# IMPROVED APERTURE MEASUREMENTS AT THE LHC AND RESULTS FROM THEIR APPLICATION IN 2015 [*]

P. D. Hermes[†], CERN, Geneva, Switzerland and University of Münster, Germany
R. Bruce, M. Fiascaris, H. Garcia, M. Giovannozzi, R. Kwee-Hinzmann,
A. Mereghetti, D. Mirarchi, E. Quaranta, S. Redaelli, B. Salvachua,
G. Valentino , CERN, Geneva, Switzerland

## *Abstract*

A good knowledge of the available aperture in the LHC is essential for a safe operation due to the risk of magnet quenches or even damage in case of uncontrolled beam losses. Experimental validations of the available aperture are therefore crucial and were in the past carried out by either a collimator scan combined with beam excitations or through the use of local orbit bumps. In this paper, we show a first comparison of these methods in the same machine configuration, as well as a new very fast method based on a beam-based collimator alignment and a new faster variant of the collimator scan method. The methods are applied to the LHC operational configuration for 2015 at injection and with squeezed beams and the measured apertures are presented.

## INTRODUCTION

Aperture measurements at the CERN Large Hadron Collider (LHC) [1] are regularly carried out in the initial commissioning phase, before high intensity beams are allowed to be injected into the machine [2–8]. The measurements are used to verify the settings of the LHC collimators required to protect the machine. The global aperture bottleneck shifts to the superconducting triplet magnets in the experimental insertions, once the beams are squeezed. One of the limiting factors for small $\beta^*$ values and thus for high luminosity is the available aperture in the triplets.

The LHC Collimation System [9] is a multi-stage cleaning system with primary (TCP) and secondary collimators (TCS) installed in the insertion regions (IR) dedicated to beam cleaning, IR3 and IR7. In addition, the experimental insertions host tertiary collimators (TCT) to protect the superconducting triplet magnets and to reduce machine induced background in the experimental detectors.

One essential tool for the aperture measurements is the LHC Beam Loss Monitoring (BLM) System [10, 11], which consists of more than 3000 cylindrical ionization chambers, installed at the outer side of the beam pipes. The BLMs measure the energy deposited by secondary shower particles which are produced when beam particles intercept the machine hardware. They can be used to identify precisely when beam losses occur at local aperture restrictions. The measurements require also transverse emittance blow ups, which are provided by the transverse damper (ADT) [12]. The ADT can induce white noise for the individual planes of both beams in a controlled manner.

In this article, we present different methods of aperture measurements, two of them newly established in 2015. We compare the measurement results obtained with the different methods.

## MEASUREMENT STRATEGIES

Aperture measurements can be subdivided into two major classes: global and local. While local measurements allow the analysis of the available aperture at specific locations of interest, global aperture measurements probe the global aperture bottleneck, i.e. the smallest available beam clearance per beam and plane.

### *Local Measurements*

Local aperture measurements [13] are realized by means of a local orbit bump shaped such that the location of interest can be touched with the beam. The bump amplitude is successively increased until losses are measured with the BLMs. Typically the bump amplitude is increased in step sizes between 0.25 $\sigma$ and 0.5 $\sigma$.

The beam envelope is defined by exciting the beam with the ADT until losses are measured at the primary collimator. The beam then fills the space between the collimator gaps and its normalized beam size is defined by the opening $N_p$ of the primary collimator. The remaining collimator settings are not relevant for the test as long as the bump is not applied in a region where collimators are present. Otherwise the corresponding collimators have to be retracted.

The normalized aperture $A_{\text{loc}}$ is given by the sum of the beam envelope $N_p$ and the bump amplitude $x_b$ at which the losses occur for the first time:

$$A_{\text{loc}} = N_p + x_b \, . \qquad (1)$$

An intrinsic advantage is that possible asymmetries in the aperture can be identified by measurements with both signs of the bump. A permanent bump can then be deployed to center the beam and gain aperture.

In the analysis of the measurement results, the expected orbit is compared to the orbit measured with the beam position monitors (BPM).

### *Global Measurements*

**Collimator Scan (CS)** The collimator scan method is an iterative measurement in which the global bottleneck is exposed to beam losses in a controlled manner.

