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Commissioning of the betatron squeeze to 1 m in IR1 and IR5

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Summary

This note summarizes the commissioning of the betatron squeeze from 1.5 m to 1 m performed during MD3. The MD3 work included measurements of the optics, setting up of the collimation system for tight settings, validation of the collimation settings and a test ramp with higher intensity to probe long-range beam-beam effects.

Contents

1 Introduction

Among the key parameters that define the LHC luminosity, β^* is presently limited by the available triplet aperture at 3.5 TeV. At the time of the start of MD3, the aperture of the triplets was still extrapolated from measurements performed at 450 GeV [1, 2, 3]. Based on those measurements β^* was limited to 1.5 m [4] with the standard collimator settings. During the Mini-Chamonix Workshop it was however pointed out that β^* could be reduced to 1 m with tighter collimator settings [5]. One of the recommendations of the Workshop was to implement such a β^* during the Summer of 2011.

After preparatory work on collimator settings at the end of fills and dry tests with the magnets of the squeeze from 1.5 m to 1 m, the actual commissioning work was performed in MD3. The commissioning work included:

- Commissioning the squeeze to 1 m in IR1 and IR5 with beam,
- Measurement of the optics at 1 m,
- Setting up and testing tight collimator settings,
- Alignment of the TCTs in IR1 and IR5 at 1 m,
- Validation of the collimator settings with loss maps and asynchronous dump tests,
- Test ramp with higher intensity for long-range beam-beam.

2 Squeeze Settings

The squeeze settings for LHC power converters are generated starting from optics strength files, in the form of MADX Twiss tables that are imported in the LSA database. Each optics is matched to a well defined value of β^*. Several intermediate optics are provided by the ABP-LCU optics team for the β^* range of interest. A "beam process" type is then built by specifying a list of matched optics that the machine will step through. Appropriate LSA generation tools calculate the minimum time required to execute the squeeze for the given list of optics, i.e. the minimum length of the beam process, taking into account the hardware parameters of circuits and magnets and using linear interpolation between consecutive optics. Settings are then generated for all converter types, with gentle rounding off of the quadrupole current functions around the matched optics. This allows stopping at the intermediate β^* for machine tuning. This is only done in the early commissioning phase until the machine is well tuned and the functions can be executed in one go.

A larger number of matched points within a given range of β^* reduces the transient errors at times where the optics is not matched but increases the squeeze duration due to the time lost for the round off. A smaller number of matched points enables a faster squeeze but induces larger errors and reduces the capability of tuning the machine (no stopping possible outside matched optics). A standard approach was established to optimize the squeeze duration while maintaining tolerable errors and appropriate operational flexibility. For a give beam process, MADX simulations are executed at different times within the squeeze to quantify the dynamics errors of key parameters like tune, chromaticity, orbit and beta-beating. These simulations are performed for different sets of optics starting from the setting functions generated in LSA. The squeeze duration is optimized while keeping small errors. Appropriate software was developed [6, 7] to perform these calculations efficiently.

Twelve intermediate optics are available between $\beta^* = 1.5$ m and $\beta^* = 0.55$ m [8]. All were imported in the database and used for setting generation even if the allowed range was only down to $\beta^* = 1$ m. Four intermediate optics are available between $\beta^* = 1.5$ m and $\beta^* = 0.55$ m (with steps of $\Delta\beta^* = 0.10$ m). If all these available optics are considered, the time required to go from 1.5 m to 1 m at 3.5 TeV is 102 s (401 s to reach 0.55 m). The β^* function in IP1 and IP5 of time is given in Fig. 1, blue line. Dynamic errors of tune, chromaticity and beta-beating in this case are given in Fig. 2. The planes were the errors are larger are shown. These errors can be considered negligible.

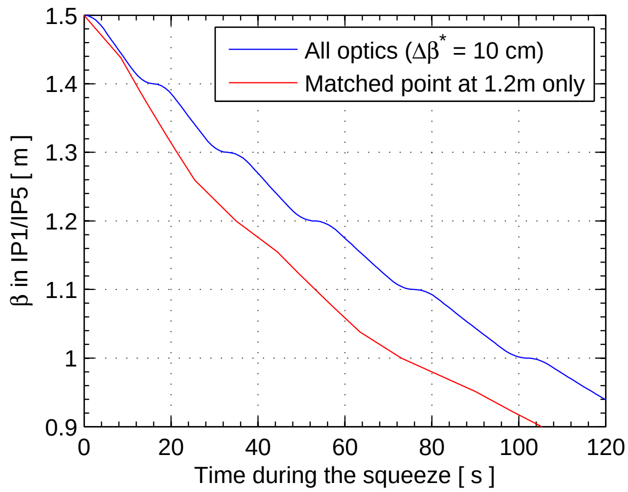

Figure 1: β^* functions versus time during the squeeze for the two cases considered for setting generation: (1) using all available optics (blue line) and (2) only one intermediate optics at 1.2 m.

The case with only one intermediate stop point at $\beta^* = 1.2$m was also considered. The duration in this case is reduced to 73 s (Fig. 1, red line). The dynamic errors of the parameters of interest are given in Fig. 3. Tune errors remain below 0.001 (QFB is on anyway), chromaticity errors below 1 unit and beta-beat errors below 1 %. The possibility to stop at one intermediate point only was considered sufficient for the range between 1.5 m and 1 m. The proposed beam process of 73 s was therefore taken as operational baseline.

