CERN-ATS-Note-2011-132 MD

December 2011
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The Achromatic Telescopic Squeezing (ATS) MD part III

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Keywords: LHC optics, Achromatic Telescopic Squeezing Scheme

Summary

This note highlights the results obtained during the third so-called ATS MD which took place in 2011. The goal of this MD was extremely challenging, targeting a pre-squeezed β^* of 40 cm in ATLAS and CMS, followed by a telescopic squeeze of these two insertions to finally reach a β^* of 10 cm both at IP1 and IP5. Due to the rather poor machine availability during the MD period, the time initially allocated to the ATS studies was hardly cut by a factor of 2, and “only” the achromatic pre-squeeze down to $\beta^* = 40$ cm was demonstrated with beam.

1 Introduction

The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet [1, 2]. This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is achieved by using exclusively, as usual, the matching quadrupoles of the high luminosity insertions IR1 and IR5. Then, in a second stage, the squeeze continues by acting only on the insertions on either side of IR1 and IR5 (i.e. IR8/2 for IR1 and IR4/6 for IR5). As a result, sizable β-beating bumps are induced in the four sectors on either side of IP1 and IP5. These waves of β-beating are then also necessary in order to boost, at constant strength, the efficiency of the chromatic correction performed by the lattice sextupoles located in the sectors 81, 12, 45 and 56.

One of the keystones of the scheme is the pre-squeezed optics, where specific matching conditions are imposed for the left and right phase advances of the low-beta insertions, and for which β^* shall be chosen within a certain interval. This interval depends on the detailed layout and gradient of the triplet, on the maximum operating current of the lattice sextupoles and on the beam energy. At nominal energy (7 TeV/beam) and for the existing triplet (205 T/m), the pre-squeezed β^* shall fulfill the following condition:

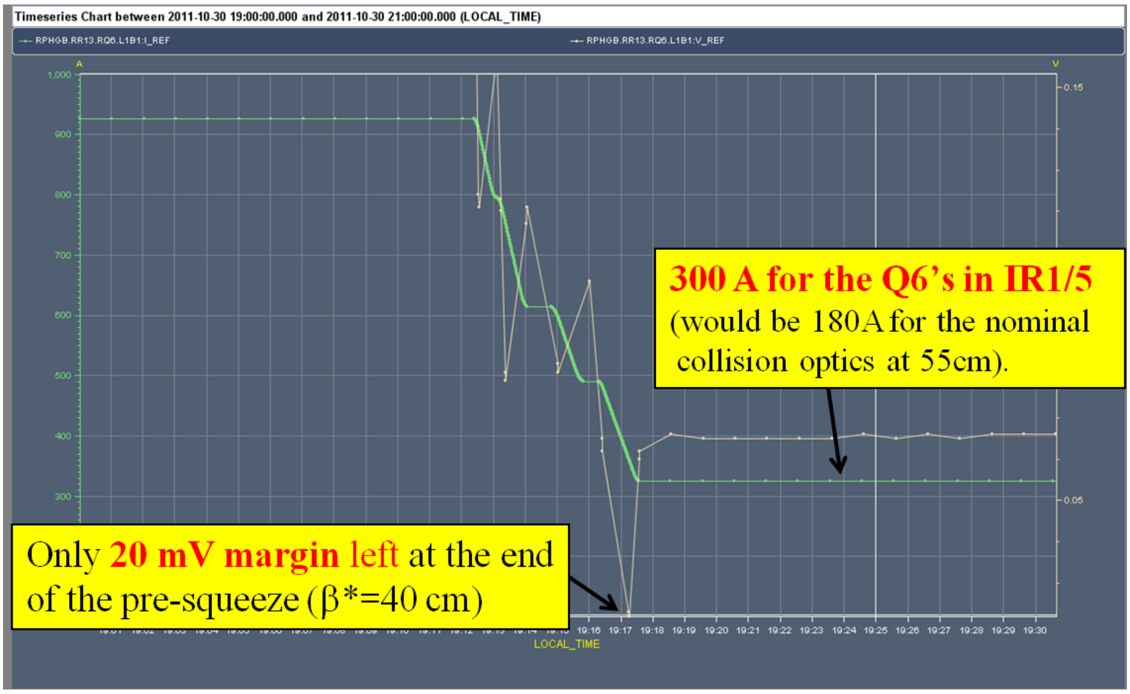
$$40\,\mathrm{cm} \le \beta^*_{\mathrm{pre-squeezed}} \le 2\,\mathrm{m}\,. \tag{1}$$

The IR phasing conditions mentioned above can indeed not be reached for a β^* larger than 2 m. Then, below a β^* of 40 cm, some matching quadrupoles of IR1 and IR5 are pushed to very low gradients, and, for an energy of 7 TeV/beam, some arc sextupole families would need to be powered beyond the so-called ultimate current of 600 A (see Fig 1).

The first ATS MD [3] commissioned the new ATS injection optics and its ramp up to 3.5 TeV. The second ATS MD [4] demonstrated an achromatic pre-squeezed optics with $\beta^* = 1.2$ m at IP1 and IP5, and then a further squeeze of IR1 down to $\beta^* = 30$ cm using the telescopic techniques of the ATS scheme. For this third MD, the first goal was to push the pre-squeezed β^* down to its limit of 40 cm and to measure the chromatic properties of the corresponding optics. Then the second goal was to use the ATS techniques in order to further squeeze β^* by a factor of 4, simultaneously at IP1 and IP5, and then reach a β^* of 10 cm in the two high-luminosity insertions of the LHC. The corresponding pre-squeezed and squeezed optics are illustrated in Fig.'s 2(a) and 2(b), zoomed in between IP4 and IP6. In particular, as showed in the right picture, the β-beating waves are clearly visible in sectors 45 and 56 for the collision β^* of 10 cm at IP5 (with factor of 4 increase for the peak β's in the arcs, corresponding to an increase by a factor of 2 in terms of beam sizes). On the other hand it is worth reminding that, even without crossing angle, such β^* values are hardly operational in the LHC due to the aperture limits imposed by the existing inner triplet and its matching section (see Fig.'s 2(c) and (d)).

While the pre-squeeze was rather fast (2h) and successful, the beam was lost during the preparation for the telescopic part of the squeeze due to a human error in the manipulation of the tune correction knobs (see later). Unfortunately a second try was not allowed in view of the the LHC ion run starting right after the MD.

The next section will summarise the various activities performed during the preparation phase which lead to a very successful dry run (hardware test without beam). Section 3 will highlight the main results obtained during the MD with beam, while Section 4 will present more details on the optics measurements and correction which took place.



