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MACHINE PROTECTION ASPECTS OF HIGH-VOLTAGE FLASHOVERS OF THE LHC BEAM DUMP DILUTION KICKERS*

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Abstract

The LHC Beam Dump System is required to safely dispose of the energy of the stored beam. In order to reduce the energy density deposited in the beam dump, a dedicated dilution system is installed. On July 14, 2018, during a regular beam dump at 6.5 TeV beam energy, a high-voltage flashover of two vertical dilution kickers was observed, leading to a voltage breakdown and reduced dilution in the vertical plane. It was the first incident of this type since the start of LHC beam operation. In this paper, the flashover event is described and the implications analysed. Circuit simulations of the current in the magnet coil as well as simulations of the resulting beam sweep pattern are presented and compared with the measurements. The criticality of the event is assessed and implications for future failure scenarios are discussed.

INTRODUCTION: DILUTION SYSTEM AND FAILURE CASES

The LHC Beam Dump System (LBDS) includes for each beam, together with the various control elements, 15 fast extraction magnets (MKD), 15 magnetic septa, 10 dilution kickers (MKB), and the beam dump [1]. The 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), which are driven by their high-voltage (HV) generators, sweep the beam over the front face of the dump block with damped sine-like oscillations and an amplitude of around 0.28 mrad.

The worst-case failure scenario considered up to now was the loss of the deflection of two horizontal dilution kickers. It can be caused by either, on the generator level, the erratic firing of one HV generator in antiphase to the remaining kickers [2–4], or, on the magnet level, the loss of two kickers during the dump execution due to a flashover in their common vacuum tank. This paper discusses the latter case, based on the analysis of the recent incident, and concludes that a worse failure case can occur.

MKBV FLASHOVER ON JULY 14, 2018

On July 14, 2018, a high-voltage flashover of two vertical dilution kickers of Beam 2 was observed during a regular beam dump with 2556 bunches at 6.5 TeV beam energy. It was the first incident of this type with beam in the machine since the start of LHC.

Figure 1 depicts the dilution kickers inside their common vacuum tank. After a dump execution, the HV generators discharge the current via the busbars into the magnet coils inside the vacuum tank. The first flashover occurred at the magnet MKBV.C and then propagated to the MKBV.D, located around 3 m downstream in the same vacuum tank. The first flashover took place about 37 µs after the dump execution, the second flashover happened 10 µs later, i.e. at about 47 µs. The initial cause and the exact location of the flashovers are not yet fully known [5].

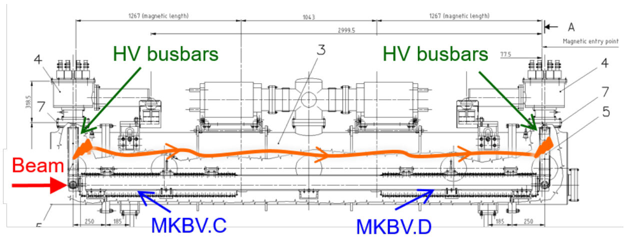

Figure 1: Overview of the two vertical dilution kickers inside their common vacuum tank. The first flashover occurred at the MKBV.C and then propagated downstream to the MKBV.D. The propagation path in orange is indicated for illustration purposes only.

The dilution pattern during the flashover event is shown in Fig. 2. The pattern was measured at the beam screen (BTVDD) located upstream of the dump block. For comparison, the simulated dilution patterns for a nominal dump and for dumps with one to three vertical dilution kickers missing are depicted with solid lines. The simulated pattern are based on the kicker waveforms from a regular dump of Beam 2 on July 22, 2016, with the corresponding number of kickers switched off in the simulation. The centre positions of the patterns have been fitted for the plot and the vertical size scaled with a correction factor of 1.04.

Until the time of the first flashover t_1 the beam follows the nominal dilution path (green curve). As expected, after t_1 the deflection of one vertical kicker is lost and the beam follows the calculated path for 5 out of 6 active kickers (blue curve). However, after the flashover of the second kicker at t_2, no

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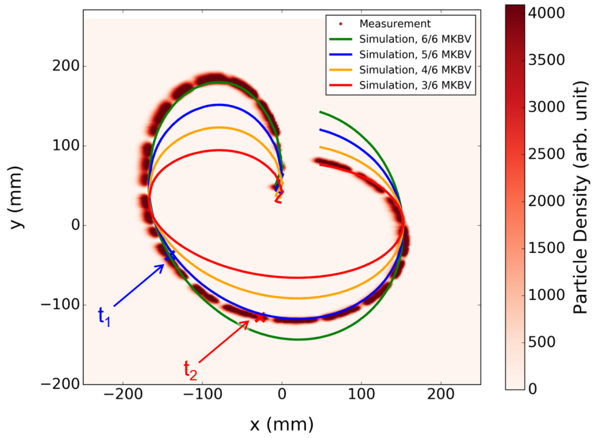

Figure 2: LHC dilution pattern for Beam 2, measured at the BTVDD (red density plot) during the flashover on July 14, 2018, compared to the simulated patterns with 6 (green), 5 (blue), 4 (orange) and 3 (red) active kickers out of the 6 installed vertical dilution kickers.

further reduction of the vertical deflection is visible and the beam stays on the blue curve for 5 active kickers. Later, after the vertical zero-crossing, the beam follows, in contrast, the calculated path with only 3 out of 6 active kickers. This behaviour indicated that the deflection of the second magnet is not, as previously assumed, lost after the flashover, but that the field in the magnet persists during the beam transit. It continues, thus, to contribute to the downward deflection and, after the vertical zero-crossing, partially cancels out the upward deflection of the remaining kickers.