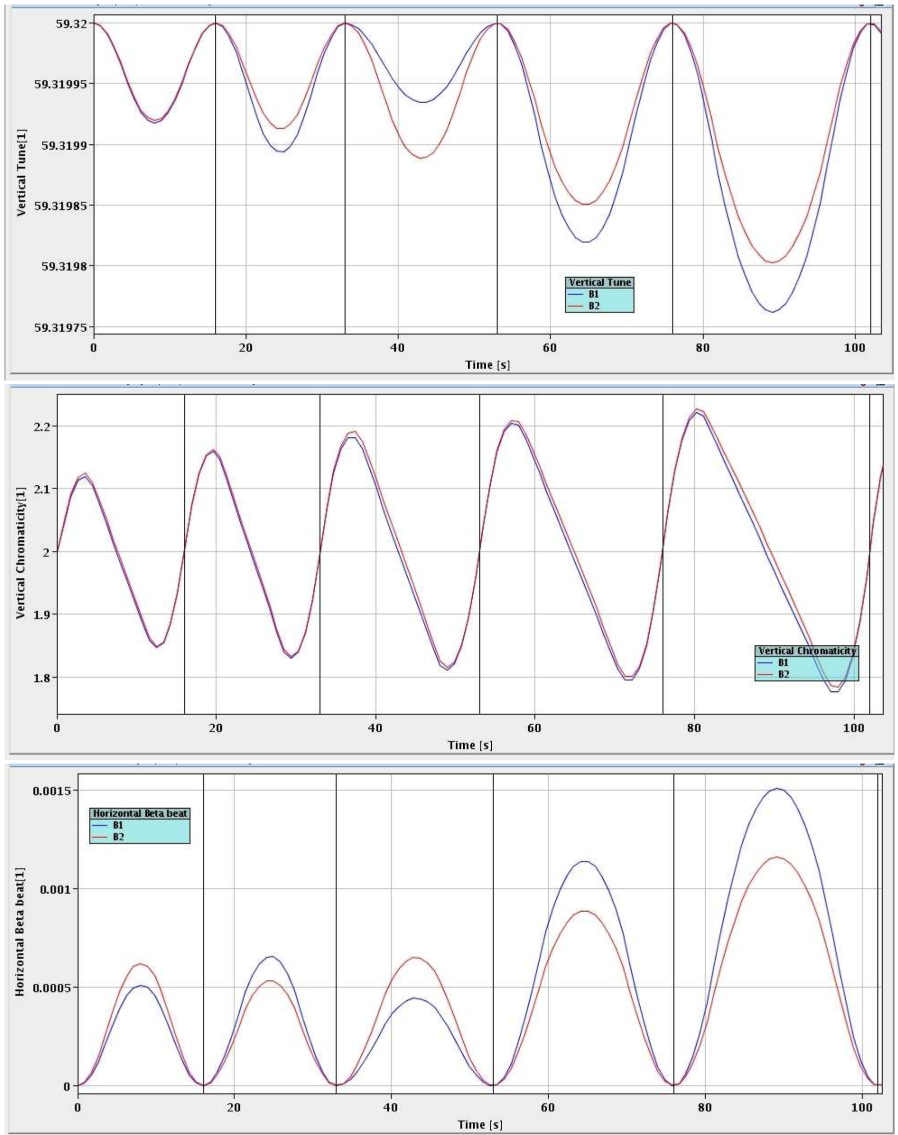

Figure 2: Transient errors as a function of time during the squeeze of vertical tune (top), vertical chromaticity (middle) and horizontal beta-beat outside the IRs (bottom) for the squeeze settings generated by using all the available matched optics. Vertical bars indicate the times of matched optics.

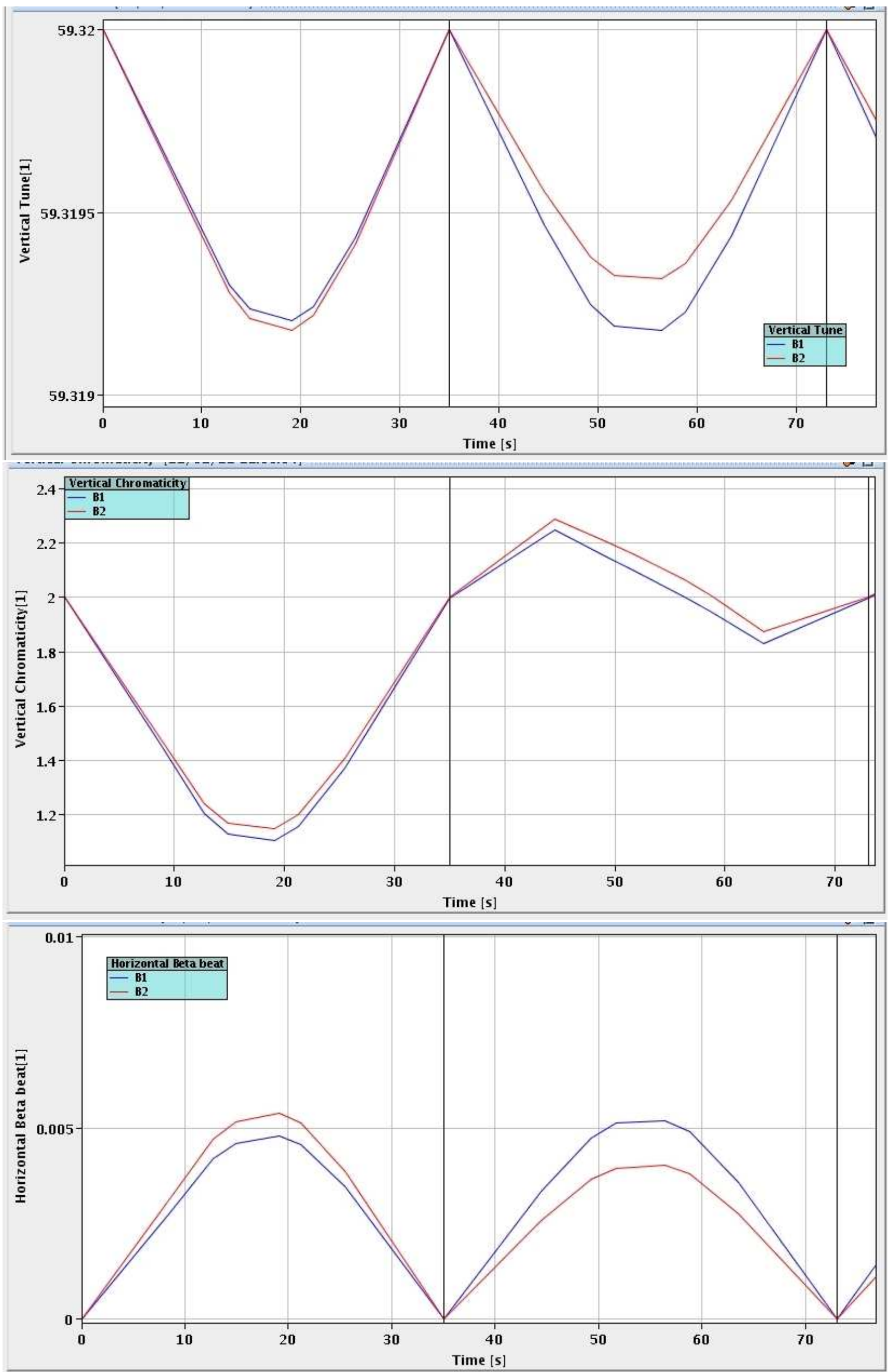

Figure 3: Transient errors as a function of time during the squeeze of vertical tune (top), vertical chromaticity (middle) and horizontal beta-beat outside the IRs (bottom) for the final squeeze settings adopted for operation, with one intermediate matched point only at 1.2 m. Vertical bars indicate the times of matched optics.

