Chapter 14

Beam injection and dumping systems

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14 Beam injection and dumping systems

14.1 Overview

The beam transfer into the LHC is achieved by the two transfer lines TI2 and TI8, together with the septum and injection kickers, plus associated systems to ensure the protection of the LHC elements in case of a mis-steered beam. The foreseen increase in injected intensity and brightness for the HL-LHC means that the protection functionality of the beam-intercepting devices (TDI) needs upgrading [1]. In addition, the higher beam current significantly increases the beam-induced power deposited in many elements, including the injection kicker magnets in the LHC ring.

The beam dumping system is also based on DC septa and fast kickers, with various beam intercepting protection devices including the beam dump block. Again, the significant change in the beam parameters for the HL-LHC implies redesign of several of the dump system devices, both because of the increased energy deposition in the case of direct impact and because of increased radiation background that could affect the reliability of this key machine protection system [1].

Since the last version of the HL-LHC Technical design report [2] several changes occurred. HiRadMat tests allowed to finalise the choice on the materials of the absorbing blocks and the back-stiffener of the injection dump (TDIS). The modification and displacement towards the IP of the auxiliary injection protection collimator (TCLIA) in Point 2, to increase the ZDC acceptance, is now part of the HL-LHC baseline. As a result of the successful tests on an upgraded injection kicker prototype, the series production of the MKIs with Cr_2O_3 coated chambers and modified beam screen was also approved and is in the project baseline. New failure types of the dilution kickers (MKB) and different weaknesses of the beam dump block itself (robustness of the different components plus vibrations) were found. Mitigation measures to improve the reliability of the MKBs will be put in place in LS2 but further upgrades of the full system are needed for a fully safe operation with the HL-LHC beams.

14.2 Beam injection systems

The layout of the LHC injection region and the associated protection devices is shown schematically Figure 14-1. The beam to be injected passes through five horizontally deflecting steel septum magnets (MSI) and receives a total kick of 12 mrad. Four vertically deflecting kickers (MKI) merge the beam on to the LHC closed orbit by applying a total kick strength of 0.85 mrad. Uncontrolled beam losses resulting from MKI errors (missing pulses, erratic, partial, badly synchronized, or wrong kick strength) could result in serious damage to the downstream equipment. In particular the superconducting separation dipole D1, the triplet quadrupole magnets near the ALICE and LHCb experiments or the magnets in the arcs of the LHC machine itself could be directly hit by the beam. Also, particle showers, generated by proton losses, could damage components of the detectors which are close to the beam pipe. Precautions must therefore be taken against damage and magnet quenches and collimators and dumps are placed at key locations in the injection regions.

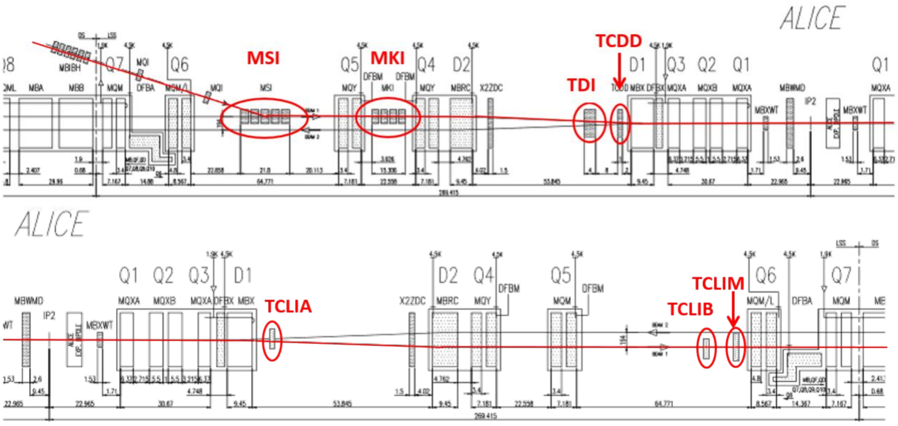

Figure 14-1: Overview of the present injection system into the LHC and the associated protection devices (Beam 1, IR2). The beam is injected from the left-hand side.

