sLHC Project

sLHC Project Report 030

Specification of the closed orbit corrector magnets for the new LHC inner triplet

S. Fartoukh, R. Tomas, J. Miles

Abstract

Various orbit correction schemes are studied for the new inner triplets of the SLHC. The figures of merit used to compare the different schemes are the peak orbit after correction, the loss of beam-beam separation at the parasitic encounters and the required integrated Corrector strength. The flexibility of the crossing bump generation is also used as a key parameter to compare the different schemes.

CERN - BE
LHC IR Upgrade Phase I

CERN
CH - 1211 Geneva 23
Switzerland

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1 Motivation

The LHC phase I upgrade aims at replacing the LHC Inner Triplets (IT) by larger aperture quadrupoles in the ATLAS and CMS experimental insertions. Recent measurements of the vertical displacements of the IT quadrupoles suggest that these elements move at a rate of approximately 0.5 mm/year, see Fig. 1. These measurements refer to the outer shell of the magnet. The movement of the magnetic center with respect to the outer shell is not well known, but is expected to be smaller.

Without any correction, a displacement of one IT quadrupole by 50 μm (approximately one tenth of the annual displacement) already has unacceptable consequences for the closed orbit. Table 1 shows the peak orbits around the ring assuming an uncorrected displacement by 50 μm for one triplet quadrupole in the case of the LHC and the SLHC (SLHC optics version 2.0 [1]). Figure 2 shows the orbits around the ring for the case of displacing Q2B only. SLHC clearly exhibits an increased sensitivity by factors of 2 or 3 with respect to the LHC. This is due to the larger beta-functions in the triplet (4.5 km for the LHC and 10.8 km for the SLHC). Therefore a robust IT orbit correction system is essential for the reliable operation of the SLHC.

The best performance of the orbit correction system towards a reference orbit is limited by the resolution of the Beam Position Monitors (BPMs). These BPMs experience displacements of a magnitude similar to the adjacent quadrupoles, though they are not attached to the quadrupole cold masses. Therefore the effective BPM resolution with respect to a reference orbit is mainly given by the BPM displacement plus the accuracy of the BPM itself. The latter is 30 μm according to the BPM specifications [2]. The BPM displacement becomes the main contribution to the BPM effective resolution when considering time periods beyond 2 months, but the BPM accuracy remains the relevant quantity on a daily basis.

	LHC		SLHC	
	x[mm]	y[mm]	x[mm]	y[mm]
Q3	2.9	6.5	10.3	10.0
Q2B	3.5	3.7	12.6	5.3
Q2A	3.3	3.0	12.0	4.0
Q1	2.3	3.6	8.0	4.8

Table 1: *Peak orbit excursion around the ring assuming an uncorrected displacement of 50 μm for one low-beta quadrupole equipping the IR5 inner triplet of the LHC and the SLHC. Calculations done with MAD using the SLHC optics version 2.0 [1].*

2 Goal of the correction system

The orbit correction system of the inner triplet shall control the trajectories of both beams with an accuracy which is sufficient in order to maintain good collision conditions at the interaction point (IP), while preserving the beam-beam separation at the parasitic collision points of the insertion and the mechanical acceptance of the low-beta quadrupoles. The functional specification of the bi-directional BPMs equipping the current LHC triplets has been based on the same considerations [2]. The first goal of the IT orbit correction system is therefore a control of the orbit at least down to the level of the BPM effective resolution. Considering periods of 2 months or more, this means that the IT peak orbit after correction should not exceed the peak misalignments of quadrupoles and BPMs, though any orbit distortion below the BPM accuracy of 30 μm is obviously irrelevant. In addition, the strength of the IT orbit correctors must be

