Squeezing with colliding beams

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Abstract

There are two main reasons why performing the squeeze with colliding beams may be beneficial for the operation of the LHC after LS1. First, this procedure allows to achieve luminosity leveling in a robust way on a large range, pros and cons of this technique are being compared to luminosity leveling with a transverse offset at the interaction point. Secondly, recent observations suggest that the beams brightness is already limited by impedance driven instabilities. It may be greatly beneficial for the beam stability to profit from the tune spread provided by head-on beam-beam collision, which is significantly larger than the one provided by the octupoles. The two options have different consequences on the operation of the LHC, both are being discussed based on 2012 operational experience and MD results.

INTRODUCTION

The possibility to squeeze with colliding beam, whereas very simple from the conceptual point of view, has many implication on the operation of the LHC. Indeed, good control of the orbit at the Interaction Points (IPs) is required to maintain the beams in collision during the procedure. The current implementation of the LHC control system uses the concept of Beam Process (BP) to operate the squeeze. The BP contains functions to be played by the power converters, collimators and RF systems for a fixed sequence of optics changes defined in advance. This implementation does not allow to have the flexibility required for Luminosity Leveling (LL) independently in all IPs. Different options to overcome the difficulties of LL with β^* will be discussed.
As discussed in [1], instabilities at the end of the squeeze have been limiting the beam brightness during the 2012 run of the LHC and are linked to some tens of beam dumps due to beam losses during the squeeze and adjust [8]. The combined effect of the transverse feedback, landau octupoles and high chromaticity does not seem to be sufficient to suppress the instability. However, the instability immediately disappears when the beams are brought into collision, which indicates that the Landau damping provided by head-on collision is far more efficient to suppress instabilities [2, 3]. The possibility to overcome this limitation of beam brightness by colliding during the squeeze is discussed in this paper.

ORBIT STABILITY AT THE IP

The key to reliably operate the betatron squeeze with colliding beams is the stability of the orbit at the IPs. Indeed, it has been shown that the stability diagram from head-on collision is drastically reduced when colliding with an offset in the order of 1 σ_{RMS} [3]. A series of experiment was performed in order to demonstrate that the squeeze can be executed with the required orbit stability at the IPs.

MD results

In a first attempt, the machine was filled with two bunches per beam with intensities approximately $1.3 \cdot 10^{11}$ proton per bunch and normalized emittances around 1.6 μm, the standard operational sequence was executed up to the $\beta^*=$ 3 m step of the squeeze. The beams were then brought into collision in IP1 and 5. The rest of the squeeze BP has then been executed in steps down to $\beta^*=$ 0.6 m. The tune feedback was turn off during the procedure, while the orbit feedback was on during the execution of the squeeze steps. After each step, a luminosity optimization was performed and the resulting corrections incorporated. The specific luminosity measurement during this procedure is shown in Fig. 1. The degradation of the luminosity observed during the execution of each step is due to the drift of the orbit at the IPs. The expected luminosity is then recovered by an optimization of the collision point, as shown by Fig. 2 which compares the optimized luminosity for each step of the squeeze during the squeeze to the computed one. The separation between the beams at each IP can then be computed from the luminosity (Fig. 3a), assuming a negligible variation of the beams emittance, which is consistent with the measurement. The variation of the separation during this first attempt would not be compatible with the usage of head-on collision during the squeeze to stabilize the beams, which requires the offset to remain below $\sim 1\ \sigma$ in order to maintain a sufficiently large tune spread. This is confirmed by the observation of an instability before the last step of the squeeze. It is necessary to test the reproducibility of the corrections applied, in order to ensure smaller orbit variation at the IPs. Therefore, the same procedure was re-run three weeks later, once with a single bunch and then with a train of 36 bunches. During these tests, the maximum drift of the separation stayed below 1 σ during the squeeze (Fig. 3b-3c), demonstrating the long term reproducibility of the corrections applied. [4]

In order to get a deeper understanding of the operational options that would allow to reliably keep the beams in collision during the squeeze, it was tried, 3 months later, to go

