EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN – ACCELERATOR AND TECHNOLOGY SECTOR

CERN-ATS-2011-136

Aperture Determination in the LHC Based on an Emittance Blowup Technique with Collimator Position Scan

R.W. Assmann, R. Bruce, M. del Carmen Alabau, M. Giovannozzi, G.J. M¨uller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, D. Wollmann (CERN, Geneva, Switzerland)

Abstract

A new method to determine the LHC aperture was proposed. The new component is a collimator scan technique that refers the globally measured aperture limit to the shadow of the primary collimator, expressed in sigmas of rms beam size. As a by-product the BLM response to beam loss is quantified. The method is described and LHC measurement results are presented.

Aperture Determination in the LHC Based on an Emittance Blowup Technique with Collimator Position Scan

R.W. Assmann, R. Bruce, M. del Carmen Alabau, M. Giovannozzi, G.J. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, D. Wollmann (CERN, Geneva, Switzerland)

Abstract

A new method to determine the LHC aperture was proposed. The new component is a collimator scan technique that refers the globally measured aperture limit to the shadow of the primary collimator, expressed in sigmas of rms beam size. As a by-product the BLM response to beam loss is quantified. The method is described and LHC measurement results are presented.

INTRODUCTION

The performance reach of a high intensity accelerator depends on the available aperture A for the beam. For example, safe operation of the LHC requires that the guaranteed minimum transverse aperture in machine magnets must be at all locations larger than 8.4 σ_z in the transverse directions $z = x, y$. In the radial direction r, the LHC specifications require a guaranteed minimal aperture of 9.8 σ_r [1, 2].

In the most basic terms, a physical aperture A_z^p can be defined at a given location s as the ratio of the half radius r_z of the beam pipe at its smallest extension over the transverse Gaussian beam size σ_z:

$$A_z^p(s) = r_z(s)/\sigma_z(s) \quad (1)$$

The beam size is modulated along s with the beta function $\beta_z(s)$. Normalized coordinates are defined:

$$\tilde{z} = z/\sqrt{\beta_z(s)\epsilon_z^{design}} \quad (2)$$

Note, that here we include the design emittance ϵ_z^{design} into the normalization. This term is used as an overall normalization factor which is obviously constant around the ring and (as we use the design value) also independent of the actual emittance that is achieved. This normalization is done purely for practical convenience as we can then express aperture in terms of number of design beam sigmas instead of an impractical number with unit of $\sqrt{m}$. The ideal normalized aperture $a_z^{ideal}(s)$ is defined as:

$$a_z^{ideal}(s) = r_z(s)/\sqrt{\beta_z(s)\epsilon_z^{design}} \quad (3)$$

This ideal aperture is reduced by a number of imperfections and allowances, for example misalignments of magnets and vacuum pipes, orbit offsets within machine elements, allowances for off-energy offsets, dispersion errors, dispersive beam size contributions, ... During the design phase of the LHC an extensive aperture design model was developed (the ”n1” concept) [1, 2] that takes into account properly all the different possible errors and added them up in a conservative way. For the purpose of this paper we lump imperfections into three components:

1) An on-energy reduction term $\Delta r_z(s)$ that is always positive and includes effects of magnet misalignments, vacuum pipe offset, orbit errors, ...

2) An aperture reduction term $\Delta a_z(\sigma_p)$ that is related to the energy spread σ_p in the beam and includes dispersive beam size effects.

3) An aperture reduction term $\Delta a_z(\delta_p)$ related to possible energy offsets from design. This term includes dispersive orbit changes and chromatic effects.

The available aperture a_z can then be written as:

$$a_z(s) = \frac{r_z(s) - \Delta r_z(s)}{\sqrt{\beta_z(s)\epsilon_z^{design}}} - \Delta a_z(\sigma_p) - \Delta a_z(\delta_p) \quad (4)$$

In practise, many of the required terms to determine $a_z(s)$ are not known with the needed precision and must therefore measured. The measurement and correction method for the β function is described elsewhere. Here, a new method to precisely determine the real machine aperture in a storage ring like the LHC is described.

APERTURE WITH COLLIMATOR SCANS

Location of Aperture Bottleneck

For various purposes (e.g. required settings of collimators [3] and machine protection) a good knowledge of the minimum LHC aperture a_z^{min} is mandatory:

$$a_z^{min} = \min_s a_z(s) \quad (5)$$

The location of the overall minimum aperture is easily determined by the following procedure:

1) Establish reference situation that is to be qualified (orbit, energy, optics, machine corrections).

2) Retract all collimators around the ring.

3) Blow up the beam emittance, for the LHC presently done by moving the betatron tune in the place of interest onto the 1/3 resonance.

4) Observe with beam loss monitors (”BLM’s”) where the beam is lost, assuming that all magnets are sufficiently covered by beam loss monitors (as is the case in the LHC with its powerful beam loss system [4]).

