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Conceptual Design of a Common Coil Dipole for VLHC

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***Abstract*— Superconducting magnet technology and cost reduction are key issues in the R&D effort towards a post-LHC, 100 TeV hadron collider. A dipole field of 10-12 T at 4.5 K operating temperature results in acceptable machine length and refrigeration power requirements, and allows taking advantage of synchrotron radiation damping to achieve low beam emittance. In this paper, the conceptual design of a react-and-wind common coil dipole is presented, which aims at these operating parameters with minimum cost and complexity.**

I. Introduction

The concept of a post-LHC hadron collider with 100 TeV energy in the center of mass and peak luminosity of 10^{34} cm^{-2}s^{-1} is being explored at several national laboratories [1]. Two approaches are considered, a low-field option with superferric magnets operating at 2 T, and a high-field option based on advanced dipoles operating at 10 to 12 T. The main challenge of the high-field machine is the development of a reliable and affordable magnet system. High-performance, brittle superconductors are required, which cannot be wound after reaction around the narrow pole keys of conventional, shell-type coils. For this reason, a "common coil" design concept for two-aperture dipoles has been proposed, where the minimum bending radius is significantly increased using racetrack coils shared between both apertures [2]. In this paper, the conceptual design of a 11 T, 30 mm aperture common coil dipole for VLHC is presented. The magnet layout is shown in Fig. 1. A two-layer hybrid design is chosen, with the inner coil made of Nb_3Sn wound after reaction, and the outer coil made of NbTi. Field quality issues are addressed without resorting to the use of auxiliary coils. A thin iron insert between coil and collars provides compensation of field errors due to conductor magnetization at low current. The collar design minimizes pre-stress at room temperature. Magnetic design, quench protection and mechanical support issues are discussed.

II. Basic Design Features

The design has been developed to meet two complementary objectives. First, to provide a set of specifications and performance parameters which can be used as

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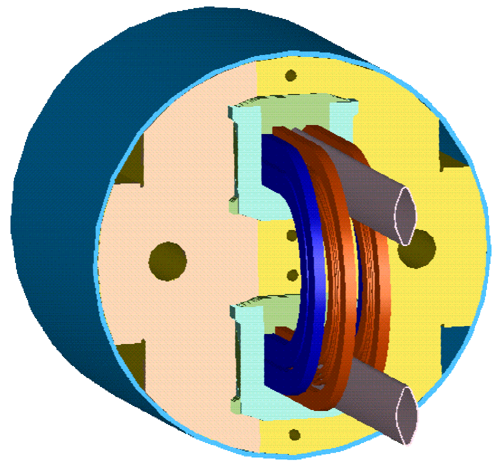

Fig. 1. Magnet design concept.

a data point for VLHC machine optimization. Second, to serve as a reference for model magnet R&D exploring the technology and fabrication of common coil dipoles using the react-and-wind technique. The issues which need to be addressed are conductor requirements as a function of design field, aperture and layout, field quality limitations, quench protection schemes, feasibility of react-and-wind technology, optimization of mechanical support structures for (hybrid) racetrack coils, tooling and assembly procedures.

The design optimization is performed under the assumption that Nb_3Sn (with critical current density between 2 and 3 kA/mm^2 at 12 T, 4.2 K) is used in the inner layer, and NbTi in the outer layer to reduce cost. To determine the basic design features, several coil cross-sections were developed and analyzed, with the following results:

1. For otherwise comparable design parameters, the conductor area requirement to achieve a design field of 12 T with a 10% margin is higher by about a factor 2 with respect to the 10 T case. While the 10 T field can be obtained using 2 layers, 4 layers are necessary to achieve 12 T, with additional complications for magnet fabrication, mechanical support and protection. In view of the cost reduction objective, a design field of 10 T was adopted, with a 10% margin.

2. In order to achieve the required field quality in common coil magnets, the use of auxiliary coils was originally proposed [2]. The auxiliary coils are located in the high-

field region close to the pole and are difficult to support mechanically. From the field quality standpoint, it is advantageous to choose a comparatively narrow cable for the auxiliary coils with respect to the main coils, where a wide cable is preferred to simplify fabrication and assembly and reduce magnet inductance. As a consequence, the auxiliary coils have to be powered on a separate circuit, or the main coils need to be split into smaller modules. In order to wind the auxiliary coils after reaction, those located away from the yoke midplane have to be returned on the outer side of each aperture without contributing to the dipole field[1]. For the above reasons, design options not requiring auxiliary coils would be strongly preferred and were actively investigated. It was found that solutions having good field quality are possible, in particular for magnets with reduced aperture, but the loss of efficiency in conductor usage is significant.

