DESIGN STUDY OF 2-IN-1 LARGE-APERTURE IR DIPOLE (D2) FOR THE LHC LUMINOSITY UPGRADE*

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Abstract

This paper analyses possible D2 magnet designs for the "dipole-first" option of the LHC luminosity upgrade based on Nb_3Sn superconductor and compares them in terms of the maximum field, field quality, and Lorentz forces in the coils.

INTRODUCTION

After LHC operates for several years at nominal parameters it will need an upgrade to higher luminosity. Replacing the low-beta insertions with a higher performance design based on advanced superconducting magnets is a straightforward step in this direction. One of the approaches being considered for the new LHC IRs is a "dipole-first" option with two separation dipoles placed in front of the focusing quadrupoles [1]. It reduces the number of parasitic collisions with respect to the "quadrupole-first" option and allows independent field error correction for each beam.

Most of key magnet designs for the "dipole-first" option have already been studied and reported. Magnetic and mechanical designs of D1 magnet were analyzed. It was demonstrated that the "open midplane" design can meet the requirements in spite of the large heat depositions [2]. 2-in-1 quadrupole magnets have also been studied. It was shown that the magnets can operate at the nominal LHC IR gradient in 100-mm apertures with the nominal LHC beam separation and good field quality [3].

This paper focuses on the design studies of the 2-in-1 separation dipole (D2) located between D1 and the 2-in-1 quadrupole magnets.

MAGNET DESIGNS

The D2 magnet should produce magnetic field of 14.1 T on the length of 10 m [1]. The magnet apertures have to provide the same field polarity for two counter-rotating beams that implies negative coupling (or mutual inductance) between the apertures. Apart from the necessity to adjust the coil geometry to compensate for the coupling, it creates an additional design challenge since a considerable part of the flux returns through the iron yoke, unlike the case of opposite polarity, when about half of the flux returns through the second aperture.

The size of magnet dynamic aperture is determined by the beam envelope at the magnet location. In this study it was assumed that the D2 magnet apertures are parallel, therefore the dynamic aperture must also account for the beam deflection under the dipole field. Beam optics studies have shown that the round beam envelope at the non-IP end of D2 is 38 mm that shrinks to 29 mm at the IP

end [4]. The maximum beam deflection off the magnet axis is 36 mm that defines the dynamic aperture of 69.5 mm. In addition to the dynamic aperture, the magnet physical aperture should include the helium channel and absorber that for the heat depositions at the luminosity of 10^{35} cm^{-2}s^{-1} [5] brings the magnet aperture to ~100 mm.

Two different design concepts were considered: one with remote "warm" iron yoke and another one with closer "cold" iron yoke. Both designs are based on four-layer coil geometry that opens an opportunity for cable grading. However, the negative aperture coupling results in the peak field point located in the outermost layer region adjacent to the second aperture that requires an inverse coil grading to maximize the efficiency with wider cable in the outer layers and narrower cable in the inner layers. The cable parameters for the inner and outer layers are listed in Table 1.

Warm yoke design

In the warm yoke design, the coils were placed inside a common cylindrical iron yoke, sufficiently remote to accommodate a cryostat. The magnetic coupling between the coils and yoke asymmetry with respect to each coil requires the appropriate asymmetry in the coil geometry to obtain a good geometrical field quality. The coil and yoke geometry were optimized by ROXIE code [6]. Due to the large yoke saturation effect even in the warm yoke design it was necessary to introduce holes in the yoke for better control of the field quality.

Fig. 1 shows the cross-section of optimized D2 coil inside the warm yoke. Unlike the 2-in-1 quadrupole magnet, also using asymmetric coils [3], the coil cross-section requires the same number of turns per layer in each quadrant. However, the turn breakdown between blocks of each layer does not have to be the same for the left and right halves of the coil giving an additional freedom during the optimization.

The warm yoke is distanced from the coils by ~ 160 mm in the midplane. That space is sufficient for the coil support structure and cryostat components including thermal shield, cold-mass supports and vacuum vessel. However, it does not result in a particularly compact magnet design since the yoke has to be relatively thick to limit the field harmonic variations within several units.

Table 1: Cable parameters.

Parameter	Unit	Layers	
		Inner	Outer
Number of strands		17	23
Strand diameter	mm	1.000	
Cable inner thickness (bare)	mm	1.685	1.650
Cable outer thickness (bare)	mm	1.881	1.915
Cable width (bare)	mm	8.627	11.694
Copper to non-copper ratio		1.2	
Insulation thickness	mm	0.18	

