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The Achromatic Telescopic Squeezing (ATS) MD part I

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Summary

This note describes the results obtained during the first so-called ATS MD where a new injection optics was commissioned and ramped to 3.5 TeV.

1 Introduction and motivations

The correction of the chromatic aberrations (off-momentum beta-beating, non-linear chromaticity, spurious H and V dispersion induced by the crossing-angles) was a long-standing problem for which no strategy is foreseen in the nominal collision optics of the LHC. A dedicated strategy has been established in the context of the Phase I IR upgrade project, but with its corresponding $\beta^*_{\rm min}$ limit of the order 30-35 cm [1], which is given by the maximum sextupole strength available at 7 TeV/beam. The Phase I optics scheme has been recently developed towards a new new scheme, called the Achromatic Telescopic Squeezing (ATS) Scheme, in order to overcome the above β^* limit [2, 3]. Implementing and testing the ATS scheme in the LHC is therefore of great relevance, both for the existing machine when β^* will approach its nominal value of 55 cm at IP1 and IP5, but also for the upgrade where optics with β^* values as small as 7.5-10 cm can be targeted with a larger aperture triplet. To do so, however, a new overall LHC optics is needed, already at injection, with substantial changes concerning the betatron phase advances all over the ring and in particular in the arcs. Such an optics has been recently built, the so-called "ATS_V6.503 optics", which is compatible with the nominal layout V6.503 of the LHC and is accessible under afs [4]. A series of MD's are foreseen in 2011 in order to demonstrate in 3 steps the operability of the ATS scheme:

Step I commissioning and measurement of the new injection optics and ramp up to 3.5 TeV.
Step II commissioning of the pre-squeezed sequence down to $\beta^* = 1.2$ m at IP1 and IP5, with measurement and correction of the linear optics (local coupling, local b_2, and β-beating) and of the chromatic aberrations induced (off-momentum β-beating, non-linear chromaticity and horizontal and vertical spurious dispersion induced by the crossing scheme).

Step III commissioning of the squeeze of IR1 down to $\beta^* = 60 - 30$ cm, by acting on IR2 and IR8 and increasing the peak β functions by a factor of 2 to 4 in the sectors 81 and 12.

The first ATS MD was then split into two parts. First a "dry run" without beam took place during a few hours on Wednesday 04/05/2011, during which a precycle of the LHC machine was achieved to reach the new injection settings and new knobs were tested and analysed for the crossing scheme and for the tune, chromaticity and global coupling correction. An 8 hours MD with beam followed on Saturday 07/05/2011 in order to commission and ramp the new injection optics. This note will mostly report on the results achieved during the MD with beam.
The next section will describe the main features of the new optics together with its implementation in the LHC control system. The main results obtained during the MD will then be presented in Section 3. Finally the last section will illustrate in more details the optics measurement results obtained with the AC-dipole at injection and flat top energy.

2 Main features of the new optics and experimental setup

2.1 Main features of the new optics, initial plan

In order to implement the ATS scheme in the LHC, a completely new overall injection optics was needed. The main features of this new optics are summarized below:

- new phase advances in the LHC arc cells, in particular strictly $\pi/2$ for the four sectors adjacent to the experimental insertions IR1 and IR5 (s81/12 and s45/56), and different QF/QD settings for the other four sectors in order to match the fractional part of the tune,
- new phase advances for the eight LHC insertions, while fulfilling the aperture constraints,
- leading all together to the new integer tunes 62/60 (instead of 64/59) while preserving the fractional part (0.28/0.31 for the injection optics and 0.31/0.32 for the collision optics).

The modification of the integer tunes, in particular with a reduction of the horizontal focusing in the arcs, affects directly the momentum compaction which is found to be about 10% larger for the new optics (from 3.2 to 3.5×10^{-4}). On the other hand, the IR optics changes were applied with special care in order to minimise the impact on certain key sub-systems of the LHC:

- the half-crossing angle ($\pm 170\,\mu$rad), the parallel separation (± 2 mm) and β^* (11/10/11/10 m in IR1/2/5/8) is kept unchanged with respect to the nominal injection optics. Therefore no change are a priori needed for the transverse adjustments of the TCTs and TDIs.
- the settings of the triplets in IR2 and IR8, together with the gradients of the Q4 and Q5 quadrupoles on the injection side (left/right side of IR2/8 for Beam1/Beam2, respectively) is kept unchanged in order to preserve the matching conditions of the transfer lines and the vertical phase advance from the MKI to the TDI. The relative vertical phase advance from the TDI to the TCLI on the other side of the IR has also been preserved.
- the settings of Q4.L6B1 and Q4.R6B2 remain the same for the new optics, since these two quadrupoles impact on the geometry of the septa and dump lines. IR6 has also been re-matched keeping constant the twiss parameters at the septa (β and α functions) in order to

preserve the optics of the extracted beam. In this respect the TCDQ settings can also be kept unchanged (at least for the injection optics).

- finally, the insertions IR3 and IR7 have been rematched to the new arc optics by only acting on the quadrupoles at Q6 and beyond, keeping nominal the value of the twiss parameters (and of the dispersion) in IP3 and IP7, and therefore at the primary and secondary collimators.

The only insertion where more substantial impacts could not be avoided is IR4, in particular concerning the new phase advances between the ADTs and the BPMs at Q7 and Q9, the latter being used by the damper system of the LHC. These changes required a specific intervention by W. Hofle in order to derive new ADT settings for the new optics.
The new injection optics can be found in [4], together with a pre-squeezed sequence of IR1 and IR5 down to $\beta^* = 40$ cm (the ATS MD part II will stop at 1.2 m), and a further reduction of β^* by a factor of 4 at IP1 by acting on the insertions IR2 and IR8 (therefore to reach $\beta^* = 30$ cm for the ATS MD part III). The plan for the first ATS MD was the commissioning of the new injection optics with, ideally, a ramp test up to 3.5 TeV and detailed optics measurements at flat top [5]. Beyond any expectation, all these items were successfully addressed during the 8h allocated time.

2.2 Preparation and Experimental setup

Stefano prepared a new beam process containing the new injection optics ATS_V6.503 and its ramp up to 3.5 TeV. The ATS beam process was completed by Gabriel with all the necessary knobs (crossing angle, parallel separation, tune, chromaticity, coupling), then by Marek for the correction of b_2, b_3, b_4 and b_5 following the FiDeL predictions, and by Jorg for a pre-setting of the orbit correctors based the latest available nominal injection process (with the contribution of the nominal crossing and parallel separation bumps subtracted). The new settings were sent to the FiDeL team (Per and Ezio) for verification.
New response matrices required for the closed orbit feed-back system were also created based on the new optics and carefully tested by Jorg. The RF settings were also modified by Stefano and checked by Andy, taking into account the 10% increase of the momentum compaction for the new optics. Finally Wolfgang calculated and applied all the necessary trims in order to readjust the damper settings to the theoretical betatron phase advances of the new optics. Trims of phases by up to 77 degrees were found necessary in the vertical plane between the ADT and Q9, while the relative changes of β-functions at the ADTs, Q7 and Q9 were considered small enough to have only marginal impact on the damping time at constant gain.
This first ATS MD was operated

- with a flat machine, being noted that the crossing angle and parallel separation knobs were successfully tested just before the ramp test (see later),
- with the TCTs, TDIs and TCLIs set to $\sim \pm 8$ mm with respect to a flat reference orbit,
- with the TCPs and TCSs adjusted to their nominal injection settings, but not programmed to be squeezed with energy during the ramp,
- injecting only one ("fat") pilot per beam (with small normalised emittance of the order of 1.5 μm and a charge ranging in between 5E9 and 10E9) in bucket 1 for Beam1 and bucket 2001 for Beam2 in order to avoid collisions in the shared area of IR1, IR2, IR5 and IR8,

- switching on the damper only for damping the injection oscillations and then switching it off after 1000 turns,
- masking several specific interlocks in order to get the beam injection permit, in particular linked to the MQ settings (which are non-nominal for the new optics).

