OBSERVATIONS OF TWO-BEAM INSTABILITIES DURING THE 2012 LHC PHYSICS RUN

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Abstract

During the 2012 run transverse coherent beam instabilities have been observed in the LHC at 4 TeV, during the betatron squeeze and in collision for special filling patterns. Several studies to characterize these instabilities have been carried out during operation and in special dedicated experiments. In this paper we summarize the observations collected for different machine parameters and the present understanding of the origin of these instabilities.

INTRODUCTION

The 2012 run of the Large Hadron Collider (LHC) has shown, despite the great physics discovery of a Higgs-like boson, several instabilities which have perturbed the accelerator performances. To achieve the required integrated luminosity several parameters had been changed and pushed compared to 2011: reduced β^* operation (from 1 m to 0.6 m) and higher brightness beams (approximately two times larger than nominal). To ensure protection collimator gaps have been reduced to tight settings with apertures close the nominal 7 TeV configuration leading to larger impedances [1]. A first type of instabilities [2] occurred during stable beams after many hours of physics and affected specific bunches colliding only in the LHCb experiment. In this paper we will focus on instabilities developing at the end of the betatron squeeze and while bringing the beams into collision. The origin of the instability is still not understood however some observations have led to considerations on the beam stability to help defining possible future scenarios. There were several other observations which need further studies and analysis will not be covered in this paper but be found in [3].

END OF SQUEEZE INSTABILITY

In 2012 the LHC peak luminosity has been more than doubled as compared to 2011. The main beam parameters, compared to those of 2010 and 2011, are in Table 1.

Table 1: LHC Operational Parameters

Parameter	2010	2011	2012	Nominal
N_p (10^{11} p/b)	1.2	1.45	1.58	1.15
N_b	368	1380	1380	2808
Spacing (ns)	150	75/50	50	25
ϵ ($\mu mrad$)	2.4-4	1.9-2.4	2.2-2.5	3.75
β^* (m)	3.5	1.5-1	0.6	0.55
L (10^{32} cm$^2 s^{-1}$)	2	35	76	100

The LHC beams were accelerated in 2012 from injection energy (450 GeV) to top energy 4 TeV then the β^*-functions at the different Interaction Points (IPs) squeezed (from 10 m to 3 m in IP2 and IP8 and further down to 0.6 m in IP1 and IP5). This process lasts around 15 min and is called the β squeeze. At the beginning of the year during the betatron squeeze at a value of β^* of $\approx$ 1.5 m several bunches were becoming unstable loosing intensity in a non reproducible manner. In particular the instability was not present in all physics fills. The bunches were unstable one after the other for several minutes till the head-on collision was established. For some fills the instability was generating very high losses causing a beam dump. Another important parameter for stability is chromaticity which might explain the non reproducibility of the instability when operating close to zero value (LHC was operating at Q' $\approx$ 2 units till the beginning of August 2012). At the beginning of AUgust 2012 the machine configuration has been changed drastically in terms of chromaticity (changed from 2 units to 15 units [4]), the polarity of the Landau octupoles (changed from negative to positive [5]) and the transverse damper (to 50 turns). The changes have been implemented from Fill 2926 but not always at the same time to distinguish the implications of the three parameters. As a result of these changes the instability has showed important aspects: it became reproducible always occurring after two minutes from the end of the squeeze and has changed to the vertical plane. An example of the bunch by bunch intensity losses versus time during this type of instability is shown in Fig. 1.

The coherent mode is shown in Fig. 2 where several frequencies are visible all spaced by $Q_s \approx 0.002$, the synchrotron tune. Several bunches were loosing up to half their intensity while coherently oscillating. Bunches where going unstable at different moments and the instability could last till the head-on collision was established and coherent motion stoped.

