HOW TO FIGHT COLLECTIVE EFFECT LIMITATIONS

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Abstract

With the LHC operation at 6.5 TeV and with 25 ns bunch spacing after LS1, the understanding and control of beam instabilities in 2015 has become at least as challenging as during Run 1 and a crucial point to be followed to guarantee a smooth intensity ramp up. As expected, electron cloud appeared to be the dominant instability driver during the early phases of Run 2 with multi-bunch operation. The instabilities caused by electron cloud at injection limited the speed of scrubbing and also prevented the efficient use of doublets. Later on, at a more advanced stage of machine scrubbing, beam coupling impedance and beam-beam effects also started to play a role, as well as their interplay with the residual electron cloud. In this talk the main observations of beam instabilities in the LHC during 2015 will be reviewed, highlighting the key tools used for the their monitoring and control. Based on our present understanding, we will then propose settings and operational procedures for operation in 2016 as well as the required diagnostics for an improved detection of potential instabilities. Finally, an outlook on open studies and future potential mitigation measures will be provided.

CONTEXT AND OUTLINE

With the ultimate goal of the LHC to provide the maximum integrated luminosity with high intensity stable beams, the limitations imposed by coherent beam instabilities become an important factor to be taken into account.

In this article we will summarize the evolution and the main observations of coherent beam instabilities in the LHC throughout 2015. We will focus on instabilities induced by electron cloud which was the dominant source of instabilities in the past year. These occurred predominantly at injection during the scrubbing periods but also appeared to have some impact on the beam stability at top energy (6.5 TeV).

The main observations along with the conclusions on beam stabilisation from an operational point of view will be reviewed. The key diagnostic tools for beam instability observation will be highlighted. Finally, we will mention the main challenges expected in terms of beam stability for 2016 and outline some strategies and proposals on how to tackle these during the next year of operation of the LHC.

TIMELINE OF INSTABILITY OBSERVATIONS DURING 2015

The main challenge in 2015 was operation at an energy of 6.5 TeV and the deployment of the 25 ns beam. As expected, this beam led to a strong build-up of electron-cloud in the machine which gave rise to several detrimental effects, among them, strong beam quality degradation and coherent instabilities.

The year can be categorised into different phases, starting with the first scrubbing periods using both the the 50 ns and the 25 ns beam right after machine commissioning followed by the 50 ns intensity ramp-up. Further scrubbing was then pursued using exclusively the 25 ns beam from the beginning of the second half of the year as the scrubbing efficiency had rapidly decreased for scrubbing with the 50 ns beam. After this, there was the 25 ns intensity ramp-up which was finally followed by physics with the 25 ns beam at flat-top during autumn.

The first periods of scrubbing with the 25 ns beam were dominated by strong coherent instabilities driven by the e-cloud. It was not possible to inject and to store long batches and it became necessary to step back in the number of injected bunches per batch from the targeted 144 bunches down to 24 bunches to suppress the e-cloud sufficiently in order to get the beam injected and stored for some time. During this stage, some experience was gained in the machine settings and beam treatment. Gradual machine optimisation together with scrubbing finally allowed to inject batches of 144 bunches and store them for enough time to generate enough heat load that would provide conditioning of the machine [1].

Even though injection and the store of a large number of bunches eventually became possible, the beam still suffered from instabilities which led to strong emittance blow-up of bunches within the beam. This degraded the beam quality and strongly compromised scrubbing efficiency. Several settings and mechanisms were found to

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be responsible for this blow-up and we will summarize the main findings in the next section. Identifying the ideal machine settings and learning how to operate the machine and keep the beam stable despite the presence of the e-cloud was an important landmark. Thanks to this understanding and continuing efforts during scrubbing, finally, up to 2400 bunches were injected and stored with a good beam quality and lifetime. This allowed for the intensity ramp-up with 25 ns beams and finally bringing the 25 ns beam stable to top energy at 6.5 TeV and into physics.

