

BPM TOLERANCES FOR HL-LHC ORBIT CORRECTION IN THE INNER TRIPLET AREA *

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Abstract

For the HL-LHC beam spot sizes as small as 7 μm are considered for the high luminosity insertions IR1 and IR5. In addition, the luminosity has to be levelled over several hours by changing β^* resulting in constant changes of the optics and thus orbit changes. The small beam size and the continuous optics changes in general make the alignment of the beams at the IP challenging. In order to avoid continuous luminosity scans for the alignment of the beams at the IP, the orbit correction has to rely on the readings of the BPMs in the IT region. In this paper we review the requirements on resolution and accuracy of the BPMs and compare different options for the placement of the BPMs in the IT region.

INTRODUCTION

The aim of the simulations presented in this paper is the definition of the precision and ranking of the BPMs in IR1/5 in terms of their efficiency. Explicitly the following points have to be specified:

- **the precision needed for a sufficient fill to fill reproducibility:** The minimum precision is defined by the precision required to find collisions at the beginning of a fill, while optimally the BPM precision should allow to find 1% of the luminosity at the beginning of the fill using only the BPMs and without the aid of luminosity scans.
- **the precision needed during one fill:** Assuming that the BPMs are recalibrated at the beginning of the fill, the BPM precision needs to be sufficiently good to keep the beams in collision without loss of luminosity, explicitly keeping the luminosity loss smaller than 1%.

ORBIT CORRECTION IN THE NOMINAL AND HL-LHC

Orbit Correction in the Nominal LHC

In the current LHC the orbit is corrected for each beam individually using a SVD and limiting the number of eigenvalue [1]. Explicitly a global orbit correction is performed and no individual correction of interaction regions (IRs). In all IRs, three BPMs per side and per beam are installed in the inner triplet area, which are however not used in standard operation at the moment. From experience in the LHC, BPMs closest to the IP are in general best for the correction of the orbit at the IP and a correction is usually still possible with 2 out of 3 BPMs.

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Furthermore, around 10 μm of orbit drift at the IP are observed from fill to fill and around 100 μm during a period of several months [2]. The behaviour of the drifts also suggests a ground motion like behavior with the orbit deviation mainly originating from the misalignment of quadrupoles.

The general strategy for the LHC orbit correction is:

1. correct to the golden orbit of the previous fill at the end of the squeeze
2. conduct a lumiscan to optimize luminosity. The obtained orbit then redefines the “golden orbit”
3. orbit correction to the golden orbit defined by the initial lumiscan. The BPMs at the IT are explicitly not included in the correction.
4. in case of a relevant drop in luminosity, additional lumiscans are conducted

Orbit Correction in the HL-LHC

Between the nominal LHC and the HL-LHC differences and similarities exist in respect of the orbit correction. As the experiments can not accept the peak luminosity delivered by the HL-LHC, β^* -leveling over several hours is foreseen in order to reach the maximum integrated luminosity. A change in β^* entails a change of the optics which in turn results in a change of the orbit. In view of the orbit correction, two cases should be distinguished for the β^* -leveling:

- leveling using the pre-squeezed optics, for which the magnet strength in IR1/5 is changed for the squeeze of the same. This is the case for $\beta^* > 0.44$ m.
- leveling using the squeezed optics, for which the magnet strength in IR1/5 stays constant but instead the strength in the adjacent IRs is changed (IR2/8 and IR4/6). This is the case for $\beta^* < 0.44$ m.

Using the squeezed optics for the β^* -leveling might be preferred in view of the orbit correction as IR1/5 stay unchanged. This case would be similar to the nominal LHC, assuming that the orbit at the entrance and exit of IR1/5 can be controlled sufficiently well.

The orbit deviations in mm due to ground motion are expected to be similar for the HL-LHC as for the LHC. The reason is that the machine stays unchanged except for the IT and the integrated quadrupole strength of the nominal and the HL-LHC triplet is approximately the same, and thus the same orbit deviation in terms of mm are expected. However, the HL-LHC envisages smaller beam spot sizes than the LHC making the luminosity more sensitive to small orbit deviations.

The general orbit correction strategy for the HL-LHC could be:

1. correct to the golden orbit of the previous fill at the end of the squeeze
2. conduct a lumiscan to “recalibrate the BPMs”. The obtained orbit redefines the “golden orbit”.
3. during the fill and explicitly during β^* -leveling the orbit is controlled using the BPMs and no further lumiscans are conducted.

Comparing the different points, the main difference between the LHC and the HL-LHC is the orbit control during the β^* -leveling by the BPMs and not by conducting more frequent lumiscans. This implies that a high repeatability, reliability and precision of the BPM readings is required during one fill in order to keep the beams in collision and deliver the requested levelled luminosity to the experiments.

