FIRST BEAM-BASED APERTURE MEASUREMENTS IN THE ARCS OF THE CERN LARGE HADRON COLLIDER

S. Redaelli, I. Agapov, R. Calaga, B. Dehning, M. Giovannozzi, F. Roncarolo, R. Tomás
CERN, Geneva, Switzerland

Abstract

The LHC injection tests performed in August and early September 2008 in preparation for the circulating beam operation provided the first opportunity to measure with beam the mechanical aperture in two LHC sectors (2-3 and 7-8). The aperture was probed by exciting free oscillations and local orbit bumps of the injected beam trajectories. Intensities of a few 10^9 protons were used to remain safely below the quench limit of superconducting magnets in case of beam losses. The methods used to measure the mechanical aperture, the available on-line tools, and beam measurements for both sectors are presented. Detailed comparisons with the expected results from the as-built aperture models are also presented. It is shown that the measurements results are in good agreement with the LHC design aperture.

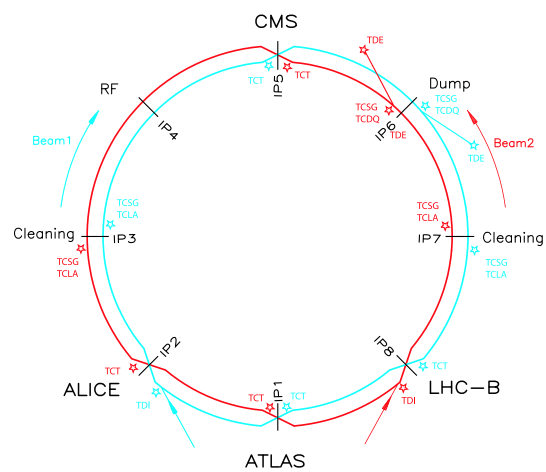

Figure 1: Layout of the Large Hadron Collider.

INTRODUCTION

The CERN Large Hadron Collider (LHC) will accelerate high-intensity proton beams up to an energy of 7 TeV. Taking into account the large stored beam intensities (for the nominal beams, 23 MJ at the injection energy of 450 GeV and 362 MJ at 7 TeV), it appears clear that a sufficient beam clearance must be ensured to avoid quench and damage of the LHC superconducting magnets. On the other hand, by design, the LHC has a small mechanical aperture of about 8.5 beam sigmas in the cold region [1, 2]. At injection the aperture limits occur in the arc, whereas at top energy with squeezed beams the bottlenecks become the superconducting triplets in the experimental regions. Aperture measurements are therefore scheduled in the early phases of the LHC commissioning to detect possible aperture restrictions and represent an integral part of the beam commissioning. During the limited beam experience of 2008, it was possible to explore the LHC aperture in two arcs during dedicated beam-based aperture measurements. This paper summarizes the results of these measurements.

LHC APERTURE MODEL

In a particle accelerator the concept of machine aperture goes beyond the simple definition of the mechanical design of the beam pipes. The clearance available for the beam depends on (1) the mechanical dimensions of the machine components; (2) the alignment errors; (3) the beam orbit; (4) the beam optics, which influences the beam size; (5) the magnetic field errors, which affect (3) and (4); (6) the collimator settings that determine population and size of the beam halo [3]. The LHC aperture has been designed by assuming typical or worst-case errors for the effects mentioned above. A complete assessment can only be done by taking into proper account all the relevant contributions. It is foreseen to determine the LHC aperture with respect to reference machine closed orbit and optics and to revise the measurements every time major changes occur.

Measurements performed in 2008 allowed only the assessment of the mechanical aperture but nevertheless it is interesting to present these measurements and comment on the achieved quality of mechanical aperture, alignment [4] and, indirectly, of the machine optics. Assessments of the orbit accuracy and of the optics errors have also been made [5, 6] but complete establishment of the beam-based LHC aperture model will need to be established during the beam operation in 2009. Other aperture measurements performed in 2008 are presented in companion papers [7, 8].

MEASUREMENT TECHNIQUE

The LHC layout is schematically shown in Fig. 1. The clockwise-rotating Beam 1 (B1) is injected in point 2 while the counter-clockwise Beam 2 (B2) is injected in point 8. Four sector tests were performed in summer 2008 [9, 10] by stopping the beam on the collimators in points 3 and 5 for B1 and in points 7 and 6 for B2.

