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Complete List of Authors:	Marinozzi, Vittorio; Fermi National Accelerator Laboratory, Technical Division Ferracin, Paolo; LBNL, ATAP Vallone, Giorgio; Lawrence Berkeley National Laboratory,
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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, in order to explore unknown regions of particle physics. 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 Nb_3Sn (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, Nb_3Sn 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 Nb_3Sn, when used beyond a 16 T magnetic field starts a considerable loss of performance. The critical current beyond 16 T is so low that it would be needed an enormous amount of conductor 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 don't suffer this performance loss. They are, however, more expensive, more difficult to protect, and subject to degradation under lower stress.

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V. Marinozzi is with Fermi National Accelerator Laboratory, Batavia, IL 80510 USA. (email: vitmar@fnal.gov)
P. Ferracin and G. Vallone are with Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

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 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 Nb_3Sn 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/mm^2 at 20 T, 1.9 K for the Bi2212 (assuming 3 as stabilizer/superconductor), and 1928 A/mm^2 at 16 T, 1.9 K for the Nb_3Sn [8]. 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 Nb_3Sn is assumed to be stabilized with copper, the Bi2212 is assumed to be stabilized with silver.

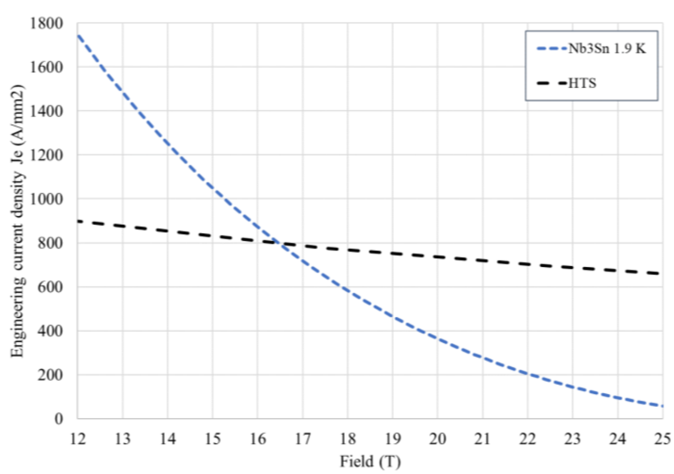

Fig. 1. Engineering current density assumed for the margin computations in Nb_3Sn and Bi2212 strands (dashed lines).

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. 1 and 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 inner-most coil (layer 1 and 2) is made of Bi2212, the two outermost coils (layer 3 to 6) are made of Nb_3Sn. 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 1, 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.

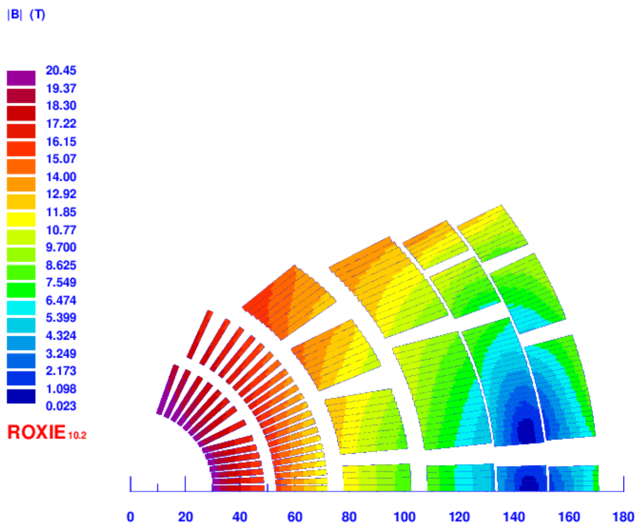

Fig. 1. Magnet cross section (1 quarter) with coil magnetic field.

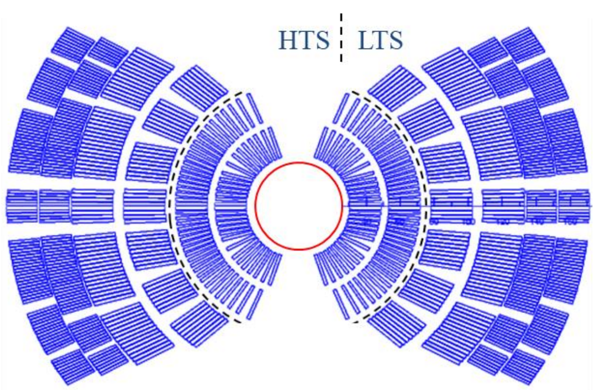

Fig. 2. Full magnet cross section. The dashed line separates the HTS (inner) from LTS (outer) parts of the magnet. The aperture is represented by the red circle (50 mm diameter).

The three coils have different conductor layouts. The first coil (layer 1-2) is composed of separate cables running 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. T choices are mainly due to mechanical behaviors, and will be discussed in details in section IV.

