OBSERVATIONS OF INSTABILITIES IN THE LHC DUE TO MISSING HEAD-ON BEAM-BEAM INTERACTIONS

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Abstract

We report the observation of coherent instabilities on individual bunches out of the LHC bunch train. These instabilities occurred spontaneously after several hours of stable beam while in the other cases they were related to the application of a small transverse beam separation during a luminosity optimization. Only few bunches were affected, depending on their collision schemes and following various tests we interpret these instabilities as a sudden loss of Landau damping when the tune spread from the beam-beam interaction becomes insufficient.

INTRODUCTION

The CERN Large Hadron Collider (LHC) is designed for highest luminosity and therefore requires operation with a large number of bunches and high intensities. Limiting effects come largely from the beam-beam interactions [1]. A particular feature of the non-linear beam-beam interaction is that it generates a rather significant detuning with the betatron amplitude and therefore a tune spread inside the bunch, often shown as a so-called footprint, the mapping of the amplitude space into the tune space. The tune spread is a consequence of head-on as well as long range beam-beam interactions. Although these contributions provide similar tune spreads, their contribution to Landau damping is very different, as discussed in detail in previous reports [2]. When non-linearities are introduced into a machine, there is always a compromise between Landau damping and dynamic aperture. The former requires a large tune spread in the core of the beam, while the latter limits the tune spread of particles at large amplitudes. While in the case of tune spread from long range interactions or octupoles the effect is strongest on large amplitude particles, the head-on beam-beam interaction fulfills both criteria. In that case possible side effects can be kept small, this makes the head-on beam-beam interaction an ideal tool to provide Landau damping [2]. Furthermore, it is basically independent of the energy and the optical parameters at the collision point (i.e. β^*). It becomes more efficient with increased beam brightness and ideal at high energy and small emittances (where octupoles become inefficient).
The effect of missing head-on collisions has been observed in the operation of the LHC and here we summarize the findings together with the quantitative analysis of the stability provided with and without the beam-beam interaction.

OBSERVATIONS

A particular feature of the LHC is the presence of four experiments with different requirements. As a consequence, the bunch filling schemes of the LHC are not equidistant nor fully symmetric [3]. This results in different collision pattern for different bunches in the bunch train, leading to different number of long range as well as head-on collisions [3].
To control the luminosity in the interaction point 8 (IP8) of the LHC [3], the beams are collided with transverse offset. The filling scheme of the LHC used in early 2012 delivered some bunches with no collisions in other interaction points but the offset collision in IP8 [4]. An offset around 1 - 2 σ entails a minimum in the tune spread provided by the beam-beam interaction and these bunches can loose Landau damping. A first observation is shown in Fig. 1 where

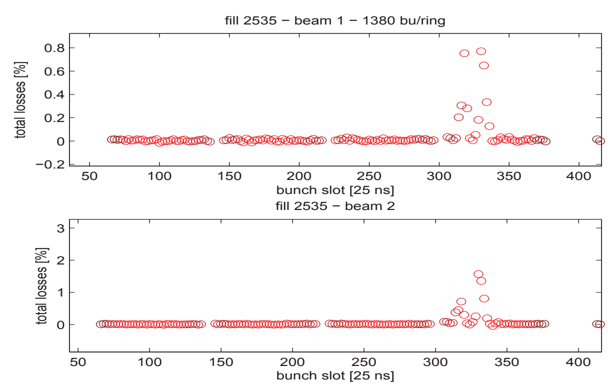

Figure 1: Losses per bunch during luminosity scan in IP1.

we plot the losses during a transverse luminosity scan in interaction point IP1, i.e. collisions with offset beams. Only few selected bunches are affected. A detailed analysis of the collision scheme showed that these bunches experience only 2 head-on collisions, i.e. in interaction points 1 and 5. Separating in one of the two interaction points strongly reduces the tune spread from beam-beam effects, i.e. a smaller beam-beam effect led to significant losses. In Fig. 2 we show the relative losses of the two beams when they are brought into collisions. It is apparent again that some of the bunches in beam 1 show very significant losses during this process. The Fig. 3 shows the relative losses during a fill while the beams are in collision for several hours. Again one can observe some bunches with significant losses. A detailed look at these bunches is shown in Fig. 4 where the intensities of these bunches are shown as a function of time during this run. It shows that the losses in collision occur many hours after the start of the collision process.