3 Highlights of the first ATS MD

3.1 Precycle, first injection, first optics measurement and adjustment, and dump test

The ATS MD with beam started at 10:00 on Saturday 7th of May. First a full machine precycle (a simple clone of the nominal LHC precycle) was achieved in about one hour. At the start of ramping down the QPS switch of Q6.L7 opened, which was also the case during the ATS dry run without beam (04/05/2011), and with the same strange behaviour just before the magnet trip (see Fig. 1). Since this effect was a priori not related to the specificities of the ATS optics and it was possible to close the Q6 switches at the first attempt, the precycle of the other magnets was completed as foreseen.

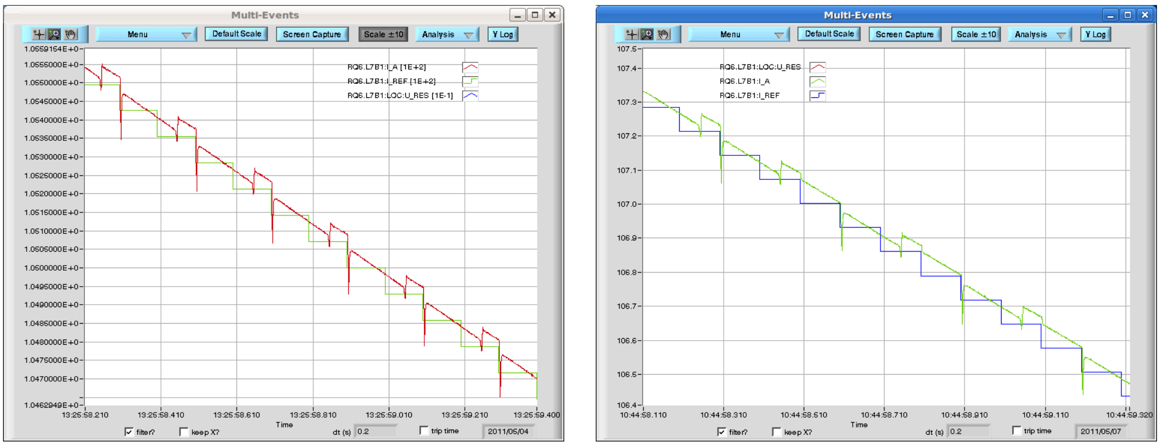


Figure 1: Behaviour of Q6.L7B1 just before it tripped starting the ramp down of the pre-cycle: first ATS MD without (04/05/2011) and with (07/05/2011) beam showed on the left and right picture, respectively. The reference current (step function) is compared to the measured values.

At around 11:30, the new injection settings were successfully sent to the hardware, the collimation and protection devices adjusted and/or retracted as foreseen, and Beam1 was ready to be injected (probe beam with 5E9). At the first injection (11:51), Beam1 was captured and circulating with a bare orbit of less than 1 mm rms, then reduced down to 0.1 mm r.m.s. half an hour later, after a few corrections and with other activities performed in parallel (see Fig. 2). The machine was first found fully coupled with a ΔQ_{min} of the order of 0.06. Acting on the new ATS global coupling knobs and after some effort (see Fig. 3), the difference coupling coefficient was reduced by a factor 10 to reach about 0.006 and the betatron tunes adjusted to their nominal injection values of 0.28/0.31.
The same procedure was applied for Beam2 which was also captured and circulating after the first injection. At around 12:30, the two beams were circulating, and were successfully dumped (see

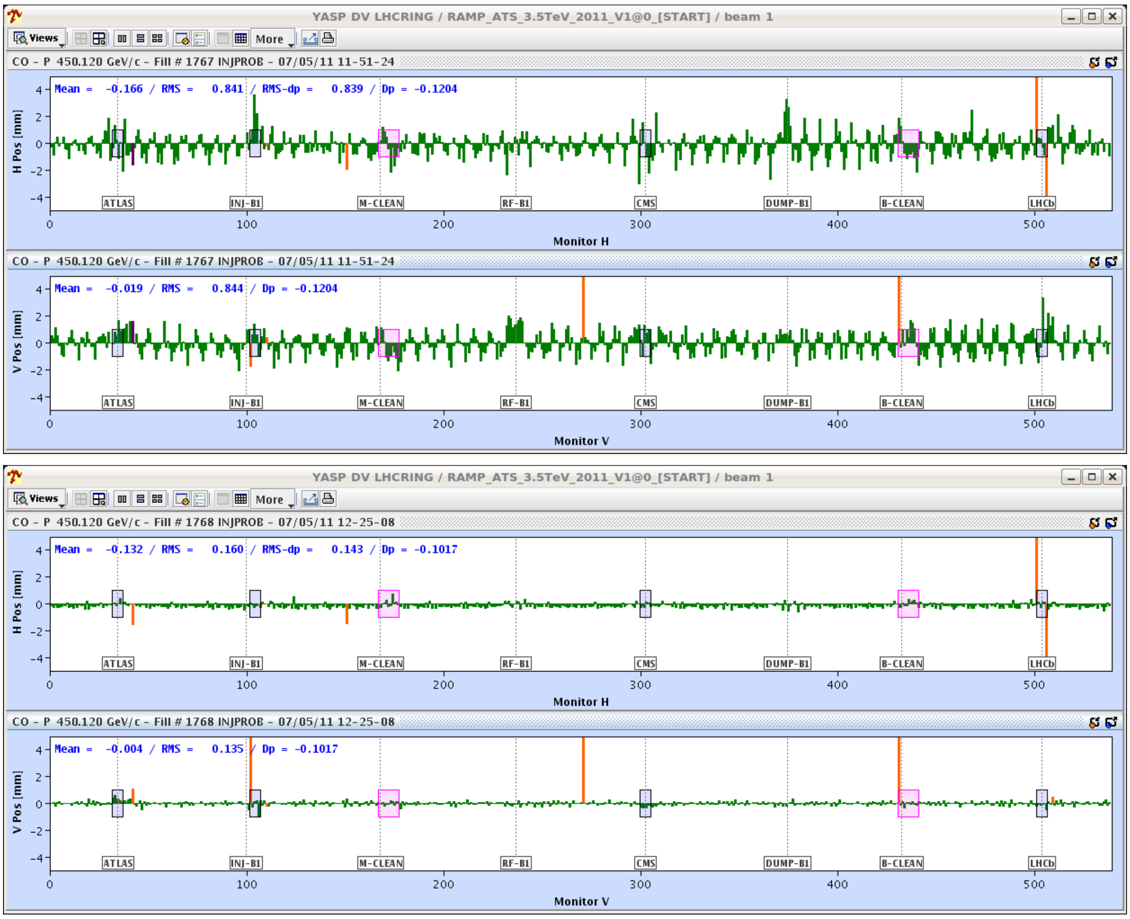


Figure 2: First closed orbit measured for Beam1, captured and circulating at the first injection attempt, before (top) and after fine correction (bottom).

