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BUNCH-BY-BUNCH SIMULATIONS OF BEAM-BEAM DRIVEN PARTICLE LOSSES IN THE LHC*

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Abstract

Recent experimental measurements in the Large Hadron Collider (LHC) have shown a clear correlation between beam-beam resonance driving terms and beam losses, with a characteristic bunch-by-bunch signature. This observation creates interesting conditions to study diffusive processes. Over the past few decades, early chaos indicators, frequency map analysis and dynamic aperture studies have been commonly used to study particle stability in circular machines. However, the underlying mechanisms driving particles to large amplitudes in the presence of high order resonances is still an open question. Leveraging on years of development on particle tracking tools, this paper presents full-fledged 6-dimensional bunch-by-bunch beam loss simulations in the LHC. The computed loss rates are shown to be in agreement with experimental observation from LHC Run 3.

INTRODUCTION

Maximizing the beam lifetime is a critical task for the optimal operation of storage rings and circular colliders like the Large Hadron Collider (LHC). In recent years, particle stability in circular machines has been extensively studied with chaos indicators, frequency map analysis and dynamic aperture studies [1]. However, the underlying mechanisms driving particles to large amplitudes in presence of high order resonances is still an open question [2, 3]. No simple model exists to describe the effect of beam perturbations on the slow loss of particles over time. This conceptual gap can be attributed, on one hand, to the fundamental limitations in fully describing chaotic systems via closed form equations outside of particle tracking codes [4], and on the other hand, to the extensive computational resources required to study a system like the LHC over any meaningful period of time. Indeed, a realistic scenario would need to include 10^{14} particles tracked over several tens of thousands of accelerator components for 10^4 turns in order to study a single second of LHC operation. To understand the steady state losses taking place after hours of operation, the number of turns would need to be increased by three orders of magnitude. That being said, following decades of progress in the development of symplectic particle tracking codes [5] and the modernization of computational tools, more complete simulations are now within reach.

In principle, diffusive models offer a promising avenue to describe slow particle losses over long periods of time by describing the behaviour of an ensemble of particles directly. Such models have already been fitted to experimental data [6, 7], but a direct correlation between diffusive parameters and the underlying machine parameters (such as the resonant driving terms (RDTs)), remains to be done [8, 9]. In this regard, realistic full-fledged beam loss simulations offer an ideal framework to validate diffusive models by having access to both the machine parameters and the ensuing beam losses. Moreover, in order to consider both the transverse and longitudinal dynamics in a complex 6-dimensional (6D) system like the LHC, full-fledged tracking simulations appear as the only solution allowing to include high-order non-linear elements without resorting to drastic approximations.

In 2022, the precise measurement of the characteristic bunch-by-bunch signature coming from the beam-beam effect was carried out in the LHC [10]. This observation offers the ideal starting point to validate full-fledged beam loss simulations, as proposed in this paper. In the following sections, beam-beam effects will be briefly introduced, the simulation tools will be explained and the resulting bunch-by-bunch losses will be presented.

BEAM-BEAM EFFECTS

Alongside electron cloud effects, the main source of non-linearities in the LHC is the beam-beam (BB) effect, coming from the electromagnetic interaction between the two colliding beams. Around the interaction points (IPs), the two beams share a common beam pipe and perturb one another. Head-On (HO) collisions take place at the center of the IPs, whereas Long-Range (LR) interactions are distributed on both sides of the IPs. These interactions, akin to multipolar errors, occur several times (≈40) per IP for each bunch and strongly contribute to high-order resonances, eventually leading to the development of diffusive processes and proton losses. The beam-beam long-range (BBLR) kick can be included in tracking simulations via a weak-strong model [11], where a given (weak) bunch is subject to a static (strong) BBLR element for every BBLR encounter. Not all bunches of a train experience the same number of BBLR interactions as they cross the interaction regions (IRs), because of different encounter schedule with the bunches of the opposite beam. As a result, every bunch needs to be tracked in a different effective lattice to account for beam-beam effects.

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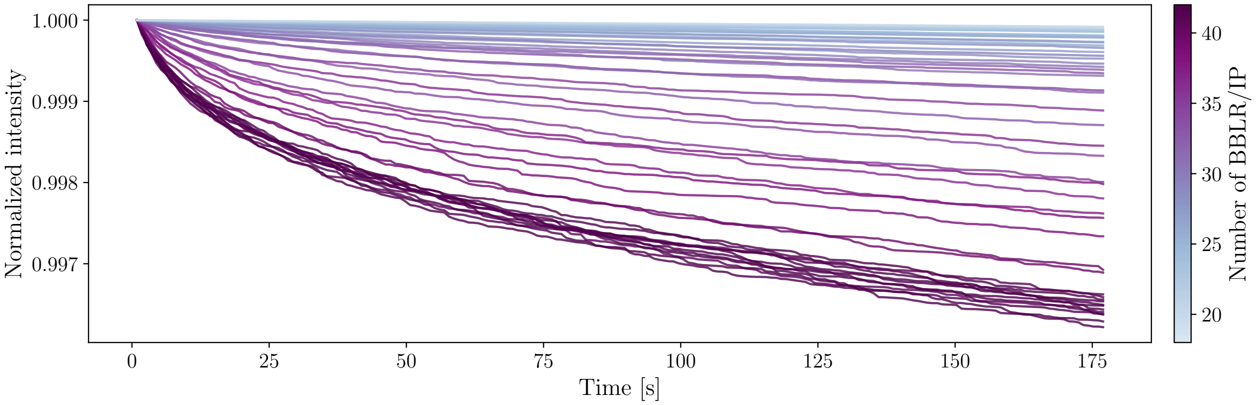

