COMPARISON BETWEEN MEASURED AND SIMULATED BEAM LOSS PATTERNS IN THE CERN SPS

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Abstract

A prototype of an LHC collimator has been tested with proton beams at the CERN SPS. The interaction of the circulating proton beam with the carbon collimator jaws generated secondary proton beams that were lost in the downstream SPS aperture. The measured beam loss patterns are compared with the results of dedicated loss simulations. The simulation package includes (1) a 6D particle tracking through the SPS lattice; (2) the scattering interaction of protons with the collimator jaw material; (3) the time-dependent displacement of the collimator jaws with respect to the beam orbit; (4) a detailed aperture model of the full SPS ring. It is shown that the simulation tools can reliably predict the measured location of losses. This provides an important assessment of the simulation tools in view of the beam loss studies for the Large Hadron Collider (LHC).

INTRODUCTION

In order to avoid regular quenches of the superconducting magnets, a powerful collimation system is required at the CERN Large Hadron Collider (LHC) [1], which must control local losses to the 10^{-7}-10^{-9} level with respect to the total stored energy of 360 MJ per circulating beam. Achieving this challenging goal demands a complex multi-stage collimation system, which in its final configuration will count up to more than 150 elements located in various positions all along the 27 km long LHC rings. Throughout the years, sophisticated simulation tools have been developed at CERN to design the collimation system, to understand and optimize its performance, to study its sensitivity to various optics and mechanical imperfections and to define the operational scenarios in various LHC phases, from the early beam commissioning to the ultimate performance at high intensities. In order to cope with the LHC challenging requirements, the simulation tools have grown in accuracy but also in complexity. This full chain of simulation packages calls for an experimental verification.

A fully operational prototype of the LHC secondary collimators [2] was installed in the SPS sextant 5 for tests with beam in the 2004 run. Goals and achievements of these tests were discussed in other papers [3, 4]. Beam loss patterns along the SPS ring have been parasitically measured during the collimator tests. Although no dedicated measurements were performed for the study of loss patterns induced by the collimator, the off-line analysis showed that useful information could be extracted from the available data. In this paper, these measurements are analysed and compared with the results of loss map simulations setup for the SPS using the LHC tools.

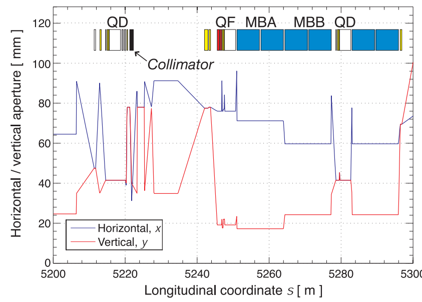

Figure 1: SPS aperture downstream of the collimator.

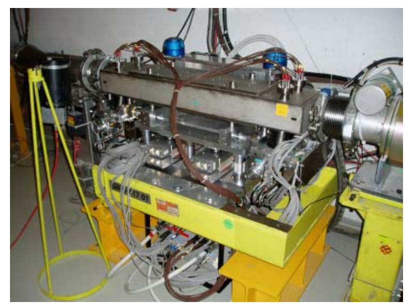

Figure 2: The LHC collimator prototype in the SPS tunnel.

BEAM LOSS MEASUREMENTS

Layout of SPS Collimator Test

Figure 1 shows the lattice elements and the corresponding horizontal and vertical apertures as a function of the longitudinal coordinate in the vicinity of the collimator location. A photograph of the collimator is shown in Fig. 2. A prototype of the horizontal LHC secondary collimator [2], with full mechanical functionalities, was used. The collimator has two 1 m-long carbon jaws whose positions and longitudinal tilt angles can be adjusted by means of four stepping motors. The collimator was installed in a dispersion-free region with small horizontal beam size (300-700 μm) in order not to introduce aperture bottlenecks with the full-retracted jaw configuration. In Table 1, the main optics and beam parameters at this location are listed. The tests were carried out at a beam energy of 270 GeV/c.

Table 1: Optics and beam parameters at the collimator

Parameter	Value
Betatron functions, β_x/β_y	24.9 m / 89.9 m
Dispersion functions, D_x/D_y	-0.2 m / 0.0 m
Typical beam sizes, σ_x/σ_y	0.7 mm / 1.3 mm
Beam energy	270 GeV
Beam energy spread, $\delta = \Delta E_b/E_b$	3.63×10^{-4}

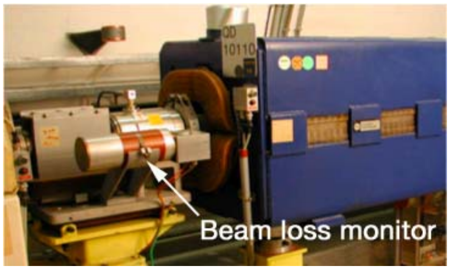

Figure 3: Beam loss monitor on a defocusing quadrupole.

