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MD 400: LHC emittance growth in presence of an external source of noise during collision

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Abstract

The interplay between head-on beam-beam interaction and external sources of noise can be a significant source of emittance growth, especially when considering large beam-beam tune shifts as for the HL-LHC upgrade project. In this experiment the emittance growth of colliding bunches with different brightness and therefore different beam-beam parameters in the presence of an external white noise source with different amplitudes is measured for different gains of the transverse feedback.

Keywords: CERN LHC, Beam-Beam Effects.

Contents

1 Motivation

The maximum achievable luminosity in a collider as the LHC and its upgrades is dictated by identifying the limits due to beam-beam interactions. One of these limits could come from an emittance increase due to the interplay of head-on collisions and external noise. The maximum achievable head-on collision and its dependency on external noise, as for example the one introduced by crab cavities, is therefore an essential study to identify possible limitation and define tolerances on hardware (i.e. crab cavities) that could deteriorate the beam emittances and consequently the luminosity reaches of a collider.

The present MD goal is to understand the interplay between beam-beam head-on and an external noise source. As a direct consequence one will be able to estimate acceptable noise tolerances to be introduced by future new elements as for example crab cavities foreseen in the HL-LHC project. As well the results presented here will be used to validate existing analytical and numerical estimations. This to gain confidence in our predicting tools for the up-grade and future accelerator designs. According to [2,3], under certain assumptions, the expected emittance growth in colliding bunches under the influence of an external noise is proportional to the frequency spread introduced and therefore to the beam-beam parameter. The emittance growth is given by,

$$\frac{1}{\epsilon_0}\frac{d\epsilon_x^{1,2}}{dN} = \frac{1-s_0}{4}\left(\Delta^2\right) S\left(\frac{g}{2\pi|\xi|}\right), \tag{1}$$

with s_0 a constant, Δ is the noise amplitude in $[\sigma]$, g is the transverse feedback gain defined as $g = 2/\tau$ with τ the number of turns to damp, ξ is the beam-beam parameter and $S(x) = 1/(1+x)^2$.

There exist as well an extensive campaign of self-consistent simulations done with the COMBI [4] code that show very good agreement against Eq. (1) (Fig. 1) for large enough damper gains. But interesting deviations for smaller ones [5]. Numerical limitations are under investigation also to identify the limits of numerical simulations of such complex systems as colliding beams.

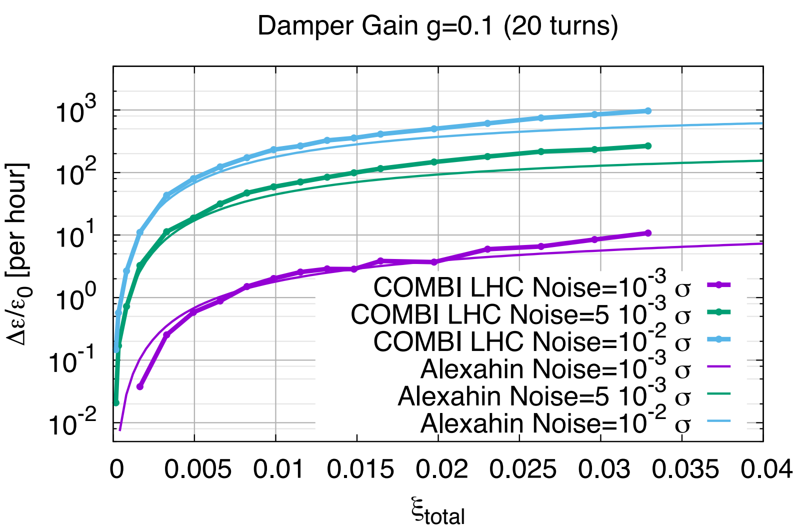


Fig. 1: Simulations by COMBI where the emittance growth of a single bunch colliding in a single IP is evaluated for different noise amplitudes and beam-beam parameters. The damper gain is set to 20 turns in this case. The agreement is fairly good with Eq. (1).

