

# PARTICLE TRACKING FOR ORBIT-BUMP QUENCH TESTS AT LHC\*

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## *Abstract*

Studying the quench levels of superconducting magnets is necessary to generate thresholds for the beam loss monitors in such a way that will ensure protection of the magnets and limit machine availability as little as possible. In order to understand the quench propagation, it is important to know not only the total energy deposition in the magnet, but also the detailed spatial distribution of lost particles. This paper presents the results of MAD-X simulations that were performed as part of the analysis of the orbit bump quench tests held at LHC and reproducing the beam-losses of various durations – between 10 ms and ~20 sec. The sensitivity of the results to various parameters is discussed.

## INTRODUCTION

To avoid beam-induced quenches of superconducting magnets during accelerator operation, it is important to know the quench levels for various beam-loss scenarios. This allows for setting Beam Loss Monitors' (BLM) thresholds, i.e. the dose levels that will trigger a beam dump once registered by the detectors. BLM thresholds should be set in such a way to locally protect equipment but not to trigger beam dumps, when the equipment is not in danger.

A series of quench tests were performed at LHC as a preparation for operation at 7 TeV. The tests covered various loss scenarios with loss durations varying from a few milliseconds to tens of seconds, reproducing losses induced by beam interaction with so-called UFOs (Unknown Falling Objects) [1] as well as steady-state losses.

## METHOD

All the quench tests discussed in the present paper are characterized by the common method of creating an aperture bottleneck through establishing of a horizontal or a vertical local orbit bump with a maximum in a focusing or a defocusing quadrupole, respectively. The beam losses were further achieved by either exciting the beam coherently (intermediate loss-duration test) or non-coherently (steady-state loss test) with the LHC transverse damper (ADT); or by increasing the orbit bump amplitude (dynamic orbit bump test). Combining the orbit-bump technique with beam excitation allowed for achieving beam losses of various durations.

The distributions of lost-particles were obtained using the thin-lens tracking module of MAD-X [2] which treats the aperture as a black absorber. The simulation steps strictly followed the experimental ones. Firstly, the beam optics parameters were chosen accordingly; the

experimentally measured tune was used as an input. Secondly, the equilibrium beam distribution with experimentally measured beam size was created. Then the respective beam-loss scenario was reproduced. Magnet errors of all the arc quadrupoles calculated using Roxie [3] were also taken into account. Validation of the simulations was done using the data from Beam Position Monitors (BPM) and/or BLMs. The BPM data could be directly compared to the position of the beam in the simulations. Comparison with the BLM data involved additional calculations. Preliminary spatial loss distributions were used as an input for particle-shower simulations performed with FLUKA [4, 5] which modelled the signal in the BLMs. Good agreement of the signals increased confidence in the obtained spatial loss distributions.

The results of the tracking simulations were tested for their sensitivity to uncertainties of experimental parameters (tune, beam size, bump amplitude), and to uncertainties in aperture geometry.

The spatial distributions of lost particles were calculated with 1 cm resolution: the quadrupoles of interest were divided into 310 thin lenses. Such a resolution was required by the following particle-shower FLUKA simulations for obtaining the energy or power deposition in the magnet (see e.g. [6]). The results were compared to the electro-thermal simulations providing estimates of quench levels for the respective beam-loss scenario (see e.g. [7]).

The following sections describe the particle tracking simulations and their results for the intermediate loss-duration, steady state loss duration and dynamic orbit bump quench tests held at LHC.

