FIRST DEMONSTRATION WITH BEAM OF THE ACHROMATIC TELESCOPIC SQUEEZING (ATS) SCHEME

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Abstract

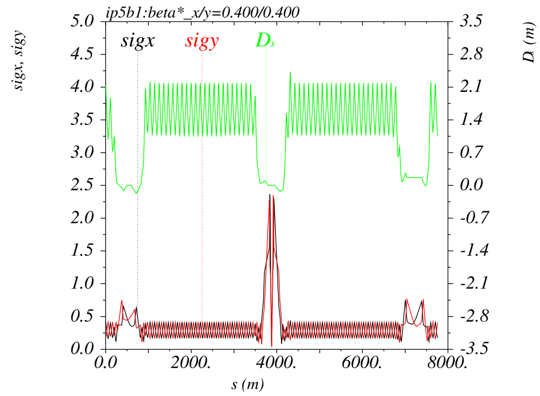
The Achromatic Telescopic Squeezing (ATS) scheme is a novel squeezing mechanism which is (almost fully) compatible with the existing hardware of the LHC, and enables both the production and the chromatic correction of very low β^*. The basic principles of the ATS scheme will be reviewed together with its basic motivation which is to deliver a very ambitious β^* of 10-15 cm in view of the even more ambitious performance commitments taken by the HL-LHC project. In this context, a few dedicated beam experiments were meticulously prepared and took place at the LHC in 2011. The results obtained will be highlighted, demonstrating already the viability of the scheme. The plans for 2012 will be discussed, with a few optics considerations which could already justify the implementation of the ATS scheme in the nominal machine, depending on which β^* limits will be met first, and that the ATS can solve (e.g. optics matchability, chromatic aberrations) and obviously cannot: the aperture of the existing triplet.

INTRODUCTION

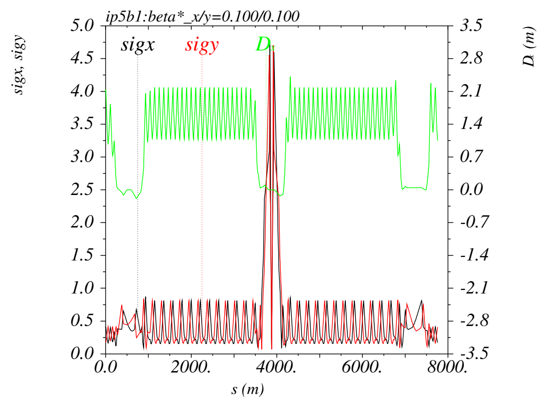
The Achromatic Telescopic Squeezing (ATS) scheme is a novel optics concept enabling the matching of ultra-low β^* while correcting the chromatic aberrations induced by the inner triplet [1, 2]. This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is achieved by using exclusively, as usual, the matching quadrupoles of the high luminosity insertions IR1 and IR5. Then, in a second stage, β^* can be further reduced by some factor (typically 4 to 8) by acting only on the insertions on either side of IR1 and IR5 (i.e. IR8/2 for IR1 and IR4/6 for IR5). As a result, sizable β-beating bumps are induced in the four sectors on either side of IP1 and IP5. These waves of β-beating are also necessary to boost, at constant strength, the efficiency of the chromaticity sextupoles located in the sectors 81, 12, 45 and 56.

An example of pre-squeezed ($\beta^* = 40$ cm) and squeezed ($\beta^* = 10$ cm) ATS optics is given in Fig. 1, zoomed in between IP4 and IP6. For the squeezed optics (Fig. 1(b)), the β-beating waves are clearly visible in the sectors 45 and 56, corresponding to an increase by a factor of 4 of the peak β-functions in the arcs. However, even in the absence of crossing angle, it is worth reminding that such β^* values are hardly operational in the nominal LHC due to the mechanical acceptance of the existing inner triplet and its matching section.

The implementation of the ATS scheme requires a new injection optics, featuring in particular strictly $\pi/2$ phase advances in the four sectors neighboring IR1 and IR5,



(a)



(b)

Figure 1: Pre-squeezed (top) and squeezed (bottom) optics with $\beta^* = 40$ cm and $\beta^* = 10$ cm, respectively, at IP1 and IP5: beam sizes [mm] and horizontal dispersion [m] zoomed in between IR4 and IR6.

namely the sectors 81, 12, 45 and 56. Then, one of the keystones of the scheme is the pre-squeezed optics, where new matching conditions are imposed for the left and right phase advances of the low-beta insertions, and for which β^* shall be chosen within a certain interval. This interval depends on the detailed layout and gradient of the inner triplet, on the maximum operating current of the lattice sextupoles and on the beam energy. At nominal energy (7 TeV/beam) and for the existing triplet (205 T/m), the pre-squeezed β^* shall fulfill the following condition:

