

THE ACHROMATIC TELESCOPIC SQUEEZING SCHEME: BASIC PRINCIPLES AND FIRST DEMONSTRATION AT THE LHC

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Abstract

The Achromatic Telescopic Squeezing (ATS) scheme [1] is a novel squeezing mechanism enabling the production of very low β^* in circular colliders. The basic principles of the ATS scheme will be reviewed together with its strong justification for the High-Luminosity LHC Project. In this context, a few dedicated experiments with beam were meticulously prepared and took place at the LHC in 2011. The results obtained will be highlighted, demonstrating the potential of the ATS scheme for any upgrade project relying on a strong reduction of β^* .

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 (IT). This scheme is essentially based on a two-stage telescopic squeeze. First a so-called pre-squeeze is performed 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 (see Fig. 1).

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, namely the sectors 81, 12, 45 and 56. Then, one of the keystones of the scheme is the pre-squeezed optics, where

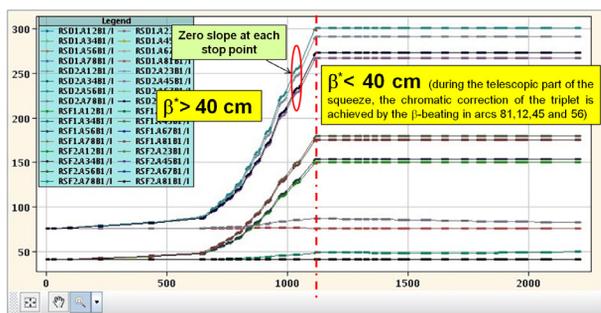


Figure 1: Typical sextupole settings [A] (assuming 3.5 TeV/beam) during the achromatic telescopic squeeze.

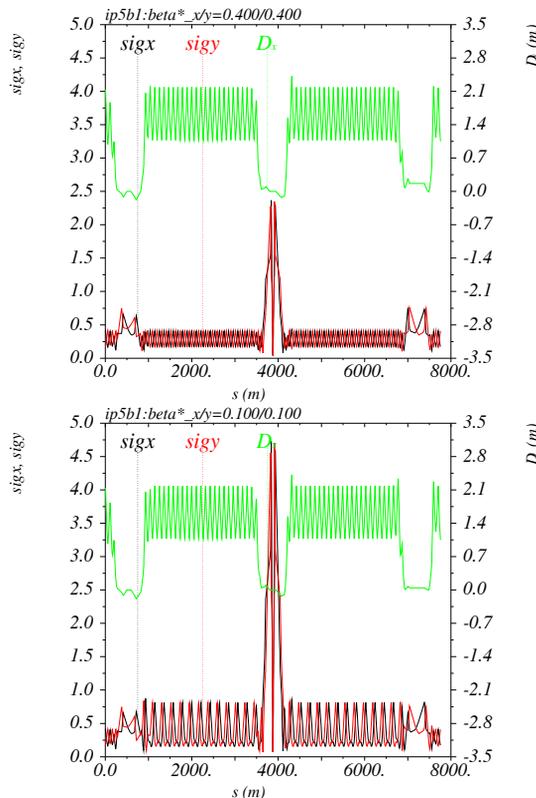


Figure 2: Beam size [mm] and horizontal dispersion [m] zoomed in between IR4 and IR6 for a pre-squeezed (top) and squeezed (bottom) optics, corresponding to $\beta^* = 40$ cm and $\beta^* = 10$ cm, respectively, at IP1 and IP5.

new matching conditions are imposed for the left and right phase advances of the low-beta insertions. These new matching constraints combined with the strength limits of the arc sextupoles imposes to choose the pre-squeezed β^* within a certain interval, which only slightly depends on the operating gradient of the inner triplet and is given by

$$40 \text{ cm} \lesssim \beta_{\text{pre-squeezed}}^* \lesssim 2 \text{ m}, \quad (1)$$

assuming a beam energy of 7 TeV and a maximum current of 600 A in the lattice sextupoles.

A pre-squeezed ($\beta^* = 40$ cm) and squeezed ($\beta^* = 10$ cm) ATS optics are illustrated in Fig. 2, zoomed in between IP4 and IP6. For the squeezed optics, the β -beating waves are clearly visible in the sectors 45 and 56, leading to an increase of the beam sizes by a factor of 2 in these arcs. Such β^* values are however not yet operational in the LHC, being limited by the aperture of the existing triplet. On the

other hand the validation of the ATS with beam was considered of primary importance, being a priori the only mean to reach the baseline β^* of 15 cm (or even below) which is requested by the LHC upgrade (HL-LHC) project [2].