3 Machine Configuration

The initial squeeze commissioning was done a crossing angle of 120 μrad in IR1 and IR5. The beam tests with this configuration proved the feasibility of the settings and were used for the optics measurements. This first test was followed by a full machine setup at β^* of 1 m for a crossing angle of 100 μrad in IR1 and IR5 Those settings were defined by the available aperture at 3.5 TeV, which at that time was still extrapolated from 450 GeV measurements. With those settings the same tolerances for orbit and beta-beat are maintained as compared to the operational β^* of 1.5 m. It should be noted that the first 3.5 TeV aperture measurements were performed in the same MD, between the first and the second part of the 1 m squeeze commissioning [9].

Group	Standard 2011	Nominal	Tight
TCP IR7	5.7	6.0	4.0
TCSG IR7	8.5	7.0	6.0
TCLA IR7	17.7	10.0	8.0
TCT IR1/5 IR7	11.8	8.3	9.3
TCSG IR6	9.3	7.5	6.8
TCDQ IR6	9.8	8.0	7.3

Table 1: Standard collimator settings in units of beam σ for operation in 2011 (column 1), nominal collimator settings (column 2) and tight collimator settings used for the MD. All numbers correspond to beam sigma for a normalized emittance of 3.5 μm.

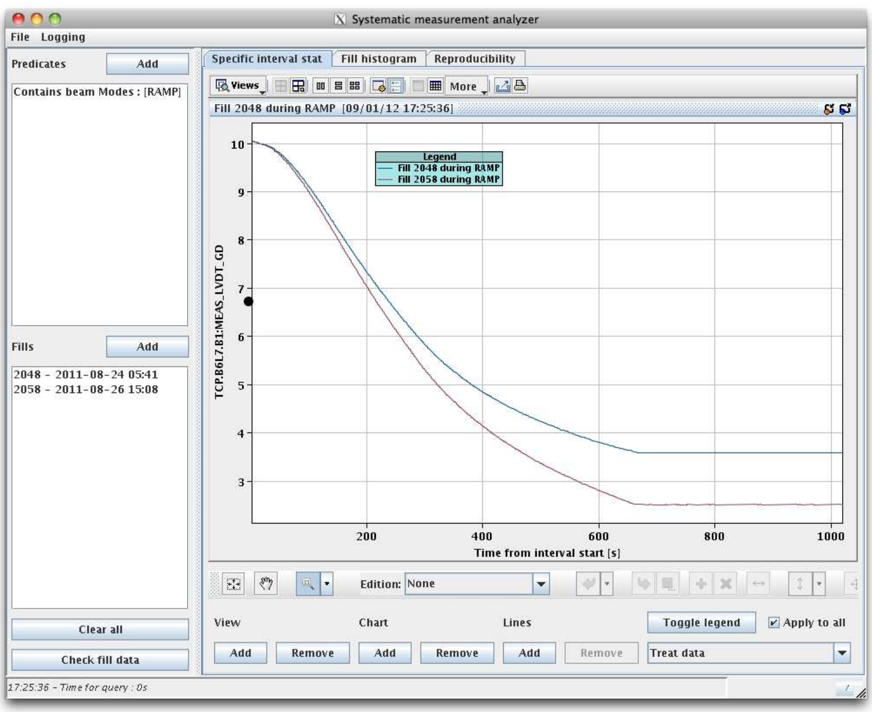

Figure 4: Comparison of the TCP gap evolution in the ramp for standard (fill 2048) and tight settings (fill 2058).

Standard and tight collimator settings expressed in half-gap settings are given in Table 1. The primary cut of the beam halo is reduced from 5.7 to 4 sigma. Figure 4 compares the gap of a TCP for standard and tight settings that are introduced along the ramp. Tight collimators had been used previously on two occasions.

- During the second MD period, similar tight collimator settings have been tested. At 3.5 TeV loss maps yielded a better cleaning efficiency than standard settings.
- At the end of fill 2037 (August 21st) with 1380 bunches, the B1 collimators in IR7 were closed to the tight settings, and no adverse effect was observed on the beam [10].

Figure 5 shows the long-range beam-beam separation in IR1 for different crossing angles and β^* values. To operate with conditions that are equivalent to β^* 1.5 m with crossing angle of 120 μrad, the crossing angle would have to be increased to 140 μrad at β^* 1 m. The reduction of the crossing angle to 100 μrad corresponds to a reduction of the beam-beam separation in the triplet by close to 3 sigma to below 6 sigma (for an emittance of 2.5 μm). This fact was not recognized before and during the MD, but it was highlighted by W. Herr after the MD period. During an earlier long-range beam-beam MDs, it was shown that a long-range separation of 8 sigma should be sufficient to ensure adequate lifetimes [11]. The later commissioning with 120 μrad at β^* 1 m showed that operation with high intensity is possible with a separation of 7σ.

