IMPACT OF LHC AND SPS INJECTION KICKER RISE TIMES ON LHC FILLING SCHEMES AND LUMINOSITY REACH

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Abstract

The 2016 LHC proton filling schemes generally used a spacing between injections of batches of bunches into SPS and LHC corresponding to the design report specification for the SPS and LHC injection kicker rise times, respectively. A reduction of the batch spacing can be directly used to increase luminosity without detrimental effects on beam stability, and with no increase in the number of events per crossing seen by the experiments. Measurements and simulations were performed in SPS and LHC to understand if a shorter injection kicker rise time and associated tighter batch spacing would lead to increased injection oscillations of the first and last bunches of a bunch train and eventually also a systematic growth of the transverse emittance. The results were used to define the minimum possible batch spacing for an acceptable emittance growth in LHC, with gains of reductions of about 10% possible in both machines. The results are discussed, including the potential improvement of the LHC luminosity for different filling schemes.

SPS INJECTION BATCH SPACING

The SPS injection kicker system has to deflect 26 GeV/c protons and 17.4 GeV/c (proton equivalent) ions with an angle of 2.069 mrad onto the machine orbit. The kicker system is composed of two types of terminated travelling wave kicker magnets. There are 12 magnets of the small aperture type kicker magnet which have a rise time of 150 ns and 4 magnets of a large type which have 225 ns rise time from specification. The magnets are distributed into four vacuum tanks and powered by four high voltage power supplies, via eight thyratron switches. Unless the reservoir is correctly adjusted, ageing effects of the thyratron tubes can lead to a flattening of the waveform rising edge or increased jitter of the waveform timing. In addition, there can be jitter from the timing module itself; both timing jitters can add up to several tens of ns. Below it will be outlined that there is strong interest from increase in LHC luminosity to operate the kicker system at a rise time of 200 ns which is tighter than specified. In order to reach this rise time, a careful setup of the timing of the different magnets has to be performed at the startup. In a first step, all but the first magnet are deliberately mistimed and then each magnet is separately shifted close to the theoretically expected time of flight delay with respect to the first magnet. The current in the terminating resistor serves as a measure which means that this inter-magnet synchronisation can be performed without beam.

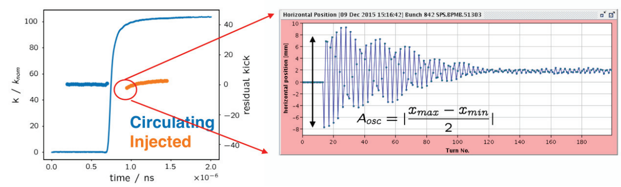

Figure 1: Using bunch-by-bunch and turn-by-turn beam position data to optimize the kicker system timing.

In a second step, the synchronisation is repeated with low intensity beam. The timing of all magnets is balanced between the last circulating and the first injected bunch. For this measurement, turn-by-turn and bunch-by-bunch orbit deviations are measured on beam position monitors and used to optimise the delay of the full kicker system to balance the mis-kick between circulating and injected beam (Fig. 1). The figure of merit observable would be the emittance, however, the precision of the emittance measurement in the SPS is not sufficient to measure this effect. The most sensitive signal to quantify effects from miskicked bunches are losses on the transfer line collimators. The oscillation of mis-kicked bunches is damped after several tens of turns by the transverse feedback system in the SPS which leads to an increased transverse tail population. In case the SPS transverse feedback system is off, an intensity loss of 25% can be measured in the LHC (Fig. 2). With the feedback system there is no measurable effect on emittance nor intensity in the SPS.

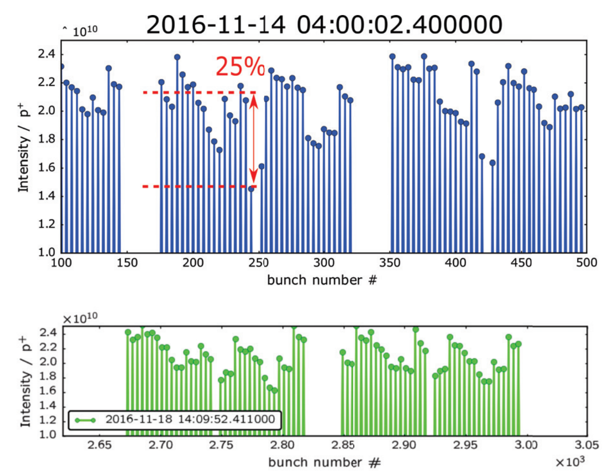

Figure 2: Intensity along the batch in the SPS without transverse damper (top) and with transverse damper (bottom).

ISBN 978-3-95450-182-3

The process of tail population can be simulated with tracking studies. For these studies, the machine non-linearities were retrieved from amplitude dependent detuning measurements and used to define the respective coefficients of the effective Hamiltonian. Also the damping time of the transverse feedback system was defined from damped injection oscillations. The change of phase advance per turn is tracked with one turn maps and the miskick of the injection kicker and the damping effect introduced as perturbations each turn. These tail population studies were performed for ion beams in the SPS [1].

