

Open Midplane Dipole Design for LHC IR Upgrade

R. Gupta, M. Anerella, M. Harrison, J. Schmalzle and N. Mokhov

Abstract— The proposed luminosity upgrade of the Large Hadron Collider (LHC), now under construction, will bring a large increase in the number of secondary particles from p-p collisions at the interaction point (IP). Energy deposition will be so large that the lifetime and quench performance of interaction region (IR) magnets may be significantly reduced if conventional designs are used. Moreover, the cryogenic capacity of the LHC will have to be significantly increased as the energy deposition load on the interaction region (IR) magnets by itself will exhaust the present capacity. We propose an alternate open midplane dipole design concept for the dipole-first optics that mitigates these issues. The proposed design takes advantage of the fact that most of the energy is deposited in the midplane region. The coil midplane region is kept free of superconductor, support structure and other material. Initial energy deposition calculations show that the increase in temperature remains within the quench tolerance of the superconducting coils. In addition, most of the energy is deposited in a relatively warm region where the heat removal is economical. We present the basic concept and preliminary design that includes several innovations.

Index Terms—Accelerators, Quadrupoles, Interaction Region and Large Hadron Collider.

I. INTRODUCTION

THE requirements of the LHC [1] luminosity upgrade [2] from $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ to $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ are such that we need (a) very high field magnets (12-15 T) based on a technology that has never been used in any accelerator magnets before and (b) superconducting magnets that are capable of withstanding a large energy deposition (9 kW/beam for each side of IR), that is an order of magnitude larger than before. This high radiation power raises several short term (magnet quench, heat removal) and long term (radiation damage, operating cost) issues. Past experience indicates that we need an extended period of R&D to develop new technologies and also to examine various design options in sufficient detail to make a well-informed choice ~5 years from now. Such work will result in magnet designs that are more suited to meeting the above challenging requirements.

The energy deposition on superconducting coils is highly anisotropic with a peak at the midplane. In a conventional design, the coils will be subjected to large energy deposition with peak power concentrated on the conductors near the midplane. The proposed open midplane design takes advantage of this anisotropic distribution by incorporating a channel to transmit the major portion of the particle spray away to a structure outside the superconducting coils.

Dipoles are the most critical part of the dipole first optics, as most of the energy is deposited there. Dipole first optics has the advantage of having the lowest long range parasitic beam-beam interaction. This is one of several options that is being currently considered for the LHC luminosity upgrade as a part of the LHC Accelerator Research Program (LARP) within the US-CERN collaboration [3]. The superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL) is carrying out R&D on the open midplane dipole design. In the following sections, we present two preliminary magnetic design concepts (Design A and Design B) and three preliminary mechanical design concepts (two for Design A and one for Design B). These design studies have been carried out to varying level of detail, with none fully completed, yet. The purpose of this paper is not to present a detailed design but to present the concept, examine various options and highlight the major features and issues. Some of these issues have been discussed earlier [4-5].

II. DESIGN A

The first and foremost objective of this study is to examine the basic premise of the open midplane design: a large energy can indeed be removed from the coil region [6]. In earlier studies for open midplane magnet [7], the cable at the midplane was replaced by a copper wedge (or other material). Those designs did not accomplish the desired results as the particles at the midplane hit copper instead of the the superconducting cable and created a large amount of secondary particles, which in turn deposited energy in rest of the coil. We now propose a design in which the coil midplane is completely free of all materials (copper wedge, structure membrane, etc.). This is a significant departure from conventional designs which rely on opposing azimuthal/vertical forces of the upper and lower coils balancing against each other. This also makes developing a magnet design with good field quality a challenging task.

In the very first design study, we made the coil midplane gap sufficiently large (larger than minimum necessary) to allow enough clear space to transport most spray particles out of the coil region. In addition, a minimum space was allowed

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for cryogenic and mechanical support structure.

