BETATRON SQUEEZE: STATUS, STRATEGY AND ISSUES

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Abstract

The betatron squeeze will be one of the most critical manipulation of the LHC beams and has required dedicate implementations in the LHC control system. At the end of the 2009 operation, a squeeze test with beam was performed at 1.18 TeV to verify the mechanics of the squeeze and the developed tools. This also gave the opportunity to have a first set of measurements with squeezed beams. In this paper, we review the status of the squeeze implementation, with particular emphasis on the issues for the 2010 operation, and we present the results of beam measurements.

INTRODUCTION

During the 2009 LHC beam commissioning, a first attempt of betatron squeeze at 1.18 TeV was made. This beam test was not carried out in ideal conditions because the machine had not been properly optimized at high energy and the test was "squeezed" in a slot of a few hours before the machine shut down. On the other hand, the test was very useful because it provided for the first time a validation of tools and procedures developed to handle this critical phase. In addition, it was very encouraging to see that the measured β^* values after squeeze were in very good agreement with the expectations. In this paper, the results of this test and the issues for the 2010 operation are discussed. In the next session, the status of the squeeze implementation in the control system is presented. Then, the requirements for the 2010 operation are reviewed. Finally, the results of beam tests are presented. Each session contains a list of issues that need to be addressed for the 2010 operation.

STATUS OF SQUEEZE IMPLEMENTATION

Software implementation

The setting functions of the magnets that are used for the squeeze, are calculated starting from strength files provided by the accelerator physics team [1]. A number of so-called *matched optics* is provided between the maximum and the minimum β^* values of the different interaction points (IPs). In these points, the basic beam parameters such as tune, chromaticity, β-beat, etc. are well defined and matched to the desired values whereas between matched points, errors can occur. The number of matched optics is chosen to

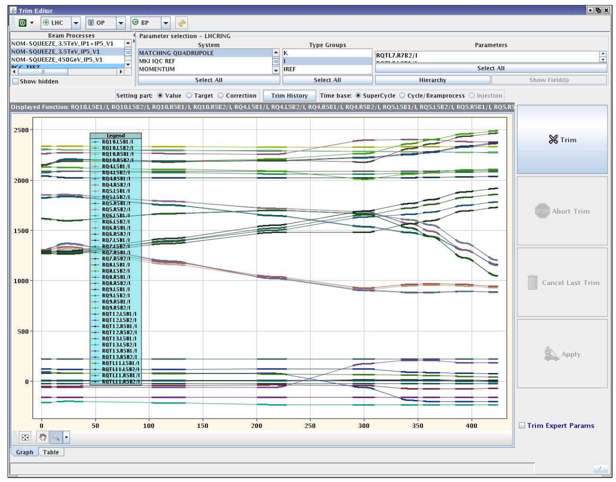

Figure 1: Example of current settings for the IP5 matching quadrupoles as generated for a 3.5 TeV squeeze to β^*=2 m. We step through 9 matched optics (13 are available for β^*=0.55 m), including the tune change at constant injection β^*=11 m. The full functions, or pieces of functions between any pair of matched points can also be sent separately.

maintain the errors to a minimum level [2]. Thirteen optics are available for the betatron squeeze in points 1 and 5 for the transition between the injection optics with β^*=11 m and the nominal 7 TeV value of β^*= 0.55m and 20 for the squeeze from 10 m to 2 m in IP2 and IP8.

The magnet strengths for each matched optics are imported into dedicated optics tables in the LSA (LHC Software Application) database and are used to calculate the power converter current settings. The transfer functions are established with the latest implementation of the FiDeL model [3]. The functions of currents versus time are then computed with a linear interpolation and gentle round-offs by using the power converter parameters established during hardware commissioning. Functions are generated with the constrain that current ramp rate and acceleration should equal zero at the matched points. The length of the squeeze is determined by the slowest magnets, typically the monopolar Q4 magnets. An example of the setting functions of the matching quadrupoles of IP5 for a betatron squeeze to β^*=2 m at 3.5 TeV is given in Fig. 1. Functions for driving collimators for cleaning and machine protection are generated in a similar way. No changes for the RF are foreseen during the squeeze.

