Modeling of the emittance growth due to decoherence in collision at the Large Hadron Collider

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The transverse emittance growth rate of colliding hadron beams driven by external sources of noise is investigated based on existing analytical model as well as on macro-particle simulations and comparison to experimental data at the Large Hadron Collider (LHC). It is shown that an analytical description of the emittance growth rate neglecting the existence coherent beam-beam mode can nevertheless provide accurate estimate for operational conditions, featuring notably a high chromaticity. The model is used to investigate the level of noise experienced by the LHC beams. The results indicate that a significant reduction of the noise floor of the transverse feedback’s beam position monitor is required for operation with a large beam-beam tune shift, as the one anticipated for the High Luminosity LHC (HL-LHC).

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I. INTRODUCTION

In existing high energy hadron colliders, such as the Large Hadron Collider (LHC) at CERN, the preservation of the transverse emittances is a major concern due to the absence of significant damping mechanisms. Consequently, all potential sources of noise, which would result in emittance growth through the mechanism of decoherence [1], are tightly controlled. The operation with a transverse feedback to ensure the beam stability was a major concern at the design stage of the Superconducting Super Collider (SSC) and the LHC [2,3], thus leading to advanced theoretical developments to estimate accurately the tolerance on the feedback noise. Two approaches yield different estimates. By modeling the beam-beam force of the opposing beam as a static lens, i.e., using a so-called weak-strong model, the contributions of the feedback to the emittance growth rate, can be estimated as follows [4]:

\[
\frac{1}{\epsilon} \frac{d\epsilon}{dt} = \frac{1}{2} \left( \delta^2_0 + G^2 \delta^2_{BPM} \right) \left( \frac{4\pi^2 (1 - \frac{G}{2})^2 \Delta Q^2}{4\pi^2 (1 - \frac{G}{2}) \Delta Q^2 + \left( \frac{\pi}{G} \right)^2} \right),
\]

where \( \Delta Q \) is the tune shift of a particle with respect to the unperturbed tune, due to the nonlinearity of the machine, normalized to the beam divergence at the location of the source. The contribution of the feedback is singled out with a term that depends on the normalized beam position monitor (BPM) noise floor \( \delta_{BPM} \) and the gain \( G \).

As in [4], we shall consider in the following a feedback with a single kicker, such that the damping time is \( \tau = \frac{2}{G} \).

The weak-strong approximation in principle does not hold for the LHC, since both beams are equally bright, such that the forces that they exert on each other are of identical strength. In this so-called strong-strong regime, an approach considering the motion of the two beams in a consistent way seems more appropriate. A closed form for the emittance growth rate was derived in a configuration featuring perfect symmetry between the beams and a single interaction point where the beams collide head-on [5]:

\[
\frac{1}{\epsilon} \frac{d\epsilon}{dt} \approx \frac{1}{4} \left( \delta^2_0 + G^2 \delta^2_{BPM} \right) \left( \frac{1}{1 + \frac{\pi^2}{G^2}} \right)^2,
\]

with \( s_0 \approx 0.645 \) a constant parameter determined numerically. The beam-beam parameter characterizes the tune shift of the particles oscillating with a small amplitude at the center of the opposing beams given by [6]:

\[
\xi = \frac{N r_0}{4\pi e_n},
\]

