Damage Levels – Comparison of Experiment and Simulation

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Abstract

The design of protection systems is based on assumptions on damage levels, which are in general derived from computer simulations. A dedicated experiment was carried out to cross-check the validity of this approach: A 450 GeV proton beam was extracted from the SPS in TT40 and directed onto material in a controlled way. A simple geometry was chosen for the high-Z target, comprising several typical materials that are used in the LHC, such as stainless steel and copper. Results of the simulations are presented and compared with the experiment. Simulation results for the damage of a beam pipe in TT40 during an accident with the high intensity extraction are also compared with the observations. An outlook is given of what is required to predict with confidence beam induced damage levels in the LHC.

INTRODUCTION AND SCOPE

The damage limit of equipment is important input for the design of machine protection procedures, design of protection elements, settings of protection systems, thresholds of monitoring systems, the "safe" beam condition, the design of operational procedures, etc. The current assumptions on damage levels are in most cases derived from simulations - especially for the new regime of LHC intensities and energies. The calculations are often based on static energy deposition calculations, [1], by e.g. means of FLUKA, [2], where dynamic effects such as bunch structure and shock waves are not taken into account. A valid question is whether this approach is sufficient for predicting damage limits of LHC beams.

An experiment was planned for comparison with simulated data. The experiment served as validity check for using simulations for calculating damage limits. The test - often referred to as the "TT40 material damage test" - will be described in this paper. Only preliminary results are available for the time being. However, even with the analysis completed, the results of the experiment cannot define generic damage limits for LHC equipment. Damage levels have to be established on a case-by-case basis, as will be become clear below.

ASSUMED DAMAGE LEVELS

The damage limit in terms of lost particles at 450 GeV is assumed to be $\sim 2 \cdot 10^{12}$ protons, [3]; at 7 TeV it needs only $\sim 10^{10}$ particles to reach the damage level according to simulations [4].

The intensity of a full nominal batch at 450 GeV is clearly well above the damage limit. During the high intensity commissioning of the SPS extraction in LSS4 a full nominal batch, which corresponds to $3.4 \cdot 10^{13}$ protons, was extracted by mistake into the QTRF vacuum chamber in TT40. The impact caused a 25 cm long slit and melted material on the inside of the chamber along $\sim$1 m, see Fig. 1.

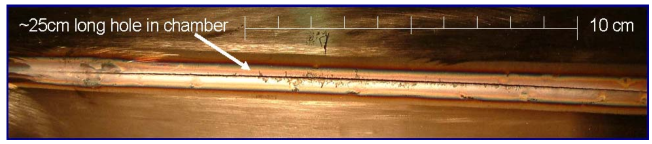

Figure 1: Damaged vacuum pipe of the QTRF pipe in TT40.

COMPARISON BETWEEN SIMULATION AND OBSERVATION

The circumstances of the TT40 accident could be reconstituted from logged data [5]. The accident in TT40 was caused by EMC from the high intensity beam of the extraction septum MSE in the SPS. This produced an interlock and tripped the MSE power converter. By the time of the extraction the MSE current was off by 5% and steered the beam into the QTRF vacuum chamber. The logged data was used to regenerate the mis-steered trajectory, see Fig. 2. From the reconstituted trajectory the impact location, impact parameter and impact angle could be roughly determined and used in FLUKA simulations, see Fig. 3.

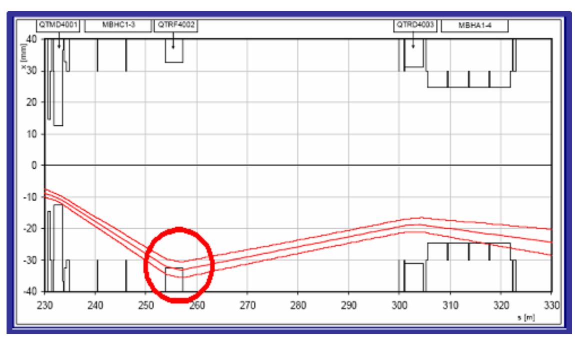

Figure 2: Reconstructed trajectory hitting the QTRF vacuum chamber during the TT40 accident.

