ENERGY DEPOSITION LIMITS IN A Nb_3Sn SEPARATION DIPOLE IN FRONT OF THE LHC HIGH-LUMINOSITY INNER TRIPLET*

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Abstract

Interaction region inner triplets are among the systems which may limit the LHC performance. An option for a new higher luminosity IR is a double-bore inner triplet with separation dipoles placed in front of the first quadrupole. The radiation load on the first dipole, resulting from pp-interactions, is a key parameter to determine the feasibility of this approach. Detailed energy deposition calculations were performed with the MARS14 code for two Nb_3Sn dipole designs with no superconductor on the mid-plane. Comparison of peak power densities with those in the baseline LHC IR suggests that it may be possible to develop workable magnets for luminosities up to 10^{35} cm^{-2} s^{-1}.

DIPOLE FIRST IR

After the LHC operates for several years at a nominal luminosity $\mathcal{L}$ = 10^{34} cm^{-2} s^{-1}, it will be necessary to upgrade it for higher luminosity. An interesting option for a new interaction region (IR) is a double-bore inner triplet with separation dipoles placed in front of the quadrupoles [1, 2]. Compared with the baseline design consisting of single-bore quadrupoles shared by both beams, this layout substantially reduces the number of long-range beam-beam collisions, allows the beams to pass on-axis through the quadrupoles, and permits local correction of triplet field errors for each beam. However, β_{max} is considerably larger for the same β^*. Increasing the LHC luminosity by an order of magnitude creates a hostile radiation environment resulting from colliding beam interactions [3], with most of the power of almost 9 kW per beam directed towards the IR magnets. The problem is particularly severe for the dipole-first layout, since most of the charged secondaries will be swept into the dipole by its large magnetic field.

Detailed MARS14 [4] energy deposition calculations have been performed to determine the feasibility of this approach. Fig. 1 shows the layout considered. The D1 dipole starts at 23 m, allowing space, as in the current IR, for a 1.8-m long TAS absorber, and there are 5 m between the D1 and D2 to allow for a TAN neutral particle absorber. The orbits shown are for a horizontal crossing angle of ±0.212 mrad, scaled up from the baseline ±0.15 mrad to allow for reducing β^* to 25 cm. In view of the reduced number of long-range collisions, such a crossing angle provides sufficient beam separation for operation with a 12.5 ns bunch spacing at the ultimate bunch intensity of $1.7{\times}10^{11}$ p/bunch. A vertical crossing can be generated by rolling the D1 and D2 by several degrees, or with strong correctors placed in front of the D1 (∼8 T-m) and behind the D2 (∼3 T-m). The dipole strengths shown are for a horizontal crossing plane; they both go to 15 T for a vertical crossing plane. The transverse size and positions of the dipole and quadrupole boxes correspond to the required coil apertures, which are 130 mm, 100 mm and 100 mm for the D1, D2 and quadrupoles, respectively, assuming that all the quads have the same coil bore. Although desirable, it would be difficult to include a hole through the yokes to allow the neutral beam to pass through the D2 and the triplet to a downstream TAN. Therefore, for the purpose of this study, the TAN is assumed to be between D1 and D2.

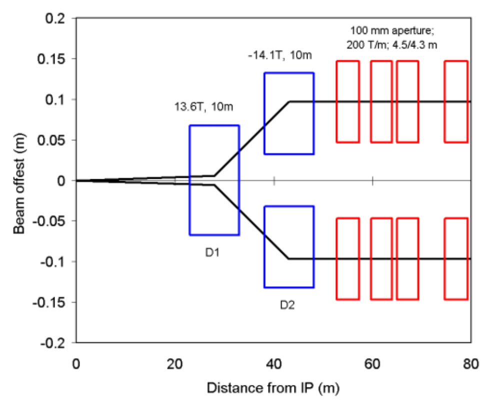

Figure 1: Interaction region layout.

The required physical aperture at the non-IP end of the D1 is shown in Fig. 2. The radial clearance about each beam (incoming and outgoing) is [2] $1.1{\times}9\sigma$ + 8.6 mm = 23.5 mm, where the factor 1.1 allows for 20% β-function errors, σ = 1.5 mm, and 8.6 mm is the sum of various orbit and alignment errors. At the non-IP end of the D1, the orbits in Fig. 1 are offset by ±36 mm, giving rise to a racetrack shaped aperture.

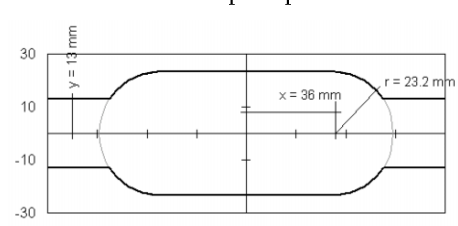

Figure 2: Required physical aperture at the D1 non-IP end.

