A FEASIBILITY STUDY OF SUPERCONDUCTING DIPOLE FOR THE EARLY SEPARATION SCHEME OF SLHC

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Abstract

In the framework of the LHC luminosity upgrade an early separation scheme is being studied for the final phase ($L \sim 10^{35}$ cm^{-2} s^{-1} with substantial changes in the IR). In this paper we compare a Nb_3Sn and a Nb-Ti cos(θ) design: the aim is to explore the benefits and the limits of a compact solution with respect to the detector's constraints and the energy deposition issues. We propose to put the dipole system (cryostat and magnet) at a location starting at 6.8 m from the IP. The preliminary cross section, the achievable integrated field, the energy deposition on the magnet are presented and discussed.

INTRODUCTION

The Early Separation Scheme is one of the proposals under study for the LHC Luminosity Upgrade Phase II (SLHC, $L \sim 10^{35}$ cm^{-2} s^{-1}) [1]. It consists of two dipoles (D0s) symmetrically positioned with respect to the IP: its aim is to reduce the crossing-angle at the IP (thereby increasing the luminosity) while alleviating the detrimental effect of the beam-beam parasitic encounters. The actual position of the dipole is still under discussion: it is strongly entangled on beam dynamics considerations, integrability in the detectors issues, magnet design optimization and energy deposition scenarios. In this paper we focus on the latter two aspects assuming that the D0 is positioned at 6.8 m from the IP and the required integrated field of 7 Tm: this corresponds to an angular kick of ~ 300 μrad per magnet for the 7 TeV LHC beam. Assuming the lower $\beta^* = 0.11$ m considered in [2] this is equivalent to increasing the beam separation by $\sim 9\,\sigma$. In that condition, assuming a residual crossing angle of $5\,\sigma$, we have, per each IP's side, two parasitic encounters (LRBBs) at $5\,\sigma$ (between the IP and the D0) followed by a transient of two LRBBs (after the D0) and a series of, in average, $5+9=14\,\sigma$ LRBBs. This scenario, with $\beta^* = 0.11$ m, yields a geometrical loss factor $F = 0.50$: without D0, considering the nominal $9.5\,\sigma$ beam separation and the same β^*, we have $F = 0.29$. In these conditions the luminosity increase given by the D0 is about 70%. An additional integrated luminosity gain can be provided by the D0 with luminosity leveling through the crossing angle [3].

MAGNET DESIGN

The D0 has several integrability issues presently under study by the ATLAS and CMS teams: to reduce its impact on the detector we propose a design that does not require shielding blocks. This implies a large aperture magnet (Φ): the investigated apertures range between 200 and 300 mm in diameter. This choice allows to lower the peak power deposition on the coils and the overall cryogenics load (see the energy deposition section).

On the other side, a larger aperture implies bigger coil ends (with a negative impact on the D0 magnetic length) and, for a given coil width, a larger ratio between the peak field and central field; in addition, the energy stored in the dipole (and consequently the coils stress) increases with the aperture for a given field. Even if it is difficult to establish a rigid threshold, we can reasonably assume a maximum stress allowed on the coils of 150 MPa.

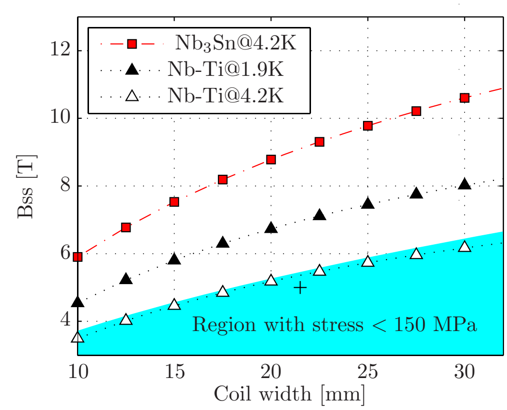

Figure 1: Short sample center field for $\Phi = 300$ mm, assuming a 60° sector Nb_3Sn and Nb-Ti coils. The region where the stress on the coil is less than 150 MPa is highlighted. The proposed working point (following section) is shown (+).

In Fig. 1, using the model presented in [4], we plotted three curves showing the short sample center field as function of the coils thickness. On the same plot [5] we show the region where the coils stress does not exceed the 150 MPa: it does not depend on the superconductor's critical surface. We can conclude that given the large aperture, the D0 is mostly limited by the mechanical stress rather than by the superconductor's properties.