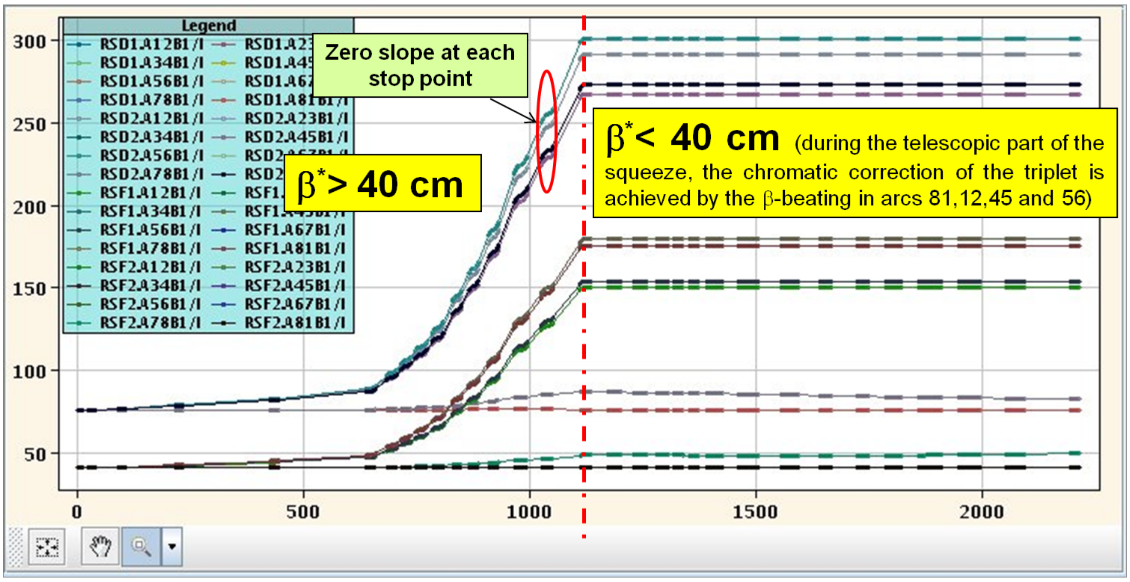
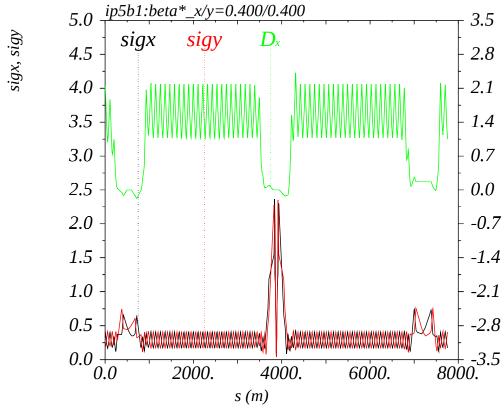
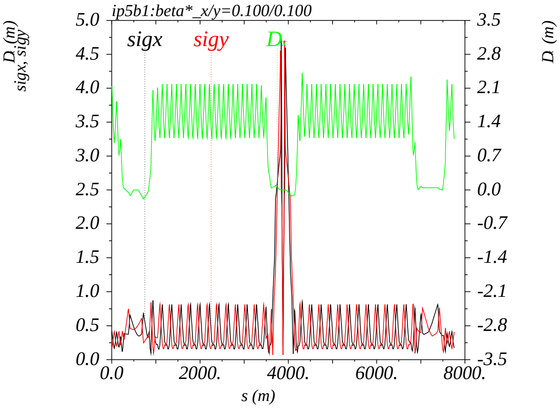


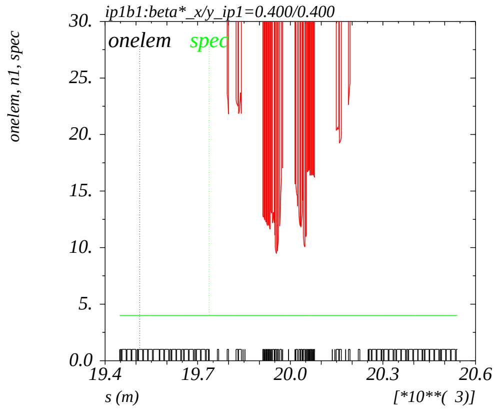
Figure 1: Various limitations associated to the 40 cm pre-squeezed optics: reference current [A] and reference voltage [V] of a typical RQ6 circuit in IR1 and IR5 during the pre-squeeze (top), and reference settings [A] sent to the arc sextupole circuits during the pre-squeeze and squeeze (bottom). While the uni-quadrant power supplies of the RQ6 circuits shall operate at very low current in IR1 and IR5 at the end of the pre-squeeze, some defocusing sextupole families are pushed to 300 A at 3.5 TeV, corresponding to the ultimate current of 600 A at 7TeV/beam.



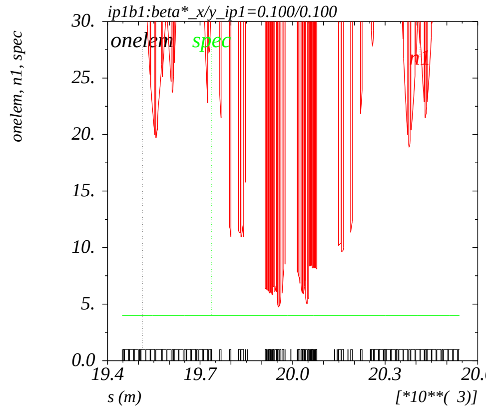
(a)



(b)



(c)



(d)

Figure 2: Illustrations of the pre-squeezed (left) and squeezed (right) optics with $\beta^* = 40$ cm and $\beta^* = 10$ cm, respectively, at IP1 and IP5: zoom of the beam sizes [mm] and horizontal dispersion [m] in between IR4 and IR6 showed for Beam1 (top), and corresponding mechanical acceptance of the low-β insertion IR5 from Q13.L5 and Q13.R5 (bottom) given in units of beam sigmas, assuming a 3.5 TeV beam with a normalised emittance of 3.5 μm. The aperture plots have been produced with the crossing angle and parallel separation switched off, and without considering any specific margin for the β-beating, spurious dispersion and closed orbit. The horizontal green bars added in Fig.'s (c) and (d) have been adjusted to 4 σ for guiding the eyes.

2 Preparation work and Dry run

The various activities performed during the preparation phase of the MD are summarized hereafter.

2.1 Optics preparation work

First of all, the optics work consisted in extending the pre-squeeze sequence of IR1 and IR5 from 1.2 m (as used for the second ATS MD [4]) down to 40 cm. Then the telescopic part of the squeeze of IR5 was added to the beam process. More precisely, a "squeeze" sequence for IR4 and IR6 was defined and validated, after checks and iteration performed in collaboration with various equipment groups (BE/BI for IR4 and TE/ABT for IR6). Profiting from certain modularity features of the ATS scheme, the IR8 and IR2 settings corresponding the telescopic part of the IR1 squeeze (from $\beta^* = 40$ cm to 10 cm) were then copied and pasted from the squeeze sequence which was used in the previous ATS MD (from $\beta^* = 1.2$ m to 30 cm at IP1).

