Luminosity Levelling techniques for the LHC

B. Muratori*, STFC Daresbury Laboratory, ASTeC and Cockcroft Institute, UK.
T. Pieloni† CERN, CH-1211 Geneva 23, Switzerland.

Abstract

We present the possibilities for doing luminosity levelling at the LHC. We explore the merits and drawbacks of each option and briefly discuss the operational implications. The simplest option is levelling with an offset between the two beams. Crab cavities may also be used for levelling as may a squeezing of the beam. There is also the possibility of using the crossing angle in order to do luminosity levelling. All of these options are explored, for the LHC and other possible new projects, together with their benefits and drawbacks.

INTRODUCTION

One of the main measures of a collider's performance is its luminosity. However, from the point of view of experiments, what is most important is not the peak luminosity but rather the integrated luminosity. For the detection of events, it is also preferable that the luminosity remain constant for as long as possible. Therefore, luminosity levelling can be introduced. This means that the natural decay of the luminosity is pre-empted and the luminosity is spoilt initially with respect to the nominal. Then, as the luminosity decays, it is spoilt less and less in order that it remain constant for as long as possible. While doing this, it is still very much worth while to start with as high a luminosity as possible as this will translate in the luminosity being constant for a longer amount of time after levelling. To explain what is meant by this, we consider the expression of the luminosity in the presence of both an offset and a crossing angle such that the crossing region is illustrated by Fig. 1 below (more details can be found in [1, 2]).

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} W e^{\frac{B^2}{A}} \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}}$$

with $A = \frac{\sin^2\frac{\phi}{2}}{\sigma_x^2} + \frac{\cos^2\frac{\phi}{2}}{\sigma_s^2}$, $B = \frac{(d_2-d_1)\sin\frac{\phi}{2}}{2\sigma_x^2}$ and $W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$. N_1 and N_2 are the number of protons per bunch for beams 1 and 2 respectively, N_b is the number of colliding bunches per beam. σ_x, σ_y and σ_s are the transverse and longitudinal bunch dimensions, ϕ is the crossing angle and d_1 and d_2 are the offsets of beam 1 and 2 with respect to the nominal.

Various types of luminosity levelling have been suggested. These are explained below, together with an analysis of their merits and drawbacks as well as a discussion of how they satisfy the requirements, from the point of view of observation, operations and the LHC experiments [3, 4, 5, 6]. The main types of levelling are: separation, crab cavities or crossing angle and β^* squeeze as illustrated in Fig. 2 below.

* bruno.muratori@stfc.ac.uk
† tatiana.pieloni@cern.ch

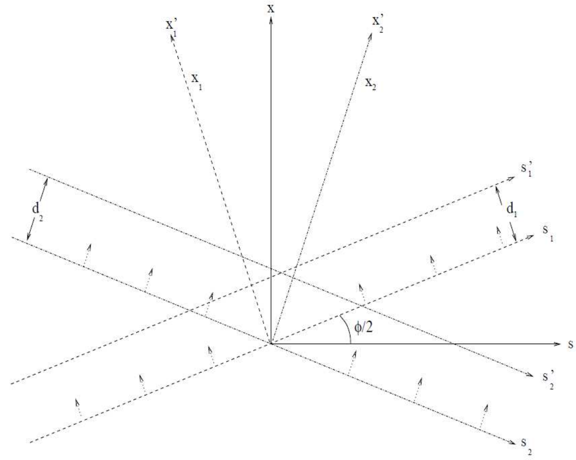

Figure 1: Geometry of interaction region with crossing angle and offset of the beams.

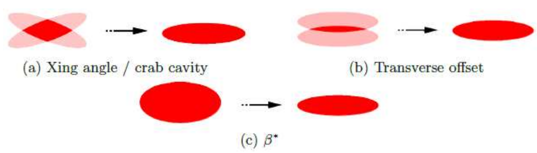

Figure 2: Sketch of the luminous region for different levelling techniques.

