Strong Focusing Insertion Solutions for the LHC Luminosity Upgrade

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Abstract

This paper shows that dealing appropriately with the geometrical loss factor opens the possibility of large luminosities with a lower beam current thanks to applying significantly stronger focusing. The peak luminosity potential is as large as 2×10^{35} cm^{-2}s^{-1} for the full upgraded beam current, with scope for achieving a luminosity of about 1×10^{35} cm^{-2}s^{-1} with reduced bunch current and/or increased bunch spacing. The required quadrupole aperture would need to be increased to about 125 mm.

INTRODUCTION

To help identifying consistent solutions in a multi-dimensional constrained space, a parametric model of an LHC insertion was prepared, based on the present LHC layout: "quadrupole first" and small crossing angle [1]. 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. The outcome [1] of a first sampling of the parameter space was to identify:

- An incentive to increase the quadrupole aperture to about 100 mm to gain luminosity,
- The need of the performance of Nb_3Sn to meet the announced parameters of the proposed solutions,
- An incentive to reduce the present distance l^* of the triplet to the crossing point to gain luminosity,
- The need for an early separation scheme to overcome the geometric luminosity loss.

The model has been upgraded and is used here to explore more systematically the parameter space. In this article, the focus is put on the potential ultimate performance of the LHC and on the identification of solutions providing high performance with a minimum increase of the beam current. The latter requires a significantly stronger focusing and appropriate control of the geometrical loss factor.

THE INSERTION MODEL

Modifications to the parametric model

The parametric model is described in detail in [1]. It is improved or modified in the following aspects:

- The required betatron aperture is increased from 9σ to 10σ to be consistent with the requirements of the baseline collimation, e.g. [2].
- The luminosity reduction due to the hour-glass effect is added owing to the low β^* values considered.
- the bunch length becomes a parameter (harmonic RF system),
- The operating magnetic fields are taken to be 75% of the quench fields (10T for NbTi, 15T for Nb_3Sn).
- The operational heat deposition limits are taken to be 0.5 mW/g for NbTi, 1.9 mW/g for Nb_3Sn.

These modifications lead to more demanding requirements than in [3]. This was felt to be acceptable as the goal of the study was to maximize performance.

Optimization Strategy

The quantity that is maximized is the *peak luminosity* even though the significant quantity for the experimenters is the integrated luminosity. This choice stems from the observation that accelerator physics allows a reasonable estimate of the peak luminosity. An estimate of the integrated luminosity would require a large number of assumptions of fault rates, availability of injectors, running policy, actual luminosity decay, etc. These are rather arbitrary, and not often verified in practice.

Ranges for the beam parameters

Three beam parameters are varied in ranges defined by their <u>nominal values</u> and the values considered for the feasibility study of the upgrade [3]. In addition, a smaller number of bunches is considered as well:

- Bunch intensity: $\underline{1.15\times10^{11}}$ p to 1.7×10^{11} p,
- Number of bunches: 1404, <u>2808</u> and 5616,
- Bunch length: 3.7 and <u>7.5</u> cm.

Design parameters

The design parameters are not changed during the optimization, given their considerable impact: interference with the experiment, choice of the superconductor:

- l^*: distance of the triplet to the crossing point,
- B_{max}: maximum magnetic field in the coil,

Optimization parameters

In the course of the optimization, the following parameters are adjusted:

- ϕ: inner coil diameter ,
- l_Q: length of quadrupoles,
- β^*: β-function at the crossing point
- Crossing angle

Constraints

- Maximum magnetic field of a given superconductor is respected, including the above-mentioned margin,
- Linear chromaticity is correctable using the installed lattice sextupoles,
- Head-on and long-range beam-beam limits are satisfied,
- The increase of the geometric aberrations is "reasonable".

Options

A change of parameters requiring an additional significant hardware system or modification is considered as an options: the early separation scheme [4] in its full (FES) or partial (PES) implementation and the bunch length reduction [3] by an harmonic RF system.

PARAMETRIC DEPENDENCES OF THE LUMINOSITY

Default parameters for the parametric study

The representation of a complex parameter space requires cuts for default values of some parameters. The default beam current and structure have their values assumed in [3]: 5616 bunches of 1.7×10^{11} protons each and the reduced bunch length of 3.7 cm. The default distance to the IP is 19 m as decided in CARE05. The default quadrupole aperture is 100 mm, i.e. 10 mm larger than in [3] and in line with the discussion in CARE05.