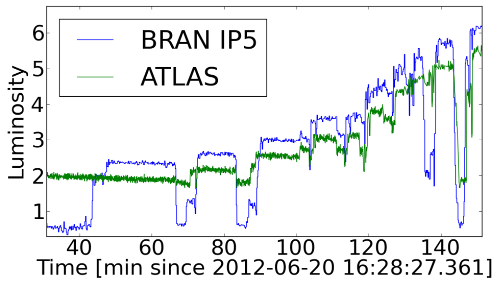


Figure 1: Luminosity during first attempt of β^* leveling

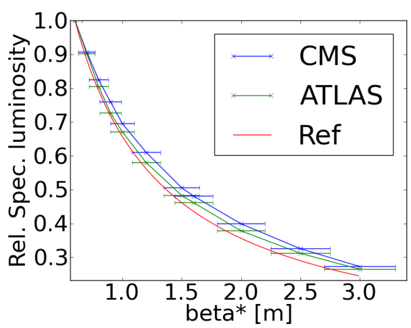


Figure 2: Measured and expected specific luminosity reduction due to β^*.

through a larger β^* range, from $\beta^*= 9$ m down to $\beta^*= 0.6$ m, with colliding beams. It was hoped that the corrections applied in the last part of the squeeze during the first tests will still be valid. This was however not the case, as separations up to 2σ were observed during the procedure. This points out that a careful setup of the orbit has to be performed, and possibly orbit corrections cleaning have to performed from time to time, to account for the slow mechanical movement of the different element of the machine [5].

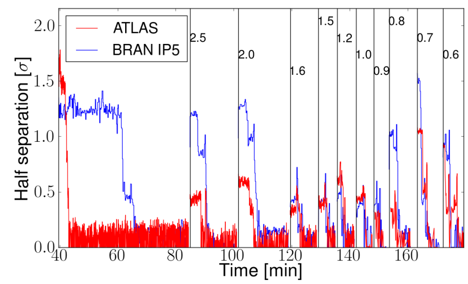
If the resolution of the Beam Position Monitors (BPMs) permits, one could use the two BPMWF located on each side of the IPs to measure the beam separation and possibly use this information in the orbit feed back. The measured beam separation during this last experiment is rather encouraging (Fig. 4).

Reproducibility in standard operation

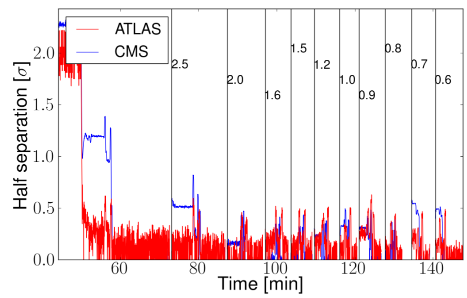
Fig. 5 shows the orbit corrections at the IPs that had to be applied to optimize the luminosity at the end of the squeeze during physics fills of the 2012 run. One observes

	IP1	IP2
Horz.	0.3 ± 6.7	0.3 ± 5.7
Vert.	-0.5 ± 5.5	-0.1 ± 5.4

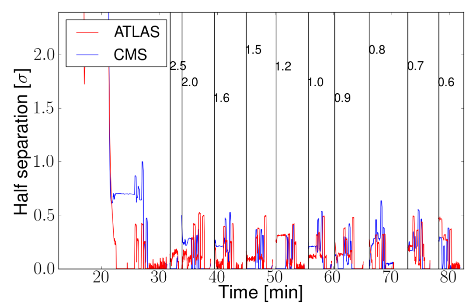
Table 1: Average fill to fill difference of the orbit correction required to optimize the luminosity in each IP1 and 5 in μm



(a) 1st attempt



(b) 2nd attempt



(c) 3rd attempt

Figure 3: Transverse separation at the IP from measured luminosity reduction factor.

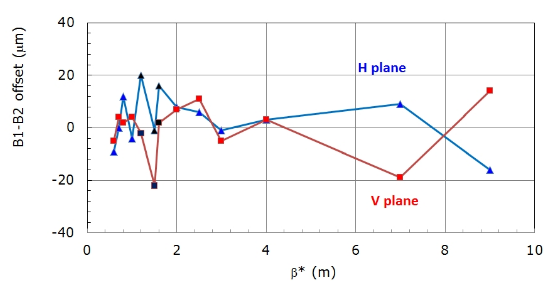
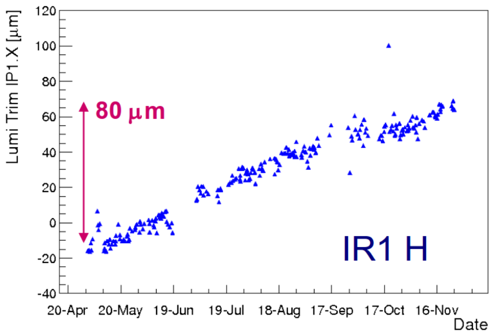
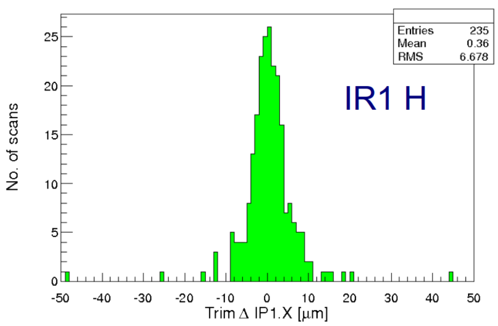


