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Authors

Marinozzi, V

Ferracin, P

Vallone, G

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Conceptual Design of a 20 T Hybrid Cos-Theta Dipole Superconducting Magnet for Future High-Energy Particle Accelerators.

V. Marinozzi, P. Ferracin, G. Vallone

Abstract— High energy physics research will need more and more powerful circular accelerators in the next decades. It is therefore desirable to have dipole magnets able to produce the largest possible magnetic field, in order to keep the machine diameter within a reasonable size. A 20 T dipole is considered a desired achievement since it would allow the construction of an 80 km machine, able to circulate 100 TeV proton beams. In order to reach 20 T, a hybrid Low-Temperature Superconductor (LTS) - High-Temperature Superconductor (HTS) magnet is needed, since LTS technology is presently limited to ~16 T for accelerator magnet applications. In this paper, we present the design of a 6 layers 20 T hybrid dipole magnet using Nb₃Sn (LTS) and Bi2212 (HTS). We show that it is possible to achieve this magnetic field with accelerator field quality, with sufficient margin on a realistic conductor, keeping the stresses within safe limit, avoiding conductor degradation.

Index Terms— Superconducting magnets, dipole magnets, Nb₃Sn magnets, HTS, hybrid magnets.

I. INTRODUCTION

IN the last 20 years, there has been an effort of the superconducting magnet community for the design of a 20 T dipole magnet [1-7]. Such a magnetic field is indeed needed for the next generation of particle colliders, enabling the 100 TeV regime with credible dimensions of the accelerator (~80 km circumference). The main challenge in the design of these magnets is that the magnetic field is not reachable using the Low Temperature Superconductors (LTS) that are the state-of-the-art of the accelerator magnet design, today. Indeed, the most performing LTS conductor, the Nb₃Sn, when used beyond a 16 T magnetic field suffers a considerable reduction of performance. The critical current beyond 16 T is so low that a significant amount of conductor would be needed to generate a > 16 T magnetic field. In order to pass the 16 T threshold, it is therefore considered unavoidable to use High Temperature Superconductors (HTS) that do not suffer this performance loss. They are, however, more expensive, more difficult to protect, and subject to degradation under lower stress. In this paper, we show the conceptual design of a 20 T hybrid cos-theta dipole. We show that it is possible to use a mix of HTS

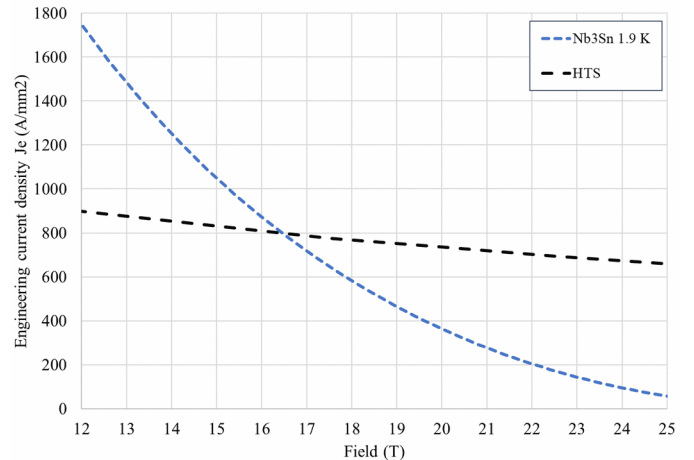
P. Ferracin and G. Vallone are with Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

and LTS conductor, optimizing the cost of the magnet, in order to reach a 20 T magnetic field with accelerator field quality (less than 3 units).

We also show that it is possible to keep the peak stresses in an infinitely rigid structure within safe limits. More details on the assumptions made for this study can be found in [8].

II. CONDUCTOR

The two conductors chosen for the design are Bi2212 as HTS, and Nb₃Sn as LTS. Fig.1 shows the engineering critical current densities considered for the design. The current densities shown in Fig.1 are equivalent to a critical current of 2944 A/mm² at 20 T, 1.9 K for the Bi2212 (assuming the stabilizer/superconductor ratio is equal to 3), and 1928 A/mm² at 16 T, 1.9 K for the Nb₃Sn [8] (assuming the stabilizer/superconductor ratio is equal to 1). These numbers are comparable with the most performing conductors that can be found on the market today. Both the conductors are considered as Rutherford cables made of filamentary strands. The Nb₃Sn is



assumed to be stabilized with copper, the Bi2212 is assumed to be stabilized with silver.

