NOVEL BEAM EXCITATION SYSTEM BASED ON SOFTWARE-DEFINED RADIO

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Abstract

A signal generator for transverse excitation of stored particle beams is developed and commissioned at GSI SIS18. Thereby a novel approach using a software-defined radio system and the open-source GNU Radio ecosystem is taken. This allows for a low cost yet highly flexible setup for creating customizable and tuneable excitation spectra. Due to its open-source nature, it has the potential for long term maintainability and integrability into the accelerator environment. Furthermore, this opens up the possibility to easily share algorithms for the generation of waveforms across accelerator facilities.

As a first application, the device is used to control the coherence and amplitude of transverse oscillations by excitation in the vicinity of betatron sidebands. It enables measurement of beam parameters like tune and chromaticity. On a longer term, it will be used for more complex tasks such as beam shaping, extraction and automated parameter scans towards these complex processes.

SOFTWARE-DEFINED RADIOS

Software-defined radio (SDR) describes an RF transceiver technology in which signal processing is implemented in software. It is widely used in radio communication systems, but has potential applications in many fields. An SDR typically consists of a frontend with ADCs and DACs, and a backend performing the digital signal processing (DSP). Here, a universal software radio peripheral (USRP) was used as off-the-shelf frontend to generate the RF signals. For implementation of the DSP the open source GNU Radio framework [1] was chosen, which allows to graphically design signal processing flow graphs. The large flexibility and low cost of modification make the device a natural choice not only for prototyping [2], but also for experiments and regular use in the accelerator environment. A general challenge with DSP is the unavoidable processing delay. However, as will be shown in this contribution, modern computer technology and active data flow control enable overcoming this obstacle.

NEW SIGNAL GENERATOR FOR BEAM EXCITATION

For transverse excitation one typically needs two independent signals for the horizontal and vertical plane which are linked to the changing revolution frequency of the accelerated beam. It must also be possible to start the signal by means of a trigger. Figure 1 depicts the working principle of the signal generator meeting these requirements. The USRP digitizes the revolution frequency reference signal (sine with frequency f_{rev}) and receives the trigger (TTL pulse) via the general purpose input/outputs (GPIOs). It streams the data via Gigabit Ethernet to an industrial PC, where GNU Radio performs the DSP. The generated signals are streamed back to the USRP and delivered at the two RF ports.

We use the model N210 and low-frequency daughterboards with parameters listed in Table 1. The DACs provide sampling rates of up to 400 MS/s. In practice, however, this is limited by the data processing rate to about 10 MS/s, allowing to handle and generate frequencies up to 5 MHz.

Table 1: Specification of the USRP N210

Frequency range	0 to 30 MHz
DAC/ADC resolution	16/14 bit (±1 V)
RF ports	2 in- and 2 outputs (50 Ω)
GPIO ports	2 × 16 (TTL)

Minimisation of Signal Delay

The challenge in using an SDR for applications requiring feedback and trigger is to achieve a low signal processing delay. A GNU Radio flow graph consists of blocks performing discrete operations on the signal data stream. The data is processed in chunks and buffered in between these blocks, which improves efficiency but introduces an artificial delay. While GNU Radio is able to optimize buffer usage and data processing to find a trade-off [3], it requires a settling time and is not optimal if a minimal processing delay is crucial. In our application, the data flows from ADC to DAC, which both have a fixed sampling rate. Until the first data sample has been processed by GNU Radio and transmitted back to the USRP, the DAC buffer lacks samples and can not

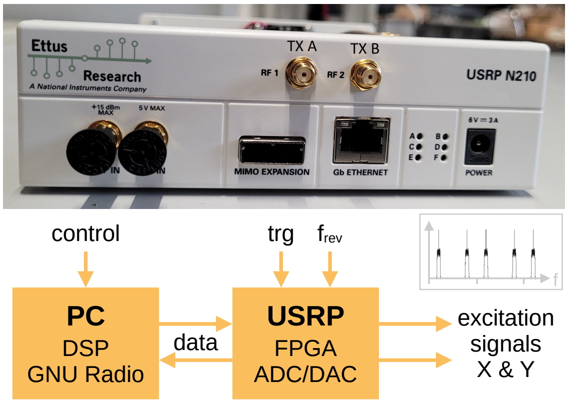

Figure 1: USRP hardware and signal generation scheme.