Since the injection energy and damping time are different for SPS proton injections, the required measurements and tracking studies will be repeated for protons. The aim is to quantitatively correlate a miskick at SPS injection to losses at the SPS to LHC transfer line collimators. These losses are continuously monitored via an automatic injection quality check and should give a beam based criterion when effects from switch ageing require a re-synchronisation of the injection kicker magnets. Also on the kicker hardware side, automatic monitoring of the current on the terminating resistor was implemented which allows to detect waveform shifts due to thyratron degradation.

LHC INJECTION BATCH SPACING

The maximum allowed ripple of the LHC injection kicker (MKI) waveform directly defines the minimum required batch spacing for the filling scheme. To define this limit low intensity bunches were injected at different locations on the MKI waveform and injection oscillations and emittances were recorded. The start of the waveform rise was measured with circulating beam which has the advantage of a clear reference for the beam orbit and emittance. This can be seen in Fig. 3 in the delay window between 60000 ns and 59800 ns, where injection oscillations and emittance show a clear correlation with the waveform rise. The part of

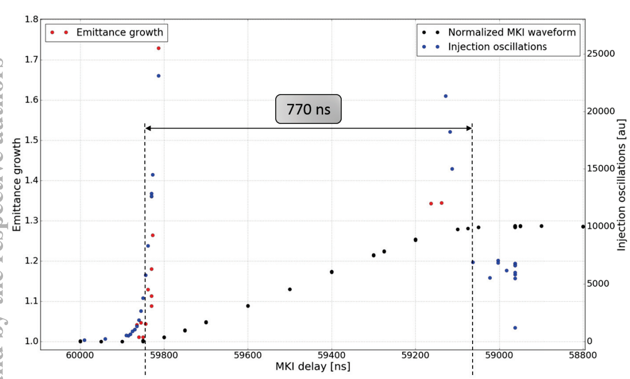

Figure 3: Emittance growth and injection oscillations along the MKI waveform.

the waveform close to 100% of the nominal kick had to be measured with injected beam since a full kick of the MKI would dump the beam directly on the injection dump (TDI). Here shot-to-shot trajectory variations reduce the measurement resolution of the injection oscillations. It can be seen that for several measurements around the delay of 59000 ns the injection oscillations do not vary. Thus, this value is assumed to be representative for the nominal kick injection. Also the measurement of the emittance growth around 100% of the rising edge is more difficult. Since the wire scanner measurements on the SPS extraction flattop are not sufficiently accurate, an average emittance value for several shots measured at nominal kick was taken as reference.

The criterion to define the minimum possible batch spacing is to keep emittance growth below the already present difference in emittances within a batch. This approach is conservative when luminosity is considered as a figure of merit. Reducing the batch spacing allows to inject more bunches and even if some of these additional bunches suffer from significant emittance growth, the overall luminosity would increase. For the part of the waveform measured with injected beam, the emittance growth cannot be taken as criterion due to limited measurement accuracy. Instead the injection oscillations can be used to define a limit since they stay at a reasonably constant level during the nominal waveform and a clear rise of injection oscillations can be measured when the beam is injected below the nominal kick value.

Putting these two criteria together, a minimum batch spacing of 770 ns can be defined. In order not to compromise availability in operation one should leave margin for the timing jitter of kicker pulses. This leads to a suggested value of 800 ns for the LHC batch spacing in operation.

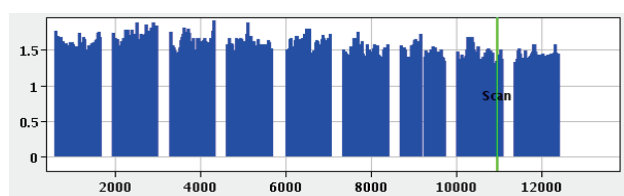

Figure 4: Vertical normalised emittance for several injections of bunch trains with 800 ns batch spacing.

This batch spacing was tested also with high intensity bunch trains in operation (Fig. 4). No visible effect on the emittance of either the last bunches of the circulating beam nor the first bunches of the injected train could be measured.

IMPACT ON LUMINOSITY

Reducing the batch spacings during injection into the SPS and LHC enables filling the LHC with an increased number of bunches. This increase can be directly related to an increase in luminosity without impacting the pile-up of events per collision in the experiments. In Table 1, a comparison of filling schemes relevant for the run in 2017 are listed. The beam types with 72 and 80 bunches per batch from the CERN PS (upper half of the table) are produced in the so called "standard" way which refers to the longitudinal gymnastics in the PS to provide the 25 ns bunch spacing. The beam types which are transferred in batches of 48 bunches from the PS (lower half of the table) are produced in a scheme

Table 1: Filling scheme comparison for the 2017 run. The first column denotes the beam types as produced in the LHC injectors, column 2 and 3 denote the batch spacings in LHC and SPS respectively, #b stands for the total number of bunches in the machine and IP1/5 denotes the number of colliding bunches in the high luminosity experiments.

