OBSERVATIONS OF EMITTANCE GROWTH IN THE PRESENCE OF EXTERNAL NOISE IN THE LHC

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Abstract

Dedicated experiments were performed in the LHC to study the impact of noise on colliding high brightness beams. The results are compared to theoretical models and multiparticle tracking simulations. The impact on the LHC operation and the HL-LHC project† are discussed.

INTRODUCTION

An external source of noise, e.g. due to power converter ripple or ground vibrations, on a beam with a tune spread result in emittance growth. In the HL-LHC, the crab cavities are another potential source of noise in the transverse plane. The tolerances for the design of those cavities are based on a given maximum emittance growth and therefore on a beam dynamics model [1]. Conservatively, the weak-strong model [2] was preferred to set the tolerances over the strong-strong model [3]. While in principle more accurate, the strong-strong model is very sensitive to the machine and beam configuration [4]. In particular it is sensitive to the position of the coherent beam-beam modes with respect to the beam's incoherent spectrum, which in turn are dependent on both machine and beam parameters (bunch brightness, phase advance between interactions points, collision scheme). The simulations shown in Fig. 1 suggest that, while the growth rate predicated by the strong-strong model is significantly lower than the one of the weak-strong model in configurations where the coherent modes are outside of the incoherent spectrum (e.g. configuration with identical tunes in the two beams), the two models' predictions become identical if this condition is not met (e.g. configuration with mirrored tunes). The transverse damper (ADT) plays a key role in those models, as it prevents emittance growth due to decoherence, as well as generates a noise due to the finite resolution of its pickups.

Some experiments were performed to test the predictions of the different models at injection energy (450 GeV) in the LHC, the results indicated an additional source of emittance growth which could not be explained within the models [5–7]. Here we discuss a similar experiment at top energy (6.5 TeV).

Thanks to the performance and to the flexibility of the LHC's injector complex, a variety of bunches with different brightnesses were injected and accelerated in the LHC. The beam-beam tune shifts computed based on measured bunch intensities and emittances are shown in Fig. 2. While the tune shift is rather low in the first attempt (before minute 150) due to the deterioration of the beam quality during the cycle caused by coherent instabilities, the beam quality was preserved in the second cycle performed with stronger octupoles to improve the beam stability allowing to reach total beam-beam tune shift up to -0.02, comparable to HL-LHC baseline parameters with two IPs.

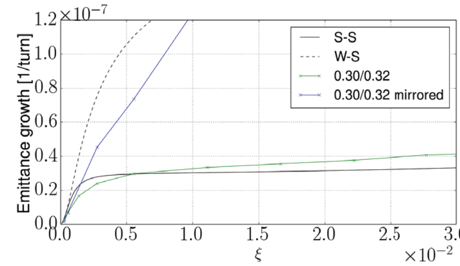


Figure 1: Transverse emittance growth as a function of the beam-beam parameter obtained with self-consistent macro particle simulation (COMBI [8]) of two beams colliding head-on at a single interaction point under the influence of a turn-by-turn orbit jitter of amplitude $3 \cdot 10^{-4}$ and a transverse feedback with a gain corresponding to a damping time of 400 turns. The tunes of the second beam are identical (green curve) or inverted in the two transverse planes (blue curve) w.r.t. the other beam. The simulations are compared to the analytical estimate from the weak-strong model [2] (dashed) and the strong-strong model in absence of overlap between coherent modes and incoherent spectrum [3]. The analytical estimates include the estimated noise introduced by the field solver in the numerical simulations [9].

Once in collision, a Gaussian noise was injected in both transverse planes of both beams, increasing in steps the strength of the excitation and monitoring the degradation of the beam quality. The noise is uncorrelated turn-by-turn, but is constant over the bunch length. Profiting from the flexibility of the ADT, bunches present simultaneously in the machine experienced different transverse feedback gain, allowing for an enlarged parameter scans within limited time.

