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TRANSVERSE STUDIES WITH IONS AT SPS FLAT BOTTOM

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Abstract

The LHC injectors upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN in view of the increased beam performance required for the High Luminosity LHC (HL-LHC) project. For the ion chain, the losses and emittance growth in the SPS impose presently the main performance limitation. The significant beam degradation encountered on the long injection plateau has been studied during the 2016 MD runs with Pb82+. In this report we present the systematic measurements of emittance, bunch length and transmission performed along the injection plateau for different bunch intensities. We present, as well, static and dynamic tune scans for the optimization of the working point and measurement of the loss rate at closeby resonances.

MOTIVATION AND MD RUNS

The LHC injectors upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN in view of the increased beam performance required for the High Luminosity LHC (HL-LHC) project. For the ion chain, the losses and transverse emittance growth in the SPS impose presently the main performance limitation [1]. The losses increase with the bunch intensity, as shown in Fig 1 for the case of 7 injections from PS as used in 2016 for the LHC p-Pb run. For comparison, the nominal bunch intensity for LIU is 3.6e+8 Pb ions at SPS injection [1, 2].

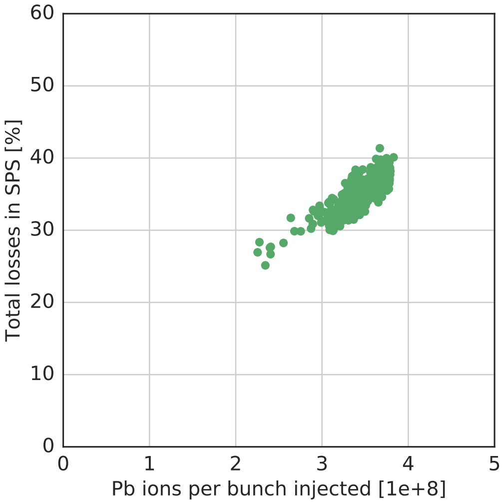

Figure 1: Total losses in the SPS as a function of bunch intensity. The nominal bunch intensity for LIU is 3.6e+8 Pb ions.

A big fraction of the beam degradation occurs on the SPS injection plateau, also referred to as flat bottom (FB) in the following. The FB length for LIU will be approximately 50 s in order to accumulate 14 injections from the PS. We suspect there are various sources for these losses; namely space charge, intrabeam scattering (IBS), RF noise, and aperture limitations. A series of machine development (MD) studies were performed during the Pb ion run between October and December of 2016 to study these effects. The FB duration of the parallel MD cycles used was 3 s. These short cycles were used to perform static and dynamic tune scans. Additionally, four dedicated MD runs took place in November 2016. The dedicated MD cycles had FB durations of 22 s, which enabled measurements of transmission, bunch length and emittance evolution along the longer injection plateau.

MEASUREMENTS

Four bunches from the PS (i.e. one batch) were injected at the beginning of the FB (defined as $t = 0$ s) of each MD cycle. Further injections were avoided in order to enable direct measurement of emittance and intensity evolution along the FB. The SPS was tuned to the default Pb-ion working point (WP) of $Q_x = 20.30$, $Q_y = 20.25$. All measurements were taken at this WP, unless stated differently.

Transverse emittances

The emittance of the beam cannot be directly measured. However, combining the measurements of the transverse beam sizes with the knowledge of the optical functions (from the lattice model or from measurements), the transverse emittances can be derived. In the SPS two sorts of diagnostic instruments were used to measure the beam size: a beam gaseous ionization monitor (BGI), which was still under commissioning, and rotational wire scanners (WS) in the horizontal and vertical planes. While the BGI enables several measurements along one cycle, the WS can only be fired twice along the same cycle. For this reason, WS measurements of the emittance evolution along the FB have been performed on different cycles. The measurements have been repeated between 5 and 15 times and the error bars indicate the standard deviation.

First the emittance evolution along the FB was studied for bunches with a constant intensity. The horizontal emittance measured shortly after injection was approximately 50% larger than the vertical one. The observed emittance evolution is also different for both planes; while it increases steadily in the vertical plane, the overall increase in the horizontal plane is much smaller, showing even a small decrease in the first half of the cycle, as plotted in Fig. 2. Measurements with the WS and the BGI show a qualitative agreement, even when taken for different bunch intensities.