Settings in LSA are organized in so called *beam pro-*

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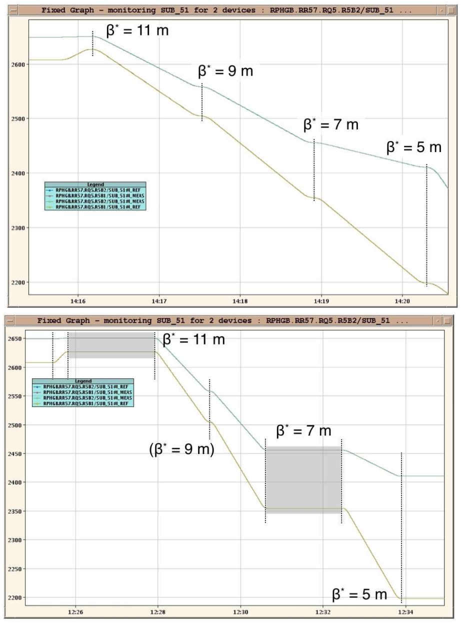

Figure 2: Measured Q5 currents during a squeeze test at 5 TeV without beam (1) with continuous run through the matched points (top) and (2) with stop at the intermediate β^* values of 11 m (after tune change) and 7 m (bottom).

cesses (BPs). Functional BPs are associated to machine contexts with a well defined time length, typically ramp and squeeze, when systems like power converters, collimators and RF are driven synchronously. "Actual" BPs are associated to machine contexts with un-defined length such as injection and flat-top *plateaux*, physics store, etc. Actual BPs are generated from functional BPs by taking snapshots of the settings at defined times. For example, the injection settings correspond to the initial point of the ramp functions. Actual settings can be trimmed as discrete parameters, without explicit time dependence. The squeeze beam processes required a special implementation to allow stopping and trimming at intermediate β^* values.

Stopping points in squeeze functions

The function settings of a beam process are normally loaded into the hardware and triggered simultaneously by hardware timing events to ensure synchronicity across the ring for different systems. The constrain of having null current rate and acceleration at the matched points allows one to stop and re-start the execution of functions at intermediate β^* values (it would not be possible to stop/start instantaneously the converter with large rates). This functionality is required during commissioning to optimize the machine at every intermediate β^* optics and to build optimized functions that can be run through without interruption. It is noted that this implementation is available for all the LSA settings and is not system-specific.

The possibility of stopping at intermediate points in the function is achieved with a new implementation in LSA, deployed in 2009, that allows sending to the hardware pieces of the functions between any pair of matched points [4]. After executing the desired function piece, one can stop at the final current levels as long as it is needed to tune the machine and then continue with the rest of the function. This is illustrated in Fig. 2, where the currents measured during a squeeze test without beam are given for a case without (top) and with (bottom) stopping points.

In order to establish reference function settings optimized for all β^* values, trims are performed at the stopping points and the new settings are incorporated back into the original functions. This requires preparing one actual beam process for each foreseen intermediate point and the appropriate incorporation rules for the different parameters.

Issues for the 2010 operation

As it will be shown in the section dedicated to the beam test results, the squeeze implementation is well advanced and provides the required functionality. The following items should be addressed to improve the implementation in preparation for the 2010 operation.

- The *betatron squeeze factor* is not yet implemented in the Safe Machine Parameter (SMP) system. This is supposed to distribute in a safe manner the information on the β^* values in the various points such as to allow one to define β^*-dependent limit functions for the collimators. The corresponding implementations in LSA (and in the front-ends) will follow the implementation in the SMP system, foreseen for after the 2010 operation.

- LSA does not offer yet the possibility of trimming properly the setting functions at intermediate times between matched points. The smoothing routines that build the gentle round-offs are available only at generation and for trims on the matched points (the latter implementation is under test). In appendix, a proposal is made for computing the β^* factor from the magnet current measurements.

- The preparation of actual beam processes at stopping points and their incorporation have to be optimized - ideally with dedicated sequencer tasks - because for the moment it is manual and hence tedious and error-prone.

- The present implementation of the management of critical settings does not work with stopping points. This is needed to handle critical limit functions for collimator and protection devices.

- The information on the times of optics changes during the squeeze should be distributed for other systems, notably for the orbit feedback system.

- Appropriate incorporation rules should be defined to make sure that after trims at stopping points, the functions are still sufficiently smooth at the matched points.

REQUIREMENTS FOR THE 2010 OPERATION

β^* in the different interaction points

The optics requirements for the 3.5 TeV operation of 2010 [5] are listed in Tab. 1, where the minimum β^* values are given for each interaction point. Note that at 3.5 TeV the optics in IP2 and IP8 do not require the pre-squeeze that overcomes the limitation of the triplet gradient at 7 TeV [5]. The crossing angle requirements for the various commissioning phases are discussed in details [6] so they are not addresses in this paper. Crossing and separation schemes are computed as "knobs" for each optics and are imported in the control system in such a way that they can simply be set to the desired values.

