BEAM LOSS MECHANISMS, MEASUREMENTS AND SIMULATIONS AT THE LHC (QUENCH TESTS)

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Abstract

Monitoring and minimization of beam losses is increasingly important for high-intensity and superconducting machines. In the case of the LHC, the collimation system is designed to absorb the energy of lost particles and confine the main multi-turn losses to regions without sensitive equipment. However many loss mechanisms produce local loss events which can be located elsewhere in the machine. A beam loss monitoring system, covering the whole machine circumference is therefore essential, and is used for both machine protection and diagnostics. In order to fully understand the measured signals and set-up the beam abort thresholds, extensive simulation work is required, covering particle tracking in the accelerator and the generation of the particle showers created by the lost particles. In order to benchmark these simulations and verify beam-abort thresholds, special tests have been performed where beam losses are provoked in a controlled manner over a wide range of duration. This work summarizes the experience in understanding beam losses in the LHC during Run 1.

INTRODUCTION

When the beam particles deviate from their optimal trajectory and hit the vacuum chamber or if they interact with objects inside the vacuum chamber (rest gas molecules, dust) they are usually lost from the beam. These beam losses are a natural aspect of every machine operation. Their effects are: decrease of beam intensity and lifetime, activation and radiation damage of accelerator elements. In case of catastrophic losses, when unexpectedly large fraction of the beam is lost in the area which is not designed to accept such a loss, their may lead to a damage of the vacuum chamber and other machine elements.

In case of superconducting accelerator the beam losses heat up the magnet coils and may lead to a sudden transition to normal-conducting state called a *quench*. In LHC the total energy stored in a circulated beam reaches 392 MJ while the quench level is only about a few $\mathrm{mJ/cm^3}$, therefore a loss of about 10^{-10} of the total beam intensity on superconducting magnet aperture may heat up the coil above transition temperate and quench the magnet.

The most obvious way to quantify the beam losses is a decrease rate of the beam current, measured typically in loss of particles per turn, per second or per a given phase of the machine cycle. This measurement is done using beam current transformers.

Another loss quantification is the beam power lost in a given location, for instance on a collimator or along the beam chamber. In case of LHC primary collimators only a small fraction ($\sim$ 2%) of the impacting beam power is deposited in the graphite jaw. The rest is deposited in the downstream collimators and absorbers. In order to allow hands-on intervention on beamline elements the activation must be limited and therefore the regular losses should be kept at the level below 1 W/m.[1]

Finally the beam losses are measured by Beam Loss Monitors (BLM) using radiation units, for instance Grays. This way of loss quantification is usually used in protection-related studies, for instance assessing the damage or quench potential of the losses. It is related to the energy density deposited inside accelerator components.

These various quantifications of beam losses are related. For instance a single proton lost in LHC generates BLM signal between 10^{-12} and 10^{-10} Gy.

This paper describes the beam losses in LHC and concentrates on a special case of controlled loss experiments called quench tests. They were analyzed and simulated with unprecedented precision using state-of-art techniques.

BEAM LOSS MECHANISMS AND TIMESCALES

Beam losses are often divided into normal and abnormal. The normal losses are those which cannot be avoided, for instance losses due to luminosity debris or due to particle diffusion from beam core to the halo which are usually caught on the collimation system. The beam instabilities due to operational variations, for instance tune change during the squeeze or ramp, are also producing normal losses. In LHC the average intensity lost during a fill, between capture and start of physics is about 3.5%. Table 1 shows the distribution of losses between various phases of the machine cycle.

Table 1: Beam Losses During Various Phases of Machine Cycle During Luminosity-production Year 2012 [1]

phase	average	maximum
RF capture	0.5%	2%
ramp	1.2%	15%
squeeze+adjust	1.7%	10%

Abnormal losses happen due to malfunction of accelerator equipment, for instance spurious discharge of the kicker magnets or dust particles falling into the beam. The last ones, called colloquially Unidentified Falling Objects (UFO), are of special concern in LHC, because they can provoke magnet quenches compromising machine operation at 6.5 TeV.