Being able to operate the machine with stable beams during injection and along the ramp despite the presence of e-cloud at the limit of the cryogenics capacity, scrubbing could be performed efficiently during physics [2]. The beam intensity was continuously increased during this time remaining just within the limits of the cryogenic capacity. Hence, the normalised heat load decreased over a period of six weeks of physics operation by a factor two. This evolution is plotted in Fig. 1.

It appears that this conditioning also had a strong impact on the beam stability at flat-top. There were two MD blocks scheduled, one before and one after the 25 ns physics run[1]. During these MDs, the stability of bunch trains was investigated. For this, a batch of 72 bunches was injected and brought to top energy with active Landau octupoles to ensure stability. At flat top, the Landau octupole current was gradually decreased and the threshold current for the first occurrence of instabilities (detected by the BBQ signals) was recorded. This was compared to the predicted threshold current, computed from the DELPHI Vlasov solver [3] based on the machine impedance. It was found that the required octupole current was approximately a factor five higher than what was predicted from the pure impedance model. After this period on the other hand the required octupole current matched these predictions rather well. This is illustrated in Fig. 2. From this it can be deduced that before operation of 25 ns in physics there was some additional source for beam destabilisation in addition to the pure machine impedance. This source disappeared after the 25 ns physics run. Comparing this observation with the conditioning that took place simultaneously, it can be concluded that most likely the machine had been scrubbed to a level of e-cloud which was no longer intense enough to significantly contribute to enhancing instabilities for batches of 72 bunches. This is strongly supported by measurements of the bunch-by-bunch stable phase which were done in parallel. The stable phase shift is a measure of the electron cloud density. During the first MD a strong stable phase shift was observed along the batches showing a typical e-cloud signature. During the second MD, no sign of stable phase shift was observed. Similar measurements octupole current threshold were done with single bunches for which a good agreement was reached throughout the year (see [4]) indicating that any discrepancies must originate from a multi-bunch effect.

[1] In fact, the first MD took place after a couple of weeks from the start of the 25 ns run. However, in this first phase the pace of the ramp up was limited by problems with the QPS non radiation hard electronics

KEY FINDINGS FOR OPERATION WITH RESPECT TO BEAM INSTABILITIES IN 2015

The key findings in 2015 to help ensuring beam stability will be summarised from injection to flat-top.

First, it became clear that to reach longer batches of 25 ns beam scrubbing was absolutely essential to condition the machine and store them at injection energy without suffering blow-up and degradation of the beam. In addition the scrubbing exercise itself helped substantially to improve the understanding of the beam and the machine in the presence of e-cloud from an operational point of view. It was found that the e-cloud has a strong impact on the beam stability at injection as well as at flat-top which is supported by the observations and measurement made during the MDs. Settings and operational procedures were found to keep the beams stable throughout the cycle and bring them into collision.

One of the very crucial devices for beam stability was the transverse damper. It is being used e.g. during injection for fast damping of injection oscillations or for the abort gap cleaning. However, it was found that its performance also had a critical impact on the beam stability and any type of unoptimised configuration of the transverse damper would potentially lead to emittance blow-up [1]. As such, the transverse damper itself is a critical device that needs careful setup and monitoring during operation.

The relevant machine settings important for beam stability were established during scrubbing and were required for physics at flat-top. They are summarised in table 1. Attempts were made to lower the chromaticity or octupole currents but these rendered the beam unstable so that the settings were maintained up to the end of the 2015 proton run.

