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ASYNCHRONOUS BEAM DUMP TESTS AT LHC*

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Abstract

The detailed understanding of the beam-loss pattern in case of an asynchronous beam dump is essential for the safe operation of the future High Luminosity LHC (HL-LHC) with nearly twice the nominal LHC beam intensity, leading to correspondingly higher energy deposition on the protection elements. An asynchronous beam dump is provoked when the rise time of the extraction kickers is not synchronized to the 3 µs long particle-free abort gap. Thus, particles that are not absorbed by dedicated protection elements can be lost on the machine aperture. Since asynchronous beam dumps are among the most critical failure cases of the LHC, experimental tests at low intensity are performed routinely. This paper reviews recent asynchronous beam dump tests performed in the LHC. It describes the test conditions, discusses the beam-loss behaviour and presents simulation and measurement results. In particular, it examines a test event from May 2016, which led to the quench of four superconducting magnets in the extraction region and which was studied by a dedicated beam experiment in December 2017.

INTRODUCTION

To avoid losses during the rise time of the LHC extraction kickers (MKD), a 3 µs long abort gap in the circulating beam 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 is swept over the machine aperture by the rising edge of the MKD fields. Therefore, dedicated diluter blocks are installed in the LHC extraction region (Point 6) to protect the downstream elements. This includes the TCDQ, which is located upstream of the Q4 quadrupole, and the TCDS, which is located upstream of the extraction septa (MSD). An overview of the LHC extraction region is shown in Fig. 1.

ASYNCHRONOUS BEAM DUMP TESTS

Dedicated asynchronous beam dumps tests at low intensity are performed routinely at LHC [1]. For these tests, a single bunch is injected in Bucket 1 close to the abort gap. An initial bunch intensity of $1 \cdot 10^{10}$ to $5 \cdot 10^{10}$ protons is required in order to assure a clear signal, without risking to quench magnets.

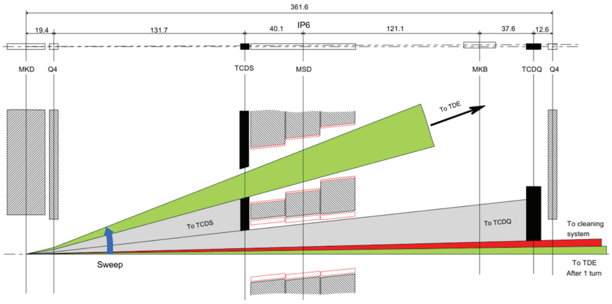

Figure 1: Overview of the TCDQ and TCDS diluter blocks in the LHC extraction region (Point 6) [2].

In addition, the beam is bumped away from the TCDQ to simulate the maximum allowed orbit excursion in the extraction region, which is currently at 1.2 mm for a beam energy of 6.5 TeV. Then, the radio frequency is switched off, thus allowing the protons to debunch and drift into the abort gap. After a waiting time of approximately 50 s at 6.5 TeV the maximum of the abort-gap distribution is expected to hit the TCDQ and the beam is dumped by the operators.

The distribution of the beam losses can then be used to validate the protection functionality in the ring and in the extraction region. High losses are expected in Point 6 at the TCDQ diluter and the downstream elements as the Q4 and Q5 quadrupoles, as well as at the TCDS diluter and the septa magnets located downstream. However, only minor losses should occur at critical elements in the ring, as the tertiary collimators (TCTs).

ASYNCHRONOUS BEAM DUMP TEST ON MAY 15, 2016

During an asynchronous beam dump test on May 15, 2016 (ABDT) at 6.5 TeV the initial bunch intensity was accidentally too high. In addition, the signal of the Abort Gap Monitor (BSRA) [3] was lost after the radio-frequency cavities were switched off. When the beam was dumped by the operators, four superconducting magnets in the extraction region quenched. Selected beam parameters during the test are summarized in Table 1. An overview of the quenched magnets is given in Table 2.

Table 1: Selected Parameters for Beam 1 during the Asynchronous Beam Dump Test on May 15, 2016.

Beam energy	6.5 TeV
Filled bunch slots	1, 1785, 3100
Horizontal rms emittance (Bunch 1)	$\varepsilon_x \approx 2.6\,\mu\text{m}$
Vertical rms emittance (Bunch 1)	$\varepsilon_y \approx 11.0\,\mu\text{m}$

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Beam Simulations

To study the beam behaviour during asynchronous beam dump tests, the beam-transport model pyExtract [4] was adapted to simulate debunched beams. In the code, the measured currents for all 15 MKD are downloaded automatically from the Post Mortem framework or the LHC Logging Data Base. The magnet current is then converted to a kick angle and the waveforms are corrected for the time of flight as well as for the measured time delays that are caused by eddy currents and the signal-propagation delays.

For the given sweep velocity of the beam, time steps of 10 ns were required to avoid artefacts in the horizontal particle distribution. The center of every time slice was transported through the extraction region up to the positions of the TCDS and TCDQ using a MAD-X [5] routine. The orbit bump was directly included in the MAD-X model.

The positions of the particles in the abort gap correspond to different loss regions in the machine, which can be identified based on the calculated horizontal displacement and the given collimator positions.