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Horizontal channels are shown along the mid-plane outside of this aperture, which could allow much of the collision debris to exit the coil region (see Fig. 4). The height of the channels must take into account divergence of the beam and the combined tolerances on orbit and alignment and the crossing angle, since the forward collision debris peak follows the outgoing beam. The dimension shown in Fig. 2 is 3σ + 8.6 mm = 13 mm. The channel dimensions, if such a design were adopted, would be subject of optimization based on energy deposition and the mechanical constraints on the magnet design.

TWO DESIGNS FOR D1

In this paper, calculations are done for D1 of two types, whose parameters are summarized in Table 1. Both designs are based on a Nb_3Sn superconductor (SC). The first one, shown Fig. 3, is a traditional cos-theta design with a 4-layer graded coil of inner radius 65 mm and a cold iron yoke. High field quality is achieved by optimizing the azimuthal sizes of each layer and of the wedges in the innermost layer. Copper spacers of half-height 10, 6, 4 and 4 mm are placed at the mid-plane, where the peak power deposition from collision fragments occurs.

Table 1: Magnet parameters

Parameter	**Units**	$\cos\theta$	**Block**
Coil aperture ID	mm	130	84
No. of layers	-	4	4
Quench bore field	T	15.8	15
Quench peak field	T	16.8	16.7
Conductor x-sec. area	cm^2	119.1	174.4
Yoke inner radius	mm	145	305
Yoke outer radius	mm	500	500

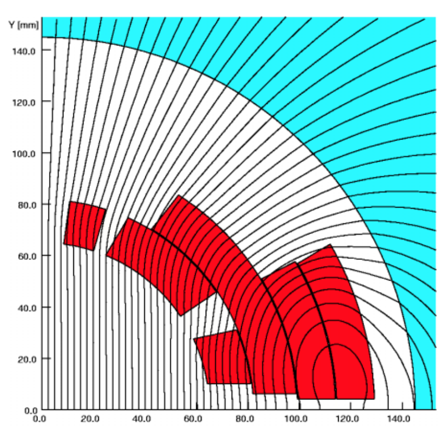

Figure 3: Cos-theta D1 magnet with a mid-plane spacer.

The second dipole design uses block type coils (Fig. 4). The iron can be either warm or cold depending on the details of the design. The required field quality (not yet optimized) is achieved by adjusting the size and position of coil blocks. All material is removed from the mid-plane region, so that the first material encountered by the dominantly horizontal spray of particles is outside the coil region. This approach, however, presents significant challenges to the magnetic and structural design. The dipole has a clear circular aperture of 70 mm and horizontal slots of height ±6 mm. The coils have a minimum vertical separation of 33.5 mm. The maximum stress in stainless steel collar is about 700 Mpa. The maximum horizontal and vertical coil deflections at 15 T are less than 0.2 mm. The magnitude of the vertical deflections can be reduced by incorporating *stress intercepts* within the coil structure that directly transfer load from the coil to collar. The magnitude of the horizontal deflections can be reduced by further strengthening the collar by increasing its size, etc.

The block-coil dipole design is very preliminary, and its aperture is smaller than the required one shown in Fig. 2. However, the MARS model discussed sets to zero all tolerances on alignment and orbit errors, which are a significant component of the aperture requirement. As a consequence the studies here allow a valid first comparison of magnet designs with and without material on the coil mid-plane, which is the main result of this paper.

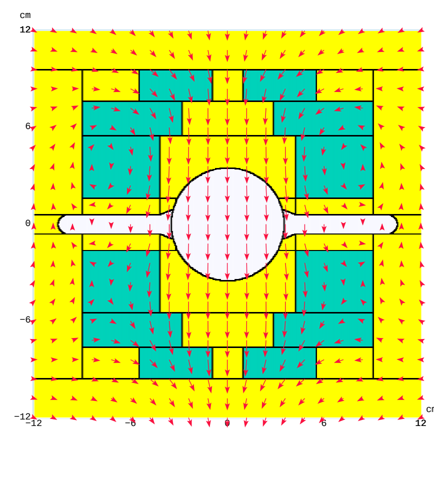

Figure 4: A MARS model fragment block coil D1 magnet with open mid-plane.

ENERGY DEPOSITION RESULTS

The MARS runs were performed for the LHC IP5 region with the layout of Fig. 1 at $\mathcal{L} = 10^{35}$ cm^{-2} s^{-1} and horizontal crossing. The CMS detector with its 4-T solenoid field is assumed here. A copper 1.8-m long TAS at z=19.45 m has a 21-mm radius round aperture (compared to the baseline's 17-mm) and 450-mm outer radius. A simple interconnect between TAS and D1 is assumed with a 240-mm ID beam pipe. The D1 dipole in both designs is 10-m long with 13.6-T bore field. A 120-mm ID and 124-mm OD stainless steel beam pipe is implemented in the cos-theta design, with no pipe in the block-coil dipole case. A copper 5-m long TAN with two corresponding apertures sits at z=33 m immediately downstream of the D1.