The full ATS sequence, including all necessary correction knobs and the crossing bumps in IR1, IR2, IR5 and IR8, can be found in the `ATS_V6.503` afs directory [5], under the sub-directory `OPTICS_round_IR1_40-10_IR5_40-10`. The latter contains in particular the injection, the pre-squeezed and the squeezed optics with $\beta^* = 11$ m, 40 cm and 10 cm, respectively, both at IP1 and IP5, and β^* kept to 10 m in the other two experimental insertions of the LHC. Arriving to this result was obviously already the fruit of a lengthy and meticulous work.

2.2 LSA preparation work and new functionalities

This being done, the new squeeze beam process, `SQUEEZE_ATS_MD4_2011_LONG_V1`, was built in LSA, together with the corresponding hypercycle and automatized sequence, including in particular the already commissioned injection and ramp beam process. The setting generation was performed with a very special care in order to anticipate any eventual hardware failure, as observed during the former ATS MD [4]:

- first of all, increasing artificially the natural decay time calculated for the MQY type magnets in order the avoid power converter trips at low current, as it was previously observed for some Q4 magnets in IR2 and IR8 towards the end of the telescopic part of the squeeze.

- concerning the setting generation of the lattice sextupoles, as done already by default for the IPQ circuits, applying a parabolic/linear/parabolic (PLP) interpolation between two consecutive matched points (see Fig. 1(b)). As a result, the slope of the sextupole current was adjusted to zero at the beginning and end of each segment during the squeeze, enabling in particular to stop at any matched point, without risking to trip the RS circuits due to a too sharp acceleration right before or right after a stop.

Finally a new functionality was added to the tune feed-back system, in order to switch from one tune correction knob to another one, to be used above and below the pre-squeezed β^* of 40 cm: the first one acting as usual on all MQT circuits of the ring, and the second one trimming only the RQT circuits located in sectors 23, 34, 67 and 78 where the β functions are kept constant during the telescopic part of the squeeze.

2.3 Dry run

A dry run then took place a few days before the MD with beam. The latter was very smooth and relatively fast (2.5 h). The injection, ramp, pre-squeeze and the squeeze down to 10 cm were successfully tested without any trip, in particular stopping during the pre-squeeze (the RS circuits did not trip) or at the end of the squeeze (the Q4's of IR2 and IR8 did not trip). All the standard and ATS specific knobs were systematically tried out during the various stops, showing a behaviour of the hardware in perfect agreement with the expectations. Unfortunately the new functionality described above for the tune feed-back was not tested during the dry run.

3 Highlights of the MD with beam

The MD with beam was initially foreseen to be split into two parts [6]: the first one of 4.5 h to achieve and correct the pre-squeezed optics with $\beta^* = 40$ cm at IP1 and IP5, and the second one scheduled a few days later in order to demonstrate the telescopic squeeze principles both in IR1 and IR5 and reach a β^* of 10 cm. Due to several problems which occurred during the MD period, the ATS MD with beam was rescheduled for the very end of the MD period and for a total allocated time of 6 hours only.

3.1 Summary of the Beam and Machine conditions

The MD was performed with pilot bunches ($\sim 1E10$) of rather small emittances of the order of 1.5 μm. The ADT was only used for damping the injection oscillations and then switched off 1'000 turns following each injection.

The crossing angles and parallel separations were switched off in the four experimental insertions, but in IR1 and IR5 where the parallel separation was kept on, set to its nominal value of ± 2 mm. Beam1 and Beam2 were then both injected in bucket 1 in order to enable collisions, eventually at a later stage.

As for the previous ATS MDs, all maskable interlocks were actually masked (e.g. BLMs, orbit excursion in point 6, software interlocks on main RQF and RQD current settings,..). The TCT, TDI and TCLI were adjusted symmetrically according to the flat reference orbit in the absence of crossing angle in IR1, IR2, IR5 and IR8.

The collimator and other protection devices (TCDQ, TCT) were not ramped. Only when arriving at 3.5 TeV and preparing the machine for the pre-squeeze, the horizontal and vertical primary collimators of IR7 were adjusted to $7\,\sigma$ and the TCTs of IR1 and IR5 were set to ± 12 mm and ± 10 mm, in the horizontal and vertical planes, respectively. In this configuration, the triplets were always shadowed by the TCTs for any β^* and the primary aperture bottleneck remained at the level of the TCPs of IR7 during the full pre-squeeze sequence.

The chromaticity was pushed up a bit to about 5-6 units when preparing the machine for the pre-squeeze. Finally, the pre-squeeze and squeeze sequences were prepared keeping the injection ATS tunes (62.28 and 60.31) as reference for the tune feed-back, that is keeping a preventive tune split of 0.03 in order to anticipate any eventual problem with coupling.

3.2 Highlights

The injection process was quite fast and easy, e.g. in terms of closed orbit, tune, coupling and chromaticity correction. The transmission of intensity through the ramp was found excellent. The pre-squeeze down to $\beta^* = 40$ cm was achieved with practically no losses, in less than 2 hours (see Fig. 3) and including a stop at $\beta^* = 1$ m for optics measurement.

