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Characterization of the PS Kickers for Improved Fast Extraction

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Summary

So far the best method for characterizing extraction magnets used for fast extraction in the Proton Synchrotron has been to monitor the current flowing into the magnet as a function of time. However, this method does not directly measure the effect on the particle beam and presents difficulties when one aims to synchronize the magnetic pulse with the beam. This document discusses the development and usage of a method for directly measuring the effect of the kicker's magnetic field on the particle beam, which is then applied to measure and correct the temporal alignment of the modules of KFA71/79, the primary fast extraction magnet of the PS. Further applications such as measuring the temporal alignment of the falling edge and measuring the effect of increasing the module voltage on the measured kick response are discussed.

Contents

1 Introduction

At CERN's Proton Synchrotron (PS) fast extraction is used to quickly move the circulating beam out of the machine for transfer to the Super-Proton Synchrotron (SPS) or physics experiments, or to safely dump it in the external beam dump. Fast extraction is usually performed on timescales of a few particle revolutions (*turns*) around the machine, which at flattop energy corresponds to timescales of a few microseconds. To extract the beam out of the machine on these timescales very fast pulsed magnets, or *kickers*, are used. It is quite difficult to characterize the magnetic field of the kicker as a function of time. This characterization is usually done by measuring the pulses sent to the kicker. This approach is blind to several effects, including the effect of the magnet on the kick pulse and any charge effects due to the beam. This paper discusses a beam-based technique that overcomes these shortcomings, and its application to measuring the relative magnet timings of KFA71/79 in the PS.

2 Background

2.1 Transverse Beam Dynamics

The motion of particles in a circular accelerator can be described using the coordinates s, x and y, where s is the position along the *design orbit* of the machine and x and y refer to the horizontal and vertical transverse displacements, respectively. The design orbit is the trajectory followed by an ideal particle with reference momentum and no transverse displacement. When travelling along the design orbit, particles undergo periodic oscillations in the transverse planes called *betatron oscillations*. These oscillations are due to the alternating focusing and de-focusing forces used to confine the beam. The amplitude of the oscillations in each transverse plane is described by the $\beta_{x,y}(s)$ function and the phase is described using $\mu_{x,y}(s) = \int_0^s 1/\beta_{x,y}(s')\,\mathrm{d}s'$. The frequency of the oscillations is called the *tune* and is usually given in units of turn^{-1} [2].

2.2 Fast Extraction

Fast extraction describes the process of quickly extracting a beam of particles from an accelerator. There are several types of fast extraction including multi-burst, multi-turn and single-turn fast extraction. A simple fast extraction setup, as shown in Figure 1, has two components: the kicker and the septum magnet. The kicker is a fast pulsed magnet or a set of fast pulsing magnets, capable of activating on timescales of less than 100 ns. The septum magnet is a magnet with a field-free region and a field region separated by a thin blade. The septum blade is engineered to be thin so that the circulating beam can be pushed from the field-free region into the field region without beam loss. Using this setup a bunched beam is extracted as follows:

1. The signal for extraction is given.
2. The kicker 'fires' in a gap between bunches, going from zero to full strength before the next bunch passes it.

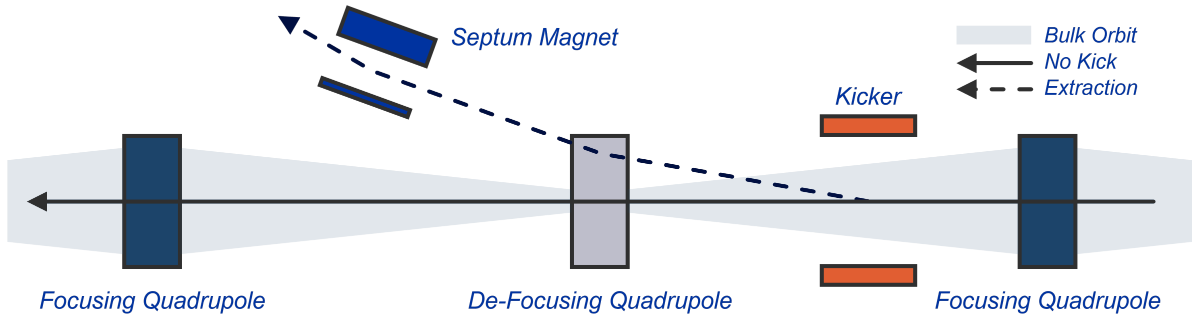


Figure 1: A simple setup for fast extraction. A fast pulsed magnet called a *kicker* is quickly fired, producing a strong magnetic field which deflects the beam. This deflection can be amplified by a defocusing quadrupole before going past the blade of the septum magnet, at which point the beam is fully extracted.