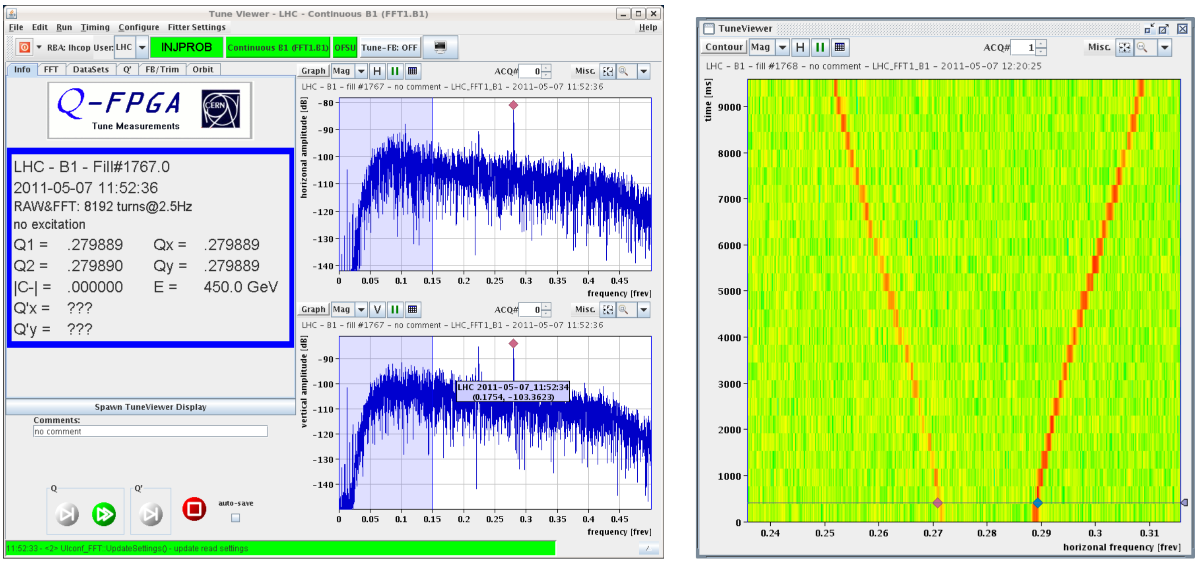


Figure 3: First tune measurement of Beam1 (left) showing a fully coupled machine and closest tune approach using the new ATS global coupling knobs (right).

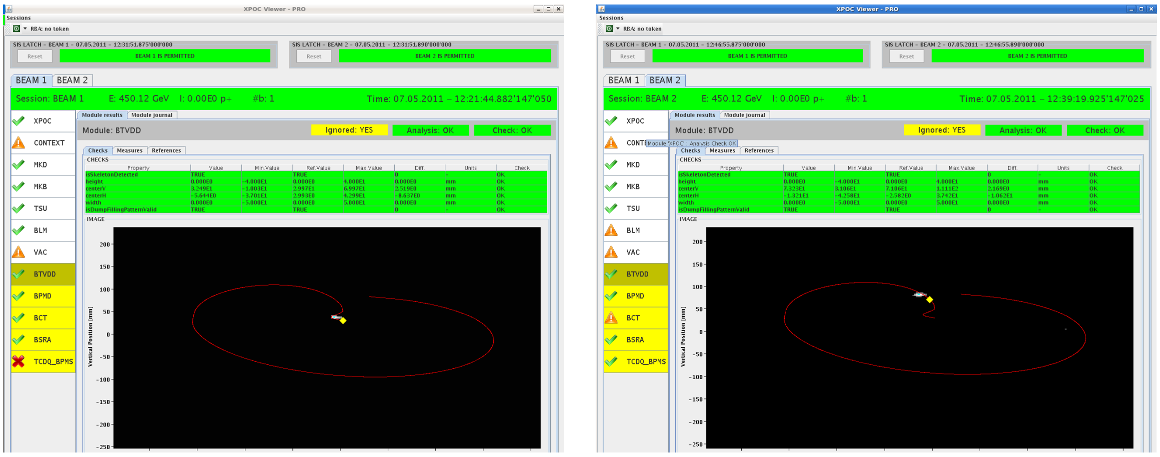
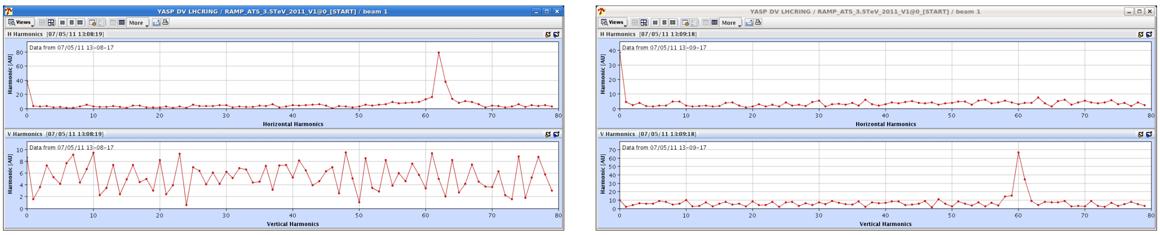
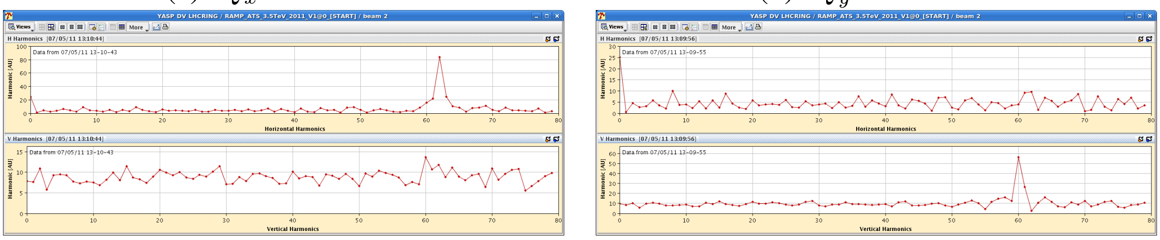


Figure 4: BTVDD image of Beam1 and Beam2 after the first programmed dump.

the BTVDD images of Beam1 and Beam2 in Fig. 4, unbelievably close to the yellow target). Half an hour later (13:00), fine tuning of the coupling helps in reaching the level of a few 10^{-3} for the coupling coefficient, the chromaticity of both beams was adjusted to a few units (starting from about +15-20 units as in the nominal LHC without the empirical chromaticity trims) and the measurement of the integer tunes gave exactly the values expected (see Fig. 5).
Reaching this level after less than 2 hours of beam was not really foreseen.



