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RECENT MEASUREMENTS AND ANALYSES OF THE BEAM-HALO DYNAMICS AT THE CERN LHC USING COLLIMATOR SCANS*

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Abstract

Controlling beam losses is of paramount importance in superconducting particle accelerators, mainly for ensuring optimal machine performance and an efficient operation. Models based on global diffusion processes, in which the form of the diffusion coefficient is the stability-time estimate of the Nekhoroshev theorem, have been studied and proposed to investigate the beam-halo dynamics. Recent measurements with collimator scans were carried out at the CERN Large Hadron Collider (LHC) with the aim of reconstructing the form of the diffusion coefficient. The results of the analyses performed are presented and discussed in detail.

INTRODUCTION

High-energy circular colliders and storage rings that use superconducting magnets are characterised by a particularly complex nonlinear beam dynamics. The non-linearities can lead to beam losses or emittance growth, which can impair the accelerator's efficiency or luminosity. A link has been established between the dynamic aperture (DA), which defines the region of bounded motion in phase space, and the lifetime of the beam [1], and this relationship has been used successfully to measure DA [2]. However, to assess the presence of emittance growth, which is crucial for determining the performance of the circular accelerator, it becomes of interest to model the evolution of the beam distribution by means of a diffusive framework. This approach involves constructing a Fokker-Planck (FP) equation, which provides a means of extrapolating the evolution of the beam distribution over time scales that would otherwise be not accessible by means of direct particle tracking. Diffusive models of transverse beam dynamics have been developed for accelerator physics in the past, as can be seen, e.g., in [3–10]. A recent diffusive framework [11–13], derives the functional form of the diffusion coefficient from the optimal estimate of the perturbation series provided by the Nekhoroshev theorem [14–16]. The FP equation resulting from this framework, which describes the time evolution of the beam distribution ρ, reads

$$\begin{aligned} \frac{\partial \rho(I,t)}{\partial t} &= \frac{1}{2}\frac{\partial}{\partial I} D(I) \frac{\partial}{\partial I}\,\rho(I,t) \\ D(I) &\propto \exp\left[-2\,(I_*/I)^{\frac{1}{2\kappa}}\right], \end{aligned} \tag{1}$$

where $D(I)$ is the Nekhoroshev-like diffusion coefficient as a function of the action variable I. This special functional form is characterised by the parameters κ and I_*. As indicated in [12], κ is related to the analytic structure of the perturbative series and the dimensionality of the system, while I_* is related to the asymptotic character of the perturbative series.

The FP Eq. (1) is well suited for studying the evolution of beam distributions in the presence of collimators with jaws that can be well defined as absorbing boundary conditions, necessary to solve the FP equation. The use of collimator scans, in which the jaws of LHC collimators are moved in a controlled manner, can be particularly useful for studying beam-halo dynamics and reconstructing the behaviour of the diffusion coefficient as a function of transverse amplitude [5, 9, 17, 18]. The collimator scan method is widely used in LHC operation and is based on small jaw displacements to different amplitudes I, combined with the measurement of resulting beam losses. These displacements can be inward or outward, causing a different and characteristic evolution of the beam losses. In a recent work [13], an optimised collimator scan protocol, based on the alternation of outward and inward collimator jaw movements, was proposed to reconstruct a Nekhoroshev-like $D(I)$. Then an adapted version of the protocol was applied to available LHC run 2 data [19] with promising results.

PROBING $D(I)$ VIA COLLIMATOR SCANS

The protocol proposed in [13] aims to reconstruct a Nekhoroshev-like diffusive behaviour of the beam halo through a measurement procedure based on alternating inward and outward jaw movements during collimator scan measurements. The main idea is to separate the observed current loss signal $J(t)$ into two distinct processes with different time scales: a global process $J_{\text{eq}}(t)$ generated by an exponentially slow erosion of the beam core and a recovery current $J_{\text{R}}(t)$ generated by local changes in the jaw position that occur on time scales much shorter than the global process, leading to a relaxation of the system into a new semi-stationary equilibrium.

