CERN-ACC-NOTE-2019-0026

17 July 2019

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Noise studies with new ADT pickups (MD4143)

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Keywords: CERN LHC, accelerator physics, beam instabilities, emittance growth, transverse damper

Summary

An experiment aiming at characterising the performance of a new engineering prototype for the ADT pickup readout electronics with a low noise floor from the point of view of beam stability and emittance growth in collision is described in this note. Whereas a small reduction of the emittance growth was observed, the impact on the beam stability is below the sensitivity of the experiments.

Contents

1 Introduction

Experimental studies in 2017 suggested that the noise floor of the ADT pickup is not compatible with a reduction of the emittance growth in collision when operating with a large beam-beam tune shift, thus requiring an improvement in view of the HL-LHC [1]. A new engineering prototype for the readout electronics of the ADT pickup has been designed, built and installed on spare pickups [2], to assess their

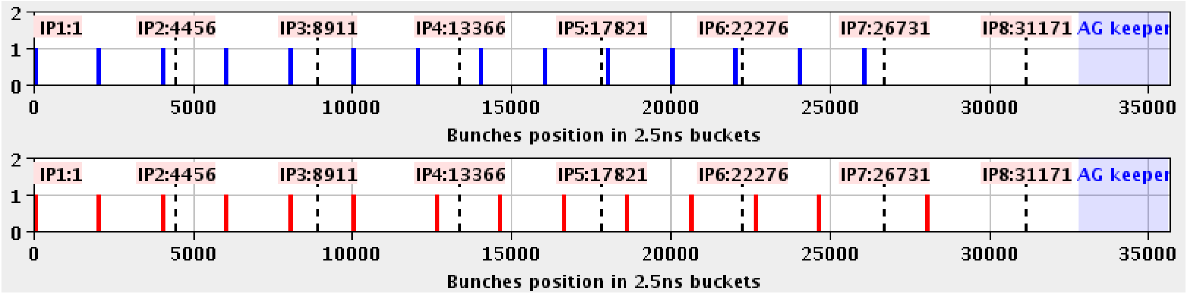


Figure 1: The filling scheme used for the experiment features a set of bunches colliding in IPs 1 and 5 and a set of non-colliding bunches, respectively the first 6 and the last 8. Each set of bunches is sub-divided in three groups acted upon by the first module of the ADT, the second module of the ADT or experience no damping.

capabilities with beam.

Moreover, recent experimental studies have shown that external sources of noise can lead to loss of Landau damping, thus it is expected that a reduction of the ADT pickup noise floor would also improve the requirement in strength of the octupole for Landau damping of head-tail instabilities [3]. The experiment aimed at qualifying the new pickups in terms of both beam stability threshold and emittance growth in collision.

2 Setup

In order to obtain as many data points as possible within a single LHC cycle, we injected 14 high brightness bunches well separated longitudinally that can be acted upon differently by the ADT, as illustrated in Fig. 1. The pickups located at Q8 and Q9, equipped with the new readout electronics are used by the module 1, whereas the usual pickups located at Q7 and Q9 with the old electronics are used by the module 2 of the ADT. The selection of which bunches each module acts upon is done via the excitation masks of the ADT. The masks were adjusted during the experiment, therefore the mask are described for the different stages of the experiment along with the results.

It is important to note that high brightness bunches are needed in order to generate a large tune spread due to head-on beam-beam interaction, such that the efficiency of the feedback at suppressing emittance growth is reduced. With the current brightness, the expected difference between the two technologies would not be measurable in terms of emittance growth. Also, since the emittance growth rate generated by the pickups' measurement noise grows quadratically with the gain, a high damper gain is desired.

3 Results

3.1 Instabilities during the cycles

3.1.1 Nominal optics

A high brightness is necessary to obtain a large beam-beam parameter, similar to HL-LHC operational conditions. Single bunches with a brightness higher than the expected one for HL-LHC trains are already available from the existing injector chain. However, the stability of these bunches is marginal at the flat top in the LHC. In similar conditions in 2017 [4], an increase of the chromaticity to 20 units was necessary to maintain the stability of those bunches. The same strategy was applied here, however it was no longer possible to incorporate the higher chromaticity into the new squeeze functions bringing β^*

