

# APERTURE METER FOR THE LARGE HADRON COLLIDER

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## Abstract

The control of the high intensity beams of the CERN Large Hadron Collider (LHC) is particular challenging and requires a good modeling of the machine and monitoring of various machine parameters. During operation it is crucial to ensure a minimal distance between the beam edge and the aperture of sensitive equipment, e.g. the superconducting magnets, which in all cases must be in the shadow of the collimator's that protect the machine. Possible dangerous situations must be detected as soon as possible. In order to provide the operator with information about the current machine bottlenecks an aperture meter application was developed based on the LHC online modeling toolchain. The calculation of available free aperture takes into account the best available optics and aperture model as well as the relevant beam measurements. This paper describes the design and integration of this application into the control environment and presents results of the usage in daily operation and from validation measurements.

## INTRODUCTION

The LHC is running with outstanding performance [1], currently being operated with small emittances and above nominal bunch population (up to  $1.4 \times 10^{11}$  p). Beams with a stored energy of 110 MJ are brought in collision and produce peak luminosities up to  $3.3 \times 10^{33} \text{ cm}^{-1}\text{s}^{-1}$ . This allows to deliver integrated luminosities topping  $110 \text{ pb}^{-1}$  per fill. Providing very good conditions for the experiments to accumulate collision data, the high energy beams impose a severe danger for the accelerator (especially the superconducting magnets) which has to be protected against beam loss induced damage.

A complex machine protection system is put in place [2], which prevents damage to the accelerator equipment by extracting the beams as soon as any of the safety systems (beam loss monitors, magnet current monitors, quench protection system, collimation system,...) detects potentially unsafe conditions. The knowledge of the available clearance around the circulating beams is of primary importance for machine protection in case of problems related to orbit and optics changes that can bring the beams too close to sensitive equipment. To help the operation team to detect critical conditions early on, an Aperture Meter was conceived and developed to monitor the machine aperture online. After introducing the concept of machine aperture, the design of the LHC Aperture Meter is presented and some first results from standard LHC physics fills and from aperture measurements are shown.

## APERTURE DEFINITIONS

The definition of the mechanical aperture of each lattice element seen by the beam is referred to as aperture model

of the machine. A continuous model that covers the 27 km of each of the two rings (B1/B2) is available for the LHC.

The concept of available clearance for the circulating beams is however more complex and requires taking into account other relevant machine and beam parameters in addition to the detailed knowledge of the aperture model. The main ingredients to evaluate the aperture in the two planes  $z = [x, y]$  at a location  $s$  are (see illustration in Fig. 1):

- mechanical aperture  $A_z(s)$  from the design specification or calculated from the movable device positions;
  - offset  $\Delta z(s)$  to take into account imperfections like misalignments of magnets (from cold bore measurements before installation) or to include the outcome of beam based alignments of the movable devices that will be described more in detail later on;
  - beam position  $z(s)$  and transverse beam size  $\sigma_z(s)$ .
- The minimal beam clearance or available aperture  $a_z(s)$  is calculated per plane and defined as

$$a_z(s) = \frac{A_z(s)/2 - |z(s) - \Delta z(s)|}{\sigma_z(s)}$$

For convenience, the aperture is normalized to the transverse beam size  $\sigma_z(s) = \sqrt{\beta_z(s)\epsilon_z^{design}}$ , where we use the design emittance  $\epsilon_z^{design}$  for the normalization. Thus the available aperture is expressed in terms of number of available design beam  $\sigma$ . The minimum normalized aperture  $a_z^{min} = \min_s a_z(s)$  for each beam and plane is referred to as the aperture bottleneck, e.g. four bottlenecks exist for the LHC.

The method for calculation of the available aperture presented here is a simplified approach to estimate online the clearance for the beams. Information of the nominal machine (optics functions and the design aperture model) are merged with online measurements (movable device positions, beam position, beam energy and the state of the machine with respect to optics and beam trajectory configuration).

