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Chapter 29

The Role of Noise on Beam Stability and Performance in HL-LHC

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The beam response to an external excitation may result in a growth of the emittance, or more generally a modification of its particle distribution. The former reduces the luminosity, and the latter might lead to a loss of Landau damping of coherent instabilities. The corresponding beam dynamics model, experimental studies at the LHC as well as extrapolations to the HL-LHC are discussed in this chapter.

1. Introduction

Beam instability models at the LHC have evolved significantly over its first two runs, allowing for a significant reduction of the need for Landau octupole magnet to a level compatible with HL-LHC requirements.[1] Nevertheless, discrepancies between observations and expectations remains, especially when the beam is circulating in steady conditions for several minutes. Here we seek an understanding of this discrepancy in order to make accurate extrapolation to the HL-LHC configurations and consequently ensure that the proper mitigation measures are put in place.

Noticing that modifications of the beam distribution, beyond the reach of transverse profile measurements, could lead to drastic reduction of Landau damping, it was postulated that non-uniform diffusion mechanisms could lead eventually to instabilities.[2] Since the time scale of the diffusion mechanisms is usually much longer than those of coherent instabilities, a key feature of this mechanism is the existence of a latency.

We start by discussing the existing models of decoherence due to an external excitation with a broad spectrum as well as a characterisation of the present machine noise through its effect on the transverse emittance in collision in Section 2. Secondly, models of the evolution of the beam distribution in the presence of noise and electromagnetic wake fields leading to loss of Landau damping are described in Section 3. Finally, mitigation strategies are addressed in Section 4.

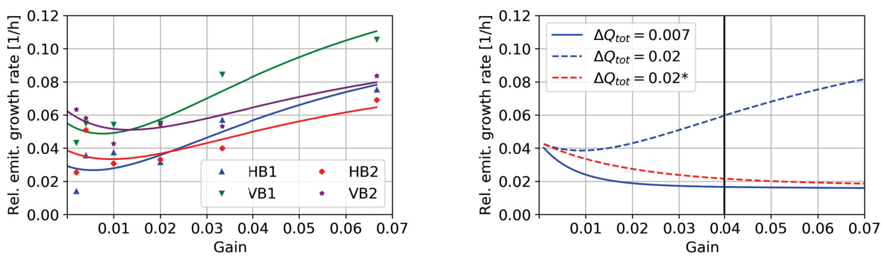
2. Decoherence

In the presence of amplitude detuning due to non-linear forces such as lattice non-linearities, octupole magnets or beam-beam interactions, a growth of the emittance is expected when the whole beam experiences a transverse kick. The decoherence is caused by the difference in oscillation frequency of the individual particles in the beam leading to desynchronization of their respective motion, often called filamentation.[3] The effect of an external source of noise is usually modelled as a series of small uncorrelated kicks leading to a slow growth of the transverse emittances.

By reducing the beam oscillations faster than the decoherence mechanism, a transverse damper is capable of mitigating the resulting growth.[4] The efficiency of such a system has limits linked to the available technology, in particular the kicker bandwidth prevents the LHC damper to act differently on the particles within a bunch. It can however act independently on each bunch.

The damper is most efficient at suppressing the effect of an external source of noise when decoherence is slow, i.e. when the amplitude detuning in the beam is small. As a result, the highest growth rate is expected when the beams are colliding due to the effect of head-on beam-beam interactions. We note that the strength of the head-on beam-beam interactions is multiplied by a factor ≈ 3 in the HL-LHC w.r.t. to the LHC due to the increase of the beam brightness and the partial compensation of the crossing angle by crab cavities (See Chapter 7). In order to probe this regime of operation, a set of experiments were conducted at the LHC by bringing in collision high brightness single bunches, which are already available from its injector chain without upgrade, their main results are reported here.

The beam dynamics models describing the emittance growth in collision could be verified experimentally at the LHC,[4–7] the main features of the model considered as the most accurate are illustrated in Figure 1b: for a low gain, the emittance growth is dominated by the integrated machine noise floor (e.g. dipole field ripple). For a high gain, the behaviour depends on the noise introduced by the damper which is proportional to its gain, the dominant source being the measurement pickups' noise floor.[8] This noise may overcome the beneficial effect of the damper and therefore lead to an increase of the emittance growth at high gain. This effect was observed in a dedicated experiment in the LHC, allowing for a beam-based measurement of the machine and damper pickups noise floor (Figure 1a). Whereas the causes for the machine noise floor are subject of several investigations,[9–11] the estimated pickup noise floor is compatible with expectations with a remarkable accuracy of about 10%.[8] A conservative extrapolation of these results, assuming an identical machine noise floor, i.e. neglecting additional source of transverse noise such as the crab cavities[12] and large β functions (See Chapter 26), shows that a reduction of the emittance growth rate below 4%/h requires an improvement of the pickups' noise floor. A new readout electronics technology was developed and tested with beam at the end of Run2 yielding promising results.[13]



