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INSTABILITY OBSERVATIONS IN THE LARGE HADRON COLLIDER DURING RUN 2

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Abstract

Instabilities of many different types and characteristics have been observed in the LHC during Run 2. The causes of these instabilities come from a variety of stabilising and destabilising mechanisms. Efforts to understand these instabilities and prevent their occurrence has improved the performance of the Large Hadron Collider (LHC) in all stages of the machine cycle. This paper aims to give an overview into some of the instability observations and details the operational steps to prevent them.

INTRODUCTION

During Run 1 of the LHC, many transverse instabilities were observed that were not understood [1]. Run 2 has been focused on attempting to identify and cure any destabilising mechanisms that are present or were present during Run 1, as well as understanding the nature of any stabilising mechanisms that are currently present or could be employed in the future to mitigate transverse instabilities [2]. This paper will present a short summary of the different studies into stabilising or destabilising mechanisms that have occurred since the beginning of Run 2, and will detail any operational steps that have been taken to ensure the instabilities do not occur.

STABILISING MECHANISMS

Second-Order Chromaticity

Chromaticity is known to have a strong impact on the interaction between a beam spectrum and the machine impedance. First order chromaticity (Q') is well controlled in the LHC, however second order chromaticity (Q'') could provide the same stabilising benefits (if the practical limit for Q' is reached in the LHC for example) [3]. In addition to its effect on the unstable modes, Q" can also provide a tune spread that depends on longitudinal action (unlike the Landau Octupoles (LOs) which rely on transverse action). This could be very useful for HL-LHC, FCC or any future high energy machine as the transverse beam emittances will be reduced (lowering the effectiveness of the LOs), but the bunch length will remain similar.

A knob was developed that changed the powering configuration of the main sextupoles in such a way that the Q" could be introduced and controlled. This knob also introduces transverse amplitude detuning, but it was shown through simulations that this amount is small and does not contribute to the Landau damping. Q" was tested in dedicated measurements in the LHC during 2016 with a single bunch at high energy [4]. Without Q", a bunch of this type will go unstable with a current in the LOs of $J_{oct} \approx 100$ A. A campaign of measurements performed in 2015 verified that for operational chromaticities ($5 < Q' < 15$), good agreement was found between prediction and measurements [5].

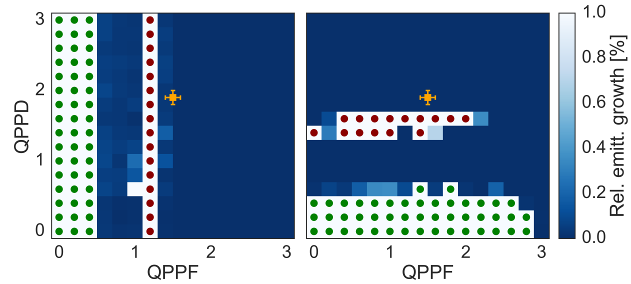

Figure 1: Simulation results showing if instabilities are expected as a function of the knob value (QPPF and QPPD). The left plot shows the horizontal case and the right shows the vertical case. The cross shows the working point used in the measurements. The green points show an azimuthal mode 0 and the red points show a mode 1. White colours refer to unstable simulations, while dark colours show stable simulations. Thin bands of higher order modes appear and care must be taken to avoid them if these knobs were to be used in operation.

With the Q" that was introduced (shown by the yellow cross in Fig. 1), the current in the LO required to stabilise was greatly reduced. In fact, 3 out of 4 bunches were stable for $J_{oct} = 0$ A while one bunch became unstable when reducing the current to 0 from $J_{oct} = 40$ A. The unstable bunch showed instability characteristics of a headtail azimuthal mode 1 that can be explained by PyHEADTAIL simulations [6, 7].

Triplet Non-Linearities

Throughout Run 2, the β^* in Interaction Points (IP) 1 and 5 has been steadily reduced, from $\beta^* = 80$ cm in 2015, to $\beta^* = 30$ cm at the end of 2017. As the β^* at the IP reduces, the value of the β-function in the nearby triplets increases. This can give rise to many additional unwanted non-linear effects, which includes amplitude detuning terms which can strongly modify the tune spread [8–10].

Figure 2 shows the tune footprint for the unperturbed LOs at high energy in the LHC and compares them to the case where both LOs and non-linearities from the full interaction region (IR) are present. It can be seen that there is a significant deviation in the tune footprint when the β^* is low.

