OPERATIONAL EXPERIENCE WITH A LHC COLLIMATOR PROTOTYPE IN THE CERN SPS

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Abstract

A full-scale prototype of the Large Hadron Collider (LHC) collimator was installed in 2004 in the CERN Super Proton Synchrotron (SPS) and has been extensively used for beam tests, for control tests and also LHC simulation benchmarking during four years of operation. This operational experience has been extremely valuable in view of the final LHC implementation as well as for estimating the LHC operational scenarios, most notably to establish procedures for the beam-based alignment of the collimators with respect to the circulating beam. These studies were made possible by installing in the SPS a first prototype of the LHC beam loss monitoring system. The operational experience gained at the SPS and the lessons learnt for the LHC operation are presented.

INTRODUCTION

In order to validate for beam operation the design of the LHC collimator [1], a full-scale prototype of the secondary collimator was installed in the CERN Super Proton Synchrotron (SPS) for the 2004 proton run (Fig. 1). Together with robustness tests performed with extracted LHC beams at 450 GeV [2, 3], the SPS beam tests have provided crucial milestones for the validation of the collimator design adopted for 100 collimators of the LHC Phase I system.

The SPS collimator prototype has a two 1 m-long Carbon jaws. It has been kept operational and used for numerous collimation studies with LHC-type proton and ion beams during four years of beam operation (2004 to 2008, except 2005 when the SPS was in shutdown the whole year). The SPS is ideal for accelerator physics studies: orbit and optics are very stable and a broad variety of LHC-type beams can be stored in 'coasting' mode. The beam conditions and parameters used during the collimator studies are listed in Table 1. The energy for stored beams is limited to 270 GeV by power constraints on the main magnet circuits. Other than that, the SPS beams are representative of the LHC conditions as far as longitudinal and transverse dynamics and stored beam energies are concerned.

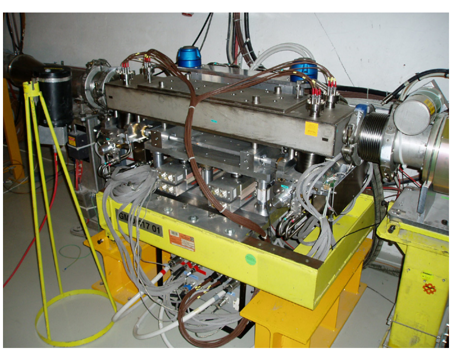

Figure 1: LHC collimator prototype installed in the SPS.

Table 1: Beam Conditions for SPS Collimation Studies

Parameter	Value
Beam energies	14, 26, 270 GeV
Total beam intensity	3.3×10^{13} p
Maximum stored energy	1.4 MJ
Minimum bunch spacing	25 ns
Number of bunch trains	1 – 4
Number of bunches	1 – 288
Normalized beam emittance	1.0 – 3.5 μm
Betatron functions (x/y)	24.9 m / 89.9 m
Typical beam sizes at 270 GeV (σ_x/σ_y)	0.7 mm / 1.3 mm
Maximum activation (contact)	780 μSv/h (2007)

The following studies were performed at the SPS:

- beam-based set-up of collimator jaws [4, 5, 6];
- verification of the mechanical design (cooling water, mechanical precision, vacuum tightness, ...);
- tests of the LHC beam loss monitoring system [7];
- halo dynamics and beam shaping by the jaws [4, 8];
- validation of electronics (switches, monitoring, motors, ...) and performance of the controls architecture in an operating high-intensity accelerator [9, 10];
- beam loss response and LHC thresholds [11, 12];
- benchmark of proton [13] and ions [14] simulations;
- collimator impedance, trapped modes and tune variation versus collimator gap values [15, 16, 17].

The conclusion of these studies was that no hidden weak points could be identified and indeed the design choices were fully validated for the LHC series production. Here, only aspects related to the system reliability, to the beam-based set-up and to the beam loss monitoring are reviewed. Note also that several Diploma and PhD thesis works have profited from the SPS collimator tests [6, 8, 12, 18].

OVERALL SYSTEM PERFORMANCE

Hardware Reliability in Radiation Environment

From the mechanical point of view, the SPS collimator prototype did not require any modification and worked reliably without failures. From 2004 to 2007, the collimator was equipped with 4 old LEP stepping motors. One failed during the cold-checkout at the beginning of 2008 and it was then decided to replace all the motors with the new LHC type. The LEP motor failure is not representative of the LHC case.

