LHC APERTURE MEASUREMENTS

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Abstract

The mechanical aperture of the Large Hadron Collider (LHC) is a critical parameter for the operation of the machine due to the high stored beam intensities in the superconducting environment. Betatron and momentum apertures must be therefore precisely measured and optimised. In this paper, we present the results of beam-based measurements of the LHC aperture. The experimental results are compared with the expectations from the as-built model of the LHC aperture, taking into account the optics imperfections of the superconducting magnets. The impact of these measurements on various aspects of the LHC operation are also discussed.

INTRODUCTION

In the 2010-2011 run, the CERN LHC will operate at 3.5 TeV/beam with intensities up to $\approx 7 \times 10^{10}$ p/bunch. The relaxed parameters compared to the design values are well above the quench limit of superconducting magnets and the damage limit of some accelerator components. Therefore, a tight control of the key machine parameters is mandatory even at this early stage. In particular, the mechanical aperture has to be controlled to ensure the required beam clearance.

In a particle accelerator the concept of machine aperture goes beyond the simple definition of the mechanical design of the beam pipes but also depends on beam properties and errors. The following aspects must be taken into account for evaluating the available aperture: i) mechanical dimensions of the machine components; ii) alignment errors; iii) beam orbit; iv) beam optics, which influences the beam size; v) magnetic field errors, which affect iii) and iv); vi) collimator settings that determine population and size of beam halo [1]. The LHC aperture has been designed by assuming typical or worst-case errors for the effects mentioned above. The LHC aperture is traditionally expressed in units of normalized beam size for given settings of the collimators, the so-called n_1 notation described in detail in [1, 2]. The design value $n_1 = 7$ for the cold elements corresponds to an aperture in betatron sigma units of 8.5 σ in the horizontal and vertical planes and 10 σ in the skew plane.

The assessment of the real available aperture by detailed beam-based measurements is an essential step of the LHC commissioning and has to be carried out in the early phases. In this paper, the strategy for aperture measurements and the techniques used for the LHC machine are described. The results of the first measurements carried out with circulating beam in 2009 and at the beginning of the 2010 run are reviewed and some conclusions are drawn.

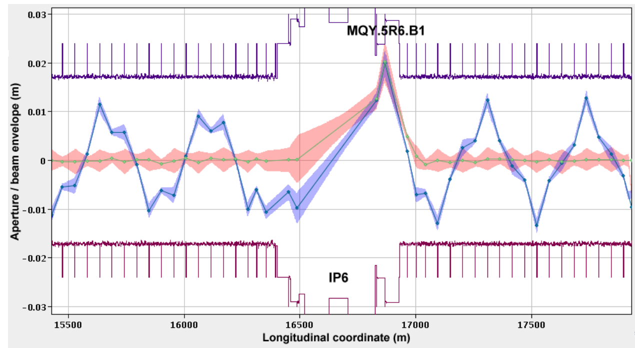

Figure 1: Examples of closed-orbit oscillation for global aperture measurements (blue) and local orbit bumps (red), with a 3σ beam envelope. The aperture model uses detailed measurements of the cold magnet profiles every 10 cm.

APERTURE MEASUREMENTS

General Strategy

Aperture measurements are naturally performed after having established "golden" reference conditions, as a part of the necessary preparation for the commissioning, of unsafe beam (higher intensities and or energy ramp, which both increase the total stored beam energy). The aperture must be known, and possible problems must be excluded, before setting up collimators (the minimum aperture is an input for the collimator settings because the bottlenecks have to be protected to avoid damage), before performing energy ramps and betatron squeeze, and before declaring physics runs. In particular, aperture measurements are performed after the following key steps: i) establishment of reference orbit; ii) detailed measurement and correction of the optics; iii) commissioning of the separation schemes in the experimental regions. Changes of the reference parameters listed above require a re-verification of the aperture. For example, a change of reference orbit can cause a reduction of the available aperture, which has therefore to be re-validated before increasing beam intensity if the reference orbit is significantly modified.

The aim of aperture measurements is to identify the minimum aperture restriction ("aperture bottleneck") for each beam and plane and to optimize, whenever possible, the available clearance for the beams. One distinguishes in general between *global* measurements that are used to find the overall bottlenecks and *local* measurements that assess