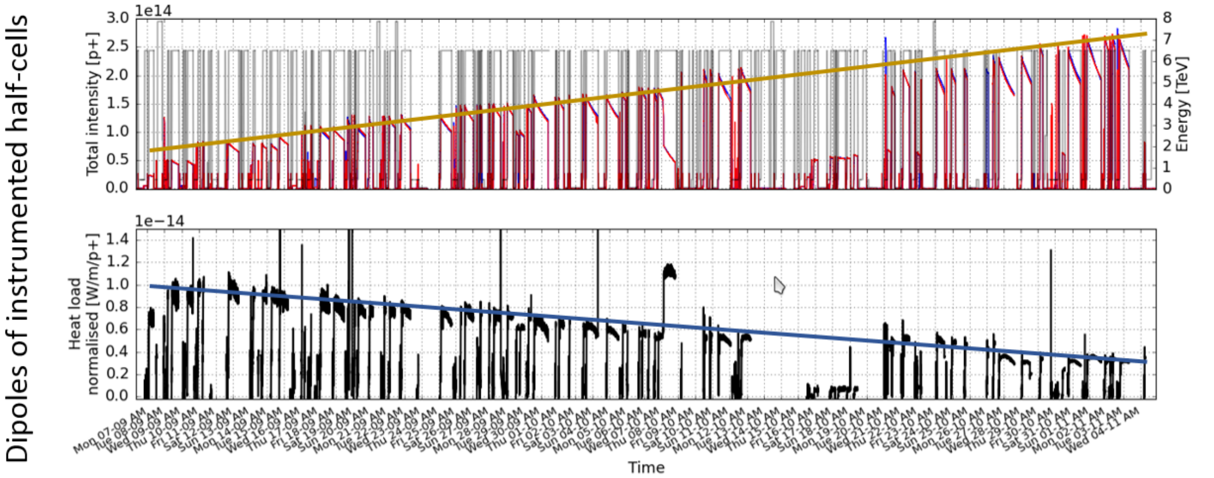

Figure 1: Observation of conditioning during 25 ns physics operation at top energy. The top plot shows the evolution of the intensity which was set to run at the limit of the cryogenics. The bottom plot show the normalised heatload in the dipoles.

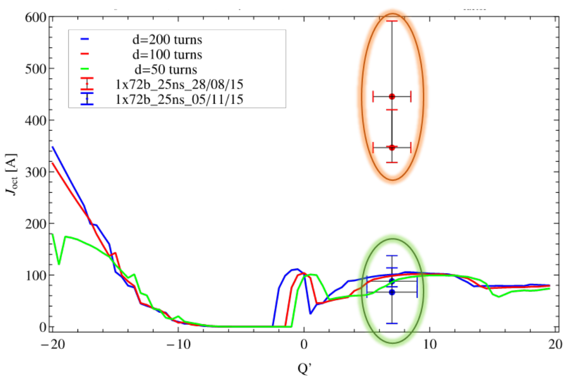

Figure 2: MD measurements (crosses) compared to predictions from simulations (solid line). Plotted is the required octupole current for beam stabilisation vs. chromaticity. The orange circle indicated measurements before the 25 ns physics run. The green circle shows the measurements made after this period.

Q'_h	Q'_v	Octupole settings	Damper gain
15	15/10	-1.5 (knob value) ≅ 20 A	0.25
15	15/10	550 A 475 A during squeeze	0.25

Table 1: Machine parameters used throughout 2015 to ensure beam stability at injection (top) and at flat-top (bottom).

As a result of the large tune spread induced by the high settings in chromaticity and octupole currents, a decrease in beam lifetime was observed. For this reason it was proposed some time in August to lower the vertical tunes. Simulations later revealed that this tune spread, if combined with e-cloud in the dipoles, indeed leads to particles crossing the third order resonance [5]. This is depicted in Fig. 3. As a consequence, the vertical tune was lowered and the beam lifetime was indeed recovered as illustrated in Fig. 4. In the course of this, also the horizontal tune was lowered so that finally the new working point at injection was Q_h=64.275 and Q_v=59.295.