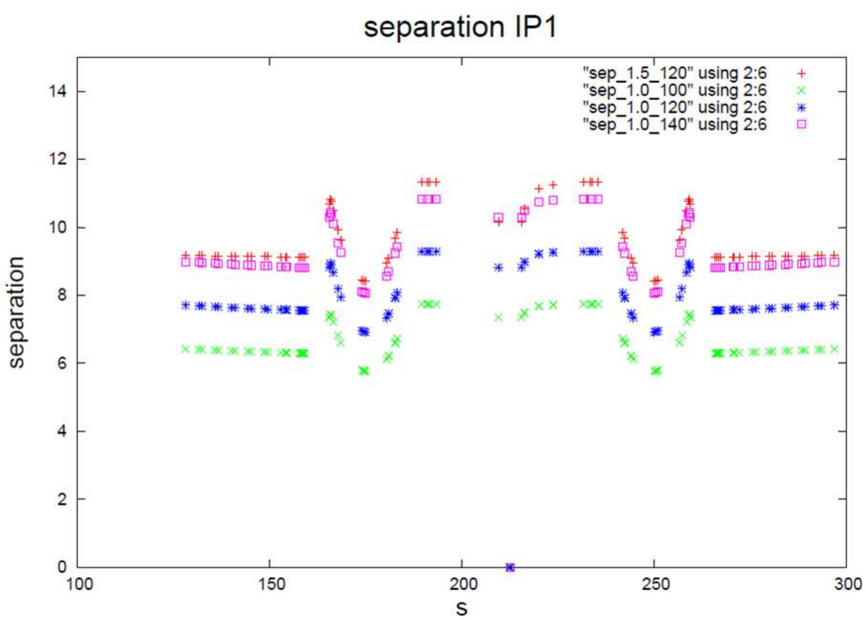

Figure 5: Beam-beam separation in sigma around a low-beta IP as a function of the crossing angle for β^* 1.5 m and crossing angle of 120 μrad (red), and for β^* 1 m and crossing angles of 100 (green), 120 (blue) and 140 μrad (magenta). The dip in separation occurs in the triplet (Q2). The beam sigma is based on an emittance of 2.5 μm.

4 Squeeze Commissioning

4.1 Sequence

The commissioning during MD3 was spread over a total of 4 fills.

- **Fill 2048** (Wed. 24^{th} of August): probe beams squeezed to 1 m and optics measurements, with a crossing angle of 120 μrad at IP1 and IP5.
- **Fill 2058** (Sun. 28^{th} of August): 2 nominal bunches per beam were brought into collision at 1 m with a crossing angle of 100 μrad at IP1 and IP5. The collimator settings in IR6 and IR7 were changed from standard to tight in the ramp. The TCTs in IR1 and IR5 were aligned. The fill was ended with loss maps and asynchronous beam dump test in collision. The loss maps validated the machine configuration with a crossing angle of 100 μrad for higher intensities. The details of the collimator setup and validation have been described elsewhere [12].
- **Fill 2059** (Sun. 28^{th} of August): 2 nominal bunches per beam were brought to collision at 1 m with all trims and collimator settings incorporated into the corresponding functions.
- **Fill 2060** (Sun. 28^{th} of August): test of long-range beam-beam effects with 84 nominal bunches per beam.

The settings for 1 m were stored in the dedicated hypercycle **3.5TeV_10Aps_1m**. Injection, ramp and squeeze are identical to the 1.5 m squeeze for all PCs. Collimator functions are different as they correspond to tight settings at 3.5 TeV. The crossing angle is reduced from 120 to 100 μrad during the 73 seconds long squeeze segment from 1.5 m to 1 m.

K-modulation

Beam	Plane	β^* IP1 (m)	β^* IP5 (m)
B1	H	1.20 ± 0.20	1.13 ± 0.15
B1	V	1.05 ± 0.13	1.20 ± 0.20
B2	H	1.14 ± 0.10	1.10 ± 0.20
B2	V	1.17 ± 0.18	1.06 ± 0.11

AC dipole

Beam	Plane	β^* IP1 (m)	β^* IP5 (m)
B1	H	0.97 ± 0.05	1.00 ± 0.05
B1	V	1.04 ± 0.17	0.95 ± 0.11
B2	H	1.01 ± 0.10	0.95 ± 0.13
B2	V	1.05 ± 0.06	0.98 ± 0.10

Table 2: K-modulation and AC dipole results for β^* at IP1 and IP5 (nominal 1 m).

4.2 Optics measurements

After preliminary 'dry' tests of the functions, the squeeze from 1.5 m to 1 m was first tested with probe beams in fill 2048. The optics measurements indicated that the beta-beating is stable between 1.5 and 1 m at around 10%. No additional optics correction had to be performed at 1 m, see Fig. 6.

Dispersion and off-momentum optics were measured by taking BPM data at various relative momentum deviations, namely $\delta p/p =$ (-0.83, 0.00, 0.75)$\times 10^{-3}$. The tunes for these settings are shown in Fig. 7, revealing a significant horizontal parabolic component while the vertical tune behaves linearly. The beating of the normalized horizontal dispersion and the vertical dispersion are shown in Fig. 8. Maximum deviations from the model are within tolerances, namely $\Delta D_x/\sqrt{\beta_x} \approx 0.04$ m$^{1/2}$ and $\Delta D_y \approx 0.25$ m for both beams. The measured chromatic functions $W_{x,y}$ are shown in Fig. 9 in comparison to the model. A good agreement between measurement and model is observed.

K-modulation and AC dipole measurements yielded β^* values consistent with 1 m when taking into account the relatively large error bars, as shown in Table 2. The K-modulation values tend to be larger than 1 m while the AC dipole results are closer to 1 m and more centered.

