LHC ORBIT SYSTEM, PERFORMANCE AND STABILITY

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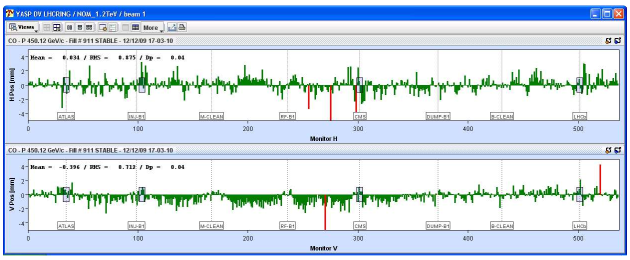
Abstract

During the LHC run period in 2009 the Orbit system proved to be very reliable. In the following the analysis results of the first data collected during various beam processes (stable periods, ramp and squeeze) are shown and several correction alternatives are proposed. The commissioning status of beam positions monitors, orbit correctors and the real time feedback system is summarized and open issues are listed at the end.

GOLDEN ORBIT

The orbit referred to in the following as the golden orbit is the orbit which was established on 12 December 2009, 17:03 ("Scanned Santa Claus reference" in the reference catalog). It was used as reference for orbit correction during the subsequent operation period. Figures 1 show this orbit for both beams and both planes.



(a) beam 1

(b) beam 2

Figure 1: Horizontal and vertical trajectories of the last golden orbit.

The orbit is very nicely centered in the horizontal plane (mean H smaller than 40 μm for both beams) but has a non-negligible offset in the vertical plane between -300 μm (beam 2) and -400 μm (beam 1). The main contributions to this offset are the systematic offsets in the arcs 23, 34 and 45 of around 1 mm, which are still not fully understood.

This orbit includes already trims for the IPs. Some of these trims were relatively strong, such that e.g. it would not be possible to scale them to 7 TeV. This is illustrated in Fig. 2, which shows a histogram of all the used corrector strengths for both beams and both planes. There it is nicely visible that there are outlayers of larger strengths (absolute values up to about 130 μrad)

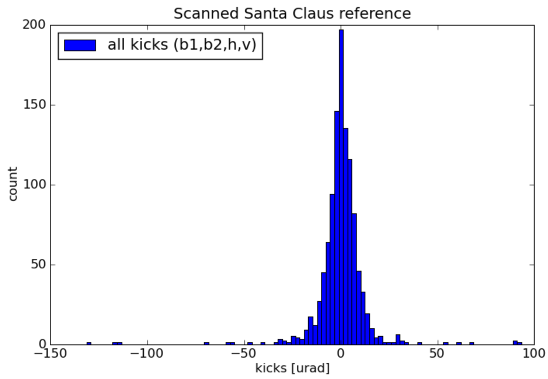


Figure 2: Distribution of corrector strengths for both beams and both planes in the settings for the 'Scanned Santa Claus reference': mean=0.08 μrad, rms=12.25 μrad.

Possible correction improvements

It would be more desirable to avoid such strong single correctors because of scalability to higher energies. Several alternative corrections scenarios were calculated to demonstrate that a better correction is possible. For example an SVD correction on the (reconstructed) bare orbit with 300 eigenvalues already improves the situation. As an example Fig. 3 shows the situation for the vertical plane of beam 2 of the original golden orbit before this correction. The (calculated) resulting orbit and kicks after the mentioned correction are shown in Fig. 4. Here the corrections are distributed over the whole ring and all the kicks are nicely below 30 μrad. This is also visible in the histogram showing the kick strengths after that correction (Fig. 5)

Using more eigenvalues for the SVD correction would improve the orbit even further. Nevertheless this has to be done carefully. For example when using more eigenvalues one starts correcting the systematic offsets in arcs 23, 34 and 56. These then transform directly into systematic offsets in the corrector settings. An example of such a correction is shown in Fig. 6 with 400 eigenvalues on the bare

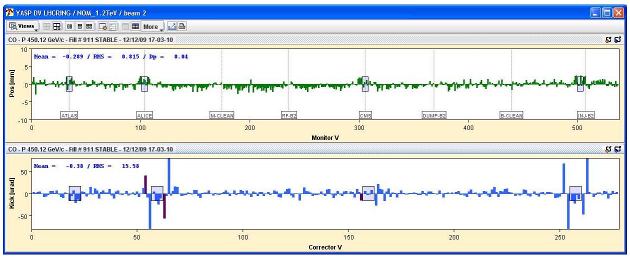


Figure 3: Vertical orbit and corrector strengths for beam 2 of the ’Scanned Santa Claus reference’. The strong corrections near the IPs are visible.