The design of jaw cooling circuits and the vacuum layout [1] were successfully validated with high beam intensities and high losses induced at the collimator jaws (maximum losses of up to $10^{12}-10^{13}$ p at 270 GeV and some 10^{14}p at 26 GeV). The maximum activation at the end of the run was measured on Nov. 23$^{\rm rd}$, 2007: up to 800 μSv/h on contact and 110 μSv/h at 40 cm from the collimator tank. In the other years the activation was at least 2 to 3 times lower. In no case we could see failures of components (mechanical or electronics) induced by radiation. The high activation of 2007 was induced by losses of 26 GeV proton beams generated a few days the end of the run for BLM calibration studies [12]: $\approx 3\times10^{14}$ p were lost on the collimator on Nov. 8$^{\rm th}$ and $\approx 10\times10^{14}$ p on Nov. 12$^{\rm th}$.

Controls Software Performance

The SPS tests also played an important role as test-bench for the LHC collimator controls. The first 2004 implementation relied on a local system derived from LEP, controlled from the control room via remote desktop connections. This was adequate for the first accelerator physics studies but not for the LHC system with about 100 collimators. The LHC final architecture based on PXI platforms by National Instruments [19] was deployed and validate for the accelerator controls in 2006, together with the first prototype of the top-level applications developed in the LHC Software Applications (LSA) environment [10] for generation, orchestration and maintenance of the collimator settings. The architecture proved to be reliable during the beam tests and was up and running without significant failures during three years of operation. The LHC system will need to exceed this achievement by far but the first results of remote commissioning are very promising [20].

BEAM-BASED ALIGNMENT

One of the main purposes of the SPS collimator studies was the validation with beam of the commissioning procedures for the collimator jaw set-up. The procedure to establish the local beam centre and size at the collimator, required to define the normalized collimator settings for optimum system performance, is now well established thanks to the extensive studies carried out at the SPS. This procedure takes full profit of the two-sided collimator design (Fig. 2): a sharp edge of the beam halo is produced with one jaw and the other jaw is moved until it becomes closer to the beam. This is seen on the signals of BLMs placed close to the collimator (2 ionization chambers in the example). The step size of collimator movements determines the accuracy of this procedure. After the first results [4], systematic studies have been performed [6] with the conclusion that (1) the resolution of this method is below 20 μm;

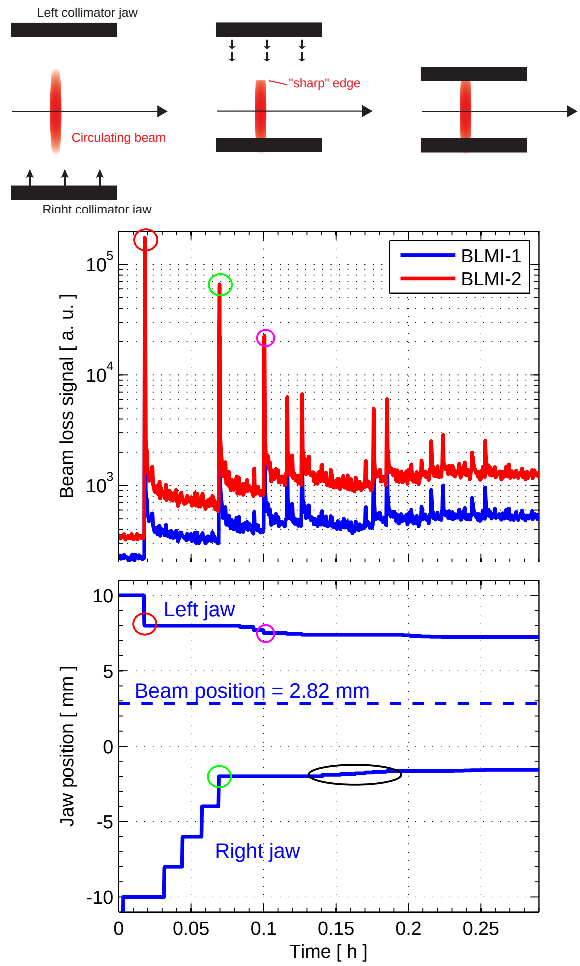

Figure 2: Example of collimator centring at the SPS: BLM signal (centre) and collimator positions (bottom) versus time. Loss spikes highlighted with circles indicate when one of the jaw goes closer to the beam the the other jaw.

