CURRENT STATUS OF INSTABILITY THRESHOLD MEASUREMENTS IN THE LHC AT 6.5 TEV

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Abstract

Throughout 2015, many measurements of the minimum stabilising octupole current required to prevent coherent transverse instabilities have been performed. These measurements allow the LHC impedance model at flat top to be verified and give good indicators of future performance and limitations. The results are summarised here, and compared to predictions from the simulation code DELPHI.

INTRODUCTION

The Large Hadron Collider (LHC), based in Geneva, Switzerland, is the highest energy particle accelerator in the world and currently collides protons with a center of mass energy of 13 TeV. In order to increase the luminosity of the machine, the bunch intensities and transverse emittances are constantly pushed to towards higher brightness, leading to increased effects from wakefields on the transverse stability. An impedance model has been developed for the LHC through simulations, bench measurements and beam measurements, and this can allow single or multi-bunch stability thresholds to be calculated under a variety of different configurations [1].

DELPHI [2] (Discrete Expansion over Laguerre Polynomials and Headtail Modes) is a frequency domain simulation code, that numerically solves Sacherer's integral equation for specified beam parameters to determine the coherent tune shift of the most unstable mode. With this tune shift, the Landau Octupole strength required to stabilise this particular mode can be computed. DELPHI can also include transverse feedback systems (ADT) with a specified damping time. When strong enough, this allows the damping of coupled bunch motion, however presently it is modelled as a perfect damper which is not representative of the real machine.

This paper will give an overview of measurements of the single bunch instability threshold that were made at 6.5TeV for the LHC in 2015. The measurements will provide a comparison for the LHC impedance model, as well as indications where the current stability model is not sufficient. In the next section, the measurement procedure will be described, before going on to compare the measured points with the DELPHI prediction.

MEASUREMENT PROCEDURE

Many measurements of the stabilising octupole threshold were made throughout 2015, but each measurement had a very similar procedure. This procedure will be explained here.

A single nominal bunch ($N_b \approx 1.1 \times 10^{11}$ppb, $\epsilon_{x,y} \approx$ 2.5um) is injected into each beam in the LHC. At this point, there are suitable octupole currents ($J_{oct} \approx$ 15A) and chromaticity ($Q' \approx 7$) to ensure bunch stability. The two bunches are then accelerated to 6.5 TeV and, when necessary, the optics configuration is moved from flat top (FT) to end of squeeze (EOS) where the β^* is reduced in IP1 and IP5 from $\beta^* = 11$m to $\beta^* = 80$cm. At this point, the chromaticity is moved to the region of interest using the trim sextupole magnets, and the current in the octupoles is at maximum (550A). Intensity and emittance measurements are repeated here, before the current in the Landau octupoles is incrementally reduced (typically in steps of $\approx$ 20A) with pauses at each step of several minutes to allow the instability time to develop. The amplitude of the bunch oscillation is measured using the BBQ (Base Band Tune) monitor, which allows the onset of instabilities to be seen. When an instability is detected, the octupole current for the beam which contained the unstable bunch is increased in an attempt to stabilise the beam without suffering losses or emittance blowup. At this point, the headtail monitor (a beam measuring instrument that allows the intrabunch motion to be determined) should trigger, revealing valuable information about the characteristics of the instability.

The octupole current at which the bunch became unstable is then renormalised with respect to the nominal bunch parameters. This allows a direct comparison for bunches with slightly different intensities or emittances, as well as for comparisons with simulations. When possible, the chromaticity was also corrected for the shift incurred from octupole feed down. When the octupole current is reduced, the chromaticity can shift by up to 1-2 units (depending on the plane) [3]. Several chromaticity measurements were made in the first few steps of octupole reduction to try and quantify this shift, however it was not always possible. This is reflected in the width of the error bars for the measured points.

SINGLE BUNCH MEASUREMENTS

Overview

Figure 1 shows the complete set of measurement points obtained in 2015 [4,5], overlaid with DELPHI predictions for different damping times. Not shown in the figure are three points at $Q' \approx 0$ at normalised octupole currents of $\approx$ 800A (see Figure 4). It can be seen that there are three distinct regimes that exist, positive chromaticity (which is where the LHC routinely operates), negative chromaticity and zero chromaticity. Each of these regimes will be discussed.

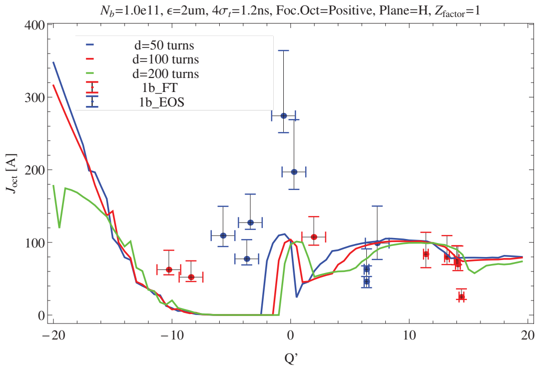

Figure 1: Overview of single bunch measurements of the instability threshold performed in 2015, plotted alongside DELPHI predictions for different damping times. Not shown are three truncated points for $Q' \approx 0$ that are slightly below 800A (see Figure 4).