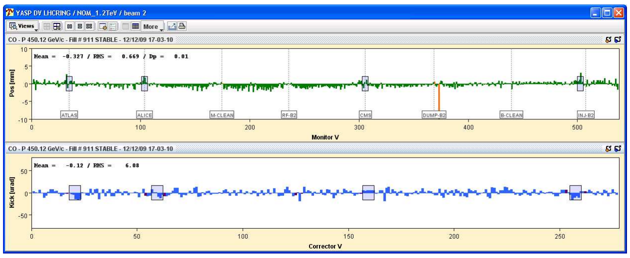


Figure 4: Vertical orbit and corrector strengths for beam 2 of the ’Scanned Santa Claus reference’ after a correction using SVD with 300 eigenvalues on the bare orbit. The correction kicks are more nicely distributed along the ring.

orbit. Before applying such corrections to the real machine the source of these systematic offsets must be investigated. Two scenarios would be possible:

- The offsets are results of e.g. some systematic misalignments of the quadrupoles in that regions. This then would mean that a correction would be advisable to maximize the aperture in that region.

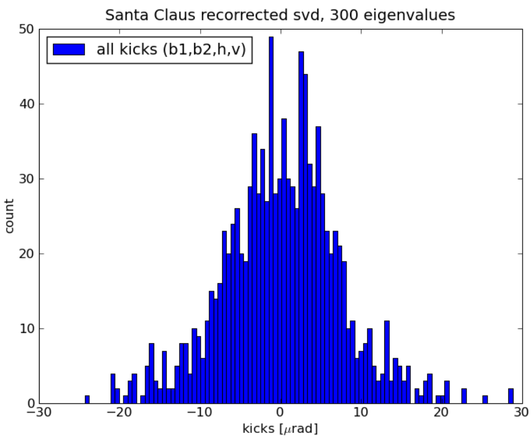


Figure 5: Distribution of kick-strengths for both beams, both planes after a correction using SVD with 300 eigenvalues on the bare orbit: mean=0.12 μrad, rms=7.31 μrad.

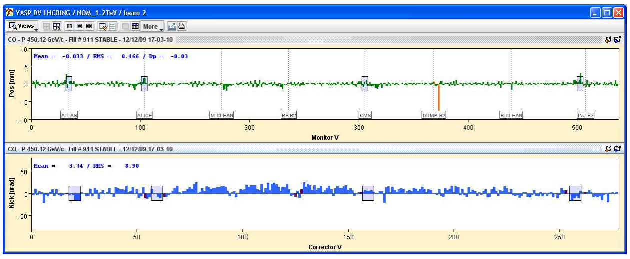


Figure 6: Golden orbit recorrected with SVD (400 eigenvalues) on the bare orbit. The systematic vertical offsets in the arcs (Fig. 3) is transformed into a systematic offset of the corrector strengths.

- The offsets are due to misaligned BPMs or false BPM readings. In this case the orbit should not be corrected in that region.

In order to distinguish these possibilities it is proposed to try a local aperture measurement in this region to verify if the vertical aperture is symmetric in this region or not.

ORBIT EVOLUTION DURING STABLE PERIODS

Data is available for two longer periods of stable beams, one for 450 GeV (8 December 2009, 02:00 to 06:00) and one for 1.18 TeV (16 December 2009, 03:40 to 05:30). Figure 7 illustrates the evolution of beam 1 during the 4 hours of stable beams at 450 GeV. It shows that the evolution of the horizontal mean is mainly dominated by the change of the radius resulting from the tidal forces of sun and moon.

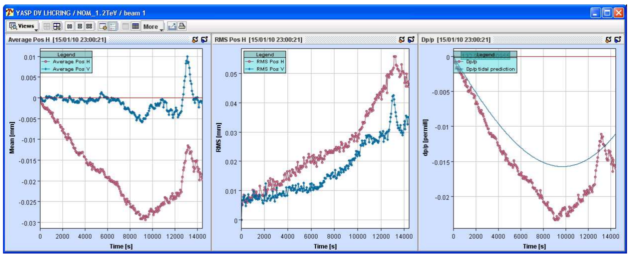


Figure 7: Evolution of the characteristic orbit parameters for beam 1 during the stable-beams period between 02:00 and 06:00 on 16 December 2009. The x-axis shows the time in seconds.The left plot shows the evolution of the mean positions (red: H, blue: V), the middle plot the evolution of the rms values (red: H, blue: V) and the right plot the evolution of the energy error resulting from the tidal forces (red: measured, blue: prediction).