## DATA PROCESSING

### Operational Cycle

During the operation cycle [3] the LHC passes four static states of undefined length to reach physics conditions: i) *Injection* when beams are injected at 450 GeV, ii) *Flat-top* after the beams have been accelerated to the collision energy

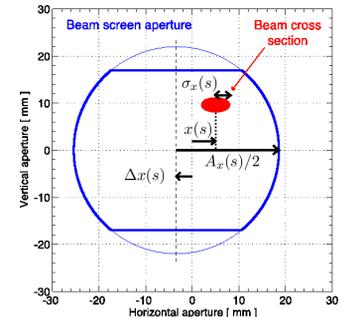


Figure 1: Beam screen aperture with relevant aperture definitions (horizontal plane)

of 3.5 TeV, iii) *Betatarget* when the optics have changed so that the  $\beta$  function at the interaction point (IP) is reduced from 11 m to currently 1.0 m  $\beta^*$  and iv) *Physics* after the parallel separation at the IPs is collapsed to put the beams in collision. In these static states adjustments to the machine can be performed. Four states with pre-defined time duration exist as the transitions between them: a) the energy *Ramp* to *Flattop*, b) the *Squeeze* to *Betatarget* and c) *Collisions* to reach the *Physics* state. To perform the transition, setting functions with pre-defined length are loaded and executed in the hardware (e.g. power converters, collimator's,...). The `OnlineStateProvider`, provided by the online modeling toolchain (OMT) [4], is used in the aperture meter to determine the current state and time in the setting functions.

### Beam Trajectory and Beam Size

The interpolation of beam position data measured by the beam position monitors (BPMs) to all machine elements is done by using the orbit interpolation with transfer matrices implemented in JMad, the JAVA API to MAD-X [4, 5]. A mechanism is provided that allows to define which monitors should be used for the interpolation. This feature is used to exclude BPM data that is flagged as bad reading by the data acquisition or data from BPMs that are excluded by the user. The `JMadOnlineService` of the OMT is used to provide the current machine state's optics functions to be used for the calculation of the transfer matrices. The current machine energy is provided in the service as well. Together with the available nominal  $\beta$  function it allows the calculation of the beam sizes.

### Collimator's and Aperture Model

A sophisticated multi-staged collimation system is installed in the LHC for beam cleaning and to provide passive machine protection. Primary (TCP), secondary (TCS) and absorber collimator's (TCLA) are installed in the cleaning insertions of point 3 and 7. Tertiary (TCT) collimator's are installed in the IP regions to complete the collimator hierarchy and protect the triplet magnets. Special collimator's are installed in the injection and dump regions. The collimation hierarchy is defined such that TCPs are the closest to the beam, followed by the TCS, TCLA and TCT. This hierarchy ensures that beam cleaning losses are caught by collimator's only, protecting the superconducting magnets and other equipment. Dangerous conditions that are difficult to observe can develop as a combination of e.g. an orbit bump outside the collimator's and a beam impact at another location. These are not covered by the collimation system and would cause beam losses at the bump location sufficient to create damage – another reason for continuous aperture monitoring.

Collimator's generally have two jaws, controlled by very precise stepping motors, that are aligned around the beam during collimator alignment campaigns. Procedures are established [6] to determine the beam based collimator center. These alignments have to be performed at each static

state in the operational cycle to produce the input for the collimator setting generation for the functional states of the operational cycle [7]. Based on these settings, the collimation system then follows the orbit (beam separation and crossing) and optics evolution in the operational cycle. The collimator jaws are aligned around the measured beam centers with the required jaw openings.

The online aperture model provided by the OMT [4] is an extension to the aperture model and calculates the mechanical aperture  $A_z(s)$  from the measured collimator jaw positions. The discrepancy between the interpolated orbit in the collimator's during the alignment and the observed beam-based collimator center (the reference for the jaw movement) is taken into account with the offset  $\Delta z(s)$ . The following procedure is used to determine  $\Delta z(s)$  for all collimator's and operational states: i) Establish a default monitor setting for the orbit interpolation module. ii) Interpolate the measured orbit at the time of the collimator alignment to the collimator positions. iii) Store the differences between interpolated orbit and measured beam based centers as  $\Delta z(s)$  for the active state. For each alignment campaign performed at the static operational states, step ii) and iii) are repeated. During operation a mechanism is put in place that ensures that the correct offsets are loaded according to the current operational state. If a functional state is active, a linear interpolation to the current time in the setting functions is performed between the offsets of the two adjacent static state.