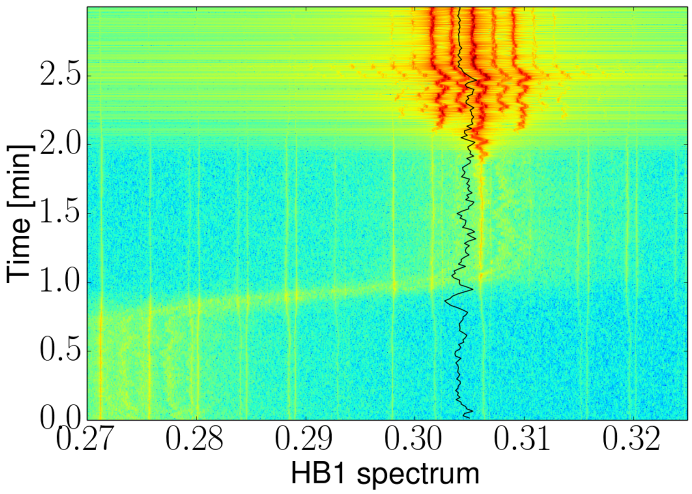
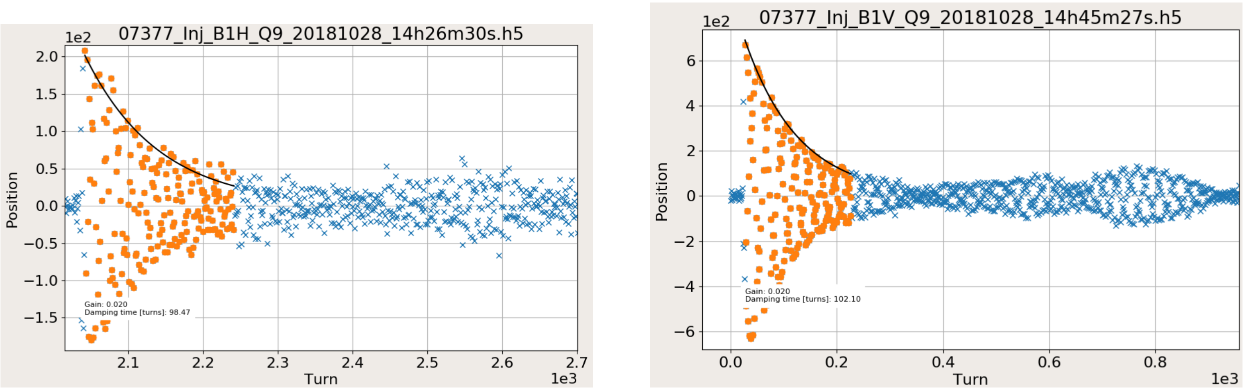
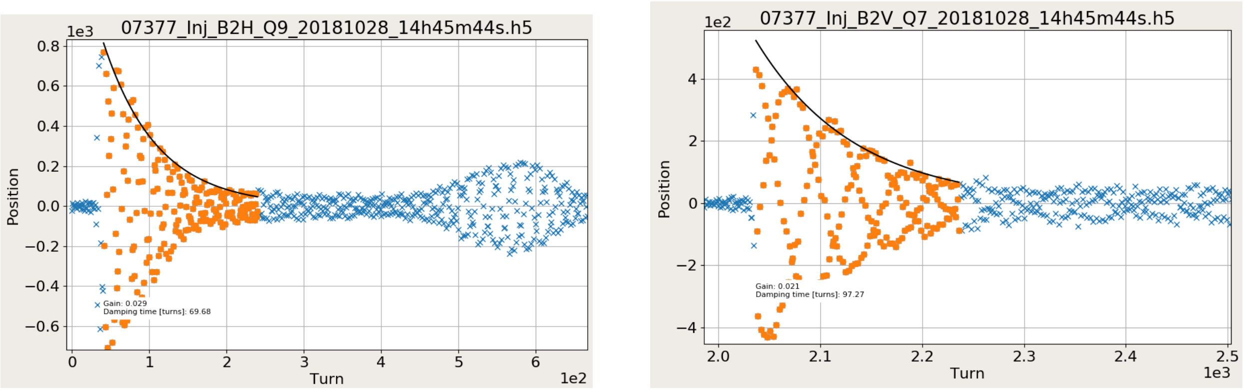


Figure 2: Spectrogram of the beam oscillation measured by the BBQ during fill 7336, showing an instability developing a minute after the end of the tune change at top energy. The instability started when the chromaticity was reduced from ≈ 18 units to ≈ 15 between minutes 1.8 and 2.0. The black line marks the correction of the tune feedback.



(a) Beam 1, horizontal (b) Beam 1, vertical



(c) Beam 2, horizontal (d) Beam 2, vertical

Figure 3: Single bunch turn-by-turn position measured by the ADTObsBox after a kick using the ADT kicker, allowing for a calibration of the damping time at flat top.