Having changed the working point, the tune separation between the horizontal and vertical tunes decreased by 33% from 0.03 to 0.02 units. An observation, that was made during injection, was that there appeared to be a strong correlation between tune separation and emittance blow-up. During injection the horizontal and vertical tunes approach each other due to the inductive part of the Laslett tune shift [6]. If this shift is not corrected, depending on the coupling in the machine, it is believed that the beam can become unstable. One potential mechanism for this could be loss of Landau damping [7]. This will lead to emittance blow-up. This was found and also checked operationally. Fig. 5 shows an example of a fill where the tunes drifted toward each other during injection and the beam eventually became unstable. The fill was dumped and then refilled without any further changes. This time the tune separation was maintained. The beam remained stable as can be seen in Fig. 6. A simulation campaign was started to

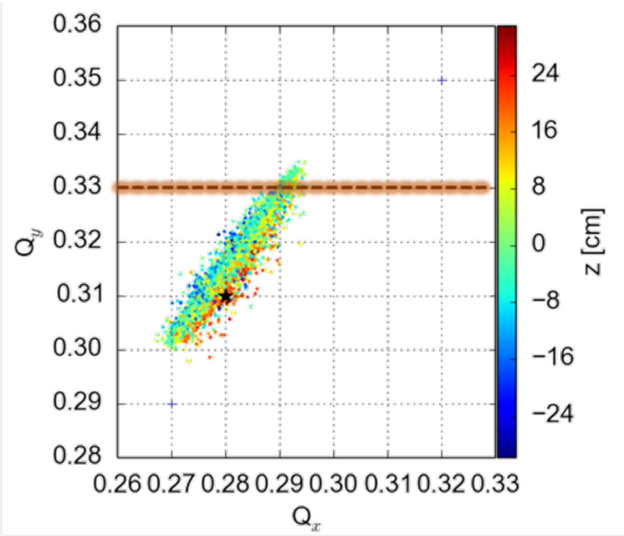

Figure 3: Simulation containing the effects of chromaticity and octupoles according to the operational parameters in addition to the e-cloud in the dipoles at an estimated density. The simulations clearly reveal the crossing of the third order resonance for these machine parameters.

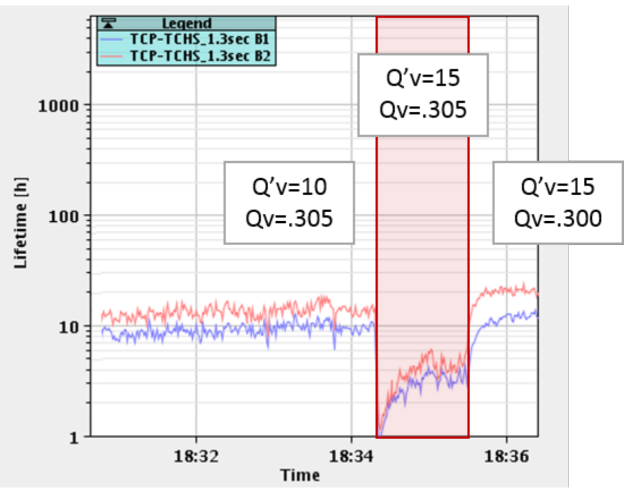

Figure 4: Measurement of the beam lifetime for different working points. Lowering the vertical tune has a significant beneficial impact on the beam lifetime as expected which is expected when comparing with the simulation results.

investigate the impact of coupling on the beam stability. First results confirm that linear coupling can negatively impact the octupole threshold currents [8]. The minimum separation necessary for the beam to remain stable depends on the coupling in the machine.

DIAGNOSTICS USED FOR BEAM INSTABILITIES

Some of the key diagnostics used throughout the year in order to characterise beam instabilities are described below.

One of the fundamental diagnostics is the Fast Beam Current Transformers (FBCT) which monitors the bunch-by-bunch intensity. It helps to characterise the bunch losses and was used to detect e-cloud signatures and to assess the beam quality evolution during a fill.

The Beam Synchrotron Radiation Telescope (BSRT) provides transverse beam size measurements on a bunch-by-bunch level. From this, the bunch-by-bunch emittance can be calculated. This allows the detection of instabilities that lead to emittance blow-up across the batch. The bunch-by-bunch resolution helps to locate which bunches are affected by the instability giving some hints on the instability mechanism itself. However, the instrument is rather slow since it scans at a rate of 10 Hz. This makes it difficult to make correlations with events that may have an impact on beam stability. Nevertheless, the BSRT was a very important tool used in 2015 to check the beam quality and detect beam degradation. It was used to prove the importance of the correct configuration of the transverse damper or the detrimental effect of coupling on beams with weakly separated tunes.