## DESIGN AND FEATURES

The aperture meter application is split in a service and a GUI implementation. As the input data from the various sources is not synchronized, a `DataStore` is implemented in the service and filled independently with: beam sizes, simulated orbit and machine state from the `JMadOnlineService` (currently when triggered and changed data available), aperture data from the online aperture model (when movable device positions change) and measured beam positions (1 Hz) from the Orbit Feedback Service Unit. A `DataSynchronizer` is triggered every 3 s to collect all data from the `DataStore`, perform the orbit interpolation, calculate the available aperture at all elements and determine the five smallest values  $a_{z,i}^{min}(s_i)$  of  $a_z(s)$  per beam and plane in the machine. The whole data set is then published to all registered listeners like the GUI.

A logging mechanism is implemented, to save the data set to xml files. In playback mode the aperture meter can be used to load either complete aperture meter data sets or to drive the aperture meter with the information from logged orbit data (logging database or file). Additionally the JMad GUI can be started from the aperture meter to perform virtual trims on the knobs that have been imported by the `JMadOnlineService` as well as to change optics.

Various displays are provided in the GUI to visualize the aperture meter data. The main display, conceived as fixed display, is composed out of four minimal aperture evolution views like the one in Fig. 2, one for each beam/plane

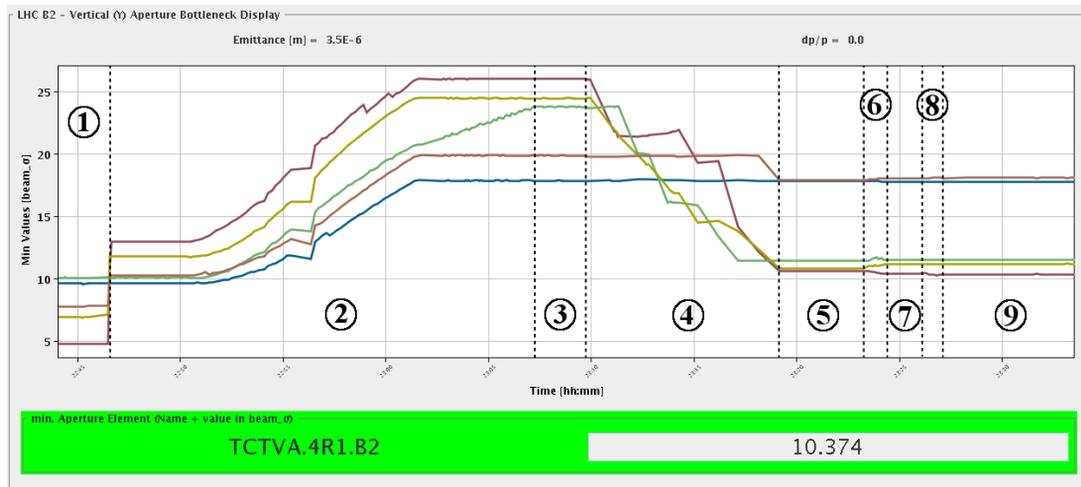


Figure 2: Minimal aperture evolution for beam 2 vertical plane over the operational cycle. The primary and secondary collimator positions are not taken into account.

combination. Each of these views shows the evolution of the available aperture  $a_z(s)$  over time for the five locations (containing the bottleneck) in the machine having the smallest values  $a_{z,i}^{min}(s_i, t)$  in the assigned beam/plane. Depending on the changes in the machine, the locations of  $a_{z,i}^{min}(s_i, t)$  change. To broaden the provided information, only the element with the smallest value per assembly is selected during the minimal aperture determination.

## MEASUREMENTS

Two examples for the visualization of the available aperture, calculated in the aperture meter, are presented in the following to demonstrate the functionality of the application.