14.2.1 Upgrade of the injection dump TDIS

The present TDI is a movable two-sided vertical absorber which is installed at about 90° betatron phase advance from the injection kicker. Its main purpose is to protect machine elements in case of MKI malfunctions and timing errors. The TDI is also used to intercept bunches during the set-up or commissioning of the injection system with low intensity beam (one bunch of 5×10^9 - 1×10^{10} ppb).

The jaws of the TDIs presently installed in the LHC are 4.185 m long and accommodate blocks of graphite (6 × 47.1 cm), aluminium (1 × 60 cm) and CuCr1Zr (1 × 70 cm). The two latter blocks are retracted by 2 mm with respect to the graphite to avoid direct beam impact on these materials, which could lead to an excessive heating and stresses of these blocks. During the first years of the LHC operation, the TDIs in both IR2 and IR8 injection insertions were affected by several anomalies including outgassing, vacuum spikes, structural damage of the beam screens and elastic deformation of the jaws due to beam induced RF heating during the fills. Several hardware changes were already applied during the first long shutdown (LS1) and the following winter stops to mitigate the encountered problems [3]. Despite a visible reduction of the beam induced jaw deformation and of the vacuum activity, it was decided to develop a new improved design in terms of mechanics, robustness, reliability, setup accuracy, impedance and operational aspects in view of operation with higher intensity and brightness beams after LS2.

Instead of having one long jaw, the new TDI (called TDIS, where the “S” stands for Segmented) will comprise three shorter absorbers (~1.6 m each) accommodated in separate tanks (see Figure 14-2). The jaws of each module will all be identical except for the active absorber material. For robustness reasons, the two upstream modules will accommodate low-Z graphite absorber blocks (SIGRAFINER R7550, 1.83 g/cm3). The third module is foreseen to host higher-Z absorber materials (Ti6Al4V and CuCr1Zr) to better absorb and efficiently attenuate the particle showers from the low-density upstream blocks.

The correct positioning of the TDIS jaws around the beam is vital for machine protection. Each module will be independently movable and redundant position measurements will be performed and checked via the Beam Interlock (BIS) and the Beam Energy Tracking Systems (BETS). The jaws of the third module will be slightly retracted compared to the upstream jaws to avoid direct beam impact on the higher-Z absorber blocks.

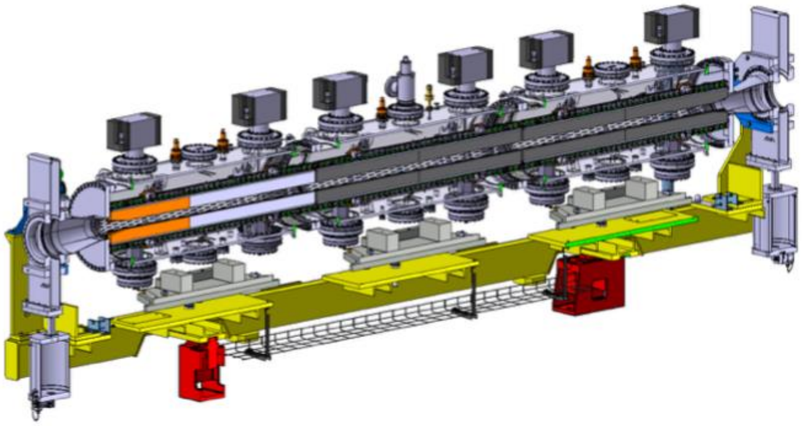

Figure 14-2: The longitudinal cross-section of the new TDIS showing the modules composed by different materials. The first two module jaws, starting from the right side of the figure, are made of graphite R7550 (dark grey), the last module is made of Ti6Al4V (light grey) and CuCr1Zr (orange).