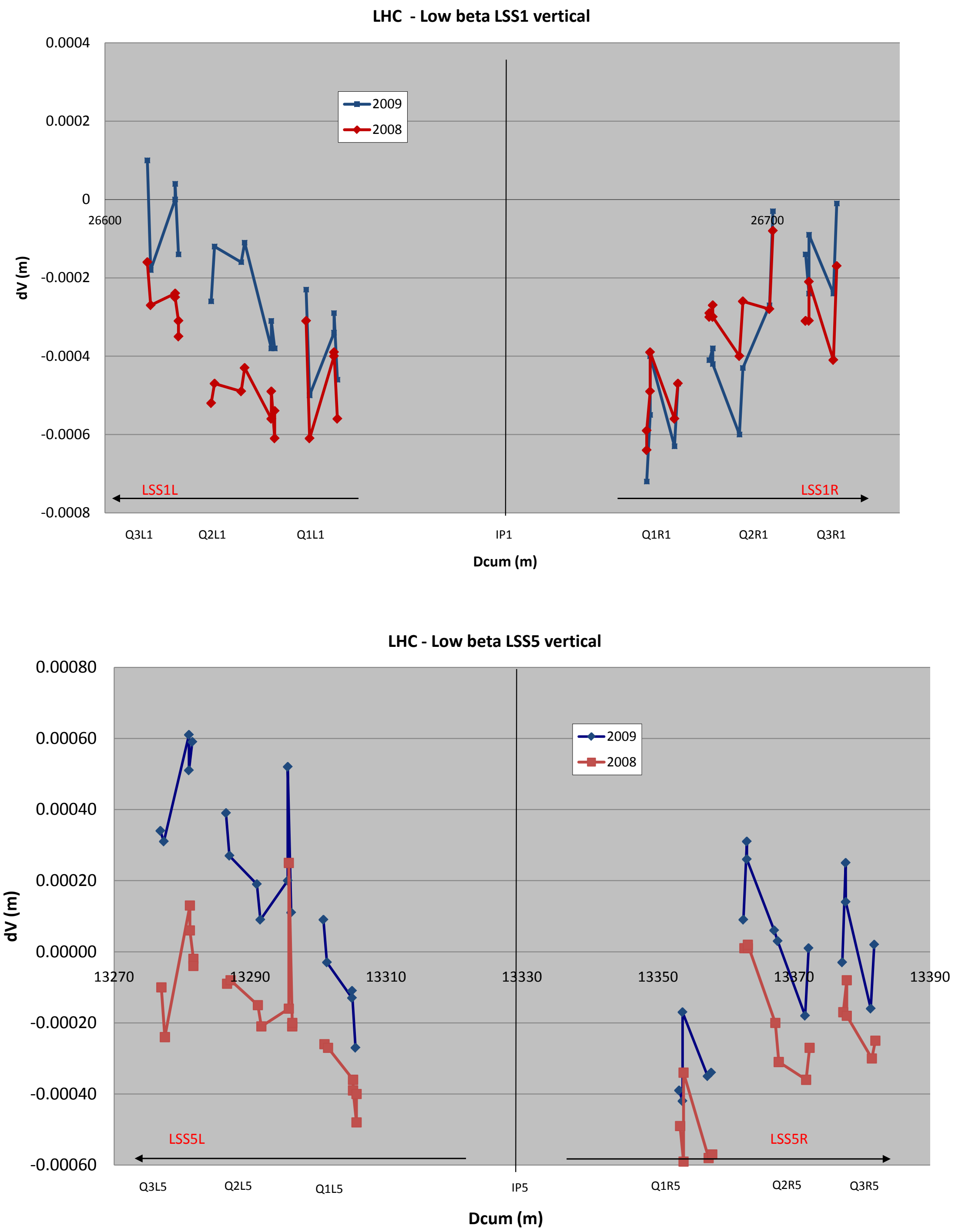


Figure 1: *Yearly measurements of the quadrupole displacements in IR1 (top) and IR5 (bottom), courtesy of Dominique Missiaen.*

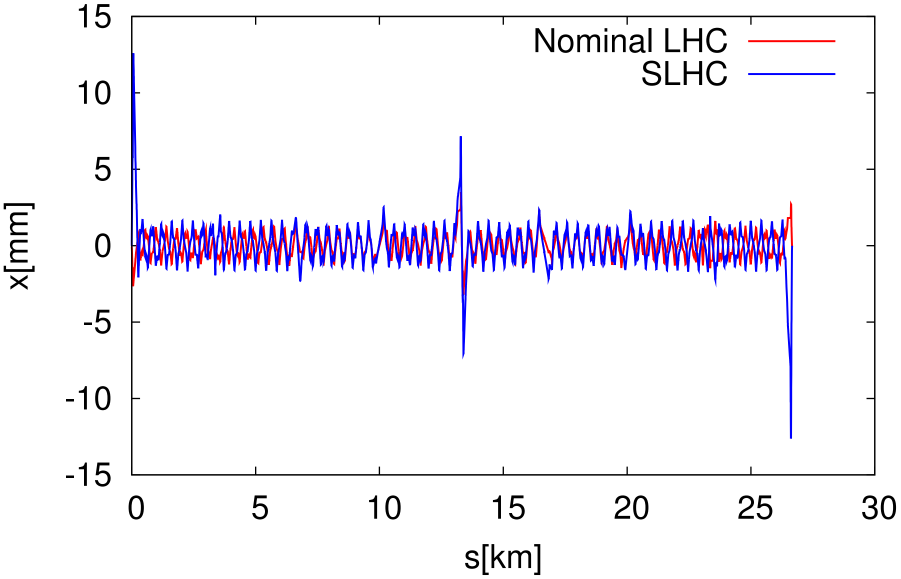


Figure 2: *Horizontal orbit excursions for the LHC and the SLHC assuming an uncorrected displacement of 50 μm for the Q2b quadrupole on the left side of IR5.*

enough to avoid frequent machine re-alignment. A few or ideally only one re-alignment per year (≈0.5 mm peak displacement) is considered to be reasonable.

The second goal is a minimum usage of the non-common orbit corrector magnets MCBY and MCBC at Q4, Q5 and Q6 for the IT correction proper, in particular concerning the special orbit corrector magnets MCBY at Q4. Indeed the latter have been designed with a certain nominal strength in order to generate a sufficient crossing angle at the interaction points. Using them as well for the correction of the IT misalignments will then inevitably reduce the optics flexibility in terms of crossing scheme.

In other words, it means that the IT orbit correction scheme shall be as local as possible such that the two conditions described above will be simultaneously fulfilled. Ideally, this would imply to equip the new inner triplet with four pairs of H/V orbit corrector magnets in order to have a perfect control of the orbit of both beams at the interaction point (that is the position and angle of the two beams at the IP, i.e. four constraints per plane), with no orbit distortion leaking from the triplet itself. In practice, only three pairs will be found to be sufficient (as it is currently the case for the LHC inner triplets), provided the latter are carefully distributed along the triplet. All these aspects will be illustrated and quantified in details in section 3 for the nominal LHC and section 4 for the SLHC where three different possible layouts will studied for the orbit correction system of the new LHC inner triplet.

3 LHC nominal IT orbit correction system

LHC is equipped with 3 double plane orbit correctors (MCBXHV) on each side of the IP. They each provide an integrated field of 1.5 Tm and they are located on the non-IP sides of Q1 and Q3, and in between Q2A and Q2B. The performance of the LHC nominal IT orbit correction system is evaluated by introducing random transverse displacements of the IT quadrupoles with a peak displacement of 0.5 mm. The orbit correction is computed by treating the LSS as a beam line and constraining the orbit positions and angles at the IP and at the exit of the LSS for both beams. This amounts to 16 constraints. Since there are only 12 “knobs” within the triplet (MCBX orbit correctors), 4 extra non-common orbit correctors are used at Q4,

