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Safe Disposal of the LHC Beam without Beam Dump: Method and Experimental Verification

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Abstract. In the extremely unlikely event of a non-working beam dumping system in the LHC, the 360 MJ of stored beam energy can be dissipated in the collimation system as a last mitigation measure. In such a situation, it is important to reduce the stored beam energy both quickly and at the same time as smoothly as possible in order to limit the risk of trips of critical systems, to avoid quenches of superconducting magnets (which would lead to changes of the beam trajectory and damage to the accelerator) and ultimately damage to the collimators themselves. Detailed steps and parameters have been developed and validated during two dedicated experiments with beam in the LHC. This paper summarizes the key aspects in view of the preparation of such a procedure for operational use, which will allow for the safe disposal of the full LHC beam by the operation crews.

1. Introduction

The 360 MJ of stored energy in the LHC proton beam [1] and about 700 MJ for its High Luminosity (HL) upgrade [2] require highly reliable machine protection systems, which ensure the controlled and safe disposal of the two proton beam at any time. The Beam Interlock System (BIS) [3] and LHC Beam Dumping System (LBDS) [4], with failure rates in the order of 10^{-7} failures/hour and an availability of 99.96 %, are the core systems of the machine protection architecture. They ensure that the beam is extracted if a beam dump is requested by an equipment system or the operator. Despite this high level of dependability of the core systems, it is important to prepare an alternative method to dispose of the stored beam energy in case an extraction cannot be executed.

2. Procedure

In case the LHC beams cannot be extracted via the LBDS, the disposal of the beam has to be done as fast as reasonably possible without increasing the likelihood of another failure. The only system available in the LHC, which can absorb significant parts of the stored beam energy is the collimation system [1]. Three different ways have been identified to do so:

- moving the collimators into the beam;
- moving the beam into the collimators;
- lowering the beam lifetime so the growing tails are scraped into the collimators.



The first two methods pose the problem, that the beam core's projected energy density in the order of 500 kJ/ μm requires a sub- μm step size in order not to exceed the damage limit of the primary collimators. Such small step-sizes are neither achievable with the current collimator movement system nor with the existing orbit correctors. Furthermore, the increased impedance during such a procedure may cause the beams to become unstable and the change of orbit or collimator settings might compromise cleaning. These reasons, in addition to the fact that the LHC transverse damper (ADT) allows to blow-up the beam emittance in a much more controlled and gentle way, using a white-noise excitation [6][7], make the third option the only viable solution.

The accepted power limit of continuous beam losses into a primary collimator of the LHC collimation system is defined as 100 kW [1], respectively 200 kW for the HL-LHC[2], which corresponds to a beam lifetime of 60 minutes or the removal of the full beam within this initial lifetime if the loss power is kept constant. The goal of the experimental verification presented in this paper was to demonstrate the feasibility of establishing controlled losses corresponding to a beam-lifetime of about 30 minutes for an extended period of time. This lifetime allows for a good compromise between execution speed and minimizing the risk of damage to the collimation system.

3. Experimental results

In order to minimize the risks associated with applying such a procedure, the proposed method was first tested at injection energy (450 GeV) by scraping 12 and 48 bunches of 1.15×10^{11} protons per bunch (ppb) [5]. The results from these experiments are illustrated in Fig. 1 and Fig. 2. The bunches were successfully scraped to an intensity of 2.5×10^{10} ppb before being dumped - as expected - by an orbit excursion interlock when falling below the sensitivity level for the bunch intensity. ADT gain values of 0.018 and 0.015 were chosen to achieve a stable 30 minutes beam lifetime following an adjustment period of approximately 5 minutes. The results of these tests showed, that the required beam lifetime could be achieved with just a small number of ADT gain changes. As the two tests were performed with different beams (B1 for the first experiment, B2 for the second one), a small gain difference was required to achieve similar lifetimes, which can be explained by a slightly different calibration of the two independent hardware ADT systems.

Once the possibility of maintaining short lifetimes with LHC beams using this method was

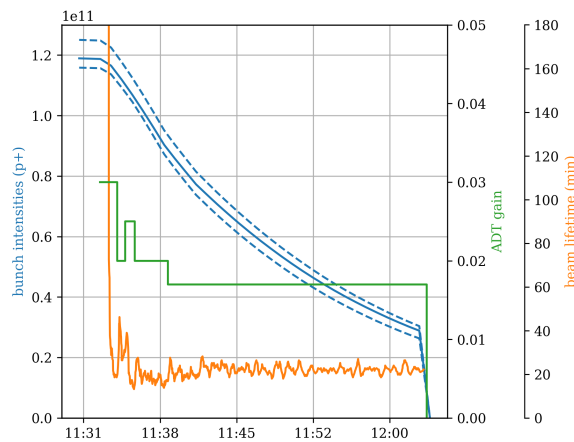


Figure 1. Average (solid blue line), upper and lower (dashed blue lines) bunch intensities, beam lifetime (orange) and ADT gain value (green) during the scraping of 12 bunches in Beam 1 at injection energy.