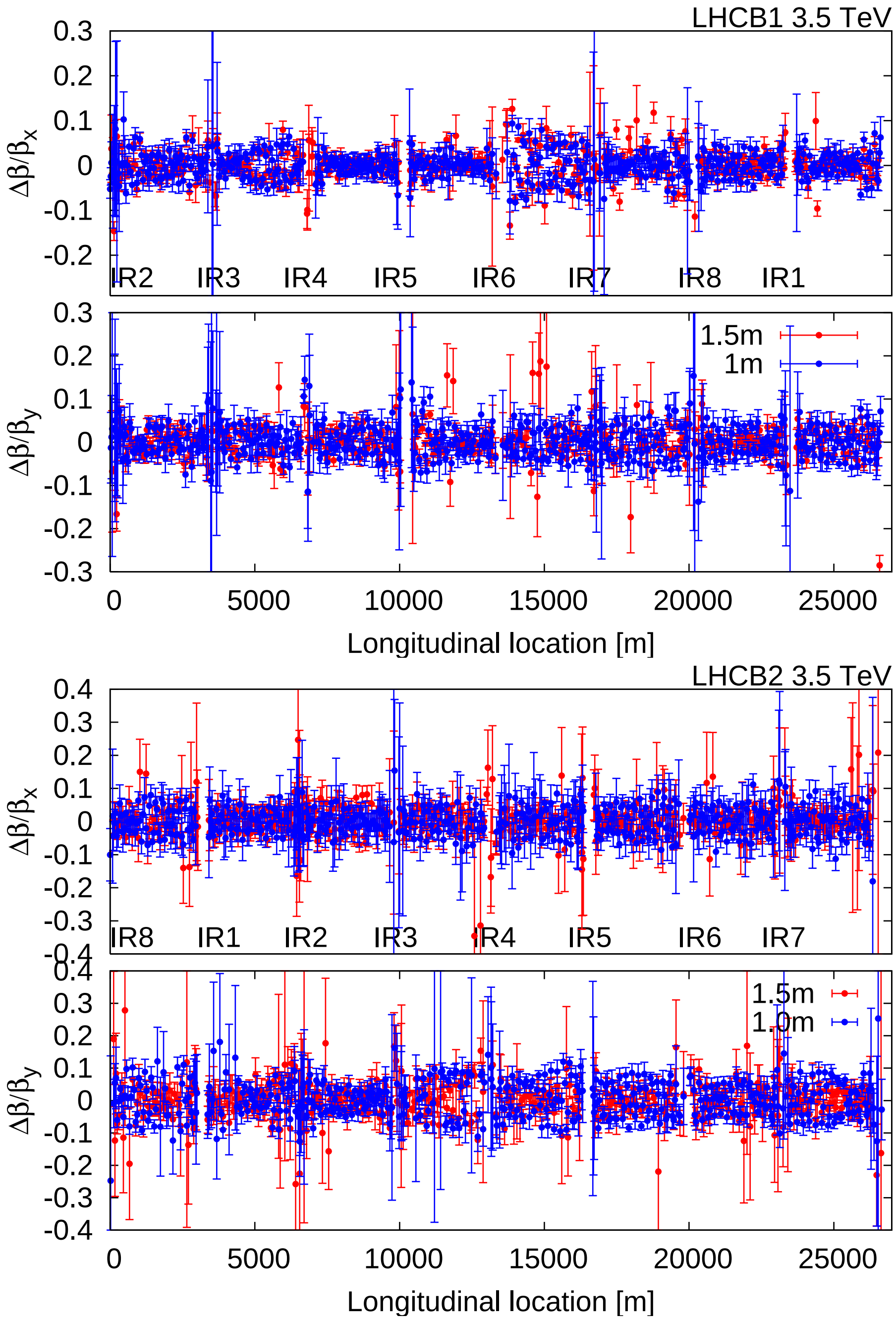

Figure 6: Beta-beat measurements at 1.5 and 1 m for Beam 1 (top) and Beam 2 (bottom). No correction is applied at 1 m with respect to 1.5 m.

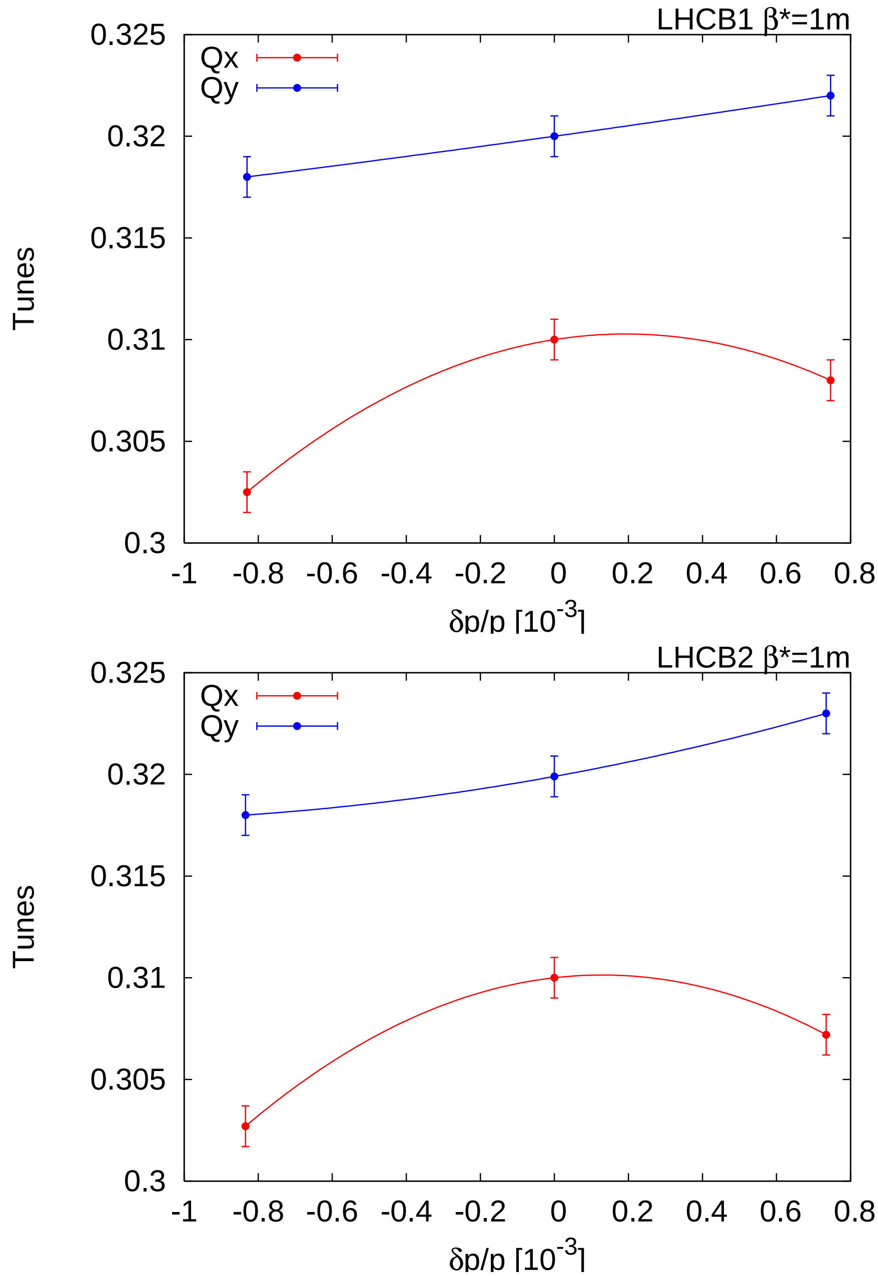

Figure 7: Measured Beam 1 (top) and Beam 2 (bottom) horizontal and vertical tunes versus relative momentum deviation together with a second order fit, showing a significant horizontal quadratic term.

