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CERN PS KICKER FOR PROTON INJECTION: FROM BEAM-BASED WAVEFORM MEASUREMENTS TO HARDWARE IMPROVEMENTS

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Abstract

For 2017 operation, the termination mode of the CERN Proton Synchrotron (PS) horizontal injection kicker was permanently changed to short-circuited, to be compliant with the future performances requested by the LHC Injectors Upgrade (LIU) project [1]. An extensive campaign of measurements was performed through a dedicated beam-based technique. The measurements identified possibilities for optimisation of the kicker system and were fundamental to properly tune the PSpice simulation model of the kicker, as well as for validating the hardware changes. The model was finally used to estimate the horizontal emittance growth for the future injection schemes in the PS.

INTRODUCTION

The PS proton injection kicker, named KFA45 (kicker fast in straight section 45) is used to transfer bunches from the BTP transfer line into the PS ring. During a PS cycle for the LHC, the kicker is triggered twice in time, spaced by 1.2 s, in order to fill the machine with a double-batch injection at a kinetic energy of 1.4 GeV from the PS Booster (PSB).

Since 2017 the four modules of the kicker are configured in short-circuit (SC) mode. This allows doubling of the current in the magnet and thus providing twice the kick strength.

Beam-based measurements of the KFA45 waveform are necessary because they represent the only way to retrieve the magnetic waveform of the installed system, required to confirm the kicker performance for LIU. A new methodology, based on fast beam position monitor (BPM) signals (PS BPM02 [2]), was validated through several measurements in 2016, when the kicker was operationally configured in terminated mode (TM) [3,4].

MODIFICATIONS IN 2016-17 END-OF-YEAR (TECHNICAL) STOP

Several modifications to the kicker system components were put in place [5–7] in order to satisfy the specifications [8] of fast (≤ 105 ns) rise time and reduced (≤ 2% peak) flat-top and post-pulse ripples. In particular (see Fig. 1) :

- A de-phasing system between the kicker modules was implemented with flexible transmission cables (blue).
- A new entry box extension at the magnet input containing a ferrite ring (orange) was installed.
- An LC filter (magenta) was inserted at the magnet termination node.

New magnet modules will substitute the present ones after the Long Shutdown 2.

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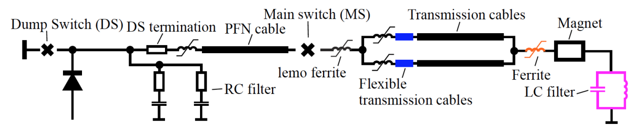

Figure 1: Sketch of the KFA45 system.

BEAM-BASED MEASUREMENTS IN 2017

Measurements with Multiple Modules

The beam-based measurements in 2017 started by continuing measurements of 2016 [3] with multiple modules using the same beam-asynchronous trigger. As an example, a measurement set using modules 3 and 4 powered at 270 kV total is shown in Fig. 2 (average plus standard deviation SD) and the resulting performances are summarised in Table 1. The voltages in this paper have to be considered as TM-equivalent, i.e. a factor ~2 larger than the SC voltage, if not otherwise specified. The current is much faster than the measured magnetic field. The SC-induced reflection after ~600 ns of flat-top is well visible in current and less in magnetic field, probably due to measurement noise, where it is in the order of ±3% of the flat-top level.