With these parameters, the maximum temperature reached in the peak of the energy deposition in the pipe, made of stainless steel 314L, is only 1350° in Fig. 3. However, the melting point of 314L is 1400°, which is close but above the simulated value and contradicting the observation of massive melting which had occurred on the inside of the pipe. Small changes of the input parameters in the

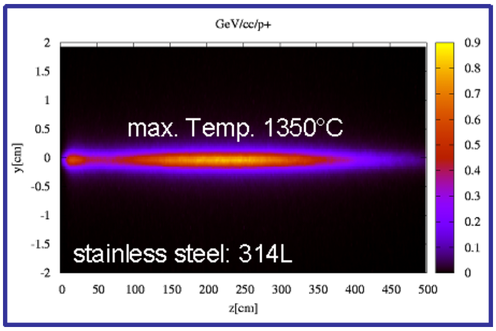

Figure 3: Results of one of the FLUKA simulations to reconstitute the observed energy deposition in the QTRF vacuum pipe.

simulation had a large effect on the resulting energy deposition. It turned out to be extremely difficult to reconstitute the observed physical damage in a simulation without accurate knowledge of the input conditions. The important conclusion here is that a meaningful comparison between simulations and reality is only possible in a controlled experiment.

CONTROLLED DAMAGE TEST

A controlled damage test was planned using a low-tech target (no extra instrumentation like temperature sensors etc.). A simple target geometry was chosen consisting of a stack of high-Z metal plates, see Fig. 4.

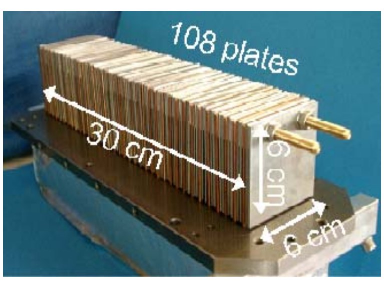

Figure 4: Core of the target for the damage test in TT40.

The plan was to irradiate the target with a 450 GeV proton beam of four different intensities. The intensities were chosen according to the simulation to attain certain effects: melting or not melting of the plates.

Target description

Four different materials were used in the core of the target, the stack of metal plates: Zn, Cu and stainless steel INCONEL and 316L. The different plates (dimensions: 6 cm $\times$ 6 cm $\times$ 2 mm) were put in a special order to form a sandwich of packages, each package consisting of the same sequence of materials: Zn, stainless steel, Cu.

Between two plates place-holders (0.5 mm thick) were installed to avoid plates sticking together in case of melting. Each plate was allocated a number to compare the results afterwards with the simulation in three dimensions: the transverse dimension of the damaged area on the plate and the longitudinal position of the damaged plate.

The core of target was wrapped in a Ti-foil to protect the outer Al-confinement from hot metal splashes. The airtight outer container was equipped with an Ti-entrance- and exit-window. A screen was fixed in front of the target for steering the beam on the target. It was mounted on a motor for moving the target in the horizontal plane (to the different impact locations; in and out of the beam).

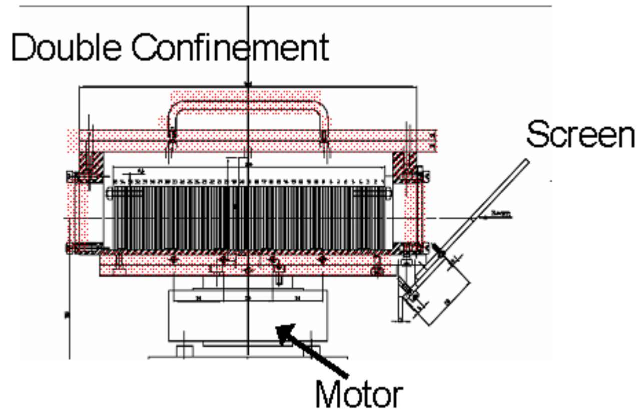

Figure 5: Target with outer confinement, motor and screen.

Simulation results with FLUKA

The geometry of the target was implemented in FLUKA including every relevant detail of the double confinement [6], see Fig. 6.

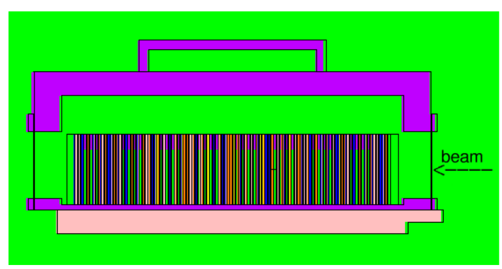

Figure 6: The model of the target implemented in FLUKA.

The target was to be installed in TT40 in front of the TED. The nominal beam size of a 450 GeV proton beam at the target location was $\sigma_x = 1.1\mathrm{mm}$ and $\sigma_y = 0.6\mathrm{mm}$. According to these input parameters, the energy deposition in the target was calculated and four different beam intensities A, B, C and D were chosen. Intensity A was chosen such that according to the simulation none of the plates should melt. Intensity B should cause melting of the Zn-plates, intensity C of the Zn- and Cu-plates and intensity D of the Zn-, Cu- and 316L-plates. None of the chosen intensities should cause melting of INCONEL plates. Table 1 gives for each intensity and material the plate number from which signs of melting should be observed. The numbers in this table are obtained by taking the heat fusion, the additional energy required to cause the phase transition from solid to liquid, into account. Fig. 7 shows the temperature in each Cu plate for the four different intensities, the heat of fusion is not taken into account.