Stable phase measurement became available with the longitudinal OBSBOX [9] having been brought into operation. This allows to measure the bunch-by-bunch synchronous phase shift which gives extremely valuable information in particular about the e-cloud activity along the batch. The e-cloud density can be estimated on a relative scale and the overall e-cloud can be quantified by the strength of the typical e-cloud signature which features strong shifts of the synchronous phase towards the end of a batch. The stable phase measurements can also be used to provide a more accurate measurement of the heat load produced from e-cloud.

Wire scanners were used to characterise the beam emittance received from the injectors but can not be used for the full beam. The BBQ was used to detect instabilities. This can be seen as an exponential growth in the amplitude of the BBQ signal. From this, estimations on the risetimes of the instabilities can be made. However, the signal is integrated along the full beam which makes the interpretation of the signals difficult when there are many bunches. On the other hand, it is very useful in detecting the onset of an instability. This

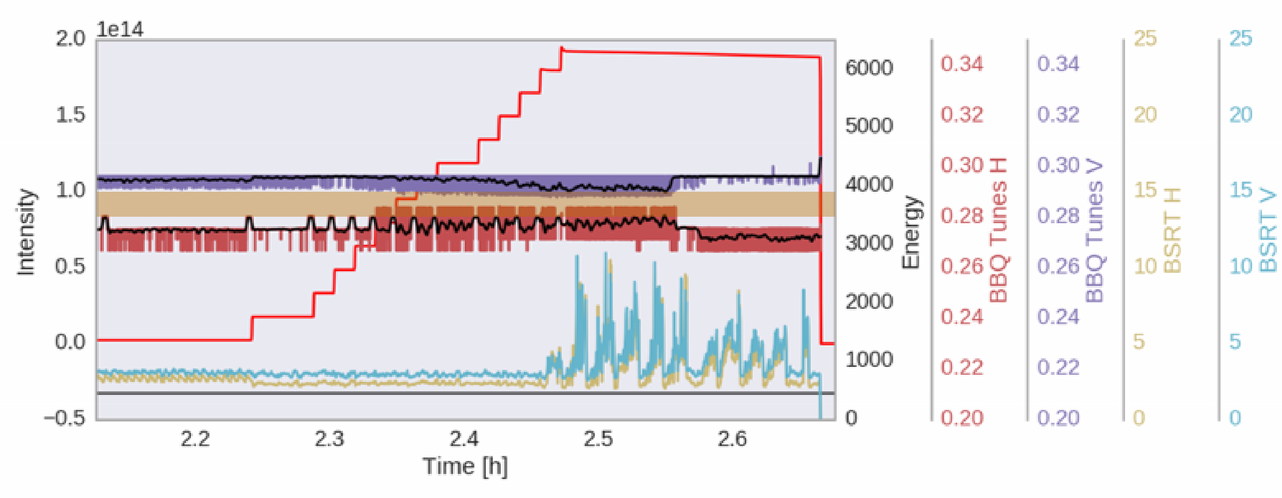

Figure 5: The plot above shows the vertical and horizontal tunes approaching each other during injection. If the separation falls below a certain level the beams become unstable which can be seen from the BSRT signals. The coupling coefficient was measured to $C^{-} \approx 0.004$.

