EXPERIENCE WITH ATS OPTICS

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Abstract

The Achromatic Telescopic Squeezing (ATS) scheme is a novel optics concept which was built up in order to cope with the optics requirements of the HL-LHC, i.e. a clean (achromatic) and strong reduction of β^* compared to the LHC nominal optics. This paper will summarize the status of the optics and the experience gained during the 2016 LHC run through a series of dedicated machine development sessions, following the first ATS tests which actually took place in Run I (2011-2012).

INTRODUCTION

The Achromatic Telescopic Squeezing (ATS) scheme is a novel optics concept enabling the matching of ultra-low β^* in the LHC (and other hadron circular colliders), while correcting the chromatic aberrations induced by the inner triplet [1]. This scheme is essentially based on a two-stage telescopic squeeze. In a first phase, a so-called pre-squeeze is achieved by using exclusively, as usual, the matching quadrupoles of the high luminosity insertions IR1 and IR5. In a second phase, the squeeze continues by acting only on the insertions located on either side of IR1 and IR5 (i.e. IR8/2 for the telescopic squeeze of IR1, and IR4/6 for IR5). As a result, sizable β-beating bumps are induced in the four sectors on either side of IP1 and IP5. These waves of β-beating are then also necessary in order to boost the efficiency of the chromatic correction performed at constant strength by the lattice sextupoles located in the sectors 81, 12, 45 and 56. In principle the first and second phases can be exchanged, interleaved or even be run in parallel (e.g. to further gain in squeeze time), as soon as the first phase has pushed β^* below a transition β^* of the order of 2 m.

The ATS scheme forms the keystone of the HL-LHC project and its complete validation at high intensity is therefore a very important milestone in the overall upgrade plan of the LHC. The first series of ATS MDs took place in Run I (2011 and 2012), where most of the ATS principles were demonstrated, but only with pilot beams:

- the first ATS MD [2] commissioned the new ATS injection optics and its ramp up to 3.5 TeV,
- the second ATS MD [3] 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,
- the third ATS MD [4] pushed the pre-squeezed β^* down to 40 cm at IP1 and IP5,
- the fourth ATS MD [5] deployed the telescopic part of the squeeze in order to reach $\beta^* = 10$ cm, both in IR1 and IR5, starting from the above pre-squeezed optics at $\beta^* = 40$ cm.

A common feature is however systematically present in all LHC and HL-LHC ATS optics versions developed so far. It concerns very unfavorable phase advances, nearly equal to 90 degrees in the horizontal plane, between the extraction kickers in IR6 and some tertiary collimators TCTs in IR1 and IR5, in particular the most exposed one in case of asynchronous dump (TCT.R5B2). When discussing the possibility to directly use ATS optics in order to restart the LHC after LS1, this feature was showed to be a clear weakness of ATS optics for the LHC [6], which rapidly discarded this option, but also raised some question marks related to the β^* reach of the HL-LHC. In practice, it also prevented to gain real experience and confidence with ATS optics at high intensity. Very recently, a new generation of ATS optics was then deployed in order to bring a definite cure to the above mentioned problem, offering phase advances very close to optimal (within 20 - 30 degrees) between the MKDs and TCTs, for both beams and both IR1 and IR5 [7]. The next section will discuss the status of the new ATS optics generation, while the main results obtained during the 2016 ATS machine development sessions will be highlighted in the third section.

ATS OPTICS NEW GENERATION: A SUMMARIZED OVERVIEW

In order to match an horizontal phase advance close to optimal between the extraction kicker MKD in IR6 and the TCTs of both beams in both IR1 and IR5, i.e. close to 0 or 180 degrees, the non-connectivity of the IR6 tunability diagram [8] was used (see Fig. 1). More precisely, the dump insertion was rematched at more or less constant vertical phase but with a phase shifted by $\pi/2$ in the horizontal plane. Due to the missing Q6 and Q7 in IR6, this phase shift is actually confined in a new waist of the beta-functions located on the right side of the MKD for beam1, and on the left side for beam2 (see Fig. 2). This localization is optimal to pass from a worst to good configuration in terms of phase advance between the LHC extraction kickers and the TCTs of both beams in IR5. For IR1 the MKD-TCT phase optimization can be achieved at constant tune using other sources of optics flexibility, as for instance the main quadrupoles of sectors 23/34/67/78. This change being done, the phase advances of other insertions were also

