BEAM-BASED WAVEFORM MEASUREMENTS OF THE CERN PS INJECTION KICKER

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project [1], a beam-based technique has been developed for measuring the waveform the CERN Proton Synchrotron (PS) horizontal injection kicker, named KFA45. The technique avoids the need for tedious magnetic measurements, especially when a spare magnet is presently unavailable and measuring the operational magnet with a magnetic field probe is complicated by integration reasons. In this paper, the technique and results of the waveform measurements are summarised. The results already provide additional information in terms of waveform characterisation for the validation of numerical simulations and are of great interest for the future LIU performance upgrade.

INTRODUCTION

The KFA45 is the horizontal PS injection kicker used to transfer bunches from the BTP transfer line into the PS ring. During a PS cycle for the LHC, the kicker is fired at two instances in time spaced by 1.2 s, in order to fill the machine with a double-batch injection at 1.4 GeV from the PSB.

The four kicker modules have two modes of operation, linked with the termination impedance: terminated mode (TM), i.e. with a matched non-zero load impedance, and short-circuit mode (SC). Before 2017, the kicker was usually operated in TM and the SC mode was used only to compensate the missing current in case of module failures. The SC allows the doubling of the current going through the magnet and thus providing twice the kick. This year the KFA45 has been permanently configured in SC. In order to guarantee a clean transfer to the PS, the 2-98% rise and fall times and the 2% flat-top ripple of the KFA45 waveform must respect the specification [2], i.e. $\leq$ 105 ns and $\leq$ 2% respectively.

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 direct measurement with a field probe is very complicated to perform as it would require the movement of two main bending units in the PS.

EXPERIMENTAL METHOD

The reconstruction of the kicker waveform is obtained from the displacement δ of the beam once it is kicked. In fact, δ at any subsequent beam position monitor (BPM) is directly proportional to the integrated magnetic field seen by the beam and to the deflection angle θ imposed by the kicker, as shown in Eq. 1:

$$\delta_{x,y} \propto \theta_{x,y} = \frac{e}{p} \int_0^L B_{y,x} dz \tag{1}$$

where p is the momentum, e is the electric charge, B is the magnetic field, L is the magnetic length and x, y, z are the horizontal, vertical and longitudinal coordinates respectively. A fast BPM, in section 02 (BPM02) [3], was used to retrieve the beam displacement information, by taking the ratio between the difference and the sum signal at the peak current location of the bunch. The kicker and the BPM signals were monitored and recorded from an OASIS scope [4].

The waveform measurements were made using the second instance of the kicker (~1 μs pulse length), which was delayed from the injection plateau to the extraction flat-top at 26 GeV. The increased rigidity of the circulating beam permitted measurements to be made and the beam extracted to an external dump without significant beam losses.

The measurement method is based on the observation of the beam's displacement at a given time after it fires. A large number of cycles (occurrences) containing a single bunch were analysed to probe the entire waveform by shifting the delay between the circulating beam and kicker trigger, covering the whole revolution period in the PS.

A challenging issue was the asynchronous triggering of the kicker with respect to the circulating beam at flat-top energy; the injection kicker timing is only designed to be synchronous with the beam at injection energy. The asynchonrous triggering induced a pseudo-randomisation of the shift in time of the beam with respect to the kicker delay. Figure 1 (left) shows the large amount of cycle occurrences that were required in order to cover uniformly the 2.1 μs revolution period in the PS. By imposing an initial shift on the KFA45 trigger of 5 ns/occurrence, and repeated at finer steps of 2 ns/occurrence, inside a span of 340 ns, the beam jittered with respect to the KFA45 trigger, which led to an uncontrollable granularity of the occurrences for a defined sampling time. The kicker trigger reference was also oscillating in the absolute reference of the OASIS scope: the jittering of the magnet input current signals with a defined signal threshold for every occurrence is shown in Fig. 1 (right).

The synchronisation issue is being solved for future measurements by adding another timing from which the injection kicker can be triggered synchronously with the beam at all energies.

EXPERIMENTAL RESULTS

A nominal single LHC bunch (~ 10×10^{10} p) was used as a probe for the measurement, because it represented a good

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compromise between signal readability (for the BPM) and reduced losses at extraction.

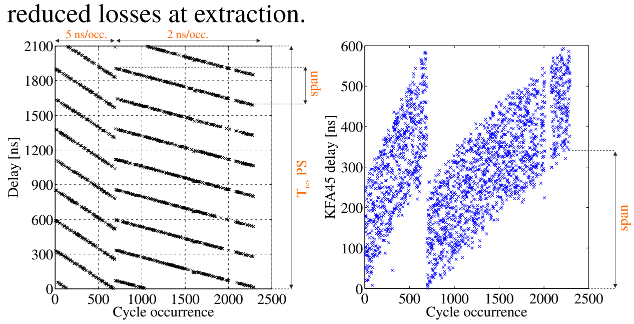

Figure 1: Beam (left) and KFA45 (right) delays.