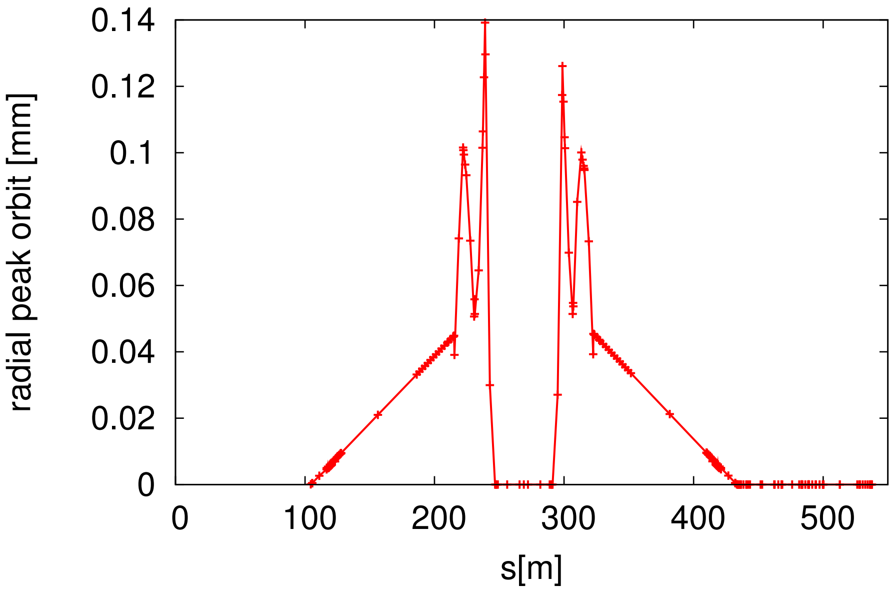


Figure 3: *Peak radial deviation over 100 machines after correction versus longitudinal position along the LHC nominal IR. The quadrupole misalignments is assumed to be within ± 0.5 mm.*

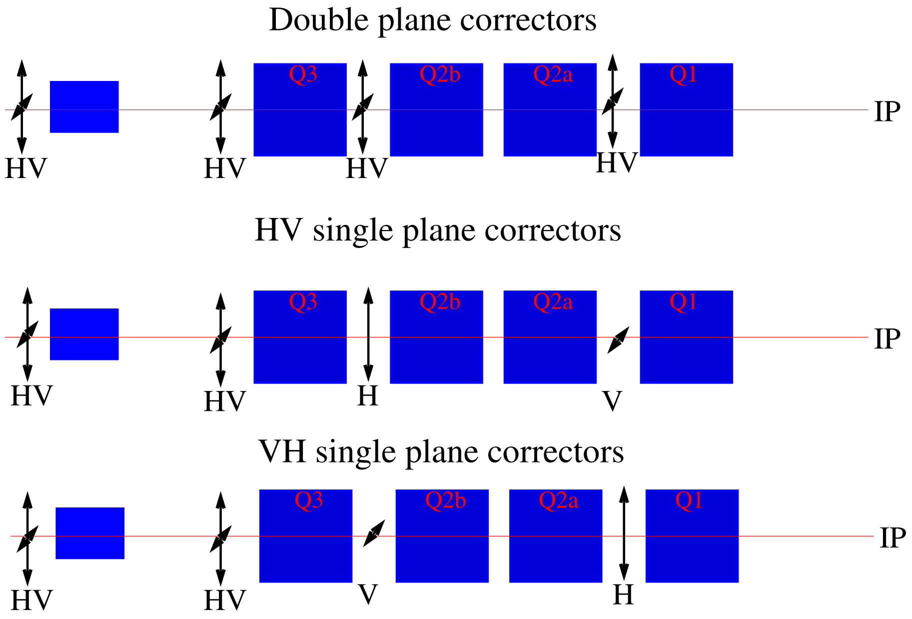
namely: ACBYHS4.L5B1, ACBYVS4.R5B1, ACBYVS4.L5B2 and ACBYHS4.R5B2. These correctors are identified as "Family A" and are chosen to act in the focusing plane of their adjacent Q4 quadrupole. The results are collected for 100 random seeds. The largest radial orbit excursion found after correction is 0.14 mm, see Fig. 3. This number is well below the 0.5 mm misalignments assumed for the triplet quadrupoles, meaning that the LHC IT orbit correction system has been designed with a safety factor. As showed in the summary performance table. 2 (next section), the maximum MCBX strength observed within the 100 seeds is 1.3 Tm, which is below the 1.5 Tm design strength of the orbit correctors. A maximum reduction of only 2.5% is observed for the beam-beam separation at the parasitic encounters. The usage of the non common orbit corrector magnets MCBY at Q4 is marginal.

4 SLHC IT orbit correction system

The nominal LHC closed orbit correction scheme is a natural choice for the SLHC. However it requires a certain amount of space between Q2A and Q2B to accommodate the double plane corrector. Furthermore, installing a 1.5 m long nested MCBX between Q2A and Q2B has the following drawbacks:

- An increase of the peak beta function by about 300 m in the IT and an increase of 6% in beta function in the matching section. Since the new triplet has only a very little aperture margin at β^* =30 cm ($n1$ 7.4 compare to a target of $n1 = 7$), the 300 m increase in the peak beta should be compensated by increasing β^*, thus reducing the luminosity scope of the upgrade.
- The Q2A/Q2B cryostat would be about 30 cm longer than that of Q1 and Q3, which is contrary to standardization of the MQXC cryostats.

A collection of different schemes to avoid placing correctors between Q2A and Q2B has then been investigated in terms of performance. The three schemes under study are illustrated in Fig. 4, namely Double, HV, VH. These names refer to the plane of the orbit correctors within the triplet on the left of the IP, as shown in Fig. 4.


