LHC PARAMETER REPRODUCIBILITY

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Abstract

This document reviews the stability of the main LHC operational parameters, namely orbit, tune, coupling and chromaticity. The analysis will be based on the LSA settings, measured parameters and real-time trims. The focus will be set on ramp and high energy reproducibility as they are more difficult to assess and correct on a daily basis for certain parameters like chromaticity and coupling. The reproducibility of the machine in collision will be analysed in detail, in particular the beam offsets at the IPs since the ever decreasing beam sizes at the IPs make beam steering at the IP more and mode delicate.

INTRODUCTION

The analysis presented in this document covers the tune, chromaticity, coupling and orbit stability of the LHC during the 2016 pp run. Depending on the case either all data is presented, or data limited to the high intensity proton fills.

TUNE

The tune is corrected automatically at injection for b2 decay by the FIDEL server and for intensity effects by a dedicated application [1]. Quality and limitations of those corrections were discussed in details at the 2015 Evian Workshop [1]. As soon as the probe bunches are injected, the tunes are measured and if necessary also corrected manually by the shift crews. The corrections correspond to un-modelled (or non reproducible) cycle to cycle tune changes. The range of trims is similar for both beams and both planes, $\Delta Q \simeq 0.015$. The spread is clearly visible in Fig. 1 that presents the superposition of all tune functions that were used throughout 2016 for beam 1 in the vertical plane. Those manual trims are still incorporated linearly into the ramp although they should be incorporated in snapback style since the tune changes seem to follow the decay / snapback model [1]. The later point could be improved for the 2017 run.

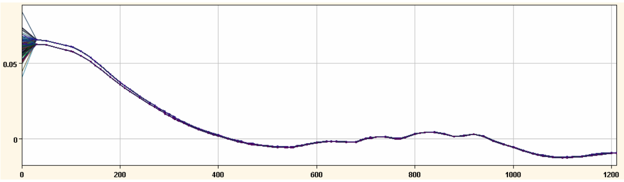

Figure 1: Superposition of all vertical B1 tune trims for the ramp.

The real-time (RT) trims applied by the tune feedback (QFB) during the ramp are presented for beam 1 high intensity fills in Fig. 2. Beyond ≈ 500 seconds the tune in the ramp is extremely stable, reproducible to better than ±0.002. In the first half of the ramp there are some systematic (Laslett tune trim incorporation) and some non-reproducible RT corrections. Possible improvements to reduce the amplitude of the RT corrections and to lower the dependence on the QFB include:

- modification of the incorporation of the Laslett tune trims to follow an inverse energy rule (1/E),
- incorporation of the manual tune trims at injection with the correct snapback-type rule by the FIDEL server.

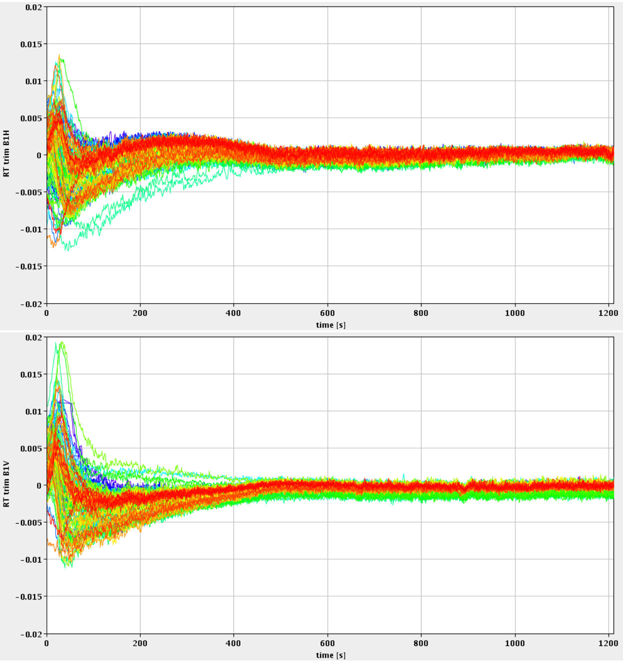

Figure 2: Evolution of the beam 1 tune RT trims during the ramp for the horizontal (top) and the vertical plane (bottom). The data is based on all high intensity cycle with beams having 25 ns bunch spacing (>1000 bunches).

The tune is extremely stable and reproducible during the squeeze, consistent with the second half of the ramp. The RT trims are stable to ±0.002 as can be seen in Fig. 3. After feed-forward the residual trims are very small, consequently the squeeze can be operated without QFB, as had to be done in certain periods when the tune quality was not sufficient.

