Cos-theta design of dipole inserts made of ReBCO-Roebel or BSCCO-Rutherford cables

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Cos-theta design of dipole inserts made of ReBCO-Roebel or BSCCO-Rutherford cables

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***Abstract*— Next generation of dipole magnets with field higher than 16 T are considered for future particle colliders. To do so, combined-technology magnets - made of Nb-Ti, Nb_3Sn and HTS materials - have to be developed to reduce the cost of such a magnet. Therefore, in the framework of the EuCARD-2 project, many HTS dipole magnet designs have to be investigated so as to find the most effective design for the HTS insert in a graded magnet. This paper discusses the Cosθ option. A 5 T standalone configuration of the HTS accelerator magnet (the first goal of EuCARD2) appears to be achievable, whereas mechanical stress distribution shows that its use as insert in graded magnet is very challenging. This paves the way for alternative designs as the so-called slot or motor-like design, briefly introduced here.**

***Index Terms*—Superconducting magnet, HTS Roebel cable, accelerator magnet, motor-like design, slot design, EuCARD2**

I. INTRODUCTION

IN the near future, one has to know if High Temperature Superconductor technology is a viable option to build the next generation of particle accelerators, such as the High Energy LHC [1] or the Future Circular Collider [2]. Therefore, in the framework of the enhanced European Coordination for Accelerator Research and Development project (EuCARD-2), the Work Package 10 (WP 10 - Future Magnets [3]) focuses on the development of HTS dipoles in a form of an accelerator quality 5 T dipole to be later used as insert in Nb-Ti or Nb_3Sn dipole magnets in order to raise their magnetic field beyond 16 T. In the task 10.3 of the previously mentioned WP 10, numerous layouts of HTS dipole inserts with accelerator field quality and made of ReBCO-Roebel cable or BSCCO-Rutherford cable are under investigation [4].

This paper deals with cosθ configuration and provides first development about the HTS dipole magnet. The magnet needs to generate 5 T in a standalone mode within an iron yoke with field harmonics less than a few units at two thirds of the aperture. The HTS magnet without the ferromagnetic yoke has to fit inside a Nb_3Sn dipole magnet, namely Fresca-2 [5, 6], with a 100 mm diameter aperture and a nominal central field of 13 T. The mechanical structure of the HTS insert has to withstand the Lorentz forces all by itself.

As for the EuCARD-2 cable technology, there are different options that are thoroughly described in [7]. In case of the cosθ design, two types of ReBCO Roebel cables and one kind of BSCCO-Rutherford cable are under investigation. Their main dimensional characteristics are reported in Table I. These cables are narrower that the ones used in the other designs in order to leave enough room for the mechanical structure – **the two-layers of cables and the mechanical support must fit inside a 30-mm-thick circular ring**. The actual Roebel cable baseline presently reported can slightly change due to recent work performed on the effective surface of such cables (Fleiter's surface) [8,9].

TABLE I
GEOMETRICAL DIMENSIONS OF COS-Θ DESIGN CABLE OPTIONS

Material and cable technology	BSCCO Rutherford	ReBCO Roebel #1	ReBCO Roebel #2
Number of tapes/strands	22*	8$^+$	15$^+$
Thickness (thin/thick edges)	1.39/1.52 mm	0.6 mm	1.2 mm
Width	9.5 mm	10 mm	10 mm
Transposition length	65 mm	126 mm	226 mm

*0.8 mm strand diameter
$^+$4.5 mm or 4.75 mm wide tapes, not defined at the time of the paper

Based on the cable characteristics, various 2D magnet cross-sections are designed by means of the Roxie code [10]. They are described in section II. Then, for one design, the Lorentz forces on the coil blocks are estimated when the magnet is inserted in the 13 T background field of Fresca-2. Finally, a 2D elastic finite element model is developed via cast3m code [11] to assess mechanical stresses and displacements within the coil cross-section.

