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UPGRADE OF THE DILUTION SYSTEM FOR HL-LHC*

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Abstract

The LHC Beam Dump System is one of the most critical systems for reliable and safe operation of the LHC. A dedicated dilution system is required to sweep the beam over the front face of the graphite dump core in order to reduce the deposited energy density. The High Luminosity Large Hadron Collider (HL-LHC) project foresees to increase the total beam intensity in the ring by nearly a factor of two, resulting in a correspondingly higher energy deposition in the dump core. In this paper, the beam sweep pattern and energy deposition for the case of normal dilution as well as for the relevant failure cases are presented. The implications as well as possible mitigations and upgrade measures for the dilution system, such as decreasing the pulse-generator voltage, adding two additional kickers, and implementing a retrigger system, are discussed.

INTRODUCTION: DILUTION SYSTEM AND FAILURE CASES

The LHC Beam Dump System (LBDS) includes for each beam the dump core and shielding, 15 fast extraction magnets (MKD), 15 magnetic septa and 10 dilution kickers (MKB) [1]. Local beam-intercepting protection devices, instrumentation, interlocks and controls complete the system. The LHC beam dump itself is composed of three main parts: (i) an upstream window made of carbon-carbon (C-C) composite on a thin stainless steel foil, (ii) a 7.7 m long graphite dump core and (iii) a downstream window made of titanium.

The dilution system is required to reduce the deposited energy density in the dump core and windows. Four horizontal (MKBH) and six vertical dilution kickers (MKBV) sweep the beam over the front face of the dump block with damped sine-like oscillations. The same kick amplitude of approximately 0.28 mrad is required for both planes. This is why the MKBH have to be operated at higher voltage, thus resulting in a higher failure probability. In addition, due to the smaller number of horizontal modules, their contribution in case of a failure is more critical and, for the given dilution pattern, the system is more sensitive to the loss of horizontal dilution. Therefore, the MKB upgrade strategy for HL-LHC focuses on the horizontal kickers [2].

For the LBDS design, two main failure cases for the dilution kickers were considered: a) the loss of two kickers during the execution of the dump due to a flash-over in one vacuum tank, which houses two magnets, and b) the spontaneous firing of one dilution kicker. The studies presented in this paper refer to the worst-case failure scenario of two missing dilution kickers.

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BEAM SWEEP PATTERNS AND ENERGY DEPOSITION FOR HL-LHC

The sweep patterns for a regular dilution and for the case of two missing kickers were calculated with the beam-transport model pyExtract [2]. The resulting sweep patterns, as shown in Fig. 1, were used as input for FLUKA [3] simulations to determine the energy deposition in the dump core and windows [4].

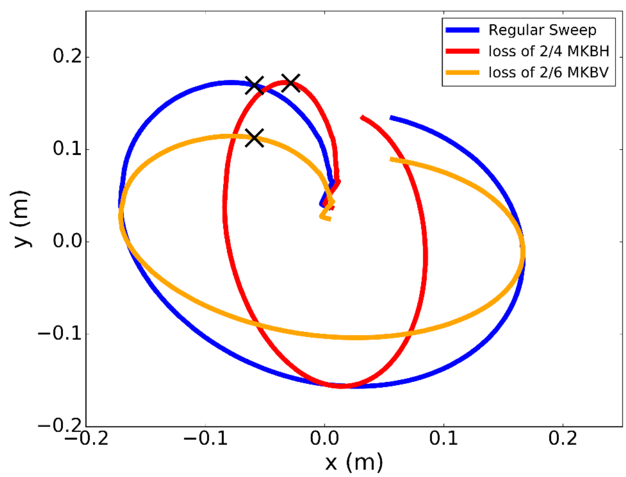

Figure 1: Simulated beam sweep patterns at the dump for a regular sweep (blue) and the failure cases of 2 out of 4 horizontal (red) and 2 out of 6 vertical dilution kickers missing (orange). The positions of highest energy deposition are marked with a black cross.

The corresponding peak temperatures in the dump core are summarized in Table 1. The beam parameters used for the simulation are HL-Standard filling pattern, 2748 bunches with 2.3×10^{11} protons per bunch and emittance of 2.08 µm [4].

Table 1: Expected Peak Temperatures in the Dump Core for a Regular Dilution Sweep and for Failures of up to Two Horizontal and Vertical Dilution Kickers.

	Active MKBV 6	Active MKBV 5	Active MKBV 4
Active MKBH 4	1860 °C	1900 °C	1960 °C
Active MKBH 3	2240 °C	2270 °C	2330 °C
Active MKBH 2	2840 °C	2890 °C	2960 °C

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For a regular HL-LHC dump, the peak temperature reaches already 1860 °C, compared to approximately 1000 °C for a regular LHC dump with Standard filling pattern and 1.3×10^{11} protons per bunch. As expected, the most critical failure is the case of two failing MKBH, when the calculated peak temperature for HL-LHC parameters increases to 2840 °C, compared to 1420 °C for LHC parameters.

