BEAM INSTABILITIES AFTER INJECTION TO THE LHC

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Abstract

Long-lasting phase oscillations have been observed at injection into the LHC since its first start-up with beam. These oscillations, however, were not leading to noticeable losses or blow-up in operation, and were therefore not studied in detail. In 2017, dedicated measurements with high-intensity bunches revealed that oscillations can lead to losses even slightly below the baseline intensity for the high-luminosity upgrade of the LHC. For the first time, high-resolution bunch profile acquisitions were triggered directly at injection and the formation of large-amplitude non-rigid dipole oscillations was observed on a turn-by-turn basis. First simulations can reproduce this instability via bunch filamentation that takes place after injection, depending on the mismatch between the bunch and bucket size in momentum at injection.

INTRODUCTION

Long-lasting injection oscillations have been observed in the LHC since its very first start-up with beam [1]. At the beam intensities used so far, however, these oscillations did not have any harmful effect on beam quality or luminosity, and were thus not studied in more detail in the past.

In measurements last year [2], oscillations continuing after injection were observed to lead to beam losses on flat bottom, for single bunches with intensities below the HL-LHC target of 2.3×10^{11} ppb [3] at LHC injection.

In Run 1 (2010-2012), and the present Run 2 (2015-2018), the 400 MHz RF injection voltage used in the LHC was 6 MV, with the 200 MHz RF extraction voltage in the SPS being 7 MV plus 1 MV at 800 MHz. In order to minimise injection losses, taking into account injection errors in phase and energy, the injection voltage was chosen to be much larger than the 'matched' voltage that is around 2 MV. Throughout Run 3 (2021-2023), a gradual increase of the beam intensity towards the HL-LHC target value is to be expected both in the injectors and the LHC. After the upgrade of the SPS RF system, an extraction voltage of 10 MV can be used, at least for increased intensities, which calls for an LHC injection voltage of 8.6 MV in order to keep the same bucket-height-to-momentum-spread ratio. The increased voltage, together with the doubled intensity from 1.15×10^{11} ppb to 2.3×10^{11} ppb by the time of the HL-LHC era (starting in 2026), results in a power consumption of the LHC RF system which will be close to its limit of 300 kW/klystron [4], should the present baseline of the half-detuning beam-loading compensation scheme be used [3,5].

A reduced injection voltage is therefore desirable to reduce the power consumption; this would also reduce the mismatch of the bucket height and the momentum spread of the bunch, and thus improve beam stability. On the other hand, an

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increased voltage is preferable to limit the injection losses that have to be on a per mil level in the LHC to be below the dump threshold [6,7].

Another concern for the future is the impact of flat-bottom oscillations on the controlled emittance blow-up during the ramp, where RF phase noise is injected through a feedback loop monitoring the bunch length. The blow-up itself is expected to be more difficult to control with increased intensity [8], and the flat-bottom oscillations have been observed to survive the ramp in some cases [9]. The LHC cannot be operated without the controlled emittance blow-up [10], as otherwise the bunches would cross the threshold of loss of Landau damping during the ramp and blow up violently, in an uncontrolled way.

The losses due to injection oscillations, the RF power consumption, and the stability of the controlled emittance blow-up in the ramp have thus to be treated as connected problems for future high intensities. In this paper, we will focus on the main considerations and observations related to long-lasting injection oscillations.

EXPERIMENTAL OBSERVATIONS

During measurements with a full machine at the nominal intensity of about 1.1×10^{11} ppb in 2016 [9], it was observed that the batches injected later into the machine had stronger dipole oscillations at the end of the flat bottom, and that the amplitude of oscillations had the same pattern along the ring at arrival to flat top as it had before the start of the ramp, see Fig. 1. In other words, the flat bottom oscillations astonishingly survived the 13-million-turn ramp, where RF phase noise is injected all along, in order to blow up the bunch emittance by a factor six.

Dedicated measurements of flat-bottom oscillations were then performed in 2017 [2] with many single bunches in the machine, probing the intensity range of $(0.8\text{-}2.2) \times 10^{11}$ ppb. One of the main observations was that a bunch with an initial intensity of 1.9×10^{11} ppb, which is below the HL-LHC target, became unstable after injection and has lost more than 4 % of its intensity over 20 minutes at flat bottom, see Fig. 2. At the same time, the bunch length was increasing by about 10 % over this period, while the natural bunch lengthening due to IBS is only around 3 %.

