MADX TRACKING SIMULATIONS TO DETERMINE THE BEAM LOSS DISTRIBUTIONS FOR THE LHC QUENCH TESTS WITH ADT EXCITATION

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Abstract

Quench tests with stored beam were performed in 2013 with one of the LHC main focusing quadrupoles to experimentally verify the quench levels for beam losses in the time scales from a few milliseconds to several seconds. A novel technique combining a 3-corrector orbit bump and transverse-damper kicks was used for inducing the beam losses. MadX [1] tracking simulations were an essential step for determining the spatial and angular beam loss distributions during the experiment. These were then used as an input for further energy-deposition and quench-level calculations. In this paper the simulated beam-loss distributions for the respective time scales and experimental parameters are presented. Furthermore the sensitivity of the obtained loss-distributions to the variation of key input parameters is discussed.

INTRODUCTION

Beam losses are one of the main concerns with increasing intensities and energies of the accelerator facilities. They lead to different consequences such as quenches of superconducting magnets, activation and damage of accelerator equipment. Depending on the reason for the beam losses, their time scales vary from nanoseconds up to hundreds of seconds for irregular losses and even longer for regular ones [2, 3]. The duration of the losses, in turn, influences the severity of the effects of the lost particles on the equipment.

Studies of the quench limits of the superconducting magnets were performed at the LHC as a preparation for the operation at 7 TeV. Several scenarios reproducing losses with time scales from a few milliseconds to a few tens of seconds were covered.

This paper focuses on MadX simulations of the tests performed with 4 TeV proton beams in which a transverse kicker (ADT) was used for creating beam losses: a fast-loss [4] and a steady-state-loss tests [5].

MODELLING THE FAST-LOSS TEST

Short durations of beam loss were achieved by combining a 3-corrector orbit bump and transverse kicks with the ADT operating in a sign flip mode [4]. An orbit bump was established to create an aperture bottle neck in the focusing quadrupole MQ.12L6.

Simulations

Simulations were performed in several steps. Firstly, the equilibrium beam distribution with the experimentally measured beam size was created. Secondly, the orbit bump was applied, and then the bunch was kicked horizontally in order to create an initial displacement followed by a coherent excitation with the ADT at 200% gain (measure of the kick strength of the ADT modules). It was taken into account that the ADT kick strength grows exponentially for 100 turns and then saturates. Tracking was performed with the thin-lens tracking module of MadX. For this reason the focusing quadrupole MQ.12L6 was divided into 310 thin lenses in order to give enough resolution for the following energy-deposition studies [6]. Magnet errors of all the arc quadrupoles calculated using Roxie [7] were also considered. The excited bunch was lost in the magnet in approximately 10 ms.

Results

The longitudinal and angular distributions of the impacting protons with respect to the centre of the quadrupole MQ.12L6 are presented in the Fig. 1.

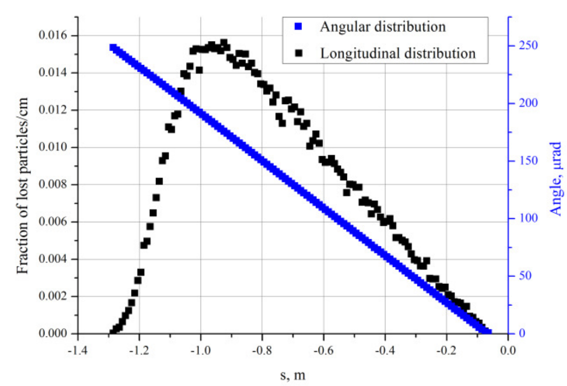

Figure 1: Longitudinal and angular distributions of the lost particles for the fast-loss case, with respect to the centre of the MQ.12L6.

The longitudinal distribution (Fig. 1) is sensitive to several parameters such as tune, beam profile, and orbit bump amplitude. Corresponding studies revealed that

- Tune variations influence the width of the distribution, however the height of the maximum stays within 20%;
- The beam size, when increased by a factor 2 (up to nominal), reduces the height of the maximum by 10%;
- The bump amplitude influences the width of the distribution and the "sharpness" of the maximum; however changes of the height are negligible.

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Besides the mentioned factors, aperture imperfections (e.g. surface roughness, misalignments etc.) need special attention. Such an imperfection was modelled as a 20÷30 cm long aperture restriction with a height of 30 μm. This limitation was placed at different locations in the quadrupole in order to study its influence on the longitudinal distribution (Fig. 2). As can be seen from Fig. 2, the front surface of the aperture restriction experiences the highest impact because of being the most outstanding part of the surface. The whole distribution shifts depending on the location of the block. However such changes have hardly any impact on the signal expected in the Beam Loss Monitors (BLM) [6]. It should be mentioned that MadX treats aperture as a black absorber, therefore gaps in the distribution appear: part of the surface is in the "shadow" of the non-uniformity.