Fig. 1. Engineering critical current density assumed for the margin computations in Nb₃Sn and Bi2212 strands (dashed lines).

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V. Marinozzi is with Fermi National Accelerator Laboratory, Batavia, IL 80510 USA. (email: vitmar@fnal.gov)

III. ELECTROMAGNETIC DESIGN

The focus of the electromagnetic design is to produce a 20 T magnetic field with acceptable field quality, and realistic conductor and coil dimensions. The bore diameter of the magnet is 50 mm. We considered as maximum allowed harmonics 3 units.

The cross section of the magnet is shown in Fig 2. As it can be seen, the magnet is composed by 6 layers, or 3 double-pancake coils. Each coil has a different conductor. The innermost coil (layer 1 and 2) is made of Bi2212, the two outermost coils (layer 3 to 6) are made of Nb₃Sn. The magnet current is 13.5 kA, and all the coils are considered in series. The design parameters for each coil are resumed in Table I, along with the main cable parameters. All the conductors have less than 40 strands. This is consistent with the state-of-the-art Rutherford cables production [13-14]. We assume a simple circular 250 mm thick iron yoke surrounds the coil, distant 20 mm from the outer diameter of the coil.

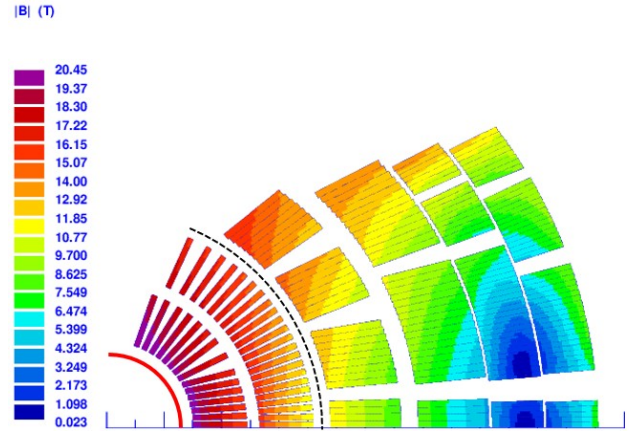
The three coils have different conductor layouts. The first coil (layer 1-2) is composed of separate cables wound into steel slots. This configuration might be practically realized with a Canted-Cos-Theta or a stress managed cos-theta layout [9-10], where every conductor is separated by a “rib” from the previous and the following conductor. The second coil (layer 3-4) is a stress-managed cos-theta [10] with ribs separating blocks of conductor. The third coil (layer 5-6) is a standard cos-theta with regular copper wedges. These choices are mainly due to mechanical behaviors, and will be discussed in details in section IV.

TABLE I
MAGNET DESIGN PARAMETERS

Parameter	Layer 1-2	Layer 3-4	Layer 5-6
Material	Bi2212	Nb ₃ Sn	Nb ₃ Sn
Current [kA]	13.5	13.5	13.5
Strand diameter [mm]	0.95	1.15	0.85
Stabilizer/Superconductor	3	1	1.2
Strands number	36	40	40
Bare width [mm]	18.59	24.38	17.73
Bare inner height [mm]	1.62	1.98	1.44
Bare outer height [mm]	1.79	2.19	1.59
Insulation [mm]	0.15	0.15	0.15
Load-line percentage (1.9 K) [%]	80.2	79.6	79.8
Total Area Per Quadrant [mm ²]	1401	3767	3109

Only the layer 1-2 is made of HTS conductor. This choice has been made in order to optimize the ideal cost of the magnet, and to reduce the peak stress on the HTS. The issue of this choice is that between layer 2 and 3 a “reverse grading” of the conductor can be observed: as it can be seen in Table I, the innermost Nb₃Sn conductor is bigger than the layer Bi2212 conductor. Ideally, it would be preferable to reduce the conductor dimensions progressively, while going farther from the center of the magnet. The magnetic field is in fact decreasing with the distance from the bore, and increasing the current density is helpful to reduce the magnet dimensions (grading). However, in this case, we preferred a less efficient magnetic design, with

