INSTABILITIES AND BEAM INDUCED HEATING IN 2015

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Abstract

Instabilities were observed during operation at injection, flat top and during the betatron squeeze. This resulted in high chromaticities and octupole currents in all stages of the machine cycle. A series of dedicated measurements at flat top and end of squeeze of the instability threshold was performed which can shine a light on expected performance in 2016. Beam induced rf heating will also be reported on, with emphasis placed on the performance of the MKI kicker and the effect of the bunch length.

INTRODUCTION

Throughout 2015, many instabilities were observed during all stages of the machine cycle. Emittance blow-up was seen when injecting trains of bunches and for trains of bunches during the squeeze (at approximately 9m β^*, specifically for B2V) [1]. Instabilities were also observed at the beginning of the ramp (mostly in B1H), often resulting in losses and emittance increase. To try and mitigate these effects, high settings were used for the chromaticity, current in the Landau octupoles and the damper gain. Despite these settings not being the optimum settings for other aspects of the machine (for example dynamic aperture or for tune measurements), it ultimately allowed the machine to take 2244 bunches from injection through to stable beams without allowing any instabilities.

In parallel with operation, a series of dedicated measurements were made both during commissioning and during the machine development blocks. These measurements aimed to probe the LHC impedance model by measuring the octupole current threshold for instability and making comparisons with simulations in frequency domain (DELPHI [2]) or time domain (PyHEADTAIL [3]). Initially this threshold was measured with single bunches only, with many measurements being performed that allowed an exploration of the threshold for a wide variety of chromaticities [4]. These chromaticity measurements were much more accurate than in 2012, due to improvements to the fitting procedure used in the online tool [5]. This allowed much greater chromatic control during the measurement process. This threshold was then examined for trains of bunches [6, 7]. Measurements of the instability threshold for tighter TCSG settings (6.5σ compared to 8σ), were attempted but conclusions were not able to be drawn [8]. The results from each of these measurements will be shown here.

In 2012, there were many problems with beam induced heating in various components, either due to nonconformities or design flaws. As a result, many components were either redesigned or replaced. Here, the performance in 2015 of some of the more critical components (with respect to heating) from 2012 will be discussed, with particular emphasis placed on the MKI. A reduction in the bunch length (a potential plan for operation in 2016) can increase the level of heating. The effect of this reduction on the performance of the MKI will also be mentioned.

INSTABILITIES IN OPERATION

Injection

At injection during operation, the dominant effect is electron cloud [9]. However, other effects in parallel can cause beam instabilities (unoptimised ADT or linear coupling for example). Tab. 1 and Tab. 2 show the evolution of some of the key parameters at injection related to instabilities throughout 2015. At injection, an octupole setting of -0.5 is equal to 6.5A (with a linear dependence) with positive LOF. The ADT gain is a normalised unit that relates to damping time (in turns) through $2/ADT_{\text{gain}}$.

Table 1: Evolution of some LHC parameters during 50ns operation, where IR refers to the intensity ramp and the octupole current is stated as the knob setting.

Event	Date	Q'H/V	J_{oct}	ADT Gain
Initial Settings	01/06	5/5	-0.5	0.15
Peak Scrubbing	27/06	15/15	-1.0	0.25
End Scrubbing	02/07	8/8	-0.5	0.15
Peak IR	07/07	10/10	-1.5	0.2
End IR	19/07	10/10	-1.5	0.2

The 50ns scrubbing run saw blowup in the beam emittance for low chromaticity and octupoles. The values had to be increased in order to mitigate the instabilities. The settings that were used at the end of 50ns operation was sufficient for the stability of $\sim$ 500 bunches.

During the 25ns scrubbing run, many attempts were made to reduce the chromaticity, octupole gain and ADT gain. However, each time it results in blowup of the beam emittance. Severe blowup limited operation throughout September and early October. It was initially thought to be an issue with the ADT (one module in B2H was offline), this was fixed on 30th September and no more instabilities were observed. However, the emittance blowup returned in early October. It was at this stage that small tune separations were observed. After correcting this, the instabilities were no longer seen.

