BEAM LOSSES AND BEAM INDUCED QUENCHES AT THE LHC

B.Salvachua#, T.Baer, M.Barnes, C.Bracco, A.Lecher, G.Papotti, S.Redaelli, M.Sapinski, B.Todd, J.Uythoven, N.Vittal, J.Wenninger, D.Wollmann

CERN, Geneva, Switzerland

Abstract

In Run 2, the LHC will operate at 6.5TeV proton beam energy. At this energy the same loss mechanisms that occurred in Run 1 (at 3.5TeV and 4TeV proton beam energy) could potentially induce quenches on the LHC superconducting magnets. The recovery of the cryogenic conditions after a quench is of the order of 5-10 hours and the risk to permanently damage machine equipment at this new energy is more important. Therefore a good understanding of the losses and how they scale with energy is crucial for the efficient operation of the LHC. This paper shows an overview of the beam losses through the LHC cycle during Run 1, with emphasis in the special cases:

- Losses from machine manipulation such as orbit changes and squeeze of the beams.
- Losses from dust particles in the beam pipe interacting with the beam,

In this paper we review the main losses scenarios during Run 1 in preparation for the next Run 2 operation.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN will resume operation in 2015 with the unprecedented beam energy of 6.5TeV. In order to keep the beams in the 27km of the former LEP tunnel, the LHC was built with 1232 superconducting dipoles that operate with superfluid Helium at temperatures below 2 K to provide a magnetic field of 8.33 T **[1].**

During Run 1 (2010-2012), the LHC operated at 3.5TeV and 4TeV, with maximum beam stored energy of 145 MJ. In the arc, the beam is contained in a geometrical aperture of 2×17.3 mm height and 2×22 mm width (beam size order of few mm). No beam induced magnet quenches at 3.5TeV nor at 4TeV occurred during Run 1, however a small amount of this beam (or the order of hundreds of mJ/cm3) could have quenched a magnet if deposited into the superconducting coils **[2].** The protection relies in well-established beam tail cleaning with collimators and beam loss monitors that would trigger a beam dump before the beam deposits enough energy to quench the magnet.

In Run 2 the energy of the LHC beams will be increased to 6.5TeV. In this scenario the main challenge is how to handle beam store energies of up to 362 MJ, a factor for 100 larger than Tevatron.

belen.salvachua@cern.

BEAM LOSSES DURING RUN I

A precise control of beam losses at the LHC is mandatory to ensure safe operation. The tails of the LHC beams contains enough energy to quench the super conducting magnets. A small fraction of it, 5×10^9 primary protons (a tenth of a nominal LHC bunch) at 7 TeV energy, could permanently damage one of the tungsten tertiary collimators **[3].** New limits have been recently calculated for secondary protons that have impacted primary or secondary collimators before reaching the tertiary collimators. This new analysis provides a new limit of 1.2×10^{11} secondary protons impacts for plastic of deformation of the tertiary collimators **[4].**

However, there losses due to beam dynamics like particle diffusion, scattering processes, beam instabilities and due to operational variations like orbit, tunes and chromaticity changes during the LHC cycle. These losses cannot be avoided and therefore need to be absorbed by the collimators to avoid heating in the superconducting magnets.

The LHC has a multi-stage collimation system with more than 100 collimators. It is optimized to clean particles with high betatron amplitudes in IR7 and off-momentum particles in IR3. The collimation system acts as passive protection of the machine, it is designed to catch undesired losses and protect the magnet aperture **[1]**. Collimators should be always the smaller aperture in the machine. During the LHC cycle, beam losses up to 500kW over a maximum of 10 seconds could be tolerated and absorbed by the collimator system without quench of the magnets. **[1].**

In addition to this type of losses, there are also abnormal losses that are difficult to control, for example due to the failure or irregular behaviour of the accelerator components. In cases where the losses exceed the specific maximum rates, the active protection of the LHC should trigger a beam dump request. The faster system reacts in 3 LHC turns (270 µs). The LHC is equipped with more than 3000 beam loss monitors placed around the machine to provide a measurement of the beam losses in Gy/s with 12 different integration times that range from 40 µs to 84 s **[1].** The dump thresholds of these monitors should be precisely set to the maximum losses allowed in the machine before a quench can occur in order to optimize the machine performance.

