INVESTIGATIONS OF THE PARAMETER SPACE FOR THE LHC LUMINOSITY UPGRADE

J.-P. Koutchouk, CERN, Geneva, Switzerland.

Abstract

Increasing the LHC luminosity by a factor of ten is a major challenge, especially for the beam-beam long-range interactions and even more for the magnet technology and insertion layout. To help identifying consistent solutions in this multi-dimensional constrained space, a parametric model of an LHC insertion was prepared, based on the present LHC layout, i.e. "quadrupole first" and small crossing angle. The model deals with the layout, beam optics, beam-beam effect, superconductor margin and peak heat deposition in the coils. The approach is simplified to obtain a large gain in the optimization time. This study puts in evidence, as critical for the luminosity upgrade, the following actions: enlarging significantly the quadrupole aperture, moving the insertion towards the interaction point, using the highest available critical field superconductors and complementing the insertion with an early separation scheme. The luminosity reach can then be extended to 2×10^{35} cm^{-2}s^{-1} while 1×10^{35} can be obtained with significantly reduced requirements (lower beam currents, simpler RF system…).

INTRODUCTION

The goal of the LHC insertion upgrade is to increase the performance of the machine, ideally, by about a factor of ten [1]. The nominal parameters of the LHC being already very much optimized, a straightforward decrease of β^* to increase the luminosity, as often used in colliders, does not apply. β^* shall be a compromise between the luminosity increase by focusing and the luminosity loss due to the crossing angle that depends itself on β^*. The goal of this parametric insertion model is to explore rapidly in a suitably simplified way the luminosity upgrade parameter space: the beam optics, the long-range beam-beam effect, the collimation, the peak field in the quadrupole coil, the field margin with respect to the critical surface and the peak energy deposition. The added values of the model are both speed and consistency. This paper concentrates on the quadrupole-first class of insertions that includes the baseline LHC insertion.

THE PARAMETRIC MODEL

The parametric model is described in [2]. It is made of a fast optical matching module that finds an optical solution by adjusting the triplet gradient and the length of Q1 and Q2, and an evaluation module that computes the beam optics/dynamics parameters, the required quadrupole aperture and an estimate of the peak energy deposition. These modules are run iteratively to converge to a solution satisfying the beam dynamics and technical constraints. Since its first version, the parametric model was upgraded with:

- an adjustable bunch length,
- adjustable drift lengths between quadrupoles,
- the "hour-glass" effect, following the much reduced β^* functions obtained,
- a more realistic 10σ (instead of 9σ) required betatron aperture for collimation and triplet protection.
- new operating fields, appropriate for a ≥ 100 mm aperture quadrupole with strong grading [7]: the operating field at the inner coil diameter is taken to be 25% of the quench field (20% margin, 5% overshoot in the coil). The quench fields assumed are: Nb-Ti: 10 T, Nb-Ti-Ta: 11 T, Nb$_3$Sn: 15 T.

METHODOLOGY

In the following, the dependences of the luminosity $L[l^*, \phi_{coil}, B_{max}]$ on l^* distance of triplet to the IP, ϕ_{coil} inner coil diameter and B_{max} operating field are investigated for several scenarios of beam parameters, and crossing schemes. The goal being the maximization of performance, we use by default the ultimate LHC parameters defined in [1]: bunch charge of $1.7 \ 10^{11}$ p, 5616 bunches of length 3.7 cm (the nominal values are respectively: $1.15 \ 10^{11}$, 2808 and 7.5). The added-value of an early separation scheme [2][3] is investigated in two variants: full scheme for the nominal bunch spacing of 25 ns, allowing co-linear collisions and partial scheme with a crossing angle reduced by a factor of two. Departing from [2], only the linear chromaticity is corrected by the lattice sextupoles. In the search of very high performance, the second-order chromaticity is assumed to be controlled through the phase advance between crossings [4]. The conjecture on the scaling of energy deposition [2] being under study, we will only briefly mention this issue.