2 Experimental conditions

Three bunches per beam were injected: 1 witness nominal, 1 nominal with increased intensity and a high brightness one (see Table 1). Damper gain was initially set to 20 turns. The octupole current was kept low at 6.5 A as well as chromaticity at 2 units which are known to have a clear impact on the measured emittance growth. The two colliding bunches will meet the partners in both IP1 and IP5. After collision

Table 1: Target beam parameters and expected beam-beam parameter for the different bunches to be used during the MD.

Bunch	I[10^{11}ppb]	$\epsilon_{n,x,y}$ [$10^{-6}\mu rad$]	$\Delta\xi_{bb}$/IP
Witness	1.15	2	0.0072
Nominal	1.3	2	0.0082
High Brightness	1.5	1	0.0189

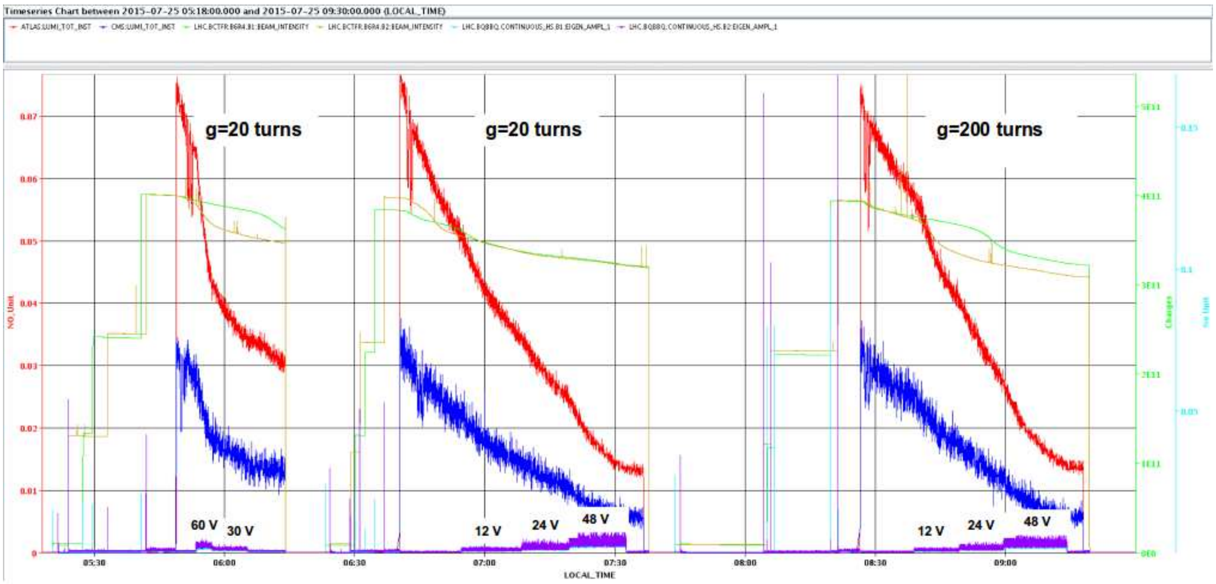


Fig. 2: The MD in a nutshell. Various TIMBER signals corresponding to the three fills done during the noise MD. Three bunches, two colliding and one witness, are injected per fill (three steps in intensity signals b1-green and b2-yellow). Afterwards they are brought into collision (luminosity signals ATLAS-red and CMS-blue). Once the collisions are optimized the external noise is introduced in both beams and both planes as shown by the BBQ signals (b1-cyan and b2-purple).

Table 2: Feedback voltage and amplitude of the white noise produced in [σ].

Voltage [V]	Noise Amp.[σ]
12	7.9 10^{-4}
24	1.6 10^{-3}
30	2.0 10^{-3}
48	3.1 10^{-3}
60	3.9 10^{-3}

optimization white noise with different amplitudes was introducing using the feedback. The emittances are monitored and recorded during 10-15 minutes per noise step. The same procedure was used in the three fills only changing the noise amplitude and the damper gain. For the first fill two noise amplitude steps were done 60 and 30 V (Table 2 and Fig. 2) with the feedback gain set to 20 turns. Since we realised that these noise amplitudes were too aggressive we backed off a bit for the next fills. For the second three noise amplitude steps were done 12, 24 and 48 V (Table 2 and Fig. 2) with the feedback gain set to 20 turns. For the third and last three noise amplitude steps were done 12, 24 and 48 V (Table 2 and Fig. 2) with the feedback gain set to 200 turns.