LEVELLING WITH OFFSET

The simplest form of levelling is achieved by introducing an offset between the two colliding beams. This is straightforward from an operational point of view and can be implemented easily and quickly if required. It also gives the possibility of doing levelling in all IPs independently, as it is done with a local orbit bump, and gives a smaller tune spread therefore leading to smaller losses. The average number of p-p collisions per bunch crossing, or pile-up, that experiments can handle is limited as different events need to be distinguished. This is particularly important longitudinally where the vertex density is critical and levelling with offset allows for this to be kept constant.

The drawbacks to luminosity levelling with offset are several. The most obvious one being that, a different separation leads to a different beam-beam force being experienced. Therefore, the effect of one beam-beam encounter with a separation of a few order the RMS beam size can change the tune spread appreciably, this is shown in Fig. 3. This leads to a decrease in the extent of the stability region as a function of the offset, as shown in Fig. 4.

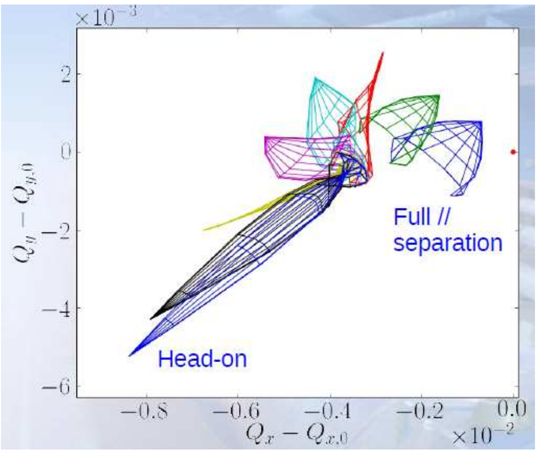

Figure 3: Tune footprint for different separations.

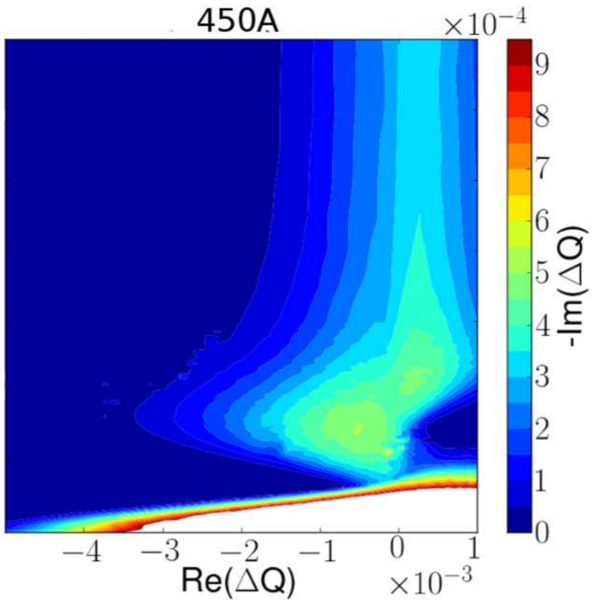

Figure 4: Real tune shift (extent of stability region) as a function of the offset.

Note that the minimum is hardly visible and lies just below the big maximum shown in white. The position and amplitude of this minimum depends on the collision schedule, the bunch intensities, emittances, octupole settings and, in particular, the transverse offset at all the different IPs and the bunches experiencing head-on collisions. The fewer the head-on collisions, the smaller the stability area shown in Fig. 4. In fact, as can be seen from the figure, there exists a critical separation at which the instability diagram is a minimum. Therefore, it is believed that, levelling with transverse offset, brings serious complications in ensuring the stability of all bunches involved. Operationally [7], it is believed that such effects have already been observed in IP8 where, during a few fills, bunches that were colliding only in IP8 were lost and suffered substantial reductions in intensity, as shown in Fig. 5, together with the full separation inferred from the measured luminosity in IP1 and IP8, given in Fig. 6. Clearly, it is expected that this effect becomes even worse when bunches collide in more IPs and not all of them experience head-on collisions. Other drawbacks include that the tune shift keeps changing as the beams are brought into and out of collision and that bunches become more sensitive to instabilities with respect to head-on collisions. The mere fact of going into collision with a separation could in itself give rise to instabilities or maximise their effect. Finally, there is a possible emittance growth resulting from the offsets used as can be seen in Fig. 7 below.