It is convenient to classify beam losses according to their duration:

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[1] This value is applicable for a beamline shielded with magnets.

ISBN 978-3-95450-173-1

- Ultra-fast losses developing in less then three machine turns (270 µs) are usually linked to injection or dump; only passive protection systems (absorbers, collimators) can protect from effect of those losses; the quench level of superconducting magnets in this timescale is determined by heat capacity of a dry cable.
- Very fast losses developing up to millisecond are typically UFO losses; in this timescale the BLM system allows to prevent magnet quenches; the quench level is driven by heat transfer to the superfluid helium inside the cable.
- Fast losses, up to several seconds can be due to various mechanisms, for instance RF trips or powering failures; there are multiple protection systems active in this timescale; heat capacity of helium inside the cable is saturated, the heat transfer outside coil starts to play important role.
- Slow losses, longer than several seconds are typically collimation and luminosity losses; in addition to protection systems the time is long enough for human reaction; quench limit is determined by the heat transfer to the cryogenic system.

MEASUREMENT TECHNIQUES

The beam particles, when interacting with accelerator material, produce showers of secondary particles which can usually be detected by radiation detectors. In LHC the BLM system uses ionization chambers [2] installed on the outside of the magnets cryostats. The current from the chambers is converted to frequency and this signal is send to the surface card performing real-time data analysis. This scheme allows for the 10^9 dynamic range of the measured current.

As BLMs are situated in the radially peripheral part of the shower, they cannot be used to determine loss pattern with accuracy better than 1-2 meters. Semiconductor detectors have been installed on the cold mass of some of the LHC magnets in order to better corelate the energy deposition in the magnet coil with BLM signal (see Fig. 1 and 2). It is planned to install those detectors inside the cold mass, very close to the coils [3]. They operate at temperature of 2 K and must withstand dose of several MGy.

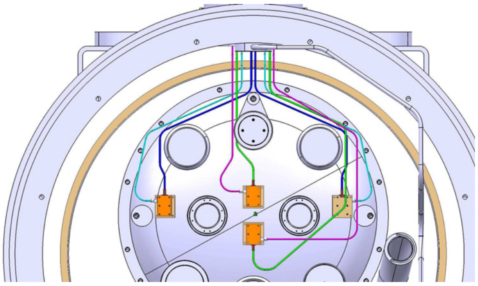

Figure 1: Drawing of cryogenic BLMs installed on the helium vessel of LHC main dipole.

The advantage of semiconductor detectors is their speed which allows for nanosecond resolution in comparison to ionization chambers with only about 40 µs resolution. Therefore the diamond detectors are installed behind the collimators, what allows for measureing bunch structure of the beam losses.

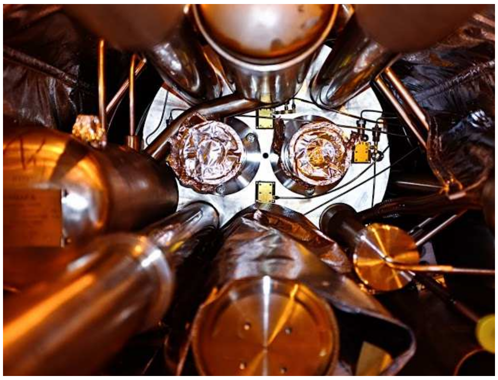

Figure 2: A photo of an installation of cryogenic BLMs on the magnet cold mass.

In some cases the beam losses are assessed measuring activation of machine elements in the intermissions of normal operation.

BEAM LOSS EXPERIMENTS

The beam losses are present in daily operation of most machines. Both, the normal and abnormal losses, limit the machine performance. For instance the debris due to luminosity production may generate losses exceeding the steady-state quench limit and therefore determine the maximum allowed instantaneous luminosity. UFO losses may lead to quenches of main ring magnets so frequent, that the recovery time (about 8 hours per quench) will not allow for an efficient operation. In order to understand better the limits imposed by quench phenomena a series of experiments, called beam-induced quench test, have been performed. The goals of the experiments are:

- Assessment of the machine performance limits due to magnet quenches.
- Determination of beam-induced quench levels.
- Validation of the BLM quench-preventing beam-abort thresholds.

