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ATS MDs in 2016

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Summary

This report presents a summary of the Achromatic Telescopic Squeezing (ATS) scheme related activities which took place in 2016, where a new generation of ATS pre-squeezed and telescopic optics was successfully probed, namely: (i) down to a β^* of 10 cm with pilot bunches, and (ii) with more emphasis at intermediate β^* values of 40 cm or 33 cm where collisions were established with nominal bunches, the triplet aperture was measured and collimation measurements with pre-squeezed or moderately telescopic ATS optics were conducted.

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1 Introduction and motivations

1.1 General context

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 plans 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 squeeze in both IR1 and IR5 to reach $\beta^* = 10$ cm starting from the above pre-squeezed optics at $\beta^* = 40$ cm.

On the other hand, a common feature can be systematically found 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 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].

1.2 Overall objectives and strategy for the ATS MDs in Run II

The primary objective of the MDs is undoubtedly to gain experience and confidence with ATS optics in view of the HL-LHC operation: in particular (re-)validate the basic principles of the scheme at 6.5 TeV, demonstrate state-of-the-art optics correction in various operation mode (injection, pre-squeeze, telescopic squeeze) and exclude unforeseen detrimental intensity effects. The ATS scheme also opens new possibilities of optics manipulation for the LHC itself, such as

- the proper production (i.e. achromatic and with a rapid squeeze) of flat optics for the LHC with quite small β^* (20-25 cm) in the plane perpendicular to the crossing plane (still compatible with the aperture of the existing triplet). Flat optics are possibly competitive in terms of performance w.r.t. to more standard (round) collision optics.
- the proper production of optics with very large $\beta^* >$ 1-2 km.
- the production of telescopic collision optics (round or flat), starting from a pre-squeezed optics with a downgraded β^* and continuing the squeeze in a telescopic manner. The aim is to generate ideal phasing configurations and beta functions at the Landau octupoles, making them more efficient for an appropriate compensation of the octupole part of the long-range

beam-beam interactions. The motivation in this case is a net reduction of the crossing angle (to mitigate the luminosity loss factor), maybe down to $7.5 - 8\sigma$ (to be confirmed), and then further reducing β^* to push even more the performance.

Combining the HL-LHC related perspectives of the ATS scheme, with the possible immediate (short term) utilization of ATS optics for the LHC, brought the emergence of the idea to fully validate in 2016 the pre-squeezed part of the ATS scheme, and make it operational as of next year to run the LHC. With this part of the scheme already used in routine operation, the next step will be to identify the most promising telescopic optics to further boost the LHC performance for Run III, and then use MD sessions in 2017-2018 in order to validate this optics choice, including some intensity ramp up.

2 Optics, beam and machine conditions

2.1 ATS MD overview in 2016 with corresponding beam and machine conditions

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

- MDs for optics measurements and correction, in block 1 (at $\beta^* = 40$ cm) and block 4 (at $\beta^* = 10$ cm), performed with probe beams, the crossing bumps generally switched off and relaxed collimator settings (see Tab. 1) in order to maximize the available aperture, and all maskable interlocks actually masked (namely, the RQ-currents, the TDI gaps upstream and downstream, all collimators, BPM, BLM, RF, and AC-dipole for the LHC SIS & BIS, and the TDI/MSI BETS for the SPS extraction BIS),

- MDs with a major component related to collimation, in block 3 (at $\beta^* = 40$ cm) and block 5 (at $\beta^* = 33$ cm), achieved with (quasi-)nominal collimator settings in IR3/6/7, and a filling scheme containing two nominal bunches (to establish collisions at the four IPs), and/or a certain number of sparse pilot bunches (for loss maps and/or aperture measurement).

Detailed procedures were written down and recorded in EDMS for these four MDs [11, 12, 13, 14], in order to precisely describe the beam and machine conditions, to streamline the objectives, and guess-estimate the timing of the various activities. In addition to the optics modifications which will be described in the next sub-section, slightly modified RF settings were used in order to take into account the small change of momentum compaction for ATS optics. Also, new ADT settings were established following the optics modifications in IR4, namely the net change of phase advances from the kickers to the BPMs with respect to the nominal optics, and which, in addition, are varying with β^* during the telescopic part of the squeeze. Associated to the new ATS optics and beam processes, new knobs were also deployed and used for tune, coupling and chromaticity correction or dedicated adjustments. The optics used were all matched to the collision tunes (.31/.32), but most of the time the tunes were trimmed to their injection values (.28/.31) in order to reduce the beam sensitivity to (not yet) corrected linear coupling. On the other hand, the

Equipment	Injection	Ramp	Just before squeeze	Squeeze (3 m→ 40 cm)
Transfer lines from SPS				
TCDI	No change	–	–	–
Injection protections and TCTs in IR2 and IR8				
TDI	± 10 mm	Parking	Parking	Parking
TCLI's, TCDD	± 15 mm	Parking	Parking	Parking
TCT's	± 15 mm	± 15 mm	± 15 mm	± 15 mm
Dump protection in IR6				
TCDQ	16 mm	16 mm	16 mm	16 mm
TCSP	$10\,\sigma$	$10\,\sigma \rightarrow 25\,\sigma$	$25\,\sigma \rightarrow 10\,\sigma$	$10\,\sigma$
Collimation in IR3				
TCPH	$12\,\sigma$	$12\,\sigma \rightarrow 30\,\sigma$	$30\,\sigma \rightarrow 20\,\sigma$	$20\,\sigma$
TCSG, TCLA	± 20 mm	± 20 mm	± 20 mm	± 20 mm
Collimation in IR7				
TCPH/V	$8\,\sigma$	$8\,\sigma \rightarrow 20\,\sigma$	$20\,\sigma \rightarrow 10\,\sigma$	$10\,\sigma$
TCPSkew	± 20 mm	± 20 mm	± 20 mm	± 20 mm
TCSG, TCLA	± 20 mm	± 20 mm	± 20 mm	± 20 mm
IR1 and IR5				
TCL's	± 20 mm	± 20 mm	± 20 mm	± 20 mm
TCTH	± 15 mm	± 15 mm	± 15 mm $\rightarrow \pm 12$ mm	± 12 mm (13σ at $\beta^* = 40$ cm)
TCTV	± 15 mm	± 15 mm	± 15 mm $\rightarrow \pm 10$ mm	± 10 mm (13.5σ at $\beta^* = 40$ cm)

Table 1: Relaxed collimator and machine protection settings for ATS MD at low intensities (`CollimatorBP-CoarseRamp-2016-ATS-MD`).

tune split was easily reduced to its nominal value of 0.01 or even below at many occasions, either to validate on-going coupling correction steps (see e.g. [15]), or just before putting the beams into collision, as in the second and fourth ATS MDs at $\beta^* = 40$ cm and $\beta^* = 33$ cm, respectively. The chromaticity was generally adjusted to $Q' \sim 10$, except during AC-dipole measurements where it was generally reduced to about 3 units. Landau octupoles were off for the MDs with probe beams only (1st and 3rd ATS MD), or simply set to their nominal values (2nd and 4th ATS MD). Empirical settings and additional knobs were directly imported from the nominal LHC cycle and successfully re-used, namely

- the COD 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 coupling 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 (MQSX pre-settings and MQX trims for controlling the triplet induced coupling and β-beating during the squeeze) [16, 17, 18, 19, 20], 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). Actually, the ATS MQX correc-

Magnet	Δk [10^{-5}m^{-2}]	
	Nominal cycle	ATS MDs
MQXA1.L1	1.23	1.23
MQXA1.R1	-1.23	-1.23
MQXB2.L1	0.65	0.65
MQXB2.R1	-1.00	-1.00
MQXA3.L1	1.22	1.22
MQXA3.R1	-1.22	-1.22
MQXA1.L5	2.00	2.00
MQXA1.R5	-2.00	-2.00
MQXB2.L5	0.27	0.26
MQXB2.R5	1.48	1.58
MQXA3.L5	1.49	1.49
MQXA3.R5	-1.49	-1.49
MQXB2.L2	-1.50	-1.50
MQXB2.R2	1.50	1.50
MQXB2.L8	-1.00	-1.00

Table 2: MQX correction strengths for the 2016 nominal squeeze cycle and the refined values for the ATS MDs.

tions are a slightly optimized version of the nominal corrections which were computed by a refined analysis of measurements from the 2016 commissioning (see Tab. 2).

