TAIL REPOPULATION MEASUREMENTS IN THE PSB

E. Benedetto, P. Zisopoulos, CERN, Geneva, Switzerland,
M. Cieslak-Kowalska, CERN, Geneva, Switzerland, and EPFL, Lausanne, Switzerland

Abstract

The PS Booster (PSB) is the first circular accelerator in the LHC injector chain providing protons for the full CERN complex. Each of its four rings provides beams in a range of intensities varying from 40 e11 p/cycle to 0.8 e13 p/cycle. Low intensity beams are produced by transverse shaving, that is by scraping the tails, in order to tailor the intensity and transverse emittances. Eventually, tails repopulate and the beam profile reshapes, under the effect of space charge, which is dominant at low energy in the PS Booster. This paper describes the results of the measurements after the shaving process, where the tails are scraped but finally re-appear in the transverse profile, and it provides a first benchmark with space-charge simulations. It highlights the challenges encountered and the lessons learned, to guide the future experiments. The final outcome of these studies is the characterisation of the halo creation mechanism and the determination of the diffusion speed, important for the design of the future PS Booster scraping system.

INTRODUCTION

Transverse shaving in the PSB consists in displacing the beam with a fast kicker and sending it in a controlled way towards an aperture restriction, to tailor transverse emittance and intensity after the multi-turn injection process is completed. Presently, it is done during the ramp at around 63 MeV (injection is at 50 MeV), while after the planned LHC Injectors Upgrade (LIU), it will occur slightly above the new injection energy of 160 MeV.

Figure 1 shows the intensity drop (top) when the kickers are pulsed (bottom). The kickers' strength reaches its maximum within 10 ms and then it decays slowly. For comparison, one PSB revolution period is ~1 μs at 160 MeV. Losses occur during the rise of the kicker up to the time when the maximum field is reached.

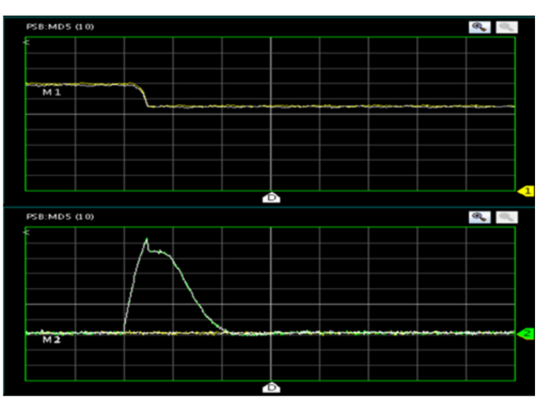

Figure 1: Signal of Beam Current Transformer (top) and kicker strength (bottom) to illustrate shaving. The horizontal scale is 20 ms /division.

Two special cycles with a long flat-top at 160 MeV and at 63 MeV were generated for the measurements, in order to disentangle the effects of acceleration.

As a first experiment, we measured the emittance evolution during and after the shaving at 160 MeV, with the wire scanners (WS). An attempt to reproduce the measurements in simulations is also presented.

The second experiment consisted in shaving the beam twice, with the same kicker strength. If there was no repopulation, there would be no intensity drop associated with the second shaving, while indeed a second intensity drop was observed. The technique is similar to the diffusion measurements in high-energy machines, such as the LHC [1], in which the beam is scraped twice by closing and opening a collimator, to measure halo formation. The timescale is very different, i.e. hours in the LHC and milliseconds in the PS Booster.

Due to the technology of the capacitive discharge kickers, it is not possible to power the same shaver twice in the 1.2 s long PSB cycle. In 2015, the shaving scheme was upgraded [2] and it was decided to keep both systems in parallel for a few years, in order to perform these studies. The strength of the two kickers was calibrated to produce the same amount of losses and both could be used in the same cycle.

The "old" shaving scheme consisted in an open bump, as explained in [2]. Due to the small difference between the vertical aperture at the absorber and at the main dipoles, losses occur at different location in the ring, depending on the tune and on the machine errors. With the "new" shaving system, instead, two kickers at about 180° phase advance create a closed bump in Period 8, i.e. at around s = 76 m, where the PSB absorber and aperture restriction is located, making it more robust with respect to loss localization.

