EMITTANCE DILUTION FROM THE CERN PROTON SYNCHROTRON BOOSTER'S EXTRACTION KICKERS

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Abstract

Understanding the different sources of emittance dilution along the LHC injector chain is an important part of providing the high brightness proton beams demanded by the LHC Injectors Upgrade (LIU) project. In this context, the first beam-based measurements of the magnetic waveforms of the Proton Synchrotron Booster's (PSB) extraction kickers were carried out and used to quantify the transverse emittance blow-up during extraction and transfer to the Proton Synchrotron (PS). In this contribution, the waveform measurement technique will be briefly outlined before the results and their implications for the LIU project and beam performance reach are discussed.

INTRODUCTION

The fast extraction kickers of the PSB (BE*r*.KFA14L1, where *r* denotes the ring number) eject the beam in the horizontal plane into the BT transfer line from each of the four vertically stacked rings. The kicker forms part of the extraction system including three bumper magnets (BE*r*.BSW14L4/15L1/15L4) and the extraction septum, (BE*r*.SMH15L1). Once in the BT line, the beam is recombined vertically into the plane of the PS by three more fast-pulsed kicker systems (BT1/4.KFA10 and BT2.KFA20) and vertical magnetic septa (BT1/4.SMV10 and BT2.SMV20), before it is transported via the BTP transfer line and injected into the PS. Figure 1 shows schematically the layout of the PSB extraction region, BT and BTM transfer lines, along with the relevant devices used in this study.

Originally designed for an extraction energy of 800 MeV [1], the extraction kickers have undergone multiple upgrades over the years [2]. The KFA14L1 is composed of four vertically superimposed in-vacuum, C-ferrite transmission line kickers, one per ring, each terminated in a short-circuit. The kicker on each ring is composed of four magnets fed in parallel with a single high voltage generator.

Today, the kicker operates at an operational voltage of 41.4 kV delivering an integrated dipole field strength of 51.6 mTm to deflect the 1.4 GeV proton beam by an angle of 7.2 mrad. When the machine restarts in 2020, the kicker will operate at the new extraction energy of 2 GeV by delivering 30% more integrated dipole field strength in the framework of the LIU project, which is well within the system's maximum strength of 72.7 mTm.

In recent years, an extensive campaign of beam-based measurements of the kicker systems involved in PSB-to-PS beam transfer has been carried out to understand the impact of imperfections in their magnetic waveforms on the emittance growth of high brightness LIU beams [3, 4]. In this context, the first beam-based measurements of the magnetic waveforms of the four KFA14L1 kickers were carried out, the flat-top ripple quantified and the horizontal emittance blow-up estimated for relevant LHC-type beams. The measurements were particularly important to rule out the extraction kicker as the source of the horizontal emittance growth observed after injection to the PS [5, 6].

MEASUREMENT TECHNIQUE

Preparation of Machine Development (MD) Cycle

A short LHC single bunch (INDIV) beam was prepared on a special MD cycle with a root-mean-square (rms) bunch length $\sigma_t \sim 10$ ns in order to resolve the fine time structure of the KFA14L1's pulse. This was achieved with an RF manipulation immediately before extraction; the main RF voltage was stepped down abruptly from 8 to 1 kV for a quarter of a synchrotron period before the voltage was reapplied. The bunch length and momentum spread at extraction could be adjusted and tuned by up to a factor of 4 by adjusting the delay between the reapplication of the RF voltage and the moment of extraction. In the case of the beam-based measurements presented here, the extraction instance was timed a quarter of a synchrotron period later for the shortest bunch length.

