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IR1 and IR5 aperture at 3.5 TeV

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Summary

This note summarises the 3.5 TeV aperture measurements in the interaction regions (IRs) IR1 and IR5. The goal of these measurements is to determine the local aperture in the triplet area with optics squeezed to 1.5 m and nominal crossing and separation bumps in order to determine the β^* reach. Aperture measurements were previously performed at injection energy with a different machine optics and with different configurations for crossing and separation schemes. Direct measurements at 3.5 TeV provide better estimates of the aperture in the conditions for physics and will be used for updated estimates of β^* reach. Based on these measurements, the decision to squeeze β^* down to 1 m in IR1 and 5 was taken and successfully put in operation for the last part of the 2011 proton physics run, for a peak luminosity reach of more than $3.5 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$. Thanks to the larger available aperture, this improvement was achieved with minimum re-commissioning time, i.e. without changing the collimator settings and without a modification of the crossing schemes with respect to the previous operation at $\beta^* = 1.5$ m.

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1 Introduction

The machine aperture is a quantity of primary importance for the performance of an accelerator. The minimum aperture available ("global aperture") defines the scale for calculating the settings of the collimators and the other protection devices. At top energy with squeezed optics, the aperture is limited by the low-β triplet quadrupoles where the β function reaches its maximum and the beam orbit is off-centre due to the crossing and separation schemes. The available aperture in the triplet magnets is directly related to the machine performance in terms of β^* reach, hence peak luminosity reach [1, 2]. This is of primary importance for the high-luminosity regions IR1 and IR5 and also for IR2 for an optimised performance of the short yearly operation with heavy ions.

Presently, the estimates of available aperture in the crossing plane are inferred from injection measurements with conservative approaches for key beam and machine parameters such as the orbit stability and the beta-beating [3, 4, 5]. In the separation plane, the aperture is pessimistically estimated from measurements of the global aperture. Direct local measurements of the aperture bottlenecks in both planes in the interaction regions can provide more accurate estimates of the available aperture and enable beam-based estimates of the β^* reach.

It is worth emphasising that the aperture measurements carried out so far have been performed only at injection energy and covered the determination of the arc aperture (during the injection tests in 2007 and 2008); the global ring aperture and local aperture in the IRs both with oscillating closed-orbit bumps (2009), local bumps (2010) and emittance blow-up method (2010 and 2011). Blow-up techniques are possible at injection where beams can be injected repeatedly but are of no practical use for the measurements at top energy. Blow-up of individual bunches within trains based on transverse damper gave promising results in a companion MD but requires more preparation for the usage at top energy [6]. A new method based on local bumps [7] was instead used.

The MD on IR1 and IR5 aperture measurements was carried out on 26 August 2011 between 9 am and 3 pm (LHC fill number 2057). Measurements were carried out in both crossing and separation planes of IR1 and IR5 for a complete determination of the available aperture. Having seen the promising results of these measurements, additional time was dedicated for further aperture investigations at smaller β^* [8]. In this note, only the results achieved during the MD are reported.

2 Measurement goals, strategy and beam requirements

2.1 Goals

The goals of the 3.5 TeV measurements were:

- Measure the local triplet aperture in the crossing planes of IR1 (V) and IR5 (H). In particular, the retraction between triplet aperture at the maximum orbit excursion (Q2) against the tertiary collimator aperture was measured.
- Measure the local triplet aperture in the separation planes of IR1 (H) and IR5 (V). In particular, the retraction between triplet and TCT was determined.
- If possible, re-centre the collision point to optimise the aperture in case of symmetric bottlenecks were encountered.

The first two items are the most important for the performance in 2011 because they determine the available space with respect to the operational configuration of crossing and separation schemes. The third item required determining the full mechanical aperture. This is of interest to cross-check aperture models but is more time consuming. It could not be addressed in the allocated time.

2.2 Strategy

The aperture measurements can be performed by increasing the crossing and separation bumps that have peak excursions at the location of the triplet magnets, or with any equivalent local bump peaked at the triplet location. Due to limitations of the RCBX orbit correctors in the common regions used for crossing and separation bumps, the scans were performed with the local crossing bumps used for the steering of the collision points (angle "lumi" scans). These knobs were added on top of the standard crossing and separation knobs. The configuration adopted for these measurements has also the advantage that it enables scans separately for Beam 1 and Beam 2 since the lumi-knobs use correctors outside the common region.

Note that the aperture will be determined in terms of retraction between triplet aperture and aperture of the tertiary collimators (TCTs) that protect the triplets. This method, described in more details in the following, has two main advantages: *i*) the triplet magnets always remain in the shadow of the TCT within half a sigma; *ii*) the retraction between TCT and triplet aperture is not dependent on the initial beam orbit, which could vary significantly with respect to the conditions for physics because probe beams have been used. On the other hand, the results obtained with this method depend somewhat on shape of the bump used to move the aperture in the triplet region and the result is sensitive to kicks from misalignments or correctors in between the TCTs and the triplets. Due to the IR optics with small phase advance between TCT and triplet, this effect is expected to be small but must be taken into account. Later analysis [9] confirmed that the results presented in this paper are compatible with a safe operation at $\beta^* = 1$ m, but that there may be significant differences between the TCT opening and the triplet aperture depending on the phase advance from the used correctors.

As far as machine protection is concerned, the whole procedure has been described in a document [7] eventually approved by the restricted MPP. The main beam and machine configuration required for the 3.5 TeV aperture measurements are listed in Table 1. The measurements have been performed with one individual probe bunch per beam of about 5×10^9 p, i.e., well within the assumed safe limit at 3.5 TeV (3.14×10^{10} p). In order to minimise the risk for quench, the TCT collimators that protect the triplet were opened to the minimum level required to measure the aperture of the triplet (0.5 retraction from the aperture at most).

Alternatively, the triplet aperture can be determined directly from the measured local orbit excursion in the triplet. This method has the advantage of not being sensitive to the shape of the bump and to possible kicks between the TCTs and the triplet but the disadvantage of relying on the BPM readings. These are known to have systematic uncertainties for large excursions and low intensities.

To avoid risks of dumps from the loss measurements of the experiments, special configurations for the BCM (beam current monitors) of ATLAS and CMS have been established. They turned out not to be necessary because the measurements were carried out with minimum beam losses: the detector's BCMs measured levels below 1 % of their standard operational dump thresholds. Furthermore, to enable movements of the tertiary collimators, their position interlocks were opened to parking limits.

2.3 Operational procedure

The procedure for aperture measurements, including the preparatory steps to be performed by the operation crew on shift, is listed below.