CHROMATICITY

The b3 decay at injection is in principle compensated by the FIDEL server. Manual Q' trims are however performed following measurements with the probe bunches at the beginning of the injection process. The magnitude of those manual trims reflect the quality of the b3 decay modelling:

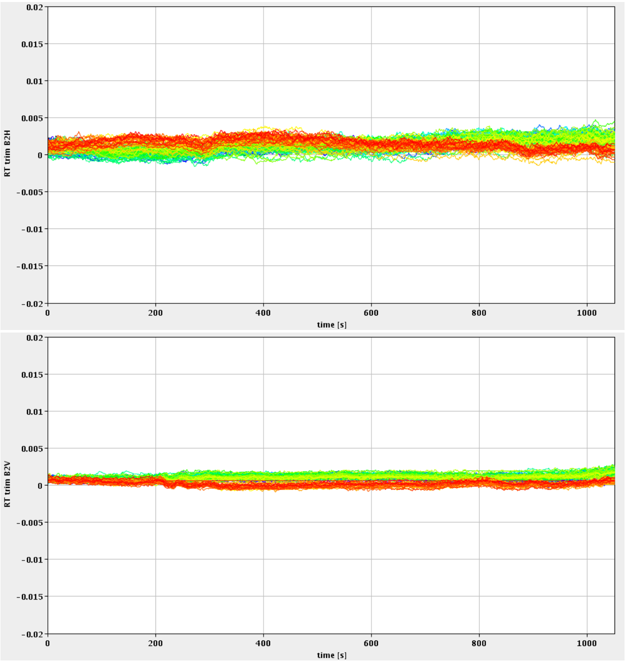

Figure 3: Evolution of the beam 2 tune RT trims during the squeeze (top: horizontal plane, bottom: vertical plane) for fills with high intensity 25 ns beams (>1000 bunches.

trims with a range of up to ≃ ±7 units are applied based on Q’ measurements with the probes, see Fig. 4. It is very likely that the incorporation into the ramp should follow the usual snapback shape instead of the linear decay as applied up to now. The solution would be similar to the case of the tune. The reproducibility of Q’ after ≈ 200 s of ramp is estimated to be around ≃ ±2 units based on the few available Q’ measurements during the ramp.

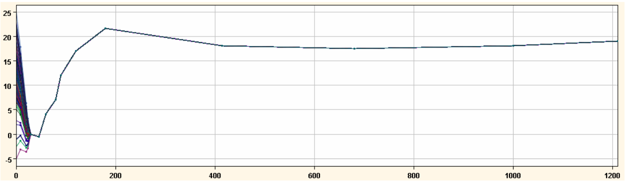

Figure 4: Superposition of all vertical Q’ trims for B1 in the ramp. At the start of the ramp one can observe the spread of the trims that are applied at injection and that are removed over the first 60 seconds of the ramp.

The Q’ functions of the squeeze have very few trims, see Fig. 5. The initial functions of 2016 were not correct for all planes: jumps of 5 units of the functions that were used after the first squeeze setup iteration turned out to be mistakes, most likely due to inconsistent Q’ target values. The mistake was corrected in June 2016.

The reproducibility of Q’ at FT and at the end of squeezes (for low, medium and high β^*, for protons and ions) is at the level of ±1-2 units. A more accurate estimate could be obtained by re-analysing all Q’ measurements performed in 2016. On one occasion (measurement series after Technical Stop 2) outliers of ±2 units (b3-style, with opposite sign for the two planes) seemed be related to a possible difference between the pre-cycle and the standard 6.5 TeV cycle.

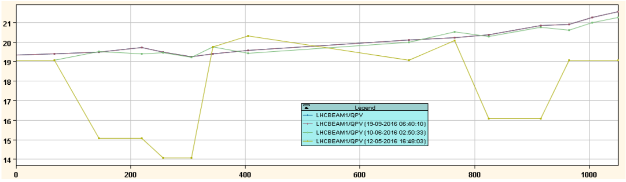

Figure 5: Superposition of all vertical chromaticity trims for B1 in the squeeze. The initial function of 2016 had strange jumps of around 5 units that were most likely due to inconsistent Q’ targets during the setup. After correction the functions were rather reproducible along the year within the limited measurement statistics.

COUPLING

In 2016 the coupling was measured and corrected systematically at injection for the first time since the LHC startup. From those measurements it was possible to confirm a clear decay of the coupling. The decay was observed online in the CCC with the BBQ when probe bunches were measured during longer time intervals. A dedicated MD in MD period 4 provided direct C- decay measurements over a few hours [2]. Figure 6 presents the coupling knob trims performed at injection for both beams along the year. It is clear that for all cases the values remain within a well defined band, there are apparently no drifts over long time scales. Figure 7 presents the same trims as a function of the time at injection: no clear decay-like signature is visible. This may be due to the fact that pre-cycle and 6.5 TeV cycles do not generate the same coupling decay (similar to tune and chromaticity): the data should in that case be separated for the two cases. Another explanation may be simply a fill to fill non-reproducibility.

The ramp functions of the coupling knobs converged slowly over a few weeks as it took some time to take measurements of coupling on the fly using the AC-dipole, see Fig. 8. The correction of C- was generally not much better that 0.01 for most of the 2016 ramps (low, medium and high β^*): this did not harm since all ramps were operated with injections tunes (0.28/0.31).

