

LHC OPTICS WITH CRAB-WAIST COLLISIONS AND LOCAL CHROMATIC CORRECTION *

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Abstract

We report the status of the optics design for a local chromatic correction with extremely flat beams at the LHC. Together with a Large Piwinski angle, this optics opens up the possibility of crab-waist collisions at the LHC, for which a new layout of the LHC insertion region (IR) is needed. We present a complete optics, and discuss the parameters of the final “double-half” quadrupole.

INTRODUCTION

We are studying a novel LHC interaction region (IR), aimed at providing the high-luminosity experiments located in interaction points (IPs) 1 and 5, namely ATLAS and CMS, with a substantial luminosity increase after 10 or 15 years of LHC operation. One original ingredient of our IR design is the use of a large crossing angle. Though the latter reduces the geometric luminosity, it allows operation at much higher brightness, and, at the same time, it allows for a significant β_y^* decrease through a reduction in the length of the collision area. A second new component is a local chromatic correction in the vertical plane. The thereby accessible low values of β_y^* facilitate the use of flat beams, which in turn open up the possibility of introducing crab-waist collisions [1]. The latter suppresses the X-Y betatron resonances excited by the beam-beam interaction.

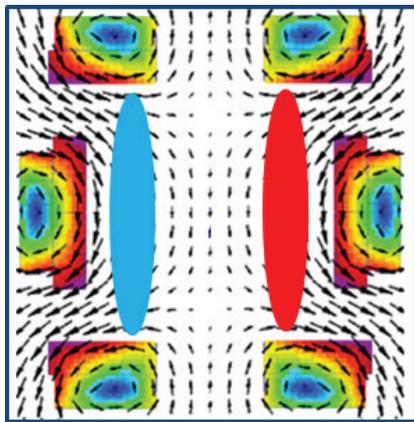


Figure 1: Maximum beam sizes in the DHQ represented as a $15\text{-}\sigma$ ellipse fitting into a square window of 80 mm side.

WORK PROGRESS

A ratio $\sigma_x^*/\sigma_y^* \geq 10$ is required to enable efficient crab-waist collisions [2]. Since the LHC beams are round, with equal emittances in the two planes, this condition translates into the extremely high β -ratio ($\beta_x/\beta_y=100$), which requires the use of a symmetric optics in the IR.

Previously we studied the IP beam parameters $\beta_x^*=1.5\text{ m}$, $\beta_y^*=1.5\text{ cm}$ [3, 4]. This low value of β_y^* induces a very large maximum β_y ($\sim 50\text{ km}$), resulting in a large chromaticity, which has proven difficult to correct locally, together with a local horizontal correction, without creating other noticeable aberrations.

In order to reduce the chromaticity, the $\beta_{x,y}^*$ values have been increased by about a factor 2.3, which allows a simplification of the chromatic correction, so that only the vertical chromaticity must now be corrected locally, while the horizontal chromaticity has become small enough to be corrected using the arc sextupoles.

The updated parameters are listed in Table 1, which also includes the previous values for comparison. In this table θ_c represents the full crossing angle and $\phi \equiv \theta\sigma_z/(2\sigma_x^*)$ the Piwinski angle.

Table 1: Parameters for Past [3] and New Flat LHC Optics

$\beta_{x,y}^*$	1.5 m, 1.5 cm	3.5 m, 3.5 cm
θ_c	4.0 mrad	2.6 mrad
ϵ_N	2.2–3.75 μm	2.2 μm
$\sigma_{x,y}^*$	15.2–26.0, 2.0–3.5 μm	32.1, 3.2 μm
σ_z	7.55 cm	7.55 cm
ϕ	9.9–5.8	3.1

DOUBLE HALF QUADRUPOLE

The first magnetic element, placed at 23 m from the IP, is a “double-half quadrupole” (DHQ) of 14 m length, which focuses both beams in the vertical plane inside a common aperture. Such DHQ is installed on either side of the IP. The element designed earlier [3] using the code ROXIE [5] is a combined function magnet which provides a combined dipole and sextupole field in a common aperture of 120 mm where the beams enter with an orbit offset of $x_c = 46\text{ mm}$.

Along with the new IP parameters the aperture of this magnet can be reduced from 120 mm to 80 mm. We also assume that the magnetic quadrupole and sextupolar field components can be made to drop each by 20%, at the location of the beam, as a consequence of the combined effect of the smaller aperture, modified magnet geometry, and

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the reduced crossing angle. The corresponding normalized gradients are $K_Q = 0.004 \text{ m}^{-2}$ and $K_S = 0.047 \text{ m}^{-3}$. Considering a normalized emittance of $\epsilon_N = 2.2 \mu\text{m}$, the maximum beam size in the DHQ is represented as a $15\text{-}\sigma$ ellipse with dimensions $a_x=6.7 \text{ mm}$, $a_y=38.5 \text{ mm}$ (Fig. 1). In this scheme, the inner normalized separation is $\sim 280 \sigma_x$, a factor 30 higher than for the present LHC.