As discussed in the previous section, the settings for each squeeze context are stored in LSA beam processes. The requirements of Tab. 1 translate into the following beam process generation needs (in addition to the ramp BP with injection optics):

- four BPs for squeezing one IP at a time (required for commissioning);
- one BP with IP1 and IP5 squeezed together to $\beta^*_{\rm min}$
- one BP with IP2 squeezed on top of IP1/5 at $\beta^*_{\rm min}$ and another with IP8 on top of IP1, 2 and 5 squeezed;
- one BP with IP8 squeezed on top of IP1/5 at $\beta^*_{\rm min}$ and another with IP2 on top of IP1, 5 and 8 squeezed;
- one BP for the un-squeeze in IP5 required by TOTEM.

For the early commissioning phase, IP2 and IP8 will not be squeezed together with IP1 and IP5 but only after the minimum β^* value is reached in both high-luminosity points. The establishment of settings for the global chromaticity correction requires additional BPs with respect to the ones with IP2 and IP8 squeezed individually. This explains the items 3 and 4 in the list above.

All together, we have to generate and maintain a dozen of beam processes each of which needs settings for all the magnets, RF and movable devices as well as knobs for tune, chromaticity, separation and crossing, parallel separation and angle in each IP, etc. Taking into account that one BP can require from 1 to more than 50 different optics (case 4 in the above list), this clearly requires a significant amount of careful work. The generation of all the knobs has been highly automated by using the MADX on-line application, which also offers a variety of tools to verify the settings imported into LSA by performing MADX calculations taking as an input the LSA settings. A detailed presentation of these tools is beyond the scope of this paper.

Updated commissioning procedures

The commissioning procedure for the betatron squeeze at 7 TeV [7] foresaw the following conservative strategy to achieve the required β^* values in all IPs, with priority given to the high-luminosity points IP1 and IP5:

Table 1: Optics requirements for minimum β^* values in the various IPs needed for the 2010 run at 3.5 TeV. The injection β^* values are also listed as a reference. No pre-squeeze is needed for IP2 and IP8 at 3.5 TeV.

Interaction point	$\beta^*_{\rm inj}$	$\beta^*_{\rm min}$
IP1 / IP5	11 m	2 m
IP2	10 m	3 m
IP8	10 m	2 m
IP5-TOTEM	11 m	90 m

1. Start with a single pilot beam 1 and squeeze IP1 without separation.
2. Verify squeeze of one beam with parallel separation.
3. Squeeze two separated pilot beams in IP1.
4. Squeeze IP5 with a single pilot beam 1 simultaneously with IP1 squeeze - try with separation ON.
5. Two beams in IP5 as well (IP1 squeezed in parallel).
6. Squeeze of IP8 follows (1), (2) and (3); then squeeze IP8 in parallel with IP1 and IP5. Similar approach for IP2, if squeeze is needed.

Having seen the remarkable quality of the LHC optics and beams, it was decided to establish and follow a shorter procedure for the 1.18 TeV beam tests:

1. Beam tests were done with two beams in the machine;
2. Multi-bunches were used (4-on-4 for a total beam intensity $I_{\rm tot}$ = 1-2 $\times$ 10^{10}p);
3. One squeeze step was done for IP1 and IP5 together at the first try;
4. Tests done with colliding beams (no separation, no crossing);

It is proposed here to update the commissioning procedures to take into account items (1) and (3): the commissioning can start with two beams in the machine and IP1 and IP5 can be squeezed together. This will shorten the commissioning time, which is particularly important after having realized the long recovery time needed after energy ramps [8]. The previous conservative strategy will be kept as a fall-back solution in case of problems with small β^* values.

Concerning item (4), the beam tests were carried out without separation and crossing because these schemes were not yet commissioned at 1.18 TeV. This shall not be the case for the 3.5 TeV: the commissioning in 2010 should be done with separation (and crossing depending on the number of bunches) active and dedicated time should be envisaged to address the closure of separation bumps with squeezed beams.

Note that the choice of using pilot beams at 7 TeV is imposed by the assumption that no beams are safe at this energy. The 4-on-4 bunch configuration for the 1.18 TeV beam tests was a factor 10 to 20 below the limit for safe beams [9] and hence was preferred because it insured higher precision measurements. The choice of beam intensities for the 3.5 TeV commissioning essentially depends on constraints from machine protection, which will impose to start with pilot beams. We should move as soon as possible to safe but higher intensities (e.g., $1 - 2 \times 10^{10}$ p) to ensure high precision in the measurements, sufficient margin in case of beam losses and improved reproducibility. One single bunch per beam is the preferred solution.