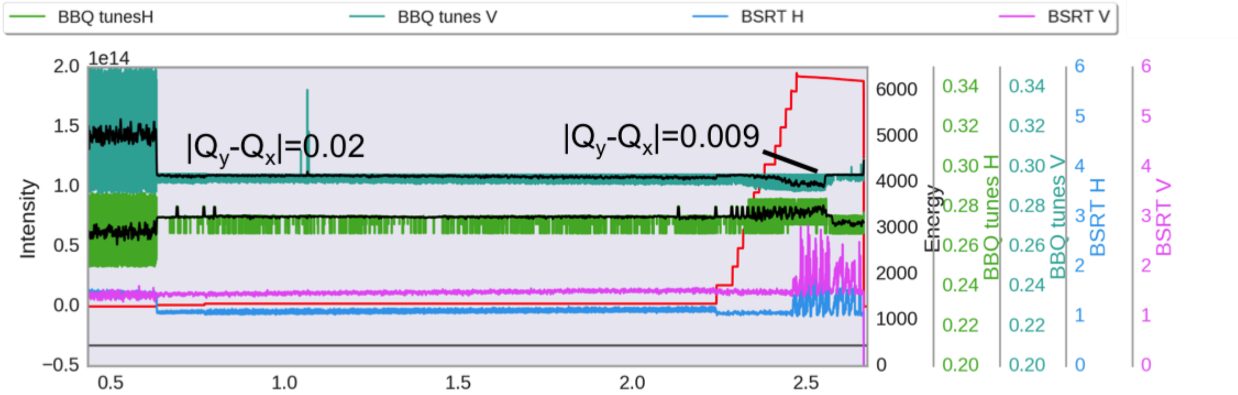

Figure 1: Tunes, beam intensity and BSRT signal for fill 4642. As the beam intensity increased, the tunes drifted closer together causing an increase in the linear coupling. This caused many injection instabilities in 2015. The fill immediately following this had the tunes corrected and no instabilities occurred.

Table 2: Evolution of some LHC parameters during 25ns operation, where IR refers to the intensity ramp and the octupole current is stated as the knob setting.

Event	Date	Q'H/V	J_{oct}	ADT Gain
Peak Scrubbing	28/07	15/15	-2	0.2
End Scrubbing	07/08	15/10	-1.5	0.25
Peak IR (i)	22/09	20/20	-1.5	0.25
Peak IR (ii)	15/10	15/15	-1.5	0.25
Final Settings	22/09	20/20	-1.5	0.25

The key to preventing blowup at injection is to maintain well separated tunes. When injecting bunches into the machine, the total beam intensity is increasing, which causes a tune shift (the Laslett tune shift [10]). This causes the tunes to move towards each other. This can be seen in Fig. 1, which shows the tunes, intensity and BSRT signal for fill 4642. When the tunes were not separated, emittance blowup occured. In the fill immediately following this, the tunes were corrected and no blowup was observed.

The linear coupling of the betatron motion between H and V is approximately dependent on $|C-|/(Q_x - Q_y)$, where $|C-|$ is the closest possible tune approach in tune units. Measurements made in 2012 of the linear coupling at injection show that there is large variation in the value of $|C-|$ over the course of the year. This is shown in Fig. 2. If the tunes are not well corrected, and $|C-|$ is at a medium or large value, then the linear coupling could become unusually strong. Preliminary simulations have shown that linear coupling can reduce the amount of Landau damping a bunch experiences, which could cause an instability. This is something that will be investigated further in 2016.

