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The Achromatic Telescopic Squeezing (ATS) MD part II

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Summary

This note describes the results obtained during the second so-called ATS MD where the record of β^* was reached at IP1 and IP5 with a "pre-squeezed" β^* of 1.2 m, while perfectly controlling the chromatic aberrations induced (non-linear chromaticity, off-momentum β-beating). Then, the ATLAS insertion was squeezed further down to the target of the former LHC Upgrade Project (Phase I), that is to $\beta^* = 30$ cm, using the Achromatic Telescopic Squeezing techniques. In view of this major achievement, the bar is fixed even higher for the next ATS MD's, with an ultimate β^* targeted to 10 cm for the two high-luminosity insertions ATLAS and CMS.

1 Introduction

The Achromatic Telescopic Squeezing (ATS) scheme is a novel concept able to reach extremely low β^* value 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, but which are also necessary in order to improve, at constant strength, the chromatic correction efficiency of the lattice sextupoles in these sectors.

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^* has to 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 (7TeV/beam) and for the existing triplet (205T/m), the pre-squeezed β^* shall fulfill the following condition:

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

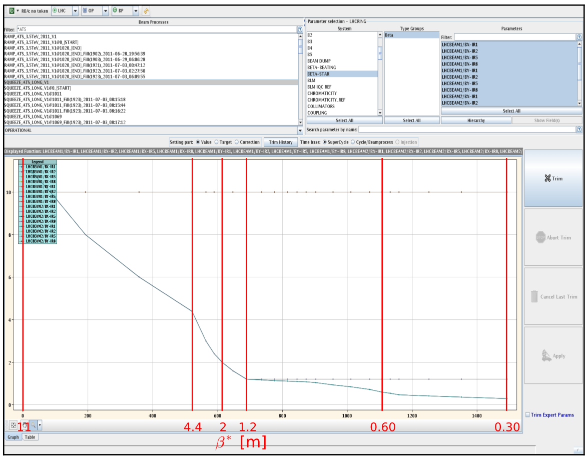
The IR phasing conditions mentioned above can indeed not be reached for a β^* larger than 2 m, while, below 40 cm, the current of the lattice sextupoles would be pushed beyond 600 A (so-called ultimate current) in order to perform the chromatic correction of the triplet (with one sector of sextupoles correcting one triplet).

For the second ATS MD, the pre-squeezed β^* was chosen to 1.2 m, leaving enough aperture in the inner triplet in order be able to continue the squeeze using the Telescopic techniques described above, and validate in fine the principles of the ATS scheme. Said differently, the pre-squeeze of the ATS scheme (i.e. still keeping the nominal FODO optics in the arcs) is already fully sufficient to reach the nominal β^* of the LHC, and even below (40 cm), while correcting the chromatic aberrations induced (which is out of reach with the nominal collision optics) and already preparing the optics of the machine for the upgrade. However, pushing the pre-squeeze down to 40 cm was not the aim of the second ATS MD.

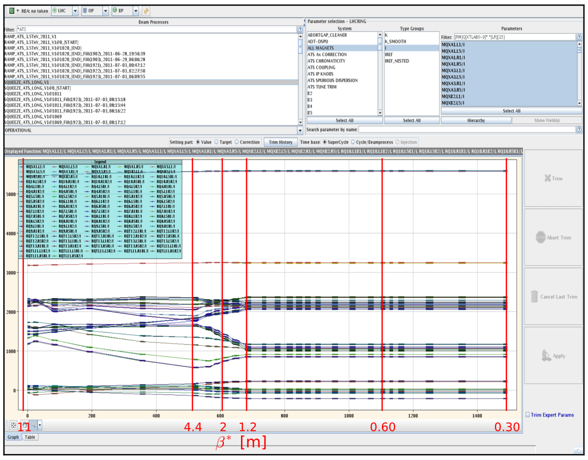
Two different series of optics files have then been prepared accordingly in the `ATS_V6.503` afs directory [3]. The first one (under the `OPTICS_MD2011` sub-directory) has been used to build the ATS-squeeze beam process in LSA (see Fig. 1) and contain the new injection optics, the pre-squeeze of IR1 and IR5 down to 1.2 m, and the squeeze of IR1 down to 30 cm with peak β-functions increased by a factor of 4 in the arcs 81 and 12. The second series of files can be found under the sub-directory `OPTICS_round_IR1_40-10_IR5_40-40` and contain a pre-squeeze sequence down to $\beta^* = 40$ cm at IP1 and IP5 and then, as above, a further reduction of β^* by a factor of 4 at IP1, bringing it down to 10 cm. In both cases, the second part of the squeeze of IR5 (acting on IR4 and IR6) is not yet available.

While the first ATS MD commissioned the new injection optics and its ramp [4], the plan for the second MD block [5] was the production, measurement and correction of the pre-squeezed optics ($\beta^* = 1.2$ m) and, eventually, an increase of the β functions by a factor of 2 in the sectors 81 and 12 for a first validation of the ATS principles (and leading to $\beta^* = 60$ cm at IP1). However, as described later, after one unsuccessful ramp, one unsuccessful pre-squeeze and finally the achievement of a "very honorable" pre-squeezed optics with not more than 20% β-beating and a coupling easily corrected, the plan changed during the MD. The fine correction foreseen for the pre-squeezed optics was sacrificed to the profit of a full validation of the ATS principle, increasing the peak β functions by a factor of 4 in the sectors 81 and 12 (i.e. 720 m compared to 180 m nominally) and reaching a β^* of 30 cm at IP1.

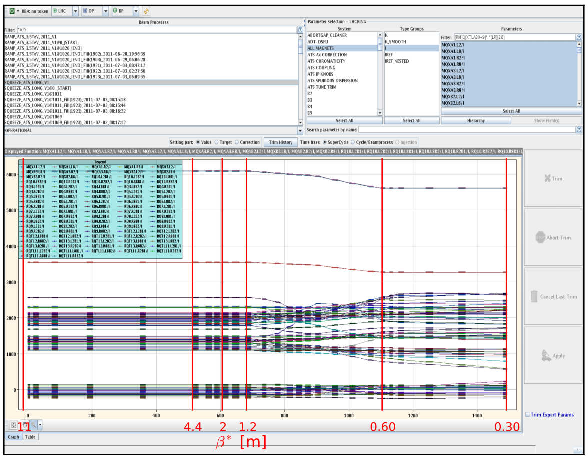
As for the first MD block, the second ATS MD was split into two parts. The first one was scheduled on Wednesday 29/06/2011, from 6H00 to 8H00, for a dry run of the full ATS hypercycle. As described in details in section 2, this dry run was found extremely useful in order to optimize the level of readiness of the MD with beam which was scheduled on Sunday 03/07/2011 from 0H00 to 8H00. The highlights of the MD with beam will be described in Section 3. The last two sections will then contain more detailed analysis of the measurement data concerning the optics (Section 4) and the losses observed during the various steps (pre-squeeze, squeeze, with or without AC dipole excitation for optics measurement with or without RF modulation for chromatic measurements, with or without AC dipole excitation for optics measurement, or with both).



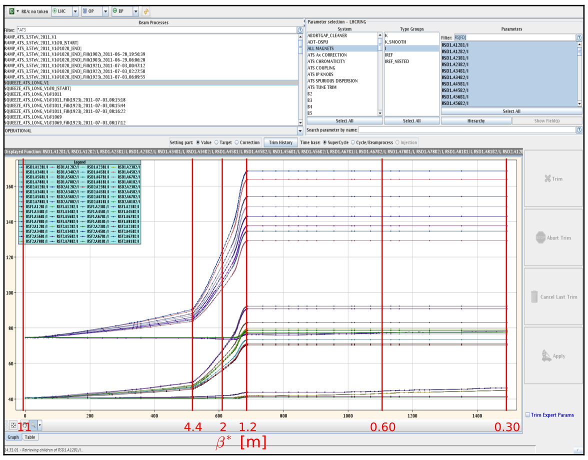
(a): β^* [m]



(b): Quadrupole settings [A] in IR1 and IR5



(c): Quadrupole settings [A] in IR2 and IR8



(d): Sextupole settings [A]

Figure 1: Main LSA functions for the ATS hypercycle [6] during the squeeze: β^* (a), IR1 and IR5 quadrupole settings (b), IR2 and IR8 quadrupole settings (c) and sextupole settings (d) versus time. The total duration of the squeeze, from $\beta^* = 11$ m down to 30 cm, is about 25 minutes (1500 s) but could be strongly reduced (e.g. removing some matched points and/or combining a part of the pre-squeeze and squeeze). The quadrupole settings in IR1 and IR5 are kept constant below the pre-squeezed β^* of 1.2 m, but the squeeze continues acting on the standalone quadrupoles of IR2 and IR8 (keeping $\beta^* = 10$ m at IP2 and IP8). Most of the 62 LHC sextupole circuits operate at almost constant current during the squeeze, with the exception of 16 circuits which are ramped up during the pre-squeeze in the 4 sectors adjacent to IR1 and IR5 (1 per plane, per beam and per sector), therefore with a ramp speed dI/dt which is four times faster than the one which would be given by a simple global correction of the linear chromaticity.

2 Dry run

The dry run was devoted to the hardware test of the full ATS hypercycle [6] containing the nominal LHC pre-cycle, the ATS injection and ramp beam process successfully tested during the ATS MD part I [4] and, more specifically, the new beam process `ATS_SQUEEZE_V1` containing the pre-squeeze of IR1 and IR5 down to $\beta^* = 1.2$ m and the continuation of the squeeze of IR1 down to $\beta^* = 30$ cm, acting on the IPQ circuits of IR8 and IR2. In addition, for the injection, pre-squeezed and squeezed optics, it was foreseen to test standard and more specific "ATS knobs" by loading and unloading trims and verifying that the currents generated by the power converters were conform to the expectations.

A summary of what has been achieved and tested is presented here after, while Sub-Section 2.2 is devoted to an in-depth analysis of one type of failure that occurred multiple times and is particularly critical for the generation of the squeeze.

2.1 Highlights

The ATS injection was successfully loaded on 2011-06-29, 05:58:25, after pre-cycling the machine, starting from the 3.5 TeV energy reached in the previous fill (90 m optics). New a_2 correction knobs, based on the magnetic measurements of the main dipoles, were tested for both beams.

On 2011-06-29, 06:04:20, the ramp was successfully loaded and completed on 2011-06-29, 06:16:40. From this time to 2011-06-29 06:42:40, the following knobs were successfully tested: tune, coupling and chromaticity trims, RQSX trims (for local coupling correction of the inner triplet, copied from [8]), and a "minimal" β-beating knob involving the Q2.R1, Q2.L5 and Q2.R5 inner triplet quadrupoles (see Tab. 1 in Section 3 for more details).

On 2011-06-29, 06:56:00, the squeeze process was loaded showing only very few missing items: the RQS circuits of sector 34, not defined in the ATS-squeeze beam process (and to be set to zero as for the injection and ramp), and idem for RF settings. This missing items did not stop the continuation of the MD study and were fixed just after its conclusion.

The pre-squeezed optics ($\beta^* = 1.2$ m at IP1 and IP5) was reached on 2011-06-29 07:08:00 without evident issues, although a detailed analysis performed soon after showed that one Q4 circuit (RQ4.R1B2) was in a state close to trigger a PC trip (see details in Sub-Section 2.2). From this time to 2011-06-29, 07:53:50, the following knobs were tested:

- the usual tune, coupling and chromaticity knobs (rematched for the new ATS arc optics), but also their substitute, the so-called `TELE` knobs, to be used beyond the pre-squeeze in order to trim the same quantities, but without acting on the corresponding lattice correctors (MQT, MQS, MS) in the sectors 81 and 12 where the peak β-functions are supposed to increase,
- the usual `IP` knobs for the generation of the crossing and parallel separation bumps in IR1, IR2, IR5 and IR8 (obviously rematched for the new ATS optics),
- new ATS specific knobs for the correction of the spurious dispersion induced by the crossing scheme in IR1 and IR5.
- again the RQSX trims mentioned above,

- and a new a_3 correction knob based on the magnetic measurements of the skew sextupole component of the LHC main dipoles. Only Beam 2 was tested, due to the unavailability of the RSS.A81.B1 circuit for Beam 1 (following a non-conformity opened in 2011 and apparently related to cryogenic regulation problems).