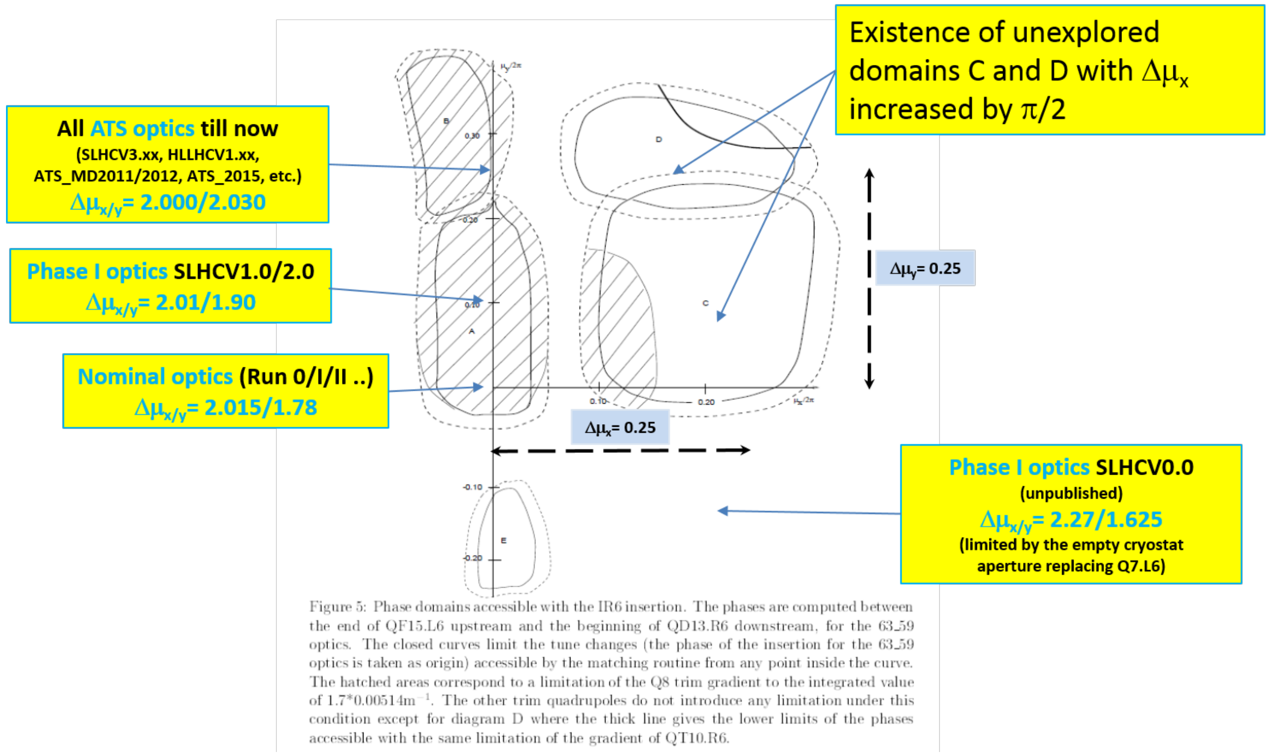


Figure 1: IR6 tune-ability diagram (from old LHC layout version [8]). The jump from one disconnected domain to the other requires to remove some optics constraints during the jump. The different tunability domains explored so far are emphasized for the nominal optics, the various versions of the Phase I optics [9], and the previous generation of ATS (LHC and HL-LHC) optics.

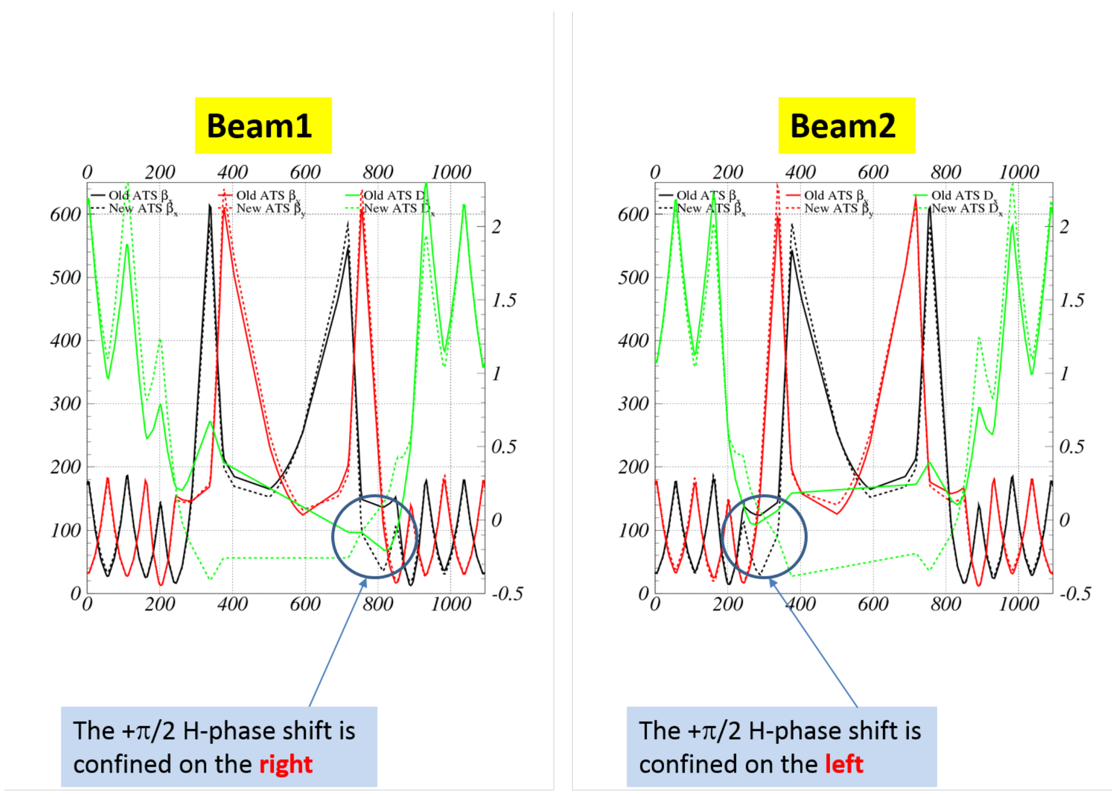


Figure 2: Modification of the dump insertion optics when shifting by $\pi/2$ its overall horizontal phase. This shift is confined on the right and left sides for beam1 and beam2, respectively, which is fundamental to correctly settle the MKD-TCT horizontal phase advance for both beams from IR6 to IR5, without compromising on any ATS optics functionalities.

modified in order to improve their functionality (e.g. IR4 for increasing the beta functions at the BSRT, similarly to the changes of nominal optics deployed between 2014 and 2015, or IR2 in order to improve its squeeze-ability for ion operation), but without compromising on the compatibility with the telescopic squeeze. The overall tunes were then rematched to 62.31/60.32 (62.28/60.31 at injection), while keeping the horizontal and vertical phase advances between IP1 and IP5 strictly equal to those of the nominal optics, let us say for a sake of precaution with respect to beam-beam effects. It is however worth noting that this phase is totally free of constraints in the vertical plane only. It was scanned during the last ATS MD at $\beta^* = 33$ cm in the presence of head-on beam-beam effects (no long-range), showing some potential gain in beam life-time by up to a factor of 2 to 3 (which justifies further investigation in the LHC to fully optimize it with beam). This new LHC phasing configuration being defined, a brand new set of optics and the corresponding LHC hypercycle were built up, and extended with the telescopic part of the ATS squeeze down to a β^* of 10 cm at IP1 and IP5.