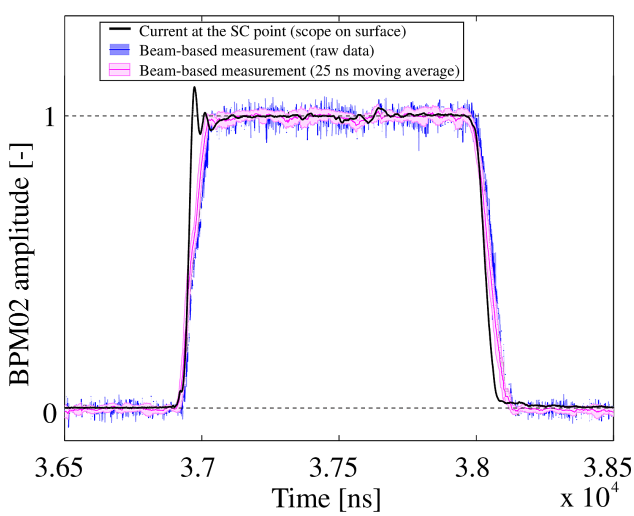

Figure 2: Measurements with modules 3 and 4 at 270 kV, normalised to the average flat-top level.

Table 1: Measurements with Modules 3 and 4 at 270 kV

Rise time [± 10 ns]		Fall time [± 10ns]		Flat-top ripple [%]
5-95%	3-97%	95-5%	97-3%	
95±1	106±1	117±3	138±1	3.6±0.6

Further measurements [4] with multiple modules showed an increase in rise and fall times, probably due to sudden un-

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synchronisation of single the main (MS) and/or dump (DS) switches of single modules during the long measurements (several hours). Studies on the source of the jitter between modules are still on-going [9].

Measurements with Module 1

Measurements of the waveforms of single module were carried out due to the problems experienced with the jitter. Module 1 was selected for the measurements. A measurement at 80 kV is shown in Fig. 3 and the resulting performance is summarised Table 2. The post-pulse ripple is well visible both in the beam-based and in the current measurements and is in the order of 5% of the flat-top level.

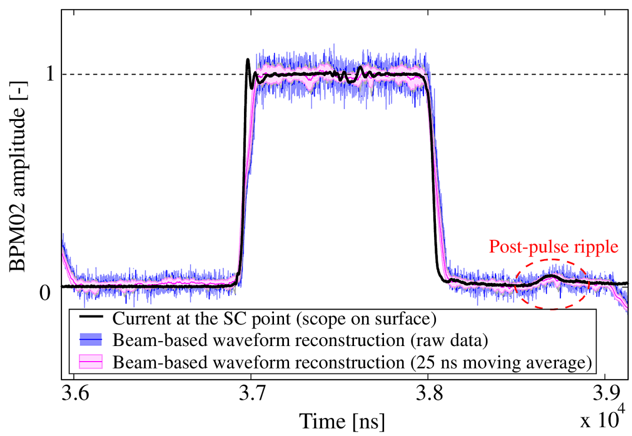

Figure 3: Measurements of module 1 at 80 kV with LC filter.

Table 2: Measurements with Module 1 at 80 kV: Rise and Fall Times Values and the Flat-Top Ripple Values for Filter Window Size of 25 ns

Rise time [± 10 ns]		**Fall time [± 10ns]**		**Flat-top ripple (%)**
5-95%	**2.7-97.3%**	**95-5%**	**97.3-2.7%**	
96	121	118	148	2.4

USAGE OF SYNCHRONOUS TRIGGER

A new beam-synchronous trigger timing was provided in order to eliminate the pseudo-random sampling [3, 4] and enabling faster, better sampled waveform measurements. By using such a trigger, measurements on module 1 with and without LC filter (in SC termination) were performed. They showed an important difference in rise and fall times, as shown in Fig. 4 and resulting performance is summarised in Table 3.

COMPARISON WITH PSPICE ® MODEL

The measurements in Fig. 4 were compared with the nominal PSpice ® model of the kicker system.

The PSpice® simulated magnetic waveforms were used to estimate the emittance growth due to the ripple on kicker

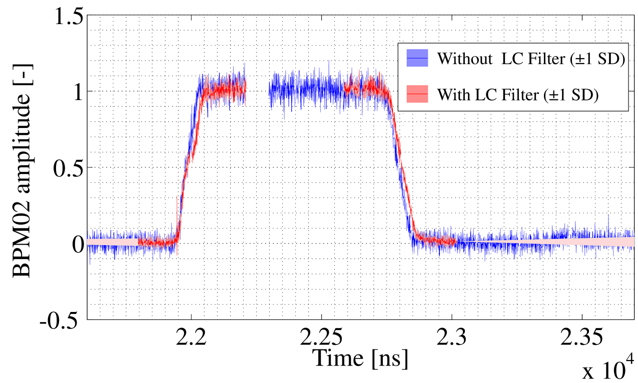

Figure 4: Comparison between measurements on module 1.