(2) the absolute accuracy, taking into account reproducibility and comparison with other alignment methods, is about 50 μm [6]. The beam size can be inferred precisely from full beam scraping, which also provides information on the beam orbit. This is a precise (within 10% of wire scanner measurements) but destructive method.

What remains to be improved is the beam-based adjustment of the collimator jaw angle with respect to the beam envelope (the jaws shall be parallel to the envelope to maximize the material seen by the beam). The approach similar to that of the centring, i.e., moving one jaw corner into the beam and then moving in the other in steps until it gets closer, did not provide reliable and reproducible data for angle set-up below 100 μrad. Under these conditions, the most reliable solution is probably to calculate the angle from beam-based measurements of the machine optics.

BEAM LOSS MONITORING

The SPS studies of collimator-induced beam losses provided a crucial benchmark for the development of the LHC beam loss monitoring system. The LHC ionization cham-

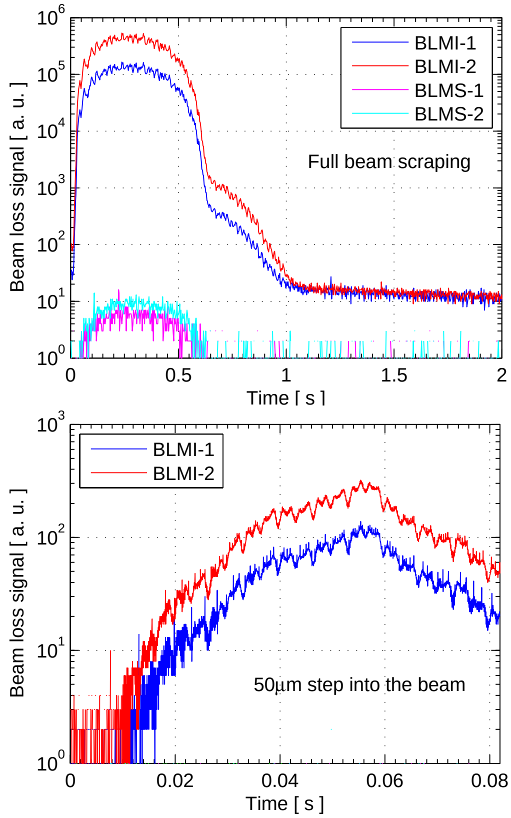

Figure 3: BLM measurements at 2.56 ms and 40 μs triggered by hardware when the jaw is moved into the beam.

bers (BLMIs) as well as the secondary emission monitors (SEMs, or BLMSs) were installed in the vicinity of the collimator prototype. The LHC BLM acquisition electronics, with 12 integration times from 40 μs to 89 s, was deployed in 2006. The software for the data concentration, necessary at the LHC to collect efficiently the measurements from 4000 monitors in the machine, was tested in 2007. In 2008 all the LHC acquisition types were available at the SPS: (1) standard acquisition at 1 Hz for all 12 integration times; (2) acquisition of buffers of 2048 points at a sampling rate of 40 μs or 2.56 ms (see Fig. 3); (3) acquisition for fast collimator set-up, triggered by dedicated synchronization signals from the collimator gateways [10]; (4) *post-mortem* buffer of 43000 points at 40 μs. Possible trigger events were timing, collimator movements and loss levels.

SPS collimator studies represented the main test-bench for evaluating the LHC BLM system and most of its functionality. It has helped to identify early potential problems in the acquisition chain (like cross-talk between channels) as well as post-processing transmission rate limits. The whole infrastructure including the expert applications was systematically evaluated before deploying it into the LHC.

CONCLUSIONS

The studies with a full scale LHC collimator prototype in the SPS were a great success. Four years of beam operation in the SPS accelerator have provided a very important feedback for the LHC collimator design, have given the possibility to perform many accelerator physics studies related to high-intensity beam collimation, have allowed the benchmark of important systems related to collimation, such as the LHC beam loss monitoring system and have provided a playground for training the LHC collimator commissioning team. This experience is invaluable in view of the preparation for the commissioning of the collimation system with LHC beams.

The collimator prototype is still in the SPS for beam studies in 2009. In the future it will be upgraded to enable studies of specific aspects of the Phase II collimation system, such as the integration of beam position monitors in the jaws, and will continue to support the .

The authors would like to thank the many colleagues who participated to the SPS collimation studies. The most important contributions can be consulted in the references.

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