## MODELLING THE INTERMEDIATE LOSS-DURATION TEST

The test was performed with a single bunch of protons at 4 TeV. After creating a horizontal orbit bump with the amplitude of  $4.3\sigma_{\text{nom}}$  around the focusing quadrupole MQ.12L6 ( $\sigma_{\text{nom}} = 380 \mu\text{m}$ ), the bunch was kicked by a tune kicker (MKQ) in order to create an initial displacement. With a delay of 1 ms the excitation by the ADT operating in a sign-flip mode started [8]: for providing the coherent excitation the transverse damper was operated with inverted polarity by flipping the sign in its digital electronics following a kick by the tune kicker to seed the oscillation. Initially the amplitude grows exponentially and once the maximum kick strength is reached, linearly with time. In this saturated regime the ADT kicks with a constant strength in either one or the other direction. This kind of excitation combined with an

orbit bump allowed for losing the full bunch in approximately 10 ms.

The obtained BPM data was used to adjust the simulations: correct the kick strength and the tune. The adjustment of the tune in the simulation was required because the tune measurements were done prior to establishing the orbit bump, which influences the final tune value. The comparison of the measurements with the simulations is shown in Fig. 1. The agreement between the simulated and experimental horizontal positions at the BPM shows that the kick strengths are matched; the agreement of the oscillation frequencies shows that the tune in the simulations is chosen correctly.

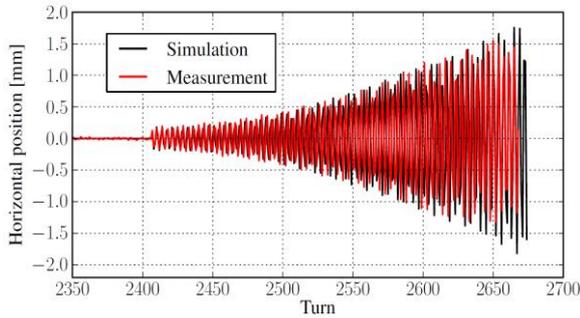


Figure 1: Comparison of the horizontal beam position calculated using MAD-X and registered by the BPM.

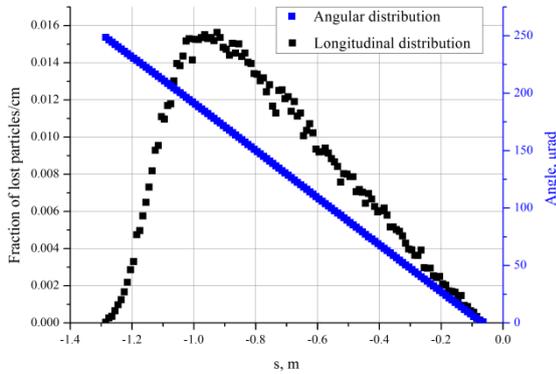


Figure 2: Longitudinal and angular distributions of the lost particles for the intermediate loss-duration quench test, with respect to the centre of the MQ.12L6.

The longitudinal and angular distributions of lost particles are shown in Fig. 2. The angular distribution only depends on the integral magnetic field seen by the particle; however the longitudinal distribution is sensitive to several experimental 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 6 (from the experimental normalized emittance of  $0.6 \mu\text{m}\cdot\text{rad}$  up to the nominal one  $3.5 \mu\text{m}\cdot\text{rad}$ ), 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.

Besides the mentioned factors, aperture imperfections (e.g. surface roughness, misalignments etc.) need special attention. Such an imperfection was modelled as a  $20\div 30$  cm long aperture restriction with a height of  $30 \mu\text{m}$ . This limitation was placed at different locations in the quadrupole in order to study its influence on the longitudinal distribution (Fig. 3). As can be seen from Fig. 3, 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 BLM [6]. Due to the fact MAD-X treats aperture as a black absorber, gaps in the distribution appear: part of the surface is in the “shadow” of the non-uniformity, however in reality beam particles would penetrate through such non-uniformity, without leaving any shadowed region.

