APERTURE AND OPTICS – MEASUREMENTS AND CONCLUSIONS

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Abstract

In 2011, the LHC has delivered collisions with different optics configurations in the four interaction points, at an operating energy of 3.5 TeV. The performance has been pushed during the year until a final configuration with 3 IPs squeezed to 1 m was achieved. Correspondingly, the machine aperture has been measured in the different configurations at injection and at top energy, to ensure a safe operation in all conditions of β^* and crossing angle configuration. In this paper, the 2011 commissioning experience of LHC optics is reviewed and the results of aperture measurements are presented. Measurement requirements for 2012 and possible improvements are also discussed.

INTRODUCTION

The performance of the Large Hadron Collider (LHC) depends, amongst others, on the available aperture that determines the reach in terms of smallest β^*, i.e. the β function at the interaction points (IPs). In the LHC, the β^* squeeze is performed at constant flat–top energy when even pilot beams are close to or above the damage limit of metals. Particular care is therefore taken with optics changes and aperture measurements in these conditions. Indeed, until Aug. 2011, the 3.5 TeV aperture was inferred from measurements at injection, and this entailed uncertainties caused by conservative calculations.

The evolution of β^* in 2010 and 2011 is shown as a function of time in Fig. 1. The black and green arrows indicate the dates of aperture measurements at 450 GeV (black) and at 3.5 TeV (green). There is a clear correlation between the measurements and the reductions of β^*. Indeed, we will show that aperture measurements indicated a larger clearance than what was assumed with conservative approaches [1]. This is in particular true for the local measurements in the interaction regions (IRs), which were measured for the first time at top energy in August 2011.

In this paper, the LHC aperture measurements are reviewed. The commissioning experience with optics changes is discussed and the squeeze performance reviewed. The commissioning of lower β^* is 2011 is also presented. Requirements for the measurements in 2012 are discussed and then some conclusions are drawn.

MACHINE CONFIGURATIONS IN 2011

The different machine configurations of 2011 are given in Tab. 1, where the main beam and machine parameters are summarized. Three different optics configurations, i.e.

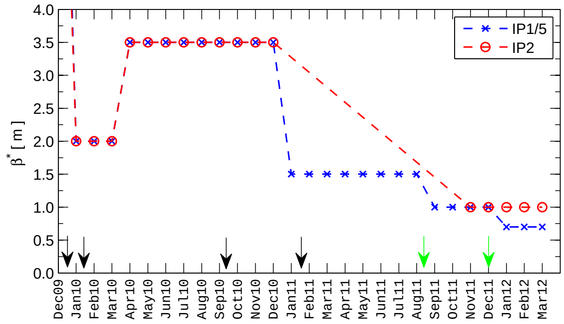

Figure 1: Evolution of the β^* in various IPs for physics production, starting from the initial commissioning in 2010. The vertical arrows indicate qualitatively the times when aperture measurements were performed, at injection energy (black) and at 3.5 TeV (green). 2012 are estimated based on the aperture measurement results [1].

three sets of β^* values in the 4 experimental regions, were used for physics production in standard fills:

1. Feb.–Aug.: first proton physics operation with $\beta^* = 1.5$ m in IP1/5, $\beta^* = 3.0$ m in IP8 and $\beta^* = 10.0$ m in IP2 (injection optics);
2. Sep.–Oct.: proton physics with further squeeze to $\beta^* = 1.0$ m in IP1/5;
3. Nov.–Dec.: ion physics with IP2 also squeezed down to $\beta^* = 1.0$ m without changes in the other IPs.

For all these operational periods, the physics value of β^* in IP8 was kept at 3.0 m even though LHCb did not take data during the ion physics period. The same ramp functions were used for all configurations.

The nominal injection crossing angles of 170 μrad were achieved in all IPs. The crossing angles are changed linearly as a function of time during the first 680 s of the energy ramp to achieve at flat–top their final values for physics. Their set point is indeed kept constant during the squeeze (their shape along the IP changes for the different optics, though). In a similar way, the parallel separation is reduced from ± 2 mm to ± 0.7 mm to achieve at top energy the same separation in sigmas than at injection. The separation bumps are then collapsed at the end of the squeeze to steer the beams into collision. This is achieved with a set of "collision" functions stored in a dedicated beam process. The length of these functions (see Tab. 1) depends on the maximum ramp rate of the RCBX magnets. Longer functions for ion operations were required to accommodate

Table 1: Machine configurations during different running periods in 2011.