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

The IR phasing conditions mentioned above can indeed not be matched for a β^* larger than 2 m. Then, below a β^* of 40 cm, some matching quadrupoles of IR1 and IR5 would be pushed to very low gradients, while, for a beam energy

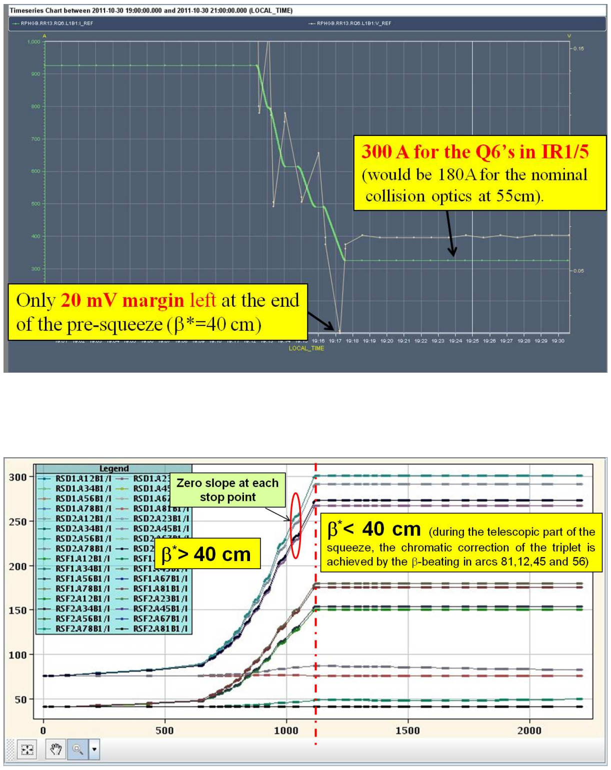


Figure 2: Various limitations associated to the 40 cm pre-squeezed optics: reference current [A] and reference voltage [V] for a typical RQ6 circuit in IR1 and IR5 during the pre-squeeze (top), and reference settings [A] sent to the arc sextupole circuits during the pre-squeeze and squeeze down to $\beta^* = 10$ cm (bottom). While the RQ6 circuits shall operate at very low current in IR1 and IR5 at the end of the pre-squeeze, some defocusing sextupole families are pushed to 300 A at 3.5 TeV, which corresponds to the ultimate current of 600 A for a beam energy of 7 TeV.

of 7 TeV, some arc sextupole families would need to be powered beyond the so-called ultimate current of 600 A (see Fig 2). Finally, as already stated, the continuation of the squeeze is achieved by the matching quadrupoles of the supporting insertions on either side of IR1 and IR5, modifying in particular the optics of the RF and dump insertions, IR4 and IR6, at flat top energy, which corresponds to a completely new operation mode of the LHC.

In view of the potential of the ATS scheme, not only for the LHC (with pre-squeezed optics already pushed beyond the nominal β^* of 55 cm, and with additional chromatic properties), but also for the HL-LHC (with accessible β^* values as low as 10 cm at IP1 and IP5), a few dedicated machine experiments were organized in 2011. An overview of the 2011 ATS machine development (MD) program will be reported in the next section, highlighting a few results that already demonstrate the viability of the scheme. The plans for 2012 will then be briefly presented, followed by a discussion on whether the ATS scheme might already be needed for operating the LHC in 2012.

THE ATS MD PROGRAM IN 2011

Overview

ATS machine studies were scheduled during the first, second and fourth LHC MD periods in 2011. A total time of 8 hours was spent for dry runs (hardware tests without beam), while around 22 h were needed to perform the first validations with beam. All dry runs were quite successful, showing sometimes some limitations, but quickly identified and fixed for the MDs with beam. The last dry run demonstrated in particular the readiness of the existing hardware (power supplies) to produce and chromatically correct a collision optics with $\beta^* = 10$ cm at IP1 and IP5.