As the performance of the machine is pushed, the contribution from beam losses is higher. If one looks at the beam dump triggers due to beam losses during Run 1, the dumps increased from 3.7% in 2010 to 9.9% in 2012, see **Figure 1.** In 2012, the majority of beam dumps occurred with stored beam energy bigger than 100MJ, reaching a maximum of 146MJ **[5].**

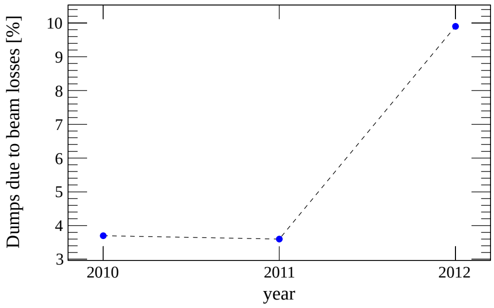

Figure 1: Beam dumps in percentage due to measured beam losses during the 3 years of Run 1 LHC operation.

Beam losses do not occur always in the same way, they can be classified in several categories depending on the time scale of the loss **[6]**. The classification is as follows:

- Slow losses (more than 1 second). A manual intervention is possible in order to apply corrections or trigger a beam dump. This could be due to problems on cryogenics, transverse instabilities, orbit or tune changes, etc.
- Fast losses of more than 15ms (170 LHC turns). The LHC is protected by multiple systems. This could be due to failure of some equipment like Radio Frequency or a quench of superconducting magnets.
- Very fast losses of more than 270 μs (3 LHC turns). The LHC is still protected by the fastest systems (BLMs and fast magnet current monitors). This could be due to failure of some equipment, like transverse damper and the interaction of dust particles with the beam (UFO effect).
- Ultra fast losses of less than 3 LHC turns. The LHC is not actively protected and it relies in the absorption of beam losses with the collimation system.

Reproducible losses during LHC cycle

In the first years of the machine 2010-2011, beam losses were nearly negligible before collisions. The transmission of the beam was close to 100%. However, in 2012 the performance of the machine was pushed to achieve 60 cm beta-star (β*) and the collimator settings had to be tightened to protect the triplet magnets. The primary collimators were placed at 4.3σ assuming normalized transverse emittance (3.5μm·rad), with collimators as close as 2 mm. This change had two significant effects:

- Important scraping of beam tails.
- Increase of impedance.

The observation was that the beam losses increased by a factor of 10 with respect to previous years.

Figure 2 shows the magnet cycle of the LHC in units of proton energy and the store beam current during the LHC cycle in 2012. Several stages could be identified in the cycle, the beam modes.

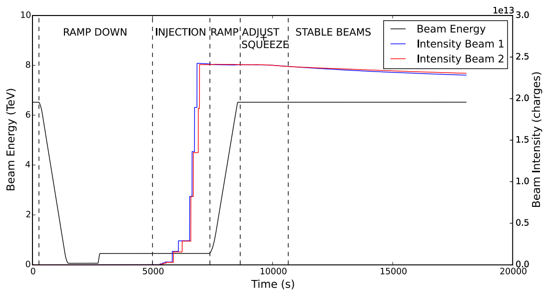

Figure 2: Magnetic cycle of the LHC (in black) in units of beam energy and beam intensity in charges (read for Beam 1 and blue for Beam 2).

- **Ramp down and setup:** there is no beam in the machine but the equipment is recovering from the previous fill and preparing for the next.
- **Injection:** Beam is being injected, in bunches of about 1×10^{11}protons/bunch, spaced 50 ns. Beam losses at each injection could appear mainly in the injection regions (Point 2 and Point 8). Dedicated injection protection collimators are placed to absorb the miss-kicked beam or losses due to injection oscillations.
- **Ramp:** The LHC beams were ramped from 450GeV to 4TeV in 2012. RF capture beam losses appear at the start of the ramp, between 450 GeV and 500 GeV. During the ramp the beam is scraped smoothly when the collimator gaps are closing to top energy tight settings, from 5.7σ at injection to 4.3σ at top energy.
- **Squeeze:** The beam size is reduced at the interaction points, during this cycle there are orbit shifts, tune, etc. that generate important beam losses.