Parameter	Injection Feb.–Dec.	Squeeze 1 Feb.–Aug.	Squeeze 2 Sep.–Oct.	Squeeze ions Nov.–Dec.
Beam energy [GeV]	450	3500	3500	3500
β^* in IP1/5 [m]	11.0	1.5	1.0	1.0
β^* in IP2 [m]	10.0	10.0	10.0	1.0
β^* in IP8 [m]	10.0	3.0	3.0	3.0
Half separation [mm]	2.0	0.7	0.7	0.7
Half crossing angle IP1/5 [μrad]	170	120	120	120
Half crossing angle IP2 [μrad]	170	80	80	80
Half crossing angle IP8 [μrad]	170	250	250	250
		Duration of setting functions		
Ramp [s]	1020	1020	1020	1020
Squeeze [s]	–	475	558	1233
Collision [s]	–	56	56	260

Table 2: Number of optics and linear knobs imported with the LHC on–line model in the controls system for the 2011 optics configurations, including special fills and MD tests.

Optics models	Number of optics	Knobs per optics
Protons/ions	90 (30 used)	50
β^*=90m (IP1/5)	18	20
ATS	57	40
TOTAL	165	7140

polarity inversions of the ALICE spectrometer that impose changing the external crossing angle.

It is noted that, in addition to the standard fills for high–intensity proton and ion operation, special fills also took place to provide collisions at 1.38 TeV, to test high β^* optics for TOTEM and ALFA etc. [2]. This paper is focused on the nominal machine configurations. For completeness, the list of required optics and knobs used during the 2011 operation are given in Tab. 2. Many more optics than the ones used for data taking are needed to prepare the settings of intermediate β^* values (see next section). The large number of optics and linear knobs required was handled by dedicated packages developed within the LHC on–line model [3] that proved to be very effective to handle the large amount of information.

APERTURE MEASUREMENTS

Summary of measurement campaigns

The following aperture measurement campaigns were carried out in 2011:

1. Feb. 25$^{\rm th}$:
   Global aperture measurements at injection.

2. Feb. 25$^{\rm th}$ and Feb. 27$^{\rm th}$:
   Local measurements in the triplet magnets of all IPs (crossing planes only) at injection energy;

3. Mar. 10$^{\rm th}$ and Mar. 11$^{\rm th}$:
   Local measurements in the dispersion suppressors of IR7 at injection energy (specific for collimation cleaning studies);

4. Aug. 26$^{\rm th}$ (Fill 2057):
   Local triplet measurements in IP1 and IP5 at 3.5 TeV (separation and crossing planes), with $\beta^* = 1.5$ m;

5. Sep. 4$^{\rm th}$ (Fills 2064 and 2065):
   Local triplet measurements in IP1 and IP5 at 3.5 TeV (separation and crossing planes), with $\beta^* = 1.0$ m;

6. Oct. 29$^{\rm th}$ (Fill 2263) and Nov. 2$^{\rm nd}$ (Fill 2272):
   Local triplet measurements in IP2 at 3.5 TeV (separation and crossing planes), with $\beta^* = 1.0$ m.

The priority given to these measurements is justified by the importance that they have for the machine performance. This is in particular the case for the local aperture measurements in physics conditions, performed for the first time at 3.5 TeV in Aug. 2011. The results obtained enabled indeed a reduction of β^* in IP1/5 from 1.5 m to 1.0 m.

The results of these measurements and of those that took place in previous operational years, including the sector tests in 2008, are summarized in the conference proceedings [4, 5, 6] and internal notes [7, 8]. Details can also be found in various presentations at different LHC meetings [9, 10, 11, 12, 13, 14]. In this paper, we focus on the highlight results. See the references for a more detailed analysis.

Aperture measurements methods

The techniques for global and local aperture measurements at injection energy are presented in [6]. An emittance blowup combined with collimator scans is used to

Table 3: Global aperture at injection energy [6] with the nominal machine configuration with half crossing angles of 170 μm and half parallel separation of 2 mm in all IPs.