The tune shift due to the beam-beam interaction (Fig. 3) will be varying during the fill due to the large variation of emittances and intensities (Fig. 4). Very good agreement between expected coherent

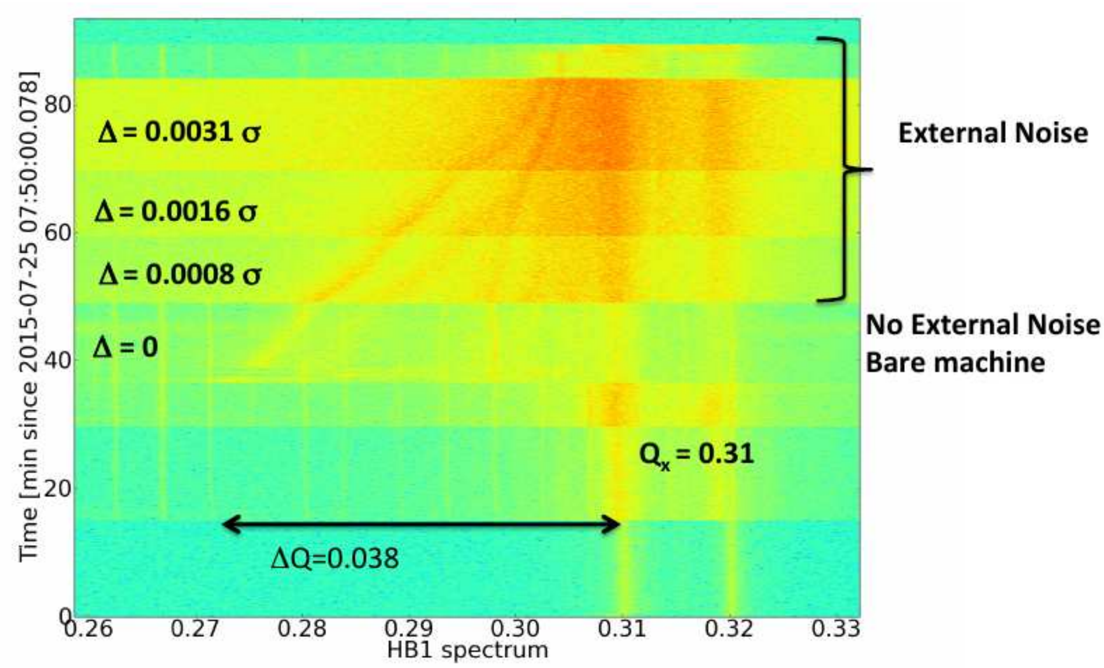


Fig. 3: BBQ signal for the third fill for Beam 1 and horizontal plane. The high intensity beams experiences a total ΔQ ~0.038 which is almost twice larger value for the HL-LHC. This is consistent with the expected coherent tuneshift from the high brightness colliding bunch in beam 2 (I=1.7 10^{11} ppb and $\epsilon = 1.35\mu$m) colliding at two IPs and assuming a Yokoya factor of 1.2.