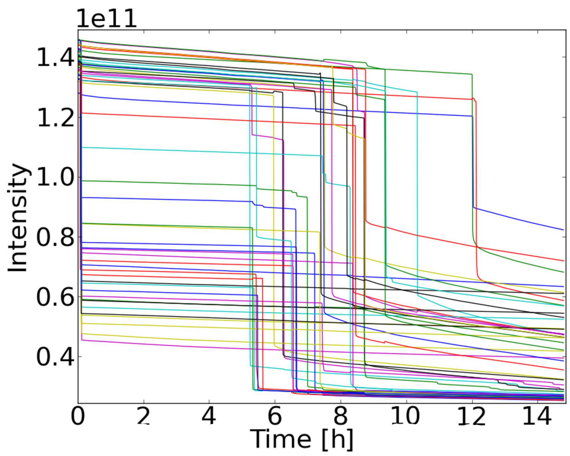

Figure 5: Intensity of IP8 bunches.

CRAB CAVITY LEVELLING

Crab cavities have been used successfully, in electron colliders, to increase the luminosity back to the nominal one in the presence of a crossing angle. In a similar way, they may be used to perform luminosity levelling by “spoiling” the luminosity initially, by artificially “anti”-crabbing the beam, and subsequently by correcting for the natural exponential decrease in luminosity through the usual crabbing of the beam. The main advantages of using crab cavities are that all IPs are independent and that it is possible to go back and forth easily by just changing the voltage of

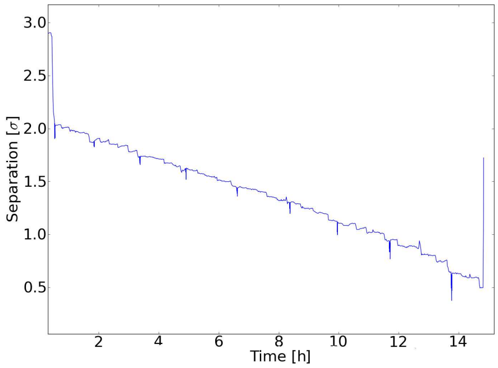

Figure 6: Full separation in IP8.

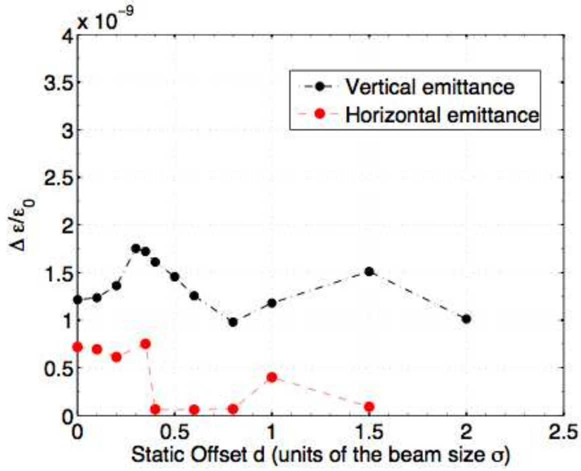

Figure 7: Emittance as a function of beam separation.

the cavities.

The drawbacks to luminosity levelling with crab cavities are several. The most obvious one is that there is, so far, no experience with applying crab cavities to proton bunches at all and this would most likely lead to additional problems from an operational point of view. The longitudinal vertex density changes with the levelled angle givng rise to all the problems which were discussed above for the offset levelling. Further, the tunes change with crossing angle and additional noise could be introduced on the colliding beams so reducing the reachable ξ_{bb}. There is also the jitter coming from the cavities which has to be dealt with. Differential phase jitter causes the two bunches to have a height mismatch, which can significantly reduce luminosity or cause the bunches to miss. Phase jitter means that the entry time of the centre of the bunch to is different for the cavities hence dx is different for the two beams as may be seen in Fig. 8 below.

