# APERTURES IN THE LHC BEAM DUMP SYSTEM AND BEAM LOSSES DURING BEAM ABORT

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*Abstract*

The LHC beam dumping system (LBDS) is used to dispose accelerated protons and ions in a wide energy range from 450 GeV up to 7 TeV. An abort gap of 3 μs is foreseen to avoid sweeping particles through the LHC ring aperture. This paper gives a brief overview of the critical apertures in the extraction region and the two beam dump lines. MAD-X tracking studies have been made to investigate the impact of particles swept through the aperture due to extraction kicker failures or the presence of particles within the abort gap. The issue of failures during beam abort is a major concern for machine protection as well as a critical factor for safe operation of the experiments and their detectors.

## THE LHC BEAM DUMPING SYSTEM

The LHC Beam Dumping System (LBDS) [1] is designed to fast extract beam from the LHC in a loss free way. For each beam a system of 15 horizontal kicker magnets (MKD), 15 vertically deflecting magnetic septa (MSD) and 10 diluter magnets (MKB) are installed. After the MKD the beam sees an additional deflection when traversing the Q4 quadrupole. The MSD put the beam in the vertical plane above the LHC machine before it is further deflected in the horizontal and vertical planes in a spiral shape by the MKB kickers, Fig. 1. After several 100 m of beam dump line the beam is absorbed by the dump block (TDE). To protect the septa from miss-kicked beams a special fixed 8 m long graphite protection device (TCDS) is placed just in front of the MSD.

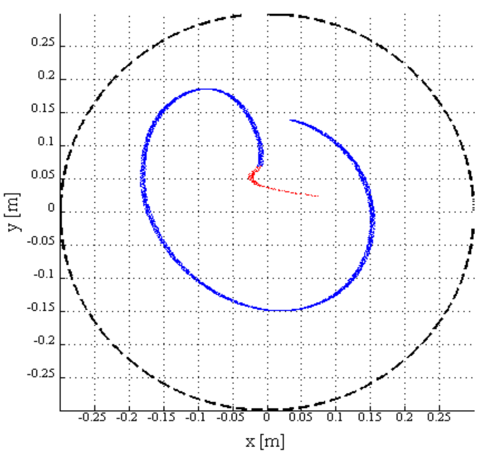


Figure 1: Diluted beam sweep on the TDE. Blue: nominal particles, red: particles in filled abort gap.

For nominal operations the MKD rise time should always be accurately synchronised with the 3 μs abort gap, so that no beam is swept through the aperture. However some failures can occur which lead to an “asynchronous” dump, and in addition some stray particles may also be present in the abort gap [2]. To protect the LHC aperture from these eventualities, a movable single-jawed 6 m long graphite protection device (TCDQ) is installed upstream of Q4, supplemented by a two-jaw 1 m long graphite secondary collimator (TCSG) and a 2 m long fixed iron mask (TCDQM).

## TRACKING STUDIES

A MADX tracking code was set up to study failure cases and losses for the LBDS. The code consists of the main program, as well as the sequence, misalignment and aperture files. Since these studies include tracking action within the long straight section 6 (LSS6) as well as in the extraction channel and dump lines, most of the sequence and aperture information was not available in MADX compatible format and had to be generated by hand. Fig. 2 shows a tracked beam at the entrance of the TCDS for nominal conditions.

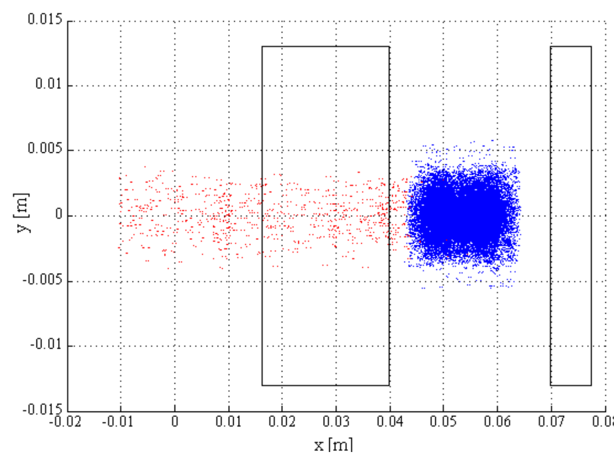


Figure 2: Swept beam at TCDS for nominal conditions (red: particles in abort gap, blue: nominal beam with halo).

### Sequence and Aperture

Sequences for both beams were produced: only Beam 1 is discussed here, as the geometries and results for Beam 2 are very similar. The sequence starts at the centre of the Q5 quadrupole upstream of the MKD. The sequence is identical to the Beam 1 sequence until it reaches the TCDS. From here onwards the extracted beam was treated differently.

A key issue for these loss studies is to have an accurate model of the concerned apertures. A complete aperture model including the critical elements as well as all vacuum pipes and transitions was generated for the sequences used in LSS6 and the dump lines, and was verified, element by element, against the installation drawings and databases.