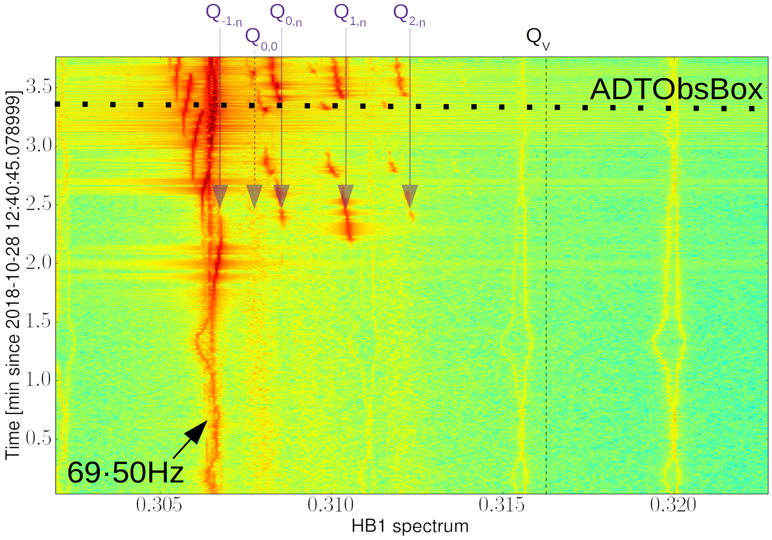


Figure 4: Spectrogram of the beam oscillation measured by the BBQ. The contribution of individual bunches to this spectrum at the dotted line is shown in Fig 5. The four lines spaced by the synchrotron tune may be identified as the contribution from different azimuthal head-tail mode and are marked with solid purple arrows. The contribution from the dipole mode is highlighted with a dashed purple arrow, with a tune shift of $\approx -7 \cdot 10^{-4}$ with respect to the frequency of radial modes with azimuthal mode number $Q_{0,n}$. The average vertical tune measured with the BBQ is marked with a vertical dashed line. To highlight its strength before the instability and its vicinity to the first lower synchrotron side band, the 69th harmonic of 50Hz at $Q \approx 0.3068$ is marked with a black arrow.

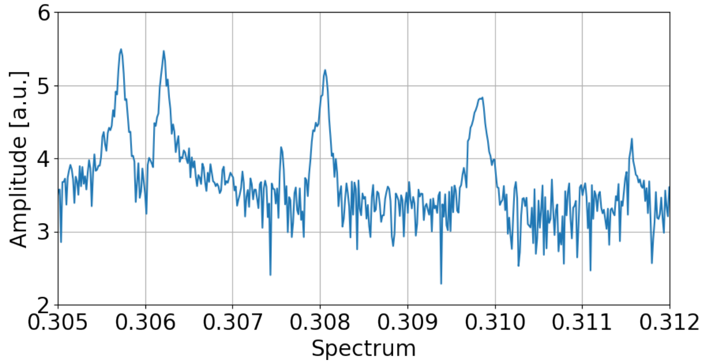
down to 30cm as opposed to 40cm in the 2017 experiment, as the strength required for the sextupoles exceeded their capability. An instability, shown in Fig. 2, developed when the chromaticity was reduced from ≈18 to ≈15 units. The beam quality degradation resulting from this instability prevented the execution of the experiment. The expected threshold at a chromaticity of 15 units and the measured beam parameters is 450 A, i.e. close to the maximum validated current in the octupoles (550 A). For a second attempt we chose to rather use the ATS optics featuring a large telescopic index ($r_{ATS} = 3.08$) at the end of the ramp boosting the strength of the octupoles by a factor ≈ 2.4 [5].

We note in Fig. 2 an unusually strong tune jitter, which perfectly correlates with the corrections imposed by the tune feedback. This is the result of a noisy tune measurement when operating with high intensity bunches, which should be avoided in a second attempt.

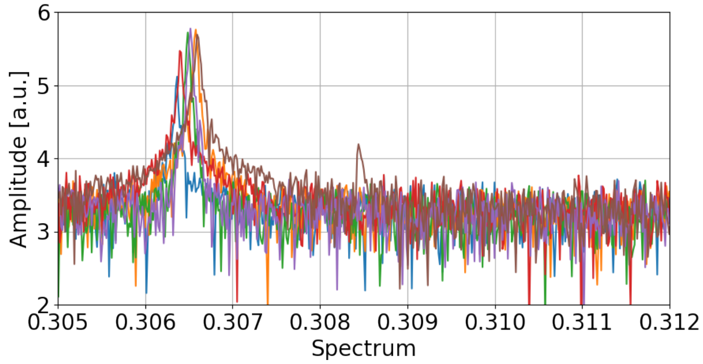
A calibration of the damper gain using single bunch kicks could be performed in spite of the degraded beam quality, the fits of the exponential decay of the beam oscillations are shown in Fig. 3, yielding an effective gain of 0.03 in the horizontal plane of beam 2 and 0.02 in the other beams and planes, corresponding to damping times of ≈66 and ≈100 turns. The real damper gain is approximatively half of the effective one, due to the additional decay introduced by chromaticity [6]. Consequently, those values are about half of the initially expected gain of 0.02, i.e. 100 turns damping time.

3.1.2 High telescopic index

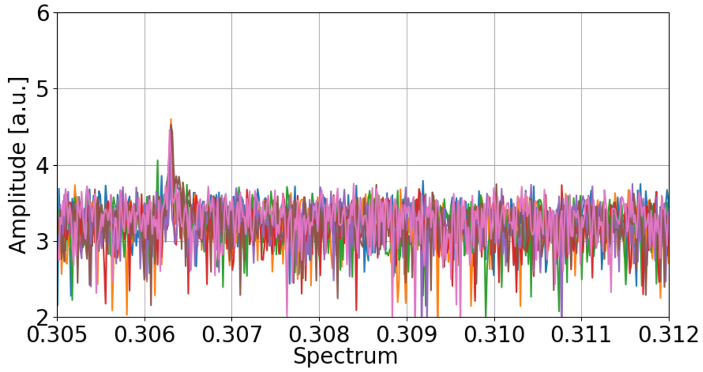
In a second attempt, the tune jitter encountered in the first fill was solved by reducing the gain on the bunch in the gated BBQ window by a factor 3 with respect to other bunches, since this measurement is