The first ATS MD [3] successfully commissioned the new ATS injection optics and its ramp up to 3.5 TeV. The second ATS MD [4] demonstrated an achromatic pre-squeezed optics with $\beta^* = 1.2$ m at IP1 and IP5, and then a further squeeze of IR1 down to $\beta^* = 30$ cm using the telescopic techniques of the ATS scheme (i.e. using the matching quadrupoles of IR8 and IR2). Finally the first goal of the third MD [5] was to push the pre-squeezed β^* down to its limit of 40 cm and validate the specific chromatic properties of this optics. An ultimate goal was then to use the ATS techniques to further squeeze β^* by a factor of 4, simultaneously at IP1 and IP5, and then reach a β^* of 10 cm in the two high-luminosity insertions of the LHC. While the pre-squeeze was rather fast (2h) and successful, the beam was lost during the preparation for the telescopic part of the squeeze due to a bad manipulation between the different sets of tune correction knobs which are foreseen in the ATS scheme (see later). Unfortunately a second try was not permitted due to the LHC ion run which was scheduled right after the MD.

These machine studies were performed using very small intensity (one pilot bunch $\sim 10^{10}$ p/bunch). The crossing angles were always switched off in order to maximize the available mechanical acceptance of the inner triplets in IR1 and IR5. The parallel separation bumps were also switched off, with Beam1 and Beam2 injected in Bucket 1 and 2001 in order to avoid collision, with the exception of the third ATS MD where the parallel separation was actually switched on and set to its nominal value at injection and during the ramp. The collimators and other protection devices (e.g. TCDQ) were never ramped. Then the procedure was a manual adjustment of the horizontal and vertical primary collimators (TCPH and TCPV) at the end of the ramp (set to fixed values in between 7 and 9 σ depending on the β^* targeted at the end of the pre-squeeze), together with the tertiary collimators (TCT) of IR1 and IR5 set to ± 12 mm and ± 10 mm in the H and V planes, respectively, in order to shadow the triplet for any β^* (pre-squeezed or squeezed).

Highlighted achievements

The new ATS injection optics The commissioning of the new ATS injection optics was impressively fast, with

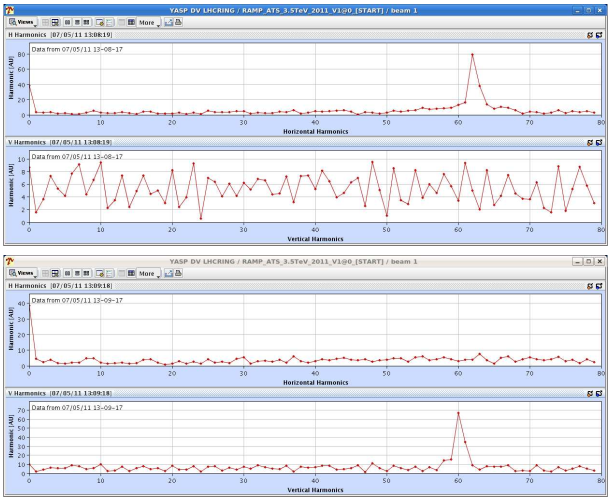


Figure 3: Integer tunes of the ATS optics measured at injection: 62/60 compared to 64/59 for the nominal LHC optics

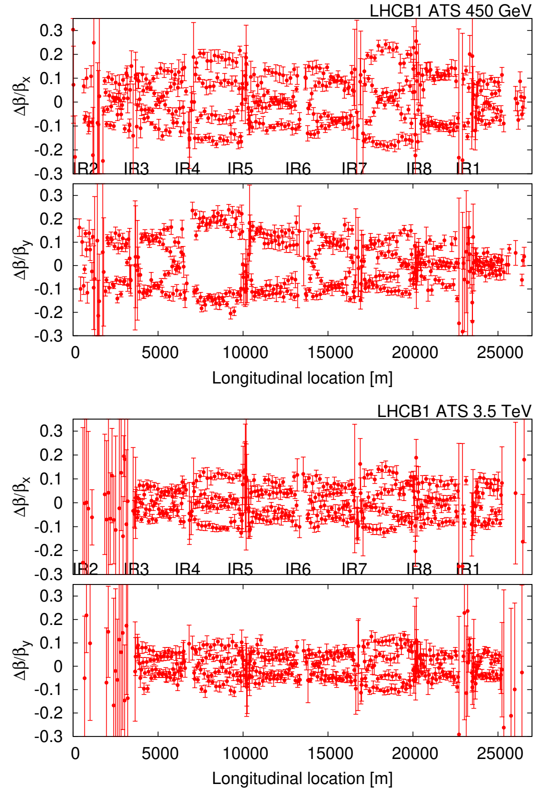


Figure 4: β-beating measurement for Beam1 with the ATS injection optics, performed at injection (top) and 3.5 TeV (bottom), without any specific correction put in place. The large errors bars obtained for Beam1 in sector 12 and 23 (3.5 TeV) are due to the fact that only 50 turns were acquired in these two sectors (courtesy of G. Vanbavinckhove).

