LHC Longitudinal Single-Bunch Stability Threshold

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Abstract

The aim of the MD studies presented here was to determine with a reasonable accuracy the single-bunch longitudinal stability threshold in the LHC. The measurements were performed by placing along the ring 8 or 20 ‘single’ bunches with different intensities but similar longitudinal emittances. Then they were accelerated and bunch stability was observed at arrival to flat top. Combining the results of two measurement sessions, the single bunch stability threshold is estimated to be $(2.4 \pm 0.2) \times 10^{11}$ ppb for an emittance of 1.89 eVs (1.0 ns) at 6.5 TeV with 12 MV RF voltage.

Measurements were taken during the MD session MD472 from 22:00 on 20th to 05:00 on 21st July 2015 and session MD365 from 17:00 on 26th to 01:00 on 27th August 2015.
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1 Introduction

Knowing the single-bunch longitudinal stability threshold of the LHC is essential for understanding the fundamental limitations of the machine and for studies that prepare the high-luminosity LHC era. The MDs in Run1 already gave an estimation of the intensity threshold, however, with an error bar of 50 % [1–4].

The threshold of loss of Landau damping (LLD) was found by opening the beam phase loop at arrival to flat top and observing at which bunch intensity oscillations are still damped, and from what intensity onwards damping is lost. As the threshold for LLD strongly scales with bunch length as well, the beam has been carefully prepared in the injectors to cover a large range in intensity, but keeping the emittance constant.

To increase the statistics in these measurements, the number of ‘single’ bunches per measurement has been increased. Up to 20 bunches have been placed in the ring with a maximal possible distance between the bunches. From the present LHC impedance model, no coupling between the bunches is expected, and hence they can be considered as single bunches [1].

2 Bunch parameters

In the injectors, clone cycles of the operational ‘LHC indiv’ bunch production cycles were used. The intensity was varied by changing the amplitude of the controlled longitudinal emittance blow-up before the longitudinal shaving in the PSB [5]. In the PS and SPS, the operational settings were used. The SPS transverse scraping was disabled in the first MD and enabled in the second one.

In the first MD, a variable bunch intensity in the range of \((0.6 \pm 1.6) \times 10^{11}\) ppb was achieved with a constant longitudinal emittance of about 0.45 eVs at injection. Eight individual bunches were injected in each ring, spaced by 1/9 of the ring circumference, that is 3960 buckets. The acceleration ramp was done with a linear RF voltage increase from 6 MV to 12 MV. The bunch length\(^1\) target for the controlled longitudinal emittance blow-up during the ramp was 0.85 ns and 0.8 ns on B1 and B2, respectively. The ‘classic’ controlled emittance blow-up was used, injecting phase noise through the beam phase loop, with a predistorsion that increases the power spectral density on the bunch core to counteract the effect of the phase loop on the noise spectrum. Although the target length was achieved on average, the blow-up during the ramp led to a bifurcation in bunch lengths, as shown in Fig. 1. Another fill was done with different settings for the blow-up (flat noise spectrum, without predistorsion) with similar results. The bunch lengths and intensities at arrival to flat top are shown in Fig. 2 for both fills.

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\(^1\)All bunch lengths mentioned in this MD Note are the 4\(\sigma\) Gaussian equivalent corresponding to the FWHM bunch length measured by the BQM. The longitudinal emittance is the phase-space area enclosed by this 4\(\sigma\) contour.
Similarly, in the second MD the bunch intensity was in the range of \((0.6 - 1.6) \times 10^{11}\) ppb with a constant emittance of about 0.45 eVs at injection. However, this time 20 ‘LHC indiv’ bunches were placed in each ring (injecting 10 pairs each), with a spacing of 4 µs (1600 buckets) between the bunches. To obtain a more uniform bunch length for all the bunches, the blow-up was performed at flat bottom. To obtain a sufficiently large longitudinal emittance that would allow to ramp bunches with lower intensities stably through the ramp, the RF voltage was first increased to the maximum of 16 MV on both beams and then a blow-up to 1.6 ns (1.28 eVs) was performed. During the ramp, the operational blow-up was disabled and the voltage was decreased linearly to 12 MV. Due to diffusion in the tails, the bunch intensity was reduced by roughly 15 % on average, however the bunch lengths were quite uniform amongst the bunches. The bunch lengths and intensities at arrival to flat top are summarised in Fig. 3.

From the measured bunch profiles, the particle distribution function \(F\) in the LHC both at flat bottom and at flat top was found to be similar for all bunches and close to a binomial with exponent \(\mu = 2\):

\[
F(H) = F_0 \left(1 - \frac{H}{H_o}\right)^2,
\]

where \(H\) is the Hamiltonian, \(F_0\) is a normalization factor, and \(H_o\) is the value of the Hamiltonian for the bunch edge. The thresholds presented in this Note are valid for this particle distribution.
3 Single-bunch stability

3.1 Stability criterion

The theoretical scaling of the loss of Landau damping (see e.g. [7]) is

\[ \text{Im} \frac{Z}{n} \propto \epsilon^{5/2} \frac{N_b}{E^{5/4}V^{1/4}F}, \]

where \( \text{Im} \frac{Z}{n} \) is the imaginary part of the effective impedance, \( \epsilon \) is the longitudinal emittance, \( E \) is the beam energy, \( V \) is the RF voltage, \( N_b \) is the bunch intensity at flat top, and \( F \) is a form factor defined by the particle distribution. In this analysis it is assumed that the particle distribution is similar for all bunches and therefore any possible variation of \( F \) is neglected. This scaling can be rewritten as a function of the bunch length \( \tau \) as:

\[ \text{Im} \frac{Z}{n} \propto \tau^{5/4} \frac{V}{N_b}, \]

where \( \tau \) is the bunch length. We will use the term on the right-hand side of Eq. (3) as a stability parameter \( \xi = \tau^{5/4} V/N_b \) for each bunch to define the loss of Landau damping threshold.