Measurement Procedure

To probe the waveform, the transverse deflection of the beam was measured as a function of the fine delay of the kicker's trigger pulse using beam instrumentation devices located in the downstream transfer lines. It quickly became apparent that a large number of machine cycles were needed to counter the machine's limited reproducibility and attain the high temporal resolution required. Typically, a few thousand shots were needed for a satisfactory measurement of the entire flat-top of the kicker, taking approximately 12 h depending on the operational conditions of the PSB at the time of the measurement. Measurements made over such a long period of time are sensitive to changes in the magnetic history of the machine and in order to improve the measurement repeatability the same cycle (ISOLDE) was always programmed before the measurement cycle. The fine delay of the trigger was sampled randomly during the measurement period to reduce the effect of any systematic drifts on the reconstructed waveforms. The kicker has a fixed flat-top length ($\sim$ 1500 ns) that is far longer than the revolution period of protons because of the historical operation of slow, heavy ion beams. With protons only the first 570 ns of

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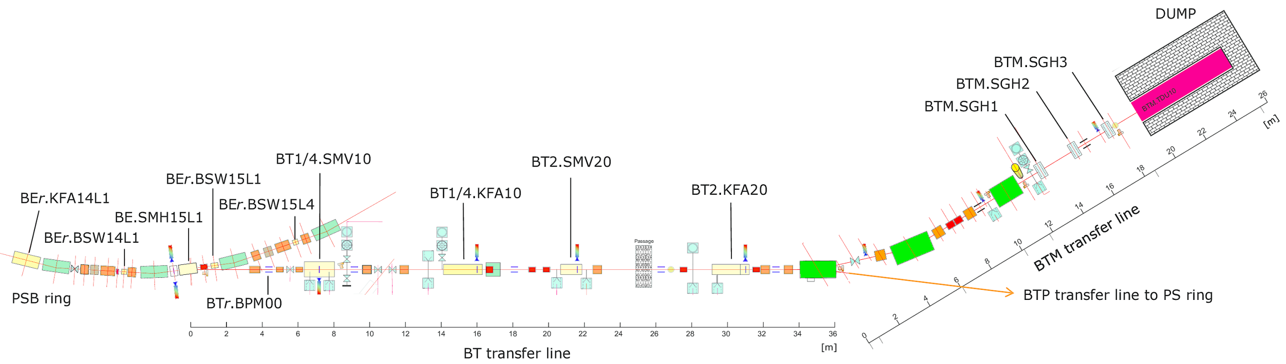


Figure 1: Plan view of the PSB extraction region, BT and BTM transfer lines and the relevant devices used in the study [7].

the flat-top is measurable. In any case, measurements later along the pulse are irrelevant as heavy ions are no longer accelerated by the PSB.

Beam Instrumentation

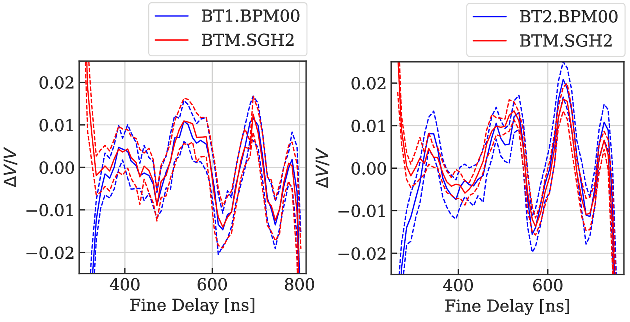
The beam position could be reliably measured using a suitably-located capacitive pick-up or Beam Position Monitor (BPM) in the BT line (BT*r*.BPM00) and at the three wire-grid profile monitors (BTM.SGH1/2/3) located in the BTM line upstream of the dump. The grids also provided the opportunity to measure the beam size. BTM.SGH2 was particularly useful for observing the perturbation of the kicker on the beam due to its suitable phase advance and location with close to zero dispersion.

