BEAM-BASED KICKER WAVEFORM MEASUREMENTS USING LONG BUNCHES

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Abstract

The increased bunch length demanded by the LHC Injectors Upgrade (LIU) project [1] to mitigate emittance growth from space-charge on the PS injection plateau puts strong constraints on the rise-times of the recombination kickers in the transfer lines between the CERN Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS). A beam-based technique has been developed to validate the waveforms of the recombination kickers. In this paper high-resolution measurements are presented by extracting the intra-bunch deflection along bunches with lengths comparable to or longer than the rise-time of the kicker being probed. The methodology has been successfully applied to the three vertical recombination kickers named BT1.KFA10, BT4.KFA10 and BT2.KFA20, and benchmarked with direct measurements of the kicker field made using a magnetic field probe. This paper describes the beam-based technique, summarises the main characteristics of the measured waveforms, such as rise-time and flat-top ripple, and estimates their impact on beam brightness.

INTRODUCTION

The BT1.KFA10, BT4.KFA10 and BT2.KFA20 kicker magnets are used to recombine the bunches coming from the four vertically-stacked rings of the PSB. The batch, constituted by several bunches, can then be directed to the dump at the end of the beam transfer measurement (BTM) line, or to the ISOLDE experiment, or to the PS through the BTP line. The single bunches going to the PS for the LHC (Standard production) are of interest for this paper. To preserve the brightness of the LHC bunches it is very important that the recombination does not disturb the vertical distribution of particles of the bunches.

The present LHC baseline (standard production) is constituted by 180 ns long bunches, spaced by 327 ns, at 1.4 GeV. The bunches, coming from different PSB rings, are labeled as "Rx", where x is the PSB ring number from which they are ejected. The LHC injections into the PS are performed with two batches separated by 1.2 s, i.e. the PSB basic period. In the first PS injection four bunches are extracted from each ring in the following sequence: R3 → R4 → R2 → R1. The second injection is composed of two bunches: R3 → R4.

BT4.KFA10 recombines R3 (un-kicked) and R4 (kicked), BT1.KFA10 recombines R2 (un-kicked) and R1 (kicked), and finally, BT2.KFA20 recombines R3-R4 (un-kicked) and R2-R1 (kicked), as shown in Fig. 1.

The recombination kickers are triggered in the time between two adjacent bunches. A relatively short rise-time is important to avoid that the transient of the magnetic field perturbs the tail of the first bunch and/or the head of the second one. In order to obtain a clean transfer for the longer 220 ns LIU bunches, the specification [2] requires the 2-98% rise-time ≤ 105 ns.

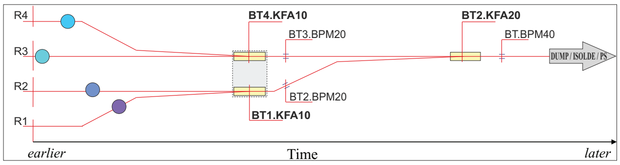

Figure 1: A simplified sketch (edited from [3]) of the recombination kickers in the BT-BTP line (lateral view) and the sequence of PSB bunches before being recombined.

The flat-top ripple of the kicker waveforms must be controlled to avoid the detrimental effects of vertical intra-bunch motion that will result in vertical emittance growth and filamentation in the PS. The specification requires ≤ 2% flat-top ripple for each recombination kicker.

These limits have to be considered without any further margin and are directly related to the emittance blow-up, which is expected from simulations [4] to be in the order of 2%.

MEASUREMENT SET-UP

The reconstruction of the kicker waveform was obtained from the measured displacement of the beam after it is kicked. In fact, the displacement δ at any beam position monitor (BPM) is directly proportional to the integrated magnetic field seen by the beam, such that the deflection angle θ at the kicker can be written 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.

The first downstream BPM after each kicker was used to retrieve the beam displacement information in time, by taking the ratio between the vertical difference (Δ_y) and the sum (Σ) signals in a defined gating time window around the peak current location of the bunch. The BPM signals were monitored on an OASIS scope [5] in the control room and recorded as a function of the delay imposed on the kicker trigger.

