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HTS Dipole Magnet for a Particle Accelerator using a Twisted Stacked Cable

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***Abstract*—High T_c superconducting (HTS) dipole magnets are expected to be used in the upgrade of existing particle accelerators. In the framework of EuCARD-2 project, a new dipole generating fields between 17 and 20 T is under consideration with a HTS insert providing 5 T. This has to provide a good field quality at two-third of 40 mm beam aperture. The HTS stacked cable is the simplest way to acquire the large current and a strong mechanical cable. A twist for half turn in the magnet ends partially transposes the stacked tapes and improves the current distribution. However, the twisted stacked cable exposes the ReBCO tape to magnetic fields perpendicular to their wide face where the engineering current density J_e is lower. In addition, the different strength and direction of forces cause shear stress between the tapes. The HTS twisted stacked insert is designed with a 4 x 4 mm block-coil stacked with 4 mm wide tape. The 46-turns of stacked cable, which is almost aligned to the background field, achieves a 5 T with the required field quality. The 3D magnet ends are designed with the racetrack and flared-ends coils. It consists of six double pancakes. One of the mechanical conditions in the coil-ends, whose block-coil is divided into four tapes, has been analyzed with the Fresca2 LTS outsert. The HTS insert is able to withstand forces by its own.**

***Index Terms*—Particle accelerator, EuCARD-2, dipole magnet, HTS magnet, twisted stacked cable, mechanical architecture**

I. Introduction

In the framework of the enhanced European Coordination for Accelerator Research and Development (EuCARD-2) project of Work Package 10, CERN aims to upgrade the LHC beam energy coupled with the magnetic field from 8.3 T to 17 - 20 T range including a 5 T contribution from a HTS insert [1, 2]. Such challenging high field is only possible using high T_c superconductor (HTS) materials that show a large engineering current density J_e under high fields.

The HTS magnet is inserted inside the Fresca2 low T_c superconducting (LTS) magnet whose field limit is about 15 T [3]. The HTS insert needs to provide a good field quality less than a few units at two-thirds of beam aperture. Besides, a large operating current I_{op} is required for the operation whose value is set to be a 5 -10 kA [4]. As a consequence, the high field and the large I_{op} cause large Lorentz forces. These are sufficient reasons to use a HTS stacked cable.

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TABLE I
HTS Insert Constraints in EuCARD-2 Project

Parameter	Symbol/ unit	Value
Dimensional & Mechanical constraints		
Beam aperture	ϕ_b / mm	40
External aperture	ϕ_{ext} / mm	< 100
Electromagnetic constraint		
Center field in standalone	B_1/ T	5
Center field in background	-/ T	17 – 20
Operating current	I_{op}/ kA	5 – 10
Field quality at 2/3 ϕ_b	FQ/ $10^{-4}B_1$	< 5

A stack of ReBCO tapes causes an inhomogeneous current distribution. A transposition of conductors assists in obtaining a more uniform current distribution. A Roebel cable with a continuously transposition is one of the solutions [5]. But the mechanical punching of the ReBCO tape raises the cost and creates a weak mechanical zone. Meanwhile, a twisted stacked cable enables the partial transposition with a simple manufacturing process [6]. Nevertheless, the field will be likely oriented along the c-axis of the tapes where the twisting of the stack occurs. This leads to the large J_e degradation, so that the twist is applied in the magnet ends where the amplitude of background field gets smaller. From a mechanical point of view, the bad field orientation could cause large stress and the delamination of the YBCO layer.

In EuCARD-2 project, three HTS inserts are studied using Roebel and the twisted stacked cable options. CERN and CEA utilize the Roebel cable forming a block-coil and a cosθ layout, respectively [4, 7]. Meanwhile, Grenoble works on the twisted stacked cable for a block-coil design.

