STUDY OF A LESS INVASIVE LHC EARLY SEPARATION SCHEME

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Abstract

The LHC Early Separation Scheme consists of a four 8 to 15 T·m dipoles (D0s) installed in the two LHC high luminosity experiments. Its aim, in the framework of LHC Phase II Upgrade, is to improve the luminosity by reducing the crossing angle between the two colliding beams, mitigating and controlling at the same time their parasitic interactions. We investigate a less invasive implementation for the detectors (D0 at 14 from the IP) with respect to those already presented (D0 at 4 and 8 m from the IP). The luminosity performance is discussed and a tentative analysis on beam-beam effect impact is given. For the new D0 position, preliminary dipole design and power deposition results are shown.

INTRODUCTION

The Early Separation Scheme (ES) is one of the proposals under study for the LHC Luminosity Upgrade Phase II (SLHC, $L \sim 10^{35}$ cm^{-2} s^{-1}) [1][2]. It consists of two dipoles (D0s) and two orbit correctors (OCs) symmetrically positioned with respect to the IP (Fig. 1). The OCs are placed just in front of the triplets in order to steer the beam closed orbits in the experimental area independently from the one in the triplets. The ES's 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

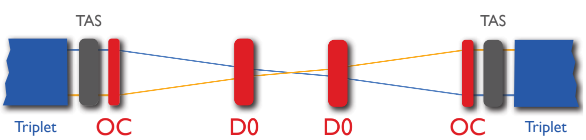

Figure 1: The Early Separation Scheme.

strongly entangled with beam dynamics considerations, issue of integrability in the detectors, magnet design optimization and power deposition scenarios. D0s at ~ 4 m [3] and ~ 8 m [4] from the IP have already been proposed. In this paper we focus on a less invasive version of the ES that assumes the D0's center at 14 m from the IP, corresponding to the ATLAS Forward Shielding region (JF) [5] and to the end of the CMS Hadron Forward calorimeter (HF) [6].

LUMINOSITY PERFORMANCE

The LHC Luminosity Upgrade is foreseen in two phases with the goal to increase the luminosity of a factor of two (Phase I [7]) and 10 (Phase II) with respect to the nominal performance.

Several Phase II scenarios are presently worked out, trying to define a hardware base that would be common to them. The foreseen new injector chain, in addition to an increase of the operation reliability and a decrease of the turn-around-time, can deliver to LHC a significantly brighter beam [8]. This has a large potential for the machine performance, but may touch a lot of the severe limitations of LHC (and SPS). Amongst them, the increased beam brightness will enhance the beam-beam effect, by increasing the head-on (HO) tune shift and the non linearities due to the parasitic encounters (LR, long-range). The ES (and, similarly, the crab cavities), decoupling the crossing angle (θ_c) from the beam separations in the triplet, can alleviate the LR interaction. In addition, thanks to the luminosity leveling [9], it reduces the HO tune shift of the collider and, at the same time, the detectors' pile-up and the power deposition in the triplet, with an overall gain on the collider's performance. In Table 1, a comparison between the nominal LHC (A),

Table 1: The Early Separation Scheme performance. See explanations in the text.

	WITHOUT ES			WITH ES		
	A	B	C	D	E	F
n_b [1]	2808	2808	2808	2808	2808	1404
N_b [10^{11}]	1.15	1.7	2.3	2.3	2.3	4.9
β^* [m]	0.55	0.25	0.2	0.2	0.2	0.2
ϵ_n[mm·mrad]	3.75	3.75	3	3	3	5
IS_{start} [σ]	9.5	9.5	9.5	13	13	18
IS_{end} [σ]	9.5	9.5	9.5	7	5	8
HO [10^{-3}]	6.3	6.4	9.2	9.2	10.2	10.1
Piwinski [1]	0.65	1.42	1.77	2.44	2.44	3.37
$\hat{L}$ [L_0]	1.00	3.32	8.1	6.28	6.28	6.39
$\overline{L}_{10h}$ [L_0]	0.39	1.01	1.95	2.13	2.30	2.27
$\overline{L}_{5h}$ [L_0]	0.50	1.33	2.69	2.93	3.16	3.13

Phase I (B), SLHC without ES (C) and SLHC with ES (D–F) scenarios are presented. From nominal LHC to Phase I the beam brightness increases by $\sim 50\%$, from the Phase I to the SLHC we assume a similar increase ($\sim 70\%$ for the 25 ns option, due to larger bunch charge, N_b, and smaller normalized emittance, ϵ_n). The β^* is reduced to 0.20 m with the entry face of the triplet at$L^* = 23$ m (with this L^* the hard limit of Nb_3Sn technology is $\beta^* = 0.15$ m, chromatic aberrations studies are on going). The IS_{start} and IS_{end} represents the beam separation between the IP and the D0, expressed in σ, at the start and at the end of the luminosity leveled flattop. The HO tune shift is computed assuming two head-on collision, while the Piwinski angle, $\frac{\theta_c \sigma_z}{2\sigma^*}$, is computed for the nominal rms bunch length, $\sigma_z = 75.5$ mm. The $\hat{L}$, $\overline{L}_{5h}$ and $\overline{L}_{10h}$ represent the peak luminosity and the average luminosity for at turn-around-time of 5 or 10 hours. The average luminosity of the presented ES scenarios is 5 to 8 times larger than the nominal one.