(a): Q_x for Beam1 (b): Q_y for Beam1

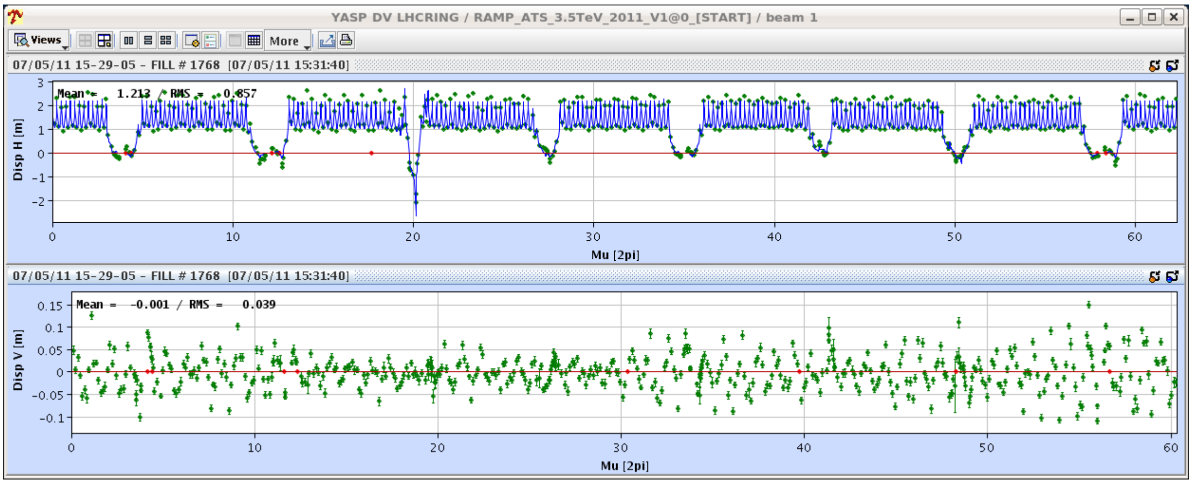


(c): Q_x for Beam2 (d): Q_y for Beam2

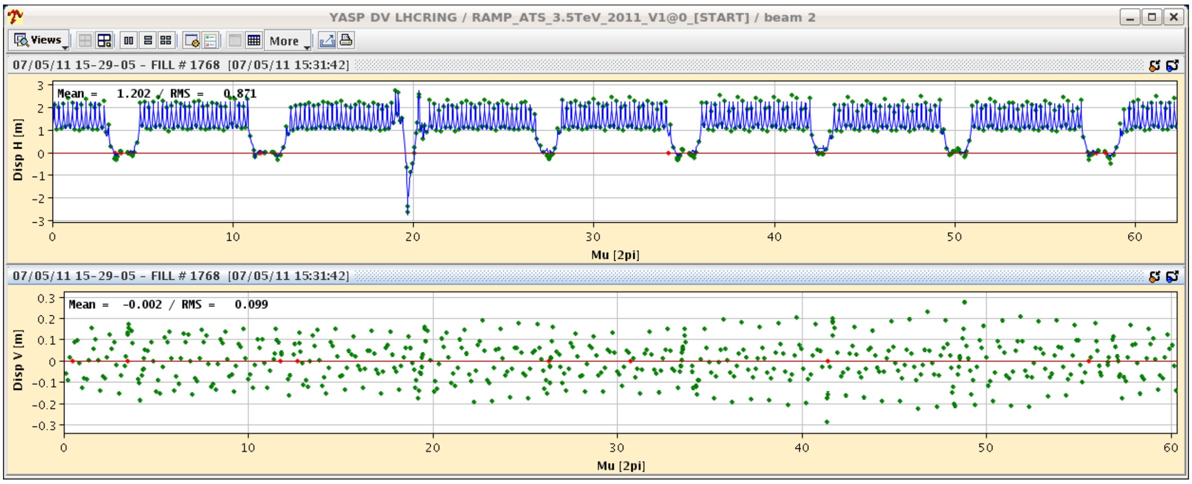
Figure 5: Integer part of the betatron tunes, measured to 62/60 as expected with the ATS_V6.503 optics.

3.2 Optics measurements at injection, series of test and preparing the ramp

The next 2.5 hours were devoted to more detailed optics measurements at injection, in particular the horizontal and vertical dispersion giving excellent results (see Fig. 6), and the local coupling and β-beating discussed in more details in Section 4.



Beam1



Beam2

Figure 6: Measurement of the horizontal and vertical dispersion [m] at 450 GeV for the ATS_V6.503 injection optics.

A series of verifications also took place, related to the orbit and tune feed-back systems, the damper system with its new phase settings (see Fig. 7), and a series of injection and dump tests. All these tests were successful at the first attempt. Finally, just before starting the ramp, it was decided to also test the crossing angle and parallel separation knobs, which were set successfully to their nominal value and induced only very moderate orbit perturbations in the rest of the ring without using any dedicated non-closure bumps (see Fig. 8).

Two fresh pilots were then re-injected at around 15:30, with a charge of about 10E9 and showing an emittance of about 1.5 μm for both beams in both planes (see the values reported in Tab. 1 taking into account the new β-functions of the ATS_V6.503 optics at the wire scanner).

Last checks and fine tunings of the chromaticity were applied, the tune and closed orbit feed-back switched on and the first ATS ramp started at around 16:00.

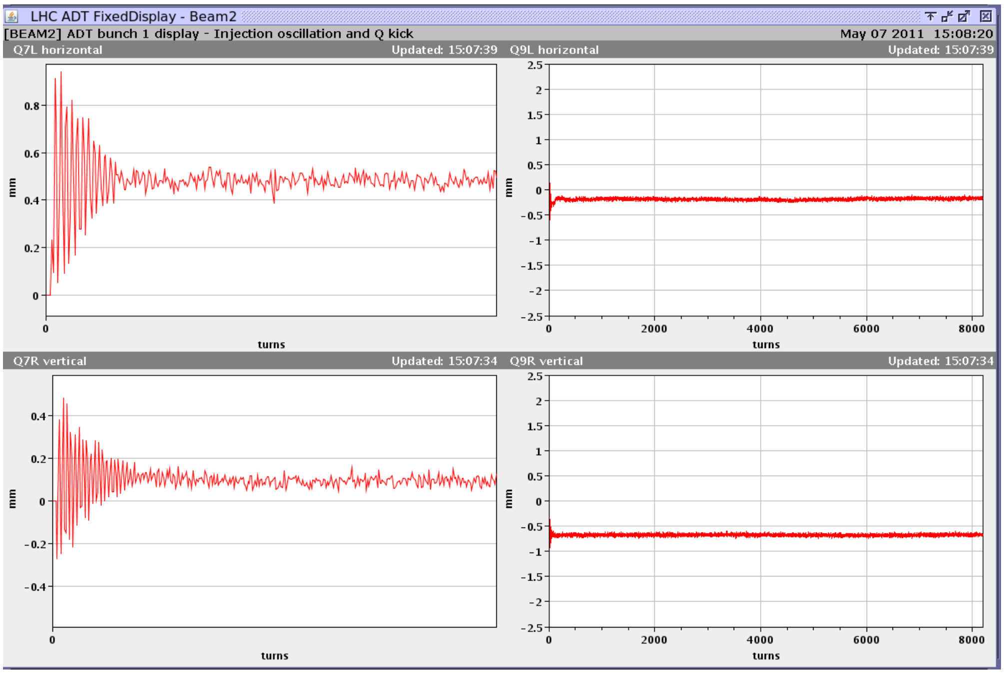
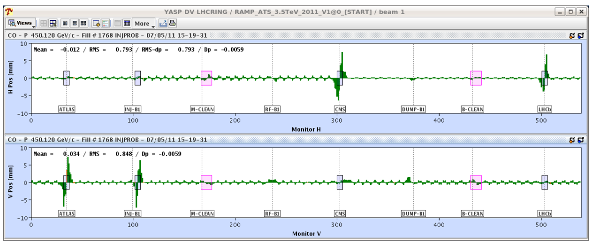
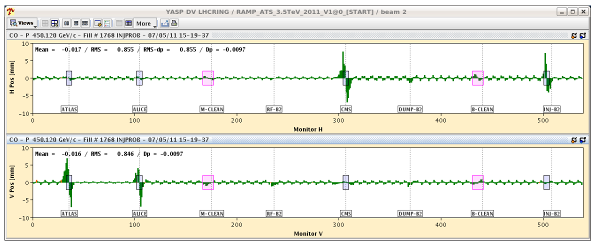


Figure 7: Test of the new ADT settings (phases). Less than 50 turns seems sufficient for damping the injection oscillations of Beam2.

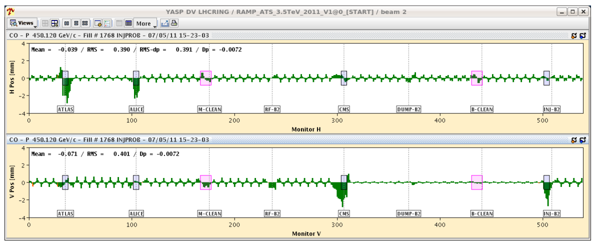


Beam1 orbit with crossing angle ON



Beam2 orbit with crossing angle ON

Beam1 orbit with parallel separation ON



Beam2 orbit with parallel separation ON

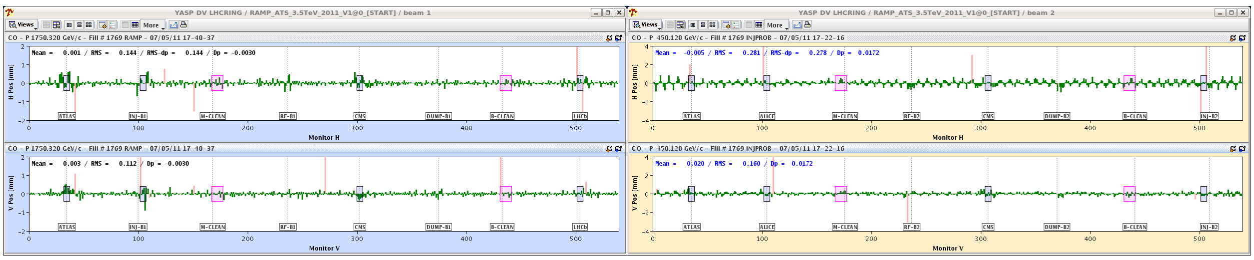
Figure 8: Test of the new crossing knobs of Beam1 and Beam2, pushed up to the nominal values of 170 μrad and 2 mm for the half crossing angles and parallel separations in IP1, IP2, IP5 and IP8.

