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MD 1691: Active halo control using tune ripple at injection

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Summary

In this MD we performed halo excitation through tune ripple. This consists in an excitation that introduces new resonance sidebands around the existing resonance lines. In presence of sufficient detuning with amplitude, these sidebands can in principle affect only the dynamics of the halo particles at large amplitudes. Tune ripple was induced through a current modulation of the warm trim quadrupoles in IR7. This is the first time this method is experimentally tested at the LHC.

Contents

1 Introduction and motivation

The collimation system performance during Run 1 and Run 2 has been demonstrated to be very good, so far. Nevertheless, possible limitations of the system in presence of overpopulated beam tails remain a concern [1, 2] in particular for the HL-LHC upgrade. This study aims at depleting beam halos in a controlled way using the present hardware in the LHC. In addition, and looking towards the future LHC upgrade (HL-LHC), if tails are depleted, fast crab cavity failures pose lower risk to send beam onto sensitive elements.

Several methods are being explored for actively controlling the halo. While it has been demonstrated that hollow electron lenses could perform the required functionality, an effort is put in understanding what can be done with alternative methods that rely on present hardware. The first one consists of using the transverse damper (ADT) to introduce a narrow-band excitation to excite particles in the transverse tails while keeping the core unaffected. This method has already been tested during other MD sessions as reported in [3]. A second method, the one reported in this note, consists of applying a tune modulation in order to excite also particles in the halo while leaving the core unaffected.

We present here the results of the MD carried out to investigate the feasibility of this method in the LHC at injection energy (450 GeV). This was the first time that this novel method was tested in the LHC and several uncertainties needed to be clarified during the course of the MD. The final goal of the MD was to first get a proper understanding of the principle of the active halo control using tune ripple and to investigate whether this method can deplete the beam tails without affecting the beam core.

2 Basic theoretical background

Ripples in the quadrupole power supply introduce sidebands around the existing resonance lines. These sidebands may generate undesirable losses if they are close enough to the tune footprint. At HERA, proton losses were significantly reduced by compensating an existing tune modulation [4]. In this experiment, we profit from this principle to excite only particles which populate the tails of the bunch. Octupoles generate the required amplitude detuning. In presence of appropriate detuning with amplitude, frequency f_{mod} should be chosen in such a way that it remains far enough from the core tune, but puts sidebands on top of the tune of the tails of the distribution.

The modulation of the tune is based on the formula [4]

$$lQ_x + mQ_y + n\frac{f_{\text{mod}}}{f_{\text{rev}}} = p \qquad l, m, n, p \in Z, \tag{1}$$

where Q_x and Q_y are the horizontal and vertical tunes, f_{mod} is the modulation frequency applied to the quadrupole power supply and f_{rev} is the revolution frequency which for the LHC is about 11 kHz. With the right modulation frequency f_{mod}, theoretically we could put resonance lines on the halo while keeping the core unaffected.

In order to get enough detuning with amplitude octupole magnets are set to a current of $I = 10\ A$. The detuning with amplitude with this octupole current was calculated using MAD-X and measured in past MDs [3]. The required modulation frequencies have been studied before the MD. For slow modulations ($\sim$ 50 Hz) the distance between sidebands and the unperturbed tune is small but the amplitude decreases slowly with increasing resonance line order. On the other hand, for fast modulations ($\sim$ 600 Hz) distance between sidebands is larger but amplitude decreases quickly for higher orders [5]. In this MD, a range of frequencies which covers the ones mentioned above is explored.

The easiest magnets to use for tune modulation are the warm trim quadrupoles in IR3 or IR7, which have proven to provide enough amplitude for the modulation [5] although there might be concerns in transmission to the beam due to the effects of the vacuum chamber. Nevertheless for high frequencies the maximum magnet current is reduced. This is an intrinsic limitation of the magnets used.

