EXPERIMENTAL VALIDATION OF THE ACHROMATIC TELESCOPIC SQUEEZING SCHEME AT THE LHC

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Abstract

The Achromatic Telescopic Squeezing (ATS) [1] scheme offers new techniques to deliver unprecedentedly small beam spot size at the interaction points of the ATLAS and CMS experiments of the LHC, while perfectly controlling the chromatic properties of the corresponding optics (linear and non-linear chromaticities, off-momentum beta-beating, spurious dispersion induced by the crossing bumps). The first series of beam tests with ATS optics were achieved during the LHC Run I (2011/2012) for a first validation of the basics of the scheme at small intensity. In 2016, a new generation of more performing ATS optics was developed and more extensively tested in the machine, still with probe beams for optics measurement and correction at $\beta^* = 10$ cm, but also with a few nominal bunches to establish first collisions at nominal β^* (40 cm) and beyond (33 cm), and to analysis the robustness of these optics in terms of collimation and machine protection. The paper will highlight the most relevant and conclusive results which were obtained during this second series of ATS tests.

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 lattice sextupoles for the chromatic correction. The complete validation of the ATS scheme at high intensity is a very important milestone in the overall upgrade plan of the LHC. The first series of ATS machine developments (MD) took place in Run I (2011 and 2012), where most of the ATS principles were demonstrated, but only with pilot beams [2]-[5]. All LHC and HL-LHC ATS optics versions developed so far however showed very unfavorable phase advances, nearly equal to 90 degrees in the horizontal plane, between the extraction kickers (MKD) in the dump insertion (IR6) and some tertiary collimators (TCT) 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 for 6.5 TeV operation in 2015, this feature was shown to be a clear weakness of ATS optics for the LHC, which rapidly discarded this option [6]. Very recently, a new generation of ATS optics was then deployed in order to bring a definite cure to the above mentioned limitation, offering phase advances very close to optimal (within $20-30°$) between the MKDs and TCTs, for both beams and both IR1 and IR5 [7]. This opened the possibility to test these new optics with higher intensity beams. Basically, two types of ATS MDs took place in 2016, namely: (i) MDs for optics measurements and corrections achieved with probe beams to re-validate the pre-squeezed and fully telescopic optics down to $\beta^* = 40$ cm and 10 cm, respectively, (ii) MDs with a major component related to collimation, conducted with (quasi-)nominal collimator settings, and a filling scheme containing two colliding nominal bunches per beam and/or sparse non-colliding pilot bunches (for loss maps or aperture measurement).

40 CM ATS PRE-SQUEEZED OPTICS

The first ATS MD commissioned 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 beams and a flat machine (crossing bumps switched off). The optics was measured, then successfully corrected at the 5-10% level in terms of β-beating, at injection, flat top, and at $\beta^* = 40$ cm (see Fig. 1). Dedicated chromatic measurements were conducted at $\beta^* = 40$ cm, showing an as-expected off-momentum β-beating pattern (shown in Fig. 5 at $\beta^* = 21$ cm) and a vanishing non-linear chromaticity, which is one key feature of the ATS scheme. Finally, a complete fill was dedicated to the first tests of the crossing bumps from injection to $\beta^* = 40$ cm. The second ATS MD demonstrated a full ATS cycle from injection to collision with two nominal bunches, and nominal or quasi-nominal collimation and machine protection settings. In particular, a new reference orbit was established, collisions at all four IPs were rapidly found and optimized (with a typical luminosity of 5E30 $\text{cm}^{-2}\text{s}^{-1}$ in ATLAS and CMS). Using the nominal collimator and dump protection settings in IR3, IR7 and IR6 (thank to the very small changes of ATS optics w.r.t. the nominal optics in these 3 insertions), and after a beam-based re-alignment of the TCTs, betatron loss maps were successfully conducted at injection, showing no particular anomalies. Loss maps done at $\beta^* = 40$ cm also

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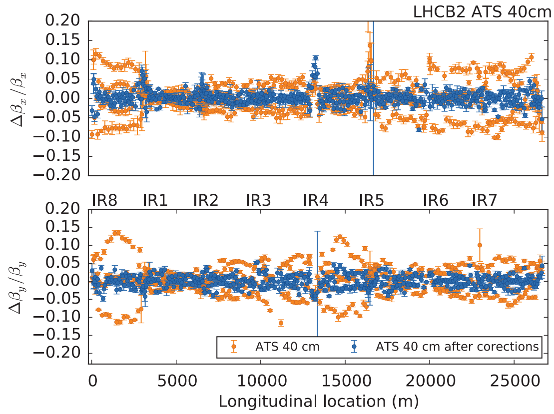

Figure 1: Hor. (H) and vert. (V) β-beating measured at $\beta^* = 40$ cm (example for beam2) before and after (global) correction. A local correction knob (triplet quadrupole trims) was preset based on the 40 cm nominal optics.