The emittance growth and particle losses are a result of non-rigid dipole oscillations, as can be seen on the bunch profiles in Fig. 3. Due to the non-rigid nature of these oscillations, many frequently used signals, such as the RF stable phase measurement, which gives the 400 MHz component of the bunch phase w.r.t. the RF phase, show a misleadingly small oscillation; in the case of Fig. 3, roughly 10° peak to peak. In reality, the peak of the bunch profile is oscillating much more violently, 50° peak to peak in our example.
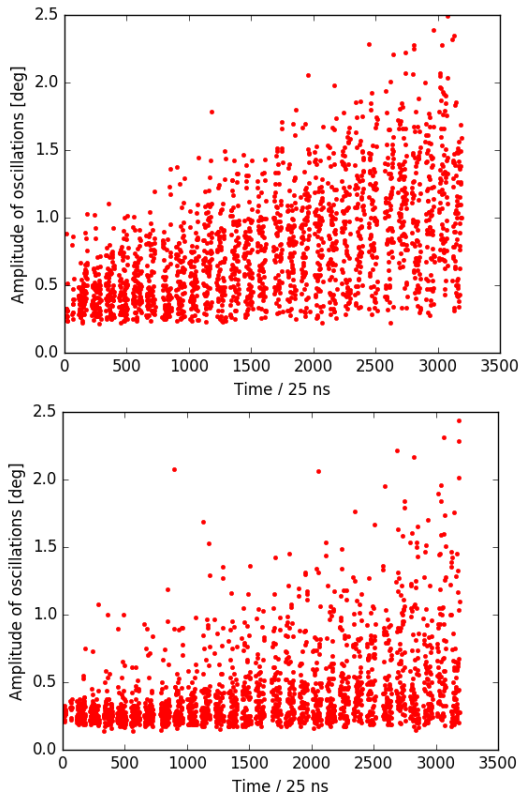
Figure 1: Amplitude of dipole oscillations at the end of flat bottom (top) and at arrival to flat top (bottom).
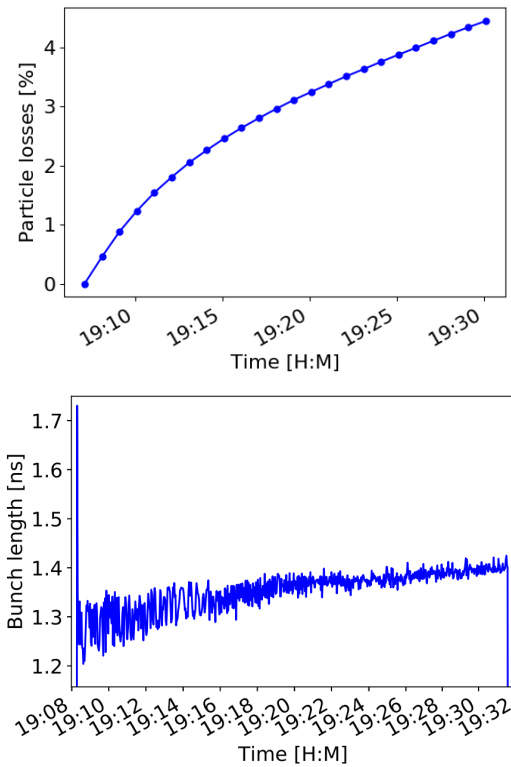

Figure 2: Evolution of particle losses (top) and bunch length (bottom) of an oscillating, unstable bunch.
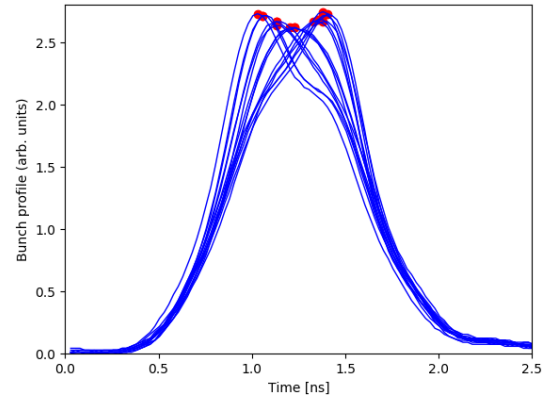

Figure 3: Non-rigid dipole oscillations seen on the bunch profile about one minute after injection.

