Title

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Coldmass for LHC Dipole Insertion Magnets*

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Abstract—**Brookhaven National Laboratory (BNL) is building a number of magnets for the insertion regions of the Large Hadron Collider (LHC). This paper presents the magnetic design and the expected field quality in 2-in-1 dipole magnets. A unique feature of this coldmass design is the use of an oblate-shaped yoke. This concept permits a variety of BNL-built magnets to have a similar overall design and allows the LHC main dipole cryostat, post, etc., to be used in these magnets. The proposed oblate-shaped yoke also offers a way to reduce the overall cryostat size in future magnets. The dipoles will use the same 80 mm aperture coils as used in the Relativistic Heavy Ion Collider (RHIC) dipole magnets, but will use stainless steel collars. The design presented here is still evolving and the magnets may be built differently than described here.**

I. INTRODUCTION

As a part of the US-CERN collaboration for the Large Hadron Collider, the Brookhaven National Laboratory has proposed building a number of superconducting insertion magnets. There are five types of 2-in-1 dipoles and one type of single aperture dipole. The overall design parameters of these magnets are given in Table I. The differences between various types of magnets (D1, D2, D3a, D3b, D4a and D4b) are given in Table II. This table also gives the proposed number of magnets (including spares). The actual number and type of magnets to be built is, however, subject to overall budget limitations. All 2-in-1 dipoles will have the field in the same direction but with a different value of spacing between the two apertures. In the design presented here, all magnets will use stainless steel collars. A detailed description of the overall design may be found in the reference manual [1].

II. OVERALL YOKE AND CRYOSTAT GEOMETRY

Figure 1 shows the coldmasses of all 2-in-1 magnets together with the coldmass of D3a magnet inside the cryostat. In the original proposal, the dipoles D3a and D3b were considered to have two separate 1-in-1 coldmasses, whereas D4a and D4b were designed with 2-in-1 coldmasses. In the design presented here, all magnets would be 2-in-1 type coldmasses and all would have a similar yoke outer surface. The yoke is made oblate so that it can fit inside the LHC main dipole cryostat. Whereas the horizontal dimensions are determined by the magnetic and mechanical design, the vertical dimensions are made equal to the yoke outer diameter of the LHC main dipole magnet. This permits the use of LHC cryostat, post and other components with only minor modifications.

In a small scale production such as this, a large fraction of magnet cost is determined by the detailed engineering, tooling and magnet R&D. The insertion magnets being built at BNL use 80 mm aperture coils developed for RHIC dipoles and cryostat and other components between the cryostat and coldmass (post, etc.) developed by CERN for LHC dipoles. An approach that makes the design of a number of magnets as uniform as possible and that modifies or adopts the geometry to use the detailed engineering design developed for other magnets translates into a significant saving in design time for this production.

The proposed oblate-shaped yoke also offers a way to reduce the overall cryostat size in future magnets. In most magnets, the horizontal size is determined by the magnetic and mechanical designs and the vertical size is determined by the heat leak budget and post design. The two are then added to determine the overall size. In modifying the circular yoke shape to an oblate shape, yoke iron is removed from the vertical plane, as this material does not contribute to the magnetic and mechanical design. The vertical space, thus saved, can be utilized by the post and thermal shielding, reducing the overall size. The validity of this design will be tested in the first model magnet to be built at BNL prior to the production run of the LHC insertion magnets.