for round beams with normalized transverse emittances \( \epsilon_n \) and a bunch intensity \( N \). \( r_0 \) is the classical proton radius. The key component responsible for the difference between the two approaches is the existence of coherent beam-beam modes, which is neglected in a weak-strong approach and...
may affect the dynamics significantly. In a simple configuration with two symmetric beams colliding in on interaction point (IP), one finds two coherent modes of oscillation called $\sigma$- and $\pi$- modes, corresponding to in or out of phase motion of the two beams at the IP. The frequency of the $\sigma$-mode lies at the unperturbed machine tune. The $\pi$-mode frequency is shifted by $-\xi$, the beam-beam tune shift, multiplied by a form factor, usually called the Yokoya factor [7]. In this configuration, the frequency of both coherent modes does not match the oscillation frequency of any of the single particles. Indeed, the so-called incoherent spectrum ranges from the beam-beam tune shift to the unperturbed tune [5]. As a result, the interaction between the coherent modes and the incoherent motion of the single particle is reduced, such that decoherence is significantly slowed down with respect to the one obtained with the weak-strong model. A detailed description of this mechanism can be found in [5]. For more realistic configurations of the LHC and of the High Luminosity LHC (HL-LHC) involving complex bunch train structures, multiple IPs with asymmetric phase advances between them, as well as chromaticity, there exists a variety of coherent beam-beam modes which frequencies may lay inside or outside of the incoherent spectrum [8]. In these conditions the formalism developed in [5] usually leads to integrals that require numerical solution. In several cases, the usage of macroparticle tracking simulation becomes more convenient. As discussed later, the limitation of the analytical treatment to first order in the beam-beam parameter also favors the usage of numerical simulations for most relevant configurations.

The Piwinski angle and hourglass parameters are rather low in the LHC [3]. Thanks to the usage of crab cavities and a luminosity leveling scheme featuring a $\beta^*$ slowly decreasing with the beam intensity, these parameters are also low in the HL-LHC [9], at least when the beam-beam interaction are the strongest. For these reasons we shall neglect the longitudinal variation of the beam-beam force [10], compatibly with the derivations of Eqs. (1) and (2).

The numerical model that is used to quantify the emittance growth for a given noise amplitude in the LHC is detailed in the first section. In the second section, the limits of the two analytical models are explored via comparison with the strong-strong macro-particle tracking simulations. In the third section, we will compare experimental results to the models and deduce the corresponding machine and feedback driven noise. Eventually, these information allow for extrapolation to the configuration of the HL-LHC [9], highlighting the need for technological improvements of the transverse feedback BPM.

**II. NUMERICAL MODEL**

In the following we use the strong-strong macro-particle tracking code COMBI [8,11,12] for the estimation of the emittance growth rate. The setup is summarized in Table I. The noise is introduced by adding to the transverse momentum of all particles in a bunch an identical contribution that varies randomly at each turn respecting a Gaussian distribution. The soft-Gaussian approximation for the estimation of the force exerted on one beam by the other is used, offering a good balance in terms of accuracy of the description of the coherent beam-beam mode [8] and computational requirement [13]. This model is based on the estimation of the beam-beam force using the analytical expression for Gaussian beams [14] based on the position and r.m.s. transverse sizes obtained from the macroparticle distribution. This method introduces a numerical noise dominated by the statistical error on the position and thus reduces inverse-proportionally to the square root of the number of macroparticles [13]. The numerical stochastic cooling effect [15] caused by the transverse feedback is also enhanced by the limited number of macroparticles, with a square-root dependence as well. The accuracy needed to study the HL-LHC configuration is high, since relative emittance growth rates below a few percent per hour are required [16], corresponding to approximately $10^{-9}$ per turn. In order to efficiently address these two issues, we perform two simulations for each configuration, only one of them featuring an additional source of noise. We report here the difference between the estimation of the steady emittance growth rate estimated in the two cases, which singles out the contribution of the external source of noise to the emittance growth, i.e., the quantity of interest. An example of simulation output is described in Fig. 1. We note in the example that the first $10^4$ turns are excluded from the fit. They are dominated by the rematching of the beam distribution in the presence of the nonlinearity caused by the beam-beam interactions and therefore do not represent the steady configuration that we are considering. The convergence of the numerical model with the number of macroparticles is shown in Fig. 2. The relative

