MODELLING THE EXPERIMENTAL DATA FOR LONG-RANGE BEAM-BEAM WIRE COMPENSATORS AT THE CERN LHC WITH DIFFUSIVE MODELS*

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Abstract

Current-carrying wires have long been proposed as measures to mitigate beam-beam effects. Dedicated hardware has been installed at CERN's Large Hadron Collider (LHC) and experimental sessions have been organised to study the beam dynamics in the presence of the wire compensators. In this paper, a diffusive model is presented to model the collected experimental data, and its performance is discussed in detail.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] and its High Luminosity upgrade [2] are high-brightness and high-energy colliders where beam-beam long-range (BBLR) interactions at Interaction Points (IPs) lead to performance limitations [3]. The reduction in beam lifetime caused by these interactions ultimately impacts the collider's luminosity performance. To address this problem, a mitigation technique using DC beam-beam compensator wires (BBCW) was introduced in the early 2000s [4], and is currently being studied as an option to enhance the performance of HL-LHC [5, 6].

BBCWs consist of thin wires placed near the interaction point of the two beams, an overview of the mechanical design is given in Ref. [7]. The wires, charged with a DC current of a few 100 A, are used to create a compensating electromagnetic field that counteracts the effects of the long-range beam-beam interactions, ideally reducing beam losses. An overview of BBCWs and recent experimental results achieved in LHC can be found in Ref. [8].

In an effort to validate the effectiveness of BBCWs, four demonstrators were installed in tertiary collimators at the LHC between 2017 and 2018 [7]. A two-year experimental campaign successfully demonstrated the mitigation of the effects of BBLR interactions under beam conditions compatible with standard physics operations and provided motivation for additional experiments, such as the Machine Development (MD) study in Ref. [9].

To further investigate the effect of BBCW on long-term beam dynamics, we consider a recent diffusive framework [10–12], based on the optimal estimate of the perturbation series provided by the Nekhoroshev theorem [13–15]. According to this framework, the evolution of the beam distribution is described as the solution of a Fokker-Planck (FP) equation that reads

$$\frac{\partial \rho(I,t)}{\partial t} = \frac{\varepsilon^2}{2}\frac{\partial}{\partial I} D(I) \frac{\partial}{\partial I}\rho(I,t) \tag{1}$$

$$D(I) = c \exp\left[-2\left(I_*/I\right)^{\frac{1}{2\kappa}}\right] \tag{2}$$

$$c\int_0^{I_\mathrm{a}} \exp\left[-2\left(I_*/I\right)^{\frac{1}{2\kappa}}\right] \mathrm{d}I = 1\,, \tag{3}$$

where the Nekhoroshev-like diffusion coefficient $D(I)$ is a function of the action variable I, and is defined by the parameters κ and I_*. Recent research [11] suggests that the exponent κ is related to the analytic structure of the perturbative series and the dimensionality of the system, while the parameter I_* is related to the asymptotic character of the perturbative series. The constant c is a normalisation factor that is evaluated depending on the position of the jaws of the primary collimator I_a, represented as absorbing boundary conditions. Finally, the parameter ε^2 represents the time scale of the diffusive process.

By applying this framework to the loss signals measured for anti-clockwise circulating beam in the LHC (Beam 2) during the 2018 MD study, we expect to gain insight into the long-term dynamics of the beam in the presence of BBCW.

EXPERIMENTAL DATA OVERVIEW

The BBCWs installed for Beam 2 were tested in various beam-beam-dominated scenarios. Three trains of symmetric bunches were tested at 6.5 TeV in collisions at different crossing angles, lower than the standard 285 µrad, to enhance long-range beam-beam effects. The BBCWs were set in the quadrupolar configuration, i.e., a wire in each collimator jaw is powered in series, doubling the odd multipolar strength of the kick, while even ones cancel out [8, 9].

The calibrated loss signal of Beam 2 is reported in Fig. 1. These data are reported in protons/s and represent a combination of the original signal, in Gy/s, from the beam loss monitors (BLMs) located in IR7 [16], converted into an estimate of the corresponding protons lost by means of a conversion factor established with dedicated measurements and simulation studies [17]. As slow diffusive losses cause variations in the loss signals at the primary collimators, we are interested in these data. The DC Beam Current Transformer (DCBCT) [18] data is also reported.

The BBCW powering is reported in Ampere and can be found in the *off* state, namely at 0 A, or in the *on* state, namely at 350 A. Note that the change of state for the BBCWs or