Beam1 and Beam2 successfully injected, circulating and RF captured at the first attempt (being said that the orbit correctors were pre-set to their nominal injection values). Tune, coupling and chromaticity were then quickly corrected using the standard knobs, of course after recalibration based on the new optics. Several LHC subsystems were also successfully tested, such as the transverse damper (with new settings imposed by the change of betatron phases in IR4) and the dump. As expected, a specific measurement gave 62/60 for the integer tunes, to be compared with 64/59 for the nominal optics of the LHC (see Fig. 3)

The beams were dumped at the very beginning of the first ramp, because some interlocks (TCDQ) were not masked. The second try was then a success showing an almost perfect transmission of intensity through the ramp, without any noticeable emittance growth. Tune, coupling and chromaticity were then quickly adjusted at the end of the ramp.

Detailed optics measurements were carried out both at injection and flat top energy, for the β-beating, dispersion or local coupling, showing no new specific features. Fig. 4 shows in particular the β-beating measured at injection and 3.5 TeV. Without any specific correction put in place, the β-beating amounts to about 20-30% at injection, essentially dominated by some contributions from the LHC insertions. Then it naturally shrinks down to the 10-15% level at 3.5 TeV, where the magnetic model of the standalone IR quadrupoles is more accurate at higher current, and keeping in mind that the contribution of the arcs (random b_2 component of the main quadrupoles) has been minimized thanks to the sorting strategy which took place during the installation phase of the LHC.

The ATS pre-squeezed optics and its chromatic properties Two ATS pre-squeezed optics were successfully established, first with a β^* chosen to 1.2 m during the second ATS MD, then pushed down to 40 cm for the third MD. In both cases the pre-squeeze was relatively fast, with no specific problems related to the control of the tune, coupling or chromaticity. For both pre-squeezed optics, it is worth mentioning that a few empirical trims, deduced from the local correction of the nominal optics [7, 8], were incorporated at $\beta^* = 4.4$ m and then kept constant for lower β^*. They were applied to preset the RQSX skew quadrupole correctors of the inner triplets in IR1, IR2, IR5 and IR8, but also to modify by about one permil the reference current of three low-β quadrupoles in IR1 and IR5, namely Q2.R1, Q2.L5 and Q2.R5.

Fig. 5 shows for instance the β-functions measured for Beam2 at $\beta^* = 1$ m and $\beta^* = 40$ cm (H plane only) during the third ATS MD. A correction of the β-beating also took place at β^* =40 cm, bringing it down below the operational level of 20% (see Fig. 6)

As already mentioned, the ATS pre-squeezed optics feature interesting chromatic properties which are due to the specific phasing conditions imposed between the inner

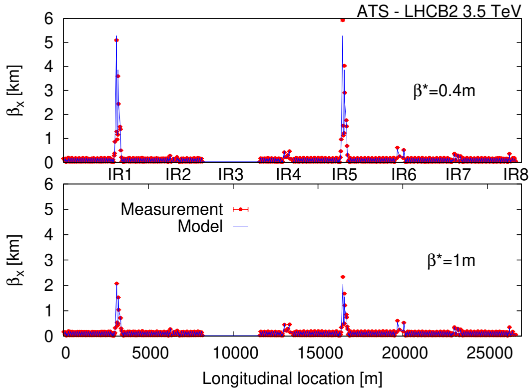


Figure 5: Horizontal β-functions measured for Beam2 at β^*= 1 m (bottom) and β^*= 40 cm (top) during the third ATS MD: model (blue lines) and measurement (red dots).

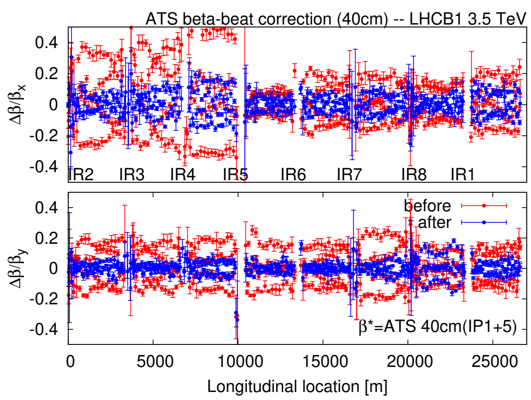
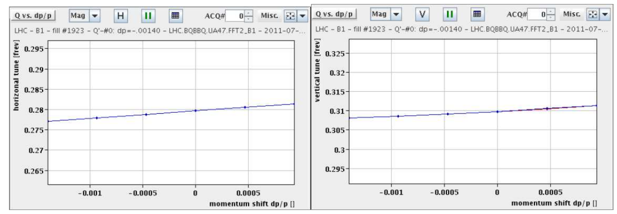
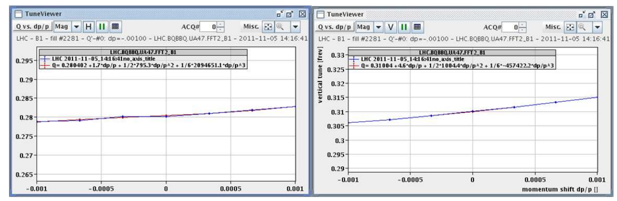


