LOSSES AWAY FROM COLLIMATORS: STATISTICS AND EXTRAPOLATION

E. B. Holzer, R. Assmann, G. Bellodi, R. Bruce, B. Dehning, E. Effinger,
J. Emery, V. Grishin, C. Hajdu, S. Jackson, J. Jowett, C. Kurfuerst, A. Marsili,
M. Misiowiec, E. Nebot Del Busto, A. Nordt, S. Redaelli, C. Roderick, A. Rossi,
M. Sapinski, D. Wollmann, C. Zamantzas

Abstract

This paper focuses on beam losses in the LHC arcs. The main task of the approximately 2200 (out of a total of about 3600 ring monitors) is quench prevention. The arcs are generally very well protected by the collimators. The aim of this work is to search for possible holes in the arc protection, and to present the impact of short (single turn to several turn) and/or highly localized losses on the arcs. The paper first extensively addresses millisecond time scale losses (‘UFO’ type losses). A detailed analysis of these events is presented and the changes in the threshold settings for cold magnets are discussed and summarized. Subsequently, other losses in the arcs are studied with the help of betatron and momentum cleaning collimator loss maps and data from periodic scraping of the beam halo. The impact of few-turn-losses is briefly discussed. To conclude, the hardware interventions and intervention times for the 2010 run are summarized and the requirements for BLM system tests at the 2011 start-up are outlined.

MILLISECOND TIME SCALE LOSSES (UFOS)

Ten beam dumps due to fast (ms scale) beam losses (less than 1% of beam intensity) have been observed. They have been called UFOs (Unidentified Falling Objects). The current hypothesis is that some sort of ‘dust’ particle intercepts the beam. None of these events lead to a magnet quench. As a consequence, cold magnet thresholds have been increased by a factor of three on 01 October 2010 and by a factor of five on 26 October 2010—both with respect to the original applied thresholds, i. e. 0.3 times the ‘best to our knowledge’ quench level—by changing the monitor factor (MF) from 0.1 to 0.3 and 0.5. With the thresholds after the last MF increase, none of the UFOs would have dumped the beam. For the start-up of 2011 the cold magnet thresholds are adapted empirically (based on quench tests, wire scanner tests, 2010 signals and UFO signals). In the millisecond range they are set similar to the thresholds at the end of 2010, above all 2010 measured UFO losses. The losses are always detected by more than six local monitors, at least three of them getting close to (or above) the abort threshold (in the 2.5 ms integration window), confirming the redundancy in the system. Furthermore, the losses from these events are seen at the aperture limits (collimation regions). Figure 1 shows the local longitudinal pattern of one of these events and the signal for the different integration times for the monitor with the highest loss, compared to the applied thresholds. Comparison with loss patterns during a wire scan confirms the similarity in shape and timescale of the loss patterns. Additional BLMs at aperture limits with a bunch-to-bunch resolution have been installed, using diamond detectors and ACEMs (Aluminum Cathode Electron Multiplier). The BLM logging data were scanned for events with the same signature, which did not trigger a beam abort (sub-threshold UFOs). The conditions for the scan were: Firstly a signal in a TCP BLM above $6 \cdot 10^{-4}$ Gy/s in the 2.5 ms integration interval; secondly three local BLMs (within 40 m distance to each other), which all have a signal above $6 \cdot 10^{-4}$ Gy/s in the 2.5 ms integration interval; and thirdly a calculated (from the signals of all integration times) loss duration in the ms range.