For the injection, the ramp and the pre-squeeze, the basics of the nominal LHC hypercycle were closely followed, but also improved whenever it was found to be possible or needed (see [10, 11] for more details), with in particular

- a combined ramp and squeeze (see Tab. 1), ending up with a β^* of 3 m at IP1, IP5 and IP8, and 10 m at IP2 (compared to 3m/10m/3m/6m at IP1/2/5/8 for the nominal cycle), and which also warrants the 7 TeV equivalent gradient of all triplet quadrupoles to be less than 205 T/m, in particular in IR2 and IR8,
- a squeeze duration of only 470 s from $\beta^* = 3$ m down to 40 cm at IP1 and IP5 (more than a factor of 2 shorter than the 1070 seconds taken by the nominal squeeze used for operation in 2016), only 8 intermediate matched optics from 3 m to 40 cm (see Tab. 2), and linear optics distortions not exceeding the 1% level between two consecutive matched points.

The beam process containing the telescopic part of the squeeze is then described in Tab. 3, with as well 8 intermediate matched optics from 40 cm to 10 cm, and taking a little bit more than 800 seconds (see [12] for more details). For each optics, new correction knobs, standard and ATS specific ones (for tune, chromaticity and coupling, but also for correcting the spurious dispersion induced by the crossing angles) were made available, together with the spool-piece and tune shift quadrupole settings, and the IP knobs (crossing bumps) for the four experimental insertions. Empirical settings and additional knobs were also directly imported from the nominal LHC cycle and successfully re-used, namely

- the closed orbit corrector settings of the flat machine at injection, which allowed to thread the beam immediately following the first injection during the first ATS MD of the year,
- the tune and chromaticity empirical correction for the entire ramp (on top of FiDeL), which certainly contributed to the immediate success of the first ATS ramp,
- the local coupling and optics correction knobs (i.e. the MQSX pre-settings and MQX trims for controlling the triplet induced coupling and β-beating during the squeeze) [13, 14, 15, 16, 17], which granted a smooth pre-squeeze ending up with not more than 15-20% β-beating at $\beta^* = 40$ cm before further global correction (see later).

In order to further accelerate the overall squeeze process, a certain fraction of the pre-squeeze from 3 m to 40 cm could still be accommodated in the ramp. More precisely, a β^* of about 1 m at IP1 and IP5 (and 10 m/3 m at IP2/8) seems to be a reasonable target for the end of the ramp, offering a sufficiently large normalised crossing angle in order to neglect the long-range beam-beam effects at flat top, while reducing the pre-squeeze segment by about 200 s (see Tab. 2). Furthermore, below a pre-squeezed β^* of 2 m, it is worth reminding that pre-squeeze (IPQ functions in IR1/5) and telescopic squeeze (IPQ functions in IR8/2/4/6) are modular enough to be combined (exchanged or interleaved). All together it is therefore not at all excluded to envisage a scenario where the 470 seconds of the present pre-squeeze would be re-distributed over the ramp and the telescopic squeeze for the HL-LHC, and something similar for the LHC.

On the other hand the 40 cm ATS pre-squeezed optics needs to be re-optimized with respect to the version tested in 2016 in order to improve the beam conditions, more precisely the normalised dispersion, at the roman pots of the forward physics experiments (AFP and CT-PPS). A snapshot of this new optics is ready, together with new possible position of the roman pots [18], and offering beam conditions very close to the ones achieved in 2016 for these two experiments. The new optics transition (from 2 m to 40 cm) remains however to be worked out. In this exercise the pre-squeeze duration is expected to re-increase by about 200 s due to the net reduction of the Q6 gradient at $\beta^* = 40$ cm, being noted that the telescopic part of the squeeze will not be impacted by the re-manipulation of the pre-squeeze sequence.

Finally, amongst the other optics work to be completed in order to reach to same level of readiness as for the nominal optics, it is worth mentioning (i) the squeeze sequence of IR2 from 10 m to 50 cm for ion operation (being said that an optics snapshot with $\beta^* = 50$ cm at IP2 is demonstrated for the new IR2 phase advance), (ii) the de-squeeze sequence of IR1/2/5/8 towards β^* values of 20-30 m for so-called "Van der Meer optics" (which is expected to be a non-issue), and towards $\beta^* = 90$ m for TOTEM-like experiments (being said that a new snapshot of the 90 m optics is available, rematched to the new arc optics and with the new IR1/5 phase advances).

Matched Point	Time [s]	Parab. fraction	Optics Name	Energy [GeV]
1	0	0.05	R2016ats_A11mC11mA10mL10m	450
2	30	0.05	R2016ats_A11mC11mA10mL10m	459
3	60	0.05	R2016ats_A11mC11mA10mL10m	485
4	120	0.05	R2016ats_A11mC11mA10mL10m	594
5	200	0.05	R2016ats_A11mC11mA10mL10m	845
6	300	0.05	R2016ats_A11mC11mA10mL10m	1323
7	400	0.05	R2016ats_A11mC11mA10mL10m	1879
8	490	0.05	R2016ats_A11mC11mA10mL10m	2412
9	565	0.12	R2016ats_A970C970A10mL970	2852
10	620	0.10	R2016ats_A920C920A10mL920	3176
11	670	0.10	R2016ats_A850C850A10mL850	3454
12	720	0.10	R2016ats_A760C760A10mL760	3755
13	780	0.10	R2016ats_A650C650A10mL650	4102
14	860	0.12	R2016ats_A550C550A10mL550	4565
15	935	0.12	R2016ats_A460C460A10mL460	4985
16	985	0.15	R2016ats_A380C380A10mL380	5284
17	1040	0.25	R2016ats_A320C320A10mL320	5608
18	1110	0.24	R2016ats_A300C300A10mL300	6002
19	1210	0.05	R2016ats_A300C300A10mL300	6500

Table 1: Beam process `RAMP-SQUEEZE-6.5TeV-ATS-3m-2016_V1` for the ATS combined ramp and squeeze. The first matched points at constant optics are used for orbit correction in the early part of the ramp. The squeeze proper starts at step number 8 (~ 2.4 TeV) and is finished at step number 18 (~ 6 TeV). β^* is reduced from 11 m (resp. 10 m) down to 3 m at IP1 and IP5 (resp. IP8). It is kept constant and equal to 10 m at IP2, but the overall IR2 optics is still modified with in mind its compatibility with 7 TeV operation (205 T/m for the maximum allowed 7 TeV equivalent gradient of the triplet quadrupoles).

