Magnetic Designs of 2-in-1 Nb_3Sn Dipole Magnets for VLHC

Vadim V. Kashikhin and Alexander V. Zlobin

Abstract—**The paper presents the results of a conceptual design study of double aperture Nb_3Sn dipole magnets for VLHC based on the cos-theta and common coil geometry with cold and warm iron yoke. The study included an optimization of the iron yoke geometry to achieve the maximum transfer function, small fringe fields and low-order field harmonics as well as an optimization of the coil geometry to correct a quadrupole field component (normal or skew) inevitable for 2-in-1 magnet designs.**

***Index Terms*— accelerator magnet, cos-theta and common coil geometry, magnetic design, superconducting cable.**

I. Introduction

FERMILAB is working on the development of 10-12 T Nb_3Sn accelerator magnets for a post-LHC Very Large Hadron Collider (VLHC). Proton beams in hadron colliders circulate in opposite directions in two crossing storage rings. These storage rings can be designed based on single-aperture magnets placed in separate cryostat (SSC) or more effectively based on double-aperture magnets with common iron yoke and cryostat (LHC). The last approach allows one to reduce the size, weight and cost of magnet and cryostat. Since the cost is an important parameter for the next generation of hadron colliders this approach was chosen for the VLHC high field magnets (HFM).

This paper presents the results of a conceptual design study of double-aperture dipole magnets being developed at Fermilab for VLHC based on both cos-theta and common coil geometry. Since the contribution of iron yoke in the enhancement of bore field in HFM is relatively small, both approaches based on cold and warm iron yoke were analyzed.

Magnetic design study and optimization was performed using ROXIE and OPERA 2D codes. Major target parameters and requirements to HFM for VLHC in this study were a nominal field B_{nom}=10-12 T, operation field range B_{nom}/B_{inj}~17, field quality similar to SSC magnets and physical aperture ≥40 mm. The requirements of mechanical stability, and quench protection, and low cost were also taken into consideration.

II. Cos-theta Magnets

These designs are based on the two-layer cos-theta coil developed for the single bore magnet [1]. The coil geometry, the thickness of spacers between the coil and the yoke as well as the fabrication technique are identical to the single aperture magnet. The design efforts were focused on the iron yoke optimization. A 2-in-1 design with independent coils allows both horizontal and vertical coil arrangements inside the iron yoke. The horizontal arrangement was chosen as it provides an enhancement of the magnetic field in each bore due to magnetic coupling between them and a compensation of the horizontal Lorentz force between two coil blocks.

A. Cos-theta Coil Parameters

The coil cross-section is shown in Fig. 1. The coil bore diameter is 43.5 mm. Each half-coil consists of 24 turns. The inter-layer spacer thickness is 0.28 mm and the thickness of the additional mid-plane insulation layers is 2×0.125 mm. Each half-coil has two floating pole inserts and eight wedges, which allow to minimize low order field harmonics and to ensure a radial turn position in the coil.

The coil utilizes a keystone Rutherford-type cable made of 28 Nb_3Sn strands, each 1 mm in diameter. The width of bare cable is 14.24 mm, the thickness is 1.800 mm and the keystone angle is 0.91degree. The nominal thickness of cable insulation is 0.25 mm. Both inner and outer layer of half-coil are made from one cable piece without an inter-layer splice.

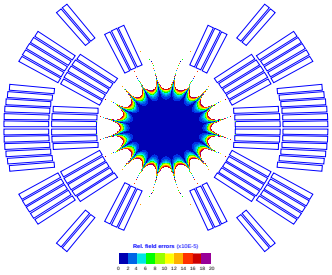

Fig. 1. Cross-section of the cos-theta dipole coil.

B. Cold Yoke Design

Two coils are placed inside the common iron yoke with all necessary technological cutouts. Special holes are used for correction of the iron saturation effect. The following parameters were optimized: a) outer radius of the iron yoke, b) aperture separation, c) correction hole geometry and position. The optimization criteria were small low-order field harmonics and fringe fields, maximum transfer function, small outer radius of yoke and comfortable aperture separation for magnet interconnection [2].