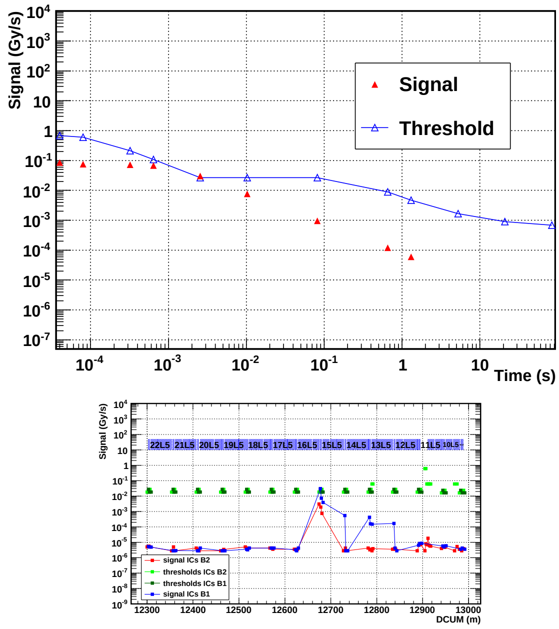

Figure 1: Longitudinal pattern of a fast loss event (top) and signal in the different integration times for the monitor with the highest loss (bottom). The beam abort was triggered on the 2.5 ms integration time.

During approximately 380 hours of stable proton beams at 3.5 TeV, 111 UFOs were identified, most of them far below the BLM beam abort threshold. The rate of UFOs was found to increase linearly with the number of bunches in the machine at a rate of $(1.35 \pm 0.17) \cdot 10^{-3}$ UFOs per bunch per hour per beam (see Figure 2). For 2000 bunches in the machine this leads to about 5.2 UFOs per hour. As the (high end of) the distribution of the magnitude of the UFO induced signal in the BLMs is poorly defined by the current statistics, no estimate can be given on what percentage will be above BLM threshold.

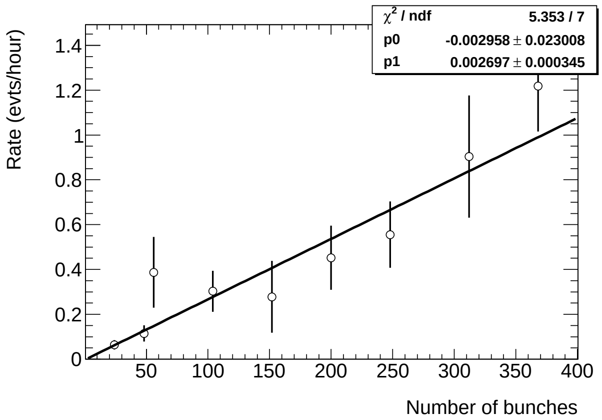

Figure 2: UFO rate (for both beams) as a function of the number of bunches (per beam)

At 450 GeV one sub-threshold UFO was detected over 88 hours of beam with mostly very few bunches in the machine. To combine measurement periods with different number of bunches the assumption is made that, at 450 GeV too, the number of UFOs is proportional to the number of bunches. The measured rate of UFOs per bunch per hour per beam is $(7.9 \pm 7.9) \cdot 10^{-5}$ at 450 GeV.

Table 1: UFO rates (measured vs. scaled) at injection and 3.5 TeV

Beam energy	**UFOs per bunch per hour per beam**
3.5 TeV, measured	$(1.35 \pm 0.17) \cdot 10^{-3}$
scaled down to 450 GeV	$(2.4 \pm 1.7) \cdot 10^{-5}$
450 GeV, measured	$(7.9 \pm 7.9) \cdot 10^{-5}$

As can be seen in Table 1, the measured rate of number of UFOs per bunch per hour per beam is significantly lower at 450 GeV. To be able to compare these numbers, however, it has to be taken into account that a particle intercepting a 450 GeV beam gives a lower signal in the BLMs than the same object interception a 3.5 TeV beam. The size of this effect can be measured with the help of the wire-scanners. There, a quadratic dependence of the BLM signal on the beam energy was found. The ratio between the signals at 3.5 TeV and 450 GeV is about 32. Scaling the BLM signals of UFOs at 3.5 TeV down with this factor, only two UFO would have passed the BLM detection limit from above (taking into account that three BLMs above detection threshold are required, and the third highest BLM is typically a factor of five lower than the highest BLM). The measured number of UFOs per bunch per hour per beam at 450 GeV is consistent with the scaled-down observation at 3.5 TeV.