3. The typical magnet aperture required for high-energy hadron colliders is about 50 mm. The SSC magnet aperture had to be increased during the R&D phase from the initial design value of 40 mm to 50 mm. The LHC magnet aperture also had to be increased from 50 mm to 56 mm. However a 30 mm aperture may be possible under specific VLHC scenarios [4]. For otherwise similar design parameters, decreasing the aperture from 50 mm to 30 mm allows a 30-40% reduction of coil area [5].

In view of the cost reduction objective, a solution with a 30 mm aperture and no auxiliary coils was adopted. It allows major design simplifications and some reduction of coil area with respect to the 50 mm case with auxiliary coils. It should be noted that the absence of auxiliary coils results in a larger vertical aperture. Although this additional space provides little advantage from the beam dynamics standpoint, it may allow cost savings in other systems (beam screen, vacuum) and indirectly result in larger horizontal aperture available to the beam with respect to a 30 mm bore shell-type structure. It was also determined that a simpler design without auxiliary coils would allow faster progress on the technological issues. An increase of horizontal aperture to 40 or 50 mm will be attempted at a later stage in the program.

III. Magnet Design

A. Superconducting Cable

Table I shows the design parameters for three different cables which are being considered for this project. Optimization of these cables is underway at LBNL using ITER-type internal-tin wire produced by Intermagnetics General [6]. Each cable will be fabricated in two versions, with or without a 0.127 mm thick stainless steel insert. Samples will be tested to select the best options for this application [7].

[1] A "4-in-1" design concept has been proposed, where the VLHC injector magnet system would be built using the same yoke structure as the main magnets [3]. In this case, the return conductors of the auxiliary coils could be used to excite the field in the iron-dominated apertures of the injector.

TABLE I
Parameters for Inner Cables.

Cable	Wire diam. [mm]	Subel.	No. of strands	Width [mm]	Thickness[a] [mm]
A	0.5	-	56	15.0	0.85
B	0.7	-	40	15.0	1.18
C	0.3	1x6	37	14.9	1.27

[a] Does not include 0.127 mm thick stainless steel foil

A coil cross-section based on cable B (with foil) will be used as reference for the following discussion. The two-level cable C is promising for react-and-wind applications and has good current carrying capability, but producing high-performance, small diameter strand in long lengths may be an issue. The cross-section is similar to cable B and design calculations apply to both cases with small differences. Cable A is also advantageous for react-and-wind applications due to the small strand diameter, but mechanical stability is more problematic with respect to cable B due to the higher number of strands. Field distributions obtained using cable A are again very similar to the ones obtained for cable B, but operating current is 30% lower and inductances are a factor of two higher.

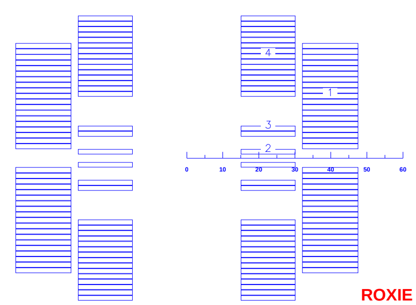

Fig. 2. Coil cross-section (Inner cable B, 1 aperture).

B. Short sample performance

A detail of the coil cross-section for one aperture is shown in Fig. 2. Cable B is used for the inner layer. The outer cable selected for this case is composed of 38 SSC-type inner strands (diameter 0.808 mm). It has a width of 15.4 mm and a thickness of 1.4 mm. The inner coil has 36 turns and the outer coil has 38 turns, resulting in a total conductor surface per aperture of 1108 mm^2 in the inner layer and 1480 mm^2 in the outer layer.

The iron yoke geometry is shown in Fig. 3. The separation between the two apertures is 26.2 cm. The yoke outer diameter is 54.6 cm.

TABLE II
Short Sample Parameters
(4.5 K, 10% Cable Critical Current Degradation).

Parameter	Unit	Short model	Full scale
J_c (12 T, 4.2 K)	kA/mm^2	2.0	3.0
Cu/Sc (inner)		0.85	1.5
Cu/Sc (outer)		1.3	1.2
I_{ss}	kA	15.0	15.3
B_{ss}	T	11.1	11.3
B^{pk} (inner)	T	11.8	12.1
B^{pk} (outer)	T	6.5	6.6

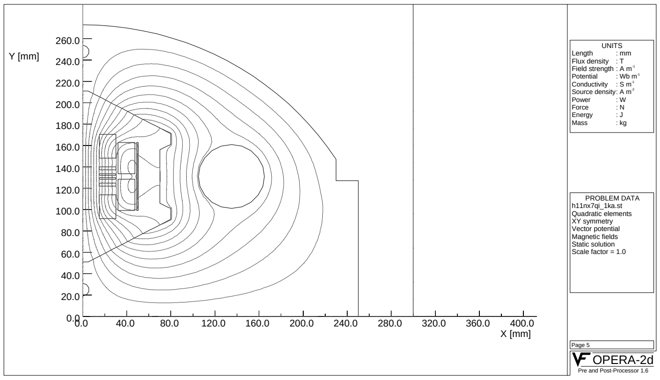

Fig. 3. Optimized iron geometry and field lines (1 kA).