II. HTS Twisted Stacked Insert Design

A. Design Constraint

A 5 T HTS twisted stacked insert using a block-coil has been optimized with a homemade analytical code under appropriate dimensional, electromagnetic and mechanical constraints (see Fig. 1) [8]. The main objective is to obtain the maximum field quality in the straight part. In addition, the operating current density J_{op} is preferred to be as small as possible to possess enough J_e margin. For this reason, the block-coil is aligned to the background field of Fresca2 LTS outsert. This also directs the Lorentz force onto the correct wide surface of the ReBCO tape. An inner and outer supporting tubes are utilized to counteract the Lorentz loads. The field quality of the magnet ends is anticipated to be poor, so the magnet ends must be as short as possible. The cross-

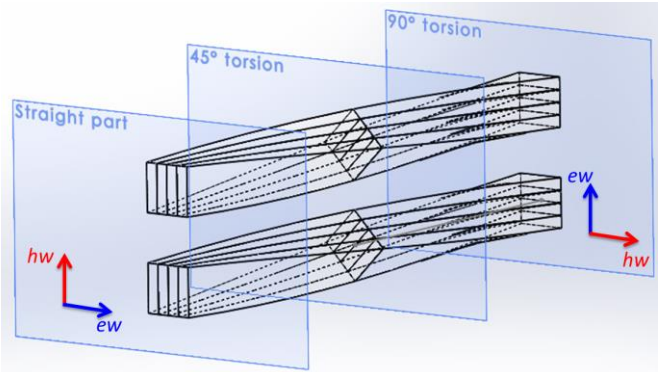

Fig. 1. Constraints for HTS twisted stacked insert. The vertical space between the stacked cables must be saved at straight part in order to avoid the *hw* bending that results in far too long magnet ends.

TABLE II
2D HTS TWISTED STACKED INSERT SPECIFICATION

Parameter	Value
Number of turn	46
Size of block-coil [mm]	4 x 4
Center field [T]	17.2
Operating current density J_{op} [MA/m^2]	650
Operating Current I_{op} [kA]	10.4
Field quality B_3 & B_5	1.5/ 0.78 units
Total inductance of 1 m long [mH]	283

section in the straight part is in the hardway (*hw*) bending is towards the vertical direction which results in far too long magnetic ends compared to that of easyway (*ew*) bending. During the twist in the coil-ends, the cross-section is rotated along the length risking the stacked cables overlapping. Hence, the vertical space between the stacked cables must be sufficient in the straight part in order to avoid the *hw* bending. Furthermore, the number and the size of block-coil placed between 40 mm and 100 mm apertures are restricted to the size of the twist cross-section. The block-coils' size can be chosen from one of the commercially available ReBCO tapes.

B. 2D Magnet Design

Fig. 2 represents the optimized HTS twisted stacked insert. A 4 x 4 mm stacked cable composed of 20 tapes and carrying 10.2 kA during operation is utilized to wind the 46-turn coil. The smaller tape width allows for smaller twist pitch (°/mm) which gives shorter magnet ends [6]. The block-coils are almost aligned to the background field and the arrows show the Lorentz forces are loading onto the correct wide surface. The 2 mm inner and 4 mm outer tubes provide the mechanical reinforcement necessary to counteract the Lorentz load experienced by the HTS insert. Three or four block-coils, which are assembled and aligned horizontally, facilitate the design of the mechanical structure and the winding. As a result, the HTS insert with LTS outsert provides a 17.2 T of well uniform field whose harmonics B_3 and B_5 are 1.5 and 0.78 units, respectively.

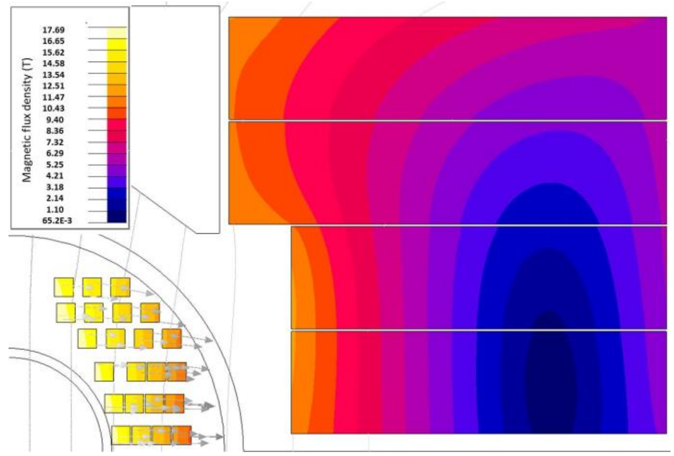

Fig. 2. Field distribution (0 – 17.7 T) of 46-turns HTS twisted stacked insert with Fresca2 LTS outsert at right-top quarter. Center field B_1 = 17 T with required field quality is achieved with J_{op} = 650 MA/m^2. Lorentz forces are directed towards the 4 mm thick external mechanical tube.