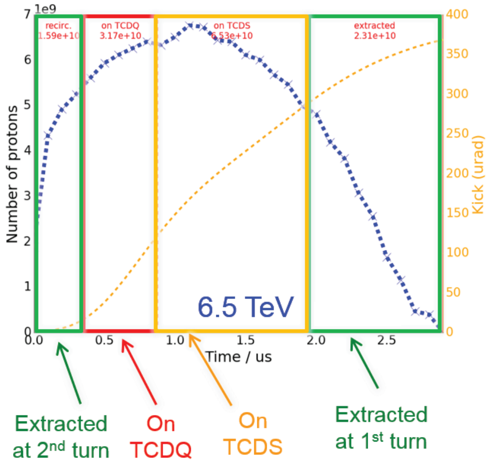

Figure 2: Abort-gap population as measured by the BSRA during the Asynchronous Beam Dump Test on May 15, 2016 (blue curve). The regions of particles that would hit the TCDQ or the TCDS, and the ones extracted on the first or second turn, respectively, are highlighted. The expected kick from the MKD is depicted in orange.

Figure 2 shows the different loss regions and the abort-gap population as measured by the BSRA [6]. The particle distribution for the 3 µs long abort gap is measured in 30 bins of 100 ns each. An estimated 3.2e10 protons are expected to have hit the TCDQ.

Four different regions can be distinguished. The particles that receive a small kick escape the TCDQ. They recirculate in the ring and are either lost at downstream collimators or extracted at the second turn. The particles that receive a stronger kick are lost on the TCDQ or on the TCDS, respectively. Finally, the particles that are close to Bucket 1 escape the TCDS and are extracted at the first turn. They enter the dump channel, but might follow a non-nominal trajectory.

For the simulations, the abort-gap distribution, as given by the BSRA, is used to assign the correct number of protons to every beam slice that hits the TCDQ. The particle distribution is then generated based on the average positions and kick angles for each beam slice and assuming a 4-dimensional Gaussian distribution [7] with

$$\sigma = \begin{pmatrix} \langle x^2 \rangle & 0 & \langle x p_x \rangle & 0 \\ 0 & \langle y^2 \rangle & 0 & \langle y p_y \rangle \\ \langle p_x x \rangle & 0 & \langle p_x^2 \rangle & 0 \\ 0 & \langle p_y y \rangle & 0 & \langle p_y^2 \rangle \end{pmatrix}, \tag{1}$$

where the matrix elements are given by [8, p. 285]

$$\begin{aligned} \langle x^2 \rangle &= \varepsilon_x / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}) \cdot \beta_x, \\ \langle y^2 \rangle &= \varepsilon_y / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}) \cdot \beta_y, \\ \langle p_x^2 \rangle &= \varepsilon_x / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}) \cdot \gamma_x, \\ \langle p_y^2 \rangle &= \varepsilon_y / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}) \cdot \gamma_y, \end{aligned} \tag{2}$$

and

$$\begin{aligned} \langle x p_x \rangle = \langle p_x x \rangle &= -\alpha_x \cdot \varepsilon_x / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}), \\ \langle y p_y \rangle = \langle p_y y \rangle &= -\alpha_y \cdot \varepsilon_y / (\gamma_{\text{rel}} \cdot \beta_{\text{rel}}), \end{aligned} \tag{3}$$

with the measured emittances ε, the simulated Twiss parameters α, β and γ and the relativistic factors β_{rel} and γ_{rel}. Note that all coupling terms between horizontal plane x and vertical plane y were assumed to be zero.

The resulting particle density distribution at the TCDQ is depicted in Fig. 3. The simulated proton distribution was used as input for energy-deposition studies using FLUKA [9]. The results are presented in [10].

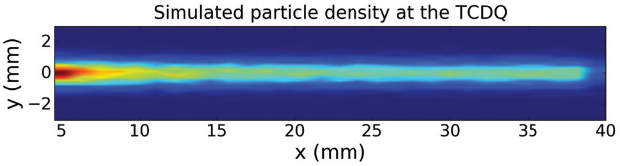

Figure 3: Simulated particle density at the TCDQ diluter during the ABDT for Beam 1. The beam moves from left to right. The particle density is higher on the left side (red color), close to the inner edge of the TCDQ, where the MKD rising edge is less steep and, thus, the sweep velocity is lower.

MD ON DECEMBER 3, 2017

A dedicated beam experiment (Machine Development, MD) to investigate the consequences of asynchronous dumps with bunched beam was performed on December 3, 2017 [11]. It demonstrated that, at least for current beam optics and intensities, even a full 450 GeV train hitting the TCDQ does not lead to a quench of superconducting magnets. This was validated with trains of 48 bunches and intensities of up to $1.25 \cdot 10^{11}$ protons per bunch.

In a second part of the MD, a single low-intensity bunch was injected into the abort gap and accelerated to 6.5 TeV.