Table II shows the short sample parameters calculated at 4.5 K assuming 10% cable critical current degradation. For the short model, a low copper to superconductor ratio allows the design field to be reached using conductor presently available. An increase of Nb_3Sn critical current density to 3 kA/mm^2 at 12 T and 4.2 K is required to reach the same performance with a higher copper fraction, as needed for protection of the long magnet. The peak field in the coil is 7% higher than the dipole field. Futher design optimization will be performed with the goal of improving this figure to 3-4%.

C. Field Quality in Straight Section

The field harmonics in the straight section at nominal current are listed in Table III. Harmonics are expressed in units of 10^{-4} of the main dipole field at a radius of 10 mm. The coil geometry was initially designed using program ROXIE [8] assuming a circular yoke. After optimization of the iron geometry to control saturation harmonics, a coil cross-section iteration was performed to correct 2 units of sextupole at nominal current. The resulting values of the sextupole and decapole are below 1 unit. Further tuning of the design cross-section to obtain essentially zero sextupole and decapole is possible. In fact, solutions with all normal harmonics below 0.1 units were found during the preliminary design study. However, field quality optimization at this level can only be effective after detailed understanding of the design is obtained through model magnet fabrication and testing.

TABLE III
HARMONICS IN THE MAGNET STRAIGHT SECTION (I=14 kA) AND IN THE RETURN END.

Normal	Body	End	Skew	Body	End
b_3	0.6	0.4	a_2	-1.2	-21.8
b_5	0.4	-0.9	a_4	0.7	0.5
b_7	0.1	0.1	a_6	0.1	0.5
b_9	-0.4	-0.1	a_8	0.0	0.0
b_{11}	0.2	0.0	a_{10}	0.0	0.0

The yoke cross-section optimization was performed using POISSON and OPERA-2D, with the goal of minimizing the dependence of low-order harmonics on current due to inhomogenous iron saturation. It should be noted, however, that large field distortions at low excitation are also expected due to persistent current effects. Compensation of conductor magnetization and iron saturation errors is desirable but difficult to achieve as both effects tend to generate errors of the same sign. In the optimized iron geometry (Fig. 3), compensation of the sextupole due to saturation at high current is obtained by adjusting the inner profile of the yoke in the pole region, and by introducing a 60 mm hole at the midplane of each aperture. This hole also serves as a cooling channel. To control the low-current saturation sextupole, a thin (1.5 mm) iron strip is inserted between the outer coil and the collar, resulting in a large positive shift of the sextupole, which rapidly decays as the strip saturates at higher excitation levels. The dimensions of the iron strip can then be adjusted based on specific conductor parameters to provide compensation of the magnetization sextupole (Fig. 4). The effect on the decapole is small in the present design due to the large width of the insert, which covers the whole outer coil to simplify manufacturing. Control of the skew quadrupole due to coupling between the two apertures at high current is achieved by adjusting the yoke radius and the separation between apertures. Higher order harmonics show little dependence on current.

D. End Field

To achieve minimal degradation of the cable critical current in a react-and-wind approach, all conductors are bent along a circular path at the magnet ends. Optimization of the end field can be achieved by longitudinal shifting of the conductor groups with respect to each other. In

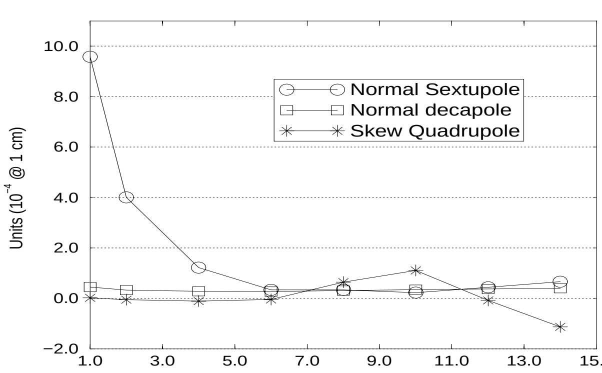

Fig. 4. Saturation harmonics.