The iron yoke was split vertically into three pieces to allow assembly of two coils in one yoke and to prestress them at room temperature the same way as the single aperture magnet. To minimize a reduction of the coil prestress after cool down, the vertical gap is always open. In order to reduce the effect of gap variation on the field quality the yoke split was designed partially parallel to the flux lines so that it crosses

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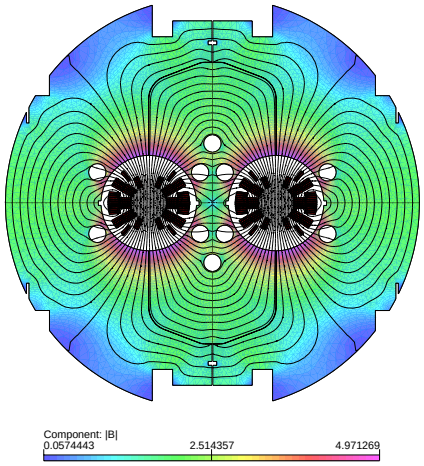

Fig. 2. Cross-section of the 2-in-1 dipole with cos-theta coils and cold yoke.

only a small amount of peripheral lines in the vertical plane. The yoke split was approximated with three straight lines and two arcs. The vertical gap thickness was chosen to be 0.5 mm per quadrant and 0.1 mm for the horizontal gap [3].

Fig. 2 presents the optimized 2D cross-section of the 2-in-1 magnet design based on the cos-theta coils and cold iron yoke. The iron outer diameter is 520 mm and bore separation is 180 mm. The other parameters are reported in Tables I-II.

C. *Warm Yoke Design*

In the warm yoke design the iron has to be remote from the coils far enough in order to accommodate the cryostat and magnet support system. The warm yoke was simulated by the iron cylinder with inner and outer radii R_{in} and R_{out}. Two coils are placed inside the cylinder with the aperture separation of 180 mm as in the cold iron design. R_{in} and R_{out} were optimized with respect to field quality, fringe fields and iron cross-section area taking also into account the considerations related to the support system and cryostat design [4].

A correction of the coil cross-section was done in order to compensate a large quadrupole component related to magnetic coupling between two apertures [5]. A relatively close distance between the apertures results in the quadrupole component b_2 of -32 units. To reduce this value a small left-right asymmetry was introduced for two pole blocks in the inner layer and one pole block in the outer layer in each half-coil. It allows eliminating geometrical field harmonics up to b_9 and also preserves the radial conductor positions and acceptable inner-layer pole width.

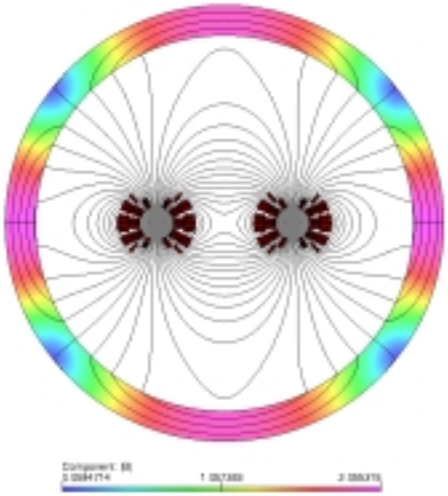

Fig.3. Cross-section of the 2-in-1 dipole with cos-theta coils and warm yoke.

A 2D cross-section of the 2-in-1 magnet design with cos-theta coils and warm iron yoke is shown in Fig.3. The iron outer diameter in this design is 580 mm and the iron thickness is 40 mm. The other parameters are reported in Table I and II.

III. Common Coil Magnets

The common coil design is an alternative approach to the double bore accelerator magnet in which racetrack coils are shared between two vertically positioned apertures [6]. It offers a simplification of magnet design and fabrication, as well as a possibility to use a reacted Nb3Sn cable. However, analysis of the high-field common coil designs [7,8] shows that all of them have multi-layer coil geometry, which complicates the support structure, magnet fabrication and creates severe mechanical problems during operation. The main features of the common coil designs proposed here are a simple single-layer coil divided into three blocks with small shift of pole blocks, and wide spacers. This allows preserving simple racetrack coil geometry, providing desirable simplicity of the design and fabrication technology, solving all mechanical problems [9], and reaching excellent field quality.

