PERFORMANCE STUDIES FOR PROTECTION AGAINST ASYNCHRONOUS DUMPS IN THE LHC

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Abstract

The LHC beam dump system has to safely dispose all beams in a wide energy range of 450 GeV to 7 TeV. A 3 μs abort gap in the beam structure for the switch-on of the extraction kicker field ideally allows a loss-free extraction under normal operating conditions. However, a low number of asynchronous beam aborts is to be expected from reliability calculations and from the first year's operational experience with the beam dump kickers. For such cases, MAD-X simulations including all optics and alignment errors have been performed to determine loss patterns around the LHC as a function of the position of the main protection elements in interaction region six. Special attention was paid to the beam load on the tungsten collimators which protect the triplets in the LHC experimental insertions, and the tracking results compared with semi-analytical numerical estimates. The simulations are also compared to the results of beam commissioning of these protection devices.

INTRODUCTION

The LHC Beam Dump System (LBDS) [1] is designed to extract all LHC beams with an energy range from 450 GeV to 7 TeV. The beam is moved into the vertically deflecting extraction septum MSD by a set of kickers MKD. In the transfer line to the dump block TDE the beam is diluted by horizontal and vertical MKB kickers. Two fixed 4 m long graphite blocks (TCDS) are placed in front of the MSD and a single-jaw 6 m mobile graphite block (TCDQ) is installed further downstream in front of the superconducting quadrupole Q4, together with a double jaw 1 m collimator (TCSG) and a 2 m fixed iron mask (TCDQM). These protection devices are foreseen to intercept any miss kicked beam, to prevent a quench of Q4 and Q5 in the case of particles within the abort gap and to protect these elements as well as other aperture limits from destruction during an asynchronous dump.

For nominal operation the MKD rise time should always be accurately synchronised with the 3 μs abort gap. However some failure cases could happen where the beam abort is not synchronised with the abort gap or where the abort gap population is unacceptably large. In both cases particles are swept over the aperture. The so called "prefire" case takes place due to a spontaneous trigger event of one of the 15 MKD kickers. In this case all other kickers will be fired immediately, without synchronisation with the abort gap [2]. Studies of the efficiency of the protection systems were made with MAD-X and are reported in this paper.

Tracking methodology

A system of MADX tracking jobs was set up to study failure cases and losses for various asynchronous dump events. A brief overview of the different jobs architecture and their basic settings is already given in [3].

SIMULATION RESULTS

Simulations for asynchronous dump events at injection and extraction energies have been performed for both nominal and prefire cases.

Table 1: Simulated time structure and intensities for an asynchronous beam dump with nominal filling scheme

Time	Duration	Intensity	Comments
0 - 475 ns	475 ns	19 bunches; 2.2×10^{12}	Beam swept over aperture
475 – 1185 ns	710 ns	28 bunches; 3.2×10^{12}	Beam swept over TCDQ
1185 – 2250 ns	1065 ns	43 bunches; 4.9×10^{12}	Beam swept over TCDS
2.3-90.5μs	88.2 μs	Rest of beam	Beam extracted

Tab. 1 shows the simulated total intensities during the different phases of an asynchronous dump. The time structure has to be compared with Fig. 1, which shows the MKD waveform and its 1st derivative which reaches its peak exactly when the swept beam starts to be intercepted by the TCDS aperture. Then the sweep velocity starts to slow down which can be seen in the simulated proton density deposited onto the TCDS front surface (Fig. 2). Here the dangerously high peak density values occur before the beam sweep finally approaches the extraction channel.

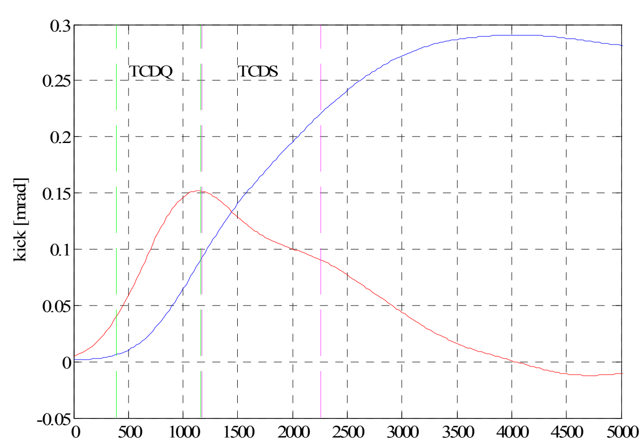

Figure 1: MKD kick waveform (blue) and its first derivative (red) with markers when sweeping over the TCDQ (green) and TCDS (magenta) apertures.