- **Adjust:** The beams are brought into collisions. The losses in this beam mode, together with squeeze, were the limitation in 2012.
- **Stable beams:** The beam is lost partially in luminosity production; in this case physics debris losses are also present.

The losses are distributed in the machine as shown in **Figure 3 [7].** The figure shows the distribution of purely transverse losses generated by doing a controlled excitation of the beam in one of the transverse planes. The BLM signal is normalized to the maximum loss and background subtracted. The maximum beam loss occurs in Point 7, where the betatron cleaning happens. The maximum loss in the cold magnets occurs in the dispersion suppressor downstream Point 7. This is the most likely region to be quenched because the leakage from beam cleaning is localized in that area. Therefore, the beam loss monitors to protect the magnets in that area needs special treatment. The next limiting location is Point 3 where the off-momentum cleaning is happening. **see Figure 4**.

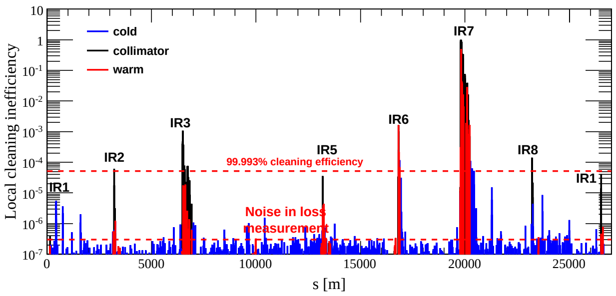

Figure 3: Distribution of beam losses in the LHC ring while exiting Beam 1 horizontally **[7].**

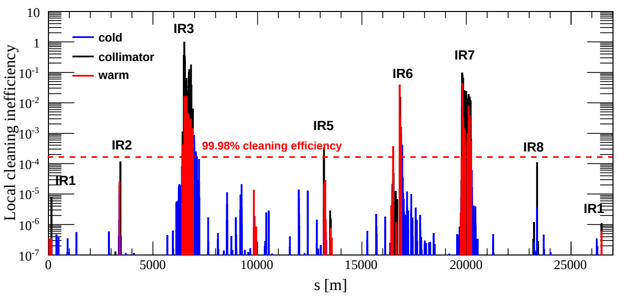

Figure 4: Distribution of beam losses along the LHC ring due to off-momentum **[7].**

Beam transmission and lifetime through cycle

The amount of beam lost through the LHC can be quantified by measuring the beam transmission:

$$\text{Intensity transmission} = \frac{I_{\text{end}}}{I_{\text{start}}}$$

where I_{end} is the measured beam intensity at the end of the LHC mode and I_{start} at the start of the mode.

Figure 5 shows the beam transmission during the squeeze from β*=1.5 m to β*=1 m in 2011. The transmission was very effective. Losses were rather small, on average, 100% for Beam 1 and 99.8% for Beam 2. In 2012 when the beta-star was pushed to β*=0.6m the losses increased by a factor of 10, with transmission on average 99.4% for Beam 1 and 98.2% for Beam 2, see Figure 6 [8].

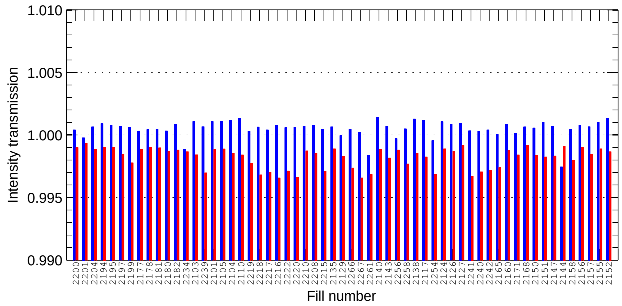

Figure 5: Beam intensity transmission in 2011 (normalized to 1) during squeeze for a selection of physics fills **[8].**

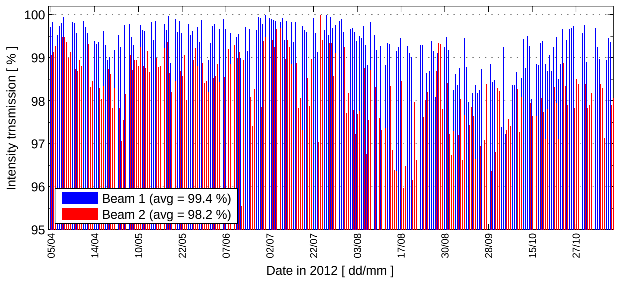

Figure 6: Beam transmission in 2012 (in percentage) during squeeze for a selection of physics fills **[8].**