INSTABILITY FORMATION

In simulations with the CERN BLonD code [11], the formation of the instability could be reproduced whenever the mismatch between the bucket height and the momentum spread of the injected bunch was large enough, i.e. the bunches have to be relatively short at injection or the RF voltage relatively high. In addition, intensity effects due to the LHC inductive impedance impact as well the threshold of these instabilities, which is why in measurements the losses were seen for high-intensity bunches with nominal bunch length and at nominal injection voltage, whereas during operation with nominal intensities no losses are observed.

A realistic injection phase error of 25° was assumed in the simulations, which represents the typical phase and energy errors translated into a pure phase error. Under the present operational conditions, that is, a bunch intensity of about 1.15×10^{11} ppb, an injection voltage of 6 MV, and a first-turn bunch length of about 1.6 ns, the bunch would simply filament and the oscillations would eventually be damped. This is reproduced also in simulations; the oscillations are damped to the noise level after about 350,000 turns, which is about 1,750 synchrotron periods.

In simulations with 1.2×10^{11} ppb using the present impedance model of the LHC at 450 GeV, and the nominal voltage of 6 MV, it is sufficient to decrease the injected bunch length to 1.5 ns to observe significantly less damping. When decreasing further to 1.4 ns, a growth in the oscillation amplitude of the mean bunch position can be observed. For the nominal bunch length of 1.6 ns, undamped oscillations can be observed over 500,000 turns when increasing the injection voltage to 8 MV or, with an even more pronounced oscillation amplitude, to 10 MV.

In an unstable case, see Fig. 4, the bunch is first filamenting in phase space, after which slowly the formation of islands close to the core can be observed. The rotation of these islands in phase space projects to the non-rigid dipole oscillations observed on the bunch profiles. Different regions of the bunch get disconnected, and local loss of Landau damping occurs. As a consequence, the oscillations
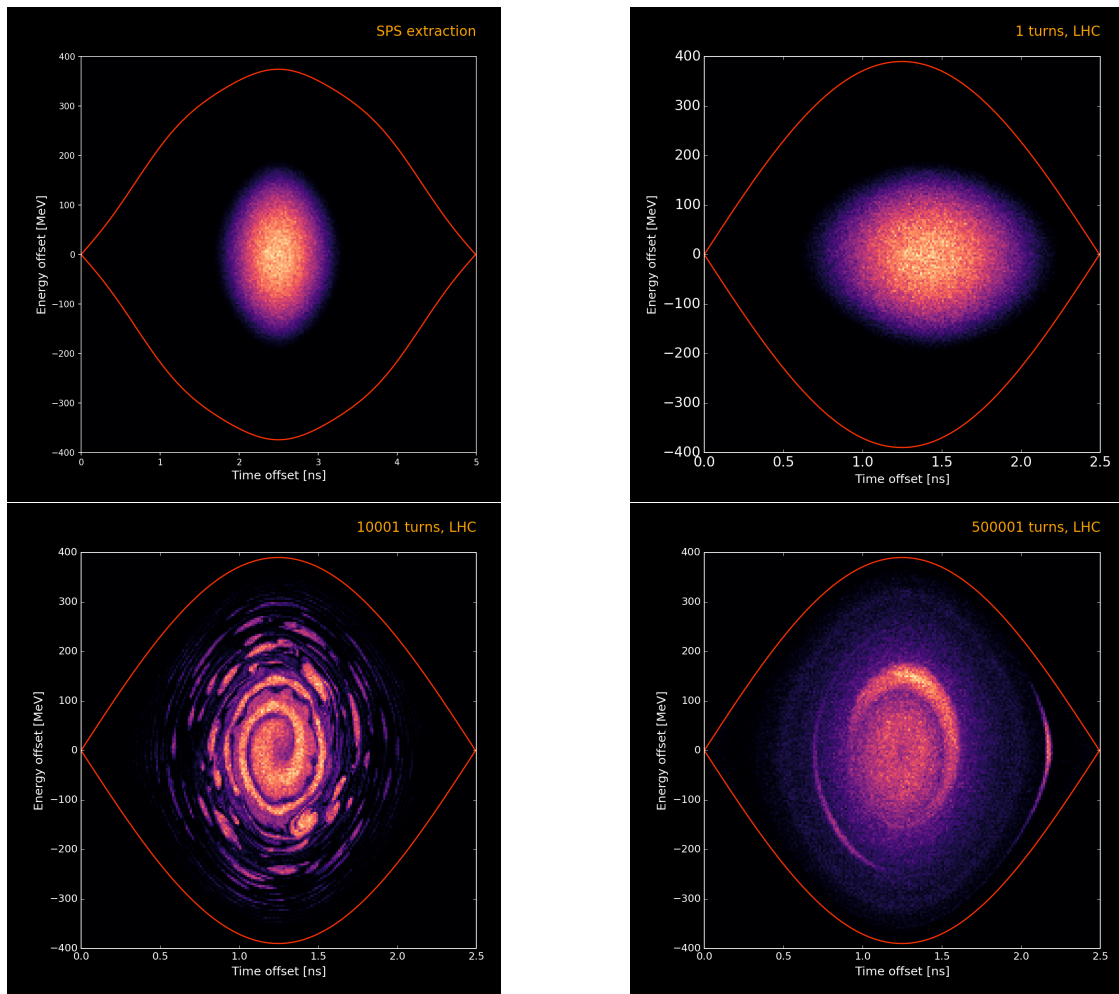
Figure 4: Formation of instability after injection at an intensity of 1.2×10^{11} ppb. The bunch is matched in the SPS double RF bucket (top left). At injection to the LHC with a 25° phase error (top right), the bunch length is 1.4 ns and the RF voltage is 6 MV. First islands form already during the filamentation process (bottom left), resulting in a more pronounced island (bottom right) eventually. A binomial distribution with exponent 1.5 was used.

