ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB344

STUDIES FOR MITIGATING FLASHOVER OF CERN-LHC DILUTION KICKER MAGNETS

A. Loebner, M. J. Barnes, W. Bartmann, C. Bracco, L. Ducimetière, V. Namora, V. Senaj
CERN, Geneva, Switzerland

Abstract

The LHC beam dump system is used for extracting beam from the LHC and, as such, is a safety critical system whose proper functionality must be assured. Dilution kicker magnets (MKBs) sweep the extracted beam over the cross-sectional area of a dump block as the energy density would otherwise be too high and damage the block. In 2018, a high voltage flashover occurred in a vertical MKB (MKBV) vacuum tank, during a beam dump, which resulted in non-ideal sweep of the beam over the block. The location of the flashover could not be identified during a subsequent inspection of the magnet. Hence, electrical field simulations have been carried out to identify potentially critical regions, to determine the most probable region of the flashover. One potentially critical region is a rectangular beam pipe (RBP) between the end of the tank and the MKBV magnet, whose purpose is to reduce plasma propagation to the adjacent tank in the event of a flashover. Mitigating measures were studied and are reported in this paper.

INTRODUCTION

The LHC beam dump system (LBDS) is a safety critical system which must operate reliably to extract beam from the LHC. During a beam dump, an extremely high and potentially damaging energy of 360 MJ per beam, at 7 TeV, must be safely absorbed in the dump block (TDE) [1]. To execute a safe beam dump the dilution kickers (MKB) sweep the beam to reduce the peak energy density on the TDE. The LBDS includes, besides the TDE and its shielding, 15 fast extraction magnets (MKD), 15 magnetic septa and 10 dilution kickers, various protection devices, instrumentation, interlocks and controls. The LBDS is illustrated in Fig. 1. All the magnets are in vacuum tanks: the dilution kickers are typically at a pressure of ~10^{-8} mbar.

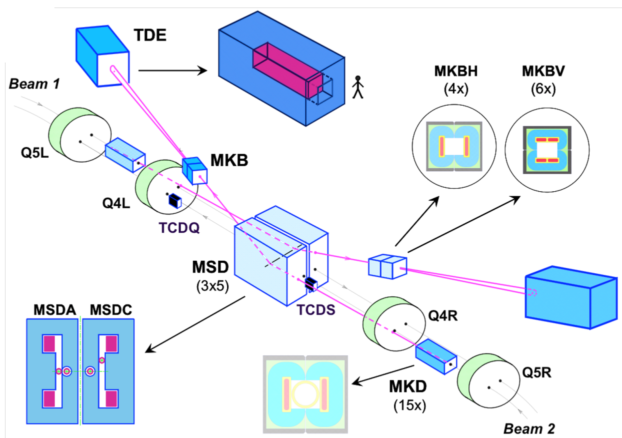

Figure 1: Schematic overview of the LHC extraction area.

RISK OF FLASHOVERS IN MKB TANKS

Four horizontal (MKBH) and six vertical (MKBV) dilution kickers sweep the beam over the front face of the dump block with damped sine-like oscillations to reduce the energy density on the TDE. In case of a failure in one or more of the dilution kickers, the sweep functionality reduces or is lost which, in a worst case, can damage the TDE [2]. The study presented in this paper refers to an incident on July 14, 2018 where a flashover occurred in an MKBV tank between the high voltage (HV) and ground of one magnet. Although the flashover incident resulted in a non-ideal beam pattern [2], fortunately there was no damage to the dump block. However, if a flashover incident happens in a MKBH vacuum tank, the situation could be more critical due to the lower number of MKBH magnets [3].

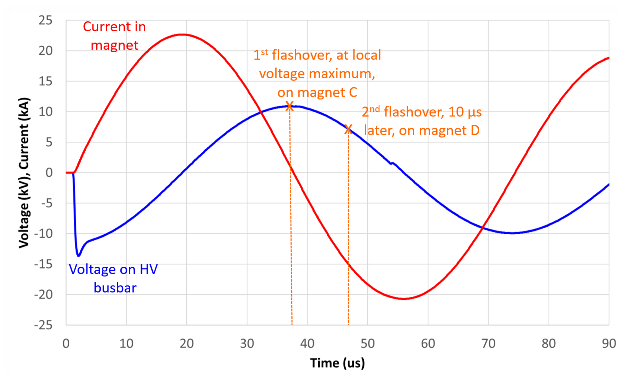

Figure 2: Simulated voltage on the MKBV busbars and current in the magnet coils for a nominal turn-on of the kicker. Times of the flashovers on July 14, 2018 are indicated [2].

