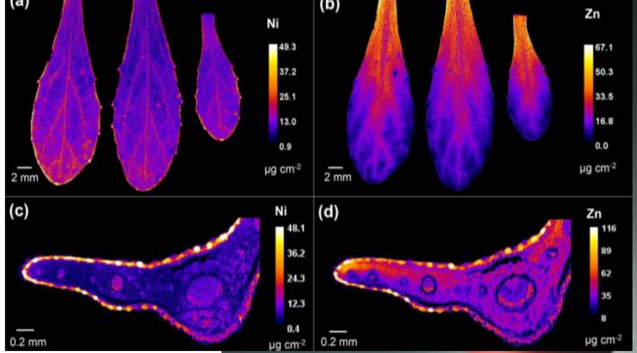
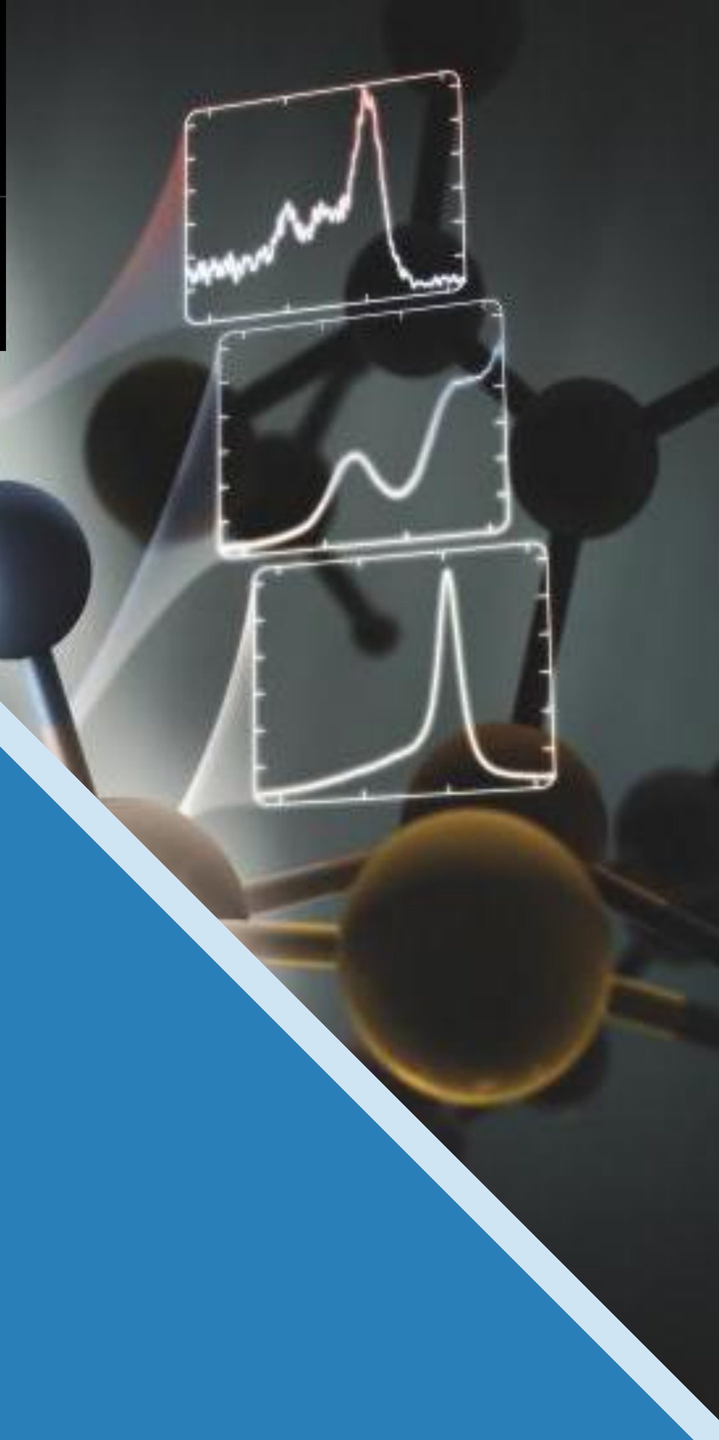




Direct pre-amplifier sampling ADC for high-count rate and high-resolution X-ray spectroscopy