1. Preparation of the beams (OP crew)
    - Inject 1 probe per beam of intensity $\approx 5 \times 10^9$ p. The RF bucket is not relevant. Blow-up transversely in the SPS to get emittances of $3 - 4\ \mu\mathrm{m}$.

Table 1: Beam parameters and machine configuration for the measurements.

Beams required	Both beams
Beam energy [GeV]	3500
Optics	Squeezed (1.5 m), separated beams (0.7 mm)
Bunch intensity	$< 1 \times 10^{10}$ p
Number of bunches	1 per beam
Transv. emittance $\mu\mathrm{m}$	3-5
Bunch length [ns 4σ]	Not relevant
Optical configuration	Nominal end-of-squeeze conditions with separated beams
Orbit change	Various types of bump have been added to the nominal orbit
Collimator configuration	Tertiary collimators in IR1 and IR5 have been moved
Feedback configuration	OFB and QFB have been switched off at the end of the squeeze, with beams separated
Special conditions	Masked BCMs in ATLAS and CMS

- Standard ramp and squeeze with nominal orbit references.
- Hand-over the machine to the MD-ers at the end of the squeeze, with separated beams.

2. Checks/preparation at the end of the squeeze (OP crew)
    - Mask the required interlocks:
        - BLMs in all IRs
        - BPM in IR6
        - Collimator positions in IR7 (for possible TCP movements), IR1 and IR5.
          (MKQ in IR6)
    - Measure the transverse emittance. If below $3-4\ \mu\mathrm{m}$, blow-up the beam with some kicks with the tune kicker.
    - Inform ATLAS and CMS that measurements are about to start and make sure that they have special configurations for relaxing the BCM interlocks.
    - Check the extension of the beam halo with small steps of the primary collimators in IR7 (both planes): check at with gap one starts seeing loss spikes. Move back the TCPs to the nominal settings.

3. Aperture measurements in the crossing plane of IR1.
    - Increase the crossing knob in steps until the vertical collimators are touched, as seen on the local BLMs on TCTVA.4L1.B1 and TCTVA.4R1.B2. Example settings: a step of $20\ \mu\mathrm{rad}$ gives $\approx\ 250\ \mu\mathrm{m}$ at each TCT, i.e. $0.5\,\sigma$. The details steps sizes should be determined on-line on the base of the loss spike signals.
    - When one of the vertical TCTs is touched, retract both TCTs by $0.5\,\sigma$.
    - Increase the angle further until one of the TCTs is touched again.
    - Iterate previous two points until the MQX aperture is exposed, i.e. until losses recorded at the triplet BLMs are larger than the ones at the TCT collimators.
    - Record the final positions and trim back the crossing knob to the nominal value.

- Move both TCTs by $2\,\sigma$ towards the beam, to protect the triplet while other measurements will be ongoing. Remark: In case of problems with the strength of the magnets used for the crossing/separation bumps, external correctors should be used to increase the bumps until the aperture is touched. These knobs can be generated on-line with YASP.

4. Aperture measurements have to be repeated in the other IR/planes in this order:
   - Horizontal (crossing) plane in IR5.
   - Vertical (separation) plane in IR5.
   - Horizontal (separation) plane in IR1.

2.4 Beam conditions for aperture measurements

The beam requirements for the proposed aperture measurements are listed in Table 1. The standard information provided in the MD request is listed, with additional details of the changes relevant for machine protection. The beam intensity measured for both beams during the aperture measurements is shown in the left graph of Fig. 1. The beam energy and the β^* function in IR1 and IR5 during the corresponding period is shown in the right graph. Aperture measurements were performed at top energy with beams squeezed to 1.5 m and then loss maps were carried out after having squeezed the beams further to 1.0 m in both IRs.

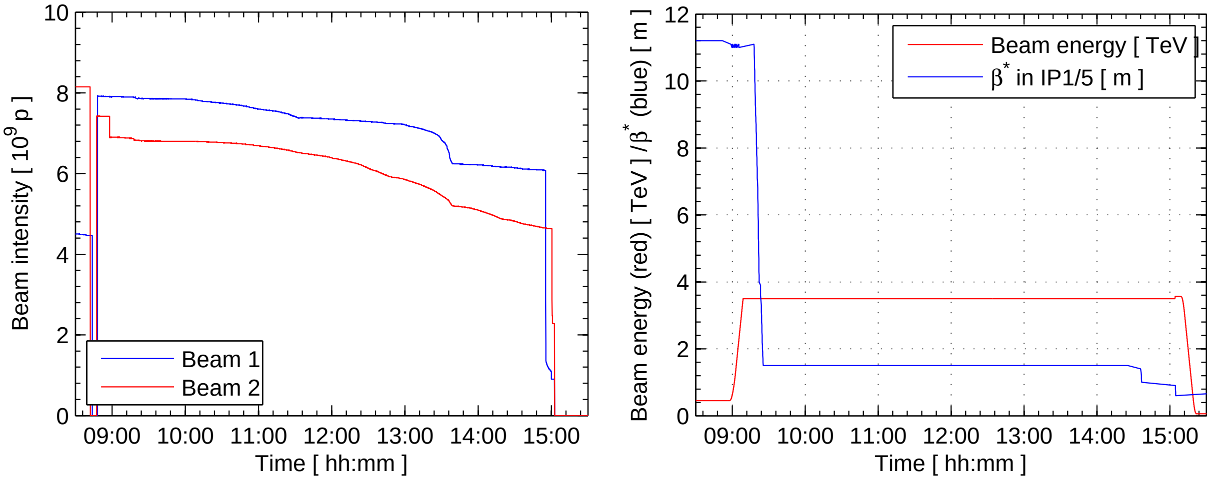

Figure 1: Beam intensity versus time (left graph) and Beam energy (red) and β^* (blue) in IR1 and IR5 versus time (right) during the fill dedicated to aperture measurements.

The bumps used to probe the IR5 triplet aperture are shown in the left plot of Fig. 2. In this example, bumps for $\pm\ 100\ \mu\mathrm{rad}$ additional crossing angles are shown. The bumps are compared with the initial orbit offsets from crossing (H) and parallel separation (V) bumps. Similar bumps were used in IR1, where crossing and separation planes are inverted with respect to IR5.