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produce a signal (underrun). While the average processing speed settles to the sampling rate, spikes in the processing time can result in further underruns. Every time this happens, the amount of samples being buffered grows, which, multiplied by the sampling rate, defines the signal delay. Since no samples are ever discarded, their amount never decreases, and the delay can quickly accumulate to several 100 ms without taking action against it.

To reduce the signal delay, two measures were taken: First, the overall processing time of the GNU Radio flow graph was improved by enabling real-time scheduling, generating baseband signals with reduced sampling rate, setting a maximum buffer size and reducing the overall flow graph complexity.

Second, the triggered operation mode allowed to implement active flow control via a novel out-of-tree (OOT) block [4]. Being the last block in the signal processing chain, it can safely discard incoming samples while waiting for a trigger. Thereby, buffers are drained and the amount of buffered samples – and hence the signal delay – is reduced to a minimum. Upon trigger, incoming samples are conveyed to the USRP. To mitigate underruns due to spikes in the processing time, a deterministic number of samples (1 ms) is inserted in front of the actual data stream. In addition, the bursty transmission mode of the USRP is exploited by adding appropriate burst start and end tags to the data stream.

Figure 2 shows how the signal delay between RF in- and output of the USRP was reduced to about 2 ms by implementing these measures. Without modifications to the FPGA image, the trigger level can only be polled, thus introducing the observed jitter which corresponds to the polling rate of 1 kHz. As can be seen by comparing the signal delay at the start and after 5 s, the build-up and accumulation of delay due to underruns is mitigated successfully. There were also no underruns logged by the USRP. The remaining delay is sufficient for the application as described in the next section, but is expected to be improved by using a newer USRP model with support for DSP directly on the FPGA.

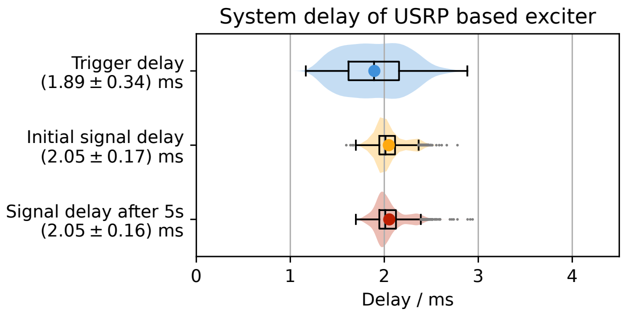


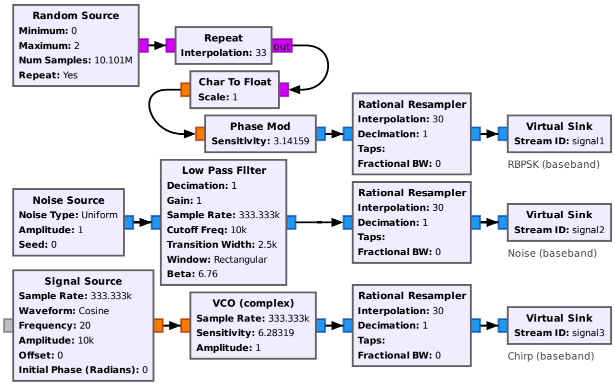
Figure 2: Benchmarking results for triggered signal generation with feedback on an industrial computer (2.1 GHz CPU, 8 cores, 32 GB RAM) running our GNU Radio flow graph at 10 MS/s. Box plots and kernel density estimates are based on 7428 events taken over about 20 hours.

Flow Graph for Signal Synthesis

Several GNU Radio flow graphs have been implemented to generate the excitation signals. The excitation signal of desired type and bandwidth is generated in baseband at a reduced sampling frequency (Fig. 3). Three basic signal types have been implemented (Fig. 4): a binary sequence randomly flipping between ±1 which yields a random binary phase-shift keying (RBPSK) modulation; a band-filtered uniform white noise; and a sinusoidal frequency modulated sine (chirp). The baseband signal is up-sampled and frequency shifted to the desired sidebands of the revolution frequency f_{rev}. The latter is determined from the supplied RF reference signal by means of a phase-locked loop (PLL) to follow the frequency ramp during acceleration, or can alternatively be specified manually by the operator (Fig. 5). Since the excitation bandwidth Δf is constant, the relative width $\Delta q = \Delta f / f_{\mathrm{rev}}$ decreases during acceleration and hence the spectral power density increases. This compensates for the increasing rigidity of the beam.

