BEAM BASED MEASUREMENTS TO CHECK INTEGRITY OF LHC DUMP PROTECTION ELEMENTS

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Abstract

LHC operation is approaching its operating goals and several upgrades are also being prepared to increase the beam intensity and brightness. In case of an asynchronous beam dump at 6.5 - 7 TeV a non-negligible fraction of the total stored energy (360 MJ during nominal operation) will be deposited on the protection elements located downstream of the extraction kickers. These elements are designed to protect the machine aperture from the large amplitude particles resulting from the asynchronous dump. A number of checks and measurements with beam have been worked out to verify the integrity of these elements, after a potentially harmful event, without opening the machine vacuum. Details on measurements performed to evaluate the validity of the proposed method are presented in this paper.

INTRODUCTION

The LHC beam dump system [1] is formed by 15 extraction kicker magnets (MKD) which deflect horizontally the beam towards a set of 15 steel septum magnets (MSD). The beam is then painted, by means of 10 dilution kickers, onto special graphite absorber blocks (TDE). The LHC is filled with trains of up to 288 consecutive bunches at the time, which are separated by 25 ns. The unfilled space between the first and the last injected train defines the abort gap and corresponds to 3 μs (120 bunches). This larger gap between bunches allows the rise time of the MKDs which must be triggered simultaneously and with the correct phase with respect to the beam abort gap to achieve a loss-free extraction. If the synchronization with the abort gap is lost or in case of a random pre-trigger of one kicker, followed by the simultaneous re-triggering of the remaining modules, some bunches are swept across the machine aperture. Protection elements, called TCDS and TCDQ [2,3], are installed after the MKDs to shield the aperture of the septa and the downstream superconducting quadrupoles (MQY4) during an asynchronous beam dump. An additional collimator (TCSP) is installed immediately after the TCDQ and allows to precisely define the horizontal beam position at this location providing further collimation of the secondary halo. A fixed mask just upstream of the MQY4 (TCDQM) intercepts the electromagnetic showers generated at the TCDQ and TCSP.

BEAM LOAD ON TCDQ AND TCDS

The LHC was designed for operation at 7 TeV with up to 2808 bunches of $1.15 \cdot 10^{11}$ protons each, corresponding to a total stored energy of ~360 MJ (129 kJ per bunch). In 2016 the LHC will operate at 6.5 TeV and with 2740 stored bunches, i.e. very close to the design values. During an asynchronous beam dump, part of this energy is deposited on the TCDS and the TCDQ. The number of intercepted bunches and their distribution on the absorber jaws depend on the failure scenario and the jaw positions. The TCDS is two-sided and delimits an aperture of ±15 mm in the extraction channel. One of the two jaws is seen also by the circulating beam; the upstream and downstream ends sit at a fixed position of 16.3 mm and 17.2 mm respectively. The TCDQ is single sided, is installed in the ring on the extraction side and, at top energy, is set at ~8 σ (i.e. ~4 mm for a normalised emittance $\varepsilon_n = 3.5$ μm). In case of loss of synchronisation with the abort gap, but correct functionality of the MKDs, the bunches are kicked following the nominal waveform (see Fig. 1). If one kicker undergoes a spontaneous trigger, the start of the MKD rise-time is slower and, as a consequence, more bunches are mis-kicked (see Fig.1). During the reliability runs performed in 2015 a new type of erratic (Type 2 in Fig. 1), with a different rise time than a standard one (Type 1), was identified.

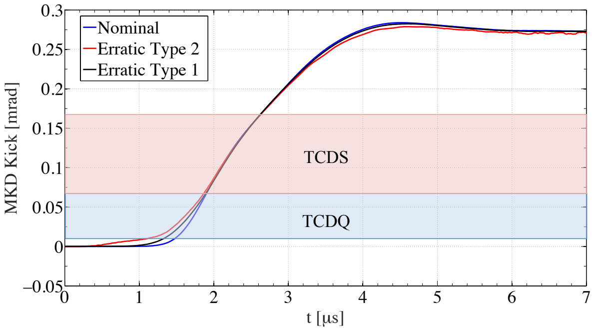

Figure 1: MKD waveform in case of synchronous triggering of all 15 kickers (Nominal) and of pre-triggering of one module (Erratic Type 1 and Type 2). Two regions are highlighted and refer to the kicks sending the bunches either on the TCDQ or the TCDS during an asynchronous beam dump.

Particles kicked with less than 10 μrad escape the TCDQ and are extracted at the following turn. The number of bunches impacting the TCDQ varies, depending on the failure scenario, from 16 to 32 (kick between 10 μrad and 70 μrad) with an uncertainty of ± 2 bunches. The particle density at this element depends on the erratic type as shown in Fig. 2. The TCDS has a width of 23 mm and intercepts all the bunches kicked within 70 μrad and 170 μrad, particles with a larger amplitude are correctly extracted. The MKD rise-time in this range is faster and 28±2 bunches are almost uniformly distributed on the TCDS in all the scenarios. The highest energy deposition (3.8 MJ for 32 bunches at 6.5 TeV) occurs at the TCDQ with a maximum close to the jaw surface, in particular for Type 2 erratics.