TABLE III
NUMERICAL SETUP

Parameter	Value
Number of tape	4
Width/ thickness [mm]	4/ 0.2
Engineering current density [MA/m^2]	1000
n-value	20
Ramp current	0.65*J_e

C. Current distribution

The dipole magnet is designed based on the hypothesis of homogeneous current density, although this is not guaranteed in the HTS conductor due to the lack of full transposition. We analyze the impact of the twisted stacked cable using a numerical model coupled with equivalent circuit. The stacked cable is divided into 4 tapes whose J_e and n-value are 1000 MA/m^2 and 20, respectively. The tapes are assumed to be insulated between each other because only a half twist per turn is applied in the coil-ends of the 15 m long insert. The stacked cable is gradually exposed to 1 T background field and then the current I_a is ramped up to the 65% of J_e that is equal to the operating current density of our HTS insert.

Fig. 3 shows the current waveforms of stacked and twisted stacked cable. The background field leads the current to flow in opposite direction in case of the stacked cable; while the twisted stacked cable has almost zero current. These are due to the magnetizations of coupled and non-coupled models, respectively. Moreover, the stacked cable (coupled model) has more magnetization compared to that of twisted stacked (non-coupled-model). The stacked cable pushes the current into the tapes, which possess the negative current. At the end of the ramp current, the tape 1 and 2 have larger current. The twisted stacked cable achieves a partial transposition. The tapes at both the edges (tape 1 and 4) and at middle (tape 2 and 3) of the block-coil show the same current. At first, most of the current passes into the edges because of the shielding effect respect to the middle tapes. At the end of the ramp current, the tapes at both edges have larger current. In reality, the twisted stacked cable contains the contact resistance at the extremity

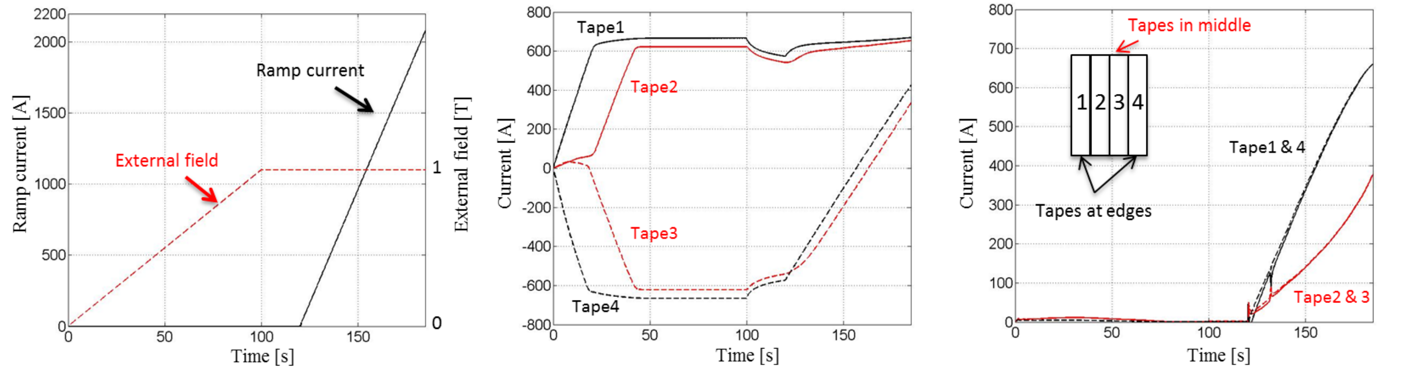

Fig. 3. Current waveform of stacked and twisted stacked cable with 4-stacked tapes under 1 T background field. (Left) Current is ramped up to 65% of the critical current of stacked cable (Center) Stacked cable with no transposition. Current distribution is extremely inhomogeneous. (Right) Twisted stacked cable is partially transposed. Tapes at both the edges and at middle have same current.