Matched Point	Time [s]	Parab. fraction	Optics Name	β^* [m] at IP1 and IP5
1	0	0	R2016ats_A300C300A10mL300	3.00
2	44	0.23	R2016ats_A220C220A10mL300	2.20
3	94	0.20	R2016ats_A160C160A10mL300	1.60
4	148	0.28	R2016ats_A120C120A10mL300	1.20
5	206	0.26	R2016ats_A90C90A10mL300	0.90
6	269	0.24	R2016ats_A70C70A10mL300	0.70
7	341	0.21	R2016ats_A55C55A10mL300	0.55
8	413	0.18	R2016ats_A45C45A10mL300	0.45
9	470	0.18	R2016ats_A40C40A10mL300	0.40

Table 2: Structure and timing of the ATS pre-squeeze (`SQUEEZE-6.5TeV-ATS-3m-40cm-2016_V1`) from $\beta^* = 3$ m down to $\beta^* = 40$ cm.

Matched Point	Time [s]	Parab. fraction	Optics Name	β^* [m] at IP1 and IP5
1	0	0	R2016ats_A40C300A10mL300	0.40
2	90	0.42	R2016ats_A37C220A10mL300	0.37
3	178	0.42	R2016ats_A33C160A10mL300	0.33
4	258	0.35	R2016ats_A27C120A10mL300	0.27
5	346	0.31	R2016ats_A21C90A10mL300	0.21
6	452	0.34	R2016ats_A17C70A10mL300	0.17
7	569	0.32	R2016ats_A14C55A10mL300	0.14
8	676	0.32	R2016ats_A12C45A10mL300	0.12
9	804	0.28	R2016ats_A10C40A10mL300	0.10

Table 3: Structure and timing of the telescopic squeeze (`SQUEEZE-TELE-6.5TeV-ATS-40cm-10cm-2016_V1`) from $\beta^* =$ 40 cm down to $\beta^* = 10$ cm. For practical reasons when running the MDs proper, this beam process was actually split into two separate pieces, above and below $\beta^* = 33$ cm, but without changing the functions and timing of each segment.

HIGHLIGHTS FROM THE 2016 ATS MACHINE DEVELOPMENTS

Out of the 5 MD blocks programmed in the 2016 LHC schedule, ATS activities were organized in block 1 (with two shifts of 10h and 8h on 27/7/2016 and 30/7/2016, respectively), and in block 3, 4 and 5, with one 10 h shift for each of these three blocks (11/09/2016, 3/10/2016 and 29/10/2016, respectively). Two types of ATS MDs took place, namely:

- MDs for optics measurements and correction, in block 1 (down to $\beta^* = 40$ cm) and block 4 (down to $\beta^* = 10$ cm), achieved with probe beams, with the crossing bumps generally switched off and relaxed collimator settings in order to maximize the available aperture, and with all maskable interlocks actually masked,
- MDs with a major component related to collimation, in block 3 (at $\beta^* = 40$ cm) and block 5 (at $\beta^* = 33$ cm), run with (quasi-)nominal collimator settings in IR3/6/7, and with a filling scheme containing two nominal bunches (to establish collisions at the four IPs) and/or sparse non-colliding pilot bunches (for loss maps and/or aperture measurement).

ATS MD in block 1: 40 cm pre-squeezed optics with probe beam

The primary goal of the first ATS MD was to commission, i.e. to establish, measure and correct, the new ATS injection optics, its ramp up to 6.5 TeV, and the pre-squeeze down to $\beta^* = 40$ cm at IP1 and IP5 (3 m at IP8), using low intensity (pilot) beams and a flat machine (crossing bumps switched off). As for any optics commissioning, the following activities were planned:

- beam threading, orbit, tune, chromaticity and coupling corrections at injection,
- then the demonstration of the ramp with optics measurement taken on the fly,
- followed by the (pre-)squeeze with optics measurements and correction at some intermediate β^* and at $\beta^* = 40$ cm, including as well the first analysis of the chromatic properties of the pre-squeezed optics (non-linear chromaticity, off momentum beta-beating at $\beta^* = 40$ cm),
- and ending up with the test of the various knobs available, in particular the IP and spurious dispersion correction knobs.

To this aim two shifts of 10 h and 8 h were allocated to ATS activities in the MD block 1. They were carefully programmed at the beginning (27/7/2016) and in the end (30/7/2016) of the MD period, in order to give enough time to properly calculate and fine tune off-line the optics correction knobs to be applied. In summary, 2+2 fills were actually needed in the first and second ATS shifts (fills 5123 - 5124, and fills 5138 - 5139, respectively). All the above objectives, and even beyond, were successfully met, in particular with

- an optics correction to the 5-10% level in terms of β-beating at injection, flat top, and at $\beta^* = 40$ cm (see Fig. 3),
- dedicated chromatic measurements achieved at $\beta^* = 40$ cm, showing an as-expected off-momentum β-beating pattern and a vanishing non-linear chromaticity, which is one key feature of the ATS scheme,
- a complete fill dedicated to the demonstration of the IP knobs using (nearly or exactly) nominal settings for the crossing bumps from injection to $\beta^* = 40$ cm. The idea was also to use this first MD to measure (with BPMs) and pre-set accordingly the new TCT centers for the forthcoming ATS MD which was already planned in block 3 with more beam intensity.

