LONG-RANGE BEAM-BEAM ORBIT EFFECTS IN LHC, SIMULATIONS AND OBSERVATIONS FROM MACHINE OPERATION IN 2016

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Abstract

To limit the number of head on collisions to only one at the interaction point in the Large Hadron Collider (LHC), two beams are colliding with a non zero crossing angle. Under the presence of such angle the closed orbits of the individual bunches in the bunch train varies due to the long-range beam-beam effects. These variations leave a signature as a non zero transverse offset at the collision points visible in the front and trail of the bunch train. When operation team aims for the optimized beam orbit and therefore maximized luminosity, those front and tail bunches due to the overall offset experience reduced luminosity. This paper describes an overview of the existing tool for simulating these effects and compares to operational data. The effects of different operational scenarios (i.e. beam brightness, reduced or asymmetric crossing angles between the interaction points etc.) are simulated and discussed.

INTRODUCTION

The LHC operates with multiple bunches clustered in train structures to reach the luminosity goals. To avoid multiple head-on (HO) collisions at the interaction regions where the counter rotating beams share a common beam pipe a finite crossing angle is needed. This guarantees strong interactions only at the center of the experiment detectors at the so called interaction points (IP). Introducing a crossing angle at the IR however, sets a finite number of parasitic encounters where the two beams will interact at a certain distance. These parasitic interactions called Long Range Beam-Beam (LR, BB) interactions are due to the presence of the electro–magnetic field coming from the second beam. Among several effects the LRBB effects lead to an orbit kick which will have an impact on the process of forming of the beams closed orbit at the bunch by bunch level. The bunch by bunch difference comes from the filling and collision schemes used in operation. Different number of LR encounters will lead to different closed orbit for bunches in the center respect to those at the edges of the bunch trains. The different closed orbits will lead to different offsets at the IPs and consequently to a luminosity reduction if not kept under control.

Beam–Beam Orbit Effect

When two beams cross each other at a collision point, the trajectories of the particles are modified by a transverse kick due to the Electro-Magnetic field of the counter rotating bunch [1]. This force depends on the bunch intensity and on the relative distance between the centroids $\vec{d_u}$. The coherent angular deflection a bunch will experience can be expressed as:

$$\Delta\vec{u}' = -\frac{2N_p r_0}{\gamma_r}\frac{\vec{d_u}}{|\vec{d_u}|^2}\left[\exp\left(-\frac{\vec{d_u}^2}{4\sigma_u^2}\right)-1\right] \tag{1}$$

where u represents the beam separation in the u-th plane (horizontal or vertical), r_0 is the classical particle radius (r_0 = 1.53469×10^{-18} m), N_p the number of particles in the opposing bunch, γ_r the Lorentz factor. σ_u is the transverse beam size in the u-th plane. The closed orbit change given at a location s by this angular kick is then given for the case of one single BB interaction at one IP and a 1 turn in the collider will depend on the bunch to bunch separation and is given by $\Delta u^* = -\frac{\beta^*}{2\cdot tan(\pi Q)}\cdot\Delta\vec{u}'$. In Figure 1 we show as an example the effect of the BB interaction on the bunch closed orbit at IP5 as a function of the BB transverse separation d_u expressed in units of the transverse RMS beam size (σ). The example compares the results from the analytical estimates of the orbit kicks to the self consistent calculations of the TRAIN code [2, 3] that was recently refurbished for new inputs requirements [4, 5]. Differences between the models are due to the self consistent treatment of the orbit effect done in the TRAIN code (blue) and not in the static model (green line).

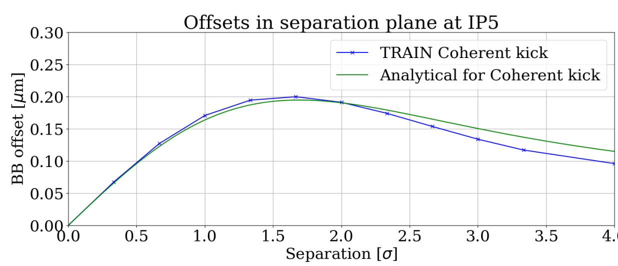

Figure 1: Analytical (green) and simulated (blue) orbit effect due to the BB kick as a function of the transverse separation.

MACHINE OBSERVATIONS

LR orbit effects have been observed in the LHC in several conditions in the presence of trains [6–8]. The effects appear very relevant when the two beams are transversally displaced as normally done during luminosity or Van der Meer scans. The BB orbit effects have to be taken into account when the luminosity is computed as a function of the transverse separation since the orbit kick will result in a modified centroid position of the two bunches. In the presence of LR interactions the luminosity scan to optimize luminosity will define the reference orbit the total luminosity is maximum. This