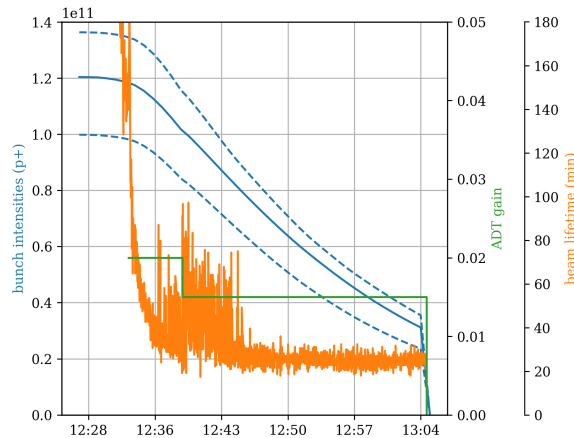


Figure 2. Average (solid blue line), upper and lower (dashed blue lines) bunch intensities, beam lifetime (orange) and ADT gain value (green) during the scraping of 48 bunches in Beam 2 at injection energy.

established, it was tested with 6.5 TeV beam in a second experiment with trains of 12, 36, 128 and 480 bunches, which were scraped sequentially [5]. To avoid unnecessary beam dumps, the scrapings were stopped when reaching 5×10^{10} ppb. Lifetimes of close to 30 minutes were achieved in all cases. Figure 3 shows the average, minimum and maximum bunch intensities for each of the four groups of bunches (top), the applied ADT gain (bottom, green) and the achieved beam lifetimes (bottom).

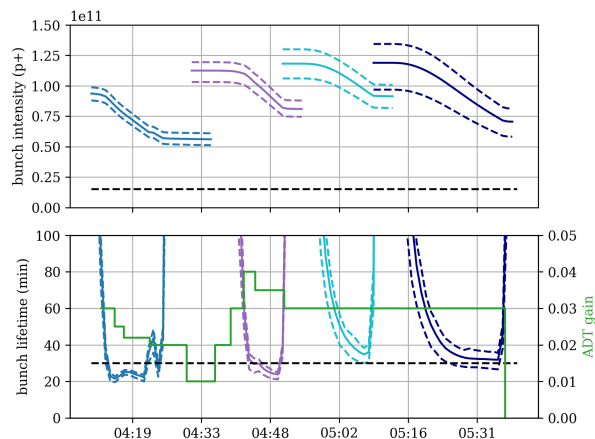


Figure 3. Average (solid lines), minimum and maximum (dashed lines) bunch intensities, lifetimes and ADT gain (green) during the scraping of 12 (blue), 36 (purple), 128 (cyan) and 480 (dark blue) bunches in Beam 1 at 6.5 TeV. The expected bunch intensity dump limit and target lifetime of 30 minutes are highlighted with dashed black lines.

These tests confirmed that the method can be applied to high energy beams as well as different lengths of bunch trains. The 12 bunch train experienced a smaller damping, therefore, a lower ADT gain was sufficient to reach the desired lifetime as compared to the other bunch trains. For the scraping of the last two trains a constant ADT gain of 0.03 was applied. The beam lifetime converged to the desired value within about 15 minutes. A peak power of 22 kW was achieved

during this experiment. These results were achieved with the ADT system in Beam 1.

In a final experiment, a train of 640 bunches in Beam 2 was scraped, starting with an ADT gain of 0.03, as previously used in Beam 1 (see Fig. 4). To reach the desired 30 minutes beam lifetime, the gain had to be increased to 0.035, which confirmed the previously observed difference between the ADT systems of the two LHC beams. A constant loss power of about 25 kW was achieved. After scraping more than two thirds of the beam the ADT gain was increased to 0.04 and then 0.06 to keep the loss power constant. The beam was finally dumped, when the individual bunches reached 1.5×10^{10} ppb.

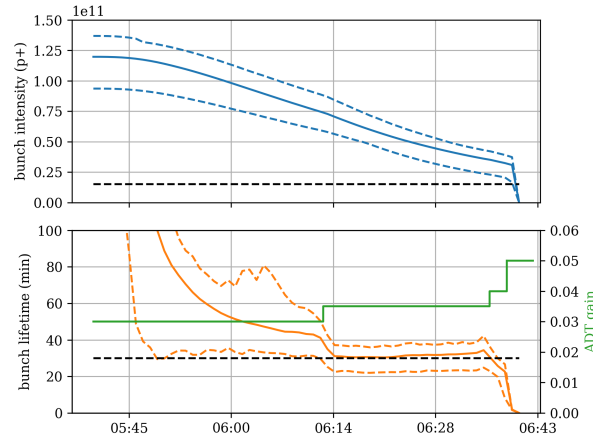


Figure 4. Average (solid line), minimum and maximum (dashed lines) bunch intensities (blue), lifetimes (orange) and ADT gain (green) during the scraping of 640 bunches in Beam 2 at 6.5 TeV. The expected bunch intensity dump limit and target lifetime of 30 minutes are highlighted with dashed black lines.