The humps which are visible in all these plots towards the end of the period can be tracked down to a few sectors, namely the regions arc 34, IP4, arc 45 and arc 78, IP8, arc 81. This is illustrated in Fig. 8 which only shows the arcs with the biggest change.

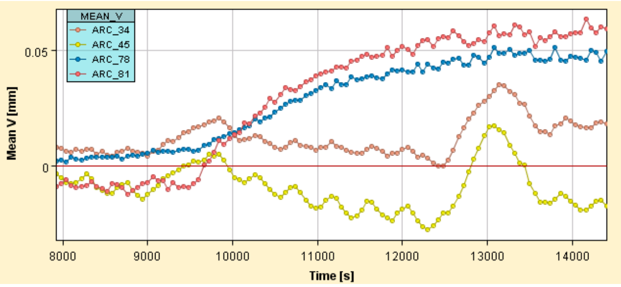


Figure 8: Arcs (beam 2) with the largest change in the vertical mean value during the last 2 hours of the 4 hours stable beams period. A drift of the mean of around 50 μm is visible for the arcs 78 and 81 and the humps in the end are clearly visible only in arcs 34, 45.

DAB temperature influence

The behavior of the arcs 34, 45 became even more visible in the data of the two-hours period of stable beams at 1.18 TeV on 16 December 2009. Figure 9 shows the evolution of the beam parameters during this period. The oscillations are again nicely visible in the evolution of the vertical mean. Calculating the data for the different arcs separately again reveals arcs 34 and 45 as the main contributors (Fig. 10). Further analysis finally revealed a correlation between the temperature of the BPM DAB cards and the beam position returned by the BPMs. Figure 11 shows the vertical mean value as shown in the previous plots in comparison with the temperature of an example DAB card located in Point 4. This shows an almost perfect correlation.

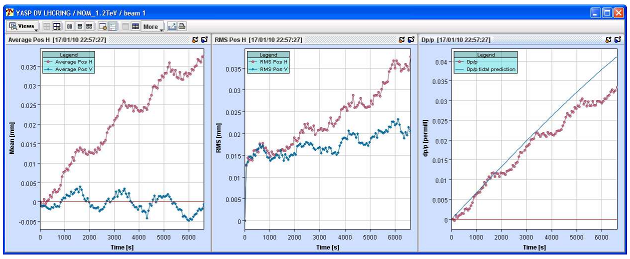


Figure 9: Evolution of mean, rms and energy error for beam one during the 2 hours of stable beams at 1.18 TeV on 16 December 2009.

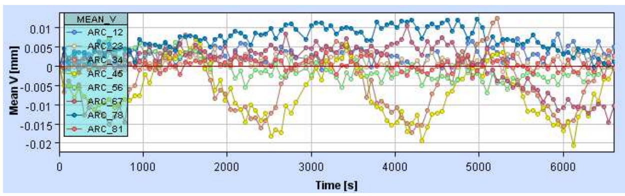


Figure 10: Evolution of vertical mean during 2 hours of stable beams at 1.18 TeV on 16 December 2009. The oscillations are only visible in arcs 34, 45.

To illustrate the influence of the temperature on one single BPM reading the oscillation during the same period on one of the concerned BPMs is shown in Fig. 12. The amplitude of the oscillation is around 100 μm peak to peak which corresponds to a temperature change of about 1°C as visible from Fig. 11. The correspondence of the oscillations to the DAB cards in point 4 is also nicely visible in Fig. 13 which shows the position reading versus time for the whole ring (beam 1). The oscillations start exactly on BPM.32.L4 and end at BPM.32.R4. This is exactly the range of BPMs whose DAB cards are located in point 4.

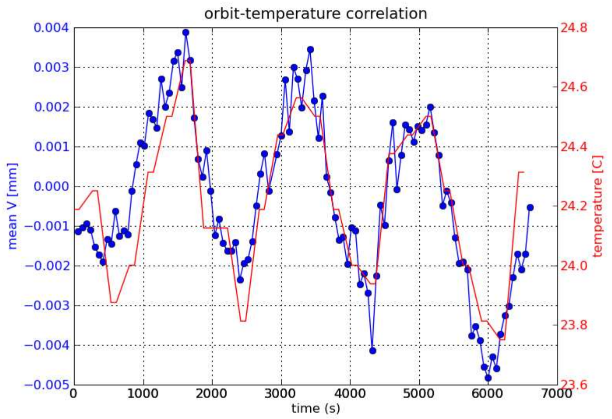


Figure 11: Vertical mean value during 2 hours of stable beams at 1.18 TeV in comparison with the temperature of an example DAB card in Point 4.