I.



bigger coil size (~140 mm width), but with lower costs for conductor [11]. This

Fig. 2. Magnet cross section (1 quarter) with coil magnetic field. The dashed line separates the HTS (inner) from LTS (outer) parts of the magnet. The aperture is represented by the red circle (50 mm diameter).

choice could be reconsidered in the future in case the HTS cost will be closer to the LTS cost. The total area of conductor is 1401 mm² of Bi2212, and 6186 mm² of Nb₃Sn. Confirming what just said, the LTS is ~5 times the amount of HTS, reducing the magnet cost, but increasing its dimension.

The load-line percentage is ~80% at 1.9 K for all the conductors. This means that the magnet design is well balanced. The target load-line margin was equal to 87% [8]. As a consequence, the design might have margin of improvements in quench protection and magnet dimensions.

In Table II we show that all the harmonics are below 3 units, and the field quality is within the requirements [8]. No even nor skew multipoles are allowed due to magnet symmetry.

TABLE II
MAGNET FIELD QUALITY

b1	10000	b11	0.06
b3	1.10	b13	-0.02
b5	2.57	b15	0.001
b7	1.81	b17	0.001
b9	-0.42	b19	-0.0002

IV. MECHANICAL DESIGN

The conductor stresses during powering were verified assuming an infinitely rigid structure around the coil, with no prestress. The material properties of the structural components are reported in Table III. This ideal condition provides a limit case that is in general better than what can actually be achieved in a real magnet. This also means that, if the cross-section design does not manage to keep the stresses below the limits in these conditions, it will not be able to do so when a real structure is considered. As an advantage, this type of optimization is independent from the final design of the structure. To avoid conductor degradation, a limit on the Von

Mises equivalent stress is imposed: 180 MPa for the Nb₃Sn,

Fig. 4. Mechanical model mesh and assumptions at the interfaces. The stress managed coils have sliding interfaces with the mandrel, while the outer coil is

and 120 MPa for the Bi2212 [8].

bonded, with separation allowed from the pole.

