Batch By Batch Longitudinal Emittance Blowup MD

T. Mastoridis, P. Baudrenghien, A. Butterworth, M. Jaussi, J. Molendijk / BE-RF

Keywords: Beam Dynamics, RF, LHC, Longitudinal, IBS

Summary

The transverse bunch emittance increases significantly at 450 GeV from the time of injection till the ramp due to Intra-Beam Scattering (IBS) [1]. Since IBS depends on the bunch charge density, it should be possible to reduce the transverse emittance growth rates due to IBS by selectively blowing up the longitudinal emittance of the incoming batch at each injection. An MD was conducted on April 22nd 2012 to test the feasibility and performance of the batch-by-batch longitudinal emittance blowup.

There were three main goals during the MD. First, to test the developed hardware, firmware, and software for the batch-by-batch blowup. Then, to measure the transverse emittance growth rates of blown-up and “witness” batches to quantify any improvement, and finally to test the ALLInjectSequencer class, which deals with the complicated gymnastics of introducing or masking the new batch to various RF loops.

1 Experimental Conditions

This MD was conducted at 450 GeV. Batches of 12 bunches at 50 ns spacing were injected 925 ns apart. Up to 11 batches were injected. The RF voltage was set to 6 MV.

With these conditions the $4\pi\sigma_r\sigma_E$ emittance is 0.53 eVs (the 95 % population in 0.81 eVs), whereas the bucket area is 1.24 eVs.

2 Observations

Five fills of three to eleven batch injections were performed. The batch-by-batch blowup settings (target bunch length, gain, maximum phase noise amplitude, on/off) were varied among fills and for various batches. More details on the settings for each fill are presented in the Appendix.

Wire scans were performed periodically during each fill. The transverse emittance data from the wire scans and the bunch length information from the BQM were used to quantify the batch-by-batch blowup performance.

In this Section, we emphasize on the results from the last fill (2556), Beam 2, since the settings and procedure most closely resembled those that we plan to use during normal operation.

2.1 Selective blowup

The selective blowup of longitudinal emittance worked very well. It was possible to excite individual batches without affecting the leading and trailing (if any) batch, in a very short time period. Some time was dedicated to timing adjustments to achieve excitation with a single bucket accuracy, effectively calibrating the excitation system with bucket 1.

Figure 1 shows the average bunch length per batch for fill 2556, Beam 2. Initially, the
bunches come in with a bunch length of about 1.5 ns. In a few milliseconds though, the bunch length is reduced to about 1.1 ns due to the mismatched capture. After that, the bunch length increases with about 400 ps/hr due to IBS. During this injection, the batch-by-batch blowup was off for the first two batches and then turned on for the rest. Within a couple of minutes the excitation has increased the bunch length to the target value (varied among batches for MD purposes). The maximum excitation amplitude was reduced by a factor of 2 for the last batch leading to smoother – but slower – approach to the target value. Notice that there is no effect in the circulating batches when blowup is applied on the newly injected ones.

2.2 Transverse Emittance Growth Rates

Through the wire scan data, it was possible to estimate the transverse emittance growth rates per batch. It should be noted that the low number of bunches per batch (12) greatly reduced the accuracy of these measurements. The following measurements and analysis were conducted by Verena Kain, Michaela Schaumann, and Maria Kuhn.

From the transverse emittance data analysis, there is some early indication that growth rates are indeed lower for blown up batches. Figure 2, shows the transverse emittance growth rates per batch. The initial values have been renormalized for comparison purposes. The two batches with the highest growth rates are indeed the ones that were not blown up (most time since their injection). There is some spread in the values for the rest of the batches, most probably due to the variations in initial emittances, bunch lengths, and intensity.

Data from physics fills once the system is operational, will provide more accurate results, since there will be more bunches per batch and we will also be able to use the bunch-by-bunch specific luminosity.

3 ALLInjectSequencer class

At injection, there is a complicated sequence of RF gymnastics for the incoming batch, as summarized in the diagram in Figure 3. For example, the first batch is captured with beam phase loop ON. Then, we turn the phase loop off and start the batch-by-batch blowup. When the blowup is finished, we turn the phase loop back on. For the later batches, we capture with
Figure 2: Transverse emittance growth rates, Fill 2526, Beam 2. Initial value renormalized for comparison purposes. Same color scheme as Figure 1

the longitudinal damper on (in development). Then, we turn the damper off and start the batch-by-batch blowup. When the blowup is finished, we incorporate the new batch in the phase loop average (masking).