WIRE SCANNERS MEASUREMENTS

Our first experiment consisted in shaving the beam at 160 MeV in the vertical plane and measuring whether and how the tails of the beam repopulate.

Figures 2 and 3 show the results from the analysis of the wire scanners measurements, during and after the shaving process. It should be noted that the points in the plots belong to consecutive cycles and fluctuations in intensity and emittance occur. Error bars are derived from the standard deviation computed at 430 ms.

The top plot of Fig. 2 shows the evolution of the mean position of the beam at the WS location (in red), which is proportional to the strength of the shaver, and the amplitude of the Gaussian fit (in blue), which is representative of the beam intensity. In the bottom plot, the fitted sigma and the residuals evolution are plotted.

ISBN 978-3-95450-182-3

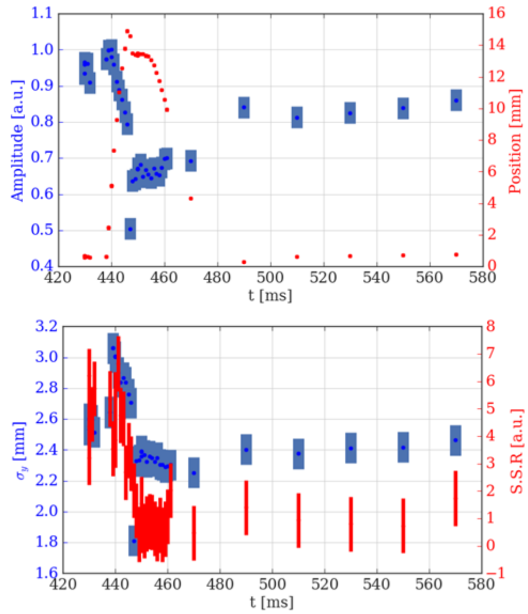

Figure 2: Analysis of the WS measurements at 160 Mev. Top: Gaussian fit mean position (red) and amplitude (blue) Bottom: sigma (blue) and the Sum of Squared Residuals (red) of the fit.

As a general trend, after a shaving of ~15% of the initial intensity, a decrease of the beam size of 10% is measured between the size at t = 430 ms and t = 490 ms, as well as a significant reduction of the residuals of the Gaussian fit.

Figure 3 presents the vertical profiles at these two time stamps. Indeed, the beam which initially had thick tails is becoming more Gaussian like. The injection working point, which is determining the beam brightness and also the tails, was (Qh=4.36,Qv=4.68)

We expected to gain a better insight of the profile evolution during the shaving by measuring the beam profile during the shaving process. By looking at Fig. 2, however, we noticed a strong correlation of both the amplitude and the sigma of the Gaussian fit with the beam displacement at the wire scanner location, which goes up to 15 mm. This correlation is not realistic and we suspect it is due either to the WS calibration curve being not precise at such a large vertical amplitude, or to deformation of the profiles due to the beam displacement during the measurement itself, which takes a few ms.

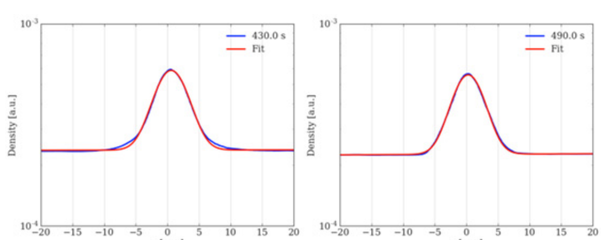

Figure 3: Vertical profiles before (left) and after (right) shaving for settings #2, from Table 1.

Simulations at 63 MeV

Similar measurements were performed at 63 MeV and compared with simulations. Numerical studies, done with PyOrbit [3] take into account space charge, the real shape of the shaver strength and the measured closed orbit distortion.

Figure 4 shows the emittance evolution over time. Every point is the average of 10 measurements and the standard deviation is used as errorbar. One should note that the wire-scanners profiles at 63 MeV suffer from Multipole Coulomb Scattering, which was negligible at 160 MeV. As analyzed in [4] an artificial blow-up of $\Delta\varepsilon$=0.512 mm mrad is expected due to the interaction with the wire scanner itself, therefore this emittance growth is subtracted to the measured emittance points.