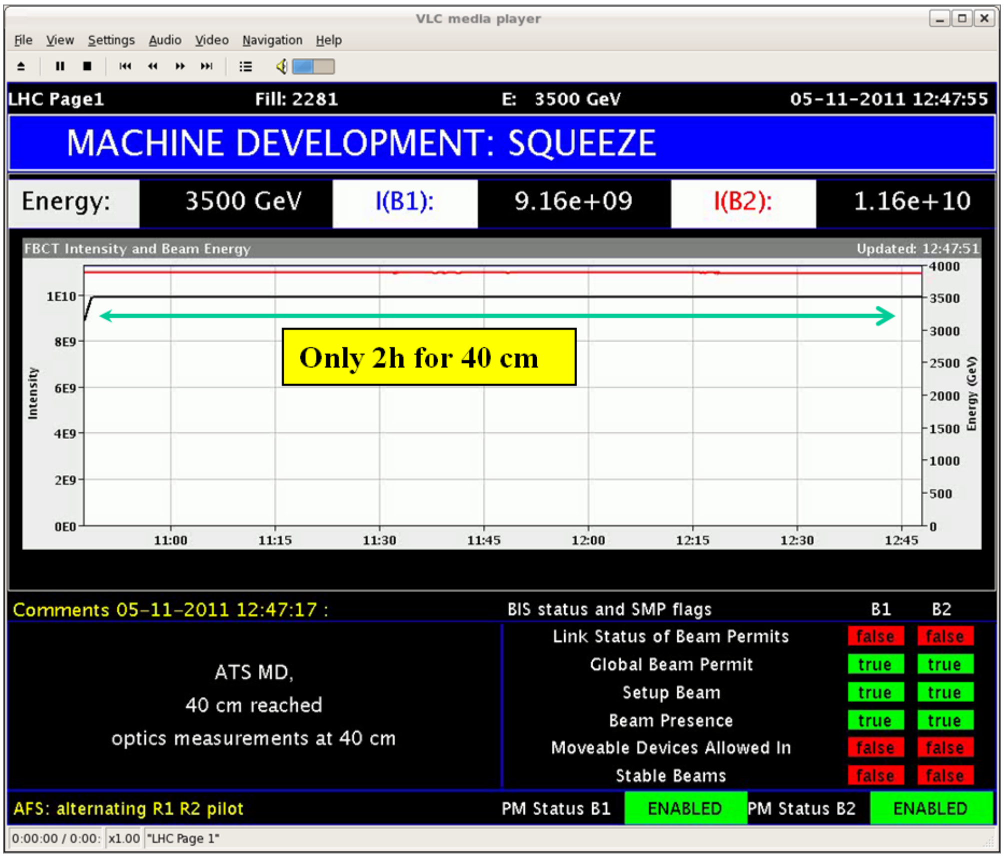


Figure 3: Screenshot of Page 1 at the end of the pre-squeeze down to $\beta^* = 40$ cm at IP1 and IP5. Only two hours spent at 3.5 TeV were needed to achieve this result, including a stop at $\beta^* = 1$ m for optics measurements.

The pre-squeeze sequence was stopped many times at several intermediate β^* between 11 m and 40 cm. The linear chromaticity was measured at each stop and found very stable. The coupling was easily corrected to the level of $1 - 2 \times 10^{-3}$ using the two usual orthogonal global knobs. On the other hand, a trend in the coupling correction was identified very quickly during the pre-squeeze (see Fig. 4), which was understood a posteriori when local coupling measurements were performed at a β^* of 40 cm and a clear source was identified coming from the inner triplets of IR5 (see Section 4).

As mentioned above, several optics measurements and/or correction were performed both at $\beta^* = 1$ m and $\beta^* = 40$ cm, including

- on-momentum measurements with the AC-dipole showing a β-beating not exceeding the 20% and 40% level at $\beta^* = 1$ m and $\beta^* = 40$ cm, respectively, with as only correction three

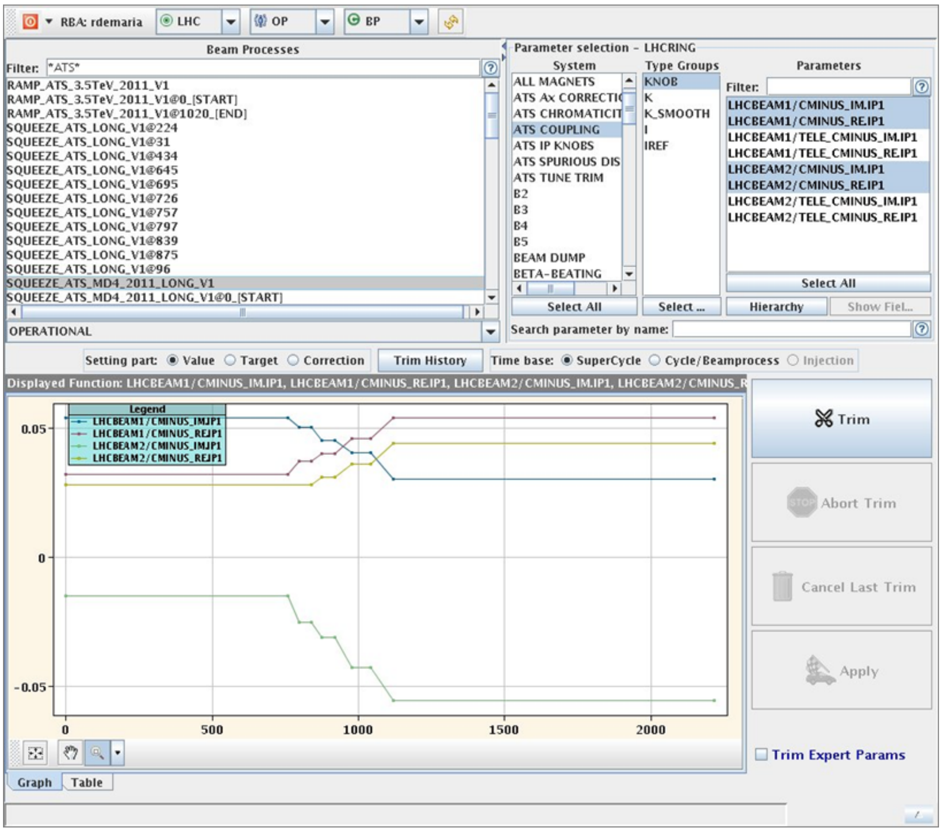


Figure 4: Global coupling correction performed during the pre-squeeze using two dedicated orthogonal knobs for each beam. A trend is clearly visible.

empirical trims of about ± 10 units applied to three Q2 magnets in IR1 and IR5, as used in the previous ATS MD [4] and extracted from [7, 8] (see Section 4 for more details).

- β-beating correction performed at $\beta^* = 40$ cm (Beam1 only), bringing back the β-beating below the 20% level (see Section 4 for more details)

- dispersion measurements performed at $\beta^* = 40$ cm (see Fig. 5), showing a net increase at the location of the inner triplets ($\propto \sqrt{\beta_{\rm max}}$). With the crossing angle switched off in all the experimental IRs, the main source of spurious dispersion comes from the arc imperfections (random a_2 components of the main dipoles for D_y, random b_2 components of the main quadrupoles for D_x). While the peak of spurious dispersion is still more than acceptable in the vertical plane (thank to the sorting of the main dipoles performed during the installation of the machine, and fortunately since D_y is hardly correctable in the LHC), the situation in the horizontal plane is more worrisome. However, the spurious horizontal dispersion can a priori be minimized together with the β-beating during the optics correction campaign.

- measurement of the non-linear chromaticities at $\beta^* = 40$ cm (see Fig. 6), showing only marginal Q'' and Q''' which is an indirect signature of the good control of the off-momentum β-beating. Unfortunately the time was too short for a univocal confirmation of this fact by measuring directly the chromatic Montague W functions.