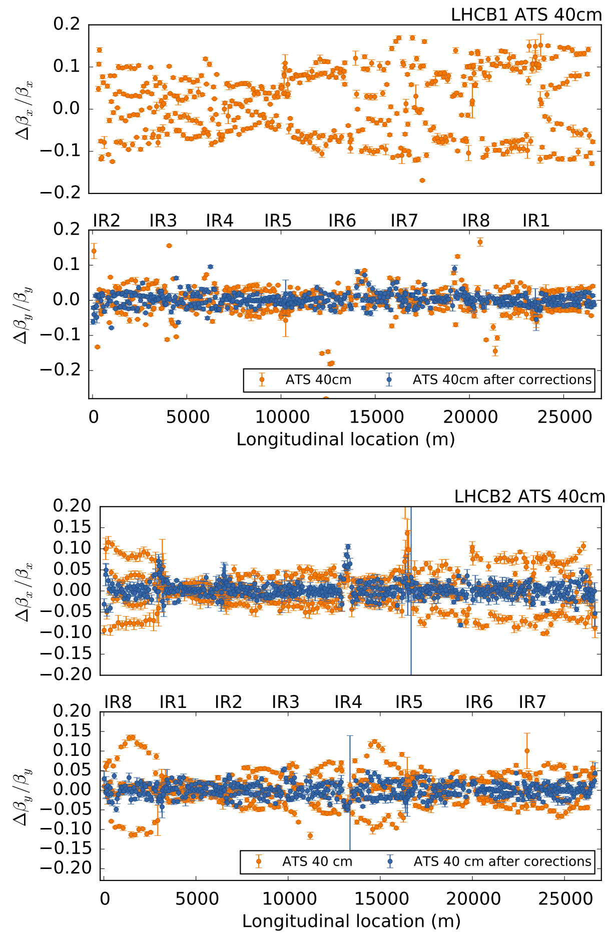
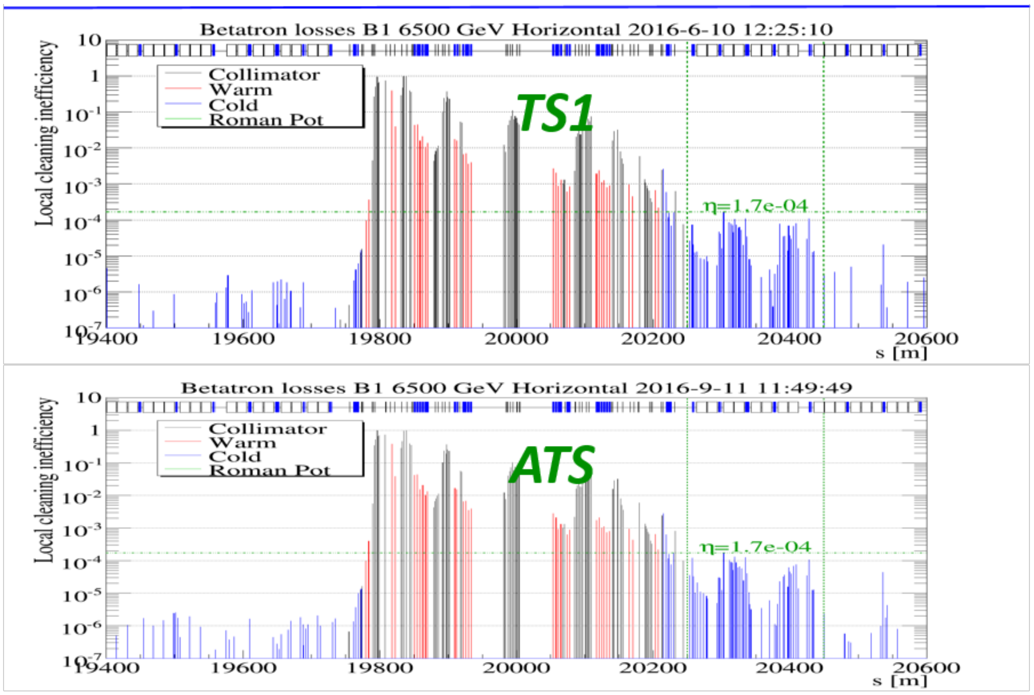


Figure 3: Beta-beating measured at $\beta^* = 40$ cm for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset based on the 40 cm nominal optics. The AC-dipole was not available for B1H to re-measure after correction. Courtesy of A. Garcia-Tabares and OMC team.



Case	Ref time	Ineff.	
		ATS	TS1
B1H	11:49:49	1.7e-4	1.7e-4
B1V	11:51:28	8.9e-5	1.2e-4
B2H	11:53:12	2.6e-4	2.6e-4
B2V	12:00:42	2.2e-4	2.1e-4

Figure 4: Example of loss map measured for B1H at $\beta^* = 40$ cm and zoomed in IR7, and collimation inefficiency recorded for both beams and both planes: comparison between the ATS pre-squeezed optics and the nominal collision optics after TS1. The IR3/7 collimator absolute settings (center and gaps in millimeter) were set to the same values in both cases. Courtesy of D. Mirarchi and collimation team.

ATS MD in block 3: 40 cm pre-squeezed optics with nominal bunches

In view of the success of the previous MD, the 40 cm pre-squeezed optics was considered to be mature enough to be tested with (a few) nominal bunches. This formed the program of the second ATS MD were the goal was to demonstrate the ATS cycle, from injection to collision at $\beta^* = 40$ cm, with two nominal bunches, and nominal or quasi-nominal collimation and machine protection settings, namely: (i) to establish a new reference orbit, and find and optimize the collisions at all four IPs, (ii) to realign the TCT centers and perform betatron loss maps at injection with nominal collimator and machine protection settings, (iii) to conduct a beam-based (re-)alignment campaign of the collimators in IR3 and IR7 at flat top, and idem for the TCTs at flat top and at $\beta^* = 40$ cm with the beam separated and in collision, and (iv) to study the losses at the TCT's after a (programmed) asynchronous dump in order to validate the new MKD-TCT phase advances. A few fills were needed to achieve this set of objectives (from 5296 to 5300).

