

# LOSS OF LANDAU DAMPING IN THE LHC

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## Abstract

Loss of Landau damping leading to a single bunch longitudinal instability has been observed in the LHC during the ramp and on the 3.5 TeV flat top for small injected longitudinal emittances. The first measurements are in reasonable agreement with the threshold calculated for the expected longitudinal reactive impedance budget of the LHC as well as with the threshold dependence on beam energy. The cure is a controlled longitudinal emittance blow-up during the ramp which for a constant threshold through the cycle should provide an emittance proportional to the square root of energy.

## FIRST OBSERVATIONS IN 2010

In one of the fills with acceleration ramp in LHC in May 2010 single bunches of both Beam1 and Beam2 with the nominal intensity of  $\sim 1.1 \times 10^{11}$  became unstable during ramp, Fig. 1. These bunches had a small longitudinal emittance  $\varepsilon$  of 0.38 eVs ( $2\sigma$ , Gaussian shape) in comparison with nominal injected emittance of 0.7 eVs in the LHC Design Report [1]. In the next fill increasing emittances to 0.5 eVs (Beam1) and 0.6 eVs (Beam2) was sufficient to stabilise the beams during the ramp, but bunches became unstable on the flat top (3.5 TeV). Losses were observed at the energy  $E$  of 1.8 TeV with the onset of the instability around 1.5 TeV, seen from the bunch length measured by the LHC Beam Quality Monitor (BQM) [2], Fig. 1. Observations of bunch profiles during the ramp suggested that this could be also non-rigid dipole instability. During these measurements a rigid dipole motion was stabilised by the phase loop.

The criterion of the loss of Landau damping due to the low frequency (reactive) impedance  $\text{Im}Z/n$  derived in [3] for the azimuthal mode  $m$  can be written in the form

$$|\text{Im}Z|/n < \frac{|\eta|E}{eF_m I_b \beta^2} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\omega_s}{\omega_s} f_0 \tau, \quad (1)$$

where  $I_b = Nef_0$  is the bunch current,  $N$  the bunch intensity,  $\Delta E/E$  the relative energy spread in the bunch,  $\Delta\omega_s/\omega_s$  the relative synchrotron frequency spread,  $\eta = 1/\gamma_t^2 - 1/\gamma^2$  (in LHC  $\gamma_t = 55.87$ ) and the form-factor  $F_m$  is defined by the particle distribution (in [3]  $F_m = m/(m+1)$  for sinusoidal azimuthal modes), see also [4].

During acceleration the threshold for loss of Landau damping scales as [5]

$$N \text{Im}Z/n \propto \frac{\varepsilon^{5/2}}{E^{5/4} V^{1/4}}. \quad (2)$$

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Figure 1: Bunch length of beam 1 (blue) and beam 2 (red) measured by BQM during ramp on 15 May 2010.

For a constant emittance the threshold quickly drops with energy as can be seen in Fig. 2, where the threshold impedance (1) during the cycle is plotted for bunches with nominal intensity and emittances of 0.4 eVs and 0.6 eVs for  $F = 1$ . In 2010 the 400 MHz voltage  $V$  ( $h = 35640$ ) was 5 MV at injection (bucket area of 1.13 eVs) and increased to 8 MV during the first 222 s of the ramp. The instability, starting at 1.5 TeV (1000 s) for 0.38 eVs bunches and at 3.5 TeV for 0.6 eVs bunches, corresponds to  $F \text{Im}Z/n \simeq 0.065$  Ohm (horizontal line in Fig. 2), to be compared with the LHC low frequency impedance budget  $\text{Im}Z/n = 0.06$  Ohm in [1].