The voltage at the busbars and the current in the magnet coil are not measured directly. Therefore, simulations with PSpice [4] were performed for a thorough understanding of the internal circuit behaviour [2]. Figure 2 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 on magnet C occurred at ~37 µs, when the high voltage reached its local maximum of ~11 kV. A time of 10 µs later a flashover occurred on magnet D, which is in the common MKBV vacuum tank: the plasma from the first flashover probably propagated to the adjacent magnet in the tank, causing the second flashover.

A subsequent inspection of the affected MKBV tank was performed, but the location of the flashover could not be identified [3]. Hence, electrical field simulations have been carried out to identify potentially critical areas, to determine the most probable region of the flashover. The regions were modelled and simulated in the finite element software Opera-3d [5], with a fine mesh, to ensure simulations whose

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB344

predictions could be compared. The regions studied include an HV feedthrough, magnet frame (Fig. 3), an unused ground connector and the rectangular beam pipe (RBP) installed at the entrance and exit of each tank (Fig. 3).

ELECTRIC FIELD SIMULATIONS

The generators used for the MKB kickers have capacitors, pre-charged to a voltage proportional to the LHC beam energy, and a stack of high power semiconductor switches for discharging the capacitors into the magnet [6]: the pre-charge is ~16 kV at 7 TeV. The inductance of the MKBV magnet and cables, together with the capacitors result in a damped oscillatory current with a frequency of 12.7 kHz [6]. Electrostatic field simulations were carried out for an HV busbar voltage of 16 kV [7].

Initial Field Simulations

The HV feedthrough, into the MKBV tank, is coaxial with alumina between the inner HV and the outer (ground): there is a high electric field in this region. In addition, there is a triple point, where conductor, insulator and vacuum meet. An HV busbar connects between the inner conductor of the feedthrough and the magnet coil. A return busbar provides a low inductance connection from the output of the magnet coil to the vacuum tank.

An unused connector, identical to one used for the return busbar, is on the inside wall of both ends of the tank: however, the unused connector faces towards the HV busbar. Its purpose is to provide symmetry, so that the orientation of the tank is not critical, for the electrical connections to the second magnet in the tank. The unused connectors edges were relatively sharp although the electric field was reasonably low: however, by incorporating a rounded cover the electric field strength was decreased by a factor of four [7].

The magnet frame surrounds the sides of the magnet coil: the magnet frame is the nearest part, which is at ground potential, to the magnet coil (Fig. 3). The corners and edges of the frame are chamfered and blended to increase the curvature to avoid excessively high electric fields.

The predictions from the above studies showed that the electric fields were not high enough to cause a flashover [7].

Rectangular Beam Pipe and Magnet Coil

Since the flashover had occurred during beam extraction, suspicion focused on the area between the stainless steel RBP, at each end of the MKBV vacuum tank, and the HV busbar (Fig. 3). In the presence of the beam, which was the case for the flashover incident in 2018, there was probably electron cloud inside the RBP at each end of the tank. Electron cloud is generated in the vacuum chamber by photo-emission or beam-induced multipacting and subsequent electron accumulation during a bunch or bunch-train passage [8]. In addition, this effect leads to dynamic pressure rise [1].

The RBP is manufactured from stainless steel: stainless steel has a maximum secondary electron yield (SEY) of 2.25 [9]. Electrons are attracted to the HV busbar during the AC voltage's positive sine wave and can form a conductive path between the RBP, which is at ground potential, and the HV busbar.

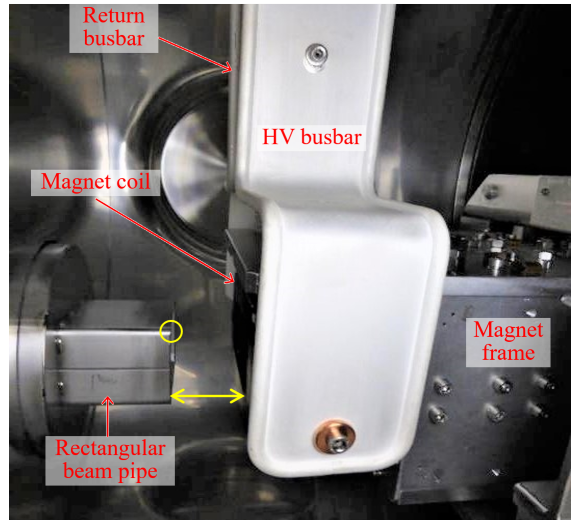

Figure 3: Photo of inside of one end of an MKBV tank.