Figure 1: Evolution of the normalized intensity as a function of time for 48 bunches in the LHC, tracked for 2×10^6 turns. The particle distribution is Gaussian ($q = 1$) and the collimators are fixed at 5 σ_{nom} in all planes. The number of long-range interactions experienced by each bunch is shown with the color code.

SIMULATION STRATEGY

In the last few years, significant efforts have been made at CERN to develop and consolidate a modernized software for multi-physics simulations in particle accelerators. Xsuite [12] was developed to replace several programs (COMBI, PyHeadTail, Sixtrack, Sixtrack-lib, MAD-X, etc.) and unify them under a common framework. More importantly, it supports different computing platforms and allows the use of Graphics Processing Units (GPUs), which can be used to parallelize computations and speed up simulations by orders of magnitude [13]. By leveraging on such a tool, is it now possible to track tens of thousands of particles over a few million turns in about 15 h of computation time[1]. Despite these improvements, the sampling of a 6-dimensional phase space with a few thousand particles is extremely sparse and additional strategies need to be employed to obtain practical results, as described below. The simulation parameters, shown in Table 1, were chosen to match the LHC operational conditions from an *ad hoc* fill (Fill 8348) in order to compare the simulation results with the experimental data collected during that fill.

Table 1: Simulation Parameters, Chosen to Match Fill 8348

Parameter		**Value**	**Unit**
Beam Energy	E	6.8	(TeV)
Bunch intensity	N_b	1.4×10^{11}	(p^+/b)
Emittance	$\varepsilon_x, \varepsilon_y$	2.0	(µm)
Beta at the IP	β^*	30	(cm)
Half-crossing	$\theta_c/2$	130	(µrad)
Octupoles	I_{oct}	430	(A)
Tune	Q_x,Q_y	(62.31, 60.32)	
Chromaticity	ΔQ_x,ΔQ_y	15	

To study the bunch-by-bunch losses, a single train of 48 bunches meeting in IP1 (ATLAS experiment) and IP5 (CMS experiment) was considered. For each bunch, the encounter schedule with the other beam was computed to determine the location and the strength of the BBLR interactions to be included in the effective lattice of the bunch.

Particle Distribution

Since beam losses are computed by counting the number of particles hitting the collimators, the particle distribution considered is of prime importance and a realistic distribution needs to be used. However, typical Gaussian-like particle distributions are highly inefficient to track, since most particles are close to the origin and will survive a large number of turns. Moreover, because of the heavy computational time, repeating the simulation to test various distributions becomes impractical. In order to solve both of those problems, the particles were distributed uniformly inside the volume of a 6D hypersphere in the normalized phase space. This choice of distribution allows to sample the entire phase space as densely as possible and to later re-weight the particles with the desired probability density function in post-processing, without needing to repeat the tracking. As such, the 25,000 particles tracked for each bunch were used to sample the phase space and the final losses were inferred after resampling the hypersphere distribution with a realistic distribution (1.4×10^{11} particles) in post-processing.

Typical particle distributions in the LHC have been observed to follow the heavy-tail q-Gaussian [14, 15], for which the beam profile in a given plane follows:

$$f_{1D}(x) = \frac{e_q(-x^2/(\sigma_x^2(5-3q)))}{C_q\sqrt{\sigma_x^2(5-3q)}}, \quad q \in [1, 5/3[,$$

where C_q is a normalization constant, σ_x^2 is the variance and $e_q(x) = \big(1 + (1-q)x\big)^{1/(1-q)}$ when $q > 1$. When $q = 1$, $e_q(x) = e^x$ and the q-Gaussian becomes a regular Gaussian

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[1] Computation done using the *NVIDIA A100 40GB GPU*

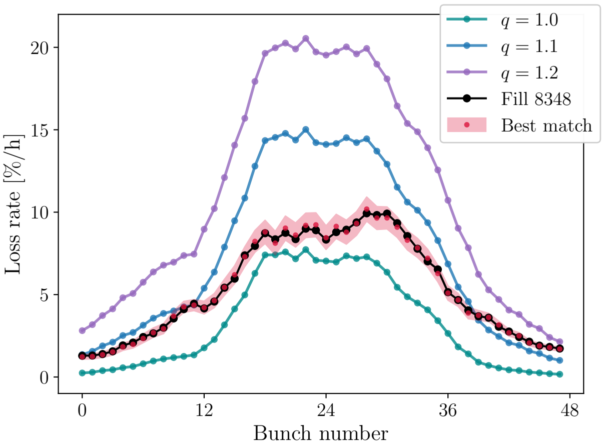

Figure 2: Bunch-by-bunch average loss rate over the full simulation window for different q-Gaussian distributions. The experimental data from Fill 8348 is shown and compared to the best match obtained when allowing q (±0.01 shaded area) to vary between the bunches.

