OUR UNDERSTANDING OF TRANSVERSE INSTABILITIES AND MITIGATION TOOLS/STRATEGY

X. Buffat, G. Arduini, D. Amorim, S. Antipov, L. Barraud, N. Biancacci, L. Carver, F. Giordano, G. Iadarola, K. Li, G. Mazzacano , E. Métral, A. Romano, B. Salvant, M. Schenk, M. Soderen, D. Valuch, CERN, Geneva, Switzerland
L. Mether, T. Pieloni, C. Tambasco, EPFL, Lausanne, Switzerland

Abstract

The observations of coherent instabilities are compared to the expectations based on the beam instability model. Their impact in the different phases of the LHC operation and the corresponding mitigation strategies are discussed, with an emphasis on the newly developed diagnostics.

INTRODUCTION

Several coherent instabilities were observed during the 2017 run of the LHC, in different operational configurations. While the impact on the performance was not significant, 16L2 induced instabilities aside [1], their presence was not expected, since the measures in place are designed to ensure the stability of beams with the brightness available from the present injectors. While presently the margins, in particular in terms of octupole strength available to provide sufficient tune spread and consequently Landau damping, are sufficient to stabilise the operational beams, the extrapolation to the beam brightnesses expected after the LHC Injector Upgrade do not leave sufficient margins. It is therefore crucial to identify and gain control over the aspects that are not understood within the existing beam stability model. This paper will detail some of the observations of coherent instabilities observed in the different phases of the LHC operation in 2017, comparing to the present understanding, thus highlighting the points to be addressed in the future.

INJECTION

The stability of the beams at injection is entirely dominated by the effect of the electron clouds. Indeed, in their absence, an octupole current below 1 A should be sufficient to stabilise the beams. In fact at its earliest stage of operation, the LHC beams could be stabilised at injection only by the tune spread driven by the un-corrected lattice non-linearities and/or space charge effects [2]. 25 ns bunch trains however require important mitigations measures in particular a high chromaticity (15 units) and strong octupoles (40 A) [3]. The ADT gain is also high at injection ($\approx$10 turns damping time), which is imposed by the damping of injection oscillations. During the scrubbing run, the nominal beam was shown to be stable with a chromaticity of 7 units and an octupole current of 13 A [4]. Yet, in operation with BCMS beams, a dedicated test showed that the chromaticity could not be reduced below 15 units with the octupoles at 40 A and damping time of 10 turns from the ADT [5]. A blow up of the vertical emittance of bunches at the tail of the trains when reducing the injected emittance by about 10% was observed and cured with an increase of the octupole current to 45 A [6], keeping the effective tune spread constant. These observations indicate that both the chromaticity and the octupole current required to stabilise the electron cloud instability with BCMS beams are significantly higher than during the scrubbing run with nominal 25 ns trains. This difference may be attributed to the different train structure with shorter gaps as well as the increased bunch intensity, however quantitative estimations of these effects are currently not within reach. Since the requirements in terms of octupole strength and chromaticity are driven by electron cloud instabilities, it is expected that their strength could have been reduced significantly when operating with the 8b4e scheme, however no actions were taken in this direction, since the degradation of the beam quality at injection was considered acceptable.

An incoherent growth of the emittance of individual bunches is observed on long injection plateaus in all planes of both beams with a clear dependence on the bunch position in the train, which results in a measurable reduction of the specific luminosity up to 20% for bunches at the tail of the trains w.r.t. those at the head [7]. Such an effect was no longer observed with the 8b4e scheme [8].
Along with the incoherent growth, two mechanisms of sudden emittance growth were visible in most fills in the horizontal plane of both beams, an example is shown in Fig. 1. The 12 bunches in the witness area, experiencing a low damper gain to allow for tune measurement ($\approx$100 turns), are affected by the injection cleaning for the last injection. Their oscillations are visible in the ADTObsBox data [9] and the resulting emittance growth is visible for example at minute 42 of Fig. 1. These bunches are not used for luminosity production, but rather for diagnostics and background measurement, their emittances are therefore not a concern. If needed, the effect of the excitation on the emittance of the bunches in the witness region could be mitigated by increasing the corresponding gain for the time of the last injection. Decreasing the strength of the cleaning is not a favoured option since the last injection would become the most critical in terms of beam losses.
A coherent instability of the circulating beam is often observed when the injection cleaning is switched on, the resulting emittance growth is visible at minute 14 in Fig. 1. The cleaning window is tens of microseconds away from the circulating bunches experiencing the blow up, and the