On 2011-06-29 08:03:00 the second part of the squeeze was started and, about 10 minutes later, two Q4 circuits tripped, RQ4.L2B2 and RQ4.R8B1, before reaching the before last and the last step of the squeeze at $\beta^* = 36\,\mathrm{cm}$ and $30\,\mathrm{cm}$, respectively. This event ended the MD study.

A detailed analysis of these trips is carried out in Sub-Section 2.2. In order to fix this problem, a new beam process was regenerated for the squeeze, the `SQUEEZE_ATS_LONG_V1` beam process, increasing by a factor of 2 or even slightly more the duration between the last 3 steps at $\beta^* = 42$ cm, 36 cm and 30 cm. This longer ATS-squeeze beam process was finalized just in time during the night of the MD with beam.

2.2 Q4 trips

During the squeeze, the current functions $I(t)$ sent to the IPQ circuits (which feed the standalone quadrupoles of the LHC insertions) are generated between two matched points using a PLP (parabolic-linear-parabolic) function with a vanishing derivative $I'(t)$ at both extremities. The time duration between two points is adjusted such that the speed and acceleration, $I'(t)$ and $I''(t)$, do not exceed a certain threshold which is given for each circuit. The thresholds are mainly specified by quench protection related criteria, which, in most of the cases, also ensures that the current delivered by the power converter can follow the reference current. If not, another protection ensures that if the difference between a requested current and the measured one is larger than 10A, then the power converter automatically trips, the voltage decays to 0V following some time constants intrinsic to the circuit, and the current discharges on the circuit resistances. Sometimes, indeed, it can happen that the unipolar power converters feeding the IPQ circuits cannot follow a given function where the current shall decrease or decelerate faster than a certain threshold, not necessarily the same as above, which depend on the time constants of the circuit but also on the actual current $I(t)$. Therefore a constant threshold imposed for the maximum ramp rate $I'(t)$ (idem for $I''(t)$), i.e. independent of $I(t)$, may in fact overestimate the time needed for a ramp down at high current (but offering a safer quench protection) and will never prevent trips of the power converters, unless additional thresholds, e.g. related to the quantity $I'(t)/I(t)$, are also taken into account to generate the LSA functions.

This is exactly what happened during the ATS dry run where a partial and complete lost of control occurred at three occasions: during the pre-squeeze for the circuit RQ4.R1B2 and during the squeeze for RQ4.L2B2 and RQ4.R8B1 (see Fig. 2).

Concerning the circuit RQ4.R1B2, the requested ramping down exceeded the natural decay of the circuit at the end of the last segment after which the reference current is supposed to increase again (see Fig. 2), leading to a difference $I_{\mathrm{MEAS}} - I_{\mathrm{REF}}$ of about $0.1\,\mathrm{A}$ (see Fig. 3). A priori, if the optics had been matched with a slightly lower normalised strength for the Q4's, a real trip would have occurred, not only for this circuit but actually for the four RQ4 circuits of Beam 2 on the left and right sides of IR1 and IR5. It is indeed worth noting that the same normalised strength is imposed for all these circuits (the left/right optics antisymmetry being always forced at least till to Q5 in IR1 and IR5), leading to almost exactly the same current settings (within tiny differences

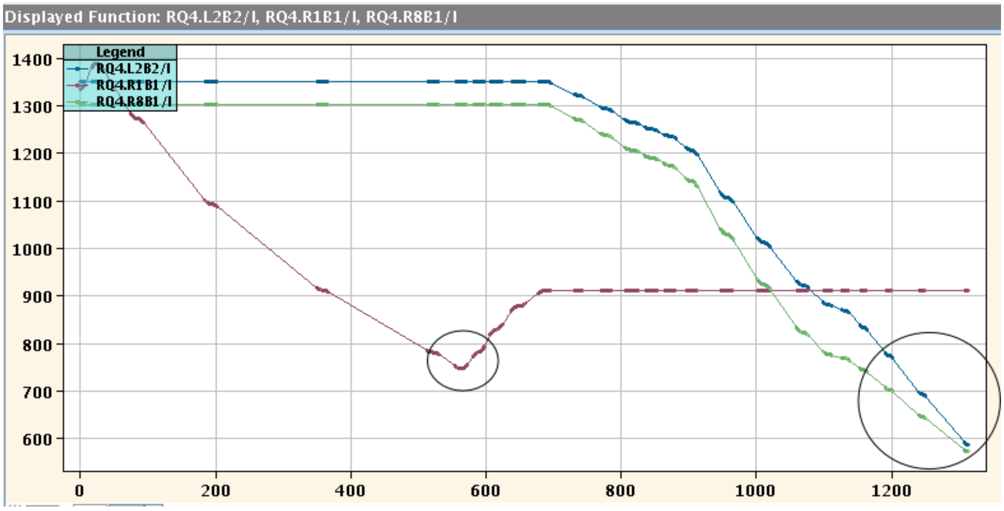


Figure 2: LSA functions exceeding the capability of the circuits RQ4.R1B2, RQ4.L2B2 and RQ4.R8B1 at low current, although compatible with the thresholds given by the QPS in terms of ramp speed and acceleration.

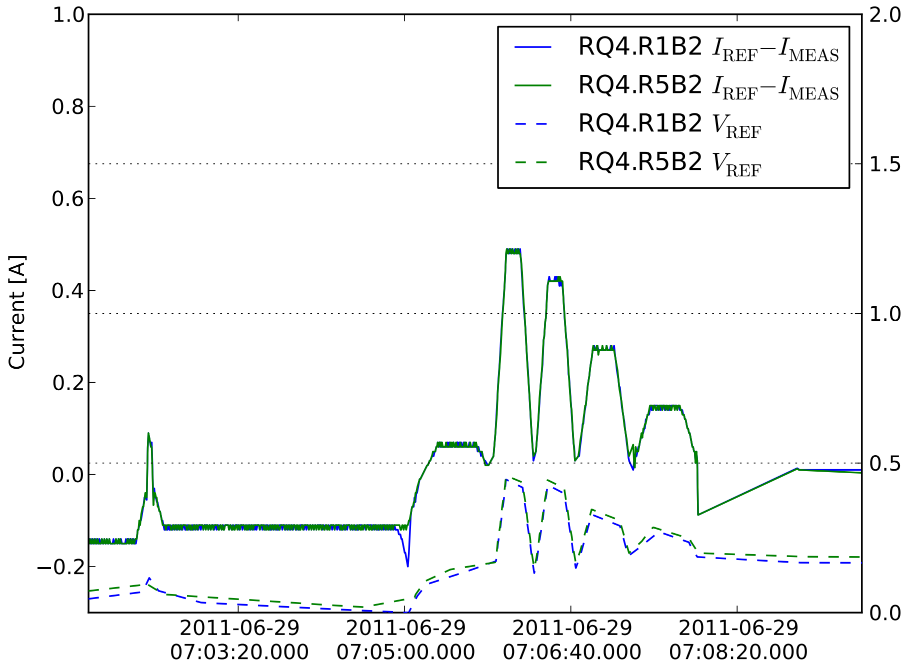
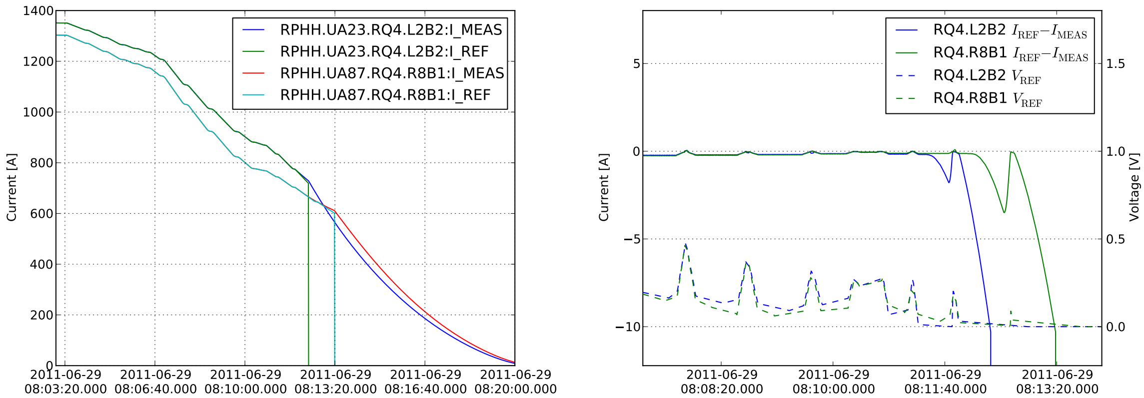


Figure 3: Difference between measured and reference currents for the RQ4.R1B2 and RQ4.R5B2 circuits, zoomed in the short period during which the RQ4.R1B2 power converter could no longer follow its reference current around 750 A (see Fig. 2). The reference voltage signal is also showed, confirming that the lost of control occurred when the voltage dropped almost to zero for the RQ4.R1B2 circuit, while very low but apparently still acceptable for the other circuit.

due to slightly different integrated transfer functions). However, as showed in Fig. 3, this problem was not observed in the case of another RQ4 circuit, namely Q4.R5B2, demonstrating that the time constants of the IPQ circuits of the LHC can be different, even for magnets of strictly the same type and operating the same reference current.

Concerning the RQ4.L2B2 and RQ4.R8B1 circuits, the current control was lost on two consecutive segments and only in the last one a trip occurred (see Fig. 4-(a)) when the difference $|I_{\rm REF} - I_{\rm MEAS}|$ exceeded 10 A (see Fig. 4-(b)). The trip of RQ4.L2B2 occurred between the segment going from $\beta^* = 42$ cm to $\beta^* = 36$ cm with a loss of control arising below a current of 776A, while the trip of RQ4.R8B1 occurred at a lower current of about 620 A during the last step from $\beta^* = 36$ cm to $\beta^* = 30$ cm.



(a) (b)

Figure 4: Measured and reference currents for RQ4.L2B2 and RQ4.R8B1 circuits during the squeeze (left picture). These circuits tripped at two different times when the difference between reference and measured currents was larger than 10A (right picture). The reference voltage signals are also showed confirming that the lost of control occurred at zero voltage.

In order to fix this issue, the time duration of the last three segments was doubled and a new squeeze beam process was generated accordingly, renamed as `SQUEEZE_ATS_LONG_V1`.

3 Highlights of the MD with beam

Not more than 3 ramps were needed to reach and in fact go beyond the ultimate goal of the Achromatic Telescopic Squeezing MD part II.

3.1 Machine conditions

3.1.1 Beam

The MD was performed with fat pilots ($N_b = 10^{10}$ pbb, 1 bunch per beam). Beam 1 and Beam 2 were injected in bucket 1 and bucket 2001, respectively, in order to avoid the collisions. The transverse emittances of the beam were measured at several occasions (injection, flat top, pre-squeeze) and were found of the order $\gamma\epsilon = 1.0 - 1.3\,\mu$rad.

3.1.2 Hypercycle

A new LHC hypercycle was specifically built for the MD, the so-called ATS hypercycle [6] which is a concatenation of the nominal LHC pre-cycle and two new LSA beam processes for the ramp and squeeze: `RAMP_ATS_3.5TeV_2011_V1` for the injection and ramp commissioned during the first MD block [4], and `SQUEEZE_ATS_LONG_V1` containing the pre-squeeze sequence of IR1 and IR5 from $\beta^* = 11$ m to $\beta^* = 1.2$ m and the continuation of the squeeze of IR1 down to $\beta^* = 30$ cm acting on the standalone quadrupoles of IR8 and IR2. All the dynamic processes (ramp, pre-squeeze, squeeze) were achieved with a flat machine, i.e. with the crossing and parallel separation bumps switched off, together with the corresponding dispersion knobs. The dispersion knobs based on horizontal and vertical orbit bumps in the sectors 81, 12, 45 and 56 were nevertheless tested for closure at $\beta^* = 4.4$ m (see later).