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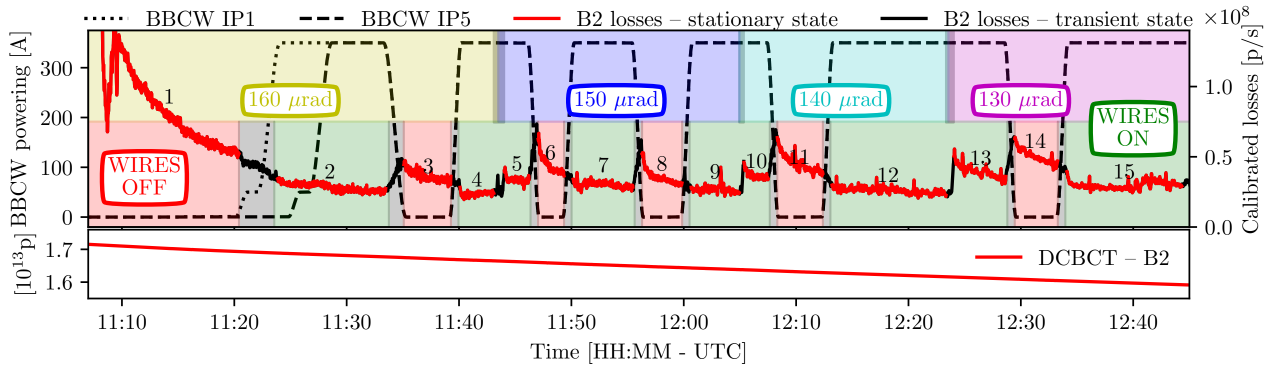

Figure 1: Overview of the Beam 2 data gathered during fill 7386. BLM calibrated losses were taken at different combinations of crossing angles and wire powering. The loss signal is classified into stationary state, when no change in wire powering or crossing angle is occurring, and transient state, when the wire powering or crossing angle is changing, indicated with a grey background. The numbers on the loss data indicate the naming conventions of the chunk. A bunch spacing of 25 ns was used [8].

the change of the crossing angle requires a non-negligible amount of time, requiring specific considerations.

It is possible to see how the data provide a variety of crossing angle configurations, along with on-off alternations of BBCW powering. Qualitatively, one can observe how the BBCW leads to a lower BLM loss signal when on, while turning them off leads to a strong peak in the losses. Moreover, it can also be seen how reducing the crossing angle leads to a slightly higher loss signal, as it increases the long-range beam-beam effects.

DIFFUSIVE MODEL APPLICATION

To apply Eq. (1), with Nekhoroshev-like $D(I)$, to the loss data for the various states of the system, we perform a fitting approach inspired by the procedure used in the work of Bazzani *et al.* [11], where the same model is used to reconstruct the evolution of the normalised beam intensity.

To construct a measure of the normalised beam intensity as a function of the number of turns, we first consider the nominal revolution frequency of 11 245 Hz. We then evaluated the relative intensity lost over an interval $[N_0, N_1]$ considering the amount of protons lost from the integrated BLM signal. Finally, we take as an initial intensity the value measured by the DCBCT at the beginning of the data interval considered, since it is the best experimental estimate of the number of protons in the beam, namely $\sim 1.72\times 10^{13}$ protons. We emphasise that, while the DCBCT provides a good estimate of the number of protons in the beam, it is not a sensitive enough instrument to detect the small variations in the loss signal that are instead detected by the BLMs at the primary collimators.

As this model makes the strong assumption that $D(I)$ does not evolve over time, we have the requirement that the magnetic lattice of the accelerator should not exhibit stronger variations than those given by the small stochastic perturbation. Such an assumption requires us to discard the data when either the BBCW powering or the crossing angle is transitioning to a new value, as our model does not cover such varying scenarios.

Due to this requirement, we separate the data between *stationary state*, where the machine state can be considered constant over time, and *transient state*, where a variation in any of the accelerator elements occurs, and therefore the parameters of the FP equation also vary. During such a transient state, we cannot make assumptions about the evolution of the transverse beam or the evolution of the values of ϵ, I_*, and κ, and therefore we are forced to discard these data slices. This distinction is reported in Fig. 1 with losses in the stationary state coloured red and losses in the transient state coloured black. The resulting chunks of stationary data are progressively numbered.

We assume that the beam distribution at the end of a stationary state can be used as the initial condition of the next stationary state. To justify this approach, we observe that the time spent in the transient state is significantly smaller than the time spent in the stationary state, making the integrated losses in the transient state negligible.

To fit the diffusive model, we consider a Gaussian beam in the action variable I, as an initial condition. This then gives us the following exponential distribution

$$\rho_0(I) = \sigma^{-2} \exp(-I/\sigma^2)\,, \tag{4}$$

where σ^2 stands for the measured beam emittance. For convenience, it is possible to scale the action variable $I \to I/\sigma^2$, which corresponds to the setting $\sigma = 1$ in the simulations without affecting the beam loss rate. Regarding the absorbing boundary condition, we consider the position of the primary collimators in IR7, which were set at their nominal position of 5σ, considering the nominal emittance of 3.5 µm. To fit the data, we then scan the values κ and I_*, and integrate the evolution of the FP equation (1) as a function of the number of turns. The parameter ϵ^2 is then fixed by requiring that the initial and final values of the relative intensity, evaluated at the beginning and at the end of the fragment, are equal. The scan in κ and I_* is performed first as a brute-force grid scan on a range of candidate values; then a least-squares fit is performed with a starting point on the best parameters found with the preliminary scan.