	Horizontal [σ]	Vertical [σ]
B1	12.0 (Q6R2)	13.0 (Q4L6)
B2	12.5 (Q5R6)	13.0 (Q4R6)

measure the aperture in units of local beam size at the primary collimators. This method allows one to directly derive the collimator settings to protect the aperture bottlenecks. On the other hand, it is not applicable at higher energies because it requires frequent injections (typically, about more than 20 per measurement plane), which makes it unpractical for measurements above 450 GeV. Blowup techniques based on the transverse damper are under investigation to address this limitation [15].

For local triplet measurements at top energy, the method discussed in [16] was used. Local IP crossing bumps are added on top of the standard crossing and separation schemes to increase the beam offset at the triplets, until the beam touches the magnet beam screen. These bumps are combined with position scans of the tertiary collimators (TCTs) in front of the triplet. From the precise measurements of collimator gaps and jaw positions, it is possible to infer the aperture of the magnet in beam size units [7, 8]. Some uncertainties are introduced by the bump shape, as the measured aperture could be slightly different for a different phase advance between correctors and aperture. Furthermore, the shape of the bump could also displace the location of the aperture bottleneck longitudinally. The aperture margins between collimators and triplet aperture were therefore confirmed by dedicated loss maps[1]. This method for IR measurements had also the advantage that the triplet magnets remain protected by the TCTs during the measurements. This is important because even small pilot beams at 3.5 TeV are above the damage limit of metal.

Global and local measurements at 450 GeV

The results of global and IR aperture (crossing plane only) measurements at injection are reported in Tabs. 3 and 4 for the machine configuration of the first column of Tab. 1. For the global measurements, the limiting magnets is also given whereas for the local IR measurements the bottlenecks were always found at the Q2 triplet magnet as expected. The results presented here are expressed in units of nominal betatron beam size, $\sigma_i = \sqrt{\beta_i \epsilon_i}$ $(i = x, y)$, for a normalized emittance of 3.5 μm[2]. This is a standard notation used at the LHC to define the aperture of machine bottlenecks in a way that is directly applicable to the definition of settings for collimator and protection devices.

[1]Loss maps carried out at β^*=1m with TCTs at 14 σ showed that the triplets remained protected. This proved that with the standard settings of 11.8 σ, a margin of more than 2 σ is ensured between TCTs and triplets.

[2]For the injection measurements the aperture is referred to the opening of the reference primary collimators assuming nominal β functions at these locations. In a similar way, for the local IR measurements at top energy the TCT gaps are used as references.

Table 4: Local aperture in units of sigma measured at the triplet magnets in the crossing planes at injection energy (first column of Tab. 1). The aperture given indicate the margins between the closed–orbit with nominal crossing angles and the triplet aperture.

	Horizontal B1/B2 [σ]	Vertical B1/B2 [σ]
IR1	–	16.0 / 16.0
IR2	–	14.5 / 16.5
IR5	15.0 / 17.5	–
IR8	15.5 / 15.5	–

The measurements of Tab. 3 are performed starting from the nominal machine configuration at 450 GeV. The global bottlenecks are better by a few sigmas than what was expected in the LHC design phase [17]. This is an important milestone because it indicates that there will be no aperture problem at injection, independently of the bunch spacing. Also note that the measurements indicated a few bottlenecks localized in the IR rather than many distributed bottlenecks around the ring, as it could be expected from the pessimistic estimate based on n_1 calculations [18]. This aspect might have some impact on LHC machine protection strategy, as it cannot be assumed anymore that in case of very fast losses the IRs are in the shadow of the arcs.

On the other hand, it is important to note that the global aperture was better by 1 σ in 2010. The source for this reduction of aperture could not be identified but could be caused by different sources (magnet alignment, differences n orbit references, etc.). It is therefore important to continue monitoring the available aperture to make sure that this good condition is maintained year after year.

It is also noted that in 2011 only the on–momentum aperture was measured. The off–momentum aperture was only partly measured in 2010 for B1, with indication of losses by 1.0–1.5 σ with respect to on–momentum measurements. The importance of the measurement with off–momentum has been lessened by the experience that chromaticity measurements are never carried out with unsafe beams in the machine. The budget for orbit shifts when the beam energy is changed, which have a significant impact on the n_1 calculation, can be reduced from the initial expectations.

The triplet aperture measurements summarized in Tab. 4 are achieved with the blowup method by adding to the nominal closed–orbit and additional crossing angle to “expose” the triplet aperture that otherwise would remain in the shadow of the global bottlenecks of Tab. 3. The results given are affected by the shape of the additional crossing bump (nominal crossing bump in this case).