14.2.2 Supplementary shielding of D1 coils

A complementary mask (TCDD in IR2 and TCDDM in IR8) is installed directly in front of the superconducting D1 separation dipole to prevent damage of the coils due to secondary showers from the TDIS in case of MKI failure, see Figure 14-1. Detailed particle simulations [4] showed that the most efficient way to further reduce the energy deposition on D1, and possibly limit the risk of quench, consists in installing additional mask-like stainless-steel protection elements directly inside the insulation vacuum of the D1 cryostat. This solution offers the advantage of intercepting shower particles closer to the magnet without affecting the present machine aperture (Figure 14-3).

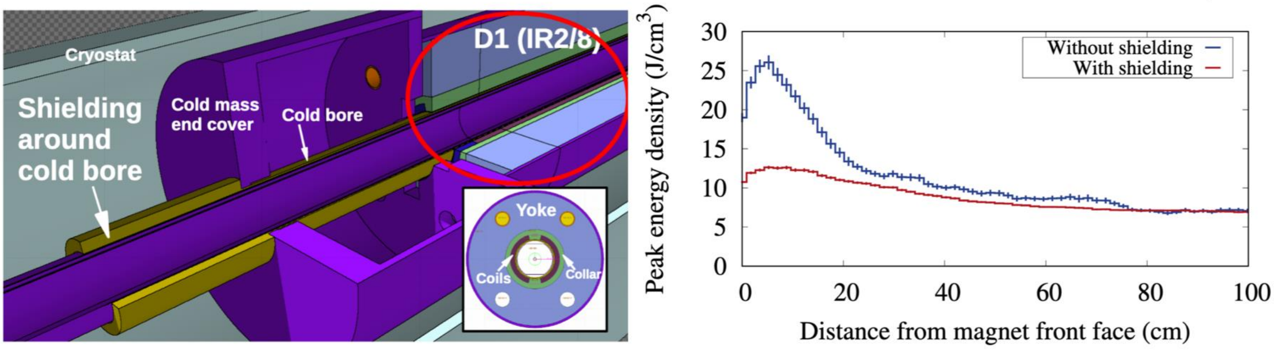

Figure 14-3: 3D model of D1 cryostat where the additional shielding is installed around the cold bore to reduce the energy deposition on the magnet coils in case of injection failure (left). The expected reduction in the peak energy is also shown (right).

14.2.3 Displacement of auxiliary injection protection collimator TCLIA

The TCLIA is an auxiliary collimator which provides additional protection from mis-kicked beam in case of MKI failures. This device is set at an aperture of ±6.8 σ (for the nominal LHC emittance of 3.5 mm mrad) during the injection process. Once the injection is completed and the MKIs are in standby, the TCLIA is opened to parking position in order not to represent anymore an aperture bottleneck. The present maximum aperture at parking (±28 mm) and the longitudinal position of the TCLIA limits the maximum crossing angle to ≤ 60 μrad (Figure 14-4) and thus the Zero-Degree-Calorimeter (ZDC) of ALICE [5]. This is not compatible with operation with 50 ns bunch spacing (i.e. the present baseline for the HL-LHC Pb−Pb physics operation) where an angle ≥ 100 μrad is needed. Studies were performed and it was found that the maximum TCLIA opening can be increased to 59 mm. Moreover, it was decided to move the collimator by 2.2 m towards the IP. These modifications will allow achieving a crossing angle of 102.4 µrad as required for 50 ns bunch spacing operation.

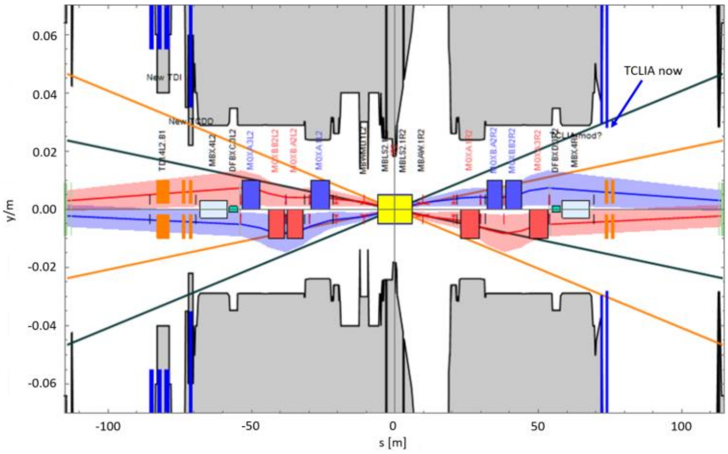

Figure 14-4: IR2 aperture layout and 100 µrad neutron cone from IP2. The present TCLIA, even when fully opened to parking position, is in the line of sight of the ZDC.

