EXPERIENCE WITH HIGH-INTENSITY BEAM SCRAPING AND TAIL POPULATION AT THE LARGE HADRON COLLIDER

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Abstract

The population of beam tails at the Large Hadron Collider (LHC) is a source of concern for the operation at higher beam energies and intensities when even small fractions of the beam could represent a potential danger is case of slow or fast losses, e.g. caused by orbit transients or by collimator movements. Different studies have been performed using the technique of collimator scans to probe the beam tail population in different conditions. The experience accumulated during the operation at 3.5 TeV and 4 TeV is reviewed.

INTRODUCTION

The Large Hadron Collider (LHC) is designed to achieve stored beam energies of 362 MJ at 7 TeV. The initial operation experience [1], when 140 MJ were routinely achieved at 4 TeV, indicates that the design goals are within reach. A further increase by about a factor 2 is foreseen by the HL-LHC upgrade study [2]. At these intensities, small fractions of the beam can potentially damage accelerator components and limit the operational efficiency if losses reach the quench limits of superconducting magnets. There is a clear interest in understanding better the beam tail population. While beam scraping options are being investigated for the LHC [3], it is also useful to review the present experience and see which conclusions can be drawn.

Beam losses in the operational cycle were not considered a major issue after the 2010-11 runs at 3.5 TeV, when losses were essentially only observed at the moment of establishing collisions. The deployment of tighter collimator setting for a β^* reach of 60 cm [4] changed this picture. Observations related to these changes will be presented and the amount of beam lost in ramp and squeeze will be quantified. Some dedicated tests of beam scraping will also be briefly recalled and then some conclusions will be drawn.

BEAM HALO DIAGNOSTICS METHODS

Presently, the LHC lacks efficient and precise methods for on-line halo diagnostics. Standard emittance measurements (wire scanners, synchrotron light telescope, beam-gas-interaction monitor) do not offer dynamic ranges adequate for precise tail measurements with full beam intensities. The results presented here rely on tail scans performed by closing the primary collimators (TCPs). The hadronic showers generated by the interaction between TCP jaws and beam particles are measured by the beam loss monitors (BLMs). Appropriate calibration allows to convert

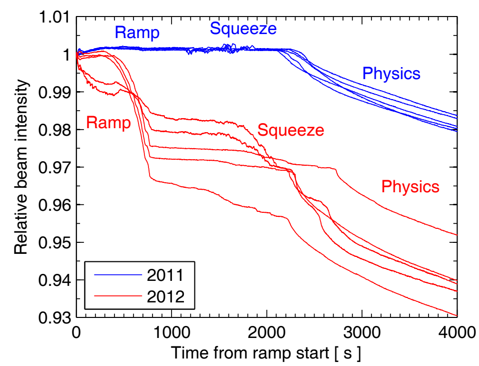

Figure 1: Beam intensity transmission during the operational cycle for 5 typical fills in 2011 (blue) and 2012 (red).

the BLM signal in number of protons lost [5, 6]. With a resolution of 2.76×10^{-9} Gy/s, a dynamic range of 8 orders of magnitude and a measurement range starting from 1.8×10^{-7} Gy/s [7], one can in theory achieve a resolution of 3.34×10^{4} p starting from 1.21×10^{6} p. Even if this range might be reduced by 1-2 orders of magnitude due to acquisition chain noise or offsets from background beam losses, the range remains sufficient for halo diagnostics.

The collimator scan method is useful and precise however it is clearly invasive and cannot be used in standard operation. The measurement results reported here concern dedicated low-intensity beam tests or so called end-of-fill studies where the detectors are switched off after a data taking period. An attempt is also made to use parasitically TCP losses to measure tails during ramp and squeeze, relying on the fact that the TCPs catch first all transverse beam losses because they represent the ring aperture bottleneck.

BEAM TAILS IN STANDARD OPERATION

Operational Aspects and Collimator Settings

Examples of losses during the 2011 (blue) and 2012 (red) operational cycles are given in Fig. 1. The primary collimator gaps in the betatron cleaning insertion are reduced in the energy ramp to follow the shrinking beam size, σ. In 2010 and 2011 they reached 5.7 $\sigma_{3.5\ \mathrm{TeV}}$ at top energy (assuming the nominal normalized emittance of 3.5 μm). The tighter settings deployed in 2012 reach 4.3 $\sigma_{4\ \mathrm{TeV}}$ [4]. The TCP gaps are closed by following linear functions of the beam energy starting from the injection settings of 5.7 $\sigma_{450\ \mathrm{GeV}}$.The real emittance achieved with 50 ns beams was about 2 μm instead of 3.5 μm [1]. Two beam size values are therefore introduced to express the

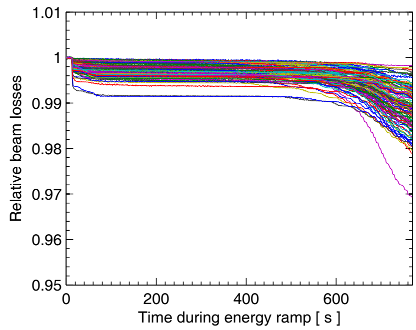

Figure 2: Beam current versus time in the ramp normalized to the initial value, for 110 fills at the end of the 2012 run.

