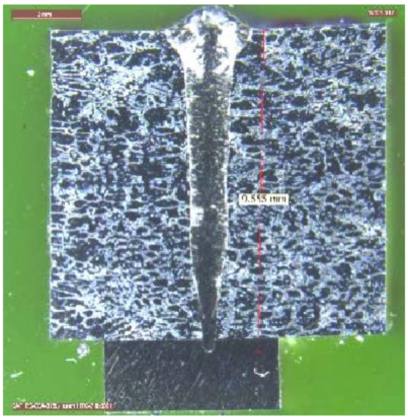


Figure 17: Electron beam welding performed at CERN.

10. HTS SOLENOIDS

It is not advisable to wind in one go a dipole insert coil with a HTS conductor. HTS magnets are being developed since only a short time and the know-how and skills are still limited. This is why several HTS solenoid insert coils have been made and tested in existing high field solenoid magnets in the partner's labs (LNCMI and KIT). The experience, which has been gained, will be used to construct a dipole insert coil. Likewise, studies have been carried out on the connections between the YBCO tapes and a procedure was developed to reach very low contact resistance, down to 20 nΩcm^2.

Some HTS solenoids have been used to validate the numerical models for the protection issues. Several coils have been equipped with quench heaters and numerous voltage taps to study the quench behaviour.

Figure 18 shows a double pancake coil. It has been tested in a background field of 18 T at the LNCMI in Grenoble with a current up to 400 A before breakage of the tape. This breakage is in agreement with the tensile strength of the tape. The current density was then 1000 MA/m^2 and the hoop stress was 700 MPa. This confirms the outstanding possibilities of HTS magnets and the margin we have with EuCARD insert.

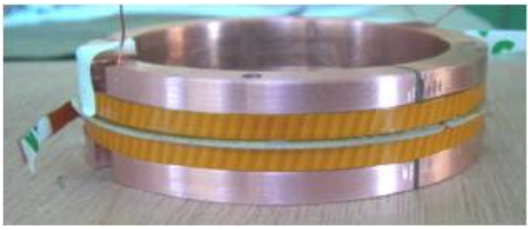


Figure 18: Double pancake for YBCO 4 mm wide tape for magnet implementation ($Ø_i$ = 80 mm).

Figure 19 shows a test at 20 K of quench triggering and propagation in the solenoid on a coil made by CEA. The transverse propagation can be clearly seen on this figure. It takes roughly 100 ms to propagate turn to turn.

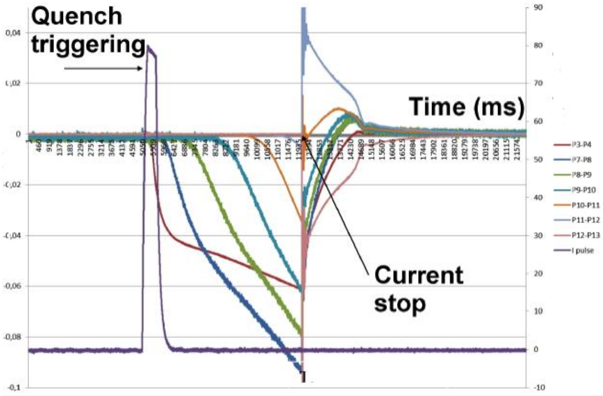


Figure 19: Quench triggering test with voltage time evolutions along a pancake solenoid.

These tests also confirms the high stability of HTS magnets, their MQE (Minimum Quench Energy) is much higher than for LTS magnets.

11. CONCLUSION, RELATION TO OTHER EUCARD WORK

The design for the HTS insert is now finished. New developments have been done and validated. A pancake prototype will be built and tested in different field directions (Figure 20) to confirm models and influence of perpendicular fields. Using these results, the insert will be built and tested in the dipole outsert to reach a central field of 19 T in the test station.

Figure 20: Test set up to study the pancake under different field orientations.