Table 5: Triplet aperture at 3.5 TeV and $\beta^* = 1.5$ m measured with local bumps. The results are inferred from the TCT collimator gaps in the condition when the triplet aperture is closer to the beam than the TCT jaws. The accuracy is determined by the used step size of TCT gaps, i.e. 0.5 σ.

IR	Plane	Type of bump in standard optics	Aperture $[\sigma]$
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

Table 6: Triplet aperture at 3.5 TeV and $\beta^* = 1.0$ m measured with local bumps in IP2. The results are inferred from the TCT collimator gaps in the condition when the triplet aperture is closer to the beam than the TCT jaws. The accuracy is determined by the used step size of TCT gaps, i.e. 0.5 σ.

Crossing angle $[\mu$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	$15.0 - 15.5$

Local IR measurements at 3.5 TeV

The results of local IR aperture measurements performed at 3.5 TeV in IP1/5 and IP2 are summarized in Tabs. 5 and 6, respectively. In IP1/5, the measurements were carried out at $\beta^* = 1.5$ m whereas in IP2 the value of 1.0 m was used. The results in unit of nominal beam size for a normalized beam emittance of 3.5 μm are given, leaving the detailed comparisons with the mechanical aperture in millimeters to other published notes [7, 8]. Note that the results in sigma units of Tab. 5 are obviously not comparable to the ones of Tab. 4 because they refer to a different machine configuration in terms of optics and orbit position at the IR. In [7, 8] attempts are made to calculate the aperture in millimeters and to compare it to the nominal mechanical aperture and to the results of injection measurements [11]. In general, a good agreement is found within the accuracy of the measurement techniques.

Unlike for the injection measurements where only the crossing planes were measured, measurements at 3.5 TeV were performed systematically in both transverse planes to determine the β^* reach that could be limited by the separation plane at the end of the squeeze before the beams are put in collision. For the case of IR2, there was also a specific request by ALICE to determine the largest possible external crossing angle to compensate the spectrometer angle at 1.0 m for both polarities [8]. This explains why measurements were carried out for both polarities (Tab. 6) and not only on the limiting side.

SQUEEZE AND OPTICS PERFORMANCE

Brief recap. of squeeze mechanics

The squeeze is achieved by driving the matching section quadrupoles to currents that produce a specified β^* value. Each IR can be treated independently, even though IP1 and IP5 are always squeezed to the same values. Appropriate sets of magnet strengths, established by the LHC optics team, are imported into the LHC controls system and then used to determine the required current in each power converter to achieve the desired fields. One cannot move in one single step from the initial injection optics to the final β^* value because the transient errors would be too large. A set of intermediate “matched” optics is required to keep transient errors of the key parameters like tune, chromaticity, orbit and beta–beating, at tolerable levels. Linear interpolations versus time with gentle round–offs of the normalized magnet strengths are used between matched points. Stopping at matched points is made possible by forcing zero derivative and acceleration of the current functions, dI/dt and d^2I/dt^2, of each converter involved in the squeeze. The procedure of stopping at intermediate optics is only done during commissioning until the setting functions are properly tuned to achieve a continuous run through the settings functions without interruption. Various aspects of the squeeze mechanics are presented in [19].

Squeeze improvements from 2010

The β^* values in all IPs as a function of time during the squeeze are given in Fig. 2. For proton physics runs, the duration of the squeeze down to 1.5 m and 1.0 m in IP1 and IP5 took 475 s and 548 s, respectively (IP1 and IP5 squeeze in parallel). IP8 could be squeezed to 3 m in the shadow. The squeeze in IP2 for ion physics was instead added in series and was performed once the other 3 IPs already reached their final optics. These additional functions took 771 s. A typical example of β^* evolution in an ion fill is given in Fig. 3. Note that since September, the squeeze in IP1 and IP5 has also been done with two separated sets of functions played one after the other. This implementation was considered optimum for incorporating into the standard operation the further squeeze down to 1 m (73 s), without changing the previous setting functions to 1.5 m validated for high–intensity operation.