The first fill was used to re-establish a good reference orbit with the crossing bumps switched on, at injection, flat top and $\beta^* = 40$ cm (the half-crossing angle was set to $\pm 140\,\mu$rad at IP1 and IP5). The collimator and machine protection settings (center and gap) were pre-set to their nominal value in mm in IR3/6/7 (profiting from the very small changes of ATS optics w.r.t. the nominal optics in these 3 insertions), while the TCT/TCSP centers were pre-set based on the beam measurements performed in block 1. After collapsing the separation bumps (but no collision proper due to a mistake in the selected filling scheme), the new TCT/TCSP centers were determined and loss maps were performed. This first fill did not show any anomalies in the collimator hierarchy and inefficiency, even without need of re-aligning the IR7 collimators [19] (see e.g. the case of B1H in Fig. 4). This fill was ended up by studying the TCT losses after an asynchronous dump (and the TCTs at $9\,\sigma$ in IR1 and IR5). This measurement was rather conclusive for beam1 but not for beam2 for which bucket 1 was unfortunately left empty.
In the second and third fills, loss maps were achieved at in-

jection, with injection protection devices in and out, which again did not show any peculiar behaviour in terms of collimation hierarchy and inefficiency [19].
The last fill was ramped up and pre-squeezed to 40 cm, collisions were then rapidly established and optimized at all 4 IPs (with a typical lumi of 5E30 in ATLAS and CMS). The TCT/TCSP and IR7 collimator were then re-aligned in collision with marginal changes found w.r.t. the nominal optics for the IR7 collimator [20] (see e.g. Fig. 5 for the case of beam1). A second asynchronous beam dump test took place with the TCTs set a $8\,\sigma$ in IR1 and IR5. This second test confirmed the good behaviour of beam1, with beam2 in the right ballpark compared to expectations [21].

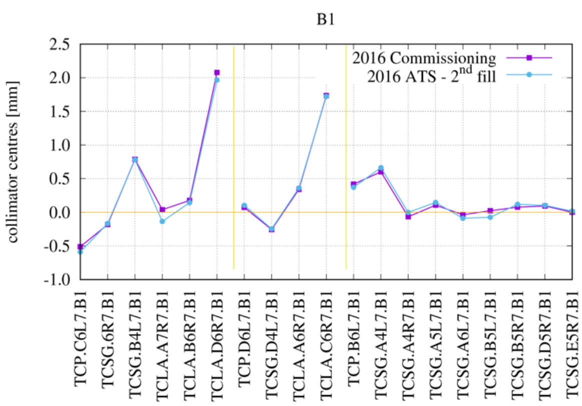


Figure 5: IR7 collimator centers for beam1, as measured at flat top with the nominal optics after TS1, and with the ATS optics at $\beta^* = 40$ cm. Courtesy of A. Mereghetti and collimation team.

ATS MD in block 4: 10 cm telescopic optics with probe beams

Considering the several validation steps already taken with the 40 cm pre-squeezed optics, the third ATS MD was dedicated to the (re-)validation of the telescopic techniques of the scheme. The target was fixed to the HL=LHC ultimate β^* of 10 cm at IP1/5, and passing through a moderately telescopic optics with $\beta^* = 33$ cm, which is an interesting candidate for running the LHC in 2017. One single fill (fill 5356) was sufficient to achieve this goal. Probe beams were injected, ramped and pre-squeezed (in one step of 470 s) down to 40 cm, where the crossing bumps were switched off, and the collimator and machine protection settings relaxed in order to liberate enough aperture to reach a β^* of 10 cm. The mechanics of the telescopic squeeze was successfully demonstrated down to $\beta^* = 10$ cm. First optics measurements took place at $\beta^* = 33$ cm, showing not more than 20% peak β-beating, which was deemed small enough in order to continue the telescopic squeeze without applying any correction yet. The first global optics corrections (since 40 cm) were calculated and successfully implemented at $\beta^* = 21$ cm, bringing the $\beta-$beating level back to the range of 5-10% (see Fig. 6). The Montague functions also showed as-expected behaviour, with off-momentum $\beta-$beating waves induced by a dedicated powering of the lattice sextupole families in the sector 81/12/45/56 adjacent to the high luminosity insertions, and arriving exactly in phase in order to compensate for the chromatic betatron kicks induced by the inner triplets (see Fig. 7). Finally, optics measurements also took place at $\beta^* = 14$ cm and 10 cm. The results obtained became however more and more noisy when reducing β^*, due to the aperture limitations therefore constraining the maximum possible AC dipole excitation and hence the measurement accuracy. Nevertheless, from these measurements, a β-beating not exceeding 20-25% can still be inferred at $\beta^* = 10$ cm without any additional correction below 21 cm (noting that the global corrections at β^*=21 cm were left in the machine down to β^*=10 cm). Dispersion measurements taken at 10 cm also indirectly confirmed the good behaviour of the optics at such low β^* (see Fig. 8).

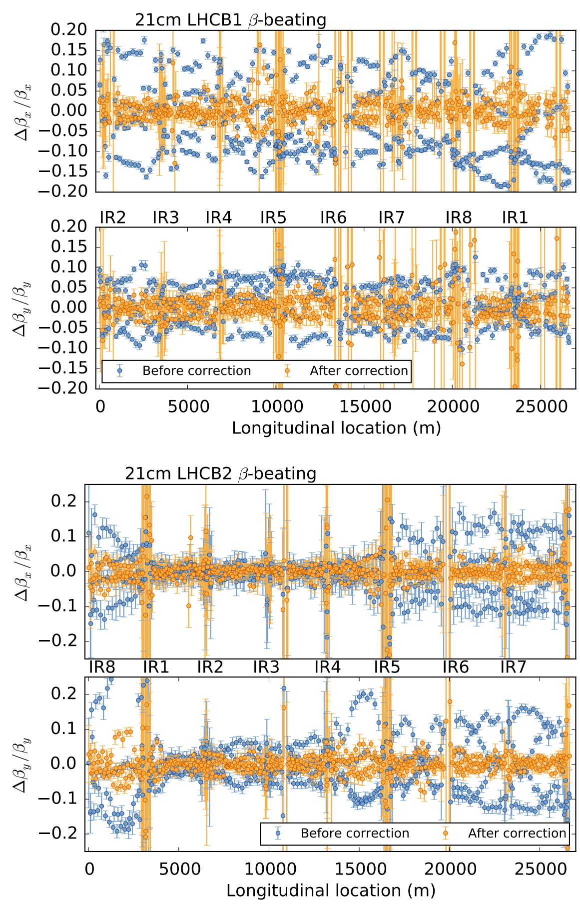


Figure 6: Beta-beating measured at $\beta^* = 21$ cm for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset based on the 40 cm nominal optics. Courtesy of J. Coello De Portugal and OMC team.