Simulations do not reproduce the drop and rise back in the emittance, which is seen both in the measurements at 63 MeV and at 160 MeV, giving one more hint that it can be an artefact of the wire scanner measurements. Moreover the simulations overestimate the final intensity value and underestimate the final emittance. This can be related to the assumption of an initial Gaussian profile, which should be relaxed in future simulations.

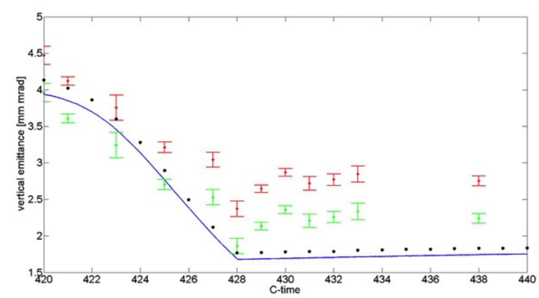

Figure 4: Vertical emittance evolution after shaving at 63 MeV. Red: result of WS meaurements. Green: measurements after scattering blow-up is removed. Blue: RMS emittance from simulations. Black: Gaussian fit from simulations.

DOUBLE SHAVING MEASUREMENTS

Profiting of the presence of both the "old" and "new" systems, we performed a vertical shaving on the beam twice in the same cycle. The idea behind was that if we were seeing a second drop in intensity it would mean that tail repopulation occurred.

The intensity measurements, which are presented here, come from the sum signal of the position pick-up (PU) in Period 8, close to where the aperture restriction is. In parallel, we performed measurements with the Beam Current Transformer (BCT) and the two agree very precisely. The advantage of the pick-up is the possibility to easily correlate intensity (sum signal) and vertical beam position (delta/sum) in Period 8.

The injection in the Booster was not very stable during the measurements, there was a variation on the initial intensities, as shown in Fig. 5, top. However, for a given first and second shaver strength, for all initial intensities, and losses from the first shaving, the second shaving loss was always a fixed percentage of the intensity after the first shaving. This can be seen in the bottom plot of Fig. 5, where the intensity is normalized with respect to the value reached at t=452 ms, after the first shaving has occurred.

In addition to this finding, we also tried different initial configurations, i.e. the injection tune was changed to have different brightness levels. Also in that case, the initial conditions were different but the ratio of the intensity after the second shaving versus the intensity after the first one was the same and depending only on the kicker strength (Table 1), indicating that machine non-linearities more than space charge are driving tail repopulation.

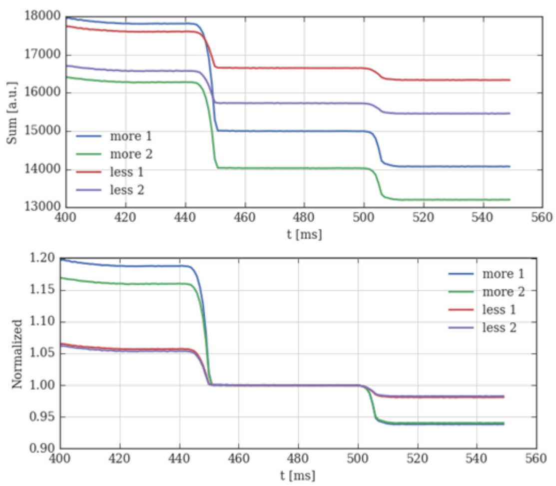

Figure 5: Intensity evolution, with large fluctuations and 2 different kicker settings. Bottom: intensity normalized with the value at t=452 ms.