Figure 2 shows an example of the sum and difference signals of BT.BPM40, which is the first downstream of BT2.KFA20. It is possible to distinguish different cases in the figure where (left) the first bunch (R4) is partially affected by the kick and R2 is fully kicked, the nominal case (centre) where R4 is un-kicked and R2 is fully kicked and (right) the case where the second bunch (R2) is partially kicked and R4 stays un-kicked.

Figure 2 also shows the magnet input current signal of the BT2.KFA20 kicker on OASIS. It should be stressed that this last signal represents the input current for the magnet and is not representative of the magnetic waveform of the kicker. Moreover the current signal appears low-pass filtered due to the attenuation in its transmission to the OASIS scope and

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thus is only useful to determine and verify the delay applied to the trigger of the kicker.

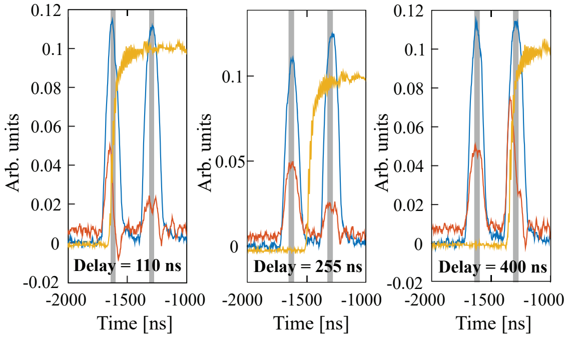

Figure 2: The BPM Δ_y (orange) and Σ (blue) signals, together with the current signal (yellow) for three different values of the BT2.KFA20 delay. The grey error-band is the chosen gating window around the peak current.

MEASUREMENT PROCEDURE

Calibration

It is important to perform a beam-based calibration of the BPM with respect to the kicker voltage at the beginning of every measurement, as shown in Fig. 3. The calibration has to be performed in a nominal regime, i.e. with the first bunch completely un-kicked and the second one fully kicked, as in Fig. 2 (centre). Due to trajectory differences in the transfer line, the BPM signals of the two bunches have to be vertically shifted by an offset in order to be both aligned to the same reference. As shown in Fig. 2 (centre), the offset corresponds, for the fully kicked bunch, to the constant term of the linear regression of the measured deflection per kicker voltage, and, for the un-kicked bunch, to the average value.

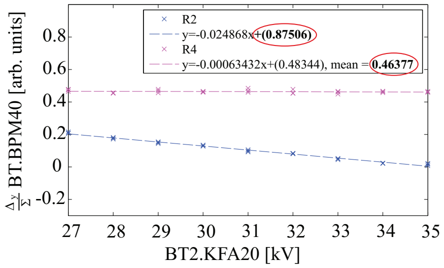

Figure 3: The calibration plot for the BT2.KFA20 kicker vs BT.BPM40 (the offsets are in the red ellipses).

Reconstruction

The measurement was performed by scanning the fine delay of the recombination kicker and acquiring BPMs signals of the two consecutive bunches. The measured signal is shown in Fig. 4 (left). The reconstruction was then completed through the vertical shift of the two waveforms determined in the aforementioned calibration process. After further statistical processing the waveform is shown in Fig. 3 (right) plotted with 1 standard deviation (SD) significance bounds. As the BPM responses are more precise at high currents [4], the bunch population at the exit of the PSB was chosen at ~ 200×10^{10} protons and, owing to the length of the bunches (180 or 220 ns), multiple intra-bunch measurement samples could be taken within individual bunches. This allowed high granularity in the measurements.

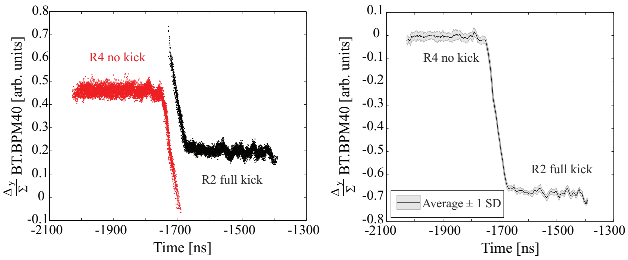

Figure 4: The magnetic waveform reconstruction process.