TABLE I
Design Criteria on Magnet Parameters

Parameter	Layer 1-2	Layer 3-4	Layer 5-6
Material	Bi2212	Nb_3Sn	Nb_3Sn
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 [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. 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 layer 3-4 conductor is bigger than the layer 1-2 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 bigger coil size (~140 mm width), but with lower costs for conductor [11]. This 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 mm^2 of Bi2212, and 6186 mm^2 of Nb_3Sn. 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 Fig. 3 we show that all the harmonics are below 3 units, and the field quality is within the requirements [8].

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NORMAL RELATIVE MULTIPOLES (1.D-4):
b 1:  10000.00000  b 2:     0.00000  b 3:     1.10186
b 4:     -0.00000  b 5:     2.56940  b 6:     0.00000
b 7:      1.80997  b 8:     0.00000  b 9:    -0.41881
b10:     -0.00000  b11:     0.05997  b12:     0.00000
b13:     -0.01606  b14:    -0.00000  b15:     0.00169
b16:      0.00000  b17:     0.00091  b18:     0.00000
b19:     -0.00023  b20:    -0.00000  b

SKEW RELATIVE MULTIPOLES (1.D-4):
a 1:      0.00000  a 2:     0.00000  a 3:    -0.00000
a 4:     -0.00000  a 5:     0.00000  a 6:    -0.00000
a 7:     -0.00000  a 8:     0.00000  a 9:    -0.00000
a10:      0.00000  a11:     0.00000  a12:     0.00000
a13:     -0.00000  a14:    -0.00000  a15:     0.00000
a16:      0.00000  a17:     0.00000  a18:     0.00000
a19:     -0.00000  a20:     0.00000  a
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Fig. 3. Field quality of the magnet. All harmonics are within 3 units. No skew harmonics are present

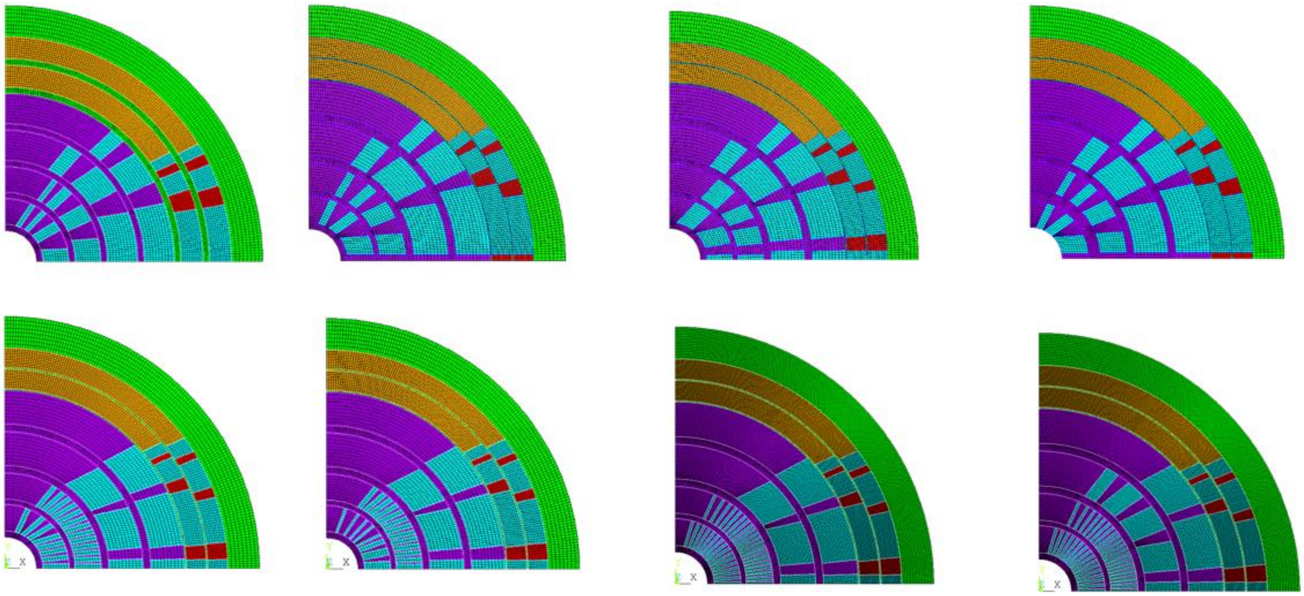

Fig. 4. Evolution of the mechanical structure. Different ideas were developed to maintain the peak stresses within design limits, converging towards a Canted-Cos-Theta-like coil on layer 1-2, stress-managed cos-theta on layer 3-4, and a standard cos-theta on layer 5-6.