Double plane correctors

HV single plane correctors

VH single plane correctors

Figure 4: *Three orbit correction schemes for the SLHC, named as Double, HV and VH.*

The simulations performed for the LHC have been repeated for the SLHC schemes. Since the HV and VH schemes have fewer correctors within the triplet, the eight Q4 orbit correctors must be used. For convenience we group them in the following 2 families,

- Family A: ACBYHS4.L5B1, ACBYVS4.R5B1, ACBYVS4.L5B2 and ACBYHS4.R5B2
- Family B: ACBYVS4.L5B1, ACBYHS4.R5B1, ACBYHS4.L5B2 and ACBYVS4.R5B2

Table 2 shows the performance of the three SLHC correction schemes together with the LHC for comparison. Figure 5 shows the peak orbit over the 100 machines versus longitudinal location for the three SLHC schemes, after correction. Figures 6 and 7 show histograms of the required strengths of the MCBX2 correctors (not involved in the crossing scheme) and the MCBX3 correctors (involved in the crossing scheme). The probability that the MCBX2 corrector strength exceeds 1.5 Tm is marginal.

With only two pairs of H/V orbit corrector magnets equipping the new triplet in the HV and VH scheme, compared to three pairs in the Double scheme (see Fig. 4), a factor of roughly 3 is lost in the quality of the orbit correction, both in terms of peak residual orbit after correction and in terms of degradation of the beam-beam separation at the parasitic collision points in the inner triplet. In addtion, the first goal of the IT orbit correction described in section 2 is out of reach for the HV and VH scheme.

Should the crossing angle have to be re-increased by $\sim 10\%$ in the HV or VH scheme in order to restore a nominal long-range beam-beam separation inside the triplet (see third column of Table 2), it is then worth mentioning that the luminosity will be reduced by about 6% at a β^* of 30 cm (due the increase of the geometric luminosity loss factor). Apparently marginal, this potential loss of performance has nevertheless to be compared with the potential gain of luminosity, of approximately the same amount, which could be obtained operating the SLHC with a β^* of 25 cm instead of 30 cm, a scenario which is currently out of reach because implying a deep modification of the matching section layout [3].

As already stated, there are enough MCBX knobs equipping the inner triplet of the nominal LHC and available in the Double scheme (see Fig. 4) of the SLHC so that the MCBY correctors belonging to Family B are not needed for the IT orbit correction. On the other hand,

Case	Peak orbit [mm]	B1-B2 separation [%]	MCBX No X-scheme [Tm]	MCBX X-scheme [Tm]	Q4 usage Family A [Tm]	Q4 usage Family B [Tm]
Double	0.5	4.5	1.8	1.9	0.06	0
HV	1.7	11.5	1.5	1.6	0.12	0.39
VH	1.6	11.0	1.5	1.5	0.13	0.38
LHC nom.	0.14	2.5	1	1.3	0.01	0

Table 2: *Performance of the different SLHC IT orbit correction schemes using the SLHC optics and layout version 2.0 [1]. The LHC nominal scheme is also shown for comparison. The Peak orbit column shows the maximum radial orbit deviation after correction for 100 seeds. The B1-B2 column refers to the maximum reduction of the relative beam-beam separation (defined as the worst case between horizontal and vertical crossing angle). The two MCBX columns show the maximum strength of the correctors. The column "No X-scheme" refers to the correctors not involved in the crossing scheme. "X-scheme" refers to the correctors generating the crossing scheme (MCBX3 in SLHC and MCBX1 in LHC). The last two columns show the usage of the two families of Q4 orbit correctors.*

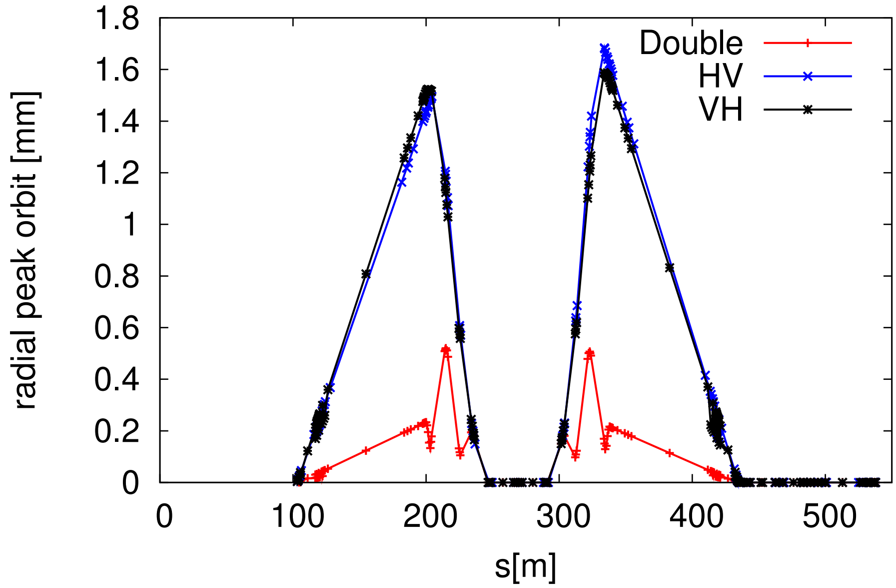


Figure 5: *Peak radial deviation over 100 machines after correction versus longitudinal position along the new IR for 3 orbit correction schemes of the SLHC. The MQX misalignments are assumed to be within ± 0.5 mm.*

