INSTABILITIES AND BEAM INDUCED HEATING IN 2016

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Abstract

Coherent instabilities have been regularly observed during operation in 2016. Issues relating to linear coupling at injection in 2015 were no longer observed in 2016 due to new applications that were made operational, however new instabilities that caused emittance blowup were sporadically observed in Adjust and Stable Beams that do not yet have a full explanation. Several MD's were performed that tried to make measurements of these instabilities, while also shining new light on some new stabilising mechanisms at the end of the squeeze. The latest issues with beam induced heating will also be discussed.

INTRODUCTION

Many instabilities were observed throughout 2016, many that were able to be cured quickly thanks to improved diagnostics and a better understanding of the relationship between linear coupling and collective effects, and others that were able to be mitigated but whose exact mechanism requires further study.

Several MD's were also carried out in 2016 that highlighted the importance of non-linear corrections in the insertion regions (IR's) as well as testing new possible stabilising mechanisms in the LHC. The effect of the amplitude detuning from non-linearities was negligible in 2015 when running with $\beta^* = 80$cm. But when squeezing to smaller values the beta-function in the triplets become much larger. This creates amplitude detuning which is not corrected. The same can be said for Q'', which has a contribution from the lattice for smaller values of β^*. Tune shift measurements were also carried out to test the DELPHI prediction for collimator running scenarios in 2017.

Several components also suffered more from beam induced heating in 2016. While none of the components limited performance, some of the more seriously affected will be described with plans on future mitigation.

These proceedings will start by providing some detail on the addition of linear coupling to the stability model, before describing observations in each stage of the machine cycle. Single bunch and single beam measurements will also be shown before an update on the beam induced rf heating will be provided.

LINEAR COUPLING

In 2015, many issues were observed at injection that appeared to be related to linear coupling. These issues arose when the tunes drifted closer together whilst injecting and the closest tune separation ($|C^-|$) was left uncorrected.

Many simulations into the effect of linear coupling on transverse stability were performed during the technical stop at the end of 2015 [1, 2]. Figure 1 shows the tune footprint from Landau Octupoles at 6.5 TeV (plotted to 4σ amplitude) for three different values of $|C^-|$ where for each case it has been rematched to collision tunes (which is what happens in the machine when coupling is increased with the tune feedback on). The black point marks a typical coherent mode that would need to be damped in both x and y (this can also be shown by a stability which is the more complete way of showing the same damping mechanism, but for simplicity just the footprint is shown). It can be seen that the detuning coefficients are strongly modified in this case, which can easily lead to a loss of Landau damping as the spread no longer covers the coherent mode. This can provide an increase in the required octupole current for stabilisation by up to a factor 5 for intermediate values of $|C^-|$.

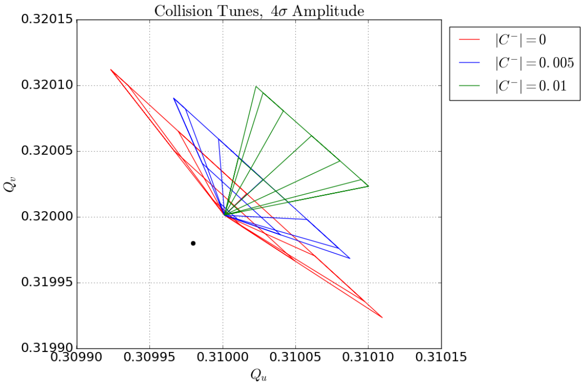

Figure 1: Tune footprint tracked in MADX to 4σ for different values of $|C^-|$ with a typical coherent unstable mode represented by the black point. For stabilisation to occur the tune spread of the bunch has to cover the coherent mode.

This mechanism was also verified by measurements made in the LHC during commissioning in early 2016 [3]. The global coupling was increased to $|C^-| = 0.01$ and the tunes were slowly moved closer together with $J_{oct} = 283$A. It was found that the bunch became unstable with a factor 3 more octupole current than is required. This verifies that the mechanism itself can have a strong impact on the transverse beam dynamics.