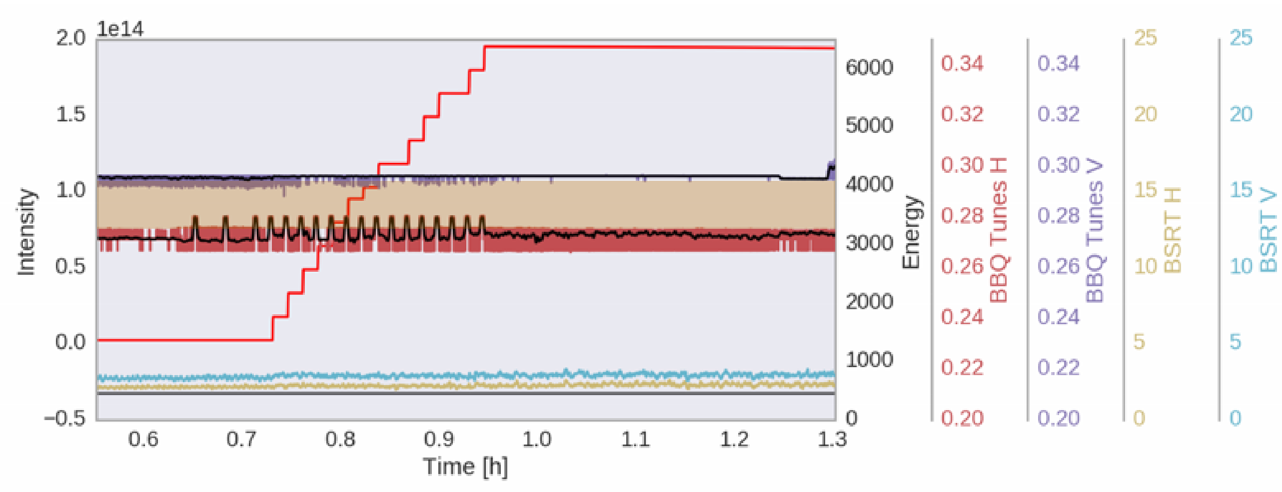

Figure 6: The plot above shows the vertical and horizontal tunes during injection when they are corrected. The beam remains stable. The coupling coefficient was measured to $C^{-} \approx 0.004$.

is why it is used to trigger other detection devices such as the headtail monitor.

The headtail monitor was brought into operation during the second half of 2015 and was connected to the white rabbit network later in the year. This allowed the acquisition to be triggered upon detection of an instability in the BBQs. The headtail monitor in principle is a scope with a sampling rate of 10 Gs/s recording turn-by-turn traces of the full beam for up to 11 turns. The instrument together with the trigger is extremely powerful in detecting and distinguishing coupled from single bunch instabilities and allows to zoom into the bunch to observe intra-bunch motion. This is an important piece of information to be compared with predictions from simulations in order to assess whether the instability mechanism is correctly modeled and understood. Moreover, it provides insight in the frequency of the instability which is a vital information if considering the design of a wideband feedback system for damping intra-bunch coherent motion. Fig. 7 shows a snapshot of an instability taken with the headtail monitor. The intra-bunch structure is clearly visible and matches well with the predictions made with simulations.

Finally, the ADT OBSBOX [9] was connected towards the end of the year and first data samples were taken. The OBSBOX has a huge buffer which continuously acquires data from the pickups of the transverse damper (ADT). That way, bunch-by-bunch, turn-by-turn data can be acquired which resolves the location and the time of the occurrence of instabilities which

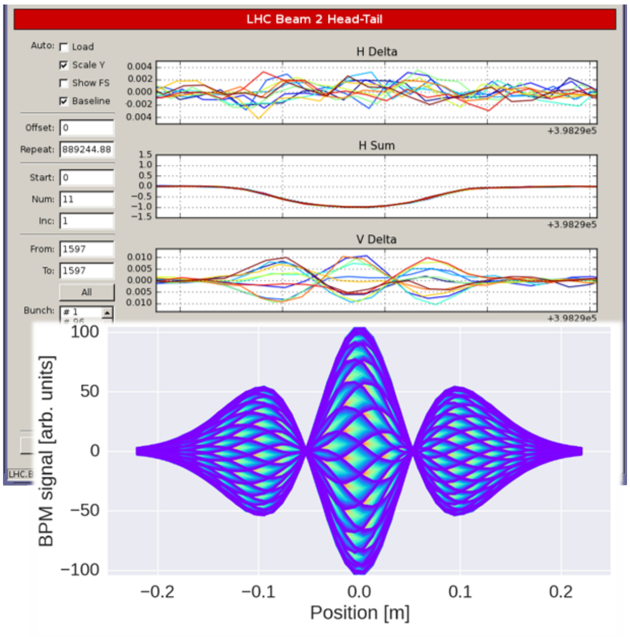

Figure 7: Snapshot of a single bunch instability taken with the headtail monitor. The plot below shows the predicted signal from a PyHEADTAIL simulation [10] indicating that the simulation model well reproduces the observations in the machine.