Measurements were performed for TM and SC modes. The kicker total voltage was set equivalent to 270 kV. In TM all the four modules of the kicker were on, sharing the voltage, while in SC modules 1 and 2 were switched off, leaving modules 3 and 4 to work in short-circuit in order to compensate the missing current.

For every cycle, the closed orbit (CO) was approximated through a sinusoidal fit of the turn-by-turn position before the kick (through Eq. 2) and used to correct the baseline from the raw signal, as shown in Fig. 2. The residual signal from this difference was then considered for the reconstruction.

$$CO_{fit}(t) = A_0 + |A_1| \sin(2\pi f t + \phi_0) \qquad (2)$$

The following parameters, shown in red in Eq. 2, are the free ones of the fit: A_0 is the measurement offset, A_1 is the closed orbit amplitude, f is the horizontal frequency of the beam correlated to the horizontal betatron tune and ϕ_0 is the initial phase in the constant gating window around the kicker trigger. Systematic changes are observed in Fig. 3 where changes to the cycling of the machine during the long measurement campaign of many hours are evident and cannot be attributed to random errors. The signal recon-

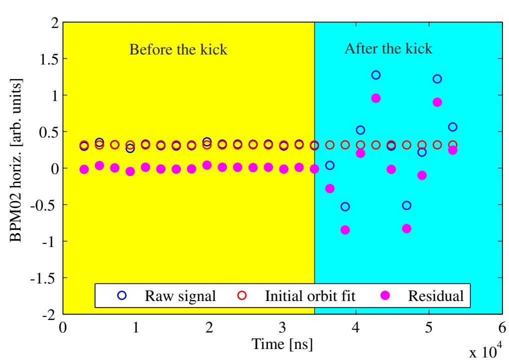

Figure 2: The BPM reading in time before and after the kick.

struction, obtained by combining the occurrences, produces a waveform whose amplitude oscillates for nine times in the observation window at the horizontal betatron frequency of the machine, as shown in Fig. 4. The following analysis is performed on the oscillation No. 2, as it presents the highest signal-to-noise ratio. The non-linearity of the BPM is being investigated, and the initial offset in the BPM before the kick appears to make oscillation No. 4 quite noisy.

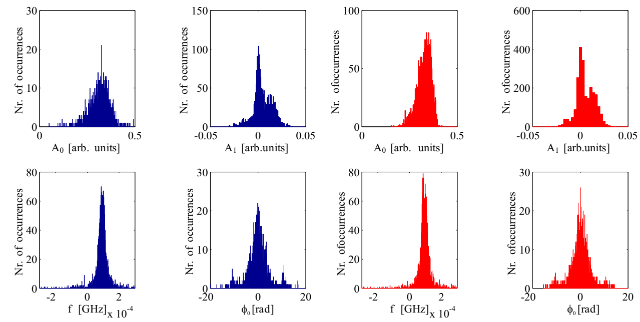

Figure 3: The distribution of the free fitting parameters for the measured occurrences in SC (blue) and TM (red).

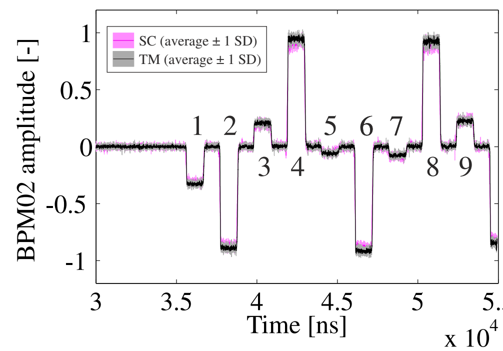

Figure 4: The numbered oscillations of the kicker waveform.

Low-Pass Filtering and Comparision with Current Measurements

One can distinguish the measurements performed in TM and SC modes, as shown in Fig. 5. The signal has been low-pass filtered to smooth the measurement noise. Filtering was needed due to the poor granularity of the measurements. A moving average filter was applied with a window sizes of 10 ns and 25 ns (for a smoother profile).

Figure 6 shows the sum of the currents of modules 3 and 4, compared with the measured magnetic field waveforms.

The integrated magnetic field has a low-pass behaviour (both in SC and TM modes), not showing the ~20 MHz damped ripples shown in the current, related to the overshoot at the end of the rise time and to the reflection after ~600 ns of flat-top.

In SC mode the current rise and fall times are sharper than the measured magnetic field because of the the location of the current measurement point at the short circuit node downstream the magnet [5]. The rising and falling edges of the measured magnetic waveforms show an inflection: faster at the beginning of the rise and slower at the end. This phenomenon is related to the filling time of the magnet, which, in SC mode, is typically almost doubled due to the reflection of the current [5].

In TM mode, the excellent agreement between the current and beam-based magnetic measurements for both time constants confirms a good choice of the filtering.