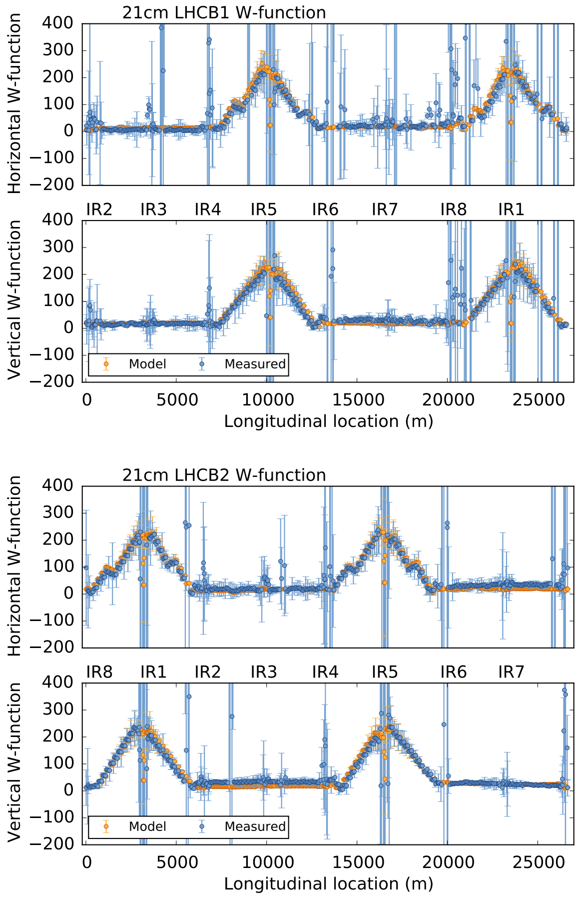


Figure 7: Montague functions measured at $\beta^* = 21$ cm for beam1 (top) and beam2 (bottom). The normalization is such that a W-function amounting to 100 corresponds to an off-momentum β-beating amplitude of 20% for $\delta_p = 10^{-3}$. Courtesy of J. Coello De Portugal and OMC team.

ATS MD in block 5: 33 cm telescopic optics with nominal bunches

The last ATS MD focused on a (moderately) telescopic collision optics with $\beta^* = 33$ cm and a half-crossing angle of $\pm 140\,\mu$rad at IP1 and IP5 (corresponding to a normalised crossing angle of $9.0\,\sigma$ assuming a normalised emittance of $\gamma\epsilon = 2.2\,\mu$m at 13 TeV c.m. energy). This optics is indeed a very interesting candidate for running the LHC in 2017. More specifically, the aim was (i) to measure the triplet aperture in the end of the squeeze, (ii) to establish and optimize the collisions at all four IP's, and (iii) to assess the collimation system via a series of loss maps (on- and off-momentum, with the beams separated or in collision at $\beta^* = 33$ cm). Since a β-beating correction knob was not established and properly tested at $\beta^* = 33$ cm in the previous MD, the one calculated and validated at 21 cm was used instead, bringing on paper the β-beating back to about 10% at 33 cm. Two consecutive fills (5476 and 5477) were needed to meet the objectives of this last MD.
The first one was dedicated to triplet aperture measurement, filling each ring with 8 pilot bunches. First all collimators were opened at 33 cm, then a pilot bunch was excited in a given beam and a given plane. The triplet quadrupole corresponding to the aperture bottleneck was then easily found by looking at the BLM response (spikes) during the excitation, and the aperture finally determined via a beam-based alignment of the TCT in front of the triplet under consideration. A normalised aperture larger than or equal to $9.7\,\sigma$ was measured for both beams and both planes, more precisely $9.7\,\sigma$ for B1H (reached at Q3.L1/Q3.R5), $9.7\,\sigma$ for B1V (reached at Q3.L1), $12.6\,\sigma$ for B2H (reached at Q2.R5) and finally $9.8\,\sigma$ for B2V (reached at Q3.R1). The plan was to finish this fill with an asynchronous dump. The beam was however dumped prematurely because real time tune trims were sent to zero by mistake, resulting in power converter trips for some RQTD circuits. In the second fill, collisions were successfully established and optimized in all 4 IPs (with a lumi of about 8E30 recorded by CMS). Before and after putting the beams into collisions at $\beta^* = 33$ cm, the TCT centers were realigned based on BPM data, and loss maps were conducted, both on and off-momentum in collision, namely applying an RF frequency trim of $\Delta f = \pm 30$ Hz corresponding to a momentum shift of about $\delta_p \sim \pm 2.5 \times 10^{-4}$. These measurements again did not show any unexpected features (see [22] for more details, and Tab. 4). Figure 9 shows a condensed summary of the collimation inefficiency measurement results which took place over the full 2016 LHC run both for the nominal and ATS optics, which is another illustration of the robust behaviour of the collimation system for ATS optics.

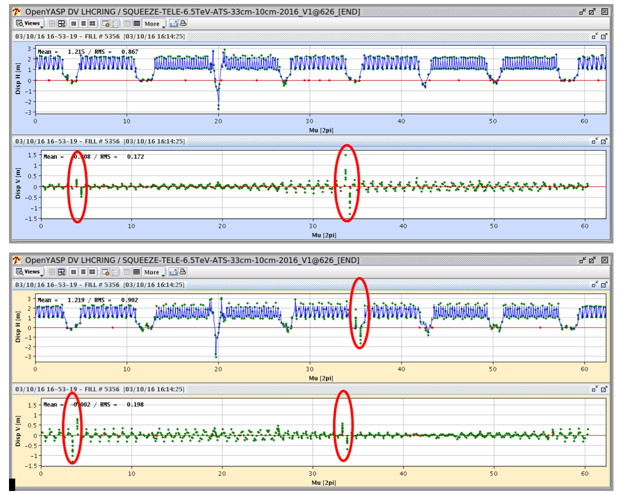


Figure 8: Horizontal and vertical dispersion [m] measured at $\beta^* = 10$ cm for beam1 (top) and beam2 (bottom). The crossing bumps were off in all experimental insertions. In the worst case a spurious dispersion of 1.5-2m can be observed in the inner triplets of either IR1 or IR5, which corresponds to a normalised dispersion beating of at most 8.5% at $\beta^* = 10$ cm ($\beta_{\max} = 24$ km), comparing with the peak dispersion of 2 m in the arcs at $\hat{\beta}_{\rm arc} \sim 180$ m.