Another set of emittance measurements was performed with different bunch intensities. The emittance measured at SPS injection increases linearly with the bunch inten-

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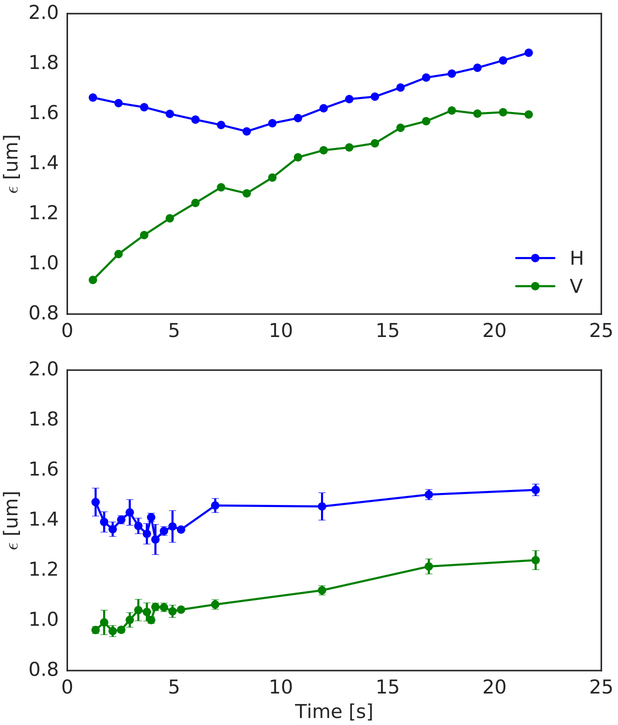

Figure 2: Emittance evolution along the FB measured with the BGI for a bunch intensity of 3.5e+8 Pb ions/bunch at injection (top), and measured with the WS for a bunch intensity of 2.6e+8 Pb ions/bunch at injection (bottom).

sity. This intensity dependence of the emittance is probably already created upstream in the injector chain (e.g. space charge effects at PS injection [3]). The emittance at the end of the SPS FB also increases linearly with bunch intensity as shown in Fig 3. In the vertical plane the emittance seems to grow by a constant amount, independent of intensity (at least in the range studied in the measurements). In the horizontal plane on the other hand there is minor blow-up for lower intensity but practically no emittance blow-up for the higher intensity bunches measured. The reason for this is not yet understood. The explanation might be linked to the observed degradation of the transmission for increasing intensity as shown in Fig. 4.

To further investigate the underlying mechanisms that define the emittance evolution on the SPS FB, it was attempted to vary the transverse emittance of the injected beam independently of the bunch intensity. However, the brightness at SPS injection (intensity/emittance ratio) remained unaffected despite 1) injecting only 3 instead of 7 Linac3 pulses into LEIR, 2) partially closing the slits placed in the transfer line between Linac3 and LEIR to decrease the bunch intensity, and 3) changing the cooling efficiency in LEIR by varying the closed orbit in the electron cooler. None of these methods enabled the independent variation of the emittance and bunch intensity, which is another indication that the dependence is created either in LEIR, or at PS injection.

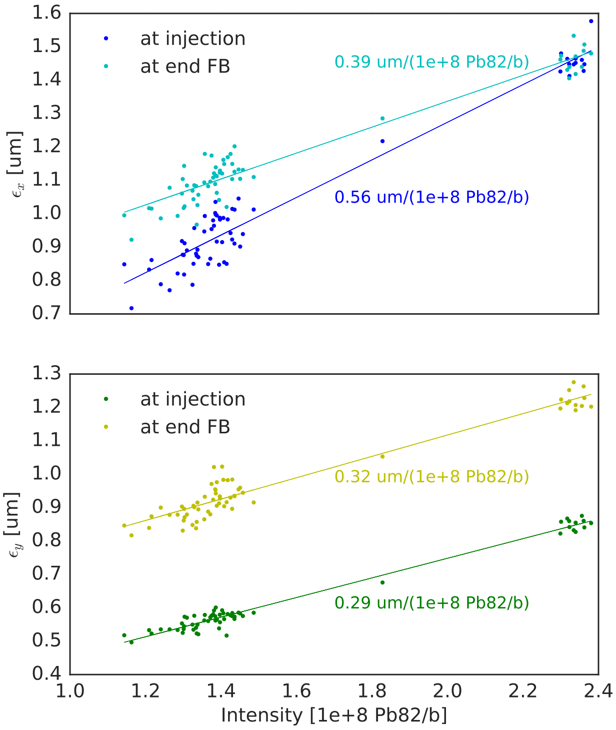

Figure 3: Emittances at injection and at the end of the FB as a function of bunch intensity for the horizontal (up) and vertical planes (down).