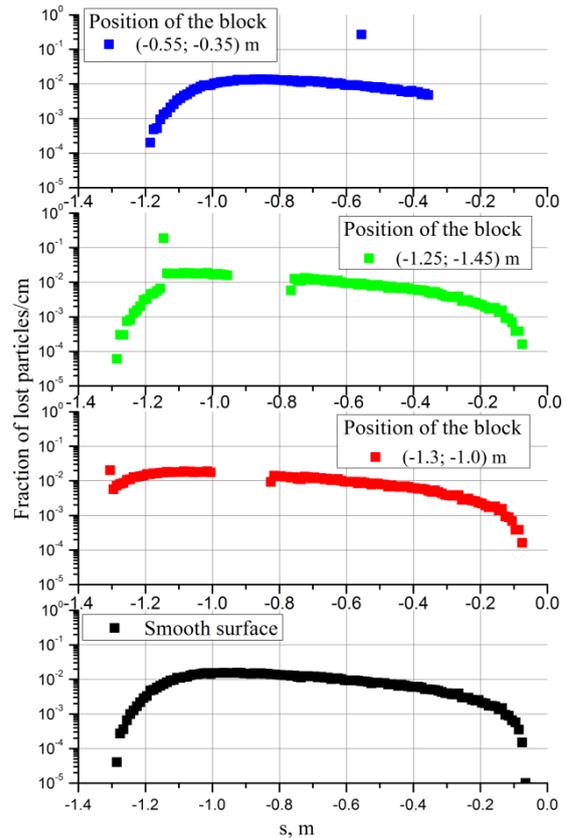


Figure 3: Longitudinal distributions of the lost particles in the quadrupole in the presence of a surface roughness (the numbers in the brackets denote the beginning and the end of the  $30 \mu\text{m}$  restriction) or without, during the fast-loss quench test.

In case of a coherent excitation the entire bunch is moving horizontally in phase space, either closer or further 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 are cut off from the bunch by the beam screen 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 beam size and the amplitude of an orbit bump. The envelope of the loss-peaks in the simulations has Gaussian-like shape (Fig. 4) and shows qualitatively similar behaviour to that, registered by the BLMs in the presented experiment [10], where the losses were strongly modulated from turn to turn. Achieving a good quantitative agreement of the time distributions was considered to be of less importance, since the spatial distribution is not very sensitive to above-mentioned experimental parameters, besides the spatial distribution was integrated over time for further particle-shower FLUKA simulations.

The duration of the loss depends on the beam profile: a narrower beam will be lost in fewer turns, given the same excitation rate of the ADT.

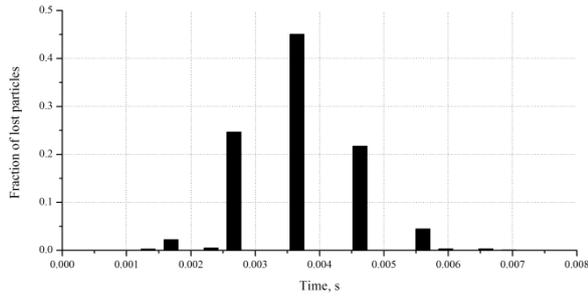


Figure 4: Time distribution of the integral beam loss in the MQ.12L6 in case of intermediate loss-duration quench test (Statistics: 100000 particles).

## MODELLING THE STEADY-STATE LOSS TEST

The steady-state-loss orbit bump quench test was performed at 4 TeV with 8 bunches and 1250 ns bunch spacing. The beam was slowly blown up by the ADT injecting white-noise: the bunch spacing was sufficient for providing random kicks to each bunch in either one or the other direction, so the beam emittance increased. The kick strength defined the diffusion rate and therefore the duration of loss. During the test the beam was lost in  $\sim 20$  sec.

In order to model this scenario, 8 separate simulations were run and the combined analysis of the results was performed. To reduce the CPU time the initial offset of the orbit bump from the aperture of the maximum of the orbit bump was decreased from  $\sim 4.4\sigma_{\text{nom}}$  to  $1.8\sigma_{\text{nom}}$ . Preliminary simulations have shown that the amplitude of the orbital bump has no influence on the longitudinal loss distribution in this case.