The squeeze duration is the result of an optimization of the setting functions based on the operational experience accumulated in 2010. The squeeze down to 2 m in all IPs took 1280 s in 2010, i. e. 2.3 times longer than the one down to 1 m in 2011. The settings for the first year of operation were prepared taking into account all the available intermediate “matched” optics to minimize the transient errors during the squeeze. After the good experience with the

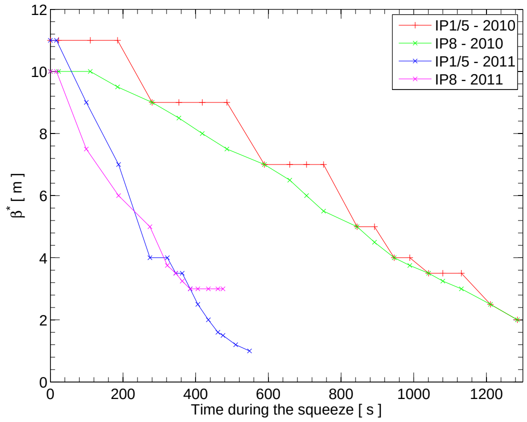

Figure 2: β^* functions versus time during the squeeze in IP1/5/8 in 2010 and 2011. In 2010, IP2 was squeezed in parallel to the other 3 IPs whereas in 2011 it was done with other IPs at the final optics, for an additional time of 771 s (ion operation only).

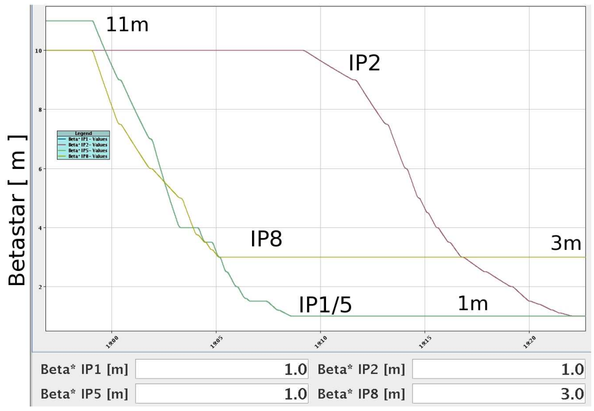

Figure 3: β^* from the on-line viewer during a typical squeeze in ion operation. The squeeze to 1 m in IP2 follows the squeeze in the other IPs. The first part of the squeeze in IP1/5/8 was untouched with respect to the proton operation.

handling of the squeeze with high intensities, the duration was optimized by reducing the number of intermediate optics. Reducing the number of optics gives faster setting functions because one avoids the round–off conditions for the magnet current functions. Tools were developed within the LHC on–line model [3] to calculate transient errors for a given set of setting functions. These calculations were used to ensure that the optimization procedure was respecting reasonable thresholds for the transient errors during the squeeze. A detailed report of this work and the results from the operational experience until August 2011 can be found in [20, 21, 22, 23].

Squeeze performance highlights

The intensity transmission during the squeeze of some 30 high intensity proton fills in 2011 is shown if Fig. 4. The transmission is calculated as the fractional ratio between initial and final total beam current measured by the

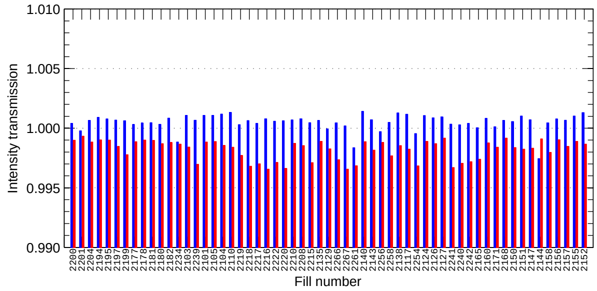

Figure 4: Intensity transmission during the squeeze of about 30 physics fills, calculated as the relative difference between initial and final beam currents measured with the fast beam current transformers.

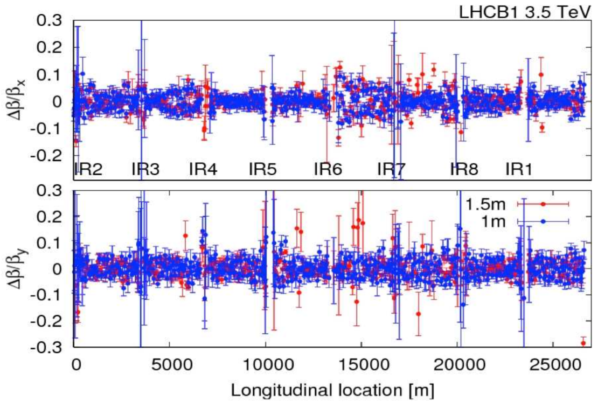

Figure 5: Beta-beating error around the ring at $\beta^* = 1.5$ m and $\beta^* = 1.0$ m. Note that an optics correction was applied at $\beta^* = 1.5$ m but no further corrections were required at $\beta^* = 1.0$ m.

fast beam current transformers (FBCT). The total losses are typically below the 0.5 % level. This indicates that the squeeze is under very good control. Beam 1 is systematically better. There are so far no indications that this performance depends on the single–bunch or total beam intensity.