Phase jitter between the cavities causes the two beams to be displaced in the x-plane which can reduce the luminosity of the collision or even cause the bunches to miss each

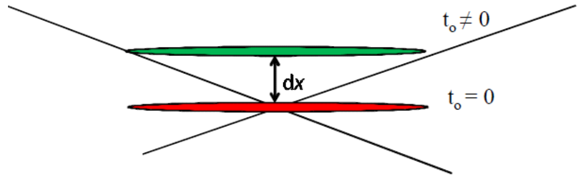

Figure 8: Effect of crab cavity jitter at the IP with t_0 the time the bunch enters the cavity.

other completely. Further information about cavity phase jitter for the ILC can be found in [8].

β^* LEVELLING

Another option for doing luminosity levelling is to start with a beam whose cross-section is larger than the nominal and then gradually squeeze it as the luminosity spontaneously reduces exponentially, this is known as β^* levelling. Now, the stability of the beam relies on impedance modes in the machine being Landau damped. This is done via a tune spread in the presence of beam-beam or other non-linearities in the machine. In the absence of colliding beams, octupoles are used to ensure the required tune spread for damping and, thereby, beam stability [9]. Beam-beam effects may be safely ignored before the β^* squeeze, however, during the squeeze, the β function grows dramatically in the region near the IP. This reduces the separation between the two beams even before they are brought into collision. The stability region before and after the squeeze with two different octupole settings is shown in Fig. 9 below.

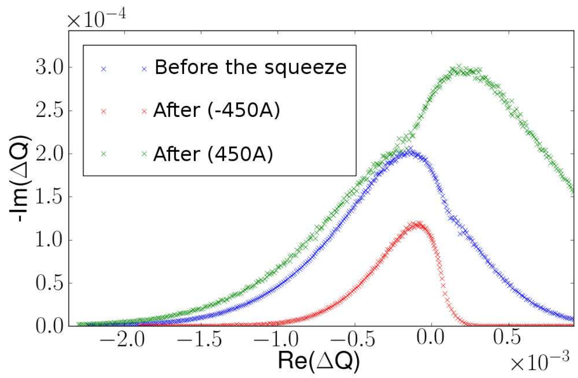

Figure 9: Horizontal stability diagram for different octupole settings before and after the β^* squeeze.

Clearly, it is preferable to use the positive octupole polarity, however, the strength required means that there are some detrimental effects associated with this, namely a reduction in dynamic aperture and feed down effect. This is avoided if the squeeze is done when the beams are already colliding head on. This ensures a much larger tune spread and hence Landau damping, giving a much larger stability diagram as shown in Fig. 10 below.

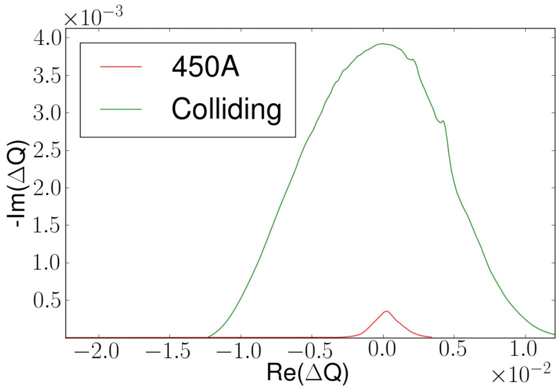

Figure 10: Horizontal stability diagram with and without head-on collision.