(a) Oscillation spectrum of bunch 0



(b) Oscillation spectrum of bunches 600, 1200, 1800, 2000, 2400 and 2600



(c) Oscillation spectrum of bunches 200, 400, 800, 1000, 1400, 1600 and 2200

Figure 5: Single bunch oscillation spectrum obtained from a $64 \cdot 10^3$ consecutive turns ADTObsBox acquisition at t=3.2 min in Fig. 4. The bunches are grouped depending on the feature exhibited in their spectrum, i.e. a strong instability characterised by 4 peaks in the upper plot, a significant signal peaked between 0.3064 and 0.3066 in the middle plot and finally a small peak at 0.3063 in the lower plot.

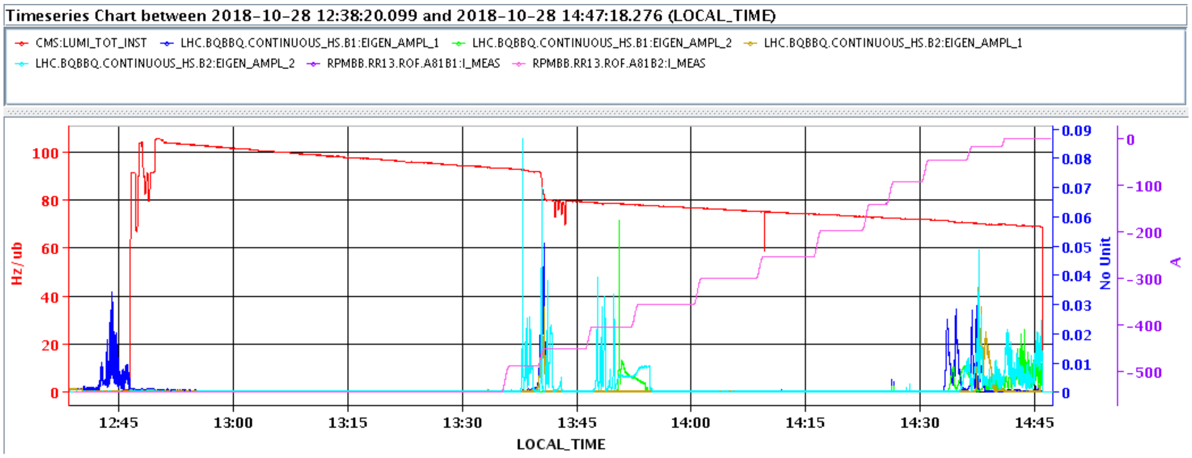
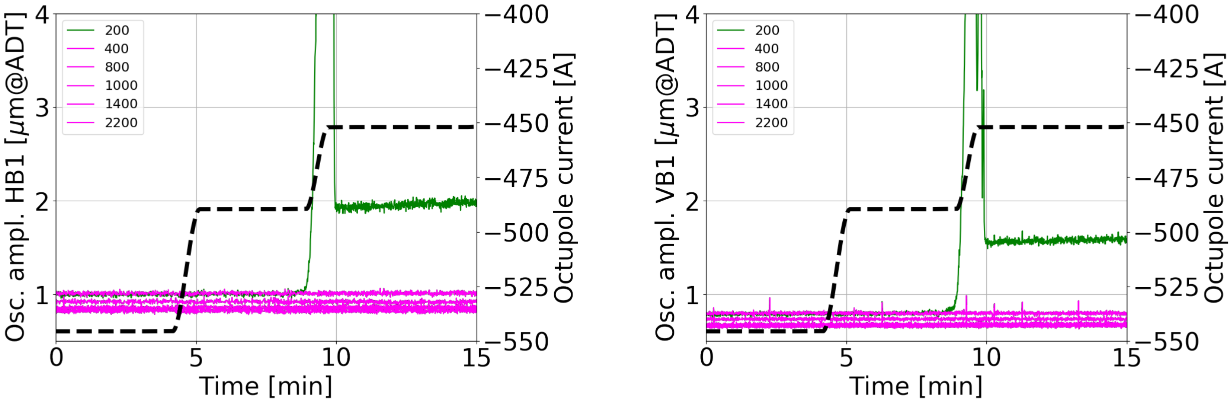


Figure 6: Overview of the beam oscillation amplitude, luminosity and octupole current during fill 7377. The instabilities during the cycle discussed in Sec. 3.1 are visible around 12:45, then instabilities occurred already in the first steps of the reduction of the octupole currents around 13:40. These are bunches without ADT gain, detailed in Fig. 7. Other bunches became unstable towards the end of the octupole scan around 14:35, details are shown in Fig. 9.

