APERTURE METER OF THE LARGE HADRON COLLIDER

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Introduction

Running with outstanding performance [1], the LHC is currently being operated with small emittances and above nominal bunch population (up to 1.4×10^{11} p). Beams with a stored energy of 110 MJ are brought in collision and produce peak luminosities up to 3.3×10^{33} cm^{-1}s^{-1}. This allows to deliver integrated luminosities topping 110 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.

Aperture Definitions

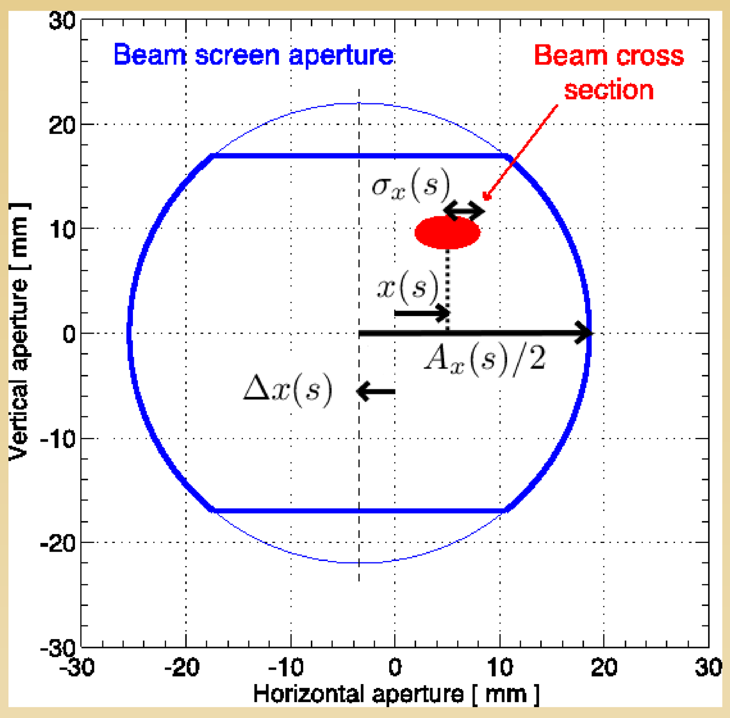

Figure 1: Beam screen aperture with relevant aperture definitions (horizontal plane)

Based on the aperture model, providing the mechanical aperture for all LHC elements, the calculation of **available aperture** $a_z(s)$ for a plane $z = [x, y]$ at a location s in the lattice requires to take into account the following main ingredients (Fig. 1):

1. mechanical aperture $A_z(s)$ from
   a) lattice aperture model
   b) movable device positions
2. offset $\Delta z(s)$ for integration of
   a) magnet misalignments
   b) beam-based collimator centers
3. beam position $z(s)$ and beam size $\sigma_z(s)$.

The available aperture $a_z(s)$ is calculated per plane and defined as

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

$$\sigma_z(s) = \sqrt{\beta_z(s)\epsilon_z^{design}}\ , a_z^{min} = \min_s a_z(s)$$

The normalization with the transverse beam size $\sigma_z(s)$ using the design emittance ϵ_z^{design} allows to express $a_z(s)$ in terms of number of available design beam σ. a_z^{min} refers to the bottleneck in one beam/plane of the LHC, e.g. four bottlenecks are found. This method is a **simplified** approach to estimate online the clearance for the beams

