SPS INJECTION AND BEAM QUALITY FOR LHC HEAVY IONS WITH 150 ns KICKER RISE TIME

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Abstract

As part of the LHC Injectors Upgrade project for LHC heavy ions, the SPS injection kicker system rise time needs reduction below its present 225 ns. One technically challenging option under consideration is the addition of fast Pulse Forming Lines in parallel to the existing Pulse Forming Networks for the 12 kicker magnets MKP-S, targeting a system field rise time of 100 ns. An alternative option is to optimise the system to approach the existing individual magnet field rise time (2-98%) of 150 ns. This would still significantly increase the number of colliding bunches in LHC while minimising the cost and effort of the system upgrade. The observed characteristics of the present system are described, compared to the expected system rise time, together with results of simulations and measurements with 175 and 150 ns injection batch spacing. The expected beam quality at injection into LHC is quantified, with the emittance growth and simulated tail population taking into account expected jitter and synchronisation errors, damper performance and SPS non-linear optics behavior. The outlook for deployment is discussed, with the implications for LHC operation and HL-LHC performance.

MOTIVATION

Reduction of the SPS injection kicker rise time to allow tighter packing of bunches in the LHC has long been identified as a means to increase the performance of the LHC for operation with heavy ions [1, 2]. Possible numbers of injected bunches in the LHC as a function of the injection kicker rise time are shown in Fig. 1, with the curves representing different numbers of bunches injected into the SPS per cycle. Note that constraints required to produce detailed filling schemes for each scenario have not been included in these figures. It is worth adding that the kicker rise time need not be a multiple of 50 ns, since the spacing between the 50 ns batches in the LHC can be any multiple of 25 ns.

INJECTION KICKER SYSTEM RISE TIME IMPROVEMENT TO 150 ns

In its nominal configuration the present injection kicker system MKP [3] needs to provide a kick strength of 2.069 mrad for the injection of 87.7 Tm rigidity 26 GeV/c protons, corresponding to 0.186 Tm MKP system strength. To date this has been achieved with a system rise time of 250 ns, somewhat below the specification of 225 ns. Alternatives for reducing this rise time for the injection of the lower energy (57.7 Tm 17.4 GeV/c proton equivalent, or 5.9 GeV/c/u) and low emittance and intensity Pb^{82+}_{208} lead ion beam have been explored [4], with a concept developed for

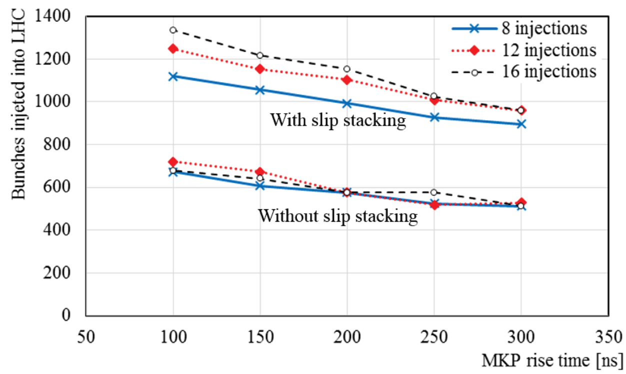

Figure 1: Possible numbers of bunches injected into LHC as a function of the SPS injection kicker rise time for 8, 12 and 16 injections into the SPS per cycle. The beneficial effect of shorter kicker rise time and slip-stacking are clear.

100 ns rise time. However, this 100 ns concept is technically challenging, requiring significant R&D effort and the provision of a complete new parallel kicker pulser system, as well as new injection septum, dump and instrumentation.

The 17.4 GeV/c proton equivalent injection momentum means that the required system voltage using all kickers was only 31 kV, to be compared to the 50 kV operational maximum. It was realised that it would be possible to reduce the required kick angle through the use of an injection bump of 6.7 mm amplitude, to allow operation only with the fastest MKP1-3 generators for ion injection, while staying at 49 kV. This was implemented in operation for ions in 2015, and the synchronisation of the individual thyratrons on modules 1-3 was also improved with the repair of a faulty timing module, and replacement of the worst tubes, gaining over 30 ns in the jitter. To note that, with the present magnet PFNs, the minimum theoretical rise time for one magnet alone is 148 ns (2-98%), which has been confirmed in laboratory measurements [3]. Timing and switch jitter will increase this value by some tens of ns for the complete system of 6 magnets, each with its individual PFN and switch.

As a result of these improvements, the residual kick for the injected/circulating bunches with 150 ns ion batch spacing was measured to be less than 5% of the nominal injection kick, at about 6 mm on both injected and trailing circulating bunches for the optimum kicker timing. This is illustrated in Fig. 2, where the residual peak kick for injected and trailing circulated bunches as a function of detailed MKP timing are plotted.

A side benefit of the reduction of the system jitter is that it should be possible to reduce the rise time for proton operation for LHC, from 250 ns to the specified 225 ns. Preliminary measurements with protons using all four MKP modules showed that residual oscillations are about 1.5 mm for the optimum timing, compared to 2.5 mm for 200 ns. This possibility will be fully tested and deployed in 2016.