Table 1: FLUKA results

Intensity	**protons**	**melting starting in plate NR.**			
	$[10^{12}]$	Zn	Cu	316L	INCONEL
A	1.3	-	-	-	-
B	2.6	17	-	-	-
C	5.3	9	18	-	-
D	7.9	6	12	23	-

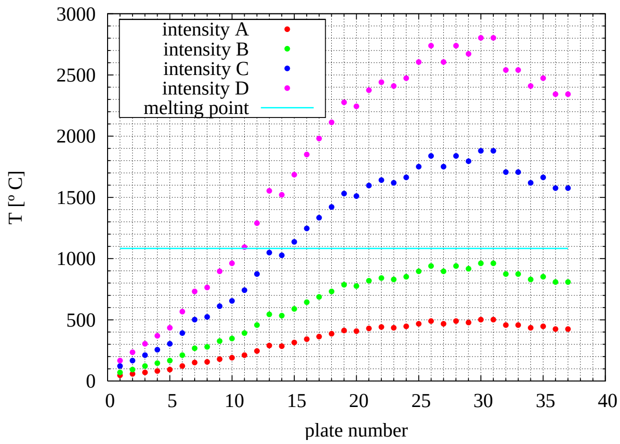

Figure 7: FLUKA results for the temperature in the Cu plates for the different intensities. Heat of fusion is not taken into account for this graph.

Damage test in TT40

The target was installed in TT40 on a girder fixed to the TT40 TED, see Fig. 8. On 8^{th} of November, 2004, it was irradiated with the intensities A, B, C and D - 4 shots on 4 different horizontal locations on the plates, see Fig. 9. Due to the activation the container could not be opened before 5^{th} of January, 2005, hence the analysis is still ongoing. Pictures were taken of some of the plates and promising preliminary results could be obtained.

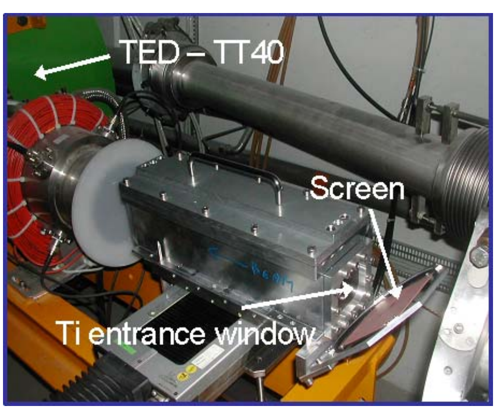

Figure 8: The target installed in TT40 in front of the TT40-TED in air.

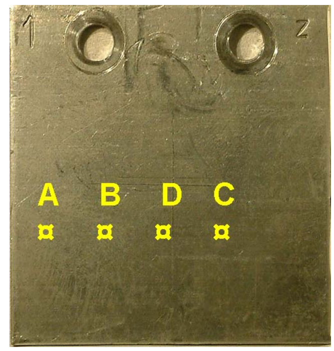

Figure 9: Plate 1 of Zn after the test. The locations of the four different intensities are indicated.

Results

The outer confinement did not show any damage; the downstream part of the inner confinement did not survive. The first observations, after having opened the outer container and having removed the inner confinement, showed that the upstream plates had not been damaged. From package number 6 on more and more damage had occurred, see Fig. 10. These results agree with the simulation. No signs of stress related damage could be found - no cracks, no twisting, no buckling of the plates.

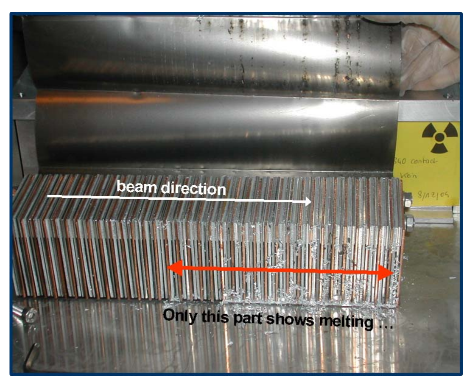

Figure 10: The core of the target after the test. On the more downstream part melted Zn can be seen.