A detailed presentation of the optics measurement and of the β corrections is beyond the scope of this paper. We just recall that the LHC optics can be corrected to levels below a beta–beating of 10–15 %, which is a remarkable achievement [24]. As an example, the beta–beating around the ring is shown in Fig. 5 for the optics of the running conditions “Squeeze 1” and “Squeeze 2” in Tab. 1 which are the most relevant for high intensity proton operation. It is interesting to note that no additional optics corrections were required after the β^* reduction to 1.0 m to maintain the same optics quality compared to the nominal model.

An important part of the optics corrections is the compensation of local sources of coupling originated in the triplet magnets. The RQSX magnets are used for this purpose. Minimizing this contribution is important for the operation of the machine because otherwise the coupling would have to be corrected with the global coupling knobs

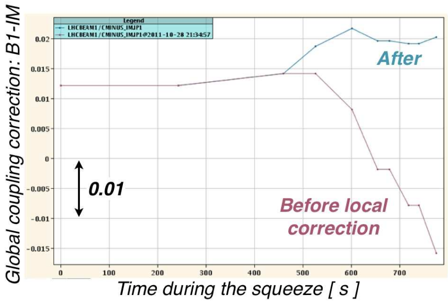

Figure 6: Global coupling corrections during the squeeze before (blue) and after (violet) the local correction of the triplet coupling.

that are not built for correcting local coupling sources. Coupling corrections during the squeeze commissioning were indeed a tedious and time-consuming procedure that in 2011 took a significant fraction of the squeeze commissioning time. The global knobs ended up working close to the hardware limits to maintain the errors under control. In practice, this made it very difficult to prepare settings functions that could be accepted by the power converters and *de facto* limited the coupling correction that could be achieved. Figure 6 shows how the global coupling knob strengths are reduced after the local triplet corrections are put in place. Typically, corrections were reduced to values that remained close to the set point at the squeeze start (first point of Fig. 6) within about 0.005.

For the operational efficiency, it is important to maintain the squeeze duration to a minimum and to optimize the turnaround. The distribution of squeeze durations achieved in 2011 is given in Fig. 7 (red histograms) and compared to the best fills of 2010 (blue) [25]. The improvement is apparent and comes, amongst others, from:

- Reduction by a factor 2.3 of the setting functions (for even smaller β^*);
- Removed manual orbit reference changes, which required stopping at intermediate points in 2010;
- Function–based operation of the collimators, which were moved in discrete steps in 2010;
- Handling of setting management for the different system (RF, ADT, setting incorporation, regeneration of actual settings, ...) by automated operational sequences;
- automated handling of tune feedback references.

It is important to mention that the squeeze at the LHC relies on the good performance of tune and orbit feedbacks [26], which are kept ON all the time during the squeeze. On the other hand, the operational robustness profits from regular feed–forward optimization that maintain the required corrections from the feedbacks to a minimum. These corrections have been monitored and feed–forwarded into the tune corrector settings when required. Indeed, thanks to

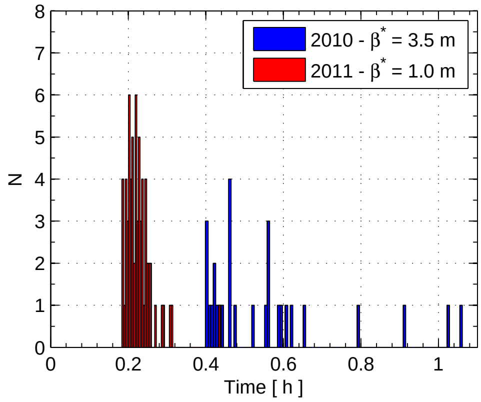

Figure 7: Distribution of squeeze duration in 2010 (blue) and in 2011 (red). Even though the squeeze was pushed down to a β^* value 3.5 times smaller, the overall duration was less than half compared to 2010.