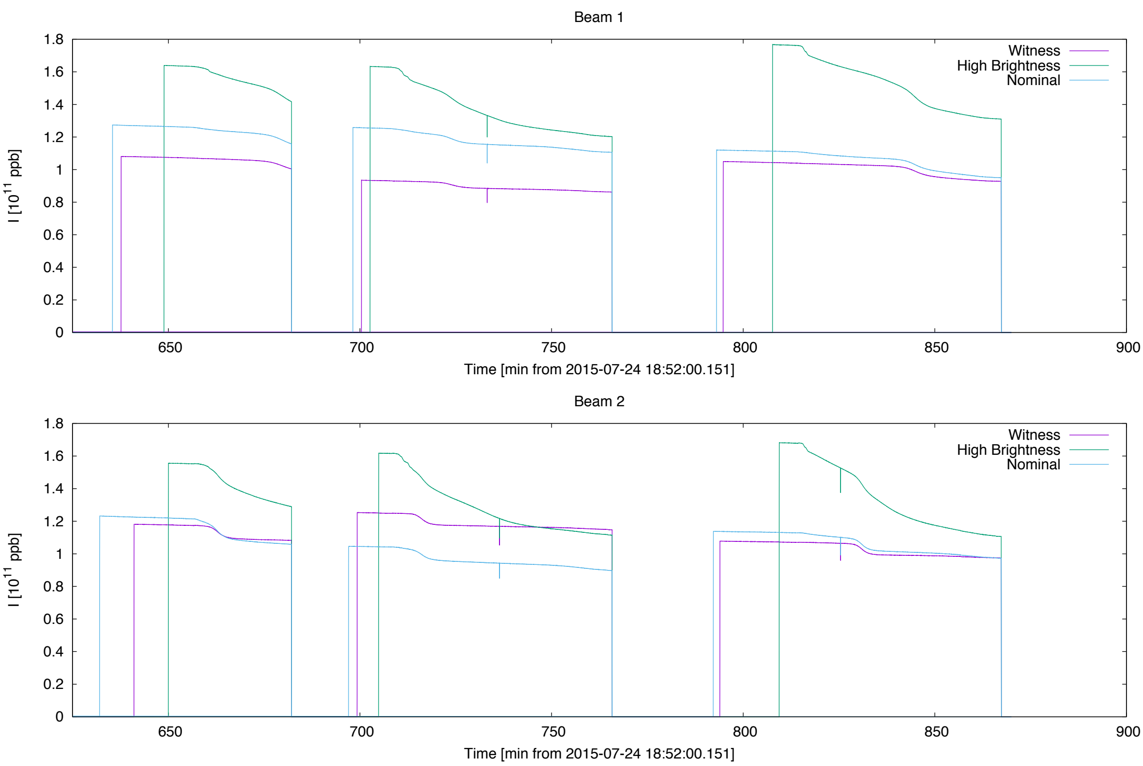


Fig. 4: Measured intensities for the 3 fills.

tune shift and the measured one is found. Fig. 3 shows the coherent tuneshift measured in beam 1 horizontal during the 3^{rd} fill of $\xi_{bb,\text{high int}} \approx 0.038$ which agrees with the beam parameters of I=1.7 10^{11} ppb and $\epsilon = 1.35\mu$m (Figs. 4 and Fig. 7) colliding at 2 IPs with a Yokoya factor of 1.2 [6]. This tune shift is almost twice the expected $\xi_{bb,\text{HL-LHC}}$.

3 MD results

During the whole MD the emittances were measured by the transverse synchrotron light monitors (BSRT) and were later post-processed to be presented in [%/per hour]. During the first fill (Fig. 5) only two steps in amplitude noise were done so the last stretch there was actually no noise applied. In the case of witness beams since there is no beam-beam interaction all the emittance growth measured is in principle purely due to the external noise and other sources related to single beam (intra-beam scattering, different working point and the external noise). A first look at the emittance growth rates between colliding and non-colliding shows a clear dependency on the beam-beam parameter. Bunches colliding show a much faster growth rate, however the witness or non-colliding bunches show a non-negligible emittance growth that can be explained only. The growth rate increases for increasing amplitude of the noise. Moreover the the high-intensity bunches, and consequently larger beam-beam parameter, always present larger growth rates.