No clear dependency of the average UFO signal on the beam intensity has been observed while the loss duration has been found to decrease with intensity (Figure 3).

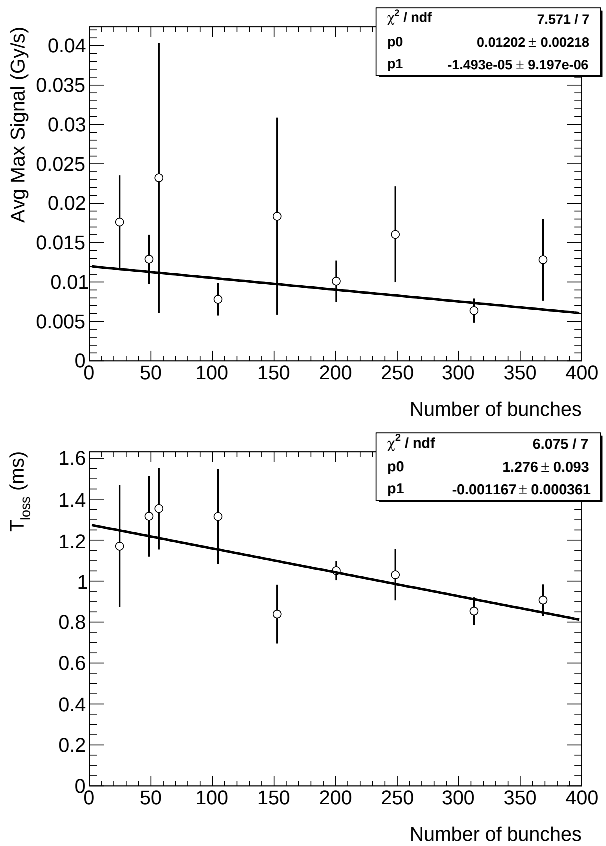

Figure 3: Average maximum UFO signal (top) and loss duration (bottom) as function of the number of bunches

The UFOs are not equally distributed along the ring. Hot spots and cold regions can be seen in Figure 4. Statistically significant hot spots are the injection kicker MKI right of IP8 (7 UFOs) and half-cells 30–31 right of IP7 (6 UFOs). The probability of measuring six UFOs within any of the 270 100 m bins is 0.13%. The probability to have three or more sections without UFO that are longer than 1400 m has been simulated [1] and calculated to less than $4 \cdot 10^{-3}$. There are three sections with lengths between 1400 m and 1700 m without any UFO. These cold regions are right of IP4, left of IP6, and left of IP7.

In a further analysis of 155 hours of ion beams no UFOs were found.

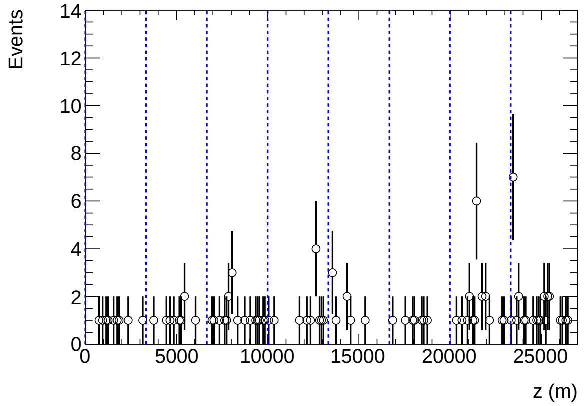

Figure 4: UFO events in 100 m bins along the LHC ring

OTHER LOSSES IN THE ARCS

Collimation Loss Maps

Leakage (signal in the arc BLM divided by the signal in the primary collimator, TCP) from collimators into the arc was analyzed with the help of betatron and momentum cleaning collimator loss maps at 3.5 TeV, for proton and ion beams. The results are compiled in Table 2. The proton leakage rate is very low ($3 \cdot 10^{-4}$ for momentum cleaning and $2 \cdot 10^{-5}$ for betatron cleaning respectively). An ion leakage rate of $2 \cdot 10^{-2}$ was measured. Preliminary comparisons of loss maps with simulations show a good agreement of magnitude and certain positions for beam 2, while for beam 1 hardly any losses are seen in the simulations.