The distance between the internal RBP and the magnet coil was designed to be ~35 mm, and is illustrated by the double-ended arrow on Fig. 3. As mentioned above, the purpose of this RBP was to limit plasma propagation between tanks in case of a flashover in one tank - thus reducing the probability of a breakdown in the adjacent tanks. The idea studied here was to extend the RBP towards the magnet coil, thus decreasing their separation, and further reducing the probability of plasma propagation between tanks. In addition, since electron cloud occurs inside the RBP, reducing the separation between it and the magnet coil, which itself is generally close to ground potential, helps to prevent electrons from being accelerated towards the HV busbar.

The MKBV magnet coil is a 2-turn coil potted in Araldite resin type-F. The surface of the resin is graphite coated (DAG) and has a resistance of ~ 500 $\Omega/\square$: the DAG is connected to the grounded magnet frame at a number of locations along its length. As a result of parasitic capacitance between the coil and DAG the potential of the coating is not 0 V at all times during energising of the coil. Thus, measurements were carried out to determine the voltage on different areas of the end face of the DAG coated coil [7]. The measurements, reported below, show that the potential of the end face during most of the applied waveform is close to 0 V. However, there is an initial transient of ~7% of the generator voltage. Hence, electric field simulations were carried out with 0 V and ~1.2 kV modelled on the DAG.

The highest field on the RBP is on the corner nearest to the HV busbar, indicated by a circle on Fig. 3. The predicted electric fields on the corner were compared for different separations between the RBP and the magnet coil. The electric field is calculated along a straight line: the line touches the DAG coated end face of the magnet coil and the corner of the rectangular beam pipe where the highest field was found: the line then continues along the outside of the

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB344

RBP. The electric field predictions for different separations between the RBP and the magnet coil are shown in Fig. 4, for 0 V on the DAG.

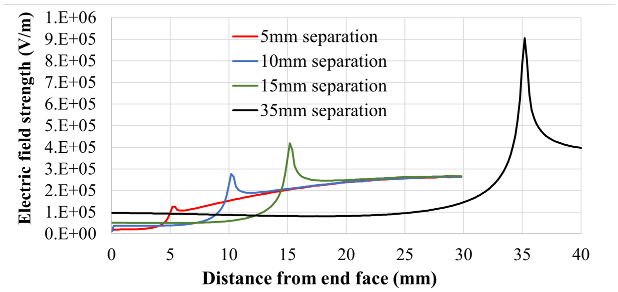

Figure 4: Electric fields along a straight line from the surface of the magnet coil (0 mm), to the corner of the RBP and then along the outside upper edge of the beam pipe: peak fields occur at the corner indicated with a circle in Fig. 3.

The simulations were rerun with 1.2 kV modelled on the DAG coating of the end face of the magnet coil. The peak value, on the upper corner of the RBP, are summarized in Fig. 5 for both 0 V and 1.2 kV on the DAG. With 0 V simulated on the DAG, the peak field on the corner of the RBP reduces monotonically when decreasing the separation to the end face of the coil: this also decreases the opportunity for a pressure wave to propagate between tanks due to a flashover outside the magnet. With a voltage of 1.2 kV modelled on the end-face of the DAG, the peak field is minimized for a separation of ~7.5 mm. It is considered unlikely that the resultant peak field of ~640 kV/m would result in a flashover: even assuming the presence of electron cloud in the RBP, the initial voltage transient on the DAG is negative (Fig. 6) and would thus repel, rather than attract, electrons.

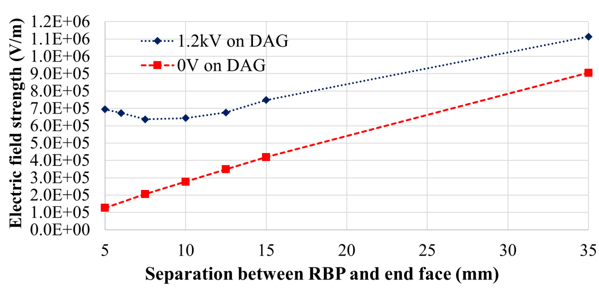

Figure 5: Peak value of field on the corner of the RBP, versus separation between the coil and RBP, for 0 V and 1.2 kV on the DAG.