Table 3: Rise and Fall Times for the Waveforms in Fig. 4

KFA45 termination	**Moving average filtering window**	**Rise time 5-95% [ns]**	**Fall time 5-95% [ns]**
With LC filter	10 ns	101 ± 5	111 ± 5
	25 ns	103 ± 4	114 ± 2
Without LC filter	10 ns	78 ± 4	100 ± 4
	25 ns	83 ± 4	103 ± 3

pulse, reflecting the approach already used for the vertical recombination kickers in the transfer line between PS Booster and PS [10].

The PSpice® model was compared to the measurements for a single module. Figure 5 shows a zoom in the rise and fall times regions of Fig. 4 and shows the differences with and without the LC filter on module 1. The nominal simulation model showed a rise and fall times underestimated by ∼15-20 ns in both cases. This effect indicated that the LC filter was not causing the discrepancy with the simulation model and that the issue was related to other parameters in the model. The simulations were only slightly dependent on the (SC) voltage: simulations at 40 kV and 60 kV were similar.

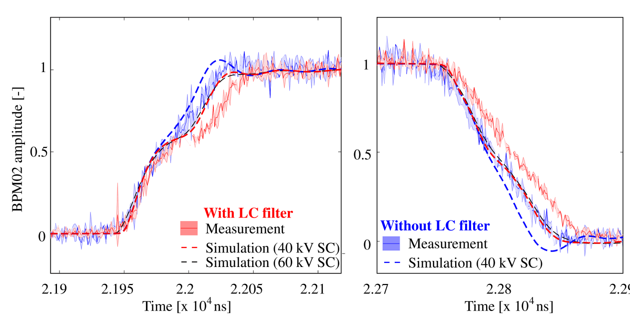

Figure 5: Measurements vs. un-tuned PSpice® simulations.

The PSpice® model was tuned to match measured data. Various changes were applied:

- **Magnet:** electrical length of the magnet, inductance and capacitance values increased by +5%. The impedance stays constant, but the magnet becomes effectively longer.
- **MS and DS thyratron model:** switching speed of both MS and DS adjusted by modifying the plasma

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drift speed in the gaps of the tube; stray coupling capacitance between ground-cathode increased by +20%.

- **Magnet ferrite entry box:** entry box model improved by properly calculating the stray capacitance given by the ferrites.
- **MS lemo ferrites:** a capacitor of 120 pF was introduced to reduce the efficiency of the ferrites surrounding LEMO® connectors, suppressing ripple for a more realistic behaviour.
- **SC termination:** improved model with stray inductances and capacitances of the LC filter and connectors.

After such modifications, the model fit the (beam-based) measured data in both cases (without and with LC filter), as shown in Fig. 6 for the case with LC filter. The post-

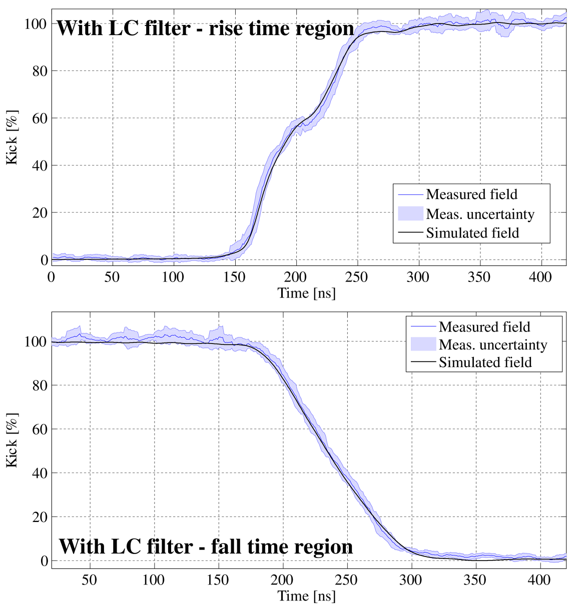

Figure 6: Measurements vs. PSpice® simulations.