Figure 6: β-beating measurement for Beam1 performed at $\beta^* = 40$ cm before and after correction (courtesy of R. Tomas and G. Vanbavinckhove)

triplets of IR1 and IR5 and the chromaticity sextupoles of the adjacent arcs, and to the different settings applied to the two sextupole families available per plane in each of the 8 sectors of the LHC (see Fig. 2). As a result, the impact of the inner triplets on the non-linear chromaticity (Q'', Q''',...) and the off-momentum β-beating can be very well controlled. This fact is illustrated in Fig. 7 showing the chromatic variations of the betatron tunes measured for Beam1 at $\beta^* = 1.2$ m (second ATS MD) and $\beta^* = 40$ cm (third MD). Off-momentum optics measurements, unfortunately only available for $\beta^* = 1.2$ m, are illustrated in Fig. 8, demonstrating as well that the induced off-momentum β-beating is well-bounded in the four sectors on either side of the two high-luminosity insertions, with no sizable leakage in the collimations insertions IR3 and IR7 and a good control in the inner triplets of IR1 and IR5.



$Q_{x,y}(\delta)$ for $\beta^* = 1.2$ m at IP1 and IP5



$Q_{x,y}(\delta)$ for $\beta^* = 40$ cm at IP1 and IP5

Figure 7: Chromatic variations of the betatron tunes measured for Beam1 at $\beta^* = 1.2$ m (top) and $\beta^* = 40$ cm (bottom), during the second and the third ATS MD, respectively. The linear chromaticity Q' was corrected to a few units using the standard knobs. The non-linear chromaticity, Q'', Q''', ..., is quasi imperceptible over a momentum window of the order of $\delta_p = \pm 1 - 1.5 \times 10^{-3}$.

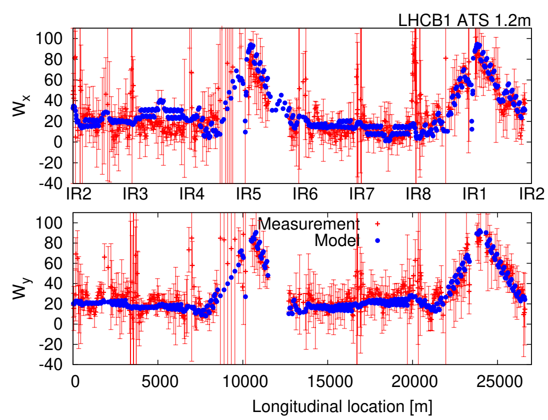
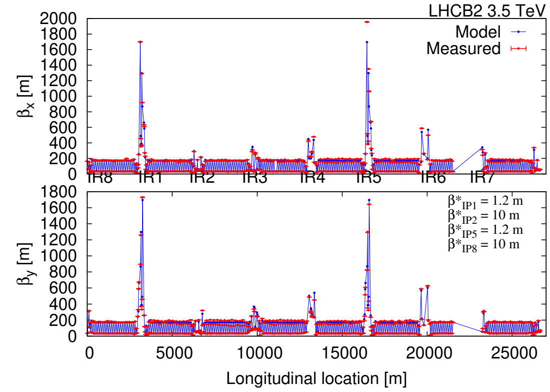


Figure 8: Montague functions W measured for Beam1 at $\beta^* = 1.2$ m (second ATS MD): measurement (red) versus model (blue). A W function reaching 100 is equivalent to an off-momentum β-beating of 10% at $\delta_p = 10^{-3}$ or, depending on the phase of the chromatic wave, to an off-momentum α-beating. The value of 100 reached in the inner triplets of IR1 and IR5 actually correspond to a peak of off-momentum α-beating, i.e. to a vanishing off-momentum β-beating. The W functions are minimized in half the ring in particular in the two collimation insertions IR3 and IR7. Due to BPM acquisition problems, some data are missing in sector 56 (courtesy of G. Vanbavinckhove).