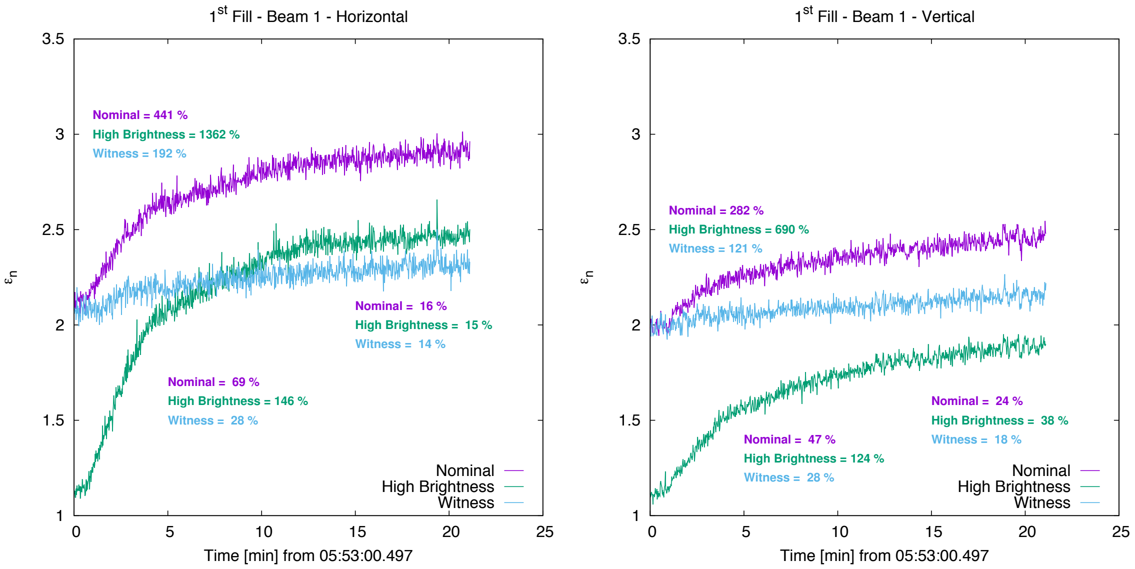
In the second fill three steps of noise amplitude were done (12, 24 and 48 V) since we realised that the range used in the first fill was too aggressive leading quickly to very large emittances and degrading the beam-beam parameter.

Figure 6 shows the emittance growth in [%/per hour] for Beam 1 and 2. The damper gain is kept to 20 turns. Comparing Fig. 5 (lower amplitude noise) to Figure 6(larger amplitude noise) we can observe that the emittance growth rates are reduced for the case with reduced noise amplitude. The growth rate scales with the amplitude of the noise as expected. A more detailed analysis and comparison with the analytical estimates can be found in [7].

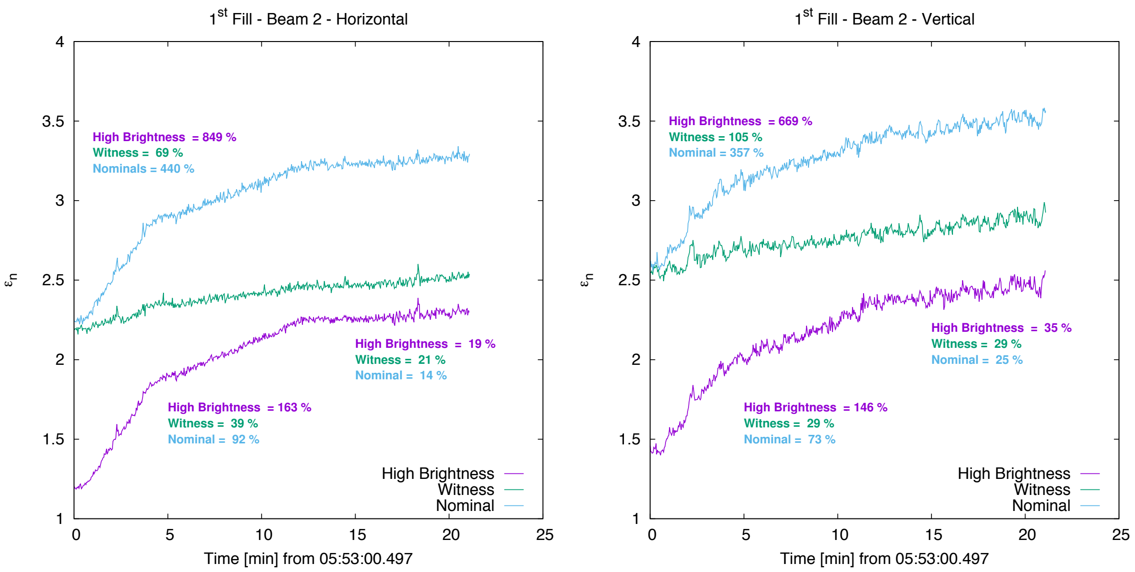
Finally, in the third fill we wanted to explore the impact of the transverse feedback gain. Again three steps of noise amplitude were done (12, 24 and 48 V) similar to the second fill. The damper gain was set to 200 turns for this case. Figure 7 shows the emittance growth in [%/per hour] for Beam 1 and 2. As in the previous fills a clear dependence between the noise amplitude and the beam-beam parameter appears. However from expectations of [2] it would reasonable to think that a weaker damper would allow larger emittance growth rates for the same noise level, which is what happens in Beam 2, but not in Beam 1. As mention in the motivation there is currently an extensive campaign of self-consistent simulations that will help us to better understand the interplay between the transverse feedback and the beam-beam and noise driven emittance blow-up. A detailed comparison to expectations can be found in [7].