2.2 ATS hypercycle

A new complete LHC hypercycle was made available in LSA in order to drive the machine till the end of the telescopic squeeze with $\beta^* = 10$ cm at IP1 and IP5. It was iteratively built up, following the needs of ATS MDs, the results obtained and the change of directions taken during the year. 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 [21, 22] for more optics details), in particular

- with a combined ramp and squeeze (see Tab. 3) which ends 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), but also which warrants the 7 TeV equivalent gradient of all triplet quadrupoles to be less than 205 T/m, in particular in IR2 and IR8, which is a new feature,

- with 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. 4), and linear optics distortions not exceeding the 1% level between two consecutive matched points.

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 3: 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 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 MQX quadrupoles).

The beam process driving the telescopic squeeze is described in Tab. 5, containing as well 8 intermediate matched optics from 40 cm to 10 cm, and taking a little bit more than 800 seconds (see also [23] for more details). In order to further accelerate the overall squeeze process, a certain fraction of the pre-squeeze from 3 m to 40 cm could be accommodated in the ramp. 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.
Concerning the crossing bumps, the IP knob values were chosen by default equal to the latest one used in nominal operation, in particular with a half-crossing angle set to $\pm 140\ \mu$rad at IP1 and IP5 for $\beta^* = 40$ cm, which was also used for the last ATS MD at $\beta^* = 33$ cm with nominal bunches.

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

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 5: Structure and timing of the telescopic squeeze from $\beta^* = 40$ cm down to $\beta^* = 10$ cm (`SQUEEZE-TELE-6.5TeV-ATS-40cm-10cm-2016_V1`). 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.

3 Main results

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

The primary goal of the first ATS MD [11] 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 and actually took place

- 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 measurement 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 β-beating at injection, flat top, and at $\beta^* = 40$ cm (see Figs. 1 and 2),
- 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 (see Fig. 3),
- and still enough time to dedicate a complete fill to the demonstration of the IP knobs using (nearly or exactly) nominal settings for the crossing bumps from injection to $\beta^* = 40$ cm, namely: the crossing and separation bumps in IR1, IR2, IR5 and IR8, but also the ATS specific knobs for the correction of the induced spurious dispersion [1]. The idea was also to use this first MD to measure (with BPM) and preset accordingly the TCT centers for the forthcoming ATS MD which was already planned in block 3 with more beam intensity.

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

In view of 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 [12]:

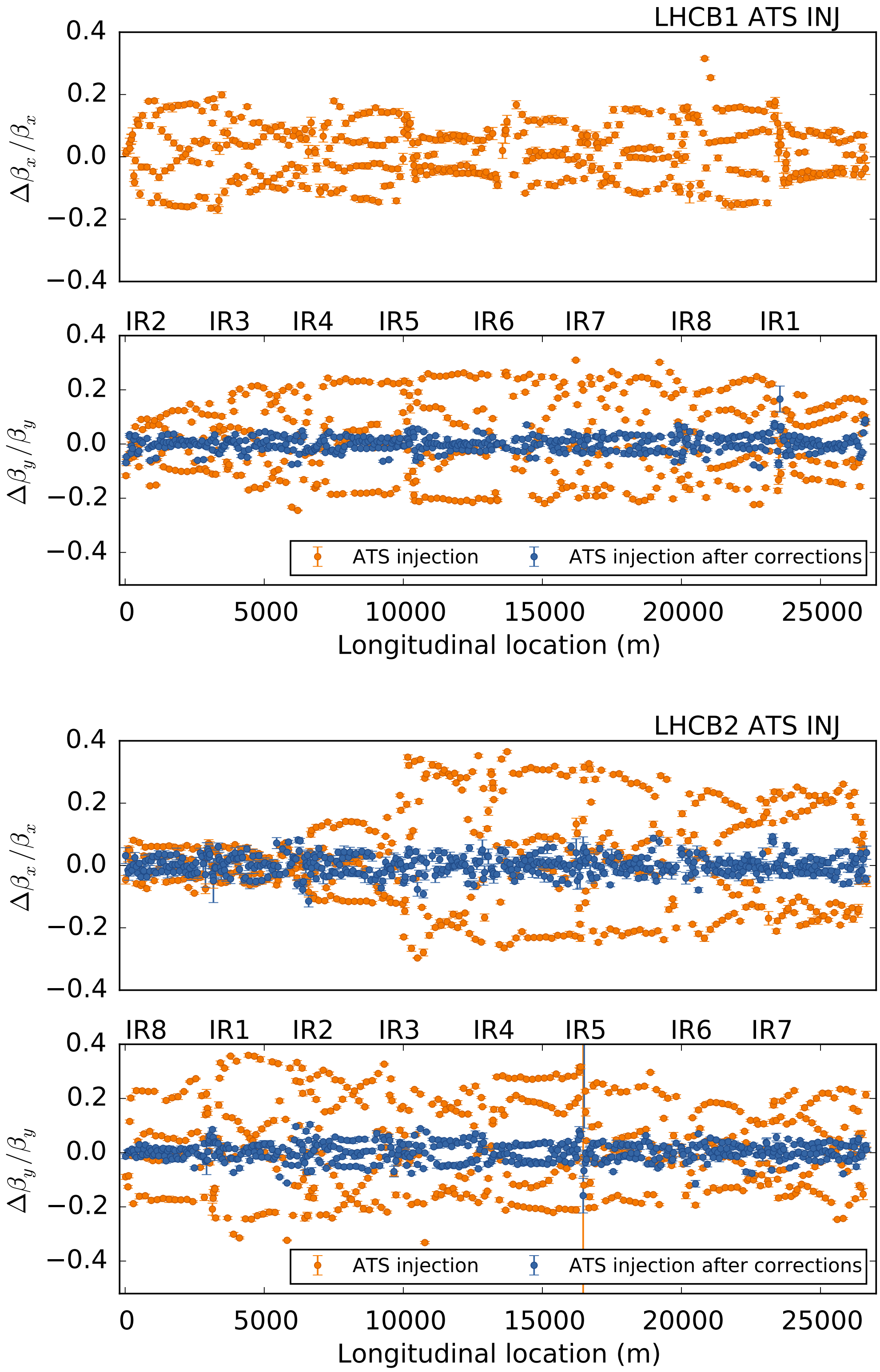


Figure 1: Beta-beating measured at injection for beam1 (top) and beam2 (bottom) before and after (global) correction. The AC-dipole was not available for B1H to re-measure after correction.