14.2.4 Upgrade of the injection kickers MKIs

The injection kicker magnets are transmission line type magnets, each with 33 cells consisting of a U-core ferrite between two high voltage (HV) conducting plates [6]. To limit the longitudinal beam coupling impedance and thus heating, while allowing a fast magnetic field rise-time, an extruded ceramic tube (99.7% alumina) with up to 24 screen conductors lodged in its inner wall is placed within the aperture of each MKI magnet. A set of toroidal ferrite rings is mounted around each end of the alumina tube, outside of the aperture of the magnet to damp low-frequency resonances. To ensure reliable operation of the MKI magnets, the temperature of the ferrite yokes must not exceed their Curie point, which is ~125°C for the ferrite used. At this temperature, the magnetic properties of the ferrite are temporarily compromised, and the beam cannot be injected.

Both the MKI kickers installed in IR2 and IR8 prior to LS1 encountered a number of issues which affected operation. These include beam-induced heating, electrical flashovers, beam losses and electron cloud related vacuum pressure rise [7] with electrical breakdown and surface flash-over. A prototype MKI, with a 50 nm thick Cr_2O_3 coating applied by magnetron sputtering to the inner part of the alumina tube, was installed in IR8 during the winter stop between 2017 and 2018 [8]. A rapid reduction of the dynamic vacuum and faster conditioning with respect to the original design was observed during the scrubbing run and in operation. In addition, the Cr_2O_3 coating has not resulted in a statistically significant change in the number of UFOs (macro particles falling into the beam).

The beam screen of all the MKIs was upgraded during LS1 to allow the full complement of 24 screen conductors to be installed. The modified design allowed the surface flashover rate to be further reduced [6]. The post-LS1 design also resulted in a considerable reduction of beam induced power deposition in the ferrite yoke [9] and no limitation was encountered in operation during Run 2 [10]. A further reduction in the yoke temperature was observed in the IR8 prototype where the beam screen was modified to reduce the total power loss and move the main losses from the yoke to the ferrite rings [11]. Thermal simulations were carried out to confirm that the calculated power losses for Run 2 agreed with the temperatures measured during LHC operation. A good agreement was found and no issues were foreseen since a maximum temperature of 110°C was calculated in the first cell at the upstream end of the upgraded magnet [10]. However, for operation with the HL-LHC type beams, the power deposition in the MKI is expected to be a factor of four greater than for LHC nominal beam parameters, which would be unacceptably high with the existing design [12]. Studies showed that, following the redistribution of power from the yoke to the ferrite rings, an active water cooled system just of the ferrite rings is sufficient to keep the temperature of the full magnet well below 100°C also for the HL-LHC beams [13]. A complete prototype with Cr_2O_3 coated chambers, upgraded beam screen with active cooling of the ferrite rings, the so called “MKI cool” (Figure 14-5 shows the modified beam screen at the beam entrance of the “MKI cool” [6]), will be installed and tested in the LHC for the final validation during Run 3 before launching the upgrade of the full MKI series.