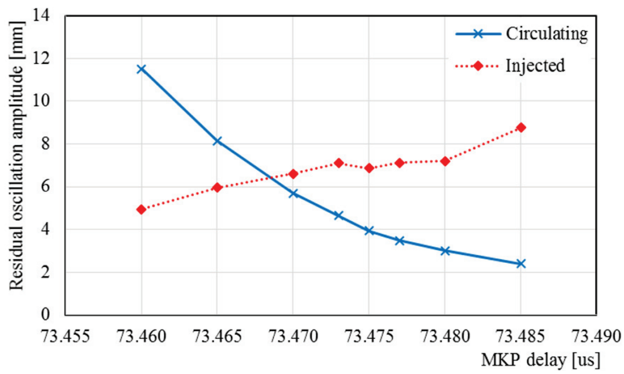

Figure 2: Measured residual oscillations on injected and circulating trailing ion bunches for 150 ns MKP rise time. For the optimum settings both bunches are kicked about 6 mm with respect to the orbit.

From the measured residual kicks as a function of kick delay the kicker waveform could be reconstructed, Fig. 3, and the rise time calculated for different definitions. The rise time is measured as 150 ns for the 5-95% definition, and 191 ns for 2-98%.

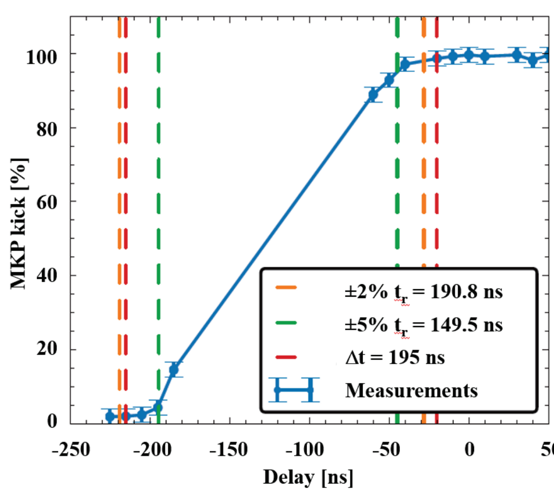

Figure 3: Measured MKP kicker waveform using magnets 1-3 at 49 kV for ion injection. A rise time of just below 150 ns is achieved (5-95%).

SPS PERFORMANCE FOR IONS WITH 150 ns MKP RISE TIME

Injection Damping

Operation of the ion beams in the SPS does not need the transverse damper for beam stability and the high brightness achieved for ion beams in the SPS before 2015 was possible without using the transverse feedback system for injection damping. The obtained 5% (6 mm) residual kick error with 150 ns MKP rise time is much larger than the 1% specified for emittance growth in the absence of the transverse damper [4]. Studies in 2012 [5] showed that a damping time of 20 turns was adequate to suppress emittance growth with 6 mm injection errors, Fig. 4. Beam measurements with the damper operating in 2015 were therefore crucial to determine whether such a large kick error is acceptable.

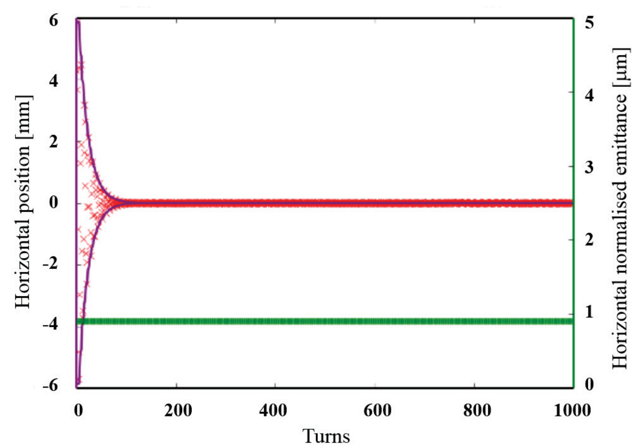

Figure 4: Simulated damping of injection oscillation of 6 mm in presence of amplitude detuning with 1/e damping time of 20 turns. No measurable blow-up is expected.

The LIU damper upgrade for ions [6] uses dedicated electronics to provide the feedback signals for injection damping. Unlike operation for protons, a frequency modulation of the main 200 MHz RF is needed to keep the RF frequency within the cavity bandwidth. This in turn means that all signals transmitted the 1 km from SPS BA3 to BA2 for the transverse damper need to be delayed by a proper amount to keep synchronism between the frequency modulation and the beam signals from pick-ups in BA2. Stabilized optical fibers delay lines will be used [6], but the final system is not yet available and without this, the beam position sampling is shifted and bunches are essentially assigned to the wrong bucket. Due to the shifting, a correct tagging is not possible and the signal processing "sees" more than 2×12 bunches. The feedback correction signal therefore shifts for subsequent injections. This results in a degraded injection damping for later batches.