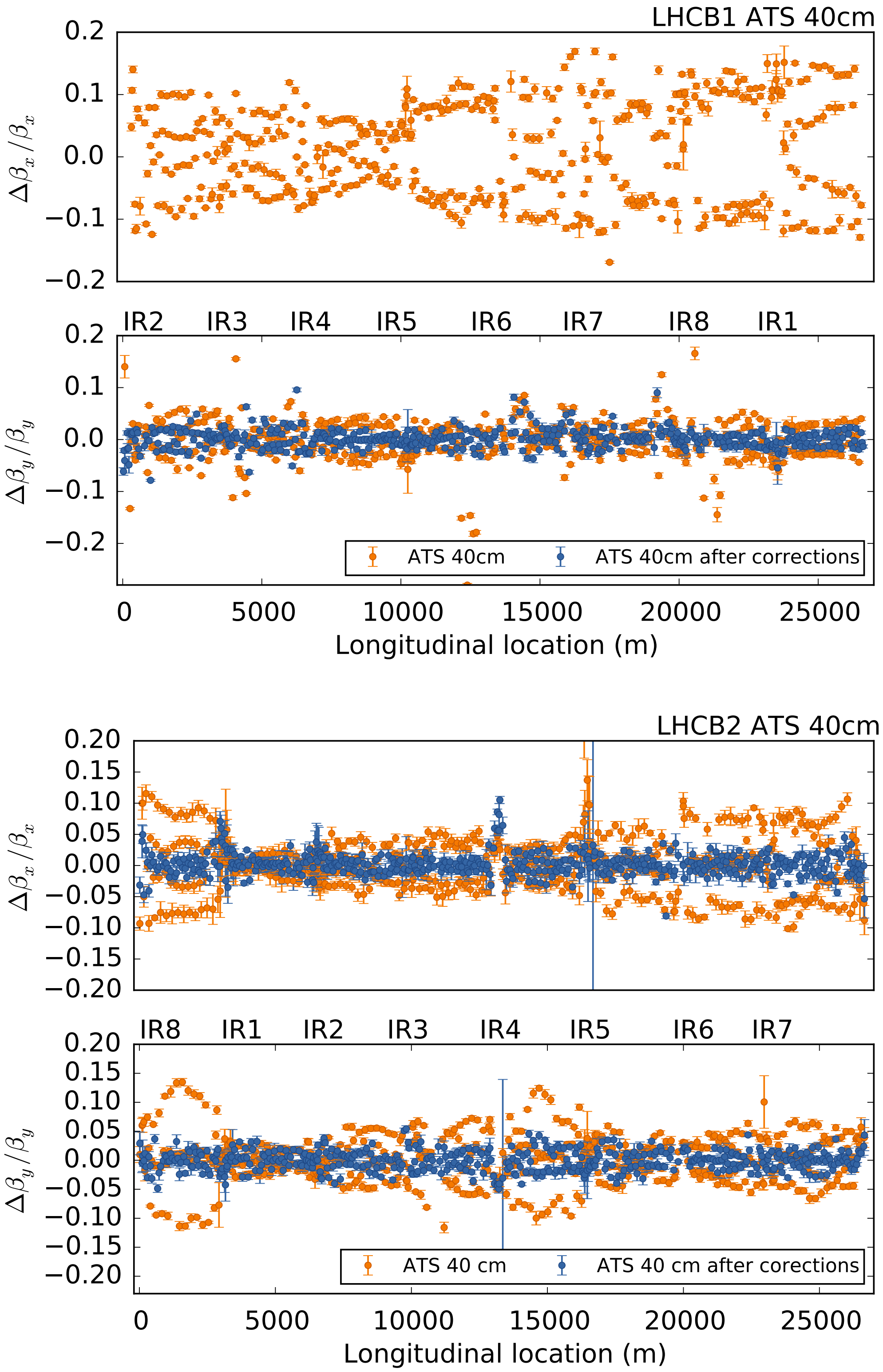


Figure 2: Beta-beating measured at $\beta^* = 40$ cm for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset from the 40 cm nominal optics. The AC-dipole was not available for B1H to re-measure after correction.

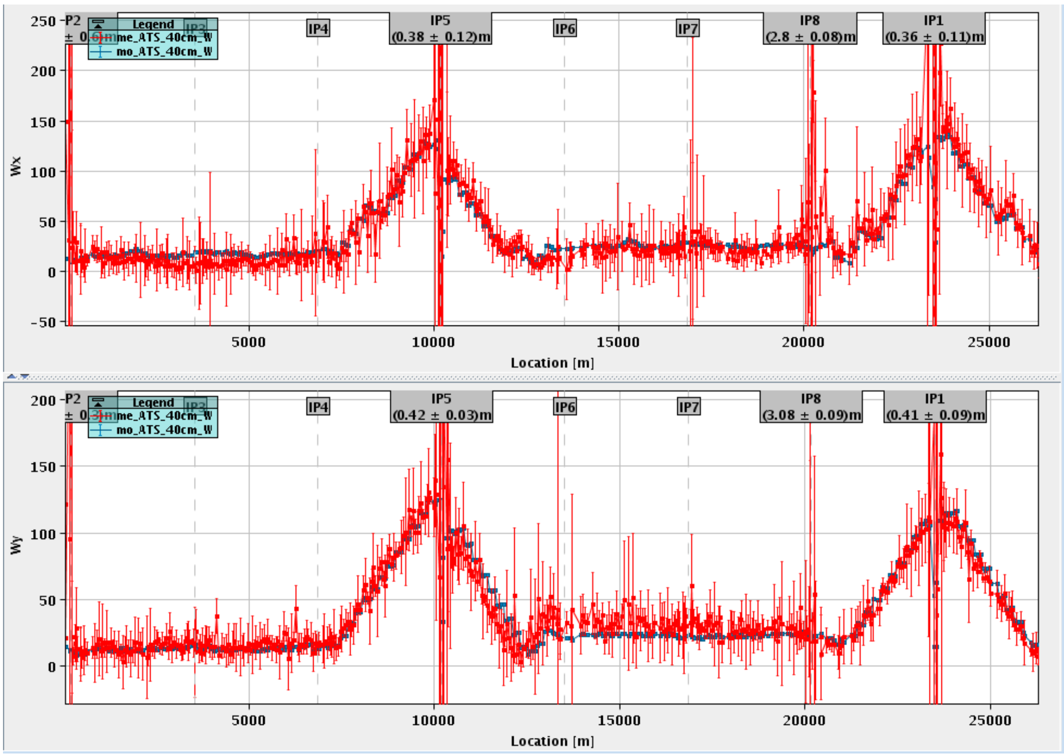


Figure 3: Montague functions measured for beam1 at $\beta^* = 40$ cm. The normalization is chosen such that a W-function amounting to 100 corresponds to an off-momentum β-beating amplitude of 20% for $\delta_p = 10^{-3}$.