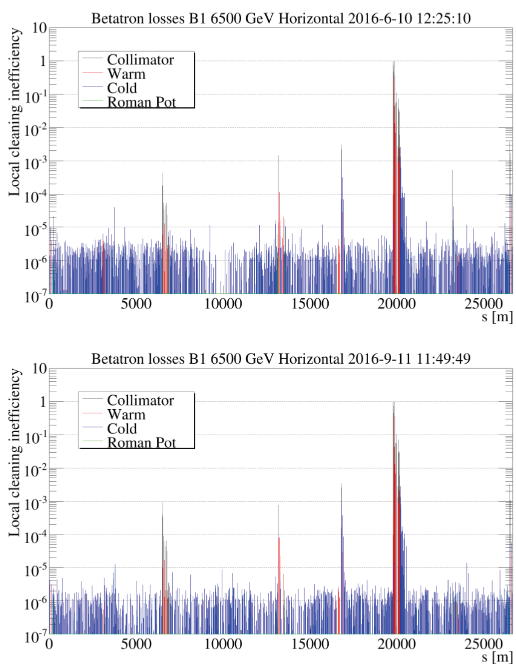

Figure 2: Loss maps measured for B1H at $\beta^* = 40$ cm: nominal (top) and ATS pre-squeezed (bottom) optics.

did not show any problems in terms of collimation hierarchy and inefficiency, even without need of re-aligning the IR7 collimators (see Fig. 2). Then, a beam-based collimator realignment campaign was conducted at $\beta^* = 40$ cm, leading to a marginal re-centering of the collimator jaws compared to the nominal optics (see Fig. 3). A few fills were needed to cover these activities. Two of them ended up with a (programmed) asynchronous dump with the TCT settings at $9\,\sigma$ and $8\,\sigma$ respectively, in order to validate the new MKD-TCT phase advances. The TCT losses measured for beam1 were rather conclusive, with beam2 in the right ballpark compared to expectations.

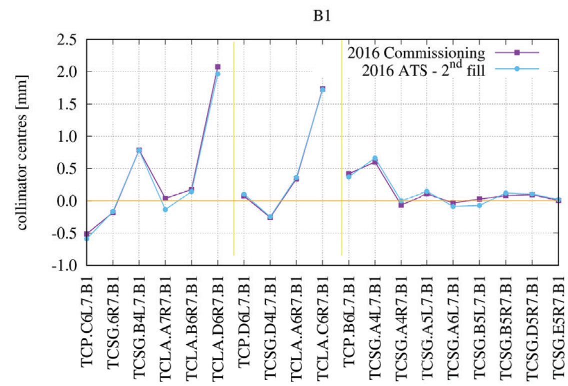

Figure 3: IR7 collimator centers measured for beam1: nominal vs. ATS optics at $\beta^* = 40$ cm.

10 CM TELESCOPIC OPTICS

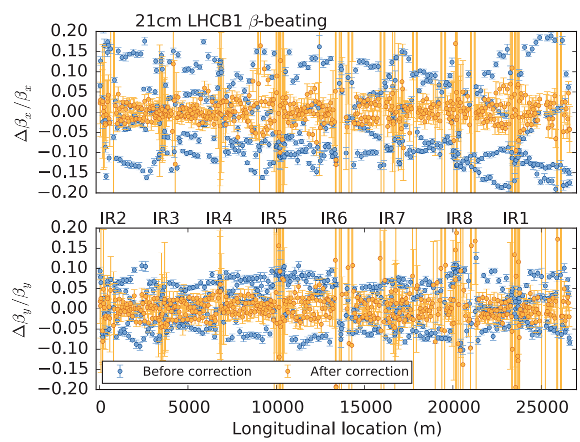

Figure 4: H and V β-beating measured at $\beta^* = 21$ cm (example of beam1) before and after (global) correction.