3. The next bunch experiences a large angular displacement (a 'kick'), pushing it past the septum blade where it is extracted.
4. The kicker stays on until all of the bunches are extracted.

Depending on the particle momentum slower magnets called closed-orbit bumpers may be used to push the beam close to the septum blade between steps 1 and 2, reducing the strength of the magnetic field the kicker needs to produce. Similarly, the kicker may be placed before a de-focusing quadrupole magnet. This configuration also reduces the strength of the magnetic field needed to extract the beam by amplifying the displacement produced by the kicker (see Figure 1) [1].

The short timescale of fast extraction of a few turns or less (for reference a turn in the PS takes roughly 2.1 µs at flattop energy) and the bunched nature of the particle beam place very stringent timing requirements on the extraction kickers, including the rise time and the amplitude of the flattop ripple. As illustrated in Figure 2 (a), the kicker needs to have a short enough rise time so that the magnetic field rises from zero to full strength between the passing of consecutive bunches. A bunch that 'sees' a changing magnetic field will be smeared, which will result in beam loss, undesired oscillations and emittance degradation. Having the proper rise time avoids these problems, reducing the induced radiation, as well as improving beam quality. The flat-top ripple will cause similar problems, albeit at a much smaller scale if the kicker is operating correctly. Lastly, in multi-magnet kickers, the synchronization of the magnets is of great importance since it affects the *effective* rise time of the magnet. The effective rise time simply is the rise time of the kicker when the individual contributions from all modules are added together.

3 Method

To study the magnetic field of the kicker as a function of time, as well as its synchronization concerning the beam's passing, the following method is employed: (i) Inject a low-intensity beam containing a single bunch. (ii) Excite betatron oscillations using a small kick produced by the kicker to be studied. (iii) Measure betatron oscillations induced by the kick using

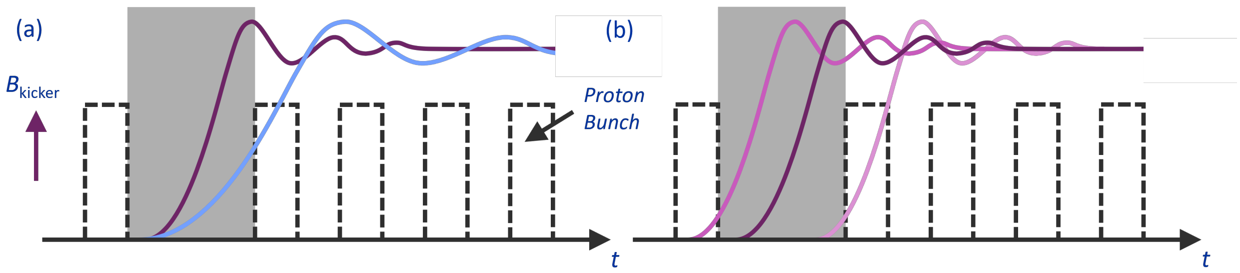


Figure 2: The timing constraints placed on the magnetic fields of the kicker. Panel (a) shows a kick with different rise times. The dark purple line shows the kicker going to full strength in the gap. The light blue line shows a kick where the kicker is not at full strength when the next bunch passes. Panel (b) shows the effect of having poorly synchronized modules in a kicker made of several magnets. The different start times lead to an increased 'effective' rise time.

beam position monitors (BPM) located around the machine. By changing the timing of when the kicker fires with respect to when the bunch passes the kicker, the field of the kicker is sampled as a function of time.

To accurately sample the *waveform* of the module a bunch length much smaller than the smallest feature of interest is needed. In the case of the operational beam used, the bunch length is measured to be 11.24 ± 0.15 ns (see Figure 3), which is sufficiently smaller than the 100 ns rise time of the modules of KFA71/79.