This complex process was tested in the later part of the MD. There were some control issues identified, which provided useful information for the final offline development of the system before deployment.

4 Conclusions

The batch-by-batch blowup MD results in successful selective blowup of individual batches. The MD has confirmed that we can modulate the cavity field on the buckets corresponding to the newly injected batch without affecting the circulating bunches (1 \( \mu \)s rise time).

The early results from transverse emittance growth rates is promising. More quantitative results will come from operation with longer batches of 144 bunches, where the data resolution will be higher and the batch-by-batch blowup will be more effective.

Possible particle loss at 450 GeV resulting from the longitudinal emittance blowup is a possible concern if/when the system becomes operational. The nominal SPS bunches (1.5 ns) are at the limit for capture in the LHC. Presently, the high intensity bunches (1.5-1.6e11 protons per bunch) extracted from the SPS often have very high emittances (up to 1.85 ns bunch length), resulting in higher capture losses. Additional phase and energy injection errors exacerbate these effects and increase possible losses due to the longitudinal emittance blowup.

5 Acknowledgments

The authors would like to acknowledge J. Tuckmantel’s many and significant contributions to this work, including the development of the noise generation algorithm used for the RF blowup. We would also like to thank the operators during the MD (Louis, Enrico, Giulia, Lasse, Verena) and Verena Kain, Michaela Schaumann, and Maria Kuhn for the transverse emittance measurements, analysis, and figures.
Figure 3: ALLInjectSequencer class diagram
6 Appendix

Average bunch length data per batch for all the fills during the MD and both beams are included here. Some details regarding the individual settings are also included.

6.1 Fill 2552

Three batches were injected on both rings. The goal was to blowup the middle batch only. Instead, for Beam 1 batches 1 and 2 were blown up. We concluded that it was necessary to better calibrate the timing of the excitation with respect to bucket 1 before proceeding. For Beam 2, the excitation did not work because we were exciting at the first revolution harmonic (instead of at baseband), the blowup mask was not on, and the phase loop was on (the phase loop cancelled the excitation).

Figure 4: Fill 2552, Beam 1.  
Figure 5: Fill 2552, Beam 2.

6.2 Fill 2553

Five batches were injected. The goal was to blowup the 2nd and 4th batches. Further and finer calibration of the excitation with bucket 1 was necessary. Excitation of individual batches on Beam 2 was successful towards the end of the fill, after the calibration was completed.

Figure 6: Fill 2553, Beam 1.  
Figure 7: Fill 2553, Beam 2.
6.3 Fill 2554

Initially 5 batches were injected in each ring. For Beam 1, we initially successfully targeted the 1st and 3rd batches. Later on, the excitation was turned on on all batches. Finally, towards the end of the fill, 3 more batches were injected, of which the last two were blown up as injected to a target length of 1.5 ns. The algorithm worked well.

For Beam 2, we initially successfully targeted the 2nd and 4th batches. Towards the end of the fill, 3 more batches were injected, of which the last two were blown up as injected to a target length of 1.6 ns. The algorithm worked well.

![Figure 8: Fill 2554, Beam 1.](image1)

![Figure 9: Fill 2554, Beam 2.](image2)

6.4 Fill 2555

Six batches were injected in both rings. The goals was to blowup all but first and last batches with a target bunch length of 1.6 ns, and a maximum phase noise amplitude of 0.005 of the carrier.

For Beam 1, the phase loop did not switch off as desired. As a result, the BPL tried to act to the coherent motion of the incoming batches, cancelled the effect of the blowup for those, but instead excited the first batch.

For Beam 2, the algorithm worked very well. The phase loop was off completely (since we hadn’t tested the ALLInjectSequencer class yet). As a result, the first and last batch experience higher bunch lengthening rate than during normal operations.

![Figure 10: Fill 2555, Beam 1.](image3)

![Figure 11: Fill 2555, Beam 2.](image4)
6.5 Fill 2556

The ALLInjectSequencer class was tested during this fill. For Beam 1, the phase loop masking did not work, so we manually blew up some batches. For Beam 2, we manually turned of the phase loop and set the algorithm to blow up batches 3 to 11. This worked very well. The maximum phase noise amplitude of 0.005 mrad was reduced by a factor of 2 for the last batch, leading to a smoother, but slower bunch length increase.

![Figure 12: Fill 2556, Beam 1.](image1)

![Figure 13: Fill 2556, Beam 2.](image2)

References