At injection in 2016, two vital applications were developed to prevent issues related to linear coupling. The first tool was developed by M. Schaumann and corrects the Laslett tune shift during the injection process [4]. The tool calculates the approximate shift that is expected as the beam intensity increases and then ensures that the tunes remain well separated [5]. The second tool was developed by T. Persson [6] and corrects the $|C^-|$ when the probe is present just before the injection process. No further issues related to linear coupling were observed at injection due to these two applications.

INSTABILITIES IN OPERATION

With less than 100 bunch trains (72b or 2x48b trains) with 25ns spacing coming from the SPS due to issues with the TIDVG, electron cloud was not going to be as dominant an effect as it was in 2015. The strategy in 2016 was to begin with parameters that would safely allow good emittance and intensity transmission from injection to collisions, and then try and check chromaticity and octupoles margins at several points throughout the year. Chromaticity is effective at stabilising electron cloud instabilities, octupoles can provide the tune spread which is required for Landau damping of the unstable modes. However in reality, a combination of the two is needed in the presence of a strong transverse feedback (ADT).

Injection

Initially the nominal beam was in operation with $\epsilon_{x,y}$ = 3.5um. With $Q' = 15/15$ and J_{oct} = 20A, injection was going very smoothly with no emittance blowup.

When the full BCMS beam was deployed with emittances of $\epsilon_{x,y}$ = 1.5um, emittance blowup was observed in the horizontal plane of both beams. This was due to a reduction in the tune spread because of the reduction in the emittance. Therefore J_{oct} = 40A was required to account for ≈ half the emittance. This cured all observed instabilities and allowed clean injections.

Measurements of the margin performed towards the end of 2016 showed very little margin for a reduction in chromaticity or octupoles, however a test was performed in a MD with an 8b+4e beam in which the machine was able to be completely filled with J_{oct} = 6A and $Q' = 5/5$ with no instabilities being observed [7]. This confirms that all the issues seen at injection are related to electron cloud as this observation matches what is expected to stabilise an instability caused by impedance only.

Ramp

Emittance blowup was observed shortly after TS2 in both B1H and B2H and it could be traced to exactly the start of the ramp. The issue was caused by a reduction in chromaticity that is linked to the correction of the b3 snapback after a pre-cycle [8]. Typically this is well corrected (as no issues had been observed before from this effect) but it is likely that the corrections were more accurate for fills following a ramp-down rather than a pre-cycle. The issue was cured by ensuring that the chromaticity remains higher during the early stages of the ramp. However it is not currently known why it became an issue after TS2.

Flat Top

At flat top, a short MD was performed during commissioning to verify the stability threshold with the 2016 flat top collimator settings (β^* = 3m). This measurement showed that the stability threshold for a single bunch agreed with the prediction from DELPHI [9], which is that for $Q' = 9/9, N_b = 1.2e11$ppb, $\epsilon_{x,y}$ = 2um, the threshold octupole current is $J_{oct} \approx$ 80A.

During operation no issues were observed at flat top, although margins were not checked at all throughout 2016. Tune shift measurements along the batch were performed which allowed a first point on the level of local electron density at 6.5TeV. It was shown to be smaller than 4e-4 in both beams and planes [10], however with large error bars.

Squeeze

During the squeeze, maintaining control of the coupling is critical due to the reduced tune separation. Observations of instabilities that could have been related to coupling were observed both for single bunch fills and multi-bunch fills. During fill 5332 (a 600 bunch fill during the intensity ramp up after TS1), instabilities were observed shortly after reaching β^* = 40cm [11]. It was noted that for $\beta^* \leq$ 45cm, the $|C^-|$ calculated from the BBQ showed high values. While this measurement cannot be trusted for high beam intensities, it can be used as an indication that something in the machine changed at this point.