Protection settings and feedbacks

Procedure aspects that were not addresses systematically during the limited 2009 commissioning experience are the operations of feedbacks (orbit, tune and chromaticity), of the Landau octupoles and of the collimator settings. Preliminary tests were only performed for the tune feedback. In absence of new inputs from beam experience, the baseline established in [7] remains the reference for commissioning. These aspects are not reviewed here.

New estimates of the n_1 parameter for the 3.5 TeV running scenarios of 2010 [11, 12] indicate that the triplet magnets will be in the shade of the arcs for β^* values above approximately 6 m. Below this value, cleaning and protection collimators will have to be moved during the squeeze to protect the triplet, as foreseen in the present procedure [10]. This will be done by time-functions for the jaw position settings. The commissioning with stopping points is also foreseen for the collimators that can use the same implementation described in the previous section for the power converters. The safety of the system will be improved with definition of β^*-dependent limit functions, which will be implemented as soon as the betatron squeeze factor will be available in the SMP system.

Issues for 2010

The optics are all available with the exception of IP2, which requires tuning to modify the version with pre-squeeze prepared for 7 TeV. The generation of squeeze settings has been well debugged in the last years and the required beam processes for individual IPs have been generated. Settings have been tested extensively with the power converters in simulations mode and, when possible, also with the real circuits (with the exception of IP2). All together, there is no known issue in terms of optics import and setting generation but the amount of careful work for the preparation of all the required squeeze beam processes should not be underestimated. This work is ongoing, in collaboration with the FiDeL team who verifies the settings generated against the magnetic models [3]. The TOTEM 90 m optics are available but were not yet imported into LSA. They will be tested with priority that depends on the confirmation of the TOTEM special runs in 2010.

The commissioning procedures should be updated to take into account the proposals of the previous section. In addition, we should include more explicitly details on the handling of function pieces, on the trim of actual settings at intermediate points and on the incorporation requirement. Details of these procedures only became clear after the detailed implementation, which was not available when the first version of the procedures was compiled.

RESULTS OF BEAM TESTS

Parameters, beam conditions and safety aspects

The beam tests were carried out at 1.18 TeV with betatron squeeze in IP5 only. The values of β^* in IP1 and IP5 and of the tunes are given as a function of time in Tab. 2. Examples of magnet currents versus time as generated by LSA are given in Fig. 3. The first step of the squeeze provides the tune change from the injection values (Q_x=0.28, Q_y=0.31) to the collision values (0.31, 0.32). This is achieved by changing simultaneously the phase advances in IP1 and IP5 at constant β^* =11 m. The following steps are performed at constant phase advance in all IPs. In our test, only IP5 magnets and chromaticity correction circuits were used.

An LSA beam process was prepared for a $\beta^*_{\rm min}$=5 m but we actually stopped at 7 m. Two squeeze steps were performed during the beam tests:

(1) tune change using IP1 and IP5 and step from 11 m to 9 m in IP5 (times 0 s to 104 s of Tab. 2);

(2) step from 9 m to 7 m in IP5 (times 104 s to 190 s).

After the first step, we stopped for the necessary time to measure the optics of both beams and then to establish the setting incorporation and to prepare the next squeeze step. This is illustrated in Fig. 4, where the measured current of the Q4 magnets in IP1 and IP5 is shown with labels that indicate when the squeeze steps were triggered. These measured currents have to be compared with the settings of Fig. 3. After the squeeze to 7 m, the beams were kept in the machine for additional beam tests (optics measurements and physics production).

Beam tests were carried out at 1.18 TeV with 2 beams in collision (separation and crossing schemes switched OFF), each with four bunches. After the energy ramp, the total intensities were about 1.2×10^{10} p for beam 1 and 2.0×10^{10} p for beam 2. This is shown in Fig. 5, where the beam currents as a function of time are given for both beams. The squeeze tests took place between 01:30 and 03:00 in the morning of Dec. $16^{\rm th}$, 2009. The normalized beam emittances measured with wire scanners at top energy were approximately 2.5 μm in both planes for beam 1 and 4 μm (H) and 9 μm (V) for beam 2. Tune values close to nominal [8] were kept after the ramp.

Table 2: β^* values in IP1 and IP5 and tune values as a function of time from the beginning of the squeeze in the beam process used for beam tests. The chromaticity set value is 2 units in both planes for all the steps.