3 Measurement results

In practise, the local orbit bumps were increased until one of the of beams touched the TCT collimators, initially set to the nominal value of 11.8 σ around the local orbit. After that, the TCTs of both beams were opened in steps of 0.5 σ, i.e. about $250-320\ \mu\mathrm{m}$ depending on the plane. After each step corresponding to the increase in the gap, the IR bump was increased by an amount that induced

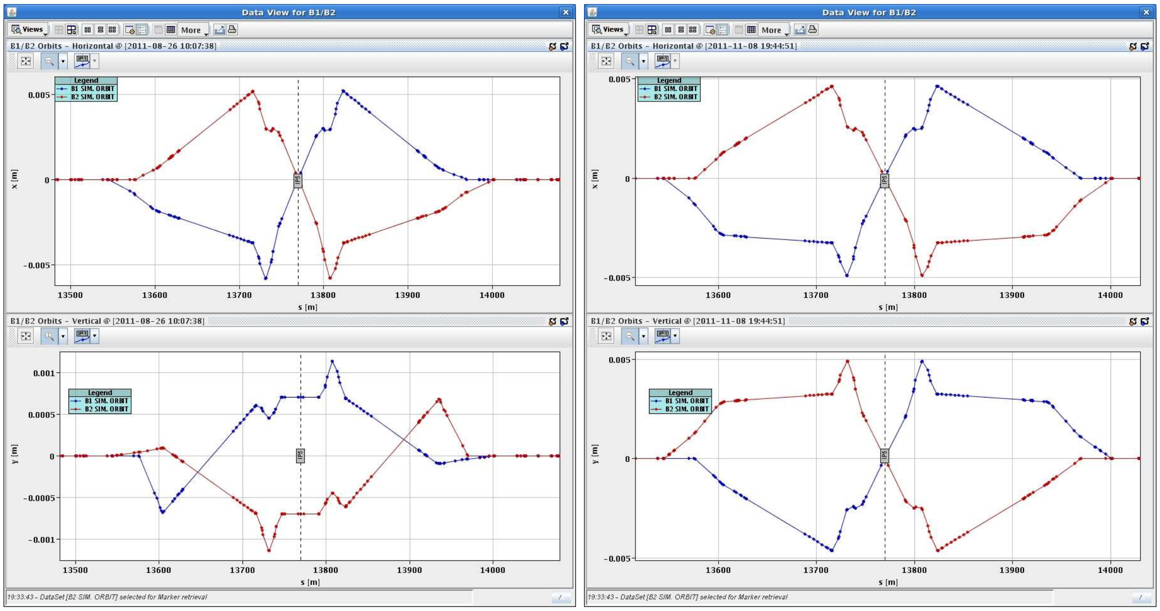

Figure 2: Simulated initial orbit in IR5 (left) and additional crossing angle knob used for aperture scans (right). The IR1 layout is equivalent but parallel separation and crossing planes are inverted. Aperture bumps on the left plot are matched for a $\pm\,100\,\mu$rad crossing angle.

an orbit shift of $\approx 0.25\,\sigma$ at the TCTs. The value of the BLM signals at the TCTs and at the triplet magnets at either side of the IR were monitored to detect when the beam loss occurred in the triplet before in the TCT. This required some careful consideration of the signal in some cases in order not to bias the measurement result by either under- or over-estimating the triplet aperture.

Note that the initial orbit excursion required to touch the TCT the first time depends on the beam emittance and halo extension, as well as on the initial orbit. The orbit could not be guaranteed to be identical to the one in standard operation due to the different bunch intensity regime (probe beam for the measurements against nominal intensity for physics fills). On the other hand, the additional orbit excursion from the TCT jaw to the triplet aperture becomes then independent on the initial orbit and on the beam emittance. This is an important advantage of the proposed measurement technique.

The global evolution of the beam intensity and gap opening for the TCTs in IR1 and 5 is reported in Fig. 4. Less than five hours were required to measure the two IRs in both planes. Nevertheless, only one side of the aperture was probed and this is a point that should be addressed in a future measurement. Another improvement could be to measure separately the aperture for the two beams, which could not be done in this first measurement due to lack of time. The resulting apertures expressed in terms of the TCT opening obtained during these measurements are reported in Table 2. The bump configurations corresponding to the cases when the triplet aperture was touched in IR5 are given in Fig. 5.

In Fig. 3 the approach of the aperture bottleneck during the aperture measurement in the vertical plane (crossing plane) in IR1 is shown. The evolution of the TCT jaw positions as a function of time (lower part) is plotted together with the variation of the interpolated vertical orbit (centre part) and the BLM signal from the TCT and the Q3 magnets on the left and right side of the IP (upper part). The losses are visible on both sides of the IP, making the identification of the actual bottleneck not easy as showers from the TCTs might generate additional losses not linked to a true primary aperture limit. Nonetheless, by inspecting the extreme values of the orbits for Beam 1 and Beam 2, one finds that they are in the range of $19.4-20$ mm. Such an interval is to be considered at the edge of the resolution of our method anyway. Hence, this argument would resolve the uncertainties observed for this case. The other situations are, however, much cleaner.

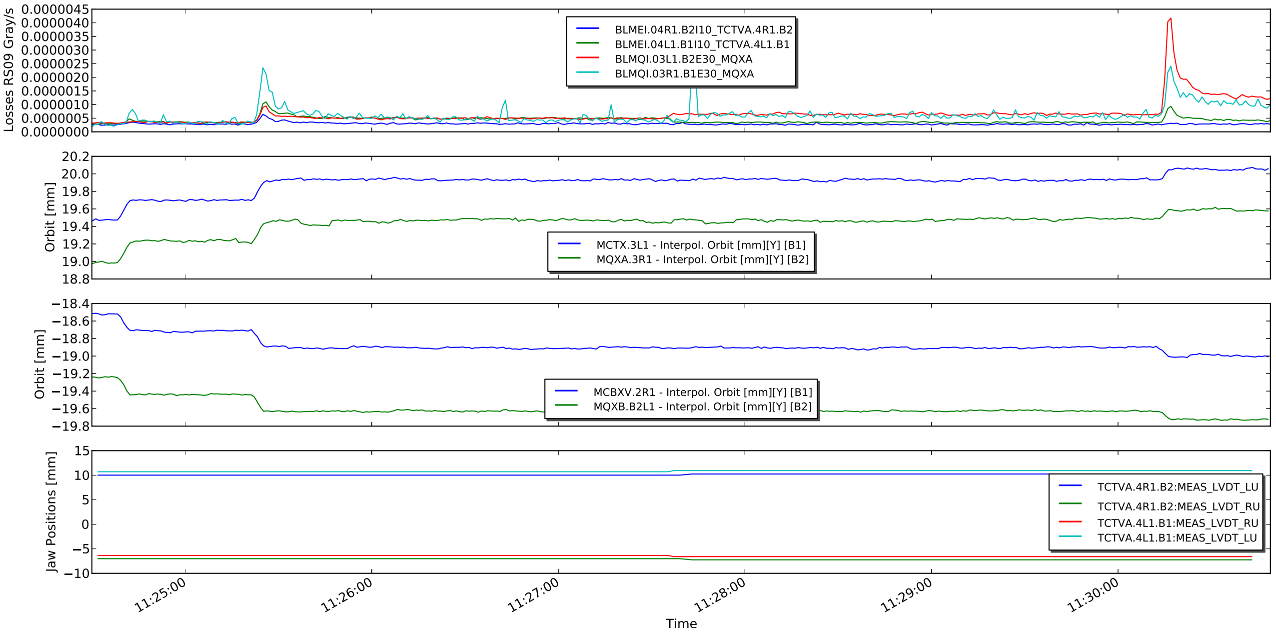

Figure 3: The evolution of the TCT jaw positions as a function of time (lower part) is plotted together with the variation of the interpolated vertical orbit (centre part) and the BLM signal from the TCT and the Q3 magnets on the left and right side of the IP (upper part). These plots represent the last approach of the aperture limit during the measurements in IP1 for the V-plane.