The next fill was therefore used for optics measurements which verified that there was one unmatched coupling point during the squeeze which was at β^* = 40cm, which corresponded to $|C^-| \approx Q_{sep}$ [12]. These values are large enough to cause instabilities.

Once these corrections were input, the following fills showed no sign of similar instabilities.

Adjust

Emittance blowup was observed sporadically in B1V that was correlated with activities during Adjust [13]. The emittance blowup typically happened for bunches at the beginning of the train (which can rule out electron cloud), and no correlation could be found with either intensity, emittance or LHCb polarity. Figure 2 shows the typical timing of the emittance blowup and it can be seen that it approximately correlates with the implementation of the TOTEM process. In the particular example shown (fill 5093) a delayed Adjust (one where 5-10 minute waits occur between each step) was employed to allow better sampling of the BSRT in order to separate between the TOTEM process and the separation collapse.

Figure 3 shows the occurrence of this instability throughout the latter part of 2016 [14]. There were two main occurrences of the instability, after TS1 until shortly after the deployment of the full BCMS beam, and before TS2 until after TS2. See the accompanying presentation for a fully annotated version of this figure. A correlation has not yet

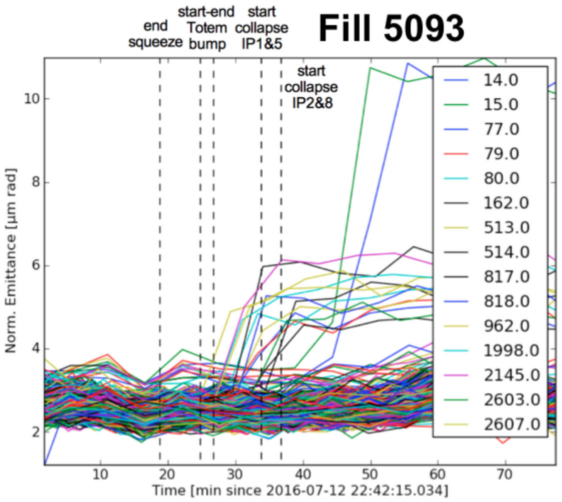

Figure 2: BSRT emittance vs time since start of the squeeze. It can be seen that the emittance blowup is approximately correlated with the TOTEM process. The shown fill is fill 5093 which employed the delayed ADJUST.

been found between either beam parameters or the timing of their occurrence.

Further research into this instability will be continued if it reappears in 2017. The Headtail monitor was not able to be triggered due to its dependence on a trigger based on the BBQ (which does not show activity for 2220 bunches). Development of an instability trigger for the ADTObsBox will allow much greater insight into the effect of the TOTEM process on the transverse beam dynamics, as well as triggering the Headtail monitor.

Stable Beams

Early in 2016, emittance blowup was consistently being observed several hours into stable teams for 72 bunch trains [15]. Typically it was always bunches towards the end of each train. A plot of the bunch by bunch luminosity from CMS can be found in Fig. 4 for fill 4964. The luminosity of each bunch was normalised to 1 at the start of Stable Beams, and a red point was marked for any abrupt reduction in luminosity, signifying emittance blowup. For subsequent fills, the chromaticity was increased from $Q'V = 15$ to $Q'V = 22$ and the issue was strongly mitigated.

Due to the fact that it was mostly bunches going unstable at the end of the trains, electron cloud was strongly suspected as the driving mechanism. The bunches at the end of the train are typically the ones with the lowest intensity, and it was observed in the past that for decreasing bunch intensity there could be an increase in the local electron density (but a decrease in the total electron density).

This was explored with simulations in PyHT-PyECloud [16]. Figure 5 shows the electron density in a dipole as a function of the horizontal position for different bunch intensities. In this case, the proton bunch would be passing through at 0mm. It can be seen that as the intensity decreases, the electron density at the location of the bunch increases. This local electron density is plotted in Fig. 6 as a function of the bunch intensity. It can be seen that for nominal bunch intensities and above ($N_b \geq 1e11$ppb) the local density is very small and therefore has a minimal effect on the beam dynamics. However, if the bunch intensity drops to approximately $N_b \leq 0.8e11$ppb, the local density becomes much larger and exceeds the electron density instability threshold which could cause emittance blowup.