Beam	Beam1	Beam2
$\beta_{x/y}$ [m] at the BWS in V6.503	175.5/287.8	123.5/404.5
$\beta_{x/y}$ [m] at the BWS in ATS_V6.503	130.0/320.0	177.9/434.6
Measured $\gamma\epsilon_{x/y}[\mu\text{m}]$	1.1/1.7	2.1/1.7
Recalculated $\gamma\epsilon_{x/y}[\mu\text{m}]$	1.3/1.6	1.7/1.6

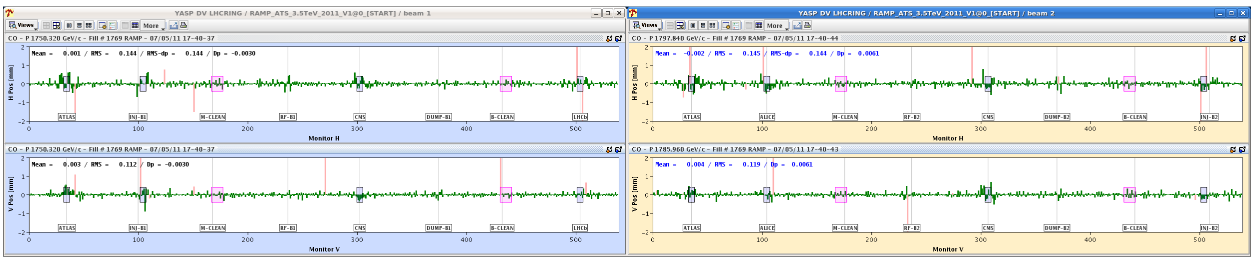
Table 1: Measured emittances for Beam1 and Beam2 (probe beam 10E9 at 450 GeV) taking into account the changes of the β-functions at the wire scanners from the nominal optics V6.503 to the new optics ATS_V6.503.

3.3 Ramp and optics adjustment at flat top

The two beams were dumped at the very beginning of the first ramp because the TCDQ interlock was not masked, and the ramp continued without beam up to 3.5 TeV. Nevertheless, in a record turn around time of about 90 minutes, the second ramp started at 17:36 and finished successfully 10 minutes later. Snapshots of the orbit, tunes and coupling at various energies demonstrates a rather acceptable behaviour of the beam during the ramp (see Fig.'s 9 and 10), in particular with a maximum coupling coefficient of the order 0.01-0.013 along the ramp (having propagated at constant normalised strength the trims performed at injection), and shifts of chromaticity of only a couple of units measured at the end of the ramp (having incorporated the empirical chromaticity trims of the nominal ramp).

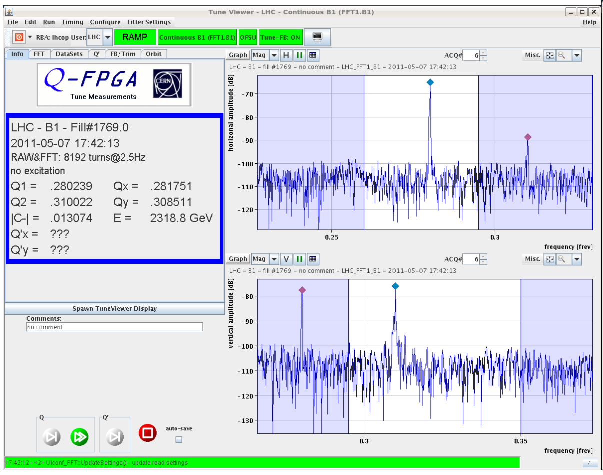


Beam1 at 1.7 TeV Beam2 at 1.7 TeV

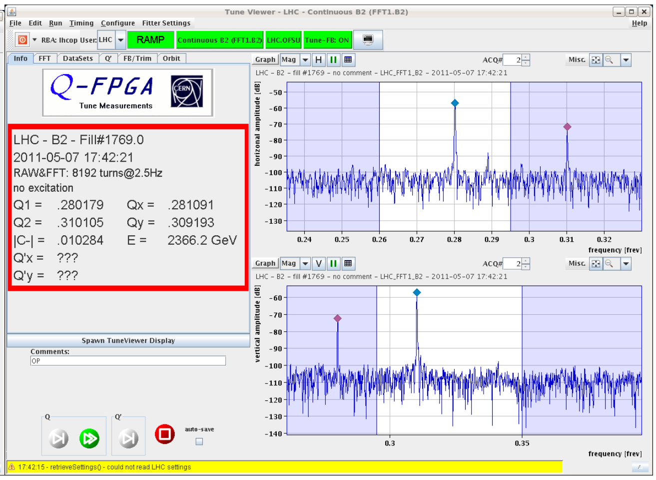


Beam1 at 3.5 TeV Beam2 at 3.5 TeV

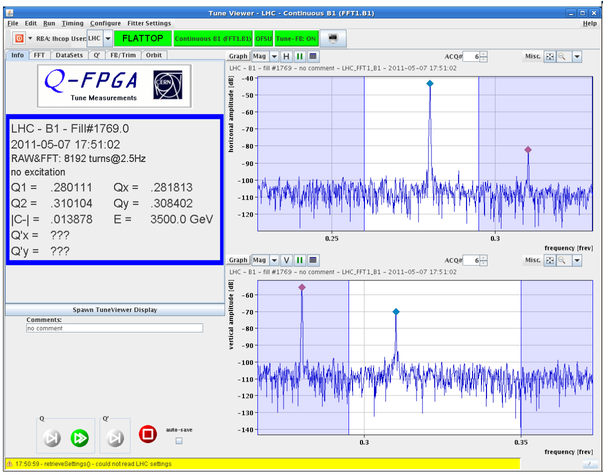
Figure 9: Beam1 and Beam2 closed orbit at 1.7 TeV (top) and 3.5 TeV (bottom).



Beam1 at 2.2 TeV



Beam2 at 2.2 TeV



Beam1 at 3.5 TeV

Beam2 at 3.5 TeV

Figure 10: Beam1 and Beam2 tunes and coupling at 2.2 TeV (top) and 3.5 TeV (bottom).

The transmission of intensity through the ramp was found excellent (see Fig. 11). The beam emittances measured at 3.5 TeV were found very close to the injection values reported in Tab. 1. The tune, coupling and chromaticity were then easily adjusted.

The last 20 minutes of the MD were devoted to detailed measurements of the β-beating, local coupling and dispersion at flat top (see Section 4 for more details). These measurements showed in particular a β-beating of less than 15% without any specific correction. Possibly, even more important, the horizontal and vertical spurious dispersion coming from the arcs was measured to be less than 15-20 cm (but for the horizontal dispersion of Beam2), which corresponds to a factor of 3 to 4 below specification and will definitely offer a substantial aperture margin for the existing and for the new triplet at low β^*.

The beam was dumped at 18:33, leaving a comfortable recovery time of 1.5 h for the following MD (collimation).