The quench tests have been performed first time with Tevatron magnets in 1980 [4]. The first beam-induced quenches in LHC took place in 2008 [5]. In the year 2010 the UFO losses were observed for the first time. This was also the year when a total energy stored in the beam increased well above safe beam limits of about 1 MJ. To address these two aspects quench tests with a wire scanner [6] and with dynamic orbit bump [7] were performed.

In 2011 two new types of quench tests were performed. The first type was a steady-state test with collimators with a goal to identify the improves the collimation system needed for high luminosity run [8]. The second one was devoted to investigation of ultra-fast losses with beam energies above injection and was performed by splashing an injected bunch on a collimator in front of magnet with increased coil current corresponding to high beam energy [9].

The year 2012 was devoted to luminosity production therefore no quench tests were performed, although an effort to prepare ones has started. This effort was concluded with a 48-hour quench test campaign in February 2013 right after the end of Run 1. During this campaign the four tests were executed, some being an extension of previous tests, other presenting a new approach to controlled beam loss generation.

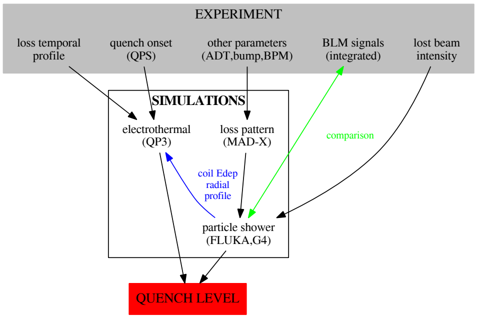

Figure 3: Quench test analysis scheme.

Figure 3 presents the analysis scheme of a typical quench test. The most important experimental measurements are the time structure of the losses the BLM signals and the amount of the lost beam intensity. Typical result of the experiment is shown in Fig. 4 for UFO-timescale test. Three simulations are needed to analyze the experiment. The particle tracking code is used to reconstruct the loss pattern on the aperture. Result of this code, together with lost intensity from the experiment, are fed to a particle shower simulation which produces BLM signals and energy density deposition in the coil. The BLM signals are compared with experimental values and general agreement gives confidence into values of energy deposition in the coil. Finally electro-thermal simulations are preformed.[2] The two quench levels: from electro-thermal and particle shower simulations, are compared. An agreement means that the quench level is correctly modelled and can be extrapolated to different magnet currents and loss duration. Because of significant uncertainties in the experiment and the simulations an agreement within factor 2 is regarded as good.

LOSS PATTERN SIMULATIONS

In LHC the global loss patterns are well understood. They occur on collimator system and follow the collimation hierarchy. The leakage to the cold sectors is well controlled and is about $3 \cdot 10^{-4}$. In Fig. 5 the measurement and the simulations of the loss maps are shown. The program used to perform these simulations, called SixTrack [10], tracks the particles, which underwent the first scattering in collimators, over several turns until they are lost in the collimation system or on cold aperture. The agreement between measured and simulated loss patterns is very good.

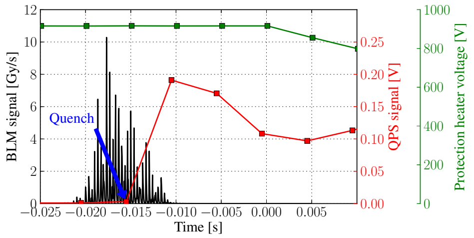

Figure 4: Result of 5 ms quench test. The BLM signal (black line) shows particular, spiky structure. The resisitive voltage on the coil (red line) indicates the quench onset 5 ms after beginning of the loss.