Rise and Fall Times, Flat-Top Ripple

The evaluations of rise and falling times and flat-top ripple shown in Fig. 7. 2-98% levels were computed with 25 ns

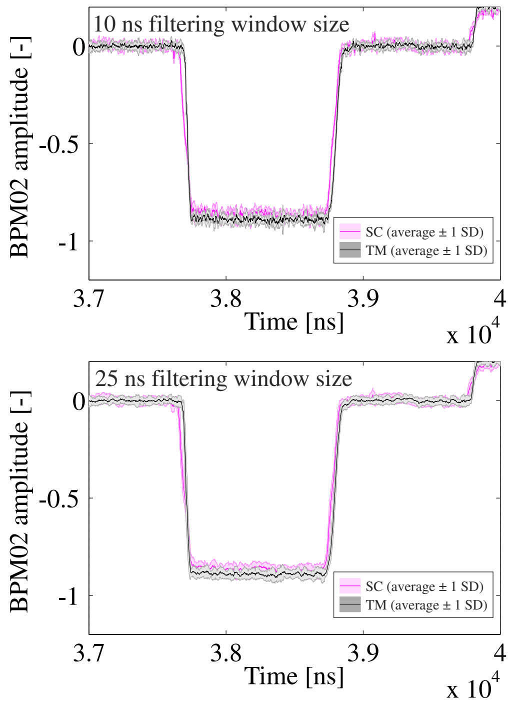

Figure 5: The (low-pass filtered) reconstructed waveforms.

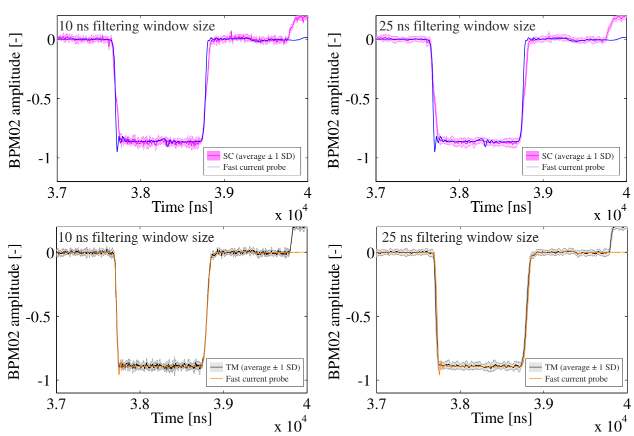

Figure 6: Reconstructed waveforms vs. currents.

time window filtering for TM, while, due to the more noisy data, a smaller interval, precisely 2.7-97.3%, has been considered for the SC. The values of rise and falling times correspond to the distances between two consecutive intersections at the bottom (top) and the top (bottom) edges of the waveform. The values of flat-top ripple correspond to the maximum deflection, all along the flat-top, with respect to the flat-top average amplitude. Due to the filtering process and to the precision level of the measurements, a ± 10 ns tolerance is considered on top of the reported values, as an educated guess. The results are summarised in Table 1.

CONCLUSIONS AND OUTLOOK

An extensive MD campaign has been carried out to perform beam-based measurements of the magnetic waveform of the PS injection kicker KFA45. These measurements were necessary to assess the performance required by LIU and present to date, the only way to probe the waveform of the magnet without moving other PS elements.

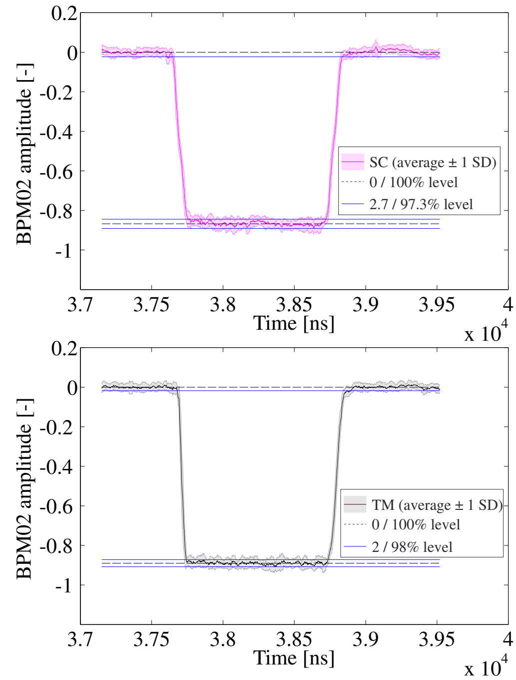

Figure 7: The rise and falling times evaluations.

Table 1: The rise and fall times and the flat-top ripple values for filter window sizes of 10 ns (and 25 ns in round brackets). Some values could not be determined (n.d.). *2.7-97.3% evaluation.

KFA45 mode	Rise time [± 10 ns]		Fall time [± 10ns]		Flat-top ripple (%)
	5-95%	2-98%	95-5%	98-2%	
SC	89 (92)	n.d. (104*)	93 (98)	n.d. (110*)	4.6 (2.7)
TM	46 (53)	n.d. (63)	96 (102)	n.d. (134)	3.3 (2.1)

Measurements have been performed both in terminated (TM) and in short-circuit (SC) modes, which is the baseline configuration from 2017. The measurements in bunched mode showed rise times just consistent with specifications for SC mode. More measurements are, nevertheless, needed to investigate the flat-top ripple and improve precision. For this purpose, a new beam synchronous trigger will be used to improve the sampling. These new measurements will be performed in MD in 2017, profiting from the hardware improvements [6].

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