For the analysis, the betatron oscillations measured by the BPMs are 'zeroed' by fitting and subtracting a low-order polynomial in order to avoid artifacts after applying a frequency filter to the data. The filter used is a Butterworth band-pass filter of order 5, centred on the horizontal tune with a window of $\pm 0.05\,\text{turn}^{-1}$. This significantly reduces the random noise and increases the dynamic range of the measurement. The error of the filtered BPM signal is taken to be close to the standard deviation of the filtered signal before the kick (roughly 1000 turns)[1]. The amplitude of the filtered oscillations $\Delta x_i = \max_n x_i(n)$ is computed, by determining the largest value of the zeroed signal over the measured turns, and normalized using the beta function. To compute the final kick response, the mean $\overline{\Delta X}$ and standard deviation $\sigma_{\overline{\Delta X}}$ of the normalized responses are computed with the latter being taken as the associated error:

$$\overline{\Delta X} = \frac{1}{\mathrm{N_{BPM}}} \sum_{\mathrm{BPM}\ i} \frac{\max_{\mathrm{n}} \left(\Delta x_i(n)\right)}{\sqrt{\beta(s_i)}}, \qquad \sigma_{\overline{\Delta X}} = \sqrt{\frac{\sum_{\mathrm{BPM}\ i} \left(\Delta X_i - \overline{\Delta X}\right)^2}{\mathrm{N_{BPM}}}}. \tag{1}$$

Having measured the waveform of a module, the timing and rise time are extracted by fitting a simple model:

$$f\left(t; \kappa, t_0, \tau, \overline{\Delta x_0}\right) = \kappa \times \mathrm{erf}\left(\frac{t - t_0}{\tau}\right) + \overline{\Delta x_0}. \tag{2}$$

[1] An interesting alternative would be to use the PyDynamic library [3] to propagate the initial signal error through the filtering step.

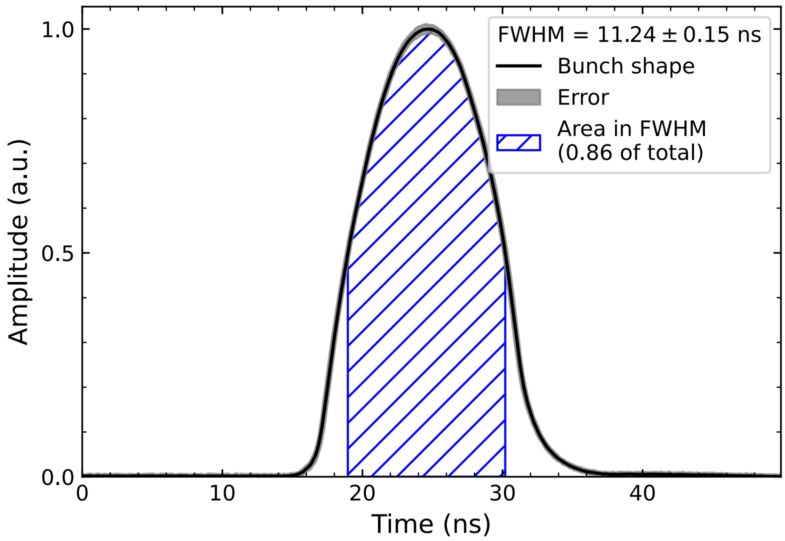
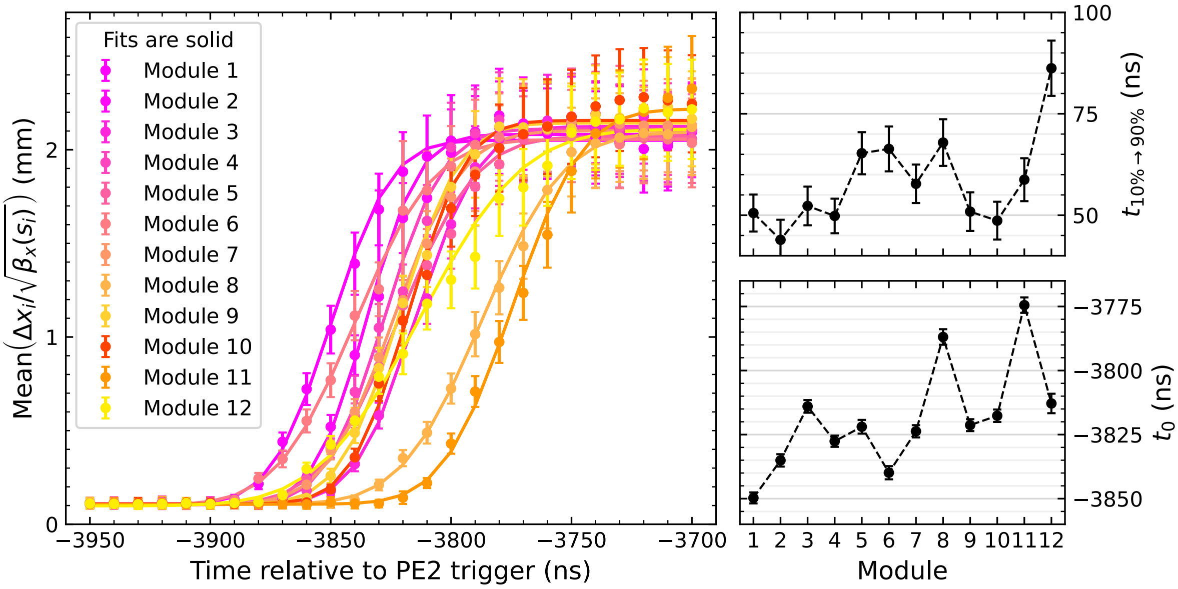