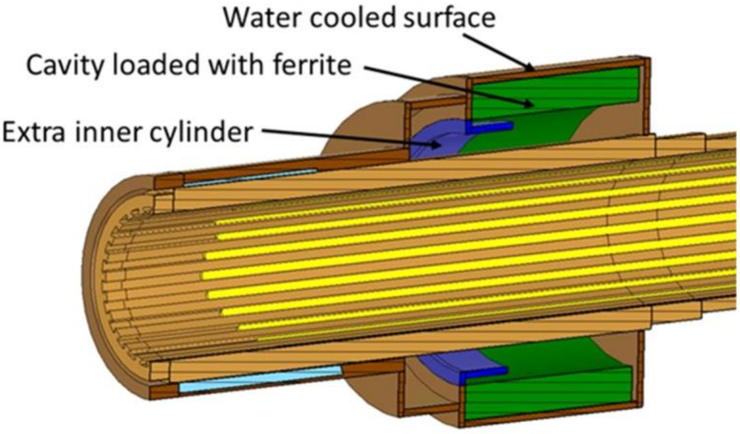

Figure 14-5: Simplified schematic illustration of the upstream end of the beam screen to be implemented in the “MKI Cool” that will be installed during LS2.

14.3 Beam dumping system

Each beam is extracted from the LHC ring, by means of fifteen pulsed extraction kickers (MKD) and DC septum magnets (MSD) located in a dedicated insertion of the LHC (IR6, schematic view in Figure 14-6, towards a long drift chamber and a graphite absorber dump block (TDE). A system of four horizontal (MKBH) and six vertical (MKBV) dilution kickers is powered with anti-phase sinusoidal currents to sweep the beam over the front face of the TDE in order to reduce the deposited energy density.

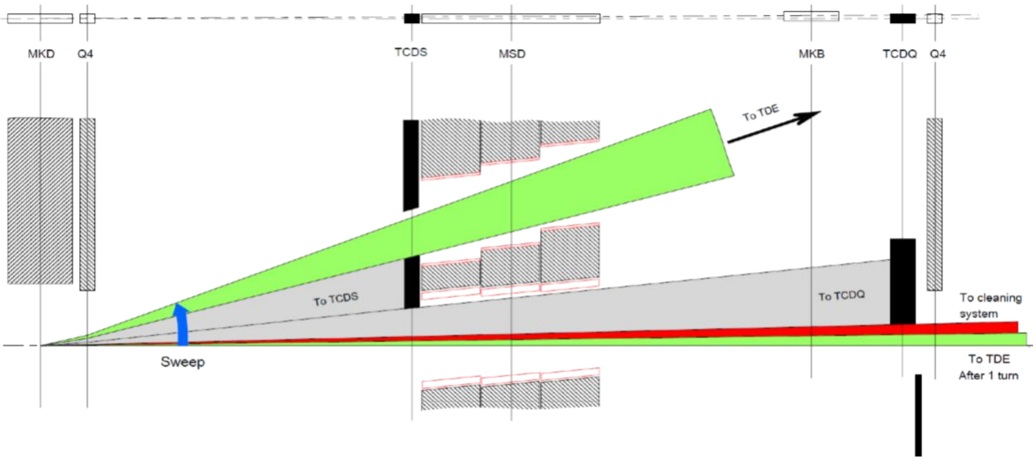

Figure 14-6: Overview of the LHC extraction region (Point 6)

To avoid losses during the rise time of the LHC MKD, a 3 μs long abort gap in the circulating bunch pattern is kept free of particles. So-called asynchronous beam dumps can be caused by loss of synchronisation of the MKD rise time with the abort gap, e.g. in case of failure of the Trigger Synchronisation Unit (TSU), or by the erratic pre-firing of an extraction kicker. In these cases, the beam can be swept over the machine aperture and dedicated absorber blocks are installed in the LHC extraction region to protect the down-stream elements.