The characteristics of the waveform were only measured at the relevant locations where the bunches sit, very close to, and either side of, the rising edge. For the BT1(4).KFA10 the flat-top ripple is relevant during only the first 220 ns before and after the rising edge as single bunches are recombined. For BT2.KFA20 up ~550 ns (from one 220 ns bunch length plus 327 ns bunch spacing) is important, as it recombines doublets (R3-R4 and R2-R1).

The beam-based reconstructions were performed at the present operational voltages for an extraction energy of 1.4 GeV from the PSB, corresponding to: 43 kV for BT1(4).KFA10 and 27 kV for BT2.KFA20. At the future 2 GeV extraction energy (+30% magnetic rigidity) the kickers will require 56 kV for BT1(4).KFA10 and 35 kV for BT2.KFA20.

The magnetic field measurements using a magnetic measurement coil for the KFA20 kickers were performed at 27 kV on the magnets installed in the machine during a technical stop, while the others were done at 50 kV for BT1.KFA10 (in the machine) and 56 kV for BT4.KFA10 (in the lab). These measurements were then scaled-up to be compared with the beam-based measurements. This comparison is valid in the assumption of an ideal "linear" response of the kicker system, which was demonstrated in dedicated beam-based measurements [4].

MEASUREMENT RESULTS

The raw measurement data was filtered using a (low-pass) median filter with a time window of 10 ns. This choice was made to smooth the signal whilst at the same time keeping a large enough bandwidth to observe any significant frequency components. The beam-based measurements could be compared with the magnetic measurements from fast magnetic measurement coils, in the machine and/or in the lab.

BT1.KFA10

The beam based measurements, shown in Fig. 5, indicate the presence of ripple and an initial overshoot that is filtered by the field measurement probe whose characteristics are unknown. The measurement results from the probe appear low-pass filtered and do not present the initial overshoot.

BT4.KFA10

The comparison between the beam-based and lab-based measurements are shown in Fig. 6. A slight disagreement is visible in the amplitude of the flat-top ripple and might be induced by the fact that only one of the two modules of the kicker was probed and the system was not exactly equal to the one installed in the machine.

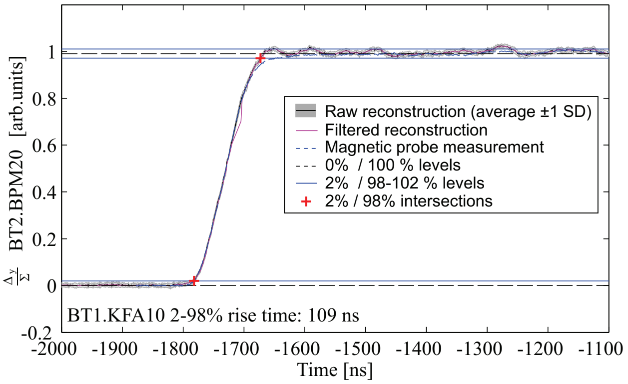

Figure 5: BT4.KFA10 waveform vs. probe in the machine.

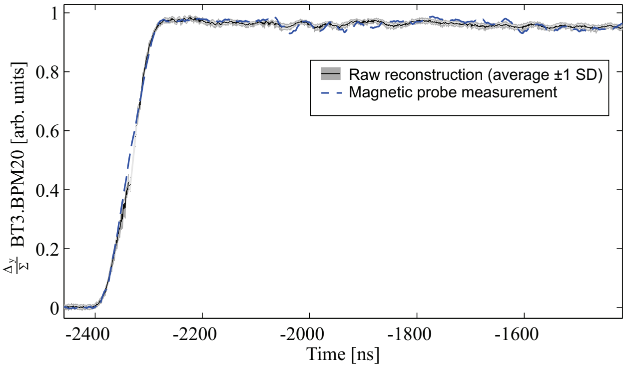

Figure 6: BT4.KFA10 waveform vs. probe in lab.