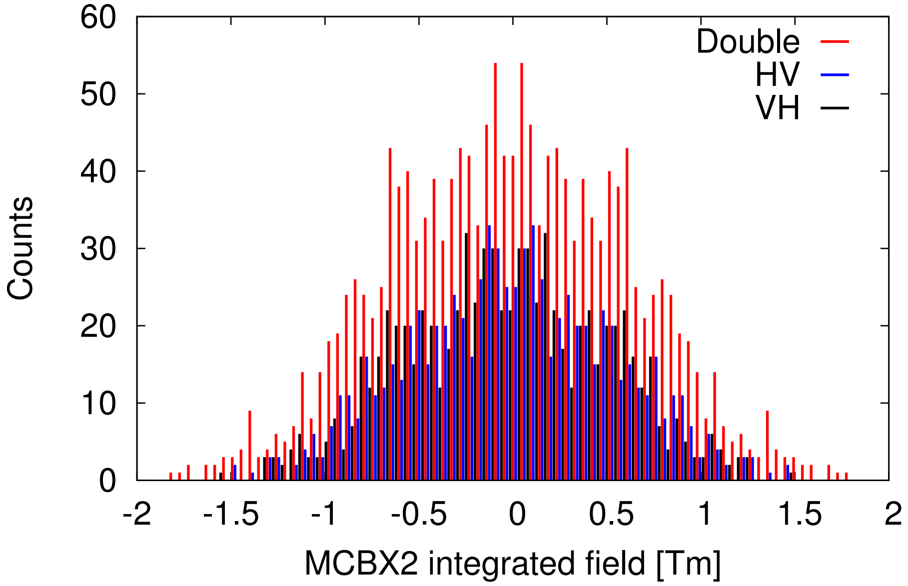


Figure 6: *Histograms of the MCBX2 correctors strengths over 100 machines after correction for 3 orbit correction schemes of the SLHC. The MQX misalignments are assumed to be within ± 0.5 mm.*

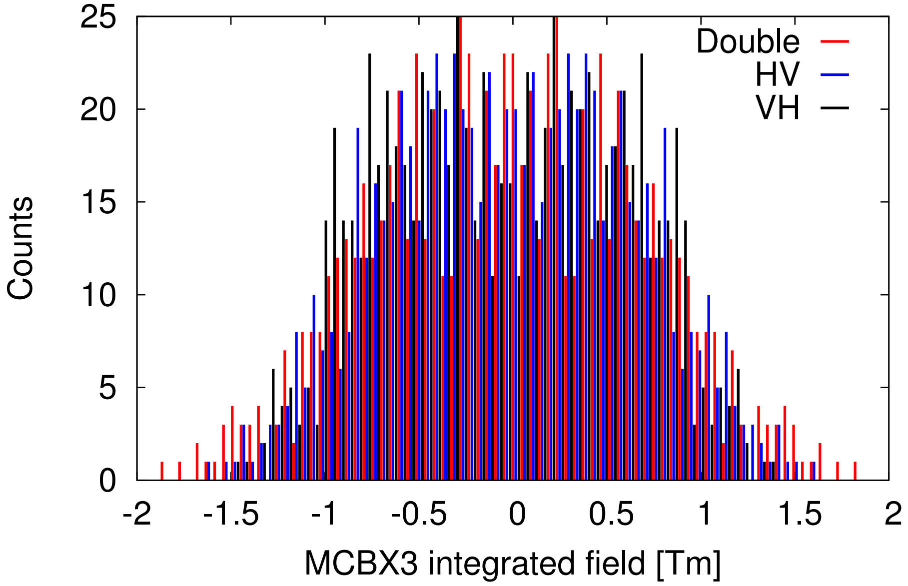


Figure 7: *Histograms of the MCBX3 corrector strengths over 100 machines after correction for the 3 orbit correction schemes of the SLHC. The MQX misalignments are assumed to be within ± 0.5 mm.*

these correctors would be crucial for the HV or VH orbit correction scheme of the new IT. In this configuration an integrated strength of 0.4 Tm shall be reserved in the MCBY's belonging to Family B for the IT correction proper (see last column of Table 2), which corresponds to a kick of 17 μrad compared to a maximum kick of 96 μrad available at nominal current. Unfortunately, these corrector magnets are also mandatory for the generation of the beam crossing scheme and, due to strength limit, are actually the ones which determine the maximum achievable crossing angle. Using the current SLHC collision optics (with $\beta^* = 30$ cm and an half crossing angle of 205 μrad, that is a 10 σ beam-beam separation), the strength of these correctors is already pushed up to 1.6 Tm (for kick of 68 μrad). Therefore, the HV and VH layout would substantially reduce the flexibility of the crossing scheme for the SLHC, either in terms of transverse adjustment at the IP or in terms of tuning the crossing angle at a given β^*.
This last aspect has been quantified precisely by performing the following exercise: in order to generate a given crossing angle at the IP, one of the MCBX equipping the triplet (MCBX3 in the case of SLHC) is adjusted in order to minimise the excitation of the MCBC and MCBY non-common orbit corrector magnets. While the two special MCBY correctors at Q4 are dedicated to the crossing scheme generation by design, the MCBC correctors at Q5 and Q6 also participate in the correction of the Q5/Q6 misalignments and contribute to the compensation of the residual closed orbit "leaking" from the dispersion suppressor. Therefore it is recommended that the MCBC correctors be used for the generation of the crossing angle with a strength not exceeding 50% of their nominal strength, that is a kick of about 50 μrad. Combining this limit with the two possible limits of 79 μrad or 96 μrad for the MCBY magnets (depending on whether 17 μrad is reserved or not for the IT orbit correction), we obtain the allowed operational window for the MCBX3 triplet correctors. Using the SLHCV2.0 collision optics with $\beta^* = 30$ cm and a half crossing angle of 205 μrad [1], this range is illustrated in Fig 8 between the blue and red vertical bars given by the MCBC and MCBY strength limits, respectively (the MCBX scale factor of 1, which is centered in the smallest range, corresponds to the actual MCBX3 setting of 30 μrad in the SLHCV2 collision optics). Regardless of the choice of the orbit correction scheme for the new IT, this range is already expected to be much narrower for the SLHC compared to the nominal LHC. The reasons are two-fold; first of all due the increase of the crossing angle at constant beam-beam separation in units of σ (a full crossing angle of 285 μrad and 410 μrad in collision for the LHC and SLHC, respectively). The second reason lies in the choice of a so-called "low-P collision optics" for the SLHC [4], imposed by the need to preserve the mechanical aperture in the matching section, where the β functions have been kept more or less unchanged at the Q4, Q5 and Q6 quadrupoles compared to the collision optics of the nominal LHC, while the peak β-function is increased by a factor of about 2.5 in the new inner triplet (4.5 km for the LHC and 10.8 km for the SLHC). As a result, if the HV and VH orbit correction scheme is chosen for the SLHC, the MCBX3 tuning range would become quite narrow, allowing an adjustment of the crossing angle of less than ± 10%.
Furthermore, we could imagine a configuration in which beam-beam considerations would require an increase of β^* in collision to further separate the beams via a net increase of the crossing angle. As an illustration, a collision optics with β^* =40 cm and a half crossing angle increased up to 280 μrad would offer a beam-beam separation of about 16σ, while preserving the IT aperture (n1$\approx$7.5), and providing a peak luminosity in the region of 2×10^{34} cm^{-2}s^{-1} at ultimate intensity. As illustrated in Fig. 8, maintaining the MCBC effective limit recommended above, does not yield a solution for the crossing scheme unless the maximum available strength of the MCBY correctors of Family B is used. This conclusion further illustrates the weakness of a VH or HV orbit correction system for the new IT of the SLHC.
Finally, the situation obtained for the nominal LHC is illustrated in Fig. 9, with, as expected,