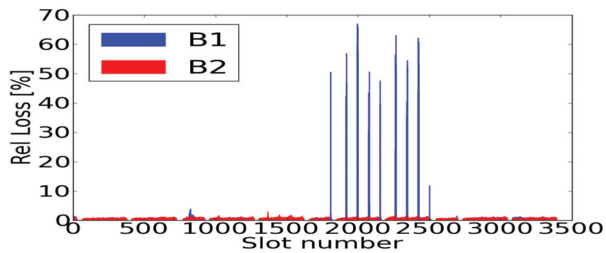

Figure 2: Relative losses bunch by bunch for beam 1 and beam 2 during adjustment.

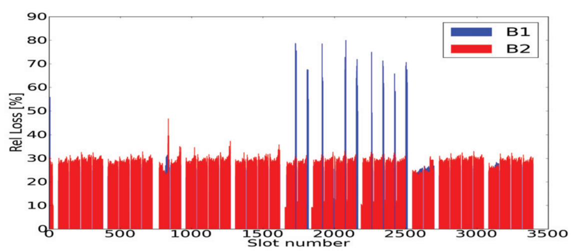

Figure 3: Relative losses bunch by bunch for beam 1 and beam 2 in collision.

The losses are very fast and not a consequence of bad life time or reduced dynamic aperture, but rather an instability. Coherent signals can be observed in the tune spectrum during the losses. The Fig. 5 shows the number of head-

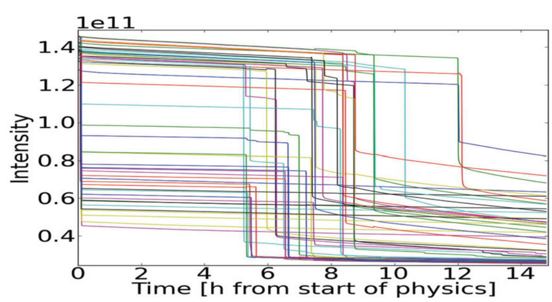

Figure 4: Time structure of relative losses bunch by bunch for beam 1 and beam 2 in collision.

on collisions for all bunches along the bunch train. Most bunches experience 3 head-on collisions, but some bunches collide only in a single interaction point. These are (48) bunches "private" to interaction point 8 where the beams collide with an offset. For these bunches the tune spread from beam-beam interactions is very small and may not be sufficient to provide Landau damping.

Our interpretation of these losses is the lack of Landau damping for these bunches. For the losses shown in Fig. 1 the tune spread was reduced by offsetting one of the two collision points, leading to a short unstable situation during the scan. Since only bunches in beam 1 were affected (See Figs. 3,4), we exclude the excitation of coherent beam-beam modes. As a first measure and to test this hypothesis,

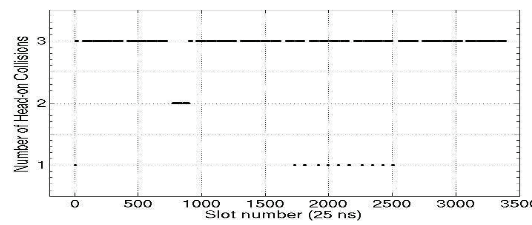

Figure 5: Number of head-on collisions for all bunches along the bunch train. Original filling scheme.

a new filling scheme was provided where only 3 bunches are private [4]. In the following only the remaining 3 private bunches suffered from the losses, supporting the assumption.

ANALYSIS

To evaluate this configuration quantitatively, one can compute the tune spread as a function of the amplitude. We show the so-called "footprints" from beam-beam interactions with full head-on collision and different offsets. It

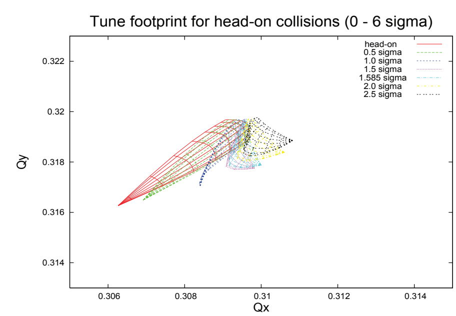

Figure 6: Tune footprints from beam-beam interaction with different offsets.

becomes a minimum in the plane with the offset at a separation around 1.5 σ of the beam size. This is shown in Fig. 6 where we show the tune footprints for different offsets in unit of the beam size. At slightly larger separation the tune spread increases due to the increasing contribution of long range interactions and goes to zero when the separation is very large. How this affects the damping of coherent instabilities has to be shown by computing the corresponding stability diagrams in the complex tune plane [5]. In Fig. 7