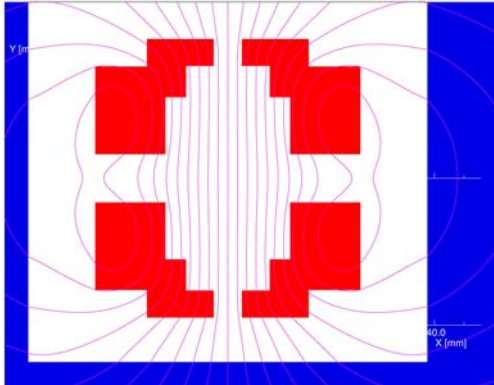


Fig. 1. Magnetic model of the open midplane dipole Design A with 90 mm horizontal aperture.

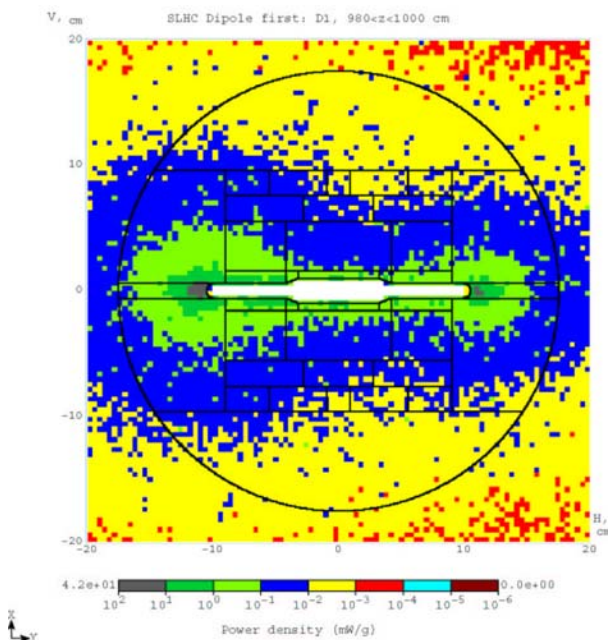


Fig. 2. Energy deposition near the end of 10 m long dipole where it is expected to be the maximum. The power density in the coils is within the limit.

The proposed model (see Fig. 1) is based on racetrack coils made of Nb_3Sn conductor. The computed short sample is ~ 15 T to allow a sufficient margin for the 13.6 T design field. The required critical current density in Nb_3Sn is 2500 A/mm^2 at 12 T and 4.2 K with a copper to superconductor ratio of 1.0. Design A was developed for smaller aperture magnet (the aperture is increased in Design B based on the requirements from the subsequent studies). The horizontal coil aperture in Design A is 90 mm and the vertical aperture is 20 mm. The minimum gap between the upper and lower coils is 40 mm. This is the best case scenario for minimum energy deposition on the superconducting coils. However, this design produces field errors that are two orders of magnitude larger than typically desired because of a large “coil midplane gap” to “horizontal aperture” ratio (~ 0.45).

This study was critical to determine if the energy

deposition can indeed be made as low as we had hoped and hence to determine if the proposed open midplane dipole design concept is worth pursuing for the LHC luminosity upgrade. It may be recalled that we have kept the energy deposition from the primary particle spray and from secondary showers (generated when particles hit material) to a minimum. The results from energy deposition calculations [6] were very encouraging as they confirmed that the proposed design worked as desired. Fig. 2 shows the energy deposition at the end of 10-meter long D1 (dipole first) magnet, where the deposition is expected to be maximum. The peak power density in the superconducting coils is only 1-1.3 mW/g at 10^{35} luminosity, which is below the quench limit of 1.6 mW/g [6].

III. COLD IRON SUPPORT STRUCTURE FOR DESIGN A

The support structure for this design employs a set of interlocking non-magnetic collar laminations. The laminations are arranged with split lines parallel to the horizontal axis. The forces in the horizontal direction are resisted by the inherent stiffness of the laminations. The large vertical forces are resisted in part by opposing laminations in compression against one another, and in part by a central shear pin, which forms adjacent laminations into a structural truss. Such a system is shown to handily limit deflections from the Lorentz forces to less than 0.25mm (as shown in Fig. 3), with relative deflections (i.e., those along any common conductor surface) smaller yet by at least a factor of two.