APPLICATION FOR TUNE AND CHROMATICITY MEASUREMENT

In order to measure the betatron tune using beam position monitors (BPMs), coherence of the betatron oscillations must be established by using transverse excitation [5] at the betatron frequency. Figure 5 shows an excitation flow graph for this purpose, which supports excitation in the vicinity of two distinct betatron sidebands at $(h \pm q)\,f_{\mathrm{rev}}$ with revolution



Random Source
Minimum: 0
Maximum: 2
Num Samples: 10.101M
Repeat: Yes

Repeat
Interpolation: 33

Char To Float
Scale: 1

Phase Mod
Sensitivity: 3.14159

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal1

RBPSK (baseband)

Noise Source
Noise Type: Uniform
Amplitude: 1
Seed: 0

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 333.333k
Cutoff Freq: 10k
Transition Width: 2.5k
Window: Rectangular
Beta: 6.76

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal2

Noise (baseband)

Signal Source
Sample Rate: 333.333k
Waveform: Cosine
Frequency: 20
Amplitude: 10k
Offset: 0
Initial Phase (Radians): 0

VCO (complex)
Sample Rate: 333.333k
Sensitivity: 6.28319
Amplitude: 1

Rational Resampler
Interpolation: 30
Decimation: 1
Taps:
Fractional BW: 0

Virtual Sink
Stream ID: signal3

Chirp (baseband)

Figure 3: GNU Radio flow graphs for baseband signals.

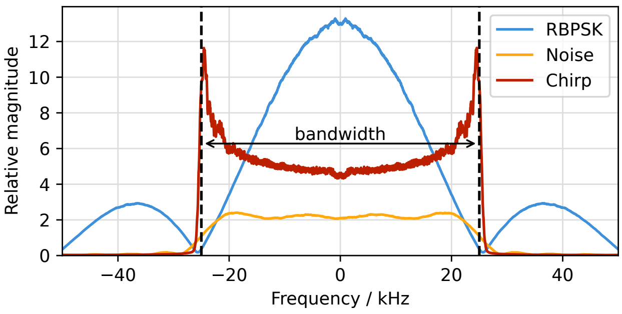


Figure 4: Frequency spectra of baseband signals.

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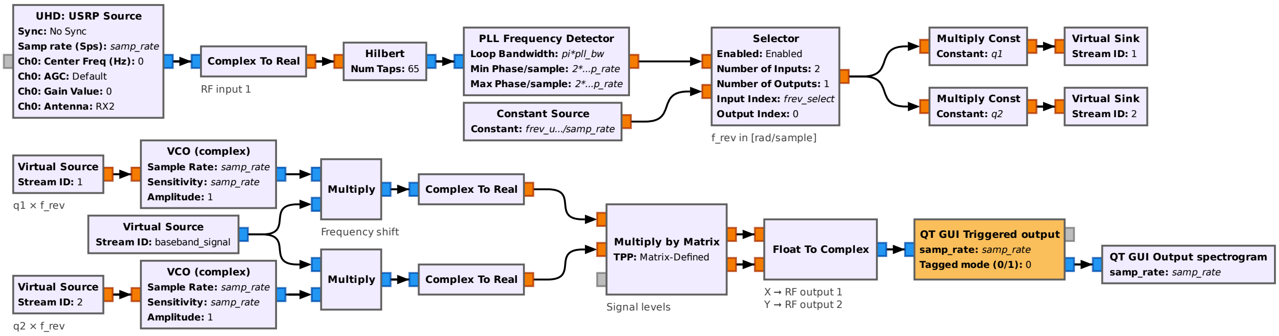

UHD: USRP Source
Sync: No Sync
Samp rate (Sps): *samp_rate*
Ch0: Center Freq (Hz): 0
Ch0: AGC: Default
Ch0: Gain Value: 0
Ch0: Antenna: RX2