We assume that with $D(I)$ as in Eq. (1), the tails of the beam distribution can be considered to be in semi-stationary equilibrium according to

$$\rho_{\text{eq}}(I,t;I_{\text{a}}) = \alpha(t,I_{\text{a}}) \int_I^{I_{\text{a}}} \frac{\mathrm{d}x}{D(x)} \tag{2}$$

$$\alpha(t,I_{\text{a}}) = \frac{\rho_0(I_0(t))}{\int_{I_0(t)}^{I_{\text{a}}} \frac{\mathrm{d}x}{D(x)}}, \tag{3}$$

where I_{a} is the jaw position, ρ_0 is the initial beam distribution, and $I_0(t) \ll I_{\text{a}}$ represents the boundary of the diffusive region, which varies over exponentially-long times. Equation (3) implies a slow-varying global current at I_{a} equal

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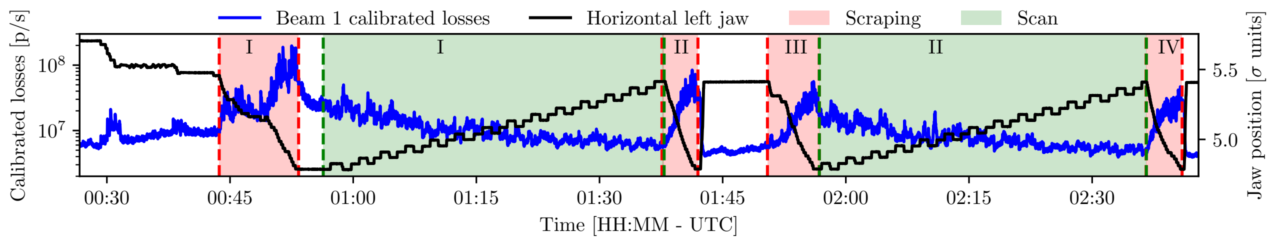

Figure 1: Calibrated beam losses from the IR7 BLM monitors and jaw positions measured in the horizontal plane for the collimator scans carried out in fill 8348. Two collimator scans, performed following the protocol proposed in [13], are shown. Before and after the scan, a beam scraping was performed. The jaw position is reported in measured sigma units.

to

$$J_{\mathrm{eq}}(t, I_{\mathrm{a}}) = D(I_{\mathrm{a}}) \frac{\partial \rho_{\mathrm{eq}}(I,t)}{\partial I}\bigg|_{(I_{\mathrm{a}},t)} = \alpha(t, I_{\mathrm{a}}) \,. \qquad (4)$$

As the global current $J_{\mathrm{eq}}(t, I_{\mathrm{a}})$ varies with the position of the jaw I_{a}, a possible method to reconstruct the shape of $D(I)$ from beam measurements consists in repeating a sequence of outward-inward-outward jaw movements, leading to an alternation of in/out steps at increasing amplitude. Before each movement, enough time is spent to allow the system to fully relax to the new equilibrium, which will manifest its specific current loss $J_{\mathrm{eq}}(t, I_{\mathrm{a}})$. Assuming that the erosion process of $I_0(t)$ can be neglected within the timescale of a collimator scan, we can then achieve estimates of $J_{\mathrm{eq}}(t = t_0, I_{\mathrm{a}})$ for different I_{a} and use it to fit $D(I)$ using $\alpha(t = t_0, I_{\mathrm{a}})$, given in Eq. (3). The initial distribution $\rho_0(I)$ can then be estimated using data from collimator scrapings, following established empirical models, such as the double Gaussian distribution [20].

EXPERIMENTAL DATA

In November 2022, collimator scans were performed at the CERN LHC with physics beams at 6.8 TeV [21]. These scans were performed in a Machine Development (MD) run, dedicated to assess the effectiveness of long-range beam-beam wire compensators [22], which where installed on on the anti-clockwise circulating beam in the LHC (Beam 2) [23]. Both the functioning of these wires and the effect they had on Beam 2 losses go beyond the scope of this article. As the wires affected Beam 2 only, the beam loss data gathered from Beam 1 measurements offers a clean ground to apply the proposed diffusive framework.

