

# LIMITS ON CHROMATICITY CORRECTION

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## Abstract

The LHC luminosity upgrade supposes from the point of view of the optics the upgrade of the Interaction Regions (IR) of the main experiments ATLAS and CMS. This upgrade is expected to provide a  $\beta^*$  of 25 cm instead of the 50 cm of the nominal one. This decreasing in  $\beta^*$  implies an increasing of the maximum  $\beta$  in the low- $\beta$  quadrupoles and subsequently a more difficult chromaticity correction. In this report we analyze the limits and possible strategies on the chromaticity correction for the different optics proposed for the upgrade of the IR.

## INTRODUCTION

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

The upgrade of the optics of the insertions, where the main experiments ATLAS (IR1) and CMS (IR5) are located, is expected to provide a  $\beta^*$  of 25 cm, i.e. half of the nominal  $\beta^*$ , increasing the luminosity by a factor of 2 approximately.

The nominal layout is not able to provide a  $\beta^*$  of 25 cm because the low- $\beta$  triplet cannot fulfill the required specifications on mechanical apertures. Furthermore the lifetime of the triplets is estimated to be limited to 9 years at the nominal luminosity due to the radiation coming from the IP.

There were different alternatives to the present quadrupole first layout. Table 1 summarizes the proposed alternatives, more information could be found in: [http://care-hhh.web.cern.ch/CARE-HHH/SuperLHC\\_IRoptics/IRoptics.html](http://care-hhh.web.cern.ch/CARE-HHH/SuperLHC_IRoptics/IRoptics.html).

## CHROMATICITY CORRECTION

The tune dependence ( $Q_{x,y}$ ) with  $dp/p$  or chromaticity is given:

$$Q_{x,y} = Q_{0x,y} + Q'_{x,y} \left( \frac{dp}{p} \right) + \frac{1}{2} Q''_{x,y} \left( \frac{dp}{p} \right)^2 + \frac{1}{6} Q'''_{x,y} \left( \frac{dp}{p} \right)^3 + \dots \quad (1)$$

where  $Q'_{x,y}$ ,  $Q''_{x,y}$  and  $Q'''_{x,y}$  are the first, second and third order components respectively of the two chromaticities.

In the LHC the first and the second order chromaticity, and the off-momentum  $\beta$ -beating are corrected globally by means of two interleaved sextupoles families, focusing and defocusing per arc (MS) and a family of spool pieces sextupole correctors (MCS). The families are equally powered and the maximum strength of these magnets are 0.38 and  $0.13 \text{ m}^{-2}$  respectively [2].

The chromaticity is increased by high  $\beta$  values, this means that the upgrade of the optics of the IR insertions, with a  $\beta^*$  of 25 cm, can be limited by the available sextupole strength of the nominal scheme. Figure 1 gives the natural chromaticity versus the  $\beta_{max}$  for the different optics of table 1. The limit is for natural chromaticities of  $Q'_{x,y} < -275$  or  $\beta_{max} > 20 \text{ km}$  ( for this set of options). Chromaticity with either flavor of dipoles first is 50-100% higher than with quadrupole first [3]. Chromaticity increases as the free space from IP to first magnet decreases [3] and [4]. The chromatic aberrations are comparable for

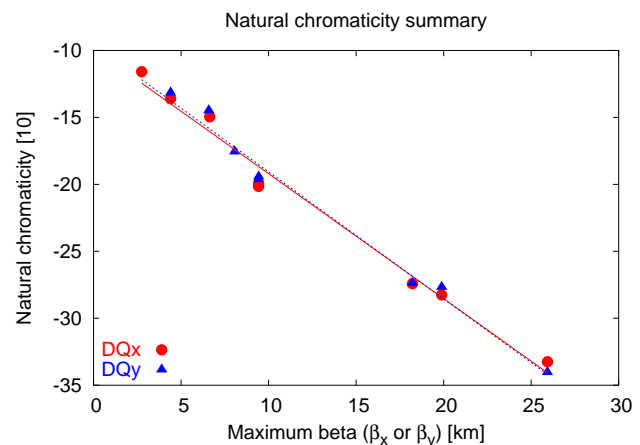


Figure 1: Natural Chromaticity versus  $\beta_{max}$  in low- $\beta$  quadrupoles.

all upgrade proposals [5].