IR OPTICS

The present final triplet has been substituted by a DHQ and three new superconducting quadrupoles located upstream, whose parameters are shown in 2. The optics for Beam 1 is shown in Fig. 2. It is a symmetric optics. For Beam 2, the β -functions are identical but the bending magnets have opposite sign, and so has the dispersion. The DHQ accomplishes a tight focusing of the vertical β -function with a maximum $\beta_y \approx 22 \text{ km}$.

Table 2: Parameters of the Final-Focus Double Aperture Quadrupoles (normalized gradient, length and aperture radius)

	K [T/m]	L [m]	a [mm]
quadr. 2	322	3.0	21
quadr. 3	275	4.0	9
quadr. 4	247	4.0	7

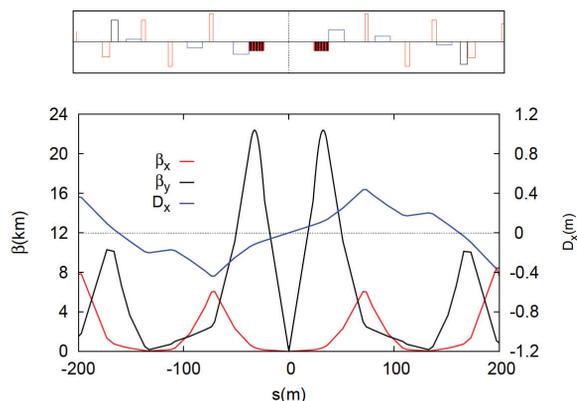


Figure 2: LHC flat-beam IR optics for Beam 1. Bending magnets are shown in blue, quadrupoles in red and sextupoles in black. The DHQ is shown in black and red stripes.

CHROMATIC CORRECTION

The vertical chromaticity, Q'_y , is compensated directly in the DHQ, making use of the large sextupole component and nonzero dispersion in this magnet. Specifically, the slope of the dispersion, D'_x , is non-zero at the IP, and its value has been matched so that the sextupolar component in the DHQ corrects the vertical chromaticity Q'_y .

One more sextupole at each side of the IP, placed in a zero dispersion region and with a phase advance of $\Delta\mu_x =$

π , $\Delta\mu_y = \pi$ from the center of the DHQ compensates most of the geometric aberrations.

Table 3 lists the total chromaticity for the LHC with the new IR introduced at IP1 and the present nominal IR (with $\beta_x^* = \beta_y^* = 0.55 \text{ m}$) in IP5. The total chromaticities are shown for the strengths of the focusing (k_{sf}) and defocusing arc sextupoles (k_{sd}).

Table 3: LHC Chromaticity of the Flat-Beam IR at IP1

k_{sf} [m^{-3}]	0	0.1035	0.1727
k_{sd} [m^{-3}]	0	-0.1709	-0.1833
Q'_x	-246	-107	2
Q'_y	-122	11	2

With all the arc sextupoles set to zero, the horizontal chromaticity Q'_x is much higher than the vertical Q'_y , because it is not locally compensated. The second column represents the case where the arc sextupoles are excited at the strength needed to correct the chromaticity in the present LHC to $Q'_x = 2$, $Q'_y = 2$. There is still a large residual Q'_x . This can be compensated by setting the sextupole strengths as shown in the third column.

If the new flat-beam IR is to be introduced in IP5 as well, the arc sextupoles alone cannot be excited strongly enough to correct the full horizontal chromaticity. Another correction scheme should then be used. Possible solutions include the Achromatic Telescope Squeeze [6], which creates a beta beating in the arc, thereby enhancing the effective sextupole strength, usage of the sextupole spool pieces in the dipole magnets, or a dedicated local correction for the horizontal plane in the IR region.

SEPARATION SCHEME

Three bending magnets are installed in place of the present LHC dipole separator magnets D1 and D2. Apart from separating the beams and providing the crossing angle at the IP, these bending magnets also bring the dispersion down to zero at the compensator sextupole. Their dipole length has been chosen equal to the one of the LHC bending magnets (14.3 m), and a technology similar to that of D2 can be used. Figure 3 compares the geometry of the new separation scheme with the existing one.

MATCHING

The LHC matching section is not flexible enough to match the highly perturbed β -functions to the values in the arc. The dispersion suppressor has, therefore, been used as well to match the IR optics to the arc, including the non-zero dispersion in the IR. As the matching is done from a symmetric (IR) to an antisymmetric optics (LHC arc), the matching sections from the IR to the arc on the left and right sides of the IP (Figs. 4 and 5) are asymmetric. In order to obtain a more regular optics, a quasi-symmetric matching has been proposed by modifying one or several arc cells [7].