The voltage at the busbars and the current in the magnet coil inside the vacuum tank are not measured directly. Therefore, simulations with PSpice [6] were performed for a more thorough understanding of the internal circuit behaviour [7]. Figure 3 shows the simulated voltage at the MKBV busbars as well as the current in the magnet coils during a nominal firing of the kicker. The flashover at the MKBV.C occurred at around 37 µs, when the high voltage reached its local maximum of approximately 10.9 kV. This corresponds to the zero crossing of the coil current. Consequently, no current and, thus, no field persisted in the MKBV.C after the flashover. However, when the flashover had propagated to the MKBV.D 10 µs later, the current had already increased to around −15 kA. After the flashover effectively short-circuited the magnet coil, this current could not immediately decay, and, thus, continued to deflect the beam downwards.

To quantify this behaviour, additional simulations were performed, for which a small plasma resistance between the MKBV busbars was added in the PSpice model at the time of the flashover. For this purpose, the value of the plasma resistance at the MKBV.D was fitted to 20 mΩ based on the current measured at the magnet's entry box. The result of the circuit simulation showed that the current in the MKBV.D coil indeed persisted after the second flashover, only showing a slow decay of approximately 8 % over 50 µs.

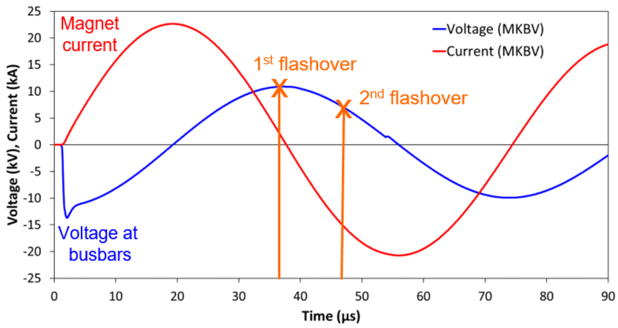

Figure 3: Simulated voltage at the MKBV busbars (blue) and current in the magnet coils (red) for a nominal firing of the kicker. The times of the flashovers on July 14, 2018 are indicated in orange.

The simulated coil currents for MKBV.C and MKBV.D have then been used as input for the beam calculations, while for the 4 regularly operating MKBV, for the 4 MKBH and for the 15 MKD the measured waveforms have been imported from the Post Mortem database. The resulting beam path is shown in Fig. 4. It agrees very well with the measurement, validating the reconstructed circuit behaviour after the flashover.

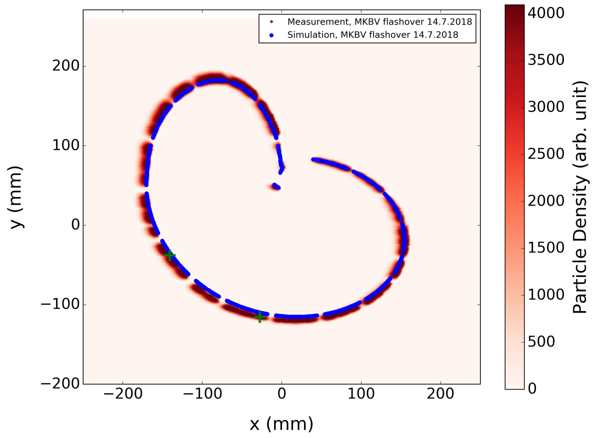

Figure 4: Simulated dilution pattern (blue) for the MKBV flashover on July 14, 2018, based on the kicker waveforms calculated with the PSpice circuit model. Very good agreement with the measured pattern (red) can be observed, validating the reconstructed flashover behaviour.

MKBH FLASHOVER CONSEQUENCES

Due to the higher number of modules and due to the shape of the dilution pattern, a flashover of two vertical dilution kickers is significantly less critical than a flashover of two horizontal kickers. To assess the criticality of the latter, the beam sweep paths for different MKBH flashover scenarios have been simulated [8]. For the simulations, it was assumed that the delay between the first and second flashover is 10 µs, and, in a conservative approach, that the current in the magnet coil remains constant after the flashover.

Since it is a priori not clear when the flashover happens with respect to the beam dump execution, the beam paths for all relevant delays between 0 µs and one LHC turn of 89 µs have been simulated. Based on the proton beam paths, the energy deposition and peak temperature in the dump core have then been calculated [9] with FLUKA [10]. The results for HL-LHC BCMS beams with 7 TeV energy, $2.3 \cdot 10^{11}$ protons per bunch and a 1.7 µm emittance, are shown in Fig. 5 (red curve).