Design

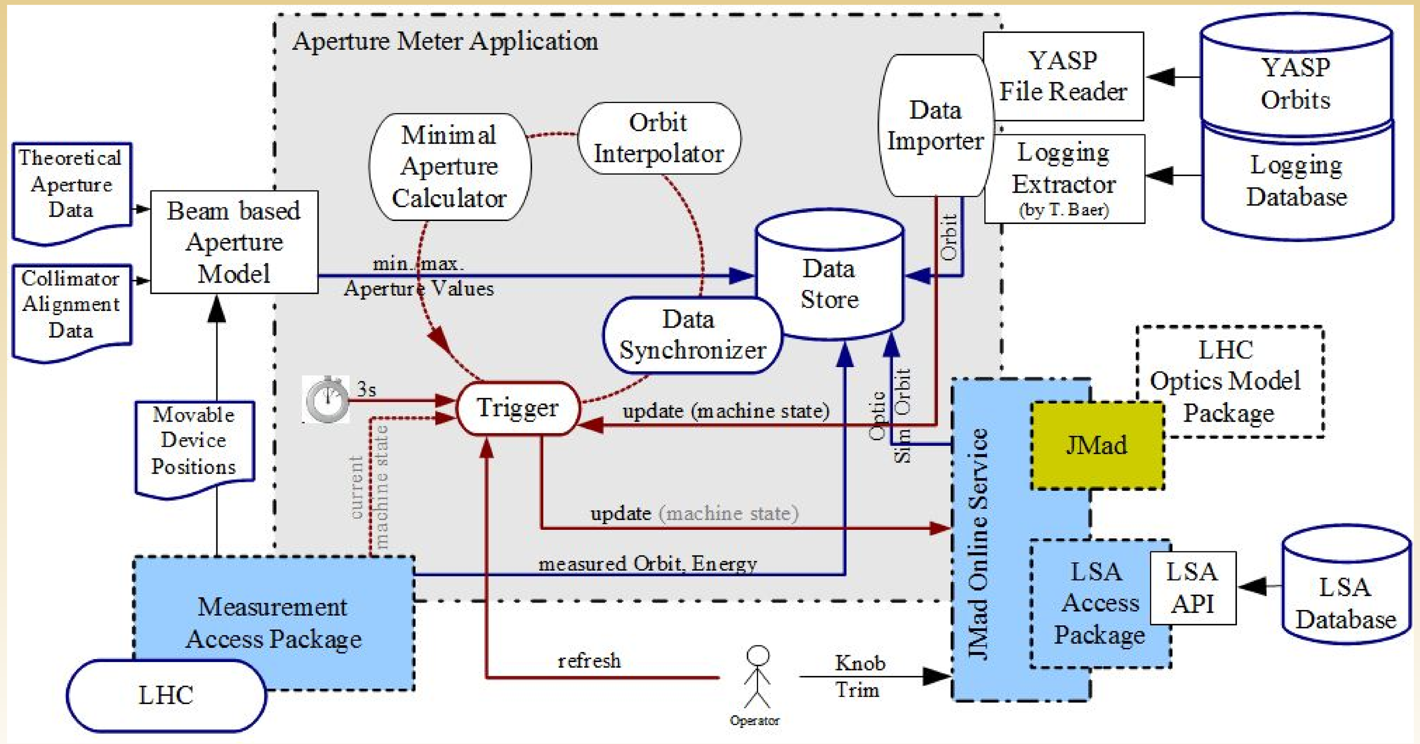

Figure 2: Aperture Meter components and their interaction for $a_z(s)$ calculation.

Modular design, based on the online modeling toolchain of the LHC [4].

Data from event driven or publishing sources are collected in a **Data Store**

Trigger to create a snap shot of the data and run the aperture evaluation

Beam-based Aperture Model provides the mechanical aperture including the movable device positions and the outcome from alignments [6, 7]

Data Import framework provides the basis for aperture meter playback

Measurement Examples

The outcome of the aperture meter is visualized as a continuous chart showing the evolution of the five minimum values $a_{z,i}^{min}(s_i, t)$ of $a_z(s)$ for a given beam/plane. The locations s_i of the $a_{z,i}^{min}(s_i, t)$ change according to the settings driven to the machine. The evolution of $a_{z,i}^{min}(s_i, t)$, calculated in the operation cycle of the LHC is shown in Fig. 3 for beam 2 in the vertical plane.

The different operational states are clearly observable:

1. Beam *Injection*
2. Energy *Ramp* to 3.5 TeV
3. *Flat-top*
4. *Squeeze*
5. *Betatarget*
6. *Collisions*

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.

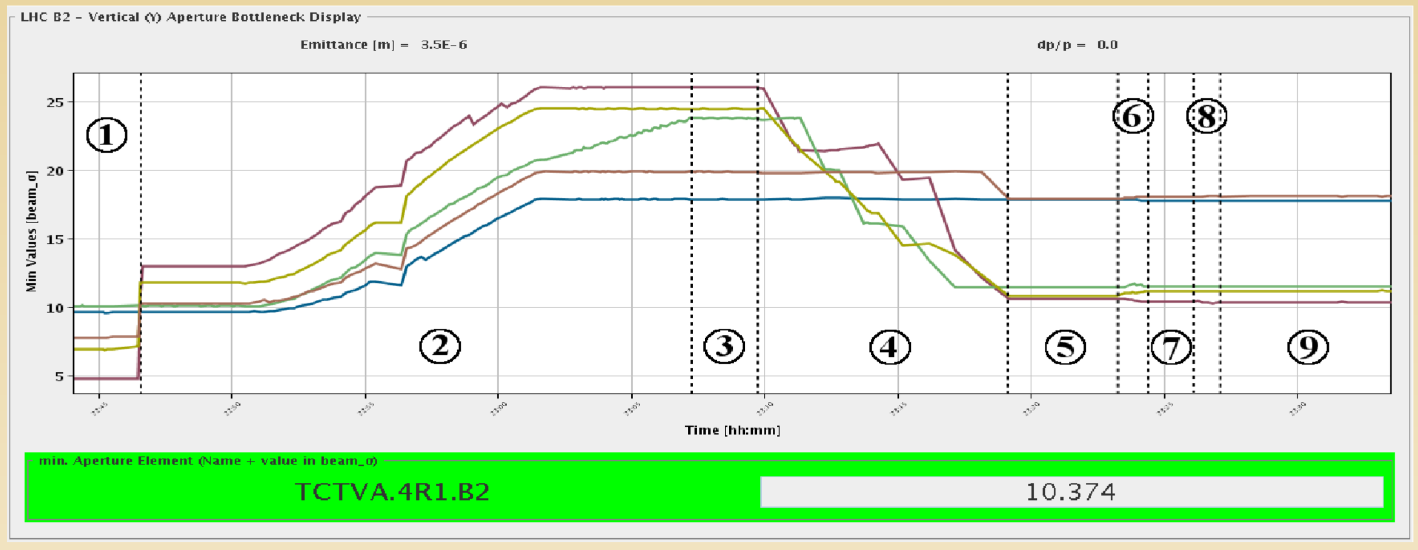

Figure 3: Minimal aperture evolution for beam 2 vertical plane over the operational cycle. The primary and secondary collimator positions are not taken into account.