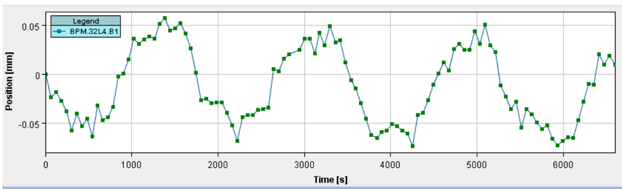


Figure 12: Oscillation of the position reading of an example BPM whose DAB card is located in Pt. 4.

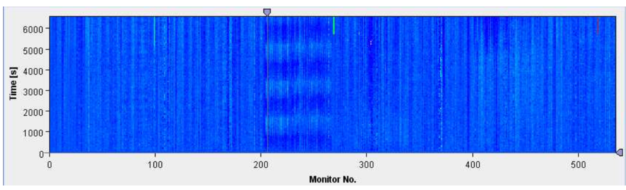


Figure 13: BPM around the whole ring versus time. Time goes from bottom to top in seconds. The oscillations start exactly in the middle of the arc 34 (around Monitor number 200) and end in the middle of the arc (around Monitor number 270)

This effect was observed and documented already in

2008 and is followed up by BI. It is due to the fact that in Point 4 the BI electronics is located in a relatively small room and not in a large hall with other racks as at the other access points. Therefore the temperature is much more dependent on the local climate control unit and local air flows, which in the end cause the temperature oscillations. There are several possible strategies to deal with this problem:

- better temperature stabilization.
- short term: monitoring of DAB temperature and corresponding calibration drifts, recalibration each fill (sequencer?)
- medium-term: compensate the position by the known DAB temperature drifts within the feedback controller
- long-term: ongoing prototyping of crate temperature control to stabilize these drifts at the source.

Stability in collimation regions

Of special interest is the change of the position - difference between primary and secondary collimators. Once the collimators are set up it is required that this difference does not change more than 0.3σ to ensure the hierarchy between the collimators.

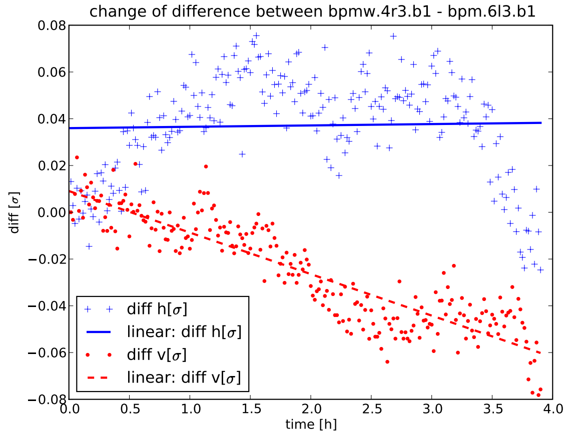
To estimate these change rates the positions at two selected BPMs in LSS3 are shown in Figs. 14 for both planes together with linear fits to the data. The average drift rates from these fits are collected in Table 1.

energy [TeV]	plane	lin. drift [σ/h]	p.t.p. change [σ]
0.45	H	0.0006	0.1
	V	-0.02	0.1
3.5	H	0.002	0.28
(scaled)	V	-0.05	0.28

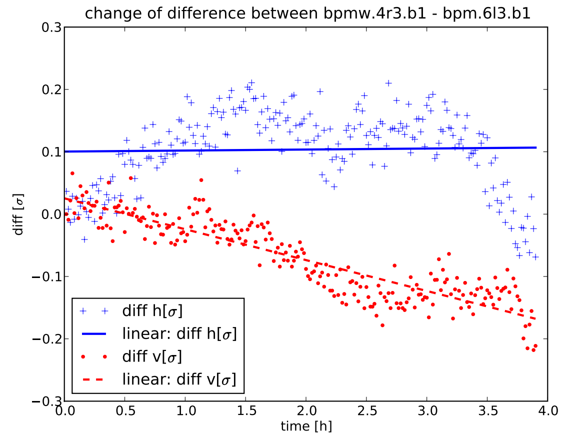
Table 1: Estimated linear drift rates and peak to peak changes deduced from Figs. 14.