To avoid the intensity threshold of loss of Landau damping decreasing during the cycle, the longitudinal emittance should be increased with energy at least as  $\sim E^{1/2}$  [5]. This leads to an emittance of 2.5 eVs at 7 TeV [1] and 1.75 eVs at 3.5 TeV. Since the bucket area also grows with energy as  $E^{1/2}$ , a constant bucket filling factor (or constant bunch length) should provide the same beam stability during ramp as on the flat bottom. The concept of the constant bunch length was used in the controlled emittance blow-up quickly commissioned after the first instability observations and is permanently used in operation since this time [6]. The preservation of natural Landau damping is especially important in the absence of a longitudinal wide-band (bunch-by-bunch) feedback system in LHC. The possibility of further increase of the synchrotron frequency spread by installing a higher harmonic RF system was also considered [7].

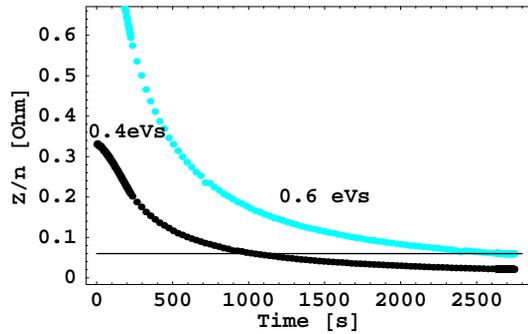


Figure 2: Threshold impedance (1) for loss of Landau damping for bunches with  $\varepsilon = 0.4$  eVs and  $0.6$  eVs and nominal intensity during the 2010 ramp. The line  $Z/n = 0.065$  Ohm corresponds to the start of instability at  $1000$  s for  $\varepsilon = 0.4$  eVs and at flat top for  $\varepsilon = 0.6$  eVs.

## RESULTS OF STUDIES IN 2011

More measurements of this instability were performed in 2011 during two Machine Development (MD) sessions [8], each with a few fills, but only one acceleration ramp. In 2011 acceleration to  $3.5$  TeV became 4 times faster and the operational voltage program is also different: injection voltage of  $6$  MV (matched voltage is  $3.8$  MV) is increased linearly during a  $680$  s long acceleration ramp to the flat top value of  $12$  MV.

In both MDs we injected 8 single bunches spaced by  $1/9$  of the revolution turn to obtain more data from one ramp. During the first MD the phase loop settings were different from the ones used in normal operation: the beam phase was obtained only from the phase of the pilot and the first bunch. During the 2nd MD the beam phase was derived from all bunches as in normal operation.

In all fills, even for bunches with small emittance  $\sim 0.4$  eVs and intensity of  $1.3 \times 10^{11}$ , bunch length oscillations were observed only on the flat top, probably due to a shorter (than in 2010) ramp. On the other hand the damping of the injection phase errors was taking a long time ( $\sim 20$  min) in comparison with the expected filamentation time. In the first MD phase oscillations were sometimes even growing after injection, Fig. 3, together with the bunch length, till the bunch length was reaching some value around  $1.2$  ns. Similar behaviour is observed for multi-bunch LHC batches during normal operation [9], when initial phase oscillations are growing for some time after injection till the bunch length becomes about  $1.25$  ns ( $\varepsilon = 0.53$  eVs).

For the fill with ramp during the first MD, 8 bunches were injected into each ring with different longitudinal emittances varying from  $0.9$  eVs to  $0.3$  eVs. For the first bunches, having larger emittances, phase oscillations were damped after injection while for later coming bunches, with smaller emittances, they grew first and then started to decay. During the ramp bunches with smaller longitudinal emittances became unstable earlier and had a larger