II. 2D MAGNET DESIGNS

A. *Magnet cross-section*

Three designs, one for each cable (Table I), have been generated (Figs 1-3). Final insulation is still to be defined but could be a fiber glass sleeve [4]. Therefore, a 100-µm-thick insulation is taken into account in all of the computations. Each magnet consists of two layers of conductors and has a

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central field of 5 T when surrounded by a 60 to 65 mm-wide iron yoke. Half a millimeter is left in-between the two insulated layers for any design. The engineering current densities J_e are less than 470 A/mm^2 (Table II). The peak field B_{peak} is about 5.3 T for all designs. Without the iron yoke the central field goes down to 3.7 T. All the designs, in both configurations (with or without yoke), have a good field quality since the first four field harmonics b3, b5, b7 and b9 are below one unit at two thirds of the 40-mm aperture. These results must be considered as preliminary ones since Roebel cables are not properly modeled in Roxie, while Rutheford cables are. In addition, dynamic effects in Roebel cables can heavily modify the current distribution [12].

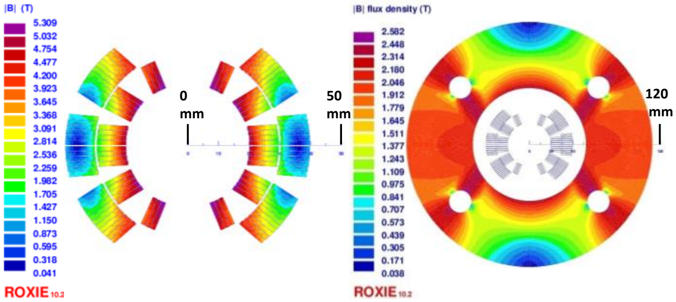

Fig.1. Five block cos-θ design made of a BSCCO Rutherford cable. Left: magnetic flux density on the conductors with B_{peak} = 5.31 T. Right: magnetic flux density in the iron yoke. The four small holes are needed to improve the field quality.

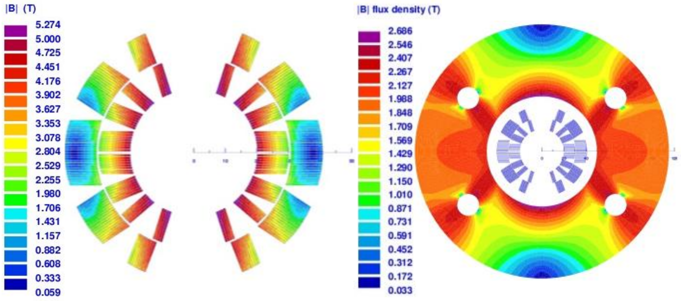

Fig. 2. Seven block cos-θ design made of a “thin” ReBCO Roebel #1 cable. Left: magnetic flux density on the conductors with B_{peak} = 5.27 T. Right: magnetic flux density in the iron yoke.

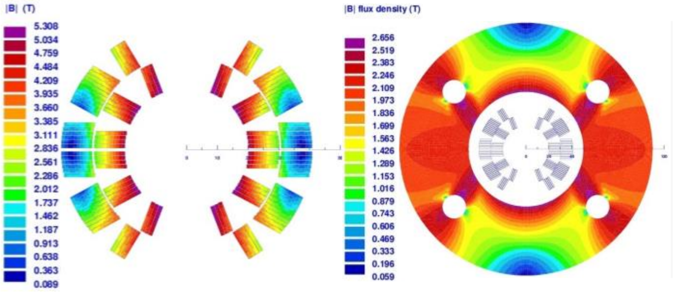

Fig. 3. Six block cos-θ design made of a “thick” ReBCO Roebel #2 cable. Left: magnetic flux density on the conductors with B_{peak} = 5.31 T. Right: magnetic flux density in the iron yoke.

The challenging part when designing a magnet is the coil ends. Even if the cos-θ end design can benefit from the constant perimeter profile criteria [13], the upper block of the inner layer will suffer from a very small bending radius of around 7.5 mm. This is still within the 5.5 to 6 mm specifications of the ReBCO tapes [14, 15] but out of some measurements on Roebel cable (11 mm in [16]). If needed, radius can be increased up to 10 mm by degrading the field quality - only b3 and b5 would be below one unit as a counterpart.