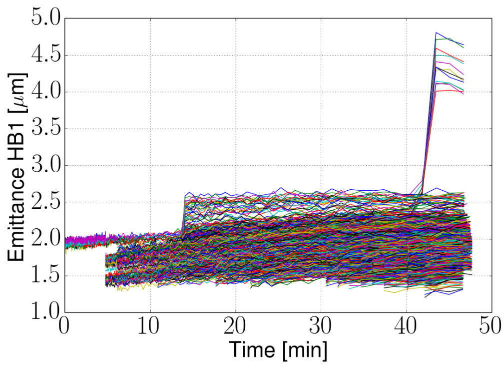

Figure 1: Evolution of the bunch-by-bunch emittances measured by the BSRT during a typical injection plateau with the BCMS filling scheme (Fill 6091).

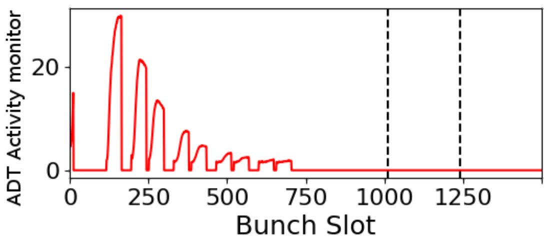

Figure 2: Bunch-by-bunch oscillation amplitude measured by the ADT Activity Monitor when the injection cleaning is switched on in the horizontal plane. The cleaning range is marked by two vertical dashed lines. A similar behaviour is observed in both beams, independently of each other.

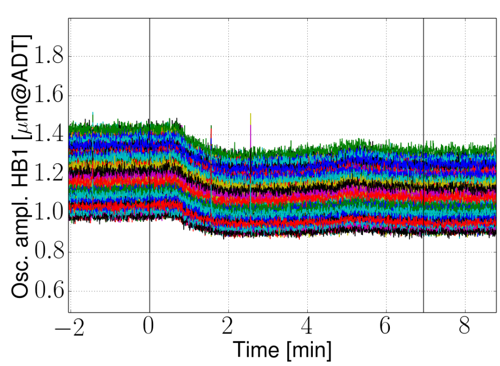

Figure 3: Evolution of the transverse oscillation amplitude of each bunch through the energy ramp measured by the ADT activity monitor in the horizontal plane of B1. A similar behaviour is observed in the other beam and plane. The beginning and end of the ramp are marked with horizontal lines.

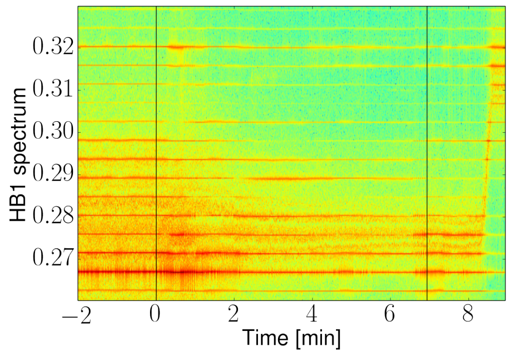

Figure 4: Transverse spectrogram obtained from the high sensitivity BBQ data during the energy ramp of fill 6396. The beginning and end of the ramp are marked with horizontal lines.

oscillation amplitude of the first bunches of the trains are not strongly affected by the cleaning, as shown in Fig. 2. The emittances of the first bunches of the train are also not affected [9], suggesting that the leakage of the cleaning to other bunches is reasonably weak and is properly damped by the ADT, thus avoiding emittance growth. Nevertheless, the leakage seems sufficient to trigger an instability that develops along the trains (Fig. 2) and results in a significant emittance growth of the trailing bunches. The emittance growth due to this instability was reduced to a level similar to bunch-by-bunch variations from the injectors when operating with the 8b4e filling pattern. While the instability triggering mechanism is not understood, the behaviour of the motion along the train as well as the strong mitigation thanks to the 8b4e scheme indicate that the electron clouds play a role in the instability mechanism.

RAMP

The typical oscillation amplitude of the individual bunches measured by the ADT activity monitor are shown in Fig. 3. The amplitude of the residual oscillation follows the slow variations of the ADT gain, the absence of fast growth of the bunches' oscillation amplitude in any of the ramp where this diagnostics was available, except for few single data points identified as an erratic in the acquisition chain, indicate that no coherent instabilities develop during the ramp. Nevertheless, it is not excluded that the beam is subject to significant sources of noise during the ramp, as suggested by the BBQ spectrogram in Fig. 4. It is unclear whether the noise lines are instrumental or are affecting the beam, in which case an emittance growth could be expected. Since a unexplained emittance growth is observed during the ramp [10], dedicated tests to assess the effect of different tunes during the ramp would be advisable.