Only few coupling measurements were performed along the squeeze. Most measurements were consistent with each other within ±0.002 (knob units). The endpoint is consistent for B1 between April and October. After TS2 however a trim on the endpoint, due to poor quality BBQ derived coupling correction, is suspected to have generated instabilities at the end of the squeeze. Some days later it was confirmed that towards the end of the squeeze (below 80 cm), the increased tune spread and degradation of the tune peak sharpness led to incorrect coupling measurements by the BBQ. The lesson

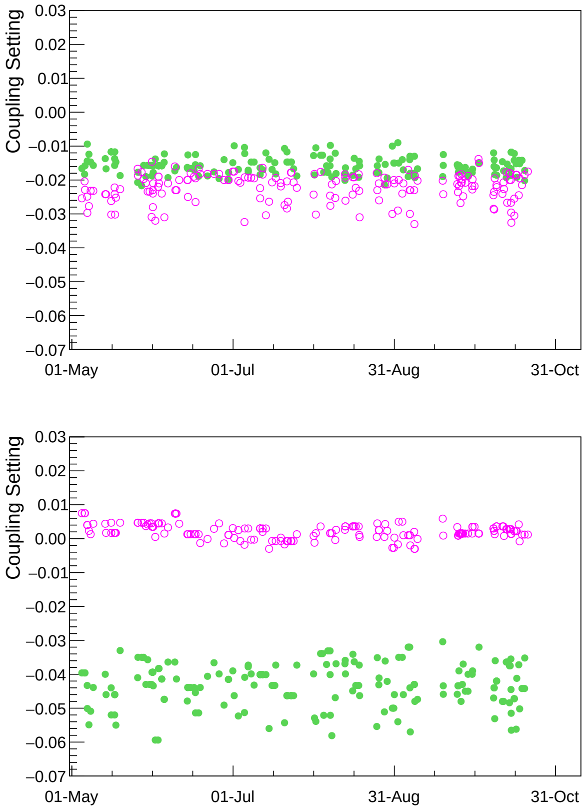

Figure 6: Evolution of the coupling trims of B1 (top) and B2 (bottom) along the 2016 run. The imaginary knob component is represented in magenta, the real component in green (filled points).

is that the BBQ only provides realizable coupling results when they are clean and unique Q peaks.

ORBIT

Since the beginning of the 2016 run, a very flexible and powerful new software is in place to generate the reference orbits along the cycle [3]. With this system a unique flat reference orbit was used for all machine configurations and cycles in 2016. All bumps (separation, crossing angles, TOTEM bump, luminosity scan knobs, ULO bump) were added to the base orbit using their LSA function settings. For the ion run the typical difference between the probe bunch and the nominal bunch orbit was added as additional 'bump' to this collection. This new system ensured for example that in IR7 the reference orbit was identical at every moment in the year, for every fill and every configuration.

The Orbit Feedback (OFB) was used throughout the run with the same configuration, manual orbit corrections were only applied during the initial setup of the cycles, and very rarely to follow triplet movements. Every one or two months, a feed-forward of the orbit corrector RT trims was applied to maintain the OFB trims as small as possible.

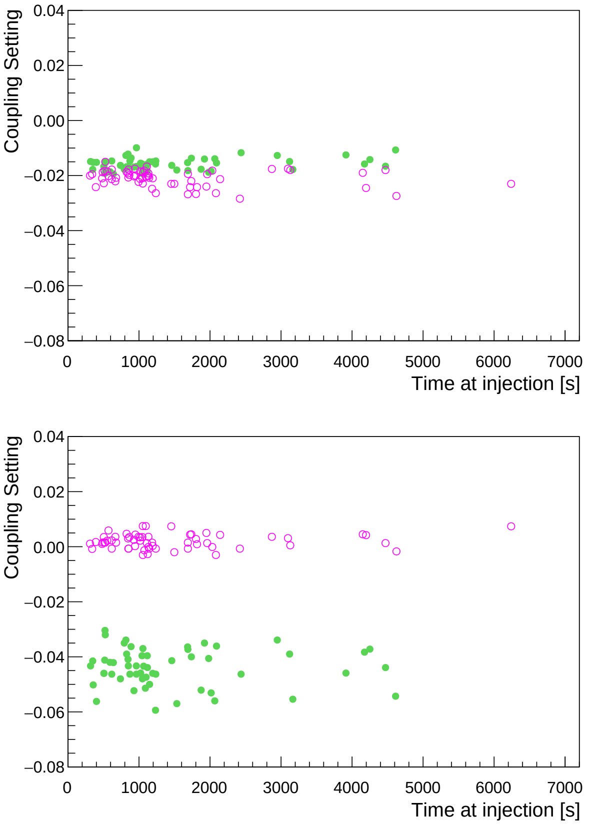

Figure 7: Evolution of the coupling trims of beam 1 (top) and beam 2 (bottom) as a function of the time at injection. The horizontal axis is the time in seconds at injection. The imaginary knob component is represented in magenta, the real component in green (filled points).

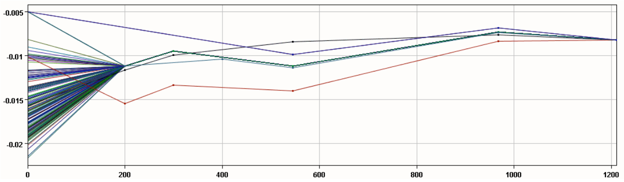

Figure 8: Superposition of all imaginary C- function trims for beam 1 in the ramp. It took some time to converge with the settings. The spread of the trims at injection is clearly visible.

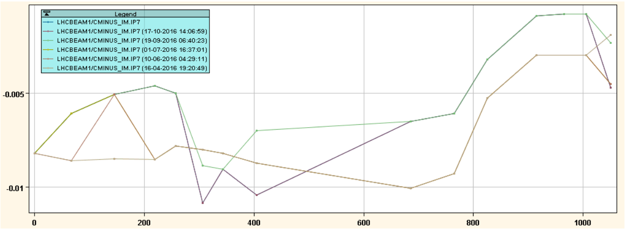

Figure 9: Superposition of all imaginary C- trims for B1 in the squeeze.