TABLE II
MAIN FEATURES OF HTS COS- Θ MAGNETS

Magnet cable technology	BSCCO Rutherford	ReBCO Roebel #1	ReBCO Roebel #2
Number of blocks	5	7	6
$J_{engineer}$ [A·mm^{-2}]	434±17	470	460
Current [kA]	6.0	2.8	5.5
Number of turns	29	63	32
Conductor area [mm^2]	1856	2056	1827
Yoke inner radius [mm]	52	50	50
Yoke outer radius [mm]	112.8	115	110
Central field (no yoke)* [T]	3.82	3.72	3.75

*5 T central field when assembled in the iron yoke for any design.

B. Lorentz forces in magnet coil blocks

Costly HTS dipole magnets are likely to be used only as insert within graded Nb$_3$Sn or Nb-Ti outer magnet in the future. Therefore, the EuCARD2 HTS dipole magnet is simulated inside the Nb$_3$Sn Fresca2 magnet to reproduce a possible future graded magnet configuration [17]. Computations of the standalone mode are carried out, too. The only difference with a real graded magnet stands in the fact that the mechanical force exerted on the HTS insert cannot be transferred to the outer magnet. Fresca2 mechanical structure has not been designed to withstand additional forces coming from an inner magnet. Therefore, enough space must be left for the mechanical structure to withstand the large Lorentz forces at the very high field.

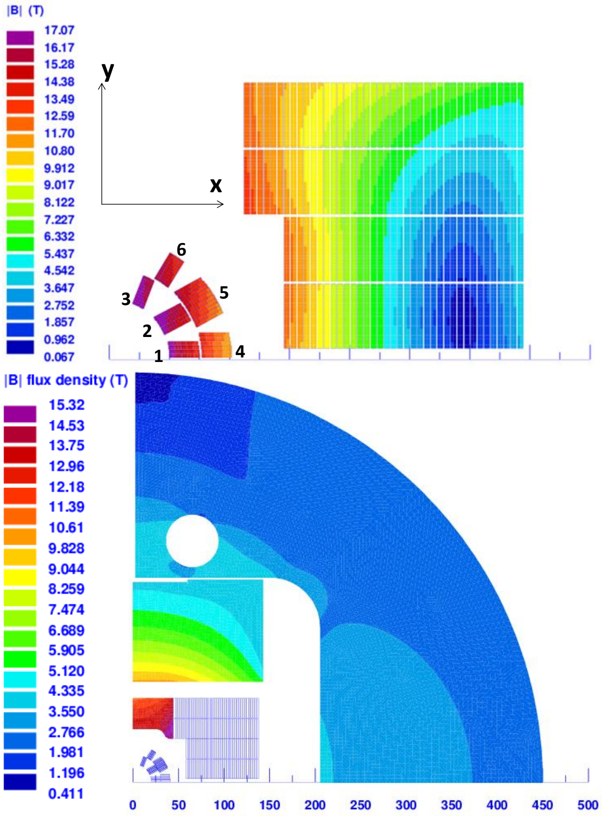

Fig. 4. One quarter of the six block cos-θ design made of a “thick” ReBCO Roebel #2 cable inserted in the coil block design of the Fresca2 magnet. Top: magnetic flux density in the conductors with B_{peak} = 17.1 T. Bottom: magnetic flux density in the iron parts.

In the following we focus on the magnet made of the Roebel #2 cable. Actually, most of the development so far carried out in the Conductor Task 10.2 of this “Future Magnets” project has been made on this 15-tape 1.2-mm-thick Roebel cable. In addition, the other designs being close in terms of magnetic field and current density, the forces are of the same order of magnitude.