Luminosity versus quadrupole aperture

The quadrupole coil diameter range is chosen from 70 mm (baseline LHC triplet) to 130 mm. If the increased aperture is used to accommodate a corresponding increase of the beam size, the linear chromaticity correction limits to 130 mm the quadrupole aperture. It turns out that the Lorentz forces on Nb_3Sn limit the aperture to about the same value [5]. For a 70 mm aperture, the increase of luminosity shown in Fig. 1 is due to:

- The increased beam current (for a factor 4.4), and
- The combined effect of the optics (due to the reduction of l* from 23 m to 19m) and of the reduced bunch length (altogether for a factor 1.5).

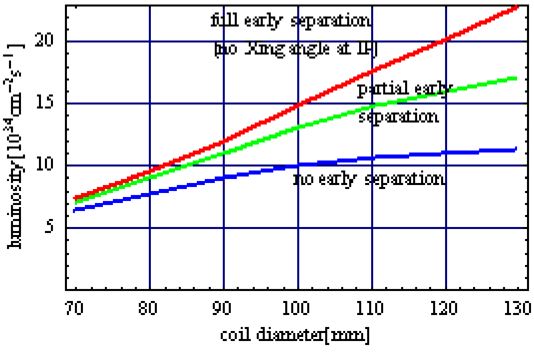

Figure 1: Luminosity potential with early separation

For the default parameters, the *potential* of luminosity increase is as much as a factor of 3 when increasing the aperture from 70 mm to 130mm. It is however believed that a full early separation scheme is not compatible with the experimental detectors. The partial early separation scheme under study would allow a luminosity increase by a factor 2.4. It should be noted that a crab cavity scheme is equivalent to the full early separation.

Luminosity versus distance to the IP

For the default parameters, the potential gain in luminosity is close to a factor of 2 when approaching the triplet from 23 m to 13 m. With an early separation scheme, the gain is about 50%. This family of solutions show the additional advantage of minimal chromatic and geometric aberrations (see Fig. 2).

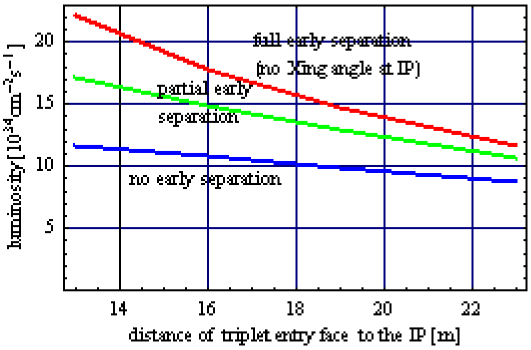

Figure 2: Luminosity vs. distance of triplet to the IP

Luminosity versus maximum field in the coil

For the default parameters, the potential luminosity gain due to the larger peak field of the Nb_3Sn superconductor is about 30%. This is due to a more compact design. The second important observation is that the LHC luminosity could be very significantly improved at constant beam current if even larger peak field could be provided (see Fig. 3).

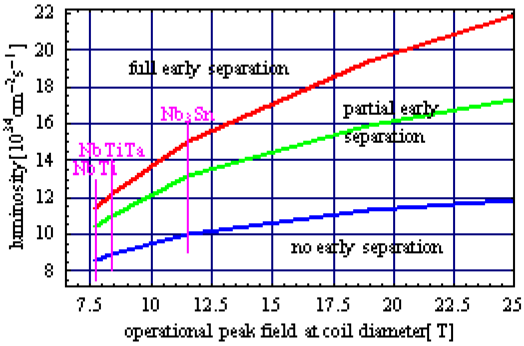

Figure 3: Comparison of luminosity potential with different superconductor technologies

Scaling of peak heat deposition from collision debris

For the default parameters, the luminosity and the ratio of estimated peak heat deposition to quench level are given in Table 1 for the Nb-Ti and Nb_3Sn technologies.