grow, the bunch length increases, and losses can occur as well.

It should be noted that the beam phase loop is closed during beam operation all the time. However, the feedback loop is acting on the average oscillation amplitude of all the bunches. Injection errors are therefore efficiently damped for the first few injections, but for later injections, the role of the beam phase loop is negligible. This is why in our measurements with single bunches we made sure that the loop is virtually not acting on the bunches and in simulations the loop has not been included at all. In the future, should the external damping of injection oscillations become indispensable, one could use the phase loop with gated phase kicks acting only on the freshly injected bunches.

FIRST SIMULATION SCANS

To avoid the formation of instabilities, a lower injection voltage is thus preferable. On the other hand, as the bunches are arriving from the 200 MHz SPS buckets with phase and energy injection errors, a higher voltage is desirable to reduce injection losses. First simulation scans have been performed to study the stability and losses as a function of RF voltage and bunch length at injection.

The nominal bunch length for bunches arriving in bunch trains is 1.6 ns at injection; it is difficult for the injectors to produce multi-bunch trains with a shorter bunch length. For a bunch length of 1.6 ns produced with 7 MV at 200 MHz and 1 MV at 800 MHz in the SPS, a more or less matched voltage in the LHC would be around 2 MV. The operationally used injection voltage of 6 MV is, as mentioned earlier, highly unmatched in order to minimise capture losses.