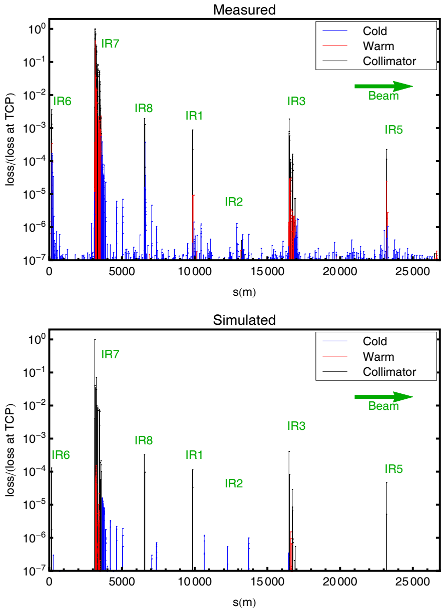

Figure 5: Beam loss distribution measured by the BLM system during qualification loss map (upper) and simulation (bottom). Reproduced from [11].

A cause for a local loss in the cold section can be UFO event, accidental orbit bump or a leak from the collimation system. A loss pattern in such case is affected by machine optics, beam dynamics, oscillations and roughness of the vacuum chamber surface.

A direct measurement of the loss pattern is limited by the accuracy of the BLM system which is defined by the longitudinal development of the shower. Better accuracy can only be attempted by a precise beam position and emittance measurement and by beam trajectory modelling. An example of such procedure is shown in Fig.6. In this experiment an injected beam was kicked with large vertical angle (750 µrad) and hit a main dipole magnet leading to a quench. The beam emittance has been measured in SPS and the trajectory has been measured by BPMs. The MAD-X modelling of previous shot with smaller angle (80 µrad) shows very good

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[2] Because of the dependence of the electro-thermal simulations from energy gradient in the coil the two analysis branches are not independent.

agreement with BPM readings. This allows to trust the large kick trajectory modelling and estimation of the loss profile.

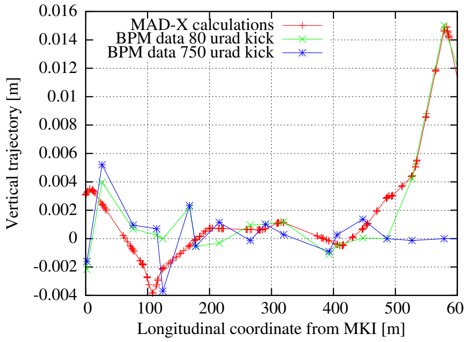

Figure 6: Beam trajectory in case of large kick event (see text). Courtesy of C. Bracco.

The above experiment features particularly large beam impact angle, but for most of the losses on the vacuum chamber this angle is much smaller. In Fig. 7 a strict correlation between distance of the lost proton from a centre of lattice quardupole magnet and the impact angle is shown. The angle reaches minimum close to the magnet center.

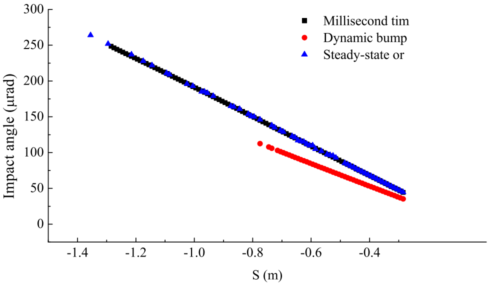

Figure 7: Correlation between proton impact angle and the loss position along main quadrupole magnet [12]. Courtesy of V. Chetvertkova.

A consequence of such small impact angles is a sensitivity of the loss pattern to the surface roughness. Even a small variation from a perfect surface (e.g. 30 μm, as shown in Fig. 8) can significantly affect the loss distribution.

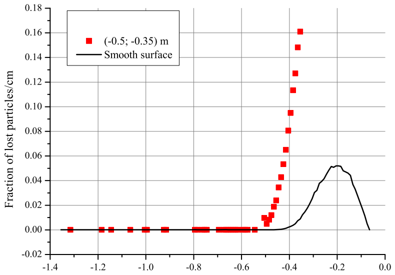

Figure 8: Influence of a hypothetical deviation from perfect surface on loss pattern [12]. Courtesy of V. Chetvertkova.