12. ACKNOWLEDGMENT

The authors wish to thank all the contributors to this task.

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PART II ONE INSERT PANCAKE PROTOTYPE COIL CONSTRUCTED WITH THE SETUP FOR A HIGH FIELD TEST

14. SUMMARY FOR PART II

Before winding the final dipole insert using HTS conductor, it was decided to build and to test a inset pancake prototype coil, using as much as possible the techniques foreseen for the final dipole insert, and a similar conductor. The winding of this coil was done at CEA Saclay in the middle of July 2013. This pancake insert will be then tested in a 10 T external magnetic field at GHMFL laboratory in Grenoble, where a setup specific for this test has been prepared.

15. INTRODUCTION

The objective of task 7.4 is to build a HTS dipole insert producing a 6 T extra magnetic field in an external field of 13 T. Only HTS conductors can be used in such high fields. As these conductors, and the magnets using them, are still in preliminary development phase, many studies, both theoretical and experimental, were needed before the construction of the dipole insert. The construction of an insert pancake prototype coil, using the same conductor and as much of the techniques as the final dipole, and its test inside an external field, were seen as a necessary step in the development program. The aim of this pancake is to study the influence of the field orientation on the current density. The pancake will be tested in 10 different field orientations.

16. CONSTRUCTION OF THE INSERT PANCAKE PROTOTYPE COIL

The superconductor is the same as for the insert: There are two transposed YBaCuO layers that behave like one 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 stabilizer is though different from the final insert; there is only one tape of stabilizer co-wound with the superconductor. Its thickness is 135 µm with a 30 µm mylar insulation.

The main characteristics of the prototype pancake coil are the following:

- Straight section of 220 mm with ends as a half circle of 10 mm radius
- 10 turns
- A heater in stainless steel will be placed after the 2nd turn in order to study quench propagation in the 3rd turn. A G10 insulation will be placed between the 2nd turn and the heater to protect the 2nd turn from the heater and orient the quench only in the 3rd turn
- The heater will be powered in four different points and 2 potential taps will be placed in its extremity to measure the evolution of the tension and to control the deposed energy
- 4 additional potential taps will be placed on the winding to study the quench propagation:
  - One on the winding mandrel

One on the external connexion
One after one turn after the heater
And one after two turns after the heater.

The prototype was wound by the middle of July at CEA Saclay with the following techniques:

- The mandrel is made of copper (see figure 1) and the current leads are directly connected to them.
- The first turn of the superconductor is soldered onto the mandrel
- The last turn is connected to an external connection in copper.

Figure 1: Copper mandrel and copper external connexion.

A trial assembly before winding was done and has validated the design: The winding is maintained by lateral clamping in G10. This clamping also isolates the winding from the current leads.

A picture of the coil after winding is given in Fig. 2.

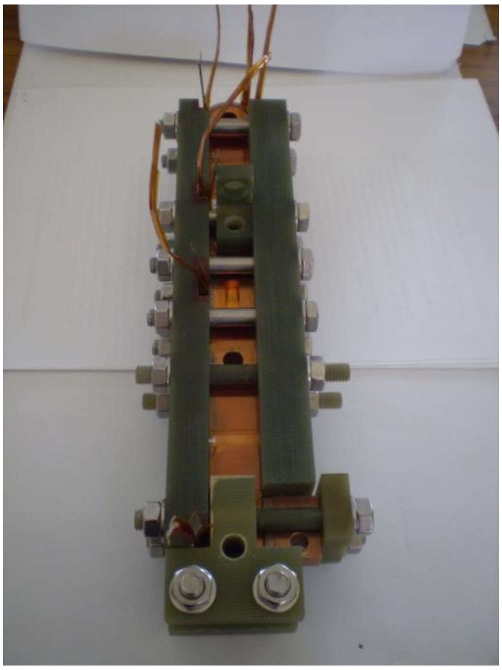


Figure 2: the insert prototype coil constructed

For the tests, the complete winding assembly (mandrel + winding + clamping) is inserted inside two copper connection bearings directly clamped to the cold electrical connections to the test station (trunnions). These trunnions permit 11 different positions to the winding assembly and are directly connected to the current leads.