Table 1: Performance of Nb-Ti and Nb_3Sn

	Nb-Ti	Nb_3Sn	
Luminosity	8.6	10	[10^{34} cm^{-2}s^{-1}]
Heat/Quench	3.75	1.4	

The Nb_3Sn technology offers both higher luminosity and significantly higher thermal stability, even though an improvement is requested in both cases. These estimates are valid for continuous losses assuming the baseline LHC triplet performance for the heat removal from Nb-Ti quadrupoles and the US/LARP models for Nb_3Sn quadrupoles [6].

SOLUTIONS FOR VERY HIGH LUMINOSITY

Using the knowledge developed in the former chapter, all parameters were optimized to provide the largest possible peak luminosity. The calculation is made for the full upgraded beam current of [3], i.e. ultimate bunch current, 5616 bunches and a bunch length reduced by a factor of 2. The scenario assumes Nb_3Sn quadrupoles; their length is found in the range of 6 to 7 m. The luminosities are given for a partial (L_{PES}) or no (L_{NES}) early separation. The results are given in Table 2.

Table 2: Peak luminosity for full upgraded beam current

l^*	β^*	ϕ	L_{PES}	L_{NES}
[m]	[cm]	[mm]	[10^{34} cm^{-2}s^{-1}]	
13	8.7	126	20.5	12.2
19	12.4	130	17.3	11.4
23	15	131	15.3	10.7

The performance limit is set by the chromaticity correction. This optimization shows that it should be possible to increase the luminosity two to three times above the results given in [3] thanks to a much stronger focusing, the early separation scheme (or an equivalently efficient system such as the crab cavities) and significantly larger aperture quadrupoles.

It turns out that this luminosity appears too high to be handled by the upgraded detectors. This potential can however be put to good use following several strategies:

- reach 10^{35} cm^{-2}s^{-1} with the nominal bunch current,
- reach 10^{35} cm^{-2}s^{-1} without doubling the number of bunches,
- use a strategy of variable β^* to reduce the initial luminosity in a run and compensate to some extent the natural luminosity decay.

SOLUTIONS WITH REDUCED BEAM CURRENT

Rate of progress of collider performance

The above-mentioned very high luminosity solutions point out that their ingredients may be used instead to allow a significant luminosity while minimizing the upgrade of the beam intensity/pattern. The motivation stems from control room experience: the increase of the beam current couples simultaneously to all collider limits all around its circumference (collective stability, electron clouds, heat deposition, risks in case of beam loss…). As a result, the increase of performance relying on a current increase is generally much slower than that due to a local optical modification. A realistic prediction of the integrated luminosity must take this important factor into consideration. An interesting synthesis and parameterization of the performance progress of colliders is made in [7]. It relies on a complexity function that was estimated for the LHC upgrade based on a comparison with other hadron colliders [8]. Reasonably optimistic scenarios show that the luminosity increase by a factor of 10 will take 4 to 5 years if based on the beam current increase, as can be seen for example in Fig. 4.

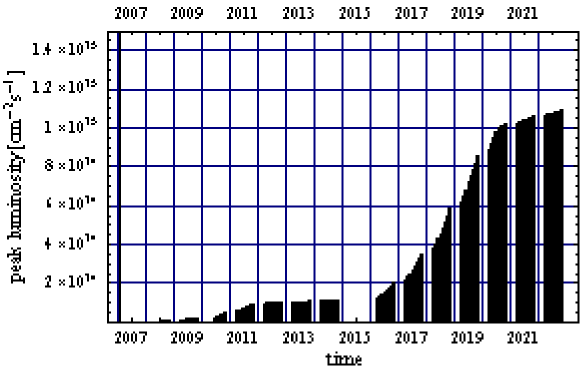

Figure 4: Expected peak luminosity increase for the reference upgrade

A meaningful comparison can be made with the ISR luminosity upgrade based on the first superconducting low-β insertion: the luminosity was increased by a factor of 7. From the dates of the publications, the time it took has to be less than 2 years and by memory probably less than one year. This was achieved in spite of a strong deficiency, i.e. an irreducible mismatch propagating in the whole machine and interfering with injection, accumulation,…The complexity [7] associated with this luminosity improvement is still at least 3 to 4 times smaller than an identical improvement from a beam current increase. An example from the Tevatron (see Fig. 5) shows a luminosity improvement by a factor 1.5 within months. Reinterpreted in terms of the complexity function [7], optics changes at the Tevatron yield performance improvement over two times faster than other improvements [9].