- to establish a new reference orbit, find and optimize the collisions at all four IPs,
- realign the TCT centers and perform betatron loss maps at injection with nominal collimator and MP settings,
- 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,
- 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 goal (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 preset 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 [8] (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 σ in IR1 and IR5). This measurement was rather conclusive for beam1 but not for beam2 for which bucket 1 was unfortunately left empty [10].
In the second and third fills, loss maps were achieved at injection, with injection protection devices in and out, which did not show any peculiar behaviour in terms of collimation hierarchy and inefficiency [8] (see e.g. the case of B1H in Fig. 5).
The last fill was ramped up and pre-squeeze to 40 cm, collisions were then rapidly established and optimized at all 4 IPs (with a typical lumi of 5E30 in ATLAS and CMS, see Fig. 6). The TCT/TCSP and IR7 collimator were then re-aligned in collision with marginal change found w.r.t. the nominal optics for the IR7 collimator [9] (see Fig. 7). A second asynchronous beam dump test took place with the TCTs set a 8 σ in IR1 and IR5. This second test confirmed the good behaviour of beam1, with beam2 in the right ballpark compared to expectations [10].

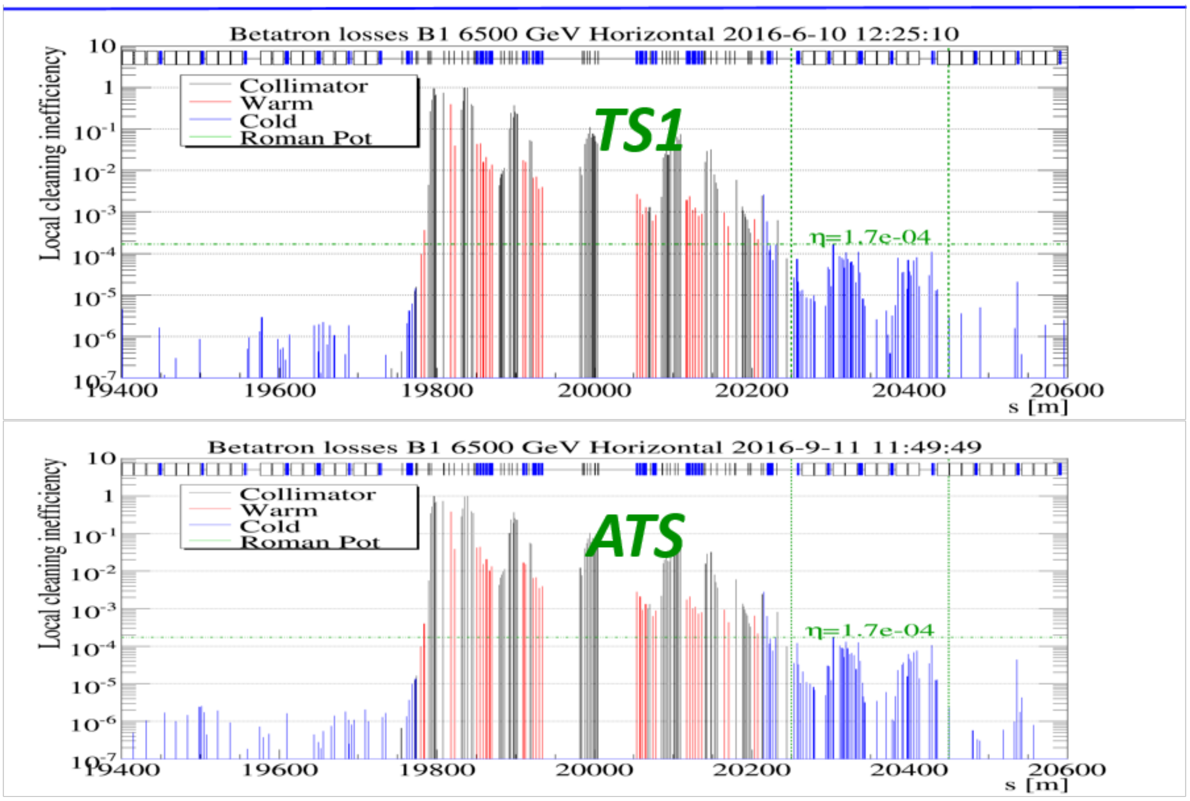
3.3 ATS MD in block 4: 10 cm telescopic optics with probes

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, targeting the 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 any correction yet (see Fig. 8). 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. 9). 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. 10).

Finally, optics measurements also took place at $\beta^* = 14$ cm and 10 cm (see Fig. 11). The results obtained became 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 addtionnal 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 well behaviour of the optics at such low β^* (see Fig. 12).

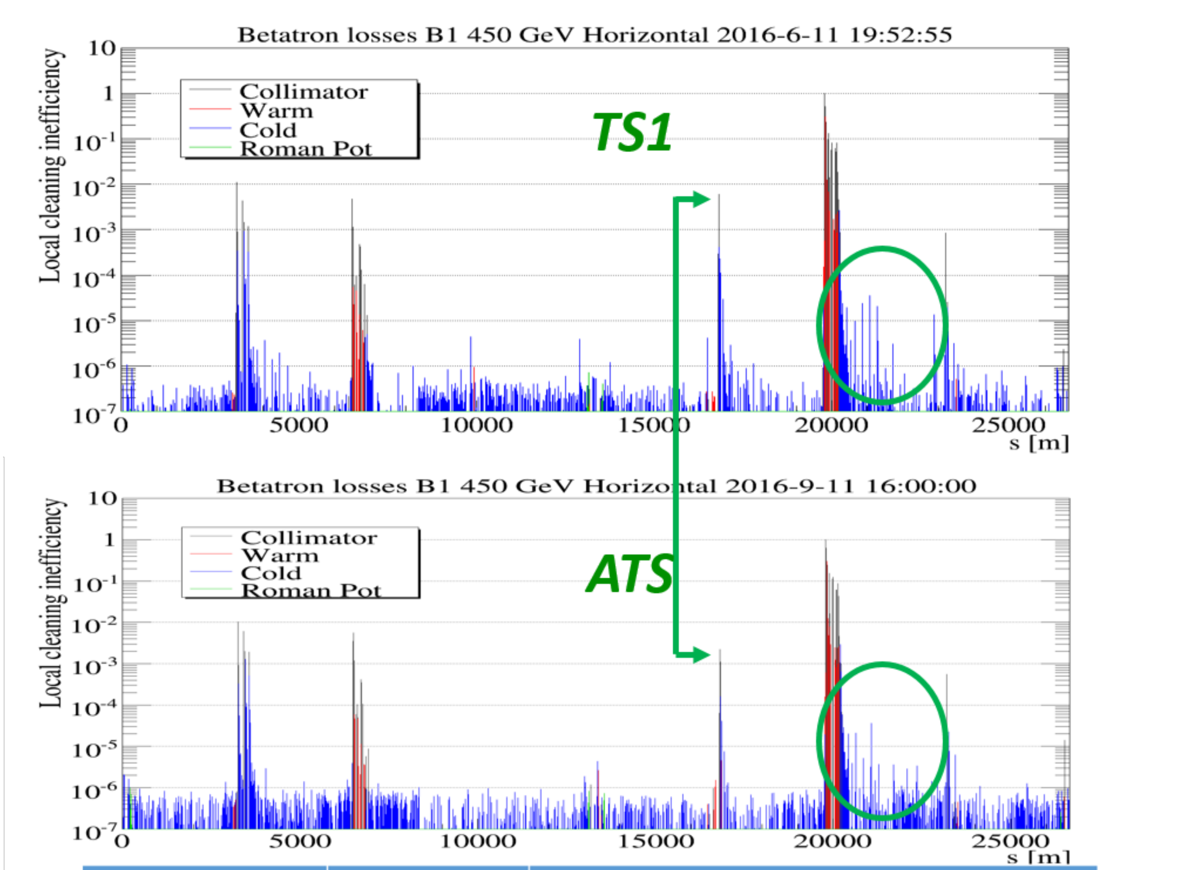
3.4 ATS MD in block 5: 33 cm telescopic optics with nominal bunches

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



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 (center and gaps) were set the same values in both cases.