Non-colliding bunches are present in the machine in order to better isolate the contribution of beam-beam interactions in the behaviour of other bunches. These bunches, however, enforce the usage of strong stabilising mechanisms, in particular the experiments described here are performed with a chromaticity of 15 units and octupoles powered with 570 A, corresponding to their maximum strength.

* This work is supported by the European Circular Energy-Frontier Collider Study, H2020 Framework Programme under grant agreement no. 654305 and by the Swiss State Secretariat for Education, Research and Innovation SERI.

† Research supported by the HL-LHC project

ISBN 978-3-95450-182-3

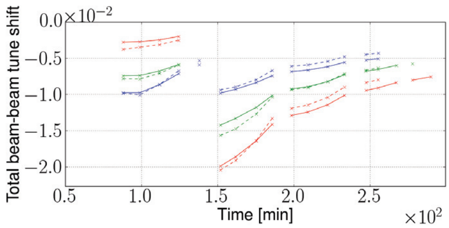


Figure 2: Beam-beam tune shift computed based on measured bunch intensities and emittances during each step of the experiment. The first two set of lines show the first cycle, the others represent tests performed in a single cycle, varying different machine settings. The blue, green and red lines correspond to low, medium and high intensity bunches respectively. The solid and dashed lines correspond to colliding bunches with full ADT gain and reduced gain respectively.

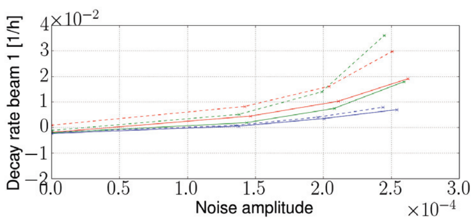


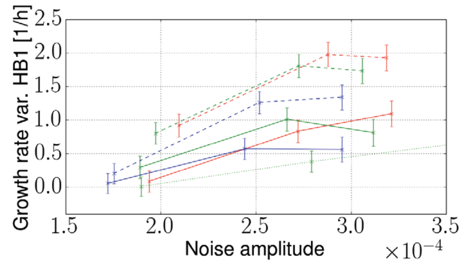
Figure 3: Bunch intensity decay rates during the second cycle, the contribution from the estimated luminosity burn off has been subtracted. The noise is expressed in units of the beam divergence at the location of the kicker. The measurement was performed with a full (solid) and reduced (dashed) ADT gain corresponding to damping times of 50 and 200 turns . The beam-beam tune shifts during the two scans are shown in Fig. 2 from minute 150 to 190 and 190 to 240 respectively. The color code is identical to previous figure.

BEAM LOSSES

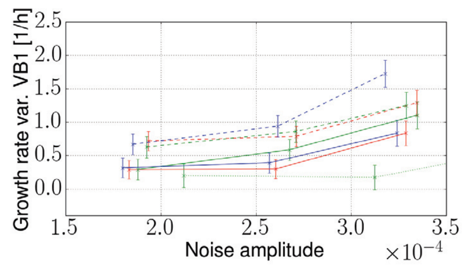
Beam losses dependent on the noise amplitude where observed during the second scan, shown in Fig. 3. Bunches with the lowest ADT gain, corresponding to a damping time of 200 turns, were mostly affected. This effect was not observed during the first scan, where the ADT gain was higher for all bunches by a factor 2. This observation is in qualitative agreement with expectation since the larger oscillation amplitude together with the increased emittance, due to the deterioration of the beam quality during the first scan, make the beam more sensitive to both beam-beam and lattice non-linearities.