The SPS Loss Map Measurements

The SPS beam loss monitoring system consists of 216 ionization chambers installed at each lattice main quadrupole magnet. De-focusing quadrupoles are equipped with a monitor fixed horizontally on the upstream beam pipe (see Fig. 3) whereas for focusing quadrupoles the monitor is fixed vertically below the pipe. During the collimator test, the measurement signals were integrated over a period of approximately 25 s, corresponding to about one SPS super-cycle. Faster measurements are in principle possible but were not carried out.

In order to disentangle the collimator-induced loss patterns from the background, the difference signals between two consecutive SPS cycles with and without collimator jaw movements is considered. An example is shown in Fig. 4. This procedure has the advantage that the difference loss patterns become to a large extent independent of DC sources of beam losses not induced by collimator movements, like for example optics imperfections (orbit, β-beat, ...) or local aperture bottlenecks.

SIMULATION OF SPS PROTON LOSSES

The simulation package used for predicting cleaning efficiency and beam loss patterns at the LHC is described in detail in [5]. A 6D particle tracking of beam halo particles is interfaced (1) with scattering routines that describe the proton interaction with collimator materials and (2) with detailed aperture models to find the exact location of beam losses, for the comparison with magnet quench limits. Ultimately, simulation outputs are fed into finite-element codes to estimate the deposited energy in various sensitive LHC components [6]. Note that this kind of energy deposition studies have not been setup for the SPS simulations and hence detailed comparison with the experimental data can only be focused on longitudinal locations of losses rather than on absolute measured radiation signals.

The setup of the LHC simulation tools for the SPS loss map studies was straightforward. Existing models of the SPS optics and aperture were adapted to the `SixTrack` and to the aperture program used for loss studies [5]. An implementation of time-dependent jaw positions with respect to the beam orbit was required to simulate the experimental procedure carried out during the commissioning of the collimator prototype with beam, which consisted in moving one or both collimator jaws inside and outside the beam

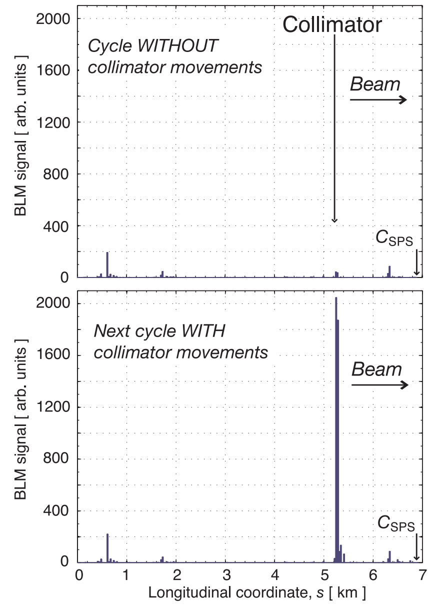

Figure 4: SPS loss patterns in consecutive cycles without (top) and with (bottom) jaw movements (C_{SPS} = 6911 m).

tails [4]. The measured jaw speed of $\approx$ 4 mm/s has been included in simulations with an equivalent jaw displacement per turn. Each tracking run typically included 500000 particles, which provide a sufficient statistics for analysing the locations of losses.

COMPARISON WITH SIMULATION

Figure 5 shows the overall losses around the SPS ring as measured (top graph) and as predicted in simulations (bottom graph). Measured data are obtained as the difference of the two loss signals of Fig. 4. The shown example represent a typical loss pattern induced when the collimator jaw(s) move into the beam core. It is seen that simulations predict well the overall distribution of losses around the whole SPS ring. As expected, the largest loss peaks are found immediately downstream of the collimator, which is the source of beam scatter as it move towards the beam centre and intercepts beam particles.

The second highest peak occurs at a longitudinal location of approximately 600 m from the SPS reference origin (i.e., $\approx$ 2.3 km downstream of the collimator), where some SPS collimators are located. Figure 6 shows in detail the loss patterns in this region. Shown are also the SPS lattice elements (color coding: dipoles in blue, quadrupoles in white, sextupoles in red, collimator/absorbers in black, other equipment in yellow). It is seen that simulations predict two peaks of similar amplitudes whereas in measurements only the second peak is clearly seen. This difference is explained by the fact that, according to simulations, the first peak (s = 450m) is induced by losses at an SPS collimator located downstream of a quadrupole. The corresponding BLM is mounted upstream of this magnet and therefore cannot see these losses at the downstream collimator. The next monitor is located several metres further