The TCDS is a critical element as its aperture is +16.3 mm for the circulating beam and -15 mm for the extracted beam, and is expected to be a main loss location for mis-steered beams or in case of an overpopulated abort gap. The TCDQ, TCSG and TCDQM have half-apertures of +15 mm, ±13.4 mm and ±21.5 mm. The MSD itself has a circular physical half-aperture of 29 mm for the circulating beam and a 20.5 mm horizontal, 30.5 mm vertical racetrack-shaped half-aperture for the extracted beam.

### *Methodology*

The tracking job is split into four main parts: the 1st part tracks the particles from Q5 to the TCDS, where the particles are either lost on the TCDS block, remain in the LHC aperture or pass in the aperture of the extraction channel; the 2nd part of the job tracks the extracted particles through the extraction channel to the dump block; the 3rd part tracks the particles in the circulating beam chamber between the TCDS and Q4 (after the TCDQ) and in the 4th part all particles which are still in the circulating beam pipe are tracked around the LHC ring. The results from this 4th part are not included in this paper.

The time-varying kicker waveforms were included in the tracking by sampling the measured kick shapes at 1 ns intervals and reading out the resulting kick depending on the bunch position. For each step in time a number of particles were randomly chosen from the initial distribution and tracked. The coordinates of lost particles as well as "surviving" particles were saved and, after the required coordinate transformations, handed over to the next sequence. Realistic random magnet errors were applied to the Q4 and Q5 (normal distribution, max. 0.5 %) as well as to the MKD (1 %) and the MSD (0.01 %). In this initial case the orbit was assumed to be well centred in the magnet apertures; the mechanical and alignment tolerances of the different elements were neglected.

For these simulations the kicker waveforms were sampled with a time step of 25 ns using 10 particles per time step, for a total of 35,600 particle tracks. Each simulation nevertheless took about one hour, due to the detailed aperture model used.

### *Particle distributions*

To investigate the loss locations expected in the extraction channel and beam dump lines at LHC injection energy of 450 GeV, an initial distribution of 50.000 particles was used, composed of large amplitude particles in a simulated secondary halo, which represent the most demanding cases in terms of particles likely to be lost on aperture limits. It should be noted that the output can not be taken as input for any stress or energy deposit calculations, which would require the use of a nominal distribution.

## SIMULATION RESULTS

Seven different cases were studied, which correspond to failures of specific interest for the extraction system. The normal random errors described above were applied for all cases.

### *Nominal case with all 15 MKDs*

For this case only losses on the TCDS and TCDQ were seen, and these came from particles in the abort gap (see Fig. 2).

### *One MKD missing*

This is an important case since this is an 'allowed' failure which is expected to happen within the lifetime of the LHC. Again losses were only observed on the protection devices, stemming from particles in the abort gap. No losses were seen at the TCDS from particles outside the abort gap – however the inclusion of orbit errors and mechanical tolerances may eventually result in small losses at the TCDS for this case.

### *One MKD missing and an additional 1.5 % error for the 14 remaining kickers*

This case was included in order to check the effects of the temperature variation of the MKD switches which has been observed to cause a ~1.5 % loss of kick strength at 450 GeV under some operating conditions [3]. Fig. 3 shows the distribution of losses along the dump line for this case – the main losses occur at the TCDS due to particles in the abort gap, but some small losses of a few particles are also seen on the downstream MSD chamber.

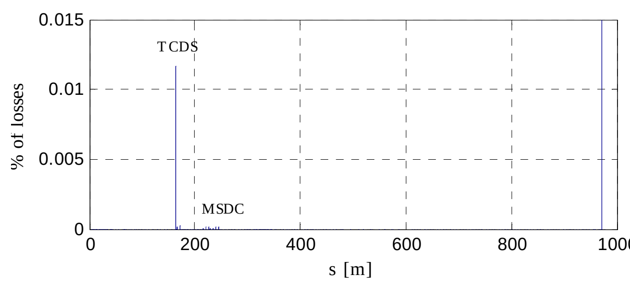


Figure 3: Losses in TD68 dump line for failure case 3.

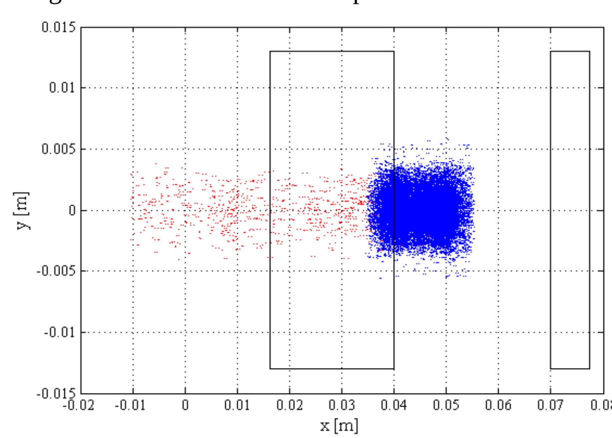


Figure 4: Particles at TCDS with 2 missing MKD.