HL-LHC CROSSING AND SEPARATION SCHEME AND BPM POSITIONS IN IR1/5

The HL-LHC crossing and separation scheme is shown in Fig. 1 for the HL-LHC optics version V1.0. For beam-beam compensation reasons the crossing plane is alternated between the two high luminosity experiments, explicitly horizontal crossing and vertical separation is chosen in IR5 and vertical crossing and horizontal separation in IR1.

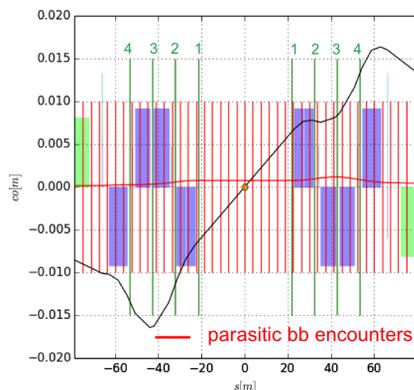


Figure 1: The HL-LHC crossing and separation scheme in IR5 for Beam 1 in the IT region. The horizontal orbit is shown in black and the vertical orbit in red. The parasitic beam-beam encounters are indicated with red vertical lines and the BPM positions with vertical green lines. The BPMs are numbered consecutively starting from the IP.

In the IT region the BPMs can only be placed between the IT magnets and thus their position is predefined by the position and length of the IT magnets. Furthermore, a placement of the BPMs close to the location of a parasitic beam-beam encounter will result in a smaller BPM accuracy as in this case it is difficult to measure the individual signal of each beam. It has been shown that the contribution of the BPMs to the overall impedance is also not non-negligible where the BPMs at the locations with high β -functions contribute most to the impedance [3]. The BPM positions should thus be optimized in respect of these two aspects, where the optimization in respect of impedance is at the moment considered the weaker constraint.

Applying these two criteria to the BPMs in the IT region, the BPM4 is placed close to a parasitic beam-beam encounter and at the position of BPM3 and BPM4 the beta function reaches its maximum which is not optimal for impedance reasons.

SIMULATION SETUP

All the simulations for the specification of the BPM precision have been conducted with the optics and beam dynamics code MAD-X [4] and for round HLLHC V1.0 optics with $\beta^* = 0.15$ m. For the matching the jacobian method has been used. Assuming that the orbit deviations in IR1/5 will be corrected locally in the interaction region, IR1/5 have been treated as line instead of simulating the complete ring. As IR1 and IR5 are fully symmetric, except for alternating the crossing and separation plane, only IR5 has been studied. The orbit deviations from the arc have been treated as uniformly distributed error of the initial/final condition, where a maximum value of $\pm 100 \mu\text{m}$ at the BPM at Q6/Q7 is assumed which is then tracked to the beginning/end of the dispersion suppressor. The BPM precision is simulated as uniformly distributed error in the matching constraints, where a reference value of $\pm 1 \mu\text{m}$ has been assumed. As all results scale linearly, the results can be rescaled to smaller/larger BPM precisions.

As a last step, also transfer function errors of the IT and correctors and longitudinal misalignment of the BPMs are included in order to investigate the sensitivity to errors.

SUMMARY OF SIMULATION RESULTS

Orbit Correction with and without Weights

The orbit has been rematched using the orbit correctors at Q5 and Q6/Q7, so that the 8 variables (corrector strengths) match the the 8 constraints $((x/p_x), (y, p_y))$ for Beam 1 and Beam 2. All correctors act separately on Beam 1 and Beam 2 and intentionally small correctors have been used with small hysteresis effects. The same simulation has been conducted, but one time with increased weights of the constraints representing the BPMs between D1L and D1R and once without (Fig. 2). Without increased weights for the BPMs in the IR region, the orbit at the IP cannot be sufficiently well matched,

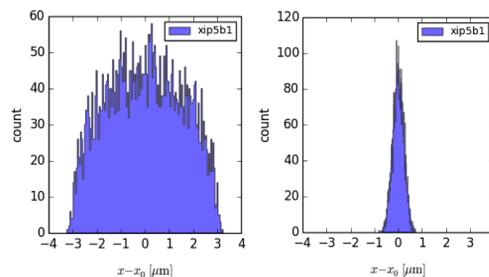


Figure 2: Orbit deviation at the IP in the horizontal plane for Beam 1 if the the crossing scheme is matched without weights (left) and with increased weights of the constraints representing the BPMs between D1L and D1R (right).