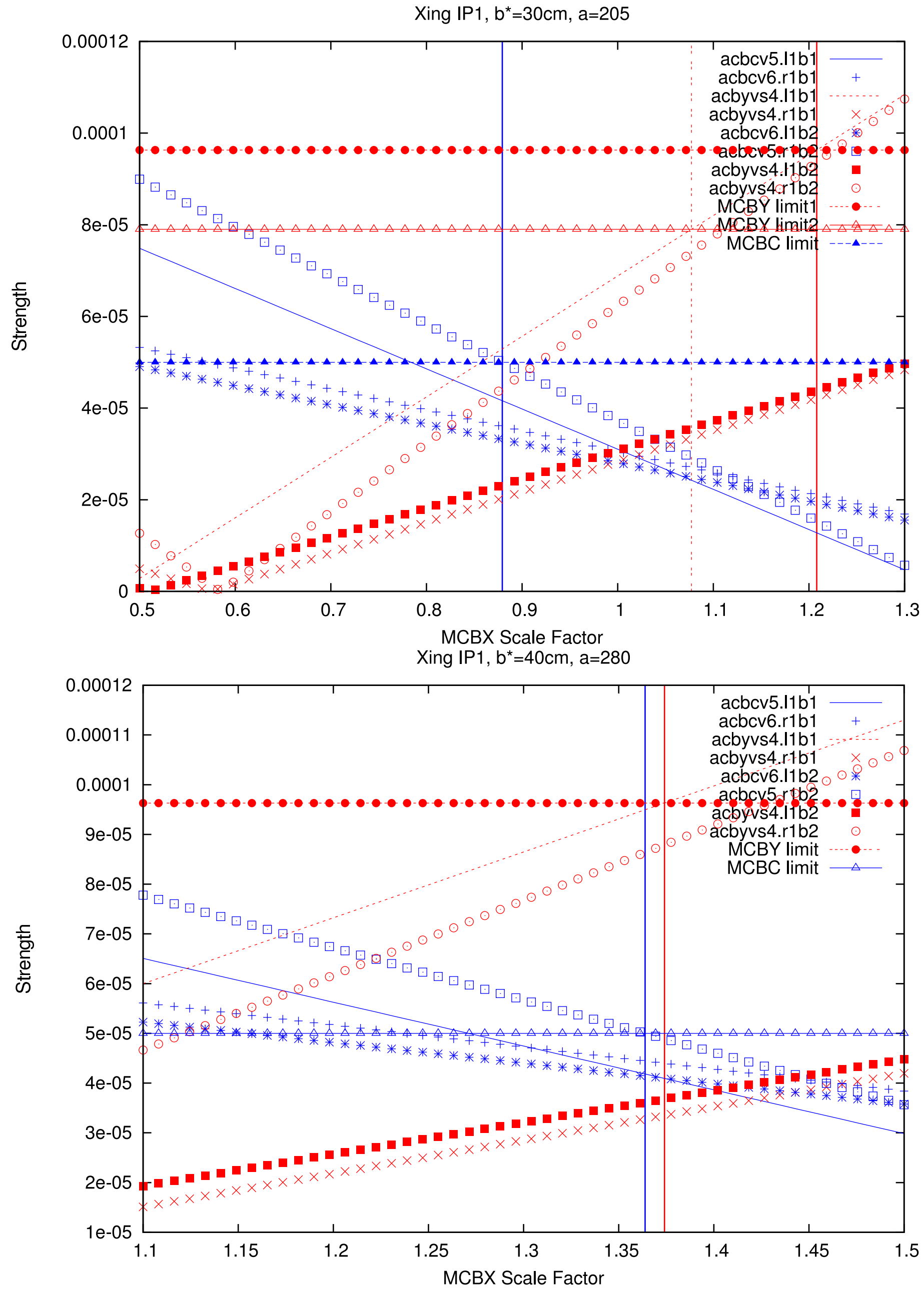


Figure 8: *Required strengths and limits of the non-common orbit correctors involved in the crossing scheme as a function of the MCBX3 scale factor (a scale factor of 1 represents a kick of 30* μ*rad provided by the MCBX3 magnet). The top plot refers to the current SLHC collision optics (*$\beta^* = 30$ *cm,* $\theta_c = 205\,\mu$*rad). The bottom plot corresponds to a backup SLHC collision optics with a larger* β^* *and larger crossing angle in order to mitigate long-range beam-beam effects (*$\beta^* = 40$ *cm,* $\theta_c = 280\,\mu$*rad). The limits in the variation of the MCBX3 strength are given by the vertical bars, showing in the first case a degradation of crossing scheme flexibility in the HV and VH layout of the SLHC inner triplet (dotted red upper limit for MCBX3 corresponding to a reduction of the available strength in the MCBY correctors magnets), and a total loss of flexibility for the second case.*