During these scans, one of the jaws of the IR7 primary collimators was moved inward and outward in small steps, starting from its nominal position of 5σ, considering the nominal emittance of 3.5 µm. The scan was performed after a beam-based alignment [24] of the collimator jaws to precisely centre them around the local closed orbit. Pauses between steps were taken until a qualitatively constant signal was observed over the span of at least 10 seconds.

The measurement is carried out with the local beam loss monitor (BLM) system [25, 26], which is provided in units of Gy/s with 100 Hz sampling rate, and different running sums (RS) [27] at 1 Hz sampling rate. The raw data can then be converted into units of p/s using a calibration factor established through simulations and dedicated measurements [28]. The resulting calibrated losses are then obtained through a weighted sum of the signals recorded by the IR7 BLMs [29].

In Fig. 1, we present a portion of the calibrated losses measured at the end of the MD period, the data is reported with 1 Hz sampling rate. The left jaw position of the horizontal target primary collimator (TCP) is reported in measured sigma units, evaluated using the nominal optical parameters and the measured value of the beam emittance, taking into account the position of the beam centre. The measured beam emittance at the beginning of collimator scans is 2.0 µm. The measurement consists of two collimator scans, with scraping performed both before and after the scan.

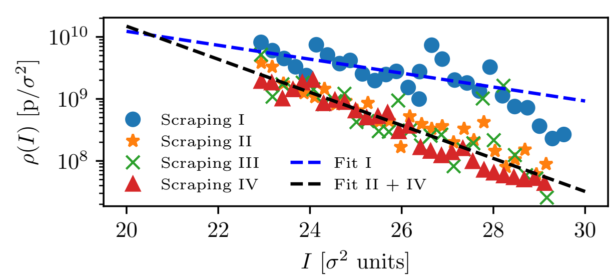

Figure 2: Beam tail distribution reconstructed from the four scrapings performed in the horizontal plane of Beam 1. The first scraping, performed after several hours of operation, exhibit a more populated tail when compared to the other three, performed less than an hour after a collimator scan. A Gaussian fit is also reported.

To obtain an estimate of the population of the beam tail $\rho_0(I)$, which is necessary to build the fitting of $J_{\mathrm{eq}}(t, I_{\mathrm{a}})$, we inspect the losses that occurred during the four scrapings, with more focus on the first one. Taking the assumption that the collimation steps were performed fast enough not to observe variations in the beam tail distribution, we can estimate the number of protons that populated an amplitude interval $[\sigma_1^2, \sigma_2^2]$ by integrating the losses that occurred after an inward collimator step from σ_2^2 to σ_1^2. The resulting beam tail reconstructions are presented in Fig. 2.

We can observe how the beam distribution reconstructed from the first scraping follows a different trend compared to

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the other three scrapings. This can be related to the fact that the first scraping was performed after more than 6 hours of continuous beam operation, while the other three scrapings were performed after less than an hour, after the first scraping removed the initial beam tails. This indicates that a long waiting time is needed for the beam tail to fully relax to a ρ_{eq} distribution, and, therefore, we should rely mainly on the first scraping to estimate ρ_0.

Following the double-Gaussian model expected in standard operation, we estimate ρ_0 by means of a Gaussian fit of the beam tail distribution reconstructed from the first scraping. The resulting fit is shown in Fig. 2, together with the beam tail distribution reconstructed from scraping two and four, which are grouped together as they were taken under almost identical conditions.

To extract the data of J_{eq} from the loss signal measured during the two collimator scans, we consider for each jaw position the loss signal registered 10 s before the next jaw movements. As movements were performed with long pauses in between, with the goal of waiting for the loss signal to be qualitatively constant over that period of time, we can consider the mean of this interval as an estimate of J_{eq}. For the uncertainty of this estimate, we consider the standard deviation of the values recorded over the intervals. The resulting data from the two scans are shown in Fig. 3.