3 MD procedure and overview

The MD was carried out the 23rd of August 2016 for 7 hours approximately. We used both beams at injection energy. The MD was performed smoothly although some issues were found in the quadrupole power supply controller as explained in detail later.

The modulation is applied on the warm quadrupole RQT5.L7 in IR7. Two nominal bunches per beam are injected. One of the bunches is blown up using a white noise excitation of the ADT, as in loss maps, to populate the bunch tails. The other bunch is kept untouched to be used as reference or witness bunch, specifically to monitor effects on the beam core from the excitations that aim at depleting tails. We use wire scanners to get the bunch profile before and after the excitation. In order to evaluate the effect of the tune modulation we monitor the bunch intensity using the BCT monitor. The losses are continuously monitored using BLMs and the emittance is obtained using the BSRT monitor. When the modulation is over, we use single jaw collimator scraping to obtain a precise measurement of the beam profile. However, since the two bunches are scraped simultaneously and the standard BLMs cannot distinguish losses bunch-by-bunch, they cannot be used to determine the profile of each bunch.

In Fig. 1 the intensity of both beams is shown during the entire duration of the MD. Different fills allowed to test different modulation settings. The general strategy was to test different frequencies at maximum amplitude. We found that the highest modulation frequency achieved by the power supply was the one wich had higher effect in terms of losses at a modulation frequency $f_{\mathrm{mod}} = 333$ Hz.

During the tune modulation, we found stability problems in the quadrupole current that were not observed in preliminary tests in the lab. Although a small perturbation of the current was expected to be possible [5] in this case when the current loop is not active, we

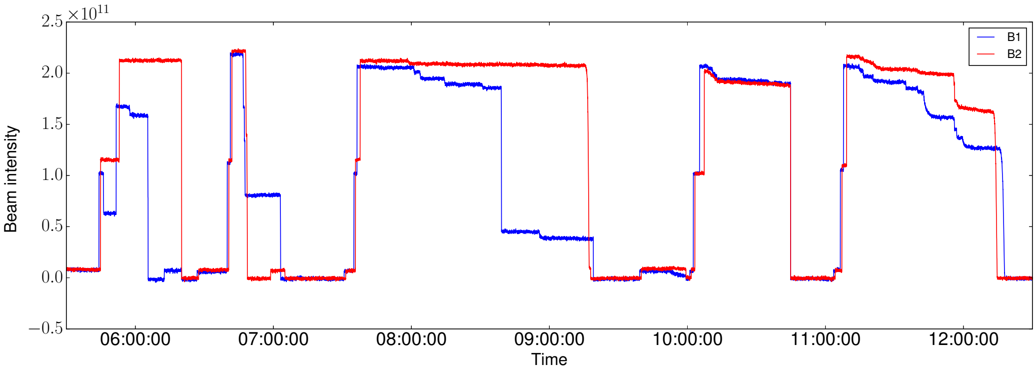


Figure 1: MD overview: B1 and B2 intensity during the MD. Different fills allowed to test different modulation frequencies.

realized however that the current can actually be doubled compared to injection settings. This was not expected and perturbed the measurements significantly because these jumps in current while exciting the beam, as can be seen in Fig. 2 for example, prevented to control the tune during the excitation (shifts up to more than 0.04 are induced as the current changes from 11.7A to 27 A on the RQT4.L7 that was used). These jumps were quite reproducible, so we found a work around to this problem by trimming the tune and even keeping the tune feedback on, during the excitation. However, this conditions was clearly not ideal and the problem shall be understood before proceeding with new beam tests. In these conditions, we collected a some useful data. The same decay pattern was observed for the different fills we performed. This issue was reported and it is currently under investigation.