Time s	β^*_{IP1} m	β^*_{IP5} m	Q_x	Q_y
0	11	11	0.28	0.31
15	11	11	0.31	0.32
104	11	9	0.31	0.32
190	11	7	0.31	0.32
266	11	5	0.31	0.32

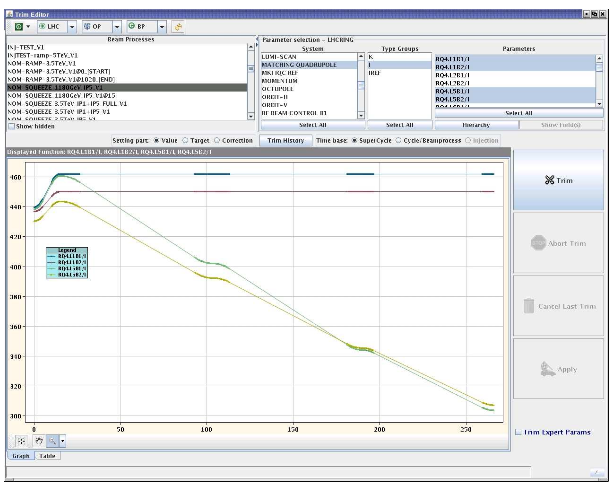

Figure 3: Settings of current versus time generated for the Q4 magnets in IP1 and IP5 correspondingly to the 1.18 TeV beam process with the parameters of Tab. 2. The matching quadrupoles in IP1 were only used for the change of tune as the betatron squeeze was only done in IP5.

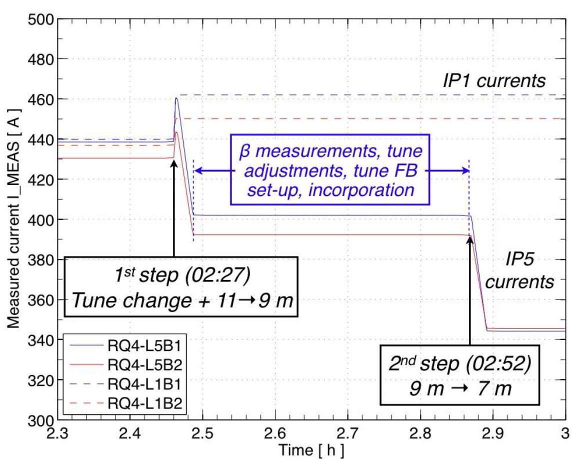

Figure 4: Measured currents of the Q4 magnets in IP1 and IP5 during the squeeze tests and a function of time in hour from 00:00 of Dec. 16$^{\mathrm{th}}$, 2009. The time 2.3 h on the x-axis corresponds to the time 02:20 on the axis of Fig. 5.

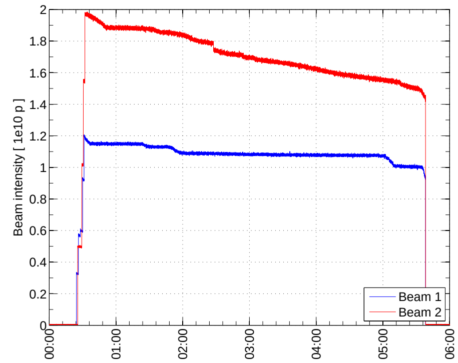

Figure 5: Total beam intensity of beam 1 (blue) and beam 2 (red) as a function of time during the squeeze beam tests. The tests took place between 01:30 and 03:00 in the night of Dec. 16$^{\mathrm{th}}$, 2009. After 03:00, the beams were kept for physics production and optics measurements.

The beam tests were carried out with intensities declared safe at 1.18TeV. The collimators for cleaning and protection were optimized to the nominal injection settings of 6.0, 7.0 and 8.0 sigmas for primary, secondary and TCDQ collimators [12] but the collimator gaps were not ramped according to the beam energy. The tertiary collimators in all IP were set at ± 15 mm and provided coarse protection to the triplet aperture. All the collimators were kept injection settings without further adjustments at flat-top nor during the squeeze steps. Therefore, the cleaning was not optimized in these conditions. Obviously, this aspect will be improved for the 2010 squeeze commissioning.