The horizontal data is again dominated by the energy change because of the tidal forces and the very small linear drift is not representative. Nevertheless even here the peak to peak excursion of 0.1σ for 450 GeV is nicely within the limit of the required 0.3σ. In the vertical plane the linear drift of $0.02\sigma/h$ would allow about 15 hours of running without correction until the limit of 0.3σ is reached.

At 3.5 GeV the limits become tighter. The values for Fig. 14(b) are calculated using the same BPM readings in mm but calculating the beam size using the emittance for 3.5 GeV. The resulting vertical drift rate of 0.05σ/h would still allow a time without correction of about 6 hours and the peak to peak changes (0.28σ) are still within the limit.



(a) σ at 450 GeV



(b) σ scaled to 3.5 TeV

Figure 14: Change of difference between BPMs near primary and secondary collimator in LSS3 during the period of 4 hours stable beams at 450GeV in units of σ. (relative to the first difference)

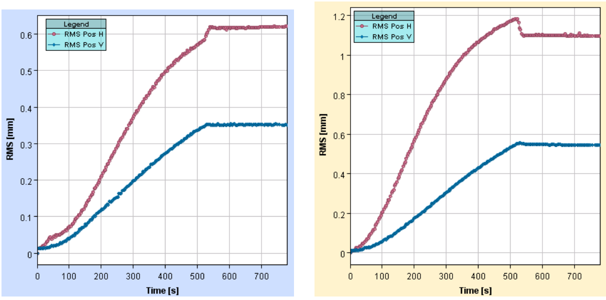
ORBIT EVOLUTION DURING RAMP AND SQUEEZE

Since ramp and squeeze are covered by two separate contributions in this workshop, only very few orbit related comments are given in the following.

Ramp

Figures 15 show the evolution of the rms for both beams and both planes during the last ramp (16 December 2009, 00:49 to 01:02). The maximum rms value is between 0.46 mm (beam 1) and 1.1 mm (beam 2).

If the rms continues increasing like this during the ramp to 3.5 TeV then the limit of the position interlocks in point 6 (3 mm) will soon be reached. So it will be necessary to use the orbit feedback system during the ramp. To estimate the orbit drift rate Fig. 16 shows as an example again



(a) beam 1 (b) beam 2

Figure 15: Evolution of horizontal and vertical rms during last ramp in 2009 (16 December 2009).

the change of the horizontal rms of beam 2 together with its numerically calculated derivative. It is visible that the maximum rms change rates are smaller than 5 μm per second which is smaller than the originally estimated 15 μ per second during the snapback, which ensures that the orbit feedback could handle these changes without problems.

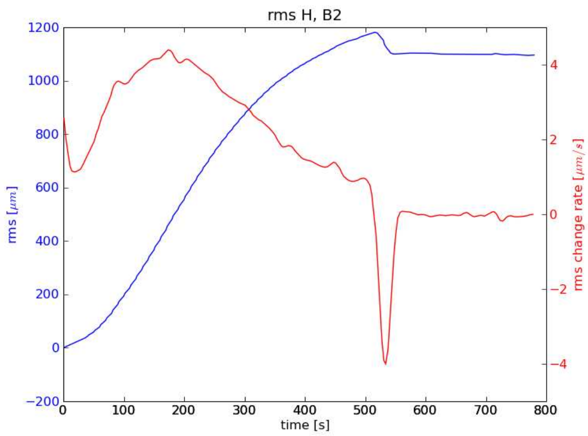
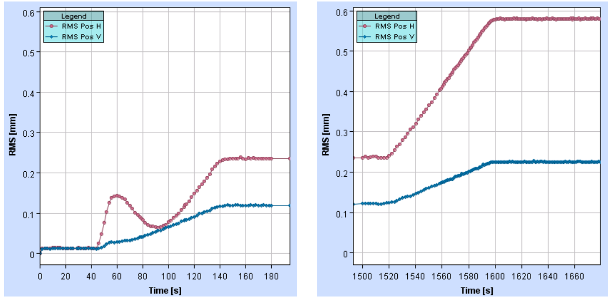


Figure 16: Horizontal orbit rms evolution for beam 2 and its change rate during the ramp.