The absolute numbers of the losses heavily depend on the bunch distribution assumed. In particular, losses depend a lot on the tail population, which is difficult to measure experimentally. An accurate way to model the bunch distribution in simulation would be to track the bunches from the controlled emittance blow-up in the SPS, which occurs towards the end of the SPS acceleration ramp, till extraction.
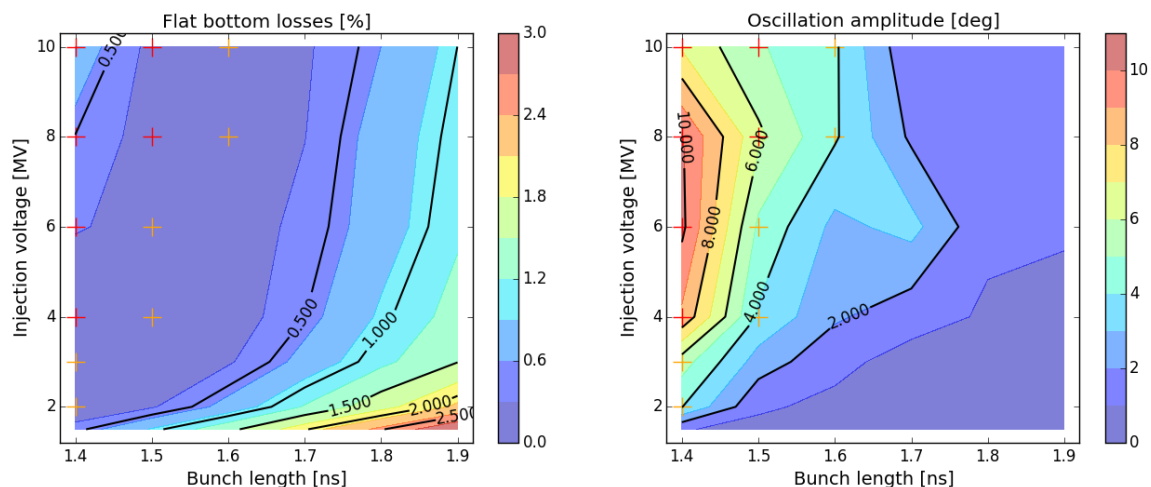
Figure 5: Flat bottom losses (left) and peak-to-peak oscillation amplitude (right) as a function of bunch length and RF voltage at injection. Binomial bunch distribution with exponent 1.5. Undamped and unstable cases are marked with orange and red crosses, respectively.
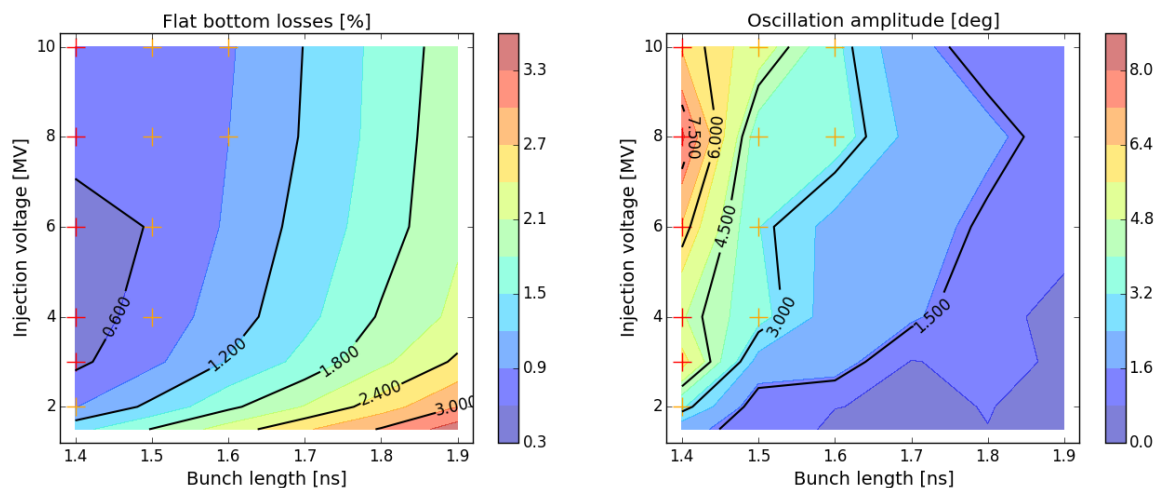

Figure 6: Flat bottom losses (left) and peak-to-peak oscillation amplitude (right) as a function of bunch length and RF voltage at injection. Binomial bunch distribution with exponent 5. Undamped and unstable cases are marked with orange and red crosses, respectively.

During the emittance blow-up, halo particles are driven up to the separatrix, while at extraction the bucket is expected not to be entirely full.

For the preliminary simulation scans presented here, two different bunch distributions have been assumed. First, a binomial distribution function of the action with the exponent 1.5, which is the best fit to (the core of) measured bunch profiles in the LHC [12]. The results are shown in Fig. 5. In a second scan, the exponent 5 was used in order to enhance the tails on purpose; see Fig. 6.