The location of the overall minimum aperture is determined precisely, however, the size of the aperture remains unknown. Here, a new method was then introduced, relying on the well calibrated primary collimators of the LHC.

Collimator Scan Method

The primary collimators [3] of the LHC can be used to define a controllable and well-known cut a_z^{coll} in the overall minimum machine aperture. Here it is assumed that the two-sided primary collimator [3] has been centered on the beam for the reference orbit of interest and that the beta function has been corrected at its location. The term a_z^{coll} is then easily derived from the collimator gap g_z^{coll}:

$$a_z^{coll} = g_z^{coll}/2\sqrt{\beta_z^{coll}\epsilon_z^{design}} \tag{6}$$

The collimator gap is known with high precision (at the 1% level) from hardware construction and direct measurements of the collimation gap.

The availability of the controllable and movable collimation cut then allows to combine the blow-up technique with a collimator scan. The scan procedure is as follows:

1) Store the beam and record beam intensity N_p.

2) Determine overall aperture bottleneck in the machine with collimators open and emittance blow-up.

3) Close primary collimator in plane of interest by a step to a known value of a_z^{coll}.

4) Store again the beam, record beam intensity N_p and blow-up the emittance in the plane of interest.

5) Record beam loss rates R_{loss} around the ring.

6) Go to 3) until the machine aperture bottleneck is in the full shadow of the primary collimator.

This collimator scan then provides beam loss rates R_{loss}^{ring} at the natural aperture bottle-neck around the ring and R_{loss}^{coll} the primary collimator for different values of a_z^{coll}. This measurement can be performed on-energy but also for any specified off-momentum working points.

Data Processing

The raw data obtained in the loss measurements is shown in Fig.1 (top). It is noted that similar beam intensities were used for the measurements but there are still unavoidable variations in intensity from fill to fill. Therefore, the BLM signal R_{loss} in Gy/s is normalized to the amount of lost beam in p, as shown in Fig.1 (bottom).

The different maximum beam loss measurements at the natural aperture bottleneck and the primary collimator reflect the different BLM response to losses of protons. This difference of BLM response is due to different optical functions, different locations of BLM's and different geometries of materials. Significant differences are expected and seen. Quantitative analysis is ongoing.

For the purpose of most accurate aperture determination we normalize the BLM signals at the collimator and aperture bottleneck respectively to the maximum signals obtained at each of these positions, when all losses occur there. This is illustrated in Fig. 2. The condition for the same aperture at the natural bottleneck and the primary collimator is then to have equal values for the two normalized loss rates $\tilde{R}_{loss}$:

$$a_z^{min} = a_z^{coll} \text{ when } \tilde{R}_{loss}^{ring} = \tilde{R}_{loss}^{coll} \tag{7}$$

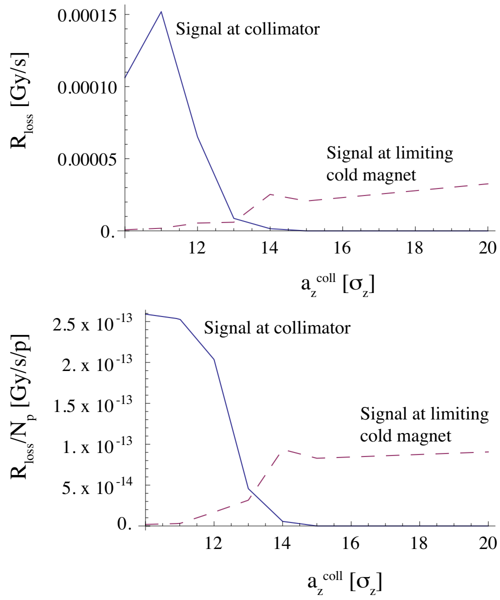

Figure 1: Measured losses at the limiting cold aperture and the collimator during a collimator scan. Raw signal (top) and the intensity normalized signal (bottom) are shown.

The value for the available minimum aperture over the whole ring is then determined. It is noted that all imperfections are naturally taken into account and a fully realistic on-momentum aperture is obtained. In case that off-momentum contributions must be taken into account, the same method is applied with an offset in beam energy. This was performed for the LHC and a reduction in aperture of about 1 σ was found in the horizontal plane.

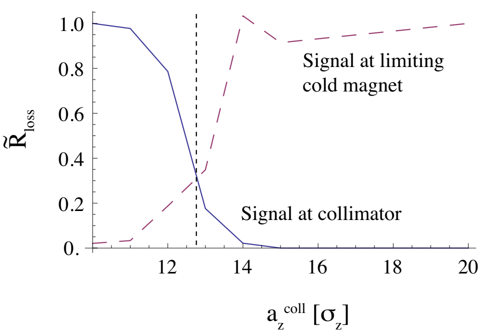

Figure 2: Fully normalized loss rates at the limiting cold aperture and the collimator during a collimator scan. Equal aperture at the magnet and the collimator is indicated by a dashed line.