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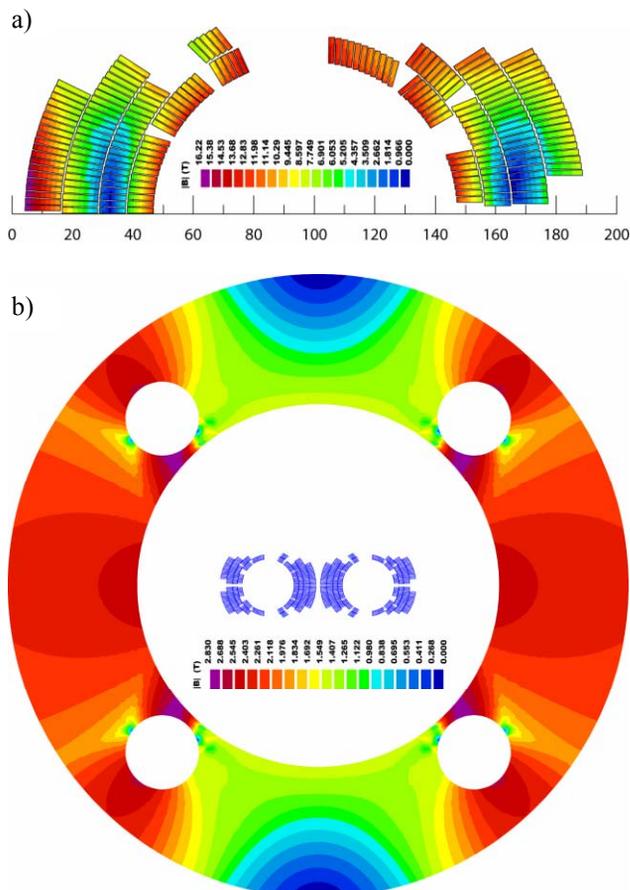
T10 Superconducting Magnets

Figure 1: Coil[a)] and warm yoke[b)] cross-section with magnetic flux density at quench current.

Cold yoke design

In the cold yoke design, the iron yoke was placed closer to the coils. Due to a complicated yoke shape required in this case, there was no analytical solution available at low fields. The coil and yoke cross-sections were simultaneously optimized for a good geometrical field quality and low yoke saturation effect using ROXIE.

The optimized coil and yoke cross-sections for the cold yoke design are shown in Fig. 2. Due to the small distance between the coils, it was impossible to shield the coils magnetically from each other in this design also, and the coils have to be asymmetric.

MAGNET PARAMETERS

Calculated parameters of the warm and cold yoke double-aperture dipoles are summarized in Table 2. The parameters responsible for the magnet mechanical performance and quench protection of the two designs are quite close.

In neither case the target bore field of 14.1 T can be achieved even with the appropriately graded state of the art Nb_3Sn cables operating at 1.9 K, although the peak field in the coils is close to 16 T. This low efficiency is related to the negative coupling that raises the peak field in the outer layer, far from the useful field region, thus limiting the magnet performance.
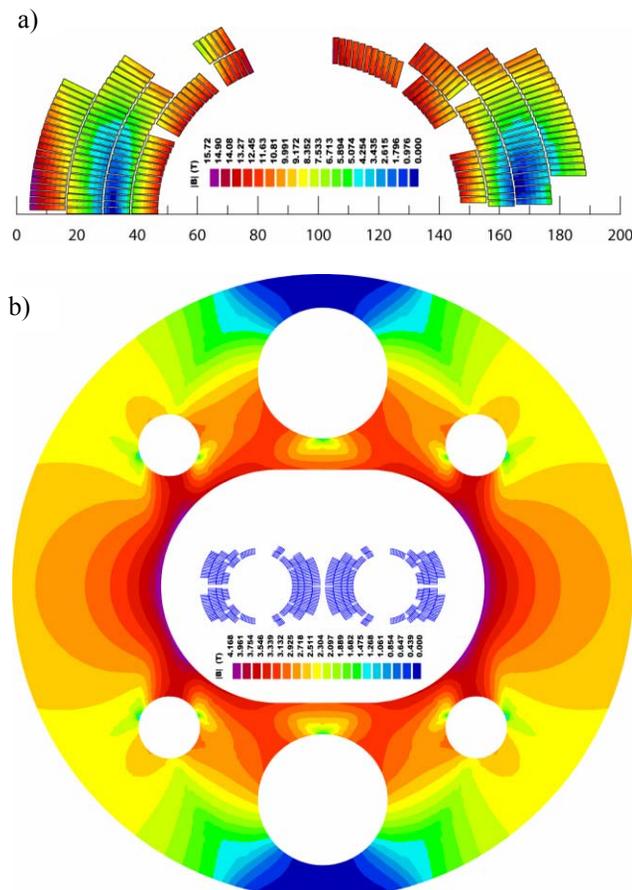

Figure 2: Coil[a)] and cold yoke[b)] cross-section with magnetic flux density at quench current.

Table 2: Magnet parameters at T=1.9 K for J_c(12T, 4.2K)=3000A/mm^2.

