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Optics studies based on V6.503 nominal configuration

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Summary

Optics studies based on the V6.503 nominal optics have been performed, aiming at improving the collimation efficiency by adjusting the phase advance from IP1 to IP5 to be π/2 off a multiple of 2π such that the off-momentum beta-beating is localized to the left side of the LHC ring. The off-momentum beta-beating in IR7 (betatron collimation section) is suppressed as expected. In addition to this main point, IR2 and IR8 injection optics are studied to improve the apertures of the inner triplet magnets. The aperture could be increased by either increasing beta* or improving the crossing scheme as proposed or both.

1. Introduction

In order to improve the collimation efficiency in the LHC, it has been investigated to adjust the phase advance from IP1 to IP5 to be π/2 off a multiple of 2π such that the off-momentum beta-beating is localized to the left side of the LHC ring and does not appear in the betatron collimation section IR7 (see also Ref. [1]). A new optics has been developed by modifying the latest nominal LHC optics V6.503.

2. Off-momentum beta-beating in the LHC

Off-momentum beta-beating is a delicate optics issue especially for the collision optics in which the beta* of IR1 and IR5 are squeezed to 0.55 m. The small beta* values with rather long straight sections (~50 m) accommodating the ATLAS and CMS physics detectors result in a beta function of more than 4000 meters at the inner triplet magnets. The off-momentum optics is then distorted due to mainly the chromatic aberration at the inner triplet magnets of IR1 and IR5.

The collimation efficiency would be largely affected by the off-momentum beta-beating as halo particles having momentum error could directly hit at the secondary collimators in the betatron collimation section IR7.

3. Optics modification

A possible strategy to improve the efficiency of betatron collimation is to adjust the phase advance from IP1 to IP5 to be π/2 off a multiple of 2π in order to close the off momentum beta-beating bump at IP1 and IP5 (the left triplet of IP1 and the right triplet of IP5 in an exact sense).

To accomplish this, the phase advances of IR2, IR3, IR4, IR6, IR7 and IR8 are modified. IR3, IR4, IR6 and IR7 will have constant optics from the beam injection to collision. IR2 and IR8 optics will be manipulated with pre-squeeze and squeeze, but the phase advance will be constant. It is worth recalling that the pre-squeeze is needed to reduce the triplet quadrupoles' strength from about 222 T/m to the below the nominal value to 205 T/m.

Due to shortness of flexibility in horizontal phase advance, the phase advances of Arc 2-3, Arc 3-4, Arc 6-7 and Arc 7-8 are also slightly modified. Table 1 summarizes the phase advances of these parts for the nominal optics and the new optics.

It is worth mentioning that the unwanted phase advance split between Beam1 and Beam2 are eliminated as much as possible as seen in Table 1.

Table 1: Phase advances of the nominal optics and the new optics.

V6.503 – collision

Beam1

	IR1	IR2	ARC23	IR3	ARC34	IR4	IR5	IR6	ARC67	IR7	ARC78	IR8	IP5	LHCB1
MUX	2.633	2.986	5.499	2.261	5.527	2.045	2.633	2.015	5.499	2.450	5.527	3.183	31.98	64.31
MUY	2.649	2.809	5.098	1.905	5.073	1.941	2.649	1.780	5.099	1.924	5.074	2.974	29.65	59.32

Beam2

	IR1	IR2	ARC23	IR3	ARC34	IR4	IR5	IR6	ARC67	IR7	ARC78	IR8	IP5	LHCB2
MUX	2.633	2.991	5.527	2.260	5.499	2.125	2.633	2.015	5.527	2.489	5.499	3.059	32.06	64.31
MUY	2.649	2.844	5.074	1.990	5.099	1.934	2.649	1.780	5.073	2.003	5.098	2.782	29.76	59.32

New optics – collision

Beam1

	IR1	IR2	ARC23	IR3	ARC34	IR4	IR5	IR6	ARC67	IR7	ARC78	IR8	IP5	LHCB1
MUX	2.633	2.986	5.583	2.272	5.612	2.13830	2.633	2.011	5.415	2.48474	5.442	3.048	**32.25**	64.31
MUY	2.649	2.809	5.098	1.990	5.073	1.95797	2.649	1.780	5.099	2.04603	5.074	2.750	**29.75**	59.32