In Table 3 we show the results from the alternative method, where the aperture has been determined from the BPM orbit data. The width of the beam envelope has been derived from the TCT opening and using the initial beam position and added to the interpolated orbit at the theoretical location location of the bottleneck. In this case, the final aperture estimate is given in millimetres and compared to the design aperture of the magnetic elements in which the limitations have been observed. In general, a good agreement is found, with a discrepancy of few millimetres, only, between the model and the measurements. In one case the obtained aperture turns out to be larger than the design one, but it is worth emphasising that this could be partly due to the intrinsic error on the measurement (about $1\,\sigma$ or 1 mm) and also the fact that only one side of the mechanical aperture was probed. Hence, a transverse offset cannot be completely excluded. It is worth noting that in the case of IR5 and for the separation plane, the strength of the dipole correctors was not enough to touch the triplet aperture. Finally, the contribution of the MCBX is under investigation.

During aperture measurements, the LHC ApertureMeter was used to evaluate on-line the available aperture. These controlled measurements with varying bumps provided an ideal testbed for this new tool [11] that, amongst other functionality, calculates the 5 smallest apertures per beam and per plane. An example is given in Fig. 6 where the evolution of the available aperture normalised by the beam size during the aperture scan in the horizontal crossing plane of IR5 (CMS) is given. When the scan is started (1) the TCT aperture is reduced due to the local change of orbit until it becomes the aperture bottleneck. The scan method applied (interplay of bump increase followed by TCT retraction) can be observed in (2) without any impact on the available aperture except for the moving TCT. As the bump amplitude increases, the triplet magnets at either side of the IR appear eventually among the five smallest aperture bottlenecks (3). The magnet MQXB.B2L5 of the triplet right from the IR becomes aperture bottleneck in (4) and the beam is gradually moved closer, reducing the available space. 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.

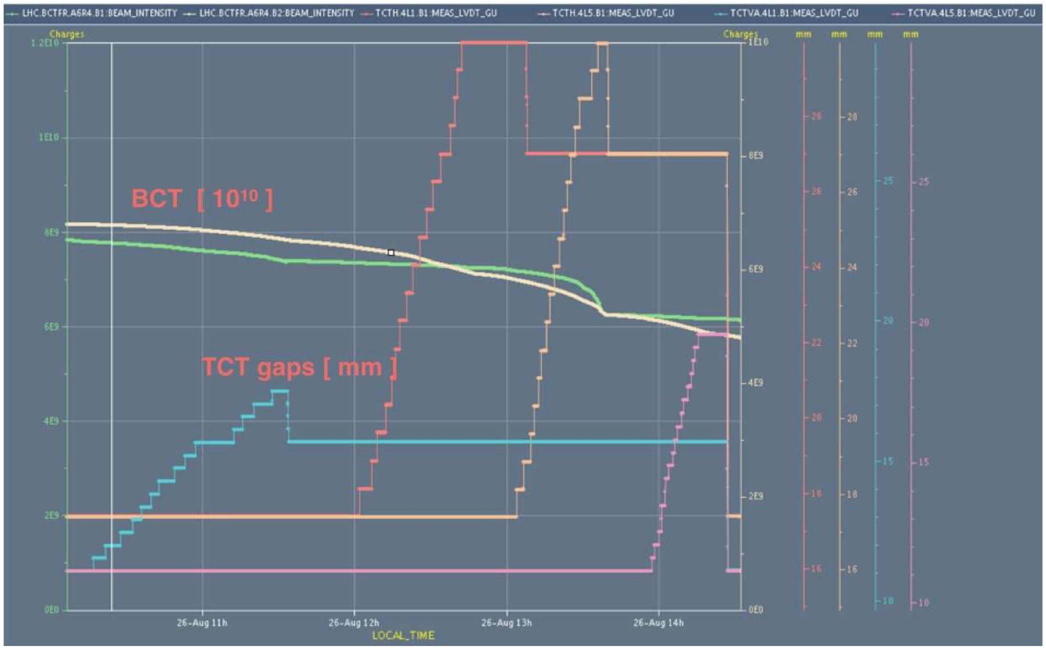

Figure 4: Global evolution of the beam intensity and TCT gaps during the whole MD. Approximately five hours were required for completing the scans of the TCT openings.

Table 2: Triplet aperture derived from the measurement in terms of TCT opening.

IR	Plane	Type of bump in standard optics	Aperture [σ]
1	H	Separation	19.8 – 20.3
1	V	Crossing	18.3 – 18.8
5	H	Crossing	19.8 – 20.3
5	V	Separation	$>$ 20.3

4 Measurement of loss maps

The initial TCT aperture was $11.8\,\sigma$, which implies that at least $6 - 7.5\,\sigma$ retraction would be available between the nominal TCT opening and the triplet aperture. The current assumption [1] is that at least $2\,\sigma$ are available.

The larger aperture found in measurements allows on paper to achieve $\beta^* = 1$ m with the same TCT settings while maintaining the $2\ \sigma$ margin to the triplet aperture. To have a preliminary confirmation of this result, before dumping the beam it was decided to proceed with the squeeze down to $\beta^* = 1$ m keeping the crossing angle at the nominal value of $120\ \mu\mathrm{rad}$, the parallel separation of $\pm\ 0.7$ mm, and the collimators with the relaxed settings used in standard operation. Even if a loss map cannot be used to define collimators' settings or to determine the actual retraction between TCT and triplet, still the absence of losses on the triplet would be an encouraging sign of triplets' protection. In Fig. 7 the results are reported for Beam 2. The usual losses in the betatron and momentum cleaning insertions are visible, as well as losses on the TCTs in IR1 and 5, but the triplets were not exposed to beam halo. Some leakage from the TCT to the triplets in IR1 for Beam 2 was