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To be able to inject the bunch into the abort gap, the abort-gap protection [12] had to be temporarily deactivated. With a bunch intensity of $1 \cdot 10^{10}$ protons, no quench occurred. However, with $1.8 \cdot 10^{10}$ protons, five magnets quenched at the right side of Point 6 (R6) and one magnet at the left side (L6).

QUENCH BEHAVIOUR

Table 2 compares the quench behaviour for the ABDT and the MD. For the debunched test an estimated 3.2e10 protons are expected to have hit the TCDQ, while for the MD a bunch of 1.8e10 protons hit the TCDQ close to its inner edge. Only magnets that are located in region R6, i.e. downstream of the TCDQ diluter for Beam 1, are shown. In the region L6, located downstream of the TCDQ diluter for Beam 2, only the first quadrupole MQY.4L6 quenched during the MD, and no magnet quenched during the ABDT.

Table 2: Overview of Quenched Superconducting Magnets during the ABDT and the MD

Magnet	Quench 15.5.2016	Quench 3.12.2017	Assumed quench reason
MQY.4R6	no	yes	beam losses
MQY.5R6	no	no	—
MB.A8R6	yes	yes	beam losses
MB.B8R6	yes	yes	heat propagation
MQML.8R6	yes	yes	e-m coupling
MB.A9R6	no	no	—
MB.B9R6	no	no	—
MQM.9R6	yes	yes	e-m coupling

The quench behaviour during both events is very similar, except the additional quench of the MQY.4R6 quadrupole during the MD. The following reconstruction of the quench events revealed that only one magnet on May 15, 2016 (MB.A8R6), and only two magnets on December 3, 2017 (MB.A8R6 and MQY.4R6) quenched directly due to beam losses. Instead, the MB.B8R6 dipole quenched due to heat propagation, following the quench of the MB.A8R6. The quench protection system of the quadrupoles Q8 and Q9 was triggered by electromagnetic coupling signals from the fast discharge of the neighbouring main dipole circuit [13].

The FLUKA simulations for the MD setup are still ongoing, while the simulated energy depositions for the ABDT are presented in [10]. The results for Beam 1 correctly predict that the first dipole MB.A8R6 should have quenched due to beam losses and the downstream magnets should not have quenched. So far, no definitive conclusion can be drawn for the quadrupoles Q4 and Q5.

Figure 4 shows the measured beam losses at the TCDQ during the MD and during the operational asynchronous beam dump tests in 2016/17 at 6.5 TeV. For each test, the number of protons that are expected to hit the TCDQ was calculated from the measured abort-gap distribution using pyExtract. This way, the correlation of measured beam losses with the number of protons lost on the TCDQ becomes visible. It shows that the beam-transport behaviour is sufficiently understood to predict and quantify losses in the extraction region based on the position of the particles in the abort gap.

For the same number of protons, the losses during the MD are higher because the particles were concentrated in a single bunch close to the TCDQ edge and not spread out as during the standard debunched tests. In addition, all events without magnet quench have consistently lower measured beam losses than the events with quenches. These results might be used in the future to determine the maximum allowed number of protons for the protection elements.

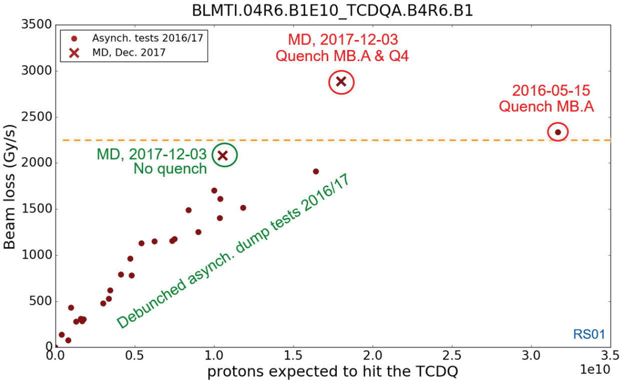

Figure 4: Measured beam losses for Beam 1 at the TCDQ diluter during operational asynchronous beam dump tests 2016/17 at 6.5 TeV (circles) and during a dedicated MD in December 2017 (crosses).

CONCLUSION

During an operational asynchronous beam dump test in May 2016, with higher abort-gap population than usual, four superconducting magnets in the extraction region quenched. The event was reconstructed with beam simulations and energy-deposition studies. The main quench behaviour is consistent with the calculations, while more detailed studies are required to understand the behaviour of the quadrupoles Q4 and Q5 and the differences between Beam 1 and Beam 2.

The test was followed up by a dedicated beam experiment in December 2017 using bunched beam in the abort gap. It demonstrated that for current beam optics, even a full 450 GeV train with up to $1.25 \cdot 10^{11}$ protons per bunch hitting the TCDQ does not lead to a quench of superconducting magnets. However, at 6.5 TeV a single bunch with $1.8 \cdot 10^{10}$ protons was sufficient to cause a beam-induced quench of one main dipole and one quadrupole magnet for Beam 1. For future operation at 7 TeV, the acceptable beam losses will be even reduced, mainly due to the higher magnet currents resulting in lower quench limits. FLUKA simulations for the beam experiment are still ongoing and will be used to further validate the understanding of energy deposition and required protection elements in case of real asynchronous beam dumps.

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