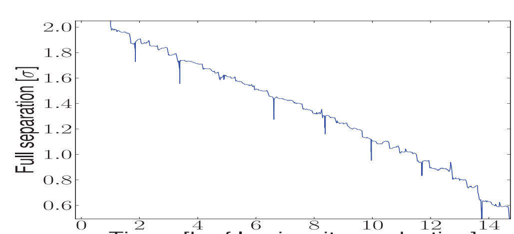

Figure 7: Separation of bunches in IP8 during levelling.

we show the separation of bunches in IP8 during a physics run. The separation decreases with time to keep the luminosity constant. The data is shown for the same fill as Fig. 4. From Fig. 4 we derive that the losses mainly occur between 5 and 10 hours into the fill. The corresponding separation of these bunches from Fig. 7 is $\approx 1.1-1.7\,\sigma$, i.e. when the tune spread acquires a minimum. The reduction of the tune spread during luminosity steering and potential loss of Landau damping was already discussed for the ISR [6].

Stability Region and Discussion

To evaluate the effect on the stability, it is insufficient to compute the tune spread. A comparison requires the computation of the stability diagram, i.e. the stability limit in the complex tune space. A full analysis requires the knowledge of the complex tunes of the coherent modes, however the machine impedance is not known well enough for the cases presented. In the evaluation of the stability diagram, we follow the strategy developped in [5] and already used in [2].

In the case of the beam-beam interaction, in particular for long range interactions, the detuning cannot be easily written down. A numerical method is required to derive the stability for this detuning. Details can be found in [7]. This numerical method was used to compute the stability diagrams shown in Figs. 8 and 9. Figure 8 shows the stable region provided by the tune spread for head-on collisions and two cases with separations of $1.4\,\sigma$ and $14\,\sigma$. It demonstrates the stability that can be provided by the head-on collisions compared with offset collisions. The tune spread at $14\,\sigma$ is mainly due to the weak long range interactions and does not provide efficient Landau damping [2, 7]. A minimum of the stability can be seen when the tune spread becomes small. Figure 9 is similar to Fig. 8 but includes the tune spread from octupoles with negative polarity as used in operation. Although the stable region is increased, for large (inductive) impedances this may be insufficient. Later in the year the octupole polarity was reversed providing a slightly larger stable region for $1.4\,\sigma$ separation. Whether this would have avoided the observed losses is not known. The interplay between the different contributions (head-on and long range beam-beam and octupoles) to Landau damping is detailed in [7]. The physical reason and the interpretation for these results are straightforward. Even when the tune spread is large, it can be insufficient when the tune distribution is not populated by a sufficient number of particles. Another important aspect of Landau damping can be observed when coherent beam-beam dipole modes are excited [8]. They can originate either from head-on or long range encounters. The analysis of the respective eigenmodes show that in the two cases different parts of the beam are involved. While for the head-on driven modes mainly core particle participate, the modes driven by long range encounters involve mainly tail particles [8]. This has strong consequences for the Landau damping since a very large tune spread is not sufficient when it is not produced by the particles participating in the oscillation [8]. In such cases the tune spread alone becomes irrelevant.

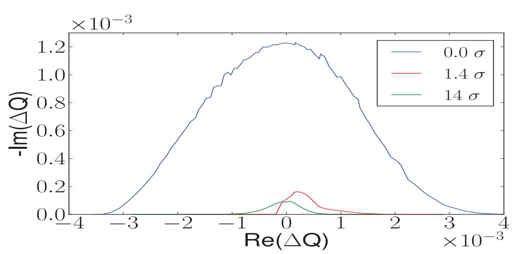

Figure 8: Stability diagram from beam-beam tune spread for different offsets. Beam-beam only, no octupoles.

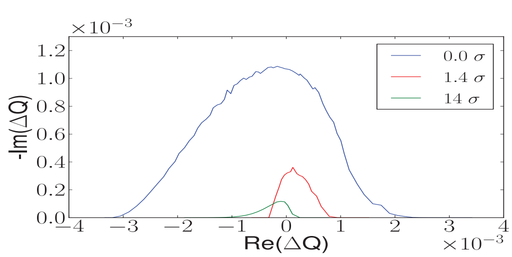

Figure 9: Stability diagram from beam-beam tune spread for different offsets. Octupoles with negative polarity, maximum strength.

ACKNOWLEDGEMENTS

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