KFA14L1 Voltage Calibration

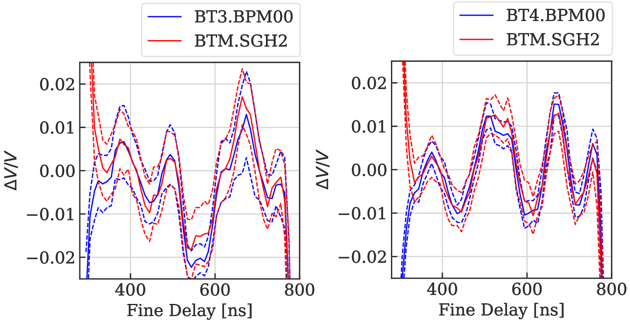
The beam movement induced by the imperfections in the kicker's pulse was calibrated at each instrument with the voltage of the kicker. This was carried out by holding the fine delay constant and measuring the beam position variation as a function of voltage. The calibration allowed the quantification of the relative magnitude of the ripple with respect to the nominal voltage ($\Delta V/V$). Using the known transfer function from voltage to integrated field, the relevant transfer matrix elements (R_{12}) could be computed from the calibration constants and compared to the MAD-X optics model, which showed reasonable agreement.

WAVEFORM MEASUREMENT RESULTS

The data was processed with a moving average using a sample window of 10 ns and filtered for occasional bad shots by removing outliers that exceeded the moving average by more than $\pm 3\sigma$. The waveform results for each kicker are collected in Fig. 2, where only the instruments with the most favourable phase advance are presented. As expected, the results show consistent waveforms for all kickers with some differences observed on BT3.KFA14L1, where the measurement conditions were less stable and the variation of the data larger. Nevertheless, the flat-top stability is typically bounded within ±1% for the first ~ 250 ns of the pulse and ±2% for the second ~ 250 ns. The dominant frequency component in the ripple is ~10 MHz corresponding to the propagation time of reflections on the pulse forming lines between the main switch and magnets. The cause of the differences measured on BT3.KFA14L1's waveform is being investigated.



(a) BT1.KFA14L1 (b) BT2.KFA14L1



(c) BT3.KFA14L1 (d) BT4.KFA14L1

Figure 2: Waveform measurements: (solid lines) moving average sampled with a window of 10 ns, (dashed lines) standard deviation.

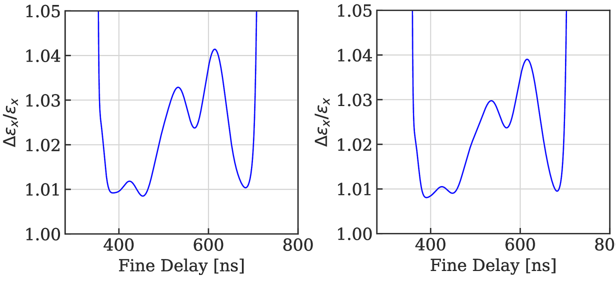
IMPACT ON EMITTANCE GROWTH

In the presence of a non-uniform kicker pulse a bunch with finite length will experience a growth in its transverse emittance due to the variation in the transverse deflection imparted by the kicker along the length of the bunch. To compute the expected emittance growth, the measured kicker waveforms shown in Fig. 2 were fitted with high-order polynomials and normalised to the nominal deflection angle of 7.2 mrad. The waveform was then applied to a simulated

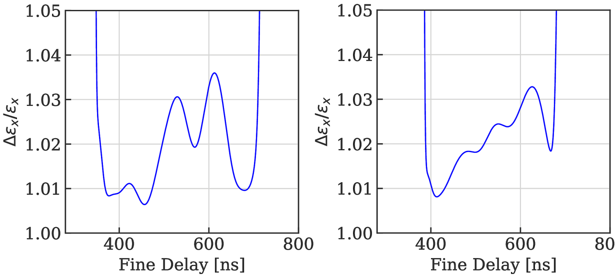
Table 1: Relevant Beam Parameters Used in the Simulation Studies. More Detailed Beam Parameters can be Found in [8].