Beam2

	IR1	IR2	ARC23	IR3	ARC34	IR4	IR5	IR6	ARC67	IR7	ARC78	IR8	IP5	LHCB2
MUX	2.633	2.986	5.612	2.272	5.583	2.13749	2.633	2.011	5.442	2.48552	5.414	3.048	**32.25**	64.31
MUY	2.649	2.809	5.074	1.990	5.099	1.95722	2.649	1.780	5.074	2.04677	5.098	2.750	**29.78**	59.32

3.1 Off momentum beta-beating

Figure 1 shows the off-momentum beta-beating of the new optics computed with the momentum deviation of +0.001. As expected, the beating appears between IP1 and IP5, but is almost zero in the rest of the ring. Although the beta-beating in the momentum collimation section IR3 is maximized, it would be at an acceptable level [2].

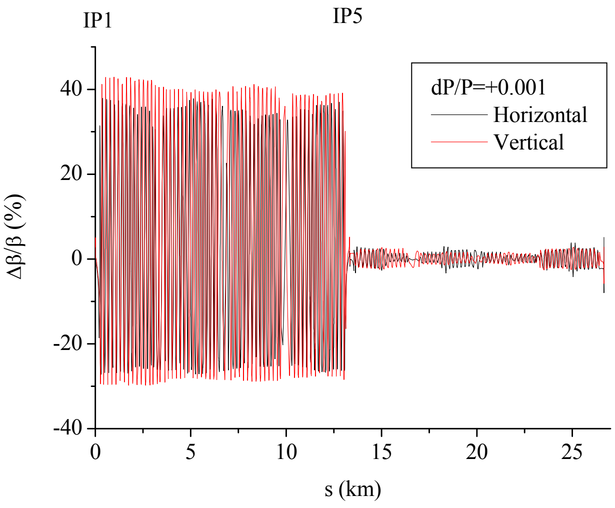

Figure 1: Off momentum beta-beating with π/2 phase advance (Beam 1).

3.2 Aperture

The beam aperture of the new optics has been checked and compared with the corresponding situation for the nominal optics. For most locations the situation is comparable. However, there are sizeable aperture deteriorations in IR3 Beam1 at MQ.11L3 (a defocusing quadrupole) with $n_1 = 6.60$ ($\Delta n_1 = -0.10$) and MQ.8R3 (a defocusing quadrupole) with $n_1 = 6.62$ ($\Delta n_1 = -0.19$). These aperture bottlenecks require orbit tolerance at the level of ~3.5 mm, which is tighter than the nominal value of 4 mm at injection energy. The aperture of IR3 Beam2 optics has comparable aperture bottlenecks both in the nominal and new optics. Therefore the better orbit control is needed in IR3 anyway. It is worthwhile quoting the visible improvement in the aperture of MQ.11R3 (a focusing quadrupole for Beam 1) where $n_1 = 6.59$, $\Delta n_1 = 0.067$.

3.3 IR3 and IR7 optics

The matching of IR3 optics seems to be harder than in the nominal configuration because of the new arc phase advance. The optics in the long straight section for Beam2 is slightly modified to ease the matching but the change should be negligible as shown in Fig. 2.

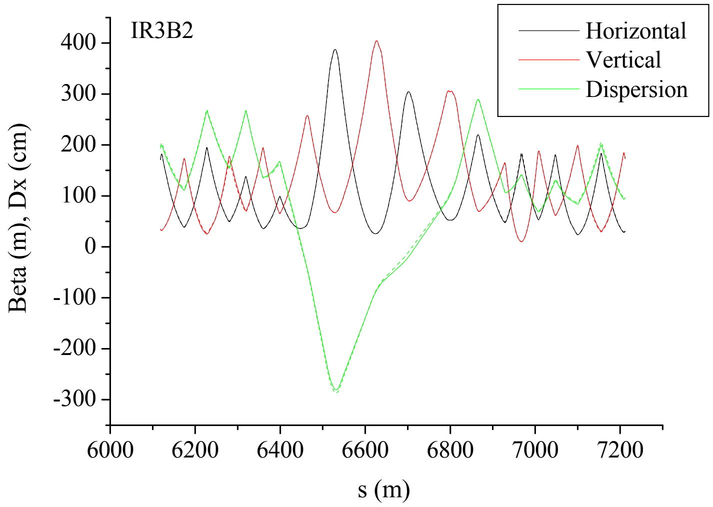

Figure 2: IR3 Beam2 optics. Dotted lines indicate the nominal optics and solid lines the new optics.