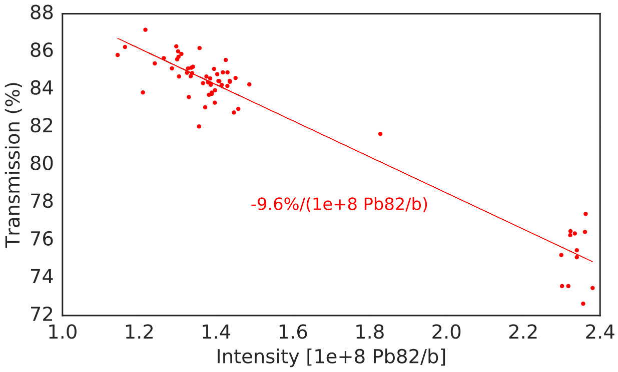

Figure 4: Transmission as a function of bunch intensity.

Bunch Length

The bunch length evolution along the FB was measured with the beam quality monitor (BQM), which is triggered at each injection timing (i.e. every 3.6 s). Additionally, the mountain range (MR) displays one trace per turn, for 50 consecutive turns. As for protons, the bunches are not perfectly matched at SPS injection due to the different RF frequency compared to the PS. Therefore, the bunch length evolution from the BQM data is only considered starting from $t = 3.6$ s (i.e. the moment where in principle a second batch could be injected) until the end of the FB at $t = 21.6$ s. A bunch length reduction of approximately 10% is observed, which slightly increases with intensity, as shown in Fig. 5. However it is important to note that longitudinal studies of the Pb beam at the SPS have shown that the amount of uncaptured beam increases along the FB [4]. This implies that there is a continuous spill of particles out of the bucket (on the order of 5% in 20 s).

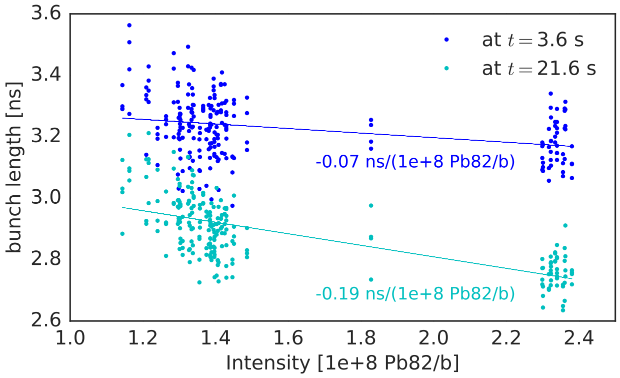

Figure 5: Bunch lengths at $t = 3.6$ s and at the end of the FB ($t = 21.6$ s) as a function of bunch intensity.

Observations without RF

It should be emphasized that the beam degradation described above, i.e. losses and emittance growth, is observed only for bunched beams. In the absence of RF (i.e. with an unbunched beam) the emittance blow-up is negligible and almost no losses are observed. This could be measured directly with the BGI when the RF tripped in the middle of a cycle as shown in Fig. 6. From this observation it seems that vacuum issues can be excluded as the source of beam degradation, since these would also affect unbunched beams. On the contrary, these observations point more towards IBS and space charge, which are negligible for the unbunched beam, and RF noise as potential sources.

Tune Scans

Dynamic and static tune scans were performed to measure the loss rate at the different resonances in view of optimizing the WP. The tune spread caused by space charge is proportional to the line density of the beam. In the case of the bunched Pb beam the tune shift at injection is large (about $\Delta Q_x = -0.2$, $\Delta Q_y = -0.3$ for the beam parameters during the MDs presented here). The resulting tune footprint overlaps many resonances, even the vertical integer, as shown in Fig 7. On the other hand, in the case of an unbunched beam the line density is so small that the tune spread created by space charge is negligible. The footprint is point-like and the resonances can be probed independently. Thus, we dynamically scanned the tune diagram while measuring the loss rate as function of the working point in the absence of RF. As shown in Fig. 8, the highest loss rates were measured at the point $Q_x = Q_y = 20.33$, where the diagonal $(Q_x - Q_y)$, the third order integer $(3Q_x)$ and the third order coupling $(Q_x + 2Q_y)$ resonances cross. Also the third order coupling resonance $(Q_x - 2Q_y)$ is clearly excited. Resonances other than the normal third order resonances and the diagonal appear to be much weaker.