IV. Mechanical Design

The conductor stresses during powering were verified assuming an infinitely rigid structure around the coil, with no pre-stress. 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 Nb_3Sn, and 120 MPa for the Bi2212.

In principle, the magnetic design proposed in [11] provided good field quality, target field and margin with a reasonable Lorentz stress value in all the layers. The maximum value was equal to 144 MPa for the LTS coils, and 119 MPa for the HTS coils. However, when checking the performances in a rigid structure, a peak azimuthal stress of 353 MPa was found on the inner radius of the inner coil, on the mid-plane. This due to the deformability of the coil, that introduces significant bending.

A. A preliminary study

The very high peak stress due to coil bending can be reduced introducing structural elements that can intercept the e.m. forces. This type of coil design is called ‘stress managed’ . Examples are SMCT [x] or CCT [x] configurations. The introduction of these reinforcements allows to intercept part of the e.m. forces, reducing the stress in the conductor. The price to pay is that the overall 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 artificially increasing the modulus of the entire layer to 200 GPa. This condition represent an upper limit for a stress managed layer, where all the conductor has been substituted by steel reinforcements. The results of this stud, in terms of azimuthal and radial stress, are provided in Table II, where the reinforced layers are marked with an x. The table show 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 II
Layer Reinforcement Optimization

Layer Stress, sxx, MPa					
1	2	3	4	5	6
x	x	x	x	90	89
x	x	x	88	103	103
x	x	73	118	124	123
83	133	169	193	x	x
83	134	x	x	x	x
x	x	169	193	x	x

Layer Stress, syy, MPa					
1	2	3	4	5	6
x	x	x	x	131	139
x	x	x	144	131	139
x	x	173	136	130	139
298	106	122	158	x	x
289	105	x	x	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. 4. Following the results of Section VI.A, the stress management was introduced only in layer 1, 2, 3 and 4. The FE model assumptions are shown in Figure 5. The stress managed coils 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. Separation with the pole is allowed. 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 wedge alignment strategy was kept in these latter designs, as it can allow to intercept part of the radial load from the inner coil.

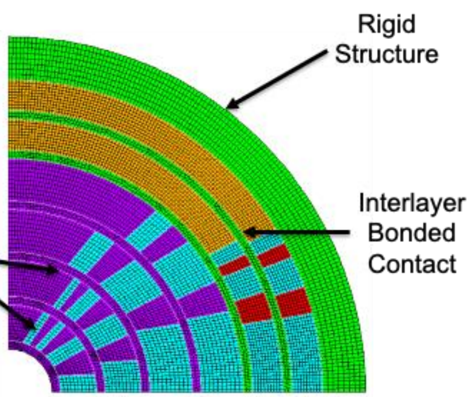

Fig. 5. Mechanical model mesh and assumptions at the interfaces. The stress managed coils have sliding interfaces with the mandrel, while the outer coil is bonded, with separation allowed from the pole.

The resulting Von Mises equivalent stress contours for this last solution are shown in Fig. 6: the stress is within the limits everywhere. Only some corners in Layer 2 exceed the limit, but these are probably 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. The displacements are shown in Fig 7: 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.

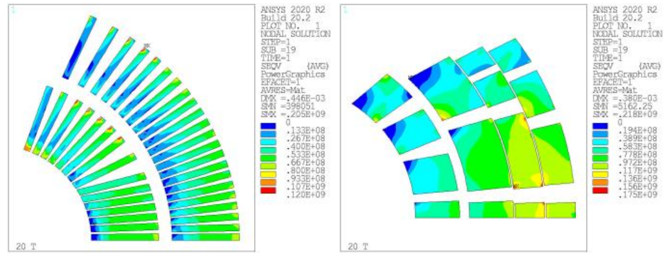

Fig. 6. Von Mises equivalent stress in the HTS (top) and LTS (bottom) coils when powered at 20 T. The peak stress is kept below the limits, except in a small corner of Layer 2.

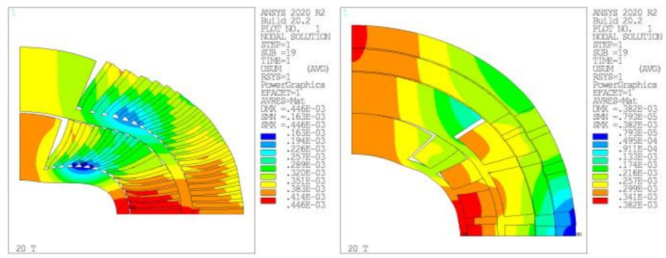

Fig. 7. Total displacement in the HTS (top) and LTS (bottom) coils, magnified. The stress spikes in Layer 2 seem to be due to the deformation of the mandrel.

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 Nb_3Sn. 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. However, it has not been ignored during magnet design, since the stabilizer current density has been maintained within 1300 A/mm^2, that can be considered a safe value for accelerator magnets. Moreover, further development 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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