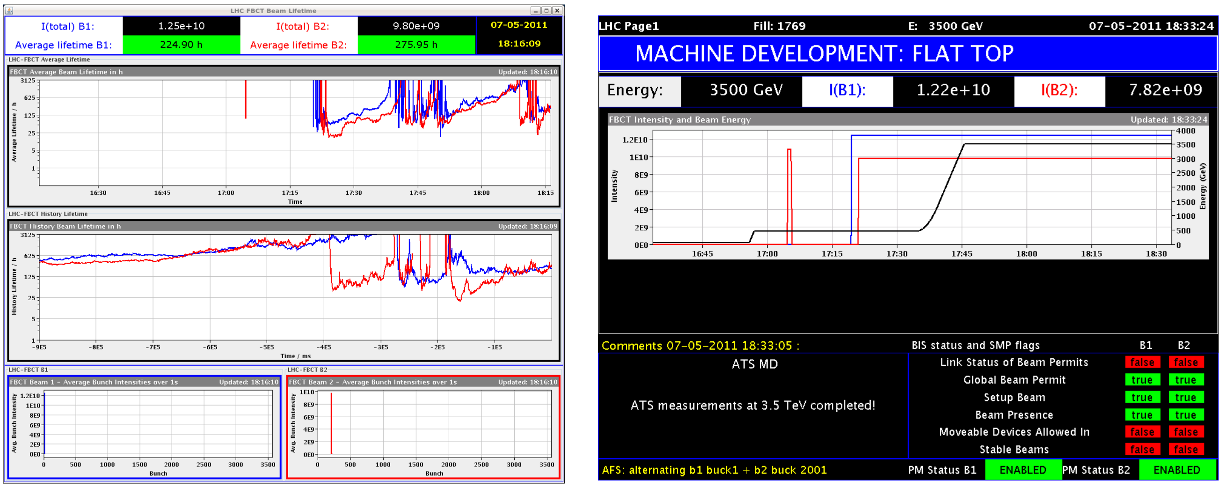


Figure 11: Life time history (25-50h during the ramp starting at 17:46) and snapshot of Page 1 just before dumping the beam at 18:33.

4 Detailed optics measurements

Measurements, both at injection energy and 3.5 TeV, were conducted to check the new ATS_V6.503 injection optics. Beta-beating, coupling and dispersion were measured using turn-by-turn data with the AC-dipole used as (non-destructive) "beam shaker".

4.1 Beta-beating

The results of the β-beating measurements at 450 GeV are shown for both beams in Fig. 12. The measured peak β-beating at injection is $\sim 25\%$ for Beam1 and $\sim 30\%$ for Beam2, which is very similar to what is measured in the machine using the nominal injection optics. In both figures some abrupt local jumps are observed around the IRs, which indicates that some local error sources are present. For a peak β-beating in the $20\% - 30\%$ range local corrections will be hard to identify. If needed, global corrections, using a response matrix, could be applied to reduce the β-beating.
The results of β-beating measurements at flat top are shown in Fig. 13. The peak values measured at flattop are $\sim 15\%$ for Beam1 in both planes, and $\sim 15 - 10\%$ for Beam2 in the H-V planes, respectively. This corresponds to an improvement by a factor of about 2 compared to the results obtained at injection. This improvement is expected since at 3.5 TeV the contribution of the persistent current in the superconducting quadrupoles of the machine disappears and therefore the field model is more precise. The residual 10-15% β-beating observed, without any specific correction and which is below the 21% initial specification, is then due to the arc magnets only (random b_2 of the main quadrupoles and main dipoles, quadrupole feed-down from the random misalignments of the MCS spool-pieces). The large error bars for Beam1 in the sectors 12 and 23 are due to the fact that only 50 turns were acquired in these two sectors. The large error bars for Beam2 in sector 23 are induced by malfunctioning BPMs.

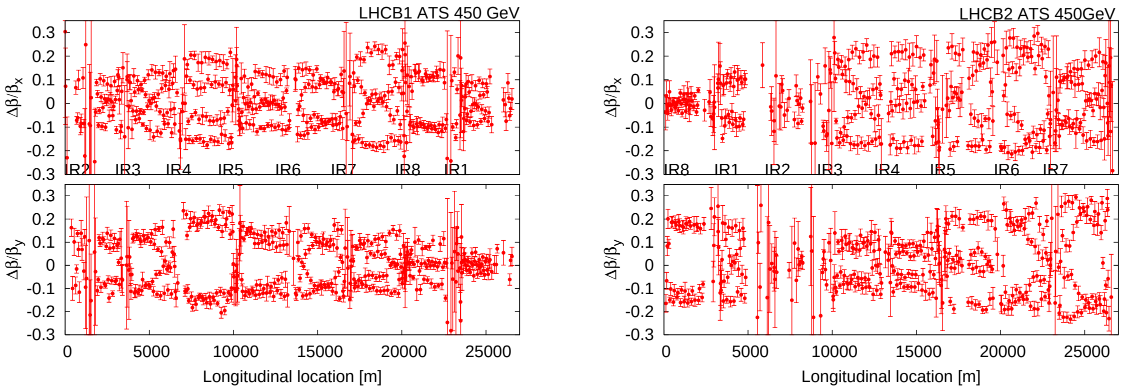


Figure 12: Measurement of the β-beating at injection for Beam1 (left) and Beam2 (right).

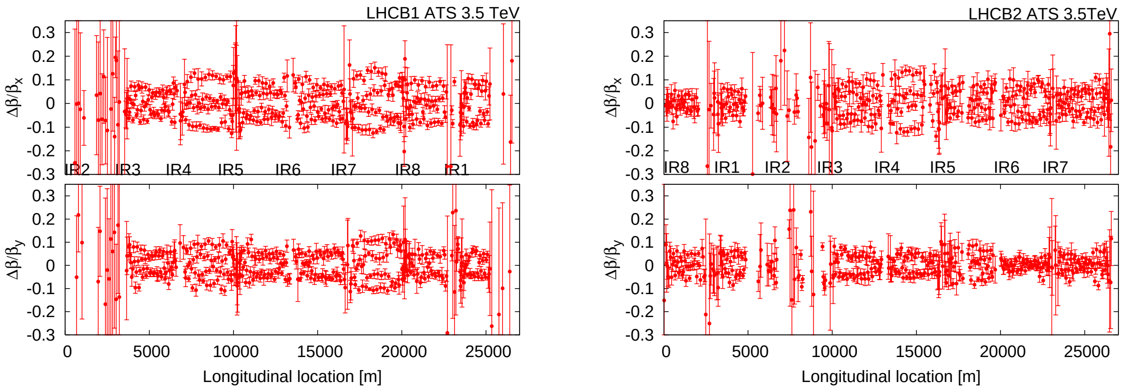


Figure 13: Measurement of the β-beating at 3.5 TeV for Beam1 (left) and Beam2 (right). The large error bars for Beam1 in sectors 12 and 23 are due to the fact that only 50 turns were acquired in these sectors. The large error bars for Beam2 in sector 23 are due to malfunctioning BPMs.

4.2 Correction of the systematic b_2 of the main dipoles

The phase advance errors, which are the differences between the measured betatron phases and those of the model, are reported on Fig.'s 14 and 15, at injection and 3.5 TeV, respectively. The measurement of Beam1 is not reliable at 3.5 TeV, at least in the sectors 12 and 23, and is being re-analyzed because of some BPM issues. Qualitatively speaking, drifts are observed in the arcs because of the systematic b_2 component the main dipoles. These drifts are followed by abrupt jumps at the beginning and end of each sectors, which coincides with the locations of the tune shift quadrupoles MQTs (from Q14 to Q21) which are available to correct the effect sector-by-sector. The situation is found to be substantially improved at 3.5 TeV, certainly due to the reduction of the β-beating, knowing that the b_2 of the main dipoles is approximately the same at injection and 3.5 TeV, before slowly vanishing at 7 TeV. More precisely, the systematic b_2 of the main dipoles is about ± 1.5 units both at 450 GeV and 3.5 TeV, changing sign from the inner to the outer aperture

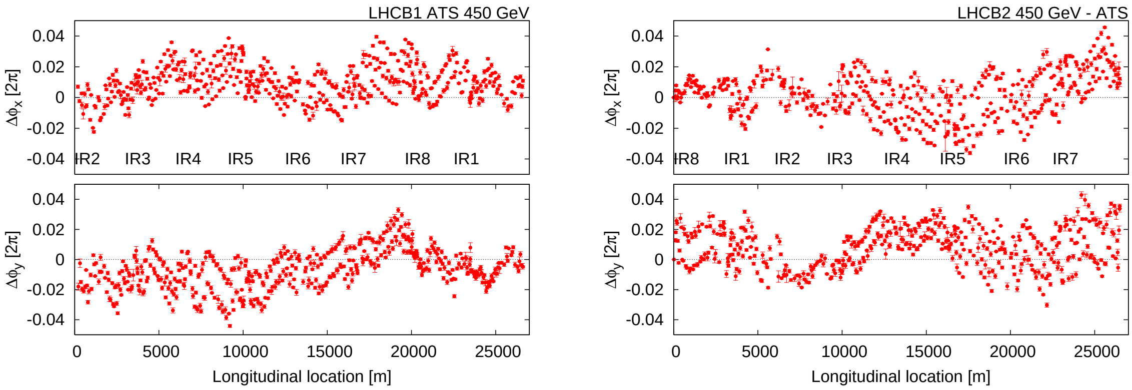


Figure 14: Phase advance errors measured at injection for Beam1 (left) and Beam2 (right). The arc-by-arc correction of the systematic b_2 of the main dipoles is achieved thanks to the tune shift quadrupole MQTs located from Q14 to Q21 at the beginning and end of each sectors.