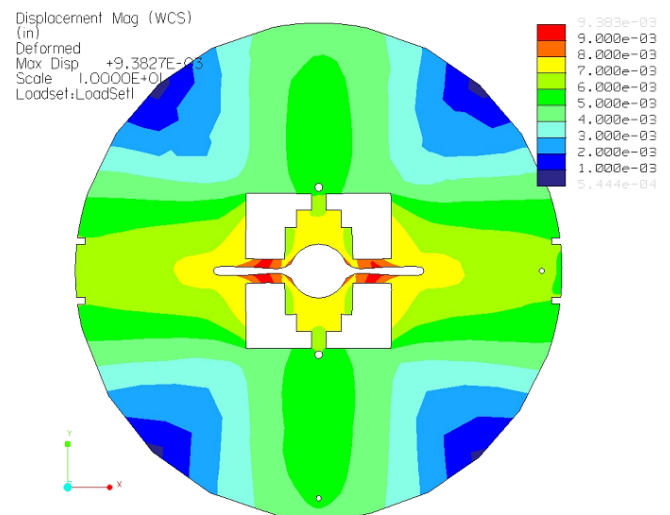


Fig. 3. Magnitude of deflections (horizontal and vertical deflections combined) in inches at the quench field in the 90 mm aperture “Design A” with cold iron structure.

The design presented in this section has been successful in protecting superconducting coils; however, the energy was still deposited in a cold structure. Since, the heat removal efficiency is poor at low temperatures, the design requires cryogenic capacity about as large as in other designs.

IV. WARM IRON SUPPORT STRUCTURE FOR DESIGN A

This design utilizes a support structure as shown schematically in Fig. 4. The coil sets are contained in stainless steel vessels, which serve to resist the Lorentz forces and also serve as the helium containment vessel. Separate structures are used for upper and lower coil sets. Each structure is self-supporting with respect to horizontal Lorentz forces. Vertical forces are reacted through an external path which includes the 300K cryostat. The obvious benefit of such a design is that secondary particles are essentially unimpeded until it arrives at a 300K mass. This makes heat removal significantly easier and cheaper. The tradeoff, however, is in the stability and conductive heat loss through the required support system for such a design. Early analysis indicates that 40W/m heat load can be achieved using supports which restrict total deflections to less than 0.8mm (see Fig. 5). While this heat load would be considered excessive in current magnet designs, in this application it compares favorably with the elimination of beam heating at 4K. Nonetheless, future work on this support system will focus on optimization of heat leak and stability and minimizing relative deflections.

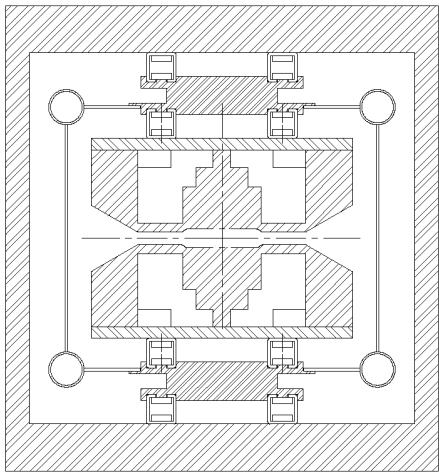


Fig. 4. Schematic of the support structure for the warm iron design.

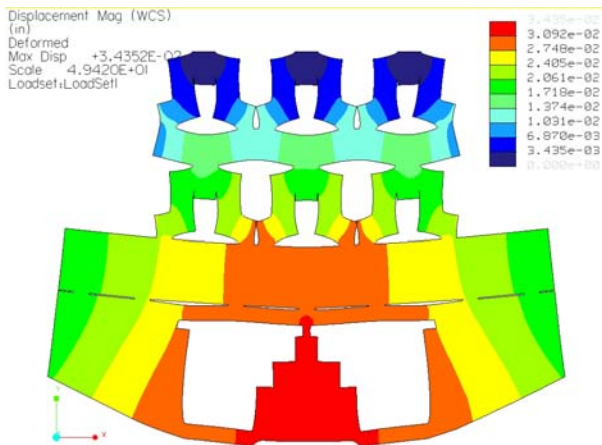


Fig. 5. Magnitude of deflections (horizontal and vertical deflections combined) in inches at the quench field in the 90 mm aperture "Design A" with warm iron structure.