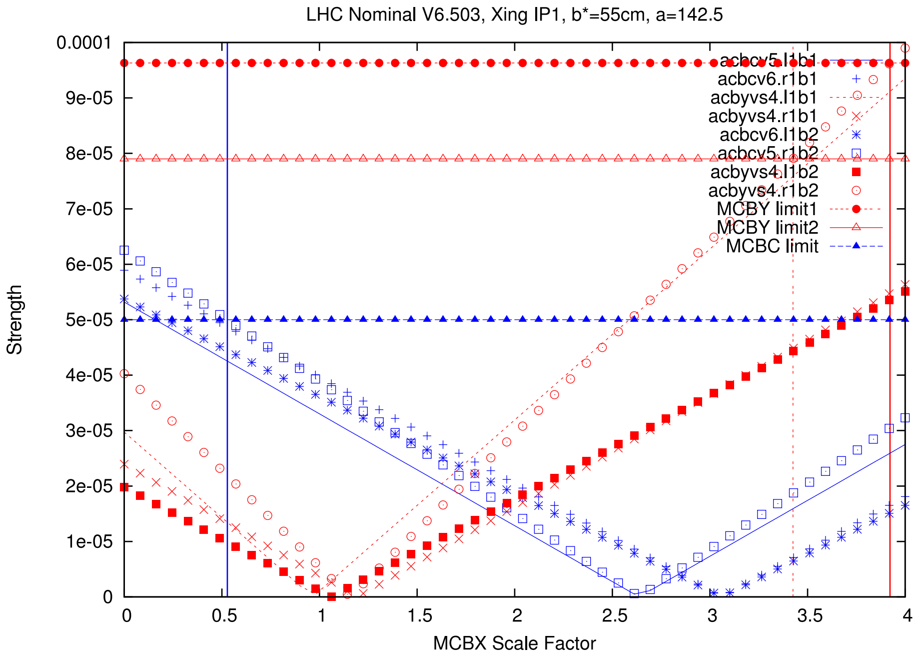


Figure 9: *Required strengths and limits of the orbit correctors involved in the crossing scheme as a function of the MCBX1 scale factor for the nominal LHC (a scale factor of 1 represents a kick of 10 μrad provided by the MCBX1 magnet). The flexibility of the nominal LHC is considerably larger than that of the SLHC and is actually used to shift transversally the IP in the crossing plane in order to better balance the mechanical acceptance of the left and right inner triplet of IR1 and IR5.*

considerably larger margins to modify the crossing scheme. A substantial fraction of this margin is then actually used to displace the IP transversely by 0.5 mm at IP1 and IP5 in order to better balance the mechanical acceptance on the current left and right inner triplets of IR1 and IR5. Since this may be required for other reasons in the SLHC (e.g. on the request of the experiments for the calibration of the vertex detector), it is then worth mentioning that the potential for IP adjustment will be strongly reduced, and possibly nonexistent, for the SLHC, if the HV and VH layout is chosen as the orbit correction system for the new inner triplet.

5 Evaluation of non-linear effects

The non-linear multipolar components of the triplet quadrupoles have a negligible impact on the performance of the orbit correction. However, the combination of the multipoles and the residual closed orbit after correction affects the machine optics due to the feed-down.

To evaluate the non-linear effects we include the IT multipole errors (b_3, a_3 and above) in IR5 only. We correct the orbit locally in IR5 following the same procedure as above and compute the tune, the β-beating and coupling term ($|c^-| = \Delta Q_{\min}$, or closest tune approach) for 100 machines. To estimate the total effect of two new ITs (IR5 and IR1) we double the maximum excursions of the tune and the β-beating. The results are shown in Table 3 and in Fig. 10. The HV and VH schemes with single correctors within the IT exhibit a factor of two larger impact on the optics parameters due to the feed-down from the residual orbit after correction. Although these numbers do not seem to pose a threat to the operation of the SLHC, the contribution from the IT residual orbit to the closest tune approach is significant ($\Delta Q_{\min}$ should be kept well

Case	Peak ΔQ [10^{-3}]	Peak $\Delta\beta/\beta$ [%]	Peak $\Delta\mathrm{Q}_{\mathrm{min}}$ [10^{-3}]
Double	0.9	1.0	1.8
HV	1.4	1.4	2.6
VH	1.7	1.8	2.6

Table 3: *Impact of the non-linear multipolar errors of the SLHC IT after orbit correction, using the SLHC optics version 2.0 [1]. Peak ΔQ refers the maximum tune excursion over 100 machines with non-linear errors and peak misalignments of 0.5 mm after correction. Peak $\Delta\beta/\beta$ refers to the maximum relative deviation of the beta-functions. Peak $\Delta\mathrm{Q}_{\mathrm{min}}$ refers to the closest tune approach after correction, which quantifies the transverse coupling of the machine.*

below 0.01).

6 Conclusion

The most convenient closed orbit correction scheme is that of the current LHC with 3 double correctors, one being placed in between Q2A and Q2B. This scheme has a safety factor since it can control the closed orbit to a level 3 times lower than the effective resolution of the BPMs (assuming misalignments above 100 μm). If implemented in the SLHC (and assuming that a nested MCBX cannot be shorter than 1.5m) this scheme would have some drawbacks in terms of luminosity performance and hardware.

The second most convenient orbit correction scheme consists of 3 double plane correctors in the non-IP sides of Q3, Q2B and Q1. This scheme allows control of the closed orbit to the same level as the effective BPM resolution. This scheme sacrifices the safety factor to maintain the luminosity performance and therefore seems to be a reasonable compromise for the SLHC. The required MCBX2 orbit corrector strengths amount to 1.8 Tm. However from Fig. 6 a compromised strength of 1.5 Tm could be adopted assuming failures to correct the orbit in the few percent level. In addition, this scheme allows a quasi-local correction of the triplet misalignments, in particular without using the most critical MCBY non common orbit correctors located at Q4 which are participating to the generation of the crossing bumps. Assuming that any modification of the matching section is beyond the scope of the Phase I mandate (and de facto concerning the MCBY and MCBC non-common orbit corrector magnets located at Q4, Q5 and Q6), it is then worth mentioning that the tunability of the crossing scheme is already substantially reduced for the SLHC with respect to the nominal LHC (compare top Fig. 8 and Fig. 9 and see section 4 for the explanation). Any further reduction will then limit the choice of operation mode of the SLHC in collision, in particular the possibility to explore the so-called large Piwinsky angle regime, with a larger crossing angle (to mitigate the beam-beam effects) and larger β^* (to preserve the IT aperture) but gaining faster in luminosity by pushing the beam intensity (see Fig. 8, top and bottom).