The validation of the results was done in the following way: the simulations were performed with various ADT

gains until the beam was lost in 20s. The strength value was obtained by scaling that of the intermediate-duration quench test. A good agreement of the experimental and estimated kick-strength values reinforced confidence in the results of the simulations.

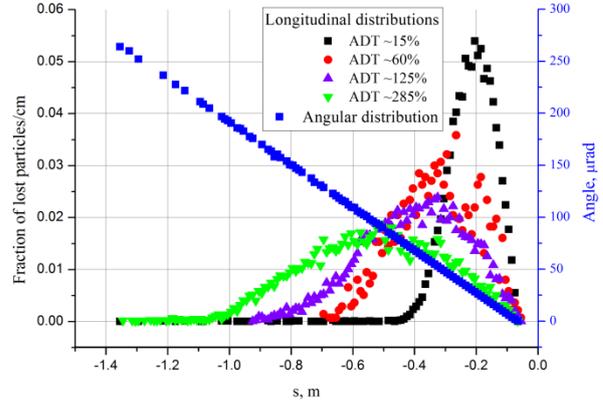


Figure 5: Longitudinal and angular distributions of the lost particles during the steady-state-loss quench test, with different ADT gains.

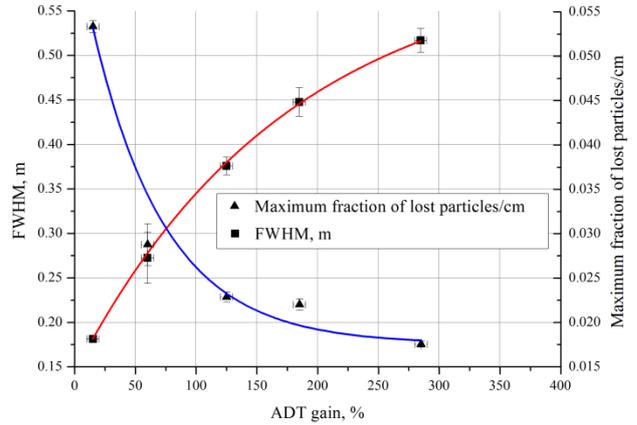


Figure 6: Dependency of the FWHM of the longitudinal distribution and the maximum fraction of lost particles per cm on the ADT gain.

The longitudinal loss distributions for various ADT gains and the angular distribution of the lost particles are shown in Fig. 5. 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, i.e. the impact angle depends on the longitudinal position of the lost particle. The spatial distribution depends on the ADT gain. Decreasing 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 at the maximum of the  $\beta$ -function, i.e. close to the centre of the quadrupole. If the gain increases, the amplitude increases faster and particles can be lost already upstream, explaining a wider distribution. According to MAD-X studies, increase of

the ADT gain to the maximum of 400% will lead to a decrease of the maximum fraction of the lost particles and an increase of the Full Width at Half Maximum (FWHM) of the distribution by a factor 3, as compared to these parameters at 15% gain (Fig. 6).

Non-uniformities of the beam screen surface were modelled in the same way and with the same parameters as for the previous, intermediate-duration test. The studies have shown that the distribution is very sensitive to surface roughnesses: the maximum of the distribution could be up to a factor 3 higher than in case of a smooth aperture (Fig. 7).

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. This behaviour was observed in the experiment during the first attempt to quench the magnet [10]. In the second experimental attempt the beam was wider and gave almost constant loss rate [10]. The simulated time distribution for the latter case is shown in Fig. 8. Nearly constant loss rate is observed because 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 phase space mixing.