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**TABLE I. Numerical parameters used for the numerical model (COMBI).**

| Parameter                          | Value       |
|-----------------------------------|-------------|
| Energy [TeV]                      | 6.5         |
| Bunch intensity [proton]          | $1.8 \times 10^{11}$ |
| Norm. trans. emit. [µm]           | 2.0         |
| r.m.s. bunch length [ns]          | 0.2625      |
| Momentum spread                   | $1.017 \times 10^{-4}$ |
| Fractional betatron tunes [H/V]   | 0.31/0.32   |
| Synchrotron tune                  | 0.0023      |
| $\xi$ per IP                      | 0.011       |
| Number of macro-particles         | $5 \times 10^5$ |
| Number of turns                   | $10^9$      |
| Beam-beam model                   | 4D Soft-Gaussian |
| Direct detuning (oct.)            | $7.7 \times 10^{-5}$ |
| Indirect detuning (oct.)          | $-5.4 \times 10^{-5}$ |
| Number of slices (wake field)     | 800         |
| Multiturn wake                    | 20          |
| Impedance model                   | LHC flat top 2017 [17,18] |
emittance growth rates are entirely dominated by numerical stochastic cooling for simulations performed with a small number of macro-particles. Additionally, we find that the difference between the simulations with and without noise is already converged at the level of 1% for $5 \times 10^5$ macro-particles, whereas more than $10^7$ macro-particles would be needed to obtain a similar level of convergence otherwise.

**III. COMPARISON TO ANALYTICAL MODELS**

The weak-strong approximation used to derive Eq. (1) is satisfied if the tune spread is generated by octupole magnets, such as those used to maintain Landau damping in the LHC [19]. Figure 3(a) shows that the numerical model is capable of reproducing exactly the prediction of the analytical model in this configuration with a chromaticity equal to 0. On the other hand, the chromaticity introduces a variation of the tune which is modulated by the energy change of the particles during synchrotron motion. The transverse feedback response is sensitive to this modulation of the particles tune as it leads to the appearance of synchrotron sidebands in the measured signal [20]. Thus it is expected that the usage of Eq. (1) using the quadratic sum of the tune spread induced by the octupoles and the chromaticity does not provide an accurate estimate of the emittance growth rate, as it neglects the response of the feedback to synchrotron sidebands. The discrepancy is illustrated on Fig. 3(a).
In the presence of both octupoles and a beam-beam interaction with a large beam-beam tune shift ($\xi \approx 0.02$), the emittance growth rate is purely dominated by the beam-beam interaction and is in agreement with the prediction of the strong-strong model [Eq. (2)], as shown in Fig. 3(b). This equivalence of the self-consistent numerical and analytical approaches in this configuration was already showed, e.g., in [21]. The nontrivial behavior of the emittance growth rate with chromaticity is shown in Fig. 4. The results are mostly in between the predictions of the weak-strong model and the strong-strong model without chromaticity. This observation may be interpreted as an impact of the multiple coherent modes developing in the presence of beam-beam interactions and chromaticity [22,23]. The frequency of most of these modes will be within the incoherent spectrum, such that the assumption behind the derivation of Eq. (2) no longer holds [5]. These simulations suggest that when many coherent modes are within the incoherent spectrum the emittance growth rate tends toward the value predicted by the weak-strong model, in spite of the strong-strong nature of the configuration. Nevertheless, to our knowledge this result was never demonstrated mathematically.

We shall illustrate further this effect by considering a machine with two IPs and asymmetric phase advances between them. In such a configuration the coherent modes may lay within the incoherent spectrum. The impact on the emittance growth rate is shown in Fig. 5(b), where we observe that the emittance growth rate is in between the predictions of the weak-strong model and strong-strong model. Again the addition of chromaticity brings the behavior closer to the one of the weak-strong model [Fig. 5(a)].

The derivation of the strong-strong formula [Eq. (2)] is based on a first order perturbation by the beam-beam force. For round beams colliding head-on, there is no coupling between the two transverse planes due to this perturbation, therefore the emittance growth rate does not depend on the tunes in the transverse planes. Also, the two transverse planes are expected to behave identically, which is verified in the simulations discussed up to here. Both statements are, however, in contradiction with the results of the simulation featuring different tune separation between the transverse planes shown in Fig. 6. Here we chose arbitrarily a vertical tune above the horizontal tune, we find that for tune splits ranging from $0.2\xi$ to $0.5\xi$, the emittance growth rate is increased in the horizontal plane and reduced in the vertical plane. This effect is observed also for a nonzero chromaticity. In both cases the emittance growth
rate remains between or slightly above the weak-strong and strong-strong model's predictions. We may interpret this deviation from the strong-strong model prediction by the fact that the vertical $\pi$-mode frequency is within the horizontal plane's incoherent spectrum, as shown in Fig. 6. As the coupling between the transverse plane only arise from a second order effect, i.e., caused by the small offsets between the beams at the IP introduced by the noise, this effect is not predicted by the first order perturbation theory.