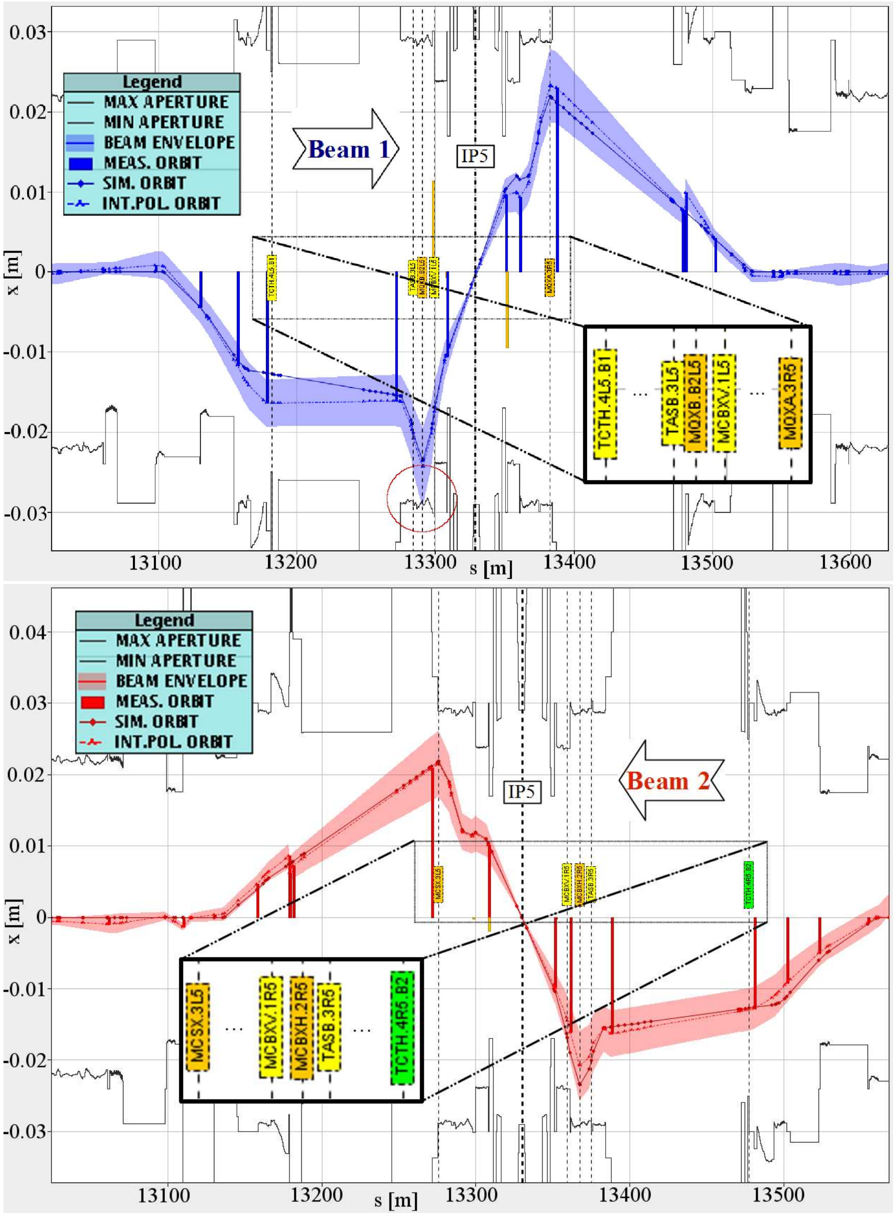

Figure 5: Beam orbit interpolated from the measurements and simulated with MAD-X on-line for the cases of maximum excursion achieved during aperture scans in IR5. A 3 σ beam envelope is added to the interpolated orbit.

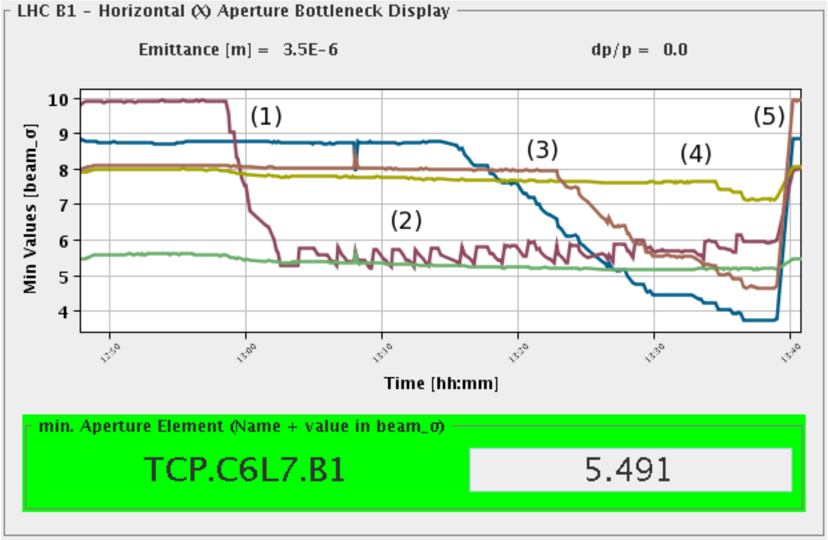

Figure 6: Example of aperture meter calculations during the horizontal aperture scan in IR5.

Table 3: Maximum orbit excursion and envelope width at the maximum orbit during aperture measurements. The design aperture and the likely element of loss location are also given. For the case of IR5 (V-plane) the lower bound given here represents the maximum excursion achieved with the bump created with the maximum strength available for the closed orbit correctors magnets.

IR	Plane	Total orbit [mm]	Envelope width [mm]	Envelope width [σ]	Total apert. [mm]	Design apert. [mm]	Element
1	H	-17.4	7.1	5.6	24.5	25.2	`MQXB.B2L1`
1	V	$+19.4$	6.7	5.0	26.1	30.0	`MCTX.3L1`
5	H	-24.3	7.0	5.6	31.3	30.0	`MQXB.B2L5`
5	V	$+18.5$	6.4	4.5	> 24.9	25.2	`MQXB.A2R5`

observed, but was not considered a serious issue. These preliminary results must be confirmed by loss maps with higher bunch intensity to produce better accuracy and to establish the reference orbit as in physics fills.

5 Tune and Coupling Measurements

In parallel with the described aperture measurements the tunes and coupling (C_{-}) were monitored as a function of the applied orbit bump.

