# LHC IR UPGRADE: A DIPOLE FIRST OPTION WITH LOCAL CHROMATICITY CORRECTION*

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*Abstract*

In the framework of the LHC Luminosity Upgrade, we develop a new layout of the interaction region (IR) with $\beta^*$ equal to 25cm in which the combination-separation dipoles come first with respect to the triplet assembly (dipole first) in opposition of the nominal layout (quadrupole first). The new layout presents several advantages (separate channel for multipole error correction, straightforward crossing angle scheme with no crossing in the triplet, early separation of the beam). The payoff is a large $\beta$ function in the triplet, which enhances the chromaticity, non-linear effects and eats up aperture. We investigate options for local chromaticity correction and their effects on long-term stability.

## INTRODUCTION

The aim of the LHC luminosity upgrade is to increase the luminosity from $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by increasing the number of protons per bunch, increasing the number of bunches, reducing the longitudinal beam size and reducing $\beta^*$ by upgrading the insertion region [1].

The upgrade of the interaction regions (IR) of the main experiments ATLAS and CMS (IR1 and IR5 respectively) is expected to provide a $\beta^*$ of $25\mathrm{cm}$ increasing the luminosity by a factor 2.

The present layout, designed for $\beta^*$ of $55\mathrm{cm}$, is not able to provide a $\beta^*$ of $25\mathrm{cm}$ because the triplet quadrupoles cannot fulfill the required specifications on mechanical aperture. In addition the lifetime of the triplets is estimated to be limited to 7 years at the nominal luminosity due the radiation [1] coming from the IP. If no relevant changes in the design with respect to the radiation protection is performed, this time is reduced by an order of magnitude at the upgraded luminosity implying a triplet replacement on a year basis.

As an alternative to the present quadrupole first layout, we propose a new one, called dipole first layout [2], which should be able to incorporate an efficient absorber in the separation/recombination dipole assembly and to obtain a $\beta^*$ of $25\mathrm{cm}$ by taking advantage of new magnet technology. A dipole first layout is expected to ease the radiation protection issues as the first dipole can act as a open midplane spectrometer and absorbs the charged debris.

## LAYOUT AND OPTICS

The new layout has been designed to maintain all the LHC parameters, all the elements but the triplets and the separation-recombination dipoles in order to keep the cost of the upgrade as low as possible.

The new magnets require a new technology, such as magnets based on Nb3Sn superconductor material, because the necessary peak field at the coil is about 15T.

The radiation heat load and radioactivity issues can be reduced by the use of an open midplane type dipole [3] which acts as a spectrometer deflecting the debris in its own absorber before they reach the triplet quadrupoles.

A detailed computation of the heat load, though quite important for a realist design, have not been taken into account and will be addressed in further studies.

Figure 1 and 2 show the beam envelope and the collision optics of the new layout.

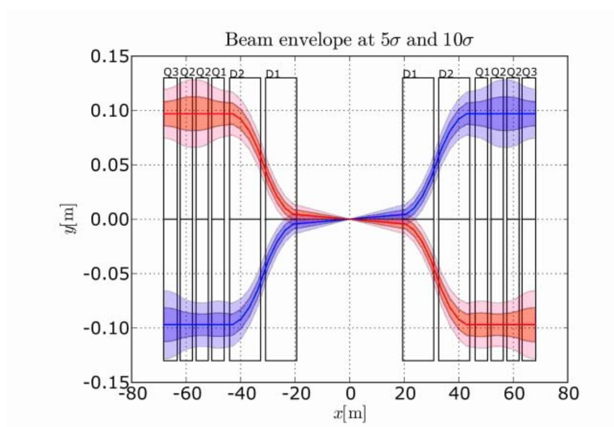


Figure 1: Beam envelope at $5\sigma$ and $10\sigma$.

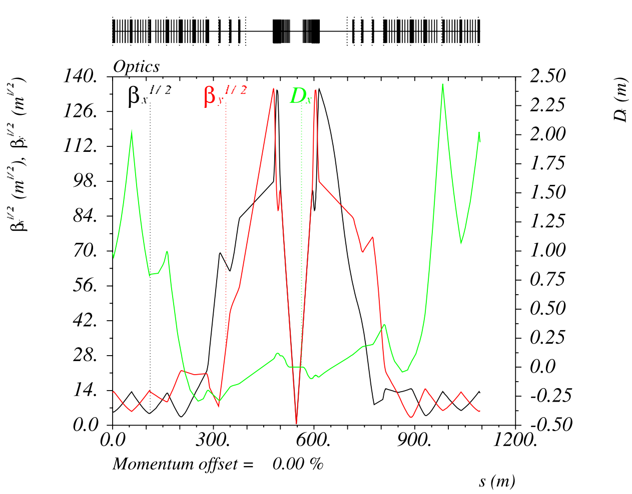


Figure 2: Collision optics for Beam 1.

Table 1 summarizes the main quantities of the layout.