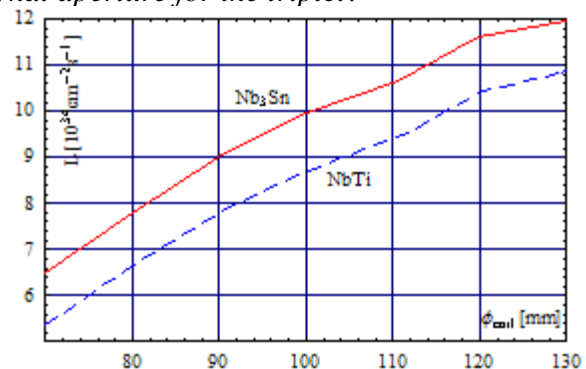## NO EARLY SEPARATION

What aperture for the triplet?

Figure 1: Luminosity [10^{34} cm^{-2}s^{-1}] versus inner coil diameter [mm] for l^*=19 m and ultimate beam current

For both superconductors, the luminosity gain when increasing the aperture from 70 mm to 130 mm is 85% (Figure 1). The operating field limit is controlled via the quadrupole length, with maxima of 9.5 m for Nb-Ti and 7 m for Nb₃Sn quadrupoles. In spite of a reduced compactness of the triplet, there is thus a definite yield to increasing the inner coil diameter. Beyond 130 mm, the correction of the linear chromaticity exceeds the lattice sextupole capability Aberrations remain small up to 100 mm and most likely acceptable above. Tracking is eventually needed to confirm the latter. The high initial luminosity for 70 mm Nb-Ti is only due to the ultimate beam current. Then the present Nb-Ti triplet is already well above its nominal quench limit (2.5 vs 1.6 mW/g).
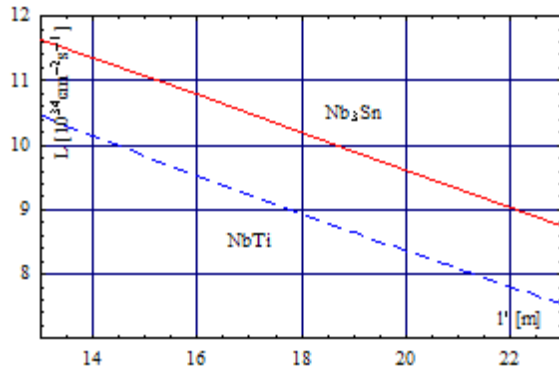
What distance to the IP?

Figure 2: Luminosity [10^{34} cm^{-2}s^{-1}] versus l^* [m] for ϕ_{coil}=100 mm and ultimate beam current

For both superconductors, the luminosity increases by 35% when the triplet is moved from the nominal position at 23 m to 13 m, that appears to be tentatively the closest position that can be contemplated [5]. The advantage of this scenario is to maintain the aberrations close to their nominal values. Notably the second-order chromaticity correction, in the l^* =13 m case, is within the range of the lattice sextupoles. The maximum quadrupole lengths demanded are 6 m for Nb₃Sn and 8 m for Nb-Ti.
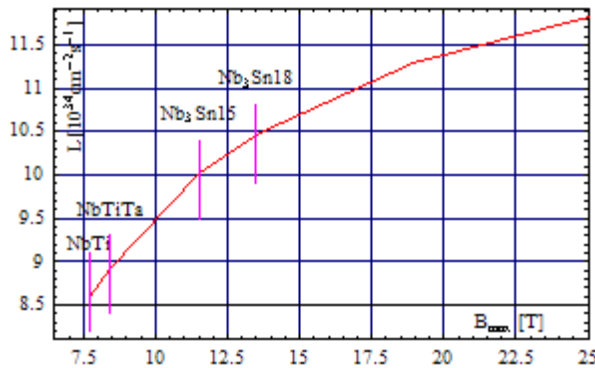
Which peak field in the coil?