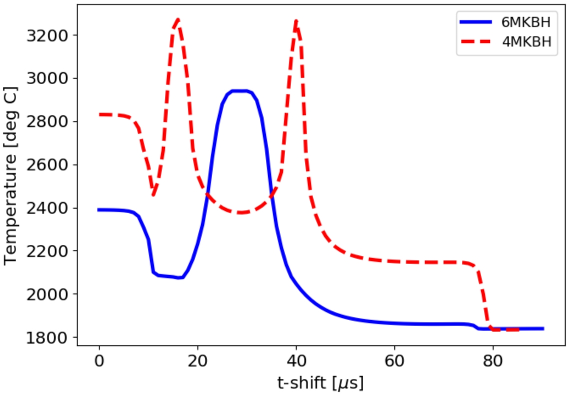

Figure 5: Simulated peak temperature in the dump core with HL-LHC BCMS beams for a flashover of 2 out of 4 (red curve, present system) and 2 out of 6 (blue curve, possible upgrade) horizontal dilution kickers as a function of the time delay between the dump execution and the flashover in the first magnet. The second flashover is assumed to occur 10 µs after the first one.

The highest peak temperatures are reached for delays around 16 µs and around 42 µs, when the last part of the sweep path overlaps with the first part of the path. The effect is visible in Fig. 6, which shows the simulated energy deposition for a flashover starting at a delay of 16 µs.

This scenario corresponds to a new worst case failure, reaching a peak temperature of 3200 °C in the dump core for HL-LHC BCMS beams, which is around 360 °C higher than for the previously considered worst case, which had assumed that 2 out of 4 MKBH are completely missing,

At the moment, not enough information about the core material behaviour at these high temperatures is available to conclude if the induced thermo-mechanical stresses are acceptable. Therefore, detailed material characterisations are presently ongoing [11]. It is, however, already clear that the expected stress levels for the dump windows would be too high for a reliable long-term operation with Run 3 or HL-LHC beams, and their upgrade is currently planned [12, 13].

MITIGATION STRATEGY

As a short-term mitigation, the voltage at the two affected MKBV was reduced by 20 % following the incident [4]. During the ongoing Long Shutdown 2, the magnets will be closely examined to decide on potentially required hardware changes. For the long term, the installation of two additional horizontal kickers per beam during Long Shutdown 3 has been proposed [4]. This would reduce the worst-case peak temperature in the dump core for a flashover of two horizontal dilution kickers to 2900 °C, as shown in the blue curve in Fig. 5. More importantly, it would allow to lower the voltage of the individual MKBH magnets to 72 % of its present value. It would, thus, significantly decrease the probability of a flashover, while keeping the same total dilution at the higher operational beam energy of 7 TeV. Furthermore, it would provide a margin to increase the width of the dilution pattern and thus reduce the peak energy density during nominal operation and during failure cases.

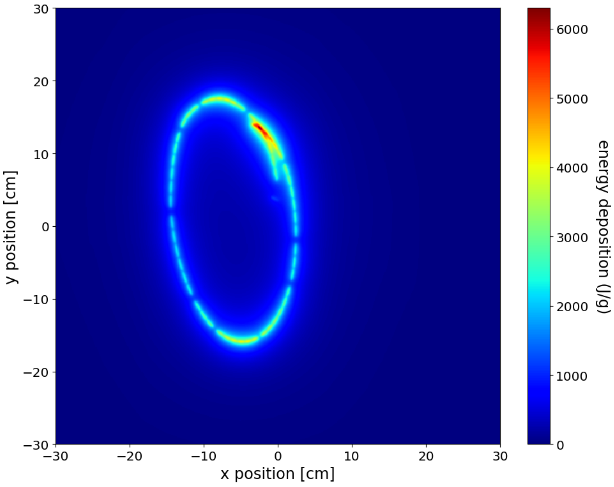

Figure 6: Simulated energy deposition in the dump core for a flashover of two horizontal dilution kickers at 16 µs and at 26 µs, respectively, after the dump execution. With HL-LHC BCMS beams, a maximum hot-spot temperature of more than 3200 °C would be reached. For Run 3 BCMS parameters, i.e. 7 TeV energy, $1.8 \cdot 10^{11}$ protons per bunch, and 1.8 µm emittance, the peak temperature would still reach around 2500 °C.

Independently, a major upgrade of the dump blocks and windows is under study to ensure the mechanical stability of the dump vessel and the material integrity of the core also for HL-LHC beams [11–13].

CONCLUSION AND OUTLOOK

The first dilution-kicker flashover during LHC beam operation occurred on July 14, 2018, at two vertical kickers during a regular dump at 6.5 TeV beam energy. The event confirmed that the flashover can propagate to the second magnet located in the same vacuum tank. However, the detailed reconstruction of the incident showed that the consequences of a flashover can be worse than previously assumed. For a flashover of two MKBH, the worst-case peak temperature could reach 3200 °C for HL-LHC beams. It is, therefore, of high machine-protection relevance.

The installation of two additional MKBH could reduce the probability and the impact of a flashover, while the upgrade of the dump assembly is under study to ensure its integrity also for HL-LHC beams.

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