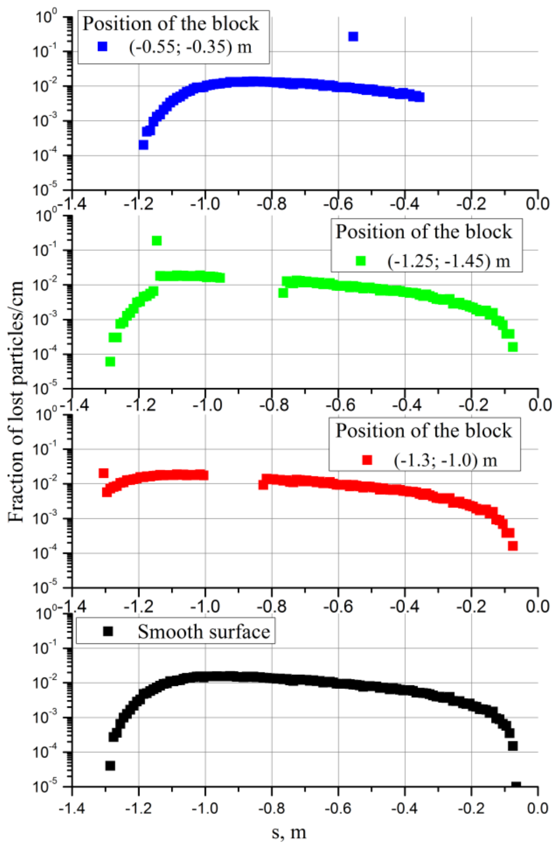

Figure 2: Longitudinal distributions of the lost particles in the quadrupole in the presence of a surface roughness or without during the fast-loss quench test.

MODELLING THE STEADY-STATE-LOSS TEST

In order to lose the beam in several seconds, the ADT was operating in white-noise excitation mode [8] for blowing up the beam horizontally. As in the case of fast-loss test, an orbit bump was established in the focusing quadrupole MQ.12L6.

Simulations

The simulation steps were similar to those of the fast-loss case, with the difference that the white-noise ADT excitation with 15% gain started right after the orbit bump was established. The experiment was done with 8 bunches and 1250 ns bunch spacing which allowed for the ADT to give purely random kicks to each bunch. In order to model this, 8 simulations were run and the combined analysis of the results was performed. This technique allowed for losing the beam in the magnet within 20 seconds.

Results

In order to reduce the CPU time needed for MadX simulations the initial offset from the aperture of the maximum of the orbit bump was decreased from ~6σ_{exp} to 2.5σ_{exp}. Preliminary simulations have shown that the amplitude of the orbital bump has no influence on the longitudinal loss distribution in this case.

The longitudinal loss distribution for 15% ADT gain and the angular distribution of the lost particles are shown in the Fig. 3. The angular distribution does not depend on the kick strength, but only on the integral magnetic field of the quadrupole seen by the lost particle. The longitudinal distribution was tested on its sensitivity to the ADT gain (Figs. 3, 4). Decrease of the ADT gain in this case leads to a compression of the longitudinal loss distribution because the reference orbit lies close to the aperture already before the white-noise excitation starts; therefore for very small excitations, the particle amplitudes increase very slowly, and all particles will be lost close to the centre of the quadrupole. If the gain increases, the amplitude growth increases and particles can be lost already upstream, explaining the wider distribution. According to MadX studies, increase of the ADT gain to the maximum of 400% will lead to the decrease of the maximum fraction of the lost particles and increase of the Full Width at Half Maximum (FWHM) of the distribution by a factor 3, comparing to these parameters at 15% gain (Fig. 4).

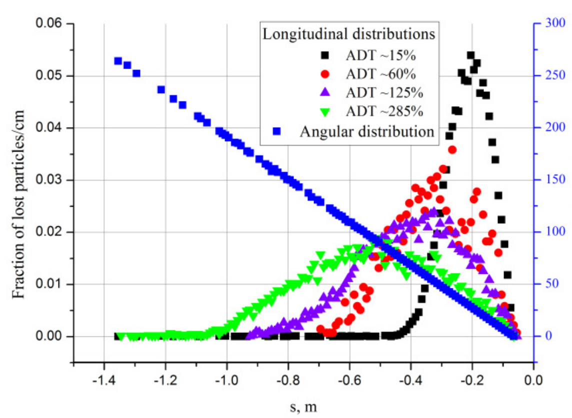

Figure 3: Longitudinal and angular distributions of the lost particles during the steady-state-loss quench test, with different ADT gains.

Non-uniformities of the beam screen surface were modelled in the same way and with the same parameters as for the fast-loss test. The studies have shown that the distribution is very sensitive to the surface roughness: the maximum of the distribution could be up to a factor 3 higher than in the case of a smooth aperture (Fig. 5).