The principle of β^* levelling is illustrated in Fig. 11 below for an experiment done in 2012 [7] where the beam was slowly squeezed, as a function of time, and the luminosity increased. Physically, there is no difference between this and keeping the luminosity constant as it naturally degrades. All parameters such as beam size, tunes and orbit should be monitored while the luminosity is being squeezed. The main advantages are that there is a constant longitudinal vertex density for the experiments, the tunes do not change and are constant over the fill and it is more stable with the largest area of Landau damping. As the

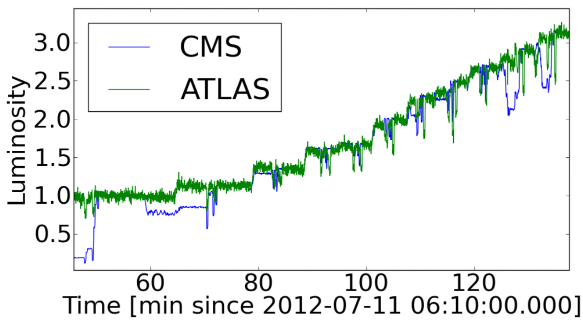

Figure 11: Luminosity evolution during fill 2828.

tune spread from head-on beam-beam does not depend on β^*, leveling with it would allow to keep a constant stability diagram during the procedure as opposed to what happens when the levelling is done with just offset. Fig. 12 shows a comparison of the measured luminosity reduction factor, when doing β^* levelling for the experiment performed at the LHC in 2012 [7], both at CMS and ATLAS as well as the expected reduction. The principal drawbacks are due to the orbit. This has to be kept constant during the squeeze, as the beams are to be kept in collision, which means a

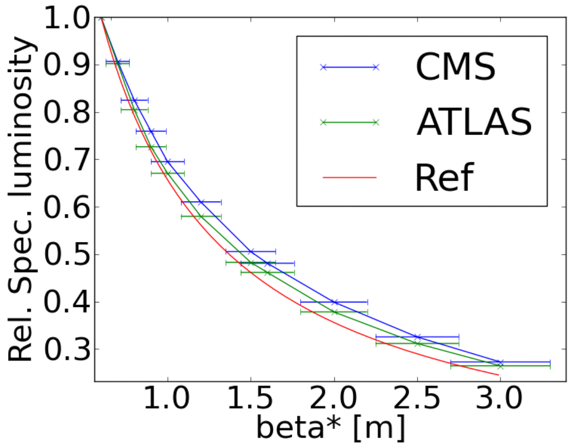

Figure 12: Measured luminosity reduction factor at CMS and ATLAS compared to expectation.

feed-forward on it is required for robustness from an operational point of view and could require several changes from normal operations.

OTHER LEVELLING POSSIBILITIES

Several other possibilities exist, these are listed briefly below, Some of them are very new and have not been fully evaluated yet while others still require experimental verifications and further studies of their viability.

- Longitudinal cogging: This means introducing a time delay of the order of a couple of RF periods longitudinally, thereby ensuring there is only a partial overlap of the two colliding bunches at the IP. So far, only 1 or 5 RF periods were implemented experimentally. It appears to be a relatively easy option to implement, however, it means that levelling is done at all IPs simultaneously and this is very restrictive for the experiments. Longitudinal cogging also moves the luminous region longitudinally.
- Large crossing (Piwinski) angle option. This is where the levelling is actually done with a variation of the crossing angle. This option also varies the length of the luminous region according to the crossing angle.
- Flat beam option. This has been proposed recently [10] and involves doing the levelling in one plane only, the same as the crossing angle plane. This means that the tune shift in the other plane can be kept constant and the collimators do not have to move much which could lead to safety issues, otherwise.

DISCUSSION

Various scenarios for luminosity levelling were presented, all valid working options, and their merits and drawbacks were discussed. The easiest to implement is the offset option, however, this could lead to instabilities. Crab cavities introduce an additional complexity which could turn out to be very non-trivial. There is also no experience of crab cavities and proton bunches and the cavities could introduce a substantial jitter as well. Several other options such as levelling with crossing angle, flat beam options or longitudinal cogging were also discussed. However, it appears that β^* levelling together with possibly some offset as well is the most promising option as it appears to satisfy most of the requirements, both from the experiments point of view and operationally. The main problem with the β^* levelling is that the orbit has to be kept constant as the levelling is being done and this may be rather complex from an operational point of view.

Ultimately, the most important thing which will decide how exactly the luminosity shall be levelled, both at the LHC and possible new projects [11], is the operational simplicity with which the method can be implemented together with the experimental requirements and constraints.

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