4 Results

In this section we show the results of the more stable fill after learning how the quadrupole stabiliy affected the modulation. In this fill, which started at approximately 11:00, we excited a ripple at 333 Hz (the maximum with the present hardware) with a peak-to-peak modulation of about 40 mA (at 20 V). We chose this configuration because we saw measurable effects on the beam, favoring higher frequencies instead of higher currents that can be achieved at low frequency. After several empirical effects, we found a work around where the initial tune were set such that the tune jumps from the current in the magnet brought the beam tunes close to the third order resonance line at the working point $(0.313, 0.323)$. Then, the excitation was kept for 15 minutes. The tune feedback (QFB) was also kept on,

4.1 BCT measurements

Beam intensity was constantly recorded using the BCT. In Fig. 3 and Fig. 4 the beam intensity during the excitation is shown for Beam 1 and Beam 2 respectively together with the quadrupole current applied. First of all, the quadrupole stability issue explained above is clearly appreciable. The quadrupole current decreased in steps by more than a factor two. Despite this undesirable effect, a clear intensity decrease in the blown up bunch was observed

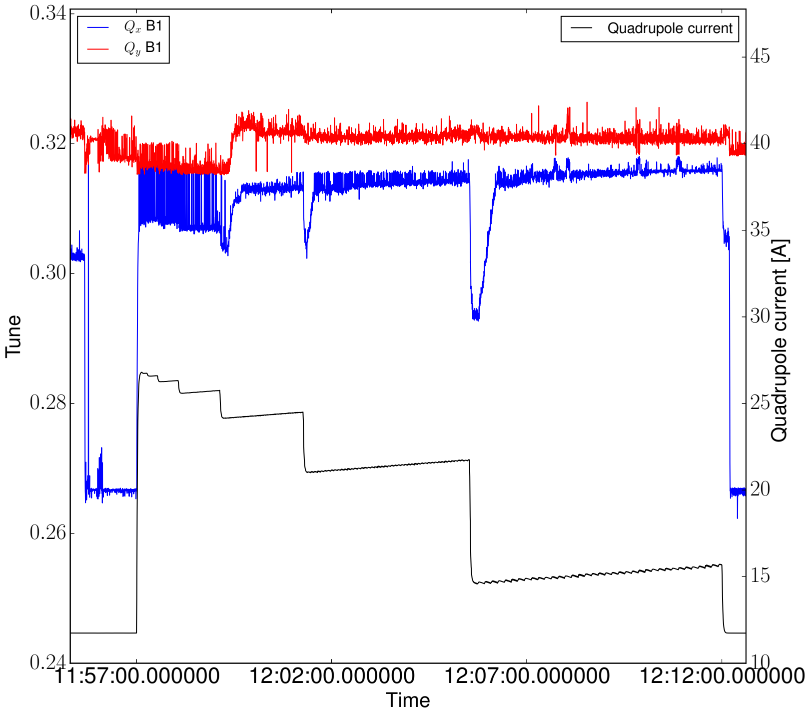


Figure 2: Quadrupole current and B1 tunes during the modulation. This modulation is not observed in this logging at 1 Hz. The jumps in intensity are clearly appreciable causing tune shifts mainly in the horizontal plane. The tune feedback was used to recover the expected tune.

in both beams during the tune modulation. About a 40% of the B1 intensity was lost and about 14% in B2. In both cases most of the intensity is lost during the first seconds of the excitation. The witness bunch does not show a significant intensity decrease with respect to the blown up bunch. Due to the stability issue, is not easy to extract final conclusions but it seems clear that, in terms of bunch intensity, the blown up bunch is more affected than the witness bunch.

4.2 Wire scanner and BSRT monitor

4.2.1 Wire scanners

In order to compare the bunch profile before and after the excitation. wire scans were taken just before and just after the modulation. As it was already observed in previous MDs [3], the resolution of the wire scanners in the area of interest, i.e. the bunch tails, is not enough to really appreciate the effect of the excitation and the possible tail depletion. Although more analysis is ongoing, it seems difficult to extract useful information from the tail from wire scanners.