(a) Measurement at LHC (b) Extrapolation

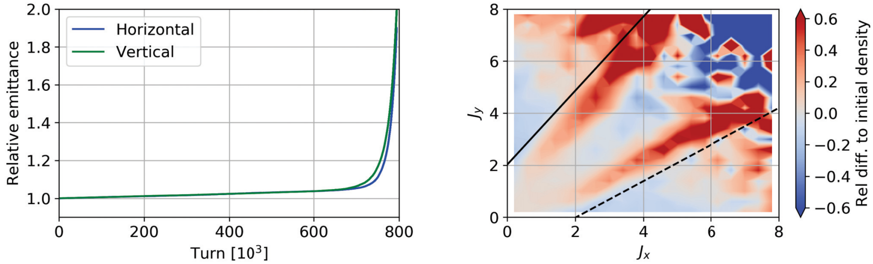
Fig. 1. Emittance growth measured at the LHC, with high brightness single bunches featuring a beam-beam tune shift comparable to HL-LHC design, with fits of the model[4] yielding a machine noise floor of $\approx 5 \cdot 10^{-5}$ times the r.m.s. beam size and a pickup noise floor of 0.9 μm. An averaged fit is reported in dashed blue on the right, along with an extrapolation to a reduced beam-beam parameter corresponding to the present LHC configuration (solid blue) or pickup resolution improved by a factor 4 (dashed red). The black line marks the current operational damper setting corresponding to a 50-turn damping time. The value corresponding to the present LHC matches the observed growth in physics conditions.[16]

Through the mechanism discussed above, while the large amplitude detuning in collision seems detrimental, on the other hand it provides a strong Landau damping, much beyond the requirement.[14] Decoherence is not a major concern for the preservation of the emittance in the rest of the cycle, i.e. without collision, however it remains a concern for Landau damping which is much more critical in this configuration. Indeed, since particles oscillating at different amplitudes are affected differently in the decoherence process, a modification of the beam distribution, and consequently of Landau damping, is expected. The decoherence model[4] was extended lately to describe the corresponding time evolution of the distribution and its corresponding impact on Landau damping.[15] However the noise amplitude required to lose Landau damping on a realistic time scale is not compatible with the measured noise amplitudes, suggesting that a key ingredient is missing from the model.

3. Noise and Wake Fields

In the presence of noise with a broad frequency spectrum, the beam is forced to oscillate, the amplitude of these oscillations is determined by the balance between the excitation strength and the damping strength. In particular, as for a harmonic oscillator, the beam response becomes significantly peaked at its natural frequency. In this regime, the wake fields generate an additional force with the spectrum of the beam oscillation, i.e. peaked at the natural frequency. It is important to note that; not only the wake fields shift the natural frequencies of oscillation of the beam, they can also amplify the corresponding transverse motion. We conclude that the combined effect of a source of noise with a broad frequency spectrum, a damper and wake fields results in an excitation peaked at the frequencies of the so-called coherent mode frequencies. This harmonic excitation results in diffusion of the resonant particles,[17] i.e. the particles that are also responsible for Landau damping of these coherent modes, eventually leading to a loss of Landau damping.

This mechanism can be modelled with macro-particle tracking simulations (Figure 2), in particular, shows that the latency is expected to increase with the damper gain and the octupole current and decrease as the noise amplitude increases.[18] An analytical model was recently developed allowing for a more detailed understanding.[19]



(a) Time evolution

(b) Distribution at turn $6 \cdot 10^5 \approx 53$ s

Fig. 2. Evolution of the transverse emittance from macro-particle tracking simulation with COMBI[2] including the effect of wake fields, transverse damper, amplitude detuning and a broad source of noise. This simulation illustrates the latency characterised by a slow growth of the emittance along with a modification of the distribution followed by an instability characterised by a fast exponential growth. The distorted distribution of transverse actions in normalised phase space at the end of the latency phase is shown. Note that the maximum normalised actions quoted on the axes correspond to an oscillation amplitude of 4 times the r.m.s. beam size. Solid and dashed lines mark the particles resonant with the most unstable modes driven by the wake fields, in the horizontal and vertical plane respectively. The simulations were performed with nominal HL-LHC settings at flat top, with an octupole current of 250 A (corresponding to approximately half of their maximum strength) and a noise amplitude of $3 \cdot 10^{-3}$, leading to a shorter time scale w.r.t. realistic configurations.