Based on the energy deposition, the thermo-mechanical stresses in the upstream and downstream windows were simulated. In case of two failing MKBH, the expected stresses in both windows are beyond their yield strength. Therefore, both windows require an upgrade to ensure the safe operation with HL-LHC beams [5]. Studies are ongoing to understand how a beam impact with HL-LHC parameters will affect the graphite core itself. [5]

UPGRADE STUDIES FOR THE DILUTION SYSTEM

Three different upgrade scenarios for the dilution system have been studied in more detail. This includes, first, the upgrade of the MKBH generators, second, the installation of additional MKBH and, third, the design of a new retrigger system for all dilution kickers.

Upgrade of the MKBH Generators

The generators for the horizontal dilution kickers will be upgraded during Long Shutdown 2 before LHC Run 3. The generator capacitance will be increased, thus allowing for operation at approximately 10 percent lower voltage for the same kick strength. This reduces the probability of spontaneous firing and improves the reliability for operation at a beam energy of 7 TeV and above.

In order to maintain the same sweep frequency with the higher capacitance, the electric circuit has to be modified, leading to a stronger damping of the waveforms. This is visible in Fig. 2, which compares the simulated dilution kicker waveform for the upgraded system with the measured present waveform.

The dilution sweep patterns that correspond to these waveforms are depicted in Fig. 3. The maximum dilution at the point of highest energy deposition is not changed significantly. The effect of the stronger damping is only observable at the, less critical, end of the sweep path. FLUKA simulations verified that there is no significant change in the peak energy deposition with the new waveforms, neither for a regular sweep nor for the failure of two kickers [6].

Additional Horizontal Dilution Kickers

The feasibility and the potential gain of installing additional dilution kickers has been studied for HL-LHC. For the beam simulations, two additional horizontal dilution kickers were added to the MAD-X [7] sequence. The vertical dilution strength was kept constant for all studies.

The dilution sweep patterns at the dump were computed for the failure cases of up to two missing MKBH. The resulting energy deposition was computed with FLUKA. Table 2 shows the peak temperature in the dump core for the present system with 4 horizontal dilution kickers and for a possible upgrade to 6 horizontal kickers. The beam parameters used for the simulation are HL-Standard filling pattern, 2748 bunches with 2.3×10^{11} protons per bunch and emittance of 2.08 µm [4].

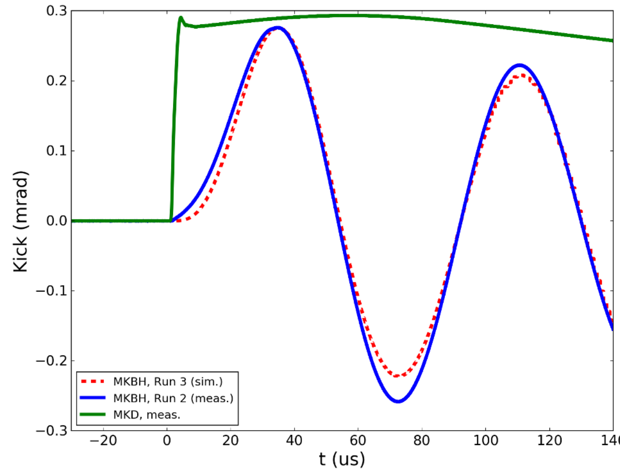

Figure 2: Measured MKBH waveform for the present system (blue) and simulated waveform after the planned upgrade for LHC Run 3 (red). The stronger damping of the new waveform is clearly visible. In addition, the MKD waveform is depicted in green.

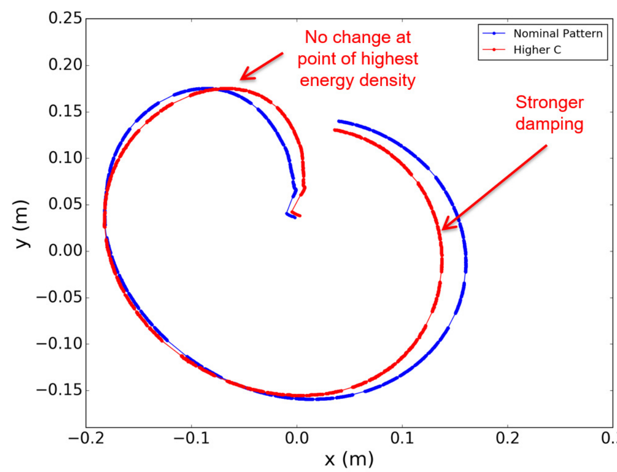

Figure 3: Dilution sweep pattern for the present system (blue) and after the planned upgrade of the MKBH generators for LHC Run 3 (red).

Table 2: Calculated Peak Temperature in the Dump Core for the Present System with 4 Horizontal Dilution Kickers and for a Possible Upgrade to 6 Kickers.