Squeeze

Figures 17 show the evolution of the orbit rms for beam 1 and both planes during the squeeze test in IP5 on 16 December 2009 (02:27 to 02:54) for both steps of the performed squeeze.

The maximum rms values at the end of the squeeze were 0.6 mm for beam 1 and 1.1 mm for beam 2 (both in the horizontal plane). The change of the orbit was distributed around the whole ring, so the error is not due to locally closed bumps but to an orbit perturbation due to a beam offset at the quadrupoles whose strengths are changed during the squeeze. So also during the squeeze the orbit feedback will be mandatory to compensate these errors.



(a) β @ IP5: 11 m $\rightarrow$ 9 m (b) β @ IP5: 9 m $\rightarrow$ 7 m

Figure 17: Evolution of the orbit rms for beam 1 during the two performed squeeze steps in IP5.

COMMISSIONING STATUS

BPM and COD polarity checks

Systematic polarity checks of BPMs (beam position monitors) and CODs (orbit corrector dipoles) were performed during the running period in December 2009. Although not totally completed the majority of the monitors and correctors was checked. The current status is summarized in Table 2. A few inverted BPMs were identified and some trickier problems (e.g. wrong rotations for BPMS monitors) were already solved at the end of the running period. The rest of the issues are currently followed up by BI.

	beam	checked	ok (of checked)
BPMs	B1	100%	97.58%
	B2	100%	98.33%
CODs	B1	95,08%	100%
	B2	73,03%	100%

Table 2: Status BPM and COD polarity checks at the begin of winter shutdown 2009/2010.

The situation for the Corrector magnets is somehow inverted: All the tested CODs were correctly functioning, but not all of them were checked so far. Especially none of the MCBX magnets were checked systematically although they all have been used heavily in the meantime and seemed to work correctly. Nevertheless at the end of the run the suspicion occurred that at least one of them might be inverted. Therefore it would be advisable to check them systematically, too.

Orbit feedback

Due to the short period of time available for commissioning the orbit feedback system was tested in an ”all or nothing” fashion. The bandwidth measured from the performed tests was as expected (0.1 Hz) which is a strong indication that all subsystems work correctly. Going to 0.5 or 1 Hz (if necessary) should not pose (big) problems. There are still some open issues which have to be followed up in order to ensure stable operations:

- The recalculation of response matrix, which is currently done in the OFC (Orbit feedback controller), has to be done in the OFSU (Orbit feedback service unit) in order to move dynamic load away from the OFC.
- Some improvements are necessary in the reference-orbit management GUI. Especially a better integration with the steering software will be necessary.
- The automated switching between optics during a beam process has to be completed (creation of timing tables + testing).
- The integration in the relevant sequences has to be completed.
- The SVD++ algorithm, which would allow faster corrections for higher eigenvalues and slower correction for lower eigenvalues, has to be tested.

Another problem which needs a long term solution are the MCBX magnets. These corrector magnet within the triplets can not be used by the feedback system at the moment since they trip very frequently because the acceleration rate of the current is limited by the QPS which can not be treated correctly by the real time feedback. Therefore these magnets are currently disabled by default in the feedback system which results in a very limited correction - capability in the insertion regions.

SUMMARY

The LHC orbit is very stable during quiet periods (drift rate estimate of 0.02 σ/h at 450 GeV, 0.05 σ/h at 3.5 TeV). It was shown that better corrections are possible. Therefore it would be worth to spend some time to establish a better global correction (and avoid strong local corrections) before setting up the collimators.

There are some well understood 'features', like tides and the DAB-temperature dependence around Pt 4 (100 μm peak to peak), but also some to be investigated and tasks to be completed:

- Drifts between Pt7 and Pt1 (maybe also temperature?)
- Vertical offsets in arcs 23,34,45. Proposal: check with aperture if orbit is centered or not.
- No experience with squeezed optics (triplet movements become more important)
- Switch of BPM high/low sensity: Check resulting orbit change. When/how to switch?

While the open BPM issues are already followed up by BI, the remaining COD (including MCBBX) polarity checks have to be completed by OP. The orbit feedback system, which will be necessary for ramp and squeeze, is basically operational but will need some improvements and dedicated time for testing.

ACKNOWLEDGEMENTS

I would like to thank all the people who contributed to this talk by collecting, sorting and analyzing data and answering a lot of questions. In particular I would like to mention J. Wenninger, R. Steinhagen, T. Baer, R. Schmidt and S. Redaelli who provided a lot of help and a great amount of time for discussions.