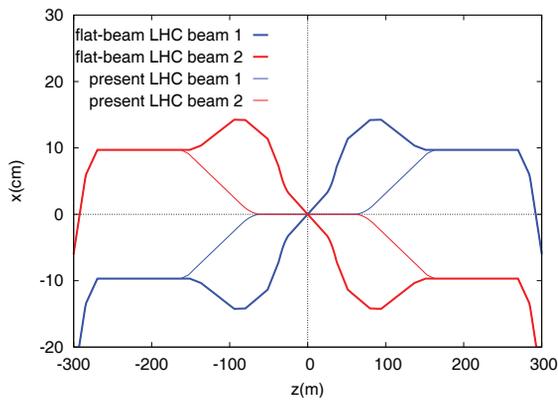


Figure 3: LHC reference orbits in the straight section for the new flat-beam optics, compared with the present LHC .

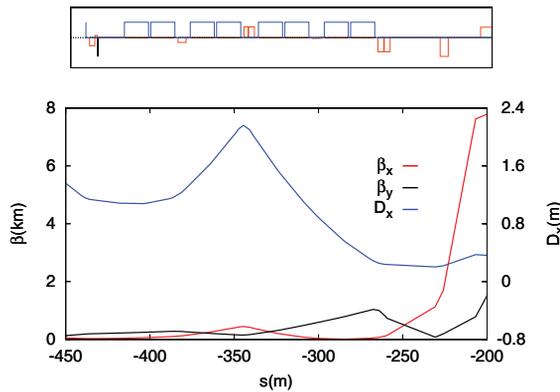


Figure 4: Matching section on the left side of IP1 for Beam 1.

LUMINOSITY

Figure 6 illustrates the peak luminosity and the beam-beam parameter as a function of bunch intensity for one interaction region. In case the flat-beam IR is substituted in both IP1 and IP5, as the crossing takes place in the horizontal plane in either IP, the values of ξ_x and ξ_y are doubled, still remaining below 0.01. For the present LHC, bunch populations above 3×10^{11} would not be possible at the

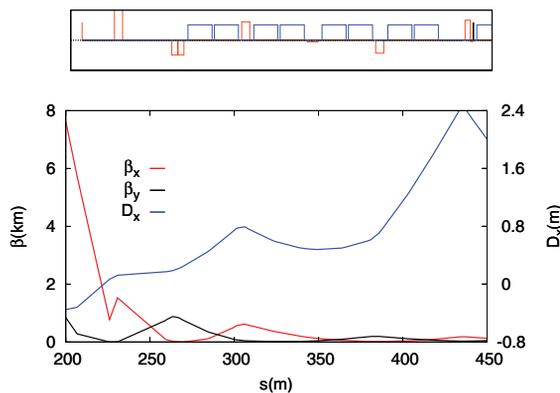


Figure 5: Matching section on the right side of IP1 for Beam 1.

same ϵ_N , due an excessive beam-beam tune shift.

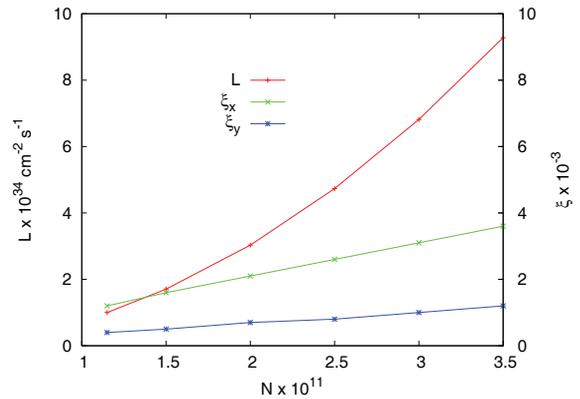


Figure 6: Luminosity and beam-beam tune shifts at one IP for $\epsilon_N=2.2 \mu\text{m}$ as a function of bunch population. For the luminosity calculation, the total number of bunches is taken to be 2808.

CONCLUSIONS

A conceptual design of a novel flat-beam IR for a possible future LHC upgrade has been presented, with a local chromatic correction in the vertical plane. The local vertical chromatic correction is realized by nonzero dispersion across the IR together with a large sextupolar field component of the first magnetic element on either side of the IP (a “double half quadrupole”).

This IR design could boost the LHC luminosity by an order of magnitude, making use of the available high-brightness beams by means of a large Piwinski angle.

The main issue here is the complete design of a new element, the DHQ, whose high order terms must be compensated in order to obtain a large dynamic aperture. Further studies will be carried out to determine the feasibility of this scheme. The beam-size ratio in collision has been chosen so as to allow for a crab-waist collision scheme, which can be realized through the introduction of a crab-waist sextupole magnet at either side of the IP.

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