Figure 3: Luminosity [10^{34} cm^{-2}s^{-1}] versus operating field [T] for l^*=19 m, ϕ_{coil}=100 mm and ultimate beam current; the index for Nb₃Sn is the quench field.

Once the distance to the IP and the coil diameter are better optimized, the incremental gain due to higher operating fields appears to become less important, though still significant (figure 3). This is a consequence of the geometrical loss factor that requires, at this level of performance, a simultaneous dedicated strategy of minimization. The early beam separation scheme [2][3] discussed in the next section is one of them.
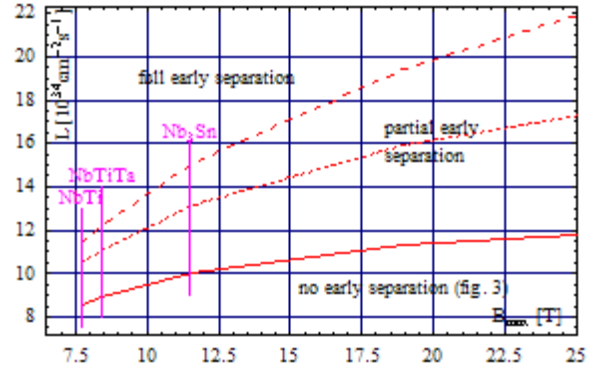
POTENTIAL OF AN EARLY SEPARATION

Figure 4: Luminosity [10^{34} cm^{-2}s^{-1}] enhanced by early separation versus operating field [T] for l^*=19 m, ϕ_{coil}=100 mm and ultimate beam current

An early separation scheme would allow colliding the beams at vanishing or reduced crossing angle [2][3], with a significant reduction of the geometrical luminosity loss. In presence of a low β*, the luminosity gain can exceed a factor of two with respect to the ultimate scenario that already includes a bunch length reduction by a factor of two. Figure 4 shows the actual gain due to increasing the operating field in presence of a full or partial early separation added to the ultimate scenario.

Similar large enhancements are noticed when increasing the inner coil diameter or decreasing the IP to triplet distance. Table 1 shows some examples of the luminosity enhancement due to an early separation.

Table 1: Luminosity [10^{34} cm^{-2}s^{-1}] versus crossing scheme for median and extreme cases and Nb₃Sn

ϕ_{coil}, l^* [mm,m]	No early separation	Partial early separation	Full early separation
100, 19	10.0	13.1	15.0
130 ,19	11.4	17.3	23.1
100, 13	11.6	17.2	22.1

HEAT DEPOSITION AND COLLIMATION

The energy deposition scaling law is on study by tracking. Its present formulation shows that the nominal quench threshold for Nb-Ti is exceeded in all scenarios while Nb₃Sn quadrupole could reach a luminosity of about 8×10^{34} cm^{-2}s^{-1} at the quench level assuming the increased tolerance by 3.5 given in [6].

If the LHC beam intensity would continue to be limited by the collimator impedance, the third power scaling of

the transverse impedance requires an enlargement of the triplet by about 10 mm to keep the upgraded beam stable. This extra requirement is not taken into account here, as there is hope that other collimator solutions would overcome this problem but has to be kept in mind.

EXAMPLES OF INSERTION SOLUTIONS

Table 1: Solutions with upgraded beam parameters; the luminosity is in unit of $L_0 = 10^{34}$ cm^{-2}s^{-1}

	Q' corrected				Q' and Q'' corrected		
$l*$	$\beta*$	ϕ_{coil}	L_{PES}	L_{NES}	$\beta*$	ϕ_{coil}	L_{PES}
m	m	mm	L_0	L_0	m	mm	L_0
13	0.087	126	20.5	12.2	0.14	97	16.3
19	0.124	130	17.3	11.4	0.195	100	12.9
23	0.15	131	15.3	10.7	0.25	105	10.5

Table 1 shows optimal Nb$_3$Sn solutions for an upgrade with partial or no early separation (PES, NES). The performance is limited by the strength of the lattice sextupoles and two chromaticity correction strategies are included. The 13 m solution with PES allows as much as two to four times the luminosity anticipated for the upgrade. The inner coil diameter is clearly best in the high part of the 100-130 mm range.