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while in the case with weights, the orbit is almost perfectly matched. With weights one obtains explicitly the values listed in Table 1. Assuming as limit 99% luminosity loss

Table 1: Orbit Deviation at IP

orbit at IP5	max [μm]	rms [μm]
x(b1)-x(b2)	1.139	0.326
y(b1)-y(b2)	1.119	0.332

for $2\text{rms}(z(b1)-z(b2))$ as orbit deviation (this is equivalent to finding back 1% of the luminosity), a BPM precision is needed from fill to fill of:

$$\text{precision}_{\text{fill to fill}} = \pm 43.9 \mu\text{m} \quad (1)$$

and during one fill assuming 1% luminosity loss for $2\text{rms}(z(b1)-z(b2))$:

$$\text{precision}_{\text{one fill}} = \pm 2.0 \mu\text{m} \quad (2)$$

For the calculation of the luminosity loss $2.5 \mu\text{m}$ normalized emittance, round collision optics with $\beta^* = 0.15/0.15 \text{ m}$ and 7.55 cm bunch length have been used.

Selecting the Efficient BPMs

To test the efficiency of the different BPMs the orbit deviation at the IP for all BPMs except one has been compared to the case with all BPMs. The larger the increase in the orbit deviation if the BPM is disabled, the more efficient is the BPM. The results are summarized in Table 2 and show that the efficiency of the BPMs decreases with the distance from the IP. Furthermore, at least one of the BPMs closest to the IP (BPM1/2) is required to ensure a luminosity loss smaller than 1-2%, while BPM3/4/5 are considerably less efficient.

Table 2: Orbit Deviation at the IP for IR5 and Beam 1. $\sigma_z = 7.09 \mu\text{m}$ is the beam spot size assuming round collision optics and $2.5 \mu\text{m}$ normalized emittance.

BPMs	orbit $ z - z_0 $ at IP5 ($z = x, y$)	
	max [μm]	$2\text{rms}/\sigma_z$ [μm]
all BPMs	1.14/1.12	0.092/0.094
no BPM1	1.41/1.44	0.113/0.115
no BPM2	1.55/1.38	0.108/0.111
no BPM3	1.48/1.48	0.106/0.106
no BPM4	1.43/1.25	0.100/0.100
no BPM5	1.14/1.19	0.093/0.095
no BPM1/2	2.09/1.98	0.147/0.152
no BPM3/4/5	1.47/1.44	0.117/0.117

Influence of Errors

Due to the large divergence in the triplet region the crossing scheme could be sensitive to already small longitudinal misalignments of the BPMs. The results yield (Table 3) that

the BPMs should be longitudinally aligned within 1-2 mm, where all BPMs have been used for the matching of the crossing scheme and a uniformly distributed error has been assigned to the IT magnets.

Table 3: Orbit Deviation at the IP for IR5 and Beam 1. $\sigma_z = 7.09 \mu\text{m}$ is the beam spot size assuming round collision optics and $2.5 \mu\text{m}$ normalized emittance.

ds(BPM)	orbit $ z - z_0 $ at IP5 ($z = x, y$)	
	max [μm]	$2\text{rms}/\sigma_z$ [μm]
0 mm	1.14/1.12	0.092/0.094
1 mm	1.34/1.30	0.097/0.092
10 mm	4.43/1.30	0.363/0.092

Another source of errors are the transfer function errors of the IT and correctors. A relative transfer function error of 10^{-4} has been assumed for both the IT (k_{err}) and the correctors $\text{acb}^*_{\text{err}}$ and the results are listed in Table 4. The triplet transfer function errors start to play a role from 10^{-4} units and the corrector transfer function errors should be well controlled within 10^{-4} . Because of the current implementation of the Jacobian method for the matching, the perturbed machine is used for the SVD and also only transfer function errors could be assigned to the correctors which are not used for the matching.

Table 4: Orbit Deviation at the IP for IR5 and Beam 1. $\sigma_z = 7.09 \mu\text{m}$ is the beam spot size assuming round collision optics and $2.5 \mu\text{m}$ normalized emittance.

error [10^{-4}]		orbit $ z - z_0 $ at IP5 ($z = x, y$)	
k_{err}	$\text{acb}^*_{\text{err}}$	max [μm]	$2\text{rms}/\sigma_z$ [μm]
0.0	0.0	1.14/1.12	0.092/0.094
1.0	0.0	1.67/1.19	0.117/0.092
1.0	1.0	1.70/1.21	0.119/0.093

CONCLUSION

To fully exploit the better precision of the new BPMs in the IT region, the weights used for the SVD of the BPMs in the IT region should be increased. Under this condition, the simulation results yield that under the assumption of a perfect machine, a BPM precision from fill to fill of $\pm 43.9 \mu\text{m}$ is required (criterion: find 1% of luminosity at the beginning of the fill) and during one fill of $\pm 2.0 \mu\text{m}$ (criterion: luminosity loss smaller than 1%). Furthermore, the longitudinal alignment of the BPMs is required to be within 1-2 mm and the relative transfer function error of the IT and correctors should not exceed 10^{-4} .

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