3.1 Summary

- A preliminary study of the effect of external noise on colliding bunches was studied at injection energy in the LHC using 3 fills amounting for a total of 5 hours.
- Different noise amplitudes were introduced using the transverse feedback as a noise generator. The amplitudes were in the order of 10^{-3} σ.
- The experiment aimed to quantify the emittance growth due to the interplay between beam-beam head-on tune spread and an external noise. The main goal was to benchmark existing analytical and numerical estimations as done in [7,8] and to define tolerances for newer devices, i.e. the crab cavities for the HLLHC.
- In addition to the noise amplitude, the transverse damper gain (20 and 200 turns) and different beam-beam parameters (ξ_{bb}=[0.02,0.04]) were scanned to get the dependency on these machine and beam parameters influence since from the analytical estimates they play an important role.
- Chromaticity was kept at 2 units since the time was limited and this is another parameter which has very strong impact on the emittance growths in the presence of noise. Simulations show an important dependence on this parameter that as well is not taken into account in Eq. (1) and seems



(a) Beam 1.



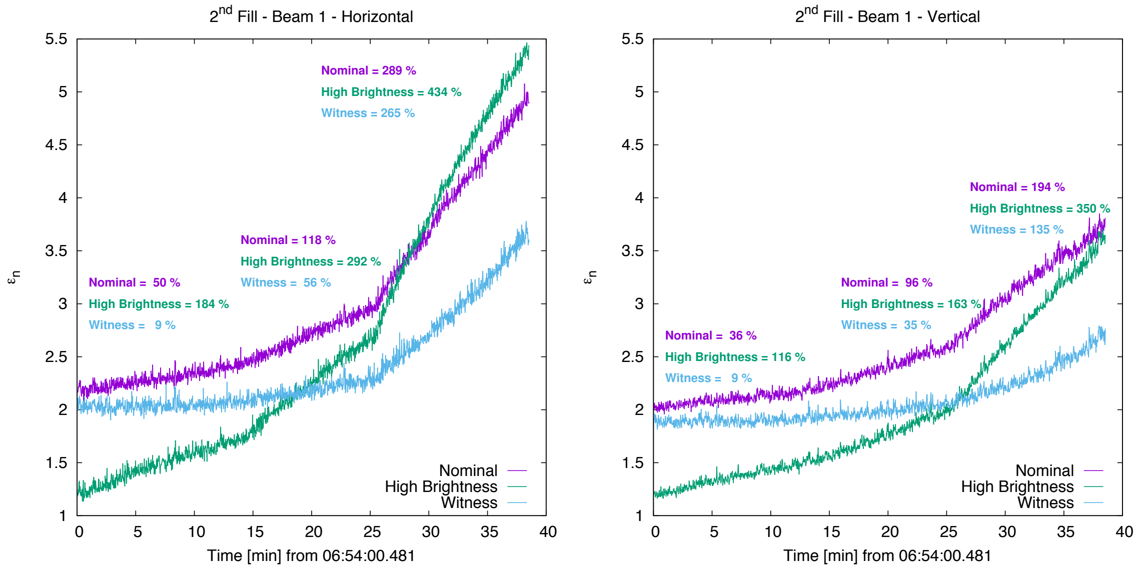
(b) Beam 2.

Fig. 5: Emittance growth in [%/hour] during the first fill. Transverse feedback gain set to 20 turns. First step noise of 60 V, second 30 V and 0 V in the last one for comparison (corresponding amplitude in σ in Table 2).