The stability of beams before going into the β squeeze is given by the Landau octupoles which ensure a given stability area under which all impedance driven modes should be damped. For the specific case of the LHC the stability region is shown in Fig. 3 (dashed lines). In red we show the stability area with negative octupole polarity and in blue the positive polarity effect. The negative polarity was pre-

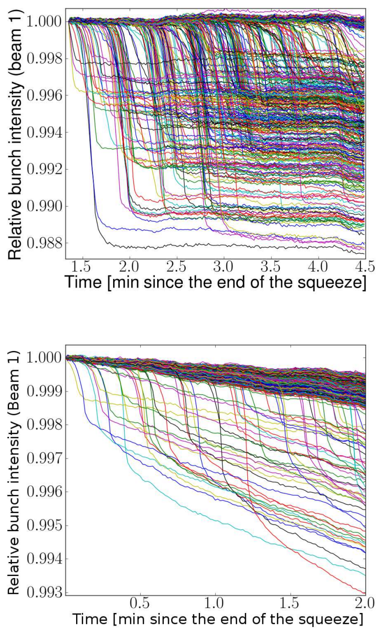

Figure 1: Bunch by bunch losses in beam 1 during an end of squeeze instability as a function of time for Fill 2648 with negative octupole polarity (top picture) and Fill3250 with positive polarity(bottom plot).

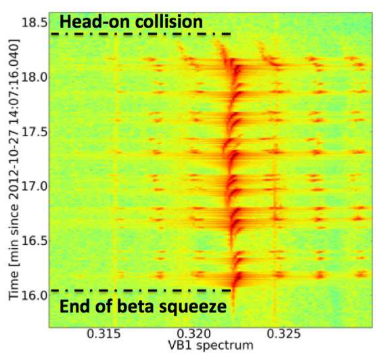

Figure 2: Beam 1 vertical frequency spectrum as a function of time during an end of squeeze instability.

ferred for single beam since gives larger area [6]. However the long-range interactions also contribute to the picture and they result in a change of the stability properties at the end of the β squeeze (solid lines in Fig. 3). For the case of negative polarity they reduce the stability area while for the positive polarity they increase it. This was the motivation for inverting the polarity of the Landau octipoles but the instabilities observed at the end of the squeeze with the positive polarity remain unexplained.

GOING INTO COLLISION

The end of squeeze instability, as shown in Fig. 2, was lasting also during the collision beam process. At the beginning of the year the process was long ($\approx$ 200 s) and was not directly going for head-on collisions in IP1 and IP5 but

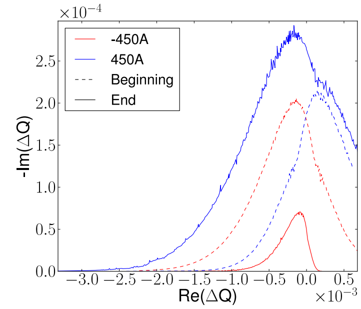

Figure 3: Beam stability diagrams for the two LHC octupole configurations: positive (blue lines) and negative (red lines) before the betatron squeeze (dashed lines) and at the end with long-range contribution (solid lines).

was slowed down to allow the tilting of IP8 crossing angle and only at the end optimized for luminosity. Several instabilities were observed developing during these steady states of IP1 and IP5 at an intermediate separation before having a head-on collision. In Fig. 4 we show the beam amplitude of oscillation and IP1 and IP5 separation reduction as a function of time. The beams are not yet in head-on collision and an exponential growth of the oscillation amplitude can be observed, causing a dump which occurred for a separation of $\approx 1-2\,\sigma$.

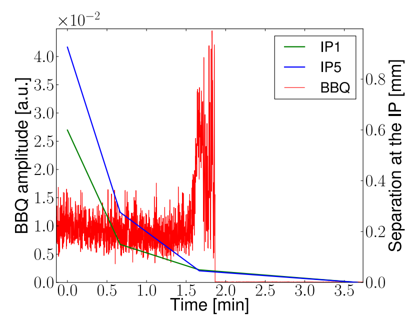

Figure 4: Oscillation amplitude of beam1 during the collapse of the separation bumps as a function of time.