Case	Ref time	Ineff.	
		ATS	TS1
B1H	16:34:19	6.4e-5	6.3e-5
B1V	16:35:57	1.6e-5	1.7e-5
B2H	16:37:46	9.0e-5	8.6e-5
B2V	16:39:00	7.4e-5	6.6e-5

Figure 5: Example of loss map measured for B1H at injection, and collimation inefficiency recorded for both beams and both planes: comparison between the injection ATS optics and the injection nominal optics after TS1. The IR3/7 collimator (center and gaps) were set the same values in both cases.

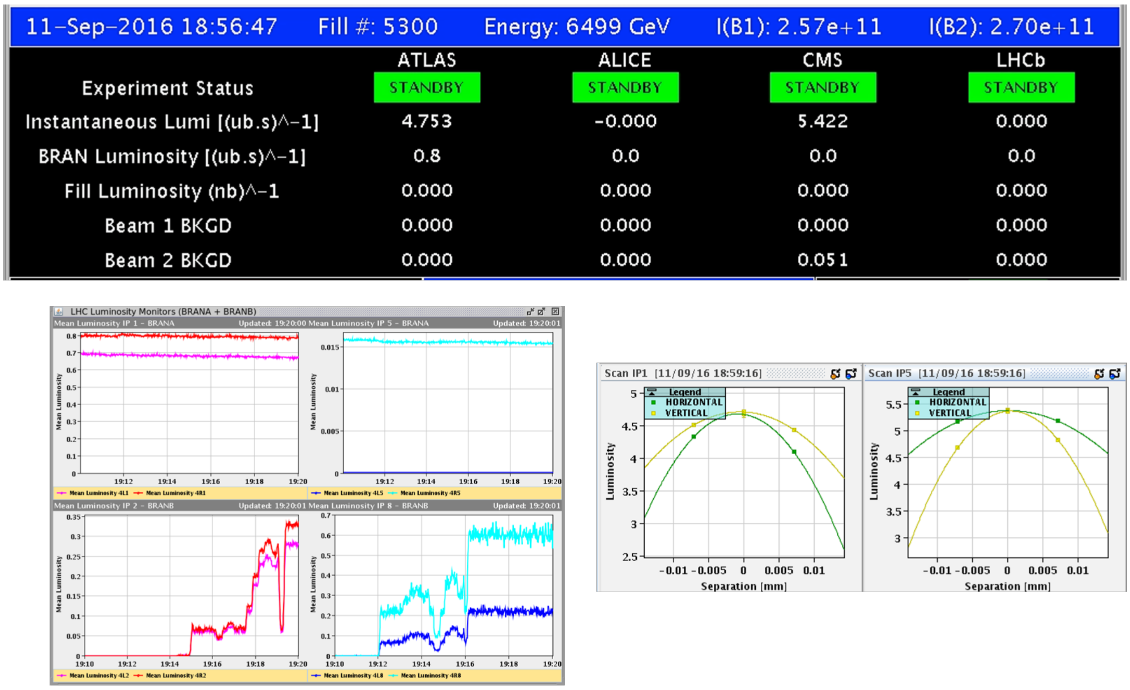


Figure 6: First collisions established and optimized in all 4 IPs with ATS optics with $\beta^* = 40$ cm at IP1 and IP5 (10 m and 3 m at IP2 and IP8 respectively). Due to a mistake in the RF settings, the bunch length was wrongly set to ~ 1.5 ns, resulting in a degradation of the ATLAS and CMS luminosity by about 20%.

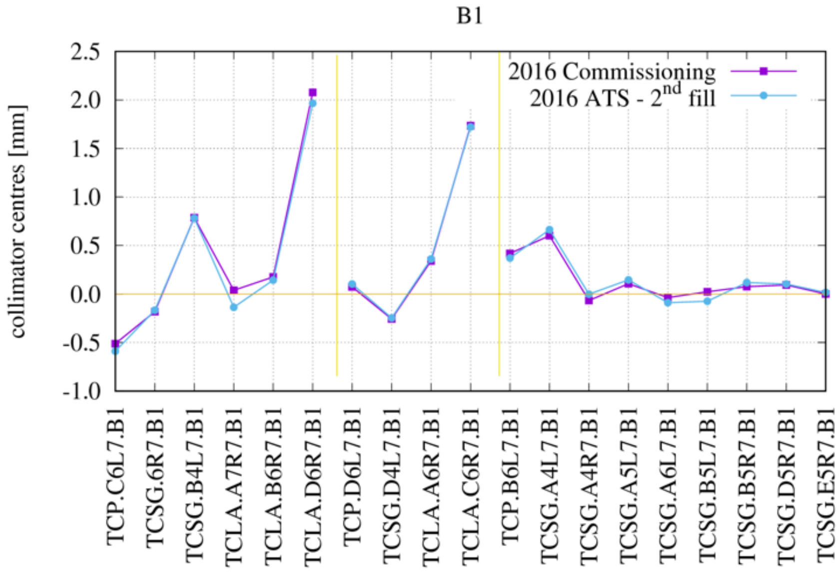


Figure 7: IR7 collimator centers for beam1, as measured at flat top with the nominal optics after TS1, and with the ATS optics at $\beta^* = 40$ cm.