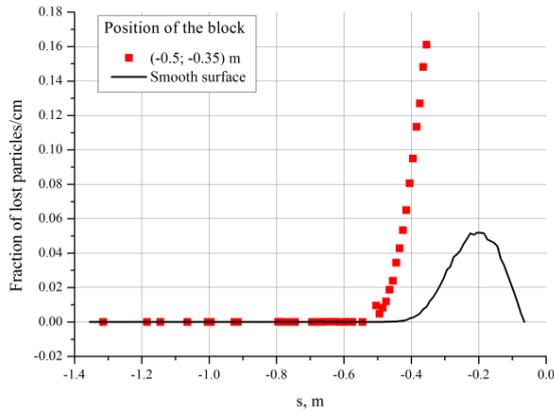


Figure 7: Longitudinal distributions of the lost particles in the presence of a  $30\ \mu\text{m}$  aperture restriction placed between  $-0.5\ \text{m}$  and  $-0.35\ \text{m}$  (dots); and without a restriction (line) for the steady-state-loss case.

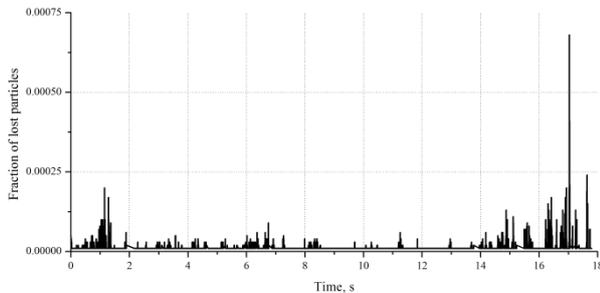


Figure 8: Time distribution of the integral beam loss in the MQ.12L6: steady-state-loss case (Statistics: 30000 particles).

## MODELLING THE DYNAMIC ORBIT BUMP TEST

The test was performed with a single bunch of protons at 3.5 TeV. Unlike in previously described tests the losses were achieved by gradually increasing the bump amplitude over  $\sim 10\ \text{sec}$ . The resulting signal was registered by the BLMs for further comparison with simulations.

In the simulations the orbit bump was increased by  $10\ \mu\text{m}$  every 50 turns, reproducing the experimental conditions on a shorter scale for reducing the required CPU time. The time distribution obtained in the simulations provided a very good agreement with the BLM data when scaled (Fig. 9), which served as a validation of the tracking results.

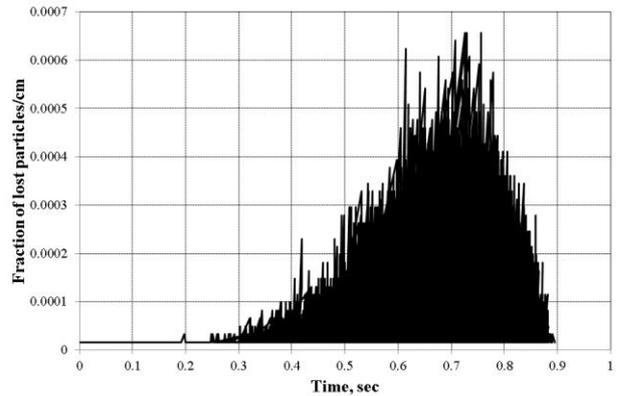


Figure 9: Time distribution in the dynamic orbit bump test (Statistics: 50000 particles).

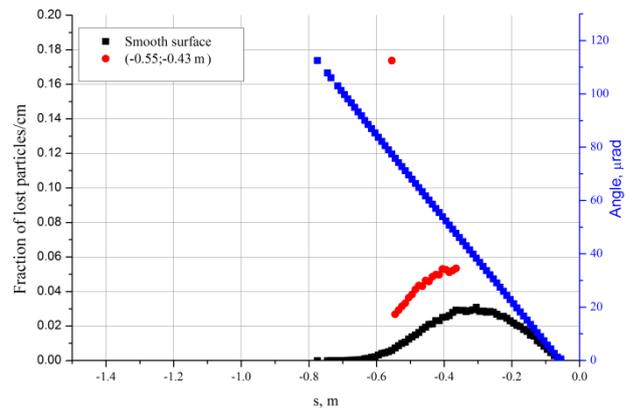


Figure 10: Longitudinal distribution in the presence of a  $30\ \mu\text{m}$  aperture restriction (between  $-0.5\ \text{m}$  and  $-0.43\ \text{m}$ ; red) and without a restriction (black); angular distribution for the dynamic orbit bump quench test.