Over the year a change of the collision beam process has been proposed and implemented in the second half of the run. The main ideas behind the change was to speed up the collapse of the separation bumps and to go straight to head-on collision to ensure stability. It is intuitive from the footprint of Fig. 5 upper plot and proved from the stability diagrams [7] that the stability area varies as a function of the beams separation and that during the collapse there is a minimum of stability. This minimum defines a weak moment in the process to bring the beams into collision which might have been the reason for the beam dumps observed in 2012 since the beams separation was reduced in steps and then stopped at some intermediate values to allow the tilting of IP8. It has been also shown that several times this process was keeping the beams at a separation of around 1-2 σ which corresponds to this minimum of stabil-

ISBN 978-3-95450-122-9

ity. Observations have also demonstrated that the only cure to this instability is the head-on collision which gives the largest possible stability area. To use this important property of the opposite beam several test have been carried out to allow for the future operation of the machine collisions before the β squeeze [8].

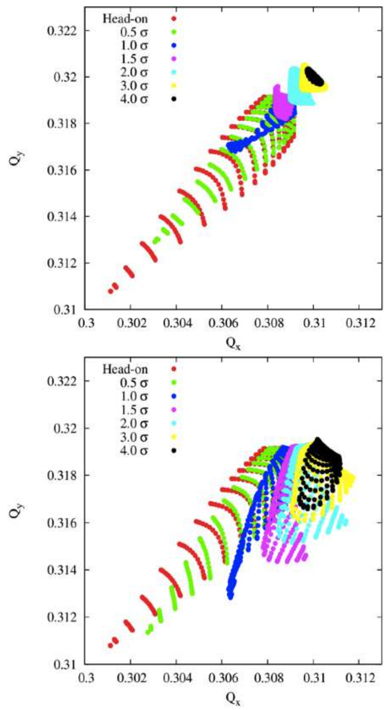

Figure 5: Footprint evolution during separation collapse in both planes synchronously (upper) and only in the horizontal plane (lower).

However to guarantee a stronger stability several configurations have been tested with simulations and have shown that a synchronous collapse of both horizontal and vertical plane separation will lead to a minimum (magenta dots) of stability in both planes at the same time, as shown in Fig. 5 upper plot, where we show the beam footprint for different beam separations equal in both planes. The lower plot shows how one can avoid this minimum by just collapsing one plane at the time. The stability for this second configuration has been studied for both cases and results from multi-particle tracking simulations are shown in Fig. 6. The figure shows the amplitude of oscillation as a function of time for the different separations in either both planes at the same time (upper plot) or only the horizontal plane (lower plot). One can see that when only one plane goes through the stability minimum the other plane helps in the damping making this option more robust compared to the one going both planes together (or as for the LHC both IPs together) where for a defined separation of $\approx$ 1.5 σ separation the system in not stable.

SUMMARY

We have shown few cases of transverse coherent beam instabilities observed in the LHC during the 2012 physics run. The instabilities were mainly occurring at the end of the β squeeze and in the collision beam process. They have changed during the year as a consequence of changed parameters (Q', octupoles currents and polarity and transverse damper gain). The origin of the instabilities is not understood yet however counter measures to have more stability are described for the different beam processes.

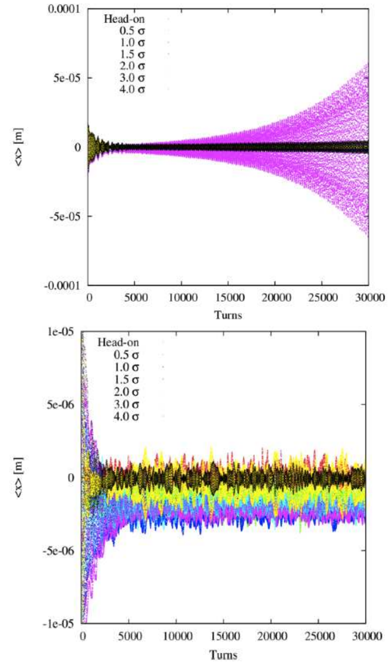

Figure 6: Beam oscillation amplitude as a function of time for different separations at the interaction point in both horizontal and vertical plane (upper) and for only the horizontal plane (lower).

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