GENERALIZATION OF METHOD

The method described above determines the minimum available aperture a_z^{min} around the ring in the plane considered. For many applications it is, however, important to determine the aperture at other important locations in the ring, for example the triplet magnets in the interaction regions. This can easily be achieved by a slight modification in the measurement procedure. At the start of the procedure, a closed orbit bump of known magnitude Δz is put into the element of interest at s_i, such that the minimum aperture bottleneck in the ring is afterwards at s_i:

$$a_z^{min} = a_z(s_i) - \Delta z \tag{8}$$

Then the same procedure from before is applied. In the end $a_z(s_i)$ is determined from the following condition:

$$a_z(s_i) = a_z^{coll} + \Delta z \text{ when } \tilde{R}_{loss}^{ring} = \tilde{R}_{loss}^{coll} \tag{9}$$

This extended method was applied for the LHC triplets and selected magnets in the dispersion suppressors around the cleaning insertions. It was also used with other collimators as a reference, in particular tungsten collimators.

OBTAINED APERTURE RESULTS

The LHC aperture was determined with the described method in 2010 and 2011 at injection energy of 450 GeV. The found locations of global aperture bottlenecks are summarized in Table 1. The identified locations correspond nicely to the locations found before with other methods and expected bottlenecks.

The determined values of the minimum guaranteed aperture are listed in Table 2. It is noted that the achieved on-momentum aperture in 2010 of $\geq 12.5\sigma_z$ is well above the specified minimum aperture of $8.4\sigma_z$ (that includes an off-momentum budget). This illustrates the excellent construction, assembly, installation, alignment and commissioning of the LHC. Taking into account the measured off-momentum aperture losses, the 2010 aperture remained with $\geq 11.0\sigma_z$ still more than 30% above the specifications. As a result, there was no need for tightening collimator protection settings and some settings were even relaxed (tertiary collimators). The comparison of results from 2010 to 2011 shows an indication that up to 1.5 σ were lost from 2010 to 2011. This could be due to imprecisions during the first measurements in 2010 or could indicate a real loss of aperture, possibly related to a degradation in magnet alignment due to ground motion (no full realignment of magnets was performed from 2010 to 2011 but a global smoothing of magnets plus a correction of the magnets in sector 7-8).

Table 1: Magnets that were identified as global aperture bottlenecks in the LHC for on-momentum measurements.

Beam	**Magnet** a_x^{min}	**Magnet** a_y^{min}
1	Q6R2	Q4L6
2	Q5R6	Q4R6

The method was also applied for determining the aperture in the triplets at 450 GeV. The results are listed in in Table 3. The data was used in determining the reach in β^* that maximizes luminosity while maintaining full protection of the triplets and the experimental detectors [5] .

Table 2: Results on the globally available minimum LHC aperture with injection optics at 450 GeV for beams 1 and 2 (b1/b2). Only the last row has used the normalization to the stored beam intensity and to the BLM response.

Year	δ_p/δ_0	a_x^{min}(b1/b2)	a_y^{min}(b1/b2)
2010	0	12.5/14.0	13.5/13.0
2010	$\pm$ 0.0015	11.0/13.0	-/-
2011	0	12.0/12.5	13.0/13.1
2011 (norm)	0	-/12.9	-/12.8

Table 3: Results from 2011 on the LHC aperture in the triplets with injection optics at 450 GeV and for beams 1 and 2. All data uses the normalization to the stored beam intensity and to the BLM response.

IR	$a_x(s_i)$ (b1/b2)	$a_y(s_i)$ (b1/b2)
1	-/-	16.0/16.2
5	15.1/17.3	-/-
2	-/-	14.6/16.4
8	15.6/15.6	-/-

CONCLUSION

A new method for precise determination of the aperture in a storage ring was proposed and commissioned at the LHC. This method relies on a full coverage with beam loss monitors along the ring and the availability of precisely controllable, calibrated collimator jaws. The method was used to measure the on-momentum and off-momentum aperture of the LHC with injection optics. Measurements were performed in 2010 and 2011, laying the basis for safe collimator settings and a successful reduction in β^* for improved LHC performance. As a side result, important data on the response of beam loss monitors against grazing beam impact was collected.

The method is further developed to include aperture measurements at 3.5 TeV, scans with other collimator types and a more controllable, feedback-based emittance blow-up which can be performed for selected bunches of a stored beam.

REFERENCES

[1] LHC Design Report, CERN-2004-003 Volume I, June 2004.

[2] J.B. Jeanneret and R. Ostojic, LHC Project Note 111, September 1997.

[3] R. Assmann et al, CERN-LHC-PROJECT-REPORT-919 (2006).

[4] E.B. Holzer et al, Proceedings 2^{nd} Evian 2010 Workshop on LHC Beam Operation (2010).

[5] R. Bruce and R. Assmann, Proceedings 2^{nd} Evian 2010 Workshop on LHC Beam Operation (2010).