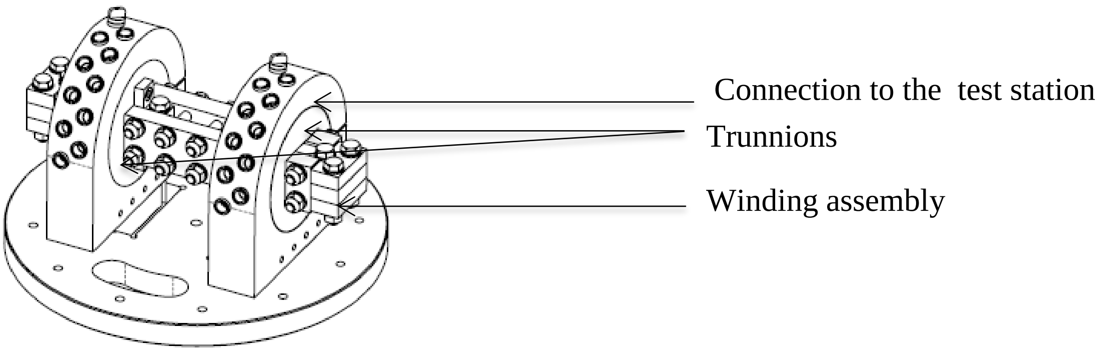
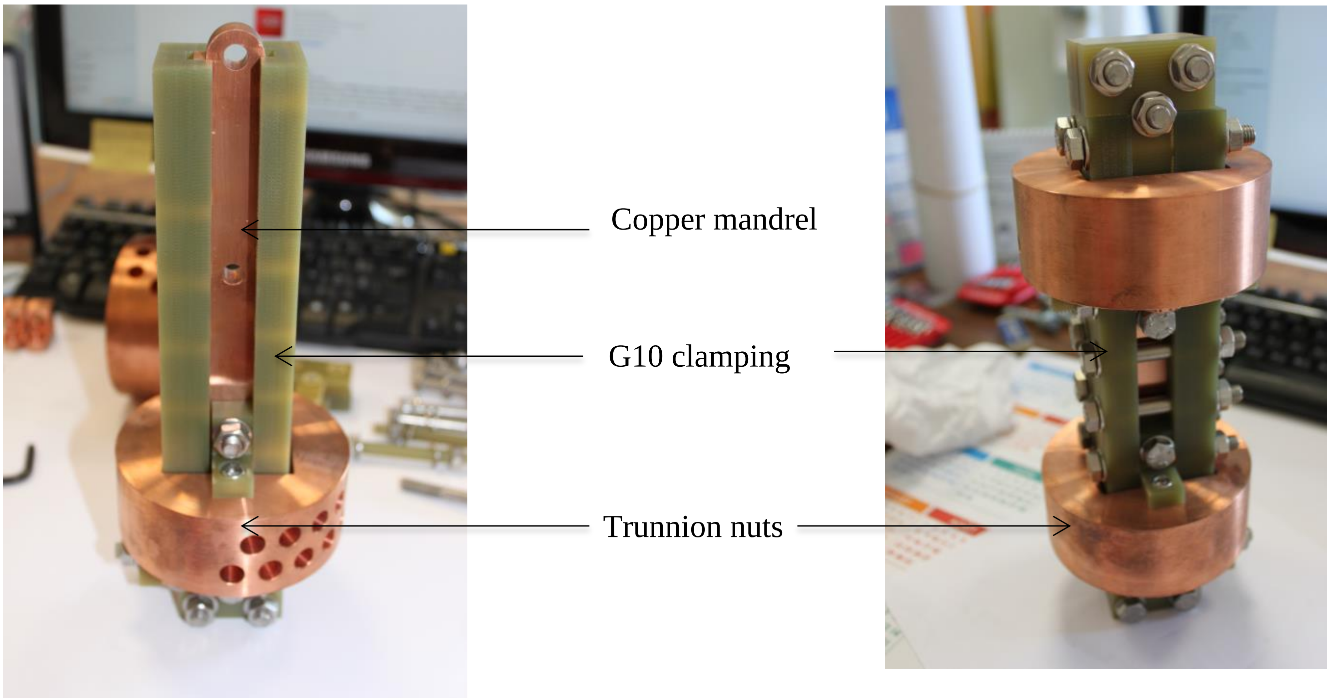