EMITTANCE GROWTH

The most interesting results are obtained with large beam-beam tune shift, since this is a configuration comparable to the HL-LHC case, with two IPs colliding. The variation of the emittance growth rate, with respect to the one mea-



(a) Horizontal, Beam 1



(b) Vertical, Beam 1

Figure 4: Variation of the emittance growth rate measured when introducing noise, w.r.t. the emittance growth rate observed in absence of artificial noise during the first scan of the second cycle (minute 150 to 190 on Fig. 2), with ADT gains corresponding to damping times of 25 and 100 turns for the two families of bunches. The color code is identical to previous figures, in addition the dotted lines show the behaviour of the non-colliding bunches.

sured in absence of external noise, is shown in Fig. 4 for the scan with the largest beam-beam tune shift. One observes a clear distinction between the different bunches with different settings, in particular the colliding bunches experiencing a reduced transverse feedback gain corresponding to 200 turns damping time (dashed) suffer the most in the presence of noise, while the colliding bunches with a higher gain corresponding to 25 turns suffer less. The non-colliding bunches, experiencing also a gain corresponding to 25 turns, are the least affected by the artificial noise. This demonstrates the possibility to use the ADT as a mitigation of the emittance growth due to other sources of noise. However, when comparing to analytical computations, the strong-strong model in absence of overlap between the coherent modes and the incoherent spectrum [3] systematically underestimates the observed emittance growth rate. Figure 5 shows the average quadratic difference between measurements and predictions of the weak-strong model [2] for all the points of the scan, varying a scale on the ADT gain and the kick strength, since significant uncertainties remain on these quantities. An agreement in the order of 20 to 30% can be achieved assuming a factor about 0.25 on the ADT gain, with respect to the values provided. Such a discrepancy is within the error on the damping time. Dedicated tests will be performed to reduce the uncertainty and possibly confirm the result of this analysis. A similar analysis on the following scan in similar conditions with an ADT gain reduced by half on all bunches

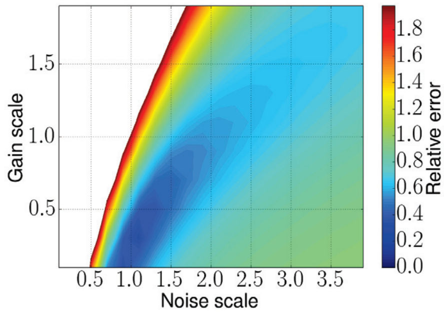


Figure 5: Relative difference between the measured increase of the emittance growth rate with the predictions of the weak-strong model, averaged over all data points of the scan with largest beam-beam tune shift for different relative errors on the ADT gain and noise amplitude.

shows the same discrepancy in the ADT gain, an agreement in the order of 50% can be achieved assuming a factor about 0.25 on the actual damping time.

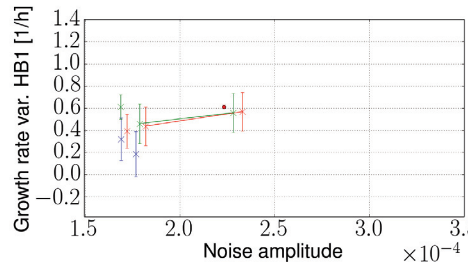
An important part of the discrepancy lies in the asymmetry between the two planes visible in Fig. 4, as well as with the other beam. The fluctuations of the bunches intensities and emittances are not sufficient to explain these differences. It is unclear whether this effect may arise from different hardware settings, e.g. in the ADT, or due to a different configuration of coherent beam-beam modes caused for example by different phase advances between IPs.

