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PB-IONS IN HARMONIC NUMBER 4653 AT SPS FLAT BOTTOM

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Abstract

Pb-ion beams suffer from strong beam degradation such as transverse emittance growth and losses on the long flat bottom of the SPS cycles used for LHC filling. A possible contribution to the losses could come from RF noise, especially due to the frequency and amplitude modulation during each revolution period of the fixed frequency acceleration mode required for the acceleration of these beams. A machine development session in 2016 was devoted to a direct comparison of a cycle with fixed harmonic number at flat bottom and a cycle with the usually used fixed frequency mode. The main results are reported here.

INTRODUCTION AND MOTIVATION

Pb-ion beams suffer from strong beam degradation (transverse emittance growth and losses) on the long flat bottom of the SPS cycles used for LHC filling. In fact, the SPS is presently *the* bottleneck for Pb-ion beams and this is in particular relevant for the performance reach in the context of the LHC injector upgrade project (LIU) [1]. To better understand the motivation for the machine development studies with harmonic number, h, of 4653, a short introduction about the RF low level needed to accelerate the heavy ion beams in the SPS should be made.

In a synchrotron the synchronism between the RF voltage for acceleration and the beam is established by choosing

$$f_{\mathrm{RF}} = h f_{\mathrm{rev}}.$$

In this case $h = const$ and $h \in \mathbb{N}$ (Fixed Harmonic Number Acceleration, FHA). For lead ions, $^{208}\mathrm{Pb}^{82+}$, FHA is not possible in the SPS. The frequency swing of the revolution frequency, f_{rev}, between injection and flat top is such that with a constant value of h, the value of f_{RF} would be outside the bandwidth of RF system at a certain time during the acceleration cycle. The solution which was adopted consists of keeping $f_{\mathrm{RF}} = const$ (Fixed Frequency Acceleration [2], FFA) and allowing a variable h

$$h = h(f_{\mathrm{rev}}), h \in \mathbb{R}$$

This comes at a price of frequency modulation (FM) and amplitude modulation (AM) of f_{RF} at f_{rev}. At each SPS revolution period of about 23 μs the RF is switched on before batches enter the Lon Straight Section (LSS) in BA3, and the RF is switched off when the beam has left LSS3 with a 50% duty cycle at the same time while it is modulated in frequency. At first sight it is expected that the RF noise in amplitude and phase would be larger with AM and FM. Therefore, in view of the future low level RF system (after Long Shutdown 2), the question was whether FHA (no FM and no AM) at the flat bottom could improve the transmission of the ion beam in the SPS.

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COMPARISON OF FFA AND FHA

Conditions

In 2016 it was the first time that a comparison of FFA with FHA was possible with the same optics and the same injected beam. To make the comparison it was required to i) make FFA and FHA ppm, ii) operate FFA with standard conditions for iLHC beam, FM, AM and iii) operate FHA with $h = 4653$, no FM, no AM.

Some limitations were encountered: The length of the flat bottom was only about 20 s (in the past it had been nearly twice as long) and no acceleration was possible due to software limitations related to the Coarse Frequency Program. Furthermore, the cavity phasing was not ppm: for $h = 4653$ $V_{\mathrm{RF}} \approx 0.5 V_{\mathrm{RF,LSA}}$, nevertheless equal V_{RF} values could be achieved at flat bottom.

In detail, the conditions for the FFA/FHA comparison were that the Q20 optics was used in both cycles, LHC_ION_7Inj_Q20, ID: 10127 (LHCION2) and LHC_ION_7Inj_Q20_2016_MD, ID: 10877 (LHCION4). The Nominal Beam with 4 bunches spaced by 100 ns was injected with about $N_{\mathrm{Q}} = 2.9 \times 10^{10}$ charges per bunch. All observations were made using the first batch and observing i) the bunch length, ii) the bunch peak amplitude and iii) the bunch position along the flat bottom.

Results

The bunch profiles at injection for the two cases of FFA and FHA are shown in Fig. 1. They confirm that the injected beam had been the same in the two cases. The bunch profiles at the end of the flat bottom are shown in Fig. 2. Also here, there is no difference between the bunch shapes for the two cases of FFA and FHA.