Figure 3: Average longitudinal profile of the beam, measured 3 ms before the excitation kick. The full width at half the maximum value (FWHM) of the average profile was measured to be 11.24 ± 0.15 ns.

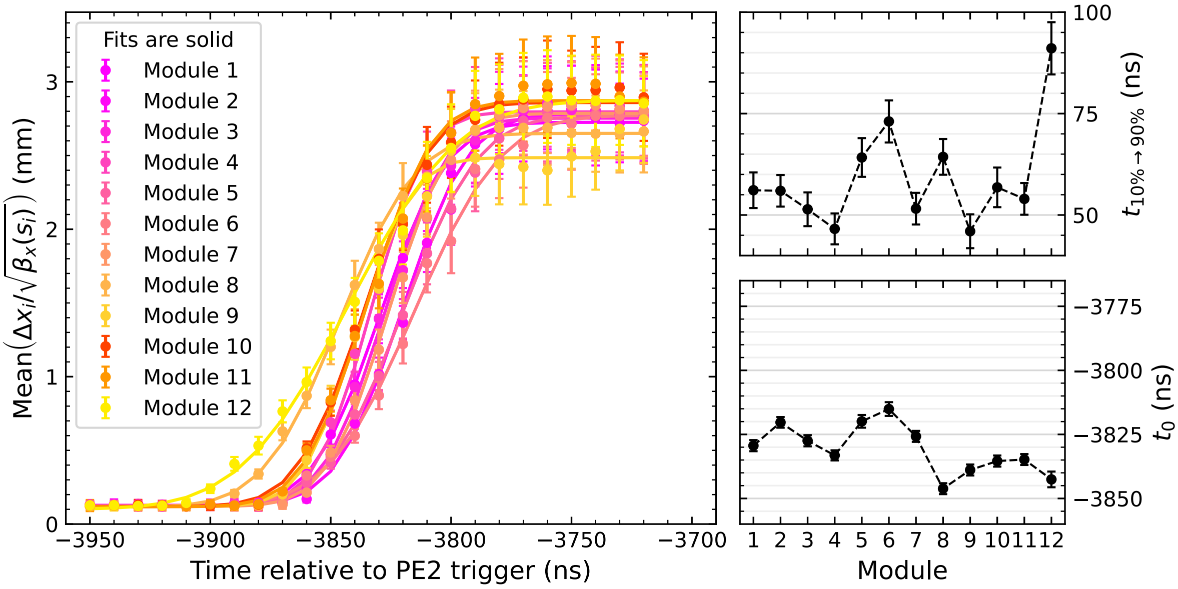
The parameters of interest are t_0 which is the time the module reaches half strength, and τ which is proportional to the rise time of the module. The time it takes for the module to go from 10 % to 90 % is given by $t_{10\,\% \rightarrow 90\,\%} \approx 1.81 \times \tau$ ($t_{5\,\% \rightarrow 95\,\%} \approx 2.31 \times \tau$). It is important to note that this function is just a coarse approximation that does not account for any ripple that might be present in the signal.

4 Results and Discussion

The method described above was used to measure the quality of the synchronization of the kicker KFA71/79, and the results were used to correct the spread in the start time of the modules from a spread of 20 ns to 9 ns (see Figure 4). The average 10 % $\rightarrow$ 90 % rise time is 60 ns which is very close to the original specification of 56 ns [4]. No ripple was observed in this measurement. However, this is most likely due to the measured time range being too short, not including enough data points along the waveform's flattop. Note that in the process of measuring and performing the alignment no attention was paid to the state of the drift correction. The drift correction is done by dedicated hardware that measures the difference between when the kicker fired and when it should have fired and adjusts the delay of the kicker in 1 ns steps based on this measurement. If the alignment is performed in the future it would be important to note the state of the drift correctors at the time of measurement (ideally this would be logged) or even turn them off for the duration of the measurement, since changes in the drift correctors likely caused the alignment to not be perfect in the end.