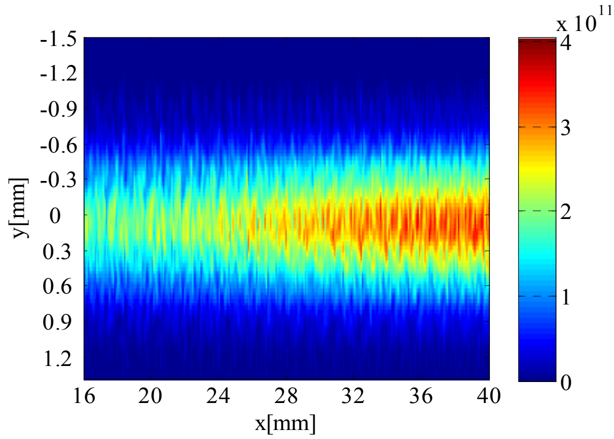

Figure 2: Particle density in p+ / mm2 for a beam sweep over the TCDSA front surface, 7 TeV.

Missing MKD cases

Fig. 3 shows a 7 TeV sweep with three missing MKD magnets. The extracted beam now impacts the inner TCDS aperture with parts of it intercepted by the TCDS graphite. The actual proton density on the TCDS edge depends strongly on the IR6 optics conditions and the circulating beam orbit. The worst case simulation showed densities of up to 2.5×10^{14} p+/mm^2 which is 50 times above the design load of the TCDS and would clearly damage the TCDS.

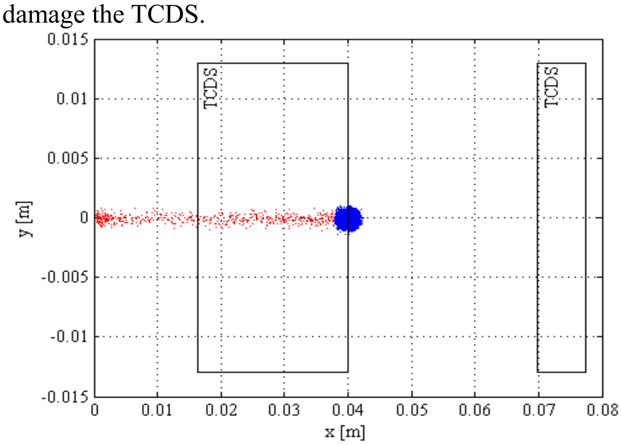

Figure 3: Beam sweep over the TCDS Aperture for 7 TeV and three missing kickers. Particles within the abort gap are indicated in red.

Simulations with only 2 missing kickers at 7 TeV showed no sign of losses over all orbit seeds; however, the beam is very close to the TCDS surface so that losses from the outer beam halo will be seen there. As the beam size is much bigger at injection energy only the case with one missing kicker can be confirmed as loss-free, as per design.

Another very special case was investigated as well: a trigger of one MKD magnet with a total retrigger failure for the other magnets. Fig. 4 shows the losses in IR7 and on the IP tungsten collimators for different TCDQ settings. Losses start to increase dramatically from the 8 sigma setting onwards as the sweep velocity for one MKD only is slower and thus more particles propagate into the ring. However these figures have to be used carefully as the TCDQ intercepts most of the beam and so sees intensities far above its design load. Thus it is expected that the TCDQ, TCSG and TCDQM are punched through and that undiluted parts of the beam will hit downstream aperture restrictions (possibly Q4, collimators). The total load for the collimation could thus increase substantially.