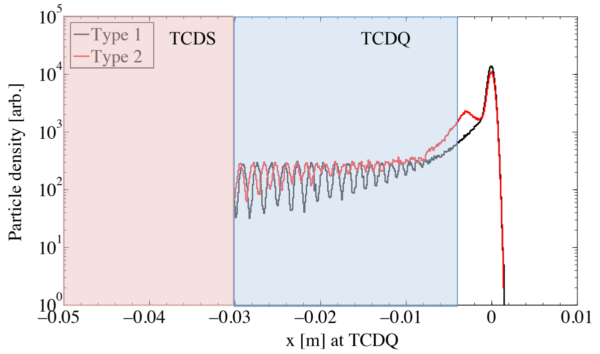

Figure 2: Calculated particle density (in arbitrary units) at the TCDQ for different amplitudes and erratic types. The areas corresponding to particles intercepted by the TCDQ is highlighted. The distribution is cut at the amplitude where losses on the TCDS (red area) take over.

An increase of the intensity up to $2.3 \cdot 10^{11}$ protons per bunch and operation at 7 TeV are foreseen for the HL-LHC era. The stored energy per bunch will increase accordingly with up to ~8 MJ deposited on the TCDQ in case of an MKD erratic. Moreover the beam emittance will be reduced by 40% with a consequent increase of the energy density. The TCDQ was upgraded during the Long Shutdown 1 (LS1) to withstand impacts of up to $2.5 \cdot 10^{11}$ protons per bunch in case of a Type 1 erratic. Studies are being performed to validate the robustness of the TCDQ and TCDS jaws for all failures and smaller beam sizes.

REFERENCE MEASUREMENTS

Only one asynchronous beam dump at 6.5 TeV occurred in 2015. The machine was almost empty and no bunch saw the MKD rising edge. Nevertheless reliability studies allowed to estimate up to three asynchronous dumps per beam per year [4]. Checks and measurements have to be periodically carried out to define a reference which could be used after a potentially harmful event to verify the integrity of the TCDQ and TCDS without opening the machine vacuum.

Preliminary Checks

After an asynchronous beam dump at high energy and intensity, a visual inspection of the extraction system in the LHC tunnel should be done to evaluate the status of the water cooling connections, the feedthroughs and the vacuum bellows. The local activation of the protection elements should be measured and compared with the RP surveys which are regularly performed at each Technical Stop (TS). The movements of the TCDQ jaw and the response of the position sensors can be remotely verified from the Cern Control Centre (CCC). No anomaly and no vacuum activity should be observed while moving the TCDQs without beam.

Aperture Measurements

Aperture measurements of the dump region are part of the standard machine protection tests which are carried out after a LS. They allow to evaluate the effective available aperture and could be used to localise unexpected aperture restrictions after an asynchronous beam dump. The ring aperture is measured with one circulating pilot bunch of $5{\cdot}10^9$ protons. A beam edge is defined by exciting the bunch with the tune measurement kickers (MKQ) until is cut by the primary collimators set at 5.7 σ. A local bump is applied to the beam orbit and the amplitude is increased until losses appear at a certain location. Two different kind of bumps are used to scan the aperture at the main elements. The measurements are repeated both in the horizontal (H) and vertical (V) plane. The results are presented in Table 1 and refer to the bump amplitude at the element where losses appeared at first. The aperture is calculated adding the 5.7 σ beam envelope to the bump amplitude: ~6 mm at the TCDS and ~10 mm at the TCDQM and MQY4. An H aperture of about +16.5 mm at the TCDS and -24 mm at the TCDQM can be calculated. The V aperture is limited by the MQY4 at ±24 mm .

Table 1: H and V Bump Amplitude Determining Losses at the Related Elements. The 5.7 σ beam envelope size has to be added to evaluate the available aperture.

	Beam 1	
H	+10.4 mm at TCDS	-14.0 mm at TCDQM
V	+13.0 mm at MQY4	-13.0 mm at MQY4
	Beam 2	
H	+11.2 mm at TCDS	-13.0 mm at TCDQM
V	+14.0 mm at MQY4	-15.0 mm at MQY4

The extraction line aperture is measured, always with a pilot bunch, only in the H plane. Orbit correctors are used to simulate the extraction with 15±N MKDs. Losses were recorded for N = 2 corresponding to a full aperture of 13 mm + 2 × 5.7 σ = 25 mm.