TABLE IV
3D HTS MAGNET ENDS SPECIFICATION

Parameter	Value
Minimal ew/ hw bending radius	6 mm/ 2 m
Twist pitch [º/mm]	1.8
Total length of magnet ends/ stacked cable	800 mm/ 22 m

of magnet ends. Besides, the current distribution of the insulated stacked cable is very sensitive to the contact resistance. Therefore, the current distribution needs to be investigated as a function of the contact resistance to see its effects on the field quality.

D. 3D Magnet ends

The twisted stacked magnet is wound as either the racetrack or the flared-ends coil. The racetrack coils, whose vertical positions are higher than the beam tube, are flat and the 180º twist is applied at one side. The flared-ends coil has to lift its vertical position up to the winding head (see Fig. 4). An 180º torsion is divided into two 90º twists. The first 90º twist orients the cross-section into *ew* bending at vertical direction (refer to Fig. 2). This makes easier to lift the stacked cable. Then, the second one is applied before the winding head. On the other side, the 360º twist, which is divided into 270º and 90º twists, is added to transpose the stacked cable. The minimal *ew* and *hw* bending are 6 mm and 2 m, respectively; whereas the twist pitch is 1.8 º/mm on 100 mm without J_e degradation [6]. The bending and the twist must not appear at the same time to avoid the weak mechanical zone. Fixing the twisted stacked cable (e.g. impregnated or glued) makes the winding impossible because some tapes start to wave. All tapes, therefore, are free to slide respect to one another.

Six block-coil assemblies composed of 46-turns have three double pancakes (see Fig. 5). Three block-coil assemblies at top are racetrack coil, while three at bottom are flared-ends coil. At the transposition side, the twists are appropriately positioned not to overlap each other and to save enough room for the mechanical reinforcement. The double pancake is connected with a layer-to-layer transposition. The layer jumps appear between the block-coil assemblies at 1st & 2nd (double racetrack coils), at 3rd & 4th (racetrack and flared-ends coil) and at 5th & 6th (double flare-ends coils). The layer jump is done either with the twist + *ew* bending or with the *hw* bending. The total length of the magnet ends is 800 mm (400 mm on each side). The ends are wound using 22 m of stacked cable.

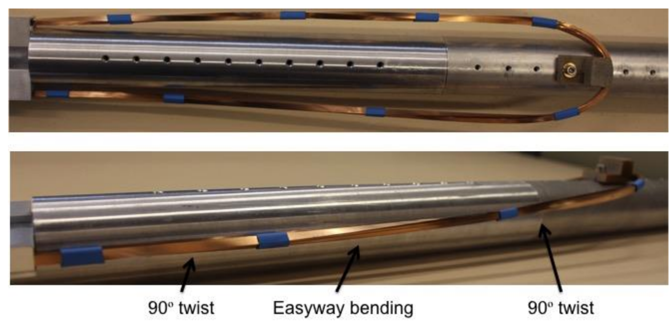

Fig. 4. Winding topology of flared-ends coil. Stacked cable is twisted for 180º at one side and for 360º at the other side. The 180º trosion is divided into two 90º twists in order to orient the cross-section into easyway bending.

In order to keep the large margin for J_e, the magnet ends' position is preferred to be outside of the LTS outsert. Fig. 6 represents the 3D field distribution in a standalone configuration for the HTS insert where the twist occurs. The closer to the straight part, the higher the magnetic field that is generated. Besides, it is obvious that the inner turns of three block-coil assemblies at top are under the high magnetic field conditions meaning that the large Lorentz forces occur at these twist parts. The minimal J_e takes place at the 90º twist when the field is perpendicular to the REBCO tapes.

III. TWISTED STACKED MECHANICAL ARCHITECTURE

The 3D field distribution in the coil-ends implies the large Lorentz forces occur at the twist part. Adding the Fresca2 LTS outsert leads to a large J_e degradation and Lorentz forces. The twist part may become the worst mechanical scenario due to the shear stress between the stacked tapes. Hence, we have analyzed the mechanical performance at one of the 3D designs' cut-plane with the straight part of Fresca2 LTS.