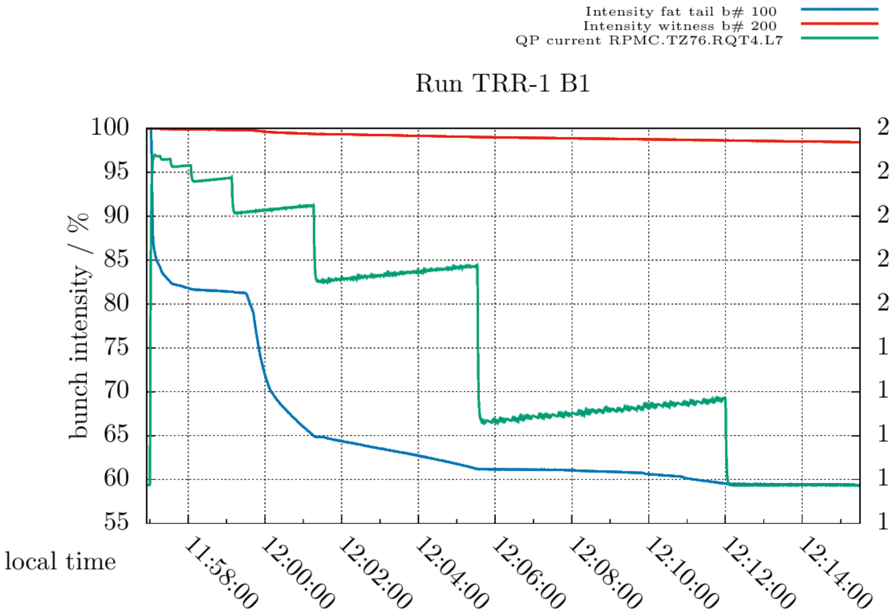


Figure 3: Nominal and fat tail bunch intensity in Beam 1 during the tune modulation. A clear intensity decrease in the fat tail bunch is observed while the nominal bunch intensity is slightly affected.

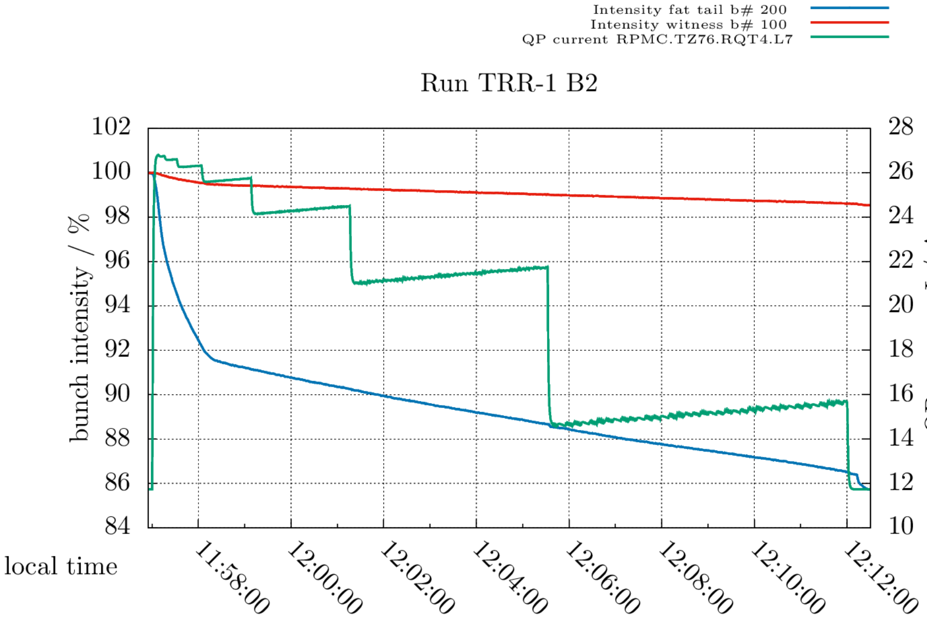


Figure 4: Nominal and fat tail bunch intensity in Beam 2 during the tune modulation. A clear intensity decrease in the fat tail bunch is observed while the nominal bunch intensity is slightly affected.