The ATS squeezed optics The ATS scheme certainly offers very attractive chromatic properties, which are already available for any pre-squeezed optics with β^* fulfilling the conditions given in Eq. (1). The second and biggest advantage of the scheme is then to be able to deliver ultra-low β^* at IP1 and IP5, by involving the insertions IR8, IR2, IR4 and IR6 in order to further reduce the pre-squeezed β^* by a factor of typically 4 to 8. As a result, β-beating waves are induced in the sectors 81, 12, 45 and 56 of the machine, which warrants the chromatic correction of the inner triplets at quasi-constant strength in the sextupoles (see Fig. 2).

The second (telescopic) part of the squeeze was then successfully tested during the second ATS MD, where β^* was further reduced by a factor of 4 at IP1, therefore passing from $\beta^* = 1.2$ m to $\beta^* = 30$ cm, keeping unchanged the pre-squeezed optics of IR5 (see Fig. 9). It is nevertheless worth mentioning a net increase of the linear coupling which was observed during this process. The coupling was indeed only partially corrected due to a lack of time, but hopefully anticipated keeping the injection tunes 62.28/60.31 (i.e. a fractional tune split of 0.03) as reference for the tune feed-back during the overall process. A more complete validation of the squeezed optics would then have been a direct measurement of the non-linear chromaticity and of the W functions at $\beta^* = 30$ cm. These additional checks however did not fit within the time allocated to the MD. On the other hand, several measurements of the linear chromaticity were taken during the squeeze of IR1 from 1.2 m to 30 cm. They demonstrated in particular one of the most astonishing features of the scheme, which is the preservation of Q' during the telescopic part of the squeeze at quasi-constant strength in the lattice sextupoles.

The ultimate goal of the third ATS MD was to reiterate this exercise, not only in IR1 but also in IR5, and starting from the pre-squeezed β^* of 40 cm in order to reach in fine a β^* as low as 10 cm both at IP1 and IP5. For this purpose an additional functionality was requested to the tune feed-back, to be used when preparing the machine for the squeeze from 40 cm to 10 cm. Without going too much into the details, the request was to be able to switch from the standard to a new set of tune correction knobs, which only act on the tune shift quadrupoles located in the sectors 23, 34, 67 and 78 where the β-functions are kept unchanged during the telescopic part of the squeeze. Unfortunately the beam was lost due to several RQT circuits tripped by the QPS right after the switch. The reason of these trips was then rapidly identified and explained by the fact that all the real time trims accumulated so far in the RQT circuits of sectors 81, 12, 45 and 56 were sharply sent to zero by the tune feed-back system when switching from the first to the second set of tune knobs. Obviously, the idea was on the contrary to keep unchanged the RQT real time trims during the switch, and then to continue to trim them later on, based on the new tune knobs.



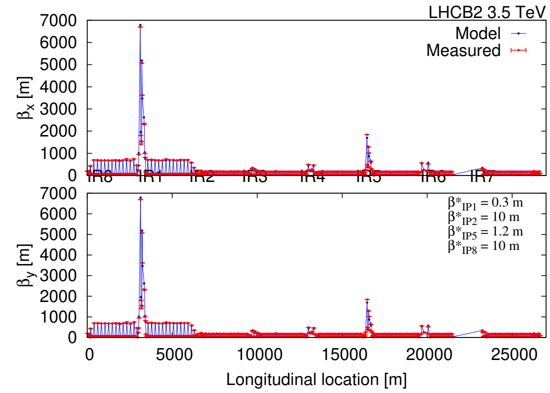


Figure 9: Measurement of the pre-squeezed (top) and squeezed (bottom) optics carried out for Beam2 during the second ATS MD. The peak β-functions are increased by a factor of 4 in the sectors 81 and 12 when the optics is fully squeezed, enabling not only to further decrease β^* by a factor of 4 at IP1, but also to work at quasi-constant strength in the lattice sextupoles for the chromatic correction of the inner triplets.

PLANS FOR 2012

MD plans

A clean pre-squeezed optics at $\beta^* = 40$ cm One of the priorities of the ATS MD program in 2012 is to establish a very clean pre-squeezed optics with $\beta^* = 40$ cm at IP1 and IP5: that is an optics not only optimized in terms of β-beating (to reach ideally the 10% level as for the nominal collision optics [9]), of course in terms of coupling and chromaticity, but also corrected for the left and right phase advances of the high-luminosity insertions which are the keystone of the overall scheme, and as well for the spurious dispersion in the horizontal plane. Indeed, when the crossing scheme is switched off in the LHC experimental insertions, the spurious dispersion comes essentially from the random field imperfections of the arc mag-