Figure 4: Beam separation at the interaction point interpolated from adjacent beam position monitors

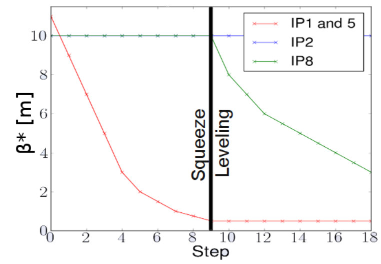


(a) Time dependence

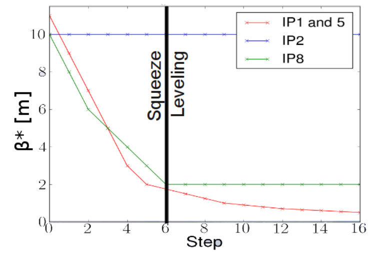


(b) Distribution of fill to fill differences

Figure 5: Correction of the orbit at the IP from luminosity optimisation during the 2012 run.



(a) β^*LL only in IP8



(b) β^*LL synchronously in IP1&5

Figure 6: Two examples of squeeze sequence for β^*LL with low flexibility.

a slow drift over the year, even though significant, this drift is not problematic. Indeed, the average fill to fill differences mainly remain within acceptable boundaries (Tab. 1). The distribution of these differences, on Fig. 5b, shows the existence of some outliers, during which the separation became larger than a few σ's. This implies that, whereas most of the time a feed forward procedure would be sufficient, the orbit at the IPs may not behave well during a few fills. In order to define a robust operational procedure, these cases, even though of limited amount, should not be neglected and therefore the effect of the lack of reproducibility for certain fills should be minimized.

To that purpose, one could consider the options of using an automatized luminosity optimization after each squeeze step or at least for a subset of them. This multiple optimization of the luminosity constitute a significant overhead compared to the current squeeze and may require some minor changes in the implementation of the settings management. One can however expect that practical experience will lead to a good balance between robustness and overhead. In particular, the possibility to use BPM data may be of great help in maintaining the beams in collision, in the cases where the machine reproducibility is not sufficient.

CONTROLS ASPECTS

The implications on the controls when imposing collisions during the squeeze largely depend on the aim that is targeted. Different scenarios have been sketched, they do not however represent the full set of possibilities. It is clear that a precise scenario that suits the needs of the experiments and maximizes the operational efficiency has to be worked out.

Up to now, the squeeze has been operated in predefined series of step, from one Matched Point (MP) to the next, each corresponding to defined values of β^* in the different IPs, that varies towards the targeted values. The sequence of MPs defines the squeeze BP, which is being played during each fill. The BP contains both global and local machine settings and corrections along the procedure [6], its full commissioning is not trivial. Therefore, the current control system does not allow to easily change the sequence of β^* configurations. We, therefore, distinguish two cases, whether the flexibility in the choice of β^* in each IP as a function of time is required or not.

Low flexibility scenario

We are considering cases where a high flexibility in the choice of β^* in each IP is not required, e.g. if head-on collision during the squeeze is required for stability reasons or in the case where the sequence of β^*s could be defined in advance and run synchronously in the IPs. There are various scenarios in which this could be the case, two of them is pictured on Fig. 6

In this cases, the present control system is appropriate, as one can define a BP and play it in steps, as it has been done during the MDs presented above. Only minor changes have to be implemented such as to maximize the operational efficiency and robustness, as already discussed in section *Reproducibility in standard operation*.

High flexibility scenario

In the case where each IP requires to change β^* at anytime, independently from the other IPs, then the present control system is no longer appropriate. Indeed, the concept of BP is no longer applicable, since the sequence will, a priori, be different at each run. Therefore, the global corrections defined for a specific sequence are no longer valid and a conceptual change of the control system is required. The required modifications allowing to change the optics independently in each IP are believed to be within reach. However, it is necessary to proceed with detailed studies and implementation in an early stage of the Long Shutdown 1 (LS1).