4.2.2 BSRT monitor

The BSRT monitor allows to have a continuous measurement of the emittance. In Fig. 5 and Fig. 6 the individual bunch intensity and the emittance measured by the BSRT monitor is shown during the modulation for Beam 1 and 2 respectively in both planes. In both cases, and despite of the intensity reduction, the emittance is not clearly affected during the modulation. This probably means that the bunch core is not significantly blown up during the excitation and most probably losses are coming from the tails of the bunch. Whether the tails are repopulated again with particles from the core is something that remains to be understood.

4.3 Collimator scraping

Just after the excitation the beam was fully scraped using a single jaw of the primary collimator in IR7. From the losses recorded by BLMs, the beam profile can be precisely reconstructed following [6]. In Fig. 7 the profile reconstructed for B1 (top) and B2 (bottom) using this technique is shown for the last fill.

No particular deviation is observed in B1, although it is not obvious since no reference scraping was taken. On the other hand, for B2 an anomaly in the tail distribution is observed. This might be due to the modulation itself or any other mechanism which, due to the issues found with quadrupole power supply jumps, remains unknown.

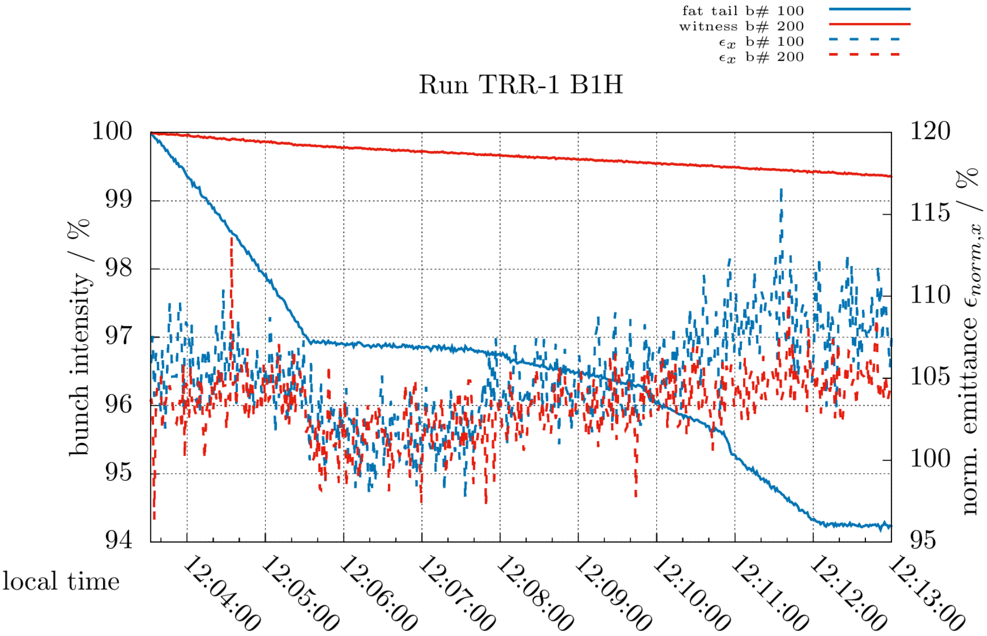
One limitation is the fact that the beam was scraped with two bunches in the machine, which makes it more difficult to understand the results, since we can't disentangle the contribution from the two bunches. If the tests are repeated, one bunch per beam will be injected at the time.

In any future studies we should perform scrapings both on beams that have and have not been affected by the tune ripple, and both on bunches with fat tails and with the tails scraped. In addition, ideally several scrapings should be performed in the same conditions in order to explore the re[prodicibility of the measurement

5 Summary and conclusions

In this MD we performed halo excitation through tune ripple. This consists in exciting sidebands around the tune resonance lines by adding a modulation to the tune, which was triggered with the warm trim quadrupoles in IR7. The ripple to the current is added by using the power converter in voltage mode.