Parameter		Warm yoke	Cold yoke
Aperture diameter, mm		100	
Number of turns/aperture		196	
Yoke outer diameter, mm		1200	960
Quench field in the bore, T		12.65	13.19
Quench current, kA		14.09	14.18
Transfer function, T/kA		0.898	0.930
Peak field – inner layers, T		14.14	14.70
Peak field – outer layers, T		15.72	16.09
Quench margin – inner layers, %		3.00	0.00
Quench margin – outer layers, %		0.00	2.23
Inductance/aperture, mH/m		16.48	17.22
Stored energy/aperture, kJ/m		1636	1731
Lorentz forces/ 1st quadrant	F_x, MN/m	5.57	6.28
	F_y, MN/m	-5.08	-5.15
Lorentz forces/ 2nd quadrant	F_x, MN/m	-0.98	-1.61
	F_y, MN/m	-3.63	-3.67

Calculated geometrical field harmonics in the warm and cold yoke designs are reported in Table 3. Due to the coil and yoke asymmetry, the whole spectrum of normal harmonics is allowed in both designs. The low and high order harmonics were effectively suppressed using wedges and midplane shims.

Fig. 3 shows the yoke saturation effect in the low order harmonics for the two designs. Variations of the quadrupole and sextupole components in both designs are limited to $\pm 2 \cdot 10^{-4}$ for up to the quench currents.

Table 3: Geometrical harmonics at 25 mm radius, 10^{-4}.

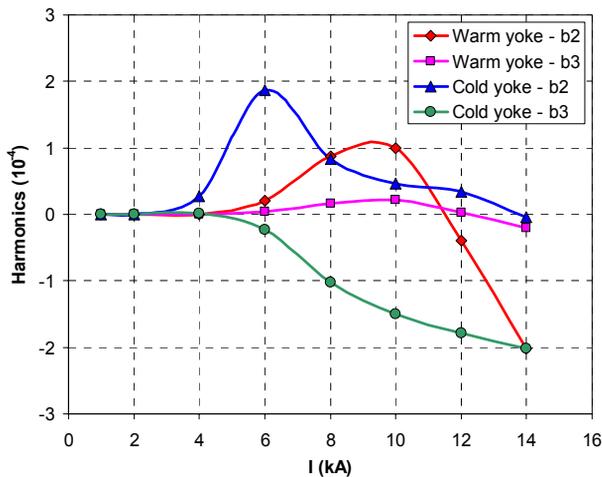| Harmonic	Magnet design	
	Warm yoke	Cold yoke
b_2	0.0000	-0.0001
b_3	0.0001	0.0001
b_4	0.0002	0.0006
b_5	-0.0027	0.0062
b_6	0.0009	-0.0038
b_7	-0.0084	0.0034
b_8	0.0606	0.0186
b_9	-0.0973	-0.0973
b_{10}	0.0889	0.0766
b_{11}	-0.0676	-0.0552

Figure 3: Yoke saturation effect.

DYNAMIC APERTURE

The D2 dynamic aperture was determined using the same criterion as for the 2-in-1 quadrupoles [3]. Fig. 4 shows the contours of 10^{-4} field uniformity in both designs considering the geometrical harmonics up to b_{18}. The harmonics that receive the active correction in baseline LHC IR optics (b_1-b_6 and a_1-a_4) were assumed to have zero values.

The maximum round beam envelope that fits into the field contours has a diameter of 56 mm that is 24% smaller than the required dynamic aperture. So, depending on the beam optics it may be preferable to either increase the magnet physical aperture to ~120 mm that would reduce the quench bore field to 11-12 T or accept larger field distortions at the edges of the beam envelope than in the baseline LHC IR optics.

SUMMARY

Two possible D2 magnet designs based on the warm and cold iron yokes were analyzed. It was shown that these designs have close operating parameters that allows

making a design choice based on a preferable mechanical or cryogenic system.

The maximum field that can be reached with the state of the art conductors in 100 mm apertures is 12.6–13.2 T, depending on the magnet design. An optimistic quench margin of 10% brings the operating fields down to 11.3–11.9 T that would require increasing the D2 magnetic length from 10 m [1] to 12.5–11.8 m to keep the same field integral.

The dynamic aperture is practically the same in both designs and smaller than the dynamic aperture required for D2 magnets.
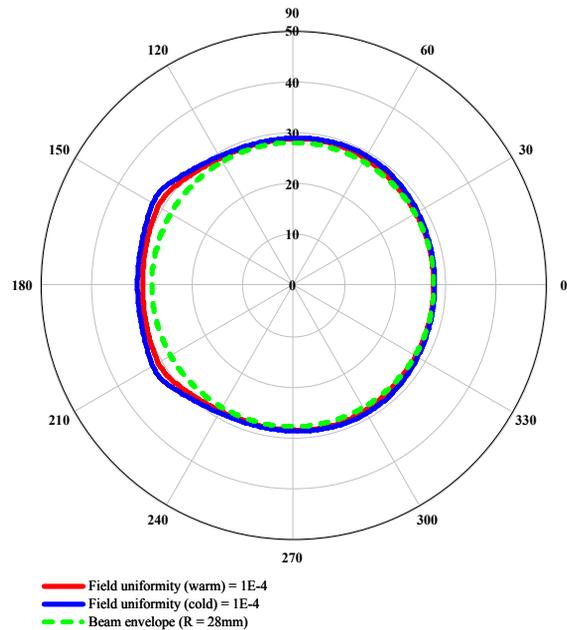

Figure 4: Dynamic aperture of the D2 magnets.

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