critical for the tune feedback. The stability issue was addressed by the usage of the ATS optics with a high telescopic index. The polarity of the octupoles was reversed with respect to the first attempt, since this optics was tested with the negative polarity [5]. In these conditions, the octupole current required was $\approx -50\ A$, even with a reduced damper gain. Unexpectedly, the bunch featuring a lower gain developed an instability approximatively two minutes after the tune change, in spite of the -545 A in the octupoles. The spectrogram of the beam oscillation amplitude during the instability is shown in Fig. 4, including an interpretation of the various lines. A single acquisition of the ADTObsBox is available during the instability. The 64 thousand consecutive turns of bunch-by-bunch position measurements allow for a reconstruction of the individual spectrum at this moment. Figure 5 shows the main instability of bunch 0 featuring a lower damper gain with respect to the other bunches, as well as the other bunches. The spectrum of the other bunches can be separated in two sets, depending of the frequency and amplitude of the peaks observed. The cause of the instability of bunch 0 and of the peaks shown in Fig 5b are not understood at the moment, nevertheless these bunches experienced a degradation of their quality and are therefore excluded from the analysis in the following.

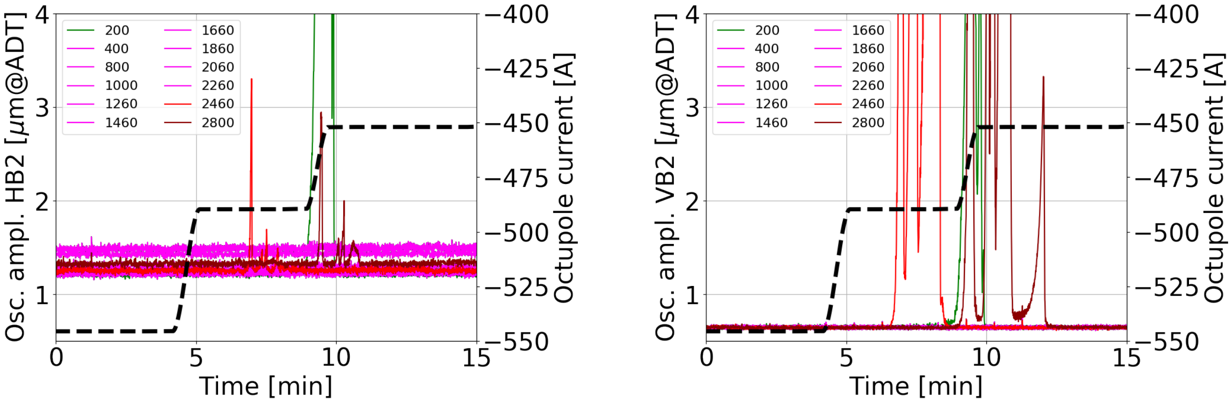
3.2 Octupole threshold measurement

Figure 6 illustrates the flow of the experiment, with a first part dedicated to emittance growth in collision from 12:50 to 13:30 which will be discussed in the next section, followed by a reduction of the octupole current in steps. Instabilities are visible at the first steps. These instabilities developed in bunches without gain, for which the individual oscillation amplitude is shown in Fig. 7. The expected instability threshold for the non-colliding bunches without gain is ≈ -190 A, but was measured at -487 A in the vertical plane of beam 2. No measurement is available for beam 1. The colliding bunches also developed a strong instability at the same octupole current, with the signatures of the coherent beam-beam π-mode, as shown by the beam oscillation spectrogram in Fig. 8 [7]. Indeed, the unstable mode frequency is shifted down with respect to the machine bare tune, the corresponding beam-beam tune shift is further discussed in Sec. 3.3. The reduction of the tune shift as the oscillation amplitude increases, as well as the correlation between the signals observed in the two beams support the hypothesis of an instability of the coherent beam-beam mode π.



(a) Beam 1, horizontal

(b) Beam 1, vertical



(c) Beam 2, horizontal

(d) Beam 2, vertical

Figure 7: Single bunch oscillation amplitude measured by the ADT activity monitor during the initial part of the octupole scan. The bunches experiencing no damper are represented in green and red, corresponding to colliding and non-colliding bunches respectively. The other bunches are represented by pink lines. The dashed black line shows the variation of the octupole current.