Global orbit

The general orbit data quality improved significantly after LS1 with the BPM rack cooling. Some remaining systematic shifts are still observed, but they are smaller by factor roughly 5 to 10 as compared to Run 1. This improvement allowed to run the OFB in stable beams since 2015 (but only with gentle correction strategy).

The orbit quality throughout the cycle evolved very little over the year. There were small degradations around the four experimental IRs (triplet region). They are most likely driven by triplet movements that are not perfectly compensated by the OFB due to the absence of the MCBX correctors in the OFB corrector set.

The orbit reproducibility (excluding the experimental IRs) in stable beams is presented in Fig. 10. The stability is excellent over the entire run, with a short term reproducibility of around 20 μm and a long term reproducibility of around 40-60 μm. An independent confirmation is the quality and stability comes from the IR7 collimator re-alignment that was performed in September for the ATS MD. The alignment results were consistent within 20 μm rms with the initial alignment performed in April 2016 (courtesy A. Mereghetti). In Fig. 10 the period when the wrong BPM calibrations were applied is clearly visible with a degradation to around 80 μm rms. During that period a BI server could not correctly set the calibration to be used, as a consequence the high sensitivity calibrations were used instead of the low sensitivity values.

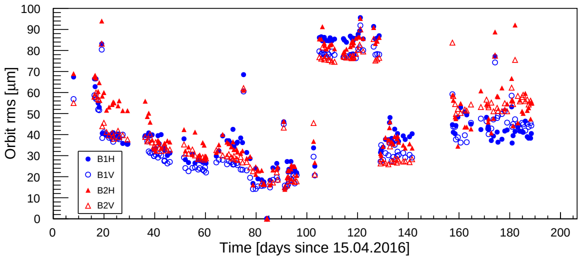

Figure 10: Evolution of the orbit rms in stable beams for 25 ns beams in 2016. The reference corresponds to a fill on July 14th. The period between days 100 and 125 was affected by an incorrect calibration (high sensitivity instead of low sensitivity). Isolated outliers are also due to incorrect calibrations, usually due to the wrong beam type selection.

Figure 11 presents the orbit rms with respect to the reference orbit along the cycle from the start of the ramp to the end of adjust for two fills. The first fill (4979) is one of the first high intensity 25 ns beam fill. The second fill (5448) corresponds to one of the last high intensity 25 ns beam fills. The difference between the two fills is very small, which highlights the excellent reproducibility of the orbit during the run which is a key ingredient of the very stable cleaning efficiency of the LHC collimation system.

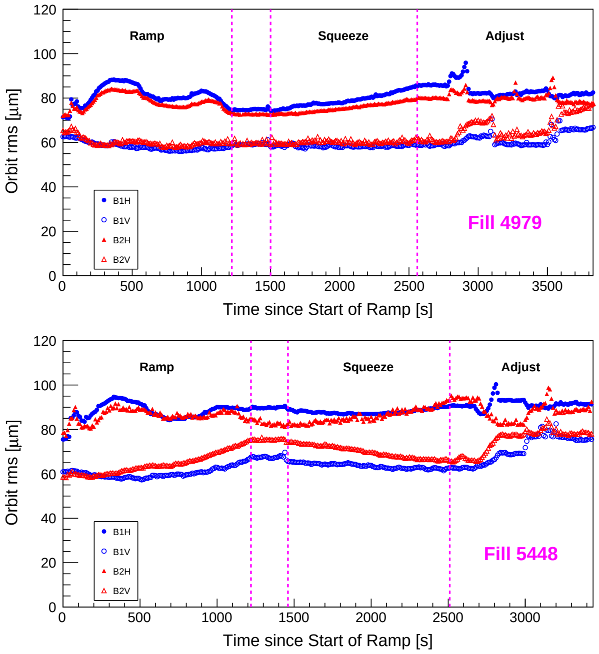

Figure 11: Evolution of the orbit rms with respect to the reference orbit through the cycle from the start of the ramp to the end of adjust. The upper figure corresponds to an early 25 ns beam fill while the lower figure corresponds to one of the last fills.

The evolution of the 60 A MCB arc orbit corrector strength can be used to estimate the machine movements during the run. The rms kick change of around 1.2 μrad over half a year corresponds to a rms misalignment of the machine quadrupoles of around 55 μm. Scaled to an entire year the misalignment corresponds to around 100 μm. This value is consistent with survey observation (already from LEP times). The misalignment is small enough to be able to bootstrap a run with the orbit corrector settings of the previous one, and obtain immediately a circulating beam without the need of threading.

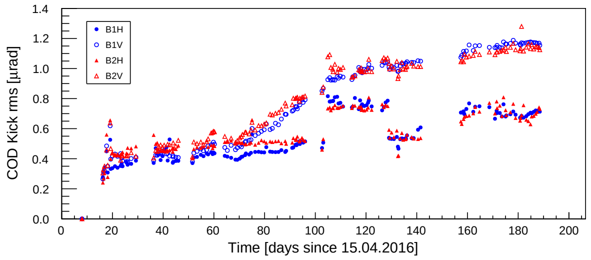

Figure 12: Evolution of the arc orbit corrector (60 A MCB circuits) kick rms in stable beams during the 2016 run.