The soft-Gaussian model for the strong-strong beam-beam interaction used for these simulations is expected to underestimate the Yokoya factor by approximatively 10% \[8\], such that the pairs of bunches are independent of each other. The experiments were performed with pairs of bunches colliding at the two main IPs located at opposite azimuth, such that the pairs of bunches are independent of each other.

Figure 7 shows the emittance growth rate caused by the presence of an external source of noise for beams colliding with a beam-beam parameter comparable to the difference between the horizontal and vertical tunes. The optics featured phase advances of few degrees away from the symmetric configuration and a chromaticity of approximately 15 units. Based on the simulations shown in Fig. 4, we expect a behavior comparable to the weak-strong formula which is confirmed by measurements.

Considering beams colliding with twice the beam-beam parameter, corresponding to the HL-LHC design \[9\], we find that the vertical emittance growth rate is significantly reduced with respect to the expectations from the weak-strong formula yet remaining above the estimation from the first order strong-strong formula (Fig. 8). The measured tune separation is reported on Fig. 6, showing that the observed behavior is compatible with the expectation from simulations.
In a second experiment we attempt to characterize the machine and feedback noise floor, respectively $\delta_0$ and $\delta_{\text{BPM}}$, by measuring the emittance growth rate of colliding bunch pairs with a similar beam-beam tune shift of $\xi = 0.01$. The controlled source of noise with a fixed amplitude was activated for 10 minutes. The emittance quoted here results from the comparison of the fit over these 10 minutes with respect to 10 minutes in absence of noise, such that it corresponds to the sole contribution of the artificial noise. The uncertainty on the measurement is dominated by the resolution of the emittance measurement, its impact on the fit values are shown with error bars. The experiment was repeated with feedback gains of 0.02 and 0.005 represented with solid and dashed blue lines. The black and green lines show the corresponding predictions using the weak-strong and strong-strong model respectively. The results are shown for the first beam, the other exhibited a similar behavior [25].

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FIG. 7. Relative emittance growth rate measured in an experiment at the LHC in 2016, during which single bunches were brought into collision at 6.5 TeV in IPs 1 and 5 reaching a total beam-beam tune shift of $\xi = 0.01$. The controlled source of noise with a fixed amplitude was activated for 10 minutes. The emittance quoted here results from the comparison of the fit over these 10 minutes with respect to 10 minutes in absence of noise, such that it corresponds to the sole contribution of the artificial noise. The uncertainty on the measurement is dominated by the resolution of the emittance measurement, its impact on the fit values are shown with error bars. The experiment was repeated with feedback gains of 0.02 and 0.005 represented with solid and dashed blue lines. The black and green lines show the corresponding predictions using the weak-strong and strong-strong model respectively. The results are shown for the first beam, the other exhibited a similar behavior [25].

FIG. 8. Equivalent of the plots shown in Fig. 7 for high brightness bunches featuring a beam-beam tune shift twice as high (red lines).

match the specifications for the acquisition electronics within 10%. On the other hand, the contribution from the rest of the machine remains unclear. Since the LHC’s first betatron line is at approximatively 3 kHz, the ground motion is naturally suppressed [26] and most of the contributions from power converter ripple are expected to be heavily attenuated by the colaminated copper layer of the beam screen [27]. Studies of the mechanical vibrations of the beam screen due to the helium flow in the cooling capillaries and the resulting field variations in the vacuum chamber suggest that this contribution could yield a noise amplitude of the right order of magnitude [28].