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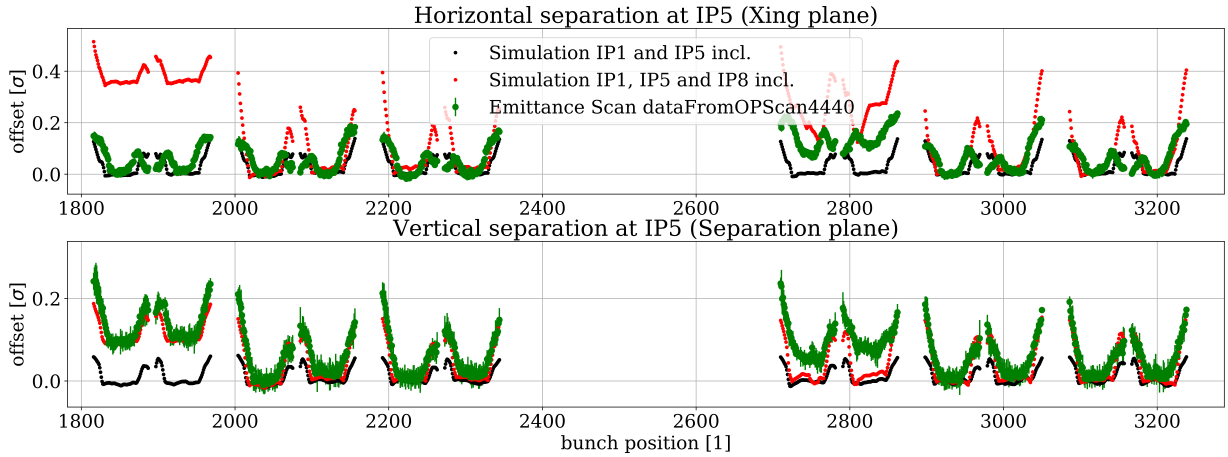

Figure 2: TRAIN simulations for two different configurations with or without IP8 contribution compared to measurements results for fill 4440. Good agreement in the V plane (the separation plane of the scanned IP) and less good in the H plane (the crossing plane of the scanned IP).

will not avoid that bunches having different number of LRs encounters (PACMAN bunches) have different closed orbits and therefore result in a transverse offset at the IPs which leads to a luminosity reduction. In regular operation during the 2015 and 2016 physics run transverse scans [9] have been made on a regular bases to obtain the bunch by bunch convoluted emittances, however only the scans in CMS (IP5) were available. As a side result one can determine the location of the bunch by bunch maximum luminosity which if displaced with respect to the reference orbits after lumi scans shows the existence of a transverse offset at the IP and has to be LR dependent in the presence of BB orbit effects. The bunch by bunch displacements of the luminosity centroids can be, in first approximation, correlated to the expected orbit offsets at the IPs in the separation plane [10]. In the measurements analysis the orbit effect due to the separated HO at the IP is not taken into account in this preliminary study while the LR impact can be qualitatively estimated and compared to expectations. An example of such analysis on the transverse OP–SCAN is shown in Figure 2 green points for the LHC 2015 physics fill number 4440 where the bunch by bunch measured offset at the IP5 in the separation plane (vertical) is plotted as a function of the bunch slot number.

One can notice the typical LR dependency expected for the scans in the crossing plane as shown in [10]. Comparison with simulation results show a good qualitative agreement in the vertical plane. An important observation is also the impact of IP8 missing BB effects on the closed orbits (bunch slots from 1800 to 2000), which is well reproduced for the vertical plane while it is not observed in the horizontal plane. Further investigation is needed to address the contribution of the lower luminosity IPs on the LHC bunch by bunch orbits.

Crossing Angles Scans

During the dedicated machine development (MD) sessions in 2016 [11] the crossing angles at the IP1 and IP5 have been reduced in steps (half angles from 185 to 105 μrad). As a consequence the BB separation is reduced and orbit effects modified. A transverse scan has been performed to acquire information on the bunch by bunch orbits at a half crossing angle of 105 μrad. In Fig. 3 we show the measured offsets per bunch pair (green points) and compare to the expected values for two angles configurations.

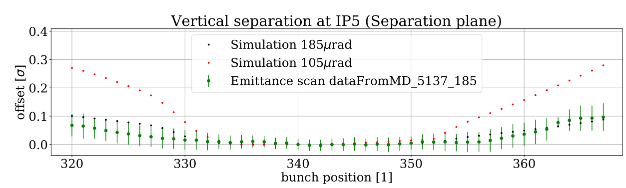

Figure 3: Measurement (green) and simulation (red and black) results for the configuration during fill 5137 with dedicated experiment session.

In late 2016 a reduction of the half crossing angle (185 μm to 140 μm) [12, 13] was proposed and operationally implemented in two high luminosity interaction points IP1 and IP5. We simulated the orbit effects for a wide spectrum of angles to study the expected differences. Figure 4 illustrates the expected offsets at the IP1 and IP5 as a function of the reduced crossing angles showing a maximum impact of 0.15 σ offset for the reduced crossing angle which could result in a less than 1% luminosity reduction.