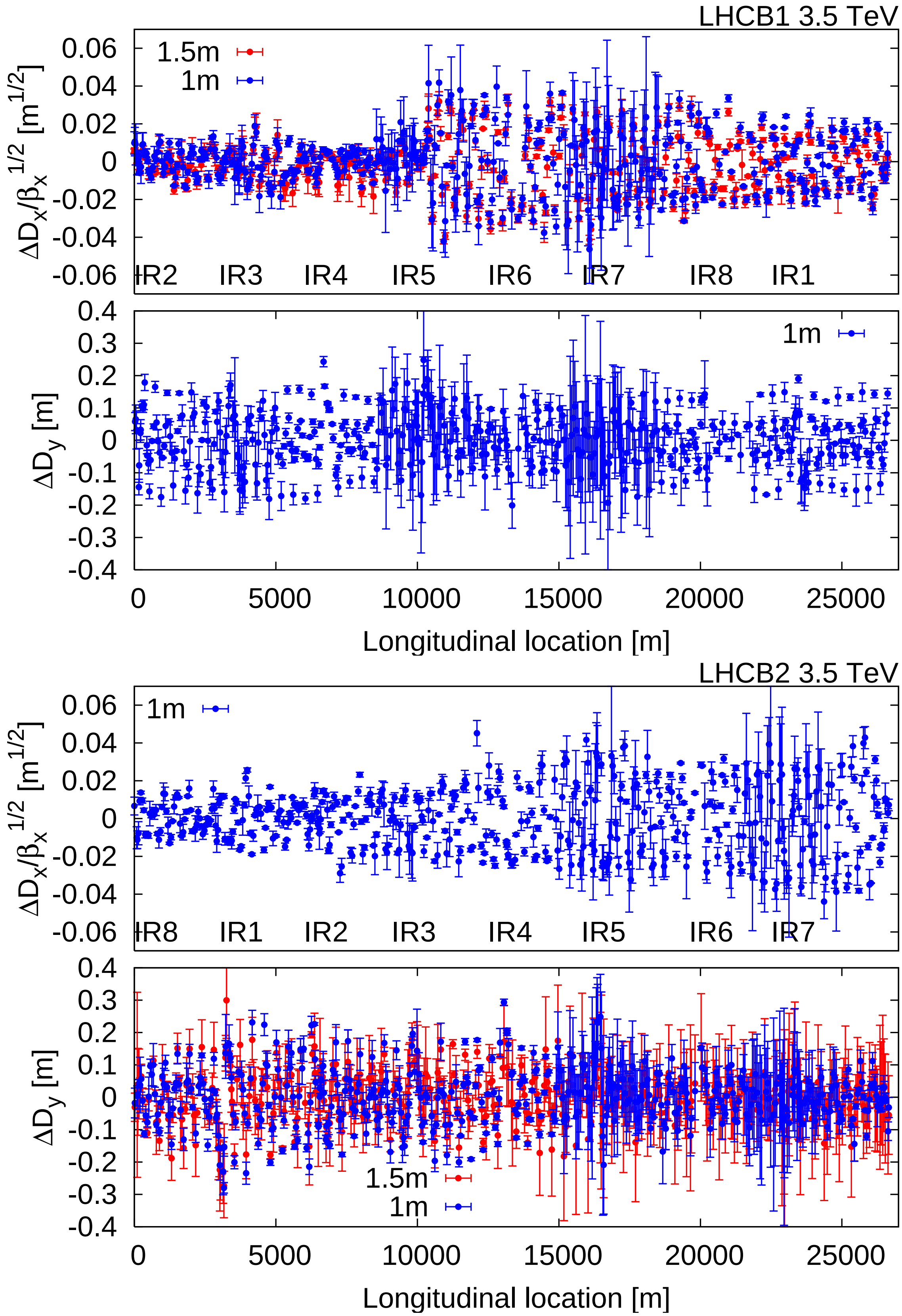

Figure 8: Deviations of the normalised horizontal dispersion and the vertical dispersion at 1 m for Beam 1 (top) and Beam 2 (bottom).