As we assume that the beam distribution at the end of a stationary state can be used as the initial condition of the next stationary state, we can use the evolved beam distribution as the initial condition for the next data chunk. This procedure, iterated for all parts, finally gives us the reconstructed $D(I)$ for the various states of the system. In Fig. 2, we show the relative intensity loss, along with the fit reconstruction. In Fig. 3, we show the reconstructed $D(I)$ for the various crossing angles and the various states of the wire.

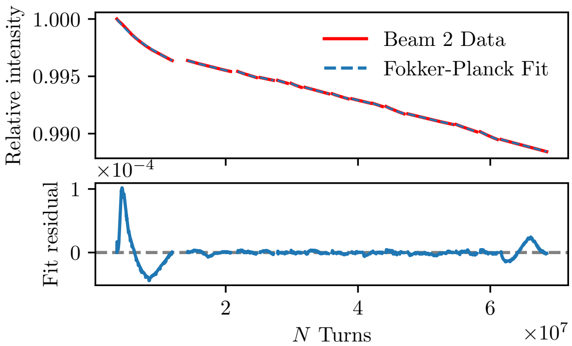

Figure 2: Relative intensity loss and fit reconstruction for the Beam 2 data, divided in chunks. As the fit residual shows, a very good agreement with the data is observed.

It can be seen that, in general, the fit reconstruction is able to reproduce the data quite well. Furthermore, it is possible to see how the reconstructed $D(I)$ is consistently different when the wires are switched on and off, with generally higher diffusion values when the wires are off. This is in agreement with the expectation that the wires are able to reduce the long-range beam-beam effects and thus the diffusion. Moreover, it is possible to see how such a reconstructed $D(I)$ for the wire being switched on also has lower values for low I amplitudes. This suggests that indeed the BBCWs might provide better long-term stability of the beam. An outlier to this trend is given by crossing angle θ_c =150 µrad, as the reconstructed $D(I)$ is not consistently lower when BBCWs are on. This can be related to the fact that changes in the state of the wire at angle θ_c =150 µrad occur at a faster rate if compared to the other angles, possibly leading to a transient-rich situation difficult to describe by means of our model.

The values of the two parameters, I_* and κ, are shown in Fig. 4, where it is observed that I_* and κ vary over very different values ranges, with the latter parameter over a much smaller interval than the first parameter. A certain correlation can be observed between κ and I_*, similar to what was observed and discussed in Ref. [12]. In future studies, the use of the same value of κ for multiple fit will be investigated, since this parameter is expected to depend mainly on the dimensionality of the phase space and therefore should be constant in physical systems with the same dimensionality of the phase space.

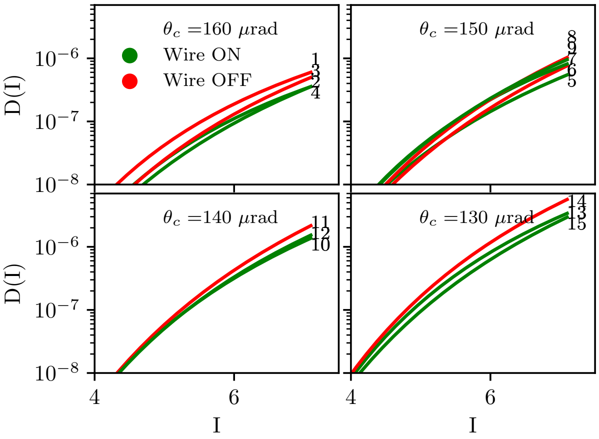

Figure 3: Reconstructed $D(I)$ for Beam 2 data, divided into chunks following the convention of Fig. 1. There is a consistent difference in the reconstructed $D(I)$ when BBCWs are turned on or off. Higher diffusion values are observed when the wires are off. The only partial exception to this trend are the chunks with a crossing angle of θ_c =150 µrad.

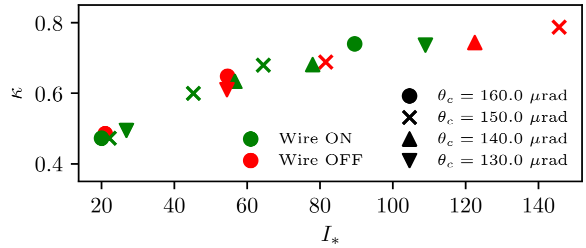

Figure 4: Evolution of the parameters I_*, and κ, for the Beam 2 data divided in chunks. No significant patterns can be observed as a function of the crossing angle, except a strong correlation between κ and I_*.

CONCLUSIONS AND OUTLOOK

An exploratory investigation of the long-term beam dynamics of the LHC was performed to evaluate the impact of BBCWs using a recent diffusive framework. Beam 2 loss data, collected during a dedicated measurement campaign, were used to reconstruct the diffusion coefficient for different configurations of the system. The reconstructed diffusion coefficient confirmed that wires have the potential to reduce long-range beam-beam effects, leading to reduced diffusion and intensity loss.

Future research will consider the new data acquired in LHC Run 3 [19], where longer time intervals with BBCWs on and off were used to better assess their long-term impact on beam losses, and will test the robustness of the framework when considering a constant κ value when reconstructing the diffusion coefficient at different machine states.

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