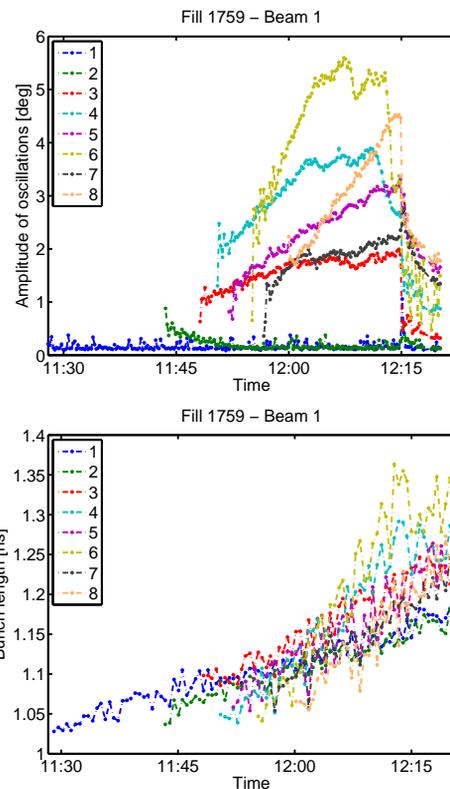


Figure 3: Amplitude of the phase oscillations (top) and bunch length (bottom) with time after injection for 8 bunches of Beam1. Bunch 1 is controlled by the phase loop. Change to the nominal phase loop setting at  $12:15$ .

amplitude of phase oscillations later on, Fig. 4. The energy thresholds of the dipole instability seems to depend both on bunch length and intensity. In Fig. 5 the energy at which the phase oscillations start to grow during the ramp is plotted as a function of the bunch length at the end of the flat bottom for all 8 bunches in both beams. For each point on this plot the energy threshold is scaled with  $N^{4/5}$  as follows from the scaling law  $E_{th} \propto \varepsilon^2 V^{1/5} N^{4/5}$  expected from (2). This curve is also plotted in Fig. 5 starting from the first measurement point during the ramp. One can see that the majority of the points lie below this line (the instability starts earlier during the ramp).

The bunch length oscillations started to grow on the flat top in addition to phase oscillations already growing during the ramp. The bunches with emittances larger than  $0.7$  eVs ( $0.7$  ns bunch length in  $12$  MV) were completely stable. The growth rates of quadrupole oscillations found from the exponential fit to the maximum and mean bunch length evolution during the first 25 min at the beginning of the flat top are shown in Fig. 6 versus the initial (flat top) bunch length.

The results obtained during the 2nd MD with phase loop on (normal operation setting) were different since the injection phase errors of the 8 bunches with nominal ( $0.5$  eVs) and lower ( $0.38$  eVs) emittances and intensity of  $1.4 \times 10^{11}$ ,

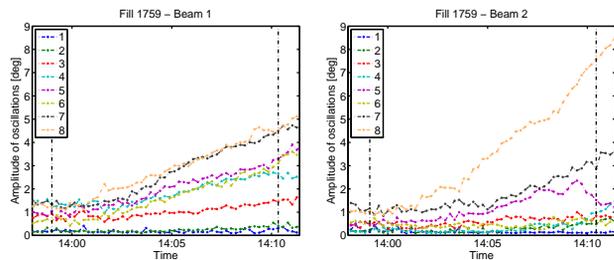


Figure 4: Amplitude of phase oscillations during acceleration cycle for 8 bunches (with different longitudinal emittances) of Beam1 (left) and Beam2 (right). Dashed vertical lines indicate start and end of the ramp.

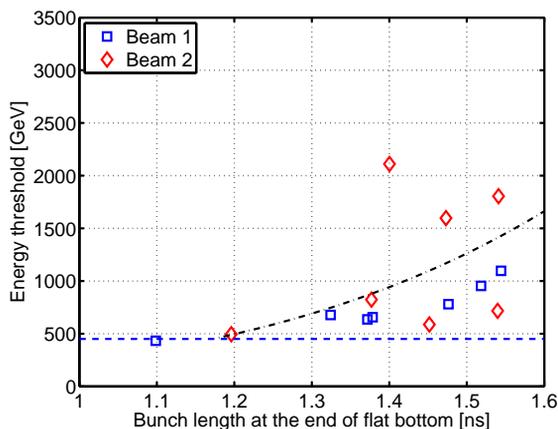


Figure 5: Energy at which the phase oscillations start to grow during the ramp as a function of bunch length at the end of the flat bottom for 8 bunches of Beam1 and Beam2 together with scaling law  $E_{th} = \tau^4 V^{1/5}$  (black curve). Each measured point is scaled in energy according to its intensity as  $N^{4/5}$ . Average bunch intensity  $1.56 \times 10^{11}$ .

