CROSSING SCHEME AND ORBIT CORRECTION IN IR1/5 FOR HL-LHC*

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Abstract

In this paper we review the orbit correction strategy and crossing scheme adjustment for the HL-LHC orbit correctors in IR1/5 in view of the new optics and layout version HLLHCV1.1. The main objectives are to optimize the crossing scheme, in particular to reduce the strength of the orbit correctors at D2, and to validate the strength specifications of the several orbit corrector magnets involved, including a budget reserved for the correction of the orbit distortions from various sources.

INTRODUCTION

One of the objectives in view of the preparation of the new HL-LHC layout version HLLHCV1.1 [1,2] compared to HLLHCV1.0 [2], was the review of the necessary orbit corrector strength based on [3,4] and investigation of a possible reduction of the strength of the correctors at D2 (MCBRD) and at Q3 (MCBX3). Such a reduction is based on the reuse of the Q4 quadrupole of the nominal LHC as a new Q5 for the HL-LHC. Thanks to the two additional orbit correctors at Q5 (Fig. 1), it is then possible to extend the crossing scheme until Q5 inclusive and reduce the corrector strength.

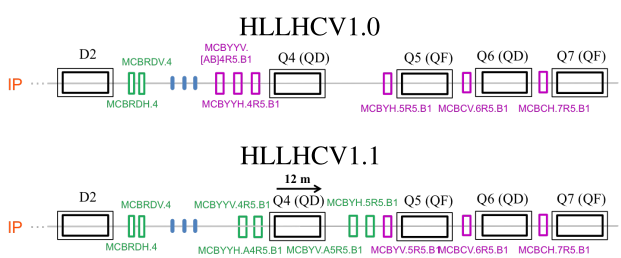

Figure 1: Schematic layout of the orbit correctors in IR1/5 in the D2 to Q7 region (longitudinal positions are not to scale). Representatively, IR5 Beam 1 right of the IP is shown. Orbit correctors used (additionally) for the crossing scheme are indicated in green and orbit correctors only used for orbit correction in pink. For Beam 2 the plane of correction is inverted for the orbit correctors at Q4, Q5 and Q6 due to the change of polarity of the quadrupoles for the other beam.

The orbit correctors in IR1 and IR5 in general have to provide sufficient strength for coping with the following aspects:

1. crossing and separation schemes,
2. beam based alignment of crab cavities,
3. luminosity and Van der Meer scans,
4. correction of inner triplet (IT) misalignment and feed-down from transfer function errors,
5. correction of closed orbit distortions generated by the arc imperfections.

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The corrector strength for crossing and separation, luminosity and Van der Meer scans, and correction of IT errors depends only on the IT strength and the chosen crossing angle and separation. During the pre-squeeze the IT strength increases from injection to pre-squeezed optics and stays constant during the telescopic squeeze [5] and for all squeezed optics (round and flat). In most cases the studies are therefore only conducted for the injection optics at 7 TeV with $\beta^* = 6$ m, and for round collision optics marking the two "corner" cases during the pre-squeeze, where the round collision optics configuration has been chosen as reference for all squeezed optics. The results for the other squeezed optics can be then obtained by linear scaling with the crossing angle and separation, if changed. All optics parameters are summarized in Table 1.

Table 1: Optics parameters for layout HLLHCV1.1 and HLLHCV1.0."xing" is the half crossing angle and "sep" is the half separation. "round" and "flat" optics are squeezed collision optics. The optics parameters for injection (inj) are given after the ramp at 7 TeV.

	$\beta^*_{x/y}$ [m]	xing [μrad]	sep [mm]
pre-squeeze	0.44/0.44	±295	±0.75
round	0.15/0.15	±295	±0.75
flat	0.30/0.075	±275	
inj (7 TeV)	6.0/6.0	±295	±0.75

In this paper we only give a short summary of the main results, explicitly points 1, 2 and 4. Further details can be found in [6].

CORRECTION OF TRIPLET MISALIGNMENT AND FEED-DOWN FROM TRANSFER FUNCTION ERRORS

In order to asses the required corrector strength for misalignment and transfer function errors of the IT, Monte Carlo simulations using MAD-X have been conducted. For all simulations 10 000 seeds have been used. As a worst case scenario uniformly distributed errors have been assumed using the following reference values:

- ±0.5 mm transverse alignment errors,
- ±10 mm longitudinal alignment errors,
- $\pm 2 \times 10^{-3}$ relative gradient errors.