TABLE III
LORENTZ FORCES ON THE 6 BLOCKS OF THE HTS DIPOLE INSERT

Inserted in:	Iron yoke	Fresca2
Central field	5 T	16.78 T
Block number (fig. 4)	[Fx , Fy] in kN·m^{-1}	[Fx , Fy] in kN·m^{-1}
1	[76 , -8]	[337 , -8]
2	[107 , -14]	[433 , -15]
3	[74 ,-10]	[269 , -11]
4	[20 , -21]	[412 , -21]
5	[83 , -78]	[737 , -81]
6	[65 , -35]	[326 , -37]
Fx total	**2 x 44 tons·m^{-1}**	**2 x 256 tons·m^{-1}**

The central field of the combined magnet showed in figure 4 is 16.78 T with J_e = 460 A·mm^{-2} in the insert coils. The field harmonics b3 and b5 are respectively 6 units and 1 unit at two thirds of the 40-mm aperture. The resulting bursting forces on one coil F_x *total* are 512 tons·m^{-1} (Table III). They are about 30 % lower than the ones foreseen in the previous EuCARD HTS insert pancakes made of ReBCO tapes – 750 tons·m^{-1} [18, 19]. For the standalone mode, they are *only* 88 tons·m^{-1}. As a first step to investigate the very high force impact in insert mode a simple 2D-elastic model of the magnet has been developed. It gives a hint about the viability of such a magnet.

C. 2D elastic mechanical model

A mechanical model was developed using the CEA in-house Finite Element (FE) code cast3m [11]. The code computes the initial pre-stress at 293 K, the stress induced by the cooling to 4.2 K, and the deformation caused by coil powering (Fig. 5).

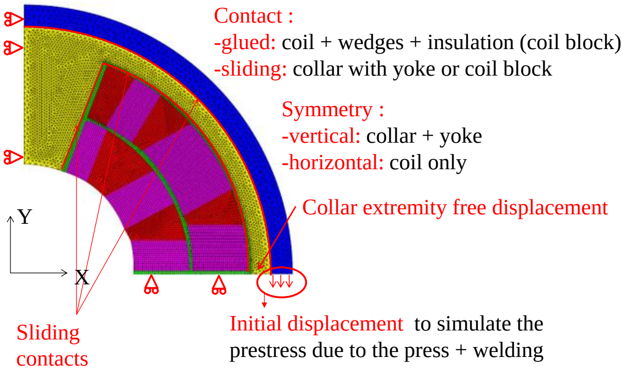

Fig. 5. Boundary conditions of the model: symmetries, contacts, initial displacement. Collars are allowed sliding on the external cylinder as well as the outer insulation of the coil block.

Actually, due to the large stability margin of HTS the assembly philosophy may differ from the manufacturing of LTS magnets. The latter ones need to be pre-stressed to avoid mechanical movements of the cable and long training [20]. Prestress to avoid movements may not be required any more for HTS-wound magnets. In addition, even if HTS ReBCO tapes can withstand a very high transverse pressure (600 MPa), a Roebel cable composed by those tapes is much more affected by transverse prestress because of i) the reduction of the effective transverse surface of the cable [8,9] ii) the shearing due to the scissors-like configuration of the tapes [4]. This leads to a mandatory impregnation of the coil that should limit this effect as well as the need for a mechanical pre-stress. No mechanical material properties of impregnated Roebel cables have been measured so far. Therefore, in the first simulations, Nb_3Sn-like impregnated material properties are used. Investigation of suitable resins is ongoing at Cern [4].

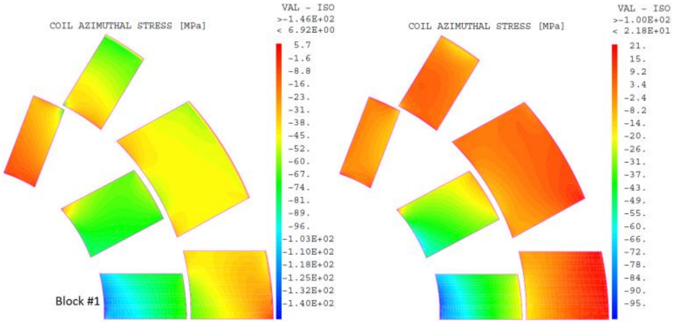

Fig. 6. Azimuthal stress distribution in the 6 block winding when the HTS magnet is inside the iron yoke in standalone configuration and excited at 5.0 T central magnetic field: Left: External tube = 5.5 mm + Prestress. Right: As-thick-as possible external tube of 8 mm to fit within Fresca2 + no prestress.