### Full Cycle of the LHC

The evolution of  $a_{z,i}^{min}(s_i, t)$ , calculated by the aperture meter during the operation cycle of the LHC is shown in Fig. 2 for beam 2 in the vertical plane. To visualize the adjustments of the tertiary collimator's (TCT) during the operational cycle the primary (TCP) and secondary (TCS) collimator  $a_z(s)$  information have been excluded from the selection of  $a_{z,i}^{min}(s_i, t)$ , they would be the dominant machine elements as they are the closest to the beam according to the collimator hierarchy. The cycle shown in Fig. 2 brings the beams into collision with no squeeze in IP2, squeeze to 3m in IP8 and to 1.5m in IP1 and IP5. The numbered segments represent the following operational steps: (1) *Beam Injection*, finalized by the retraction of the injection protection devices which can be observed by the step change at the end of the segment. Absorber collimator's (TCLA) in point 3 and 7 and the TCT collimator's in the vertical plane are the  $a_{z,i}^{min}(s_i, t)$  locations afterwards. (2) *Energy Ramp* to 3.5 TeV. Caused by *adiabatic damping* the beam size shrinks with increasing beam energy, observable by the increasing  $a_{z,i}^{min}(s_i, t)$ . The sharp edges might be caused by orbit changes, but have to be investigated further. (3) *Flat-top*, const.  $a_{z,i}^{min}(s_i, t)$  and prepare *Squeeze*.

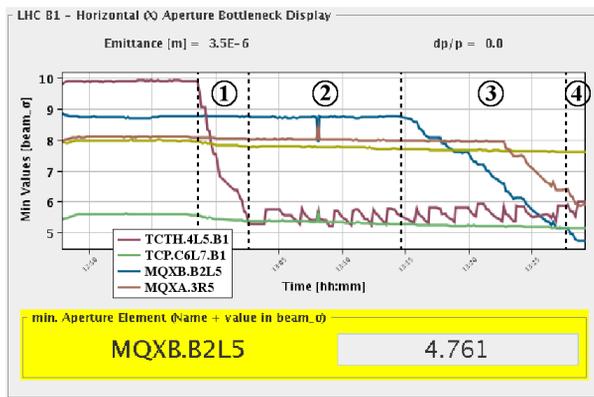
(4) *Squeeze*, the  $\beta$  function changes around the IPs and the TCTs are moved closer to the beam. (5) *Betarget*, const.  $a_{z,i}^{min}(s_i, t)$ , prepare *Collisions*. (6) *Collisions*, parallel separation closed which can be observed by small changes in  $a_{z,i}^{min}(s_i, t)$ . In segments 7, 8, and 9 physics conditions are reached. Segment 8 shows marginal changes of  $a_{z,i}^{min}(s_i, t)$  caused by luminosity scans. The transitions in the *Squeeze* are not smooth as the adjustment to changed optics takes  $\approx 45s$ .

### Triplet Aperture Measurements

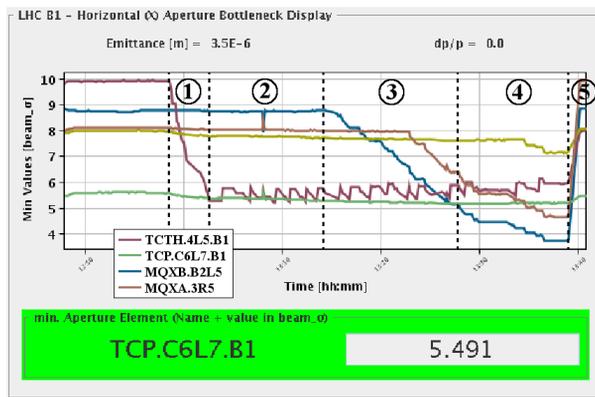
To check and verify the triplet aperture before operating at reduced  $\beta^*$  (the extremal  $\beta$ -function in the interaction points) of 1.0 m, scans have been performed in the triplets by using the angle and separation scan knobs created for the luminosity optimization and leveling. These knobs are defined for both beams and have been trimmed simultaneously to create bump shapes comparable to the nominal crossing and separation. The following steps were performed during the scan:

- increase the bump amplitude until one of the beams touches the corresponding tertiary collimator (TCT), observable by the created beam losses;
- retract both TCTs left and right from the IR by  $0.5 \sigma$ ;
- repeat steps (a),(b) until the triplet aperture is exposed, observable by larger loss spikes in the triplet magnets.