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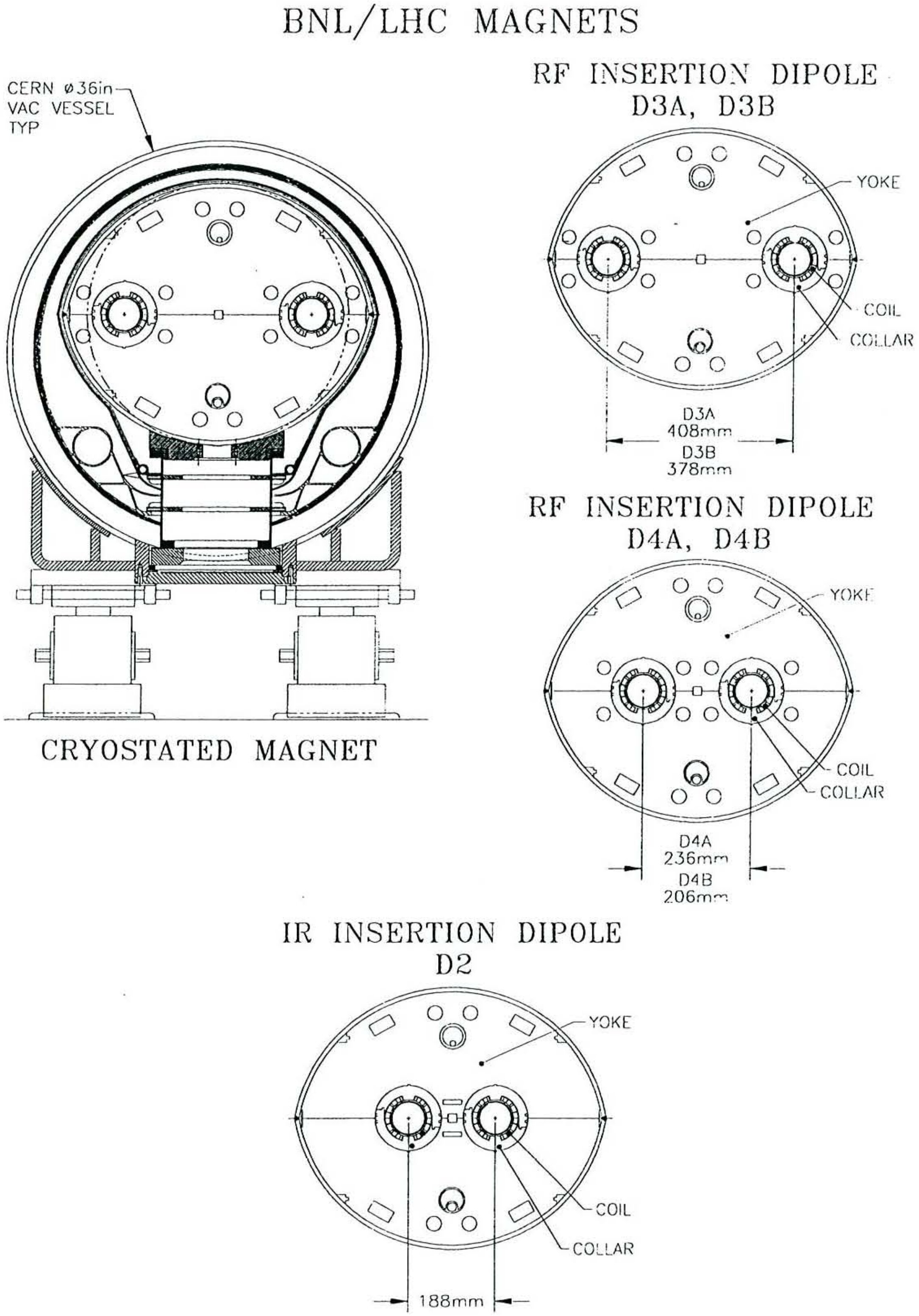

Figure 1: LHC insertion dipole magnets being built at BNL. The picture on the top left shows the oblate coldmass inside the circular cryostat.

TABLE I

GENERAL PARAMETERS COMMON TO LHC INSERTION DIPOLES D3A, D3B, D4A AND D4B TO BE BUILT AT BNL.

Coil inner diameter	80 mm
Coil Outer diameter	100 mm
Beam tube inner diameter, nominal	73 mm
Collar thickness in straight section	20 mm
Collar thickness in magnet ends	30 mm
Yoke shape	oblate
Yoke diameter (for horizontal size)	670 mm
Vertical yoke size	550 mm
Cryostat outer diameter	914 mm
Cable width, nominal	9.73 mm
Cable mid-thickness, nominal	1.166 mm
Number of wires in cable	30
Cable insulation	Kapton CI
Copper to superconductor Ratio	1.8
Number of turns per quadrant	32
Number of current blocks per quadrant	4
Magnetic length	9.45 m
Maximum design field	3.8 T
Maximum operating current	6 kA
Maximum operating temperature	4.6 K
Computed short sample at 4.6 K	4.7 T at 7.6 kA
Stored energy at 3.8 T in each coil	0.4 MJ
Inductance, each coil	28 mH

TABLE II

A PARAMETER LIST OF LHC INSERTION MAGNETS WHICH BNL HAS PROPOSED TO BUILD AS A PART OF THE US-CERN COLLABORATION. THE GENERAL PARAMETERS FOR 2-IN-1 DIPOLES ARE GIVEN IN TABLE I. D1 IS A RHIC DIPOLE COLDMASS. THE DESIGN AND PARAMETERS ARE SUBJECT TO CHANGE.

Magnet Name	Magnet style and type	Separation (mm)	Aperture (mm)	Number +(spares)
D1	1-in-1 dipole	---	80	4 + (1)
D2	2-in-1 dipole	188	80	8 + (1)
D3a	2-in-1 dipole	408	80	2 + (1)
D3b	2-in-1 dipole	378	80	2 + (1)
D4a	2-in-1 dipole	236	80	2 + (1)
D4b	2-in-1 dipole	206	80	2 + (1)

III. FIELD HARMONIC DEFINITIONS

The field quality in the LHC magnets is expressed in terms of the normal and skew harmonic coefficients, b_n and a_n by the following expansion

$$B_y + iB_x = 10^{-4} \times B_1 \sum_{n=1}^{\infty} (b_n + ia_n)[(x+iy)/R]^n$$

where x and y are the horizontal and vertical coordinates, B_1 is the dipole field strength and R is the "reference radius" which is chosen to be 25 mm. The definition used above (European convention) differs from that used in our previous publications [2] for RHIC dipoles (US convention). The values of the field harmonic are given in units of 10^{-4}.