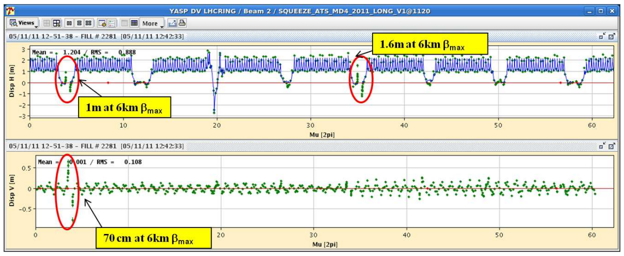


Figure 10: Dispersion measurement for Beam2 carried out at $\beta^* = 40$ cm during the third ATS MD. In the present configuration, the crossing angle is switched off in the four experimental IRs, which means that the main source of spurious dispersion is located in the arcs, induced by the a_2 and b_2 random components of the main dipoles and quadrupoles, respectively.

nets, more precisely from the random a_2 components of the main dipoles (MB) impacting on D_y, and the random b_2 components of the main quadrupoles (MQ) impacting on D_x. While the MB installation sequence was also optimized for the vertical dispersion, the situation was much more tricky for the main quadrupoles, due the many different types of cryo-assemblies. Consequently, the minimization of the β-beating was the only criteria retained to define the MQ installation sequence. As a result, depending on the betatron phase of the dispersion wave, peaks can show up in the inner triplet of IR1 and IR5 with a magnification factor scaling with $\sqrt{\beta_{\rm max}} \propto 1/\sqrt{\beta^*}$. Thus, while no more than $D_y \sim 70$ cm was measured in the vertical plane at $\beta^* = 40$ cm (for Beam2 in the inner triplets of IR1), up to 1.6 m was reached in the horizontal plane in the inner triplets of IR5 (see Fig. 10). On the other hand, contrary to the vertical dispersion where no correction knobs are available in the LHC, the spurious dispersion can in principle be minimized in the horizontal plane, together with the β-beating, during the optics correction campaign.

A safe pre-squeezed optics at $\beta^* = 40$ cm The idea is then to establish accordingly safe settings for the various collimator and protection devices (TCP, TCS, TCT, TCSG6, TCDQ,..) and then offer to the ATLAS and CMS experiments the opportunity to take physics data with a very high pile up rate. Indeed, up to $\sim 100-110$ events per bunch crossing are a priori within reach, assuming a few circulating bunches of very high brightness (e.g. with $N_b = 2.0 \times 10^{11}$ and $\gamma\epsilon = 2.5\,\mu$m) colliding at 8 TeV in the center of mass, without crossing angle at IP1 and IP5, and with $\beta^* = 40$ cm.

The squeezed optics at $\beta^* = 10$ cm Finally, coming back to pilot bunches, the goal is to complete the validation of the ATS scheme, at least for round optics, approaching and hopefully reaching a β^* of 10 cm at IP1 and IP5, carrying out on-momentum and off-momentum optics measurements at $\beta^* = 10$ cm, and if possible β-beating correction.

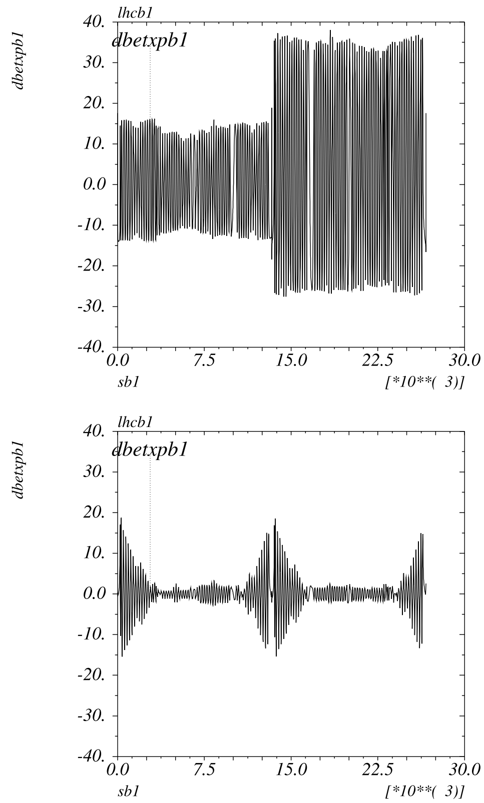


Figure 11: Comparison between the nominal LHC optics (top) and the ATS pre-squeezed optics (bottom) in terms of off-momentum β-beating [%] at $\delta_p = 0.001$ (Beam1, H-plane), with $\beta^* = 60$ cm at IP1 and IP5 and $\beta^* = 10$ m at IP2 and IP8.