A. 2D Mechanical Analysis

One of the worst expected scenarios in the coil-ends, whose 1st and 3rd stacked cables are twisted for 45º, has been selected

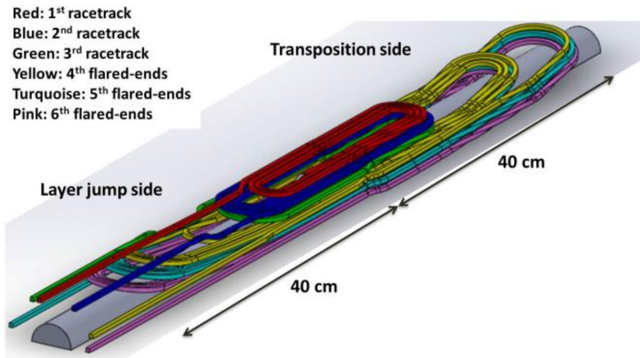

Fig. 5. 3D magnet ends consists of three double pancakes. Three block-coil assemblies at top forms racetrack coils while three assemblies at bottm forms flared-ends coil. Double pancakes are connected with layer jump. The total length of magnet ends and stacked cable are 800 mm and 22 m, respectively.

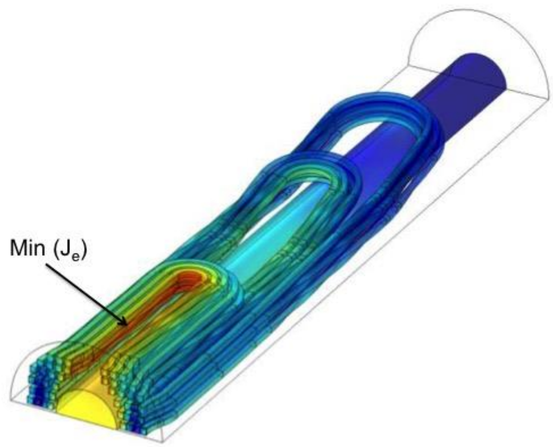

Fig. 6. 3D field distribution of magnet ends. Minimal J_e occurs at 90º twist of three top block-coil assemblies when field penetrates into c-axis.

to see the Van Mises (V.M.) and the shear stress (see Fig. 7). This 2D cut-plane is located just after the straight part where the high background field of 17.2 T is expected. The background field directs the Lorentz force toward the outer mechanical tube. As a preliminary step, the block-coil 'A' has been divided into four stacked tapes whose thickness is 1 mm. These tapes are assumed to be in sliding contact. On the other hand, the perimeter of HTS conductor is set to be in sliding contact or glued on the copper.

As an initial step, the cool-down from 293 K to 4.2 K has been simulated using the thermal stress analysis. Then, the combined stress due to the thermal contraction and the Lorentz forces calculated from the electromagnetic analysis are loaded on the model using the mechanical analysis with displacements constraints. Fig. 8 shows the total V.M. stress distribution under the cool-down (thermal loads) and the magnetic field (Lorentz loads). This mechanical design shows a good performance and it proved that the 4 mm thick external tube is able to withstand the forces. The maximum V.M. stress of the 2nd SS 316 plate sticking into the titanium, however, is slightly higher than the allowable stress whose value is the two-third of its yield strength.

In case the HTS conductor 'A' is in sliding contact on its perimeter, the cool-down and Lorentz forces induce a maximum shear stress of 49 MPa. On the other hand, if the

TABLE V
MECHANICAL PROPERTY

Material [9]	Young Modulus [GPa]	Poisson's ratio	Thermal expansion coefficient [K^{-1}]
Stainless steel 304	210	0.279	1.02e-5
Stainless steel 316	208	0.282	1.02e-5
Copper	138.6	0.338	1.1211e-5
Titanium	130.6	0.302	0.5225e-5