An off-axis beam travelling through the IR will undergo a tune shift if encountering non-linear fields, due to feed down to either normal gradient or linear coupling. The principal measurable feed down for various multipoles are detailed in Table 4. As described in [12] observations of the tune under the influence of selected IR bumps have formed a basis for non-linear optics corrections at

Table 4: Normal gradient (ΔQ) or coupling (ΔC) feed down from non-linear multipoles

	b_3	a_3	b_4	a_4	b_5	a_5	b_6
H bump	ΔQ	ΔC	ΔQ	ΔC	ΔQ	ΔC	ΔQ
V bump	ΔC	ΔQ	ΔQ	ΔC	ΔC	ΔQ	ΔQ

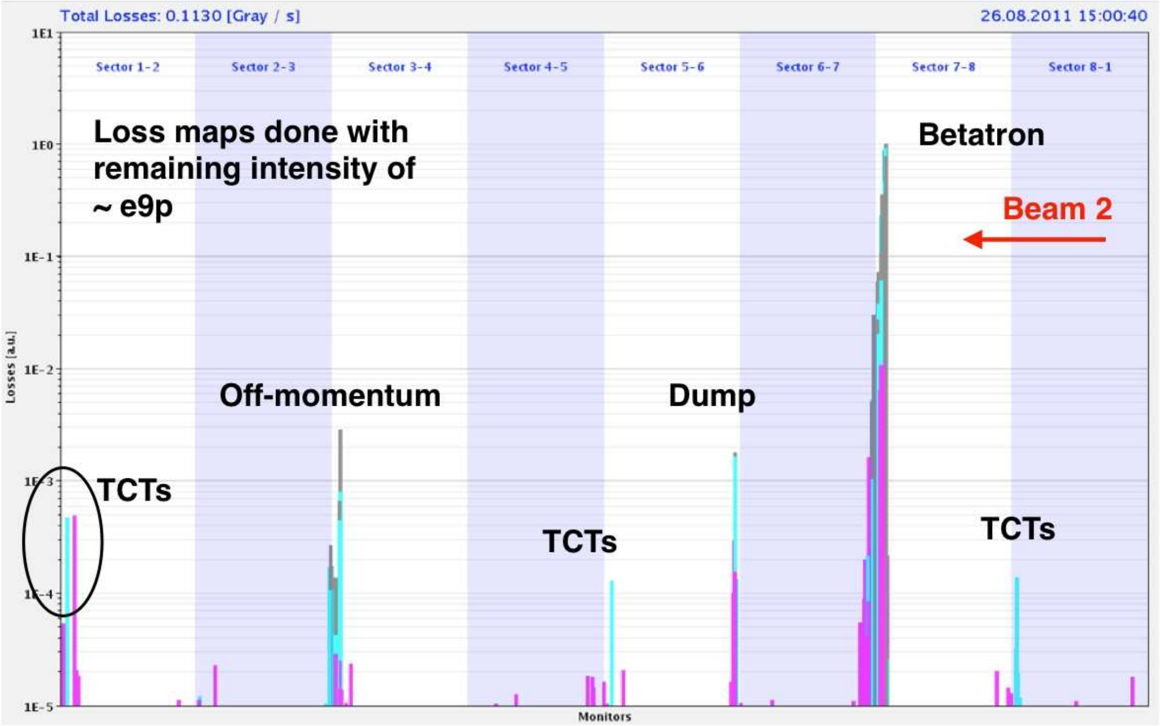

Figure 7: Loss map for Beam 2 measured at the end of the aperture measurement.

RHIC. The measurement of the coupling during the recent aperture measurements at the LHC represents a further improvement of the IR bump method.

Measurements were performed using the continuous FFT BBQ. Data was cleaned and averaged within each trim plateau. The results have been compared to a model constructed in MAD-X including measured normal and skew non-linear multipoles in the IRs. The initial tunes in all cases have been matched to measurements at the start of each series of orbit bumps, the initial coupling in the models were matched to 0 and the trends compared to the observations. Both modelled and measured data are presented in Figs. 9, 10, 11, 12. Evidence of the existence of significant non-linear multipoles is apparent for both IRs. Perhaps the clearest example comes from the Beam 1 coupling measurement during the vertical aperture scan in IP1 (figure 10). A substantial increase in C_-, with corresponding tune shift, is observed with a non-linear dependence on the orbit bump. This is in disagreement with the predictions of our MAD-X model, suggesting the existence perhaps of unidentified skew octupolar multipoles. In IP1 the change in coupling of Beam 2, as predicted from MAD-X, is within the errors. There is however a notable disagreement in the variation of tune with applied trim for both horizontal and vertical orbit bumps (see, e.g., Fig.s 9 and 10).

Considering the aperture measurements performed in IP5: while Beam 1 agrees well under the vertical scan, the remaining three measurements differ substantially. Notably the large increase in the coupling predicted for Beam 2 during the vertical scan was not observed.

The data shown should be further analysed with respect to the model in order to attempt to determine the location and type of any unidentified non-linear multipole errors.