A. *Single-Layer Common Coil*

The cross-section of the single-layer common coil is shown in Fig.4. The coil is made of wide rectangular Rutherford-type cable with 60 Nb_3Sn strands, each 0.7 mm in diameter. To use a "reacted and wind" technique the cable bending radius must be ≥90 mm for the chosen strand size. The width of the cable is 21.09 mm and the thickness is 1.245 mm. The insulation thickness is 0.10 mm. Each coil consists of 56 turns grouped into three blocks and separated by 6mm thick spacers. There are also two 3mm thick spacers in each middle block. The pole blocks are shifted horizontally by 5 mm with respect to the middle blocks. The size and position of blocks and spacers were optimized to provide the maximum transfer function, minimum coil volume and small low-order geometrical harmonics within the largest possible aperture. The gap between pole blocks is 40 mm that determines the magnet aperture. Two coils are wound simultaneously into the coil support structure (collars) and then the collared coil assembly is impregnated with epoxy [9]. There is one splice connecting left and right coil in series.

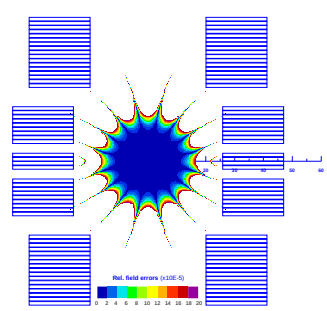

Fig. 4. Cross-section of the single-layer coil for the common coil dipole.

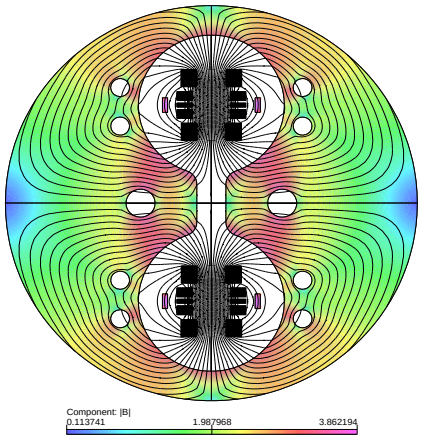

Fig. 5. Cross-section of the common coil dipole magnet with cold iron yoke.

B. *Cold Yoke Design*

Fig. 5 presents the 2D cross-section of the single-layer common-coil dipole with cold iron yoke. Two coils with mechanical support structure are placed inside the round iron yoke. The iron yoke is split vertically into two pieces. To provide a contact between the collared coil and the yoke at all temperatures the vertical gap between yoke pieces is always open. Special holes and magnetic inserts are used for correction of the iron saturation effect. The following parameters were optimized: a) yoke inner surface, b) yoke outer radius, c) geometry and position of correction holes and inserts. The optimization criteria were as above: good field quality, low fringe fields, maximum transfer function and small yoke outer diameter.

As a result of top/bottom asymmetry of the iron yoke relative to the magnet aperture there is a skew quadrupole component a_2 of –6.8 units in case of symmetric coils. This component is reduced using a small (within 0.5 mm) top/bottom asymmetry in block arrangement with respect to the mid-planes of each aperture. The optimized yoke outer diameter is 564 mm at the bore separation of 280 mm. Magnet parameters are reported in Tables I-II.

C. *Warm Yoke Design*

Fig. 6 presents a cross-section of the single-layer common coil dipole with warm iron yoke. In order to compensate the reduction of magnet transfer function and maximum field in the design with warm iron yoke the number of turns in the coil was increased from 56 to 61. Magnetic coupling between the two apertures in this design creates a skew quadrupole component of –34.7 units. To reduce this value an asymmetry was introduced in the position of pole blocks and in spacer thickness as well as in number of turns in the middle blocks. It allowed meeting the field quality target requirements without noticeable change of magnet geometry (block horizontal and vertical displacements as in the previous case are less than 0.5 mm). Multipole deviations due to the iron yoke saturation were reduced by optimizing the yoke inner and outer diameter. The optimal yoke outer diameter in this design is 710 mm and iron thickness is 55 mm. The other magnet parameters are reported in Table I and II.