The HV and VH single plane orbit correction schemes show similar performances and requirements. These schemes control the orbit to a level 3 times larger than the effective BPM resolution. This would have important consequences in machine operation and closed orbit feedback performance. New reference, or “golden”, orbits would need to be frequently re-established, in particular to retrieve good collision conditions, taking time from luminosity production. For 0.5 mm peak misalignments of the inner triplet quadrupoles, the beam-beam separations at the parasitic encounters would be reduced by slightly more than 10%, see Table 2. This would necessitate increasing the crossing angle (if allowed by the triplet aperture,

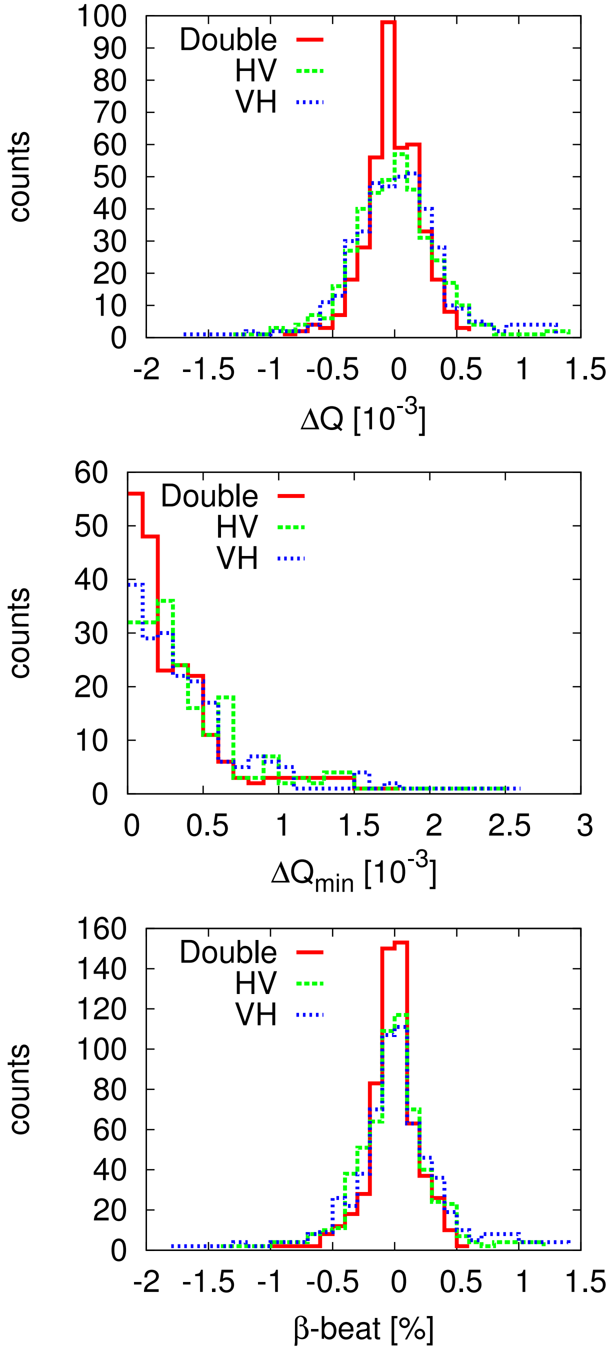


Figure 10: *Distribution of tune shift (top), closest tune approach (medium) and beta-beat after the orbit correction in the IT of the Double, HV and VH schemes, including the IT and D1 non-linear components.*

and/or increasing the β^* otherwise) to comparable relative values, thus reducing the luminosity performance by about 6% via an increase of the geometric luminosity loss factor. Apparently marginal, this potential loss of performance has nevertheless to be compared with the potential gain of luminosity, of approximately the same amount, which could be obtained operating the SLHC with a β^* of 25 cm instead of 30 cm, a scenario which is currently out of reach because implying a deep modification of the matching section layout.
These schemes require that some specific MCBY corrector magnets at Q4, already widely used for the generation of the crossing scheme, must also participate in the orbit correction of the new triplet. Given that the available strength left for orbit correction is only 0.6 Tm for the most critical MCBY magnets, we conclude that there is little margin left to explore other crossing bump configurations in collision. The flexibility in the choice of the crossing angle is then seriously reduced for the HV and VH IT orbit correction schemes, when compared to the SLHC Double scheme, and then completely marginal when compared to the nominal LHC, while the crossing angle is without any doubt a critical parameter if beam-beam effects become dominant.
The SLHC IT has only a little aperture margin ($n1 \sim 7.4$), taking into account the already challenging nominal orbit tolerance (3 mm) and the β-beating tolerance (20%). The HV and VH schemes absorb 50% of the orbit tolerance by design, see Table 2. This leaves no provision for unexpected effects or Van der Meer scans with amplitudes larger than $\sigma/2$. The non-linear effects from the residual orbit after correction are a factor of two more severe for these schemes than for the Double case. Even if the absolute values do not pose a threat to SLHC operation they might represent an important source of error, requiring dedicated correction.

We therefore strongly recommend the development of double plane orbit corrector magnets, as short as possible ($\leq 1.5 - 2$ m), offering an integrated strength of at least 1.5 Tm in both planes, in order to equip the Q2B (non-IP side) and Q2A (IP side) cold masses of the new inner triplets foreseen for the LHC IR upgrade Phase I.

Acknowledgments

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