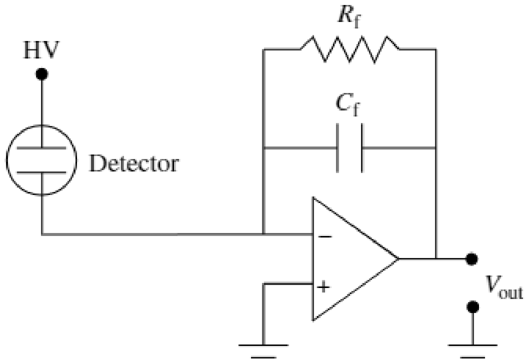
A. Abba, V. Arosio, F. Caponio, E. Carlotti, M. Carminati, S. Carsi, C. Fiorini, B. Pedretti, C. Tintori

Nuclear Instruments SRL
Politecnico di Milano – DEIB
CAEN SPA

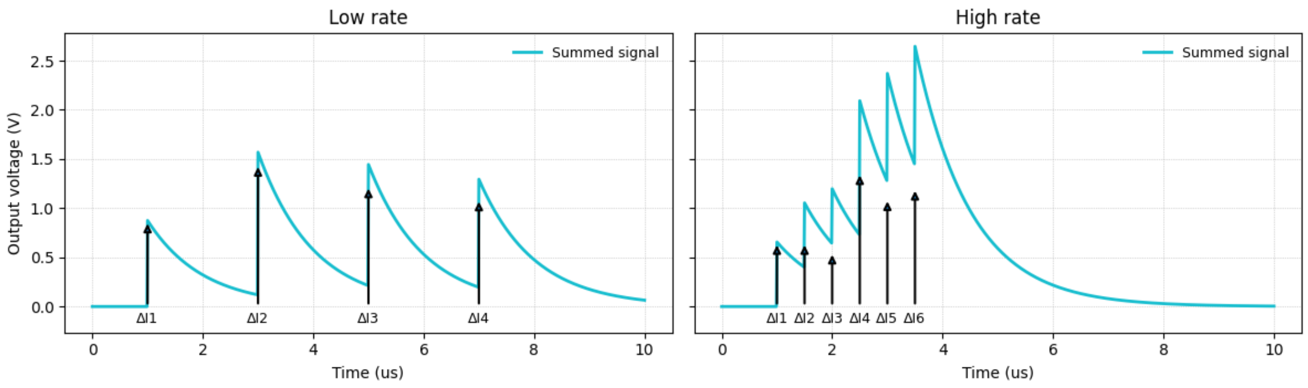
Nuclear Instruments
CAEN Tools for Discovery
RadLab POLITECNICO MILANO 1863