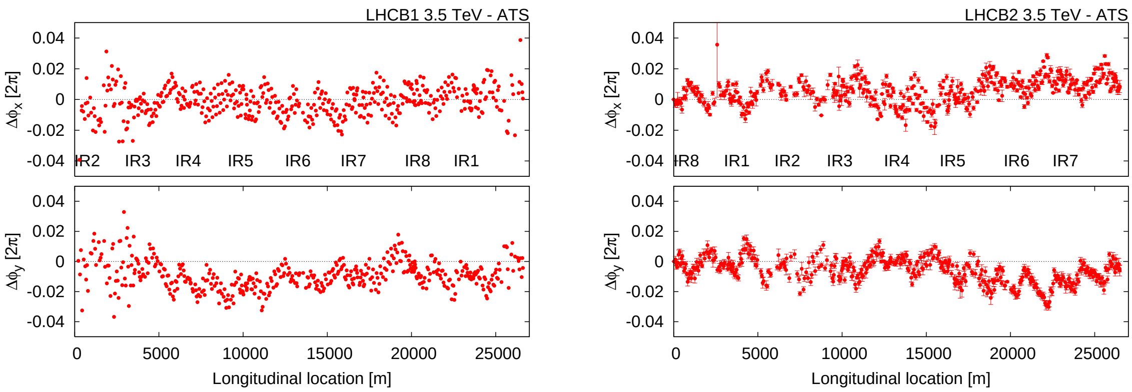


Figure 15: Phase advance errors measured at 3.5 TeV for Beam1 (left) and Beam2 (right). Beam1 data are showed without error bars because not 100% reliable due to some BPM issues.

of the ring. This corresponds to a phase shift of about ± 0.055 per sector without correction. Taking into account that the MQT's are supposed to correct half of the effect on either side of each sector, and that, $N_{MB} = 35$, 38 main dipoles are located from Q7 to the last MQT on a given side of a sector (at Q20 and Q21, respectively, for the last focusing or defocusing MQT), the peak phase errors should not exceed $(77 - N_{MB})/77 \times 0.055/2 \approx 0.015$ for a perfect correction (assuming also no random b_2 and no β-beating). In view of Fig.'s 14 and 15, such a level precision is not reached with the systematic b_2 clearly undercompensated or overcompensated in some sectors. While a fine tuning of the correction is not really necessary at injection, the situation may become more critical at 3.5 TeV in the sectors where the peak β-functions are supposed to increase by a factor of up to 4 (or even 8 for the flat optics proposed in [2] for the upgrade) during the second part of the new squeeze (i.e. sectors 81 and 12 for the ATS MD's in 2011, and sectors 45 and 56 later on). In this respect, the quality of the b_2 correction shall be improved for the ATS optics.

4.3 Coupling

Measurements performed at injection for the difference coupling driving term are shown in Fig. 16, before and after a local correction using the RQSX circuits of the experimental IR's was incorporated and the global coupling correction retuned accordingly. This knob was calculated from the nominal injection optics and tested during the 90m MD [6]. The name of the knob in the LSA database is local_coupling_ATS_2011. The trims applied are reported in Tab. 2. As can be seen in Fig. 16, local jumps of the coupling driving term amplitude were reduced at these locations. After this correction, however, a jump occurred for Beam2 around IP7 (blue markers in the right plot of Fig. 16), for the real and imaginary parts of the driving term but not for its amplitude. These jumps are explained by the rapid variation of the phase split $\mu_x - \mu_y$ and therefore of the phase of the driving term across IR7 (and IR3 as well). Then the effect has been made more visible after the local correction due to the fact that the amplitude of the driving term has increased at this specific location. A detailed analysis of the situation has nevertheless been achieved and reported in Fig. 17, using the so-called "segment-by-segment" technique [7]. The jumps of the real and imaginary parts of the coupling driving term (blue and red markers, respectively) are clearly visible. The propagated model is however in good agreement with the measurements, which indicates that these jumps do definitely not correspond to a real source of local coupling in IR7.

Corrector	Strength $[m^{-2}]$	Corrector	Strength $[m^{-2}]$
kqsx3.l1	0.0008	kqsx3.l5	0.0006
kqsx3.r1	0.0008	kqsx3.r5	0.0006
kqsx3.l2	-0.0009	kqsx3.l8	-0.0007
kqsx3.r2	-0.0009	kqsx3.r8	-0.0007

Table 2: Summary of the trims applied to the RQSX circuits of IR1, IR2, IR5 and IR8.

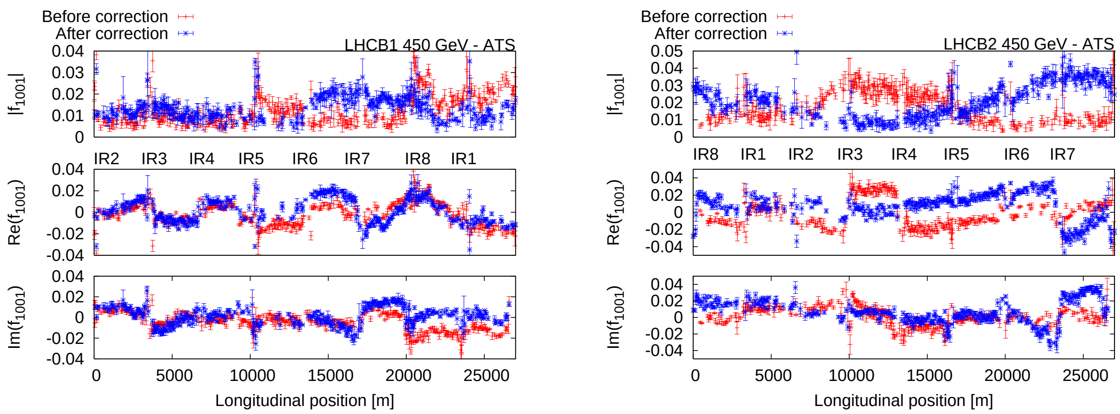


Figure 16: Local (1,-1) resonance driving term measured at 450 GeV for Beam1 (left) and beam 2 (right), without and with trims applied to the RQSX circuits (see Tab. 2). In both cases, the global coupling knobs (acting only on the arc RQS circuits) where optimized using the closest tune approach. Acting on the RQSX circuits reduced some local jumps in the experimental IRs.

