LBDS PERFORMANCE IN RUN II

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Abstract

The performance of the LHC Beam Dump System (LBDS) during Run II beam operations are presented in terms of rate and type of failures of the extraction (MKB) and dump (MKD) kickers. New faults were also identified and they are described together with their impact on the beam distribution at the dump protection elements and the TDE assembly. Foreseen and proposed mitigations, on the MKB/MKD magnets, generators, and controls, in order to minimise possible beam intensity and brightness limitations, are addressed. The reasons and functionality of the BETS TCDQ are reminded together with the present operational constraints, which will still hold in Run III. Main changes and issues encountered with the XPOC analysis and acknowledgment procedure are treated. Updates are given on the operational experience with the variable AGK after the accidental injection of bunches in the abort gap in 2017. The evolution of the execution and validation procedure for the asynchronous beam dump test and the further planned improvements are covered. Finally, recommendations are given for a proper scheduling of the LBDS commissioning time after LS2.

INTRODUCTION

The LHC extraction system consists of fifteen horizontal kickers (MKD) and fifteen septa (MSD) which deflect the circulating beam into the extraction line towards the dump (TDE) any time a beam abort request is triggered. The extracted beam is then painted on to the dump by means of four horizontal (MKBH) and six vertical (MKBV) dilution kickers. In normal operation the rise time of the extraction kickers is synchronised with a beam free region, the so called abort gap, to prevent mis-kicking bunches which would then be lost in the machine. Several failure modes exist in the synchronisation 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.

When one MKD fires erratically, all the other kickers are triggered, within 1.3 μs, without any further synchronisation with the RF, to avoid that the pre-fired module kicks the full beam directly into the TCDQ. Thus, for the pre-fire case, the rising edge of the global MKD waveform becomes shallower and more particles are transmitted into the ring than in case of a simple loss of synchronisation.

The loss of two MKBs, either due to erratic firing of one kicker and perfect phase opposition with respect to the other kickers or due to a simultaneous flash-over affecting the magnets sharing the same vacuum tank, was considered as the worst failure scenario for the dilution kickers. 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.

RUN I FINDINGS AND LS1 ACTIVITIES

Safety holes were found in the LBDS powering system logic in Run I (possible self-triggering of two MKD generators, lack of redundancy and unreliability of WIENER power supplies, common failure mode of VME and 12 V DC power feed line of the TSU crate with consequent risk of no dump execution in case of request). Moreover, a high rate of electrostatic discharges in the GTO stacks, with possible spontaneous MKD/MKB triggers, limited operation to $\leq$5 TeV.

Several upgrades were put in place in LS1 to increase reliability (reduce the rate of spontaneous MKD triggers), safety and resistance to radiation (details in [1]). Further improvements concerned the power distribution architecture and the Trigger Synchronisation Unit (TSU) which is now fully redundant and equipped with an internal surveillance. A direct connection was created between the LBDS re-triggering system and the BIS to insures that, in case of problem with the Triggering Synchronisation and Distribution System (TSDS), the beam is dumped, even if asynchronously with respect to the RF system. The two missing MKBV vere installed in the dump line to accomplish the nominal painting on the TDE. A third module was added to the existing TCDQ and the graphite was replaced by Carbon Fibre reinforced Carbon (CFC) to be compatible with operation with HL-LHC beams [2]. The control and the survey system of the TCDQ were deployed on separate PLCs. The TCDQ position was integrated in the BETS and interlocked to add another layer of protection.

RUN II PERFORMANCE

After LS1 the beam energy at physics was increased from 4 TeV up to 6.5 TeV. The consequently higher operational voltage resulted in an increased number of MKD/MKB failures during the first years of Run II, as shown in Fig. 1. One asynchronous beam dump (MKD pre-firing) occurred in 2015 with four nominal bunches in the machine. None of them was kicked by the rising edge of the extraction kickers and the beam was cleanly extracted. A high rate of spontaneous triggers of the horizontal dilution kickers was recorded in 2015 and a clear correlation between dirt and sparking