All results can be scaled linearly as the transverse alignment and relative quadrupole gradient errors both scale linearly

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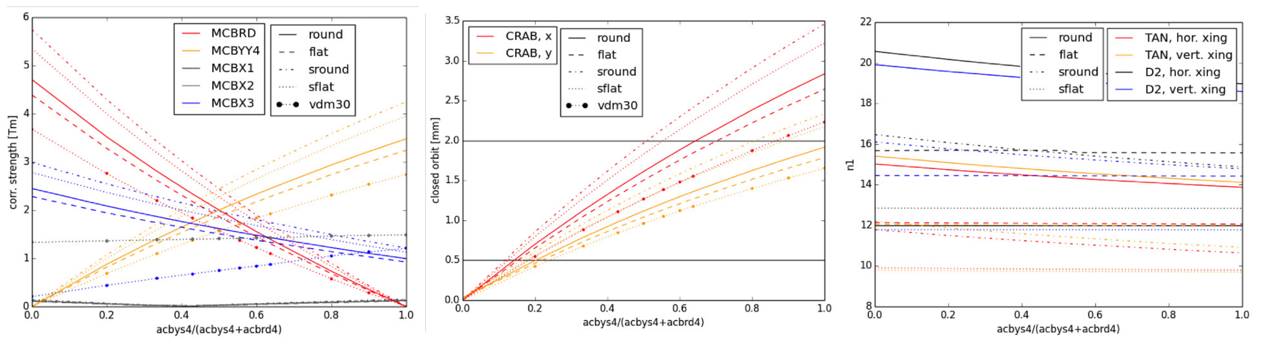

Figure 2: Maximum corrector strength (left), maximum orbit in the crab cavities (center) and aperture in terms of n_1 [8, 9] (right) as a function of the corrector strength ratio between MCBRD (acbrd4) and MCBYY4 (acbys4). The tolerances of 0.5 mm if the crab crossing is active and 2.0 mm if not are marked with a black line.

with the maximum error and the longitudinal misalignment in the case of small displacements [7].

As orbit correction method, the orbit has been matched to the usual constraint of zero orbit at the entrance/exit of the dispersion suppressor (DS) and the desired crossing angle and separation at the interaction point (IP) using the MCBX1, MCBX2 and MCBX3 corrector and the 2 MCBRD correctors with smaller strength. The interaction region is treated as a transfer line from the end of the DS on the left side to the start of the DS on the right side. The residual orbit from the arc is assumed to be zero.

The orbit corrector strengths required to correct the misalignment and transfer function are compared in Table 2. It is clearly visible that the main contribution to the total corrector strength comes from the transverse alignment error.

Table 2: 1σ standard deviation of the corrector strengths for only longitudinal alignment error (long mis), transverse alignment error (trans mis) and transfer function error correction (trans func) in the crossing plane and for HLLHCV1.0 round collision optics. Similar results are obtained in the separation plane. The location (loc) of the correctors is shown in Fig. 1

		corrector strength [Tm]		
	loc	tranf func	long mis	transv mis
MCBX1	Q1	0.07	0.01	0.46
MCBX2	Q2	0.17	0.02	0.68
MCBX3	Q3	0.12	0.01	0.37
MCBRD	D2	0.01	0.00	0.02

CROSSING SCHEME OPTIMIZATION

To minimize the orbit at the location of the crab cavities, the crossing scheme has been closed at the D2 in the layout version HLLHCV1.0 resulting in a quite large MCBRD strength. This choice has been imposed by the request of having zero closed orbit at the location of the crab cavities. However, this tolerance has been later relaxed in the layout HLLHCV1.1 where the crossing scheme is optimized in respect of the reduction of the MCBRD strength by sharing it with the corrector at Q4 (MCBYY4) at the cost of a non-zero orbit at the location of the crab cavities.

Initially, the main limitation for sharing the corrector strength between MCBRD and MCBYY4 was considered to be the residual orbit in the crab cavities, where ±0.5 mm is the upper acceptable limit when the crab crossing is active. In case the crab crossing is not active, the acceptable orbit increases to ±2.0 mm [10, 11]. By aligning the crab cavities along the crossing scheme, the tighter limitation of ±0.5 mm could be mitigated. In case the machine would then be operated without crossing, which is for example the case for Van der Meer scans, and therefore with no crab crossing, the larger upper limit of ±2.0 mm would apply.

Beside the MCBRD strength and the orbit at the location of the crab cavities, the use of the MCBYY4 mostly influences the orbit and aperture in TAXN and D2 (in TAXS, MQX and D1 orbit and aperture stay approximately constant). The different figures of merit - strength of MCBYY4, MCBRD and MCBX3 (MCBX1 and MCBX2 only vary slightly), orbit at the location of the crab cavities and the available aperture in TAXN and D2 - are illustrated in Fig. 2.

BEAM BASED ALIGNMENT OF CRAB CAVITIES

Assuming that the crab cavities are aligned along the crossing scheme, the margin of ±0.5 mm tolerable orbit deviation is allocated for eventual changes in the crossing angle during the run. This means that the correction of all orbit deviations from the reference orbit at the location of the crab cavities has to be accounted for in the orbit corrector budget.