Table 2: Collimation leakage into the arcs for 3.5 TeV protons and ions

Test data		Collimation	Detection limit	Maximum measured
Loss maps	p	betatron	$> 7 \cdot 10^{-6}$	$\approx 2 \cdot 10^{-5}$
		momentum	$> 3 \cdot 10^{-6}$	$\approx 3 \cdot 10^{-4}$
	Pb	betatron	$> 2 \cdot 10^{-5}$	$\approx 2 \cdot 10^{-2}$
		momentum	$> 4 \cdot 10^{-5}$	$\approx 2 \cdot 10^{-2}$
Periodic halo scraping	p	betatron	$> 3 \cdot 10^{-5}$	none
		momentum	$> 1 \cdot 10^{-5}$	$\approx 4 \cdot 10^{-3}$

Halo Scraping

Leakage out of the collimation region was further studied by using data from periodic scraping of the beam halo with the primary collimator. This leads to a modulated BLM signal on the TCP and at 'leakage' locations which can be identified using a Fourier transform. Figure 5 shows the leakage for ion betatron scraping for all LHC monitors (including the collimator regions). For ions, the sensitivity of this method is similar to the procedure using loss maps. It identifies, however, only about half of the monitors with a few additional ones. The observed leakage rate is about five times smaller than in the loss map method.

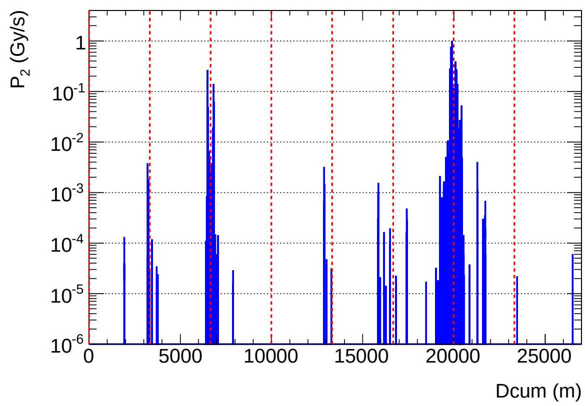

Figure 5: Leakage for ion betatron scraping for all LHC monitors (including the collimator regions)

The sensitivity for proton beams was significantly lower, no leakage into arc monitors could be identified. The slower TCP movement for ion beams (every 8 seconds) compared to the proton beam (every 3 seconds) yields better separated peaks in the Fourier transform and thus a higher sensitivity. The results are summarized in Table 2.

The data from halo scraping of the proton beam was also analyzed for luminosity induced losses, of which none where found in the arcs.

Few Turn Losses After Injection

Two loss events have been analyzed to determine whether they could be potentially dangerous to arc magnets. A three-turn loss of the proton beam on 10 December 2009 lead to a small signal in only one monitor ($1.8 \cdot 10^{12}$ Gy/s in 40 μs integration time), which was probably noise related. Even if not attributed to noise, the signal, if scaled to nominal injection intensity, corresponds to less than 20 % of the damage level.

A loss of the ion beam on 15 November 2010, which occurred 10–20 seconds after injection was due wrong beam chromaticity. It turned out to be a 2–3 seconds loss ($9 \cdot 10^{11}$ Gy/s in 1.3 s integration time). It was not fast enough to cause a problem for the magnets.

COLD MAGNET THRESHOLDS FOR 2011 START-UP

For the 2011 start-up the cold magnet thresholds are changed empirically based on 2010 measurements and quench tests. Table 3 compiles their typical evolution from the 2010 start-up to the 2010 end-of-run and to the 2011-start-up.