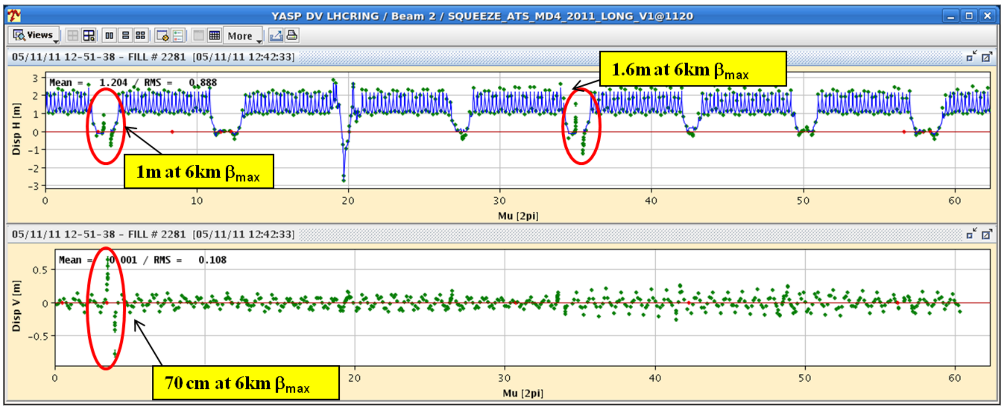
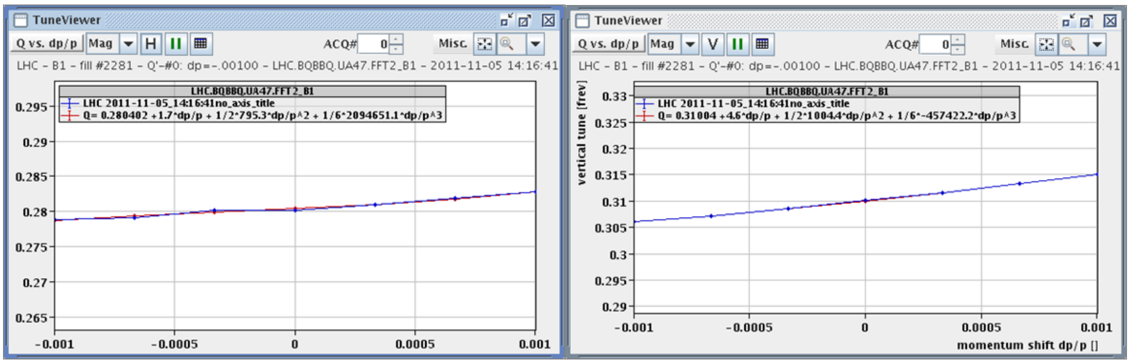


Figure 5: Measurement of the horizontal and vertical dispersion [m] showed for Beam2 (worst case) at $\beta^* = 40$ cm. In the present configuration, the crossing angle is switched off in the four experimental IRs, which means that the main source of spurious dispersion is located in the arcs, induced by the a_2 and b_2 random components of the main dipoles and quadrupoles, respectively. Depending on the betatron phase of the dispersion wave, peaks will show up or not in the inner triplets of IR1 and IR5 with a magnification factor scaling with $\sqrt{\beta_{\rm max}} \propto 1/\sqrt{\beta^*}$.



$Q_x(\delta)$ $Q_y(\delta)$

Figure 6: Chromatic variations of the horizontal (left) and vertical (right) betatron tunes measured for Beam1 at $\beta^* = 40$ cm. The non-linear chromaticity is found to be marginal, which is also the signature of the good control of the off-momentum β-beating.

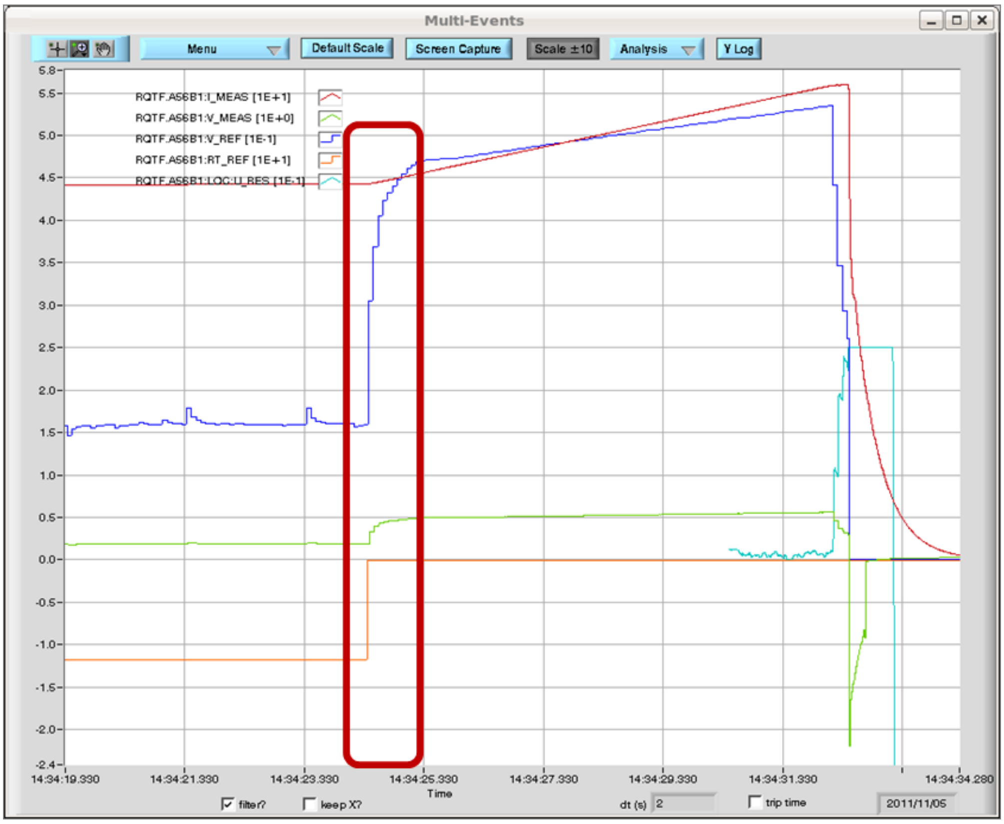


Figure 7: Measured and reference current and voltage of the RQTF.A56B1 circuit during the few seconds preceding and following the switch of the tune correction knobs. The real time trims (orange curve) were wrongly sent to zero during the switch and the QPS tripped the circuit a few seconds later (and idem for the other RQT circuits).

Finally, during the last preparation step before loading the telescopic part of the squeeze, the beam was lost due to several RQT circuits tripped by the QPS. The reason of these trips was then rapidly identified and explained by the fact that the all real time trims accumulated so far in the RQT circuits were sharply sent to zero by the tune feed-back system (see Fig 7) when switching from the first to the second set of tune knobs to be used for $\beta^* < 40$ cm (see Section 2.2 for more details). Obviously, the idea was on the contrary to keep unchanged the RQT real time trims during the switch, and then to continue to trim them later on based on the new tune knobs.