Hilbert
Num Taps: 65

PLL Frequency Detector
Loop Bandwidth: *pi*pll_bw*
Min Phase/sample: *2*...p_rate*
Max Phase/sample: *2*...p_rate*

Constant Source
Constant: *frev_u.../samp_rate*

Selector
Enabled: Enabled
Number of Inputs: 2
Number of Outputs: 1
Input Index: *frev_select*
Output Index: 0

Multiply Const
Constant: *q1*

Virtual Sink
Stream ID: 1

Multiply Const
Constant: *q2*

Virtual Sink
Stream ID: 2

Virtual Source
Stream ID: 1

VCO (complex)
Sample Rate: *samp_rate*
Sensitivity: *samp_rate*
Amplitude: 1

Virtual Source
Stream ID: baseband_signal

Virtual Source
Stream ID: 2

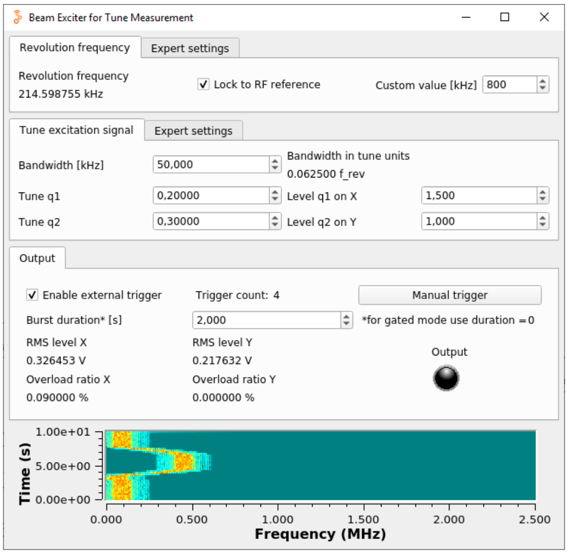
VCO (complex)
Sample Rate: *samp_rate*
Sensitivity: *samp_rate*
Amplitude: 1

Multiply by Matrix
TPP: Matrix-Defined

QT GUI Triggered output
samp_rate: *samp_rate*
Tagged mode (0/1): 0

QT GUI Output spectrogram
samp_rate: *samp_rate*

Figure 5: GNU Radio flow graph for excitation of betatron oscillations in both planes. The revolution frequency is recovered from the signal on RF input 1, and the baseband signal is frequency shifted to the respective sidebands corresponding to the tunes q_1 and q_2. The highlighted custom OOT block is used to trigger and deliver the signals to the RF outputs.


Beam Exciter for Tune Measurement

Revolution frequency
214.598755 kHz
☑ Lock to RF reference
Custom value [kHz] 800

Bandwidth [kHz] 50,000
Bandwidth in tune units
0.062500 f_rev
Tune q1 0,20000
Level q1 on X 1,500
Tune q2 0,30000
Level q2 on Y 1,000

☑ Enable external trigger
Trigger count: 4
Burst duration* [s] 2,000
*for gated mode use duration = 0
RMS level X
0.326453 V
RMS level Y
0.217632 V
Overload ratio X
0.090000 %
Overload ratio Y
0.000000 %
Output ●

Figure 6: Control interface for tune measurements.

harmonic h and tune q. In the absence of coupling, q_1 and q_2 correspond to the horizontal and vertical tune; but it is also possible to excite a single plane at two distinct frequencies by specifying non-zero crosstalk signal levels. The operator interface built with GNU Radio to run the flow graph and adjust the excitation parameters is depicted in Fig. 6.

For each plane, the generated excitation signal is split by a 180° divider into two signals of opposite polarity, each of which is amplified with a 50 W RF amplifier and transmitted to a stripline unit [6] whose E- and B-fields deflect the beam, their contributions being of the same order of magnitude. In short lens approximation, the resulting angular kick is

$$\Delta x' \approx \frac{E_x}{E\rho} l + \frac{B_y}{B\rho} l \approx \left[\frac{1}{E\rho} \frac{l}{d_x} + \frac{1}{B\rho} \frac{l \mu_0}{\pi R w_x} \arctan\left(\frac{w_x}{d_x} \right) \right] \Delta U$$

where $B\rho = p/q$ and $E\rho = pv/q$ are the magnetic and electric rigidity of the beam, ΔU is the voltage between the electrodes, $l = 37\,\mathrm{cm}$ the electrodes' length, $d_x = 20\,\mathrm{cm}$ or $d_y = 7\,\mathrm{cm}$ their spacing, $w_x = 12\,\mathrm{cm}$ or $w_y = 22\,\mathrm{cm}$ their width before bending and $R = 50\,\Omega$ the impedance.