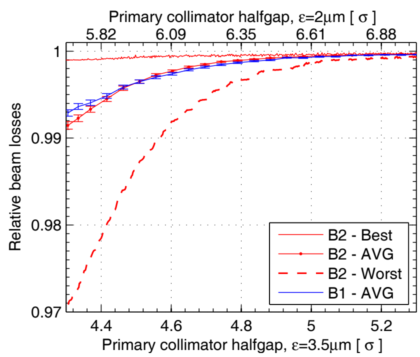

Figure 3: Average B1 and B2 losses during the ramp versus TCP half gap, for $\epsilon = 3.5\mu$m (bottom axis) and $\epsilon = 2.0\mu$m (top). Best and worst loss cases for B2 are also given. Errors on the average are estimated as the R.M.S. of the measured points divided by $\sqrt{n_{\text{fill}}}$ ($n_{\text{fill}} = 110$).

distance from the beam core: "nominal" σ_{nom} and "real" σ_{real}, respectively. The quoted nominal TCP settings at flat-top are 7.5 σ_{real} in 2010-11 and 5.7 σ_{real} in 2012. Note that the 2012 TCP settings correspond to the design 7 TeV TCP gaps in millimeters.

Tail Scraping and Losses During the Energy Ramp

The relative losses of Beam 2 (B2) during the ramp, calculated by dividing the measured beam current by its initial value at t=0, are shown in Fig. 2 for about 60 physics fill in Sep. to Dec. 2012. Losses appear in the last 200 s. The spread between different fills depends on the initial beam emittance and on the local orbit at the TCPs. Average losses for both beams are calculated and expressed as a function of the primary collimator half gap in Fig. 3, neglecting orbit shifts[1]). Significant beam losses start below 5 σ_{nom} or 6.6 σ_{real}. About 1 % of the beam is lost on average by the end of the ramp, see Table 1. This is above the value of ≤ 0.1 % expected for a Gaussian distribution.

A single measurement was carried out on May 15$^{\text{th}}$, 2012 to understand to what extent these ramp losses are related to the tail population at injection. The tails of a full physics beam of 1380 bunches were scraped down to 4.2 σ_{nom} - i.e. below the normalized TCP settings at flat-top - with the horizontal and vertical TCPs. In Fig. 4, the ramp losses of this fills are compared to the ones of fills close in time, showing that the scraping has no beneficial effect. Beam tails causing the losses in Fig. 3 are thus (re)populated in the ramp. In this test, the tail population of a full-intensity physics beam was measured. The amount of beam in the amplitude range of the scan was calculated by converting the BLM signals in number of protons, see Fig. 5. About 1 % (B1) and 0.5 % (B2) of the beam was lost found[2], which indicated over-populated tails. This is illustrated by the magents and cyan lines in Fig. 5 calculated for Gaussian beams (note that the measured B1 emittance was 2-2.4 microns).

[1]The measured flat-top orbit spread of ± 30 μm (B1) and ± 40 μm (B2) [8] adds maximum uncertainties of 0.07 and 0.2 σ_{nom} (horizontal and vertical planes) to the abscissa of Fig. 3.

Table 1: Tail populations measured in ramp and squeeze of standard physics fills in 2012.

	Ramp		Squeeze	
	B1	B2	B1	B2
Percent losses	0.7 %	0.9 %	0.7 %	1.8 %
Amplitude, σ_{nom}	4.3-5.7	4.3-5.7	4.0-4.3	3.9-4.3

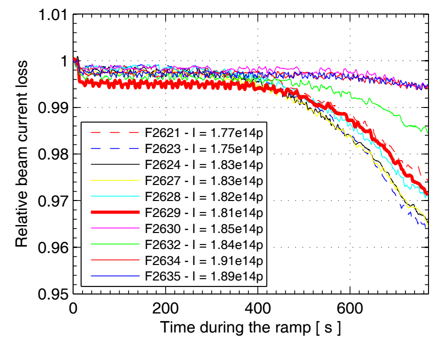

Figure 4: B1 losses during 10 consecutive ramps of physics fills. Fill 2629 (bold) is done after tail scraping at injection.

Loss Spikes in the Squeeze

The average losses during the squeeze are given in Fig. 6. This phase is performed without optics and collimator changes in IR7 so TCP losses are driven by local orbit jitters. The maximum orbit drifts at the TCPs with respect to the absolute reference for collimator alignments are around 0.36 σ_{nom} (H) and 0.43 σ_{nom} (V) for B2 and about 0.1 σ_{nom} better in both planes for B1. The average losses in Fig. 6, i.e. up to a few percent of the beam or several 10^{12} p, are thus concentrated in tail amplitudes between 4.0 (H) / 3.9 (V) and 4.3 σ_{nom} (see Table 1). B1 losses are on average less than a factor 2 smaller than for B2. This is clearly an approximated figure. More detailed analysis will address the correlation between the orbit and peak intensity losses.