The obtained spatial and angular distributions are shown in Fig. 10. Additional studies were performed for checking the sensitivity of the distribution to the speed of increasing the orbit bump and to the aperture restrictions. The results showed that a faster increase of the bump amplitude leads to a wider longitudinal distribution. For example in the extreme case when the amplitude of the

bump is instantaneously set to touch the aperture of the quadrupole, the losses will be observed in several accelerator components upstream that quadrupole.

The aperture restrictions, as well as in the previous cases, were modelled as a rectangular block along the beam screen with a length of 10 cm and a 30  $\mu\text{m}$  thickness. The influence of such a block on the spatial distribution is demonstrated in Fig. 10. By varying the location and length of such an aperture restriction it is possible to change the average impact angle by 50%.

## CONCLUSION

The results of the MAD-X tracking simulations showed correlation of the spatial distribution with loss duration: with increasing duration of losses the width of the distribution decreases. Fig. 11 shows the longitudinal distributions for all the discussed orbit bump quench tests. No losses were observed downstream the centre of the quadrupoles, due to a focusing magnetic field in the respective plane.

The time distribution strongly depends on the loss scenario and is influenced by many experimental parameters, such as tune, beams size and diffusion rate.

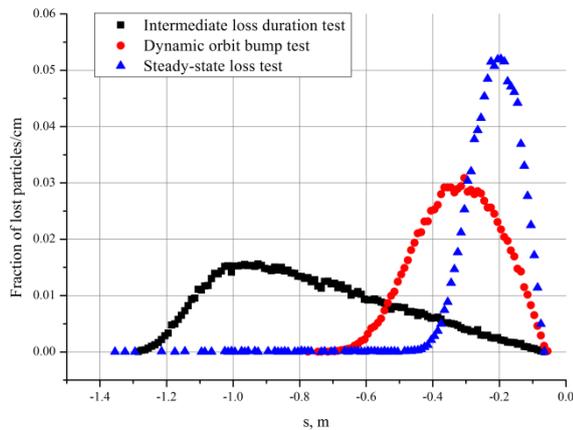


Figure 11: Longitudinal distributions in all the presented simulations.

The angular distributions (Fig. 12) showed dependence on the quadrupole coefficient only, and not on the loss scenario. For this reason the angular distribution for the dynamic-orbit-bump case differs from the other two cases – the test was performed in a defocusing magnet. An impact angle of a projectile depends only on the location of the loss, therefore by shifting the distribution it's possible to change the average impact angle of the lost particles.

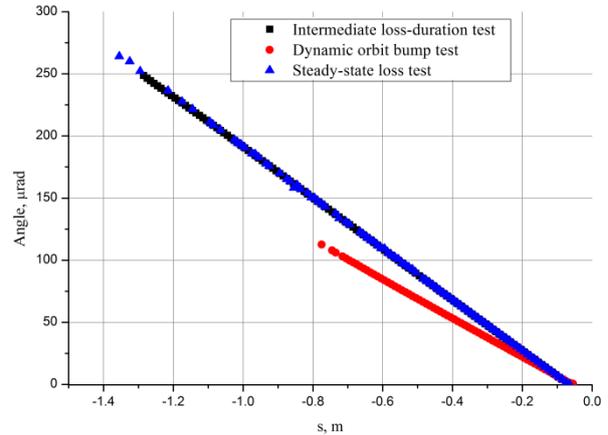


Figure 12: Angular distributions in all the presented simulations.

The presented simulations were the initial step for the analysis of the quench tests. The spatial distributions were an essential input for obtaining the energy deposition in the magnet coils. The results were further compared with the estimates of the electro-thermal simulations. This approach allowed getting a better understanding of the quench thresholds and respective signals in the BLMs [11].

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