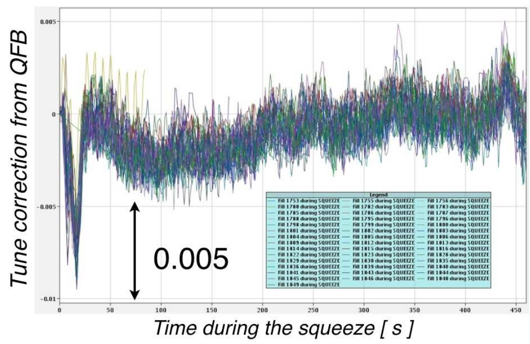

Figure 8: Corrections from the tune feedback applied for about 30 fills in 2011. The initial "bump" is caused by a mismatch between the duration of the tune change from injection to collision values and the length of the QFB settings functions.

the remarkable stability of the machine (see an example in Fig. 8), it turned out that just 2–3 iterations were sufficient in the whole year. An example of feed–forward correction the reduces the work of the tune feedback is given in Fig. 9.

β^* reach and commissioning to 1 m

The results of triplet aperture measurements in IP1 and IP5 at 3.5 TeV (Tab. 5) indicated larger margins than what had been calculated based on extrapolations from injection measurements [27]: 18–20 σ instead than the assumed 14 σ. The reason for this discrepancy was found to be the use of additional error tolerances for orbit and beta–beating, which turned out to be unnecessary, as well as the use of an overly pessimistic aperture in the separation plane, since no local measurements had been done[1].

Even within the measurement uncertainty, e.g.from the detailed shape of the bumps, it was clear that these margins could be used to push the β^* performance of the LHC. If one assumes that (1) the same orbit stability in the IRs could be achieved with smaller β^* values, (2) the same

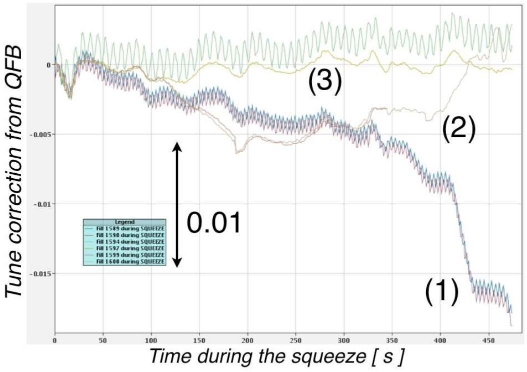

Figure 9: Example of feed–forward tune correction for the squeeze to 1.5 m in IP1/5. Two iterations were sufficient to converge to corrections of a few 0.001 (3).

crossing angle value of 120 μrad is sufficient to avoid detrimental effects of long–range beam–beam encounters, (3) the β–beating can be corrected to similar level as at 1.5 m, then one can simply rescale the β^* reach starting with the following formula (obtained by equalizing the mechanical aperture at the triplet for $\beta^* = 1.5$m and for the new β^*):

$$n_\sigma^{\rm new}\sigma^{\rm new} - \Delta_i = n_\sigma^{1.5\rm m}\sigma^{1.5\rm m},$$

where the betatron beam size is calculated at the limiting aperture location. The values of $n_\sigma^{1.5\rm m}$ are the ones listed in Tab. 5 and Δ_i represent the orbit shift in the planes $i = x, y$ due to the change of crossing bump shape for the new β^* value. For example, assuming a minimum n_σ of 18 for the various IPs/planes, one can achieve a β^* of 1.0 m while keeping the same margin of 14σ to the triplet aperture that was adopted with the previous assumptions. Indeed, this configuration was preliminary tested by loss maps with pilot beams immediately after the first aperture measurements on August 26$^{\rm th}$.

Clearly, more detailed studies were scheduled before proposing a change of β^* in the middle of the run. In particular, profiting from the start-up after a technical stop at the end of August, the following commissioning steps were carried out [28]: (1) verify that orbit and beta–beat (see Fig. 5) at 1.0 m were comparable with those at 1.5 m; (2) prove that beam–beam separation with 120 μrad is appropriate at 1.0 m for 50 ns spacing; (3) confirm the good aperture with direct measurements at 1.0 m; (4) verify that the triplets are not exposed with TCTs at 14 σ, i.e. with 2 σ more opening than the nominal gaps; (5) verify that the loss maps with high–intensity bunches are appropriate with TCTs at 11.8 σ, after new beam–based alignment of these collimators. All these tests were successful and were then confirmed by the subsequent commissioning of higher intensities up to 1380 bunches [29].