Figure 3: the connexion between the station tests and the pancake



Figures 4 and 5: The winding assembly: the mandrel, the clamping and the trunnions

17. SETUP FOR A HIGH FIELD TEST

The HTS insert coil will be tested in a dedicated setup in an external field of 10 T. This test is scheduled at Grenoble in September 2013 at LNCMI in Grenoble in a very large bore magnet ("M10"). This specific setup makes it possible to vary the angle between the pancake axis and the external field (figure 6). The test pancake has two current leads in the form of a ring (trunnion nuts) with holes (eleven, Figure 6) to have eleven fixed orientations in the external field (0° to 10° by steps of 1°). The rings may rotate in the fixed current leads with eleven holes as well. A pin fixes the eleven positions.

As soon as the pancake axis is not aligned with the external field there is a torque, which is very large especially for an angle of 10°. The mechanical design of the set-up has been carefully carried out to withstand these huge forces. Special copper has been used for example and a thick tube to withstand the torque with a very little displacement.

The set-up is highly instrumented to measure temperatures, voltage taps and to feed the heaters. More that 100 wires are foreseen in total (Figure 7).

The lower part of the current leads use YBaCuO superconducting tapes (blue parts in figure 6) soldered on brass supports whereas the upper part is a concentric copper current lead. The current leads were designed for a current of 3000 A. Figure 8 shows the lower part with the two current leads and one trunnion nut. The electric contact parts have been coated with silver.

This set-up is completed and the final preliminary tests will be carried out in August to be ready to make the tests with the test pancake.