injected one after another, were damped by the phase loop. Small residual dipole oscillations (with amplitudes below 2 deg at 400 MHz) started to grow during the ramp for bunches of Beam2 and no growth was observed during ramp for bunches of Beam1, which became unstable only on the flat top. On the flat top the two beams had very similar bunch lengths (0.5 ns) and therefore emittances ( $\epsilon \simeq 0.45$  eVs). The main difference between them was the capture voltage (matched, 3.8 MV for Beam1 and operational 6.0 MV for Beam2) with the result that, apart from a slightly different particle distribution, for Beam1 phase error oscillations at the end of the flat bottom were completely damped. This dependence of the instability onset during the ramp on the initial phase oscillation amplitude could probably explain the large scatter of points in Fig. 5.

## SUMMARY

Loss of Landau damping has been observed in LHC in different parts of the cycle (flat bottom, ramp and flat top)

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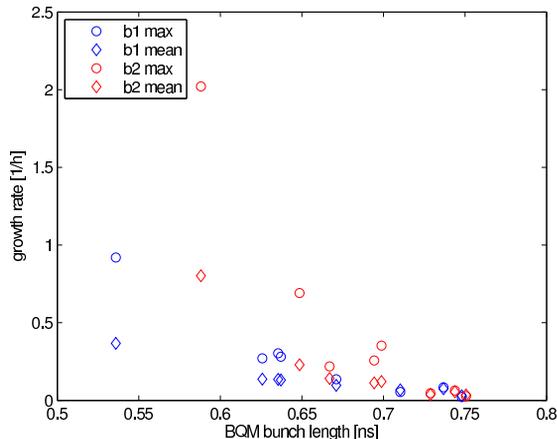


Figure 6: Growth rate of the maximum and mean bunch length during first 25 min of the flat top as a function of initial (flat top) bunch length for 8 bunches of Beam1 and Beam2 (measured by BQM) in 12 MV voltage.

for bunches with small longitudinal emittances. For intensities around  $1.5 \times 10^{11}$  injection phase oscillations are not damped on the flat bottom for emittances less than 0.5 eVs. Quadrupole (or non-rigid dipole) instability has been observed during acceleration for emittances below 0.4 eVs (ramp in 2010) and on the flat top below  $\sim 0.7$  eVs. During normal operation the beam is stabilised by controlled emittance blow-up during the ramp [6]. With the phase loop using only one bunch as reference, bunches with emittances up to 0.75 eVs become unstable during the ramp. As expected the thresholds and growth rates have strong dependence on bunch emittances and beam energy. The influence of initial conditions on measured instability thresholds should also be taken into account. We plan to continue studies of this instability with the phase loop off.

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## REFERENCES

- [1] LHC Design Report, vol. 1, CERN-2004-003, 2004.
- [2] G. Papotti *et al.*, these Proc., TUPZ022.
- [3] F.J. Sacherer, IEEE Trans. Nucl. Sci. NS-20, p.825, 1973.
- [4] A. Burov, Proc. PAC'11.
- [5] E. Shaposhnikova, CERN LHC Project Note 242, 2000.
- [6] P. Baudrenghien *et al.*, these Proc., TUPZ010.
- [7] T. Linnekar, E. Shaposhnikova, CERN LHC Project Note 394, 2007.
- [8] T. Argyropoulos *et al.*, CERN ATS-Note-2011-041 MD and ATS-Note-2011-056 MD, 2011.
- [9] T. Argyropoulos *et al.*, CERN ATS-Note-2011-031 MD, 2011.