14.3.1 Beam dump system absorbers TCDQ and TCDS

Several failure modes exist in the synchronization system and in the kicker switches that could lead to an asynchronous dump where part of the beam would be swept across the LHC aperture. Without dedicated protection devices this would lead to massive damages. The protection devices against asynchronous beam dump damages are: the TCDS, which is a fixed absorber that directly protects the downstream extraction septum MSD and the TCDQ, which is a movable absorber that protects the superconducting quadrupole Q4 and further downstream elements, including the arc and the tertiary collimators (TCTs) around the experiments. A fixed mask (TCDQM) is installed right upstream of Q4 to intercept secondary particle showers and thus reduce the energy deposition in the superconducting coils. The TCDQ was already upgraded in LS1. The new design, which is described in detail in Ref. [14], includes an extension of the absorber length from 6 m to 9 m, and the replacement of the higher density graphite absorber material with different grades (1.4 g/cm^3 and 1.8 g/cm^3) of carbon fibre composites (CfC). This design was supposed to be compatible with operation with the HL-LHC beams. During the reliability runs performed in 2015 a new type of MKD erratic firing (Type 2), with a different rise time than the standard one (Type 1), was identified. This case is more critical since a higher number of bunches can impact the TCDQ with a large density close to the jaw surface (see Figure 14-6). New studies were carried out to verify the robustness of the TCDQ also for this new failure scenario. Depending on the optics, the TCDQ jaw will have to be set at an aperture which could vary between 2.5 mm and 3.9 mm. No damage is expected if the TCDQ sits at ≥ 3 mm from the beam while, for smaller gaps, the peak dose could go above 2.7 kJ/g (Figure 14-7) corresponding to a temperature ≥ 1500°C. The present knowledge of the material properties at such temperature is quite poor and does not allow to exclude possible failures. A further TCDQ upgrade is not part of the HL-LHC baseline and presently, alternative mitigations (i.e. Type 2 erratic prevention, improved monitoring of the local orbit, suitable optics conditions, etc.) are being evaluated.

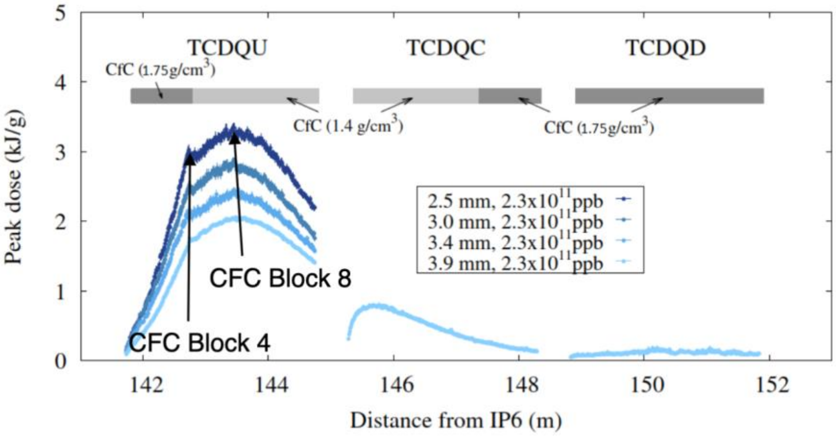

Figure 14-7: Peak dose along the TCDQ modules in case of asynchronous beam dump with the TCDQ sitting at different apertures depending on the optics requirements.

The BETS monitors the position of the TCDQ as a function of the beam energy. This HW interlock was implemented in LS1 to have a redundant check of the TCDQ positioning in case of failure of the standard control system. This forbids moving the TCDQ outside pre-defined thresholds at fixed energy and might be a limitation for the ATS optics when the β-function at the TCDQ changes during the squeeze and the protection element should vary its position accordingly. In case this affects the HL-LHC β* reach, the BETS should be upgraded to allow for TCDQ movements during the squeeze. This activity is not part of the present baseline.

The robustness of the TCDS and the protection of the MSD magnets, in case of an asynchronous beam dump with the full intensity HL-LHC beams, was verified for all types of erratics. A maximum energy density of 2.5 kJ/cm^3 (giving a maximum temperature of ~1150°C) was calculated in the low-density blocks (graphite and CFC) and of ≥ 1 kJ/cm^3 in the Ti block. Thermo-mechanical studies indicate that the Ti block will experience plastic deformation and some low-Z blocks could fail due to the high stresses and elevated temperatures reached. The calculated energy deposition at the first downstream MSD septum corresponds to a temperature increase of less than 100 K (∼130°C absolute temperature). This temperature is not critical concerning possible changes in the magnetic properties of the steel (up to 150°C is considered acceptable). Moreover, the peak temperature is reached in a peripheral part of the yoke so that no issue is expected for the insulation of the coils. Further studies are needed to evaluate if a temperature increase of up to 100 K could induce a deformation of the vacuum chamber of the circulating beam. Moreover, FLUKA and ANSYS calculations have to be performed to quantify the temperature increase of the water in the MSD cooling pipes and thus to evaluate the pressure rise and the consequent risk of shock-waves. The TCDS upgrade is included in the HL-LHC baseline.