Results

Overall, the squeeze test was very successful. The β^* values measured with kick response method before starting the squeeze and after each step are listed in Tab. 3 [13]. The measured values are in good agreement with the expectations but in some case the error bars are large. Both beams survived the two squeeze steps performed and the intensity transmission was close to 100 %, as shown in Fig. 6. Approximately 3 % of beam 2 was lost in the first step. This loss was actually localized in time window during the change of tune rather than during the optics change, as shown in the bottom graph of Fig. 6. As the beam 2 emittances were large and the initial tunes were not optimized before starting the squeeze tests, one cannot draw firm conclusions from this observation. The loss pattern around the ring at the peak loss rate are given in Fig. 7. The primary loss location are the collimator in the betatron cleaning insertion and the highest loss spike in a cold element (blue lines in the plot) is found at the Q2 on the left of IP5. The collimators were not setup at 1.18 TeV and this explains the cleaning efficiency of only about 99.4 %, poor compared to the values at injection [12].

The closed-orbit was not corrected during the tests but was only monitored during the squeeze. The static RMS

Table 3: Values of horizontal and vertical β^* as measured on-line in IP5 at the end of the ramp and after each squeeze step (courtesy of R. Tomás for the β-beat team [13]).

Nominal	Measured hor.	measured ver.
11 m	10.2±1.0 m	11.8±1.0 m
9 m	8.8±1.0 m	11.7±3.0 m
7 m	6.8±0.3 m	7.5±0.5 m

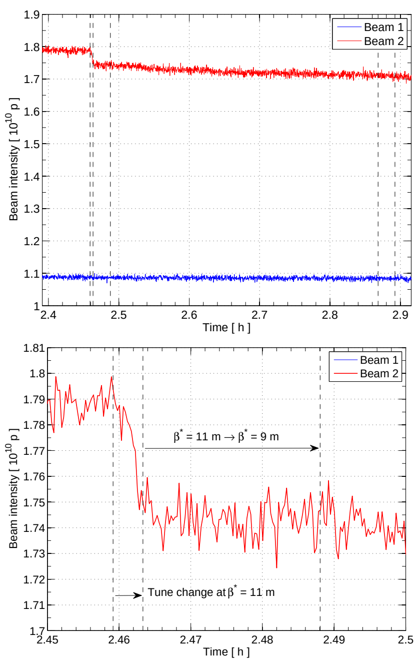

Figure 6: Beam intensities versus time during the squeeze test. Vertical dashed lines represent the time of matched optics according to the nominal times of Tab. 2.

and peak errors measured at the end of each squeeze step, calculated on the difference orbits with respect to the end of the ramp, are given in Tab. 4. Errors are dominated by the kicks induced by the feed-down dipole components in the matching quadrupoles and indeed the orbit drifts are correlated with the magnet currents, see Fig. 8. The orbit drifts are well above the stability tolerance of a fraction of the beam size in the collimator and experiment regions. These drifts could have been optimized by reducing the initial offset in the IP1 and IP5 quadrupoles. On the other hand, the commissioning shall be done with orbit feedback operational. As a fall-back solution, one could add additional stopping points and re-optimize the orbit at each step, but this would considerably lengthen the squeeze process.

The tunes of both beams were monitored during the squeeze. No correction is applied to the tune correction circuits during the β^* steps because the required changes are done with the lattice quadrupoles of the matching sections. The measured tunes during the first squeeze steps are given in Fig. 9. Note the excellent tune resolution below

Table 4: Measured RMS and peak (in brackets) orbit errors at the end of the squeeze steps. Errors are calculated with respect to the initial orbits at the end of the ramp.

Orbit error during squeeze: RMS (peak) in mm		
	$\beta^* = 11$ m $\rightarrow 9$ m	$\beta^* = 9$ m $\rightarrow 7$ m
Beam 1 HOR.	0.245 (0.769)	0.589 (1.690)
VER.	0.123 (0.472)	0.228 (0.842)
Beam 2 HOR.	0.473 (1.430)	1.100 (3.280)
VER.	0.132 (0.353)	0.283 (0.790)

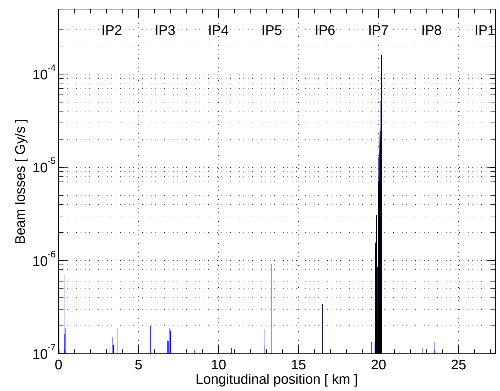

Figure 7: Beam losses around the ring at the peak loss rate during the squeeze. Black bars are losses at the collimators and blue bars are losses in cold elements.

the 10^{-4} level. This first step was done with tune feedback off in order to allow the tune variation during the change from injection to collision values. The measured shifts are summarized in Tab. 5, to be compared with the nominal shifts ΔQ_x=0.03 and ΔQ_y=0.01. The agreement is very good for beam 2 whereas the horizontal tune change for beam 1 is 20 % less than expected. The likely source of this discrepancy is that the beam 1 corrector circuits were changing during the execution of the step. This was only realized at the end of the tests.