Aperture measurements were performed systematically in sectors 2-3 and 7-8 with injected beams by exciting ‘free oscillations’ of the beam trajectory with variable amplitudes and betatron phases. Oscillation scans are done to explore the available beam clearance in the horizontal or

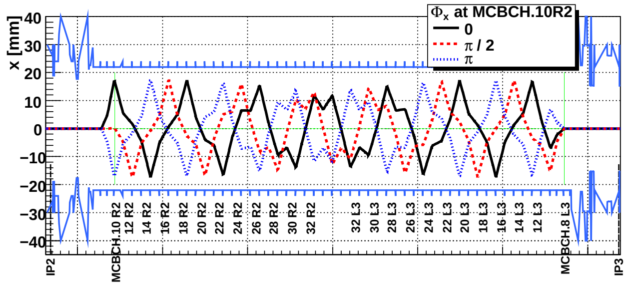

Figure 2: Example of oscillations generated with MADX on-line.

vertical planes. The oscillations are induced by exciting two pairs of horizontal and vertical orbit correctors, typically located at a $\pi/2$ betatron phase advance difference. By changing the ratio of corrector currents, oscillations at betatron phases of 0, $\pi/6$, $\pi/3$, $\pi/2$, $2\pi/3$, and $5\pi/6$ were generated. This is considered sufficient to exclude major bottlenecks. A complete scan provides then global aperture measurements of the section that is explored. This is illustrated in Fig. 2.

Appropriate 'knobs' were generated for each oscillations phase and for each plane with the MADX on-line model [11] and were imported into the LHC control system. The as-built LHC aperture model was used to identify the possible bottlenecks. Operationally, the procedure was: for each phase, the oscillation amplitude (both signs) was increased gently until the beam touched the aperture, as see with the beam loss monitoring system. As no reliable intensity measurements were available at the end of the sectors, only beam loss measurements could be used to determine when an aperture restriction was encountered, and the loss locations. For convenience, the amplitude of the oscillations was generated in units of nominal beam sigma. The beam trajectory measured by the beam position monitors gives a direct measurement of the available aperture in millimetres with accuracy of approximately 10% [9]. The local beam size also has to be added. Due to the difference of normalized aperture between the insertions and the arcs, separate sets of knobs for the scans in different LHC sectors were prepared. Knobs for the arcs were generated using pairs of orbit correctors in the dispersion suppressor upstream of the arc itself. Measurements were performed with 1 μm normalized emittance beams of 2×10^9 to 5×10^9 protons.

MEASUREMENT RESULTS

In Figures 3 and 4 the results of global aperture measurements in sectors 2-3 and 7-8 are shown. The horizontal and vertical beam trajectories are given as function of the longitudinal coordinate for all the oscillations induced during the aperture scans. The nominal machine aperture (without alignment errors) is also shown. In Figure 5, an example of beam losses in the arc 7-8 recorded on-line during the aperture scan is shown. The elements with larger loss spikes are also listed. It is seen that oscillations up to 18 mm (horizontal plane) and 12 mm (vertical plane) were generated with-

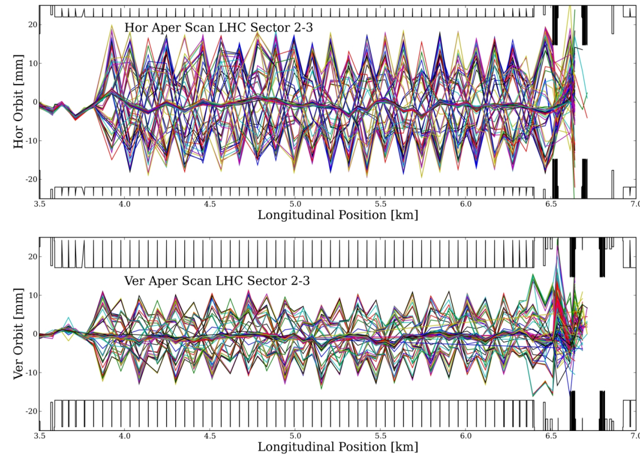

Figure 3: Measured trajectories of the injected beam 1 during the aperture scans in the LHC sector 2-3. Longitudinal (clockwise) position from point 1 is given.

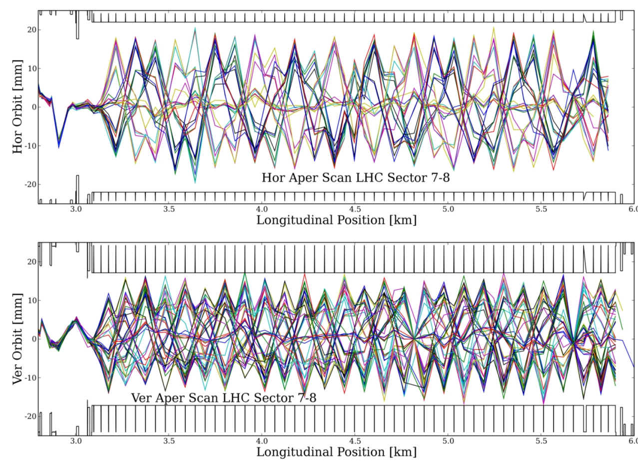

Figure 4: Measured trajectories of the injected beam 2 during the aperture scans in the LHC sector 7-8. Longitudinal (counter-clockwise) position from point 1 is given.

out significant beam losses. The vertical aperture limitation in sector 2-3 occurs in the region of the Q6.L3 quadrupole, which is a known bottleneck of the LHC point 3 (momentum cleaning). This prevented larger excitations in the vertical plane and hence the real aperture of the arc upstream could not be explored to the same extent as for arc 7-8 (this would have required closing the trajectory oscillation just upstream of Q6.L3).