Comparing the bunch length versus time, in each case for the four bunches of the first batch, there is no visible difference, see Fig. 3. The same applies for the bunch peak amplitude versus time as can be seen in Fig. 4. Also with a higher vertical resolution, there is no difference between the two cases of FFA and FHA. This is true both for the bunch length and the bunch peak amplitude versus time, see Fig. 5 and Fig. 6. The numeric values of the bunch length reduction and the bunch peak amplitude reduction between $t_1 = 294$ ms and $t_2 = 20\,000$ ms are identical, see Table 1. Also the values of the standard deviation of the bunch positions, a measure of the RF noise, during the same period, do not show any difference.

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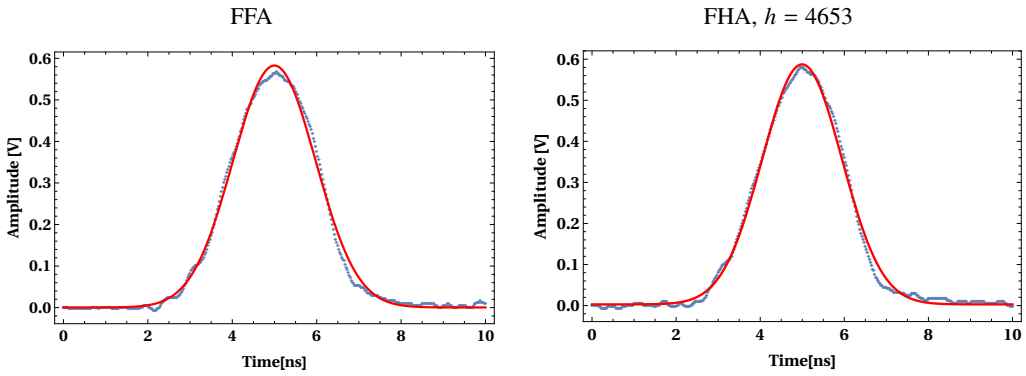

Figure 1: Typical bunch profile of the first injected bunch for the two cases of FFA and FHA.

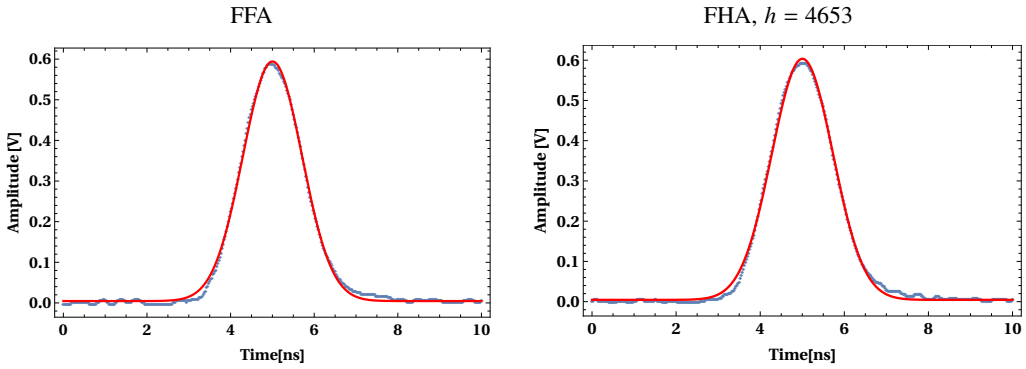

Figure 2: Typical bunch profile of the first bunch at the end of the flat bottom for the two cases of FFA and FHA.