While this is currently only a theory that is backed up by simulations, it is a strong contender as an explanation for this instability. However, it needs to corroborated with measurement results in order to be completely satisfactory.

INSTABILITY MEASUREMENTS IN 2016

Tune Shift Measurements

In 2017 there is a possibility of further squeezing to $\beta^* = 30/33$cm which will require tighter collimator settings. Several measurements of the single bunch instability threshold were made in 2016 with the primary collimators (TCP's) at 5.5σ and for different secondary collimator (TCSG) gaps [17]. The results can be found in Fig. 7 compared with the DELPHI predictions. Reasonable agreement can be found for the TCSG gaps of 6σ and 6.5σ, however a jump is seen between gaps of 6.5σ and 7.5σ which is not yet understood.

The plan in 2017 is to go to a TCP gap of 5σ and a TCSG gap of 6.5σ. The expected octupole threshold in this scenario is $J_{oct} \approx 200$A. This should be fine for the case of a single bunch, but some work is still needed to understand the MD results.

Beam Stability at $\beta^* = 40$cm

Measurements at $\beta^* = 40$cm show that both a single bunch and full beam (2076 bunches) are stable for $J_{oct} = 0$A [18]. At end of squeeze (EOS) there are two additional stabilising mechanisms present that could cause the beam to be stable. The first is Q" from the lattice, and the second is non-linearities from the high value of β-function in the IR's which can provide strong amplitude detuning. Due to a knob developed by R. De Maria [19], it is possible to either introduce or correct Q" at both flat top and end of squeeze by varying the strength of the main sextupoles. Q" can stabilise either by shifting the unstable mode (by changing the interaction between the machine impedance and the bunch power spectrum) or by providing Landau damping by a spread which is introduced that depends on the δ^2. MD1831 sought to disentangle between these two effects [19].

The MD made 2 key conclusions [20]. Firstly that it is possible to stabilise a single bunch using only Q" at flat top, and second that the stability at the EOS is coming only from the amplitude detuning that arises from the non-linearities in the IR's. This will be explored further in 2017, but it is clear that if agreement with the stability model is desired, then the corrections to the non-linearities must be implemented.

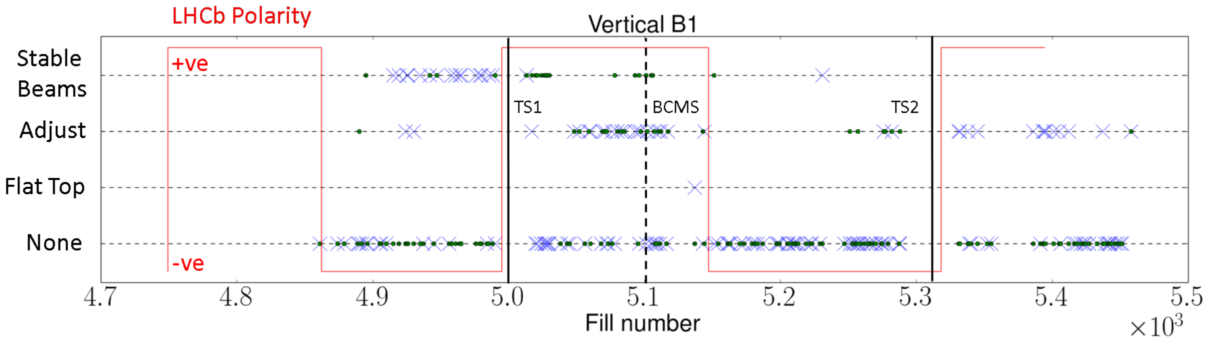

Figure 3: Instabilities in B1V vs fill number. Most clusters of points can be attributed to MD's or other tests. There were two main times the Adjust instability appeared, after TS1 and then shortly before and shortly after TS2. Also shown is the LHCb polarity (red). The green dots are instabilities in the non-colliding bunches, and the blue crosses are instabilities in the colliding bunches. For a fully annotated version of this diagram, see the accompanying presentation.

