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SPS BATCH SPACING OPTIMISATION

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INTRODUCTION AND MOTIVATIONS

Until 2015, the LHC filling schemes used the batch spacing as specified in the LHC design report. The maximum number of bunches injectable in the LHC directly depends on the batch spacing at injection in the SPS and hence on the MKP rise time.

As part of the LHC Injectors Upgrade project for LHC heavy ions, a reduction of the batch spacing is needed. In this direction, studies to approach the MKP design rise time of 150 ns (2-98%) have been carried out. These measurements gave clear indications that such optimisation, and beyond, could be done also for higher injection momentum beams, where the additional slower MKP (MKP-L) is needed.

After the successful results from 2015 SPS batch spacing optimisation for the Pb-Pb run [1], the same concept was thought to be used also for proton beams. In fact, thanks to the SPS transverse feed back, it was already observed that lower batch spacing than the design one (225 ns) could be achieved. For the 2016 p-Pb run, a batch spacing of 200 ns for the proton beam with 100 ns bunch spacing was requested and finally used.

Thanks to the good performance of the 200 ns scheme, this was proposed as operational scenario for 2017 p-p physics with BCMS beams.

In order to confirm the first observations and to evaluate the operational settings, the 2016 MD sessions were carried out.

SPS INJECTION SYSTEM

The SPS injection system is composed by a horizontal septum, MSI, and kicker, MKP. The MSI steers the beam coming from TT10 onto the nominal closed orbit (CO) and the MKP adjusts the angle to match the one of the circulating beam.

The MKP system is composed of four tanks, each of them connected to a high voltage generator. The first three tanks host 12 magnets of small aperture type with a rise time of 150 ns. The last tank hosts 4 large types which have a rise time of 225 ns (from specifications). Each generator is connected to two thyratron switches where each of them is connected to two magnets.

The total rise time, which then directly translates in the minimum batch spacing, is the result of the proper synchronisation of the individual magnets field waveforms. To this, ageing effect of the thyratron should also be added, because they will increase the response time of the switches and hence increase the rise time. Another source of error which contributes to the rise is the jitter of the triggering. All this can add up to several tens of ns.

ROAD TO 200NS batch spacing

To aim to have 200 ns batch spacing at injection, two possible optimisations are possible: fine synchronisation of each individual switches, optimal sharing of residual oscillations between injected and circulating batch. The main constraints are given by emittance growth and large intensity reduction due to high populated tails during scraping (or transport).

Fine synchronisation

The overall rise time depends on the individual rise times and on the synchronisation of them with respect to the beam passage. Theoretically, the optimum overlap is obtained when the individual delays are calculated accounting for the beam time of flight from one magnet to another.

The stability of the waveform then depends on the reproducibility of each individual waveform and on the stability of the conduction time of each individual switches. This can translate in a jittering optimum, which, if it becomes comparable to the bunch spacing, makes the optimum delay very unstable. Hence, switches health is a key parameter to achieve a clean and durable short rise time. In Fig. 1 an example of terminating magnet resistor (TMR) current measurements is shown, when the delay are set as the time of flight between individual magnets.

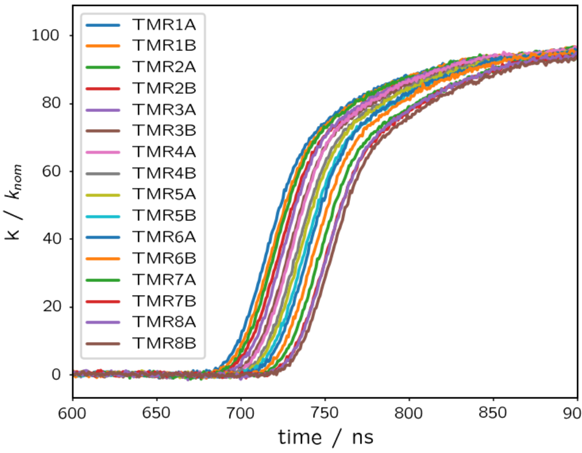

Figure 1: Example of TMR measurements accounting for perfect delay, calculated as time of flight between magnets.

Optimum delay

The other parameter to adjust to achieve a good injection with tighter batch spacing is the delay of the whole MKP system with respect to the injected batch. The optimum is reached when the residual oscillation is evenly shared between the last bunch of the circulating batch and the first of the injected one, as shown in Fig. 2.