TOP ENERGY

Single bunch stability

While the octupole strength needed to stabilise single bunches in standard operational conditions were in good agreement with models in 2015 [11] and 2016 [12], a discrepancy of about a factor 1.5 to 2.0 w.r.t. expectations

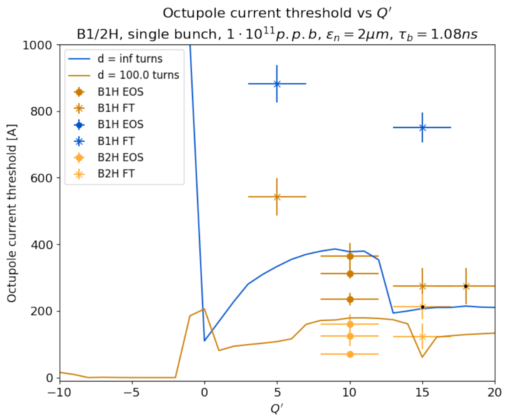

Figure 5: Instability threshold obtained by reduction of the octupole current for single bunches in different configurations, rescaled with the measured beam brightness to 10^{11} p per bunch and transverse emittances of 2 μm. All instabilities occurred in the horizontal plane, therefore the threshold in the vertical plane couldn't be measured. The predictions are based on the current impedance model and the Vlasov solver DELPHI. The yellow data points corresponds to configuration with a damping time due to the ADT of $\approx$100 turns, the two measurements marked with a black dot were performed with a higher gain corresponding to a damping time of $\approx$ 30 turns.

was measured consistently in the horizontal plane of B1 during several dedicated tests, as shown in Fig. 5. The same measurementd in B2 revealed overall a good agreement with the predictions, except for a measurement with high ADT gain which resulted in a degradation of the threshold that is not expected.
Figure 5 also shows measurements of octupole threshold in non-operational conditions, with either reduced ADT gain or low chromaticity. In all these configurations the discrepancy between model and observations is larger than a factor two. A large discrepancy was already observed in dedicated experiments probing the beam stability with low chromaticities in 2015 [11] and is not yet explained.

The rise time of the coherent instabilities affecting single bunches in operational configurations obtained by exponential fit of the newly implemented ADT bunch-by-bunch activity monitor data are shown in Fig. 6. While the average of the distribution is not incompatible with the predictions based on the impedance model, several instabilities were observed with rise times up to a factor $\approx$2 faster than the most pessimistic predictions. While slower instabilities with respect to the linear model can be explained qualitatively due to the effect of strong non-linearities present in the machine, faster instabilities can only be explained by an underestimation of the driving force, namely the effect of the impedance.

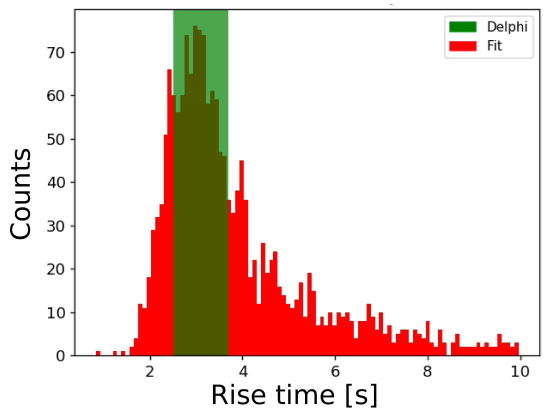

Figure 6: Rise times of coherent instabilities observed at top energy during the 2017 run computed based on an exponential fit of the transverse oscillation amplitude of individual bunches (ADT activity monitor) and normalised to a bunch intensity of 10^{11} p/bunch based on the FBCT bunch-by-bunch intensity measurement. The green shaded area shows the expectation based on the linear model, i.e. in absence of damping due to the tune spread.