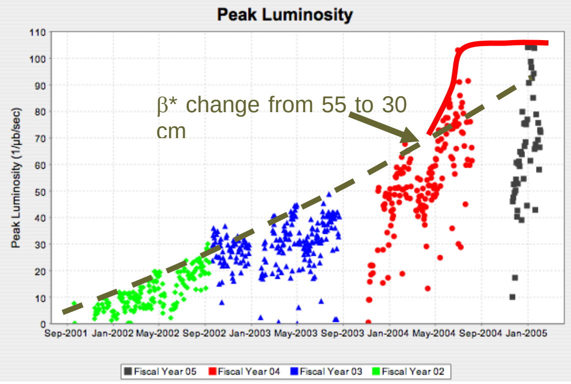

Figure 5: Luminosity increase following an optics change at the Tevatron; courtesy V. Shiltsev and E. Todesco.

Solutions with 25 ns bunch spacing

The performance of this family of solutions is evaluated for the nominal number of bunches (2808), the nominal bunch length (7.5 cm) and either the nominal or ultimate bunch current. The quadrupole aperture is assumed to be 120 mm and a practical partial early separation scheme is included. The results are given in Table 3. The last column gives the ultimate performance assuming reduced bunch length and full early separation or crab cavities.

Table 3: High performance is possible with reduced beam current and strong focusing

l^* [m]	β^* [cm]	N_p [10^{11} p]	L_{PES} [10^{34} cm^{-2}s^{-1}]	L_{max}
13	8.7	1.7	**7.5**	13.7
		1.15	**3.6**	6.2
16	10.7	1.7	**7.5**	12
		1.15	**3.6**	5.4
19	13	1.7	**7.3**	10.5
		1.15	**3.5**	4.9

For the practical scenario assumed, it is remarkable that the distance to the IP is neutral versus the luminosity. It has of course an impact on the aberrations. In this approximation however, the requirements on aberrations are fulfilled for all solutions. Tracking is needed to investigate this unexpected result. The potential or ultimate performance is however clearly improved by reducing the distance to the IP.

Solutions with 50 ns bunch spacing

A 50 ns spacing was lately suggested by the LHC experimental physicists. This large bunch spacing allows an almost full early separation scheme in a position where it is only partial for a 25 ns spacing. The corresponding gain in geometrical loss factor partially compensates the luminosity loss due to the reduced number of bunches. In this scenario much more favourable for beam stability, electron cloud and machine protection, the ultimate bunch current shall be assumed. Table 4 shows that reasonably large luminosities can still be reached.

Table 4: Performance for 50 ns bunch spacing

l^* [m]	β^* [cm]	ϕ [mm]	L [10^{34} cm^{-2}s^{-1}]	L_{max}
13	8.8	117	6.8	8.0
19	12.2	120	5.5	5.8

The luminosity estimates assumes a residual crossing angle necessary to obtain a sufficient beam separation at the first long-range encounter. The last column gives the maximum luminosity assuming halving the bunch length (or crab cavities). With a reduced number of bunches, the multiplicity increases accordingly to about 250. A bonus in integrated luminosity can be expected from this simpler and less demanding operations scenario.

CONCLUSION

The outcome of this study is to reveal the possibility of producing a significant increase of the peak luminosity by local modifications of the machine. These are optical (significantly stronger focusing) and long-range beam-beam related (another strategy to cross the beams). The current increase provides an option to further improve the luminosity and should allow reaching peak luminosities higher than can be accepted by the upgraded experimental detectors. This should make possible a staged approach to the luminosity upgrade, with some flexibility in choosing the scenario for given hardware - a useful feature given the unknowns. It may be possible to combine doubling the bunch spacing with a large increase in luminosity.

A second important observation is that a quadrupole of about 125 mm aperture is a common denominator for all presented solutions. For the Nb_3Sn technology, the triplet length is comparable to that of the baseline. The peak heat deposition is a common problem to all upgrade solutions. The characteristics of heat transfer from the conductors to superfluid helium favour Nb_3Sn technology due to its higher temperature margin. Using this material the luminosity can be increased by 30% for a 50% increase in gradient. However, while the LHC luminosity is limited by the performance of triplet quadrupoles, there is scope for further improvement at constant beam current.

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