3.1.3 Damper and feed-backs

The transverse damper (ADT) was only used for damping the injection oscillations and then switched off after 1000 turns following each injection. The ADT settings (phases) were the ones calculated for the new ATS injection optics and successfully tested during the first MD block [4]. All dynamic beam processes were achieved with the orbit and tune feed-backs (OFB and QFB). The QFB reference tunes were kept equal to the injection tunes 62.28/60.31 all along, in particular during the pre-squeeze and squeeze in order to keep a comfortable tune split of 0.03 and avoid the beam to be lost in case of a badly corrected coupling. Said differently, the tune feed-back was set up to cancel the tune jump $\Delta Q_{x,y} = (0.03, 0.01)$ to go from the injection to the collision tunes, and which is normally performed during the first step of the (pre-)squeeze.

3.1.4 Collimation and protection devices

With the crossing scheme switched off in all IR's, the injection protection devices and the TCTs were adjusted with relaxed (symmetric) settings. Except for the first ramp, the TCP's and TCS's of IR3 and IR7 were not ramped, i.e. remains to their injection settings till reaching 3.5 TeV (idem for the TCDQ/TCSG of IR6). At the end of the ramp, the horizontal and vertical primary collimators of IR7 (4 collimators for both beams) were manually retracted to about 9 nominal sigma's. These settings are roughly 1 σ and 3 σ deeper than the normalised aperture of the triplet which was estimated at $\beta^* = 1.2$ m (pre-squeezed optics), with and without a full crossing angle of 340 μrad, respectively. The pre-squeeze was then achieved at constant collimator (and TCT) settings. Finally, stopping at $\beta^* = 1.2$ m, the TCTH and TCTV settings were retracted to ± 12 mm and ± 10 mm, respectively, which corresponds to a normalised aperture still larger than that of the primary collimators at $\beta^* = 1.2$ m, but able to protect the triplet for any β^* below 1.2 m with or without a crossing angle of up to 340 μrad. With such a setting up, the TCTs of IR1 then became the primary aperture bottleneck at some intermediate β^* during the squeeze from 1.2 m to 30 cm. Surprisingly, this intermediate β^* was found as low as $\beta^* \approx 55$ cm as seems to indicate the analysis of the losses measured at the TCP's and TCT's during the squeeze (see section 5).

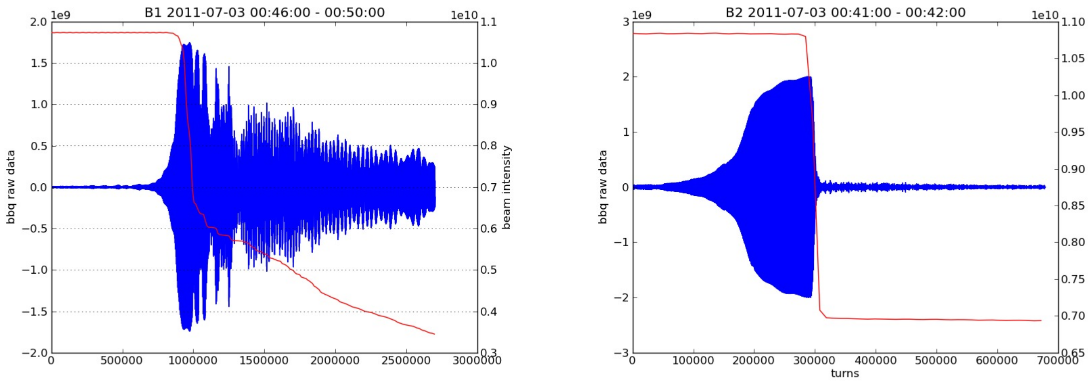


Figure 5: BBQ measurement data in arbitrary units (blue) and beam intensity (red) during the first ramp for Beam 1 (left) and Beam 2 (right): a clear horizontal instability can be observed due to a negative chromaticity which was estimated to $Q'_x \approx -10$ units or lower during the ramp.

3.2 The first attempt loosing the beam in the first ramp

Beam 1 and a big fraction of Beam 2 were lost during the first ramp due to a bad incorporation of the chromaticity trims performed at injection. A strongly negative chromaticity of about -10 units or lower was then reached during the ramp, leading to a mode $m = 0$ instability (see Fig. 5). It was decided to dump the (residual) Beam 2 at 3.5 TeV, recycle and refill.

3.3 The second try triggering a beam dump in the pre-squeeze at $\beta^* \approx 3$ m

The incorporation rules for Q' were re-adjusted and the second ramp was successful with, in addition, a preventive chromaticity trims of +8 units performed at injection. The coupling and chromaticity were measured and easily corrected at 3.5 TeV. The OFB and QFB were switched on to start the pre-squeeze, with stop points foreseen at $\beta^* =$ 10, 8, 6 and 4.4 m for a careful monitoring and eventual correction of the coupling and chromaticity. The later were found actually rather stable and therefore no further correction was applied. First corrections and incorporations took place at $\beta^* = 4.4$ m concerning the closed orbit correctors, but also specific trims of the order of ± 10 units given to the Q2.R1, Q2.L5 and Q2.R5 inner triplet quadrupoles (see Tab. 1). Actually, these three trims constitute a very small subset of the knobs which are used in nominal operation since 2010 after a so-called local and global β-beating correction [7].

Magnet	Nominal K (as seen by Beam 1)	ΔK $[10^{-5}\text{m}^{-2}]$ (as seen by Beam 1)	Relative trim [units]
Q2.R1 (MQXB type)	-0.008714	-0.8	9.2
Q2.L5 (MQXB type)	0.008714	1.0	11.5
Q2.R5 (MQXB type)	-0.008714	1.3	-14.9

Table 1: Empirical trims from Ref. [8] applied to three inner triplet quadrupole Q2's in IR1 and IR5, incorporated at β^* =4.4 m and kept constant for lower β^*.

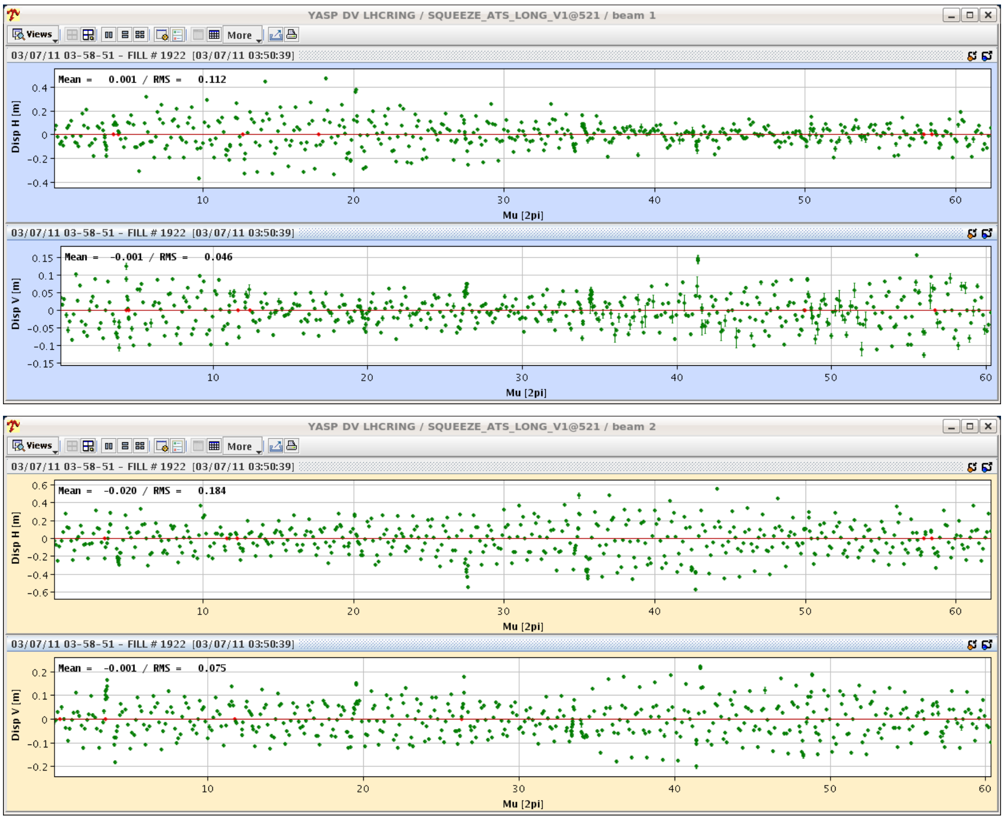
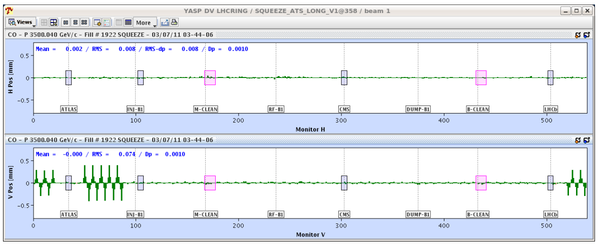


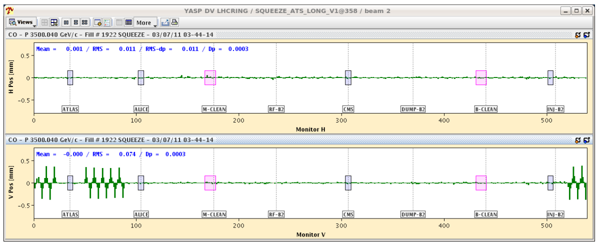
Figure 6: Horizontal and vertical spurious dispersion [m] (i.e. deviation w.r.t. the model) measured at $\beta^* = 4.4$ m for Beam 1 (top) and Beam 2 (bottom). The machine starts at the mid-arc of sector 81 and is oriented clock-wise for both beams. The peak spurious dispersion does not exceed 15-20 cm in the vertical plane but can be more than doubled, in particular for Beam 2, in the horizontal plane (while still within the specification set to 60 cm in the arcs).

Several measurements were also performed at $\beta^* = 4.4$ m. The spurious dispersion was measured with YASP (see Fig. 6), giving excellent results in the vertical plane (not more than 15-20 cm in the arcs, i.e. a factor of up to 4 less than the specification), but degraded by a factor of 2-3 in the horizontal plane (but still fulfilling the 60 cm specification). This phenomenon was already observed with the injection optics during the first ATS MD [4], both at 450 GeV and 3.5 TeV. It is very likely related to the fact that the sorting strategy applied to the main quadrupoles was optimized for β-beating only, with the selection of quadrupole pairs to be separated by $\pi/2$ in betatron phase (i.e. spaced by one FODO cell), while the induced horizontal dispersion was only checked a posteriori. A simultaneous optimization of the β-beating and spurious horizontal dispersion induced by the random b_2 of the main quadrupoles would have indeed implied additional pairing constraints, which have been found totally impractical during the production and installation phases of the machine (with too many different hardware types for the MQ cold masses). On the other hand the vertical spurious dispersion, dominated by the random skew quadrupole components of the main dipoles, was carefully taken into account during the installation phase of the LHC (together with the induced sum and difference coupling coefficients and the 3rd order resonance driving terms).