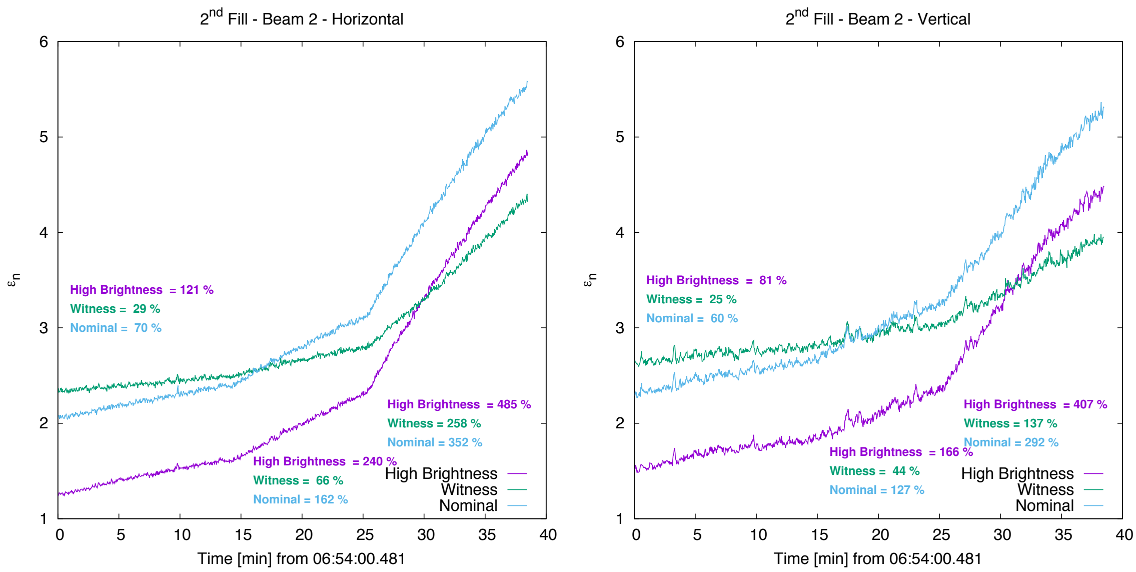
also very non-linear. For this reason we will like to repeat this MD in the future with different values of chromaticity to validate the expectations.

- Non-colliding bunches were used during the MD for comparison and even in the case of no external noise applied a non-negligible emittance growth rate of 15-30%/hour depending on which beam and plane.
- Beam 2 seems to be more sensitive to the noise introduced.
- All studies have been performed at injection energy to save time and have the possibility to explore and scan the parameters since the problem has too many uncertainties to be addressed. A test at top energy could clarify the impact of energy dependent processes.

A detailed analysis and a comparison between analytical model and self-consistent simulations and the LHC data collected during this MD has been presented at [7]. A clear mismatch between measurements and expectations have been stressed. It has been showed that the emittance growth measured



(a) Beam 1.



(b) Beam 2.

Fig. 6: Emittance growth in [%/hour] during the second fill. Transverse feedback gain set to 20 turns. First step noise of 12 V, second 24 V and 48 V in the last one (corresponding amplitude in σ in Table 2).

in the LHC during the MD is by factors larger than what expected from simulations and analytical models. The emittance growth measured in the LHC shows the expected beam-beam dependency as in [2] but the amplitude is consistent with a factor 3-4 larger noise amplitude. This points to either a noise sourse at injection energy that already acts on the beams and that needs to be understood and reduced. Or could be due to some interplay with mechanism present at injection. A detailed analysis of the data is still on-going to understand how to quantify the effects on emittance growth on the single beam that is normally subtracted from the colliding beam effects. The finding in this MD are worrying since they show a much stronger sensitivity to noise of colliding beams. The conditions during the MD were also different respect to the normal operation since we were testing the noise effects at injection energy.