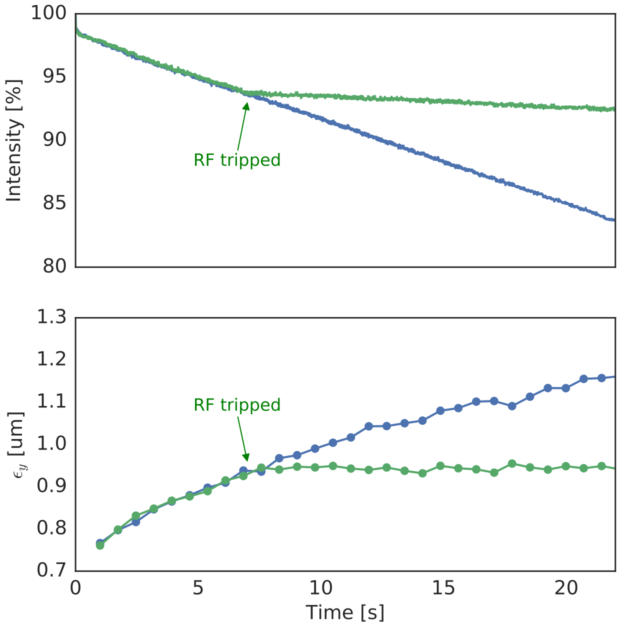

Figure 6: Comparison of losses (up) and emittance blow-up (down) along the FB for two consecutive cycles; the first one with the RF ON (blue) and a second one in which the RF tripped at $t = 7$ s (green).

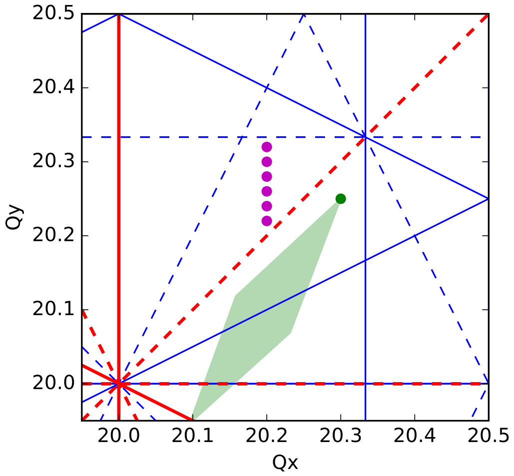

Figure 7: Tune diagram showing resonances up to third order. The standard WP is represented by a green dot. Other WP considered as alternatives are represented by pink dots. Solid line correspond to normal resonances and dashed lines to skew resonances, where systematic resonances are indicated by red colors and non-systematic by blue.

The standard WP for Pb-ions, $Q_x = 20.30$, $Q_y = 20.25$, is situated in an area of low loss rates. We also measured an area with low loss rates placed opposite of the diagonal. We explored some alternative WPs in this area, represented as pink dots in Fig 7, by measuring the transmission and

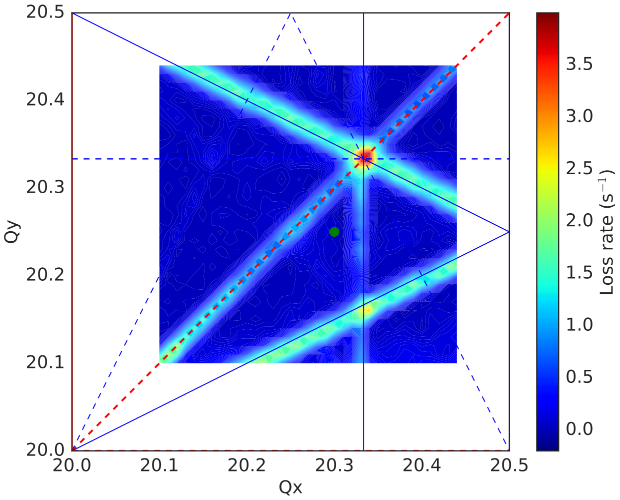

Figure 8: Dynamic tune scan using an unbunched beam.

transverse emittance blow-up along the 22 s FB in the case of a bunched beam. As shown in Fig. 9 all alternative WPs have a lower transmission compared to the standard WP. It is interesting to note that the standard WP has a lower horizontal emittance blow-up but a higher vertical emittance blow-up compared to the alternatives studies.