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[†] phermes@cern.ch

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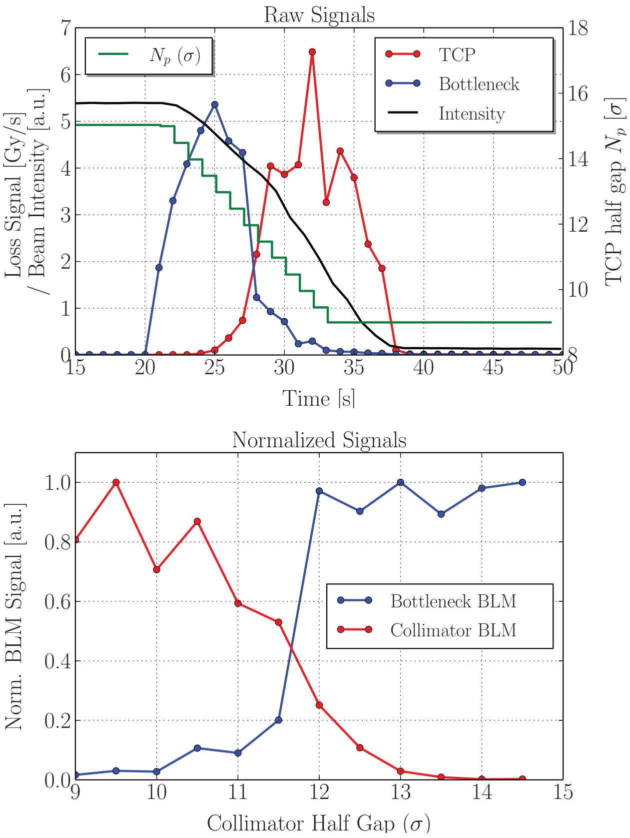

Figure 1: Raw data and normalized BLM signals in the post-processing of aperture measurements with the FCS method.

The measurement is prepared by retracting all collimators but leaving one dedicated collimator in place.

The collimator is retracted in steps of 0.5 $\sigma$ and the beam is blown up at every step. When the collimator setting is such that the aperture at the global bottleneck becomes unprotected, the highest measured loss peak in the machine moves from the collimator to the aperture bottleneck. The measurement is continued until all losses have moved to the bottleneck.

The aperture is deduced from the collimator half gap at which the normalized BLM signal at the bottleneck is higher than at the collimator. The normalization of the BLM signals is explained in more detail in the next section.

**Fast Collimator Scan (FCS)** As a complementary method to the lengthy procedure with manual beam excitation and collimator retraction, a semi-automatic faster method for aperture measurements with the collimator scan method was established in 2015.

The BLM signals, beam intensity evolution and TCP setting during a FCS measurement are shown in the upper frame of Fig. 1. The ADT is set up to excite the beam continuously over an extended period of time. The collimator is programmed to open or close automatically in steps of 0.5 $\sigma$ at a defined frequency. Once the final setting (in the shown example 9 $\sigma$) is reached, the measurement is stopped. The aperture is calculated in the same way as the CS method, but the method is significantly faster. In practice, the FCS method is applied to confirm the measurement result by the CS, to first identify the global aperture bottleneck in a controlled and secure way.

The frequency of the collimator movement should be chosen low enough, to allow for the extraction of the BLM signals at each step. This requires a bunch intensity large enough to provide a sufficient loss rate during the whole excitation.

The BLM response with respect to a defined amount of beam loss is in general varying for the different loss locations. Furthermore, it depends on the intensity lost at each step. This introduces an uncertainty on the aperture deduced directly from the collimator setting at which the BLM signal at the bottleneck becomes larger than at the collimator. The measured BLM signals are normalized to abolish these uncertainties. The peak BLM signals $b_b$ (bottleneck) and $b_c$ (collimator) at each step are extracted from the measurement and normalized by the intensity drop $\Delta I$ during the excitation. In a second step, the signals are normalized to their respective maximum $max(b_b)$, $max(b_c)$, to take the different BLM responses at full exposure into account. The aperture at the global bottleneck is the interception of the two interpolated normalized signal lines (see bottom plot of Fig. 1). A detailed description of the CS method and the normalization is given in [14]. The method has the advantage that the resulting aperture is expressed in terms of the collimator gap, which is the best way to define the collimation hierarchy. On the contrary, the extensive normalization is a possible source of uncertainty, especially if the intensity drop is in the same order of magnitude as the noise of the measuring device.

**Beam-Based Alignment (BBA)** The global aperture measurement via beam-based alignment is a new method which has been established and tested in 2015.

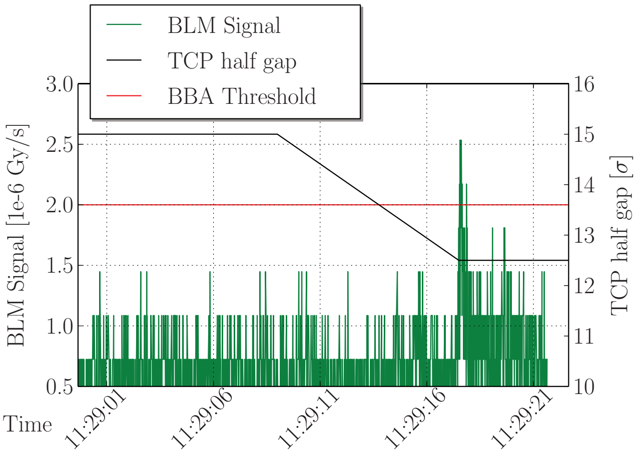

Figure 2: Aperture measurement via BBA. The TCP is closed until the BLM Signal at the collimator exceeds a previously defined threshold.

