LEAKAGE FROM LHC DUMP PROTECTION SYSTEM

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Abstract

A single-sided mobile diluter (TCDQ) and a horizontal secondary collimator (TCSG) are installed in the extraction region of the LHC to protect the downstream elements from damage in case of asynchronous beam dump. These collimators have to be precisely set up to shield the arc aperture at 450 GeV, the triplet apertures and the tungsten tertiary collimators (TCT) at the low beta collision points. During the LHC beam commissioning, several machine protection tests were carried out to validate collimator setup and hierarchy at different beam energies and intensities. The outcomes of these measurements are presented in this paper together with the results of particle tracking simulations for asynchronous beam dump. These studies allowed to quantify the leakage expected from dump protection collimators to the downstream elements and to validate the system performance towards higher beam intensity.

INTRODUCTION

The LHC beam dump system 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 dilution kickers, onto special graphite absorber blocks (TED) [1].

The filling pattern in the LHC is constituted by batches of 72 consecutive bunches, which are separated by 25 ns. The unfilled space between the first and the last injected batch defines the abort gap and corresponds to 3 μs (120 bunches). This larger gap, between bunches, allows for the rise time of the MKD 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 RF system, which defines the correct bunched structure of the beam, loses the synchronization with respect to the MKDs or if it breaks down, the beam populates the abort gap and enters in the extraction region when the kicker voltage is still rising and part of it is swept across the machine aperture. Two protection elements, per each beam, are installed downstream of the MSD and have to absorb the beam swept during an asynchronous beam dump in order to avoid damage of the downstream elements. The first protection element is a horizontal mobile diluter (TCDQ) made up by one single 6 m long CFC (Carbon Fiber Compound) jaw which is located at the extraction side of the machine. A standard horizontal secondary collimator (TCSG), with two 1m long CFC jaws, 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.

TCDQ AND TCSG SETUP

The extraction protection collimators have to be precisely set up respecting a well established hierarchy valid for the full LHC collimation system [2]. They do not have to intercept the primary halo since this could increase the loss load on the downstream superconducting magnets and potentially induce a quench [3]. On the other hand they have to be closed enough to shield and minimize the energy deposition on the tungsten tertiary collimators (TCT: horizontal TCTH, vertical TCTV) which protect the triplet apertures at the experiments. At injection the TCDQ has to be set up at 8σ, where σ is the beam size, and the TCSG at 7σ while, at the low beta collision points, the retraction between these two elements has to be reduced to 0.5σ (TCSG at 7.5σ for 7TeV and 0.55 m β*).

Several manual setups of the full collimation system, including the extraction protection elements, have been performed during the first year of the LHC beam commissioning and, in particular, for any significative change in optics and beam conditions. The TCDQ and the TCSG have been set at the nominal aperture at injection and, due to the low energy (3.5 TeV) and bigger β* (3.5 m), at 9.8σ and 9.3σ at collision. An accuracy of about 1σ has been defined for the positioning of the TCDQ with 0.1 mm resolution. The protection level provided by the these collimators depends strongly on the relative settings of the TCT with respect to the TCDQ. A 5σ retraction (TCTs set up at 15σ), which takes into account triplet protection,collimator setup errors, dynamic orbit change and dynamic beta-beat, has been used up to now. This retraction has to be reduced by a factor of 10 for nominal LHC operation. An upgrade of the TCDQ motor system and a better control of the machine stability are necessary to reach this target.

ASYNCHRONOUS BEAM DUMP TESTS

Loss map studies have been periodically carried out to validate the hierarchy of the collimation system and, in particular, asynchronous beam dump tests have been performed to quantify the leakage from the TCDQ towards the downstream elements. These tests consisted in switching off the RF cavities and leaving the beam particles populating the abort gap for about 90 s (0.01% energy loss). A beam dump was then triggered by means of the emergency switches located in the CERN Control Centre (CCC) and loss maps recorded. For both beams the highest losses were registered at the collimators in the extraction region but the two beams showed a different loss pattern due to the geometric asymmetry of the machine.