V. DESIGN B: WARM INTERCEPT DESIGN

A new design concept is presented here that allows a smaller coil midplane gap to improve field quality to a level desired in accelerator magnets. The proposed Design B (see Fig. 6 and Fig. 7), has a horizontal coil aperture of 135 mm (increased from 90 mm in Design A) and the minimum vertical coil-to-coil midplane gap is reduced to 20 mm (decreased from 40 mm in Design A). The design has been developed such that the blocks closer to the midplane (lower blocks) have net force away from midplane (upward) and the blocks away from midplane (upper blocks) have net force towards the midplane (downward). In addition, the design was devised to have a large gap between the upper and lower blocks of conductors. This gap facilitates a segmented support structure to deal with the large downward forces on upper blocks. A continuous horizontal support element in the gap between coil blocks transfers the vertical force to the outside structure. Since the net vertical force on the lower blocks is small and upward, only a thin structural material is needed. Therefore, the coils can be brought closer to the midplane to obtain better field quality.

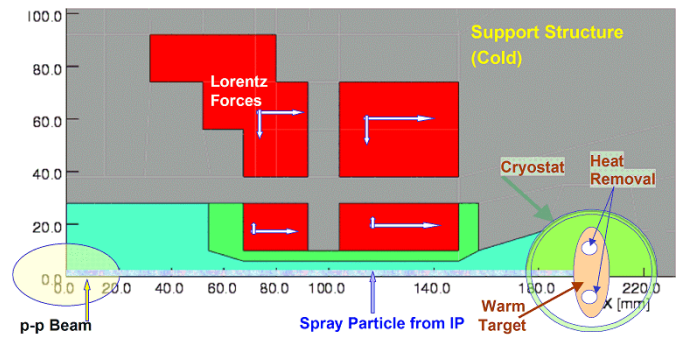


Fig. 6. Schematic of the warm intercept Design B (the schematic does not represent the actual dimensions of the beam or cryostat, etc.). Particle spray from the IP deposit heat on a warm target within a cold support structure. The arrows show the direction of the Lorentz force on each block. The design has been developed such that the blocks near the midplane have no net vertical downward force. This picture shows the two counter-rotating beams at the IP end of the magnet with no separation. The two beams are separated out on the other end of the magnet.

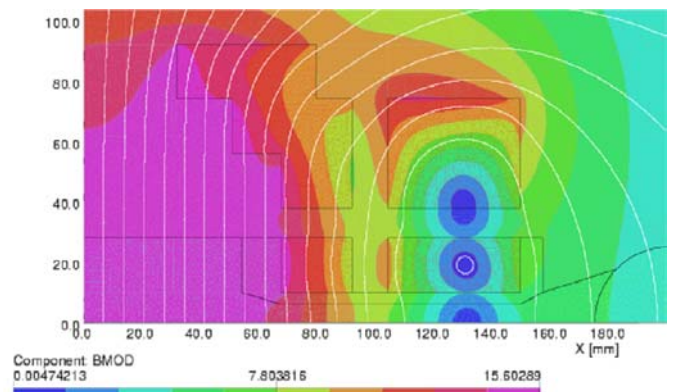


Fig. 7. Magnetic model of Design B with 135mm horizontal aperture with field contour and field lines superimposed. The design creates reasonably good field quality (relative error 10^{-4}).

The proposed design contains a warm thermally insulated target within the support structure that absorbs energy from spray particles from the IP and efficiently removes the heat generated by them at a temperature of 80 K or even possibly at room temperature. The proposed design is expected to have a small heat leak.

The computed quench field is little over 15 T for Nb₃Sn superconductor having a critical current density of 3000 A/mm² at 12 T and 4.2 K. The assumed non-copper to copper ratio in the inner blocks is 1:1 and in the outer blocks is 1.8:1. The integrated forces on the four blocks are given in Table I.