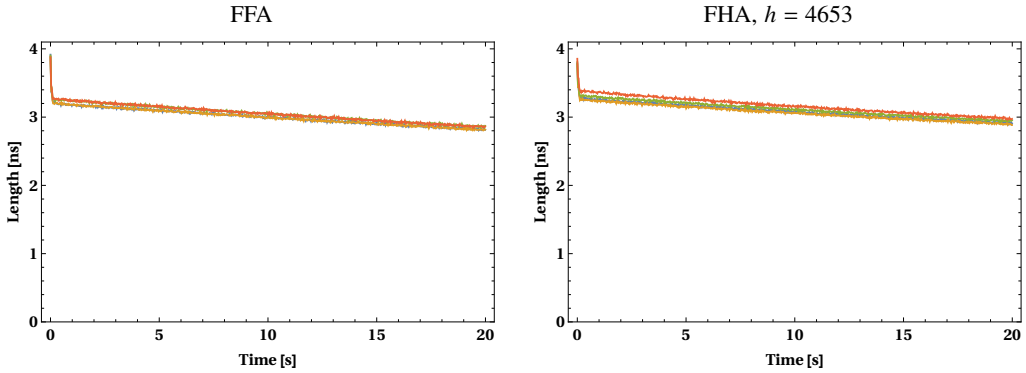

Figure 3: Bunch length of the four bunches versus time for the two cases of FFA and FHA.

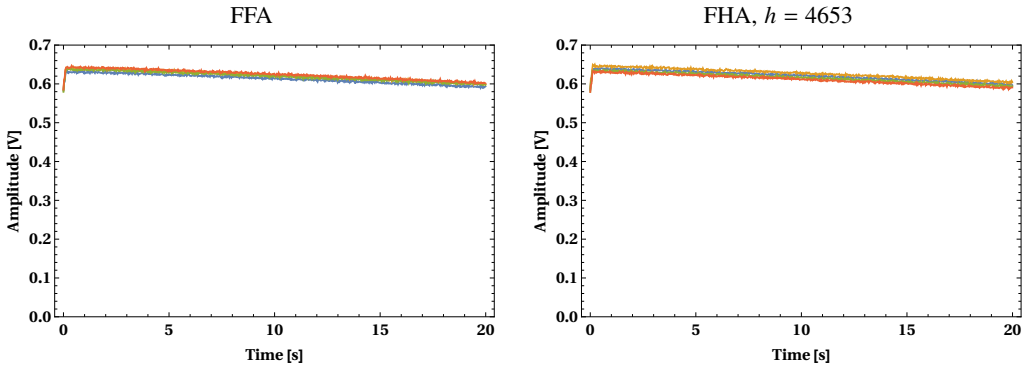

Figure 4: Bunch peak amplitude of the four bunches versus time for the two cases of FFA and FHA.

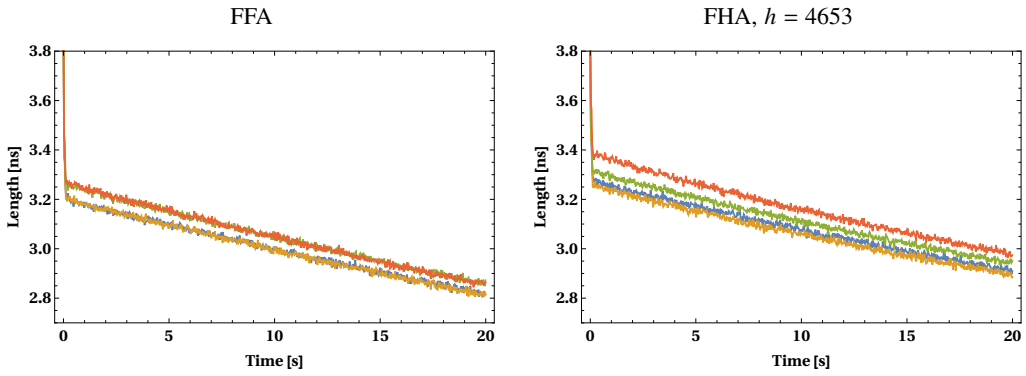

Figure 5: Bunch length of the four bunches versus time for the two cases of FFA and FHA.