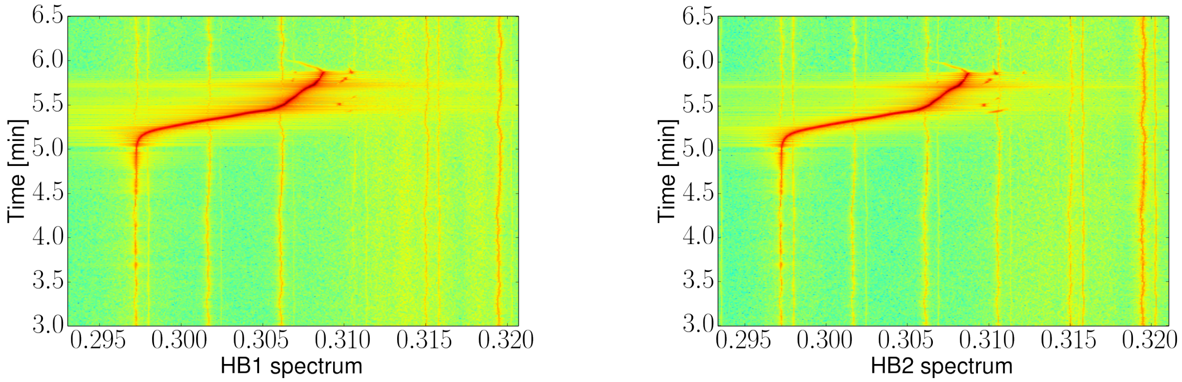
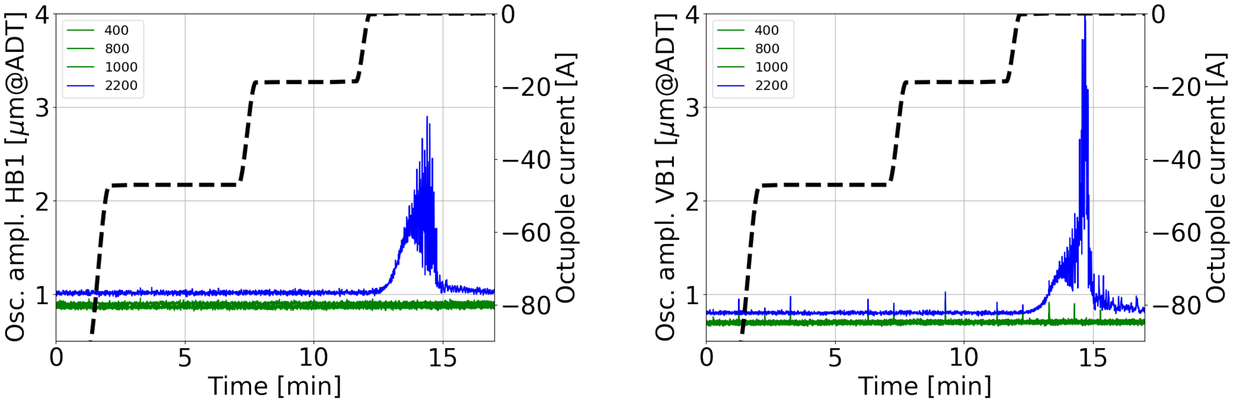
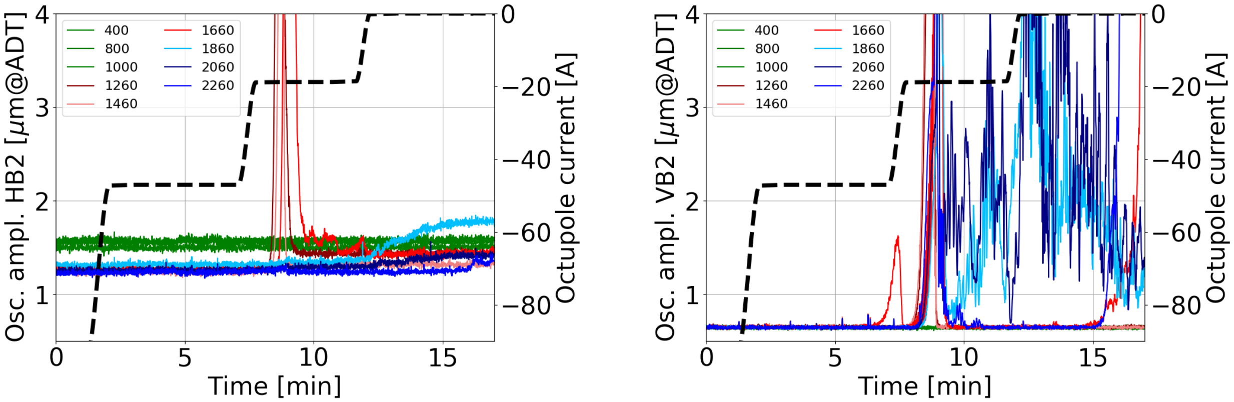


Figure 8: Beam oscillation spectrogram in the horizontal plane of each beam measured by the BBQ during the instability of the colliding bunches which do not experience damping from the ADT. The current in the octupoles at the moment of the instability was -487 A.



(a) Beam 1, horizontal (b) Beam 1, vertical



(c) Beam 2, horizontal (d) Beam 2, vertical

Figure 9: Single bunch oscillation amplitude measured by the ADT activity monitor at the end of the octupole threshold measurement. The dashed black line represent the octupole current, while the solid lines represent the activity of the colliding bunches (green), the non-colliding bunches acted upon by the ADT module setup with the new pickups (red) and the non-colliding bunches acted upon by the ADT module with the old pickups (blue). All bunches having experienced an instability earlier in the fill have been excluded.