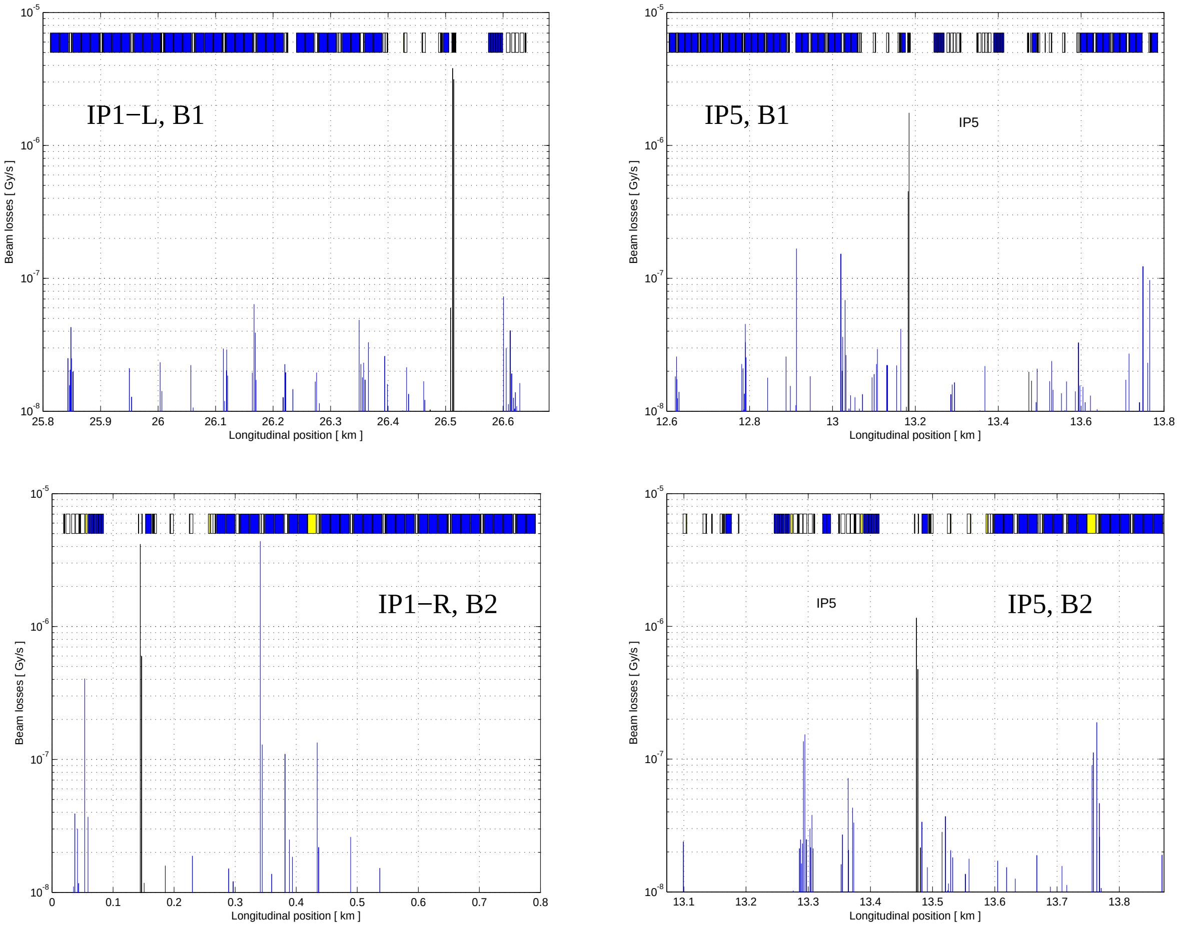

Figure 8: Beam losses in IR1 (left) and IR5 during vertical loss maps for Beam 1 (top graphs) and Beam 2 (bottom). Blue and black lines indicate losses in the cold magnets and in the collimators, respectively. Losses in the Q9.L5 for B2 were not confirmed in later loss maps. Note that this loss maps were performed with low intensities.

6 Conclusions and outlook

The aperture of the triplet region was measured at 3.5 TeV in IR1 and IR5 for the first time. A squeezed optics with $\beta^* = 1.5$ m was used. Both the crossing and the separation planes were tested using local crossing angle bumps added on top of the standard crossing angle and separation bumps to probe the triplet aperture. Only the aperture on the limiting side was measured (no symmetric scans to check both sides of the aperture). The TCTs were used in order to provide a certain level of protection to the triplets and hence minimise the risk of quench. The precise TCT gap measurement was also used for quantitative estimates of the settings required to ensure triplet shielding, which is the key ingredient for ensuring protection and hence defining whether a given value of β^* is acceptable. The results of these measurements had indeed an important impact on the LHC performance.

The preliminary analysis performed so far indicates a triplet aperture of $\approx 18 - 20\,\sigma$, inferred from the retraction of the TCTs that sit at $\approx 12\,\sigma$. These results refer to the optics with $\beta^* = 1.5$ m, half-crossing angle of 120 μrad and parallel separation of ± 0.7 mm. These figures are consistent with previous measurements performed at injection energy within few millimetres. Furthermore, the triplet aperture is compatible with a well-aligned machine, a well centred orbit and a design mechanical aperture. It is worth stressing, though, that only one side of the mechanical aperture was tested

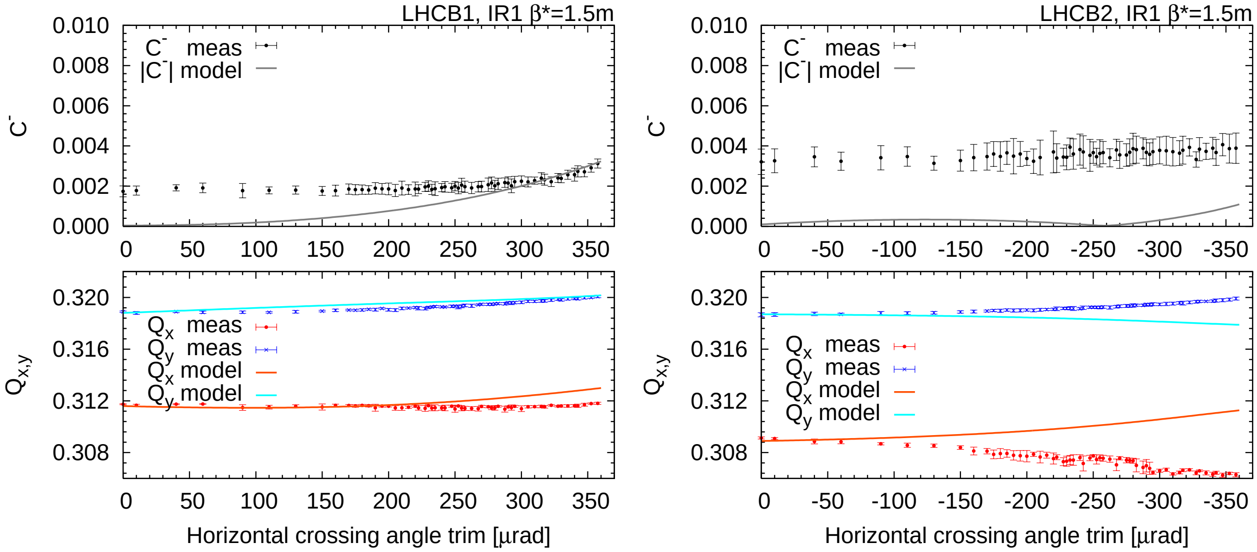

Figure 9: Variation in tune and coupling of Beam 1 and Beam 2 respectively with the applied horizontal “lumi” scan crossing angle trims in IP1.