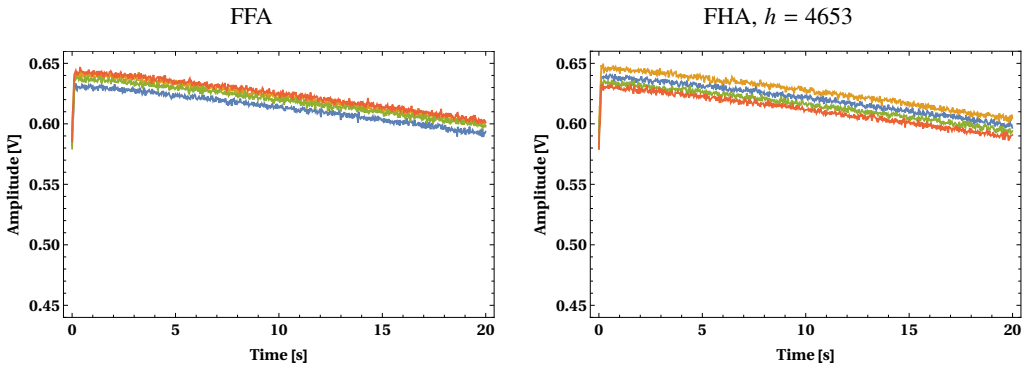

Figure 6: Bunch peak amplitude of the four bunches versus time for the two cases of FFA and FHA.

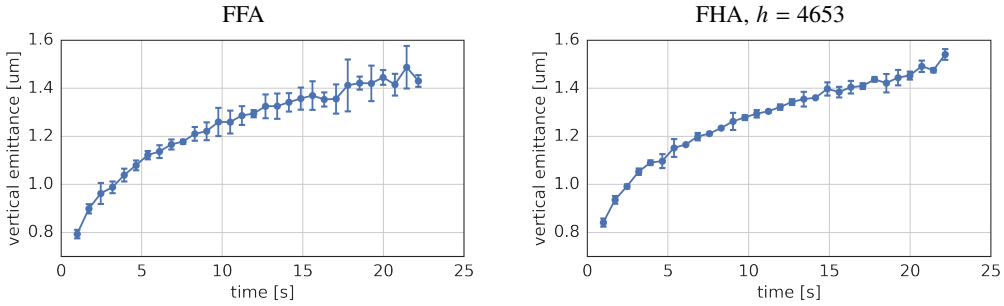

Figure 7: Vertical emittance measured with the BGI along the flat bottom with FFA and FHA.

Table 1: Comparison FFA and FHA

	FFA	FHA
bunch length reduction	-12%	-12%
bunch peak amplitude reduction	-6%	-6%

Another comparison was made in terms of transverse emittance blow-up. As reported in [3], relatively strong vertical emittance blow-up is observed along the flat bottom of the operationally used cycle with FFA. The same behaviour is observed in the cycle with FHA, as seen by the vertical emittance evolution measured with the Beam Gas Ionisation (BGI) monitor illustrated in Fig. 7. Unfortunately the horizontal BGI monitor could not be used during the MD.

BEAM LOSS ALONG FLAT BOTTOM

As discussed in the previous section, the beam behaviour in FHA compared to FFA is very similar both in terms of bunch length and bunch peak amplitude evolution along the flat bottom. Similarly, the evolution of the intensity along the flat bottom was the same on both cycles. In particular, important losses out of the RF bucket were observed. This is shown in Fig. 8 for the case of the FHA. The integrated longitudinal bunch profile measured with a wall current monitor clearly shows that some particles are not captured into the RF bucket at injection (about 2%), but they remain in the machine as observed by the DC beam current transformer (BCT) measurements. In addition, since the discrepancy between integrated bunch profiles and BCT signal grows along