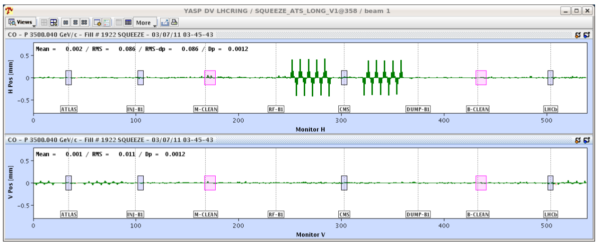
Another source of spurious dispersion, which actually dominates at very low β^*, is that induced by the crossing angle in the high-luminosity insertions. This source was not activated during



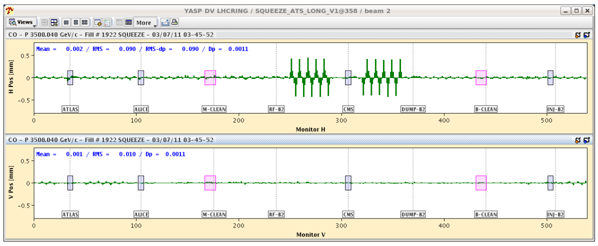
(Beam 1)



(Beam 2)



(Beam 1)



(Beam 2)

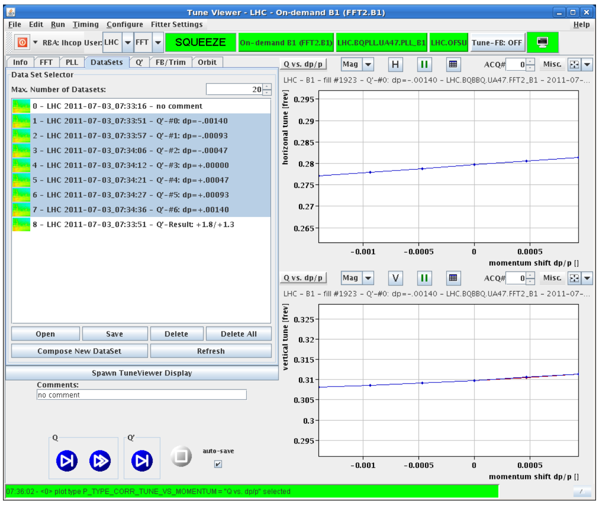
Figure 7: Specific ATS knobs for correcting the vertical and horizontal spurious dispersion induced by the crossing angle in IR1 and IR5. The strategy consists in generating vertical (top) and horizontal (bottom) orbit bumps in the two sectors on either side of IP1 and IP5, respectively. The above picture stands for a test performed at β^* =4.4 m, leading to orbit excursions of the order of ± 0.5 mm peak to peak in the sectors 81, 12, 45 and 56, with almost no leakage in the other parts of the ring. The amplitude of the bumps should increase up to $\pm 2 - 2.5$ mm peak to peak for the pre-squeezed β^* of 1.2 m, then remains unchanged for lower β^*, assuming a full crossing angle of 340 μrad kept constant at IP1 and IP5 during the squeeze.

the MD since the crossing scheme were off in all experimental IR's. Nevertheless it is worth reminding that corresponding correction knobs are foreseen by the ATS scheme. They are based on the generation of orbit bumps in the two sectors adjacent to each of the two high-luminosity insertions, in the horizontal and/or the vertical planes, depending on the orientation of the crossing plane. While the time was short to qualify the efficiency of this correction, these bumps were nevertheless switched on and off, and successfully tested at least for closure (see Fig. 7). Finally local coupling and β-beating were also measured with the AC-dipole at $\beta^* = 4.4$ m, showing excellent results which are reported in Section 4.

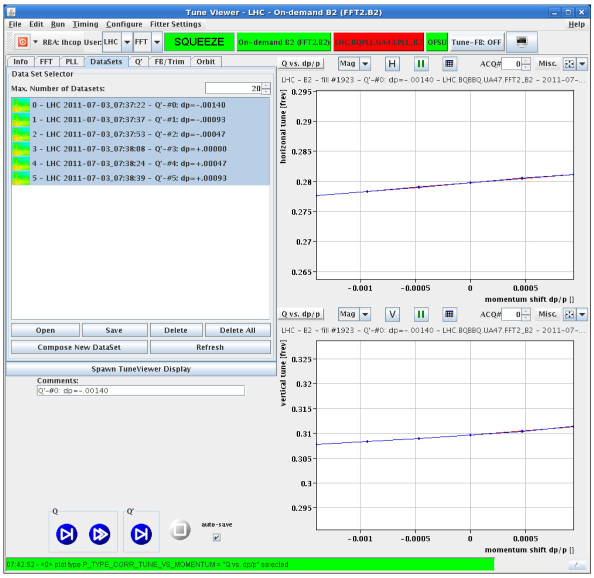
Then the pre-squeeze restarted with the next stop point successfully reached at $\beta^* = 3$ m. However the two beams were dumped just after leaving the stop point at 3 m, due to a trip of the sextupole circuits RD1.A45B1 and RD2.A56B2 triggered by the QPS. These two circuits belong precisely to the 8 defocusing sextupole families which participate to the chromatic correction of the triplet during the squeeze (see Fig. 1-(d)). Since these trips were not observed during the dry run, the explanation could then hardly be related to an excess in ramp speed dI/dt (1.5 A/s maximum specified for the RS circuits). On the other hand, during the dry run, the pre-squeeze was performed without any stop from 11 m to 1.2 m. Also, it was realized that, contrary to the IPQ circuits, the rounding procedure with zero slope at each stop point (see Sub-Section 2.2) was not foreseen for the sextupole circuits in LSA. As a result, we were rapidly convinced that the reason of these trips was not related to an excess of slope dI/dt, but to a too sharp acceleration, when restarting the pre-squeeze just after the stop point at $\beta^* = 3$ m.

3.4 The third try reaching $\beta^* = 30$ cm at IP1 and 1.2 m at IP5

The machine was then recycled, two fresh pilots injected, and the third ramp started at around 6H15 Sunday morning. The optics was squeezed in one go, from $\beta^* = 11$ m to $\beta^* = 6$ m where the chromaticity was checked, without any correction needed. Then the pre-squeezed β^* of 1.2 m was reached at 6H47, without any stop in order to avoid any eventual trips of the sextupole circuits. The closed orbit, chromaticity and coupling were corrected and the corrections incorporated. The chromatic variations of the betatron tunes were measured and found extremely linear up to $\delta_p = \pm 1.4 \times 10^{-3}$ (see Fig. 8). The spurious dispersion was also checked with YASP (see the two pictures on the top of Fig. 9), showing a similar behaviour as the one observed at $\beta^* = 4.4$ m (with peaks in the arcs not exceeding 50 cm and 20 cm in the H and V planes, respectively), but with an additional feature which is the magnification of the spurious dispersion with $\sqrt{\beta_{\max}}$ at the location of the inner triplets of IR1 and IR5. Other measurements also took place with the AC-dipole, leading to extremely encouraging results. In particular, the β-beating was found in the range of 15-20% with, as single correction with respect to the model, the Q2 trims incorporated at $\beta^* = 4.4$ m (see Tab. 1). The off-momentum β-beating was also measured with RF trims as large as 120 Hz showing, as expected, two closed bumps from IR2 to IR8 and from IR4 to IR6 and, in particular, a marginal off-momentum β-beating in the collimation insertions IR3 and IR7 (see Section 4 for more details).



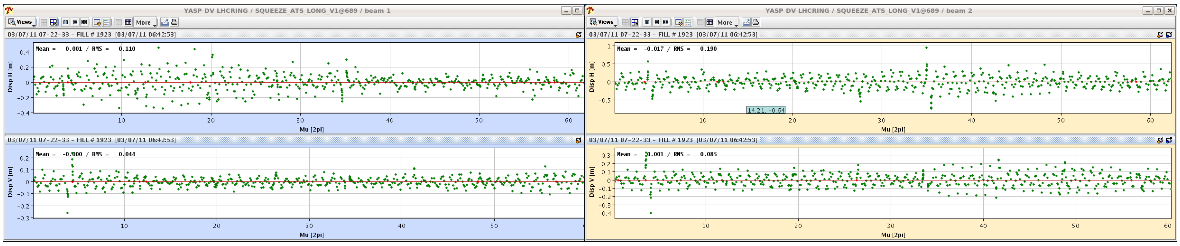
Beam 1



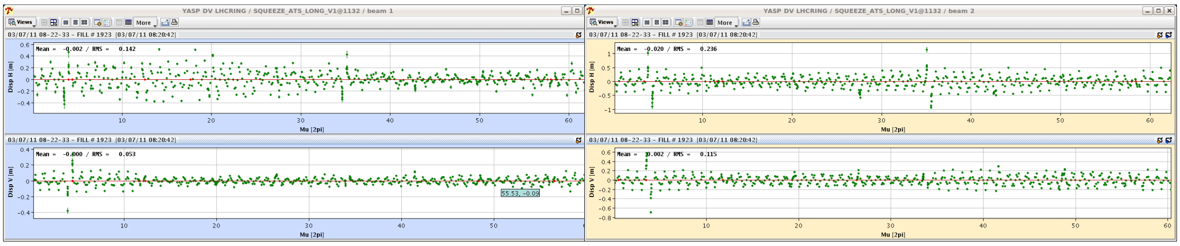
Beam 2

Figure 8: Chromatic variations of the betatron tunes measured at the pre-squeezed β^* of 1.2 m for Beam 1 (left) and Beam 2 (right). The behaviour seems perfectly linear, up to a maximum momentum excursion of $\pm 1.4 \times 10^{-3}$.

The second part of the squeeze then started for reducing β^* at IP1 only, using the ATS techniques, i.e. acting on the standalone quadrupoles of IR2 and IR8 (at constant $\beta^* = 10$ m at IP2 and IP8). A β^* of 54 cm, i.e. already 1 cm below nominal, was reached at 8H21. At this stage, the β-functions were more than doubled in the two sectors 81 and 12 surrounding IR1, which was explicitly confirmed by the β-beating measurement which took place (see Section 4). Even if the



Beam 1 at $\beta^* = 1.2$ m Beam 2 at $\beta^* = 1.2$ m



Beam 1 at $\beta^* = 54$ cm Beam 2 at $\beta^* = 54$ cm

Figure 9: Horizontal and vertical spurious dispersion [m] (i.e. deviation w.r.t. the model) measured at $\beta^* = 1.2$ m and $\beta^* = 54$ cm. The machine starts at the mid-arc of sector 81 and is oriented clock-wise for both beams. Compared to Fig. 6, there are no qualitative changes in the arcs with peak values of 40-50 cm and 15-20 cm reached in the horizontal and vertical planes, respectively. On the other hand, the magnification of the spurious dispersion with $\sqrt{\beta}$ is clearly visible in the inner triplets of IR1 and IR5, in particular at $\beta^* = 54$ cm and for Beam 2 where the 1 m level is reached in the horizontal plane.

coupling was about to go beyond the 0.01 level, it was not corrected due to a lack of time but also because it was still a factor of 3 to 4 below the preventive tune split of 0.03 which was forced at the beginning of the squeeze (see Sub-Section 3.1 and the illustration in Fig. 10). The chromaticity was also checked: no corrections were needed. Finally, a measurement of the spurious dispersion took place and is reported on Fig. 9 (bottom pictures). The inner triplets of IR1 can now be clearly identified on these plots where, in the worst case of Beam 2, the spurious dispersion reaches ± 1 m and ± 60 cm in the horizontal and vertical planes, respectively.

The last part down to $\beta^* = 30$ cm was loaded, with a stop point at 48 cm, then 42 cm, and finally skipping the before last stop at 36 cm to go directly to $\beta^* = 30$ cm. Last β-beating measurements took place, giving for Beam 1 around 40% and 20% in the horizontal and vertical planes, respectively, and conversely for Beam 2 (see Section 4 for more details). Kicking the beam by up to 2.5 σ generated several alarms for the losses measured at the TCTs of IR1, but still with losses in the inner triplet measured a factor of 300 to 1000 below the quench limit (see Section 5). Nevertheless, it was decided not to perform any RF trims under these conditions, which would have definitely validated the fundamental chromatic properties of the ATS scheme.