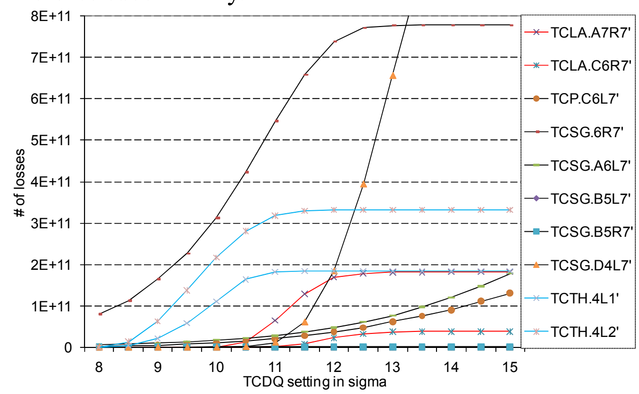

Figure 4: Losses for the TCTH and TCLA collimators for the 1 MKD case, 7 TeV, 10 orbit seeds.

7 TeV prefire

Fig. 5 shows the loss pattern for an asynchronous dump at 7 TeV triggered due to a prefire event. All losses are seen on collimators mainly in IR6 and 7 but also on the TCT's in IR 1 and 2, even for nominal 8 σ TCDQ settings. This was a rather surprising result which can be explained by the phase advance deviation from 90° between the kickers and the TCDQ as well as the actual beam size which allows also transmission of particles with px different than zero. The TCDQ settings need to be tighter for such circumstances, since particles with an offset, a certain px and a phase advance different from 90° can potentially reach the TCTs at nominal TCDQ settings.

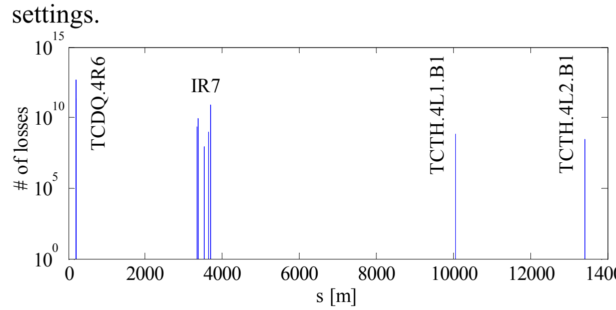

Figure 5: Loss patern for an asynchrounous dump at 7 TeV, prefire case, and TCDQ at 8 σ.

Variation of Q4 & MSD strength

The Q4 strength was varied separately in simulations between 45% and 145% of the nominal value, for an energy of 450 GeV where the beam size is largest. Beam losses on the TCDS/MSD are plotted in Fig. 6 as a function of the Q4 strength. Losses begin to occur at an error of about minus 6% and plus 25%.

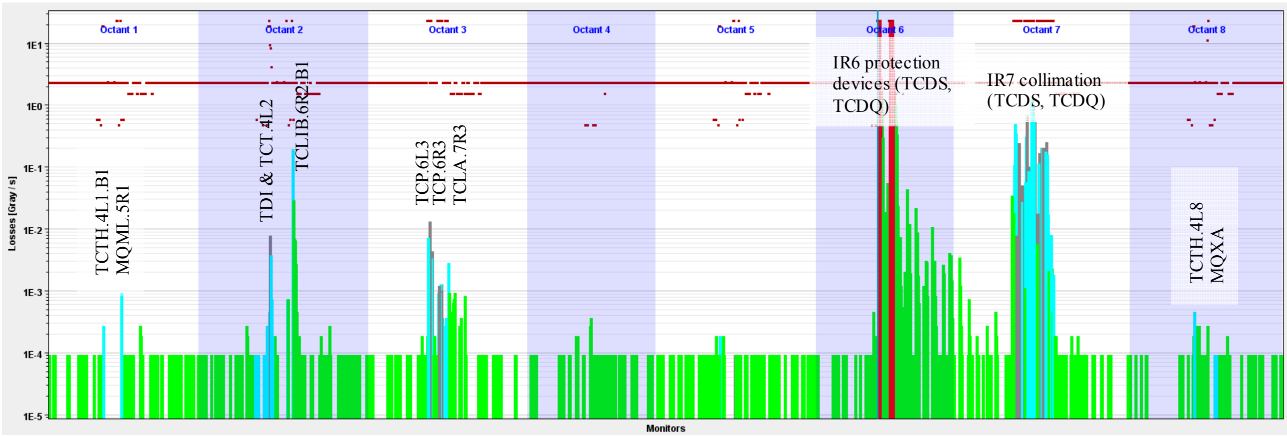

Figure 8: BLM signals during a provoked asynchronous dump at 450 GeV, 1×10^{11} p^+ total intensity.