Ramp & Squeeze

Losses were observed in B1H at the beginning of the ramp for $Q' < 10$. Emittance blowup also occured routinely in B2V at $\beta* =\sim 9$m i.e. during the squeeze. The squeeze

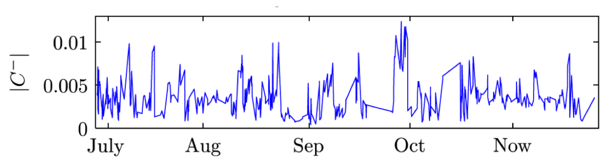

Figure 2: Coupling measurements made at injection throughout 2012 [11].

instability is very reproducible, it always occurs for the first $\sim$ 30 bunches in the first batch of 144 bunches.

Both of these instabilities were cured by moving the Q' from 10 to 15.

One possible cause for these instabilities arises from the fact that they occur during very dynamic parts of the machine cycle. The chromaticity is known to vary during these stages [12], and it is possible that the chromaticity varied to a value that was too low for the current settings, which caused the beam to become unstable.

In 2016, the ADT ObsBox will allow a greater insight into each of these two types of instability.

BCMS

The fill immediately before and after the BCMS fill with 2244b reached stable beams without any instabilities. For the same machine settings, the BCMS beam saw many instabilities in all stages of the machine cycle. The instabilities were caused due to the increased bunch brightness.

The beams were blown up by the time they reached injection in the LHC, there was the pre-ramp instability in B1H and the squeeze instability in B2V during the squeeze. There was activity in stable beams, but no losses or emittance blow up. The observed instabilities had the same characteristics as the relevant instabilities observed during normal operation. It is likely that during operation, the LHC is operating at the threshold of stability. However, this was only one BCMS fill with $\sim$ 500 bunches. More data would be needed to draw any conclusions about the stability of BCMS beams.

There is currently a proposal to use a blown up BCMS beam, and then incrementally reduce the bunch emittance over adjacent. From the point of view of instabilities, this is the ideal way forward.

INSTABILITY MEASUREMENTS

Single Bunch Measurements at 6.5 TeV

In order to better understand both the impedance model of the LHC at flat top and the operational limits relating to stability, many measurements of the instability threshold were performed throughout 2015. The general procedure for each measurement was to incrementally lower the current in the Landau octupoles until an instability develops. For single bunches, a series of measurements were made with chromaticities ranging from -10 to 15. Each point was then re-scaled to nominal bunch parameters ($\epsilon = 2\text{um}, N_b = 10^{11}$ppb). The results are compared to predictions from the simulation code DELPHI. An overview of the single bunch measurements made in 2015 can be found in Fig. 3. Not shown in the figure are three additional points at $Q' \approx 0$, with octupole thresholds that are above 600 A.

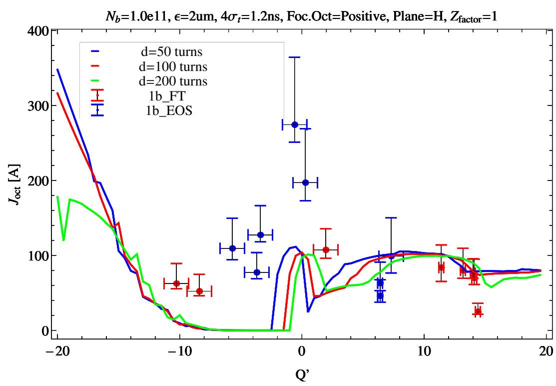

Figure 3: Overview of single bunch measurements of instability threshold performed in 2015, plotted alongside DELPHI predictions for different damping times. Not shown are three truncated points for $Q' \approx 0$ that are slightly below 800A.

There are three different chromaticity regimes present. Each one will be briefly described. Firstly, it can be seen that for positive chromaticities ($Q' > 2$), good agreement is found between predictions and measurements. Typically the LHC operates in the region between $Q' = 5$ and $Q' = 15$, and in this region the measurements are not sensitive to the damping time, showing similar results for $d = 50 - 200$ turns.