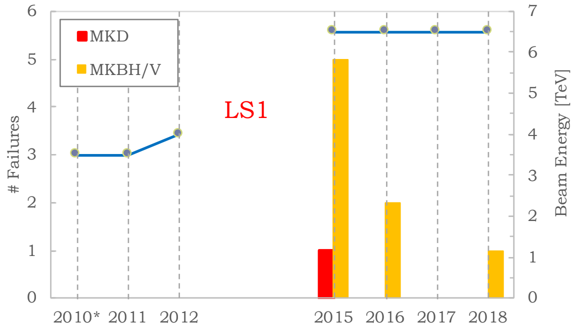

Figure 1: Number of failures with beam at top energy (erratics and/or flashover) of the MKD (red bars) and MKB (orange bars) magnets over the different years of LHC operation. To be noticed that after LS1 the beam energy in physics, and thus the kicker operational voltage, increased from 4 TeV up to 6.5 TeV (right y-axis).

activity in the generators was found. An improved cleaning procedure, better sealing and dust traps at all the MKBH generators plus the implementation of a lower value resistor on the GTO gate-cathode allowed reducing the flashover rate. No new erratic was recorded since EYETS 2016/2017 while two MKBVs were affected by a flashover on July 14^{th} 2018. An unexpected 10 μs delay characterised the propagation of the flashover between the two magnets and, due to anti-phase, resulted in the loss of more than two MKBVs. This and other unforeseen failure types of the LBDS kickers are described in the following.

New LBDS Kickers Failures and Mitigatons

During the reliability runs performed in 2015 a new type of MKD erratic (Type 2), with a different rise time than the standard one (Type 1), was identified (see Figure 2). The bunches are almost uniformly swept at the TCDS for both failure scenarios. On the other hand, the number of bunches and the density of particles at the TCDQ strongly depend on the effective position of the jaw with respect to the beam centre and on the erratic type. Type 2 is much more critical than Type 1 and, depending on the optics and required TCDQ settings, there could be a limitation in the maximum allowed bunch intensity if Type 2 erratic cannot be prevented or no further HW upgrade is implemented.

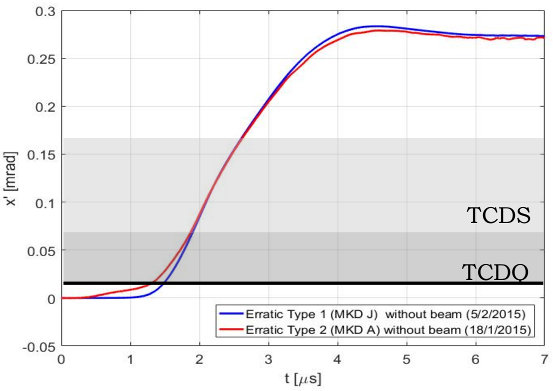

Figure 2: Resulting MKD waveform in case of Type 1 and Type 2 erratic. The grey areas define the range of kicks sweeping the beam either on the TCDQ (dark grey) or the TCDS (light grey).

During tests without beam at 7 TeV, some parasitic electromagnetic coupling, through the re-triggering line, caused the firing of the neighboring MKB generators [3]. This event, combined with anti-phase could determine the loss of more than two MKBs (Fig.3). Moreover, up to three MKBVs were lost, at one occasion, due to the previously mentioned flash-over propagation with delay and anti-phase in two kickers sharing the same vacuum tank (Fig. 4). All these cases might have dramatic effects on the beam dump when operating with high intensity beams, in particular in case of MKBH failures [4]. Different upgrade scenarios for the dilution system are being considered [5]. The MKBH generators will

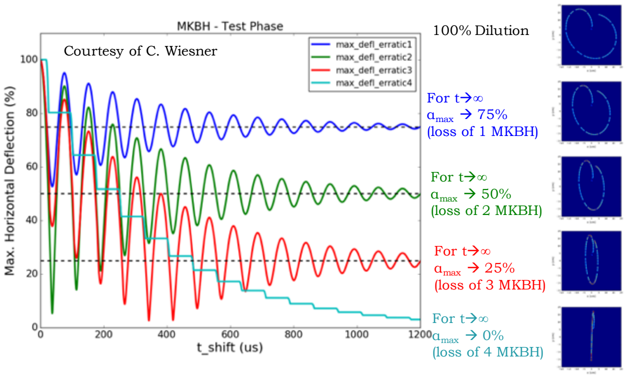

Figure 3: Resulting waveforms in case of erratic in one (blue), two (green), three (red) or four (cyan) MKBHs as a function of the delay between the failure and the beam dump execution. As an effect of the phase opposition, it is possible to loose more than two MKBHs and this strongly affect the sweep pattern and the energy deposition on the beam dump.