During the ramp and at arrival to flat top the beam phase loop largely reduces the RF phase noise and can prevent the bunches that are at the limit of loss of Landau damping from becoming unstable. To find the stability threshold at top energy, we first waited a few minutes after arrival to flat top with the phase loop closed, in order to disentangle from transient oscillations that might occur at this moment. Then the phase loop was opened to observe stability.

To determine for which bunches oscillations are still damped and for which they are not, the stable phase of each bunch was acquired using the beam phase module of the low-level RF [6]. The amplitude of the dipole oscillations is obtained by the Fourier analysis of the stable phase data. An example of these signals for stable and unstable bunches is shown in Fig. 4.

The amplitude of the dipole oscillations for stable bunches is mainly dominated by the measurement noise and RF phase noise with phase loop open, but there are other factors that can increase the amplitude of this signal for the stable bunches and make it difficult to define an absolute threshold that is valid for all the cases. For example, if a bunch is unstable with the phase loop closed, the phase loop will couple and excite other bunches. This was the case during the first MD, when a few bunches became unstable during the ramp due to the bifurcation in bunch lengths described above. For this reason, the threshold is defined for each particular fill and beam by looking at the bunches that show an approximately constant and small amplitude of dipole oscillations (stable).
In order to determine the stability threshold, first the stability parameter $\xi$ defined above is calculated for each bunch. Then we select from the unstable bunches the one with the highest $\xi$, and from the stable bunches the one with the lowest $\xi$. The average of these two values gives the stability threshold and the difference between them the errorbar.

### 3.2 Stability threshold

Based on the above criteria, the cases of stable and unstable bunches in Beam 1 and 2 are shown as a function of intensity and bunch length, for both MDs, in Fig. 5, where different symbols are for the two different beams and for different fills in the first MD. The bunches that were unstable during the acceleration were not considered (only in the first MD). The threshold $\xi_{th} = \tau^5 V/N_b$ from the scaling law (3) was found to be $\xi_{th} = (5.3 \pm 0.7) \times 10^{-5} (\text{ns})^5 V$ from measurements in the first MD and $\xi_{th} = (4.8 \pm 0.7) \times 10^{-5} (\text{ns})^5 V$ from the second MD. If we combine both results, we get a threshold of $\xi_{th} = (5.0 \pm 0.5) \times 10^{-5} (\text{ns})^5 V$.

From this value of $\xi$, for a nominal bunch length of 1.0 ns, corresponding to an emittance of 1.89 eVs in 12 MV, the threshold bunch intensity is $(2.4 \pm 0.2) \times 10^{11}$ ppb. Inversely, for a nominal intensity of $1.15 \times 10^{11}$ ppb, the threshold emittance is $(1.41 \pm 0.05)$ eVs, corresponding to a bunch length of $(0.86 \pm 0.02)$ ns.

For comparison, in 2012 the stability threshold was found to be $\xi_{th} = (6.0 \pm 2.0) \times 10^{-5} (\text{ns})^5 V$ and is shown in Fig. 6 together with the thresholds measured in 2015. The uncertainty of the threshold has been reduced by a factor of 4.

### 4 Conclusions

With measurements performed during two MD blocks in 2015, a more accurate intensity threshold of the loss of Landau damping has been obtained for single bunches in the longitudinal plane. At top energy with 6.5 TeV and 12 MV, the intensity threshold is $(2.4 \pm 0.2) \times 10^{11}$ ppb for bunches with 1.0 ns (1.89 eVs) 4$\sigma$ bunch length. The threshold emittance is $(1.41 \pm 0.05)$ eVs $(0.86 \pm 0.02$ ns) for an intensity of $1.15 \times 10^{11}$ ppb. This threshold is in principle valid only for bunches with a particle distribution close to the one defined by Eq. (1) and may vary for other distributions.

It was also observed during this MD that the operational controlled longitudinal emittance blow-up during the ramp was leading to a bifurcation in bunch lengths. Dedicated simulation and measurement studies on controlled emittance blow-up are required to understand the issue.

The next step to study longitudinal beam stability in the LHC is to find the threshold of longitudinal coupled-bunch instability, which is presently still unknown. During the second MD presented here, a first attempt of measuring coupled-bunch instability was done with a fill with two short bunch trains in each
Fig. 5: Stable (green) and unstable (red) bunches in the intensity and bunch length range covered by the two MDs. The black line is the estimated stability threshold for 6.5 TeV and 12 MV RF voltage. The shaded area represents the uncertainty of the measurement. Different symbols are for the two different beams and fills. On the left plot, yellow squares are bunches that were unstable during the ramp and were not considered in the calculation of the threshold.

Fig. 6: Comparison of the stability thresholds measured in 2012 at 4 TeV and 12 MV (blue curve) and in 2015 at 6.5 TeV and 12 MV RF voltage during the first MD (red curve) and the second MD (black curve). The shaded areas represent the uncertainty of the measurement.

ring. Due to large variations in injected bunch length and intensity, however, the measurements were inconclusive. Further MDs with improved beam quality are planned in the near future (2016).

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5 References


