# LHC BEAM DUMP PERFORMANCE IN VIEW OF THE HIGH LUMINOSITY UPGRADE

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*Abstract*

The High Luminosity Large Hadron Collider (HL-LHC) project will increase the total beam intensity in the LHC by nearly a factor of two. Analysis and follow-up of recent operational issues as well as dedicated studies of the LHC Beam Dump System (LBDS) have been carried out to ensure the safe operation with HL-LHC parameters and to decide on possible hardware upgrades to meet the HL-LHC requirements. The fail-safe design must ensure the LBDS performance also for abnormal operation such as asynchronous beam dumps or failing dilution kickers.

In this paper, we report on newly observed failure scenarios as the erratic firing of more than one dilution kicker, and discuss their consequences as well as possible mitigation measures in view of the high luminosity upgrade.

## INTRODUCTION

The beam dump system [1] is one of the most critical systems for reliable and safe operation of the LHC. For each beam, it consists of 15 fast extraction magnets (MKD), 15 magnetic septa (MSD) and 10 dilution kickers (MKB) together with the various control system elements. The dilution kickers deflect the beam in both planes with damped sine-like oscillations. For the chosen phase relation between horizontal and vertical kickers, this results in the nominal beam pattern shown in Fig. 1 (green plot).

To avoid losses during the rise time of the extraction kickers, a 3 μs long, so-called abort gap in the circulating ring is kept free of particles. In case of a nominal or synchronous dump, the extraction kickers are fired synchronously with the abort gap. In case of a spontaneous, erratic firing of the extraction kickers, an asynchronous beam dump is produced. Particles are lost in the ring and have to be absorbed by dedicated protection elements.

The LHC beam dump itself is composed of three main parts: An upstream window made of carbon-carbon (C-C) composite on a 0.2 mm thin stainless steel foil [2], a 7.7 m long graphite dump core as well as a titanium downstream window.

## LBDS EXTRACTION MODEL

To study the extraction of the LHC beams, a beam-transport model was developed. The relevant beam parameters at the time of the dump, e.g. energy, emittance, filling pattern, as well as the measured current waveforms for all MKD and MKB are downloaded directly from the LHC Logging Data Base or the Post Mortem framework. Then, using the measured calibration factors, the current is converted to a kick angle and the waveforms are corrected for the time of flight as well as for the measured time delays that are caused by eddy currents and the signal-propagation delays. As a last step, a MAD-X [3] routine is used to transport every bunch center from the first extraction kicker to the LHC dump. The result can then be used to generate the proton distribution on the dump or serve as input for energy-deposition studies using the FLUKA code [4].

## FAILURE SCENARIOS

### *2016 Operation*

During 2016 operation with an unprecedented availability of the machine, no asynchronous dump occurred and only two erratic firing of an MKBH generator were observed [5]. In the latter cases, the failure was properly detected and the beam safely dumped.

Figure 1 shows the beam distribution measured at a beam screen (BTVDD) upstream of the LHC dump for the erratic firing of one MKBH generator in red. The bunch pattern that was simulated using the LBDS extraction model is depicted in blue and, for comparison, the simulated nominal pattern in green. As visible, the width of the dilution pattern is reduced when compared to the nominal one. However, the shape and structure of the pattern agrees well with the predictions of the simulation.

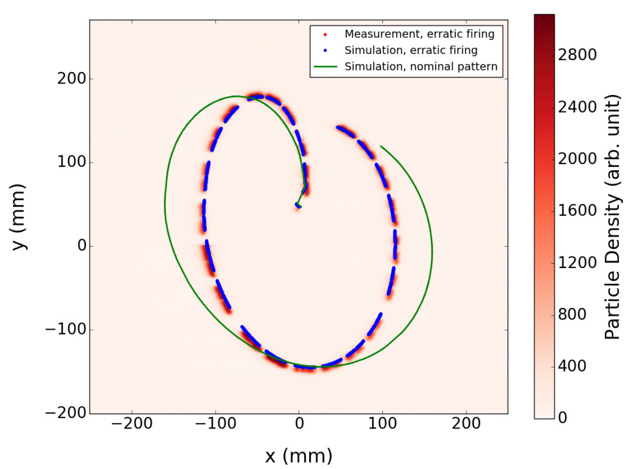


Figure 1: Simulated bunch pattern (blue) and measured distribution at the BTVDD screen (red) for an abnormal dump event on October 1, 2016 due to the spontaneous firing of one horizontal dilution kicker of Beam 1. For comparison, the simulated bunch pattern for a nominal dump is depicted in green. Note that the simulated data was scaled by a factor 1.04 in the vertical plane.

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### Dilution Failures and MKB Coupling

There are two main failure cases concerning the dilution kicker considered in the LBDS design: a) the loss of one or two kickers due to a flash-over during the execution of the dump and b) the spontaneous firing of a dilution kicker. The latter will result in a synchronous beam dump where the extraction kicker and thus the remaining dilution kicker are fired synchronously with the abort gap. However, the time difference between the spontaneous firing of the dilution kicker and the abort gap arriving at the extraction kickers is not fixed. This implies that the erratically fired MKB can be in phase opposition to the remaining MKB.