- Beam 1 (clockwise rotation): the swept particles, which are not absorbed by the TCDQ and TCSG, are lost at the downstream betatron cleaning insertion which is designed to withstand high beam loads without being damaged. Particles exiting this insertion have an oscillation amplitude small enough to perform one full turn and be correctly extracted by the dump system.
- Beam 2 (counterclockwise rotation): particles escaping the extraction protection collimators encounter the CMS straight section where the tertiary collimators define a bottleneck. Losses are recorded at these elements and have to be kept as low as possible due to their low damage threshold.

The asynchronous dump of Beam 2 represents the most critical case. For this reason, the results presented in this paper refer only to this beam. The leakage from extraction region to tertiary collimators is taken as the key parameter for the validation of the TCDQ and TCSG setup with respect to the horizontal TCT. The leakage is defined as the ratio between the losses measured at the TCTs and at the extraction protection collimators (in particular the TCDQ).

Tests Results

Asynchronous beam dump tests have been performed at injection an collision energy for increasing beam intensities. Table 1 summarizes the results of the tests carried out during the first year of the LHC beam commissioning. Losses at the TCDQ and TCTs have been measured for the 40 μs integration time of the Beam Loss Monitors (BLM) [4].

In several cases an orbit offset has been applied at the TCDQ location, where a positive sign means that the beam was moved away from the collimator jaw. Tests have been repeated for different β* values and after switching on the crossing angle at the experiments. Losses at the TCTs start appearing for intensities higher than 9×10^{10} protons (p^+) at 450 GeV. At collision, the BLMs at the dump protection collimators saturate for an intensity of 2×10^{10} p^+. The BLM saturation prevents to get a quantitative information about the leakage to the TCTs. Additional Resistive Capacitive (RC) delays have been applied in order to increase the upper limit of the dynamic range of the BLM ionization chambers. The readings of the filtered BLM must be multiplied by a factor which depends on the delay applied and on the integration time (180 for TCDQ, TCSG and 40μs). These delayed BLMs might fail to catch very fast loss signals. For this reason, filters have been initially applied only at one of the two TCDQ BLMs (TCDQB) and a supplementary delayed BLM has been installed at the TCSG. All

Table 1: The results of asynchronous beam dump tests, performed at injection and collision energy during the first year of the LHC beam commissioning, are shown in the table. Beam intensity, orbit offsets, β* (11 m when not specified) and crossing angle at CMS are presented together with the leakage at the TCTs. The presence of RC delays is also indicated.

450 GeV			
Intensity	**Test Conditions**	**TCT/ TCDQ**	**RC**
$9\times10^9p^+$		0	No
$9\times10^9p^+$	+4 mm Offset	0	No
$1\times10^{10}p^+$		0	No
$1\times10^{11}p^+$		5×10^{-4}	Yes
$1\times10^{11}p^+$	+4 mm Offset	1×10^{-4}	Yes
$1\times10^{11}p^+$	-3.5 mm Offset	3×10^{-4}	Yes
$9\times10^{10}p^+$	+1.7 mm Offset 170μrad cross. angle	4×10^{-5}	Yes
3.5 TeV			
Intensity	**Test Conditions**	**TCT/ TCDQ**	**RC**
$1\times10^{10}p^+$		0	No
$2\times10^{10}p^+$	2 m β* +2 mm Offset	BLM saturated	No
$2\times10^{10}p^+$	3.5 m β* +2 mm Offset	4×10^{-4}	Yes
$7\times10^{10}p^+$	3.5 m β*	9×10^{-4}	Yes
$9\times10^{10}p^+$	3.5 m β* +1.7 mm Offset 100μrad cross. angle	4×10^{-4}	Yes
$9.5\times10^{10}p^+$	+1.7 mm Offset 170μrad cross. angle	3×10^{-5}	Yes
$7.5\times10^{10}p^+$	Start of Squeeze +1.7 mm Offset 110μrad cross. angle	3×10^{-5}	Yes
$8\times10^{10}p^+$	3.5 m β* +1.7 mm Offset 110μrad cross. angle	2×10^{-4}	Yes

the cases show a leakage of the order of 10^{-4} with a maximum of 9×10^{-4} recorded at 3.5 TeV, for a beam intensity of 7×10^{10} p^+.