Considering the several validation steps already done with the 40 cm pre-squeezed optics, the aim of the third ATS MD was to (re-)validate the telescopic techniques of the scheme. The target was fixed to be the HL-LHC ultimate β^* of 10 cm at IP1/5, and passing through a moderately telescopic optics with $\beta^* = 33$ cm, as one potential candidate for pushing the LHC performance in the end of the 2017 Run. Probe beams were injected, ramped and pre-squeezed 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 $\beta^* = 10$ 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 (below $\beta^* = 40$ cm) were calculated and successfully implemented at $\beta^* = 21$ cm, bringing the $\beta-$beating level back to the range of 5-10% (see Fig. 4). The Mon-

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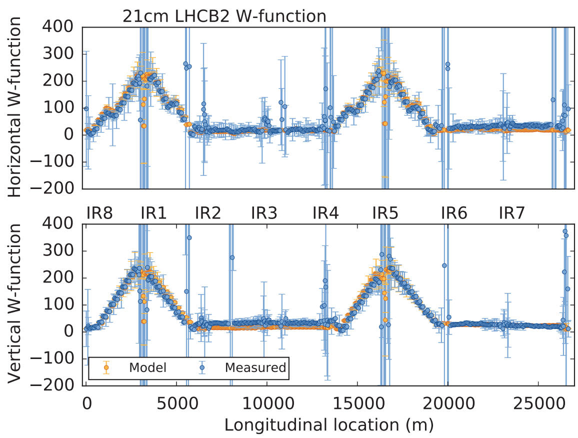

Figure 5: H and V Montague functions measured at $\beta^* =$ 21 cm (example of beam2). $W \equiv 100$ units corresponds to an off-momentum peak β-beating of 20% at $\delta_p = 10^{-3}$.

tague functions also showed as-expected behaviour, with off-momentum $\beta-$beating waves induced by a dedicated powering of the lattice sextupole families in the sectors 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. 5). Optics and dispersion measurements also took place at $\beta^* = 14$ cm and 10 cm, showing a β-beating in the 20-25% range (without any further corrections).

33 CM TELESCOPIC OPTICS

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 (i.e $9.0\,\sigma$ for an emittance of $\gamma\epsilon = 2.2\,\mu$m at 13 TeV c.m. energy). 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 preliminary 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). Two consecutive fills were needed to meet these objectives. The first one was dedicated to triplet aperture measurement, filling each ring with 8 pilot bunches and using techniques described in [8]. First, all collimators were opened at 33 cm, and a pilot bunch blown up 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. In the second fill, two nominal bunches were injected per beam. Collisions were successfully established and optimized in all 4 IPs (with a luminosity of about 8E30 cm^{-2}s^{-1} 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 (applying an RF trim of $\Delta f = \pm 30$ Hz corresponding to a momentum shift of $\delta_p \sim \pm 2.5 \times 10^{-4}$). These measurements again did not show any unexpected features. Figure 6 shows a condensed summary of the collimation inefficiency measurement results which took place over the full 2016 LHC run, which is a clear illustration of the robust behaviour of the collimation system for ATS optics.

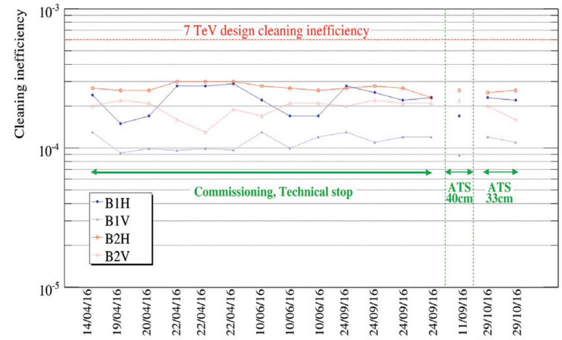

Figure 6: Collimation inefficiency measured over the 2016 LHC run in various optics and machine conditions [9].

SUMMARY AND OUTLOOK

Using the latest ATS optics solution, 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 [10]-[14], 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^*. ATS pre-squeezed optics or moderately telescopic optics were also tested for the first time with a few nominal bunches, to establish and optimize collisions in all experimental insertions, and to re-assess the LHC collimation system with ATS optics. Completing these beam tests with dedicated studies, in particular beam-beam studies [15], the decision was taken to switch to ATS optics for the 2017 LHC luminosity run.

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