Beam type	LHC [ns]	SPS [ns]	#b	IP1/5	Luminosity [$\cdot 10^{34}$ Hz/cm^2]
4x72b	900	225	2748	2736	1.278
4x72b	900	200	2760	2748	1.284
4x72b	800	225	2760	2748	1.284
4x72b	800	200	2760	2748	1.284
4x80b	900	225	2744	2732	1.244
4x80b	900	200	2744	2732	1.244
4x80b	800	225	2812	2800	1.274
4x80b	800	200	2812	2800	1.274
2x48b	900	225	2220	2208	1.321
2x48b	900	200	2220	2208	1.321
2x48b	800	225	2364	2352	1.408
2x48b	800	200	2364	2352	1.408
3x48b	900	225	2412	2400	1.436
3x48b	900	200	2412	2400	1.436
3x48b	800	225	2412	2400	1.436
3x48b	800	200	2556	2544	1.522

which is called BCMS and stands for batch compression, merging and splitting in the PS. In order to compare the schemes in terms of instantaneous luminosity in ATLAS and CMS, the beam parameters which have been reached in 2016 out of the injectors are used [2]. The standard beam with 72 bunches has a normalized rms emittance of 2.5 µm out of the injectors, the 80 bunches scheme was produced with 2.6µm, and the BCMS scheme with 1.7µm. All stated emittances refer to a bunch intensity of 1.15×10^{11}. These beam parameters are conservative in view of production in the injectors and can safely be reached as experience during 2016 has shown. However, the calculated luminosities do not take into account any emittance blow-up nor intensity loss in the LHC cycle. Thus, the luminosities should only be used as relative comparison between the different beam types and batch spacings.

The BCMS scheme provides filling schemes with fewer colliding bunches in ATLAS and CMS, but the significantly reduced emittance compared to the standard scheme leads to an overall higher luminosity and is therefore the choice for 2017. The maximum number of 3x48 bunches per SPS-LHC transfer is due to the cryogenic system's limit of the electron cloud induced heat load on the beam screen [3]. Even without this limit, the full 4x72 bunches of the nominal transfer could not be reached with the BCMS scheme since the LHC injection protection absorbers would not provide the required attenuation in case of large amplitude trajectory oscillations [4]. The scheme with 2x48 bunches per transfer is considered in the list since it was the operational scheme in 2016 due to limits of the SPS dump.

In the previous sections, reduced batch spacings from 225 ns to 200 ns for the SPS and 900 ns to 800 ns for the LHC injection kickers were suggested. Considering 144 bunches per transfer, this results in a luminosity increase of 6%. Compared to 2016, where only 96 bunches could be injected, this gives a luminosity increase of 15%.

Some additional points should be noted. The list of filling schemes is not exhaustive, and an additional batch might be squeezed in for some cases. However, this would be at the expense of the filling scheme symmetry and therefore reduce the number of colliding bunches in LHCb.

As seen from the comparison it seems that the SPS injection batch spacing has no impact at all on the luminosity. This is true only for the collision in ATLAS and CMS given the above mentioned constraint of maximum number of colliding bunches in LHCb. If the luminosities of ALICE and LHCb are calculated, differences between the 200 ns and 225 ns SPS batch spacing can be seen.

The scheme consisting of 80 bunches per batch from the PS would lead to a total of 320 bunches per SPS-LHC transfer. It was tested if the LHC injection kicker pulse length can be lengthened by 10% as compared to the nominal batch length of 288 bunches. The injection kicker pulse length is adjusted by firing a so called dump switch, at the charging end of the pulse forming network (PFN), at a certain timing with respect to the main switch which is at the load end of PFN. If the pulse length or the time between firing the main and dump switch is too long, the energy left in the PFN is not anymore sufficient to correctly trigger the dump switch. The kicker system magnetic field at this maximum pulse length was measured by kicking a low intensity probe bunch. The result from the kick response is at the limit of the waveform ripple definition, thus, only injection of a full batch of 320 bunches will allow to validate this scheme for operation.

As a final remark, the abort gap of the LHC is protected by an injection inhibit system called abort gap keeper. This system was upgraded during the 2016/2017 end of the year stop to be adjustable to the injected batch length in operation. All the filling schemes in Table 1 assume the respective optimum abort gap keeper length.

CONCLUSION

Until the end of the 2016 proton run, the operational batch spacings at SPS and LHC injection were as defined in the LHC design report. Measurements of both kicker systems and operational experience during the 2016 ion run motivate a reduction of both batch spacings by about 10% which gives a 6% increase in luminosity.

The suggested batch spacings will be operationally deployed in 2017 and their impact on intensity and emittance of miskicked bunches will be monitored. As long as emittance growth or intensity loss of affected bunches does not lead to undesired beam dumps, a further reduction of the batch spacings might be envisaged.

ISBN 978-3-95450-182-3

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ISBN 978-3-95450-182-3