The difference between the Nb_3Sn and the Nb-Ti is on the temperature margin they can offer and on the cryogenic power needed for the cooling due to the different operating temperature. Working almost at the edge of the 150 MPa region the Nb-Ti at 4.5 K is not a viable choice since it does not provide any margin. Considering one layer design, 15 mm-width cable and 300 mm-aperture, we can reach a field 4.6 T working at $\sim 79\%$ (for the Nb-Ti at 1.9 K) and $\sim 61\%$ (for the Nb_3Sn at 4.2 K) of the B_{ss}. In comparing these solutions we have to consider the different thermal

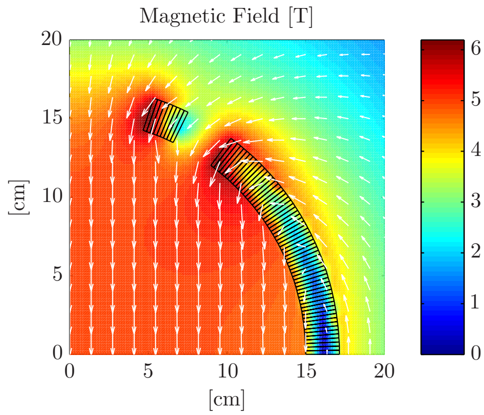

Figure 2: Preliminary cross section layout for the D0.

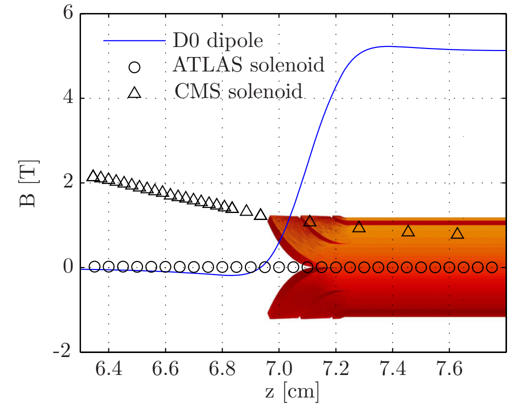

Figure 3: The magnetic field of the D0 and of the detectors along the longitudinal axis.

behavior of the cables (Nb-Ti and Nb_3Sn) and of the helium bath (1.9 K and 4.2 K)[6].

Concerning the field quality the constraints are not stringent: the integrated field is very low compared to that of a LHC arc dipole, the number of D0's is low (2 D0s for each of the two high luminosity experiment) and above all, the good-field-region requested is very small with respect to the magnet aperture. The latter one is in fact driven by the energy deposition issues and not by the beam size (like the largest part of magnets). For a $\beta^* = 0.11$ m at 9 m from the IP (end of the D0, $\beta \sim 740$ m) the LHC's σ at collision is about 610 μm. The D0 is a single aperture magnet: if we assume a maximum separation of 16 σ and we consider 10 σ beam width, the good-field-region should have a diameter of less than 10% of the magnet aperture.

Due to the large aperture of the magnet, about 1 m of the cryostat will be occupied by the interconnections and the dipole's ends: for efficiency with respect to the D0's magnetic length we consider a 2 m cryostat. From Fig. 1 we can conclude that one layer can meet the specifications with the advantage of a simpler design. For designing the cross section we consider a Nb-Ti at 1.9 K solution: its manufacture is simpler than Nb_3Sn and the Nb-Ti at 4.2 K does not provide enough margin. We adopted a 2×20 strands, 21.5 mm width, keystoned cable, using the strand of LHC dipole inner cable. Even if the cable is large its windability due to the large D0's aperture will not be a problem. Starting from a three-block iron-less design $(0° - 33.3°,\ 37.1° - 53.1°,\ 63.4° - 71.8°)$, and trying to find a trade-off between the peak field-center field ratio (λ) and the field quality, we end up with a two-block solution. The first block has 61 conductors and the second one 9 (Fig. 2). In the layout of Fig. 2 we have a $\lambda = 1.28$. powering the cable with 18 kA (71% of the load line) the peak field on the coil is 6.4 T and the field at the center is 5.0 T (Fig. 1). In this solution the sextupolar component (at a radius of 11 mm) is 0.61 units, all the others are much smaller. In Fig. 4 we assumed the coldmass cross-section: we consider 40 mm thick aluminum collar, 10 mm thick stainless steel cylinder an 2 mm stainless steel cold tube.

Considering a 3D model (Fig. 3), the required 7 Tm integrated field can be reached on a coil physical length (including ends) of 1.7 m. In Fig. 3 it is shown the actual position of the coil (only half coil is visible) with respect to the IP (with the cryostat starting at 6.8 m). The solenoidal field of ATLAS is almost negligible while the CMS's one is not (3). This has several effects and this is the reason why we considered an iron-free solution: the ferromagnetic material would be completely saturated (in CMS) by the solenoid and would exchange with the detector a big force. A simplified 3D model (2D with axial symmetry, using Maxwell stress tensor method for computing the force [7]) was produced: one meter long cylindrical block of iron (inner radius of 200 mm, outer radius of 400 mm), starting at 6.8 m from the IP would be pulled towards the center of CMS by a force of $\sim$ 40 t force (in the ATLAS case, $\sim$ 0.2 t force).