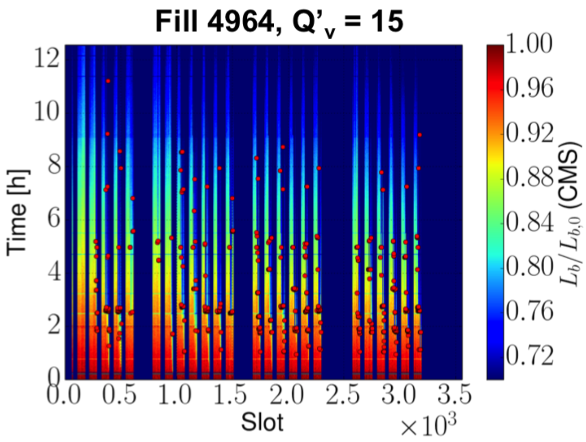

Figure 4: Bunch by bunch luminosity from CMS normalised to 1 at the start of stable beams. Abrupt reductions indicate emittance blowup which is marked by a red point.

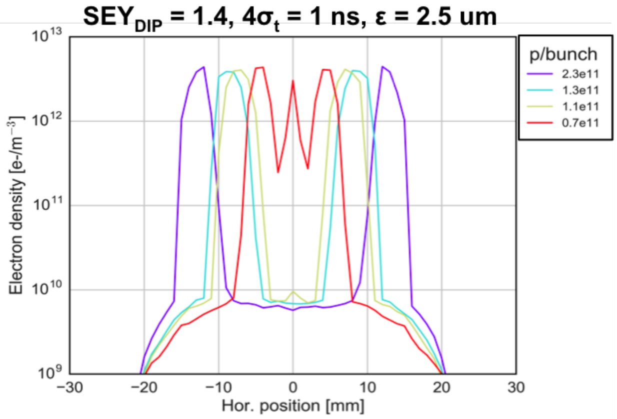

Figure 5: Local electron density versus horizontal position in dipoles for different bunch intensities.

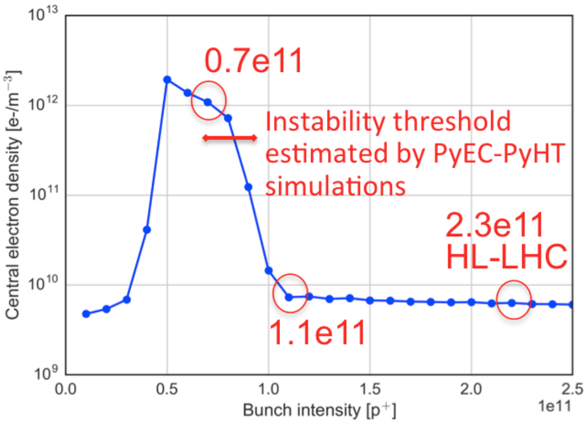

Figure 6: Central electron density versus bunch intensity. The electron density instability threshold stays the same as in single bunch stability thresholds.

BEAM INDUCED HEATING

General

In 2015, most heating issues were effectively addressed by redesigning the problematic components and in cases adding new cooling systems. Issues with the TDI heating were addressed, but now some strange vacuum behaviour while injecting has been observed which requires further study [21]. The MKI was addressed with additional temperature probes and observed no performance limiting behaviour in 2016. Some of the issues observed in 2016 will be addressed below.

VMSI

After TS2, a spring detached on the LSS8 vacuum module, such that the rf fingers are no longer in contact. This is shown in Fig. 8. Simple impedance modeling show significant resonant modes at ≈ 200MHz. These modes could potentially extract ≈ 200W from the beam (of which about 30% to 60% could go to the rf fingers) if the modes sit on the beam spectrum. However, this did not limit performance in 2016, and will be replaced during the EYETS.