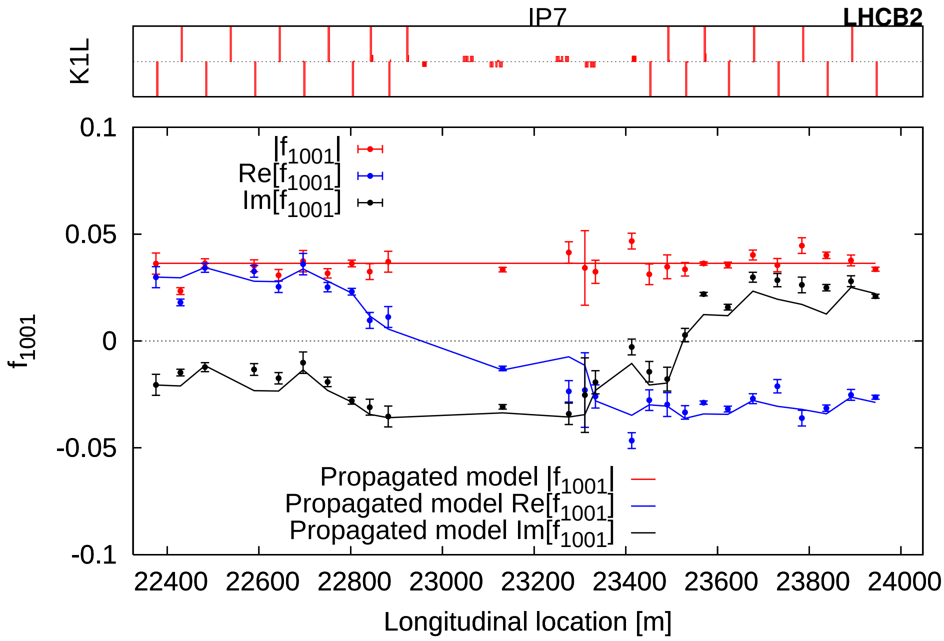


Figure 17: Zoom in IR7 for Beam2 at injection using the segment-by segment technique. The fast variations of the real and imaginary parts of the driving term are clear. However, the average amplitude remains quite constant and the propagated model is in good agreement with the measurements. This demonstrates that these jumps do not correspond to a real source of coupling error.

The same measurements were performed at 3.5 TeV and reported on Fig. 18. The sectors 12 and 23 are not plotted for Beam1 because of the filtering in the coupling algorithm and the 50 turns acquisition in the BPMs. For both beams, the amplitude of the difference coupling driving term range in between 0.01 and 0.02 at 3.5 TeV, which, for the normalization used, corresponds to

$$|c_-| \approx 4\,|Q_x - Q_y|\ \langle f_{1001}\rangle \sim 0.0012 - 0.0024$$

and, therefore, to a very "honorable" local or global coupling correction. On the other hand, as for the b_2 correction, the ATS scheme might require to push further down the accuracy of the local coupling correction, more precisely by the factor of 4 (to 8) by which the β-functions will be increased in the sectors 81, 12, 45 and 56. A safe requirement for the local coupling correction in these four sectors would then be

$$|f_{1001}| \sim \text{ a few } 0.001\,.$$

Starting by imposing a pre-setting for the arc RQS circuits would then be very beneficial, based on the magnetic measurement of the a_2 component of the main dipoles. These pre-settings are already available for the new optics (while missing for some reasons in the nominal beam process) and will be tested during the next ATS MDs, hopefully together with dedicated tools for the local measurement and correction of the difference coupling driving term accumulated in a given arc.

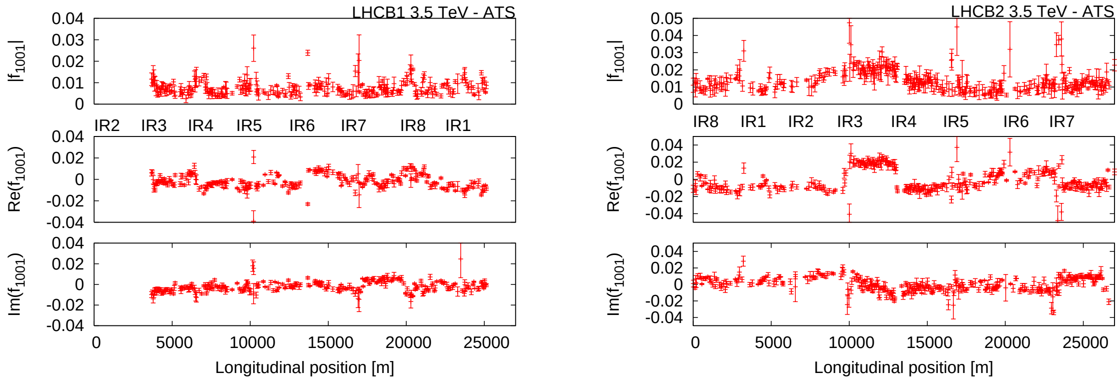


Figure 18: Measurement of the (1,-1) resonance driving terms at 3.5 TeV. The sectors 12 and 23 are not plotted for Beam1 because of the filtering in the coupling algorithm and the 50 turns acquisition in the BPMs.

4.4 Dispersion

The measurement results of the dispersion at injection were discussed in Section 3 (see Fig. 6). An additional measurement took place at 3.5 TeV and is reported on Fig. 19. The top plot shows the deviations of the normalized horizontal dispersion with respect to the model, i.e. $\frac{\Delta D_x}{\sqrt{\beta_x}}$, while the raw data for the vertical dispersion are reported on the bottom picture. The momentum shift applied for this measurement has been accurately estimated to be $\delta_p = -0.428 \times 10^{-3}$ and $\delta_p = -0.423 \times 10^{-3}$ for Beam1 and Beam2, respectively. The horizontal spurious dispersion is substantially larger for Beam2 (but still within specification) while the vertical dispersion is similar for both beams and a factor of 3 to 4 below specification.

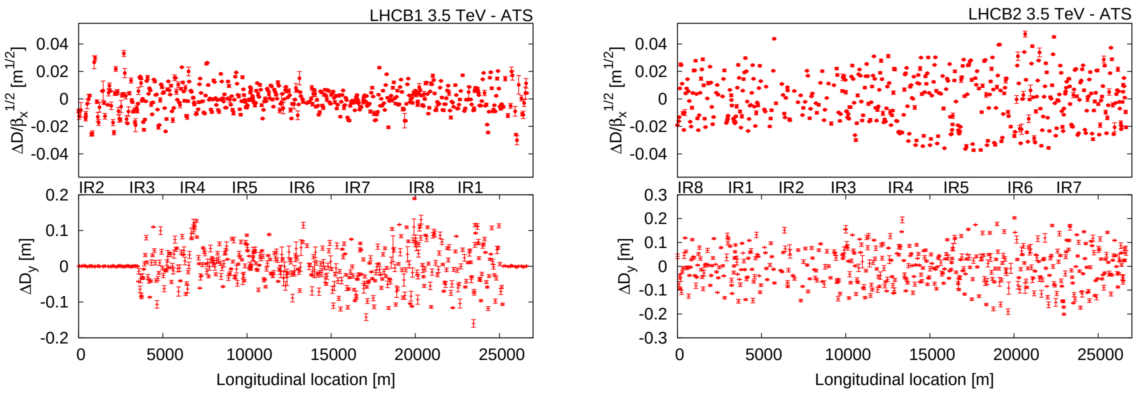


Figure 19: Horizontal and vertical spurious dispersions measured at 3.5 TeV for Beam1 (left) and Beam2 (right). The dispersion is normalised in the horizontal plane. The BPM data are not reliable for Beam1 in sectors 12 and 23, because only 50 turns were acquired in these two sectors.

5 Conclusions and outlook

Several factors certainly influenced the incredible success of the first ATS MD: of course the reliability of the injector chain, the impressive expertise and experience of the OP crew and of the LHC sub-system responsibles but also, simply, the machine itself, after the meticulous efforts of conception and specifications, the dedication of all the project teams to meet the targets and, whenever possible, the sustained effort to add a layer of perfection to the overall system during the installation phase. This includes, in particular, the amazing amount of mechanical and magnetic measurement data taken during the production and installation phases, which were as many inputs for the magnet sorting strategy which took place, helped in defining the best possible alignment of each magnet and were essential to build an as precise as possible survey and field model of the machine. All these elements, together with the reliable beam diagnostics available, seem to have built considerable and exploitable margins in the LHC, otherwise one would not have been able to commission and ramp a new injection optics in a couple of hours.

Provided that beam-based corrections are applied for an accurate arc by arc compensation of the magnet imperfections, in particular for a_2 and b_2, either using the existing techniques or upgrading them, it looks very likely that, even if the LHC was initially not designed for the ATS scheme, the margins accumulated will be more than appropriate to push the scheme up to an adequate level (in terms of β^*), both for the upgrade but also for the nominal machine (at smaller than nominal emittance).

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