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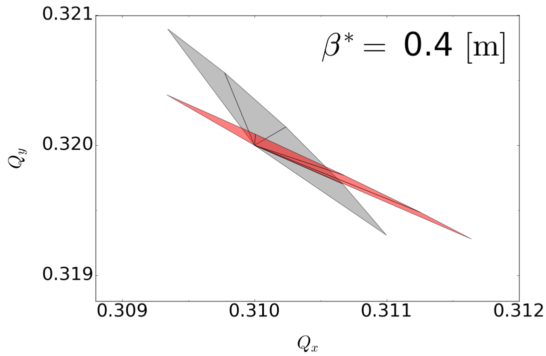

Figure 2: Tune footprint at β^* = 40cm for the case with octupoles only (in grey) and with octupoles and IR non-linearities (in red).

Stability measurements were performed at the end of the squeeze with β^* = 40 cm. A single bunch of nominal population (N_b = 1e11 p) was circulating in the machine and the current in the LOs was slowly reduced. It was found that even for J_{oct} = 0 A, the beam was stable [4]. This means that the non-linearities alone were large enough to provide stabilisation for a single bunch.

The triplet non-linearities at low β^* make stability predictions very difficult as the non-linearities are required to be both known and included in the simulation. Correction schemes are under study by the LHC optics teams to attempt to fully correct the triplet non-linearities [11].

DESTABILISING MECHANISMS

Linear Coupling

It has been shown through simulations and measurements that the presence of linear coupling can severely inhibit the effectiveness of LOs [12, 13]. This is a critical issue in the LHC because the tune separation is small once high energy is reached (Q_x = 0.31, Q_y = 0.32). Any increase in the linear coupling ($|C^-|$) or if the tunes were to drift closer together could cause the detuning coefficients of the LOs to change which can cause previously stable modes to become unstable [14]. This effect is demonstrated in Fig. 3.

While it is not possible to make a definitive statement as to whether linear coupling was the cause of the instabilities in Run 1, previous results have shown that strong linear coupling was present during some of the stages of the machine cycle. It is clear that linear coupling had a key impact on machine performance during this period.

Many operational steps have been taken to try to minimise the $|C^-|$ and maintain well separated tunes during the machine cycle. The first steps toward a coupling feedback have taken place, where the coupling can now be accurately measured during the cycle and immediate trims to skew quadrupole correctors can be applied [16–18].

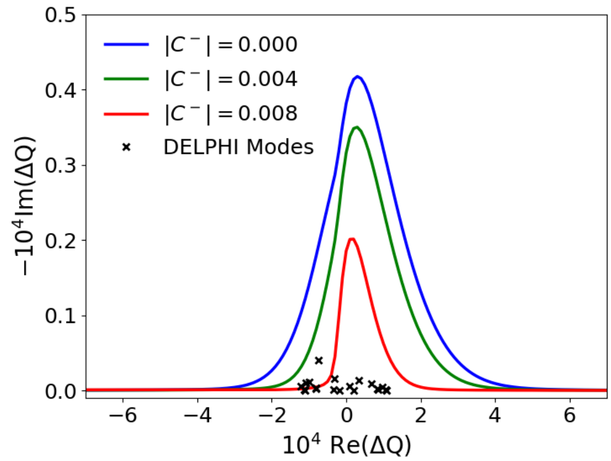

Figure 3: Reduction of stable region with increase of linear coupling. In each case the tunes are matched to Q_u = 0.31, Q_v = 0.32 after coupling is introduced. If the unstable modes (as simulated in DELPHI [15]) lie outside the curve then the mode is unstable.

Electron Cloud

Electron cloud effects have been a major limitation in Run 2 with the move to bunches with 25 ns bunch spacing. Stability issues relating to electron cloud have been observed at both low energy (450 GeV) and high energy (6.5 TeV) [2, 12, 19].

During the injection process with 25 ns beam variants, it was seen that high chromaticity (Q'_H, Q'_V) = (20, 20), LOs (J_{oct} = 20 A) and transverse feedback gain (τ_d = 10 turns) was needed in order to prevent instabilities from occurring during 2015. The working theory was that the high chromaticity provided very large detuning within the particles inside the bunch, which was lowering the rise time of the instabilities. When the rise time is low enough, it is able to be stabilised by the high LO current. These machine parameters were adiabatically reduced as the beam scrubbed the machine throughout Run 2 and the level of electron cloud reduced.

As a test for HL-LHC, a filling scheme called 8b-4e (8 filled 25 ns buckets, 4 empty 25-ns buckets) was employed to see if electron cloud issues (stability and heat loads) persisted [20]. This scheme does not allow the electron cloud to fully develop. It was shown in measurements that the 8b-4e scheme could be used with up to a maximum of 1920 bunches that were injected using "ideal" machine parameters (Q'_H = 5, Q'_V = 5, J_{oct} = 5 A, τ_d = 50 turns). This verified that the main limitation relating to beam stability at injection does indeed come from electron cloud.