The history of the orbit and tune feed-back trims performed during the overall period of pre-squeeze and squeeze is showed in Fig. 10. Concerning the orbit feed-back some activities are clearly visible at around 8H:10 and after, that is occurring when starting the second part of the squeeze where the peak β-functions are magnified in the sectors 81 and 12. However, the variations were smooth enough to be digested by the orbit feed-back. Concerning the tune feed-back, the sharp variations observed at the beginning (6H28) are explained by the cancellation, on purpose, of

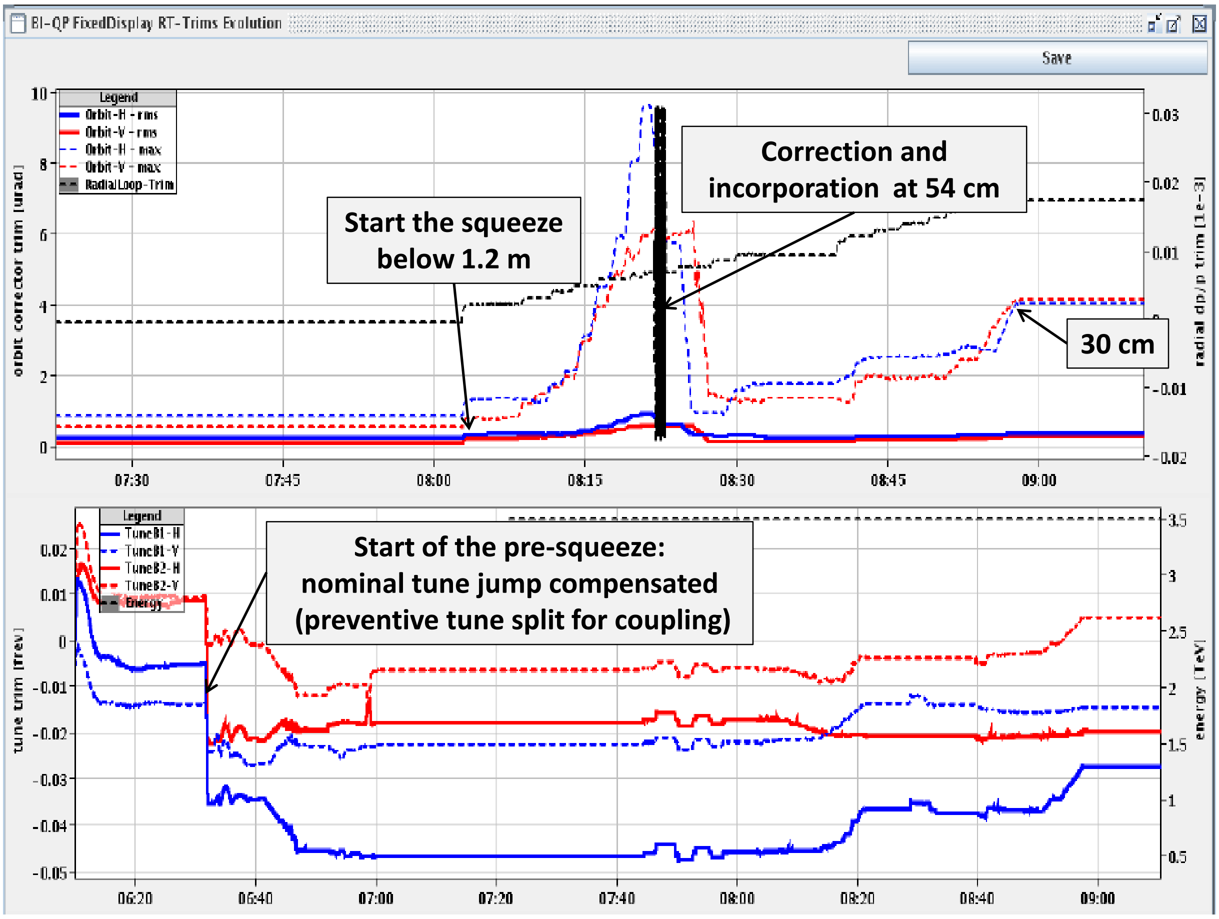


Figure 10: Orbit and tune feed-back trims over the last hours of the MD period.

the tune jump which is normally applied at the beginning of the pre-squeeze (see Sub-Section 3.1). Otherwise the tune variations never exceeded ± 0.015 during the full process. Of course all these variations will be mitigated, if not completely disappear, following a careful correction and incorporation procedure. This result is certainly one of the most exceptional of the MD with beam, not only because we are talking about testing for the first time a new squeeze sequence but also and mainly because one shall remind that this result is obtained with the ATS scheme which transforms the insertions IR1 and IR5 into two 7 km long insertions, each containing more than 25% of the magnets of the LHC ring!

The beam was dumped at 9H09, a bit more than one hour later than initially foreseen in the MD schedule.

4 Detailed optics measurements with the AC-dipole

As mentioned in the previous Section, several optics measurements were carried out using the AC-dipole, both during the pre-squeeze of IR1 and IR5 (with $\beta^* = 4.4$ m and 1.2 m at IP1 and IP5) and the squeeze of IR1 (with $\beta^* = 54$ cm and 30 cm at IP1, and $\beta^* = 1.2$ m kept constant at IP5). The AC-dipole kicks applied at these various occasions are summarized in Tab.'s 2 and Tab. 3 for

Beam 1 and Beam 2, respectively. The maximum AC-kick amplitude was about 2.4σ, exciting the beam in both transverse planes simultaneously. This amplitude gives an idea of the minimum aperture margin needed at the TCP and/or TCT in order to carry out such a measurement.

β^* [m]	Time	$\frac{dp}{p}[10^{-3}]$	H amplitude [σ]	V amplitude [σ]
$\beta^*_{\mathrm{IP1}} = 1.20$ m	7:15:34	0.000	2.3 $\pm$0.2	2.3 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	7:17:01	0.000	2.3 $\pm$0.1	2.3 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	7:18:47	0.000	2.3 $\pm$0.2	2.3 $\pm$0.2
	7:48:11	-0.880	1.8 $\pm$0.2	1.9 $\pm$0.2
	7:51:45	0.876	1.9 $\pm$0.2	1.9 $\pm$0.2
	7:54:12	-0.447	2.2 $\pm$0.2	2.3 $\pm$0.2
	7:56:46	0.433	2.2 $\pm$0.1	2.3 $\pm$0.2
$\beta^*_{\mathrm{IP1}} = 0.54$ m	8:38:51	0.000	1.2 $\pm$0.2	1.2 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	8:37:29	0.000	1.2 $\pm$0.2	1.2 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	8:39:46	0.000	2.1 $\pm$0.2	2.3 $\pm$0.2
$\beta^*_{\mathrm{IP1}} = 0.30$ m	9:03:46	0.000	1.6 $\pm$0.2	1.7 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	9:05:16	0.000	2.3 $\pm$0.3	2.4 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	9:06:51	0.000	2.0 $\pm$0.2	2.1 $\pm$0.2

Table 2: Amplitude of the AC-kicks applied for Beam 1. The kick amplitudes are reported in units of beam sigma, calculated at 3.5 TeV for a normalised emittance of $3.5\,\mu$m. Problems of crate configuration for the BPM acquisition were fixed but prevented a measurement of Beam 1 at $\beta^* = 4.4$ m.

β^* [m]	Time	$\frac{dp}{p}[10^{-3}]$	H amplitude [σ]	V amplitude [σ]
$\beta^*_{\mathrm{IP1}} = 4.40$ m	4:18:42	0.000	1.6 $\pm$0.2	1.5 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 4.40$ m	4:20:18	0.000	2.0 $\pm$0.2	1.8 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	4:21:46	0.000	2.0 $\pm$0.2	1.8 $\pm$0.2
$\beta^*_{\mathrm{IP1}} = 1.20$ m	7:15:34	0.000	2.4 $\pm$0.2	2.1 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	7:17:01	0.000	2.4 $\pm$0.2	2.1 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	7:18:47	0.000	2.0 $\pm$0.2	1.8 $\pm$0.2
	7:47:54	-0.876	2.3 $\pm$0.2	2.1 $\pm$0.2
	7:51:39	0.896	2.0 $\pm$0.2	1.8 $\pm$0.2
	7:54:12	-0.436	2.3 $\pm$0.2	2.1 $\pm$0.2
	7:56:43	0.449	2.0 $\pm$0.2	1.8 $\pm$0.2
$\beta^*_{\mathrm{IP1}} = 0.54$ m	8:06:24	0.000	2.0 $\pm$0.2	1.7 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	8:37:29	0.000	2.0 $\pm$0.2	1.7 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	8:39:10	0.000	1.3 $\pm$0.2	1.1 $\pm$0.2
$\beta^*_{\mathrm{IP1}} = 0.30$ m	9:05:06	0.000	2.3 $\pm$0.2	1.9 $\pm$0.2
$\beta^*_{\mathrm{IP5}} = 1.20$ m	9:06:32	0.000	2.3 $\pm$0.2	2.0 $\pm$0.2
$\beta^*_{\mathrm{IP28}} = 10.00$ m	9:07:52	0.000	2.4 $\pm$0.2	2.0 $\pm$0.2

Table 3: Amplitude of the AC-kicks applied for Beam 2. The kick amplitudes are reported in units of beam sigma, calculated at 3.5 TeV for a normalised emittance of $3.5\,\mu$m.

The basic principles of the ATS scheme, validated for the first time by measurements with beam, are illustrated in the next Sub-Section, in terms of peak β's reached in the triplet and in the two arcs adjacent to IP1, but also in terms of left and right phase advances of the high-luminosity insertions which play a crucial role in the overall scheme. The results obtained in terms of β-beating and local coupling will be reported in Sub-Sections 4.2 and 4.3, respectively. Finally dedicated off-momentum measurements also took place at the pre-squeezed β^* of 1.2 m and will be described in Sub-Section 4.4, discussing only the off-momentum β-beating which is one of key quantities which motivated the invention of the ATS scheme.

4.1 The main features of the ATS scheme: model versus measurement

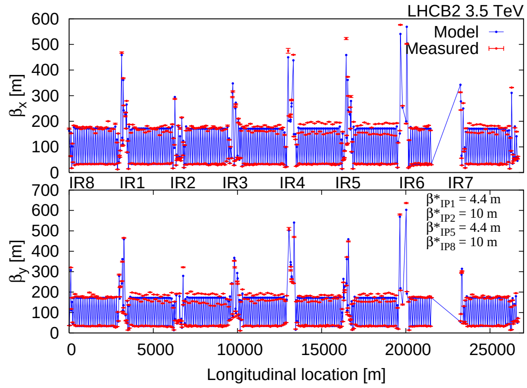
Figure 11 illustrates the first evidence of the operability of the ATS scheme principles. The β-functions of the model are plotted in blue and the measurement results are superimposed in red. The measurements were carried out for two different values of β^*, above or equal to the pre-squeezed β^* of 1.2 m (namely 4.4 m and 1.2 m at IP1 and IP5, see Fig.'s 11-(a) and 11-(b)) and for two β^* values below (namely 54 cm and 30 cm at IP1, see Fig.'s 11-(c) and 11-(d)). As for any squeeze procedure, the peak β-functions reached in the inner triplet increases with $1/\beta^*$. It is close to 8 km at $\beta^* = 30$ cm for the existing triplet but actually a bit less at the BPM location (in the absence of BPM in between Q2a and Q2b).

Something very specific to the ATS scheme is, in addition, an increase of the peak β-functions in the two arcs adjacent to the low-β insertions as soon as the squeeze is pushed beyond the pre-squeezed β^* (IR1 only in this case). The relation between the pre-squeezed β^*, the peak β-functions in the two arcs adjacent to the low-β insertion, namely $\hat{\beta}_{\rm arc}$, and the actual squeezed β^* is then

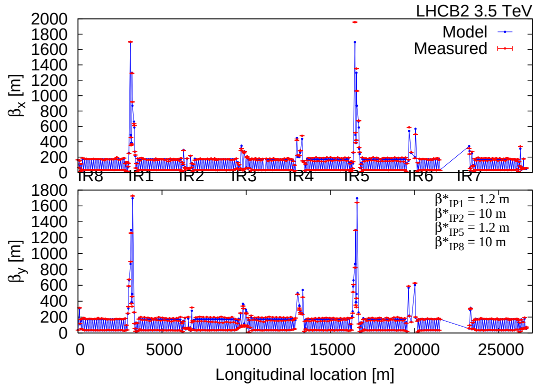
$$\beta^*_{\rm Squeeze} = \beta^*_{\rm Pre-Squeeze} \times \frac{180}{\hat{\beta}_{\rm arc}\,[\rm m]}\,, \qquad (2)$$

where the above numerical factor of 180 stands for the nominal FODO optics of the LHC arcs. As an example, the squeeze of IR1 from 1.2 m to 30 cm was done at a price of increasing the peak β-functions by a factor of exactly 4 in the sectors 81 and 12, and therefore reaching 720 m in those two sectors (see Fig. 11-(d)).