BGI

Temperature probes were connected to the BGI and confirm that there is heating. There is a clear dependence on

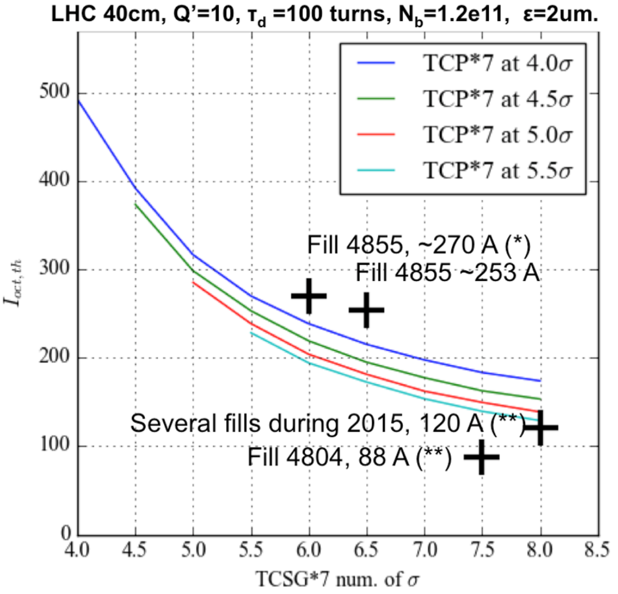

Figure 7: Octupole current instability threshold for different TCSG gaps. The coloured lines show the prediction of different TCP gaps from DELPHI simulations. The measurements were made with the TCP's at 5.5σ. *Scaled to horizontal from vertical with factor 1.2 from impedance. ** Scaled to $\beta^* = 40$cm with factor 1.1 from impedance.

Figure 8: LSS8 vacuum module shows that a missing spring has caused rf fingers to no longer be in contact. This can cause heating due to the excitation of resonant modes with frequencies close to the beam spectrum.

the heating with intensity, as shown in Fig. 9. In order to mitigate this heating, the recommendation was to remove 2 BGI's during the EYETS while keeping the other 2 in, and check for damage. Afterwards, mitigation techniques can be developed before replacing all 4 and re-installing them. With the current design, approximately 170W could be deposited by the beam if the spectrum lies on the narrow modes at ≈ 500MHz.

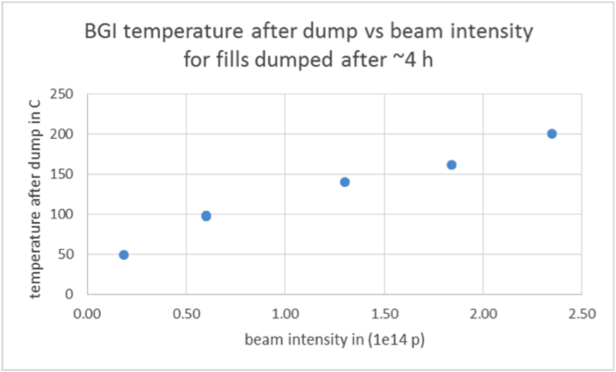

Figure 9: BGI temperature after a beam dump for fills that were in collisions for approximately 4 hours. A clear dependence on beam intensity can be seen.

CONCLUSION

2016 was a very successful year from the point of view of coherent instabilities. During the high pileup test, a bunch with a brightness that is 1.4 times more than the HL-LHC brightness was taken to collisions without suffering an instability.

The instabilities in operation that limited performance were able to be cured, whereas those that require further study had little impact on the luminosity output.

A greater understanding of the interplay between optics and collective effects has been gained, both in terms of fundamental instabilities as well as in specific machine configurations.

There were no performance limitations related to beam induced heating in 2016, but there is always the possibility for non-conformities in 2017. Increasing the intensity per bunch to $N_b = 1.25e11$ and the number of bunches to $N = 2760$ should increase the power loss by around 40% for all devices.

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