The Effect of Chromaticity

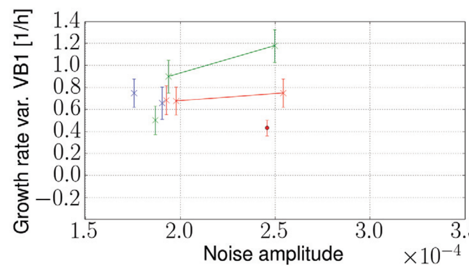
The chromaticity introduces a significant tune spread which, following the weak-strong model, should increase the emittance growth rate in the presence of external noise. The effect is qualitatively observed in the horizontal plane, where the reduction of the chromaticity lead to a reduction of the beam's sensitivity to external sources of noise (Fig. 6a). However, the opposite is observed in the vertical plane when reducing the chromaticity to 10 units, leading to an increase of the emittance growth rate in the presence of noise w.r.t. previous scans despite the reduction of the beam-beam tune shift. A further reduction to 5 units had a negligible impact in the horizontal plane and lead to a decrease of the growth rate in the vertical plane. This non-trivial effect of the chromaticity cannot be explained in the weak-strong model. Within the strong-strong model, such an effect could be explained by a modification of the coherent modes frequencies with respect to the incoherent spectrum. Numerical simulations are however needed to verify quantitatively this effect.

CONCLUSION

High brightness bunches with an intensity just below $2 \cdot 10^{11}$ protons within an emittance of 1.5μm were brought into collision, along with bunches of lower brightness and were used to experimentally probe the effect of external sources of noise on colliding beams experiencing a total



(a) Horizontal, Beam 1



(b) Vertical, Beam 1

Figure 6: Variation of the emittance growth rate when introducing noise, w.r.t. the emittance growth rate observed in absence of artificial noise. The color code is identical to previous figures, the crosses indicated the results obtained in the second last scan (minute 240 to 270 in Fig. 2) with a chromaticity reduced to 10 units. The dots indicate the last step, with a chromaticity reduced to 5 units.

head-on beam-beam tune shifts as high as -0.02, corresponding to the HL-LHC design with two colliding experiments. Overall the measured contribution of the interplay between beam-beam effects and external noise to the emittance growth seems in agreement with the weak-strong model, provided a factor about 0.25 between the expected and effective ADT gain. These observations are not in contradiction with the strong-strong model, but rather suggest that the LHC is currently running in a configuration where all coherent beam-beam modes are within the incoherent spectrum, e.g. due to the high chromaticity. In particular, the difference between beams and planes, as well as a non trivial dependence on chromaticity, reveal important effects that are observed in strong-strong simulations. Quantitative comparisons with simulations are needed to shed light on the underlying mechanisms.

ACKNOWLEDGEMENTS

The authors would like to greatly thank the operators of the injector chain, as well as H. Bartosik for providing high brightness single bunches *à la carte* with a remarkable flexibility.

REFERENCES

[1] P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to RF noise in the high-luminosity LHC crab cavities", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 101001, Oct. 2015.

ISBN 978-3-95450-182-3

[2] V. A. Lebedev, “Emittance growth due to noise and its suppression with the feedback system in large hadron colliders”, in *AIP Conference Proceedings 326.1*, pp. 396–423, 1995.

[3] Y. Alexahin, “A study of the coherent beam-beam effect in the framework of Vlasov perturbation theory”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 480.2, pp. 253–288, 2002.

[4] T. Pieloni, “A Study of Beam-Beam Effects in Hadron Colliders with a Large Number of Bunches”, Ph.D. thesis, EPFL, 2008.

[5] R. Alemany *et al.*, “Head-on beam-beam tune shifts with high brightness beams in the LHC”, CERN, Geneva, Switzerland, Rep. CERN-ATS-Note-2011-029 MD, June 2011.

[6] M. Albert *et al.*, “Head-on beam-beam collisions with high intensities and long range beam-beam studies in the LHC”, CERN, Geneva, Switzerland, Rep. CERN-ATS-Note-2011-058 MD, July 2011.

[7] J. Barranco *et al.*, “MD 400: LHC emittance growth in presence of an external source of noise during collision”, CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2016-0020, Jan. 2016.

[8] X. Buffat, “Transverse beams stability studies at the Large Hadron Collider”, Ph.D. thesis, EPFL, 2015.

[9] X. Buffat *et al.*, “Simulation of head-on beam-beam limitations in future high energy colliders”, in *Proceedings of the 7th International Particle Accelerator Conference*, Busan, South Korea, May 2016, paper TUPMW009.