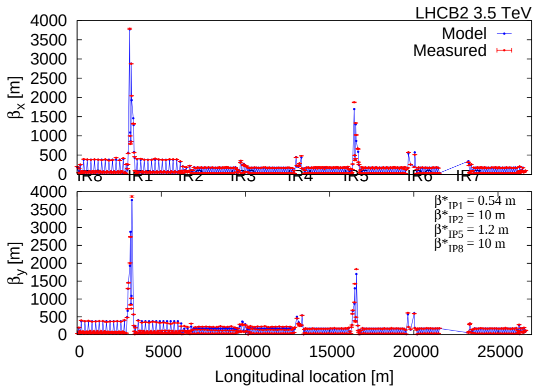
One of the keystones of the ATS scheme is the pre-squeeze optics where specific betatron phase advances shall be reached on the left and right side of the low-β insertion, before starting the second part of the squeeze. More precisely, phase advances close to $\pi/2\,[\pi]$ (but not exactly $\pi/2$, see [1] for more details) shall be achieved between the IP and the last (on the left) and first (on the right) lattice sextupole participating to the chromatic correction of the left and right inner triplets, respectively. The sextupoles to take into account for Beam 1 are the focusing sextupoles attached to Q14.L1 and Q15.R1, and the defocusing ones at Q15.L1 and Q14.R1, and conversely for Beam 2. In order to check that these phasing conditions were achieved for the pre-squeezed β^* of 1.2 m, but also preserved during the continuation of the squeeze of IR1, a detailed analysis was carried out, extracting from the turn by turn data the measured phase advance between the corresponding arc BPM's (e.g. BPM.14L1.B1 for the focusing sextupole MS.14L1.B1 of Beam 1) and the last BPM available in the triplet, namely the warm beam position monitor BPMSW installed on the non-IP side of Q1. Taking into account that the phase advance between the IP and the triplet is very close to $\pi/2$ when the optics is squeezed, the expectation was then to obtain numbers very close to 0 modulo $[\pi]$. As showed in Tab. 4, the measurements were conform to the expectations



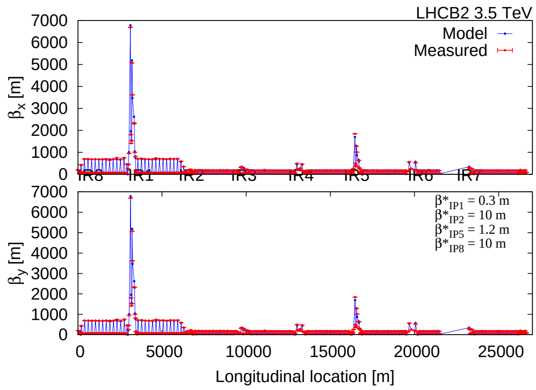
(a) $\beta^*_{\rm IP1} = \beta^*_{\rm IP5} = 4.4\,\rm m$



(b) $\beta^*_{\rm IP1} = \beta^*_{\rm IP5} = 1.2\,\rm m$



(c) $\beta^*_{\rm IP1} = 54\,\rm cm$ and $\beta^*_{\rm IP5} = 1.2\,\rm m$



(d) $\beta^*_{\rm IP1} = 30\,\rm cm$ and $\beta^*_{\rm IP5} = 1.2\,\rm m$

Figure 11: Snapshot of the β-functions around the ring for various values of β^* during the pre-squeeze of IR1 and IR5 and the continuation of the squeeze of IR1: model (blue) versus measurement (red).

with deviation w.r.t. the model of the order of 2.8 degrees in the worst case at $\beta^* = 1.2$ m, and even decreasing below the degree level during the squeeze.

β^* [m] at IP1	Selected BPMs in the H plane	$\Delta\phi_x$ [2π] measured	Deviation w.r.t. model [$10^{-3} \times 2\pi$]
1.20	BPM.14L1.B1/BPMSW.1L1	0.0322 $\pm$ 0.0001	3.8 $\pm$ 0.1
	BPMSW.1R1/BPM.14R1.B2	0.0229 $\pm$ 0.0004	2.7 $\pm$ 0.4
	BPMSW.1R1/BPM.15R1.B1	0.4840 $\pm$ 0.0006	-6.4 $\pm$ 0.6
	BPM.15L1.B2/BPMSW.1L1	0.4953 $\pm$ 0.0009	-3.2 $\pm$ 0.9
0.54	BPM.14L1.B1/BPMSW.1L1	0.0145 $\pm$ 0.0006	1.7 $\pm$ 0.6
	BPMSW.1R1/BPM.14R1.B2	0.0106 $\pm$ 0.0028	1.5 $\pm$ 2.8
	BPMSW.1R1/BPM.15R1.B1	0.4939 $\pm$ 0.0017	-1.7 $\pm$ 1.7
	BPM.15L1.B2/BPMSW.1L1	0.4983 $\pm$ 0.0026	-1.0 $\pm$ 2.6
0.30	BPM.14L1.B1/BPMSW.1L1	0.0085 $\pm$ 0.0012	1.4 $\pm$ 1.2
	BPMSW.1R1/BPM.14R1.B2	0.0056 $\pm$ 0.0009	0.5 $\pm$ 0.9
	BPMSW.1R1/BPM.15R1.B1	0.4953 $\pm$ 0.0011	-2.3 $\pm$ 1.1
	BPM.15L1.B2/BPMSW.1L1	0.4983 $\pm$ 0.0014	-1.3 $\pm$ 1.4
β^* [m] at IP1	Selected BPMs in the V plane	$\Delta\phi_y$ [2π] measured	Deviation w.r.t. model [$10^{-3} \times 2\pi$]
1.20	BPM.15L1.B1/BPMSW.1L1	0.4936 $\pm$ 0.0029	-5.5 $\pm$ 2.9
	BPMSW.1R1/BPM.15R1.B2	0.4819 $\pm$ 0.0050	-7.9 $\pm$ 5.0
	BPMSW.1R1/BPM.14R1.B1	0.0271 $\pm$ 0.0023	7.3 $\pm$ 2.3
	BPM.14L1.B2/BPMSW.1L1	0.0345 $\pm$ 0.0053	5.3 $\pm$ 5.3
0.54	BPM.15L1.B1/BPMSW.1L1	0.4967 $\pm$ 0.0033	-2.9 $\pm$ 3.3
	BPMSW.1R1/BPM.15R1.B2	0.4923 $\pm$ 0.0012	-3.1 $\pm$ 1.2
	BPMSW.1R1/BPM.14R1.B1	0.0123 $\pm$ 0.0030	3.4 $\pm$ 3.0
	BPM.14L1.B2/BPMSW.1L1	0.0150 $\pm$ 0.0012	1.8 $\pm$ 1.2
0.30	BPM.15L1.B1/BPMSW.1L1	0.4986 $\pm$ 0.0040	-1.2 $\pm$ 4.0
	BPMSW.1R1/BPM.15R1.B2	0.4955 $\pm$ 0.0028	-1.9 $\pm$ 2.8
	BPMSW.1R1/BPM.14R1.B1	0.0067 $\pm$ 0.0041	1.7 $\pm$ 4.1
	BPM.14L1.B2/BPMSW.1L1	0.0086 $\pm$ 0.0026	1.3 $\pm$ 2.6

Table 4: Left and right phase advances of IR1, given for Beam 1 and Beam 2 in the horizontal or vertical plane depending on the pair of selected BPMs: measurement (reported modulo 2π, in units of 2π) and deviation w.r.t. the model for various β^* during the pre-squeeze and squeeze of IR1. By construction of the ATS optics, these phase advances shall be very close to 0 modulo π.

4.2 β-beating

Measurements of the β-beating were conducted at different β^* and reported on Fig. 12. The measurement at $\beta^* = 4.4$ m is missing for Beam 1 due to an acquisition problem which was then fixed for the next measurement. The measurement of the pre-squeezed optics at $\beta^* = 1.2$ m revealed a peak β-beating of 20% reached in the horizontal plane of Beam 1 and 15% reached in the vertical plane of Beam 2. This has to be regarded as a spectacular result reminding the "minimal" empir-

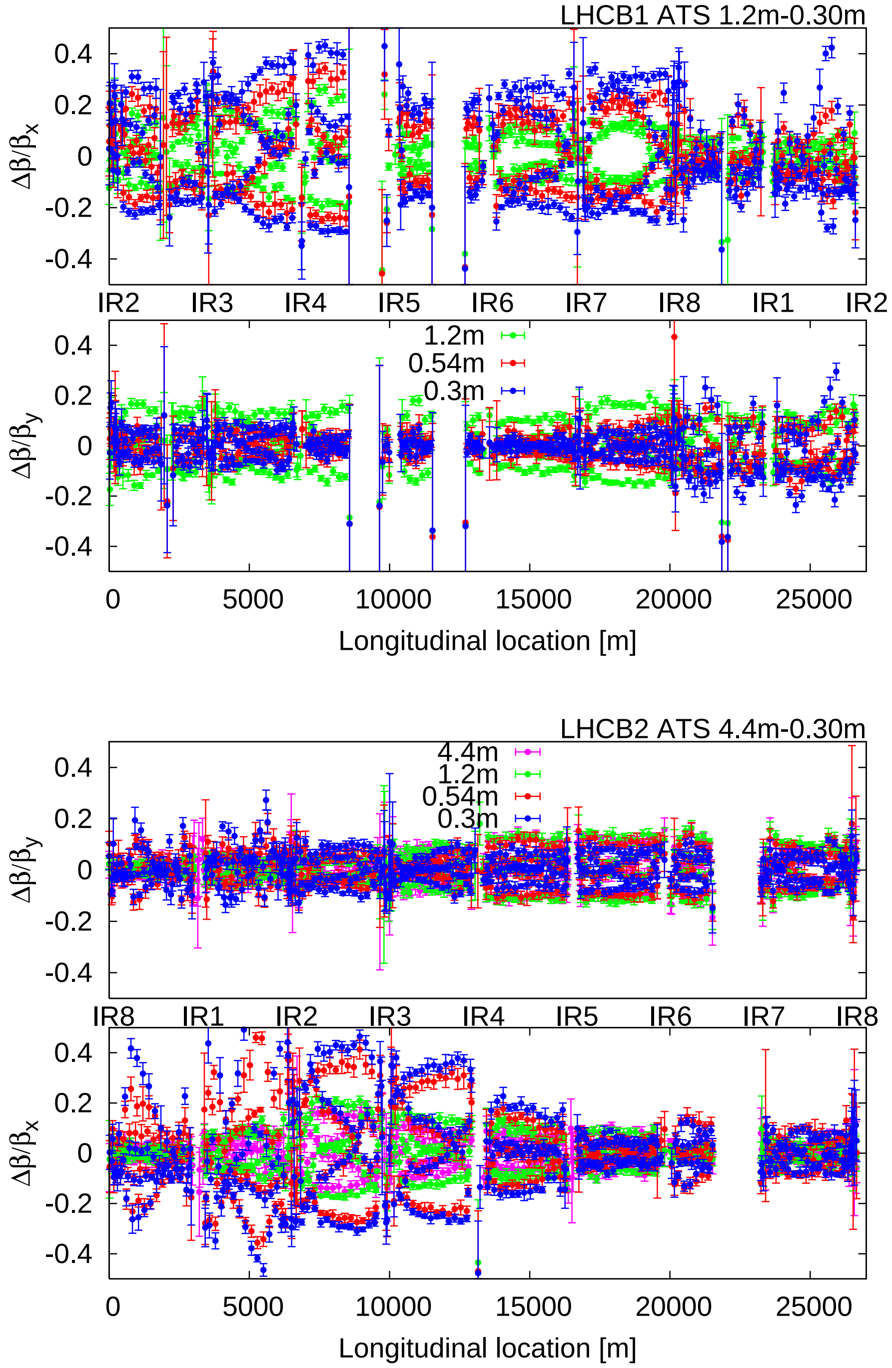


Figure 12: β-beating measurement results for Beam 1 (top) and Beam 2 (bottom) carried out at several β^* during the pre-squeeze and squeeze. Due to acquisition problems, some data are missing for Beam 1 in sectors 45 and 56, and for Beam 2 in sector 67.

ical β-beating trims incorporated at $\beta^* = 4.4$ (see Sub-Section 3.3 and Tab. 1). Said differently without these trims, the situation would have been much worse, with peak β-functions already at the level of 2 km in the inner triplets of IR1 and IR5.