In IR7, the dispersion function is preferred to be zero in the long straight section for betatron collimation, but this is not realized already in the IR7 Beam1 nominal optics. In the new optics it was attempted to make it as small as possible. The aperture for Beam 1 at MCBV.10R7 (a defocusing quadrupole) is, however, connected with the value of the dispersion in the long straight section. Indeed, the closer is the dispersion to zero the worse is the aperture at this corrector magnet. A compromise between the dispersion and the aperture has been made namely Dx = -9 cm at Point 7 and n_1 = 6.64 at the magnet location. Figure 3 shows the proposed optics for Beam1 in IR7.

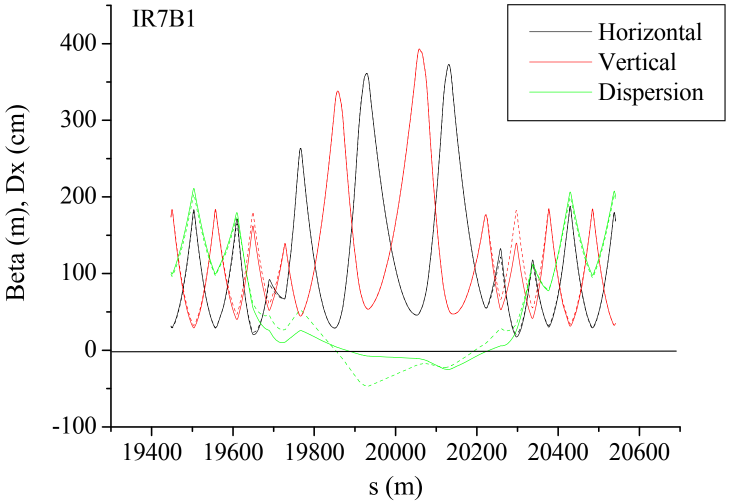

Figure 3: IR7 Beam1 optics. Dotted lines indicate the nominal optics and solid lines the new optics.

3.4 IR2 and IR8 injection optics and crossing scheme

When Beam 1 and Beam 2 are separated with certain crossing angle at IP2 and IP8 during the beam injection, the aperture at a location in between the Q1 and Q2 magnets becomes problematically small (typically n_1~6.4) because of the separation and crossing bump orbit plus the maximum beta function at Q2 (see Ref. [3]). This is a common optics issue both for the nominal optics and the new optics discussed in previous sections, and the results shown in this section are for the nominal optics.

To overcome the aperture problem, it is proposed to introduce a transverse shift of the crossing point [4] and an orbit tilt in the parallel separation. Beam1 and Beam2 have the same tilt such that the parallel separation is kept. Thus the beam-beam effect will not be largely affected. The apertures at the known bottlenecks are effectively improved through these treatments. Figure 4 shows the changes of the bump orbit in IR2 for Beam1 and Table 2 summarizes the aperture improvement.