TABLE VI
MAX VAN MISES STRESS

Material	Yield strength [MPa]	Thermal load [MPa]	Lorentz load [MPa]	Total [MPa]
HTS	890	342.5	295	511.7
External tube	980	311.9	168.6	429.2
Copper	1077	293.6	351.2	585.5
Plate	980	444	376.3	699.5
Titanium	1200	325.8	431	460.7

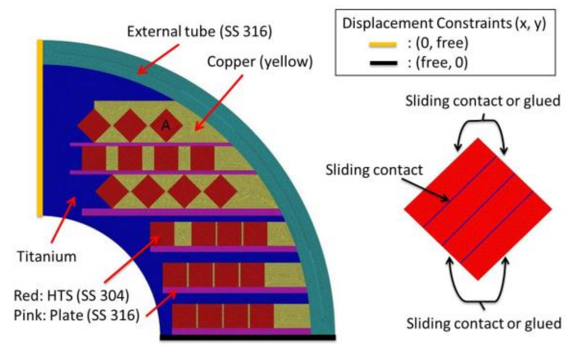

Fig. 7. Mechanical architecture of 46-turns HTS twisted stacked insert whose 1st and 3rd block-coil assemblies are twisted for 45º. HTS conductor 'A' is divided into 4 tapes. Conductor is in sliding contact or glued on its perimeter.

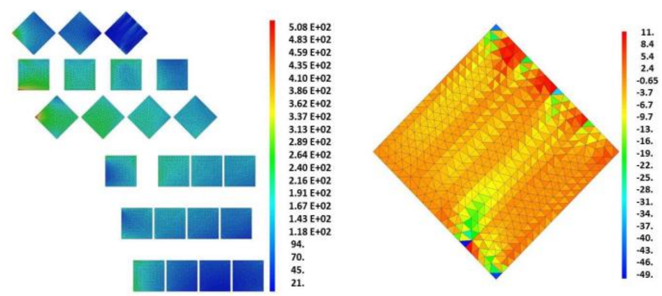

Fig. 8. Von Mises (V.M.) distribution of 46-turns HTS conductor. (Left) Maximum V.M. stress of 511 MPa occurs at inner turn of 2nd block-coil assembly (22 – 511 MPa). (Right) Shear stress distribution in HTS conductor 'A' in case its perimeter is in sliding contact on copper (-49 – 11 MPa).

HTS conductor is assumed to be glued to the copper on its perimeter, the max shear stress becomes 188 MPa. In reality, there are frictions at the stacked tapes and at perimeter of HTS conductor. Therefore, the shear stress of the conductor is expected to be between those two limiting values.

IV. RELATIVE IMPACT BETWEEN HTS AND LTS

The HTS insert must possess enough safety margin for both the J_e and the mechanical integrity. The J_e of HTS insert is determined at the twist part in magnet ends. The background field amplitude of the LTS outsert becomes smaller as it goes from the straight part to the coil-ends' extremity. The smaller fields allow larger J_e but also reduce the Lorentz forces. Nevertheless the mechanical analysis indicates the structure can withstand the forces even in the worst case scenarios (high field region inside the LTS outsert)

V. Conclusions

The 46-turns HTS insert using a twisted stacked cable has been designed with the Fresca2 LTS outsert in the framework of EuCARD-2 project. The insulated twisted stacked cable is partially transposed and has less magnetization compared to that of the stacked cable; nevertheless the current distribution is still inhomogeneous during the ramp of the current. In addition, its current distribution is very sensitive to the contact resistance and it may affect the field quality. The twisted stacked cable especially wound as flared-ends coil results in long and complicate magnet ends. Nevertheless the length of magnet-ends is still short compared to the straight part which is 15 m long. The ReBCO tape possesses the large J_e that is required as the field of 17 T is expected to penetrate into c-axis at the twist part. The preliminary mechanical structure in the coil-ends has been analyzed to study the V.M. and the shear stress distribution. The mechanical support structure envisioned successfully withstands the thermal stress and the Lorentz forces. However, the actual thickness of the ReBCO tape that is 0.2 mm will cause other concerns such as the deflection. To possess enough safety operating margin, the HTS insert ends must be located inside the LTS outsert ends, where the amplitude of the field becomes smaller.

Acknowledgment

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