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Aperture measurements in the LHC interaction regions

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Abstract

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The aperture of the LHC interaction regions is crucial for the LHC performance because it determines the smallest achievable β^*. The aperture has been measured at top energy for different energies and optics, following optimized procedure to allow safe measurements at high energy. In this paper, the aperture measurements, whose results determined the LHC operational configurations in 2011 and 2012, are presented.

INTRODUCTION

The knowledge of the interaction region (IR) aperture is crucial for the performance reach of the Large Hadron Collider (LHC) in terms of minimum β functions at the collision points (β^*). The expected aperture bottlenecks with squeezed beams are the triplet apertures in the experimental IRs, where the β functions reach their maxima and the excursions of the beam orbits are also large due to the crossing and separation schemes. It is therefore of paramount importance to know precisely the aperture with the optics and orbit configurations for physics data taking. On the other hand, the aperture measurements in these conditions are difficult because even low-intensity beams are above quench limits of super-conducting magnets and the assumed damage levels for metals. In this paper, the methods established for precise and safe aperture measurements at the LHC are presented. The results of IR aperture measurements at 3.5 TeV and at 4 TeV are given and their implications of the LHC running configurations in 2011 and 2012 are discussed.

MACHINE CONFIGURATIONS

The main parameters for the machine configurations in 2011 and 2012 are summarized in Tab. 1 [1]. In 2012 the LHC is operating at higher energy – 4.0 TeV instead of 3.5 TeV – and at the smaller β^* of 60 cm. It is important to note that already in 2010 the nominal configuration at injection, suitable for ultimate LHC intensity, was achieved. The crossing (Xing) angles are adjusted as a function of energy and β^* to keep under control the long-range beam-beam effects. A smaller β^* requires a larger crossing angle, which makes aperture constrains even tighter.

Table 1: Proton machine configurations in 2011 and 2012.

Parameter	Injection 2011/12	Squeezed 2011	Squeezed 2012
Beam energy [GeV]	450	3500	4000
β^* in IP1/5 [m]	11.0	1.0	0.6
β^* in IP2 [m]	10.0	10.0	3.0
β^* in IP8 [m]	10.0	3.0	3.0
Separation [mm]	± 2.0	± 0.7	± 0.65
Crossing IP1/5 [μrad]	± 170	± 120	± 145
Crossing IP2 [μrad]	± 170	± 80	± 90
Crossing IP8 [μrad]	± 170	± 250	± 220

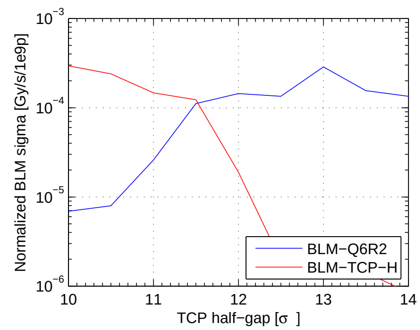

Figure 1: BLM signals at TCP and aperture bottleneck for B1-H versus TCP gap (emittance blowup method).

APERTURE MEASUREMENT METHODS

Tune resonance blow-up with collimator scans

This method has been used since 2010 for global aperture measurements at injection [2]. The beam transverse emittance is blown up by crossing the 3rd order resonance, causing at the same time beam losses that are detected by the beam loss monitors (BLMs) around the ring. With collimators open, losses are observed at the global aperture bottleneck. The blowup is then repeated for different primary collimator (TCP) settings: the TCP is closed in steps of 0.5 σ until it shields the aperture bottlenecks, i.e. until losses are recorded at the TCP location. This gives directly the global machine aperture in units of beam size at the collimator. An example for the horizontal Beam 1 aperture is given in Fig. 1. By adding local bumps in selected locations this method can easily be extended to measure local bottlenecks, notably in the IRs [2]. This method is very powerful, however, it is limited to injection measurements because it requires frequent injections as the beams must be re-injected after having crossed the tune resonance.