SIXTRACK SIMULATIONS OF AN ASYNCHRONOUS BEAM DUMP

Tracking simulations have been performed with SixTrack to define the expected leakage at the TCTs in case of a full bunch impacting at the TCSG collimator (worst scenario). An energy of 3.5 TeV and a 2 m β* at CMS

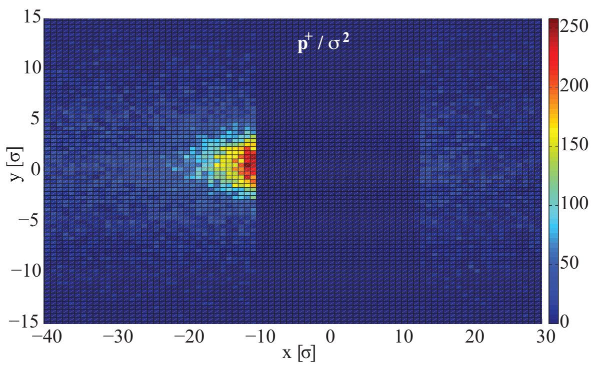

Figure 1: Proton density (p^+/σ^2) on the horizontal TCT for a total initial number of 8.5×10^{10} protons.

have been assumed. A total number of 8.5×10^{6} particles have been tracked starting from TCDQ until the downstream TCTs. More than 90% of the tracked particles are absorbed at the TCDQ, while less than 1% grazes the jaw surface and either is absorbed at the TCSG or reaches the TCTs. The TCSG collimator intercepts 8% of the primary protons while the tertiary collimators are reached only by scattered particles. In total, 0.3% of a single bunch is absorbed at the TCTH corresponding, for a nominal LHC bunch (1.1×10^{10} p^+), to 3.3×10^{8} p^+ (conversion factor at TCT: 1×10^{12} p^+/Gy). The density of the protons absorbed at the TCTH, in units of p^+/σ^2, is shown in Fig.1. The peak density is about 0.016% of a single bunch that is equivalent to 2.5×10^{6} p^+, for the nominal LHC emittance. These results are consistent with previous estimates which predicted that a full bunch on the TCSG would be attenuated by factor of 10 with a factor of 180 increase in emittance. The loss map resulting from SixTrack simulations is displayed in Fig.2 (top). Here, the local cleaning inefficiency η_c, that is the number of particles locally lost with respect to the total number of particles tracked, is plotted as a function of the longitudinal machine coordinate. Losses at the dump protection collimators are a factor of 120 higher than at the TCTs corresponding to a leakage of 8×10^{-3}. Results of the simulations have been compared with a loss map measured during an equivalent asynchronous beam dump test (second case at 3.5 TeV in table 1, see Fig.2 (bottom)). Since the 40μs BLM signals at the TCDQ were saturated, the 1.3 s signals (conservative) were used to measure a 1×10^{-2} leakage to the TCTs, in a good agreement with simulations. The patterns of simulated and measured loss maps are also compatible, provided that SixTrack does not track showers of secondary particles. The other measurements, presented in Table 1