TABLE I
LORENTZ FORCES ON THE CONDUCTOR BLOCKS AT THE QUENCH FIELD IN DESIGN B WITH 135 MM APERTURE. THE CONDUCTORS ARE GROUPED IN FOUR BLOCKS ACCORDING TO LOCATION.

Block	Horizontal Component (N/mm)	Vertical Component (N/mm)
Inner Lower	1632	16
Outer Lower	728	-4
Inner Upper	6908	-2248
Outer Upper	1302	-3909

In order to guide the concept in desired direction, we adjusted parameters one at a time in a controlled fashion rather than using a multi-parameter coil optimization code for field quality. With this method a design with relative field errors better than 5 parts in 10⁻⁴ on X-axis between x=0 mm to x = 40 mm was obtained at the design field (see Fig. 8). This is the order of magnitude of field quality that is desired in typical accelerator magnets. Future design iterations will minimize field harmonics in the entire range of operation with the help of multi-parameter coil and yoke optimization codes. Those iterations will also incorporate feedback from mechanical structure and energy deposition calculations.

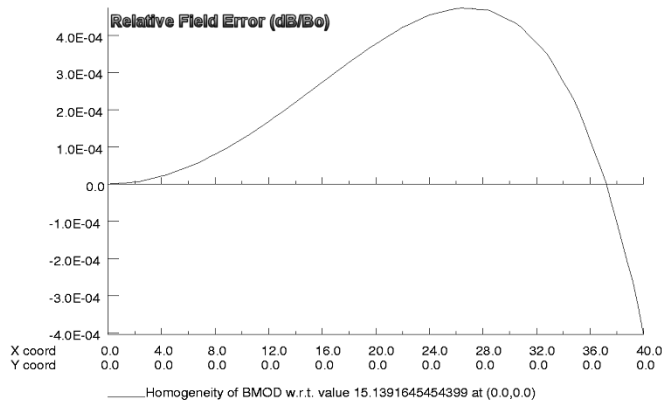


Fig. 8. Relative field error on the X-axis for Design B.

VI. SUPPORT STRUCTURE FOR DESIGN B

The initial model of a cold iron support structure for Design B was made and is shown in Fig. 9. In spite of the relatively larger forces associated with the 135 mm aperture, stresses and deflections have been kept small compared with previous results. Iron outer diameter was increased

consistent with the increase in aperture to maintain structural integrity. More work will be required to complete the mechanical analysis, to take into account effects of discontinuities from the segmenting of the collar laminations on stresses and deflections.

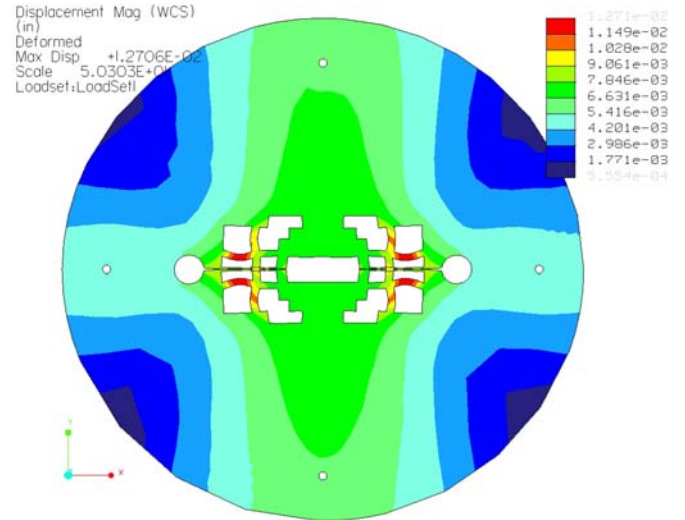


Fig. 9. Magnitude of deflections in inches at the quench field in the 135 mm aperture "Design B" with warm intercept in cold support structure.

VII. SUMMARY

The proposed open midplane dipole design concept for LHC luminosity upgrade appears promising. It is expected to significantly reduce the energy deposition on the superconducting coils of the critical IR region. It should also significantly reduce the need for a large increase in cryogenic capacity and operating cost with a large increase in luminosity. The next phase of this development will be to obtain a good field quality design that is consistent with good mechanical and cryogenic performance.

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