The limitation on the chromaticity correction could be solved with two different approaches:

- local chromaticity correction
- global nonlinear chromaticity correction

## LOCAL CHROMATICITY CORRECTION

The natural way to compensate the chromaticity created by a low- $\beta$  insertion is the local correction. A complete

Table 1: Performance of LHC upgrade IR optics options.

Optics	Dipole first			Quadrupole first						units
	triplet	triplet	doublet	nominal	low-grad	triplet	flat	$Q_0$	crab	m
$\beta^*$	0.25	0.25	0.25	0.55	0.25	0.25	0.9/0.3	0.275	0.25	m
$L^*$	23.0	19.45	23.0	23.0	21.251	23.0	23.0	13.0	23.0	m
$\beta_{max}$	25.9	18.2	24.4	4.4	19.9	9.4	2.8/8.1	6.6	9.5	km
$Q'_x$	-332.5	-274.2		-136.0	-282.5	-199.9	-115.8	-149.5	-208.2	
$Q'_y$	-340.3	-273.7		-131.5	-276.7	-194.3	-175.6	-144.9	-203.3	
$\theta_{cross}$	400	400	400	225	400	400	225	692.2	8000	$\mu\text{rad}$
technologies	Nb <sub>3</sub> Sn	Nb <sub>3</sub> Sn	Nb <sub>3</sub> Sn	NbTi	NbTi	Nb <sub>3</sub> Sn	NbTi	NbTi	Nb <sub>3</sub> Sn	
$K_{1,max}$	200	280	200	220	70	200	220	220	200	T/m
$B_{max}$	13.4	15.1	13.4		8.7					T
$L/L_0$				1.0			1.18			

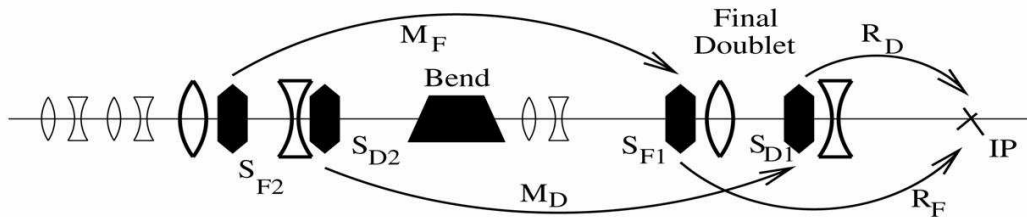


Figure 2: Optical layout of a FF for a LC including local chromaticity correction.

description of a local chromaticity correction for the Final Focus (FF) of a Linear Collider (LC) could be found in [6]. The basic scheme is made of two sextupoles interleaved with the low- $\beta$  quadrupoles (Final Doublet) and a bend upstream to generate dispersion across the low- $\beta$  quadrupole will locally cancel the chromaticity. The sextupoles generate geometric and chromatic aberrations, so two more sextupoles in phase with them and upstream of the bend, in a place where the dispersion,  $D_x$ , is zero, are required. A schematic is shown in Figure 2. The second order aberrations and third order geometric aberrations generated by the sextupoles must be corrected imposing certain conditions to the transfer matrices between the focusing  $M_F$  and defocusing  $M_D$  pairs of sextupoles, the transfer matrices between the sextupoles and the interaction point (IP)  $R_F$ ,  $R_D$  and the strength of the sextupoles. The angular dispersion at the IP,  $D'_x$ , is necessarily nonzero, but small enough to avoid the increase of the beam divergence. More information could be found in [6] and [7].

When we try to apply this kind of scheme to the LHC insertions, the main differences with respect to the LC are:

- momentum spread is two orders of magnitude smaller than in LC (less sensitivity of phase slippage of the off-momentum particles)
- beams are round (scheme is optimized for flat beams, vertical emittance is three orders of magnitude larger than in LC)
- insertions are anti-symmetric this could create problems with overcompensation in one part of the IP and

less compensation in the other part of the IP.

- non vanishing dispersion across the LHC IR insertions (dispersion has to be zero downstream the bending magnet, i.e. where the sextupoles for compensating the aberrations are located)
- no space available

these differences make very difficult to implement such a scheme on the LHC without carrying out modifications that go beyond the IR regions.