The measurement was complicated since jumps in the quadrupole current were observed. Taking into account previous tests without beam, these jumps were unexpected and this issue is currently under investigation.



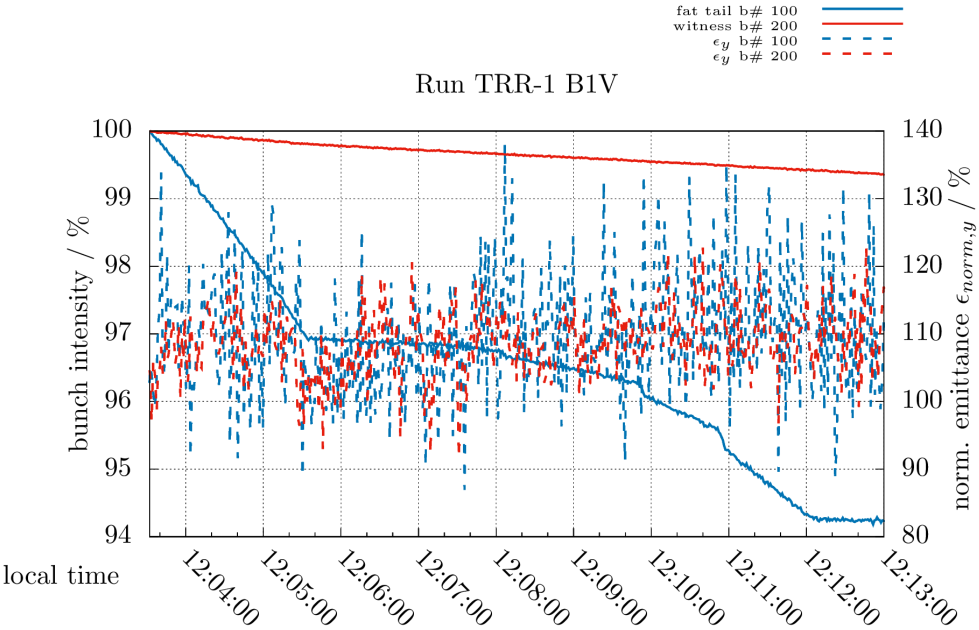


Figure 5: Individual bunch intensity and emittance for Beam 1 during tune modulation for the horizontal (top) and the vertical plane (bottom).