Positive Chromaticity

The first regime is for positive chromaticity, $Q' \geq 2$. It can be seen from Fig. 1 that good agreement is found between measurements and DELPHI predictions, for both flat top and end of squeeze optics. The prediction does not vary much in this regime for changing damping time. This means there is less sensitivity to the damping time. The typical chromaticity values used in operation vary between $Q' = 5$ and $Q' = 15$. It is clear that here the impedance model and the damper model used in DELPHI is adequate to explain single bunch stability.

Figure 2 shows the headtail motion of a single bunch with chromaticity at $Q' \approx 10$. Simulations were performed in the particle tracking code PyHEADTAIL [6] that also revealed similar intra bunch patterns for the same beam parameters.

Negative Chromaticity

For negative chromaticity, $Q' \leq 2$ there is large disagreement between measurements and DELPHI predictions. The DELPHI prediction for the region $-10 < Q' < -2$ is zero in the presence of a perfect damper. This is because the most unstable mode has 0 nodes in its headtail motion. When a perfect damper is present, this mode 0 is interpreted as coherent motion causing an offset to the mean bunch position, which the damper then corrects. It is in this regime that the perfect damper model begins to break down, and new models need to be applied. Simulations were made using BimBim that uses an imperfect damper model [7]. The bunch is modulated from head to tail with different mode numbers, and the damper now acts on the average position of the bunch, which is not necessarily the average position of the unperturbed bunch. This model is plotted alongside the measurements in Fig. 3, where it can be seen that there is an offset of the required current in the negative chromaticity regime. While this does not fully explain the origin of the discrepancy, it is a step in the right direction and future work will attempt to improve the realism of the damper model.

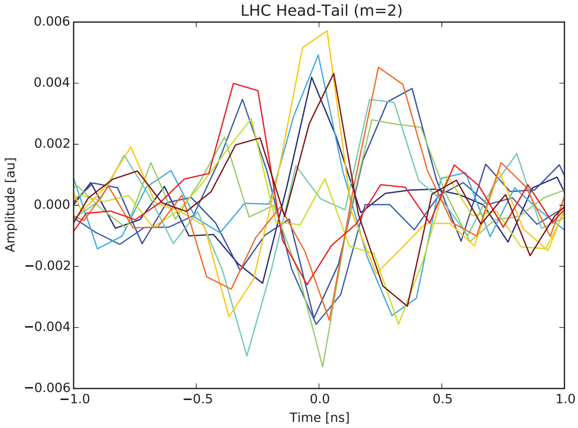

Figure 2: Plot of the intrabunch motion captured by the Headtail monitor. Bunch traces of 11 adjacent turns are recorded and overlaid, clearly showing 2 nodes. This is in good agreement with simulations from the particle tracking code PyHEADTAIL.

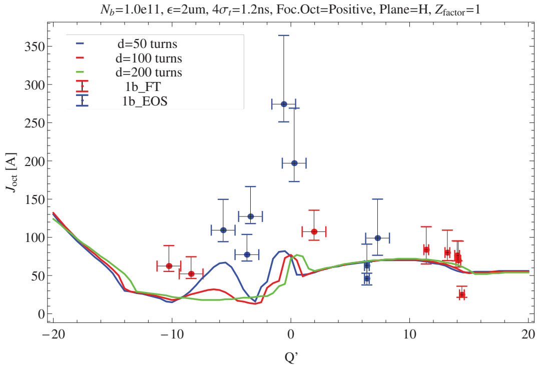

Figure 3: Overview of measurements vs predictions from BimBim with an imperfect damper model. An offset of approximately 30 A is seen for weak damping, while a peak is also observed for strong damping. This does not explain the measurements entirely, but offers a possible avenue of further exploration.

Zero Chromaticity

Large discrepancies were found when attempting to make measurements at $Q' \approx 0$. At this point, DELPHI predicts an instability threshold of $J_{oct} \approx 100$ A. There could be several factors at work here. The first is that it is difficult to make measurements of the chromaticity when it is very low. Chromaticity measurements rely on a slow modulation of the dp/p and the monitoring of the tune $\Delta Q/Q$ in each plane [8]. For $Q' \approx 0$, it becomes very difficult to make an accurate measurement over the base level of noise in the tune signal. The other factor is that the transverse damper might not be well setup for performance with $Q' = 0$. Indeed, Figure 4 shows a zoomed overview plot, with an additional

DELPHI curve for the case where the ADT is off, where it can be seen that some of the points fall close to the curve. This is something that will be explored further in 2016.