Brightness Dependency

In July 2016, the LHC operations has changed beam types allowing for much smaller emittances. Analysing the physics fills of that period of operation helps understanding the impact of the transverse emittances on the orbit effects. For this characterisation we followed the data set presented in [14] and extracted bunch intensities for few selected fills (5068, 5078, 5097 and 5107) at the start and the end of the given fill. With this input we performed the simulations assuming constant bunch by bunch emittance (averaged from the

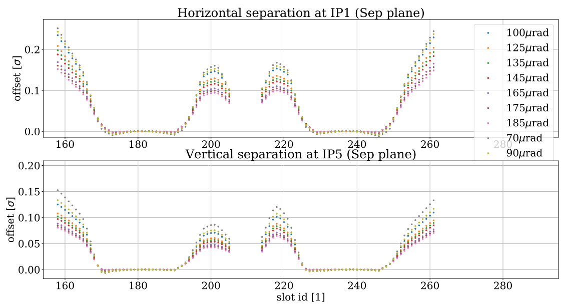

Figure 4: Simulations for different crossing angles proposed during the 2016 crossing reduction campaign. No effect more than 0.1σ is expected in the bunch by bunch view at the overall IP separation.

BSRT measurements). Figure 5 illustrates the results of the scans. There is not a clear reduction of the offsets despite the beam emittances were reduced from 3 to 2.4 μm. In Fig. 6 we show simulation results for different fills with different brightness. Both measurements and simulations show that no major separation ($>0.1\sigma \approx 2$ μm) at the IP is expected.

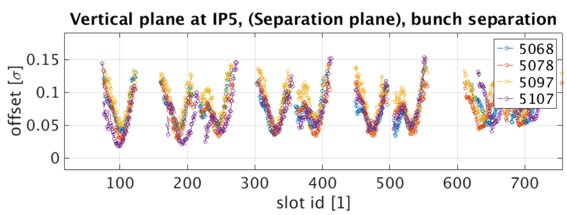

Figure 5: Bunch pair centroid displacements for selected fills during LHC Run 2 in July 2016.

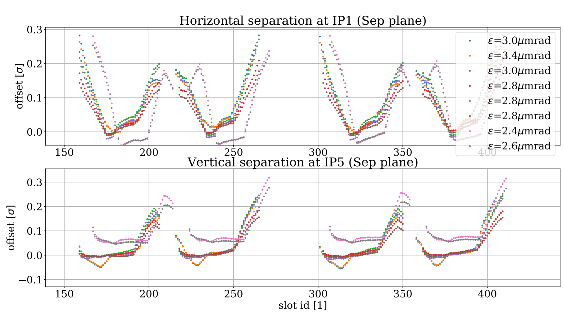

Figure 6: Selected simulation results for the LHC Run 2 fills in July 2016 corresponding to Figure 5 cases.

Simulations With Crossing Angle Asymmetry

Luminosity production in 2016 was showing an important imbalance between the luminosities of IP1 and IP5 [15]. In parallel the LR experiment have shown an unexpected tune shift which could be due to a possible asymmetric configuration of the LR encounters. Such asymmetry can occur for example if the two IPs crossing angles are different as shown in [12] with a direct impact on the luminosity geometric reduction factor of the two IPs. The impact of a possible asymmetry in the two main luminosity experiments angles on the orbit effects is at the level of 10% in the crossing angles can explain offset changes of the level 0.05 σ which can lead to less than a 1% on the luminosities. Therefore orbit effects from IP1 and IP5 LRs cannot explain the observed luminosity imbalance between the ATLAS and CMS experiments in Fig. 7.

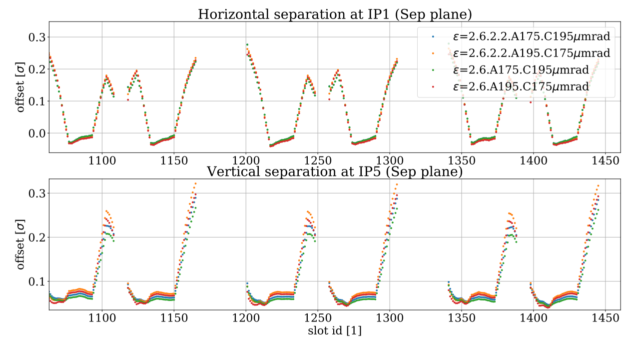

Figure 7: Bunch by bunch separations computed for different crossing angle imbalance values and for different emittances ratio (H/V)

CONCLUSIONS

The TRAIN code to compute bunch by bunch orbits has been updated to the LHC operational needs and preliminary comparisons to the luminosity peak positions have been shown. The measurements analysis needs still to take into account the orbit deflection coming from the separated HO during the scan. First comparisons show a good agreement specially for the vertical planes. Several observations (i.e. IP8 effects, horizontal effects) still have to be studied with more systematic analysis but gives good insight in the LR BB effects. Several scenarios for the 2016 LHC operation have been investigated and results reported. The explored method should be extended to the ATLAS experiment and made operational to follow up possible impacts of BB orbit effects to the different IPs during an operational cycle. In parallel, we plan to adapt and prepare TRAIN for future machines studies.

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