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Table 1: Specifications of the dipole first layout.

| Mag. | Pos. | Length | Field | Inner D. |
|---|---|---|---|---|
| D1 | 19.45m | 11.4m | 15.0T | 0.130m |
| D2 | 32.653m | 11.4m | 15.0T | 0.080m |
| Q1 | 46.05m | 4.5m | 231.0T/m | 0.080m |
| Q2A | 51.87m | 4.5m | -256.6T/m | 0.080m |
| Q2B | 57.69m | 4.5m | -256.6T/m | 0.080m |
| Q3 | 63.25m | 5.0m | 280.0T/m | 0.080m |

A previous study [4] shows that the present layout fulfills the requirements imposed by the optics squeeze (Q5 excluded due aperture limitation), presents a good tunability and allows a smooth transition to the injection optics.

## CHROMATICITY

For the LHC the energy acceptance of ($\delta p/p = 0.8\,10^{-3}$) has to be preserved.

The chromaticity, tune dependence with energy $Q(\delta)$, is enhanced by high $\beta$ values and, if not properly corrected, can lead to a limitation of the energy acceptance. In addition a positive slope of $Q(\delta)$ is required in order to avoid the head-tail instability.

In the LHC there are two interleaved sextupoles families per arcs (MS) and a family of spool pieces sextupole correctors (MCS). They can be used to correct globally the first and the second order chromaticity and the off momentum $\beta$-beat [5].

For the correction of the linear part, all the sextupoles in the two families focusing and defocusing are equally powered. Also the spool pieces are used at the 70% of their nominal strength in order to reduce the strength of the main defocusing family.

For the correction of the second order chromaticity each family is powered individually, the first and the second order chromaticity are then calculated and minimized. Table 2 and 3 show the required sextupole strengths.

The margin in the sextupoles strengths can be still used for a compensation of the off-momentum $\beta$-beat.

Table 2: Required strengths of the arc sextupoles for the correction of the linear part of the chromaticity. All focusing and defocusing families respectively equally powered.

| Family | $k_2$ max | Strength |
|---|---|---|
| MS Defoc. | 0.380m$^{-2}$ | 68% |
| MS Foc. | 0.380m$^{-2}$ | 75% |
| MCS | 0.130m$^{-2}$ | 70% |

Table 3: Required strengths of the arc sextupoles for the correction of the linear and second order part of the chromaticity. The MS families are individually powered.

| Family | Average Str. | Max Str. |
|---|---|---|
| MS Defoc. | 68% | 74% |
| MS Foc. | 75% | 79% |
| MCS | 70% | 70% |

An attempt for a local chromaticity correction has been done. A set of sextupoles correctors is installed in front of each quadrupole magnet where a small dispersion (about 10cm) is present due the dipole first layout.

The local $\beta$-beating proportional to the chromatic function $W$ [6] is then minimized (Figure 4). The procedure minimizes the $\beta$-beating in all the machine and the chromaticity (Figure 3) is corrected with the help of the sextupoles families in the arcs.

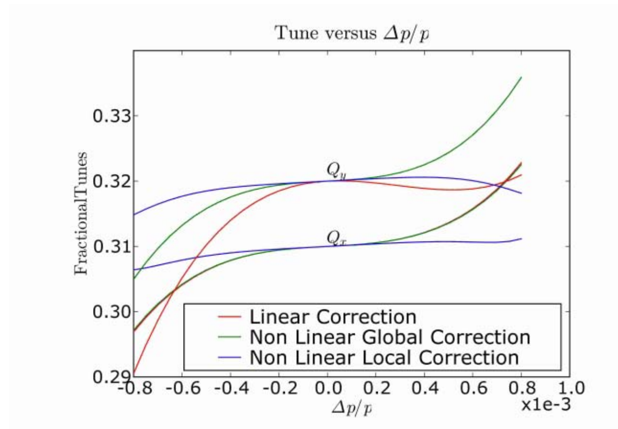


Figure 3: Horizontal and vertical chromaticity for Beam 1 after several correction options.

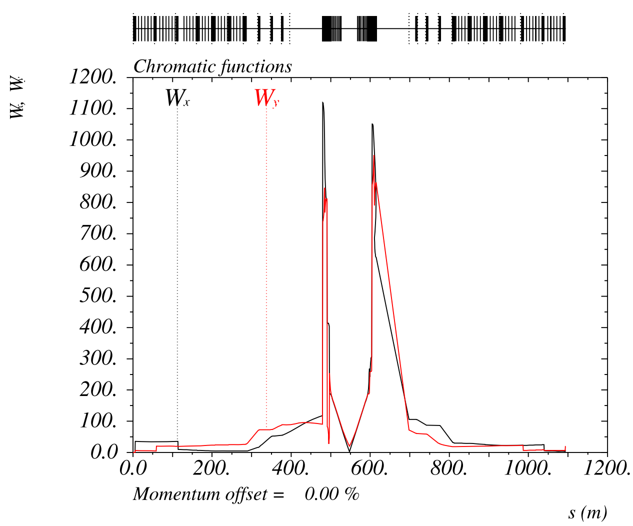


Figure 4: W function of IR5 after correction for Beam 1.