Beam offsets at the IPs

The beam separation corrections that are applied during the run to bring beams back to head-on collisions are presented in Fig. 13 for ATLAS and CMS for the low β^* configuration (40 cm). The beam size is indicated by the small

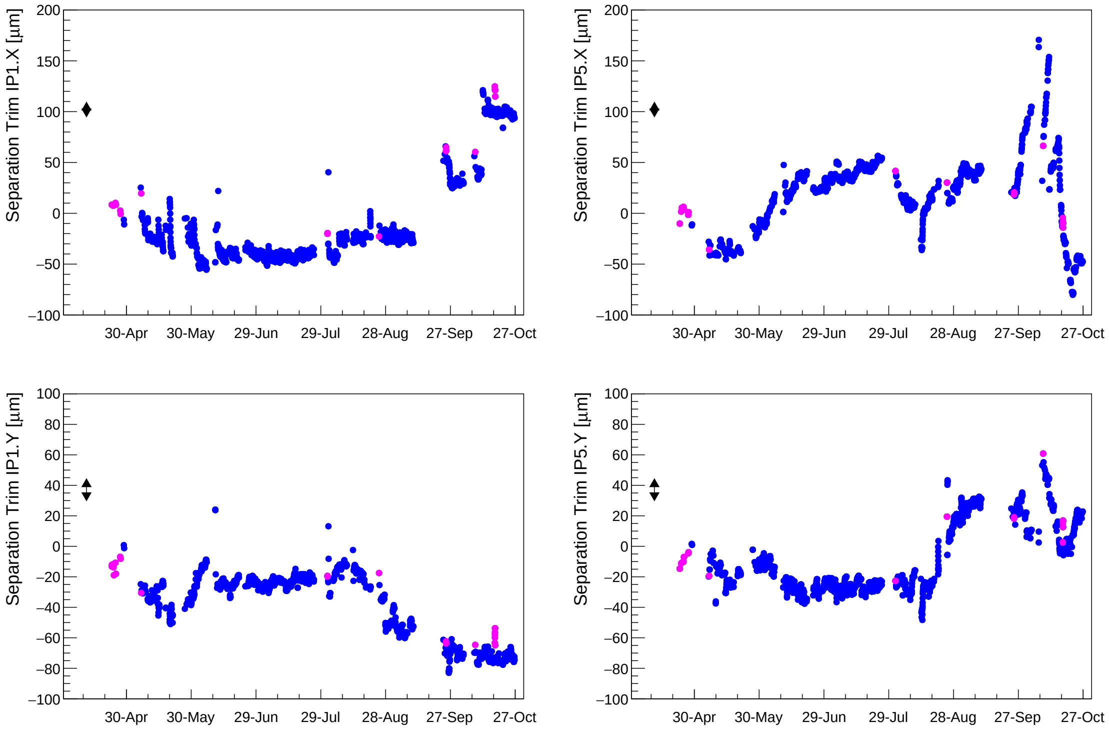

Figure 13: Evolution of the beam separation corrections at IP1 and IP5 for the horizontal (top row) and vertical (bottom row) planes. Each point corresponds to a luminosity optimization during stable beams or in adjust.