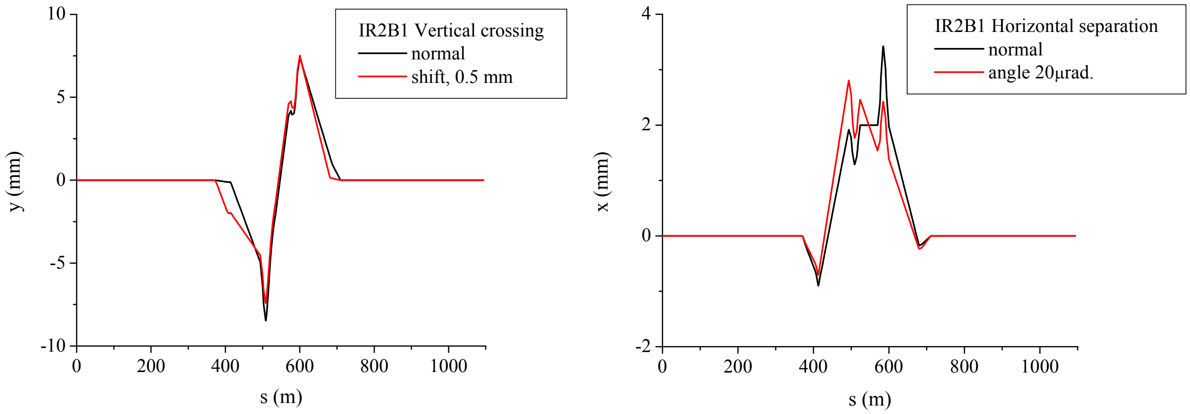

Figure 4: Crossing and separation bump orbit with and without transverse shift and tilt. It is clearly seen that the peak bump orbit is effectively reduced for the proposed crossing scheme.

Table 2: Aperture improvement with the shift and tilt to the crossing and separation scheme. n_1 is computed including crossing and separation bumps and spurious dispersion from the other insertions. The markers represent aperture bottlenecks in between Q1 and Q2.

	n_1 at VSSL.2L2/8.A	n_1 at VSSL.1R2/8.B	tilt / shift at IP
IR2 Beam 1	6.49→6.78 (D)	6.45→6.96 (F)	20 μrad / 0.5 mm
IR2 Beam 2	6.47→6.97 (F)	6.49→6.78 (D)	20 μrad / 0.5 mm
IR8 Beam 1	6.41→6.79 (D)	6.52→7.00 (D)	15 μrad / 0.7 mm
IR8 Beam 2	6.46→6.92 (F)	6.33→6.72 (F)	15 μrad / 0.7 mm

Yet another aperture improvement can be made by increasing beta* of which is 10 m in the nominal injection optics. Table 3 summarizes the aperture improvement obtained when beta* is increased up to 11 m. The optics with the beta* of 11 m are generated for this study.

Table 3: Aperture improvement by increasing the beta*. n_1 is computed including crossing and separation bumps and spurious dispersion from the other insertions. The markers represent aperture bottlenecks in between Q1 and Q2.

	n_1 at VSSL.2L2/8.A	n_1 at VSSL.1R2/8.B	Beta*
IR2 Beam 1	6.49→6.76 (D)	6.45→6.72 (F)	10 m → 11 m
IR2 Beam 2	6.47→6.74 (F)	6.49→6.77 (D)	10 m → 11 m
IR8 Beam 1	6.41→6.68 (D)	6.52→6.80 (D)	10 m → 11 m
IR8 Beam 2	6.46→6.74 (F)	6.33→6.60 (F)	10 m → 11 m

Obviously, the combination of these two improvements maximizes the aperture as summarized in Table 4.

Table 4: Aperture improvement with the shift and tilt, and increasing the beta*. n_1 is computed including crossing and separation bumps and spurious dispersion from the other insertions. The markers represent aperture bottlenecks in between Q1 and Q2.

	n_1 at VSSL.2L2/8.A	n_1 at VSSL.1R2/8.B
IR2 Beam 1	6.49→7.08 (D)	6.45→7.27 (F)
IR2 Beam 2	6.47→7.27 (F)	6.49→7.08 (D)
IR8 Beam 1	6.41→7.10 (D)	6.52→7.30 (D)
IR8 Beam 2	6.46→7.23 (F)	6.33→7.02 (F)

In the optics with increased beta*, the overall aperture in IR2 and IR8 is better than that for beta* = 10 m since the optics gets more "natural state" with the less squeezed beta*. On the other hand, the injection constraints such as the phase advance between the injection kicker and the collimators are slightly deteriorated, and a re-matching of the injection line is necessary. Figure 5 shows a comparison of aperture for the nominal and the proposed optics with increased beta*. Table 5 shows the phase advances between injection devices and the optics at injection point.