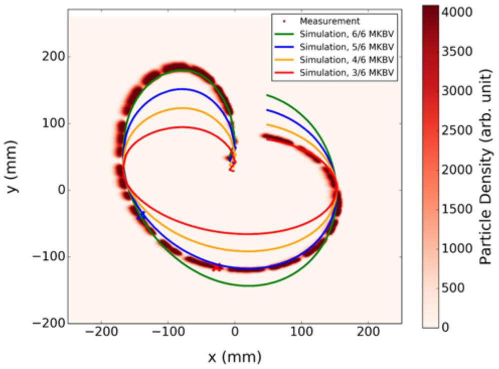

Figure 4: Simulated beam sweep patterns at the dump for a regular sweep (green) and the failure cases with one (blue), two (orange) and three (red) missing MKBVs. The measured beam distribution during the flashover occurred on July 14^{th} 2018 is also shown.

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 5. 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 open the possibility to increase the nominal sweep pattern to reduce the stresses on the dump also during nominal operation. Also the diagnostic tool (IPOC) will be upgraded and a sparking activity surveillance system will be implemented to monitor the status of the generators, allow reacting in case of signs of non-conformity and provide statistics for a better understanding of the correlation between sparks and erratics.

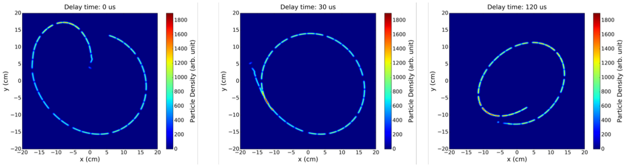

Figure 5: Simulated sweep patterns in case of MKB re-triggering for different delays (0 μs , 30 μs and 150 μs from left to right) between the erratic event and the synchronous dump execution.

All the changes and upgrades foreseen for the LBDS kickers require that adequate time is allocated and insured for the commissioning without and with beam before the next Run. This will allow to have enough time for reaction in case of problems and non-conformities without impacting the machine availability.

THE ABORT GAP KEEPER

The Abort Gap Keeper (AGK) window is given by the sum of the abort gap and the maximum injected bunch train length, which corresponds to the injection kicker (MKI) flattop. Originally a hard-coded AGK was used that was fixed for a certain number of injected bunches (nominally 288). Since 2017 it was possible to regenerate the AGK window via software. This allowed to adapt the different filling schemes to the maximum injected train length and maximise the number of stored bunches. A revised procedure was released after an accidental injection of eight bunches in the abort gap and additional checks were implemented in the Software Interlock System (SIS) which blocks injections in case all the requested conditions are not matched (details in [6]). Since then no more accident occurred.

ASYNCHRONOUS BEAM DUMP TESTS

Checks are periodically performed to validate the settings of the dump protection elements and insure that no damage occurs in the machine in case of an asynchronous beam dump. These tests consist in letting the beam de-bunch and populate the abort gap by switching the RF cavities off. A beam dump is then triggered and losses in the extraction region and at sensitive locations of the machine are checked. These tests are of vital importance for machine protection and detailed procedures [7] were provided to the operation team to insure that they are correctly performed. A key element is the definition of the waiting time between RF-OFF and the dump since it determines the particle distribution in the abort gap and this corresponds to different loss regions in the machine (Fig. 6). The analysis of each dump is done offline by using a Python script which checks the position of all collimators, the beam orbit at the TCDQ and, based on the measured particle distribution in the abort gap and the MKD waveform, predicts the expected losses at the different locations. The losses measured at critical components (e.g. tertiary collimators TCTs) are then compared with reference tests which were previously performed in equivalent conditions. The main limitation of this procedure consists in the need of a past measured reference to complete the validation. As a next step, one-turn tracking simulations will be instead performed to predict the expected loss location along the ring and will be used for comparison with measurements.