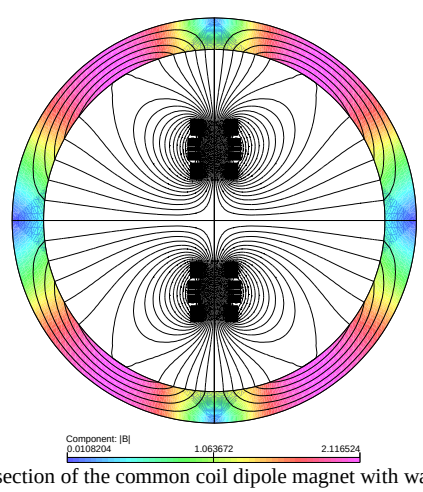

Fig.6. Cross-section of the common coil dipole magnet with warm iron yoke.

IV. Magnet Parameters

The main parameters of the 2-in-1 magnet designs described above are summarized in Table I.

TABLE I
CALCULATED MAGNET PARAMETERS.

	Cos-theta design		Common coil	
Yoke design	Cold	Warm	Cold	Warm
B_{max}, T	12.05	11.34	10.75	10.69
I_{max}, kA	21.9	24.0	24.5	25.4
Aperture, mm	43.5	43.5	40	40
Aperture separation, mm	180	180	280	280
Coil area, cm^2	2×22.3	2×22.3	2×26.7	2×29.1
Iron yoke OD, mm	520	580	564	710
Iron yoke area, cm^2	1735	680	1762	1132
B/I @11T, T/kA	0.56	0.47	0.44	0.42
Stored energy @11T, kJ/m	2×259	2×295	2×440	2×478
Inductance @11T, mH/m	2×1.34	2×1.08	2×1.39	2×1.37

The values of B_{max} presented in Table I were calculated for the cable packing factor of 0.88, Cu/nonCu ratio of 0.85:1 and strand J_c(12T,4.2K) in the coil of 2.0 kA/mm^2. Assuming the 10% I_c degradation the described designs can provide the maximum field of ~10-11.5 T using commercially available Nb_3Sn strand (see Fig.7). A nominal field of 10.5-11 T with 10-15% margin will be achieved using the new R&D strands with J_c(12T,4.2K)=3 kA/mm^2 and Cu/nonCu~1.2:1.

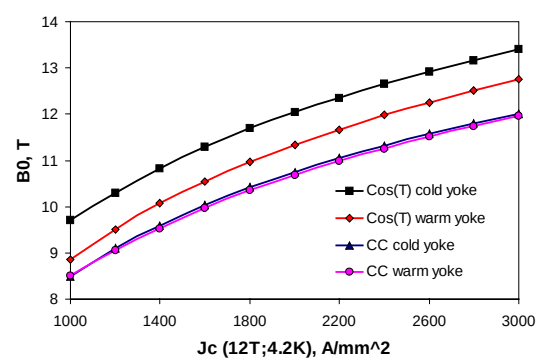

Fig. 7. Maximum (quench) field in the magnet aperture @4.2K vs. the critical current density of superconducting strand in the coil.

Calculated geometrical harmonics and their RMS spread for ±50 μm random displacements of current block at 1 cm radius for the cos-theta and common coil designs with cold and warm iron yoke are summarized in Table II.

TABLE II
GEOMETRICAL HARMONICS (SYSTEMATIC VALUES AND RMS SPREAD) AT 1 CM RADIUS ,10^{-4}

Harmonic #	Cos-theta design			Common coil design		
	Cold yoke, bn	Warm yoke bn	RMS ($\sigma_{a,b}$)	Cold yoke bn/an	Warm yoke bn/an	RMS ($\sigma_{a,b}$)
2	-	0.000	1.198	/0.005	/0.000	1.040
3	0.000	0.000	0.564	0.000/	-0.005/	0.360
4	-	0.000	0.279	/-0.001	/0.002	0.141
5	0.000	0.001	0.103	-0.001/	-0.001/	0.046
6	-	-0.012	0.047	/-0.002	/-0.003	0.017
7	0.000	-0.011	0.021	-0.001/	-0.032/	0.006
8	-	0.031	0.008	/0.011	/-0.128	0.003
9	-0.091	-0.130	0.005	-0.046/	-0.059/	0.002
10	-	-0.011	0.001	/0.003	/-0.004	0.000
11	0.099	0.129	0.003	0.000/	-0.004/	0.000