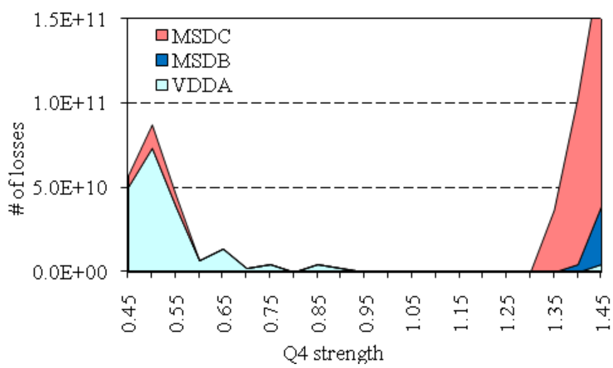

Figure 6: Losses in the extraction channel (TCDS not shown) for Q4 strength failures, 450 GeV.

The MSD strength was varied between 80% and 120% and losses were seen on the MKBH kickers and on the VDDA pumping devices. Losses begin to occur at an error of about ±5%.

Simulations with orbit offset in IR6

The orbit in IR6 is required to be stabilised by the orbit feedback to within ±2.0 mm. To investigate the suitability of this limit, the orbit in IR6 was artificially degraded, and then the 450 GeV asynchronous dump tracking simulations for each new orbit were performed. The losses on the dump system elements (TCDS, MSD, MKB) are plotted in Fig. 7 as a function of the orbit offset in IR6. For specific orbit seeds first losses appear at around ±2.5 mm offset where first particles are lost on the TCDS, MSD, MKB, VDDA surfaces.

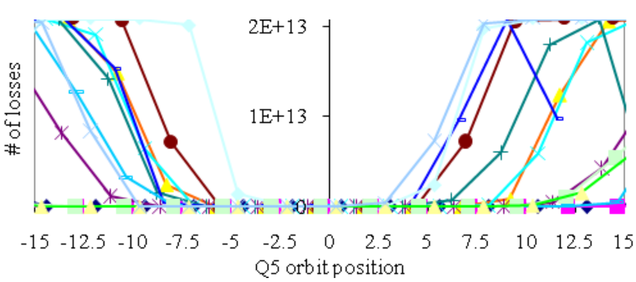

Figure 7: Total losses in the extraction channel for extractions with orbit offset at Q5, 450 GeV.

MEASUREMENTS

During LHC commissioning dedicated measurements concerning the loss pattern of asynchronous dumps were done with debunched beam at low intensity. Fig. 8 shows the loss pattern of such a dump for beam 1 at 450 GeV, with 10^{11} p+. Losses are limited to the dump protection elements and the beam cleaning collimation system, with no losses in the LHC arcs or experimental insertions.

At 3.5 TeV with a β* squeeze to 2m, the overall behaviour was as expected but losses were also seen on TCT collimators which are understood to come from the protons which impact the short TCSG device in P6 and scatter through the 1 m of graphite. Detailed cross-checks are still under way for an accurate quantification of this effect, but so far it seems to agree with the expectations.

CONCLUSIONS

Simulations of asynchronous dumps were performed and loss patterns analysed, where additional losses at the TCTs could be identified and their origin confirmed. Measurements with beam have started, to validate the system protection. The behaviour is largely as expected, with the addition of the scattering process for the beam impacting the TCSG device. Future work has to focus on calculations and settings adjustments to minimize the transmission of potentially dangerous swept particles from the TCDQ system onto the TCTs, for operation with high energy and small β*.

REFERENCES

[1] O. Brüning et al., "LHC Design Report Volume 1", ISBN 92-9083-244-0, Geneva 2004, Chapter 17.
[2] R. Aßmann, B. Goddard, "The Consequences of Abnormal Beam Dump Actions on the LHC Collimation System", LHC Project Note 293, Geneva, May 2002, p4.
[3] T. Kramer, et al., "LHC Beam Dump System - Consequences of Abnormal Operation", Proc. PAC09, Vancouver 2009.