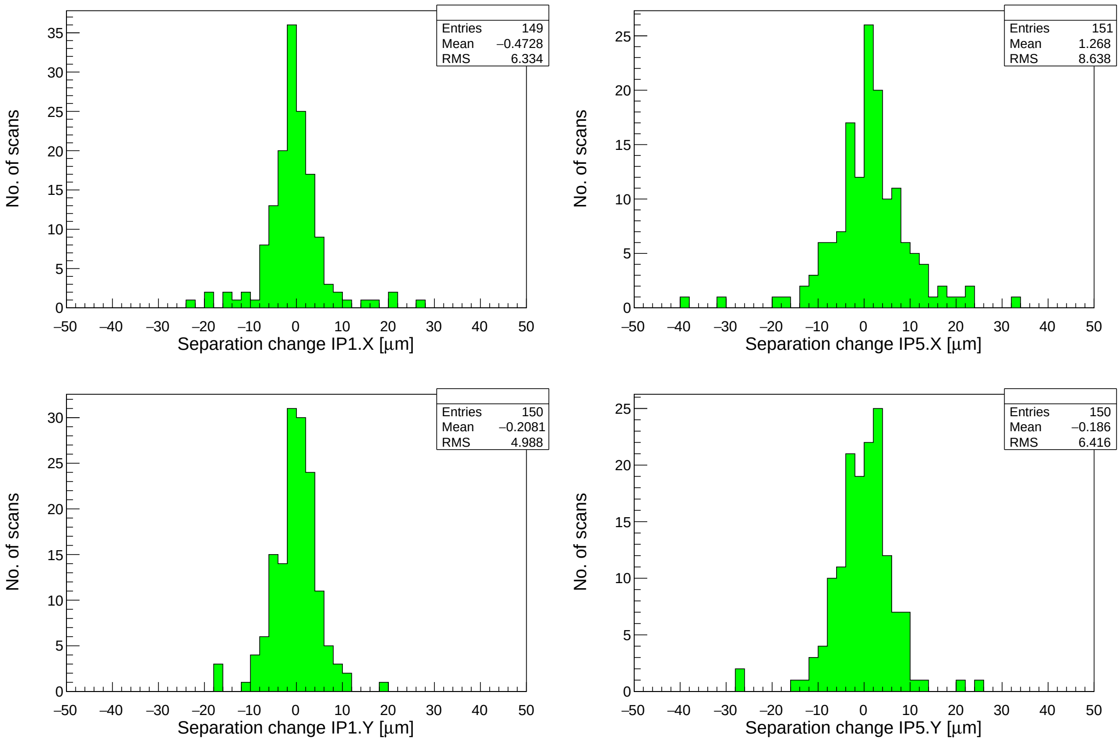

Figure 14: Distributions of the fill to fill beam separation changes at IP1 and IP5 for the horizontal (top row) and vertical (bottom row) planes.

arrow on the left side of the plots. The corrections are very large, exceeding 10 rms beam sizes over the year. In general the vertical plane is slightly quieter than the horizontal plane that is affected by support issues. The main effects that drive beam separation changes are movements of the triplet quadrupole magnets. Those movements are induced by:

- triplet magnet quenches that lead to sudden position jumps,
- cryogenic transients with large pressure transients (for example the weasel event in May 2016 affecting point 8),
- triplet thermal screen temperature changes [4],
- and sudden unexplained movements as was observed for the IP5 triplet in October and November 2016 [5], see top right plot of Fig. 13.

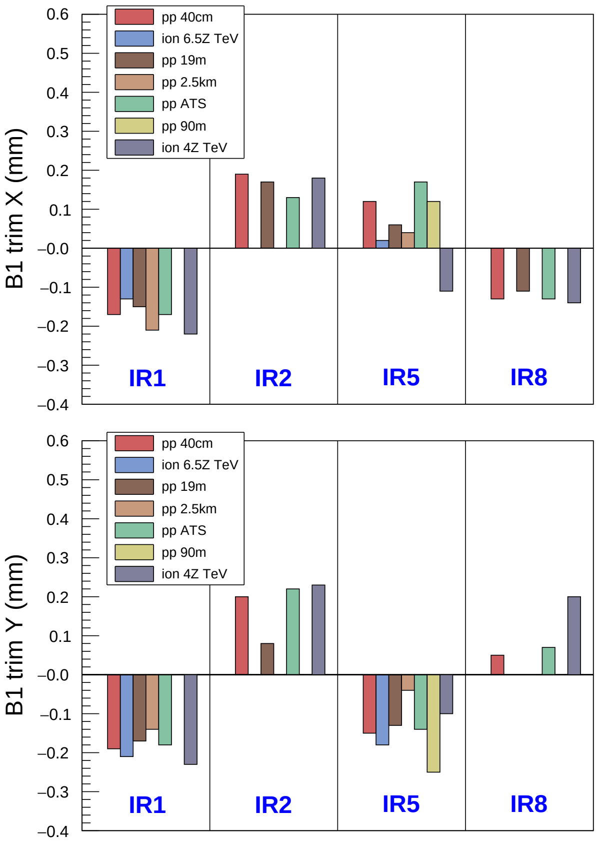

Figure 15: Typical beam offset corrections at the IPs for beam 1 (the beam 2 corrections have the opposite sign) for different machine configurations and energies.

The fill to fill (short term) rms beam separation change amounts to $\approx \sigma/2$ as can be seen in Fig. 14. The vertical plane of IP1 has the best reproducibility as it was only affected by slow drifts. In all planes the core of the reproducibility distribution is similar, but the tails due to the perturbations described earlier are quite different. The reproducibility expressed in units of rms beam size at the IP is presented in Table 1 and is similar between 2012, 2015 and 2016.

Table 1: Rms spread of the fill to fill beam separation changes for IP1 and IP5 in the horizontal and vertical planes for 2012 (β^* = 60 cm), 2015 (β^* = 80 cm) and 2016 (β^* = 40 cm).

IP	Run	H plane [μm]	V plane [μm]
1	2012	13.4	11.1
5	2012	11.4	10.9
1	2015	8.2	8.7
5	2015	7.5	8.3
1	2016	6.3	5.0
5	2016	8.6	6.4

The beam offset corrections that must be applied to bring the beams head-on are rather reproducible with optics and energy as can be observed in Fig. 15 where the typical offsets are compared for the various optics configurations used in 2016. A positive side effect is that once the corrections are known for one optics, they can be used to efficiently bootstrap other configurations. This is another positive side effect of the orbit reference system based on a unique base orbit for all configurations.

If the resolution and long term accuracy would be sufficient, the Q1 BPM position measurements performed with the DOROS acquisition system could be used to steer the beams deterministically into collision. Unfortunately this is not possible because the fill to fill reproducibility of the DOROS readings, interpolated to the IP, is much worse than the fill to fill machine reproducibility as can be seen in Fig. 16. The DOROS IP position fill to fill accuracy is around 20 μm in the separation plane and over 100 μm in the crossing plane. This difference is explained by the $\approx$ 3 mm beam offset in the Q1 for the crossing plane. The short term accuracy (time scale of 15-60 minutes) of the DOROS readings is however excellent, at the level of 1 μm.