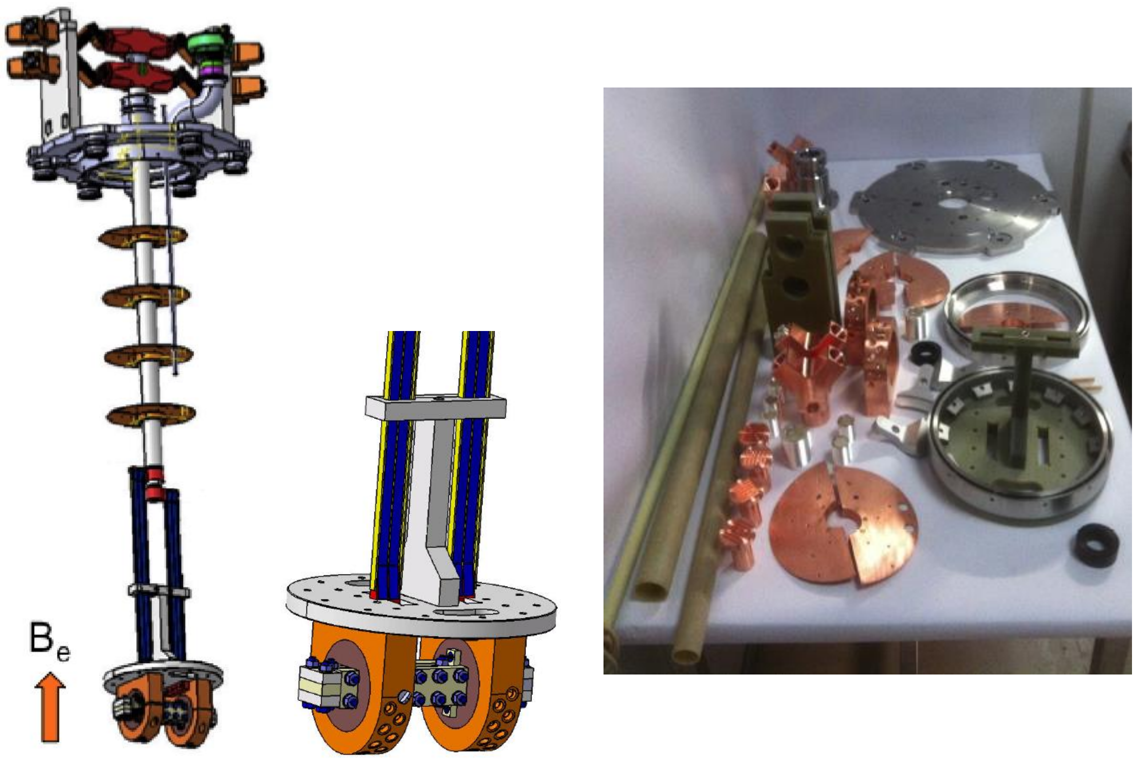


Figure 6: Test set up to study the pancake under different field orientations (left 2 pictures), all the components of the setup (right).

Figure 7: top of the setup with the two 3 kA current leads, some connectors for instrumentation, the two helium transfer tubes and the safety valve.

Figure 8: the two current leads and one trunnion nut.

18. FUTURE PLANS / CONCLUSIONS FOR PART II

The construction of the insert pancake prototype coil was done at CEA Saclay in the middle of July 2013. A test of this coil is foreseen in an external field of 10 T. The setup for this test has been built at Grenoble. The test is scheduled at GHFML Grenoble in the September 2013.

PART III ALL INSERT COMPONENTS ORDERED

19. SUMMARY FOR PART III

The components that were ordered for the construction of a HTS insert coil consist of two main parts:

- a HTS specific conductor, made of two YBaCuO tapes soldered around a copper tape. After a long work of both theoretical definition and experimental tests on short length pieces, the final quantity ofthis conductor to make the insert was ordered to the company SuperPower in December 2012. The expected delivery of this final length of conductor will be in September 2013.

- a set of mechanical pieces used for the winding (mandrel, etc.). The drawings were completed and approved by end of May 2013. The last order was placed in the first week of July 2013. The mandrel was delivered in April 2013, the delivery of the last pieces is expected by November 2013.

20. INTRODUCTION

The objective of task 7.4 is to build a HTS dipole insert producing 6 T extra magnetic field in an external field of 13 T. Only HTS conductors can be used in such high fields. As these conductors and the magnets using them are still in preliminary development phase, many studies, both theoretical and experimental, were needed before reaching the complete design of this dipole insert, and so, the components of this insert could only be ordered in the last year of the project.

21. PROCUREMENT OF HTS CONDUCTOR

Following a number of discussions and interactions with SuperPower and the first order of 10 m of cable, a total quantity of 450 m of HTS cable was ordered by CERN in December 2012. The cable is expected to be delivered to CERN in September 2013. The 450 m length of conductor is specified to be split in: 4 unit lengths of 40 m, one unit length of 50 m, and 2 unit lengths of 120 m.

The cable consists of two SuperPower YBCO tapes soldered together with interleaved a copper strip 0.07 mm thick. The HTS layer of each tape, which is deposited on a 0.05 mm thick Hastelloy substrate, faces the copper strip. The cable has a width of 12.1 mm and a thickness of 0.215 mm. The minimum guaranteed critical current at 77 K and in self-field is 750 A, with a critical current homogeneity corresponding to better than ± 10 % (1 standard deviation). The critical tensile stress is higher than 550 MPa. Two additional CuBe strips, each 0.1 mm thick, are added during magnet winding on both sides of the HTS cable to provide the mechanical performances and the enthalpic stabilization. In addition, two of such conductor assemblies - HTS cable plus two copper strips – are wound together to form a final conductor with a total cross section of 12.1×0.92 mm^2 and will be able to transfer a current of 2.8 kA at 4.2 K in nominal conditions – with a 13 T background field plus 6 T generated by the insert itself. The cross section of the final conductor is reported in Figure 1.