For the actual measurement of the machine tune, the turn-by-turn beam position is recorded using capacitive shoebox-type pickups and Libera Hadron signal processors [7]. A Fourier analysis then yields the eigenfrequencies of transverse motion normalized to the revolution frequency in the interval $0 < f/f_{\mathrm{rev}} < 0.5$, where the tune is observed as resonance peak. Fractional tunes with $q > 0.5$ are visible at $1 - q$ due to aliasing. Likewise, the tune can be measured as a function of time by using a Short-time Fourier transform (STFT).

The new excitation system was commissioned at the Heavy Ion Synchrotron SIS18 at GSI in May 2022 using a 195.7 MeV/u uranium U^{28+} beam. At this highest rigidity of 18 Tm the maximum deflection angle provided by the excitation system for a sinusoidal signal is $\Delta x' = 0.19\,\mathrm{\mu rad}$ and $\Delta y' = 0.38\,\mathrm{\mu rad}$.

Figure 7 shows the measured tune during injection and acceleration using the new excitation system. The excitation produces a clear response up to the maximum beam rigidity. At 0.25 s the excitation was switched off, resulting in a decay of the tune response as the transverse oscillations are damped and become incoherent. Even for the high ramping

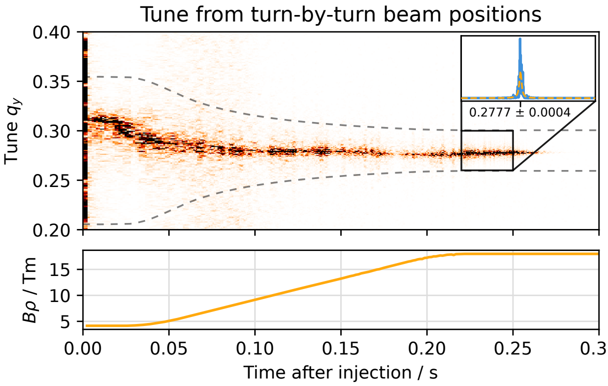


Figure 7: Continuous tune measurement during acceleration using noise excitation with a bandwidth of 16 kHz (dotted lines) and an RMS signal level of 0.088 V (prior to amplification). The bottom plot shows the increasing beam rigidity.

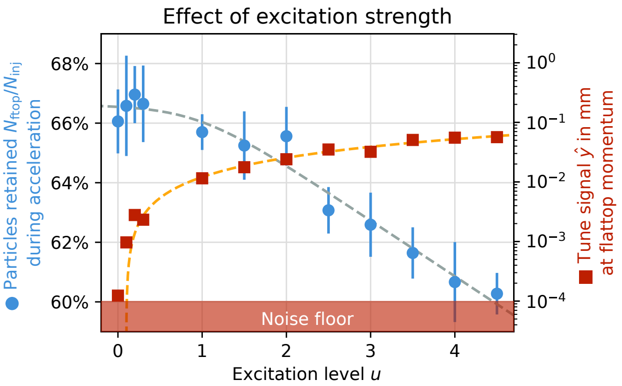


Figure 8: Left: fraction of particles reaching flat-top N_{ftop} versus injected particles $N_{\mathrm{inj}} \approx 2.1 \times 10^{10}$, fitted by a soft-plus function centred at $u_0 = 0.9(4)$. Right: amplitude of betatron oscillation $\hat{y}$ and noise floor $\hat{y}_{\mathrm{noise}} \approx 0.09(1)$ µm, fitted by a linear function with slope $\hat{y}/u = 0.0134(6)$ mm.