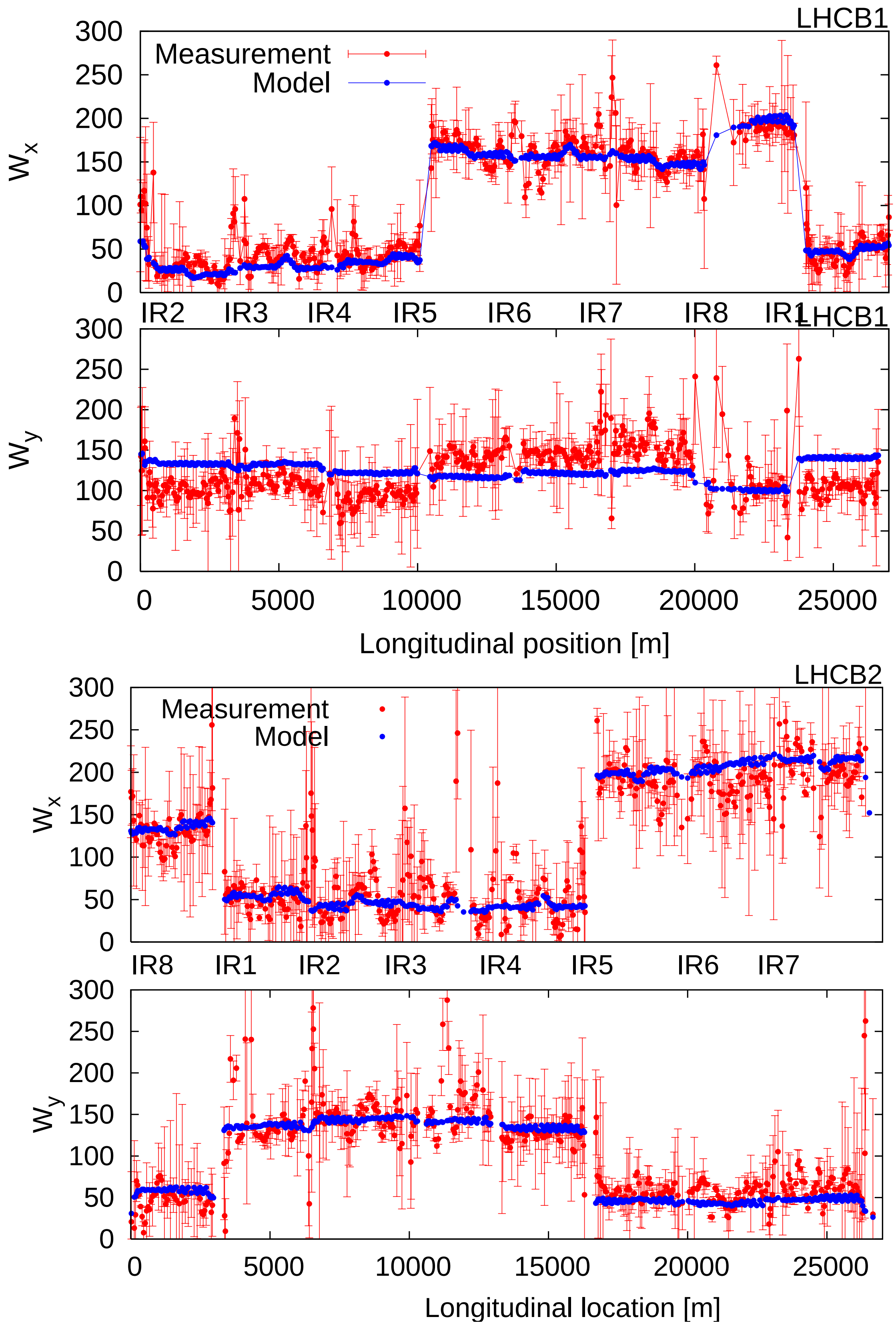

Figure 9: Off-momentum optics measurements at $\beta^* = 1$ m for Beam 1 (top) and Beam 2 (bottom) in comparison with the model.

4.3 Ramp observations

With collimator settings moving from 5.7 to 4 nominal sigma (corresponding to an emittance of $3.5\ \mu$m) one can clearly observe a beam intensity reduction in the ramp, see Fig. 10, which is not present for standard collimator settings. The loss is at the level of 0.5% and correlates well with the closing of the collimator jaws in the top part of the ramp. Such a proton population in the last beam sigma is consistent within a factor 2-4 with other beam halo population measurements performed with high intensity beam in 2011 [13].

Figure 10: Beam intensity evolution in the ramp. The ramps with tight collimator settings correspond to the 3 fills with a significant intensity loss starting around 500 seconds after the beginning of the ramp.

4.4 Squeeze observations

As a consequence of the tighter settings of the collimator gaps, and the higher beam density at the edge of the beam, even small orbit movements in the squeeze lead to significant losses and/or BLM loss spikes at the collimators in IR7. Rather larger spikes were observed with tight settings in the squeeze. Those spikes are due to reproducible orbit excursions that occur at fixed times in the squeeze sequence, see Fig. 11. The origin of those spikes was only explained in October/November 2011 when it was realized that they were already present in the model [14]. The orbit excursions are due to the leakage of the crossing and separation bumps in the IRs between the matched optics points. The crossing bump of IR8, with an angle of 250 μrad, actually dominates the leakage in the squeeze to 3m. The time structure of the leakage leads to fast orbit changes around the matched optics points that cannot be corrected with the orbit feedback (with its standard settings). Correction requires higher feedback bandwidth (which comes with its own problems) or feed-forward [14].

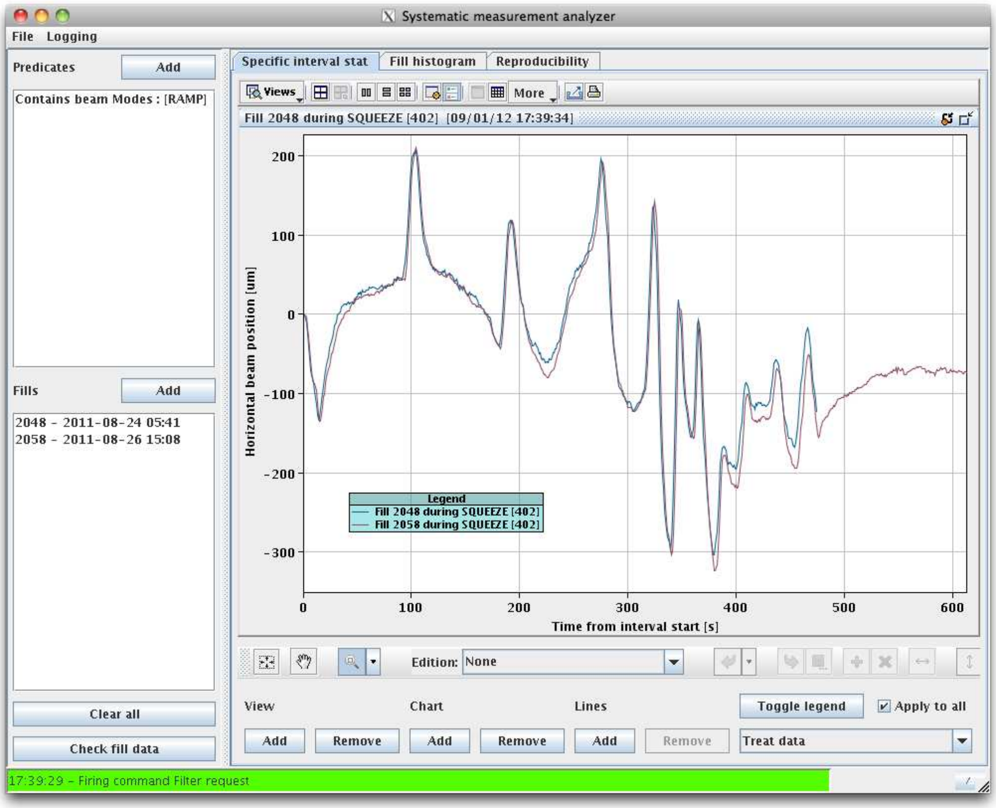

Figure 11: Horizontal beam position at a BPM close to a TCP in 2 selected fills, one with standard (2048) and one with tight collimator settings (2058). The orbit excursions are very reproducible.