ATS EXPERIMENTS IN 2011

Overview ATS machine studies were scheduled during the first, second and fourth LHC machine development (MD) periods which took place 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 limitations, which were however quickly 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 third MD [5] successfully pushed the pre-squeezed β^* down to its limit of 40 cm and validated the specific chromatic properties of this optics. All these studies were performed using a beam of very small intensity (one bunch with $\sim 10^{10}$ protons), without crossing angle in IR1 and IR5 in order to maximize the mechanical acceptance of the inner triplet, and with the orbit and tune feed-back switched on during the ramp and squeeze.

The new ATS injection optics The commissioning of the new ATS injection optics was impressively fast, with 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. The ramp was also a success showing an almost perfect transmission of intensity, without any noticeable emittance growth at 3.5 TeV. Detailed optics measurements were carried out both at injection and flat top energy for the β -beating, dispersion and local coupling, without revealing any new specific features (see [3] for more details).

The ATS pre-squeezed optics 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

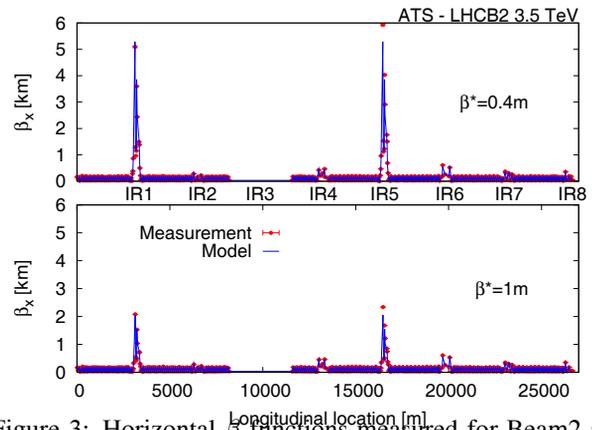


Figure 3: Horizontal β -functions measured for Beam2 at $\beta^* = 1$ m (bottom) and $\beta^* = 40$ cm (top) during the third ATS MD: model (blue lines) and measurement (red dots).

was relatively fast, with no specific problems related to the control of the tune, coupling or chromaticity. For both pre-squeezed optics, very few empirical trims, deduced from the local correction of the nominal optics [6], were applied to the inner triplets of IR1 and IR5, incorporated at $\beta^* = 4.4$ m and then kept constant for lower β^* . Fig. 3 shows the β -functions measured for Beam2 at $\beta^* = 1$ m and $\beta^* = 40$ cm (H plane only) during the third MD [5]. A correction of the β -beating was also performed at $\beta^* = 40$ cm, bringing it down below the operational level of 20%.

As already mentioned, the ATS pre-squeezed optics features interesting chromatic properties due to 1) the specific phasing conditions imposed between the IR1 and IR5 triplets and the chromaticity sextupoles of the adjacent arcs, and 2) the different settings applied to the two sextupole families available per plane in each of the 8 sectors of the LHC (see Fig. 1). These properties are first illustrated in Fig. 4 which shows the quasi-linear chromatic variations of the betatron tunes measured for Beam1 at $\beta^* = 1.2$ m

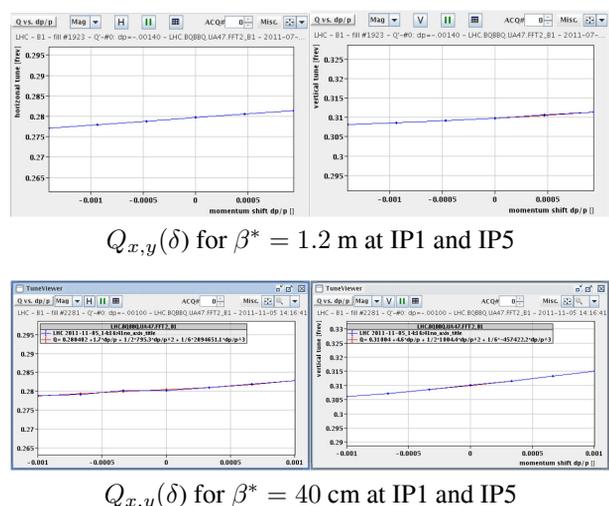


Figure 4: Chromatic variations of the tunes measured for Beam1 at $\beta^* = 1.2$ m (top) and $\beta^* = 40$ cm (bottom).