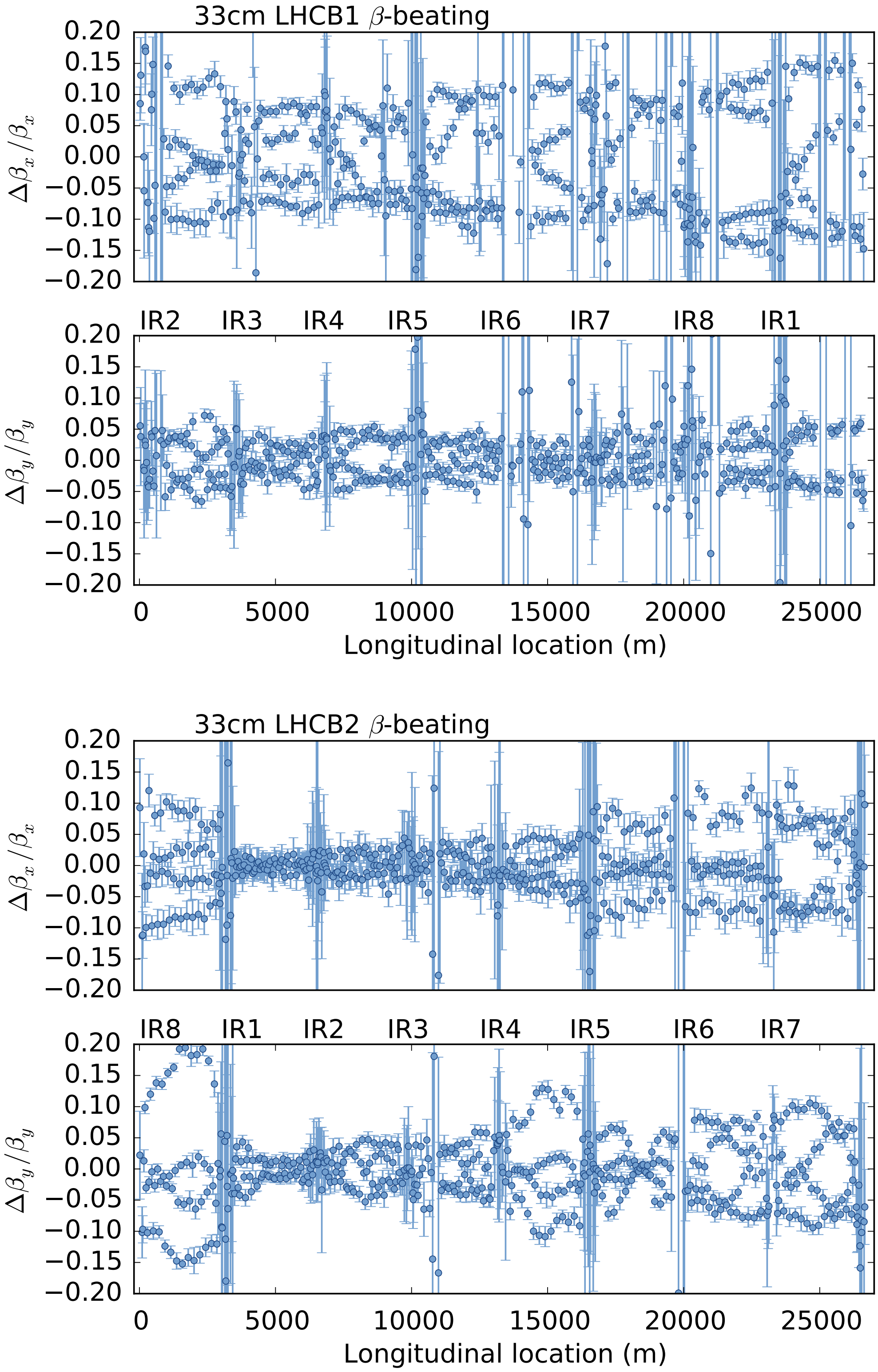
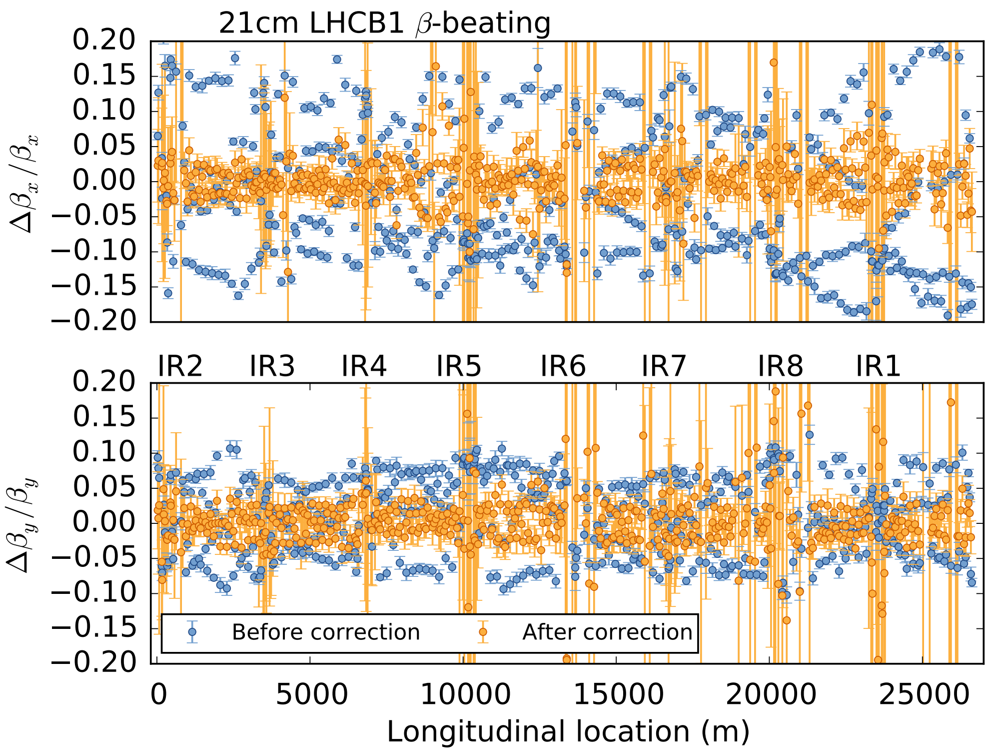


Figure 8: β-beating measured at $\beta^* = 33$ cm for beam1 (top) and beam2 (bottom). No global correction was applied. A local correction knob (MQX trims) was preset from the 40 cm nominal optics.



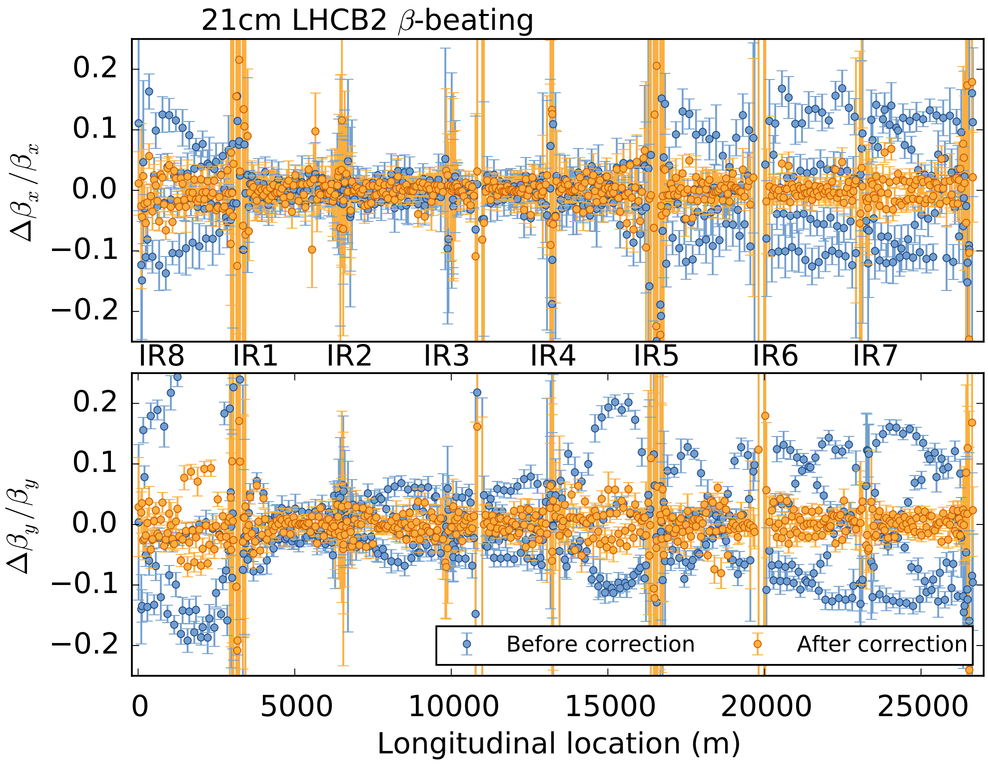


Figure 9: β-beating measured at $\beta^* = 21$ cm for beam1 (top) and beam2 (bottom) before and after (global) correction. A local correction knob (MQX trims) was preset from the 40 cm nominal optics.