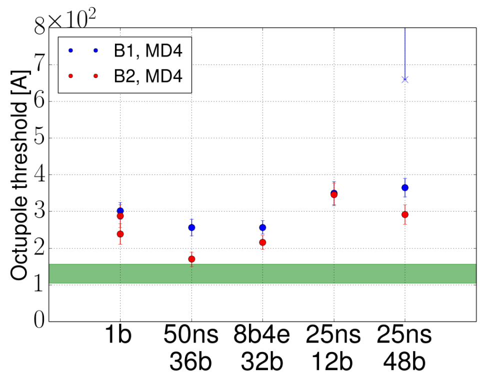

Figure 7: Instability threshold of different bunch train structures obtained by reduction of the octupole current at flat top, with a damping time from the ADT of $\approx$30 turns. The measured threshold was normalised to the measured bunch brightness based on the BSRT and FBCT bunch-by-bunch emittance and intensities to 10^{11} p per bunch and transverse emittances of 2 μm, assuming a linear dependence between the threshold and the bunch brightness. The predictions (green area) are based on a measured chromaticity of 18 ± 2 units and including the uncertainty on the measured emittance and bunch length.

Bunch train stability

An unexpected instability of the bunches at the head of the train was observed during MD blocks 2 and 3, the details of which can be found in [13]. It was however not observed in the last MD block in an experiment dedicated to its study. The mechanism for its disappearance remains to be understood, we rather focus here on the result of the last

MD block, mostly relevant for the operation in 2018. The instability threshold measured for different train structures are reported in Fig. 7, for non-colliding beams at flat top. The instability affected all bunches of the 50 ns and the 8b4e trains at a similar level of octupole current as the single bunch. The bunches at the tail of both the 12b and the 48b 25 ns trains became unstable with 10 to 20% more octupole current, indicating a contribution of the electron clouds to the beam stability of high energy beams.

Instabilities were observed at flat top in the horizontal plane of both beams during proton physics operation when reducing the beam brightness thanks to the 8b4e BCS scheme. While such an instability was not expected from the model, Fig. 8 shows that this observation is compatible with a factor 2.0 on the effect of the impedance, which is consistent with the threshold measured in MDs in absence of beam-beam interactions.

Two beam effects where ruled out as a possible source of the discrepancy since the tests were performed with filling schemes designed to avoid the simultaneous presence of the two beams in the common chambers. The impact of linear coupling could also be excluded by performing tests with injection tunes, featuring a large separation, together with the implementation of dedicated measurements and corrections. Both the rise time measurements and the measurements of the tune shift with the intensity [14] suggests that the impedance could be underestimated, motivating further beam based measurements. While the measurements and corrections of the non-linear optics lead to a significant improvement of the control of the amplitude detuning [15] and therefore on Landau damping, an important unknown in the evolution of the beam distribution in the different phases of the LHC cycle leads to large uncertainties on the evaluation of the strength of Landau damping, i.e. of the stability diagram. In order to gain control over this aspect of the beam stability, it is crucial to pursue the development of beam transfer function measurements [16] and of the halo monitor [17].

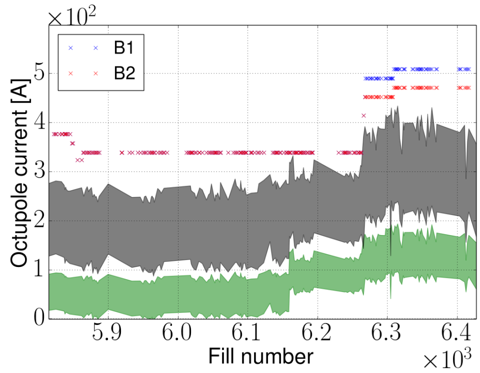

Figure 8: Octupole threshold expected based on the impedance model, the measured convoluted emittance based on the luminosity measured in ATLAS and CMS, as well as the intensity measured by the FBCT, taking into account the spread in individual bunch brightnesses and bunch length as well as a chromaticity of 15±2 units (green shaded area). The contribution of long-range beam-beam interactions to the tune spread was taken into account in the estimated octupole current requirement. The gray shaded area shows the same quantity, multiplying the effect of the impedance by a factor 2.0 in the model. The octupole strength used during physics operation operation for the two beams is shown with crosses.