Table 1: Intensity evolution for different initial injection tunes (affecting brightness) and kicker current

Injection settings	Start I [1e10]	After 1st drop [1e10]	After 2nd drop [1e10]
#0(7.5 A)	115	82 (72%)	72 (94%)
#1(7.5 A)	115	80 (70%)	75 (94%)
#2(7.5 A)	72	62 (84%)	56 (94%)
#0(6.5 A)	115	102 (90%)	100 (98%)
#2(6.5 A)	72	68 (94%)	67 (98%)

In order to estimate the characteristic time of the tail repopulation, we advanced the second shaver earlier in the cycle in steps of 10 ms, as shown in Fig. 6, top, while keeping the first one at a fixed time. We expected a progressive decrease of the losses while reducing the delay, but the final intensity level stayed constant (or proportional to the displacement), indicating that repopulation occurs in a timescale which is faster than 20 ms. Unfortunately, we could not get closer than 20 ms, without significant overlap of the rise and fall of the two shavers. Figure 6, bottom, shows the correlation between the losses and the position at the PU, showing that losses are proportional to the displacement.

CONCLUSIONS

The goal of the study was to characterize the tail repopulation mechanism after transverse shaving. Despite several difficulties, the experiments gave useful information on the dynamics and set the guidelines for future measurements.

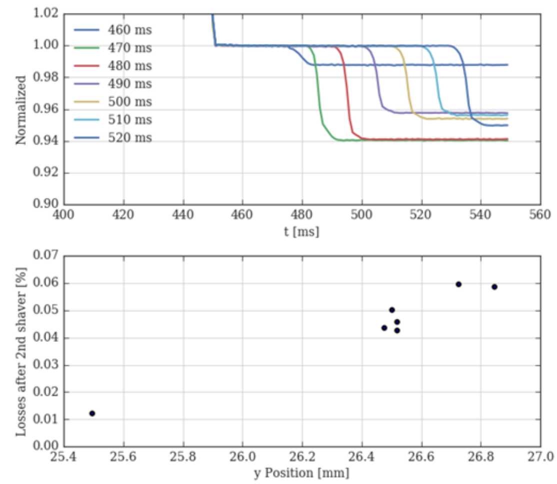

Figure 6: Intensity evolution, with large fluctuations and 2 different kicker settings. Bottom: percentage of losses after 2nd shaving vs. vertical position at the PU.

We have defined two experiments: 1) measure the profiles after transverse shaving and 2) shave the beam twice to measure the drop in intensity for different time delay, kicker strength and initial beam brightness.

From the profile measurements and analysis, we observed how a beam with initial thick tails become Gaussian after a shaving of ~15% of the intensity. The measurements however did not reveal the details of the shaving process, due to the large displacement at the wire-scanners location, which affected the precision of the measurements. Future measurements should be performed with the "new" shavers, as the displacement at the WS location is small. Moreover, when using the WS at low energy (i.e. 63 MeV), it is necessary to correctly take into account the Multipole Coulomb Scattering at the wire itself, which creates up to 0.5 mm mrad blow-up. In [4], indications are provided on how to possibly include this effect in the data analysis. The initial distribution plays an important role in the losses and final emittance value and needs to be correctly taken into account in future simulations.

From the experiment of powering the shavers twice, a second drop in intensity was observed, meaning that tail repopulation occurred. By reducing the delay between the kicks we observed that the final intensity is always the same or proportional to the displacement at the aperture restriction, indicating that the repopulation characteristic time is smaller than 20 ms. The overlap between 2 kickers needs to be considered to explore this time interval.

ACKNOWLEDGMENTS

The authors would like to thank the PSB Operation team for the support during the measurements.

ISBN 978-3-95450-182-3

REFERENCES

[1] G. Valentino *et al*., "Beam diffusion measurements using collimator scans in the LHC", *Phys. Rev. ST Accel. Beams*, vol. 16, p. 21003, Feb. 2013.

[2] M. Cieslak-Kowalska *et al.*, "New Shaving Scheme for Low-Intensity Beams in the CERN PS Booster and Feasibility at 160 MeV", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper THPF087, pp. 3893-3896.

[3] A. Shischlo *et al*., "The Particle Accelerator Simulation Code PyORBIT", *Procedia Computer Science*, vol. 51, 2015, p. 1272.

[4] M. Cieslak-Kowalska and E. Benedetto, "Interpretation of Wire-Scanner Asymmetric Profiles in a Low-Energy Ring", in *Proc. HB2016*, Malmo, Sweden, July 2016, paper MOPR023, pp. 115-119.