Secondly, there is the region for $Q' < -2$. DELPHI predicts that the bunches will be stable in this regime, even for 0 A in the octupoles, for a perfect transverse damper. However, it can be seen clearly that there is a disagreement between measurements and predictions. One possible explanation for this disagreement is due to the fact that in the simulations a perfect damper model is used, whereas in operation the damper has noise and other effects that can limit performance. Simulations performed by X. Buffat *et al* [13] have shown that by using a more realistic transverse damper, the prediction in this regime increases from 0 A to ≈ 50 A. While increasing the agreement between measurements and simulation, it still does not fully explain the situation. This will be explored further in 2016.

Finally, there is poor agreement in the region for $-2 < Q' < 2$. Partly this is due to the re-scaling of some of the bunches (due to emittances or intensities that are far from the nominal parameters), however this does not entirely explain the discrepancy. The DELPHI prediction only accounts for Q', it does not include the second order chromaticity, Q''. Further analytic and simulation studies are underway to determine the stabilising effect of Q''. Additionally, it is possible that the ADT is not well optimised to operate for chromaticities in this region. This area will be further studied in 2016.

Train Measurements

Having performed measurements of the instability threshold using single nominal bunches, further measurements were made using trains of 72 bunches with 25ns spacing. At flat top, the transverse damper should be able to damp any bunch by bunch instabilities, reducing the threshold to that expected with single bunches. These measurements aimed to verify this effect.

Initially, during MD2, two separate ramps were performed for $Q' = 7$ with trains of 72 bunches with 25ns spacing. The instability threshold in this case was measured to be approximately 5 times higher than for single bunches. The rise time of the instability was much faster (~ 1s vs ~ 15s for single bunch) and the headtail mode of the unstable bunch was different (1 node compared to 2 nodes). This led to the conclusion that a different type of instability had occurred. One possible explanation for this was that it is due to the presence of electron cloud (something which is missing for single bunches). This was because a synchronous phase shift was measured along the train at flat top. As a result, further measurements were made that aimed to measure the instability threshold for trains of bunches both with and without electron cloud. However, these also showed instabilities with single bunch thresholds.

Ultimately, during MD3, the instability threshold was re-measured for 72 bunches with 25ns spacing. For this fill, there was a small level of phase shift in the synchronous phase along the train, and the train became unstable at single bunch thresholds. The instabilities observed in this case was consistent with the measurements made for single bunches. The two measurements for 25ns trains can be found in Fig. 4.

Between MD2 and MD3, many hours of high intensity physics occurred at flat top. This has scrubbed the machine at 6.5TeV, thereby reducing the secondary electron yield which has reduced the level of electron-cloud. It appears that some threshold has been crossed during this period, and the factor of 5 in the instability threshold is no longer present.

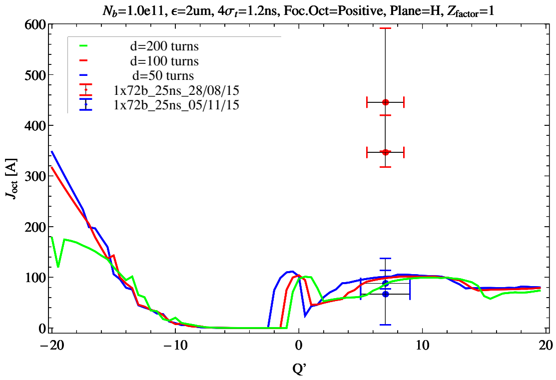

Figure 4: Two sets of measurements were made, one during MD2 and one during MD3. Due to electron cloud, the measurements during MD2 had an increase in the octupole threshold by a factor of 5. This was then re-measured during MD3, and the effect had been scrubbed away because of the high intensity physics at flat top.