4 Detailed optics measurements and correction

4.1 Beta-beating measurement and correction

As already mentioned, the pre-squeeze of IR1 and IR5 was carried out down to β^*= 40 cm keeping the ATS injection tunes $Q_{x,y} = 62.28/60.31$ as reference for the tune feed-back. A very few empirical trims extracted from [7, 8] were implemented, more precisely the ones used in the previous ATS MD [4] for the pre-settings of the RQSX skew quadrupole triplet correctors and three trims of the order of ± 10 units applied to Q2.R1, Q2.L5 and Q2.R5. AC dipole measurements were

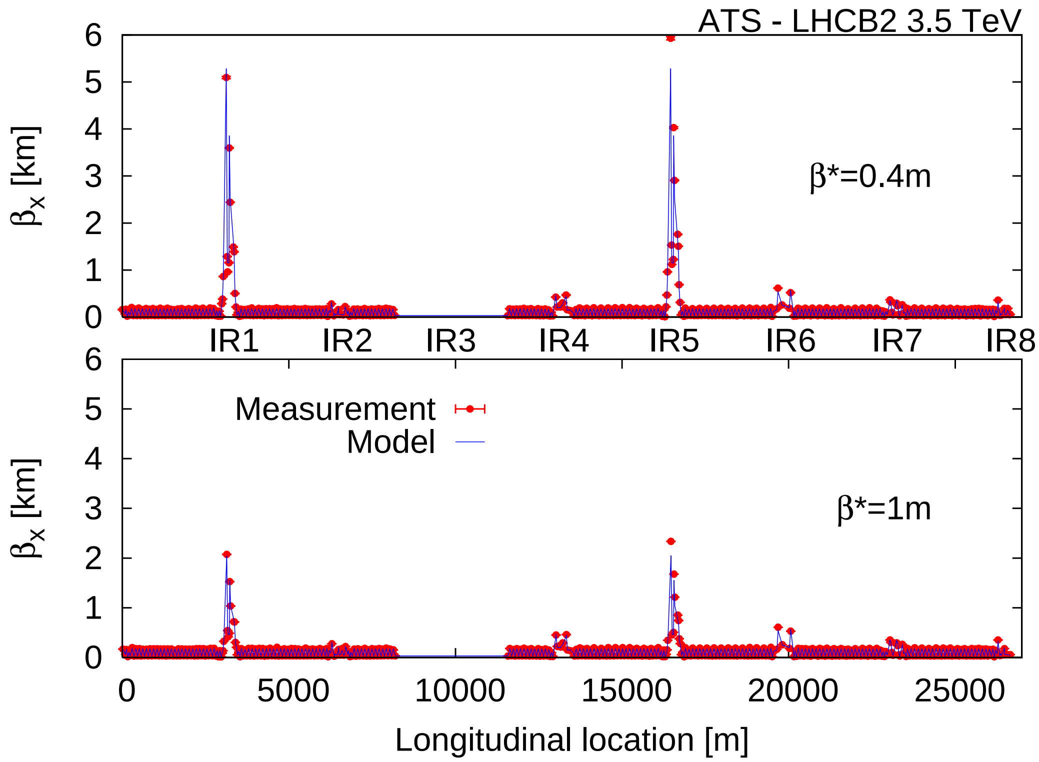


Figure 8: Horizontal β-functions for Beam2 at β^*= 1 m (bottom) and β^*= 40 cm (top): model (blue lines) and measurement (red dots).

performed at β^*= 1 m and β^*= 40 cm. Corrections were computed on-line and applied only for Beam 1 at β^*= 40 cm via the system knob `ATS_correction_40cm_B1`.

Figure 8 illustrates the ATS pre-squeeze by showing the horizontal β functions of Beam2 measured at the BPMs for β^*= 1 m and 40 cm (red dots), and compared to the model (blue lines). At $\beta^* = 40$cm, a peak β-function of the order of 5-6 km is reached at the BPMS's in the inner triplets of IR1 and IR5.

The level of β-beating was measured of the order of 20% at $\beta^* = 1$ m and rised up to 40% at $\beta^* = 40$ cm (see Fig.'s 9 and 10 for Beam1 and Beam2, respectively).

A β-beating correction was applied for Beam1 using the corrector as shown in Fig. 11 and the β-beating shrank down below the 20% level (see Fig. 12). The correction did however not follow the usual procedure since the local correction using the segment-by-segment technique was skipped and the global correction only used quadrupoles belonging to IR1 and IR5. The performance of the correction is not fully satisfactory since the deviations with respect to the model for the left and right phase advances of IR5 increased after the correction (see Tab. 1), and the peak β-beating did not reach the 10% level as for the nominal optics [9]. It is important to note that the IR5 correctors were slightly stronger than the IR1 ones as shown in Fig. 11. This correction should be revisited

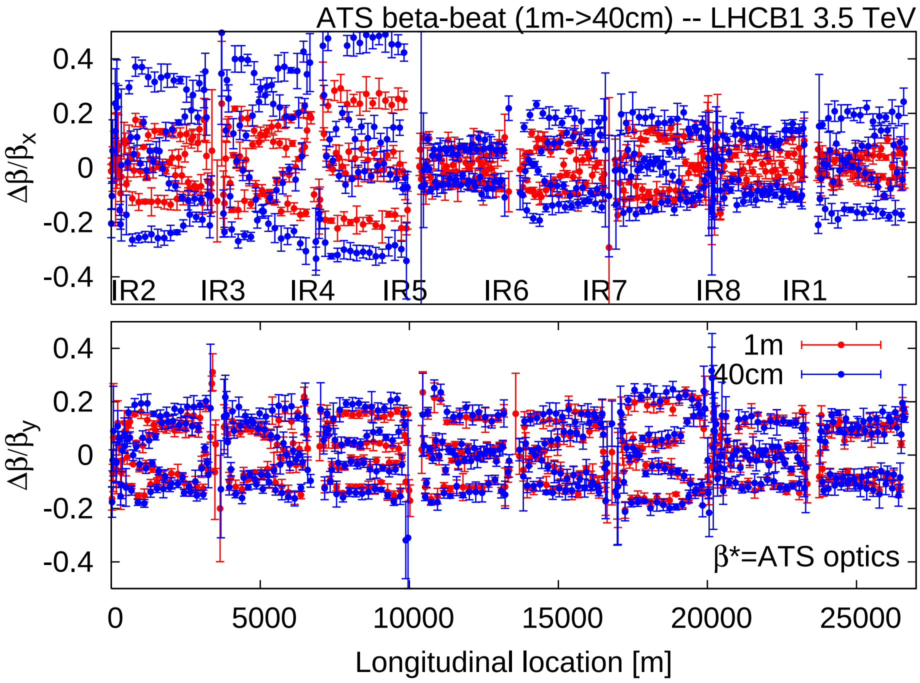


Figure 9: β-beating measured for Beam 1 at β^*= 1 m and 40 cm.