As already a small change in orbit in the crab cavities induces a visible change in induced voltage, the crab cavities themselves act like high precision BPMs, explicitly with a precision of around 0.01–0.1 mm [12]. As the misalignment of the IT and the arc imperfections are already accounted for in the corrector strength budget (see “error” and “arc” in Table 4), only the corrector strength required for compensating the misalignment of the crab cavities themselves and the residual orbit (0.01–0.1 mm) has to be considered in addition,

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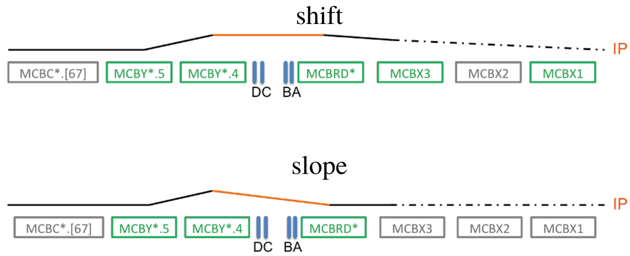

Figure 3: Sketch of the knobs for beam-based alignment of the crab cavities. The correctors that are not used are marked in grey.

referred to as "beam based alignment of crab cavities". The crab cavities can be aligned within 0.5 mm [10, 11], meaning that the maximum distance between two crab cavities in respect to the reference orbit is 0.5 mm.

Between the crab cavities no orbit correctors are installed, thus it is only possible to choose the "best straight line" through the cavities. As a larger misalignment is expected between the two cryomodules on each side of the IP than between the two cavities in a single cryomodule, the orbit is centred around the centre of the cryomodule using two knobs (Fig. 3). The corrector strength needed for the two knobs for round collision optics is summarized in Table 3.

Table 3: Maximum corrector strength required for shift (ccp, ccm) and slope (ccs) knob.

	corrector strength [Tm]		
knob	ccp	ccm	ccs
MCBX1	0.37	0.00	0.00
MCBX3	0.40	0.14	0.00
MCBRD	0.31	0.14	0.52
MCBYY4	0.42		0.95
MCBY5	0.43		0.44

CONCLUSIONS AND OUTLOOK

The maximum corrector strength of the different contributions is listed for round collision and injection optics at 7 TeV in Table 4 as well as the sum over all contributions (sum) and the maximum available corrector strength (max). In summary all corrector strength are within limits, however the MCBRD and MCBYY4 strength are right at the limit for round collision optics. As the maximum value of the corrector strength over the pre-squeeze and squeeze are either reached for injection optics at 7 TeV or collision (pre-squeezed or squeezed) optics, the maximum values listed in Table 4 are also valid during the pre-squeeze and squeeze assuming a constant crossing angle and separation. In this paper only part of the contributions have been discussed and for the other contributions it is referred to [6].

The ratio between MCBX1 and MCBX2 has been chosen in order to equalize the corrector strength and optimize the strength margin for injection optics at 7 TeV and a half crossing angle of ±295 μrad, for which the limiting correctors are MCBX1 and MCBX2. The MCBRD and MCBYY4 strength has been equalized for round collision optics with a half crossing angle of ±295 μrad for which the limiting correctors are the MCBRD and MCBYY4. The choice of sharing the strength between the MCBRD and MCBYY4 corrector entails an alignment of the crab cavities along the crossing scheme as the residual orbit in the crab cavities would otherwise account to approximately ±1.5 mm maximum exceeding the tolerance of ±0.5 mm.

Beside the contribution from the crossing scheme, the main contribution to the MCBRD and MCBYY4 corrector budget is the beam based alignment of the crab cavities, for which a value of ±0.6 mm has been assumed (±0.1 mm residual orbit plus ±0.5 mm misalignment of the crab cavities). With the current value of ±0.6 mm, both correctors are almost at maximum strength for round collision optics. By lowering the alignment errors of the crab cavities, the MCBRD and MCBYY4 corrector strength could thus be considerably decreased, more margin obtained and larger crossing angles reached.

Table 4: Summary of different contributions to the orbit corrector budget in the crossing plane for round collision and injection optics at 7 TeV. For MCBX1/2 the average strength (MCBX1+MCBX2)/2 is given. The different contributions are: "xing" - crossing and separation scheme, "offset" - the transverse shift of the IP, "error" - correction of alignment and transfer function errors, "crab" - beam-based alignment of crab cavities, "lumi" - luminosity scans and "arc' - correction of arc imperfections. For the different limits and further details it is referred to [6].

	MCBX[12]	MCBX3	MCBRD	MCBYY4
round collision optics 7 TeV - corrector strength [Tm]				
xing	0.10	1.81	2.88	1.30
offset	0.34	0.72	0.09	0.09
error	1.16	0.72	0.09	0.09
crab	0.22	0.65	1.16	2.15
lumi	0.00	0.00	0.27	0.20
arc	0.00	0.00	0.00	0.70
sum	1.81	3.96	4.44	4.44
max	2.50	4.50	4.50	4.50
injection optics 7 TeV - corrector strength [Tm]				
xing	0.56	0.89	2.57	1.16
error	1.16	0.78	0.04	0.00
arc	0.00	0.00	0.00	0.70
sum	1.72	1.67	2.61	1.86
max	2.50	4.50	4.50	4.50

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