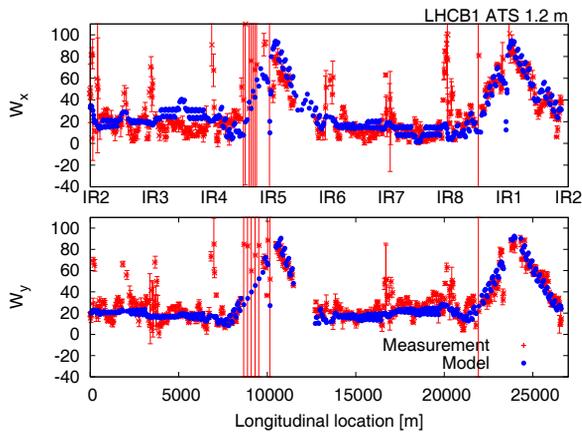


Figure 5: Chromatic Montague functions W for Beam1 at $\beta^* = 1.2$ m: measurement (red) versus model (blue).

(second ATS MD) and $\beta^* = 40$ cm (third MD). Then, off-momentum β -beating measurements, unfortunately only available for $\beta^* = 1.2$ m, are reported in Fig. 5, demonstrating as well that the off-momentum β -beating induced by the IT is well-bounded in the four sectors on either side of IR1 and IR5 with, in particular, no sizable leakage into the collimation insertions IR3 and IR7.

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 lies in the possibility 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. This novel squeezing mechanism was successfully demonstrated 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 while keeping unchanged the pre-squeezed optics of IR5 (see Fig. 6). A complete validation of this optics would 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. This 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 plan for 2012 is to squeeze simultaneously IR1 and IR5, starting from the pre-squeezed β^* of 40 cm and reaching an ultimate β^* as low as 10 cm at IP1 and IP5.

SUMMARY AND OUTLOOKS

The goal of the ATS scheme is twofold: the production of ultra-low β^* optics for the HL-LHC which, in addition, offers certain chromatic properties related to the control of

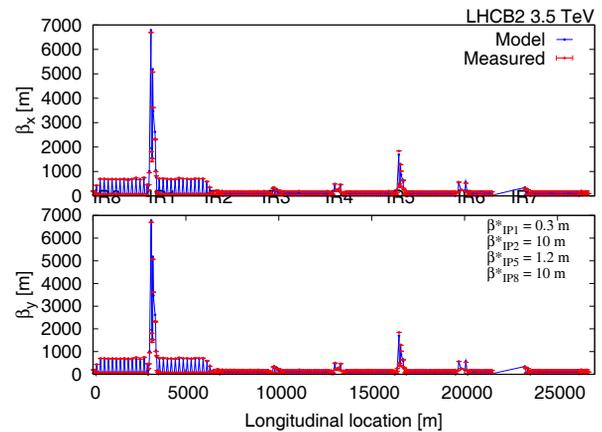


Figure 6: Squeezed optics measured for Beam2 during the second ATS MD. The peak β -functions are increased by a factor of 4 in the sectors 81 and 12, enabling not only to further decrease β^* by a factor of 4 at IP1, but also to work at constant strength in the arc sextupoles.

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 to fully validate 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, would correspond to a new operational mode of the LHC since the optics of these two insertions are presently kept strictly unchanged from injection to collision. Finally, all these pieces will need to be combined for a simultaneous squeeze of IR1 and IR5, 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.

REFERENCES

- [1] S. Fartoukh, *An Achromatic Telescopic Squeezing (ATS) Scheme for the LHC Upgrade*, IPAC'11 Proceedings.
- [2] L. Rossi, *LHC Upgrade Options and Plans*, IPAC'11 Proceedings.
- [3] S. Fartoukh *et al.*, ATS-Note-2011-033 MD, CERN, 2011.
- [4] S. Fartoukh *et al.*, ATS-Note-2011-060 MD, CERN, 2011.
- [5] S. Fartoukh *et al.*, ATS-Note-2011-132 MD, CERN, 2011.
- [6] R. Tomas *et al.*, *The LHC Optics in Practice*, 2nd Evian 2010 Workshop on LHC Beam Operation, CERN-ATS-2011-017.