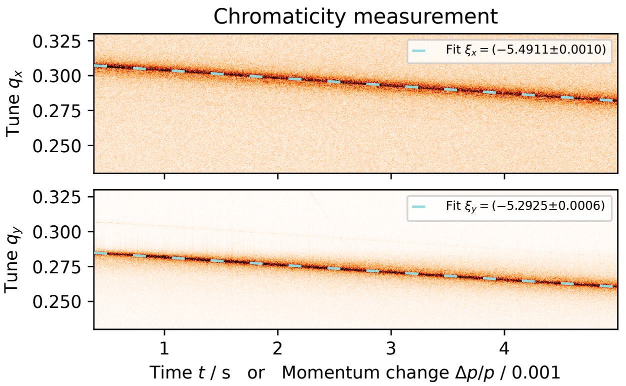


Figure 9: Determination of chromaticity $\xi = \Delta q/(\Delta p/p)$ by continuously measuring the tunes while changing the beam momentum via an RF detuning.

speed of 8 T/s as foreseen for SIS100, the signal delay of 2 ms is non-critical for excitation at the first sidebands: The resulting maximum displacement of the excitation band at the beginning of the ramp was measured to be 0.008 tune units, which is easily compensated by the bandwidth. It was found that excitation at the sideband $0 + q$ also produces the highest signal-to-noise ratio and is therefore preferred for excitation.

Excitation with the RBPSK signal and the bandlimited noise signal showed no systematic difference for the investigated bandwidths; the chirp excitation however was found to be less suitable because of its pulsed response. Compared to the previously used fixed pseudo-random noise generator, the new excitation signal with variable spectral power resulted in a more homogeneous amplitude in the tune spectra throughout the acceleration ramp.

Figure 8 shows the effect of noise excitation strength on the induced beam losses and the achieved tune signal strength. The bunching and acceleration efficiency of the machine as set up for this measurement was about 66 % without excitation. Small excitation levels $u < 0.9$ lead to no additional losses while still producing sufficiently large betatron oscillations for observation of the tune in the spectra. A beam size measurement showed no blow-up beyond the measurement resolution of 2 mm.

The excitation is also used for measurement of the chromaticity $\xi = \Delta q/(\Delta p/p)$. Here, the beam momentum p is changed by detuning the RF cavity frequency with a programmed linear ramp. The resulting tune change is then measured over time as shown in Fig. 9 and the chromaticity is calculated from the linear fits.

FURTHER APPLICATIONS

The new excitation signal generator was also already used successfully for tune measurements at the Experimental Storage Ring ESR of GSI. In addition to tune and chromaticity measurements, the flexibility of the device allows usage for further applications such as Radio Frequency Knock Out (RF-KO) extraction. The feasibility of this approach was first demonstrated at Heidelberg Ion Beam Therapy Center (HIT) [2], and recently also demonstrated at GSI SIS18.

The new developments for usage in feedback systems and triggered applications as described in this article are made available through the repository [4] and can be used and adopted at other facilities. The repository also provides an easy way to share GNU Radio flow graphs for the generation of excitation signals.

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REFERENCES

[1] GNU Radio, `https://www.gnuradio.org`

[2] E. Feldmeier *et al.*, "Upgrade of the Slow Extraction System of the Heidelberg Ion-Beam Therapy Centre's Synchrotron", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2509–2512. `doi:10.18429/JACoW-IPAC2022-THPOST029`

[3] B. Bloessl *et al.*, "Benchmarking and Profiling the GNURadio Scheduler", in *Proc. GNU Radio Conference*, Huntsville, AL, USA, Sep. 2019.

[4] Software Radio Beam Exciter, repository available on GSI git, `https://git.gsi.de/p.niedermayer/exciter`

[5] R. J. Steinhagen, "Tune and chromaticity diagnostics", in *CERN Accelerator School: Course on Beam Diagnostics*, Geneva, 2009. `doi:10.5170/CERN-2009-005.317`

[6] P. Kowina *et al.*, "Digital base-band tune determination", in *Proc. BIW10*, Santa Fe, NM, USA, May 2010, pp. 341–344.

[7] A. Reiter *et al.*, "Comparison of beam position calculation methods for application in digital acquisition systems", in *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 890, pp. 18–27, 2018. `doi:10.1016/j.nima.2018.02.046`