The situation then degraded by a factor of about 2 when reducing β^* by a factor of 4 at IP1 ($\beta^* = 30$ cm), with peak β-beating of the order of 40% for the horizontal (resp. vertical) plane of Beam 1 (resp. Beam 2), but remaining at the level of 20% in the other plane. This "β-beating antisymmetry" between the two beams and the two planes certainly deserves a special attention. Therefore, further analysis with special tools, such as the Segment-by-Segment technique [7], will be used to try to identify any eventual source of local errors, and propose accordingly an appropriate correction. As initially planned [5], a sector by sector beam-based correction of the systematic b_2 errors of the main dipoles will improve as well the situation.

4.3 Coupling

The sum and difference coupling resonance driving terms measured during the squeeze are shown in Fig. 13. Global coupling correction were carried out and incorporated down to $\beta^* = 1.2$ m, but not below due to a lack of time. This explains the substantial increase of the difference coupling driving terms observed at $\beta^* = 54$ cm and 30 cm, i.e. the f_{1001} coefficients in Fig. 13 which, for the injection tunes which were used, can be directly compared to $\Delta Q_{\min}$ with the following normalization:

$$|f_{1001}| = 0.12 \leftrightarrow \Delta Q_{\min} \approx 0.01 \text{ for an unperturbed tune split of 0.03}\,. \quad (3)$$

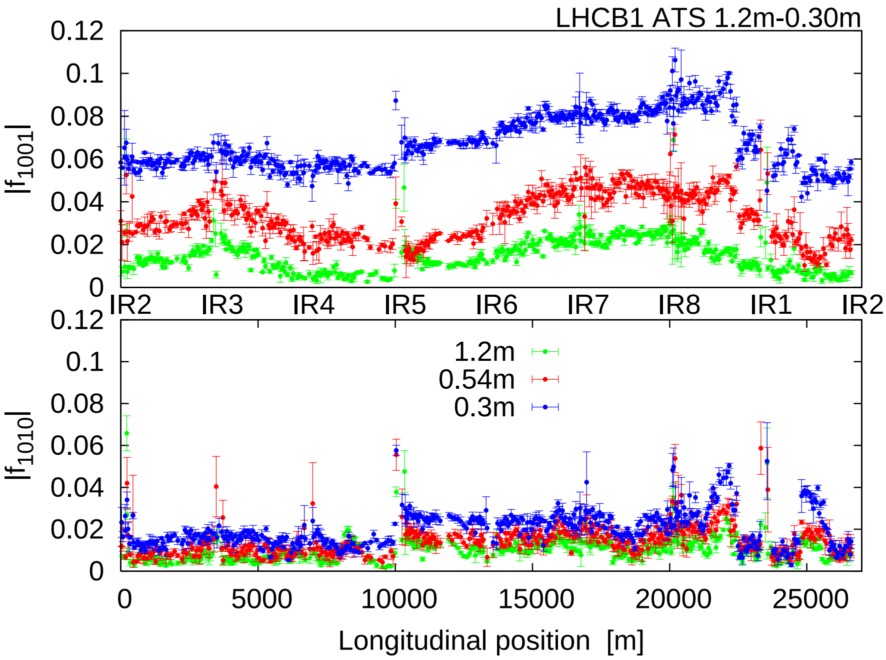
Local jumps in IR5 are observed for both beams, which indicates that a fine tuning of the RQSX settings might be appropriate at this location. Perhaps even more important are the drifts observed in the various LHC sectors, in particular in the arcs 81 and 12 where the β-functions increase, and especially for Beam 1. In this respect, a beam-based a_2 correction carried out sector by sector is certainly necessary, as initially planned [5] but skipped in order to better fit with the time allocated for the MD.

4.4 Off-momentum β-beating

Off-momentum measurements were conducted at $\beta^* = 1.2$ m, applying RF trims of 120 Hz, 60 Hz, -60 Hz and -120 Hz (see Tab.'s 2 and 3). For the momentum compaction of the ATS optics of the order of 3.5×10^{-4}, i.e. increased by about 10% with respect to the nominal LHC optics [4], an RF trim by 60 Hz corresponds to a relative momentum shift of about $\delta_p \approx 0.44 \times 10^{-3}$. The chromatic variations of the betatron tunes together with the horizontal dispersion function were measured accordingly (see Sub-Section 3.4). In addition, measurements of the off-momentum β-beating were carried out with the AC-dipole. The results obtained are reported on Fig. 14, where the so-called chromatic Montague functions have been extracted from the turn by turn off-momentum data:

$$W_{x,y} \stackrel{\text{def}}{=} \sqrt{\left(\frac{1}{\beta_{x,y}}\frac{\partial \beta_{x,y}}{\partial \delta_p}\right)^2 + \left(\frac{\partial \alpha_{x,y}}{\partial \delta_p} - \frac{\alpha_{x,y}}{\beta_{x,y}}\frac{\partial \beta_{x,y}}{\partial \delta_p}\right)^2}\,. \quad (4)$$

Model and measurement are in extremely good agreement. By construction of the ATS optics, the off-momentum β-beating wave induced by the inner triplets of IR1 and IR5 is contained within the



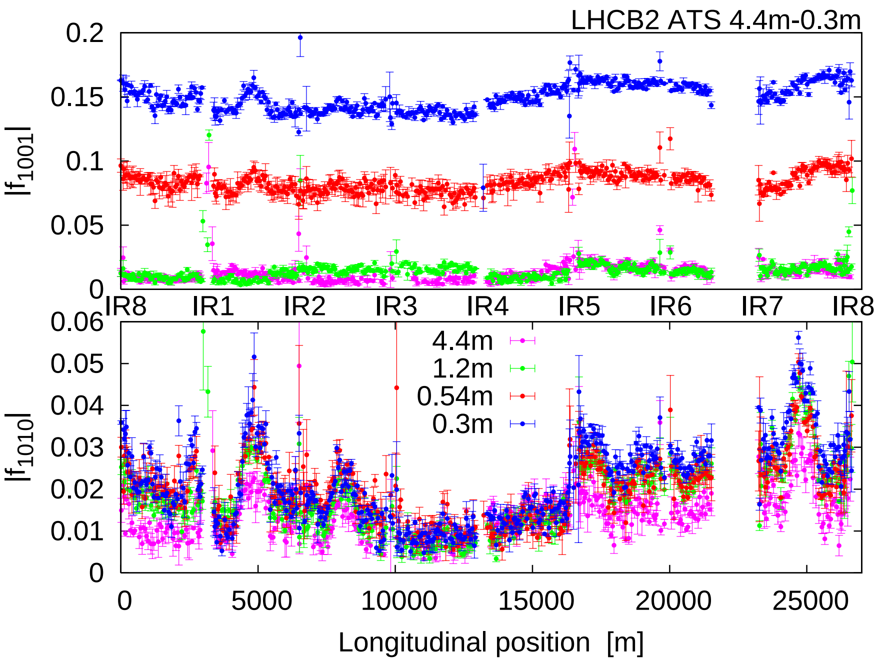
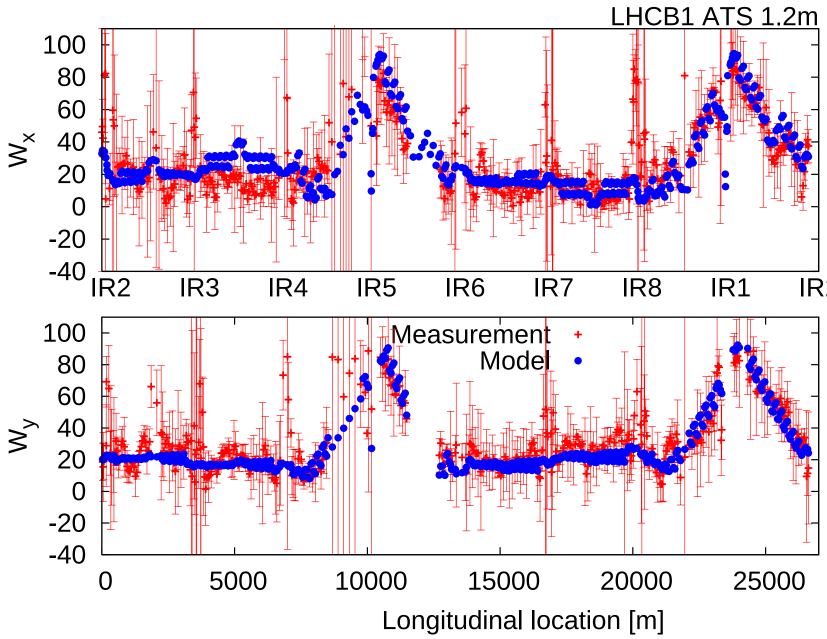


Figure 13: Coupling measurement results for Beam 1 (top) and Beam 2 (bottom), carried out at several β^* during the pre-squeeze and squeeze. Due to time constraints, global coupling corrections were not performed below $\beta^* = 1.2$ m but the beam was not lost due to the preventive tune split of 0.03 kept since the beginning of the pre-squeeze (see Sub-Section 3.1). Due to acquisition problems, some data are missing for Beam 2 in sector 67.



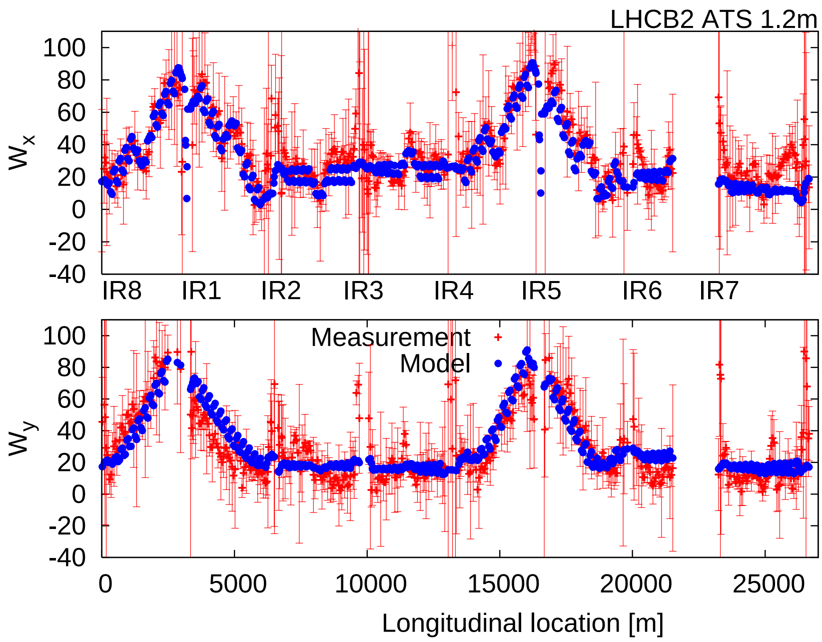


Figure 14: Chromatic Montague functions W (see Eq. 4) for the pre-squeezed optics ($\beta^* = 1.2$ m): measurement (red) versus model (blue) showed for Beam 1 (top) and Beam 2 (bottom). A W function reaching 100 is equivalent to an off-momentum β-beating of 10% at $\delta_p = 10^{-3}$ or, depending on the phase of the chromatic wave, to an off-momentum α-beating. The peaks of the W functions reached in the inner triplets of IR1 and IR5 actually correspond to a peak of off-momentum α-beating. This peak is expected to scale with $1/\beta^*$. Unfortunately it was not possible to validate this prediction with similar measurements carried out with $\beta^* = 30$ cm at IP1. Due to BPM acquisition problems, some data are missing for Beam 1 and Beam 2 in the sectors 56 and 67, respectively.

two sectors directly adjacent to IP1 and IP5, thank to the specific phasing conditions imposed on the left and right sides of the high-luminosity insertions (see Tab. 4) and to the dedicated powering configuration of the 62 sextupole families of the LHC ring, as illustrated in Fig. 1-(d). In particular, the off-momentum β-beating is really marginal in the collimation insertions IR3 and IR7.