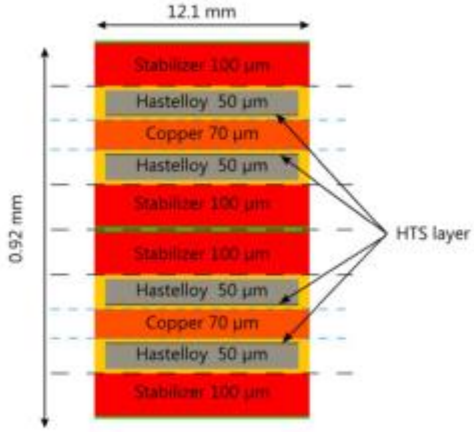


Figure 1: HTS conductor for the EuCARD HTS insert, stabilizer is CuBe.

22. PROCUREMENT OF HTS DIPOLE PARTS

All components are fully designed and are under consultation (tendering) since June the 5th 2013. The end of the consultation was June 21 2013 and so the order was placed on July 2nd 2013. Last components are expected by November 2013. The scheme of the different components is presented in figure 2:

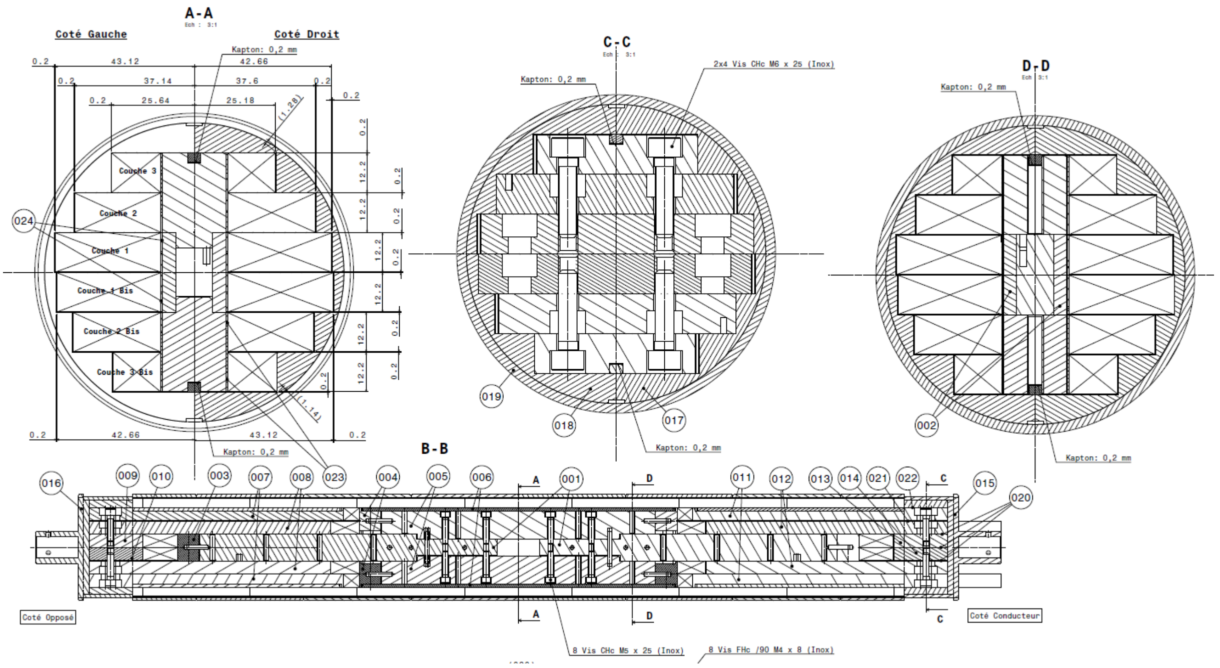


Figure 2: Scheme of the HTS dipole parts.