Figure 6 represents the azimuthal stress σ_θ in the coil in standalone mode for two different mechanical configurations. In Fig. 6 left, the External Tube (ET) is 5.5 mm thick and a prestress is applied to the coil. This leads to a significant pinching of the inner-shell mid-plane block, namely block #1. The peak stress is around 150 MPa. In Fig. 6 right, a reduction of this pinching effect is obtained by increasing the thickness of the outer mechanical structure as well as cancelling the prestress (no initial displacement of the external tube at 293 K, see Fig. 4). In this extreme case still fitting inside the Fresca2 aperture the external tube is 8 mm thick. The collar is reduced to a protection sheet (collar thickness < 0.5 mm). In this best configuration available for the EuCARD2 project the peak stress is then of the order of 100 MPa in standalone mode. This value of stress is still bearable.

The conditions previously described have been simulated in insert mode and displayed in Fig. 7. Unfortunately, when inserted in a high field facility the forces lead to huge pinching of the coil and a very high azimuthal stress in the coil block#1. A decrease of the peak stress is observed when no-prestress is applied and the maximum 8-mm external tube thickness is implemented: 800 MPa down to 600 MPa. Mechanical characterization of the block coil, namely E-modulus measurements of stack of impregnated Roebel cables combined to electrical tests, are foreseen soon, to determine what is the actual maximum transverse stress at which such coils can operate. However, it seems from this analysis that this could be a clear show stopper for classical cosine-theta magnet in view of the EuCARD2 project. Fortunately, as shown in Fig. 8, an increase of the tube to a thickness of the same order of the coil (20 mm) drastically reduces the peak stress to - still challenging – but acceptable values: 30 MPa in 5 T standalone mode and 250 MPa in 16 T insert mode. All the main results are summarized in Table IV. Classical cosine-theta magnets could thus be used as HTS insert in field above 16 T but not in the framework of the EuCARD2 “Future Magnets” project. Not enough room is left for the mechanical structure in order to reduce the coil pinching and, so, the stress down to tolerable values. To get around this, one can reduce the current density or resume previous designs and coil lay-outs hoping to reduce stress accumulation and pinching effect.

TABLE IV
PEAK AZIMUTHAL STRESS IN BLOCK #1

Field [T]	ET thickness [mm]	Prestress	Peak stress [MPa]	Fig.
5.00	5.5	Yes	146	6 left
5.00	5.5	No	118	N/A
5.00	8.0	Yes	187	N/A
5.00	8.0	No	100	6 right
16.78	5.5	Yes	782	7 left
16.78	5.5	No	684	N/A
16.78	8.0	Yes	805	N/A
16.78	8.0	No	600	7 right
5.00	20.0	No	30	8 left
16.78	20.0	No	250	8 right

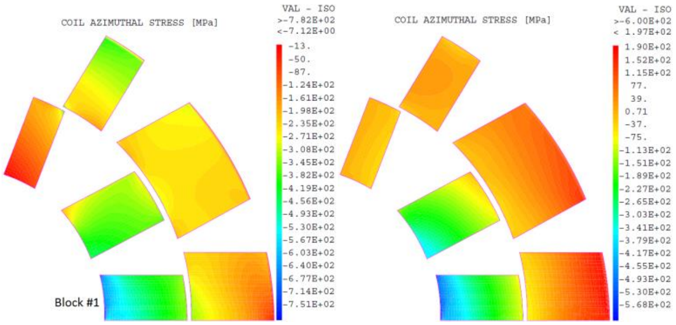

Fig. 7. Azimuthal stress distribution in the 6 block winding when both of the magnets (Fresca2 and the HTS insert dipole) are fully energized – 16.78 T central magnetic field. Left: External tube = 5.5 mm + Prestress. Right: As-thick-as possible external tube of 8 mm to fit within Fresca2 + no prestress.