Emittance blow-up with ADT excitation

Emittance blowup combined with collimator scans can be improved by having a controlled blowup mechanism. This was achieved with the LHC transverse damper (ADT) by adding white noise excitation [3, 4]. The main advantages of this method are that (1) the speed of transverse blowup is controlled very well so several scans can be done

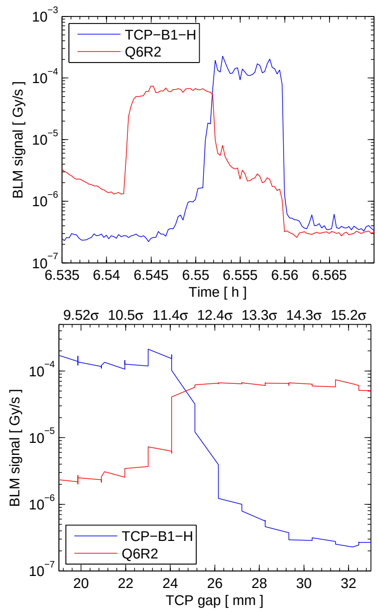

Figure 2: Collimator scan with a continuous ADT excitation: BLM signals at the TCP (blue) and at the bottleneck (red) versus time (top) and versus TCP gap (bottom).

with one single beam; (2) the method can be used at top energy with several bunches, spaced by a number of RF buckets that allows individual blowup [4]. An example of a fast scan at injection using this method is given in Fig. 2

Local bumps in the triplet region (top energy)

Local IR measurements at top energy were carried out with orbit bumps and collimator scans as discussed in [5]. This method was used in 2011 for the measurements in IR1/2/5. With tertiary collimators (TCT) at their nominal settings, additional crossing bumps are added on top of standard crossing and separation schemes until the beam touches the TCTs. These bumps are combined to TCT gap scans until the TCT positions that expose the triplet aperture are found. This allows determining the TCT settings that protect the triplet. An example is given in Fig. 3. This method ensures the triplet protection during the measurements because they remain in the shadow of the TCTs within about 0.5 σ (TCT step size). On the other hand, the aperture results are expressed in terms of TCT retraction and have a small dependence on the shape of the bump used for the scan and on kicks from misalignments or correctors in between the TCTs and the triplets.

This method was used for the first time in Aug. 2011 [6] and revealed larger aperture margins than what was calculated from injection measurements [9]. This allowed a change of β^* from 1.5 m to 1 m in IR1/5 [8] and the operation at 1 m in IR2 during the ion run [6, 7].

Global measurements at top energy

Global aperture measurements at top energy were performed for the first time in 2012 by combining the TCT

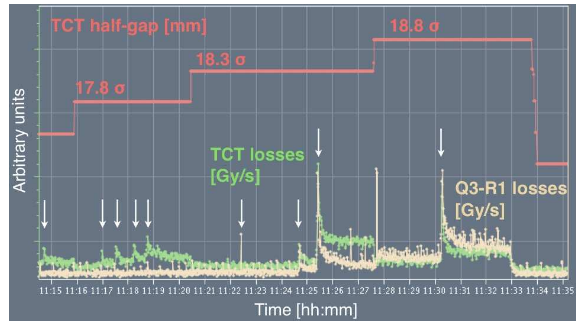

Figure 3: TCT gap and losses at the TCT and at the triplet during aperture scans. The white arrows indicate the time of outwards increases of the orbit bumps. Losses are moved to the triplet location when the TCT goes from 18.3 σ to 18.8 σ (B1-V, 3.5 TeV, $\beta^* = 1$ m).

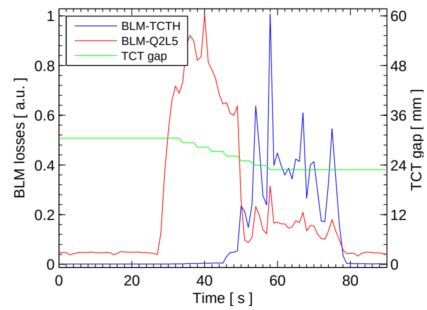

Figure 4: Losses at TCT and triplet and TCT gap during aperture measurement at 4 TeV and $\beta^* = 60$ cm. The ADT excitation lasted from 26 s to 80 s.

scan method with the controlled ADT blowup. The low loss rates achievable with the ADT allowed safe excitations with ring collimators and dump protection opened beyond the triplet aperture, so the IR aperture could be probed without adding any bumps. An example of this measurement, which shows how the losses are moved from the triplet to the TCT during an inward TCT scan in presence of ADT losses, is given in Fig. 4.