Triplet wire position system

The Wire Position Sensors (WPS) installed for each triplet monitors the position of the cryostat outside shell with respect to a wire stretched from the IP side of Q1 to the end of the D1 separation dipole as shown in Fig. 17. Provided the cryostat movement reflects the movement of the cold mass, it should be possible to estimate the beam separation at the IP from the WPS readings by reconstructing the total effective kicks for each triplet and by taking into account the action of the OFB. This was done with good success for the the slow movement of the triplet on the right side of IP8 in 2015 [6].

The prediction of the IP shift from WPS data at the end of adjust with a simple effective kick and scale factor ($\simeq$ 36 μm/μrad) agrees with the observed beam separation only for the horizontal plane of IP5, see Fig. 18. For the

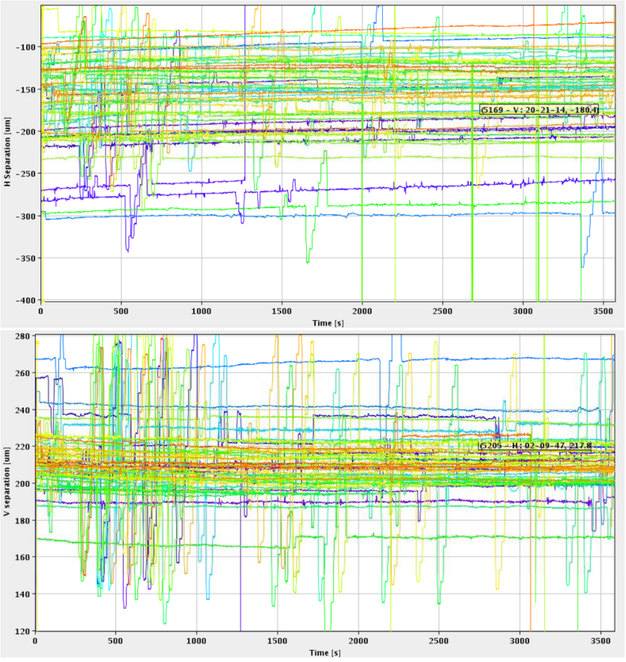

Figure 16: Predicted horizontal (top) and vertical (bottom) beam separation at IP5 during the first hour of stable beams based on the DOROS Q1 readings for around 80 high intensity fills with 25 ns bunch spacing.

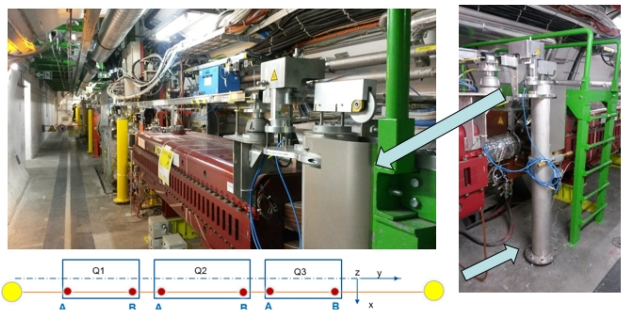

Figure 17: Triplet area in the left side or IP5 (left) with the layout of the WPS system and the WPS support pillar next to D1 (right).

other cases the correlation is not very good. This may be an indication the the cold mass and cryostat movement are not (always) identical, for example during sudden changed following quenches or other violent events. For smooth and slow movements on the other hand, the correlation is more satisfactory.

Orbit feedback improvements

It is very likely that the dominant contribution to the beam separation changes (Fig. 13) observed in stable beams is due to an imperfect correction of the local orbit by the OFB. Triplet movements cannot be corrected locally because the common MCBX correctors are not included in the set of correctors used by the OFB. The reason is the presence of the Quench Protection System (QPS) that is very sensitive to acceleration changes of the circuit current. The other LHC orbit correctors are self-protected and operate without QPS. If the MCBX were included in the OFB corrector set, the situation could improve significantly provided the BPM fill to fill reproducibility is at the level of 10 μm or better (exact value to be confirmed). If the BPM fill to fill reproducibility is too poor, the OFB could even degrade the situation with the MCBX by propagating BPM errors to the IP [6]. An MD that tested the MCBX in the OFB in 2016 highlighted again that to use the MCBX the OFB will have to control (limit) the acceleration rates that it is using to steer the beams. Limiting the acceleration will effectively apply a low pass filter to the OFB RT trims, fast corrections will be slowed down and high frequency noise will be suppressed. An analysis should be made on past orbit corrector data of the 2016 run to understand what the impact of an OFB acceleration limiter would be. It may be possible to prepare an implementation in the OFB with a switch to enable/disable the acceleration limits that could be be tested in 2017 during MDs.

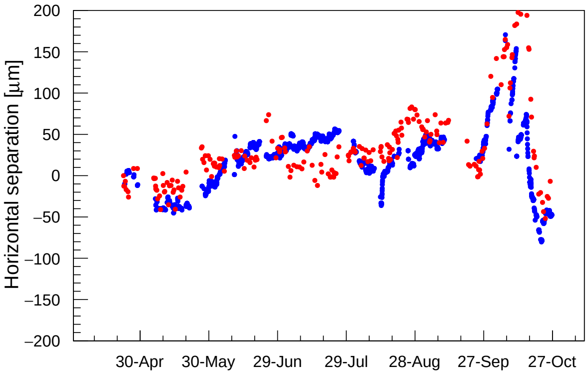

Figure 18: Comparison of the measured beam separation in IP5 in the horizontal plane (blue circles, see also Fig. 13) with the predicted separation based on the triplet WPS data (red circles). The overall agreement is fair.