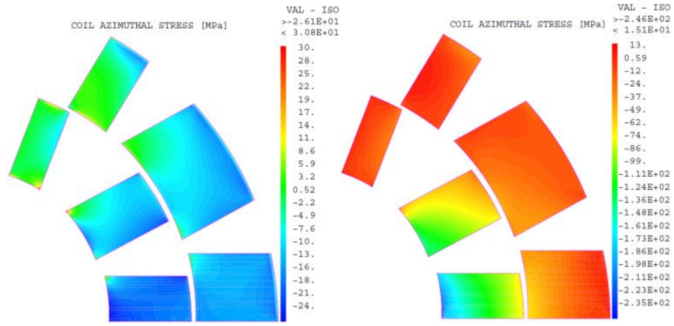

Fig. 8. Azimuthal stress distribution. **No prestress. External tube thickness of 20-mm that does not fit in Fresca2**. Left: 5 T standalone mode. Right: 16.78 T insert mode.

III. FUTURE DIRECTION

A. Perot’s magnet design

In the early 80’s a series of Perot’s dipole was built at CEA Saclay using *“accurately punched laminations with slots for conductor location”* [21] (see Fig. 10). The design has been lately called motor-type design due to the similarity with electrical motor laminations [22, 23]. Initially developed to reach very high precision in the conductor location, Perot’s dipole could be very useful to add mechanical stages in-between the coil blocks to avoid any accumulation of the magnetic forces in the median-plane.

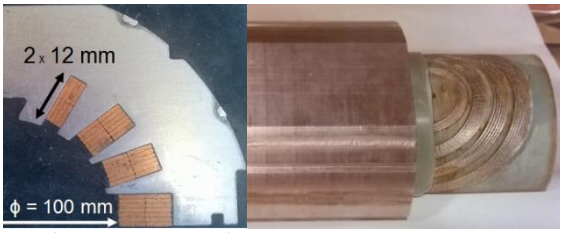

Fig. 9. Left: Collar with slots filled with Nb-Ti conductors. Right: Half of a 4.4 T dipole made of the motor-like collar technology [21].

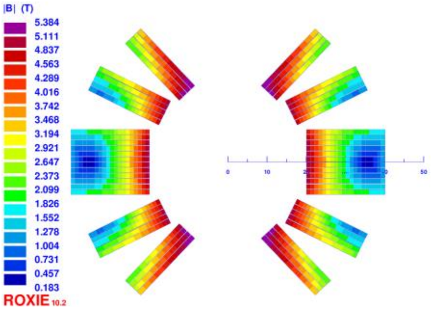

Fig.10. Three slot motor-like design made of a “thick” ReBCO Roebel #2 cable with B_{peak} = 5.39 T within a yoke and J_e = 475 A/mm^2 in conductors.

Based on the slot design a 2D electromagnetic model has been done with Roxie to check its validity in terms of current density since a lot of space is lost in the outer layer of conductors. In the case of this design (Fig. 11) the Roebel cable #2 was used. In order to reach 5 T when inserted inside a 60-mm thick iron yoke the coil is powered with a current of 5700 A leading to an engineering current density J_e = 475 A·mm^2. The harmonics b3 and b5 are below one unit.

IV. CONCLUSION

An investigation on the possibility to use cosine-theta magnet to build HTS insert was conducted. A mechanical FEM gives a glimpse of how challenging would be the coil manufacturing for the EuCARD2 HTS dipole due to very high azimuthal stress strongly depending on the stiffness and/or thickness of the mechanical structure. The peak stress is coming from the structure ovalization and would apply to any coil design. For cos-theta coil it seems that the stress would rise - in insert mode - up to 600 MPa (100 MPa standalone mode). Actually, not enough space is left to have a strong structure between the HTS insert coils and Fresca2. A mechanical structure as wide as the two layer coil would be needed to get bearable stress values: 30 MPa, 250 MPa, respectively standalone and insert mode. For the EuCARD2 “Future magnets” project, an attempt to possibly overcome all of this is the use of laminations with fingers on which the block of conductors would be seated, the so-called slot design, in which engineering current density is around ~475 A·mm^{-2}.

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