2/4 MKBH missing	2/6 MKBH missing	2/6 MKBH missing with increased dilution
2840 °C	2420 °C	1860 °C

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The installation of two additional horizontal dilution kickers would directly reduce the failure sensitivity. For the case of 2 missing kickers, the expected temperature in the dump core is reduced from 2840 °C (2 out of 4 MKBH missing) to 2420 °C (2 out of 6 MKBH missing). Moreover, assuming that the total kick strength is held constant, the operating voltage of each generator can be reduced by one third, which would significantly decrease the failure probability. Finally, it provides margin to increase the horizontal dilution. This would reduce the peak energy deposition for all nominal HL-LHC dumps and for the failure cases of missing kickers. Assuming that the individual deflection of each MKBH could be held constant, the total horizontal deflection would increase by 50 % and the temperature for the most critical failure case would be reduced even further to 1860 °C. However, the maximum deflection strength might be limited by energy deposition in the dump vessel from secondary particles escaping the graphite core. Consequently, the trade-off between increasing the deflection and reducing the operational voltage has to be carefully assessed.

Regarding the required horizontal apertures in the dumpline and the integration of the two additional kickers, so far no show-stopper was identified.

MKB Retrigger System

During tests without beam, a new failure mode was found in 2016. Due to a parasitic electromagnetic coupling signal between the MKB generators, a generator that is spontaneously firing could also trigger adjacent ones. In case of antiphase between the spontaneously firing generators and the remaining ones, this can result in the loss of more than half of the horizontal dilution.

A possible long-term mitigation could be the installation of a dedicated retrigger system for the dilution kickers. However, this solution implies that, in order to ensure synchronicity with the particle-free abort gap, the MKD are now fired with a time delay after the MKB, which leads to a change of the sweep path of the beam on the dump. This time delay depends on the initial reaction time of the system and, more important, on the position of the abort gap in the ring. The latter can add a delay of up to one LHC revolution period of 89 µs.

Sweep patterns for different delay times between retriggered MKB and synchronously firing MKD have been presented in [2] together with the corresponding energy deposition. Since the higher damping of the new MKBH waveforms after Long Shutdown 2 will also change the energy deposition for the retrigger scenario, the calculations were repeated for the new waveforms [8]. The results are summarized in Fig. 4. The main effects, such as overlapping of the sweep path (marked in orange) or localized density hotspots due to low sweep velocity (marked in yellow) [2] are highlighted. The inverse minimum beam sweep velocity at the dump is plotted in blue. As visible, it is directly correlated to the peak energy deposition at the upstream window, except for delay times where the beam sweep path overlaps and thus increases the energy deposition [2].

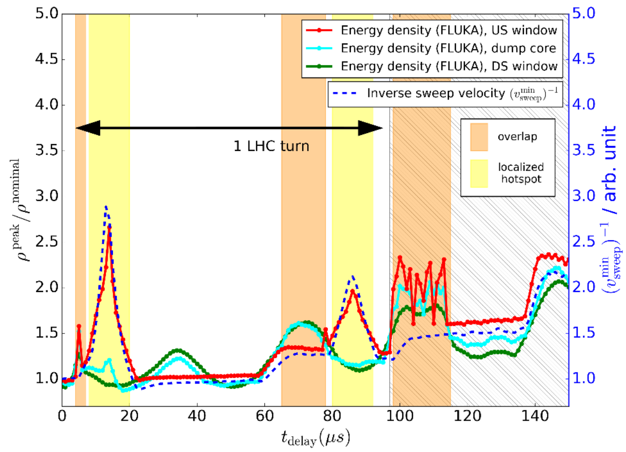

Figure 4: Simulated increase of the peak energy deposition for the MKB retrigger scenario in case of a spontaneously firing dilution kicker. The density increase in the upstream window (red), the dump core (cyan) and the downstream window (green) is depicted for different delay times between the MKB and the MKD. HL-LHC standard filling pattern was used for the calculations.

Also for the new waveforms, the worst-case energy deposition in the dump core is below the energy deposition for the failure case of two missing MKBH. For the upstream window, the highest peak energy deposition is found for a delay time of 14 µs. First simulations of the thermo-mechanical stresses show that this case is much less critical than the failure of 2 MKBH [5].

CONCLUSION

Different challenges have been identified for the safe operation of the dilution system during operation with HL-LHC beams and possible mitigation measures have been studied. The present system shows a high sensitivity on failures of the horizontal dilution kickers. For the most critical case of two failing MKBH, a high peak temperature of 2840 °C would be reached in the dump core.

As a first mitigation, the MKBH generators will be upgraded during Long Shutdown 2 to allow operation at lower voltage and reduce the failure probability. The installation of two additional horizontal dilution kickers was studied and proved to significantly reduce the energy deposition for the most critical failure cases. The newly observed failure mode of electromagnetic coupling between the MKB generators, might be mitigated by implementing a new retrigger strategy for the dilution system.

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