A second effect is the Lorentz force on the coil's end due to the solenoidal field. Given the problem geometry, we use the simplified approach $F = L\ I\ B$ (considering the $L = 0.2$ m, $I = 18$ kA$\times$70 conductors, $B = 1$ T), it yields $\sim$ 25 t force on each coil. Its direction (horizontal or vertical) will depend on the crossing angle plane of the beams. The cantilevering of the structure is challenging. Shielding the coils with an anti-solenoid may solve the problem: this possibility is still to be investigated. For an assessment on the additional stress due to this force a full 3D model is needed. Furthermore the solenoidal field reduces the working margin of the coil but its impact on that respect is modest. The proposed parameters for the D0 are summarized in Table 1.

Φ	W_{coils}	L_{coils}	$\int Bdl$	**Material**
300 mm	21.5 mm	1700 mm	7 Tm	Nb-Ti

Table 1: Proposed parameters for the D0.

ENERGY DEPOSITION

An energy deposition study was performed using the FLUKA code [8]. We made the following assumptions:

- the luminosity is 10^{35} cm^{-2}s^{-1}
- the divergence of the primaries, the crossing angle the detector solenoidal field are neglected; the D0's fields is 5 T (ideal dipolar field only in the D0'aperture without fringe effect due to the dipole's ends)
- the superconductor is modelled in a 60° sector coil (copper); the collars (aluminum), the cold tube (iron) and the cylinder (iron) are included (Fig. 4), no other element of the detector or of the machine is considered in the simulation. The D0's coil length is 1.7 m and it starts at 6.95 m from the IP.

We performed the computation over a 14000 *pp* collisions statistic: the results of the simulation are summarized in Figs. 4-5 and in Table 2. The peak power deposited is the coil ($\sim 4\ \frac{\mathrm{mW}}{\mathrm{cm}^3}$, not visible in the plots due the averaging) is below the Nb-Ti suggested limit in [9].

The maximum power per meter is $\sim 40\ \frac{\mathrm{W}}{\mathrm{m}}$: it is higher than the $\sim 10\ \frac{\mathrm{W}}{\mathrm{m}}$ limit taken as reference in [9] but, due the large thermal exchange surface (high number of turns in this particular design), that is still compatible with a Nb-Ti coil [6]. A free helium channel shall be made available between the coils and the cold tube to evacuate the heat longitudinally.

The 74 W deposited on the D0 (4 D0s in the machine) should be compared to the $\sim$ 1.1 kW per single triplet (rescaling at higher luminosity the results presented in [9]).

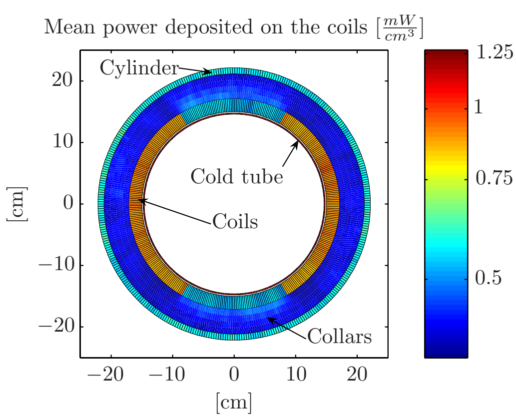

Figure 4: Cross section power deposition map (it is averaged along the longitudinal direction).

Coils	Collars	Cylinder	Cold tube	Total
30 W	27 W	11 W	6 W	74 W

Table 2: Power deposited on the different cryostat components.

CONCLUSIONS

In this work we made a first feasibility study of a superconducting dipole for the Early Separation Scheme. Given the detector constraints and the energy deposition issues a

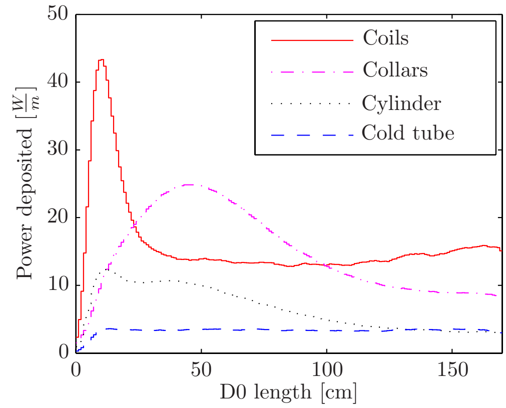

Figure 5: D0 heat load along the longitudinal direction.

30 cm aperture magnet is proposed. In that condition the performance is limited by the stress on the coil: Nb-Ti coils at 1.9 K can deliver the required 7 Tm in a 2 m long cryostat starting at 6.8 m from the IP. Given the aperture a shorter cryostat would not be efficient.

The power deposition peak is manageable even without shielding blocks. The total heat load of 74 W is a small fraction of that of a single triplet.

The Lorentz force on the coils due to the detectors solenoid is an issue in CMS: shielding the D0 with an anti-solenoid, as proposed for ILC, may be investigated.

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