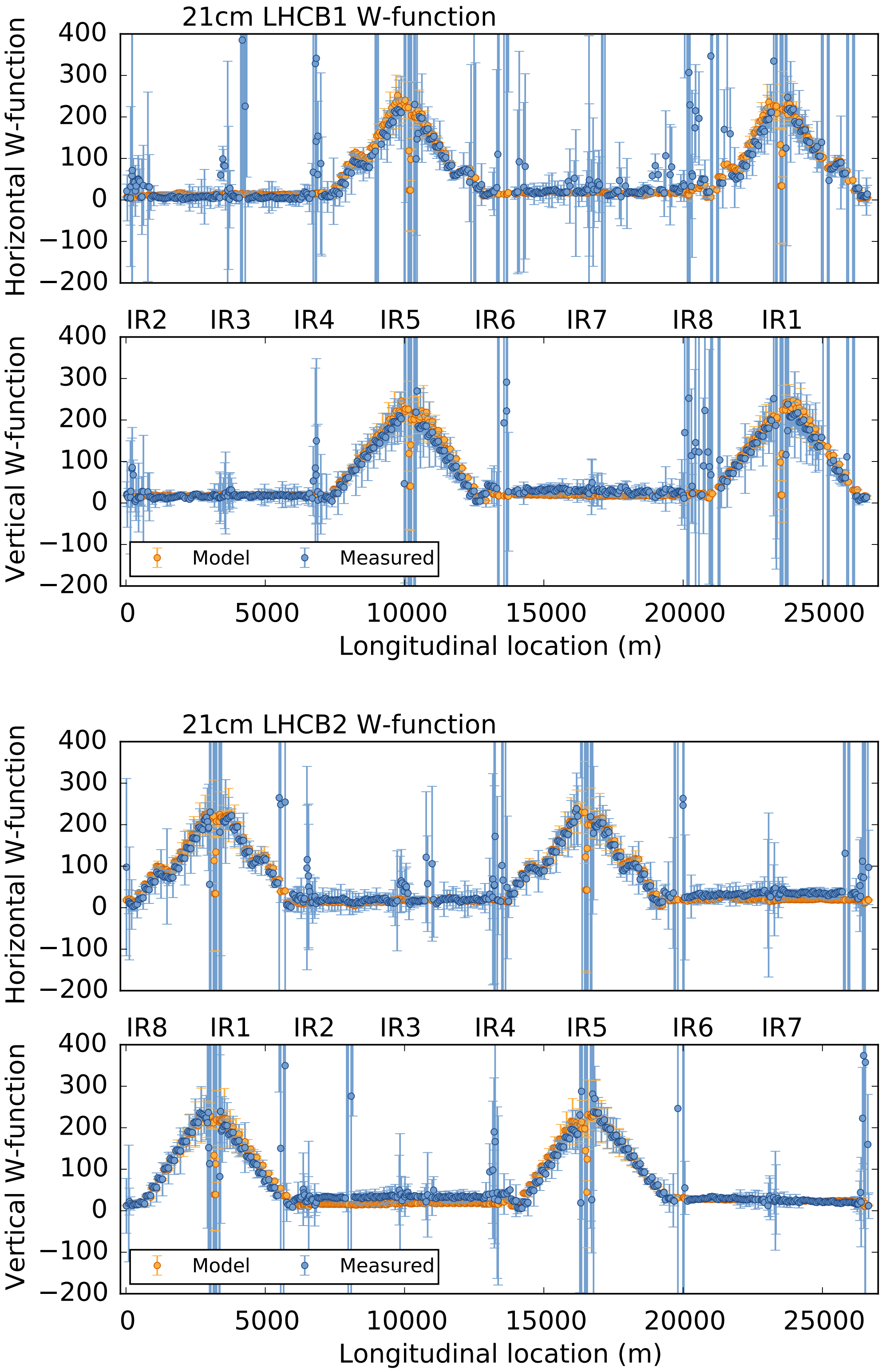


Figure 10: Montague functions measured at $\beta^* = 21$ cm for beam1 (top) and beam2 (bottom). The normalization is chosen such that a W-function amounting to 100 corresponds to an off-momentum β-beating amplitude of 20% for $\delta_p = 10^{-3}$.