pulse ripple was not fully characterised by the simulations, as shown in Fig. 7; investigations are on-going.

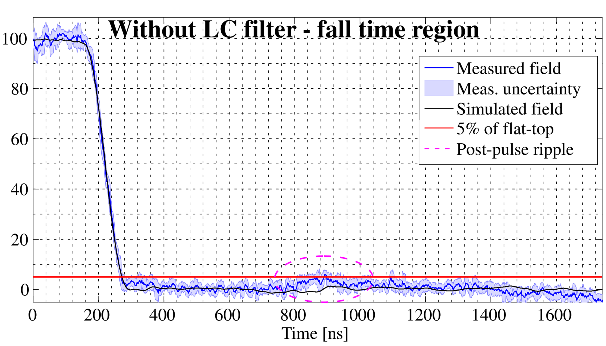

Figure 7: Measurements vs. PSpice® simulations.

EMITTANCE GROWTH SIMULATIONS

The emittance growth estimates were calculated for all future PS beams, injected at a kinetic energy of 2 GeV, by sweeping the PSpice® simulated magnetic waveform across two consecutive bunches [4]. The injected bunches $b_{i,j}$, where i is the bunch number and j is the injection batch number, were considered independently in the analysis. Figure 8, as an example, shows the emittance growth predictions of LHC Standard beams around the rise time and flat-top regions in the case without LC filters.

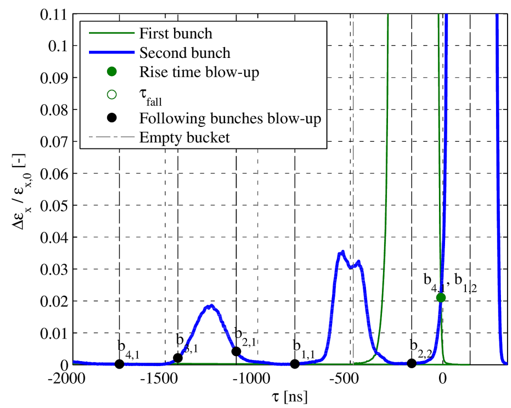

Figure 8: Emittance growth simulations.

The LIU LHC-type beams, i.e. Standard and BCMS [11], showed a maximum emittance growth per bunch of 3.5% in the case with LC filter, and 2.8% in the case without LC filter [4]. This leaves ~4% emittance blow-up per bunch (added in quadrature) to other potential sources, if one considers the 5% budget allowed by the LIU project.

CONCLUSIONS

The campaign of the KFA45 beam-based measurements continued in 2017 [3], providing crucial feedback to assess and plan hardware modifications during the Long Shutdown 2 (LS2). Measurements with only one module and a new beam synchronous trigger were performed, showing a clear advantage of operating in direct SC termination, i.e. without LC filter. As a consequence, this configuration was chosen as operational scenario in the 2018 run.

The measurements were used to benchmark and tune the PSpice® simulation model of the kicker system. The model was well characterised, apart the post-pulse ripple region, which is still not well reproduced. Better measurement resolution is needed to resolve the expected flat-top ripple predicted by the model. The model was used to estimate the horizontal emittance growth induced by the kicker after the LIU upgrade. The estimates leave ~4% per bunch, to be added in quadrature, to other potential sources.

A new test stand will be built and completed in 2019 to perform direct measurements of the magnetic field of the KFA45 in the laboratory.

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