For each combination of injection voltage and bunch length, a single bunch was matched in the SPS double-harmonic RF bucket with intensity effects with the chosen bunch distribution to obtain the desired bunch length. After injection into the LHC with 25° phase error, the bunch

was tracked for 500,000 turns corresponding to about 2500 synchrotron periods.

To determine the overall losses due to long-lasting oscillations (left-hand sides of Figs. 5 and 6), the particles outside the separatrix were counted every 10 turns. First-turn capture losses were ignored. The flat-bottom losses start to take off typically after the oscillations become strong enough; for the case presented in Fig. 4, this happens after roughly 220,000 turns, see Fig. 7. The evolution strongly depends also on the blow-up that occurs in parallel; if violent losses and blow-up occur initially, the slope of the losses becomes less steep afterwards.

The peak-to-peak oscillation amplitude of the mean position of the bunch is shown on the right-hand sides of Figs. 5 and 6. In order to disentangle from the initial oscillations due
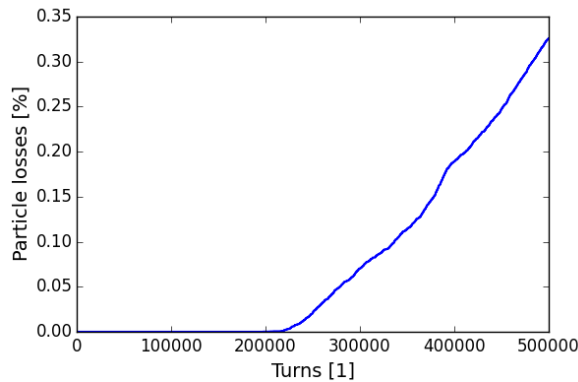
Figure 7: Flat-bottom losses corresponding to the case presented in Fig. 4.

to the phase error at injection, the maximum peak-to-peak amplitude was observed after 250,000 turns. Cases where the oscillation amplitude was undamped after injection till the end of the simulation are marked with orange crosses. Unstable cases where the oscillation amplitude was growing after 250,000 turns are marked with red crosses.

Comparing the two different bunch distributions used, it can be seen that the large tails provide somewhat more damping in this case and reduce the oscillations by about 25 %. On the other hand, the loss levels increase. Globally, however, the overall tendencies of losses and oscillation amplitudes are very similar in both cases.

If we look for a compromise between not-too-high losses and a reasonable stability margin, the regions around 0.5 % losses in Fig. 5 and 1.2 % losses in Fig. 6 are promising. For the nominal beam with 1.6 ns initial bunch length, there seems to be enough margin in terms of losses in order to reduce the injection voltage to 4 MV. This would reduce also the RF power consumption and be beneficial for beam stability. Measurements are scheduled for the near future to verify the optimum injection voltage experimentally.

CONCLUSIONS

Bunch oscillations after injection to the LHC can persist and develop into an instability, depending on the bunch intensity, the injection errors, and the mismatch between the bucket height at injection and the momentum spread of the arriving bunch. In phase space, the formation of islands close to the bunch core during the filamentation process is characteristic for the instability. These islands lead to non-rigid dipole oscillations, as seen on the bunch profiles. The measured peak-to-peak oscillation amplitudes of the profile can be as high as 50°. Under certain circumstances, the oscillations can even survive the controlled emittance blow-up during the ramp and persist till flat top.

The presently used 6 MV injection voltage, although unmatched, was used to reduce capture losses from large bunches arriving with injection errors. The formation of instabilities can be avoided by somewhat decreasing the RF voltage at injection. This will reduce the mismatch at injection and stabilise the beam. A decreased voltage is also advantageous for reducing the power consumption of the RF system, which will be pushed close or beyond its limits with future high intensities otherwise. First simulations show regions of a good compromise between acceptable losses and oscillations; measurements will be performed soon to confirm the optimum injection voltage.

The injection oscillations can furthermore be damped by the beam phase loop. Presently, the phase loop feedback is acting on the average of all circulating bunches, and as a consequence, is less and less efficient with every new batch injected. In addition, already circulating bunches get kicked with the injection of new bunches. To avoid this, a batch-by-batch operation mode could be implemented, where the phase loop could be 'masked' to only act on the freshly injected beam for a while.

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