Tune excursions between matched optics are expected because the optics is not fully optimized in the intermediate times. The variations between the step from 11 m to 9 m is shown in Fig. 10, where measurements are compared to simulations performed by running MADX on the LSA settings extracted every 1 s between matched points. The maximum tune error of approximately 0.0011 is in good agreement with the expectations. These simulations will be used to validate the settings generated for all squeeze settings in the future.

The chromaticity was not measured during the squeeze test. The sextupole corrector settings required to correct the chromatic aberration during the squeeze were incorporated onto the flat-top chromaticity settings optimized in previous ramp tests. This mechanism worked well but there is no feedback from direct measurements. For completeness, it is worth mentioning that the coupling changed significantly

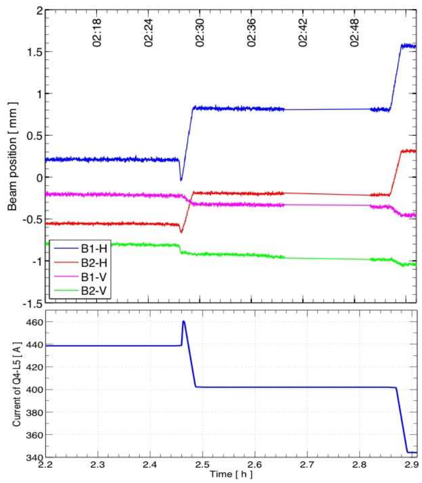

Figure 8: Orbit drift as a function of time at the Q4 magnet on the left side of IP7 (betatron cleaning insertion) and current on the Q4-L5-B1 magnet.

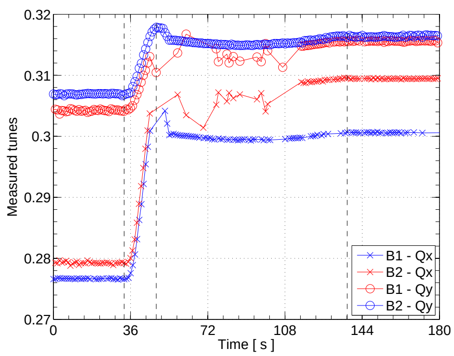

Figure 9: Measured tunes for both beams and both planes during the first squeeze steps with tune changes and β^* jump from 11 m to 9 m.

Table 5: Measured tunes shifts after the first squeeze step that included the change to collision tunes. The nominal tune differences are ΔQ_x=0.03 and ΔQ_y=0.01.

	ΔQ_x	ΔQ_x
Beam 1	0.024	0.009
Beam 2	0.030	0.011

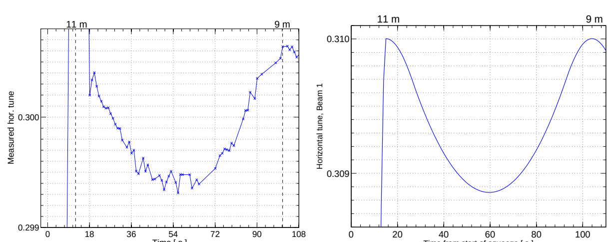

Figure 10: Measured (left) and simulated (right) tune excursion during the β^* step from 11 m to 9 m. Simulations are performed by running MADX on the LSA settings extracted every second (simulations by X. Buffat, EPFL).

during the squeeze and this aspect is under investigation.

Lessons learnt

The following feedback was gained from the beam tests.

- The availability of the orbit feedback seem to be a pre-requisite for a successful and fast commissioning of the betatron squeeze.
- Tune errors between matched optics are in agreement with numerical simulations.
- The knobs for tune and chromaticity were missing for some optics. The automatic checks with MADX on-line should be improved to avoid this problem in the future.
- The incorporation of settings for all the intermediate actual beam processes did not always work reliably.
- The accuracy of on-line β measurements was poor due to the limited available kick strength from the tune kicker. This should be improved in view of the operation at higher energies, where even the aperture kicker could be too weak.
- The measurements were affected by missing multi-turn BPM data.