(a) Before alignment



(b) After alignment

Figure 4: KFA71/79 rising edges measured before (a) and after (b) adjusting the hardware delays. The adjustments were carried out based on the results from (a). The standard deviation of the module timings in (a) is 20 ns compared to 9 ns in (b).

4.1 Suggestions for Improvement

The most significant improvement is likely made by computing an accurate estimate of the β function in the machine when doing the measurement. At the moment the analysis uses the β function provided on the `acc-optics` repository[2]. The easiest way of computing a more accurate estimate would involve measuring the tune and computing the β function using MADX, providing the measured tune as an input parameter. It might also be interesting to use the measured tune as the center frequency of the filter used to remove noise from the BPM signal. Computing a better estimate of the β function should help with decreasing the error seen on the data points of the flattop region in the rising and falling edge measurements. Reducing the error is critical to be able to determine the scale and timescale of the ripple. It might also be interesting to analyze the signal on a BPM-by-BPM basis instead of averaging them all together. Since there is no averaging, there would be no need to know the β function at all.

Once the signal error is sufficiently reduced it would be interesting to generalize the data output from the analysis by computing the deflection angle induced by the kicker $\Delta x'_{\text{kicker}}$. The angle is computed using the following expression [1]:

$$\Delta x'_{\text{kicker}} = \frac{\Delta x_{\text{BPM}}}{\sqrt{\beta_{\text{kicker}}\beta_{\text{BPM}}}\sin\left(\mu_{\text{kicker}\to\text{BPM}}\right)}, \qquad \mu_{\text{kicker}\to\text{BPM}} = \int_{s_{\text{kicker}}}^{s_{\text{BPM}}} \frac{1}{\beta(s')}\,\mathrm{d}s' \tag{3}$$

By using the kick angle, the measurement could then be made independent of the particle momentum and hence the kicker would be characterized fully.

4.2 Further Applications

In multi-burst fast extraction, the fall time is as important as the rise time, since the bunches not included in the extraction burst should be disturbed as little as possible. The beam-based technique can be used to measure the timings of the falling edges (see Figure 5). The measured timings can then be used to align the falling edges and improve the ‘effective’ fall time of the kicker.

Another exciting application is to obtain a calibration curve for beam displacement as a function of the voltage supplied to the kicker. To do so, the oscillation amplitude induced by the kicker can measured at constant delay, chosen so that the beam ‘sees’ the flattop region. By measuring the beam displacement as a function of the kick voltage, a calibration curve can be created for each module. Figure 6 shows one such measurement done for module 1 of KFA71/79. In this case, the measurement was done at flattop (kick delay of 3000 ns and flat bottom 4500 ns.

5 Conclusion

A beam-based method for characterizing the magnetic field of any extraction kicker was developed and successfully applied to reduce the spread in the module start times of KFA71/79

[2]The computed β functions are available on the CERN acc-modules website. For this report, the β function from 2023 LHCINDIV flattop was used. The functions may be computed using the scripts in the ps-acc-models repository.