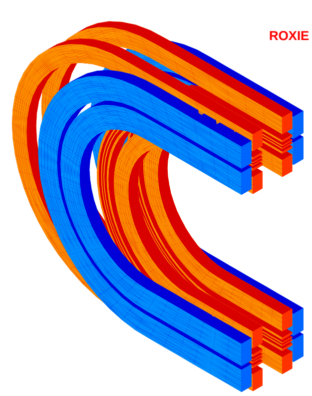

Fig. 5. Optimized coil end geometry.

the basic configuration all groups have the same longitudinal position and the yoke is terminated 10 cm from the end of the straight section. In this case, a peak field enhancement of 18% with respect to magnet body is observed for the outer layer, together with large integrated harmonics. Figure 5 shows a ROXIE model of the optimized end geometry. The peak field margin is 13% in the inner layer, but only 2% in the outer layer. The difference between physical length of the coil and magnetic length is 17 cm. Table III shows the integrated harmonics in unitmeter at the reference radius of 10 mm (L_m=0.21 m). Simulataneus optimization of peak field, normal sextupole and skew quadrupole is difficult to achieve with the present configuration. Preliminary estimation of the effect of these field errors on beam dynamics would be useful to guide further optimization work. Further increasing the relative distance between blocks provides little additional peak field margin, and the field quality rapidly degrades. End field optimization by splitting the conductor groups using additional wedges will be investigated.

E. Quench Protection

With a total stored energy of 0.42 MJ/m, active protection in the event of a quench is required. Preliminary analysis and optimization of protection schemes was performed both for the short (1 m) and the long (10 m) magnets, with the goal of restricting the peak temperature to less than 300 K and the maximum voltage to ground below 2 kV. The Nb_3Sn conductor of the inner layer is the most critical from the quench protection standpoint. Due to lower specific heat it has a smaller MIIts allowance for a given temperature with respect to NbTi. The brittle Nb_3Sn filaments are also more sensitive to thermomechanical impulses due to a fast temperature rise during a quench, and may undergo irreversible damage. A temperature limit of 300 K corresponds to a thermomechanical strain of 0.3%. In the short model, overheating due to high copper current density is prevented by quenching all turns with heaters. The long magnet has a high inductance. In this case, a slower current decay is required to avoid developing excessive voltage. Table IV shows the calculated quench parameters assuming a heater coverage of 100% for the short model and 50% for the long magnet. The heater delay time is 35 ms. Special consideration is needed for protection of a magnet made with cable A. The small MIIts margin in the inner layer requires fast current decay and its high inductance leads to coil to ground voltages up to 5 kV. Quench protection for this design can only be achieved with dump-resistors for short models and by splitting the coil into several electrically independent circuits in the long magnet.

TABLE IV
QUENCH PROTECTION PARAMETERS (I=14 kA).

Magnet Type	Heater cover [turns]	j_{Cu} inner kA/mm^2	L mH	τ curr. ms	T_{max} inner K	V_{max} ground kV
Short	100%	1.9	4.3	40	295	<0.3
Long	50%	1.5	43	75	270	<1.3

TABLE V
ELECTROMAGNETIC FORCE (ONE QUADRANT) AND MAXIMUM STRESS ON (BARE) CABLE AT 14 kA.

Parameter	Unit	Inner	Outer
$\sum F_x$	MN/m	1.9	0.5
$-\sum F_y$	MN/m	0.5	0.4
σ_x	MPa	90	24
σ_y	MPa	31	28

F. Coil Support Structure

Table V shows the electromagnetic force for one quadrant and the maximum stress on conductors at the design field (the effect of the inner layer is not included in the x-values listed for the outer layer). The coils are mechanically supported by combined action of the collar and yoke laminations. The yoke has a vertical split with an overlap and holes for locking rods. It provides support against the large horizontal force and locks the pairs of U-shaped collars through a 6 cm wide 1 cm thick extension at the midplane. Shrinkage of collar pairs in opposite directions during cooldown allows the thermal contraction of the coil support structure to be effectively increased, minimizing pre-stress requirements at room temperature. All vertical preload is provided by the collars. The high horizontal stress generated by the inner layer is intercepted by a 2 mm thick plate between the inner and outer coils and transfered to the collar structure and yoke. The central wedge in the outer layer is used as a force bypass. The addition of two more wedges at symmetric locations in the outer blocks is being considered for the same purpose. Mechanical analysis is underway to refine the structure and determine target preloads.

IV. CONCLUSIONS

The conceptual design of a common coil dipole for VLHC has been presented. Mechanical analysis and technology R&D is underway. Fabrication of a short model magnet is expected to start in one year.

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