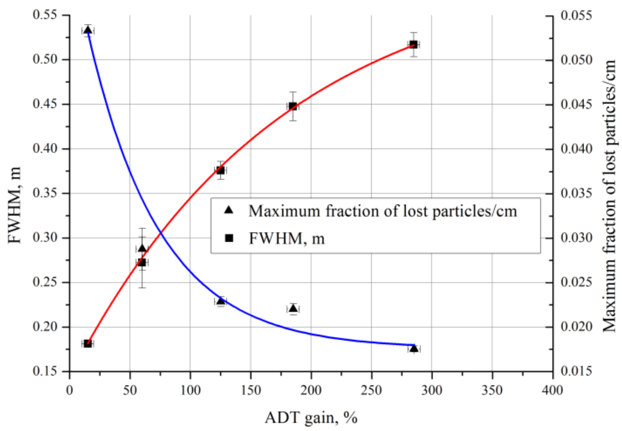

Figure 4: Dependence of the FWHM of the longitudinal distribution and the maximum fraction of lost particles per cm on the ADT gain.

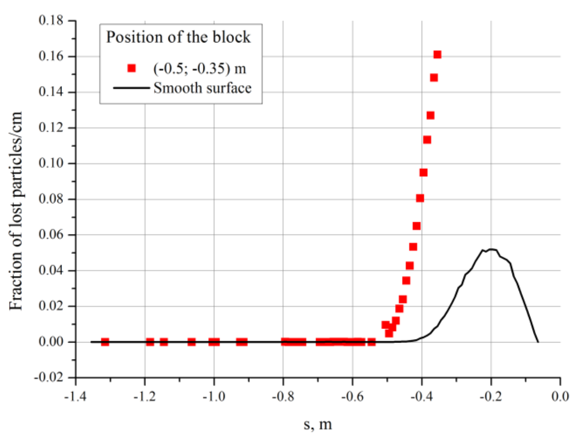

Figure 5: Longitudinal distributions of the lost particles in the presence of an aperture restriction (dots) or without (line) for the steady-state-loss case.

DISCUSSION

In case of a coherent excitation (fast loss) the entire bunch is moving horizontally in phase space, either closer or farther from the aperture from turn to turn. The emittance growth due to the usage of the ADT itself [9] can be neglected because of the short duration of the excitation. Particles in the bunch with amplitudes exceeding the beam screen are "cut off" and the redistribution of the remaining particles does not happen (there is no time for phase space mixing). The time structure of the loss strongly depends on the tune. The envelope of the loss-peaks has Gaussian-like shape (Fig. 6, upper). The time pattern of the loss depends on the width of the initial distribution: a narrower beam will be lost in fewer turns. A qualitatively similar behaviour was registered by the BLMs [5] in the presented experiment, where the losses were strongly modulated from turn to turn.

In case of the incoherent excitation (steady-state loss) bunches are randomly kicked and the emittance increases slowly with time, i.e. the beam does not become narrower when the particles are lost because of the phase space mixing.

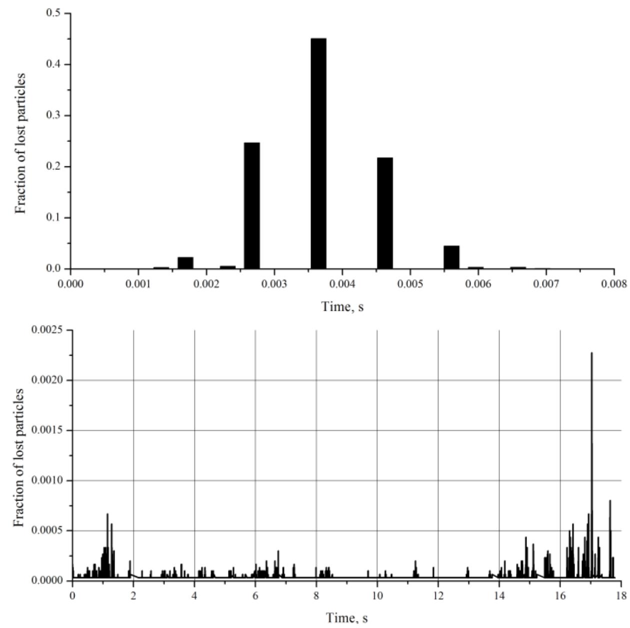

Figure 6: Time distribution of the integral beam loss in the MQ.12L6: fast-loss case (upper) and steady-state-loss case (lower).

The time pattern of the loss in this case depends on the width of the initial distribution: a very narrow beam will give an increasing BLM signal with time, whereas a wide beam will give almost constant loss rate (Fig. 6, lower). Such behaviour was registered by the BLMs in the experiment [5].

CONCLUSION

MadX simulations of the longitudinal and angular loss-particle distributions were performed for the analysis of the fast-loss and steady-state-loss quench tests. The studies showed the increase of the width of the longitudinal distribution with the increase of the loss rate within the quadrupole. The maximum number of the lost particles at a certain location did not exceed 2% in fast-loss case and 6% in steady-state-loss case, when an aperture was smooth. If an aperture was non-uniform, local losses could reach ~30% and ~20% for fast and steady-state cases, respectively.

The simulations proved that the incident angle of the lost particles only depends on the integral magnetic field seen by the particles, and not on the excitation scenario.

The presented results were further used for energy deposition and quench level calculations [6].

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