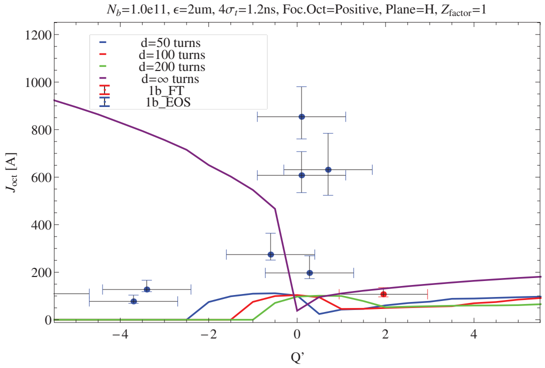

Figure 4: Overview of single bunch measurements of instability threshold performed in 2015, plotted alongside DELPHI predictions for different damping times with an additional curve for the case where there is no damper.

TRAIN MEASUREMENTS

Having shown that the single bunch instability thresholds were in relatively good agreement with predictions for $Q' \approx 7$, measurements were also made with trains of 72 bunches with 25ns spacing [5, 9]. The first set of measurements occurred on 28/08/15 and showed that there was an increase in the threshold of approximately a factor of 5 (see Figure 5). During this measurement, a shift in the synchronous phase was observed along the train, which is indicative of the presence of electron cloud [10]. Also, the rise time of the instability was on the order of 2 seconds, over 6 times faster than the rise times observed with single bunch measurements ($\approx$ 15 seconds) and the number of nodes seen in the headtail motion was 1 (compared to 2 nodes which was predicted and observed single bunches). This instability triggered an immediate beam dump.

A repeat set of measurements were performed for the same settings on 05/11/15. It was found in this case that the synchronous phase shift along the train was much reduced, and the rise times were on the order of 15 seconds. In this case, bunches in the train were going unstable as individual bunches with thresholds consistent with the single bunch stability model. An overview of these measurements can be found in Figure 5.

It appears that the presence of electron cloud has a strong effect on the instability threshold. In between the two sets of measurements was a period of high intensity physics, which had the effect of prolonged scrubbing of the machine at 6.5 TeV (similar to the intentional scrubbing that is performed at the injection energy of 450 GeV). Further measurements are required in order to determine whether the level of electron cloud is a gradual or threshold effect. It is expected that for an increased number of bunches per train (144 or 288 bunches) this increased stability threshold can still be observed.

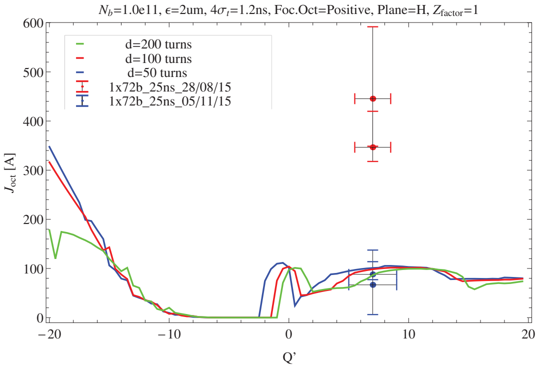

Figure 5: Overview of train instability measurements made in 2015. After a period of high intensity physics, the machine was scrubbed at 6.5TeV and the required octupole current for stability was reduced.

MEASUREMENTS FOR 40 CM β^*

In order to push to $\beta^* = 40$cm, tighter collimator settings are required [11]. The most critical of these (from the point of view of machine impedance) is the secondary collimators in IP7 (TCSG), where they will be moved from their 2015 position of 8σ to 7.5σ or 6.5σ (to be decided) [12].

Measurements of the single bunch stability threshold were performed with the TCSG at 6.5σ, however large discrepancies were found whose origin could not be explained [13]. 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.

FUTURE WORK

In 2016, the β^* is being reduced to $\beta^* = 40$cm in IP1 and IP5. To achieve this, some collimators are required to be closer to the beam, increasing the transverse impedance. Repeat measurements will be required to validate the instability threshold with the new collimator settings. Additionally, instabilities were also seen at injection that may have been caused by linear coupling. This will also be investigated, both at 450GeV and 6.5TeV.

CONCLUSION

Single bunch and multibunch measurements were made in 2015 of the octupole current threshold for stability. Good agreement was observed for all operational chromaticities, however for small or negative chromaticities, some additions to the model are required to explain the measurements. The octupole current instability threshold for bunch trains was found to be greatly increased due to the presence of electron cloud. Measurements were made before and after a period of high intensity physics which scrubbed the machine at 6.5 TeV. It was found that the octupole current instability threshold was decreased once the level of electron cloud was reduced.

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