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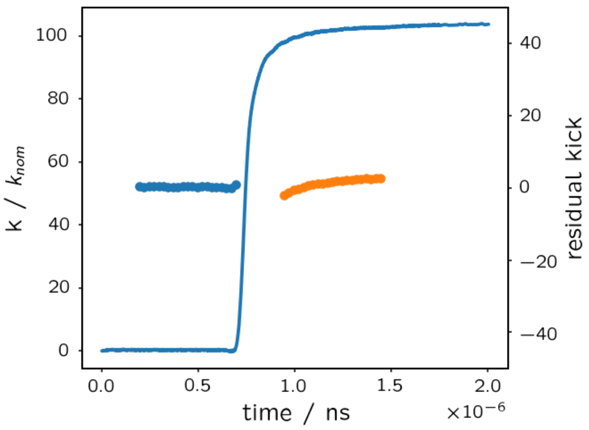

Figure 2: Schematic view of synchronisation of the normalised MKP waveform with injected batch (orange) and circulating one (blue).

In the SPS, the emittance growth that could be produced by such a residual kick is too small to be measured with the present profile measurements available. One way to evaluate how much each individual bunches are kicked by the MKP is to use the LHC BPMs in LSS5. These are BPMs which can resolve position bunch-by-bunch and turn-by-turn (Fig. 3).

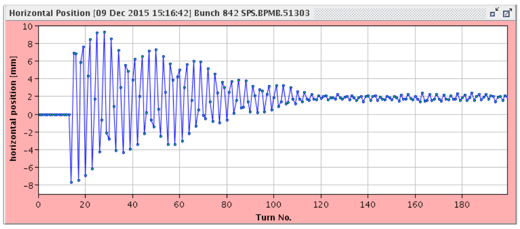

Figure 3: Example of horizontal position evolution of the first injected bunch as measured with one of the LHC BPMs.

The figure of merit used to evaluate the residual oscillation on the first injected and the last circulating bunch is the half amplitude:

$$A_{osc} = \left|\frac{x_{max} - x_{min}}{2}\right| \qquad (1)$$

where x_{min} and x_{max} are the minimum and maximum horizontal amplitude excursions recorded around the injection event. The delay for which A_{osc} is the same for both bunches under analysis represents the optimum. In Fig. 4, the results for 225 ns and 200 ns batch spacing are shown. The increase in the residual oscillation when passing from 200 to 225 ns is only 1.5 mm.

The beam obtained with 200 ns batch spacing was then delivered to the LHC, where the final conclusion on the quality of such a scheme can be drawn. In Fig. 5, the intensity bunch-by-bunch is compared between 250 (top) and 200 ns (bottom) after injection into the LHC. No significant differences between the two schemes could be observed. In Fig. 6, the emittance bunch-by-bunch, as measured with the BSRT, is shown when a 200 ns batch spacing beam is injected. The emittances of the bunches at the discontinuity are in the range of the intra-bunch jitter.

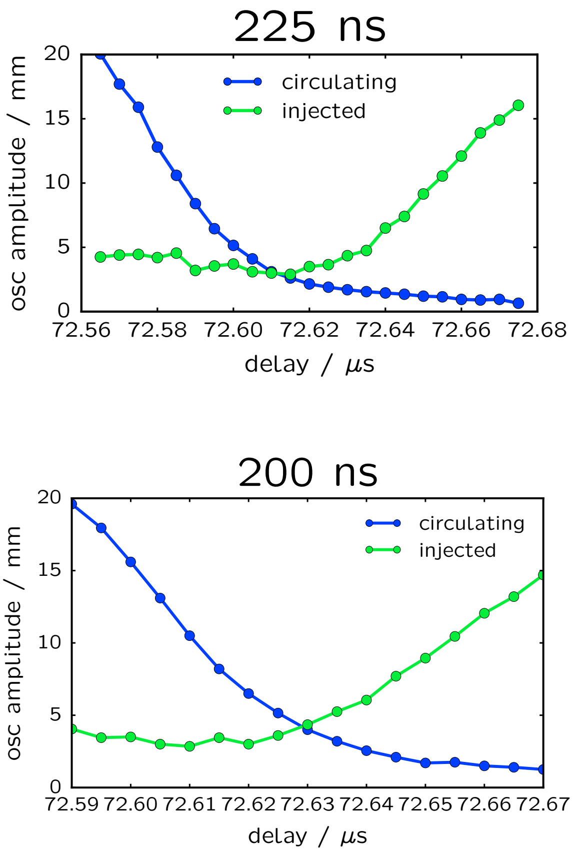

Figure 4: Results of delay scan with 225 ns (top) and 200 ns (bottom).