One first attempt of this kind of scheme with only two interleaved sextupoles in the low- $\beta$  quadrupoles for the upgrade of the LHC with a dipole first option is found in [8] and [10]. Dynamic aperture (DA) studies shows that the correction of the high order nonlinear aberrations are crucial. A complete system including two more sextupoles, at proper location, are necessary for a complete cancellation of chromatic and geometric aberrations. Same kind of scheme has been tested for quadrupole first option [9] without success.

Another attempt with four sextupoles for correcting the geometric and chromatic aberrations has been tried for the IR upgrade optics with a quadrupole first and crab cavities [11]. The optimization of the four sextupoles has been made with the code MAPCLASS following the recipe used in CLIC [12]. The results are also inefficient.

Furthermore a local chromaticity approach based in a scheme developed for SSC could be found in [4]. Initial results are promising but have to be confirmed by DA studies.

## GLOBAL NONLINEAR CHROMATICITY CORRECTION

The second approach that could be used for correcting the large chromaticity in the upgraded IR of the LHC is to correct globally the first and second order chromaticity, by using all the sextupoles in the families, focusing and defocusing, and the spool pieces but individually powered.

This method has been tested successfully for some of the LHC IR upgrade optics: optics with a dipole first scheme [8] and [10], optics with low-gradient quadrupole first option [9] and [5] and optics with quadrupole first and crab cavities [11]. In all the cases the arcs sextupoles correctors have the required strength for compensating the first and second order chromaticity with some additional margin for a  $\beta$ -beating correction.

## CONCLUSIONS AND OUTLOOK

The present layout of the IR upgraded insertions of the LHC are not suitable for an effective local chromaticity correction without a major modification of the insertions.

However the global nonlinear chromaticity using the existing sextupoles families and correctors individually powered is enough to correct the linear and second order chromaticity in most of the IR upgraded optics.

Furthermore DA studies for identifying the most dangerous multipole components in the triplet or doublet low- $\beta$  quadrupoles ( $b_6, b_{10} \dots$ ) and first dipoles ( $b_3, b_5 \dots$ ) could be very useful for doing a multipole compensation scheme to ameliorate the DA [13].

## REFERENCES

- [1] F. Ruggiero, "LHC Accelerator R&D and upgrade Scenarios," Technical Report LHC Project Report 666, CERN August 2003.
- [2] O. Bruening *et al.*, "LHC Design Report," Technical Report CERN-2004-003, CERN 2004.
- [3] T. Sen, J. Johnstone, V. Ranjbar and R. Tomas "Dipole First Option," these proceedings.
- [4] T. Sen, J. Johnstone, V. Ranjbar and R. Tomas "IR Upgrade with Quadrupoles First," these proceedings.
- [5] O. Bruening and R. de Maria "Low Gradient Triplets Magnets," these proceedings.
- [6] P. Raimondi and A. Seryi, "A Novel Final Focus Design for Future Linear Colliders," SLAC-Pub-8460 and LCC-0039, May 2000 and Phys. Rev. Lett. 86, 3779 (2001).
- [7] A. Seryi, "Discussion on Recipe for Design a Compact Final Focus," 26th Advanced ICFA Beam dynamics Workshop on Nanometre-Size Colliding Beams, September 2002.
- [8] R. de Maria, O. Bruening and P. Raimondi, "LHC IR Upgrade: a Dipole First Option with Local Chromaticity Correction," Proceedings of EPAC 2006, June 2006.
- [9] R. de Maria and O. Bruening, "A Low Gradient Triplet quadrupole layout compatible with NbTi magnet technology and  $\beta^* = 0.25\text{m}$ ," Proceedings of EPAC 2006, June 2006.
- [10] R. de Maria, "LHC IR Upgrade: Dipole First with Chromaticity and Dynamic Aperture Issues," these proceedings.
- [11] R. Tomas, R. Calaga, R. de Maria and F. Zimmermann "Crab cavity IR design with  $\Theta = 8\text{ mrad}$ ," these proceedings.
- [12] R. Tomas, H. Braun, D. Schulte and F. Zimmermann, "CLIC Final Focus Studies," Proceedings of EPAC 2006, June 2006.
- [13] A. Faus-Golfe and A. Verdier, "Multipole compensation in the LHC low- $\beta$  insertions," Proceedings of PAC 97, May 1997.