In this type of measurement all collimators are retracted and the beam is excited, such that losses are measured at the global aperture bottleneck. The beam has then been scraped by the aperture bottleneck which defines the beam envelope.

The extension of the beam envelope is measured by performing a beam-based collimator alignment with the primary collimator. In this type of alignment, the collimator is closed until the BLM signal at the collimator exceeds a previously defined threshold [15] (see Fig. 2). Once it is ensured that both collimator jaws have individually touched the beam, the normalized collimator gap can be directly translated into the available aperture at the global bottleneck.

The aperture can be directly deduced without the requirement for post-processing. The method is particularly suited for measurements at the triplet magnets, where the required settings of the local TCT collimators may be concluded from the measurement. On the contrary, the beam edge is not sharply defined and the measurement result depends on the setting of the BLM signal at which the BBA is stopped. The method thus risks to underestimate the available aperture. Being still under development, the BBA aperture measurement is so far used as a complementary method applied in addition to the methods mentioned above.

## RESULTS

### *Injection Energy*

For the aperture measurements at injection energy (450 GeV) in the 2015 commissioning phase, three different methods (local, FCS/CS, BBA) have been used. The measurement results are compared in Tab. 1. Note that in this operational period, the FCS method was still in its test phase. Only the B1V measurement result could be compared to the manual CS method. The results are in full agreement.

The global aperture bottleneck for B1H was found in a separation dipole. An appropriate bump can not be matched at this location, such that only global measurements have been carried out. The BBA result is smaller than the aperture measured with the collimator scan method. For the measurement of the vertical plane of B1, the local measurements show an aperture larger by $1\sigma$ compared to the collimator scans. This difference is consistent with the aperture asymmetry of $1\sigma$ which was identified in the local scan. The BBA measurement returns an aperture close to the result measured with the CS method. The aperture for B2H measured locally and with the CS method agrees within their uncertainties of $0.5\sigma$ and $0.7\sigma$. The BBA measurement result is slightly below. For B2V, the collimator scan data was corrupted, so the aperture was evaluated using only local measurements and the BBA method. The result from the BBA is below the aperture measured with the local scan.

Table 1: Measured apertures at the global aperture bottleneck at injection energy in 2015.

| | Bottleneck | BBA | CS/FCS | Local |
|---|---|---|---|---|
| B1H | MBRC.4R8 | 11.6 | 12.5-13.0 | - |
| B1V | Q6L4 | 12.1 | 11.5-12.0 | 12.4-12.9 |
| B2H | Q4L6 | 12.5 | 12.8-13.3 | 13.0-13.7 |
| B2V | Q4R6 | 12.0 | - | 12.7-13.0 |

The measurements with the BBA method can potentially be improved when the beams are strongly blown up, such that the population at the edge of the beam envelope is higher and gives more pronounced loss spikes.

Table 2: Global aperture measurement results with squeezed and colliding beams at 6.5 TeV in 2015. The measurement was carried out using the CS method.

| Plane | Squeeze Aperture [$\sigma$] | Collision Aperture [$\sigma$] | Bottleneck |
|---|---|---|---|
| B1H | 16.7-17.7 | 17.2-18.2 | IR5 |
| B1V | 15.7-16.2 | 15.7-16.2 | IR1 |
| B2H | - | 16.2-16.7 | IR1 |
| B2V | 15.7-16.2 | 15.7-16.2 | IR1 |

### *Top Energy*

The measurements at top energy were carried out at the end of squeeze and at collision, with proton beams at 6.5 TeV and beams squeezed to $\beta^* = 0.8$ m in IP1 and IP5, $\beta^* = 10$ m in IP2 and $\beta^* = 3$ m in IP8. In collision, additional bumps are applied to control the luminosity, which can move the orbit and either improve or worsen the available aperture. The aperture measured with the CS method are listed for the two configurations in Tab. 2. Apparently, the measured aperture was similar in the two configurations, while in the collision mode the measurement is even compatible with a larger global aperture than at squeeze.

## SUMMARY AND CONCLUSIONS

Aperture measurements in the LHC play an essential role for the achievement of safe operation and small $\beta^*$ values with high beam intensities. Different techniques can be employed to probe the available aperture in the machine. In the last years of LHC operation, aperture measurements have shown to provide reproducible and reliable results. In this note we presented well-established and novel measurement strategies. Besides local aperture measurements with orbit bumps, two global measurement strategies have been presented: collimator scan and beam-based alignment. The collimator scan method can be applied manually or in a new fast and semi-automatic manner.

The apertures measured at injection, squeeze and with colliding beams were presented. As expected, the measurements via beam-based alignment have the tendency to predict slightly smaller apertures than the other methods. The method is still under development. With the upcoming improvements we aim to reach an accuracy similar to the CS methods. The results from local scans and the CS method agree within their uncertainties.

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