ADDITIONAL REQUIREMENTS FOR COMMISSIONING

As already mentioned, good orbit stability at the IPs is a requirement to reliably operate the squeeze with colliding beams. Based on the excellent performance of the orbit feed back system, it is not considered to operate the squeeze without it. It is possible to improve the orbit stability and in particular improve the effect of the orbit feed back by proper cleaning of the orbit corrections. Indeed, the feed back uses an SVD based method to compute the proper settings for each corrector based on the BPMs data, with specific algorithm to maximize robustness in case of noisy or faulty BPMs. These algorithm have side effects on the orbit reproducibility that can be minimized by proper correction of the orbit during the commissioning as well as regular re-correction during the year [5]. This represents an overhead of a few shifts compared to current commissioning time.

Optics corrections are now focused on the fully squeezed machine. In case β^*LL is used, the intermediate optics will require as much attention, which will cost another few shifts.

MACHINE PROTECTION

Collimator Impedance and beam stability

The LHC impedance is largely dominated by the one of the collimators [7]. The β^* reach depends on the collimator hierarchy that must be put in place to protect the triplet magnets [8, 9]. There is therefore an interest to close the collimators to the tightest achievable settings which increases the machine impedance. In 2012, the movement of the primary and secondary collimators from their settings at injection to the tight settings required at the end of the squeeze has been performed slowly during the ramp, in order to maintain the losses due to the halo scraping well below the dump threshold. This results in an increased impedance from flat top on, whereas the tight settings are strictly required only at the end of the squeeze. One could drastically reduce the beam brightness limitation due to impedance driven instabilities by moving the collimators, in particular the secondaries, to tight settings only once the beams are in collision, i.e. once the stability is ensured by the large detuning of head-on beam-beam collision. This, of course, implies that the beams are being brought into collision before the end of the squeeze, and that the scraping of the halo caused by the collimator movement is done while colliding, before or during the squeeze. Extrapolations for the experience at 4 TeV indicates that this option is in principle feasible but requires more studies. Indeed, while TCP collimators are moved into the beam, loss spikes must remain below dump and quench limits.

Collimator movement and leveling

The tertiary collimator have to be moved during the squeeze, in order to follow the modification of the crossing angle orbit bump, having important implications on machine protection in case of LL with β^*. Indeed, the full validation of the collimator settings, now only done for the last step of the squeeze, would then be required for each one of them. Moreover, collimator movement during stable beam mode were not allowed up to now. The potential machine protection issues of the transition from one step to next have to be properly addressed. If it were considered unsafe for the experiments to keep acquiring data during the leveling steps, the overhead could have a significant impact on integrated luminosity. A possible workaround is presented below, by the means of flat beams. It is however important to recall that these considerations are important only in the frame of LL, but not if colliding during the squeeze is only meant to improve the beams stability.

Flat beam option

Colliding flat beams, i.e. $\beta^*_x \neq \beta^*_y$, presents some interesting advantages when considering β^*LL. Indeed, by first fully squeezing in the crossing plane, before LL with β^* in the separation plane, one can minimize the modification of the crossing angle orbit bump, thus reducing the tertiary collimator movements during the LL procedure. Further studies are nevertheless required to fully assess the machine protection issues in this configuration. It is also important to note that this would reduce the leveling range by the square root.

There can be interests in the flat beam option from the experiments point of view, to improve detection efficiency during LL [10], which should be taken into account.

As opposed to colliding with separated beams, the separation bump is collapsed during the execution of the squeeze, leaving extra aperture in the separation plane which may be used to squeeze further, in the this plane only. The luminosity gain in the different post LS1 scenarios varies from 0 to 18% [9].

It is however important to note that, due to the lack of time, flat beam collisions were not tested in the LHC. Experience in the $\mathrm{sp\bar{p}s}$ did, however, not raise any detrimental effect from operating with flat beams [11].

CONCLUSION

Experiments have been conducted at the LHC, demonstrating the feasibility of colliding the beams during the squeeze. In particular, it has been shown that the required orbit stability at the IP can be achieved, suggesting that the changes of the operational cycle to account for this new procedure are not out of reach. Colliding during the squeeze could improve the performance of the LHC for mainly two reasons. First, the large tune spread provided by head-on collision enhance the beam stability during the squeeze, allowing to push further the limits on beam brightness due to impedance driven instabilities. Secondly, LL with a transverse offset, while used extensively in IP8 during the 2012 run, has brought up some critical stability issues for bunches without head-on collision in any other IPs. The stability of all bunches during the LL procedure is however ensured with β^*LL. Many scenarios can be envisaged, having different implications on operation. The preferred scenario and the operational details have to be worked out, taking into account the experiments' desiderata. In order to leave appropriate time for the preparation of new software and procedures, discussions should take place early in the LS1.

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