A workaround was found whereby damping was only active at the injection plateau, with the damper deactivated after the 11th injection due to the too-large bunch position shift. Only one of the two horizontal dampers was used, with the feedback phase arbitrarily detuned by +20°, as there were erratic beam losses when using the theoretical optimum feedback phase. Despite these difficulties the damper worked well for damping the large injection oscillations with 150 ns batch spacing, Fig. 5, with damping times of around 24 turns achieved. To note that all of these problems will be solved for 2016, when the fibre links ensuring the correct bunch synchronisation will be in place.

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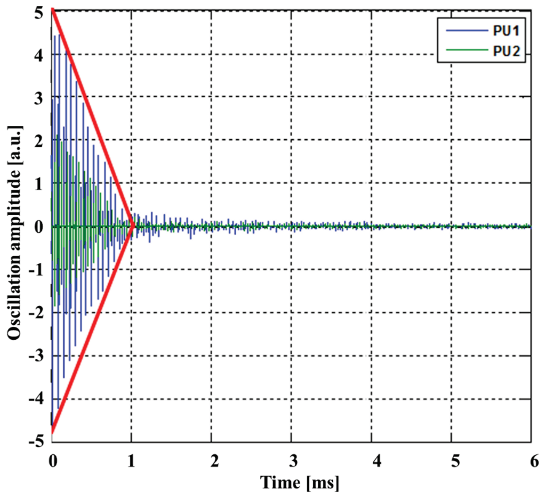

Figure 5: Measured damping of injection oscillation of 6 mm, with oscillations completely damped within 1 ms (40 turns). The 1/e damping time is about 24 turns.

Emittance Growth and Tail Population

No measurable emittance growth was found with the injection damper operating, within the measurement error of the SPS wire-scanners. This conforms to the expectation with the 5% kick error and the achieved injection damping time. Non-Gaussian horizontal tail population is a more interesting aspect, since in the presence of non-linearities the damping of a large injection error will give a significant non-Gaussian tail to the bunches, despite the overall emittance growth remaining small. This was observed in the first attempts to inject the ion beam with 150 ns batch spacing into LHC, before the extra 30 ns jitter in the MKP timing had been solved. The residual kick was around 10%, and although this was eventually damped in the SPS, large emittances (around 7 μm normalised, twice the required value) and large beams losses (above 75% of the beam dump threshold) in the SPS to LHC transfer line collimators (TCDI) were seen, attributed to large tails on the bunches.

Particle tracking simulations were made to check the expected tail population for different injection kicker errors, for the SPS model and actual damper performance. From the results shown for different residual kick errors in Fig. 6 it can be seen that an injection error of 10% increases the number of particles outside the TCDI collimator setting of 5 σ by a factor of about 50, compared to the 5% injection error case, and that for this error about 1% of the injected beam will be scraped on the TCDI jaws. A reduction of the kick by a factor two makes a very large improvement in the tail population. These studies will be continued, as they are also interesting for protons where beam losses at the TCDIs are a performance concern for injection into LHC. To this effect reference measurements of the detuning with amplitude were also made in 2015 to allow more detailed studies of the expected tail populations for both LHC proton and ion beam injection.

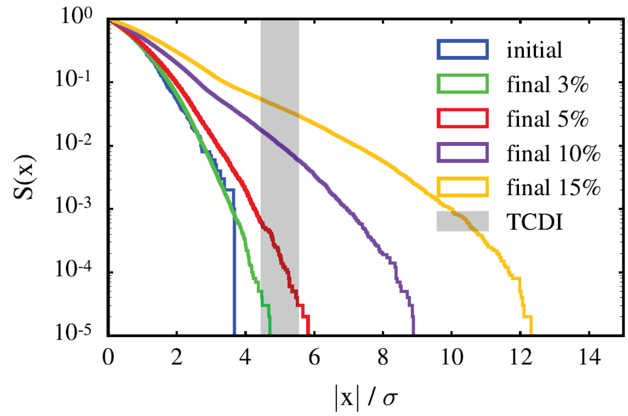

Figure 6: Simulated bunch distribution after injection damping of the initial truncated Gaussian, for different SPS residual injection kick errors. The TCDI jaw at 5±0.5 σ is shown.

OUTLOOK FOR SPS AND HL-LHC PERFORMANCE

150 ns SPS injection kicker rise time has been achieved and is operational for ions. This will allow injection of 92% of the 1248 bunches requested for the LHC ions, with slip-stacking. This could be further increased if injection and extraction in LHC can be incrementally improved - a reduction of the injection kicker rise time to 800 ns (from 900), and of the abort gap to 2900 ns (from 3300) would allow injection of 1200 bunches. This possibility has already been raised and reference measurements made at LHC injection and extraction - it will be tested with ion injection and the damper in machine development in LHC in 2016.

Overall the improvements made in 2015 in the SPS injection kicker rise time have made a significant step in the performance potential of the SPS for the HL-LHC ion operation, and with some other relatively minor improvements in the LHC it is hoped that the number of bunches can approach to 4% of the number requested for the specific operational scenario defined. The improvements will also benefit proton operation at 225 ns batch spacing.

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