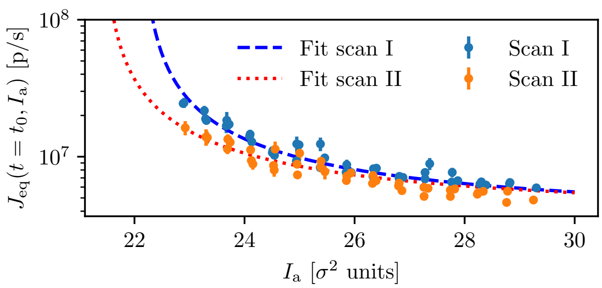

Figure 3: Fitting of $J_{eq}(t)$, measured at different I_a, for the two collimator scans. The fit enforces the same I_* and κ for the two scans, while I_0 is a free parameter for both distributions.

We then fit $J_{eq}(t, I_a)$ for both scan data, with the working hypothesis that the same diffusion coefficient $D(I)$ characterised the evolution of the system. We can treat $I_0(t = t_0)$ as a free parameter to fit along with I_* and κ. However, while we enforce that I_* and κ are equal for the two scan data, we consider two separate values I_0 for the two distributions, as we expect some erosion process to have occurred over the span of more than one hour. To fit the data, we perform a scan over a range of possible choices of κ, and fit the remaining free parameters I_*, $I_{0,\mathrm{I}}$, and $I_{0,\mathrm{II}}$ by combining an initial brute-force scan over a range of possible parameters and a least squares method using as starting point the best result obtained from the previous brute-force scan.

The fit results are presented in Fig. 3, with the fit parameters reported in Table 1. From the fit parameters, it is possible to construct a new estimate of ρ_0 using Eq. (2), with I_a set to the starting position of the jaw for the first scraping. The resulting distribution is shown in Fig. 4, compared to the initial Gaussian fit. It is possible to see how the new estimate of ρ_0 more accurately captures the features of the terminating part of the beam tail.

Table 1: Results of the Fitting of $D(I)$ for the Two Collimator Scans

$I_{0,\mathrm{I}}$	$I_{0,\mathrm{II}}$	κ	I_*
22.13 ± 0.06	21.4 ± 0.1	0.47 ± 0.01	61.5 ± 0.2

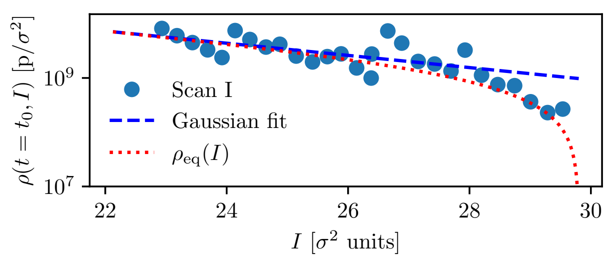

Figure 4: Beam tail distribution reconstructed from the first scraping. The initial Gaussian fit is compared with the ρ_{eq} distribution of Eq. (3), using the $D(I)$ values reported in Tab. 1. The ρ_{eq} captures more features of the scraping data compared to the Gaussian fit.

CONCLUSIONS AND OUTLOOK

A non-linear diffusive model based on the Nekhoroshev theorem was used to model the beam loss signal observed during recent LHC collimator scans. The scans were performed using an optimised protocol that enables the separation of the loss signal into two processes characterised by different timescales. The data available for the horizontal plane of Beam 1 offered the possibility of inferring the shape of the distribution of the beam tail and fitting a Nekhoroshev-like diffusion coefficient based on the reconstructed global current at different collimator jaw positions.

Future research will further inspect the promising result achieved in fitting the global current trend observed from the two collimator scans discussed here. As the semi-stationary equilibrium distribution, constructed from the fitted diffusion coefficient, captures multiple features observed by the first collimation scraping, we will look for other similar consistency checks in recent and past LHC data, to further test the robustness of this framework and assess its capabilities in modelling the long-term beam tail evolution.

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