PARTICLE SHOWER SIMULATIONS

Particle shower simulations are needed to assess the effect of the beam loss on accelerator equipment and to reproduce the BLM signals. Typically the input to the particle shower simulations is the loss pattern, obtained from tracking code.

The results of the particle shower simulations must be normalized to the amount of lost particles in order to be compared with the values of measured BLM signals. The agreement of the BLM signals enhances confidence to the results of the simulations of the energy deposited in the coils, which cannot be measured. The ratio of the BLM signals to the energy density in the coil gives a base to the protection function of the BLM system. Because the particle shower is small in the first centimeters of its development (coil) and grows downstream (BLM), the relation between the BLM signal and the energy in the coil depends on the scale of the losses.

In Fig. 9 the dependence of the BLM threshold, which is proportional to the ratio between BLM signal and energy deposit in the superconducting coil, is shown as a function of the longitudinal spread of the loss. This curve explains why even a small deformation of the vacuum chamber wall leading to concentration of losses in one location can affect significantly the energy deposit in the magnet coil leaving the BLM signal unchanged.

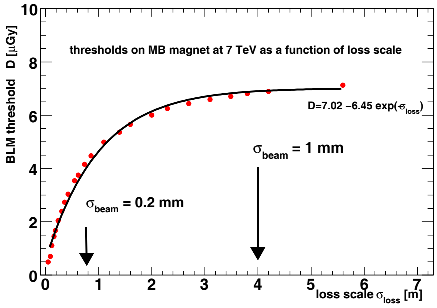

Figure 9: Dependence of the ratio of BLM signal to energy density deposited in the coil in function of loss length [13].

Figure 10 shows a quench test in which a particular good agreement between FLUKA simulations and measurements of the BLM signals was achieved. In most tests the agreement was much better than a factor 2, especially for the monitors with the highest signals.

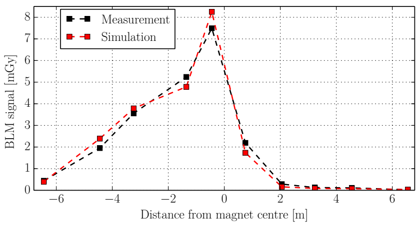

Figure 10: Measured and simulated BLM signals in case of 5 ms quench test. Courtesy N. Shetty [14].

ELECTRO-THERMAL SIMULATIONS

One of the beam loss effects is heating of the accelerator elements, for instance the magnet coils. To estimate the temperatures the heat transfer must be taken into account. This is particularly interesting in case of superconducting magnets, because of complex heat transfer mechanisms to superfluid helium. The electro-thermal codes allow for estimation of the coil temperature in the presence of heating from the beam loss and cooling mechanisms. They also estimate the energy deposit at which the magnet quenches. The code used to simulate quench tests is QP3 [15]. Input to the code are Rutheford cable parameters (amount of superconductor, type of insulation), the amount of liquid helium in the cable, the current density and shapes of the radial (from patricle shower simulations) and temporal (from experiment) distributions of energy density in the coil. The program performs iterative search for a minimum energy deposition causing the quench.

Results of the quench level determination for selected quench tests are presented in Table 2. In most cases the quench levels agree within factor 2. Only in case of 5 ms loss the disagreement is wors. The discrepancy is attributed to spiky structure of the loss obtained in this experiment (see Fig. 4), which is not simulated in QP3.

Table 2: Quench Levels for Selected Tests

timescale	E_{beam}	Part. Shower	El.-Thermal.
ns	450 GeV	≤ 36 mJ/cm^3	38 mJ/cm^3
$\sim$ 5 ms	4 TeV	250 mJ/cm^3	58 mJ/cm^3
$\sim$ 5 s	4 TeV	> 50 mW/cm^3	115mW/cm^3
$\sim$ 5 s	4 TeV	208 mW/cm^3	180mW/cm^3
20 s	4 TeV	41 mW/cm^3	70 mW/cm^3

Due to uncertainties in magnetic field value, liquid helium contribution and additional stress due to cable bending the estimation of quench limit in the ends of the magnets is less accurate. Unfortunately many realistic beam loss scenarios foresee the maximum energy deposit in these regions.