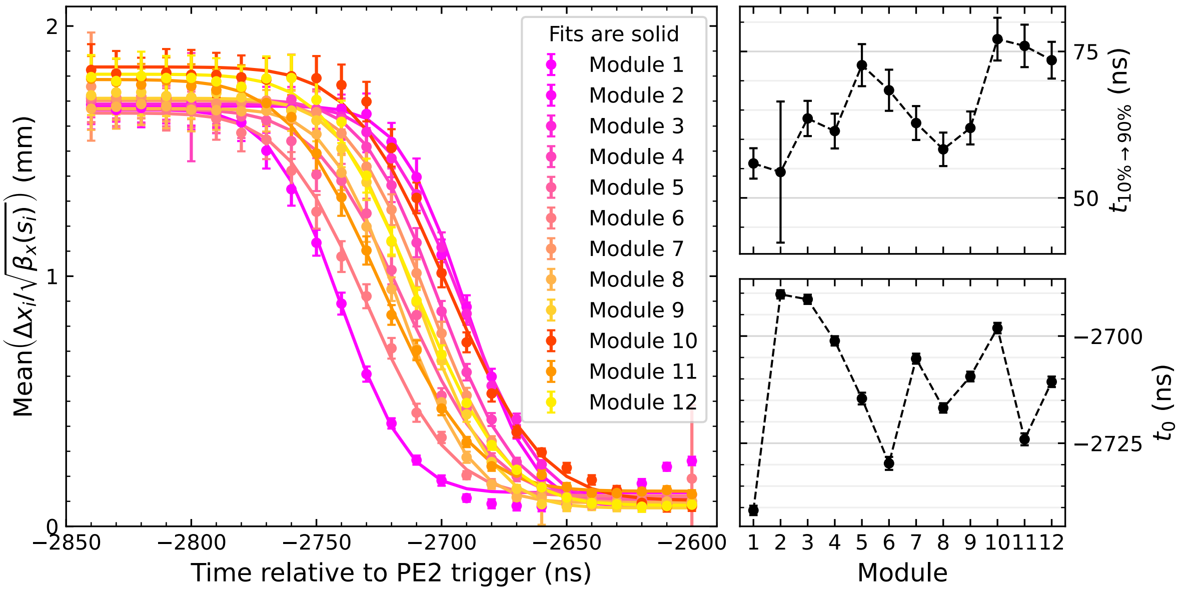


Figure 5: Falling edges of KFA71/79 measured using the same procedure outlined above.

from 20 ns to 9 ns. Further applications of the technique were demonstrated including measuring the temporal alignment of the falling edges of KFA71/79 and measuring the relationship between the beam displacement produced by the kicker and the applied voltage. Suggested improvements include measuring the tune before a measurement run and using the measured tune to compute a more accurate estimate of the β function. Furthermore, it would be beneficial to compute the kick angle by normalizing the measured kick response using the beta function of the kicker along with the phase advance between the kicker and each BPM.

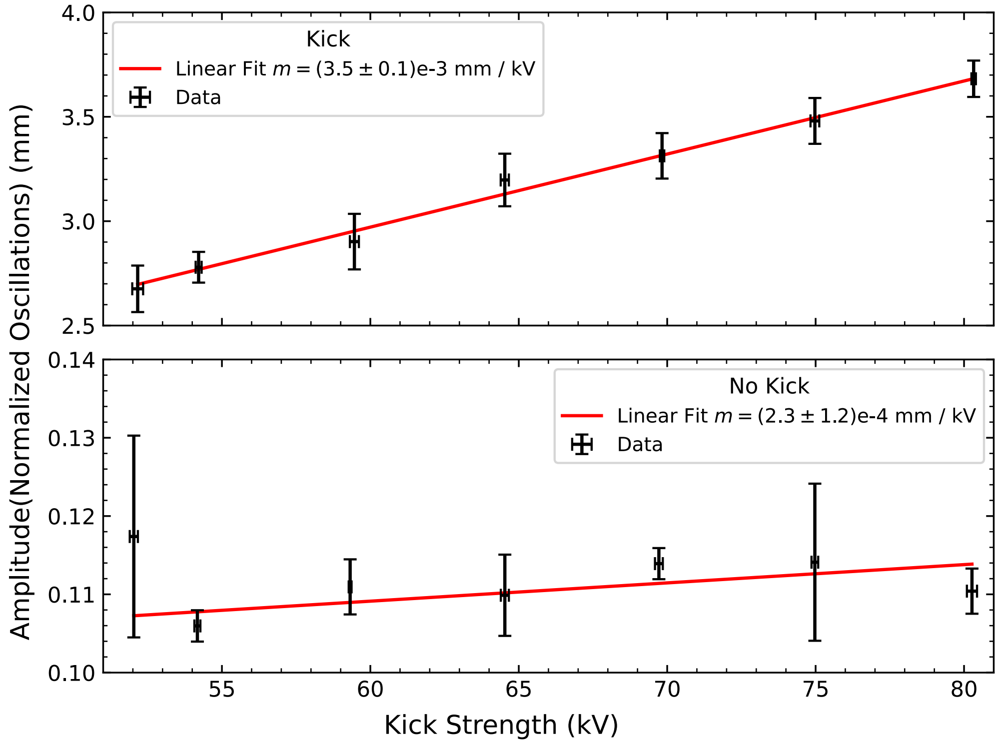


Figure 6: An example voltage calibration done for module 1. Data was taken at two delays set so that the beam 'sees' the flattop ('Kick') and the other so that the beam sees no kick.

References

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A Appendix: Measuring the Module Timings of KFA71/79

All the relevant code for performing a timing measurement of KFA71/79 can be found on GitLab as part of the kfa71_kick_response group. To run a simple measurement and analyze the result consult the Measurement repository in the same group. For some more information about the other repositories view the Info repository.