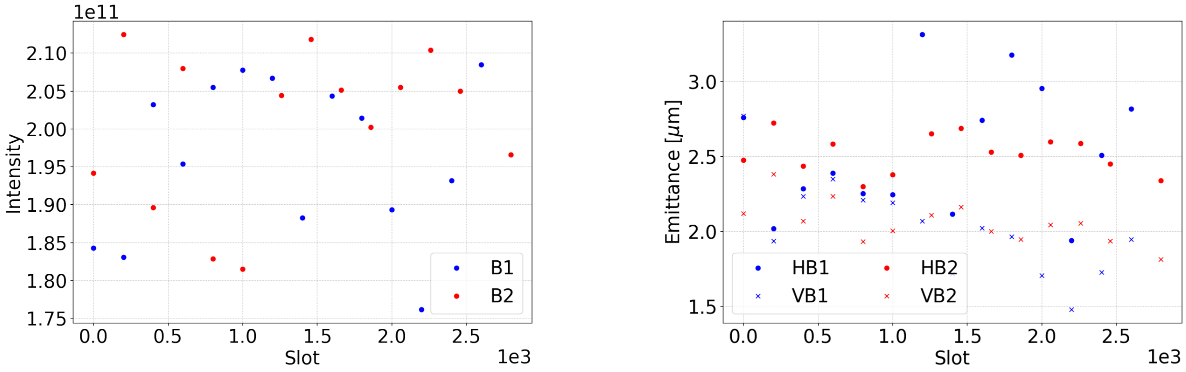


Figure 10: Bunch intensities and emittances measured by the FBCT and BSRT at the start of the experiment (12:55).

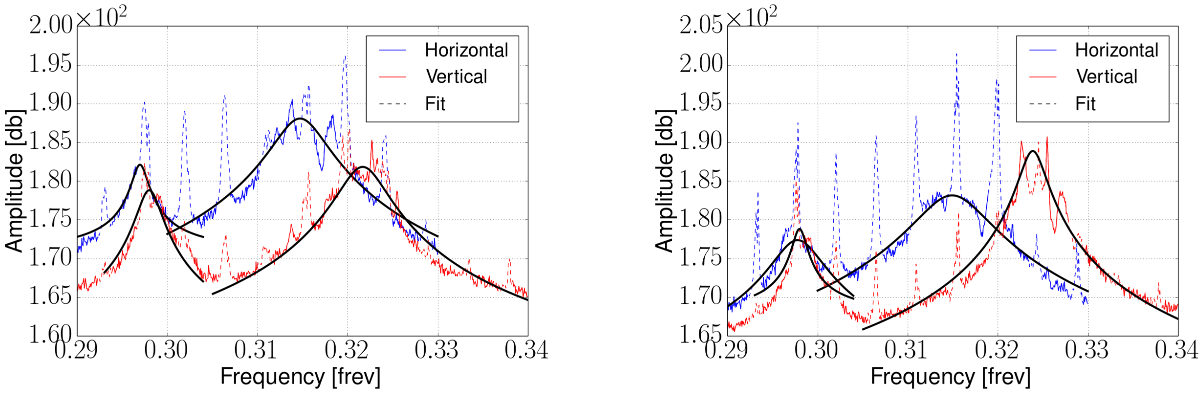
The bunches experiencing active damping became unstable later on in the octupole current scan, starting around 13:35, except the colliding bunches which remained stable even with the octupoles switched off. The activity of the individual bunches during the last steps of the current scan is detailed in Fig. 9. For beam 1, a comparison between the old and new pickups cannot be done as only one non-colliding bunch was not affected by instabilities in the first part of the cycle. The remaining bunch experiencing active damping based on the old pickups became unstable during the step from -19 A to 0, whereas the expected threshold is -63 A. For beam 2, one of the three bunches experiencing active damping with the new pickup became unstable after 5 minutes spent at -48 A, all the other bunches became unstable when reaching -19 A. The expected threshold for these bunches is ≈-75 A.
The difference between the old and new pickup is extremely mild and is hardly conclusive due to the large steps in octupole current and the short time spent steady in each configurations. The original plan for this experiment featured finer and longer steps in the expected range of instability threshold, however the observation of an instability during the cycle cast strong doubts on the expectations and the procedure was reviewed with coarser steps to remain within the allocated time slot.

The measurement of instability thresholds below expectations is compatible with previous experiments in similar conditions, i.e. using the ATS optics with $r_{ATS} = 3.08$ and the negative polarity of the octupoles [5], but with a reduced bunch intensity. With this polarity of the octupole such a low stability threshold could be the result of a large tail population [8]. However, these seemingly robust observations are in contrast with the instability observed before the establishment of collision, with ≈ 30 times more octupole strength, which remains unexplained.

3.3 Emittance growth in collision

The bunch intensities and emittances at the start of the collision are shown in Fig. 10. With a measured average r.m.s. bunch length of 8.2 cm, the expected average total beam-beam tune shift is $2.2 \cdot 10^{-2}$. Consistently, Fig. 11 shows the spectrum of the beam oscillation measured by the BBQ, featuring the two peaks of the coherent beam-beam σ and π modes.