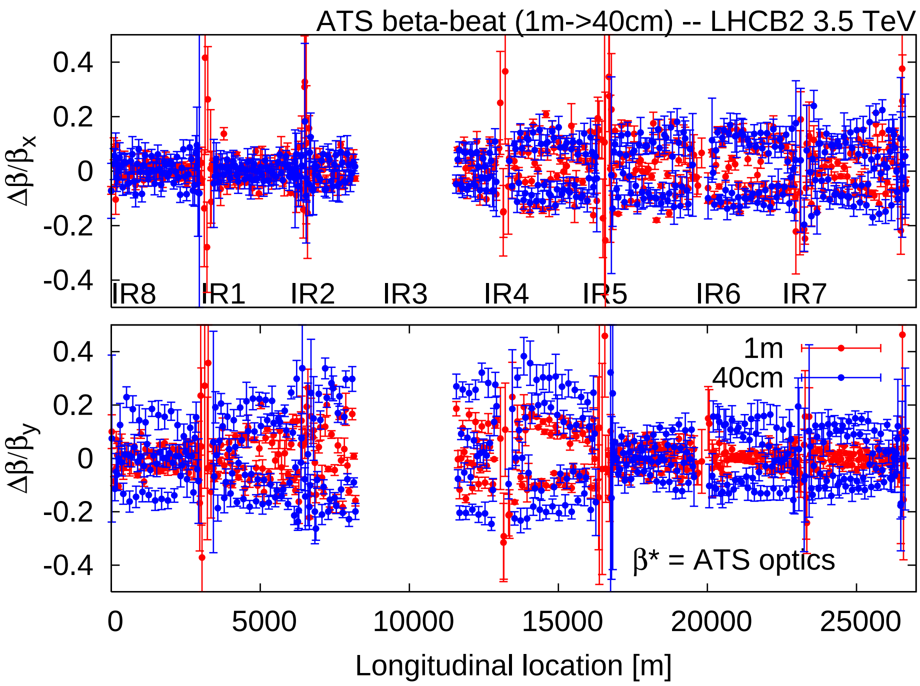


Figure 10: β-beating measured for Beam 2 at β^*= 1 m and 40 cm.

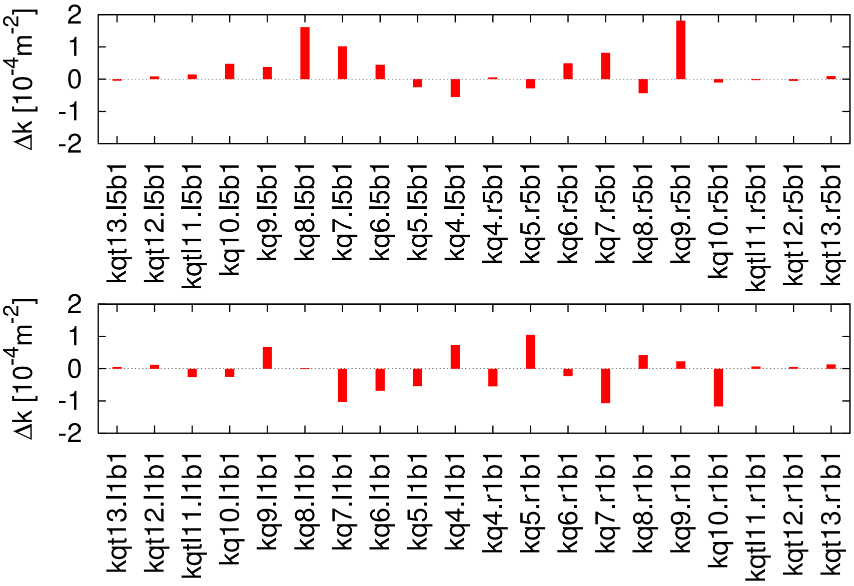


Figure 11: β-beating correction calculated for Beam1 at $\beta^* = 40$ cm and sent to the hardware via the corresponding LSA knob ATS_correction_40cm_B1. The correction involved only the IPQ circuits of IR1 (bottom) and IR5 (top). The triplets were not trimmed.

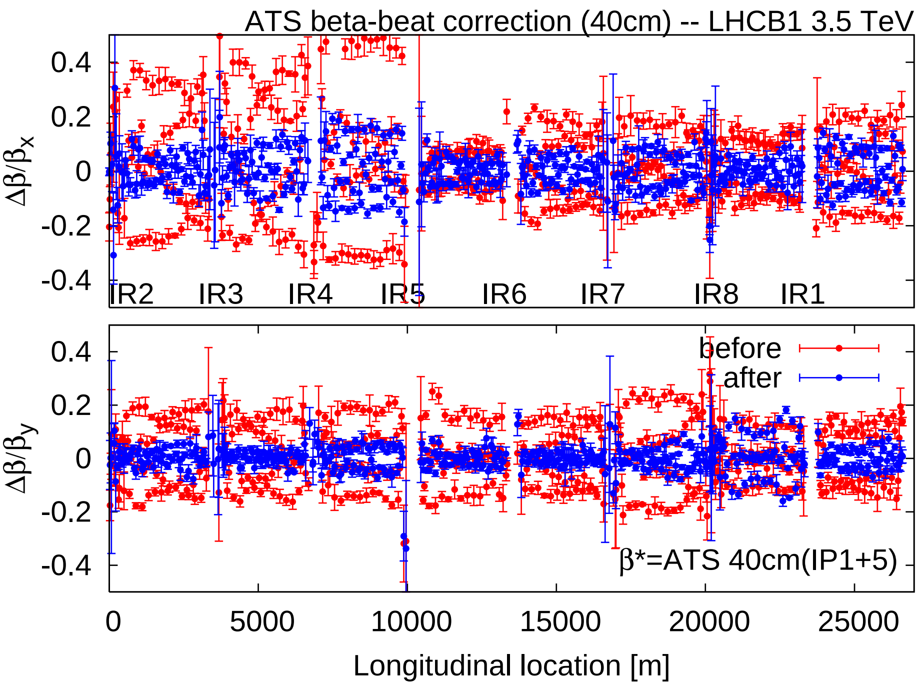


Figure 12: β-beating measurement for Beam1 performed at β^*= 40 cm before and after correction.

IR1			
Selected BPMs in H plane	$\Delta\phi_x[10^{-3}\times 2\pi]$		
	$\beta^* = 1$m	$\beta^* = 0.4$m	Correction
BPM.14L1.B1/BPMSW.1L1	4±2	5±2	5±2
BPMSW.1R1/BPM.14R1.B2	4	3±2	-
BPMSW.1R1/BPM.15R1.B1	-8±2	-10±2	-1±2
BPM.15L1.B2/BPMSW.1L1	-5	-6±3	-
Selected BPMs in V plane	$\Delta\phi_y[10^{-3}\times 2\pi]$		
	$\beta^* = 1$m	$\beta^* = 0.4$m	Correction
BPM.15L1.B1/BPMSW.1L1	-8±3	-5±3	-9±4
BPMSW.1R1/BPM.15R1.B2	-7	-6±7	-
BPMSW.1R1/BPM.14R1.B1	-12±3	-11±3	-2±5
BPM.14L1.B2/BPMSW.1L1	1	3±6	-
IR5			
Selected BPMs in H plane	$\Delta\phi_x[10^{-3}\times 2\pi]$		
	$\beta^* = 1$m	$\beta^* = 0.4$m	Correction
BPM.14L5.B1/BPMSW.1L5	3.5±0.5	0.4±1.8	15±2
BPMSW.1R5/BPM.14R5.B2	-19	3±2	-
BPMSW.1R5/BPM.15R5.B1	0±2	3.6±1.0	14.8±1.0
BPM.15L5.B2/BPMSW.1L5	-7	5±2	-
Selected BPMs in V plane	$\Delta\phi_y[10^{-3}\times 2\pi]$		
	$\beta^* = 1$m	$\beta^* = 0.4$m	Correction
BPM.15L5.B1/BPMSW.1L5	4.1±0.5	7±2	-10±3
BPMSW.1R5/BPM.15R5.B2	-7	-5±7	-
BPMSW.1R5/BPM.14R5.B1	5±2	5±3	3±4
BPM.14L5.B2/BPMSW.1L5	11	4±6	-

Table 1: Deviations of the left and right phase advances of IR1 and IR5 w.r.t. the model, as measured at $\beta^* = 1$ m and 40 cm, before and after β-beating correction for Beam1. As far as only these phases are concerned, the situation gets worst in IR5 after the correction.

to understand if we are facing real limitations or we need a more refined approach to correct this pushed optics. Furthermore the on-line Beam 2 correction did not converge successfully. Hence it was not applied. In conclusion the correction algorithms need to be revised before the next ATS MD.