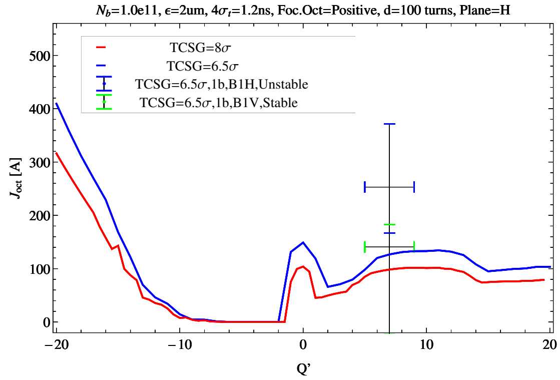

Figure 5: Instability threshold measurements with TCSG's at 6.5σ performed during MD2. Contrary to what is expected, the plane with the larger emittance became unstable first.

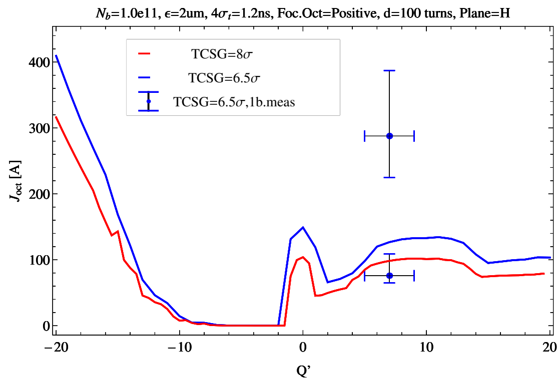

Figure 6: Instability threshold measurements with TCSG's at 6.5σ. In the second ramp, similarly confusing results were observed, with the unstable plane being the plane with the largest emittance.

Trains with more bunches will be used in 2016 in order to make more accurate determinations on what this threshold is.

Measurements for 40cm $\beta*$

To move to $\beta* = 40$cm, tighter settings for the TCSG's in IR7 are required. This involves moving the TCSG's from their current position of 8σ down to 6.5σ (for the most conservative case, it is also possible to reach $\beta* = 40$cm with the TCSG's at 7.5σ) [14]. Therefore, instability measurements were performed with the TCSG's at 6.5σ.

During the MD, several issues hampered the results. During the initial ramp, B2 suffered heavy losses on the collimators during qualification of the collimation hierarchy. This rendered both bunches in B2 unsuitable for use in the measurements. While measuring the instability threshold for the remaining bunch in B1, a large disagreement was observed with DELPHI predictions. It was also observed that the plane that became unstable was the plane with the largest emittance, contrary to what would be expected. This is shown in Fig. 5

Another ramp was performed immediately afterwards. This ramp showed similar results to what was seen previously, with the horizontal plane becoming unstable first for both B1 and B2, despite having a larger emittance. These results are shown in Fig. 6.

These measurements will need to be repeated in 2016. However 6.5σ was a very strict setting for the TCSG's, an intermediate measurement will be made at 7.5σ, to ensure we fully understand the result before repeating another measurement at 6.5σ.

BEAM INDUCED HEATING

General

In 2012, there were many components that suffered from severe beam induced heating and therefore limited performance. As a result, most of these components were redesigned and redeveloped with beam induced heating in mind. Most of these issues observed in 2012 have been seriously and efficiently addressed. Several of these components will be mentioned in more detail below.

TDI

There were many issues with TDI8 during 2015 and it has since emerged that this was due to a compromise in the applied coating [15]. This resulted in a transverse impedance increase by a factor of ≈ 4 (and a longitudinal impedance increase by a factor of ≈ 2). Both TDI's are being replaced during the YETS, and the heating of each TDI will need to be monitored closely in 2016.

Collimators

A collimator non-conformity (TCTVB) was observed and solved during 2015. There is currently an issue with non-physical temperature readings which are currently being investigated. It is believed that this TCLIA issue is an artifact, but it will need to be monitored in 2016.

BGI

The BGI will have new temperature probes installed which will provide more insight into the pressure increase.

MKI

The LHC injection kicker (MKI) magnets are travelling wave devices: the yoke of the magnet is ferrite. With LHC beam, which has high peak current, the impedance of the ferrite yoke can provoke significant beam induced heating. To limit beam coupling impedance, while allowing a fast magnetic field rise-time, a ceramic tube with screen conductors on its inner wall is placed within the aperture of the magnet. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end.