Switching to the ATS pre-squeeze in 2012

With the so-called tight collimator settings [10], and some further reduction of the margins between the various protection devices of the LHC ring, an operational β^* as low as 60 cm is not at all excluded for operating the LHC in 2012 [11]. A careful evaluation of the chromatic aberrations induced is therefore very relevant to decide on whether the ATS pre-squeezed optics might already be needed for the luminosity production in 2012. The most relevant observable is the off-momentum β-beating. Assuming a β^* of 60 cm at IP1 and IP5 (with $\beta^* = 10$ m at IP2 and IP8), the nominal LHC optics leads to an off-momentum β-beating at one permil in the range of 25-35% (see top of Fig. 11). This value is sizable not only for the uncaptured beam (keeping in mind that the momentum cut given by the IR3 collimation is around $\delta_p = 1.5 \times 10^{-3}$), but corresponds already to about 10% at $2\,\sigma_{\delta_p}$ inside the RF bucket ($\sigma_{\delta_p} \sim 0.15 \times 10^{-3}$ expected for the LHC beam at 4.0 TeV [12]). This situation can then be directly compared to the very small off-momentum β-beating which would be obtained using instead an ATS optics pre-squeezed to

$\beta^* = 60$ cm (see bottom picture of Fig. 11).

The possible impact of the off-momentum β-beating on the machine performance might be of different nature, possibly degrading the collimation efficiency (with less retraction between primary and secondary collimators for off-momentum particles), increasing the background to the experiments coming from the uncaptured beam, or even exciting synchro-betatron resonances via the strong non-linearities induced by the head-on beam-beam forces. All these effects are however hardly predictable in the LHC in order to give a strict limit to the off-momentum β-beating and therefore decide to deploy already now the ATS optics in order to exploit the machine in 2012, which of course would not be without any risk in terms of additional commissioning time.

SUMMARY

The goal of the ATS scheme is twofold:

- first producing ultra-low β^* optics for the HL-LHC,
- while targeting certain chromatic properties, related to the control of the non-linear chromaticity and off-momentum β-beating.

Contrary to the nominal collision optics of the LHC, these chromatic properties are already available for the so-called pre-squeezed optics (i.e. without β-mismatch in the arcs), which makes the ATS scheme also very attractive for the existing machine.

Concerning the validation of the ATS scheme with beam, several milestones have been already reached during the few machine studies which took place in 2011: the new injection optics with different integer tunes, the pre-squeezed optics pushed down to its limit of $\beta^* = 40$ cm, the telescopic part of the squeeze demonstrated to further reduce β^* by a factor of 4 from 1.2 m to 30 cm, but only at IP1.

Several important pieces are however still missing for a complete validation of the ATS scheme, in particular applying the telescopic squeeze to IR5, that is using the matching quadrupoles of the RF and dump insertions, IR4 and IR6. This, indeed, corresponds to a completely new operational mode of the LHC since the optics of these two insertions are presently kept strictly unchanged from injection to collision. Then, all these pieces will have to be combined together for squeezing IR1 and IR5 simultaneously, pushing the pre-squeeze down to $\beta^* = 40$ cm and then hopefully reach, measure, and correct a fully squeezed optics with $\beta^* = 10$ cm at IP1 and IP5.

ACKNOWLEDGMENTS

The results presented in this paper are obviously the fruit of the work of many people, who played a very active role before the ATS MDs, in particular for the setting generation, during the MDs, in particular for the machine operation and the detailed optics measurements which took place, and after the MDs for the post-processing and analysis of the obtained data. Others, somehow less active, gave however very punctual contributions and/or advices which sometimes where found mandatory in order to progress a step further. Therefore I would like to thank warmly all of them, who contributed in a way or another to the success of the ATS MDs in 2011: C. Alabau, M. Albert, R. Alemany Fernandez, R. Assmann, R. Bruce, A. Butterworth, R. Giachino, B. Goddard, P. Hagen, W. Hofle, D. Jacquet, M. Giovannozzi, V. Kain, G. Kruk, M. Lamont, E. Maclean, A. Macpherson, R. de Maria, R. Miyamoto, G. Mueller, L. Normann, G. Papotti, M. Pojer, L. Ponce, S. Redaelli, N. Ryckx, R. Steinhagen, M. Strzelczyk, R. Suykerbuyk, E. Todesco, R. Tomas, D. Valuch, V. Venturini, G. Vanbavinckhove, J. Wenninger, D. Wollmann, F. Zimmermann.

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