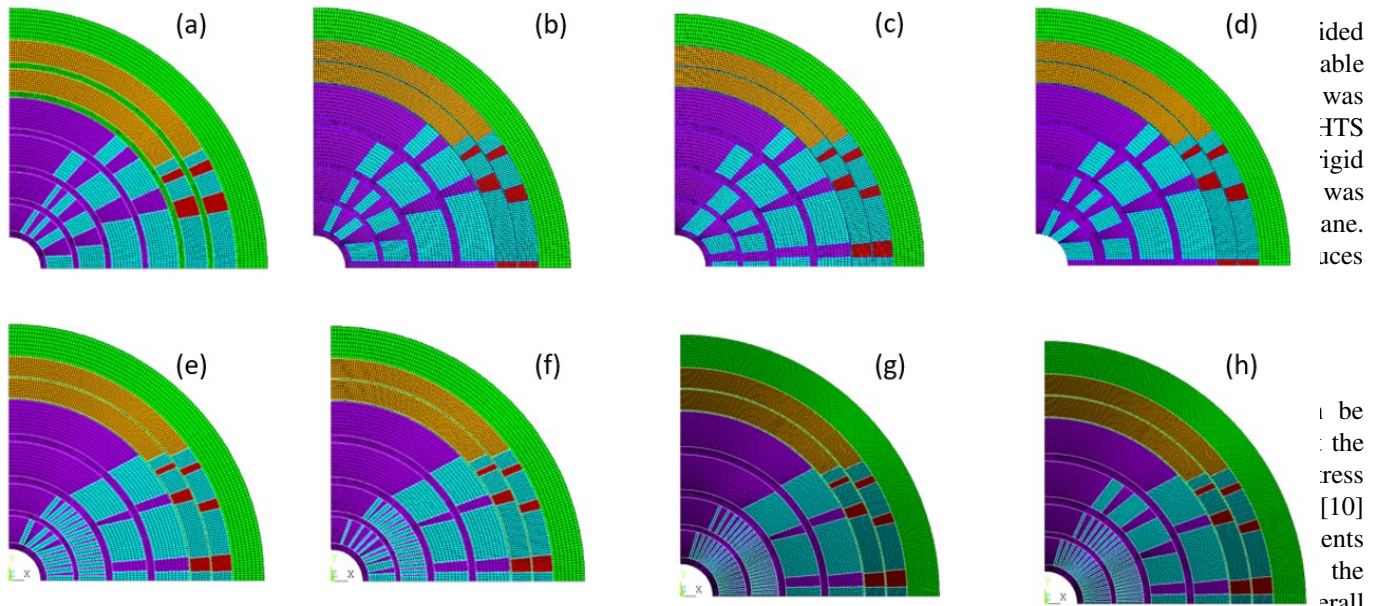
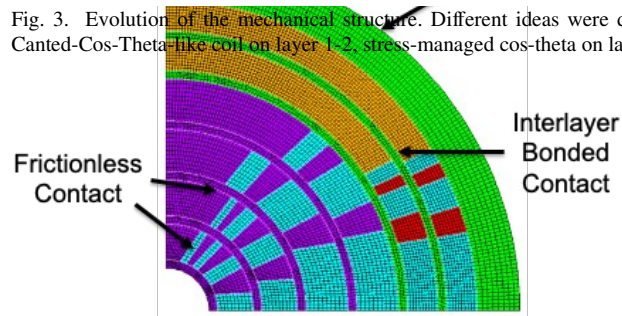
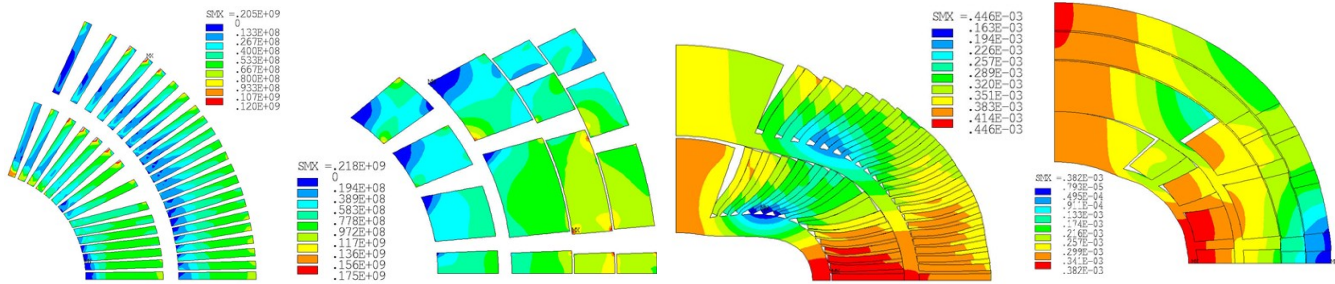


Fig. 3. Evolution of the mechanical structure. Different ideas were developed to maintain the peak stresses within design limits, converting to conductors. Canted-Cos-Theta-like coil on layer 1-2, stress-managed cos-theta on layer 3-4, and a standard cos-theta on layer 5-6. efficiency and margin are reduced, increasing the conductor cost needed to obtain similar performances.



In principle, the reinforcement does not have to be present in all the layers. Adding reinforcement to the outer layers can reduce the amount of bending of the overall coil pack. Reinforcing the inner layers can instead directly remove part of the load from the coils that see the higher stresses.



In an attempt of finding the best possible solution, many test cases were studied, virtually reinforcing some of the layers. The reinforcement is introduced by increasing the modulus of the entire layer to 200 GPa. This represents a bounding condition for a stress managed layer, where all the conductor has been substituted by steel reinforcements. Any real coil will provide lower stiffness to the overall system. As a consequence, this study is only used to provide an indication on the respective advantages obtained by reinforcing selected coils. The results of this study, in terms of azimuthal and radial stress, are provided in Table IV, where the reinforced layers are marked with an x. The table shows that it might be possible to stress manage only layer 1 and 2. However, when doing so, the azimuthal stress in layer 3 becomes very close to the limit. Interestingly, adding reinforcements to the outer coil does not allow to remove the bending effects, and the peak azimuthal stress in layer 1 stays above 280 MPa.