5 High Intensity Test

The last test of the setup for β^* of 1 m consisted in a high(er) intensity fill with a special filling pattern optimized by W. Herr and G. Papotti to probe all long-range and head-on beam-beam configuration with 50 ns beams. The filling scheme consists for each beam of 1 probe bunch, the standard 12 non-colliding nominal bunches for injection, and finally 2 trains of 36 nominal bunches.

The total intensity in each beam was 1.1×10^{13} protons, i.e. 1.3×10^{11} protons per bunch.

Both ramp and squeeze to 1.5 m went smoothly, except for the rather large loss spikes due to the orbit excursions in the squeeze that have been described previously. The squeeze to 1 m was smooth, but as soon as the squeeze was finished the beams became unstable, and a large fraction of the beam intensity was lost, see Fig. 12. At that moment the beams were still separated at all IPs. The bunch-by-bunch data indicate that only bunches with head-on and long-range encounters in IPs 1 and 5 suffered losses, see Fig. 13. The loss was finally stopped when the Landau octupole currents were increased from 150 to 300 A, but it is not clear if the instability had not died out naturally at that moment.

The instability that was observed is consistent with a transverse coupled bunch instability (TCBI), mode m=1 and Q $\sim 4-6$, if Landau damping is lost [15].

Figure 12: Evolution of the beam intensities during the high intensity test squeeze. A strong loss started exactly at the end of the squeeze to 1 m.

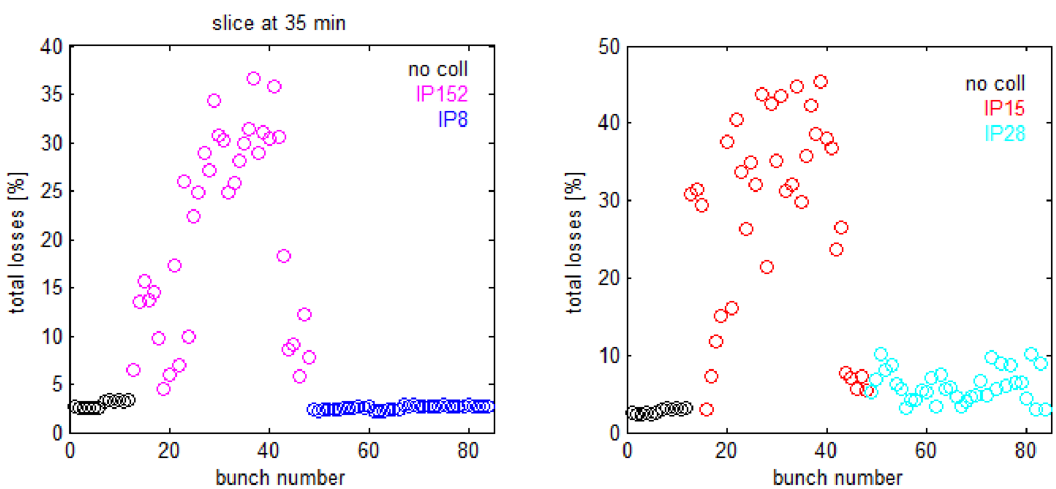

Figure 13: Bunch-by-bunch losses due to the instability at the end of the squeeze to 1 m (the time corresponds to 35 minutes after the beam mode was changed to FLAT TOP). The plot clearly shows that only bunches with head-on and long-range encounters in IPs 1 and 5 suffered losses.

6 Conclusions

The squeeze commissioning to β^* of 1 m was performed successfully with low intensity beams during MD3. No optics corrections had to be performed as compared to 1.5 m. The commissioning itself (optics, orbit and collimators) was performed in only 3 fills, with a fourth fill for a high intensity test. This includes a full MP validation for high intensity beams.

A test ramp with trains to evaluate the effect of long-range beam-beam with the reduced crossing angle of 100 μrad indicated however a problem of beam stability which may be a combination of the increased impedance due to tighter collimators and long-range beam-beam. Indeed only bunches with long-range interactions in IR1 and IR5 suffered from losses. The beam may well have been stabilized by pushing further the strength of the Landau octupoles, and reducing further Q', but there was not enough time during the MD period to perform such an additional test.

In the LMC just following the MD3 period [16] it was decided to pursue the effort on commissioning β^* 1 m, but instead of using tighter collimators, to take advantage of the first triplet aperture measurements [9] that had been performed in the same MD period. Those measurements indicated that it is indeed possible to operate at 1 m with standard collimator settings and with a crossing angle of 120 μrad.

The direction decided at the LMC was implemented in the startup after the TS. It was also combined with a polarity reversal of the ALICE solenoid, ALICE internal and ALICE external crossing angles. Profiting from the work done on optics and settings during MD3, the commissioning of β^* of 1 m was performed in a record time between Friday 2^{nd} of September and Wednesday 7^{th} September (first Stable beams with 264 bunches). The intensity ramp up followed within the next two days and four fills (264, 480, 920, 1380 bunches), leading into a very successful operation period with β^* of 1 m and a luminosity gain of 50%. In November 2011 a further squeeze step was commissioned for the Lead ion run, bringing β^* at IP2 down to 1 m.

Acknowledgments

The participants of this MD would like to thank the collimation team for the setting up of the TCT collimators and for the loss map analysis that have been presented in a separate note [12].

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