IV. COLLARED COIL GEOMETRY

All insertion dipoles will use the same 80 mm aperture coil which was optimized for RHIC arc dipoles. However, the RHIC dipoles used yokes as the collars, whereas the LHC insertion dipoles will use 20 mm wide stainless steel for the collars. This difference may introduce a small mechanical difference in the collared coil geometry and hence in the geometric harmonics between the RHIC arc dipoles and LHC insertion dipoles. To remove the measured non-zero b_3 and b_5 harmonics, the size of the coil pole shim and/or midplane-to-coil gap will be changed, if necessary. This adjustment will be made after the measurements in the first model magnet. The changes in harmonics from a 25 μm change are given in Table III.

TABLE III

CHANGE IN FIELD HARMONICS FROM A 25 MM CHANGE IN MIDPLANE-TO-COIL GAP AND COIL POLE SHIM AT 25 MM REFERENCE RADIUS. THE COMPUTED RESULTS LIST THE HARMONICS IN UNITS.

	b_3	b_5	b_7	b_9
Midplane Gap	-1.71	-0.60	-0.17	-0.05
Pole Shim	1.23	-0.18	0.04	-0.02

The width of the collar in the straight section is 20 mm and in the ends is 30 mm. These widths are based on the mechanical design.

V. YOKE GEOMETRY OPTIMIZATION

The yoke is optimized to minimize the current dependence of harmonics at high fields. Unlike the usual 2-in-1 magnets, the direction of the field in the two apertures is the same here. This means that the flux from one aperture cannot return through the other. To reduce cross-talk induced harmonics (such as normal quadrupole term in the dipole), the yoke width should be adequate to contain the flux lines at the maximum design field. Since more yoke is required at the midplane, the oblate shape is proposed. The horizontal size is determined by the goal of reducing the cross talk at the maximum design field and by the magnets having the maximum separation. The vertical size is made equal to the LHC dipole yoke outer diameter so that its cryostat and other hardware can be used. In the proposed solution the yoke outer diameter is 670 mm and, after removing the material at the midplane, the two centers, above and below the midplane, are separated by 120 mm to match the vertical size of LHC dipoles, which have an outer diameter of 550 mm.

The high field current dependence due to iron saturation is minimized by optimizing the size and location of the saturation control holes or cutouts. In the optimized solution, the computed change in the saturation-induced harmonics (allowed and non-allowed) is well within one unit in all dipoles. In the D2 dipoles (minimum separation) the harmonics are controlled by two rectangular cut-outs having a width of 40 mm and height of 10 mm located 30 mm above and below the midplane on the vertical axis. In the other dipoles (D3a, D3b, D4a and D4b), the saturation is controlled by four 15 mm radius holes symmetrically located at a radius of 100 mm from the center of each aperture. The optimized angular location depends on the separation between the two apertures and is respectively 28°, 28°, 30°, 31° in the first quadrant of dipoles D3a, D3b, D4a and D4b.

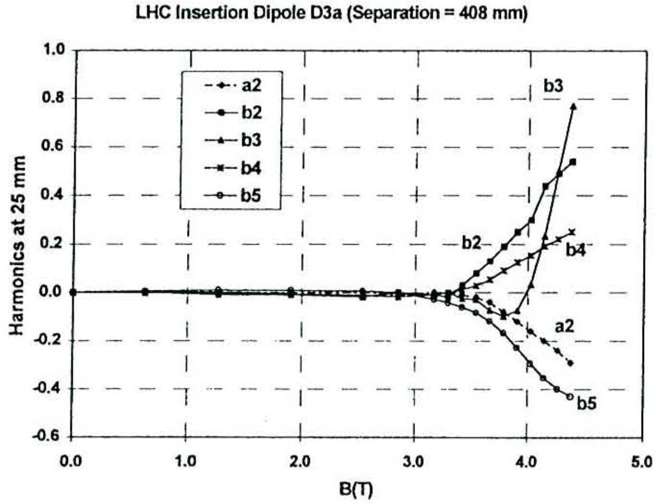

Fig 2. The computed current dependence in field harmonics (European convention) in the right aperture of LHC 2-in-1 insertion dipole D3a. The maximum design field in the magnet is 3.8 T.

The computed current dependence in field harmonics in dipole D3a is shown in Fig. 2. The optimized design of the other 2-in-1 dipoles (D3b, D4a and D4b) produces a similar current dependence in field harmonics. The skew harmonics are created at high field by a top-bottom asymmetry between the yoke and cryostat iron. This may be compensated by adjusting the difference in the yoke weight between the upper and lower halves.