Another example is the scan of the triplet aperture. An orbit bump was created to move the beam close to the triplets (MQX) left and right of IP5 (CMS). The tertiary collimator (TCT) is retracted in 0.5 σ steps until the triplet is exposed.

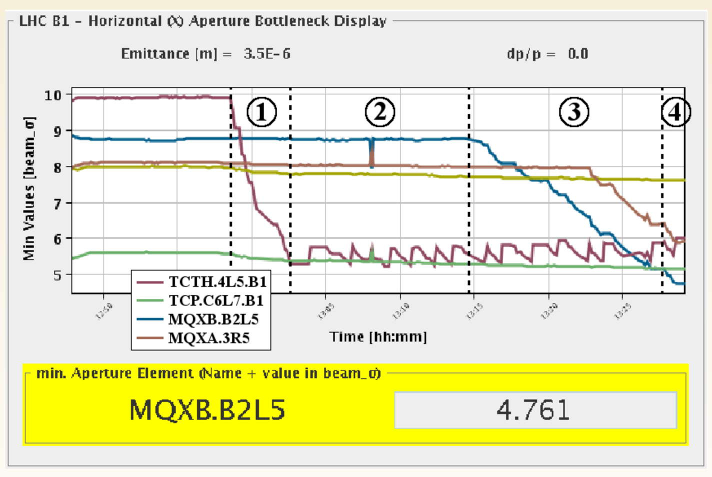

Figure 4: Beam 1 Horizontal, minimal aperture evolution during triplet scan in IP5 (CMS)

1. increase bump until TCT is touched
2. repeat: retract TCT and increase bump
3. bump approaches triplets, they appear in $a_{z,i}^{min}(s_i, t)$
4. triplet is bottleneck a_z^{min}

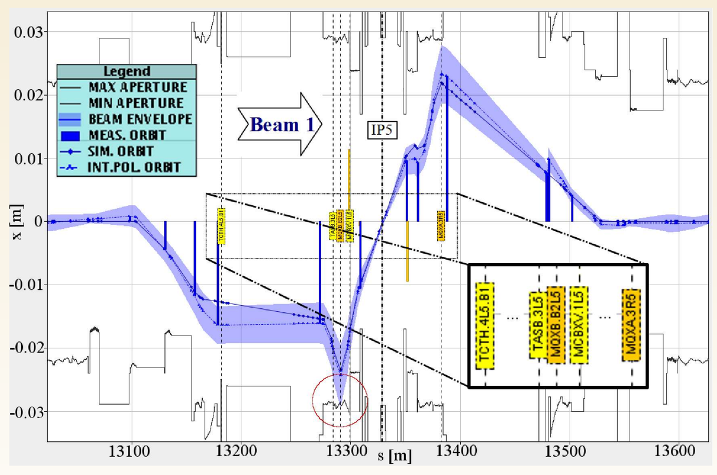

Figure 5: Beam 1 Horizontal, beam trajectory in mechanical aperture at max. bump excursion during triplet scan in IP5 (CMS)

Features

The following features are implemented in the LHC aperture meter application:

- Determination of the current state of the machine in the operation cycle [3]
- Continuous, setting based machine optics and orbit calculation using the online extension JMadOnlineService [4] to JMad [5]
- Interpolation of the measured orbit to all machine elements.
- Continuous monitoring of $a_{z,i}^{min}(s_i, t)$
- Replay of the minimal aperture evolution from logged orbit data and archived settings
- simulation of knob and optic changes by using the JMad GUI interface to the modeling

The main view components are:

Minimal Aperture Evolution View Display the evolution of $a_{z,i}^{min}(s_i, t)$ for the five locations s_i with the smallest $a_z(s)$ in the machine.

Beam View Display the orbit, mechanical aperture and beam size for all machine elements.

Conclusions and Outlook

A first implementation of the aperture meter 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.

References

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[4] G. Müller, *et al.*, *Toolchain for online modeling of the LHC*, these proceedings.

[5] K. Fuchsberger *et al.*, *Status of JMad, the JAVA-API for MAD-X*, Proceedings of IPAC'11, 2011.

[6] D. Wollmann *et al.*, *First Cleaning with the LHC Collimators*, Proceedings of IPAC'10, 2010.

[7] R. Bruce *et al.*, *Principles for Generation of time-dependent Collimator Settings during the LHC cycle*, Proceedings of IPAC'11, 2011.