It is also important to know how fast are the losses. The Beam lifetime measures the decay time of the beam intensities. **Figure 7** shows that 90% of the fills had lifetime below 10h, while in 2011 only 30%. The limiting modes were squeeze and adjust with about 50% of the fills with lifetime below 1 hour in adjust (the dump limit was set to 0.2 hours) [9].

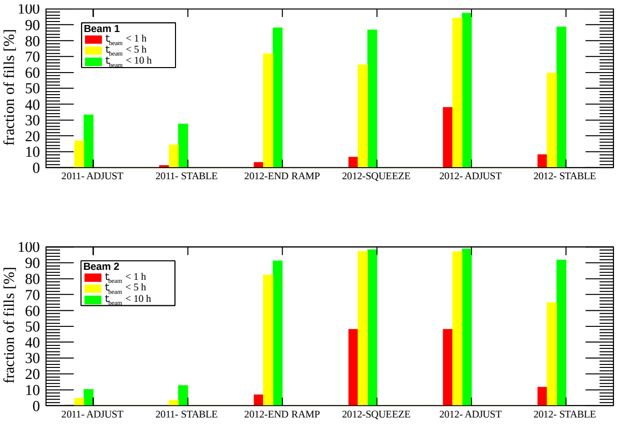

Figure 7: Fraction of fills with beam lifetime below 1 hour (red), 5 hours (yellow) and 10 hours (green) for Beam 1 (top) and Beam 2 (bottom) **[9]**.

Unidentified falling objects (UFO)

In addition to the regular LHC cycle losses, a new phenomenon appeared during Run 1. With a very short duration, few LHC turns and in unconventional loss locations (like the arcs) very high beam loss events occur randomly throughout the LHC cycle. A total of 58 beam dumps occurred in Run 1 due to this effect. The reason for these dumps is macro particles falling into the beam from the top of the vacuum chamber and generate uncontrolled and very fast losses. In the case of the injection kickers the UFOs were identified as Al_2O_3 particles from the ceramic tube **[6]**.

Although the UFO losses could occur anywhere in the ring, they were specially appearing close to the injection kicker magnets. For these cases, there has been several mitigation procedures set in place during the LHC long shutdown 1, mainly:

- Improved cleaning procedure of the ceramic tube during installation of the screen conductors.
- Installing 24 (instead of 15, pre-LS1) screen conductors in the ceramic tube, reducing the electric field further and thus decreasing the UFO rate.

The situation is therefore improved close to the injection kickers but the arcs have not been changed. Still for Run 2 the UFO losses are one of the biggest concerns for machine operation.

Beam induced quenches

The operational quenches took place exclusively during the injection process **[10].** An overview of all beam induce quenches at the LHC from specific quench tests and from operation in Run 1 can be found at **[11].**

Half a dozen beam induced quenches occurred at 450 GeV during operation of the LHC. One of them happen on 7th September of 2008 in an attempt to probe the quench limit. A bunch of 2×10^9 protons quenched a main dipole with a large vertical kick (MB.B10R2.B2). The reason was a mistyped kick amplitude of 750μrad instead of 75μrad **[12]. This** event was used in 2008 for the analysis of the quench levels at injection energy **[13].**

CONCLUSION

The main challenge of the LHC will be to operate at high current of the LHC magnets, close to 10kA, with 362MJ beams in the machine, keeping in mind that the recovery of cryogenic conditions after a magnet quench in the LHC can take between 5 to 10 hours.

In 2012, up to 2% of the beam was lost during standard operation of the squeeze. Extrapolating a similar loss scenario to Run 2 deals with about 7MJ absorbed by the collimation system with the risk of quenching the magnets due to cleaning leakage.

It is also expected about 5 to 10 times increased UFO activity with 25 ns bunch spacing (without mitigation measures). Extrapolation to 7 TeV predicts about a factor of 4 more energy deposited which emphasizes the need to review the quench limits in order to operate the machine effectively.

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