4.2 Coupling measurements

Figures 13 and 14 show the difference and sum coupling resonance driving terms around the machine for Beam 1 and Beam 2, respectively, measured at $\beta^* = 1$ m and $\beta^* = 40$ cm. A clear jump is observed for both beams in the triplets of IR5, indicating the need of retuning the RQSX correctors at this location.

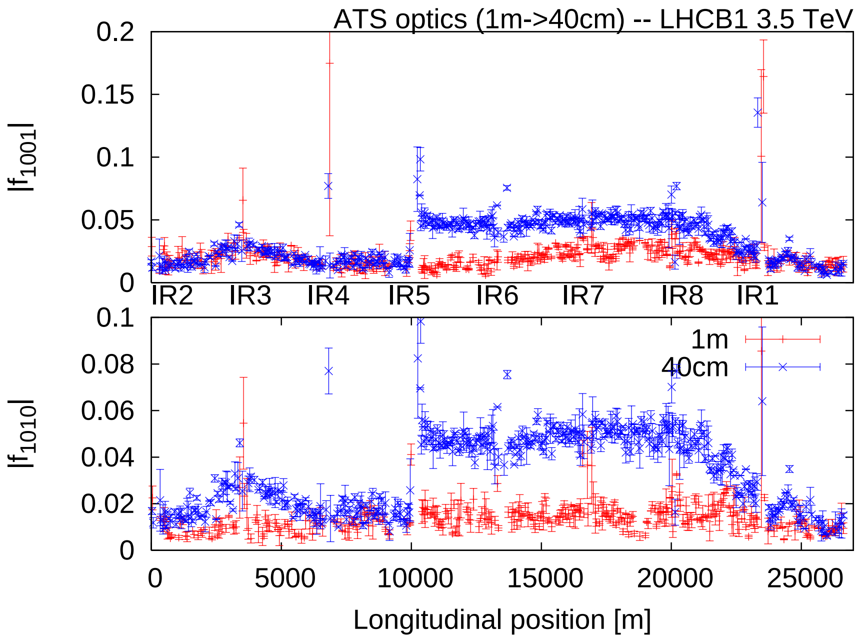


Figure 13: Measurement of the sum and difference coupling resonance driving terms for Beam1 at β^{*}= 1 m and 40 cm.

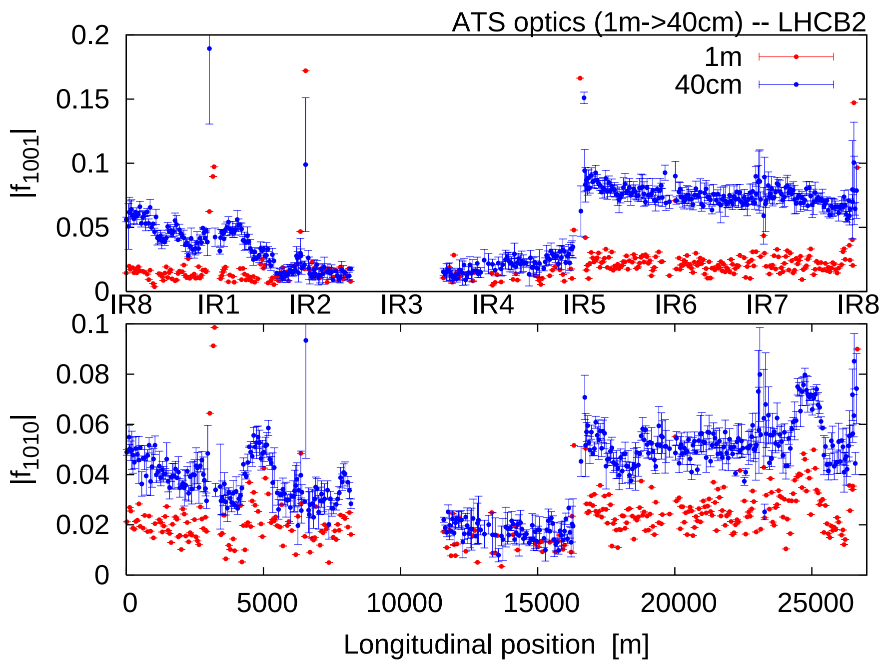


Figure 14: Measurement of the sum and difference coupling resonance driving terms for Beam2 at β^{*}= 1 m and 40 cm.

5 Conclusions and outlook

The results obtained in this third ATS MD are two-folds. First of all, the nominal collision β^* of 55 cm, and actually even 40 cm, has been reached, quite smoothly and rapidly, which is an important result for the LHC. Secondly the 15 years long-standing problem of correcting the chromatic aberrations induced at low β^* is definitely solved with the pre-squeezed ATS optics (even if a direct confirmation by measuring the W functions remains to be done). The minimum β^* below which this correction is actually needed is however not yet precisely known for the LHC, and will be assessed next year during dedicated MDs.

On the other hand the quality of the pre-squeezed optics, even after correction, still requires some improvement, before envisaging the telescopic part of the squeeze and finally reach 10 cm at IP1 and IP5. A 20% β-beating has indeed been achieved at β^*= 0.40 m after one global correction, for Beam 1 only, but a careful inspection of the IR phases revealed some deterioration in IR5. The Beam 2 on-line correction did also not converge successfully. The horizontal spurious dispersion coming from the arc imperfections can now exceed 1.5 m in the inner triplet at β^*= 0.40 m ($\beta_{\max}$ =6 km), which would mean more than 3 m at β^*= 0.10 m. Therefore the correction algorithms certainly need to be revised in many aspects, also including the correction of the horizontal dispersion, before the next ATS MD. Finally, the RQSX settings need to be re-adjusted in IR5, in order to keep a good control on the coupling when β^* will approach 10 cm, i.e., $\beta_{\max}$ will exceed the 20 km level in the inner triplets of IR1 and IR5.

To summarize, several complications start to show up, as expected at low β^*, but not any show-stopper proper for the ATS scheme.

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