[2]This measurement was performed with injectors not fully optimized. See [9] for tail measurements of optimized injector conditions.

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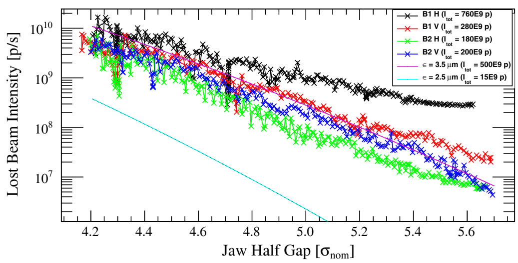

Figure 5: Beam tail population calculated from the BLM signals at the TCPs, during the scan on May 15th, 2012. Expected populations for two emittance values are given.

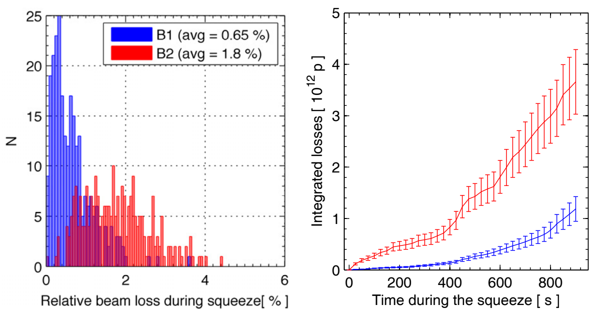

Figure 6: Distribution of squeeze losses in 2012 (left) and average losses vs. time for 65 squeeze processes (right).

DEDICATED TAIL SCRAPING TESTS

Various dedicated scraping tests were performed at the LHC [5]. The most accurate beam tail measurement was done at 4 TeV [10]. An amplitude range between 2 $\sigma_{\rm nom}$ and 7 $\sigma_{\rm nom}$ was covered with 1 single nominal bunch, before and after establishing collisions, and the first 4 TeV measure of diffusion speed versus amplitude was achieved.

The off-momentum tails were probed with a scan of the momentum TCPs in IR3, performed on Dec. 16th, 2012 after more than 6 hours of collisions (396 bunches at 25 ns spacing, intensity of 3.5×10^{13}p, peak luminosity of 6×10^{32}cm^{-2}s^{-1}). For each beam, the TCP jaw on the negative off-momentum side was closed in steps from 12 to about 6 $\sigma_{\rm nom}$ while monitoring beam losses in IR3/7, beam intensity and population of the abort gap (AG). A summary plot for the scan on B2 is given in Fig. 7. Beam intensity and AG population versus the TCP momentum cut at zero betatron amplitude is given in Fig. 8. Disregarding the initial beam loss rate in collision, only a fraction of a percent of beam was found in the $\Delta p/p$ range between 0.8 and 1.0×10^{-3}. Note that the abort gap population could be reduced to similar levels as achieved with the active cleaning that uses transverse damper excitations, opening the possibility to establish a passive AG cleaning with the TCPs.

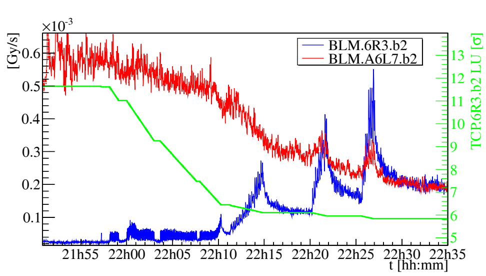

Figure 7: Beam losses recorded in IR3 (red) and IR7 (blue) and half gap of primary collimators in IR3 (green) versus time during the off-momentum scraping test (16/12/2012).

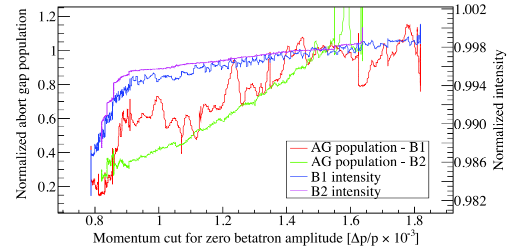

Figure 8: Beam current and abort gap population versus the momentum cut during the scan of Fig. 7, normalized to their initial value at the beginning of the scan.

CONCLUSIONS

Beam scraping and tail population measurements during the full-intensity LHC fills were presented, including first measurements of off-momentum tails. The observations rely on the analysis of the losses at the collimators in IR7 that provide a method to quantify the beam halo at different transverse amplitudes. The results presented are preliminary because there is a clear lack of systematic studies on this topics for the LHC. It was found that on average up to 1% of the beam is found in the beam tails between 5.7 and 6.6 $\sigma_{\rm real}$ in the ramp, with peaks up to a few percent. Tails are dynamically populated in the ramp, as no improvements were observed after cleaning the tails at injection. In the squeeze, up to several percent of beam is found above 5.2 $\sigma_{\rm real}$ and lost at the TCPs due to orbit drifts. The induced loss spikes can become a concern at higher energies and need a better understanding.

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