Local aperture measurements can be performed by generating local orbit bumps at the element to be probed. These local measurements are obviously time-consuming because a complete scan has to be performed at each location. We could only perform such a scan at the location of the magnet Q7.L3 (B1), next to the dipole MB.A8L3.B1 that quenched with the beam during the first night of beam tests [9]. Figure 6 shows the beam loss monitor signal as a function of the local bump amplitude (the nominal corrector calibration is used to estimate the bump amplitude). One can see that the beam clearance before observing beam losses is about 23 mm. This is larger than the value that

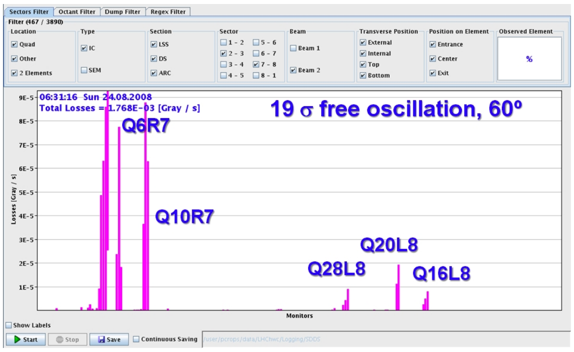

Figure 5: Beam losses recorded in arc 7-8 for a horizontal oscillation amplitude of 19 nominal beam σ.

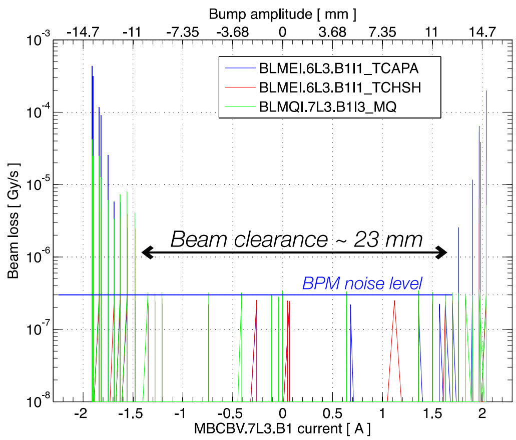

Figure 6: Beam losses versus bump amplitude (top axis) during the local aperture scan at MQ.7L3.B1. The MBCBV.7L3 corrector current is given in the bottom axis.

limited our arc scans and therefore the bottleneck is probably located further downstream.

The aperture scans are ideal to identify coupling errors. In presence of transverse coupling the large free oscillations in one plane induce linearly correlated oscillations in the other plane. During the scans of the arc 2-3, small vertical oscillations were observed while inducing large horizontal oscillations. To quantify the coupling, a linear fit of the vertical excursion at every BPM versus the rms of all the horizontal BPMs readings has been computed. The slopes of these fits are plotted versus the longitudinal location of the BPM on the bottom plot of the Fig. 7 for two different scans with almost π phase difference. If π-separated waves get anti-correlated after some point, some coupling error must occur there. Indeed, this occurs at around 5000 m, corresponding to Q31.L3. The top plot shows the reference vertical orbit with a negative peak at the same location. This orbit causes coupling through, e.g., the feed-down effects at lattice sextupoles. However it has been verified with MADX models that this error alone cannot explain the observed coupling. For example, three main quadrupole tilts in the order of 3 mrad in the same region should be added to reproduce the measurements. The small signal-to-noise ratio forbids a more precise identification of the sources. Note that no measurable coupling was observed during the aperture scans in sector 7-8.

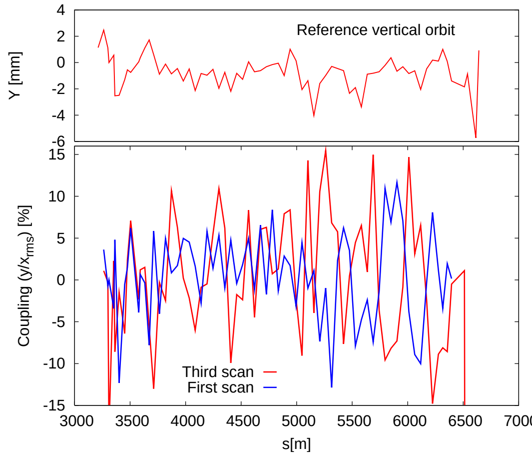

Figure 7: Vertical reference orbit (top) and coupling coefficient (bottom) versus longitudinal position during two horizontal oscillations

CONCLUSIONS

The results of aperture measurement performed in two LHC sectors have been presented. Even if these measurements were performed in an early commissioning phase, before detailed optimization of the machine optics, an aperture close to the nominal mechanical aperture was found in the arcs 2-3 (beam 1) and 7-8 (beam 2). This indicates a very good overall performance of the machine alignment and of the magnetic model. These measurements represent another example of the usefulness of the LHC sector tests. Measurements will be repeated early on in 2009 in preparation for the circulating beam operation.

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