Such good results are combination of kicker synchronisation with beam and transverse feed back performances. A clear indication of the importance of the SPS transverse damper is shown in Fig. 7. In the top plot, the intensity bunch-by-bunch in the LHC with SPS damper off is shown and compared with the case with damper on (bottom). An intensity reduction of about 20% on the bunches close to the batch gap is observed. In comparison, essentially no reduction in intensity was observed in the LHC when the SPS damper is active.

CONCLUSIONS

The second part of 2016, the LHC proton physics run was carried out with 225 ns SPS batch spacing. In the 2016 Pb-p run instead, the 200 ns SPS batch spacing was already used.

For 2017 operation, the 200 ns SPS batch spacing has been proposed for operation, where, when combined with LHC batch spacing reduction (800 ns), an overall gain in luminosity of about 16% is foreseen [2]. With 200 ns batch spacing, the injection quality is more sensitive to the switches

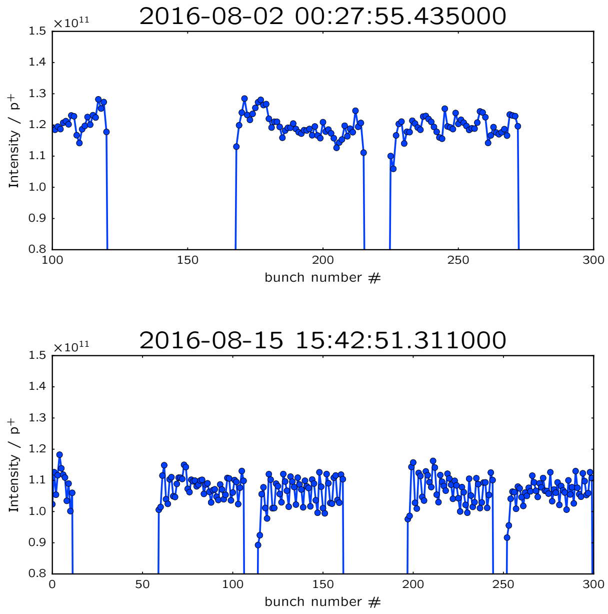

Figure 5: Bunch-by-bunch measurements with 250 (top) and 200 ns batch spacing at injection in the LHC.

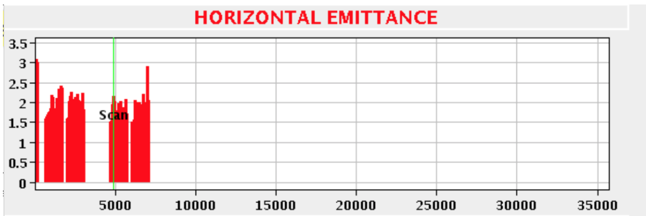

Figure 6: Emittance measurement done with the BSRT in the LHC at injection for 200 ns scheme.

drift, hence a constant monitoring of the individual delays is needed.

The MD time dedicated to this topic has been essential for both LHC Pb-Pb, Pb-p and proton physics of the last two years.

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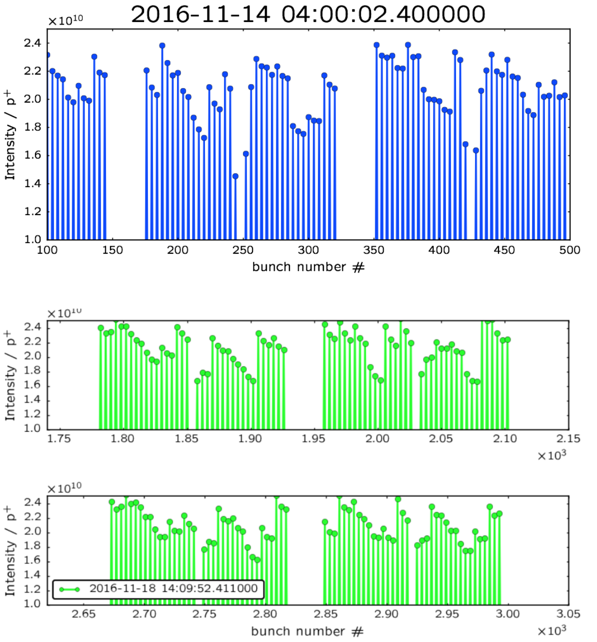

Figure 7: Bunch-by-bunch intensity comparison of the 200 ns scheme with damper off (top) and on (bottom).