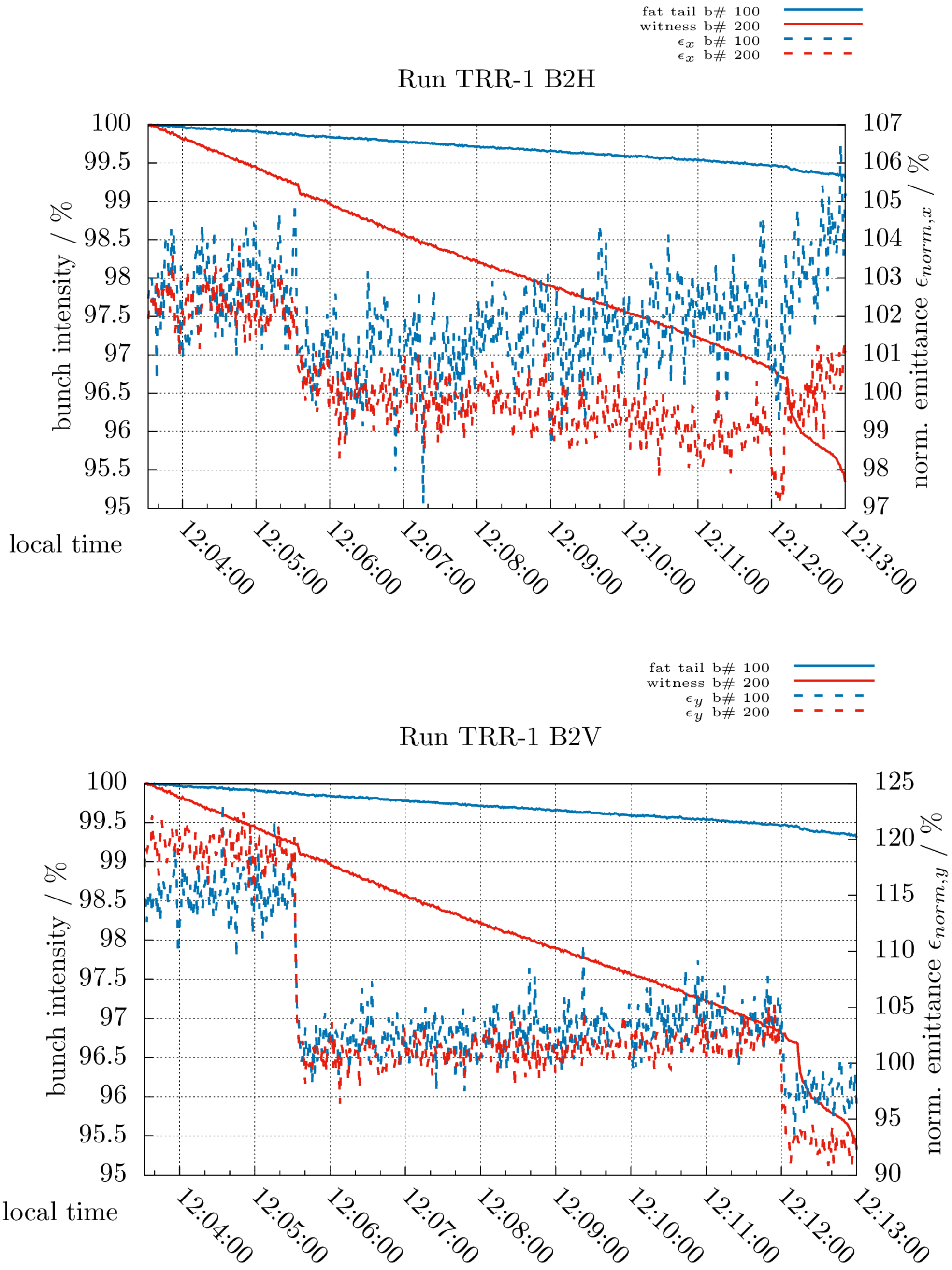
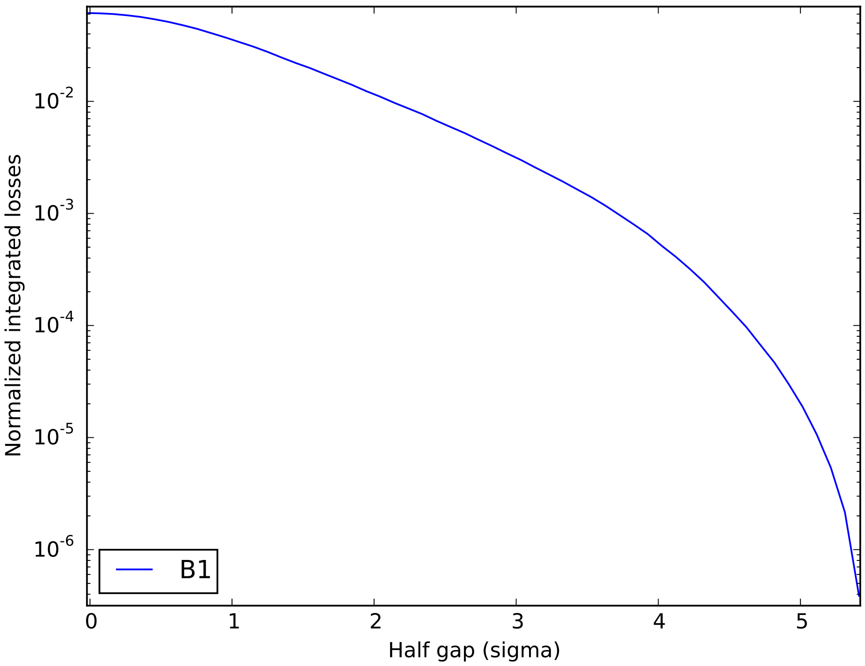