During the 2010 run the thresholds have already been raised via the monitor factors to avoid dumping on UFOs. Still, this has not lead to any magnet quenches. Therefore,

Table 3: Typical evolution of the cold magnet thresholds over time; the applied thresholds are master thresholds × monitor factor

Integration time	Date	Monitor factor	Change factor with respect to 2010 start-up Master threshold	 Applied thresholds
40–80 μs	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	3	3
0.3–2.5 ms	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	5	5
10 ms	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	1	1
80 ms–84 s	2010 start-up	0.1	1	1
	2010 end-of-run	0.5	1	5
	2011 start-up	0.1	1 (triplets) 0.33 (others)	1 (triplets) 0.33 (others)

this increase has been kept in the applied thresholds for the millisecond range integration intervals, which are the only ones sensitive to UFOs. Similarly, for microsecond range integration intervals the applied thresholds have been raised to accommodate for losses measured during the high luminosity proton runs. For the long integration intervals, preliminary results of the quench tests from 2010 showed that already the 2010 start-up thresholds were a factor of 2–3 to high. Hence, these applied thresholds have been lowered with the exception of the triplet magnets (to accommodate for luminosity losses). As the monitor factors have now been consistently lowered to 0.1 again, they allow for operational increases of up to a factor of ten.

SYSTEM PERFORMANCE

Hardware Interventions and Intervention Times

Table 4 summarizes the hardware interventions of February to December 2010. Most of the interventions were prompted by the onset of system degradation detected by regular offline checks. Hence, the component was replaced before malfunctioning. Some interventions became necessary because a failure was detected by one of the automatic internal system tests, preventing beam injection. Interventions mostly took place during scheduled technical stops or in the shadow of other interventions. The availability of the LHC was not seriously compromised by BLM system failures and repairs.

With respect to the intervention times, no changes are expected in 2011. Changes of monitor factors take approximately half an hour and master threshold changes take about one hour. For hardware interventions approximately one hour is required (plus the time for tunnel access, if necessary).

System Tests 2011

Before releasing the new firmware for the 2011 start-up it is tested on the vertical slice test system. Tests cover, among others, linearity, response to predefined patterns of input signals and tests of the XPOC and PM buffers. The exhaustive threshold triggering test of the ring monitors, covering every channel, every threshold and selected energy levels, will take about six days without beam. The system tests with pilot beams will need about six hours of beam time. They consist of a global test (injecting pilot beams, de-bunching them and initiating a beam dump) and of threshold triggering tests, for which one collimator jaw of a TCP is closed and pilot beams are injected a few times. As in 2010, the signal reception and the system status will be assessed continuously during the run.

CONCLUDING REMARKS

Until today the machine protection by the BLM system has been fully reliable. No avoidable quench occurred. There is no evidence of a single beam loss event having been missed. Hardware issues never caused a degradation of the reliability. The number of false beam aborts due to hardware failures are as expected and within requirements. Noise events never caused beam aborts. The initial thresholds (even though set conservatively) proved mostly adequate 2010 operation. No big deviation has been detected between the protection thresholds and the magnet quench levels. Losses were always seen by several local monitors and at the aperture limits, showing a certain protection redundancy.

This paper has summarized the analysis concerning losses in the arcs. It revealed that the arcs have been well protected at all times. The study on millisecond loss events (UFOs) showed that such events are frequent. Their rate increases with the beam intensity. The induced signals are

Table 4: Hardware interventions due to channel degradation or failure since february 2010

Element	**Details**	**Number**	**Out of total installed**
IC	bad soldering	12	3600
tunnel electronics	noisy analogue component (CFC)	7	359
tunnel electronics	bad soldering	2	720
tunnel electronics	low power optical transmitter (GOH)	9	1500
tunnel electronics	damaged connector	1	1500
surface electronics	weak optical receiver	12	1500
surface electronics	failed SRAM	2	350
VME64x Crate	failed CPU RIO3	3	25
VME64x Crate	failed power supply	1	25

mostly below the BLM thresholds. During the 2010 run the thresholds have already been raised via the monitor factors. Still, this has not lead to any magnet quenches. Therefore the shape of the master thresholds was changed for the 2011 start-up based on the 2010 measurements .

REFERENCES

[1] T. Baer, "On the Statistical Significance of Cold UFO Regions", private communication, February 2011