In the scenarios C–F, the total HO tune shift is kept $\lesssim 10^{-2}$. In the scenarios D–F, the parasitic encounters (BBLRs) effect can be alleviated with an average beam separation of 12 σ in the triplets. In Fig. 2, an example of beam separation patterns of the scenarios C (○) and D (●) is shown. From the beam-beam point of view the pattern are similar: the reduced separation encounters (6 LRs at 7 σ) move from the triplet (C) to the IP (in D). On the other hand, a larger integrated luminosity for a lower peak luminosity is provided by D with respect to C. The scenario

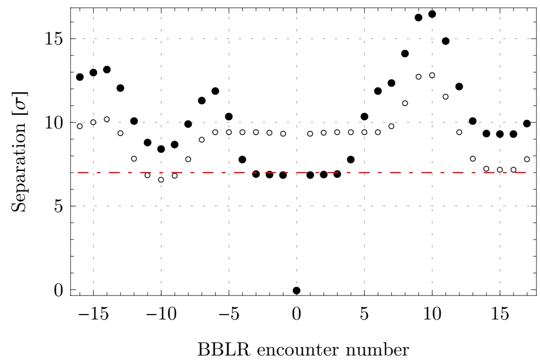

Figure 2: Comparison between an example of beams separation pattern of Table 1 scenarios C (○) and D (●).

F refers to the 50 ns option (it decreases the electron-cloud at the expense of a larger detector pile-up): the luminosity leveling and an increase of the normalized emittance to 5 mm·mrad can limit the HO tune shift without the need of longitudinal flat bunches.

The Requirement of the D0 Integrated Field

The magnetic field required for the D0 can be computed via the following equation

$$\left|\int_{D0} Bdl\right| = \frac{B\rho\;|IS - OS|}{2\,(s_{OC} - s_{D0})}\sqrt{\frac{\epsilon}{\beta^*}}\,s_{OC}$$

where the $B\rho$ is the beam magnetic rigidity, the s_{D0} and the s_{OC} represent, respectively, the distance of the D0's and OC's center from the IP ($s_{D0} < s_{OC} < L^*$), ϵ is the emittance of the beam and β^* the β-function at the IP (we assume round beam at the IP). The OS (Outer Separation) is the beam separation (expressed in σ) in the drift space between the OC and the first quadrupole of the triplet. The D0's integrated field is a factor s_{OC}/s_{D0} stronger that the OC's one. The magnet strength has to be increased proportionally to the beam divergence and to the difference between the OS and the IS. It decreases by increasing the D0-OC distance and/or by reducing the D0's distance from the IP. Assuming the OC'center at 21 m from the IP (e.g., integrated in the TAS), to have a minimum IS of 5 σ, an OS of 12 σ with a normalized emittance of 3.75 mm·mrad the needed integrated field for the D0 and the OC is shown in Fig. 3: 12 T·m for a β^* of 0.20 m.

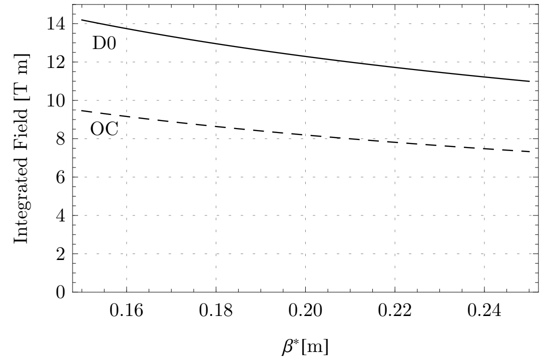

Figure 3: D0 and OC integrated magnetic field ($IS = 5\ \sigma$, $OS = 12\ \sigma$, $\epsilon_n = 3.75$ mm·mrad D0's center at 14 m and OC's center at 21 m from the IP).

POWER DEPOSITION

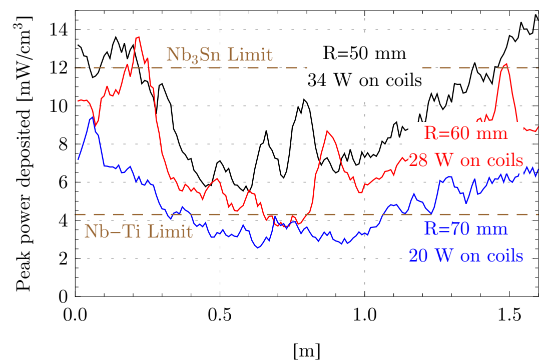

Figure 4: Power deposition result for an D0 aperture radius of 50, 60 and 70 mm (15 mm thick coils).