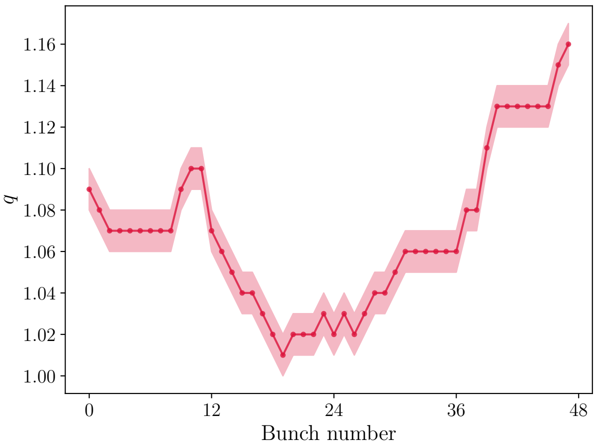

Figure 3: Bunch-by-bunch q-Gaussian parameter, q (±0.01 shaded area), for the best fit with the experimental data.

distribution. The 4D elliptically-symmetric generalization of this distribution [16] was used for the transverse plane and a 2D multivariate Gaussian was used for the longitudinal plane, assumed to be independent from the transverse one.

Beam Aperture

To compute the losses, the three primary collimators of the LHC (horizontal, vertical and skew collimators) were considered as the beam aperture. Similarly to the particle distribution, the computations were done in post-processing after tracking the particles. To do so, the maximum excursion of each phase space variable was binned every 10,000 turns and recorded for every particle, allowing to infer whether or not the particle would hit one of the three collimators, placed at an arbitrary position over time. The advantages of this method are twofold. First, the disk space required to store the data is reduced by a factor 10^4. Second the aperture can be moved over time in the transverse plane to study collimator scraping, once again in post-processing, without having to repeat the simulation. The large binning considered reduces the time resolution of the losses, which was deemed acceptable to study slow diffusive losses in the context of this paper.

BUNCH-BY-BUNCH LOSSES

After tracking the particles for each bunch, the losses were computed with the collimators at 5 σ_{nom} in each plane, where σ_{nom} is the nominal sigma value, computed with the nominal emittance of 3.5 µm. The evolution of the intensity over time is shown for each of the 48 bunches on Fig. 1 for the case of a Gaussian beam ($q = 1$). The loss rate evolves rapidly in the first few seconds of the simulation and stabilizes by the end of the time window. A longer simulation window would be preferable to model realistic beam losses accurately. One way to accelerate the process is to bring the collimators at 4 σ_{nom} for the first 10,000 turns, before retracting them to 5 σ_{nom} afterwards to measure the losses. This procedure aims at mimicking the numerous perturbations *cleaning* the beam over the several hours of typical operation. The next results were obtained following this aforementioned procedure.

In Fig. 2, the bunch-by-bunch loss rate is compared to the experimental data from Fill 8348 for different q-Gaussian distributions. Even for the most conservative distribution (6D Gaussian, $q = 1$), the results are in agreement with the experimental data, both in terms of the order of magnitude of the loss rates and in terms of the bunch-by-bunch signature. However, the precise value of the bunch-by-bunch loss rate depends on several parameters, such as the bunch-by-bunch intensity, emittance, q-value and the parameters of the bunches from the other beam. To highlight this effect, the particle distribution was allowed to vary separately for each bunch by changing the q-value, while keeping the bunch intensity and emittance constant. By doing so, the agreement with the experimental data is found to improve, and the q-value for each bunch is reported in Fig. 3. These results suggest that with all free parameters held constant between the bunches, the loss rate is underestimated for bunches with a few BBLR interactions and overestimated for bunches with numerous BBLR interactions.

SUMMARY

This paper presents simulation strategies to allow for full-fledged 6-dimensional bunch-by-bunch beam loss simulations in a complex accelerator like the LHC. As a result, it is shown that the loss rate obtained with a limited number of assumptions is in good agreement with the experimental data observed in the LHC. Moreover, by allowing the bunch distribution to vary, the agreement is improved. Such simulations can be used to study diffusive models in more details, by allowing to inspect both the machine parameters and the ensuing beam losses.

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