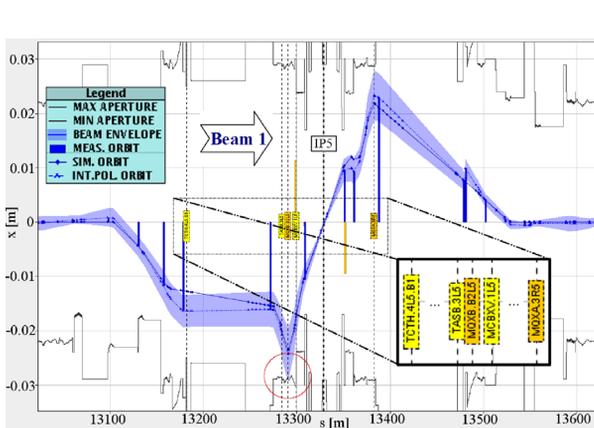
This procedure can be nicely observed by the aperture meter as shown in Fig. 3. The Figures 3a and 3b show the evolution of  $a_{z,i}^{min}(s_i, t)$  during the scan. Figure 3a is an example how the bottleneck display notifies about  $a_{z,i}^{min}(s_i, t)$  below the warning limits (currently set to  $5.0 \sigma$ ). The evolution plots show that under normal conditions the primary collimator (TCP.C6L7.B1) is the bottleneck  $a_x^{min}$  in the horizontal plane for beam 1. When the scan is started (1) the TCT is moved towards the beam until it becomes  $a_x^{min}$ . The approach of the aperture with the scan according to step (c) can be observed in (2) without any impact on the  $a_{z,i}^{min}(s_i, t)$  except for the moving TCT. In (3) the two magnets of the triplets right and left of the IP appear in



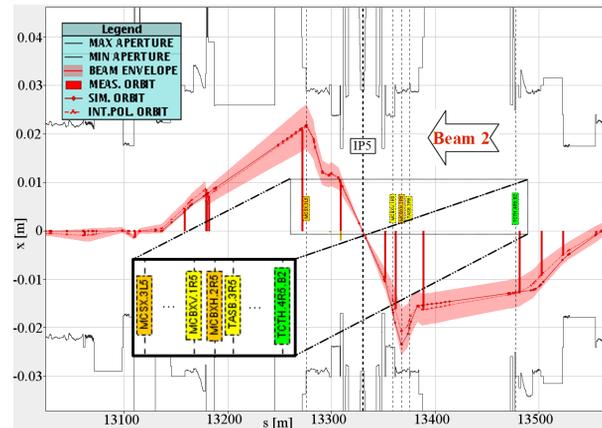
(a) Minimal Aperture Evolution: Triplet Exposed.



(b) Minimal Aperture Evolution: Full Aperture Scan.



(c) Beam 1 display: Max. Hor. Bump.



(d) Beam 2 display: Max. Hor. Bump.

Figure 3: Horizontal triplet aperture scan in IP5 (CMS) at 1.5m  $\beta^*$

$a_{z,i}^{min}(s_i, t)$ . The magnet MQXB.B2L5 of the triplet right from the IP becomes  $a_x^{min}$  in (4) and the beam is gradually moved closer, reducing  $a_x^{min}$ . Finally the triplet is exposed, observed by the created losses. In (5) the collimator's are moved out and the scan knob is trimmed back to zero, to remove the orbit bump and recover nominal operational conditions.

Figures 3c and 3d are the beam views of the aperture meter at the maximum bump excursion achieved during the horizontal scan performed in IP5 (CMS). The simulated, measured and interpolated orbit is plotted in the visualization of the mechanical aperture model. A  $3\sigma$  beam envelope is added to the interpolated orbit. The result in the aperture meter (beam envelope touches aperture of MQXB.B2L5 – red circle in Fig. 3c) agrees with the beam loss observations during the scan.

### CONCLUSION AND OUTLOOK

The principles for minimal aperture calculation and the design of the aperture meter application have been presented. A first implementation is available for operation and has been especially useful for aperture measurements. Validation is ongoing to determine the accuracy of the calculation results. Further work has to be devoted to optimize the configuration of the system and to improve the visualization and playback features.

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