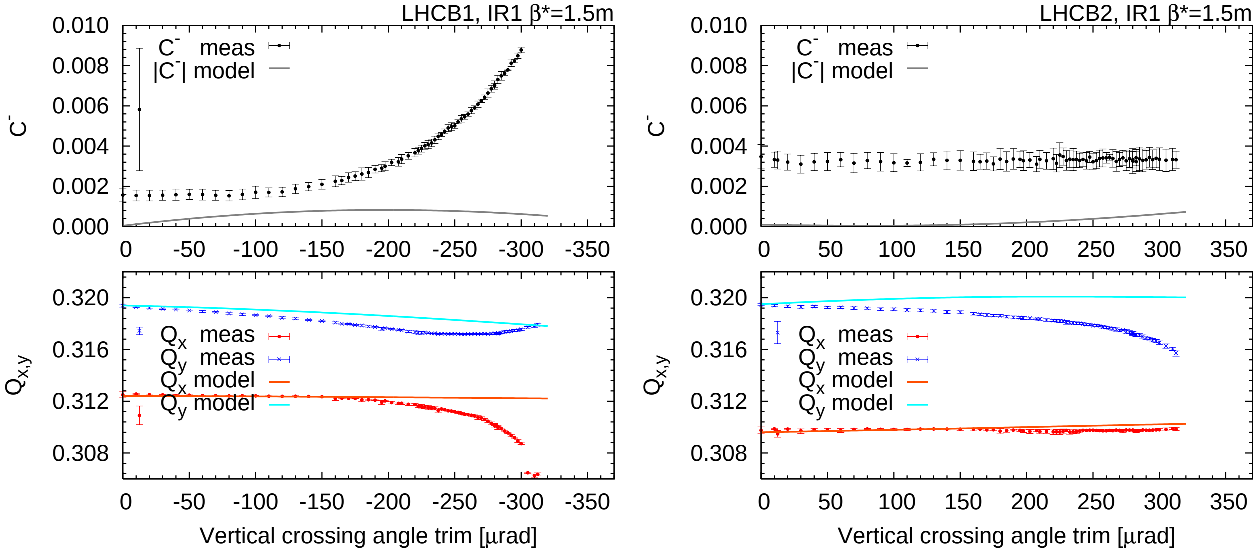

Figure 10: Variation in tune and coupling of Beam 1 and Beam 2 respectively with the applied vertical “lumi” scan crossing angle trims in IP1.

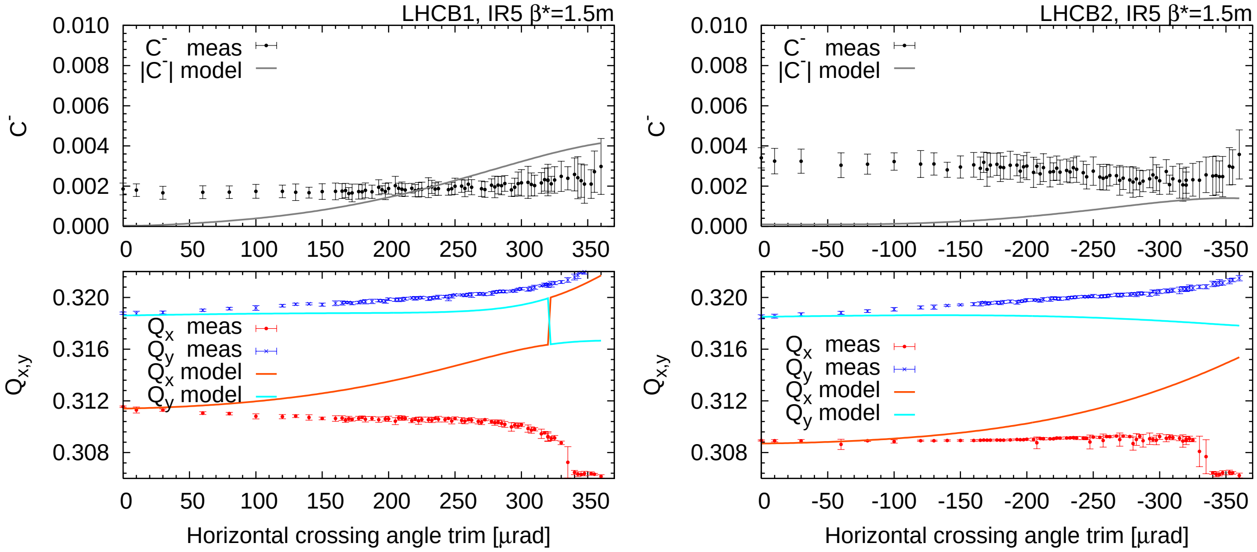

Figure 11: Variation in tune and coupling of Beam 1 and Beam 2 respectively with the applied horizontal “lumi” scan crossing angle trims in IP5.

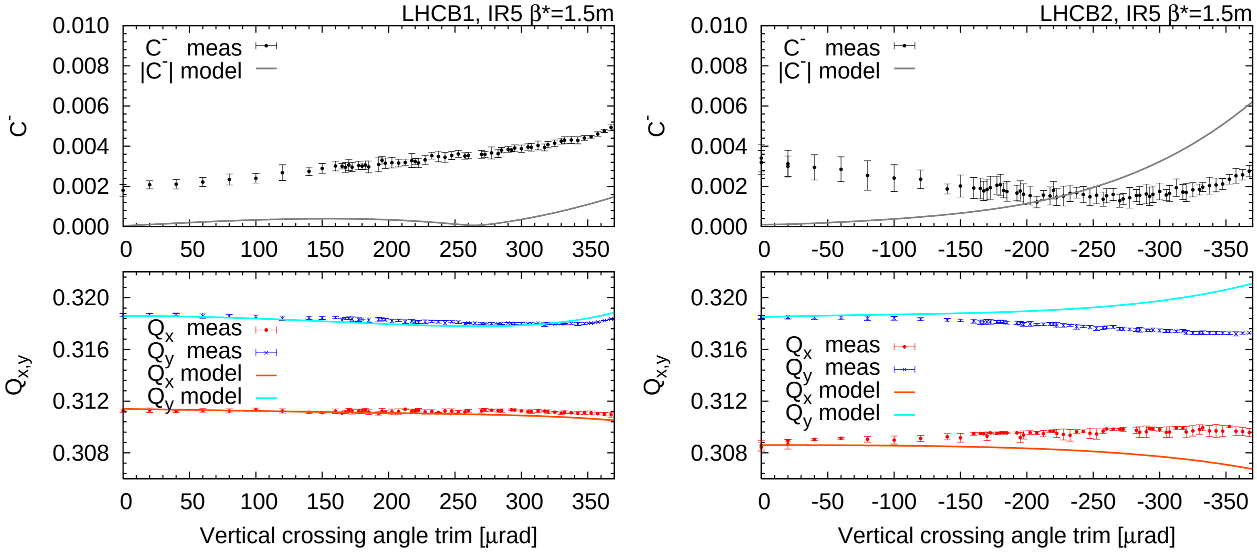

Figure 12: Variation in tune and coupling of Beam 1 and Beam 2 respectively with the applied vertical “lumi” scan crossing angle trims in IP5.

during these measurements: a detailed scan should be scheduled in the future.

Based on these results, the decision was made to operate the LHC at $\beta^* = 1$ m during the period of September and October 2011. The appropriate level of triplet protection was verified with beam by additional aperture measurements and by a complete loss maps campaign carried out at $\beta^* = 1$ m.

The parasitic data-taking of the tune and coupling variation as a function of the bumps used for the aperture measurements proved to be very useful. The good-quality data have be preliminarily analysed and some aspects have been presented in this note. A more detailed analysis will follow.

Acknowledgements

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