Table 2: Full early separation, nominal bunch number (2808) and nominal or reduced bunch length σ_s

$l*$	Np	$\beta*$	ϕ_{coil}	$L_{\sigma s/2}$	$L_{\sigma s}$
m	$10^{11}p$	m	mm	L_0	L_0
13	1.7	0.086	121	16.4	13.7
19		0.123	124	11.6	10.9
23		0.15	125	9.5	9.25
13	1.45	0.086	119	-	10
13	1.15	0.086	118	-	6.7

In Table 2 we investigate solutions that would compensate a limitation in beam current or bunch length. The FES and proximity to the IP can produce the target luminosity increase with only a 25% increase of the nominal beam current and even close to 7×10^{34} cm^{-2}s^{-1} with the LHC nominal beam and a 118 mm aperture.

POTENTIAL FOR FURTHER UPGRADES

Table 3 shows that yet another significant increase of performance is possible with superconductors showing significantly higher operating fields.

Table 3: potential of performance of LHC

B_{max} [T]	ϕ_{coil} [mm]	$\beta*$ [m]	L [10^{34}cm^{-2}s^{-1}]
24	114	0.066	41.1
18	117	0.075	25.6

CONCLUSIONS

In [2], we showed that the proposed solutions for the upgrade required in fact a higher performance superconductor, a somewhat larger quadrupole aperture

(100 mm) and a smaller IP to triplet distance (19 m). In this paper, we explored systematically the parameter space farther away from the solutions studied before, relaxing the constraint of the correction of the second-order chromaticity and without a-priori on implementation issues. This investigation confirms the former results as particular solutions of a larger space with the following salient features:

- With the assumed beam parameters of the upgrade [1], the luminosity reach can possibly be increased to 2×10^{35} cm^{-2}s^{-1} or the luminosity goal of 10^{35} cm^{-2}s^{-1} can be reached with less risks. It should be noted that the beam-beam limit is respected and no further increase of the beam current is involved.
- A full or partial early separation scheme is a key element for reaching the goals above.
- The next highest luminosity gain is obtained by enlarging the quadrupole aperture. An inner coil diameter of at least 100 mm is necessary. A diameter of 130 mm seems optimal and universal as it could be used whatever the insertion solution chosen. The maximum magnet length needed amounts to 7 m for Nb$_3$Sn.
- A large gain of performance is obtained by shifting the triplet from the present 23 m to 13 m from the IP.
- Nb$_3$Sn potentially offers a 30% (to 40% for 18T quench field) increase of luminosity with a potentially higher quench level versus energy deposition.
- The Nb$_3$Sn technology does not saturate the potential of LHC for a luminosity upgrade. Magnets with higher critical fields could allow up to 4×10^{35} cm^{-2}s^{-1}.

ACKNOWLEDGMENTS

REFERENCES

[1] F. Ruggiero *ed.*, LHC Luminosity Upgrade: A Feasibility Study, LHC Project Report 626, 2002.
[2] J.P. Koutchouk, Possible quadrupole-first options with β*<=0.25 m, Workshop CARE-HHH LHC-LUMI-05, Arcidosso, 2005.
[3] J.P. Koutchouk, G. Sterbini, An early beam separation scheme for the LHC, this conference.
[4] A. Verdier, Phase between IP's and non-linear chromaticity, LHC Project Note 103, 1997.
[5] P. McIntyre *et al.*, « Towards an optimization of the LHC interaction regions using new magnet technology", PAC 2005
[6] A.V. Zlobin et al., "Large-Aperture Nb$_3$Sn Quadrupoles for 2nd generation LHC IRs", EPAC2002, Paris, June 3-7 2002, p.2451
[7] L. Rossi, E. Todesco, About the electromagnetic design of superconducting quadrupoles in particle accelerators, submitted for publication.