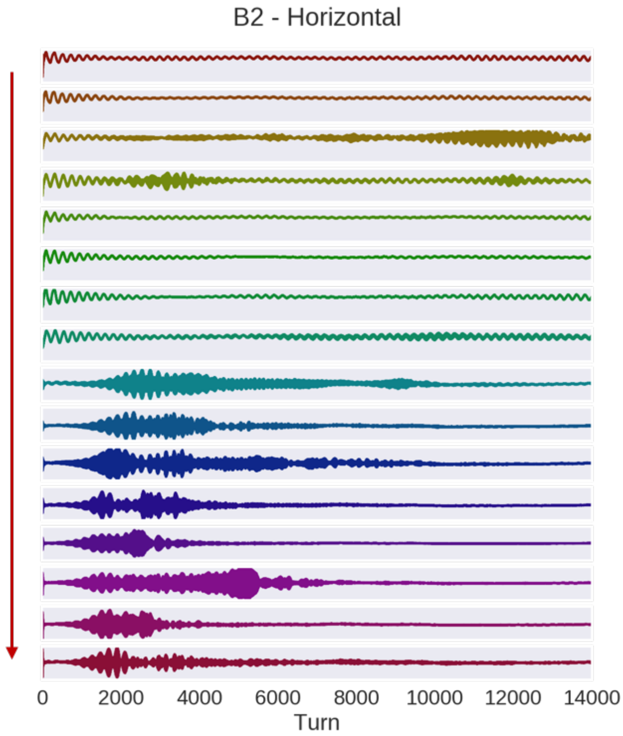

Figure 8: Signal from the ADT pickups from 16 bunches after injection. Unstable bunches are clearly detectable towards the end of the batch (bottom).

will help to improve the understanding of the source and the mechanism of the observed instabilities. Knowing where and when in the beam coherent activities were observed will enable correlations to be made with changing machine parameters, for example, or instability triggering events that were undetected so far. The signals will deliver growth and damping rates, tunes, frequency composition of coherent motion all on a bunch-by-bunch level. A reduced version of this instrument was already used during scrubbing where 16 bunches were acquired right after injection of each batch for up to 30000 turns roughly. A snapshot of such an injection is shown in Fig. 8. The ADT OBSBOX still needs some setup and work in particular with regards to data streaming and storage. But it has a high potential in becoming a powerful tool to significantly help in advancing the understanding of instabilities in the LHC.

MAIN CHALLENGES EXPECTED FOR 2016 - STRATEGIES AND PROPOSALS FOR OPERATION

Based on the experience from the 2015 run, we will state the main challenges seen for 2016 in terms of instabilities. We will then propose strategies and operational procedures to combat potentially arising beam instabilities.

Main challenges for 2016

The main challenges for 2016 will be the intensity ramp-up to a total of 2748 bunches while pushing the intensity per bunch as far as 1.3e11 ppb (or what can be delivered from the injectors). This has to be achieved in the presence of e-cloud, which makes the understanding of the beam dynamics and the handling of the beam a lot more involved. There is hope that further conditioning will mitigate e-cloud in the dipoles but it is expected that e-cloud will continue to persist in the quadrupoles and in the triplets. Consequently, an understanding will have to be established how to run the full machine with high intensity bunches despite the presence of this e-cloud.