Table 4 shows the required strengths for the sextupole families in the arc. The local sextupoles require at maximum a sextupole integrated strength of about 6 times the integrated strength of one of the MS sextupoles. This field in the high $\beta$ region is sufficient to make the dynamic aperture almost vanish.

The dispersion at the triplet can be increased without wasting too much mechanical aperture and luminosity allowing the derivative of the dispersion to be different from zero. At the first order the required sextupole strength should scale with the dispersion, but this is not the case

Table 4: Required strengths of the arc sextupoles for the correction of the linear and second order part of the chromaticity with local chromaticity correction.The MS families are individually powered.

| Family | Average Str. | Max Str. |
|---|---|---|
| MS Defoc. | 27% | 31% |
| MS Foc. | 26% | 23% |
| MCS | 0% | 0% |

because the non linear terms, which are probably created by a second order dispersion, are dominant.

The exercise demonstrates that the local chromaticity correction requires a careful calculation of the non linear terms up the third order and that a naive layout is not sufficient for such a task. In the particular case in which the correction is effective, the dynamic aperture is spoiled.

A true Pantaleo-Raimondi scheme would be required but the available space of the insertion is not sufficient for creating the necessary phase advance for a complete cancellation of chromatic and geometric aberrations and therefore implies modifications that go beyond the IR region.

## DYNAMIC APERTURE

The dynamic aperture (DA) of the LHC at collision is dominated by the field quality in the high $\beta$ region, that is triplet and separation recombination magnets.

The tracking studies are performed with SIXTRACK using $60$ seeds and $10^5$ turns [2].

In the LHC the triplet is equipped with a corrector package used to minimize the Hamiltonian driving terms which are close to the working point.

Tracking studies for the nominal configuration shows that the minimum DA of LHC without triplet correction is about $13\sigma$.

The new layout, because of the high $\beta$ values, requires a careful definition of the field quality allowed in the triplet and the implementation of a correction scheme.

Tracking studies are on going in order to explore the parameter space (multipole errors) for the definition of the required field quality needed for such design.

A preliminary study using an ideal machine and the field quality of the present LHC triplet magnets (Figure 5) for the new ones shows that the minimum DA over $60$ seeds is about $2.7\sigma$ without correction. Scaling by a factor of $10$ the triplet errors shows an increase of the minimum dynamic aperture to $8.3\sigma$.

An efficient correction scheme or a better field quality is required to meet the specification of $10\sigma$. Tracking studies are on going for the dipole first layout with triplet correction.

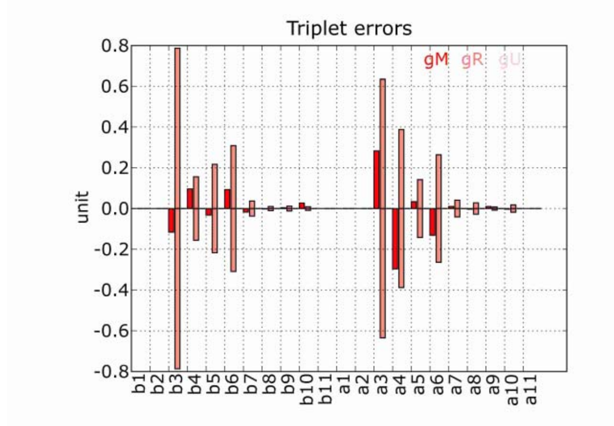


Figure 5: Triplet error used for DA studies."gM gR gU" stays respectively for mean, random, uncertainty of the geometric component of the multipole errors.

## CONCLUSION

The present layout, challenging in terms of magnet technology and beam stability, shows that its requirements in terms of field quality and chromatic aberration can be taken under control.

The arcs sextupole correctors have the required strength for compensating the first and the second order chromaticity with some additional margin for a beta-beating correction.

The low value for the dynamic aperture may probably be restored to the LHC requirements by a corrector package or a further improvement of the field quality. A tracking campaign for their definitions is on going.

Studies for the protection of the magnets, still missing, should investigate the options for the neutron flux protection and give a complete picture of the feasibility of this upgrade path.

## REFERENCES

[1] Francesco Ruggiero. LHC Accelerator R&D and Upgrade Scenarios. Technical Report LHC-Project-Report-666, CERN, August 2003.

[2] O. Bruening, et al. LHC Luminosity and energy upgrade : A Feasibility Study. Technical Report LHC-Project-Report-626, CERN, dec 2002.

[3] R. C. Gupta, et al. Optimization of open midplane dipole design for LHC IR upgrade. *Particle Accelerator Conference (PAC 05)*, may 2005.

[4] R. de Maria. LHC IR Upgrade: a Dipole First Option. To appear in HHH-Lumi05 proceedings, sep 2005.

[5] O. Bruening, et al. LHC Design Report. Technical Report CERN-2004-003, CERN, 2004.

[6] F. Christoph Iselin. The MAD Program Version 8.13 Physical Methods Manual, sep 1994.