Loss maps with increased collimator settings

In order to verify the aperture assumption, in particular the required retraction between TCTs and triplet aperture, special loss maps with increased TCT settings were used. For example, a margin of 2 σ was required in 2011 for a safe operation [9]. Loss maps were performed at 3.5 TeV and $\beta^* = 1$ m with TCTs at 13.8 σ instead than their operational settings of 12.8 σ. Losses were still observed only at TCTs and not at the triplet so it was concluded that enough margins were available. This approach was also applied in 2012, taking full profit of the ADT blowup.

MEASUREMENT RESULTS

The results of aperture measurements done in 2011 at 3.5 TeV for IR1/5 ($\beta^* = 1.5$ m) and IR2 ($\beta^* = 1$ m) are

Table 2: IR1/5 aperture measured with the bump and TCT scan method at 3.5 TeV with $\beta^* = 1.5\,\mathrm{m}$ [6].

IR	Plane	Bump type	Measured aperture $[\sigma]$
1	H	Sep	$19.8 - 20.3$
1	V	Xing	$18.3 - 18.8$
5	H	Xing	$19.8 - 20.3$
5	V	Sep	> 20.3

Table 3: IR2 aperture measured with the bump and TCT scan method at 3.5 TeV with $\beta^* = 1.0\,\mathrm{m}$in [7].

Crossing angle $[\mu\mathrm{rad}]$	Beam–Plane	Bump Type	Aperture $[\sigma]$
-80	B1–H	Sep	$16.0 - 16.5$
-80	B2–H	Sep	$15.5 - 16.0$
-80	B1–V	Xing	$15.5 - 16.0$
-80	B2–V	Xing	$16.0 - 16.5$
$+120$	B1–V	Xing	$12.5 - 13.0$
$+120$	B2–V	Xing	$15.0 - 15.5$

listed in Tabs. 2 and 3, respectively [2, 6, 7, 8, 10]. The method of local bumps and TCT scans was used, so results are expressed in terms of TCT half-gap in σ units equivalent to the triplet aperture. Only the aperture sides with tighter aperture, i.e. the "external" side of crossing and separation bumps, were measured for IR1/5. For IR2, both crossing polarities were considered. The results of IR1/5 measurements indicated larger aperture margins than what was originally estimated [9] and these findings were exploited to reduce β^* to 1 m in Oct. 2011. The available margins between TCTs and triplet aperture were verified by loss maps with increased TCT gaps, as explained above. Aperture measurements were also repeated at 1 m (Tab. 4).

The IR measurements performed in 2011 suggested that a β^* of 60 cm could be achieved at 4 TeV [9]. This was confirmed by measurements done at the beginning of 2012, using the ADT blowup for global measurements, see Tab. 5. These results agree within $0.5\,\sigma$ with what can be estimated from Tab. 2 taking into account the new β^* and crossing angle values (Tab. 1). Note the several differences between the two measurement conditions: reference orbit, optics corrections, scans for luminosity optimization, etc. It is noted that the bottleneck for B2-H is found in IR1 even if this is the crossing plane for IR5 (Tab. 5). This discrepancy will be addressed in future measurements, but does not pose immediate limitations because the required margins for the safe operation at 60 cm are respected.

Table 4: Triplet aperture measured with the TCT scan method at 3.5 TeV with $\beta^* = 1.0\,\mathrm{m}$.

IR	Plane	Bump type	Measured aperture $[\sigma]$
1	H	Sep	> 16.0
1	V	Xing	$14.8 - 15.3$
5	H	Xing	$15.3 - 15.8$
5	V	Sep	> 16.0

Table 5: Global bottlenecks at 4 TeV and $\beta^* = 60$ cm.

Beam	Plane	Elem.	Measured aperture $[\sigma]$	Calculated aperture $[\sigma]$
B1	H	Q2-L5	$11.5 - 12.0$	12.0
B1	V	Q3-L1	$11.0 - 11.5$	11.6
B2	H	Q3-R1	$11.5 - 12.0$	12.0
B2	V	Q3-R1	$11.0 - 11.5$	11.6

CONCLUSIONS

The results of aperture measurements in the LHC interaction regions were reviewed. The operational experience has shown that these measurements are mandatory to understand in detail the aperture limitations and hence to push the luminosity performance by reducing the β^*. The results obtained in 2011 led to a reduction of β^* from 1.5 m to 1 m, with a major impact on the yearly luminosity production, and created the basis for the operation at 60 cm at 4 TeV in 2012. Thanks also to the development of new procedures and techniques, like the controlled blowup with the transverse damper, the IR aperture measurements have become a standard part of the LHC commissioning.

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