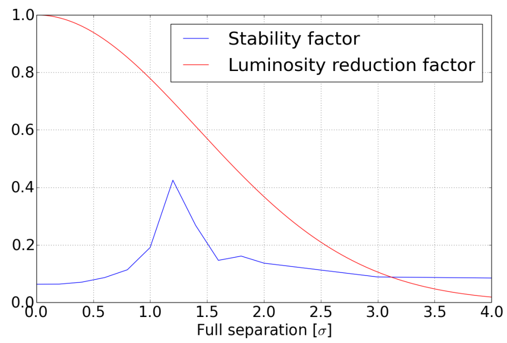

Figure 9: Luminosity reduction factor (red) and coherent stability factor (blue) as a function of the separation between the beams at the IP corresponding to the operating conditions with 8b4e scheme. The levelling range of IPs 1 and 5 extended up to full separation of $\approx 1.5\ \sigma$.

Luminosity levelling

When colliding beams with a transverse offset, the tune footprint varies strongly due to the modification of the beam-beam force experienced by the beams, in particular it leads to a minimum of Landau damping close to a full separation between the beams of $\approx 1.5\ \sigma$ [18]. This minimum is illustrated in the operational conditions of the 2017 run with 8b4e beams in Fig. 9. The margin for coherent stability is represented by the multiplicative factor that would bring all the coherent modes of oscillation to stability. The levelling range extended up to the minimum of stability in several fills, however no instabilities were observed since the stability factor remains below 0.5, corresponding to a factor 2 margins with respect to the instability threshold. This margin was however reduced during Van Der Meer scans, in particular due to the absence of long-range beam-beam interactions contributing significantly to the tune spread. Also, a reduction of the octupole current to 300 A requested by the experiments to minimise non-Gaussian tail formation reduced significantly the effect of Landau damping. As a result, coherent instabilities were observed during scans in IPs 2 and 8 (Fig. 10). In order to fulfil the various constraints during Van Der Meer scans, in particular the minimisation of the octupole current as well as the absence of other beam-beam interactions than the single head-on interaction the experiment in order to avoid dynamic beam-beam effects [19], it is advisable to

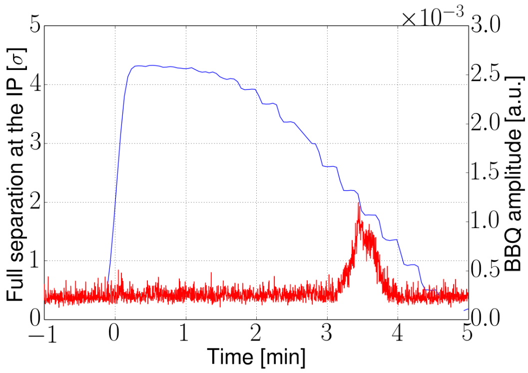

Figure 10: Separation between the beams at IP8 (blue) computed based on the luminosity measurement and beam oscillation amplitude measurement from the high sensitivity BBQ (red) during a Van der Meer scan for LHCb.

profit from the larger β^* w.r.t. regular physics conditions to retract the collimators accordingly, thus reducing significantly the impedance.

BUNCH-BY-BUNCH TURN-BY-TURN POSITION MEASUREMENT

The ADTObsBox, allowing for treatment and storage of the bunch-by-bunch turn-by-turn positions became operational during the 2016 run, however several features became available during the 2017 run and are briefly described here. The amplitude of oscillation based on an estimation over about a thousand consecutive turns is published every 0.3 second. The information is brought to the operator via a fixed display and logged via the CALS, allowing for a clear resolution of of the instability timing, where the other diagnostics failed to provide bunch-by-bunch informations (BBQ) or sufficient time resolution (BSRT).
An internal trigger based on running sums of different length allows for an improved robustness of the instability detection and is now connected to the LHC Instability Trigger Network (LIST), along with the BBQ and the head-tail monitor. The full stream of data being to large for full storage, only subset of data can be saved from a rolling buffer up to a maximum of 64 thousand turns, trigger upon request or via the LIST. The data is currently saved on a local storage along with the ADTObsBox, it is however planned to port it to the next generation of CALS when available.

CONCLUSION

The performance of the LHC during the 2017 run was not limited by collective effects, nevertheless the presence of electron clouds imposes the use of strong mitigations measures at injection. Dedicated experiment suggests that electron clouds may have an impact on the beam stability at top energy, however the main driver for collective instabilities remains the impedance. The octupole strength required during the 2017 run suggests that the margins are insufficient to cope with the beam brightness promised by LIU. This observation is in clear disagreement with the results obtained in 2015 and 2016, it is therefore crucial to invest the necessary time to understand the reason behind this behaviour, in particular by direct measurement of the effect of the impedance, as well as pursuing a complete understanding of the machine non-linear model as well as of the beam distribution needed for an accurate estimation of the Landau damping.

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