Some outstanding issues

In Figure 10 the orbit measured in the vicinity of the primary collimators in IR7 is given during the squeeze in IP1/5/8. One can see transient orbit drifts close to the times

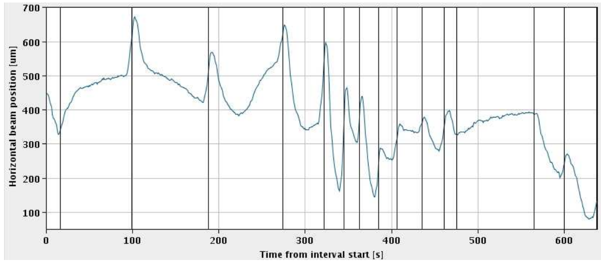

Figure 10: Horizontal orbit versus time during the squeeze in IP1/5/8. The measurement is taken in the vicinity of a primary collimator of the betatron cleaning insertion (IR7). Vertical lines indicate the times of the matched points.

of the matched points (vertical black lines). These orbit patterns are very reproducible and induced a RMS orbit error up to more than 100 μm. The time scale was too fast for being corrected by the orbit feedback with the standard settings used for proton operation. This issue did not cause problems with the collimators at 5.7 σ but it must be addressed for the operation with tight collimator settings in 2012 [1]. Details and proposals to improve the orbit stability were discussed in a dedicated LBOC meeting [30].

The squeeze mechanics and the settings generation is under good control. On the other hand, two areas of improvements were identified: (1) the inductance of slow single–quadrant quadrupoles Q4, Q5 and Q6 is not taken into account properly (overestimated for low currents) with the result that the functions generated for power converters are too fast for the magnets to follow. This was revealed by trips that occurred during dry–runs. The problem is solved by stretching the duration of the setting functions. (2) The round-off of current settings at the matched points is not enforced for tune, chromaticity and coupling knobs nor for orbit correctors. This can cause trips when starting/stopping the function execution.

2012 MEASUREMENT REQUIREMENTS

Having seen the importance of aperture measurements for the LHC performance, we propose that in 2012 the aperture measurements should be carried out for all the relevant operational configurations. In particular, we will request to (1) measure the global aperture with nominal machine configuration at injection; (2) local IR aperture in IP1/2/5 for the final β^* value for physics. In particular, (2) should be performed for both polarities of crossing and separation schemes in order to avoid the uncertainty entailed by one–sided measurements. We suggest to perform the measurement for the smaller β^* value foreseen (presently, the optics commissioning at various intermediate values below 1 m is foreseen). We see no need to repeat the detailed aperture measurements in the dispersion suppressors of IR7. On the other hand, if time permits, we should measure the off–momentum aperture for both beams.

In order to commission the optics down to a β^* of 0.6 m optics measurements should be performed for the bare machine throughout the entire LHC cycle, from injection to the end of the squeeze. The bare machine should not include any corrections. This request is motivated by the difficulties experienced during the optics correction in the ATS MD at a β^* =0.4m [31]. It has been observed that the local errors considerably change between 1 m and 0.4 m. Therefore computing dedicated local corrections for the different β^* values in 2012 is mandatory. Global corrections should be applied only after having implemented and verified the local corrections.

CONCLUSIONS

The LHC aperture and optics configurations in 2011 have been presented. In both respects, the performance of the LHC is outstanding: the aperture measurements indicate aperture compatible with a well aligned machine, with small manufacturing tolerance and with a well centred beam orbit. The optics is correctable well to the model, with beta–beating errors below 15 %. In 2011, the aperture was measured for the first time at top energy with squeezed beams. This measurement allowed to push the β^* from 1.5 m to 1.0 m, with an important impact on the integrated luminosity performance. The results also provide a solid basis for future beam–based β^* reach estimates. This demonstrated that it is crucial to measure precisely the aperture in the conditions for physics (reference orbit, final optics, etc.) in order to push the β^* reach to the limit. These measurements shall be repeated in the future with high priority and in particular after long LHC technical stops. A proposal for measurements in 2012 has been outlined to ensure a good performance in 2012, when the β^* will be pushed further down.

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