Table 4: Collimation inefficiency [10^{-4}] for telescopic ATS optics, as measured in various conditions at $\beta^* = 33$ cm and with $\pm 140\,\mu$rad for the half-crossing angle in IR1/5.

Case	Beams separated on-momentum	Beams colliding on-momentum	Beams colliding off-momentum (-30 Hz)	Beams colliding off-momentum (30 Hz)
B1H	2.3	2.2	2.3	1.4
B1V	1.2	1.1	0.9	n/a
B2H	2.5	2.6	2.6	2.5
B2V	2.0	1.6	2.1	n/a

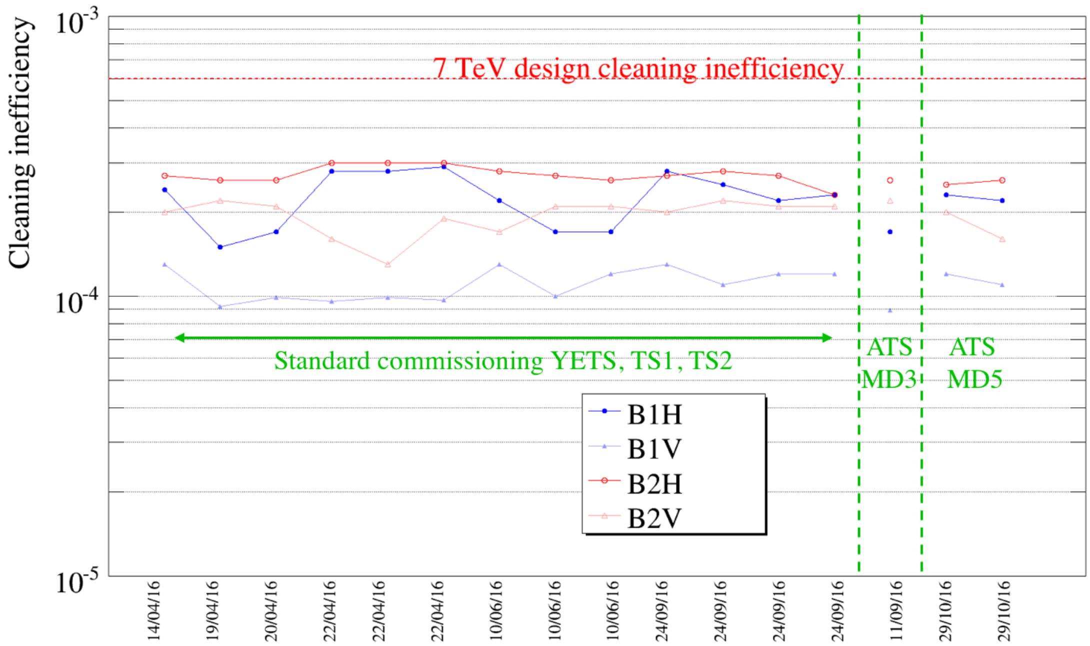


Figure 9: Measurements of collimation inefficiency summarized over the 2016 LHC run for various optics and machine conditions. Courtesy of D. Mirarchi and collimation team.

SUMMARY AND OUTLOOK

The 2016 year was certainly very prolific for the validation steps of the ATS scheme, where the latest ATS optics solution was used with close to optimal phase advances between the extraction kickers in the dump insertion IR6 and the tertiary collimators in the high luminosity insertions IR1 and IR5. The fundamental principles of the scheme were re-demonstrated with probe beams, in particular the telescopic squeeze down to $\beta^* = 10$ cm at constant sextupole strength beyond the 40 cm pre-squeezed optics. But also, state-of-the-art optics and coupling measurement and correction techniques, which were developed for the LHC nominal optics [13, 14, 15, 16, 17], such as β^*/α^* measurement with K-modulation, segment by segment local corrections and weighted global corrections, were successfully applied for the first time to telescopic optics, demonstrating their universality but also robustness at unprecedentedly small β^* (21 cm). Last but not least, ATS pre-squeezed optics or moderately telescopic optics were tested for the first time with a few nominal bunches, to establish and optimize collisions in all experimental insertions, but also to re-assess the LHC collimation system with ATS optics. All together the main LHC milestone has been undoubtedly met, which was to demonstrate the readiness of the pres-squeezed 40 cm ATS optics for operating the LHC in 2017, and actually going even beyond with an optics of even lower β^* (33 cm) in the pipeline. In the same effort, the full validation of the ATS scheme for the HL-LHC is now very well-engaged.

Regardless of the decision to directly switch to the ATS optics in 2017, the continuation of the ATS MD program in 2017/2018 will cover the production and commissioning of flat optics (e.g. 60/15 cm), very likely with synergies which will be established with the long-range beam-beam compensation program using electromagnetic wires (putting the so-called HL-LHC Plan B in perspective [23, 24]). In the same (HL-)LHC framework, the ATS program will also further develop and benchmark with beam its intrinsic long-range beam-beam compensation techniques, relying on telescopic collision optics (which could be compatible with the LHC aperture when increasing the pre-squeezed β^*) and switching back to negative the polarity of the Landau octupoles. This operational mode also corresponds to the baseline running scenario of the Landau octupoles in the HL-LHC [25], which is still to be demonstrated. Last but not least, some priority will be given in order to motivate, develop and validate with beam, de-squeezed optics of intermediate or very high β^*, using the telescopic techniques of the ATS scheme.

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