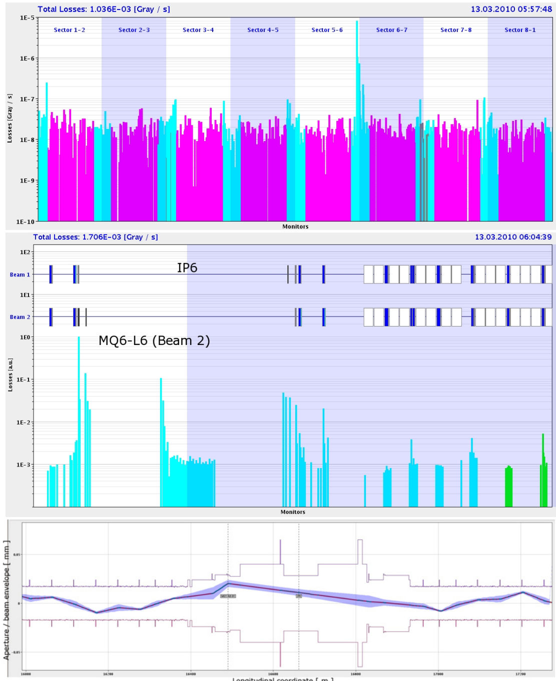

Figure 2: Beam losses around the ring (top) and in IP6 (middle) and beam orbit during a global aperture scan. The main bottleneck is the quadrupole Q6-L6. Secondary loss peaks appear at other location due to the scattering at the primary loss location.

the aperture of selected elements. The general strategy for the measurements is based on the following steps: i) measurement of global machine aperture; ii) identification of local aperture bottlenecks; iii) correction - whenever possible - of local problems (e.g., improved orbit steering, optics corrections). In the worst case, the identification of serious problems might lead to intervention in the tunnel to modify the vacuum layout.

Global Measurements

Global measurements can be performed by exciting oscillations of the circulating beam closed-orbit. The phase of the orbit excitation is varied by using a pair of correctors at about $\pi/2$ betatron phase advance. Oscillation phases of $k\pi/6,\ 0 \leq k \leq 5$ (both signs) are considered sufficient to exclude hidden bottlenecks. The settings for the oscillations and the analysis of the beam orbit data is performed with the MADX online model [3]. An example of global oscillations if given in Fig. 1, top graph. For each phase, the oscillation amplitude is increased until measurable beam losses are induced. The available aperture in millimetres at the bottleneck location is then given by the amplitude of the orbit and by the extension of the beam envelope at this location. The latter depends on the extension of the beam envelope (measured with wire scanners) and by the local beta functions, measured as a part of the optics optimisation [4]. The longitudinal location of losses is determined by measuring beam loss maps around the ring. An example of global measurements is illustrated in Fig. 2.

Global aperture measurements can also be performed using kickers to excite beam oscillations covering all betatron phases. For machine protection constraints, the LHC "aperture kickers" have been limited in strength to an amplitude of about 6σ to reduce the risk to send the beam in one single turn onto the aperture. This strength is not sufficient to probe with one kick the aperture. Hence, the aperture kickers were instead used to excited a controlled blow-up of the emittance, to identify the minimum available aperture with small losses. An example of beam profiles from wire scanner for the two cases is shown in Fig. 3. This method was compared with the orbit oscillation technique and gave consistent results.

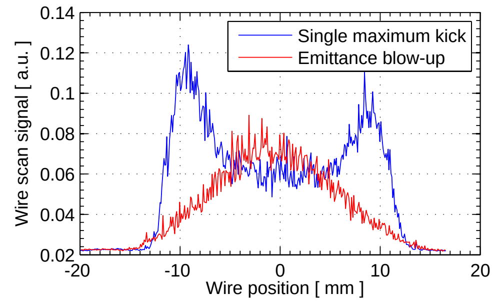

Figure 3: Vertical transverse beam profile at the wire scanner location after one single kick at the maximum kicker strength (blue) and after slow emittance blow-up (red). The typical hollow beam shape is clearly visible. The maximum aperture seen with the slow blow-up is about 1 mm more, as seen in the small tail at position -15 mm.

Local Measurements

Local measurements are essentially performed with local orbit bumps with maximum amplitude at the location of the restrictions, e.g. the ones identified with the global measurements. In a similar way as for the global measurements, the bump amplitude is increased to positive and negative amplitudes until beam losses are seen. Different bump shapes can be used. Typically, a 3- or 4-corrector bump is sufficient to identify local bottlenecks. Local scans allows to establish the local aperture in millimetres and to determine the mechanical centre of the aperture. This can be done by looking at the beam losses versus amplitude, as illustrated in Fig. 4, were local beam loss measurements (BLM) are given. Similarly, one can use the beam current data, however for the measurements performed with low bunch intensities the BLM are found to be more precise.

A special example for local scans is given by the aperture measurements in the experimental regions. Individual local bumps are generated separately for the two beams by using correctors outside the shared region at the inner triplet locations. An example is illustrated in Fig. 5. This is the only way to probe the triplet aperture at injection because these magnets are well in the shadow of the LHC arcs with the injection optics. The optics asymmetry imposes that the bumps for both beams have to be used to probe the triplets aperture at either side of the interaction point. In order to improve the estimate of the available mechanical aperture the beam halo was precisely shaped with the primary colli-

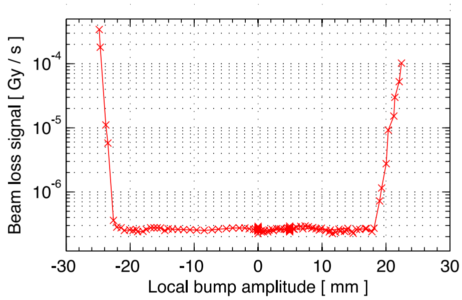

Figure 4: Beam losses versus amplitude of orbit bump during a local scan at the quadrupole MQY-4L6-B1. Beam losses are measured with BLMs installed on the quadrupole and increase as the beam is lost on the magnet aperture. Note that the loss values at the two bump sides depend on the amount of beam that is cut.