This does not represent a critical failure for the spontaneous firing of only one dilution kicker because the worst case would be to lose the effective deflection of one additional kicker due to phase opposition. Therefore, this scenario is less critical than the accepted failure case of two MKB missing due to a flash-over.

However, a new failure mode was found during tests without beam in 2016. Due to a parasitic coupling signal between the MKB generators, an erratically firing generator could also trigger adjacent ones. In case of antiphase, this could lead to the loss of more than half of the horizontal dilution.

Therefore, a high priority during 2017's extended year-end technical stop (EYETS) was to mitigate the propagation of the erratic triggering: the retrigger boxes were electrically insulated from the top of the generator housings and common-mode filtering was applied by installing nanocrystalline toroids on the retrigger line. During dedicated tests to validate the hardware changes, the erratic signal propagation disappeared as desired. However, the immunity margin for future operation at 7.0 TeV with HL-LHC parameters has to be further evaluated.

## POSSIBLE UPGRADES OF THE DILUTION SYSTEM FOR HL-LHC

In the present setup, there exist 6 vertical dilution kickers (MKBV) operated at 16 kV, compared to 4 horizontal kickers (MKBH), which have to be operated at a significant higher voltage of 26.6 kV for the nominal 7 TeV beam energy. Therefore, the failure probability of the MKBH is higher due to operation at higher voltage and the failure sensitivity is higher due to the smaller number of kicker modules. In addition, for the given dilution pattern, the loss of horizontal deflection is more critical than the loss of vertical deflection. This is why the MKB upgrade strategy for HL-LHC is concentrated on the horizontal kickers.

### Hardware Upgrades

At the moment, different long-term solutions for HL-LHC operation are under investigation. One approach is to upgrade the existing hardware in order to reduce the required MKBH voltage such that the probability of a spontaneous firing, as well as the probability of an erratic signal propagation, is further decreased. Nevertheless, the dilution strength should be kept constant.

To achieve this goal, two main options are discussed. The first option is to add one tank with two additional MKBH. Since the total deflection angle would be kept constant, the voltage for each generator could be reduced accordingly. This would directly reduce the failure probability due to the lower voltage as well as the failure sensitivity due to the higher number of modules. However, the required apertures and especially the integration of the additional magnets and generators have to be carefully evaluated.

The second option under investigation is to increase the main capacitance of the MKBH generators. This way, while storing the same amount of electric energy, the operational voltage could be reduced. However, these modifications change the MKBH waveform resulting in a larger damping factor, which could lead to increased energy densities in the dump. Therefore, the changes in the dump pattern are currently being studied.

### MKB Retriggering

An additional, complementary approach consists in defining a new retrigger strategy for the MKB. The idea is that after the fast detection of the spontaneous firing of one generator all other MKB generators are directly retriggered. This way, the risk of phase opposition between the dilution kicker waveforms is eliminated.

However, assuming that an asynchronous beam dump should be avoided, this would imply that the extraction kickers are fired with a certain time delay $t_{\mathrm{delay}}$ after the dilution kickers. This time delay depends, first, on the total reaction time until the execution of the dump $t_{\mathrm{react}}$ and, more important, on the position of the abort gap $\Delta t_{\mathrm{AG}}$ in the ring: $t_{\mathrm{delay}} = t_{\mathrm{react}} + \Delta t_{\mathrm{AG}}$, where $\Delta t_{\mathrm{AG}}$ can take any value between zero and a full LHC revolution period of 89 µs. For each delay time, a different dump pattern is produced.

The resulting patterns for selected delay times and for the nominal pattern are depicted in Fig. 2, while Fig. 3 summarizes the peak energy deposition in the upstream window, in the dump core and in the downstream window for delay times up to 150 µs. These values were computed using the FLUKA code based on the simulated pattern at the beam dump. They are normalized to the densities for a nominal dump event. In addition, the blue curve in Fig. 3 shows the inverse minimum beam sweep velocity at the dump, which is directly correlated to the proton density at the upstream window, except for delay times where the beam overlaps. For the simulations, the HL-LHC standard filling scheme was used.

Different scenarios have to be distinguished. Close to delay times of 14 µs (Fig. 2, top right) and of 86 µs, the horizontal beam movement at the point of highest proton density is significantly slowed down or even cancelled out by the overshoot of the MKD waveform [6, 7] acting against the horizontal dilution kickers. The large increase of the peak energy density at the upstream window, caused by the small minimum sweep velocity for these time delays, is clearly visible in Fig. 3 (highlighted in yellow). However, the increase is not critical in the dump core and at the downstream