14.3.2 The beam dump TDE

The LHC beam dump consists of an upstream window made of carbon-carbon composite on a thin stainless steel foil, a ~8 m long graphite dump core, a downstream Ti window and is kept under N_2 gas at higher than atmospheric pressure. The TDE and its entrance and exit windows will need to withstand the repeated dumps of high intensity HL-LHC beams. Simulation studies show that, in case of a regular dump of the HL-LHC beams a peak temperature of ∼1800°C (a factor ∼2 higher than for the LHC Run 2 beams) will be reached in the core. In case of failure of the dilution kickers, the sweep pattern is altered (Figure 14-8) and significantly higher temperatures and stresses can be reached. The originally assumed worst case failure scenario was the loss of two MKBs due to either the erratic firing of one kicker and perfect phase opposition with the remaining ones or a flashover simultaneously affecting two MKBs sharing the same vacuum tank. 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. In case of two missing horizontal MKBs, the peak temperature can go up to 2800°C for these failure cases. No information is available about the core material behaviour at this temperature and mechanical characterisation studies are being performed to evaluate if any modification of the present design is needed.

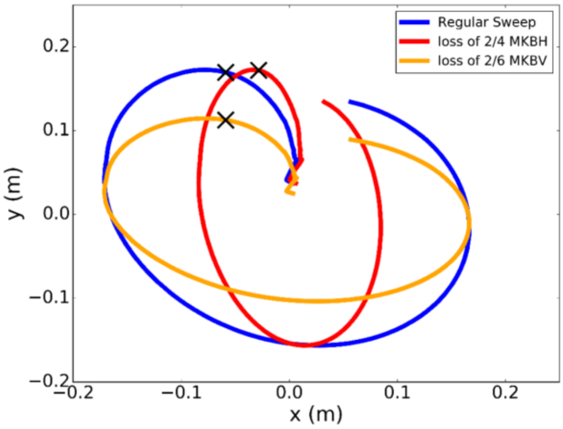

Figure 14-8: Simulated beam sweep patterns at the dump for a regular sweep (blue) and the failure cases of 2 out of 4 horizontal (red) and 2 out of 6 vertical dilution kickers missing (orange). The positions of highest energy deposition are marked with a black cross.

The expected stress level at the present windows, also in nominal operational conditions, would be too high to insure a long term and reliable operation with the HL-LHC beams. For this reason, they will be upgraded already in Run 3 to ensure their survival also in case of dumps with two missing MKBs.

Moreover, during Run 2, a series of N_2 leaks appeared at the flange connections and were ascribed to large vibrations of the whole dump due to beam energy transfer during high intensity dumps.

No dump upgrade was originally included in the HL-LHC baseline since detailed studies, identifying weaknesses and defining needed modifications, were missing. Studies evaluating all limitations are under way and the goal is to have all the information required for defining the complete upgrade strategy at hand by 2021 in order to define the upgrade layout and to be ready for installation in LS3. The HL-LHC project committed to upgrade the dump with the help of the Russian in-kind contribution.

14.4 LBDS kickers, generators, and control system

A number of erratic triggers due to electric breakdowns and unexpected failures were encountered during reliability runs, tests and operation with beam of the LBDS kickers.