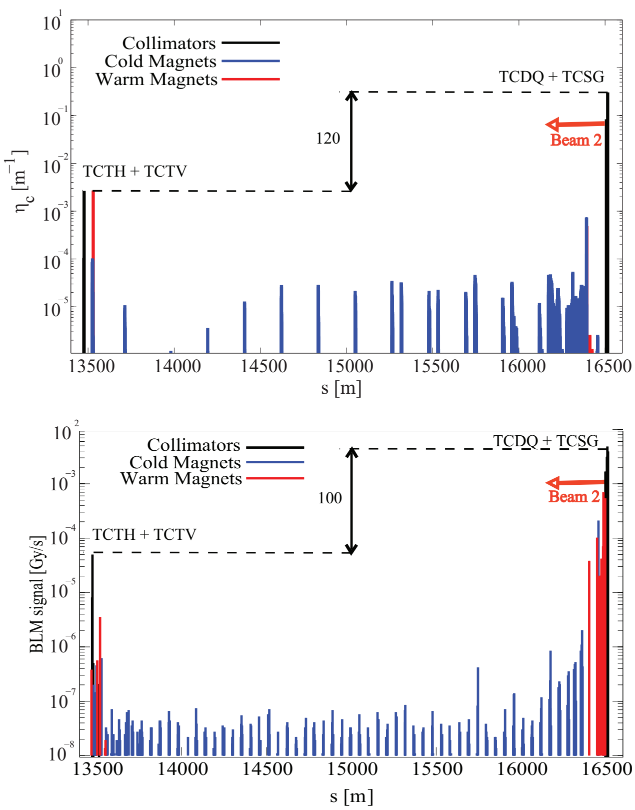

Figure 2: Loss map during an asynchronous beam dump for SixTrack simulations (top) and measurements (bottom). Black peaks represent particles absorbed at the collimators, while red and blue bars represent losses at the normal conducting and superconducting magnets respectively.

(for collision with a 3.5 m β*), showed to be consistent and not worse than simulations. This confirms the good shielding provided by the dump protection collimators and the reliability of simulations predictions in view of nominal LHC operation at top energy.

BSRA MEASUREMENTS

Two synchrotron light telescopes (BSRA) are installed in the LHC to provide the transfer profile of the two beams and monitor the abort gap population citeBSRA. BSRA readouts were used to define the number of protons lost at the TCDQ during the asynchronous beam dump test, at 3.5 TeV, for which the BLM were saturated. According to the BSRA, 4×10^{9} p^+ were in the abort gap during the dump. Previous studies demonstrated that 36 bunches, out of the 120 which can fill the full gap, would be intercepted by the TCDQ [5]. With this assumption, 1.2×10^{9} p^+ were absorbed at the TCDQ, during the test, with a leakage of

2×10^{-2} to the TCTs. This result is in a very good agreement with simulations and with estimates from the 1.3 s BLM measurements.

The LHC is also equipped with a transverse feedback system that will be used for abort gap cleaning. The overall system, BSRA and feedback, is still under commissioning but, when in operation, it will provide an excellent method to control the abort gap population [7] reducing the risk of quench and damage during an asynchronous beam dump.

CONCLUSIONS

Performance of dump protection collimators, during the first year of the LHC beam commissioning, has been presented. Asynchronous dump of Beam 2 was shown to be the most critical case, due to the potential damage of the tungsten TCTs installed downstream of the TCDQ. Results of tests performed with different beam conditions (energy, intensity, orbit offsets, squeezed β* and crossing scheme at the experiments) have been analyzed. All the presented cases refer to Beam 2 and show a leakage to the TCT smaller than 1×10^{-3}, proving an adequate protection from the TCDQ. An improvement of the TCDQ setup accuracy and a better control of the machine reproducibility are needed for nominal operation at 7 TeV, when the retraction between TCTs and TCDQ will be reduced by a factor of 10. Results of tracking simulations, for the most conservative case, showed to be in a good agreement with the measurements (BLM and BSRA). Simulations can then be considered as a reliable tool for predicting the beam load at the TCTs in view of LHC operation at top energy. The combined use of BSRA and feedback system demonstrated to be a promising tool to control the abort gap population and reduce the risk of quench and damage in case of an asynchronous beam dump.

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