4 Acknowledgement

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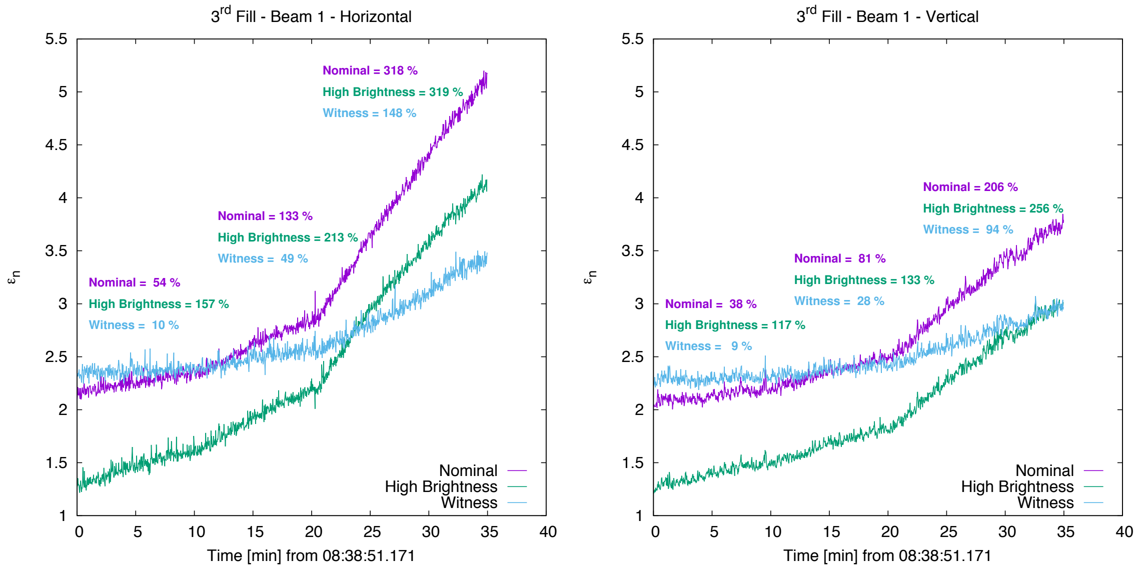
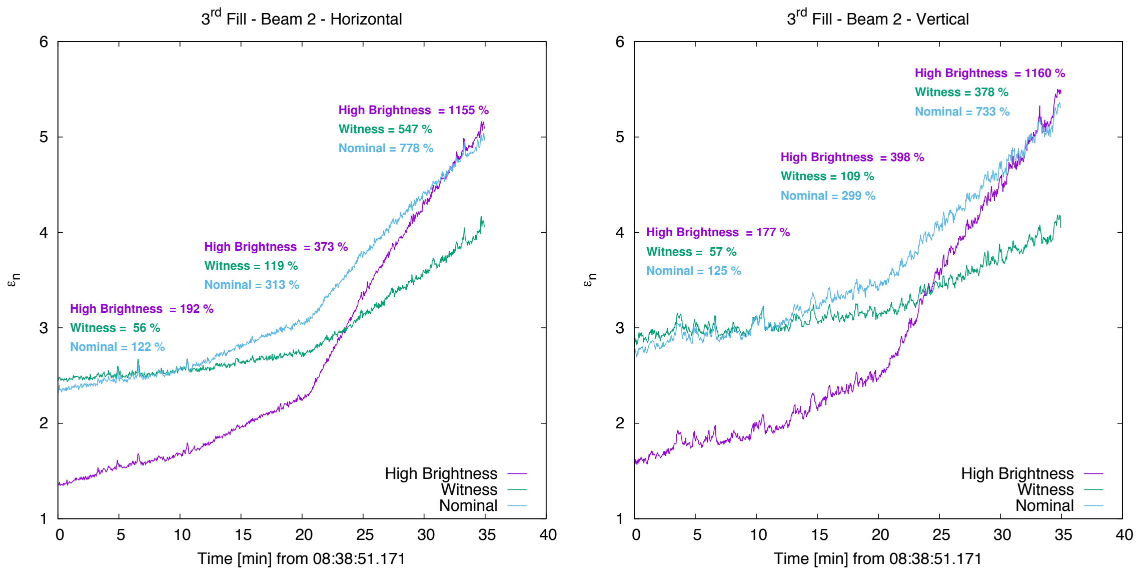


(a) Beam 1.



(b) Beam 2.

Fig. 7: Emittance growth in [%/hour] during the third fill. Transverse feedback gain set to 200 turns. First step noise of 12 V, second 24 V and 48 V in the last one (corresponding amplitude in σ in Table 2).

damental verification will be to check the effect of noise at top energy to reduce the parameter space to be studied.

5 References

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