### *Two MKD kickers missing*

With two missing kickers about one fifth of the beam halo is intercepted by the TCDS, confirming that this failure case is ‘beyond design’. Fig. 4 shows the particle positions at the TCDS for this case.

### *Nominal kick with MSD failure of $10^{-3}$ and $10^{-2}$*

These failures were included to check the effect of an MSD septum trip, which is protected by a current surveillance and interlock but which could nonetheless produce a relative error of several $10^{-4}$.

For the 0.1 % error no extra losses are observed in the extraction channel or dump line. For 1 % error most of the beam is dumped correctly, Fig. 5, with a vertical offset as expected. Fig. 6 shows that the MSD vacuum chamber intercepts some particles; there are also losses seen at the differential pumping device in the TD68 line. A few particles are even lost on the vertical dilution kickers.

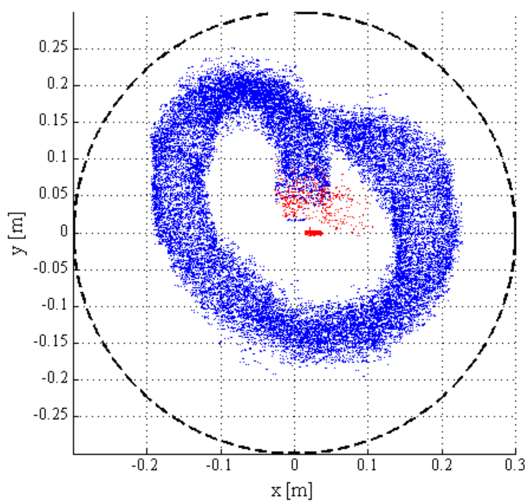


Figure 5: Sweep at TDE for 1% MSD error.

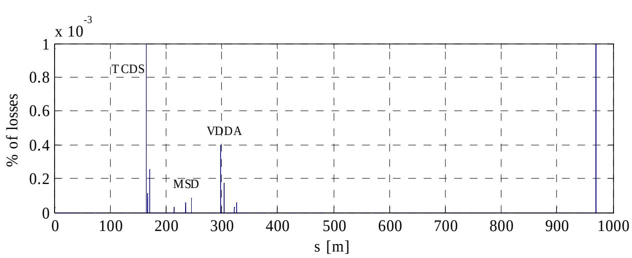


Figure 6: Losses along TD68 for 1 % MSD error.

### *Q4R6 failure of 5 %.*

Q4 provides about 25 % of the deflection needed to extract the beam. The Q4 current is surveyed by the LBDS beam energy tracking system with a maximum error of about 1 %. The case was tested with MKD nominal kick and a large random error of 5 % applied to the Q4. No extra losses were seen in the extraction channel or dump line.

### *Losses on the TCDQ system for asynchronous dump*

For an asynchronous dump the pattern of losses on the LHC ring elements between TCDS and TCDQ system is shown in Fig. 7. The losses are limited to the protection devices, as designed, with no losses on the Q4 magnet or the TCDQM device.

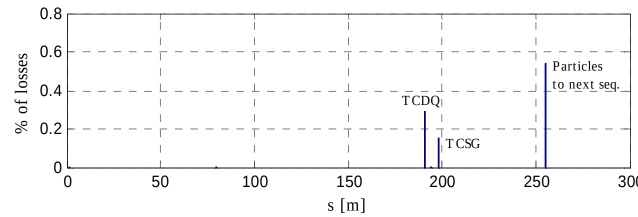


Figure 7: Losses in the LHC ring in LSS6 for an asynchronous dump.

## CONCLUSION

MADX jobs have been set up to study the detailed aperture of the LBDS extraction system. These have been applied to different failure cases using a preliminary particle distribution with secondary halo. The efficiency and settings of the protection devices in shielding the local downstream elements was tested. The sections from the first Q4 to the TCDS and also from the MSD to the second Q4 seem to be well protected. No losses were seen before the TCDS; near the second Q4 all loses were found on protection elements for all cases. This confirms that the aperture in this region is correctly specified and defined. The MSD itself saw losses for some of the failure cases, and some losses on the differential vacuum pumping module in TD68 have also been observed. The MSDC chamber alignment from the database differs slightly from the specification (by 1 mm) which may explain the result. These cases will be investigated in more detail with more realistic and extensive particle distributions, and by ‘zooming’ in on the regions of interest, to keep the computation time low. The studies will be extended to include orbit errors and mechanical tolerances, and continued to track the small-angle particles, which stay inside the TCDQ aperture and are of interest for the collimation system and the LHC experiments. The tolerances on the settings of the protection devices will therefore also be included, in particular to determine the operational tolerances for the TCDQ protection devices.

## REFERENCES

[1] O. Brüning et al, “LHC Design Report Volume 1”, ISBN 92-9083-244-0, Geneva, 2004, Chapter 17.
[2] A. Koschik et al., “Abort Gap Cleaning Using the Transverse Feedback System: Simulation and Measurements in the SPS for the LHC Beam Dump System”, these proceedings.
[3] J. Uythoven et al’, “Results from the LHC Beam Dump Reliability Run”, these proceedings.