Similar measurements performed at $\beta^* = 30$ cm in IP1 would have definitely validated the chromatic properties of the ATS optics, but were not conducted due to a lack of time and several alarm triggered by the losses measured at the TCTs in IR1 (see Section 5). Nevertheless, at the zeroth order and as already mentioned, it is important to note that the second part of the squeeze down to $\beta^* = 30$ cm was carried out at constant sextupole settings, as foreseen by the ATS scheme, and without any empirical trims needed for controlling the linear chromaticity during this operation.

5 Losses

Figure 15: BCT signals over the last 3 hours, including the ramp, pre-squeeze and squeeze.

Fig. 15 shows the intensity of both beams recorded during the last hours of the MD, covering the injection, ramp, pre-squeeze and squeeze. The transmission of intensity has been found excellent during the overall process, with the exception of some losses for Beam 2 at the beginning of the ramp (at the percent level) and some "fluctuations" observed for both Beams during the optics measurements carried out with the AC-dipole during the squeeze.

More specifically, Fig. 16 illustrates the losses recorded for Beam 1 in IR7 (TCP.C) and IR1 (TCTH/V) over the last hours of the MD period. The pattern obtained for Beam 2 is similar. Within the exception of a few specific spikes (see hereafter), no losses have been observed during the pre-squeeze and squeeze, neither at the primary collimators of IR7 nor at the tertiary in IR1. The loss spikes coincide with the optics measurements performed with the AC-dipole (compare

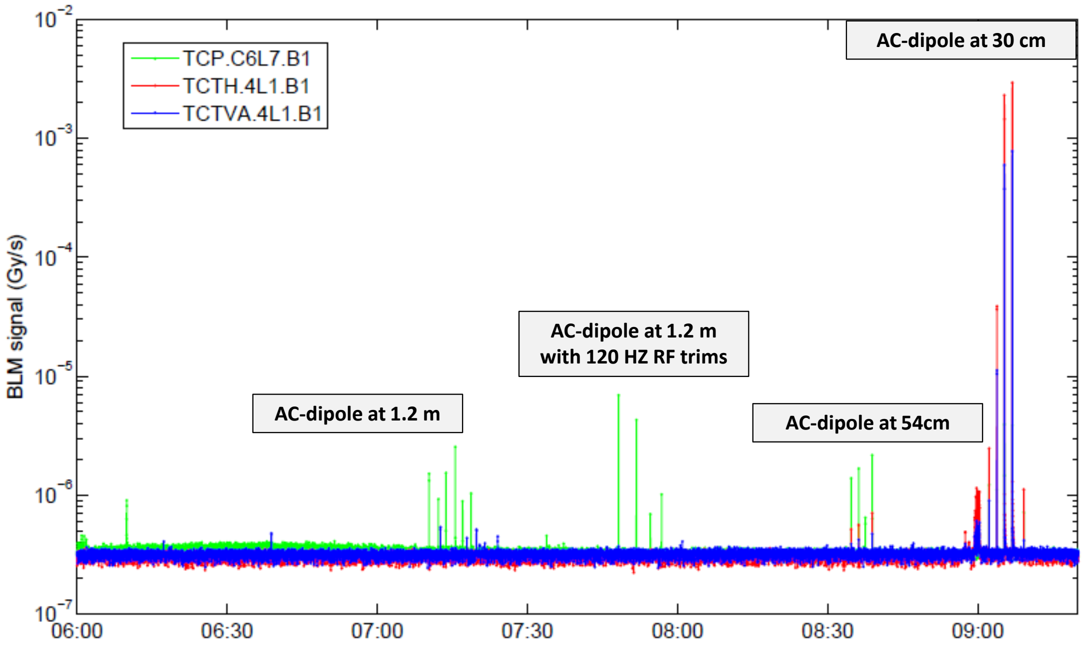


Figure 16: History of the losses measured for Beam 1 in IR7 (TCP) and IR1 (TCT) over the last hours covering the pre-squeeze and squeeze.

with the time stamps of the AC-kick given in Tab. 2). Furthermore, losses are visible at the tertiary collimators of IR1 only at and below $\beta^* = 54$ cm, which indicates that the TCT's became the primary aperture bottleneck of the ring at $\beta^* \approx 55$ cm. Said differently, and reminding the $\sim 9\,\sigma$ opening of the TCP's (see Sub-Section 3.1), this means that the normalised aperture of the inner triplet was measured for the first time with the nominal collision β^* of the LHC, and found to be above 9 nominal σ's at 3.5 TeV, i.e. more than $12.5\,\sigma$ at 7 TeV, but still without crossing angle.

As shown in Fig. 17, during the last measurement performed with the AC-dipole at $\beta^* = 30$ cm, the losses exceeded the recommended TCT thresholds by a factor of 2 to 3 in IR1. However the losses measured at the BLMs of the inner triplet were still a factor of a least 300 below the quench limit. Said differently, if time would have permitted, off-momentum optics measurements could have been safely conducted, with RF trims superimposed to AC-kicks, even at $\beta^* = 30$ cm.

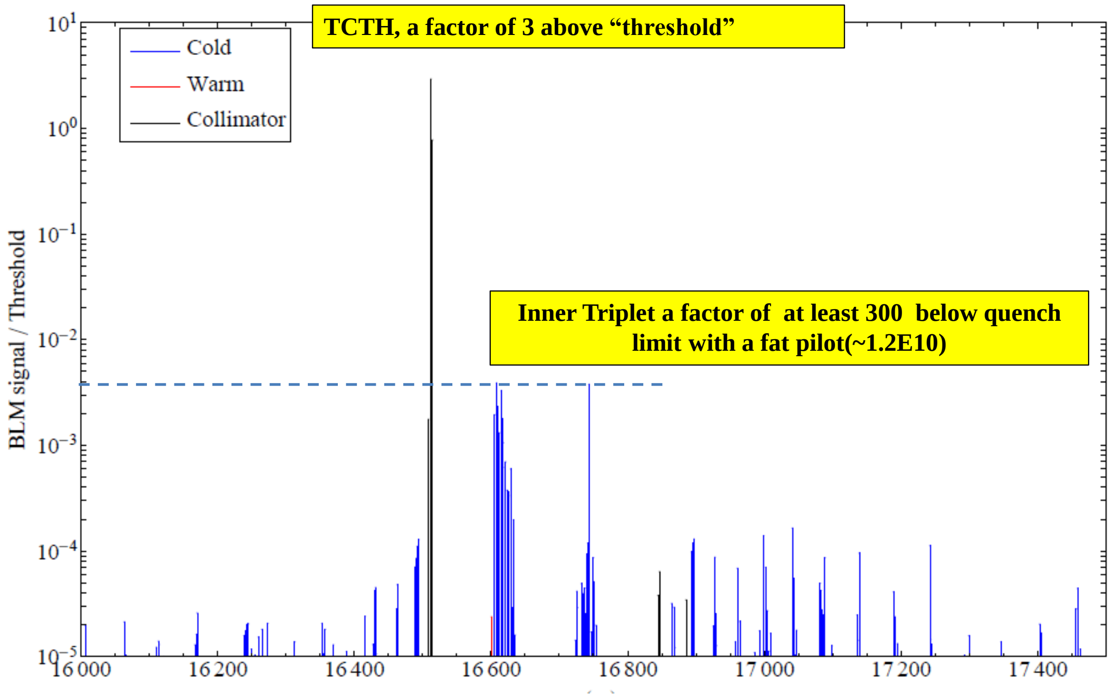


Figure 17: BLM signals (ratio to thresholds) zoomed in the region of the inner triplets of IR1 during the last AC-dipole measurement at $\beta^* = 30$ cm. For the cold elements, in particular the IT, the threshold corresponds to an estimate of the quench limit, with eventually a safety margin by a factor of 3.

6 Conclusions and outlook

The Achromatic Telescopic Squeezing (ATS) MD part II has been an incredible success. It demonstrated the operability but also most of the properties of the ATS scheme, with a pre-squeezed optics where the chromatic aberrations are well under control, and the continuation of the squeeze, at constant settings in the lattice sextupoles, and acting only on the two insertions located on either side of the low-β insertion.

There are actually several possible options for the next step:

- **Option I** pushing the achromatic pre-squeeze sequence down to its limit of $\beta^* = 40$ cm at IP1 and IP5. This direction is very relevant for the existing machine, with a β^* smaller than nominal while offering a definite cure for the long-standing issue of correcting the chromatic aberrations which are already substantial at $\beta^* = 1$ m and below (non-linear chromaticity, off-momentum β-beating, horizontal and vertical spurious dispersion induced by the crossing angle in the high-luminosity insertions),
- **Option II** reiterating the exercise for squeezing IR5 (i.e. acting on IR4 and IR6), which is crucial to meet the β^* target of the HL-LHC,

- **Option III** producing luminosity with flat collision optics, which is an interesting alternative for both machines.

However the optics are ready only for the first option (the corresponding LSA beam process is not). Concerning the second option, the existing ATS optics should preferably be first corrected down to an adequate level (with the coupling compensated, at least globally during the second part of the squeeze, and typically with a β-beating of less than 20% for $\beta^* = 30$ cm at IP1), before envisaging to implement a similar squeeze for IR5. Furthermore, the corresponding squeeze sequences of IR4 and IR6 have still to be calculated. The last option has a big potential both for the nominal LHC (with a β^* aspect ratio of 4 and $\beta^* = 25$ cm in the plane perpendicular to the crossing plane [9]), and represents as well a back-up solution to reach the performance targets of the HL-LHC without crab-cavity [1, 2]. For this option, everything remains to be done (squeeze sequences, beam processes,..)

Under these conditions, a wise but ambitious approach is to fix an unique goal combining at least two of the above options. The most natural one is to target a β^* of 10 cm both at IP1 and IP5, using the following ingredients:

- a pre-squeezed β^* pushed to 40 cm at IP1 and IP5 (corresponding to a max current of 300A in the lattice sextupoles at 3.5 TeV/beam),
- and, using the tight collimator settings presently developed [10] (i.e. TCPH/V set to 4 nominal sigma's in IR7), a continuation of the squeeze acting on the IPQ circuits of IR8, IR2, IR4 and IR6 in order to blow up the β-functions by a factor of 4 in the sectors 81, 12, 45 and 56 and, consequently, reduce β^* by the same factor at IP1 and IP5 to finally reach 10 cm.

This program is expected to be difficult and therefore very interesting, in particular due to the change of the IR4 and IR6 optics during the squeeze, and the challenging control of the linear imperfections and/or several dynamic aperture related limitations possibly showing up, with peak β-functions of 24 km reached in the inner triplet (leading to a DA estimated to about 4-5 nominal sigma's with no correction at 3.5 TeV), combined with peak β-functions of more than 700 m in four arcs of the machine and the lattice sextupoles pushed to their nominal normalised strength for the chromatic correction.

Acknowledgments

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