The new optics will move towards a tighter squeeze in the IPs down to a β^* of 40 cm. This will lead to high β-function of several kilometres in the triplets. Although the impedance in the triplets is not expected to have a large impact, any unconsidered impedance will be strongly enhanced with the new optics. E-cloud is also known to exist in the triplets and the larger beam will stronger sample the non-linearities of the e-cloud fields which leads to stronger distortions of the tune footprint from e-cloud. This may lead to unexpected effects in terms of beam stability. Finally, non-linear optics effects in the triplets will also have a stronger impact with the larger beams. In the new optics the TCSG collimators will have to be moved closer to the beam by 0.5 σ (from 8 σ to 7.5 σ). From the impedance model this is not expected to have a significant impact on beam stability, however. Also the long-range beam-beam separation will decrease from 11 σ down to 10 σ. The dynamic aperture will remain above 6 σ even for high settings of chromaticity and octupoles so that no detrimental effects are expected from beam-beam, either.

The BCMS beam which is a high brightness variant of the nominal 25 ns beam comes with a lower emittance at comparable intensities with a higher potential in peak luminosity. The low emittance leads to less effective Landau damping which may render the beam significantly more unstable. The beam-beam parameter is strongly enhanced and gives a tune footprint which is comparable to the situation of the 2012 run of the LHC. The dynamic aperture is significantly reduced and incoherent losses become important causing poor lifetimes and potential loss of Landau damping. Moreover, the low emittance beams are also more subject to e-cloud effects. As such, the BCMS beam is seen as the most challenging item for the 2016 run and should be tested once the nominal beam is stable and operational.

Strategies, procedures and fall-back solutions

Apart from the challenges mentioned above, 2016 will also bring several improvements. The machine has undergone a long continuous period of conditioning [2]. This state should be quickly recovered after the year-end-technical-stop (YETS) which will ease the start up compared to 2015. Some experience has been gained in the handling of the cryogenics system suffering from the heatload induced by e-cloud. Therefore, operation should become more reliable. Faulty elements such as TDI8 were replaced removing an important source of impedance at injection [11].

For 2016 as a general strategy it must be clear that a good control of the machine is the basis upon which one can hope to maintain control over beam stability. In particular, it will be important to have a good monitoring and control over the damper gain, chromaticity, tunes and coupling. These parameters have proven to have a crucial impact on beam stability. Important diagnostics brought into operation in 2015, specifically for the characterisation of instabilities, were the head-tail monitor and the ADT OBSBOX. These tools are still in an early phase of deployment and need more development and configuring to be invested in 2016 in order to exploit their full potential.

The proposed procedure is then to complete intensity ramp-up with the standard 25 ns beam. Once this beam is stable and operational one could think of deploying the BCMS beam for increased luminosity. The start-up would be done with the established settings for chromaticity, octupoles, damper gain and working point. These settings should be probed at an early stage to see whether chromaticity and octupoles could be lowered in order to gain some margin in dynamic aperture. The intensity ramp-up with 288 bunches will then be performed with settings based on measurements with the machine state as it emerged from the YETS. In any case, chromaticity and octupoles should be lowered as far as possible once in collision when the stabilising head-on beam-beam effects become dominant. This will need to be compatible with ensuring stability of the non-colliding bunches which do not benefit from the Landau damping granted by the tune spread from the head-on collisions.

In case instabilities do continue to appear the chromaticity can be further raised – in particular with the new working point – beyond 15 up to 20 units or more. This was done in 2015 and did not lead to any noticeable problems. Long bunches will help to relax both instability effects and heatloads and one can step back in bunch length as far as possible to relax the requirements on beam stability. The transverse emittance is another important parameter especially for the BCMS beam. It is likely that this beam will not be stable initially (indeed this beam could be unstable even in the absence of electron cloud based on 2012 scaling) and one possible strategy is to try and get some controlled emittance blow-up from the injectors to create lower brightness variants of the BCMS with emittances somewhere between the standard 25 ns beam and the nominal BCMS. This is a staged approach where the nominal BCMS beam can be matched gradually allowing for an incremental optimisation of the beam and of the machine.

The wideband settings of the transverse damper should be tested at an early stage to assess the potential for beam stabilisation. And finally the second order chromaticity Q'' will be investigated as a potential knob for enhanced beam stabilisation.

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