A power deposition study was performed using the FLUKA code [10] over a statistic of 10000 *pp* collisions. We made the following assumptions:

- the peak luminosity is 10^{35} cm^{-2}s^{-1};
- the divergence of the primaries, the crossing angle the detector solenoidal field are neglected;
- the superconductor is modelled in a 60° copper sector coil with aluminum collars' noses. A tungsten shielding of 150 mm thickness is added in front to the D0 starting at 13 m from the IP (start of the ATLAS JF, end of the CMS HF). No other elements of the detector or of the magnet is considered in the simulation. The D0's aperture ranges from 50 to 70 mm. The length and the field of the D0 is chosen to be compatible with the 13 m cryostat starting position and the 14 m D0' center assumption: this yields to a D0's coil length of ≈ 1.6 m (it starts at 13.2 m from the IP) and to a D0's field of ≈ 10 T (ideal dipolar field only in the D0'aperture without fringe effect due to the dipole's ends).

The peak power deposited in the coil ($\sim$ 12 mW/cm^3, Fig. 4) is above the Nb-Ti limit but is still compatible with a Nb_3Sn solution [11]. Increasing the radius has a beneficial effect since it reduces, on average, the peak power deposited and the total power deposited (Fig. 4). Liners are not used not to enhance the back scattering to the detectors.

A D0 with 60 mm radius appears adequate and, in order to cope with the peak power deposition and with the field required (≈ 10 T), the Nb_3Sn superconductor is required.

MAGNET DESIGN

Using the scaling laws of [12] and [13] (see Fig. 5), it is possible to conclude that, given the large aperture required, the D0 is limited by the mechanical stresses. The best solution for maximizing the D0 magnetic field is to use Nb_3Sn at 4.2 K with two layers cross-section ($\sim 30\%$ more integrated field than a single layer solution). The largest beam

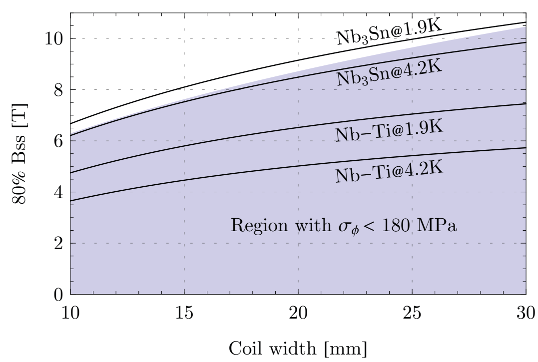

Figure 5: D0 field (80% of the short sample field) for different coil thickness, different superconductors a with respect to the mechanical limit of 180 MPa.

σ (scenario F of Table 1) is $\approx$ 1 mm at 15 m from the IP (end of the dipole): assuming, during the leveling a maximum IS separation of 20 σ and a beam halo of 10 σ this corresponds to a radius of the good field region of 20 mm: due to the large D0 aperture this can easily be achieved. A possible cross section is shown in Fig. 6. We considered the same 15 mm cable (30 strands of 1 mm diameter) for the two layers. To reach 10 T field in the aperture a 14.2 kA power supply is needed. The peak power deposition be-

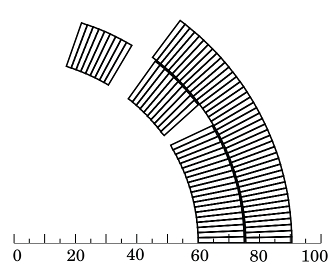

Figure 6: A possible cross section for the D0.

comes 12 W/cm^3 (inner layer) and 7 W/cm^3 (outer layer) with 56 W total deposited on the coils: the D0'coils heat load is thus a small fraction of the expected total heat load in the triplets. We cross-checked the scaling laws for the mechanical stresses with a FE model. As discussed in [13], these can underestimate the stresses. In fact, to keep them in the range $150 - 200$ MPa, the dipole field cannot exceed the 9 T: it is possible to reach the needed integrated field ($12 - 14$ T·m, depending on β^*) in a 2 m long cryostat.

CONCLUSION

An Early Separation Scheme with a D0 at 14 m from the IP has been considered. In addition to a less difficult integration, this proposal still has a significant impact on the luminosity performance of the collider: it increases by 20% the integrated luminosity reducing at the same time the peak luminosity by 30%, with a consequent reduction of the pile-up in the detector and of the dynamic heat load on the IR magnets. It decouples the beam crossing angle from the beam separation in the triplet, adding an useful degree of freedom during the machine operation. Additional integrated luminosity can be gained pushing to their expected limit the other machine parameters.

A tungsten shielding ring (150 mm thick) is used to reduce the power deposition on the D0 due to the debris coming from the IP: even considering a large aperture magnet (60 mm radius), Nb-Ti cannot cope with the expected peak power deposition. We presented a preliminary cos(θ) cross-section for Nb_3Sn at 4.2 K: it is limited to 9 T by the mechanical stresses ($150 - 200$ MPa). This solution offers a large temperature margin and can provide the needed integrated field within a 2 m long cryostat.

The author thank B. Bordini, F. Borgnolutti, F. Regis, E. Todesco and J.-P. Koutchouk for the fruitful discussions.

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