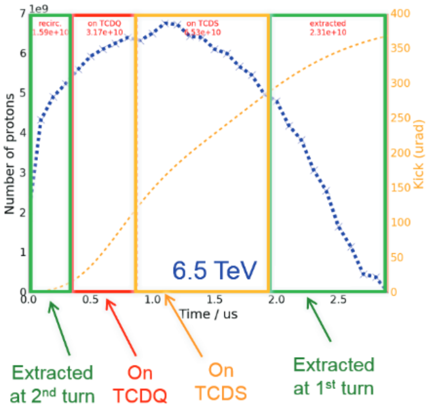

Figure 6: Abort-gap population as measured during an Asynchronous Beam Dump Test (blue curve). The regions corresponding to particles hitting theTCDQ or the TCDS, and particles extracted at the first or second turn, are highlighted. The expected kick from the MKD is depicted in orange.

BETS TCDQ

The Beam Energy Tracking System (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 [1]. Any movement of the TCDQ outside pre-defined thresholds at fixed energy is forbidden.

This clashes with the ATS optics since the β-function at the TCDQ changes during the squeeze and the protection element should vary its position accordingly. During Run II this problem was overcome by setting the TCDQ and the BETS limits at the end of the energy ramp already at the position required during physics (i.e. 7.3 σ) as shown in Fig. 7. This implied that, due to the different optics, at the end of the ramp the TCDQ of Beam 1 and Beam 2 were sitting at a different aperture (7.9 σ and 7.4 σ respectively) which was slightly larger than the ideal nominal settings. Nevertheless, the hierarchy of the full collimation system was preserved and the machine aperture protected during all the operational phases. No upgrade of the BETS will be possible in LS2 and the present constraints will still old for the next Run. In case this will affect the HL-LHC β^* reach, the system should be upgraded to allow for TCDQ movements during the squeeze.

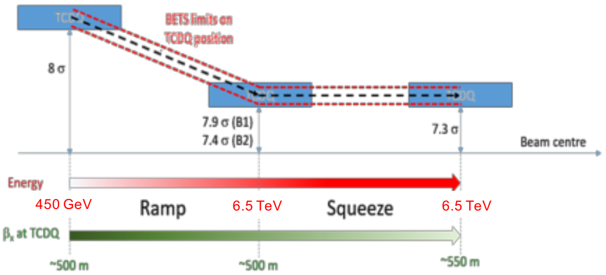

Figure 7: Schematic view of the TCDQ position during the energy ramp and the β^* squeeze

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XPOC

The various signals of the beam dump control systems and beam instrumentation measurements are automatically analysed, after every dump, by the eXternal Post-Operational Checks (XPOC) system. In case of non-conformities, operation is blocked until the problem is understood and the system reset by operators, only for non-critical systems (BLM and context), and by the LBDS experts (kickers, generators, TSU, etc.). In general XPOC worked reliably and allowed to diagnose and solve major problems insuring a safe operation of the machine without limiting its availability. The encountered issues were due to missing or corrupted data, mainly from masked channels (BTVDD, BCT, etc.), wrong operation (RF resynchronisation with LBDS armed inducing a TSU faults), noisy pickups and residual magnetisation of the MKD capacitor box which determined a fault for every dump at 450 GeV after a long fill at top energy. Improved signals from diagnostics and better grounding should fix the mentioned problems; no change in the acknowledgment logic and roles is foreseen.

CONCLUSION

The LBDS is one of the most critical LHC machine protection systems. A few kicker failures per year (erratics and flashover) occurred and cannot be excluded in the future, especially when operating at higher energy (higher voltage). Some mitigations were already put in place and others are already part of the HL-LHC upgrade program. Weaknesses and new kicker failure types were identified during the past Runs which increase the beam load on dump protection elements and the TDE. The installation of two additional MKBHs per beam and possible further upgrades of the TCDS, TCDQ and TDE are being evaluated. These activities cannot be completed before the end of LS3 and an impact on the intensity and brightness reach in Run III is expected.

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