The evolution of the luminosity of individual colliding bunch pairs, as well as the corresponding specific luminosity during about 40 minutes in steady conditions is shown in Fig. 12. The relative decay rate of the specific luminosity is the relative growth rate of the convoluted transverse emittances of the two bunches in collision and can be compared to the growth rate measured with the BSRT (Fig. 13).



(a) Beam 1

(b) Beam 2

Figure 11: Beam oscillation spectrum measured by the BBQ over 2 minutes. The harmonics of the 50Hz lines are marked in dashed and are excluded from the fit. Two fits with a Lorenzian function are shown in black around the σ and π mode frequencies.

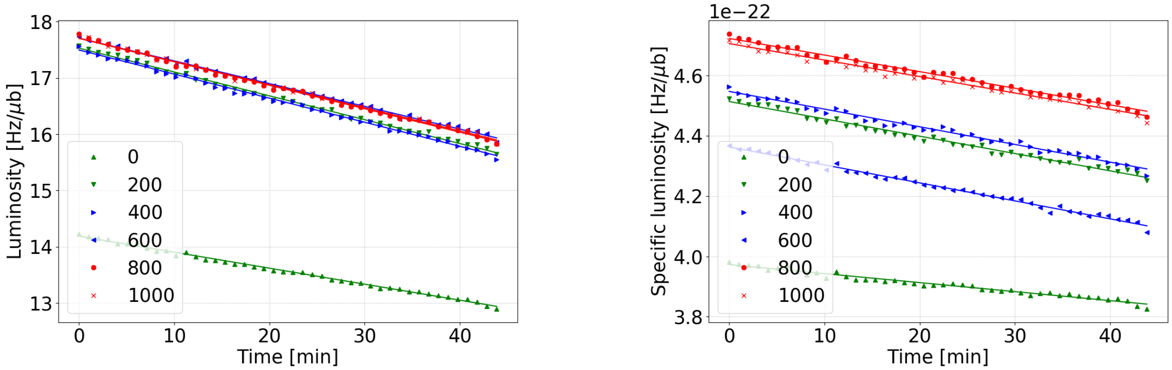


Figure 12: Luminosity and specific luminosity evolution of individual bunch pairs colliding in IPs 1 and 5, measured by CMS during the steady phase in collision from 12:55 to 13:37.

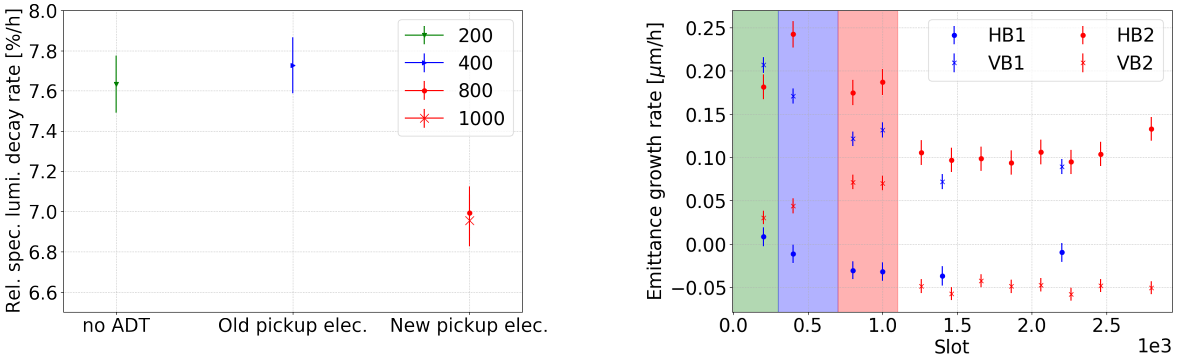


Figure 13: The relative decay rate of the specific luminosity (left plot) is used as a measure of the convoluted emittance growth rate. The corresponding fits are shown in Fig. 12. The right plots shows the emittance growth rate measured by the BSRT, the bunches without damper, with the old pickup electronics and the new pickup electronics are shaded with the same colour code as for the left plot, i.e. green, blue and red respectively. In both plots the error bars are computed based on the quality of the fit.

While the reduction of the emittance growth rate thanks to the new pickup readout electronics is clear in the growth rates measured through the luminosity, the behaviour of the emittances in each plane does not follow a clear pattern. In both planes of beam 1, the emittance growth is slowest with the new pickup, intermediate with the old pickup and higher without damper. In the horizontal plane of beam 2, the bunches with the new pickups and the ones without damper behaved similarly, while the ones with the old pickup grows faster. Only in the vertical plane of beam 2 is the emittance growth faster with the new pickup, intermediate with the old pickup and slower for the bunches without damper.

4 Conclusion

The engineering prototype of new pickup readout electronic featuring a reduced noise were tested with beam. No major issues were observed with the new technology. Its impact on the beam stability is beyond the sensitivity of the experiment performed. The relative emittance growth in collision was reduced by $1.5\%/h$ with respect to the damper operating with the old technology. Nevertheless significant differences where observed between the two planes and beams, which requires further investigations.
While this test did not reveal any major issue with the new technology, further tests with beam will be required to fully assess its potential.

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