The nominal LHC beam consists in four times as many bunches as this last test but the good scaling observed up to 640 bunches and the fact the excitation method used is far from the power limitations of the ADT [6] guarantee it would also work with up to 2480 bunches [1]. These experiments demonstrated that a rather simple procedure can be used to scrape the full LHC beam with the collimation system in a controlled, yet timely manner.

4. Diffusion model

The expected response of the beam to a constant white-noise excitation and simultaneous damping from the ADT is a linear growth of the emittance [8] which is not compatible with a stabilization of the lifetime. A dedicated finite-difference diffusion model was therefore developed in order to reproduce the observed behavior, described by equations 1-4, where N is the particle density, j the particle flow, J the particle action in units of beam emittance and D the diffusion coefficient in units of beam emittance per hour, $\mu\text{m}/\text{hour}$. The initial transverse beam distribution is assumed to be Gaussian, resulting in a negative exponential distribution of the particles as a function of action. The primary collimator cut is assumed to be at $n_{\text{coll}} = 5 \sigma$, with σ the standard deviation of the transverse particle distribution, assuming $\epsilon = 3.5 \mu\text{m}$ [1].

$$j(J, t) = -D \cdot \frac{d N(J, t)}{dJ}, \quad (1)$$

$$\frac{d N(J, t)}{dt} = -\frac{d j(J, t)}{dJ}, \quad (2)$$

$$\text{hence: } \frac{d N(J, t)}{dt} = D \cdot \frac{d^2 N(J, t)}{dJ^2}; \quad (3)$$

$$\text{with: } N(J, t) = 0 \text{ for } J \geq (n_{coll})^2 \epsilon. \quad (4)$$

The model described above allows reproducing stable beam lifetimes of X minutes after a short convergence to steady state, if the diffusion coefficient is increased from an initial value of $24.5 \mu\text{m}/\text{hour}$ (which corresponds to observed beam lifetimes of 40 hours in the LHC) to $5.6 \times 10^3/X \mu\text{m}/\text{hour}$. The inverse relationship from lifetime to diffusion coefficient and ADT gain corresponds well to the observations during the experiments. The measured beam lifetimes can therefore be reproduced with $D = g \cdot 5.3 \times 10^4$ for Beam 1 and $D = g \cdot 6.2 \times 10^4$ for Beam 2, where g is the ADT gain.

Figure 5 illustrates the comparison of LHC measurements during the latest experiment presented in the previous section with the model described above. During the simulation, the diffusion coefficient was increased to match the ADT gain of 0.03 for 32 minutes, then 0.035 for 27 minutes, using the previous correspondence. One can observe that the convergence of the lifetime in the simulation matches the one of the fastest decaying bunches, suggesting a dependency on initial conditions. This is caused by the average emittance being smaller than the design one mentioned earlier, which is equivalent to a larger initial setting of the collimators (n_{coll}) in terms of beam standard deviations, hence longer time is required to reach steady-state. This is also the cause of the gap between the remaining bunch intensities which stabilizes once steady-states lifetimes are reached which suggests a good modeling of the behavior in the excitation-dominated lifetime-regime.

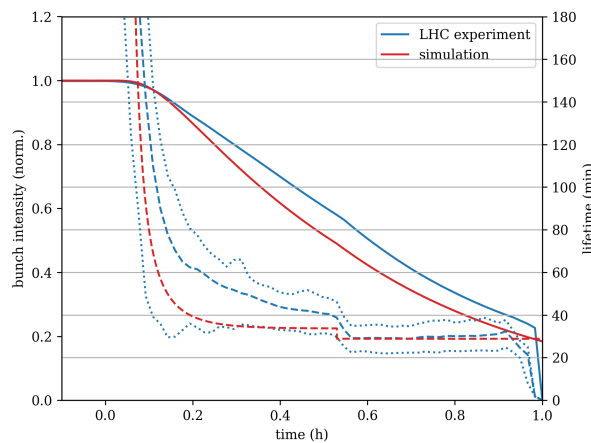


Figure 5. Comparison of normalized bunch intensities (solid lines) and beam lifetimes (dashed lines) for the simulation (red) and measurement (blue). The minimum and maximum measured beam lifetimes are indicated with dotted lines.

5. Conclusion

A procedure to safely dispose the complete LHC beam energy into the collimation system, using the white noise excitation of the LHC ADT system, was proposed and experimentally verified. It was shown that constant beam lifetimes could be reproduced with the same ADT gain independently of the number of excited bunches. Slight differences in the required gains were observed between the two beams, which can be explained by small differences in the setup

and calibration of the two independent ADT systems. A beam diffusion model was developed, allowing reproducing the stable and reproducible beam lifetimes which have been observed experimentally. Table 1 summarizes the applied ADT gains to reach stable beam lifetimes of 30 minutes as a function of the chosen beam and the beam energy.

Based on these results, a machine protection procedure along with some semi-automated sequences can be developed to support the operation crews to safely dispose the LHC beam energies even in the extremely unlikely case of a failure of the LHC beam dumping system.

Table 1. ADT gain needed to achieve 30 minutes lifetimes

Energy	450 GeV	6.5 TeV
Beam 1	0.018	0.03
Beam 2	0.015	0.035

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