FAST ORBIT OSCILLATIONS

The levelled experiment's luminosities clearly exhibit the signatures of different types of small amplitude (μm) periodic orbit oscillations visible in Fig. 19 [7]. Two main oscillation patterns can be observed. A first pattern lasts typically 30-40 minutes with periodic orbit changes every 15 seconds. This pattern repeats roughly every 4 hours. A second pattern is more erratic, with sudden jumps roughly every 6 minutes. This also affects manly beam 2 in the horizontal plane. For both cases the orbit change is clearly visible on the DOROS Q1 readings.

CONCLUSIONS

With the exception of decay and snapback effects, the LHC reproducibility proves to be remarkable, in particular

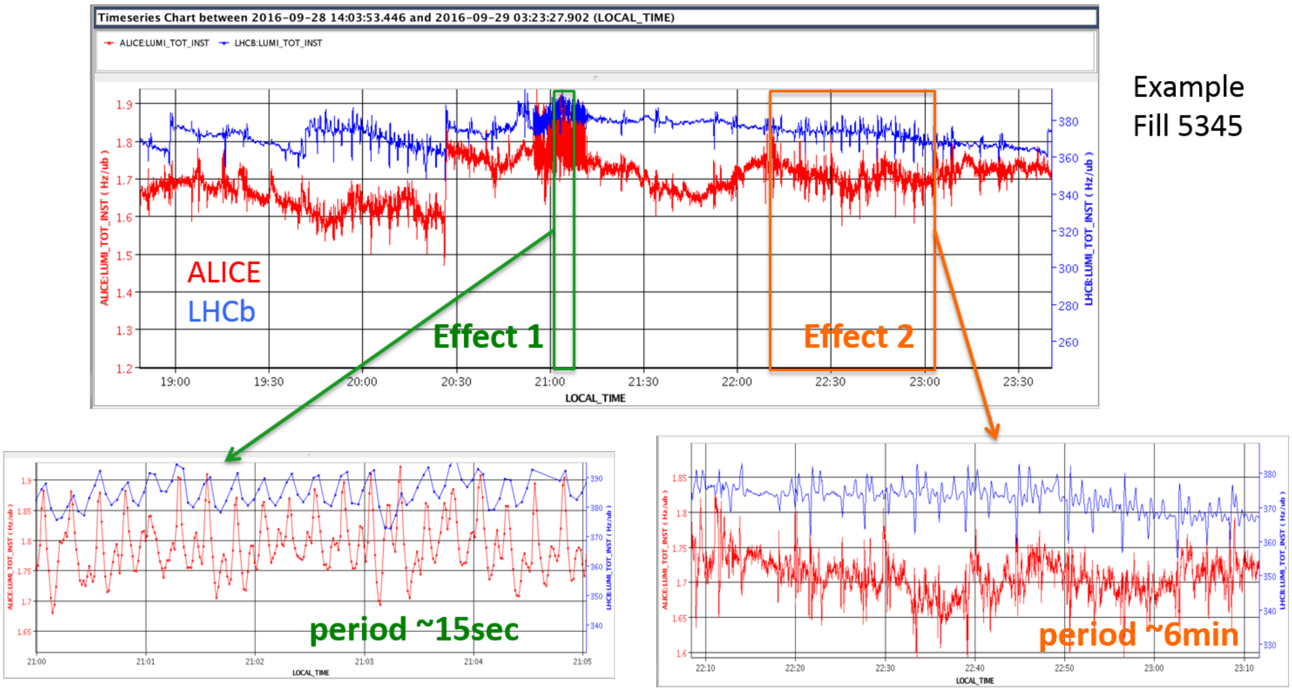

Figure 19: Example of fast orbit oscillations that can be observed periodically on the luminosity of the levelled experiments ALICE and LHCb [7].

at 6.5 TeV with a tune stability of ±0.002 , a chromaticity stability of ±2 and probably a coupling stability of ±0.002. With the OFB acting on the beam, the arc orbit stability is $20 - 50$ μm.

The potential impact of poor(er) coupling could be reduced by moving the tune change (from injection to collision tunes) to the end of the squeeze as was done during the ATS MDs.

The reproducibility of the machine is so good that there is no real need for extensive test cycles when settings for special configurations are reused after a longer interruption (for example medium or high β^*). The impact of triplet movements during a period where settings were not used can be assessed and even corrected.

The triplets are the most notable source of orbit perturbation, and their impact affects mainly the beam separation for stable beams at low β^*. The overall behavior and the impact of triplet movements has been clarified in 2016, in part due to the systematic monitoring of the WPS data in the CCC. Including common correctors in the OFB may be the only qualitative jump that one could envisage for the orbit control, provided the BPM reproducibility is adequate.

The origin of the periodic fast orbit oscillations with μm amplitudes, clearly visible on levelled luminosities and on the DOROS BPMs, remains a mystery.

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