The breakdowns were located at regions with large electrical fields of around 3 MV/m at the edges of the insulators in the generators. A redesign of the switch stacks of the MKD generators is ongoing with the aim of keeping the electrical field below 1.5 MV/m in all areas in order to allow reliable operation at 7 TeV. Moreover, the upgraded system is compatible with operation at the ultimate energy of 7.5 TeV. The replacement of the generator switch stacks is foreseen for LS2. Simultaneously, the power triggering and re-triggering system of the MKD switches will be upgraded. The power triggers are presently rated at a current of 500 A and a dI/dt of 400 A/µs for a voltage of 3.5 kV. The upgraded system will double the current and almost double the dI/dt for a reduced voltage of 3.0 kV. The new parameters are better in line with the specifications of the manufacturer, will increase the lifetime of the GTO switches, will result in a shorter rise time, and will make the power trigger less sensitive to radiation. The re-trigger system triggers all the extraction and dilution kickers as quickly as possible in case of an erratic closing of an extraction kicker switch. The present re-trigger delay is about 900 ns and the aim is to try to reduce it even further to minimise the load on the TCDQ and the ring elements, in particular the tertiary collimators, in case of an asynchronous dump. Also the diagnostic tool (IPOC [15]) will be upgraded and a sparking activity surveillance system will be implemented to monitor the status of the generators, allow to react in case of signs of nonconformity and provide statistics for a better understanding of the correlation between sparks and erratics. At the same time, the electronics of the re-triggering system, which is becoming obsolete, will be replaced.

Beside Type 2 erratics for the MKDs, unexpected failures affected also the dilution kickers. In particular, the parasitic electromagnetic coupling, through the re-triggering line, caused the firing of neighbouring MKB generators [16]. This event, combined with anti-phase could determine the loss of more than two MKBs, which was identified as the worst failure scenario in the original design of the system.

Moreover, up to three MKBVs were lost, on one occasion, due to a flash-over propagation with some delay and anti-phase in two kickers sharing the same vacuum tank. All these cases might have dramatic effects on the beam dump when operating with the HL-LHC beams, in particular in case of MKBH failures. Different upgrade scenarios for the dilution system are being considered [17]. The MKBH generators will be upgraded to reduce their operational voltage (presently higher than the MKBV voltage due to the lower number of MKBHs). A new re-triggering system for all the MKBs will be put in place to eliminate the risk of anti-phase in case of erratics. Different sweep patterns are then expected at the dump depending on the delay between the erratic and the execution of a synchronous dump as shown in Figure 14-9. The consequent energy deposition on the dump windows and the core are being evaluated for all possible relative delays. Finally, it is proposed to install two additional MKBHs per beam since this is the only fully reliable solution to reduce the risk and the sensitivity to any possible failure and opens the possibility to increase the nominal sweep pattern to reduce the stresses on the dump also during nominal operation. The HL-LHC project has approved the upgrade and implemented it through the Russian in-kind contribution. The installation is foreseen for LS3.

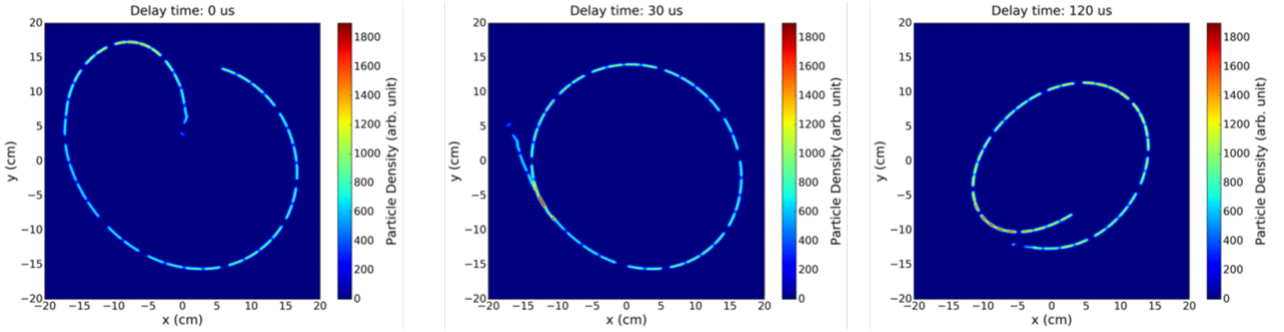

Figure 14-9: Simulated sweep patterns in case of MKB re-triggering for different delays between the erratic event and the synchronous dump execution.

14.5 Acknowledgments

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