Thanks to figure 2, we can extract a list with the ordered components, this list can be found in Table 1.

Table 1: List of the ordered components.

Drawing number	Quantity	Designation
1	2	316 L SHIM
2	2	316 L COMPRESSION PLATES
3-4	2-4	G 10 ENDS SHIMS
5	2	IRON SHIM
6	2	316 L HEEL
7-8-9-10-11-12-13-14	2-2-1-1-2-2-1-1	316 L ENDSHOES
15-16	1-1	316 L CAPS
17-18*	8-8	316 L EXTERNAL PADS
20-21-22	3-2-2	G10 PLANE INSULATION
23-24	8-4	G 10 SHIMS

*It has to be noticed that the external pads are electro-cut at LNCMI Grenoble and are already partially procured (see Fig.3).

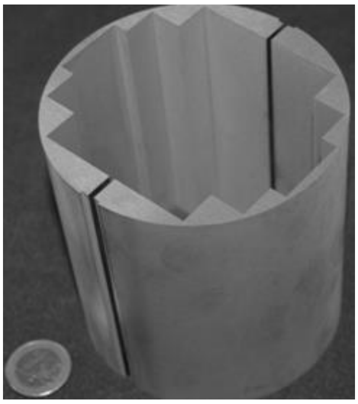


Figure 3: Photo of the 316 L external pad

23. FUTURE PLANS

An intermediate test is foreseen before the winding of the insert dipole with the test in an external field of 10 T of a pancake prototype coil (part II of the deliverable report). This test is scheduled in September 2013 at LNCMI in Grenoble using a dedicated set-up to vary the angle between the pancake axis and the external field (figure 4). The test pancake has two current leads in the form of a ring with holes (Figure 5) to have ten fixed orientations in the external field. As soon as the pancake axis is not aligned with the external field there is a torque, this torque is already very large for an angle of 10 °. The mechanical design of the set-up has been carefully carried out to withstand these huge forces. Special copper has been used for example. The lower part of the current leads use YBaCuO superconducting tapes (blue parts in figure 4) soldered on brass supports whereas the upper part is concentric copper current leads. This set-up is completed and the final preliminary tests will be carried out in July to be ready to make the tests with the test pancake (figure 5).

Once the dipole insert is wound, it will be tested, alone in a first step, then within the FRESCA2 dipole.

Figure 4: Test set up to study the pancake under different field orientations with all the components.

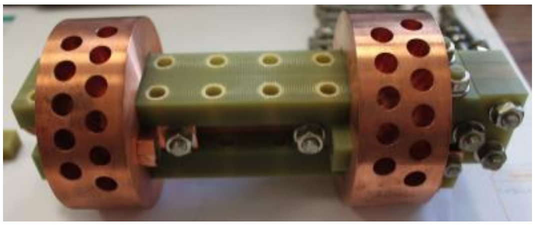


Figure 5: Set up for the YBaCuO pancake test; the ten holes in the two current leads correspond to the ten orientations in the external field.

24. CONCLUSIONS FOR PART III

All components for the dipole insert coil were ordered between December 2012 (conductor) and beginning of July 2013 (coil parts). Delivery is expected from September (conductor) to November 2013 (coil parts).

GENERAL CONCLUSIONS

Only very few insert dipole coils have been built and successfully tested up to now. This type of coils is a must for the future very high field (B ≥ 16 T) accelerator dipoles The work done within task 4 of EuCARD HFM is a new contribution to this development, thanks to many theoretical and experimental results. Even if the program has some delay, of the order of 9 months, everything is ready to complete it by the end of 2013. Moreover, the teams involved in this project have already scheduled to test the dipole insert inside the main Nb_3Sn dipole once this dipole is ready, test which is not part of the task, but which will bring a lot of information.