Figure 6: Individual bunch intensity and emittance for Beam 2 during tune modulation for the horizontal (top) and the vertical plane (bottom).



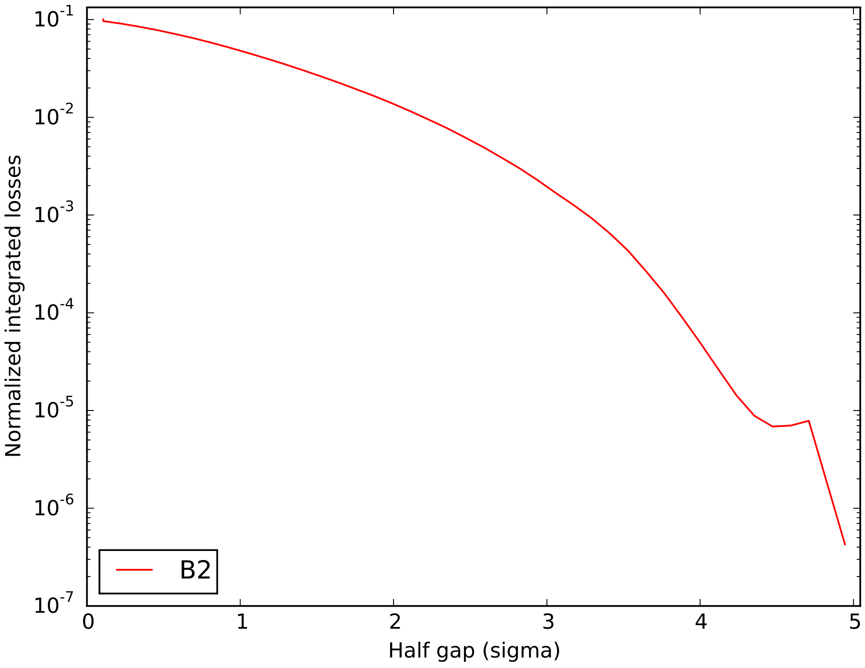


Figure 7: Reconstructed profile from collimator scrapings in the horizontal plane for Beam 1 (top) and Beam 2 (bottom).

We injected two nominal bunches per beam and populated the tails of one using a white-noise ADT excitation (non blown up bunch gives the reference for the effects on the core).

Then, we applied the modulation and observed the losses using the BCT. Wire scanners measurements were performed before and after the excitation to compare the beam profiles and the fills were ended with a collimator scraping.

We performed different tests in order to find the optimal modulation settings. A wide range of frequencies (10-333 Hz) and amplitudes were tested. The settings wich induced an appreciable amount of losses were those corresponding to the maximum frequency and maximum amplitude. With these settings we obtained the best scan, where we excited a ripple at 333 Hz with a peak-to-peak modulation of about 40 mA (at 20 V). With this configuration we observed a clear intensity decrease in the blown up bunch while the nominal bunch intensity just suffers a very light decrease. With the data collected using wire scanners and collimator scrapings it is difficult to conclude if there was a clear tail depletion or not. Further tests are needed to conclude on the feasibility of the tune ripple method. Based on the experience in this MD and the ADT halo control MD, we propose to carry out such studies using single-bunch injections. However, such tests are meaningful only once the issue with the quadrupole current jumps has been resolved.

6 Acknowledgements

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