LHC beam type	**Status**	E **[GeV]**	I **[$\times 10^{11}$ ppb]**	$\epsilon_{x,n}$ **[mm mrad]**	ϵ_z **[eVs]**	$4\sigma_t$ **[ns]**
Operational - BCMS	achieved	1.4	7.50	1.0	0.9	145
Machine Development - BCMS	achieved	1.4	7.50	1.1	1.5	155
LIU - BCMS	targeted	2.0	16.25	1.4	1.5	135
LIU - Standard	targeted	2.0	32.50	1.8	3.0	205

particle distribution as a function of the fine delay between the bunch and the kicker's trigger pulse, assuming a thin lens approximation and using the nominal optics model. The expected rms emittance blow-up for the different LHC beams collected in Table 1 is shown for BE3.KFA14L1 in Fig. 3, where the horizontal β-function at the kicker was taken as 5.9 m. The transverse distribution was generated as Gaussian (σ_x) and the longitudinal bunch shape modelled as parabolic ($\propto 1 - t^2$) and parameterised by the rms bunch length (σ_t).



(a) Operational - BCMS ($\epsilon_z = 0.9$ eVs) (b) MD - BCMS ($\epsilon_z = 1.5$ eVs)



(c) LIU - BCMS ($\epsilon_z = 1.5$ eVs) (d) LIU - Standard ($\epsilon_z = 3.0$ eVs)

Figure 3: Simulated relative emittance growth induced by BE3.KFA14L1 using the waveform in Fig. 2(c).

In all cases, the emittance growth can be controlled to approximately 1% with careful synchronisation of the kicker. It should be emphasised that the synchronisation will be far more critical for future operation of the longer Standard LIU beam.

Comparison to Measurements

To observe directly the impact of the BE3.KFA14L1's ripple on the beam, the operational and MD BCMS beams were transferred to the dump as the fine delay was sampled. A comparison between the measured and simulated beam size at BTM.SGH2 is shown in Fig. 4, where the perturbed particle distribution was tracked from BT3.KFA14L1 to BTM.SGH2. The measured data corresponds to the rms (σ_x) of a Gaussian function fitted to the profiles measured on the grids. The measurement was reproduced by binning and fitting the simulated particle distribution with a Gaussian function to extract σ_x.

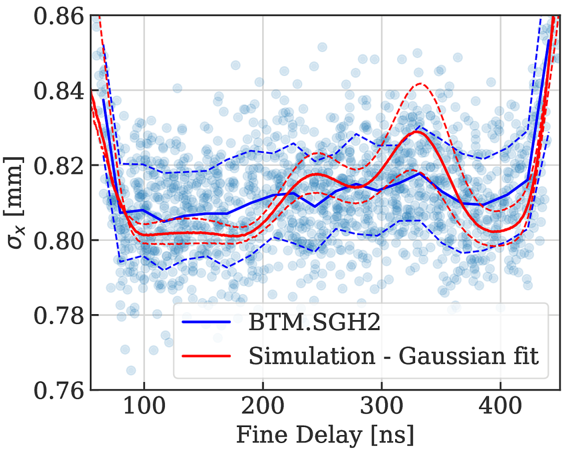


Figure 4: Comparison between the measured and simulated beam size at BTM.SGH2 downstream of BT3.KFA14L1 on the BCMS OP beam, corresponding to the case in Fig. 3(a).

As expected, a similar behaviour was observed for the MD beam and no variation in the beam size was observed for the short LHC INDIV beam.

CONCLUSION AND OUTLOOK

Beam-based measurements of the PSB extraction kicker were presented and used to quantify its contribution to the observed emittance blow-up of LHC-type beams during transfer to the PS. At approximately 1% the emittance blow-up is small, even for future LIU beams, however, the fine synchronisation of the kicker is important and should be optimised. As a next step, the kicker waveforms involved in PSB-to-PS transfer will be used to assess if the PS transverse feedback system can cope with damping the emittance blow-up during the first few turns after injection.

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