As in the baseline [3], the TAS protects the upstream end of the first magnet against severe energy flux from the IP, absorbing a power of 1.75 kW. The peak power density ϵ_{max} at shower maximum is 89 mW/g. The power dissipated in the TAN is about 2 kW, depending on which dipole is used in the study, and ϵ_{max} = 870 mW/g. Active cooling will be required for both absorbers.

The strong magnetic field in the D1 deflects charged particles horizontally left and right, concentrating power deposition in the mid-plane, which reaches its maximum at the non-IP end of the dipole. The power density 2D distributions at the longitudinal maximum are shown in Fig. 5 and 6 for the two dipoles. One clearly sees the local peak on the left (closer to the outgoing beam): in the SC coils for the cos-theta dipole and deep in the "trap" for the block coil type magnet. The peak power density in the copper spacers on the mid-plane of the cos-theta magnet is 49 mW/g. The maximum power density in the SC coils is 13 mW/g, as shown in Fig. 7, more than 20 times the peak power in the quadrupoles in the baseline LHC IR at $\mathcal{L}$ = 10^{34} cm^{-2} s^{-1} [3]. Dealing with this will present a significant challenge to the magnet designers.

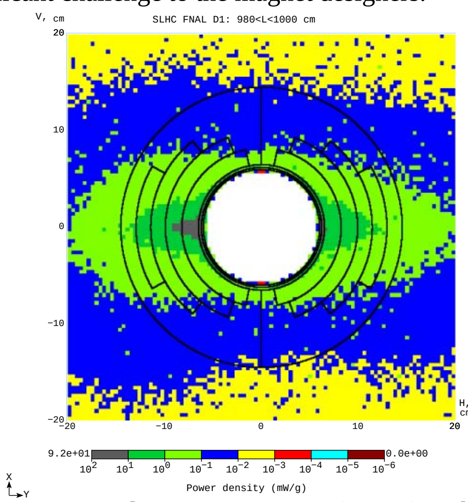

Figure 5: Power density isocontours (mW/g) at the non-IP end of the cos-theta dipole.

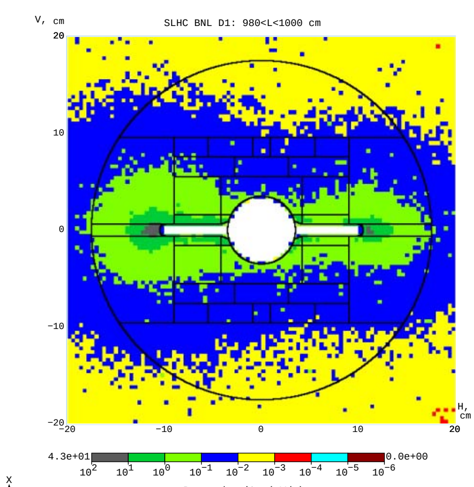

Figure 6: Power density isocontours (mW/g) at the non-IP end of the block-coil dipole.

In contrast, ϵ_{max} in the coils of the block-type dipole with no material on the mid-plane is only 1.1 mW/g, about

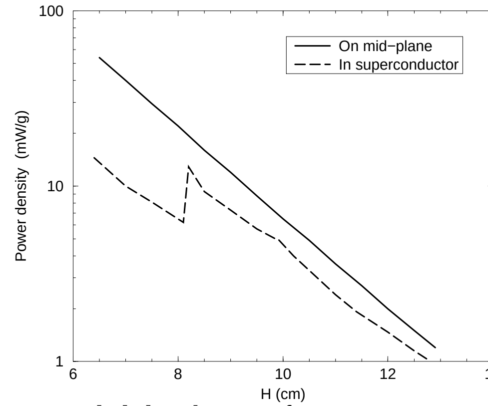

Figure 7: Radial distribution of maximum power density in the cos-theta dipole coil: on the mid-plane and in the superconductor.

twice the peak power in the quadrupoles in the baseline LHC IR at the baseline luminosity. While this is an encouraging result, it must be emphasized that such a design has never been tried, and substantial R&D must be done before the feasibility of a magnet of this type can be demonstrated.

The total power dissipated in the dipole is about 3.5 kW in either design. Efficient removal of such a power from the cryogenic system is also a major challenge for implementing this IR design as part of an LHC upgrade.

CONCLUSIONS

The radiation environment for a dipole-first IR is quite severe: the peak power density at $\mathcal{L}$ = 10^{35} cm^{-2} s^{-1} is up to two orders of magnitude larger than in the baseline inner triplets at 10^{34} cm^{-2} s^{-1}. The dipole-first layout is attractive because it reduces number of long-range beam-beam collisions and allows more robust correction of triplet errors, encouraging us to find a solution for the energy deposition problem. The preliminary results presented here show that the power deposited in the coil can be reduced to a level comparable to that in the baseline LHC in a dipole with no material on the coil mid-plane. However, much work remains to be done to demonstrate that a dipole of such a design can be made to reach high field, maintain good field quality, and meet all other requirements for use in a very high luminosity IR.

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