Fig. 11 and 12 show pictures taken from Zn-plates to compare the damaged area with predictions from the simulations. Plate 7 in Fig. 11 shows melting for intensity D as predicted by the simulation. Also for plate 8 in Fig. 12 melting should only occur for intensity D. For plate 9 the simulation predicted melting for intensity D and C, and for both intensities melting was observed as can be seen in Fig. 12. Plate 20 in Fig. 12 shows impressive holes for D and C and melting for B as predicted by FLUKA.

Clean holes were drilled through the plates, the material surrounding the holes does not show any damage apart from metal splashes ejected from the holes.

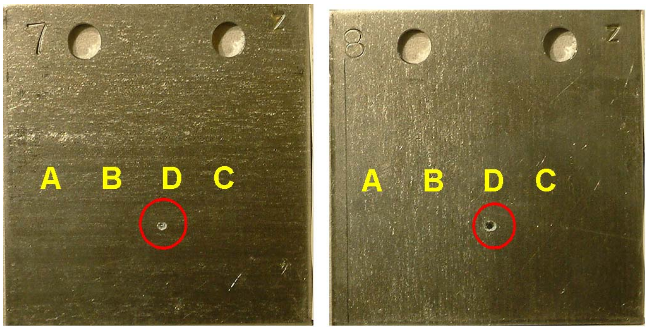

Figure 11: Zn-plates 7 and 8. The melting agrees with the simulation.

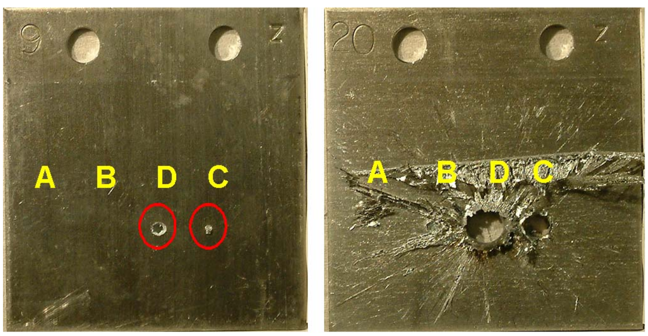

Figure 12: Zn-plates 9 and 20. Holes and melting agree with the simulation.

The results also agree reasonably well for Cu, see Fig. 13 and INCONEL. None of the INCONEL plates has holes or signs of melting. Like INCONEL, 316L was not obviously damaged. This disagrees with the simulated results. 316L should have melted for intensity D from plate 23 onwards. There are several possible reasons for the discrepancy; one might be inaccurate specific heat as function of temperature and melting point for the alloy. A complication of the analysis of 316L plates is that metal splashes from Zn and Cu ended up on these plates due to the order of materials in the packages. These splashes might cover the potentially damaged area. Further investigation is necessary.

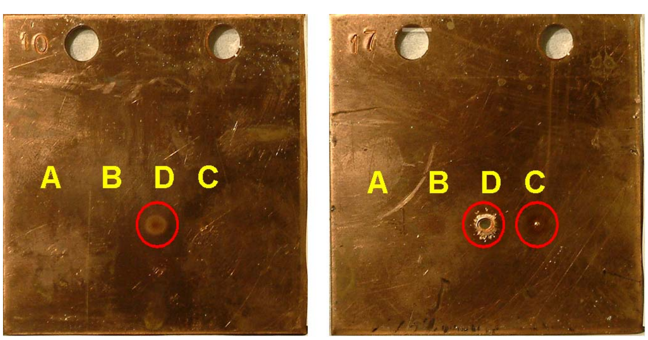

Figure 13: Cu plates 10 and 17. Prediction for plate 10: no melting. Observation: signs of heating, no melting. Prediction for plate 17: melting for D. Observation: melting for D and C. However, prediction for plate 18: melting for D and C. Agreement within 0.5cm.

CONCLUSIONS

A controlled damage test was carried out with a high-Z metal target consisting of a series of plates. The target was irradiated with 450 GeV beams in TT40 extracted from the SPS. The first examinations of the caused damage in the longitudinal plane shows good agreement with the simulations. Zn-, Cu- and INCONEL-plates are damaged at those longitudinal locations, which had been predicted by the simulation with relatively high accuracy. 316L is still unclear and will be further investigated.

The results so far give some confidence that damage limits could be adequately simulated. However, the difficulties in reproducing the damage profile observed in the TT40 accident showed that geometry has a large effect on the results, the acquired energy deposition is sensitive to details of beam impact and that full modeling on case-by-case basis is essential. Simple scaling might not be valid and establishing generic damage limits for the LHC thus seems to be difficult.

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