As mentioned above, a concern is that the beam creates electron cloud inside the RBP, and can thus cause flashovers between the beam pipes and HV busbars. The separation of the RBP and magnet coil will be reduced to ~7 mm, to significantly reduce the electric field on the corner of the RBP: in addition, to try and eliminate the formation of electron cloud, it is proposed to coat the interior of the RBP with amorphous carbon (a-C). a-C has a maximum SEY close to 1.0, while the maximum SEY of stainless steel is 2.25 [9].

MAGNET COIL MEASUREMENTS

The voltage of the DAG on the end face of the coil, facing the RBP, was measured using a spring loaded probe, with a rounded contact to avoid scratching the surface coating, while the MKBV magnet was pulsed. A measurement with 1 kV on the generator is shown in Fig. 6. The transient voltage measured on the DAG (yellow waveform), with HV (blue waveform) applied to the busbar, has a width at half of the peak negative voltage of ~500 ns: as a result of parasitic capacitance between the coil and DAG, the peak and width are expected to be dependent upon the switching speed of the semiconductor switches. After the transient, the peak-peak voltage measured on the DAG is only ~0.6% of the generator voltage.

Figure 6: Measured voltages with generator at 1 kV: HV busbar (blue) 200 V/div, and DAG (yellow) 10 V/div. 20 µs/div.

CONCLUSION

A flashover of a vertical dilution kicker magnet occurred during a regular LHC beam dump operation on July 14, 2018. The initial cause and the exact location of the flashovers were not known and, hence, simulations have been carried out to predict electric fields in several regions. The most probable cause has now been identified as electron cloud, inside a stainless steel rectangular beam pipe in the MKBV tanks, in the presence of the beam, resulting in a flashover from the HV busbar to the beam pipe. The rectangular beam pipe was re-designed, to allow adjustment for moving it closer to the magnet coil, thus reducing the predicted electric fields. In addition, reducing the gap will further reduce pressure wave propagation to the adjacent tank, in case of a flashover outside the magnet. Furthermore, a thin layer of a-C will be applied to the inside of the rectangular beam pipe to mitigate the development of electron clouds. The modified MKBV magnet is presently undergoing HV testing in the lab.

ACKNOWLEDGEMENTS

The authors thank F. Pelloux, Y. Sillanoli, and R. Noulibos for modifications to the RBP and for the setup for the DAG measurements. In addition, the authors thank P. Costa Pinto, Y. Maxence Delaup and M. Taborelli for a-C coating of the inside of the modified, prototype, RBP.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB344

REFERENCES

[1] S. Myers, “The Large Hadron Collider 2008-2013”, *Int. J. Mod. Phys. A*, vol. 28, p. 1330035, 2013. doi:10.1142/S0217751X13300354

[2] C. Wiesner *et al.*, “Machine Protection Aspects of High-Voltage Flashovers of the LHC Beam Dump Dilution Kickers”, in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2418–2421. doi:10.18429/JACoW-IPAC2019-WEPMP040

[3] L. Ducimetière *et al.*, “LBDS kickers: HW upgrade”, presented at LHC Beam Dump System Review and its readiness for the Run3 and HL-LHC operation, Geneva, Switzerland, Fev. 2019.

[4] PSpice, https://www.pspice.com

[5] Dassault Systèmes, https://www.3ds.com/products-services/simulia/products/opera/

[6] O. Brüning *et al.*, “LHC Design Report”, CERN, Geneva, Switzerland, Rep. CERN-2004-003-V-1, 2004.

[7] A. Loebner, “Simulation for mitigating dilution kicker high voltage flashover incidents”, CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2021-0007, Mar. 2021.

[8] F. Zimmermann, “The Electron Cloud Instability: Summary of Measurements and Understanding (Invited)”, in *Proc. 19th Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper FOAB001, pp. 666-670.

[9] C. Yin Vallgren *et al.*, “Amorphous carbon coatings for the mitigation of electron cloud in the CERN Super Proton Synchrotron”, *Phys. Rev. ST Accel. Beams*, vol. 14, no. 7, p. 071001, 2011. doi:10.1103/PhysRevSTAB.14.071001