VI. ESTIMATED HARMONIC ERRORS

The measured harmonics may be non-zero in the magnets due to design and construction errors. At injection field the errors in the allowed harmonics (b_3, b_5, ...) will be dominated by the persistent currents. The injection field in these magnets may be around 0.2 T, depending on the magnet location and on the optimized LATTICE. The measured low order allowed harmonics in RHIC arc dipole DRG107 at low fields are given in Fig. 3. At medium field (~1.5 T to 3 T), the errors will be dominated by magnet geometry and at high fields the iron saturation contribution may be significant. The estimated integral values of field harmonics are given in Table IV. The saturation-induced harmonics in all magnets are so small that they are included in the uncertainty in the mean. This permits a single table of expected harmonics for all BNL-built insertion magnets. The estimated values of persistent current-induced allowed harmonics around injection (~0.3 kA or ~0.2 T) are given in parenthesis. A non-zero value of geometric a_3, a_5, etc. is primarily from the harmonics in the lead end, as measured in the RHIC arc dipoles.

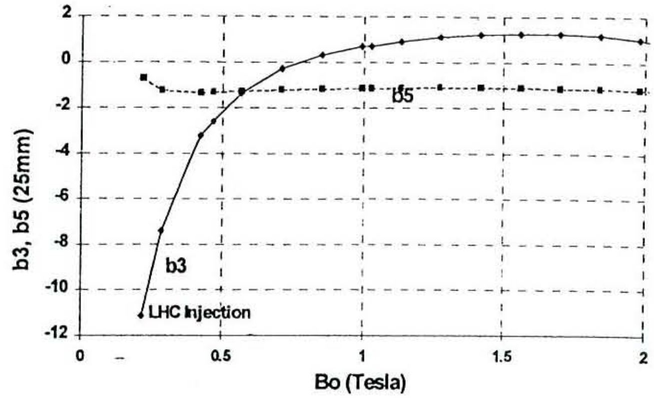

Fig 3. The measured current dependence during up-ramp in the sextupole and the decapole harmonics in the 80 mm aperture RHIC arc dipole DRG107. At the low fields, the value of sextupole harmonic is dominated by the persistent currents.

TABLE IV

THE ESTIMATED FIELD ERRORS IN LHC INSERTION DIPOLES. $\langle b_n \rangle$ AND $\langle a_n \rangle$ ARE THE EXPECTED MEANS OF THE NORMAL AND SKEW TERMS. $d(b_n)$ AND $d(a_n)$ ARE THE COMBINATION OF *(i)* THE UNCERTAINTY IN THE MEAN AND *(ii)* THE SATURATION INDUCED HARMONICS. $\sigma(b_n)$ AND $\sigma(a_n)$ ARE THE EXPECTED SIGMA. THE EXPECTED ERRORS ARE THE LARGEST AT INJECTION (GIVEN IN PARENTHESIS) DUE TO PERSISTENT CURRENTS. OTHER VALUES ARE GIVEN FOR MODERATE TO HIGH FIELDS. (NOTE: SEXTUPOLE IS n=3).

n	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	0	0.5	0.4	0	0.5	1.6
3	0(-9)	2(4)	2 (3)	-1.1	0.2	0.2
4	0	0.2	0.1	0	0.2	0 .5
5	0(0)	.6(.9)	.6 (.7)	0.2	0.05	0.1
6	0	0.03	0.04	0	0.1	0.2
7	0.1(-0.4)	.1(.2)	.1(.15)	-0.1	0.03	0.03
8	0	0.01	0.01	0	0.03	0.05
9	0.05(0.3)	0.03(.1)	0.02	0.02	0.01	0.01
10	0	0.01	0.02	0.04	0.02	0.01
11	-0.5(-.6)	0.02(.1)	0.02	-.01	0.01	0.01

VII. CONCLUSIONS

The overall magnetic design of BNL-built LHC insertion dipoles has been presented. The design is still evolving and hence is subject to change before production. However, the proposed design will produce magnets with small field errors except at injection; there the allowed harmonics will be dominated by persistent currents. The techniques described here should keep the geometric and saturation-induced allowed harmonics low, as was observed in RHIC magnets.

The concept of an oblate shaped yoke allows an overall uniform design for all magnets. This concept may also be useful in future magnets as it reduces the overall size of the cryostat.

REFERENCES

[1] LHC Design Manual, in preparation.

[2] R. Gupta, et al., "Field Quality Control Through the Production Phase of RHIC Arc Dipoles", Proceedings of the 1995 Particle Accelerator Conference, Dallas, Texas , pp. 1423-1425 (1995).

[3] Kapton is a registered trademark of DuPont Corporation.