TABLE IV
LAYER REINFORCEMENT OPTIMIZATION

Layer Stress, sxx, MPa						Layer Stress, sxx, MPa					
1	2	3	4	5	6	1	2	3	4	5	6
X	X	X	X	90	89	X	X	X	X	131	139
X	X	X	88	103	103	X	X	X	144	131	139
X	X	73	118	124	123	X	X	173	136	130	139
83	133	169	193	X	X	298	106	122	158	X	X
83	134	X	X	X	X	298	106	122	158	X	X
X	X	169	193	X	X	X	X	122	158	X	X

B. Coil Optimization

Numerous designs were tested before a solution that could satisfy the design parameters was attained. A ‘story’ of these designs is shown in Fig. 3. Following the results of Section IV.A, the stress management was introduced only in layer 1, 2, 3 and 4. The FE model, coded in ANSYS 2020 R2 [15], assumes a plane stress condition. A typical mesh is shown in Figure 4. Coils are represented, for simplicity, using isotropic elastic material properties. The stress managed coils (layers 1-4) are wound in steel mandrels and non-bonded at the end of the impregnation. The standard coils use instead titanium poles and aluminum bronze wedges, and are bonded together, assuming the two layers are impregnated together with the wedges. Separation from the pole is allowed after energization, since no prestress is introduced at this stage of

the design. The first stress managed design test was performed keeping the same coil geometry from [11], but introducing steel spars between the layers (1-4). The resulting stresses were very high in the HTS coil (479 MPa peak). In an attempt of reducing the stresses, three solutions were tested: introducing a mid-plane wedge in stainless steel (b), aligning the wedges (c), and using a shared mandrel for layer 1 and 2 (d). None of these solutions allowed to bring the stresses within the limits. Significant improvement was found instead by increasing the number of blocks for the inner coil. First, the coil blocks were limited to 2 cables (e), then between 1 and 2 cables (f), and then to 1 cable per block (g). Finally, the number of blocks in layer 3 was also increased (h). The first block wedge alignment strategy was kept in these latter designs, as it can allow to intercept part of the radial load from the inner coil.

The resulting Von Mises equivalent stress contours for this last solution are shown in Fig. 5: the stress is within the limits everywhere. Only some corners in Layer 2 exceed the limit (205 MPa in HTS, 218 MPa in LTS), but these are contained in the insulation and not reaching the conductor. The condition at these corners might also change when a non-ideal structure is introduced around the magnet, and they will be further analyzed when a real structure will be designed. The displacements are also shown in Fig 5: the corner stresses seem to be due to the local deformation of the layer 2 mandrel, which brings the conductor edges in contact with the layer 3 mandrel. The ribs of layers 1 and 2 are 0.5 mm or more thick. While this is useful for a comparative analysis and the identification of the most efficient magnet, their feasibility will be explored further in future studies, with a complete mechanical structure analysis.

V. CONCLUSIONS

In this paper, we presented the design of a 20 T hybrid cos-theta dipole magnet for future particle accelerator. The magnet is composed by 3 coils, each one composed by 2 layers. The innermost coil is made with Bi2212, the two other coils are made with Nb₃Sn. The magnet can achieve the 20 T target with a current of 13.5 kA and working at 80 % of the load-line at 1.9 K, which gives some margin for future modifications to the design. One of the main challenges of the design is keeping the stresses within safe limits. This challenge was faced by introducing ‘stress-management’ of the layers 1 to 4

of the magnet, with a turn stress management on layers 1 and 2, and a block stress management on layers 3 and 4. Layers 5 and 6 are instead a standard cos-theta. Further developments of the design are planned in the future. Quench protection is one of the first problems that will be addressed. Moreover, further developments of the mechanical structure are expected, bringing it from a conceptual to an engineered design, as well as a 3D analysis for forces and ends design.

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