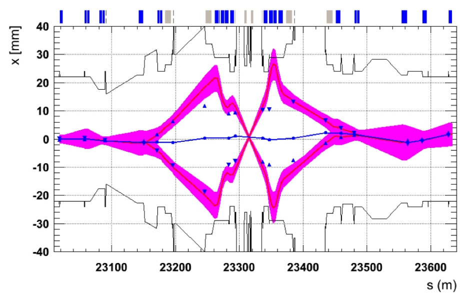

Figure 5: Local aperture bump in IP8 (LHCb).

mators to an amplitude of about $4.5\,\sigma$. This allowed detecting easily the amplitude at which the beam locally touched the triplet aperture. Similar measurements were repeated for all the experimental regions and no significant bottlenecks were encountered.

MEASUREMENT RESULTS

LHC aperture measurements have been performed in two main campaigns. Global measurements for both beams were performed after establishing the reference orbit and optics at injection energy of 450 GeV. Local measurements in critical locations found in the previous measurements were then performed to improve the knowledge of these bottlenecks. In addition, during the 2009 run local measurements in the triplet region were also carried out. Indeed, the measurements had started during the various injection tests carried out in 2008 and in 2009 prior to the circulating beam commissioning [5].

The measurement results for both beams and both planes are summarised in Tab. 1, were the list of bottlenecks are given. The minimum aperture a measured for each magnet where losses were found is shown, as well as the modeled aperture, which is the physical aperture after subtracting the tolerances and the maximum profile along the magnet. The corresponding n_1 parameter computed from the measured aperture, optics and closed orbit is also shown for each magnet, as well as the n_1 from the model, computed with the measured optics and closed orbit but with the modeled aperture. The centre c of the measured aperture for the local scans is also quoted.

Table 1: Results from the global and local measurements (the latter correspond to the cases notified by "*").

BEAM 1 - HORIZONTAL			
Magnet	$a_{mod/meas}$(mm)	$n_{1,mod/meas}$	c (mm)
MQM.6R2*	21 / 20	9.7 / 9.0	1.2
MQM.6R8	21 / 16	10.0 / 7.4	
MQY.4R6	28 / 26	9.4 / 9.1	
BEAM 1 - VERTICAL			
Magnet	$a_{mod/meas}$(mm)	$n_{1,mod/meas}$	c (mm)
MQ.13R8	17 / 13	10.6 / 8.5	
MQ.8R7	17 / 14	9.8 / 8.4	
MQ.14L8	16 / 14	10.3 / 8.9	
MQ.25R8	17 / 15	10.5 / 9.7	
MQY.4L6*	28 / 25	9.1 / 8.2	-0.3
MQM.6L2	22 / 18	9.6 / 8.1	
MQ.11L5	17 / 15	9.9 / 9.4	
MQY.6L4*	28 / 22	10.0 / 7.8	-2.4
MQY.5R6*	28 / 24	9.6 / 8.1	-1.5
BEAM 2 - HORIZONTAL			
Magnet	$a_{mod/meas}$(mm)	$n_{1,mod/meas}$	c (mm)
MQML.10R1*	21 / 19	9.7 / 9.4	1.0
MQY.4L6*	27 / 24	9.1 / 8.2	
MQY.5R6*	27 / 25	9.7 / 9.0	2.4
BEAM 2 - VERTICAL			
Magnet	$a_{mod/meas}$(mm)	$n_{1,mod/meas}$	c (mm)
MQY.4R6*	28 / 21	10.4 / 8.0	-0.7
MQ.9R7	16 / 16	11.2 / 11.2	
MQ.29L2	16 / 15	11.1 / 10.3	
MQ.21L2	16 / 15	11.4 / 10.2	
MQ.13L2	16 / 15	11.7 / 10.8	

CONCLUSIONS

The results of on-momentum aperture measurements at the LHC were presented. The analysis is carried out by taking into account beam-based measurements of orbit, optics and emittance. The conclusion of these measurements, confirmed by two months of operational experience, is that the LHC has a good aperture that for the moment has not caused problems for the beam operation. No significant aperture bottlenecks were found even if some problematic cases that are in discrepancy with the nominal model are still under investigation. Measurements will continue to determine the off-momentum aperture and to measure in more detail the interaction region aperture in preparation for the operation with squeezed beams and crossing angles.

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