3.1. *Experimental validation*

While clearly visible in phase space, the expected distortion of the beam distribution is beyond the capabilities of existing transverse profile measurements. In order to measure directly the modification of the stability diagram, beam transfer function measurements were introduced in the LHC in Run2. However, a direct measurement of a distortion of the stability diagram due to noise could not be achieved so far due to various technical issues, in particular the required accuracy was not reached and the generation of instabilities by the harmonic excitation needed for the measurement itself strongly limited the investigations.[20,21]

An indirect experimental validation of the mechanism was obtained using the damper as a controlled source of noise,[19] similarly to the experiment discussed previously but without collision. The main feature of the instability, i.e. a latency that depends on the amplitude of the external excitation is shown in Figure 3.

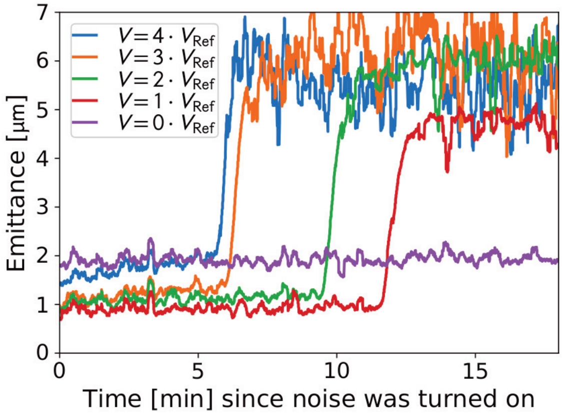


Fig. 3. Transverse emittance evolution of bunches experiencing different amplitudes of artificial noise characterised by the corresponding voltage at the electrostatic kicker, at top energy in the LHC. The latency and the instability can be clearly distinguished, with a shorter latency for bunches experiencing noise of higher amplitude. We note that the emittance growth rate is marginal during the latency phase for the low noise bunches.

4. Mitigation

The most robust mitigation addresses the root causes, i.e. the impedance (see e.g. Chapter 8) and external sources of noise. As discussed previously, the damper was identified as a source of noise and a mitigation could be put in place. Identifying the other contributors to the machine noise and minimising their impact remains the topic of experimental studies.[9–11]

The crab cavity noise is a major concern for the preservation of the emittance in collision, however its impact on the beam stability is critical only if the cavities are enabled prior to the establishment of head-on collisions, a feature that is not required in the present baseline (see Chapter 5).

The increase of the latency with the octupole current is usually stronger than with linear,[18] enhancing Landau damping is therefore a possibility. In fact, the current design accounts for an empirical factor two in the Landau damping requirements (based on experience from the LHC).

Since this instability mechanism features a latency, possibly of several minutes, its impact on the machine performance can be reduced by limiting transient times in the cycle. During Run1 and Run2, the LHC was operated with tens of minutes spent at flat top without collision, mainly to perform the betatron squeeze. This operation is no longer required in the nominal HL-LHC thanks to the combined ramp and squeeze as well as the luminosity levelling with β^*. The establishment of collision right at the end of the ramp to improve the beam stability was already considered in Run1[22] and could be implemented in the HL-LHC final operational scenario if necessary.

A detailed understanding of this mechanism is crucial to determine the optimal working point in terms of tune, chromaticity, octupole strength and damper gain, possibly allowing a reduction of the requirements for the mitigation measures mentioned above.

5. Conclusion

The impact of noise on the beam quality, and consequently on the collider performance, had been extensively studied in particular in the presence of head-on beam-beam interactions and a transverse damper.[4,5] The models could be tested against experimental observations at the LHC, allowing for a characterisation of the integrated machine noise, under the assumption of a broad spectrum. While acceptable in the LHC, the damper pickup noise is not compatible with the required preservation of the emittance in collision in the HL-LHC, due to the larger beam-beam tune shift, thus requiring a technological improvement.

On the other hand, the noise was identified as a source of instabilities, first in simulation and later demonstrated experimentally and analytically. The main feature of this new instability mechanism is the existence of a latency, during which the beam remains stable but the combined effect of the noise and the wake fields generates non-uniform diffusion that eventually leads to a loss of Landau damping. The models are currently refined, to steer efficiently mitigation measures and determine optimal running conditions that maximise the latency to a level that does not impact the machine performance.

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