CONCLUSION

The main conclusions which can be drawn from the beam-induced quench tests performed during LHC Run 1 are:

- The experiments should involve an attempt where one of the parameters, is below the quench; this allows for determination of the quench level range.
- For fast tests the synchronization of the BLM and QPS signals are crucial for test analysis.
- BLMs cannot resolve the local loss pattern; even a small surface roughness may result in a loss pattern giving significantly different energy deposition in the coil.
- Parametric study of simulation parameters is very important to understand the sources of uncertainties on the quench test results.
- Transverse damper, used in various excitation modes, is a very good tool to generate controlled losses.
- Particle tracking is often more uncertain than particle shower simulations and probably requires more conceptual development.
- The maximum of energy deposition often takes place in complex regions of the magnets where both, the particle shower and electro-thermal simulations give more uncertain results.

ACKNOWLEDGMENT

The author wants to thank numerous researchers who contributed to this work, especially: B. Auchmann, T. Baer, M. Bednarek, G. Bellodi, C. Bracco, R. Bruce, F. Cerutti, V. Chetvertkova, B. Dehning, P. P. Granieri, W. Hofle, E.B. Holzer, A. Lechner, E. Nebot, A. Priebe, S. Redaelli, B. Salvachua, R. Schmidt, N. Shetty, E. Skordis, J. Steckert, D. Valuch, A. Verweij, J. Wenninger, D. Wollman and M. Zerlauth.

REFERENCES

[1] G. Papotti et al., *Beam Losses through the Cycle*, Proceedings of the 2012 Evian Workshop on LHC Beam Operation

[2] `http://cern.ch/blm`

[3] C. Kurfuerst, *Cryogenic Beam Loss Monitoring for the LHC*, CERN-THESIS-2013-232

[4] R. Dixon, N.V. Mokhov, A. VanGinneken, *Beam Induced Quench Study of Tevatron Dipoles*, Fermilab FN-327

[5] M. Sapinski et al., *Beam-induced quenches of LHC magnets*, Proceedings of IPAC13, THPEA045

[6] M. Sapinski et al., *LHC magnet quench test with beam loss generated by wire scan* , Proceedings of IPAC11, WEPC173

[7] A. Priebe et al., *Beam-induced Quench Test of LHC Main Quadrupole*, Proceedings of IPAC11, WEPC172

[8] D. Wollman et al., *Collimation Losses in the DS of IR7 and Quench Test at 3.5 ZTeV*, CERN-ATS-2011-042 MD

[9] Ch. Bracco et al., *Experiments on the Margin of Beam Induced Quenches for LHC Superconducting Quadrupole Magnet*, Proceedings of IPAC12, MOPPC004

[10] G. Robert-Demolaize, R. Assmann, S. Redaelli, and F. Schmidt, Proceedings of the 21st Particle Accelerator Conference, 2005 (IEEE, Piscataway, NJ, 2005), p. 4084.

[11] R. Bruce et al., *Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider*, Phys. Rev. ST Accel. Beams **17**, 081004 (2014)

[12] V. Chetvertkova et al., *MadX Tracking Simulations to Determine the Beam Loss Distributions for the LHC Quench Tests with ADT Excitation*, Proceedings of IPAC14, THPRI094

[13] M. Sapinski, B. Dehning, A. Priebe, *Simulation of Beam Loss in LHC MB Magnet and Quench threshold test*, CERN-LHC-Project-Note-422

[14] N. Shetty et al., *Energy Deposition and Quench Level Calculations for Millisecond and Steady-state Quench Tests of LHC Arc Quadrupoles at 4 TeV*, Proceedings of IPAC14, MOPRO019

[15] A. Verveij, *QP3: Users Manual*, CERN EDMS 1150045, 2008