In 2016, it was seen that individual bunches were going unstable vertically during collisions that had approximately 2000 bunches per beam [19]. The instabilities would take several hours to develop (hence the nickname "popcorn instability") and would cause dramatic losses of luminosity

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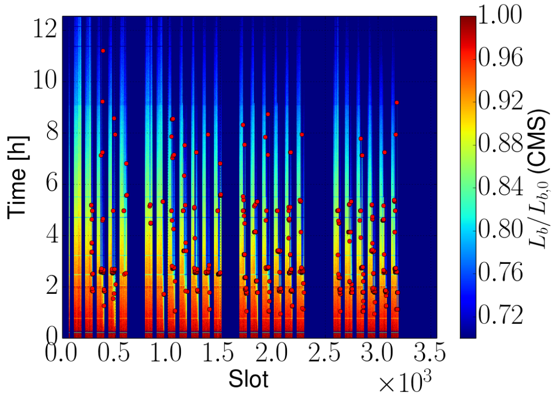

Figure 4: Bunch by bunch luminosity taken from the CMS experiment. Abrupt reductions in luminosity show that one of the colliding-pair has gone unstable (and suffered emittance blowup) and is marked by a red point.

from the colliding-pair due to emittance blowup. This can be seen in Fig. 4.

At this stage of the machine cycle (during collisions) the chromaticity was set to $(Q'_H, Q'_V) = (15, 15)$. This vertical emittance blowup was dramatically reduced by increasing the vertical chromaticity by 7 units at the start of collisions. It was found that over time, the instability stopped occurring which could be due to a change in the level of scrubbing in the machine.

High Latency Instability

In 2017, a peculiar instability was observed during operation which also reappeared in measurements which does not yet have a full explanation. When trains of bunches (48 bunches or 96 bunches) with 25ns bunch spacing were accelerated to 6.5 TeV, the bunches were all completely stable for the first 7 minutes at high energy. After 7 minutes, single bunches started to go unstable within the train with instability characteristics (rise time, headtail mode number) that are consistent with predictions from impedance without Landau damping, despite the fact that the octupole current was approximately 3 times higher than needed for stability [21]. Additional instability threshold discrepancies were also found with several beam variants. A summary of all the performed measurements relating to this instability can be found in Fig. 5, a more detailed discussion of these results can be found in Ref. [22].

Instabilities have often been found to have a latency time that varies from 7 minutes to approximately 40 minutes. It has been proposed in the past that the latency could come from the effect of noise impacting the particle distribution in frequency space [23]. This could cause strong deformation of the stability diagram and cause previously stable bunches to go unstable. Measurement campaigns using the beam transfer function (BTF) method [24, 25] are planned for 2018 to test the predictions of this theory.

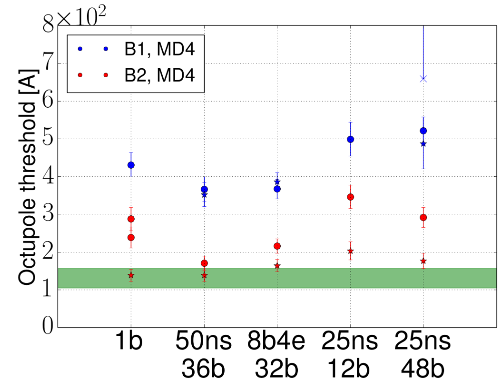

Figure 5: Octupole threshold measured for different train structures throughout 2017. The green bar indicates the predicted threshold for a single bunch with a transverse damper and considering uncertainties in the measured intensity and emittance. The cross marks the measured threshold in 2016. The dots show the measured threshold with damping time of 30 turns, while the stars represent the results obtained for a damping time of 100 turns.

16L2 Instability

Significant issues were observed in 2017 that were instigated by a cell in one of the LHC arcs (cell 16L2 which corresponds to the 16th cell to the left of interaction point 2). High beam losses were observed in this cell [26], followed by short spikes of even higher beam losses which was often followed by a strong beam instability with rise times on the order of 10–100 turns. A full characterisation of the loss profile and the instability can be found in Refs. [27, 28] at this conference.

Transverse Damper at Low Chromaticity

It was seen in single bunch measurements of the instability threshold that there is a large discrepancy between prediction and measurements in the region of $-1 < Q' < 1$ [5]. This does not yet have an explanation.

There has been significant analytical work on the effect of the transverse damper at low chromaticity, the results of which are reported in a companion paper [29], but it does not seem to explain the observation in this region. It is clear that another destabilising mechanism still needs to be identified.

CONCLUSION

There has been a wide range of instability observations during Run 2 of the LHC. In many cases, the instabilities were unexpected but adequate explanations could be found using the existing stability model. In other cases, simulations were needed to determine what is causing the onset of the instability which then improves the understanding of the LHC beam stability.

There are still instability observations that do not yet have a full explanation, but simulation and measurement campaigns are currently in progress to further improve the stability model as the HL-LHC upgrade approaches.

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