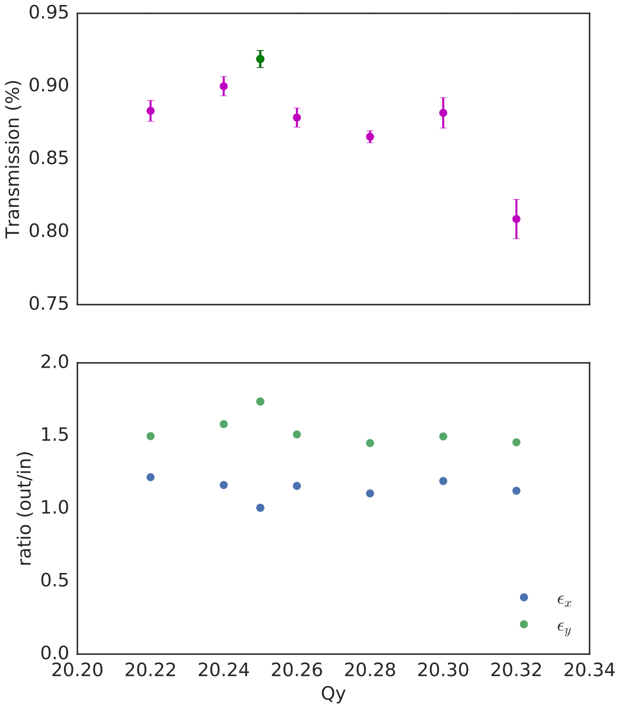

Figure 9: Top: transmission along the FB for the standard WP (green dot) and alternative WP (pink dots). Bottom: transverse emittance blow-up.

We repeated the transmission measurement along the FB for many more points on the tune diagram. However, the scan of a much larger area could only be done in parallel MDs using the cycle with a 3 s long FB. In this case the transmission difference between the standard and the alternative WP is not observed. Further analysis and investigations need to be done.

Closed orbit distortions from BGI magnets

An additional observation was done during the MD runs which we consider worth to be mentioned: the transmission along the FB decreased as a function of the BGI vertical dipole current. The transmission went down to 60% when the BGI magnets were powered to their maximum current, 60 A. Simultaneously, the BPMs show large deviations from the reference closed orbit (c.o.), which is a clear indication that the orbit bump created by the dipoles is not fully closed. After re-optimizing the correctors to minimize the orbit deviations the transmission could be recovered, as shown in Fig. 10. This shows that the vertical closed orbit correction is critical for the ion beams, as the beam size is large compared to the available aperture.

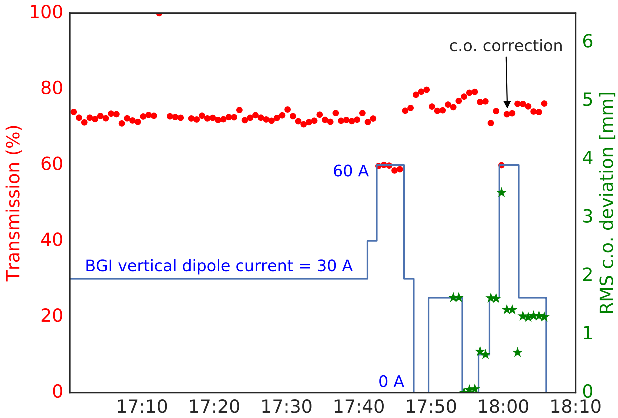

Figure 10: Transmission along the FB (red dots) and RMS c.o. deviation (green stars) for different current values of the BGI vertical dipoles.

CONCLUSIONS

Strong degradation of the Pb-ion beam is observed on the long injection plateau of the SPS, consisting of a significant reduction of the transmission and a transverse emittance blow-up. The transmission of the beam decreases linearly with the bunch intensity. For the beam parameters used during the MDs, i.e. about 50% larger horizontal than vertical emittance at injection, the emittance blow-up occurs mainly in the vertical plane. A bunch length reduction of the order of 10% has also been observed along the FB.

The beam degradation is most likely due to collective effects (IBS, space charge), RF noise, and aperture limitations. Vacuum seems to play a minor role, since there is no blow-up and the losses stabilize when the RF is switched OFF.

It has also been observed that powering the vertical BGI dipoles leads to c.o. distortions and a reduced transmission along the FB. The transmission can be recovered if the corrector settings are re-optimized.

WP scans have been performed to explore the tune diagram and measure the excitation of the beatron resonances. So far no better WP has been found. However, a big amount of experimental data is still available for further analysis.

During the year 2017 no Pb beam runs are planned. Therefore, these measurements will only be continued in 2018. However, machine development runs with Xe beams in SPS could be of interest for exploring another region of the parameter space.

REFERENCES

[1] H. Bartosik, *LIU Baseline for Ions*, presentation at LHC Performance Workshop 2017.

[2] *LHC Injector Upgrade, Technical Design Report, Volume II: Ions*, EDMS 1626950 (2016).

[3] A. Huschauer, H. Bartosik, and A. Saa Hernandez *Pb ion emittance evolution across the injector chain*, these proceedings.

[4] H. Bartosik and T. Bohl, *Test of fixed harmonics in SPS*, these proceedings.