The temperature of the ferrite yoke is measured indirectly, using two PT100 temperature sensors. A SoftStart is run following a beam dump and the measured data analysed to determine whether the ferrite is approaching its Curie temperature, at which point it starts to temporarily lose its magnetic properties. If the ferrite has not reached its Curie temperature the SIS interlock threshold can be raised to this measured temperature: if the ferrite has reached its Curie temperature, the SIS interlock must be left below this measured temperature to avoid risk of mis-injecting beam due to high ferrite temperature.

Prior to LS1 most of the MKI magnets had 15 screen conductors in the aperture of each magnet. However one of these had a non-conforming ceramic tube which resulted in a 90 degree twist in its conducting screen. Thus the ferrite yoke of this magnet was exposed to wakefields, causing an average heating of 160 W/m: this resulted in the ferrite yoke approaching its Curie temperature, during long high-intensity fills, and thus this magnet occasionally delayed injection into the LHC. All other MKI magnets had straight ceramic tubes: the average power deposition in these kickers was approximately 70 W/m and they did not limit LHC operation due to heating.

As a result of the heating of the non-conforming MKI magnet, studies were initiated into means of reducing beam induced power deposition. The high voltage performance of the beam screen was significantly improved allowing a full complement of 24 screen conductors to be installed during LS1. Based on extensive computer simulations and beam impedance measurements in the laboratory, and assuming uniform power deposition in the yokes of the upgraded MKI magnets, the post-LS1 ferrite temperature is expected to be below 80°C.

During LS1 the ferrite yoke PT100s were moved from the end plates to the side plates, to give a better indication of the ferrite temperature. Thermal simulations of the upgraded MKI magnets indicate that ferrite temperatures of 80°C and 120°C (i.e. the ferrite Curie temperature) correspond to measured side-plate temperature of approximately 55°C and 75°C, respectively. However the SIS interlock threshold is deliberately set to below 75°C (presently 55°C) and gradually increased with experience, to avoid risk of mis-injecting beam due to high ferrite temperature.

Post LS1 temperature measurements show ferrite yoke upstream (capacitively coupled end) temperature readings, for all MKIs, which are higher than the downstream end. Theoretical studies to fully understand the cause and consequences of the non-uniform distribution of beam induced power deposition are ongoing. As expected, based on beam impedance measurements carried out in the laboratory, MKI8D has the highest measured ferrite yoke temperature.

Beam induced heating of the MKI magnets has not shown any show-stopping behaviour during 2015 and similar performance is expected in 2016. A decrease in bunch length to 1 ns, throughout the fill, is not expected to cause excessive heating in the MKI magnets.

CONCLUSION

Transverse instabilities occurred regularly during operation in 2015. The ADT gain, chromaticity and octupole currents all had to be increased to mitigate blowup. By the end of November, these instabilities were able to be routinely suppressed. The ADT ObsBox will allow a deeper insight into the characteristics of each instability, which will ultimately help in determining the cause behind each one.

Instability measurements show good agreement for operational chromaticities, however further work is required for negative chromaticities, or chromaticities close to zero. The instability threshold was increased by a factor of 5 in the presence of electron-cloud. This factor was removed by scrubbing at flat top during the high intensity physics run. This caused the stability threshold for 72 bunches to revert to the expected single bunch thresholds.

Beam induced heating has not shown any surprises in 2015 (excluding the TDI). Similar performance is anticipated in 2016 (barring any new non-conformities). Heating monitoring will be pursued in 2016 with all the new tools that have been put in place. SIS interlock threshold for MKI's is still deliberately set quite low and the threshold is incrementally increased upon verification that there are no non-linearities in the ferrite yoke behaviour.

Decrease in bunch length to 1ns (throughout the fill) should not cause excessive heating in the MKI's.

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