Transmission Measurements

A set of measurements was worked out to try to quantify the beam transmission through the TCDQ in nominal conditions. If a clear reference could be established, it might be used to detect a critical deterioration of the TCDQ jaw material due to a high energy deposition during an asynchronous beam dump. A schematic view of the used setup measurement is shown in Fig. 3. The TCSP jaw which sits on the extraction side is aligned on the measured beam centre in order to cut half of the incoming beam. The other jaw is fully open at -25 mm. The TCDQ is retracted by 1 σ (i.e. 2 mm at 450 GeV and for ε_n = 3.5 μm) with respect to the TCSP. A pilot bunch is injected and extracted after one turn to ensure that it hits the jaws only once. The measurements are repeated applying a local orbit bump of increasing amplitude (i.e. 2 mm, 4 mm and 6 mm). The TCDQ jaw is tilted with different angles (from -1 mrad to +1 mrad with 0.5 mrad steps) always keeping the corner which is closer to the beam at 2 mm (see Fig. 3). The same procedure of impacting the jaws with increasing bump amplitudes is reiterated for every

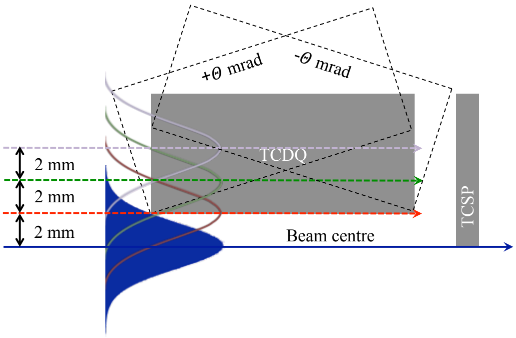

Figure 3: Schematic view of the setup used for the TCDQ transmission measurements.

angle. The ratio between the losses at the TCSP and the TCDQ is recorded for each setting.

These measurements were performed twice (in 2015 and 2016 during the LHC beam re-commissioning) and the results are shown in Fig. 4. The average between the two measurements is plotted and the error bar indicates the discrepancy between the average and the measurements. The qualitative behaviour of the loss ratio is similar for both beams. For positive tilts, the losses at the TCSP increase with the TCDQ angle due the reduction of the effective jaw length seen by the beam. This is not clearly visible for negative angles due to the smaller distance between the shower source position and the Beam Loss Monitor at the TCSP (less detected particles). A bump of 6 mm corresponds to a 2 σ impact parameter at the TCDQ: only a few percent of the primary protons (2% assuming a perfectly Gaussian beam) escapes the TCDQ and losses at the TCSP are dominated by secondary showers. For smaller amplitudes the contribution of the primary protons becomes more important and the loss response is more sensitive to shot-to-shot trajectory variations. This reflects a non negligible discrepancy between measurements and thus a large error bar. The effect is more evident for Beam 1 due to the unfavourable phase advance between the injection point and the TCDQ (60° with respect to 20° for Beam 2). In order to provide a quantitative reference these measurements need to be repeated several times in a year (e.g. after each Technical Stop) and with a larger statistics (more shots for each setting) to mitigate the shot-to-shot fluctuations. Moreover FLUKA calculations have to be performed to benchmark the measured reference and define which damage level could be assessed with this technique.

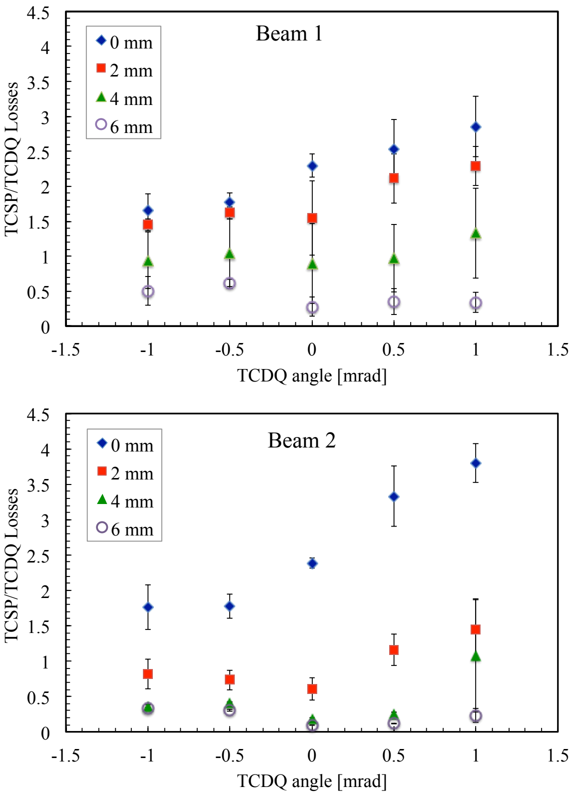

Figure 4: Results of the transmission measurements performed in 2015 and 2016 for Beam 1 (top) and Beam (2). The average between the two measurements is shown and the error bar indicates the discrepancy between the measurements and the average value.

CONCLUSIONS

In case of an MKD erratic, at 6.5 - 7 TeV and with high intensity beams, a non negligible amount of energy will be deposited on the dump protection elements and in particular on the TCDQ. A series of measurements is periodically performed with the goal of providing a quantitative reference to evaluate if any component was damaged during the asynchronous beam dump. The beam transmission through the TCDQ was measured twice in a year. A discrepancy was observed between the two sets of measurements due to a high sensitivity to shot-to-shot trajectory fluctuations. It is proposed to repeat these measurements more regularly during the year and with a higher statistics. FLUKA simulations should be used to validate the reference and evaluate the damage level that could be measured with this technique. The gained experience will be particularly valuable in view of operation with higher intensity and brightness beams during the HL-LHC era.

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