V. EXTRAPOLATION TO THE HL-LHC

Due to the complex bunch train structure, the multiple IPs and the asymmetry in the phase advance between them in each beam, the complexity of the beam-beam interactions of the LHC and HL-LHC in operational conditions is not easily addressed with macroparticle tracking simulations. Yet in such configurations it is expected that the coherent modes are inside the incoherent spectrum [8]. As discussed in Sec. III, the weak-strong model may provide a reasonable estimate of the emittance growth rate in such a configuration, in particular when operating with a
high chromaticity. In the following we attempt to extrapolate from the experiments performed in a simplified configuration featuring an independent bunch pairs colliding at two IPs (Sec. IV) to the operational configuration of the LHC and HL-LHC.

Figure 10 shows such an extrapolation using Eq. (1) with the noise amplitudes in Table II averaged over all beams and planes. The beam-beam parameter in the experiment is approximatively 0.02 (solid blue line). In standard condition during the run 2 of the LHC, the beam-beam parameter was approximatively 0.007 (dashed blue line). The extrapolated emittance growth rate is 2% per hour which is compatible with measurements in operational conditions [31]. The emittance growth rate is expected to be twice as high in absence of feedback. Yet, the latter can not be verified experimentally as the LHC is normally not operated without transverse feedback in collision to avoid coherent instabilities.

The efficiency of the suppression of the emittance growth by the feedback is low when the tune spread is significantly larger than the feedback gain. This can be seen as the average term in Eq. (1) tends to one for $G \ll 4\pi\Delta Q$ [4]. In such conditions, the emittance growth is expected to increases with the feedback gain due to the BPM noise floor. This behaviour was observed in the experiment described in the previous section and is expected to occur in the HL-LHC configuration as the nominal beam-beam tune shift is 0.02, i.e., comparable to the one obtained in the experiment. The extrapolations shown in Fig. 10 (green and red curves) suggest that an improvement of the feedback BPM noise floor by a factor 2 and 4 is also shown. A vertical dashed line was added to indicated the current operational feedback gain.

| Beam 1 | Beam 2 |
|-------|-------|
| Horizontal | Vertical | Horizontal | Vertical |
| $\delta_0 \times 10^{-5}$ | 3.8 ± 0.2 | 5.3 ± 0.2 | 4.4 ± 0.4 | 5.6 ± 0.2 |
| $\delta_{\text{BPM}} \times 10^{-5}$ | 220 ± 13 | 250 ± 9 | 190 ± 15 | 210 ± 9 |

FIG. 9. Measured relative emittance growth rate as a function of the feedback gain for single bunches colliding at 6.5 TeV in IPs 1 and 5 featuring a total beam-beam tune shift of 0.02 during a dedicated experiment at the LHC in 2017. Other contributions to the emittance growth rate such as intrabeam scattering [29] are remove based on the measurement of the emittance growth rate of a noncolliding bunch with similar properties. The data is fitted with Eq. (1), the corresponding parameters are shown in Table II. The details of the experiment may be found in [30].

FIG. 10. Extrapolation of the emittance growth rate based on Eq. (1) and the parameters obtained empirically to a configuration featuring a reduced beam-beam tune shift with respect to the experiment. The potential impact of a reduction of the feedback noise by a factor 2 and 4 is also shown. A vertical dashed line was added to indicated the current operational feedback gain.
Taking into account the tune separation and the phase advance between IPs.

VI. CONCLUSION

The present understanding of the emittance growth rate of colliding beam due to decoherence in the LHC was described, including a comparison of the existing analytical model with a numerical model based on macroparticle tracking simulations. Experimental data compatible with this approach justify its usage for extrapolation for to the HL-LHC configuration, featuring a significantly larger tune spread due to head-on beam-beam interactions with respect to the LHC. The experiments revealed a significant contribution of the existing transverse feedback to the emittance growth driven by its BPM noise floor, such that a mitigation is required to achieve the HL-LHC performance. The other sources of noise in the LHC remains to be identified.

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