BT2.KFA20

The beam-based measurements were compared with the measurements from a fast and more reliable magnetic field probe, which was inserted directly inside the magnet in the machine. The results, in Fig. 7, show an excellent agreement. The flat-top peak ripple is confined inside ±2%, except for a reflection inside the black dashed ellipse. The ripple induced from this reflection creates some undesired vertical emittance blow-up, and the KFA20 system will be recabled into the same configuration as KFA10 as part of the LIU project to remove this reflection.

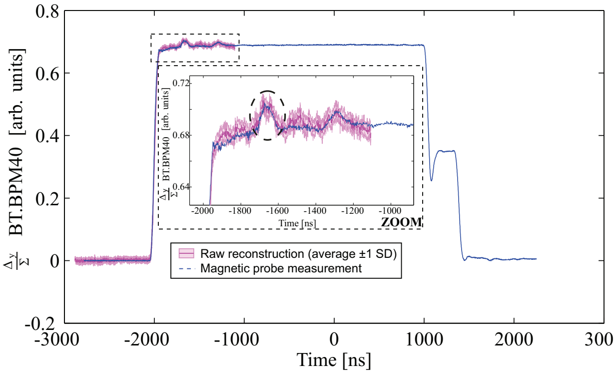

Figure 7: The BT2.KFA20 beam-based magnetic waveform.

Rise-times, Flat-top Ripples, Frequency Responses

The rise-time and flat-top ripples estimated from the beam-based measurements, which are summarised in Tab. 1, are just in specification.

After considering all the error sources such as the BPM sensitivity to current, the calibration technique, the beam reproducibility, the jitter of the firing trigger of the kicker, etc., the tolerance on the final rise-time measurements was conservatively set to ±10 ns and the lab-based field measurements validated.

Table 1: The Rise-times and Flat-top Ripples

	2-98% rise-time [± 10 ns]	Flat-top ripple $\hat{B}/\bar{B}$ [%]
BT1.KFA10	109	2
BT4.KFA10	104	2
BT2.KFA20	105	2

In order to have high resolution needed for a fast Fourier transform (FFT), a detailed flat-top measurement was necessary. From the measurements in Fig. 8 the frequency components that need correction by the PS transverse feedback could be assessed: there is no significant component measured over 20 MHz (-3 dB bandwidth of the feedback). Moreover, the applied median filtering reproduced well the main frequency components of the raw signal.

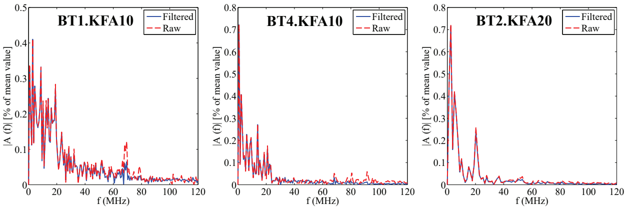

Figure 8: The measured frequency spectra of the flat-top ripple for BT1.KFA10 (left), BT4.KFA10 (centre) and BT2.KFA20 (right).

CONCLUSIONS

A new method to measure the magnetic waveform of the recombination kickers BT1(4).KFA10 and BT2.KFA20 was introduced. This method is valid for measurements in transfer lines where the waveform transients are comparable to the bunch length of the beam being used as a probe. The waveforms have been benchmarked with direct magnetic probe measurements, showing excellent agreement for all the kickers measured. The measured rise-times and flat-top ripples appear just within specification. The frequency components of the kickers are in the PS transverse feedback -3 dB bandwidth specification. Simulations of the incurred emittance growth using the measured waveforms show a blow-up per ring up to 2.7% for 220 ns bunch lengths and 327 ns bunch spacing at 1.4 GeV [4]. Hardware modifications are on-going inside the framework of the LIU project to reduce the BT2.KFA20 ripple and increase the operational voltage margin at 2 GeV by recabling it as the KFA10.

ACKNOWLEDGEMENTS

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