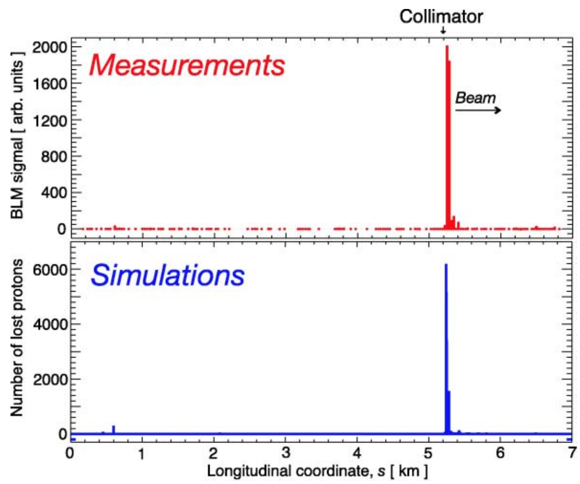

Figure 5: Measured (top) and simulated (bottom) beam losses around the whole SPS ring.

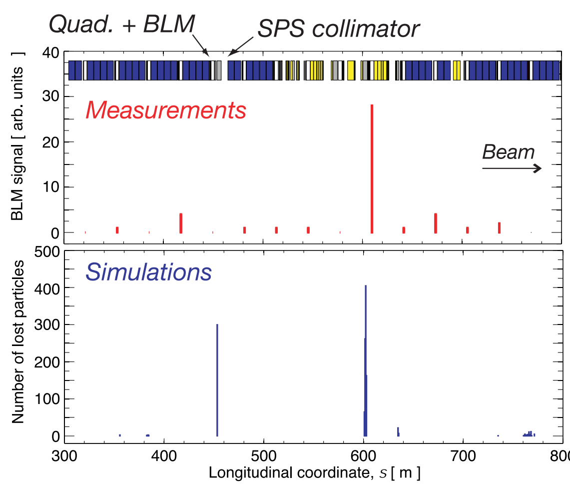

Figure 6: Measured (top) and simulated (bottom) losses at the SPS P2 ($\approx$ 2.3 km downstream of the collimator).

downstream and does not see significant losses (possibly because the shower developed upstream are shielded by the various dipole magnets). Note that we are considering small peak at the resolution limit of the BLM's, with amplitudes 1000 times smaller than the largest peaks measured immediately downstream of the collimator.

As another example, in Fig.7 the loss patterns measured (top graph) and predicted by simulations (bottom) in the region about 1 km downstream of the collimator are shown. Even if the spatial resolution of losses is less precise in measurements than in simulations, it is clearly seen that qualitatively the measured losses are well reproduced in simulations.

CONCLUSIONS

The comparison between measured and simulated proton loss patterns at the CERN SPS was discussed. It has been shown that the simulation tools developed for LHC collimation studies could predict with good precision the longitudinal locations of losses around the SPS ring as they

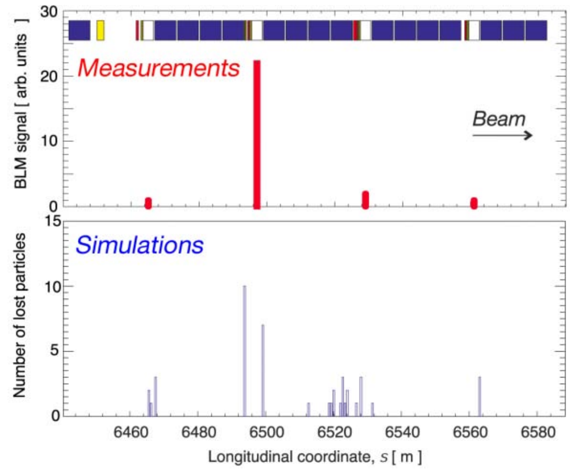

Figure 7: Measured (top) and simulated (bottom) losses at the SPS P6 ($\approx$ 1.2 km downstream of the collimator).

were induced by the interaction of the collimator jaws with the circulating proton beams. The overall loss patterns around the whole SPS ring as well as small local loss peaks located several km downstream of the collimators (amplitudes 1000 times smaller than the largest spikes) could be reproduced. Small differences between simulations and measurements were understood by taking into account the installation layout of the beam loss monitors. These results provide an important validation of the simulation tools that are used for the LHC loss studies.

A quantitative benchmark of the simulation tools (i.e., a comparison of absolute and relative heights of loss peaks) could not be performed due to the lack of simulations of the deposited energy in the loss monitor per impacting proton on the vacuum chamber. These calculations are carried out with showering codes for the LHC but these tools are not yet set-up for the SPS. The comparison discussed in this paper was also limited by the poor acquisition frequency of the used beam loss monitoring system, which prevented measuring losses on the millisecond time scale, and by the uncertainty of the measurement conditions (the analysis of beam loss data was done off-line and was not based on dedicated measurement campaigns). The first encouraging results discussed here suggested to plan more detailed measurements at the 2006 SPS collimator tests.

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