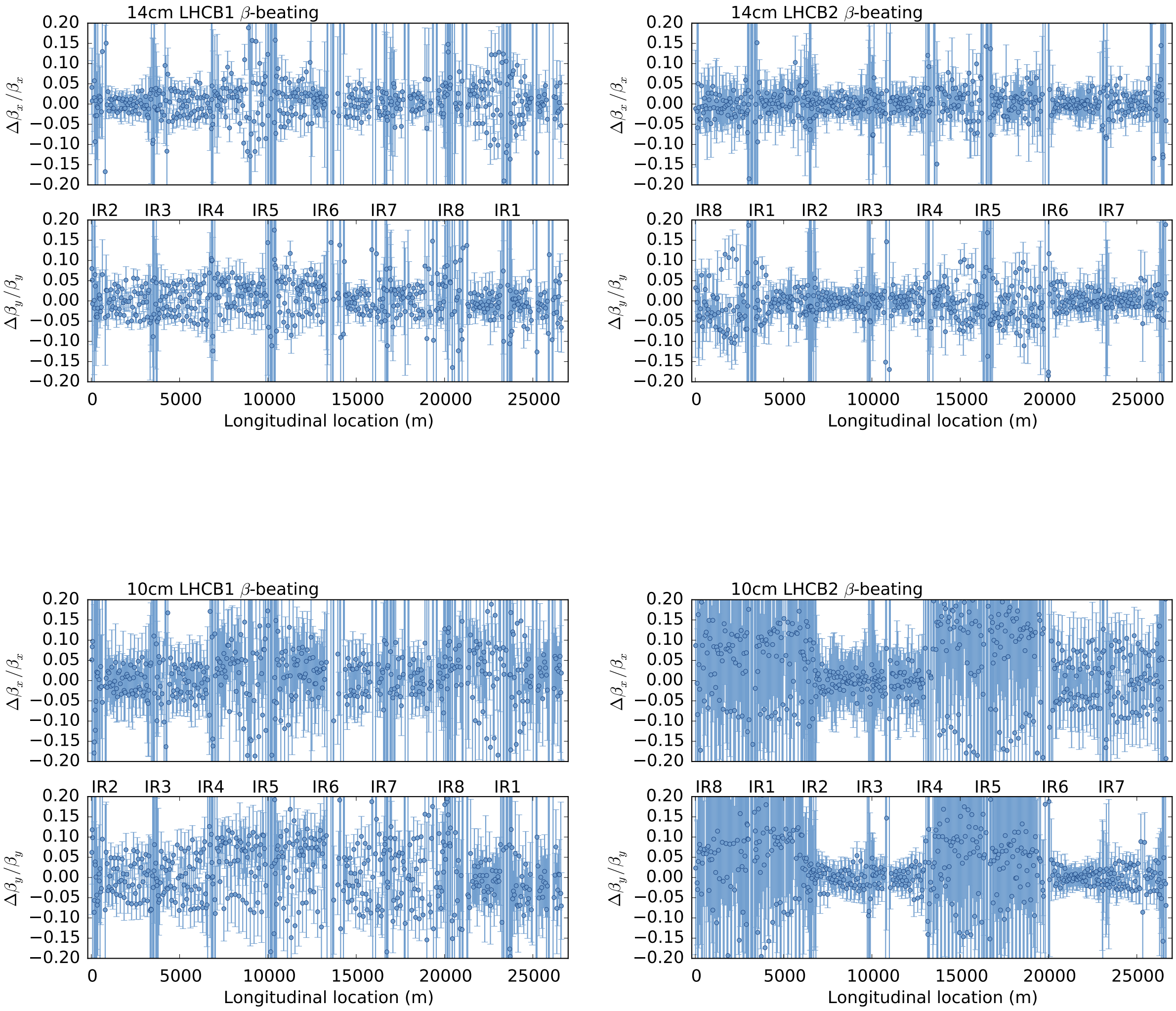


Figure 11: β-beating measured at $\beta^* = 14$ cm (top) and $\beta^* = 10$ cm (bottom) for beam1 (left) and beam2 (right). No global correction was applied. A local correction knob (MQX trims) was preset from the 40 cm nominal optics. The degradation of the measurements quality is explained by the triplet aperture limitations at such low β^*, and therefore the maximum possible excitation amplitude of the AC-dipole.

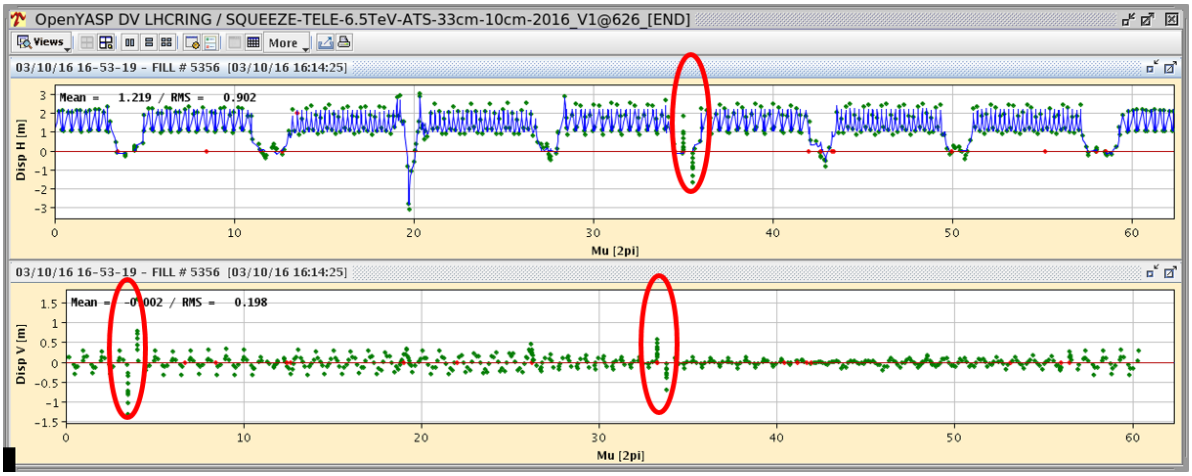


Figure 12: Horizontal and vertical dispersion [m] measured at $\beta^* = 10$ cm for beam1 (top) and beam2 (bottom). The crossing bumps were off in all experimental insertions. In the worst case a spurious dispersion of 1.5-2m can be observed in the inner triplets of either IR1 or IR5. Taking into account the huge peak β-function of 24 km which is reached in the triplet at $\beta^* = 10$ cm, this value of spurious dispersion nevertheless corresponds to a normalised dispersion beating of only 8.5% compared to the normalised dispersion at the main focusing quadrupoles in the arcs (~ 2 m at $\beta \sim 180$ m).

$9.0\,\sigma$ 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 to measure the triplet aperture in the end of the squeeze, establish and optimize the collisions at all four IP's, and assess the collimation system via a series of loss maps (on-momentum 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, see Fig. 13). 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 ($\Delta f = \pm 30$ Hz, i.e. $\delta_p \sim \pm 2.5 \times 10^{-4}$). This again did not show any unexpected features (see [24] for more details and Tab. 6 for a summary of the collimation inefficiency measured in various conditions).

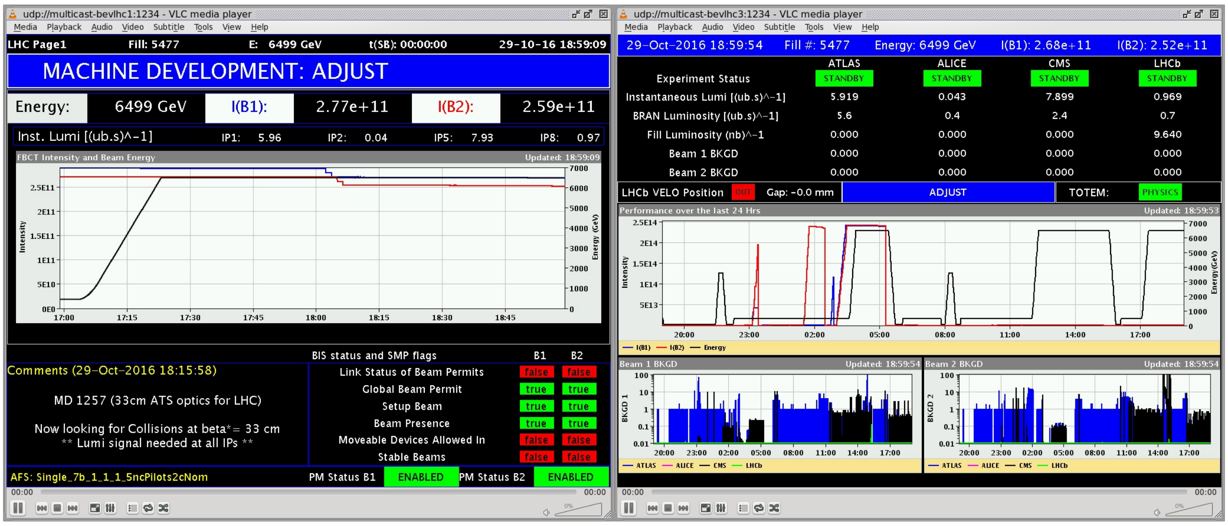


Figure 13: First collisions established and optimized in all 4 IPs at $\beta^* = 33$ cm (10 m and 3 m at IP2 and IP8 respectively), using a (moderately) telescopic ATS optics. The luminosity published by ALICE was not correct on page 1, although it was clearly optimized based on the BRAN data.

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

Table 6: Collimation inefficiency $[10^{-4}]$ for telescopic ATS optics measured in various conditions at $\beta^* = 33$ cm and $140\,\mu$rad half-crossing angle in IR1/5.

4 Summary and Outlook

The 2016 year was certainly very prolific for the validation steps of the ATS scheme, using on purpose the latest ATS optics solution recently developed, which was retuned 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 [16, 17, 18, 19, 20], as K-modulation 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, 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 [25, 26]). 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 compatible with the LHC aperture (starting from a pre-squeezed optics of down-graded β^*), and Landau octupole of negative polarity, as this operational mode also corresponds to the baseline running scenario of the Landau octupoles in the HL-LHC, which is still to be demonstrated (see e.g. [27]). 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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