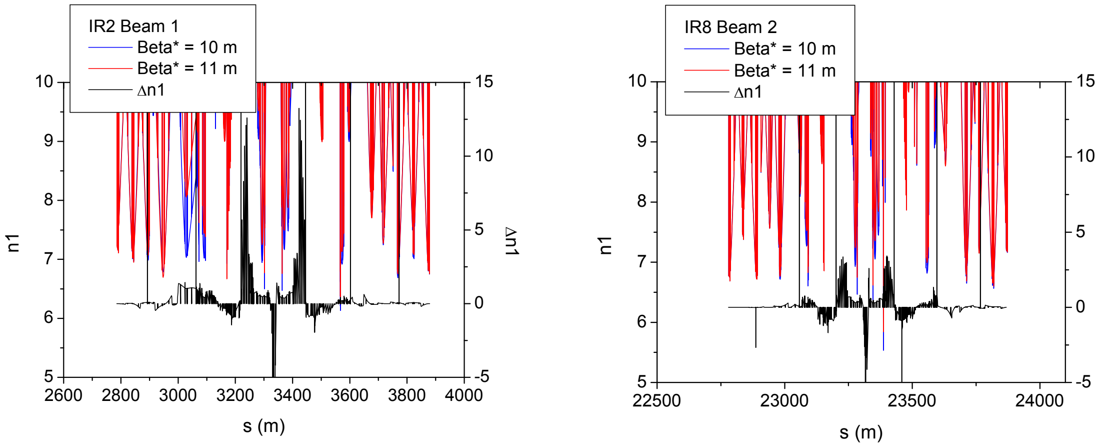

Figure 5: Aperture comparison for beta* = 10 m (blue) and 11 m (red).

It is worth recalling that the nominal values of the phase advance between MKI-TDI, TDI-TCLIA, TDI-TCLIB, was required to be 90° and an integer multiple of 180°±20°, respectively as from Ref. [5]. These values were finally changed to cope with integration issues. The nominal values of the phase advance between MKI-TDI, TDI-TCLIA, TDI-TCLIB, should be 90°, 180°+30°, 360°-30°, respectively [6].

Table 5: Phase advance between injection elements and optics conditions at injection point.

IR2 injection optics

	Vertical phase advance (deg)		
	MKI to TDI	TDI to TCLIA	TDI to TCLIB
beta* = 10 m	93.7	180+18.7	360-29.7
beta* = 11 m	90.8	180+20.5	360-29.5

	Optics at injection point (MSI.EXIT.B1)					
	Beta x (m)	Alpha x	Beta y (m)	Alpha y	Dx (m)	Dpx
beta* = 10 m	127.4	-1.86	71.5	1.76	-0.143	-0.0028
beta* = 11 m	130.0	-2.08	68.0	1.57	-0.137	-0.0030

IR8 injection optics

	Vertical phase advance (deg)		
	MKI to TDI	TDI to TCLIA	TDI to TCLIB
beta* = 10 m	85.8	180+23.6	360-29.6
beta* = 11 m	83.0	180+25.8	360-29.5

	Optics at injection point (MSI.EXIT.B2)					
	Beta x (m)	Alpha x	Beta y (m)	Alpha y	Dx (m)	Dpx
beta* = 10 m	123.5	1.26	89.4	-1.67	-0.136	0.0022
beta* = 11 m	129.0	1.49	89.4	-1.59	-0.132	0.0023

4. Summary

A new optics having the phase advance of $\pi/2$ off a multiple of 2π has been developed aiming an improvement of the collimation efficiency. The optics of IR2, IR3, IR4, IR6, IR7 and IR8 together with the arcs 2-3, 3-4, 6-7 and 7-8 are modified to adjust the phase advance. The off-momentum beta-beating in IR7 (betatron collimation section) is suppressed as expected. The off momentum beta-beating in IR3 (momentum collimation section) is maximized to about 40%, but it would be still an acceptable level.

The aperture of the ring has been checked and is comparable to the nominal optics at the most of the locations except for the IR3 Beam1 optics, and this requires a better orbit control. The aperture of IR3 Beam2 optics has comparable aperture bottlenecks both in the nominal and new optics. Therefore the better orbit control is needed in IR3 anyway.

The persisting optics issue, that is, the aperture at IR2 and IR8 triplet when Beam 1 and Beam 2 are separated during the beam injection can be overcome by introducing shift and tilt into the crossing scheme. Increasing the beta* from 10 m to 11 m also improves the aperture. However, the latter change would require a re-matching of the optics of the injection line and a verification that the new phase advance are acceptable for maintaining the protection function of the collimation in the injection region. The study of the crossing scheme has been performed for the nominal optics but it is in principle applicable to the new optics as well.

The new optics deserves to be tested with collimation simulations or directly with MD.

5. Acknowledgements

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