As it can be seen, all the designs provide an acceptable level of field quality for accelerator magnets. An additional source of random field variation for the warm yoke designs is the coil misalignment inside the iron yoke. The analysis shows (see Table III) that both cos-theta and common coil designs with warm yoke allow a coil/yoke misalignment within 1-2 mm without a significant degradation of field quality and overload of the cold mass support system.

TABLE III
SENSITIVITY ANALYSIS.

Magnet type	Coil/yoke misalignment, mm		Force imbalance, kN/m		Multipole deviations, 10^{-4}				
	Δx	Δy	ΔF_x	ΔF_y	Δb_2	Δb_3	Δa_1	Δa_2	Δa_3
Cos(θ)	1.0	0.0	2.1	-	0.14	0.02	-	-	-
	0.0	1.0	-	1.2	0.00	0.00	0.60	0.08	0.01
CC	1.0	0.0	1.5	-	0.07	0.00	0.54	0.00	0.00
	0.0	1.0	-	3.2	-	0.01	-	0.15	-

The effect of iron saturation at high fields on low order field harmonics and on magnet transfer function is shown in Fig. 8 and 9.

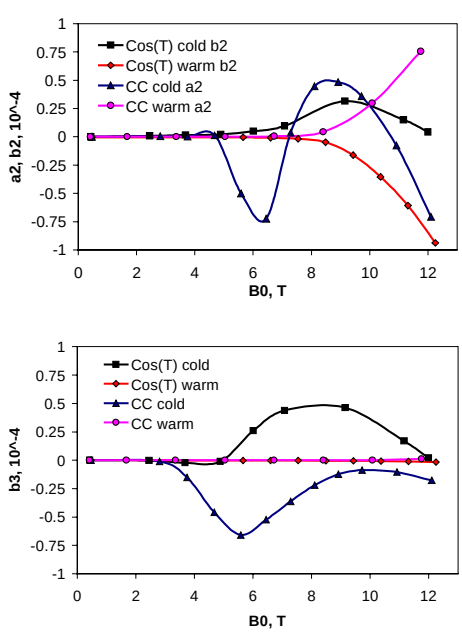

Fig. 8. Low order field harmonics vs. bore field.

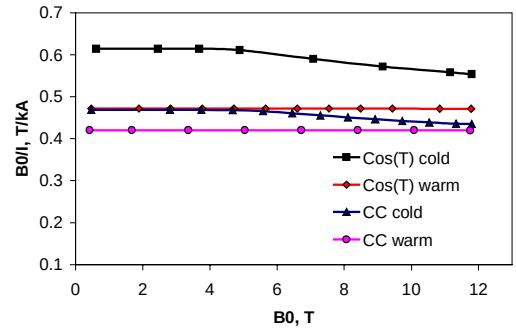

Fig. 9. Magnet transfer function vs. bore field.

As it can be seen, the iron saturation effect on the normal and skew quadrupole and sextupole is effectively suppressed in the field range up to 12 T in all designs by optimizing the yoke size and correction hole geometry. There is no iron saturation effect on magnet transfer function in both warm yoke designs. A reduction of the transfer function in the cold yoke designs reaches ~10% at the bore field of 12 T.

V. CONCLUSIONS

The magnetic design of 2-in-1 dipole magnets for VLHC based on the cos-theta and common coil geometry with cold and warm iron yoke has been developed. All magnets met the target requirements. A comparison of parameters of these magnets developed using the same requirements and design criteria shows that magnets based on the cos-theta coils provide higher maximum field in the same bore, have 60-70% lower stored energy and 20-30% smaller coil volume. The cos-theta design with warm yoke allows also a significant reduction of magnet size without a noticeable degradation of its characteristics. The developed single-layer common coil design offers a simplification of magnet fabrication. A final comparison of advantages of different designs, their performance and cost effectiveness should be done based on the results of model magnet fabrication and tests.

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