CONCLUSIONS

The results of the first beam commissioning of the betatron squeeze at the LHC were presented. The first priority of these tests was to validate the mechanism to handle the squeeze. Even if some areas of improvements have been identified, the implementation of this mechanism in LSA seems adequate for the challenges of the LHC operation. In addition, the achieved β^* values are in very good agreement with the expectation. This is another confirmation of the excellent quality of the LHC optics and magnetic model. Clearly, it is difficult to extrapolate this results to the squeeze to smaller β^* values, which are known to be more critical. On the other hand, to good agreement found so far is very encouraging.

Important aspects like the set-up of movable devices and the detail operation of the feedbacks during the squeeze were not addressed by beam tests and therefore the available procedures will have to wait for a validation with beam. Various issues were identified on several fronts. They are being addressed with high priority in order to ensure the readiness for the 2010 operation.

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APPENDIX: COMPUTATION OF BETATRON SQUEEZE FACTOR

A method is proposed to compute the betatron squeeze factor from the measurements of power converter currents. The computation from direct current measurements is preferred to other possible solutions, based for example on setting checks or on high-level software implementations, in order to make the computation independent of LSA, notably independent of the machine/beam mode as well as of the resident beam process. This would improve reliability of the computation and reduce the dependence on other software (current measurements only rely on the subscription to the power converter front-ends).

The natural choice is to consider the currents of the matching quadrupoles used for the squeeze, which are not dependent on settings of the machine such as orbit, tune, chromaticity, etc. It is proposed to consider the ratio of magnet currents in order to make the calculation independent of the beam energy[1]. Pairs of magnets whose current

[1]Depending on the operating energy, one might have variation of the current ratios due to dynamic or saturation effects. This will be checked for the ranges relevant for the 2010 operation.

Table 6: Pairs of matching quadrupoles used to compute the β^* values from the current ratios.

IP	Ratio of magnet currents
IP1/IP5	RQ10-R5B2 / RQ7-L5B1
IP2	RQ5-L2B1 / RQ7-R2B2
IP8	RQ5-L8B1 / RQ7-R8B2

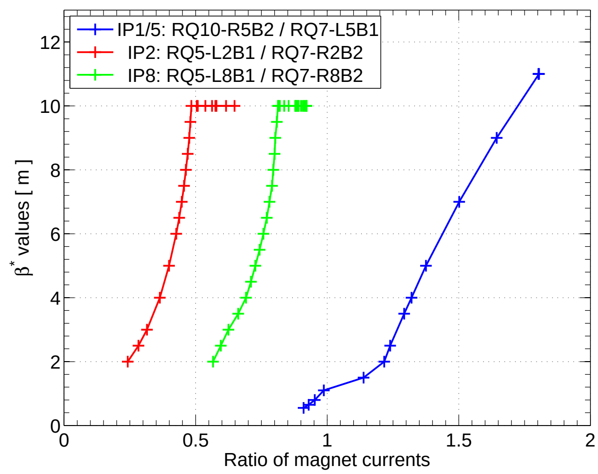

Figure 11: β^* in all IPs as a function of the current ratio of selected matching quadrupole pairs.

ratios provide a monotonic function of β^* have been identified. This pairs are listed in Tab. 6 for the different IPs. In Fig. 11, the β^* as a function of the magnet current ratios are given for all three cases. These functions are calculated starting from the LSA settings generated for a 5 TeV beam process. The cases of IP2 and IP8 are calculated for the squeeze with pre-squeeze at constant β^* value of 10 m, which explains the flat parts in the red and green lines of Fig. 11. Additional pairs of magnets could be found for redundancy. Note that for IP1 and IP5 the RQ10 magnet is preferred to the RQ5 because the latter is used for the tune change at constant β^* with current changes of opposite signs that the one of the squeeze (see Fig. 1).

A similar exercise will be repeated for the special TOTEM optics as soon as the corresponding beam process will be available.

It is clear that tests must be performed with real measured currents (with or without beam) in order to assess the feasibility of calculating β^* from the current ratios as well as to establish tolerance windows around ratio values of the functions in Fig. 11. Also note that it remains to be decided whether one squeeze factor per IP, or one single factor with the minimum β^* of the machine should be provided.

It is important to realize that the safety of the machine does not only depend on the β^* value but also on the crossing and separation schemes, which reduce the available triplet aperture. This aspect will be addressed after having gained experience with the 2010 operation with the IP bumps switched ON.