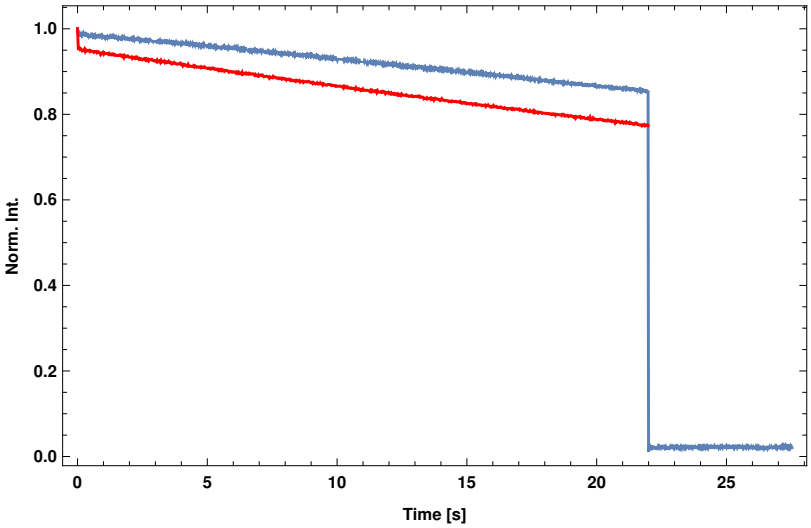

Figure 8: Intensity along the flat bottom of the FHA cycle as measured with the DC-BCT (blue) and as obtained from integrating the longitudinal profile measured with the wall current monitor (red).

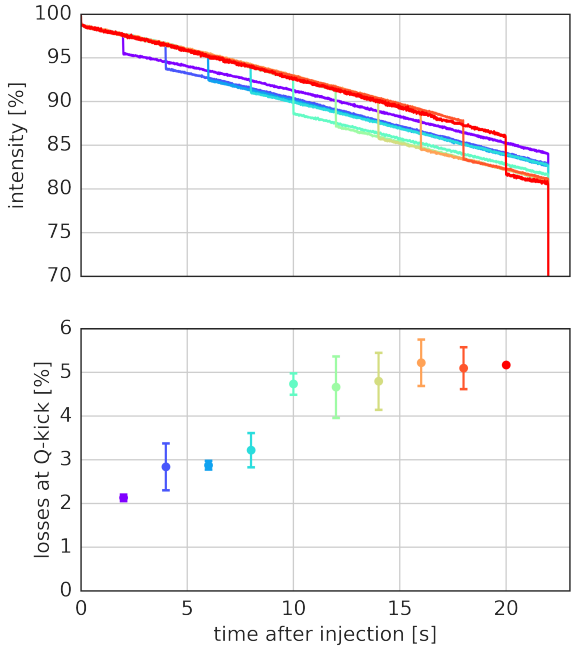

Figure 9: Evolution of intensity along the flat bottom of the FHA cycle as measured with the DC-BCT (top) and losses at the moment of the tune kick to eliminate uncaptured beam (bottom). The different colours correspond to different trigger times of the tune kicker. An average of about 3 cycles were used in each configuration and the errorbars indicate the standard deviation.

the flat bottom, some particles are continuously spilling out of the RF buckets. At the end of the flat bottom more than 5% of the particles are outside of the RF buckets. This was also verified with an independent measurement by pulsing the SPS vertical tune kicker at maximum voltage with a waveform adapted to cover only the empty RF buckets of the SPS circumference. By adjusting the trigger time of the tune kicker the amount of uncaptured beam along the flat bottom can be obtained from the BCT measurement as shown in Fig. 9. Also this measurement shows that the amount of uncaptured beam increases along the flat bottom, from about 2% at injection to more than 5% at the end of 20 s storage time, which is consistent with the measurement above.

SUMMARY AND CONCLUSION

The comparison of the two Q20 cycles with a 20 s long flat bottom shows no significant differences between the operation with FFA and FHA at $h = 4653$, both in terms of bunch length and bunch peak amplitude evolution along the flat bottom. Also the losses and the vertical emittance evolution (horizontal could not be measured) are very similar. Measurements in the FHA cycle show that more than 5% of particles are spilled out of the RF bucket along the flat bottom, similar as with FFA. No improvement of the flat bottom transmission was observed with FHA compared to the operationally used FFA.

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REFERENCES

[1] "LHC Injectors Upgrade Technical Design Report, Volume 2: Ions", EDMS 1626950, CERN, Geneva, Switzerland (2016).

[2] D. Boussard, J. M. Brennan, T. P. R. Linnecar, "Fixed Frequency Acceleration in the SPS", CERN SPS/89-49 (ARF), December 1989.

[3] A. Saa Hernandez *et al.*, "Transverse studies with ions at SPS flat bottom", these proceedings.