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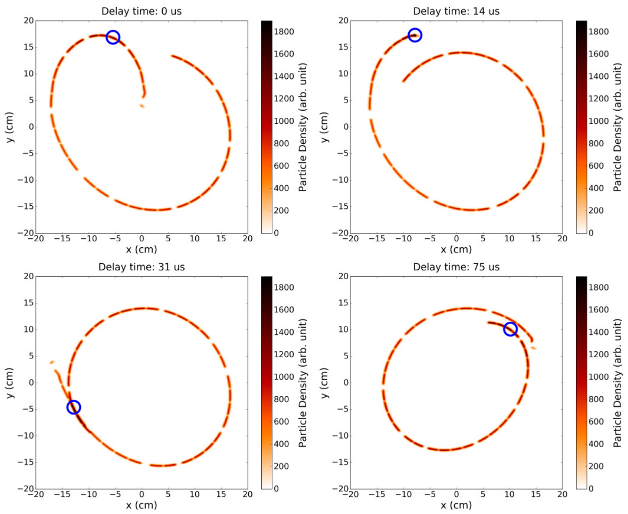


Figure 2: Simulated proton densities at the LHC beam dump for the MKB retrigger scenario in case of an erratically firing dilution kicker. The nominal pattern (top left) and the patterns for three characteristic delay times are shown. Considering only delays within the first 100 µs, 14 µs (top right) represents the worst case for the upstream window, 31 µs (bottom left) represents the worst case for the dump core and 75 µs (bottom right) represents the worst case for the downstream window. The position of the peak density is highlighted with a blue circle.

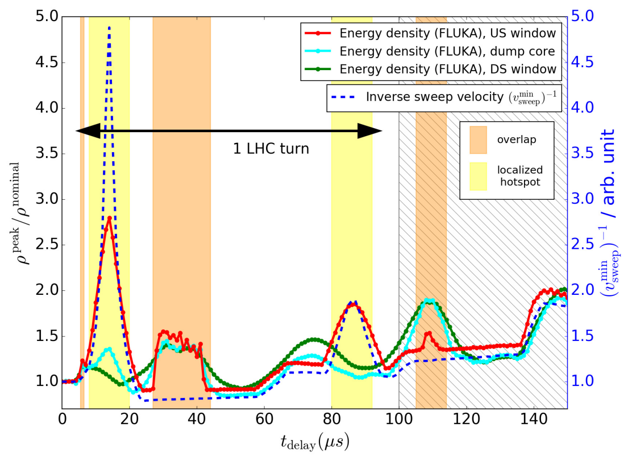


Figure 3: Simulated increase of the peak energy deposition for the MKB retrigger scenario in case of an erratically firing dilution kicker. The density increase in the upstream window (red), the dump core (cyan) and the downstream window (green) is depicted for different delay times between the MKB and the MKD. The main effects, such as overlaps (highlighted in orange) or localized density hotspots due to low sweep velocity (highlighted in yellow) are described in the text. For illustration, the inverse minimum beam sweep velocity at the dump is depicted in blue. It is directly correlated to the proton density at the upstream window, except for delay times where the beam overlaps.

window, because here the energy density is dominated by overlapping showers of secondary particles and not by the very localized hotspot at the upstream window.

At a delay time around 6 µs, between 27 µs and 44 µs (Fig. 2, bottom left) and again between 105 µs and 114 µs, the bunches at the start and end of the patterns overlap, which results in increased energy densities in all parts of the dump (Fig. 3, highlighted in orange). However, the overlap occurs at relatively high sweep velocities. Therefore, for delay times below 100 µs, the energy-density increase in the dump core is not prohibitive and remains below the expected energy deposition for the failure case of two missing MKBH.

Notably, the worst case for the downstream window, at least within the first 100 µs, is given by a delay time of 75 µs (Fig. 2, bottom right) where the branches of the dump pattern do not overlap. However, they are close enough such that the showers of the secondary particles created in the dump overlap at the downstream window.

For large delay times above 100 µs, the damping effect of the MKB waveforms leads to a gradual decrease of the sweep velocity and thus to an overall increase in the energy density. Therefore, the present strategy is to concentrate on an immediate retriggering with a maximum delay time below 100 µs.

## CONCLUSION AND OUTLOOK

For safe and reliable operation of the beam dump system with HL-LHC parameters, different upgrade options are currently under investigation. For the hardware upgrade of the dilution system, adding two additional MKBH and increasing the MKB generator capacitance, will be studied in more detail.

A fast retrigger system in case of an erratically firing generator might be implemented to eliminate the risk of MKB coupling for future HL-LHC operation. The resulting changes in the dump pattern were systematically investigated for different delay times and the main consequences on the energy deposition (such as overlaps or local density hotspots due to low sweep velocity) were identified.

The worst-case density increase in the dump core and in the downstream window is below the expected energy deposition for the existing failure case of two missing MKBH due to a flash-over. However, in the upstream window the worst-case increase based on HL-LHC parameters (emittance $\epsilon = 2.08\,\mu\mathrm{m\,rad}$, bunch intensity $N_\mathrm{p} = 2.3 \times 10^{11}$) would probably be above the acceptable stress value. As mitigation measures, one could either replace the stainless-steel part of the upstream window with a more stress-resistant material or try to avoid the localized density hotspot by modifying the overshoot and the damping factor of the MKD and MKB waveforms, respectively.

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