Comparison between resistive feedback and transistor reset charge amplifier

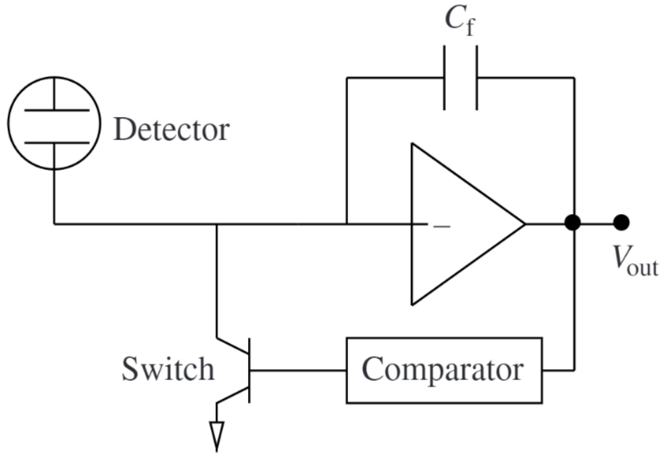
RESISTIVE FEEDBACK CHARGE PRE-AMPLIFIER

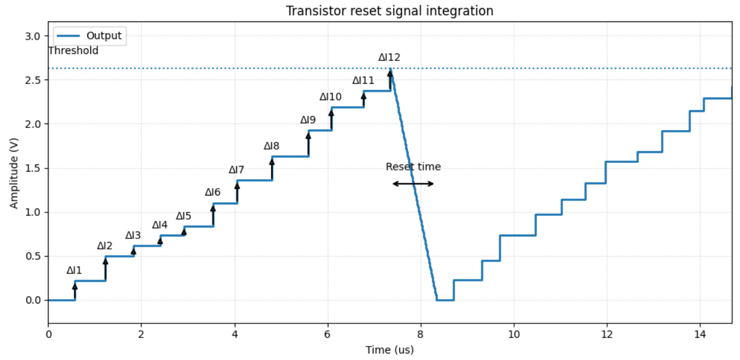


Detector output

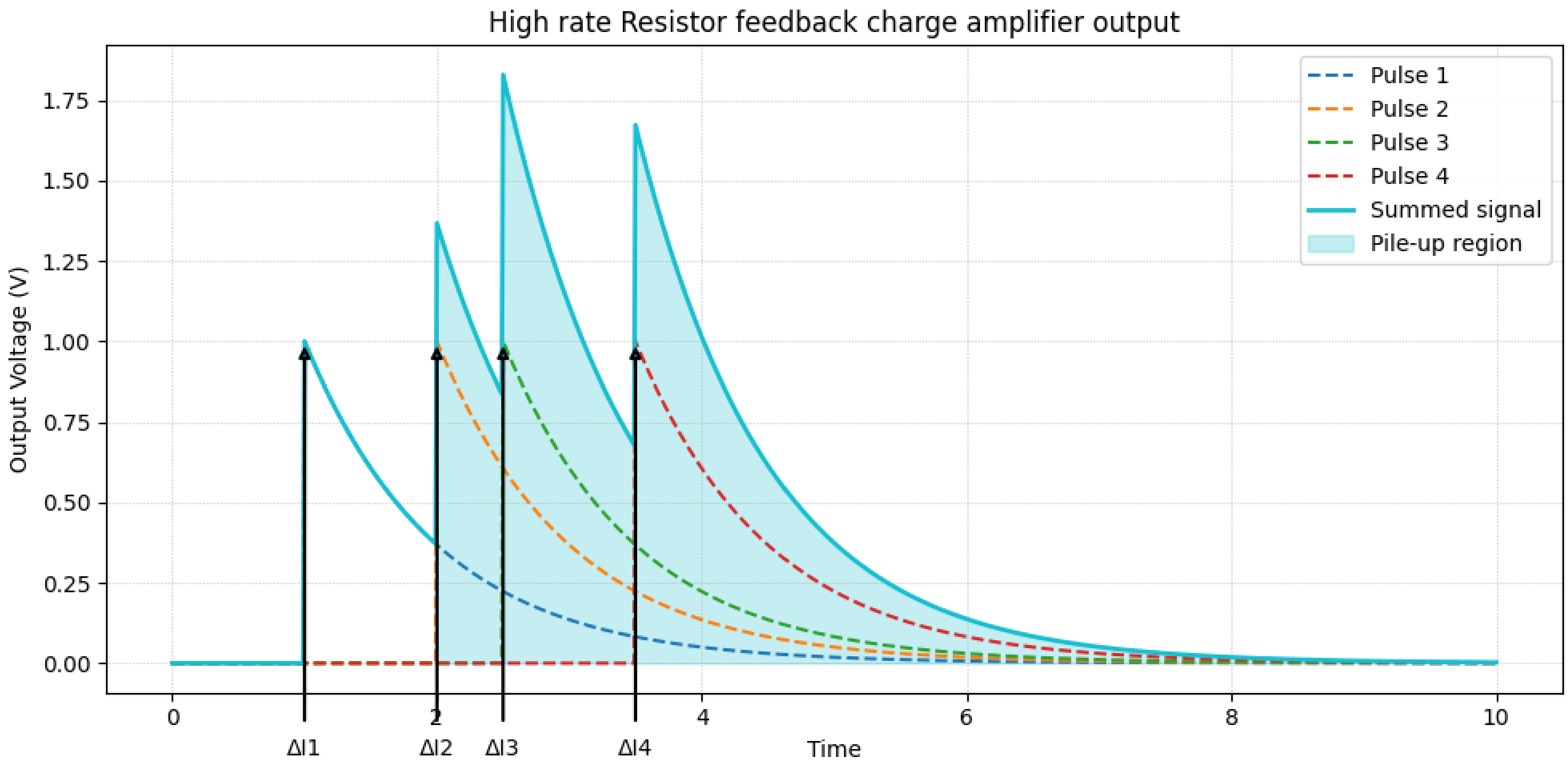


TRANSISTOR RESET CHARGE PRE-AMPLIFIER

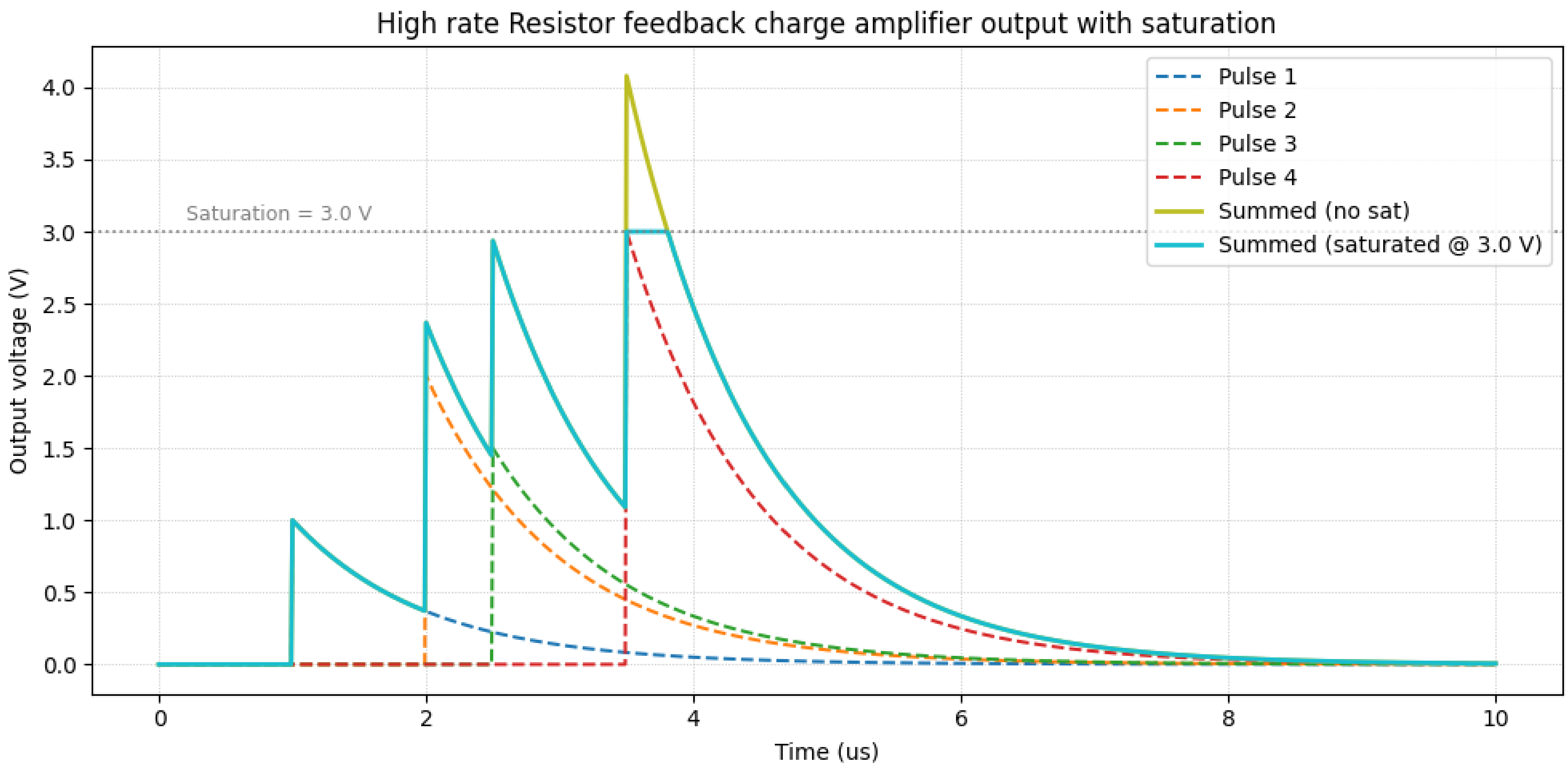




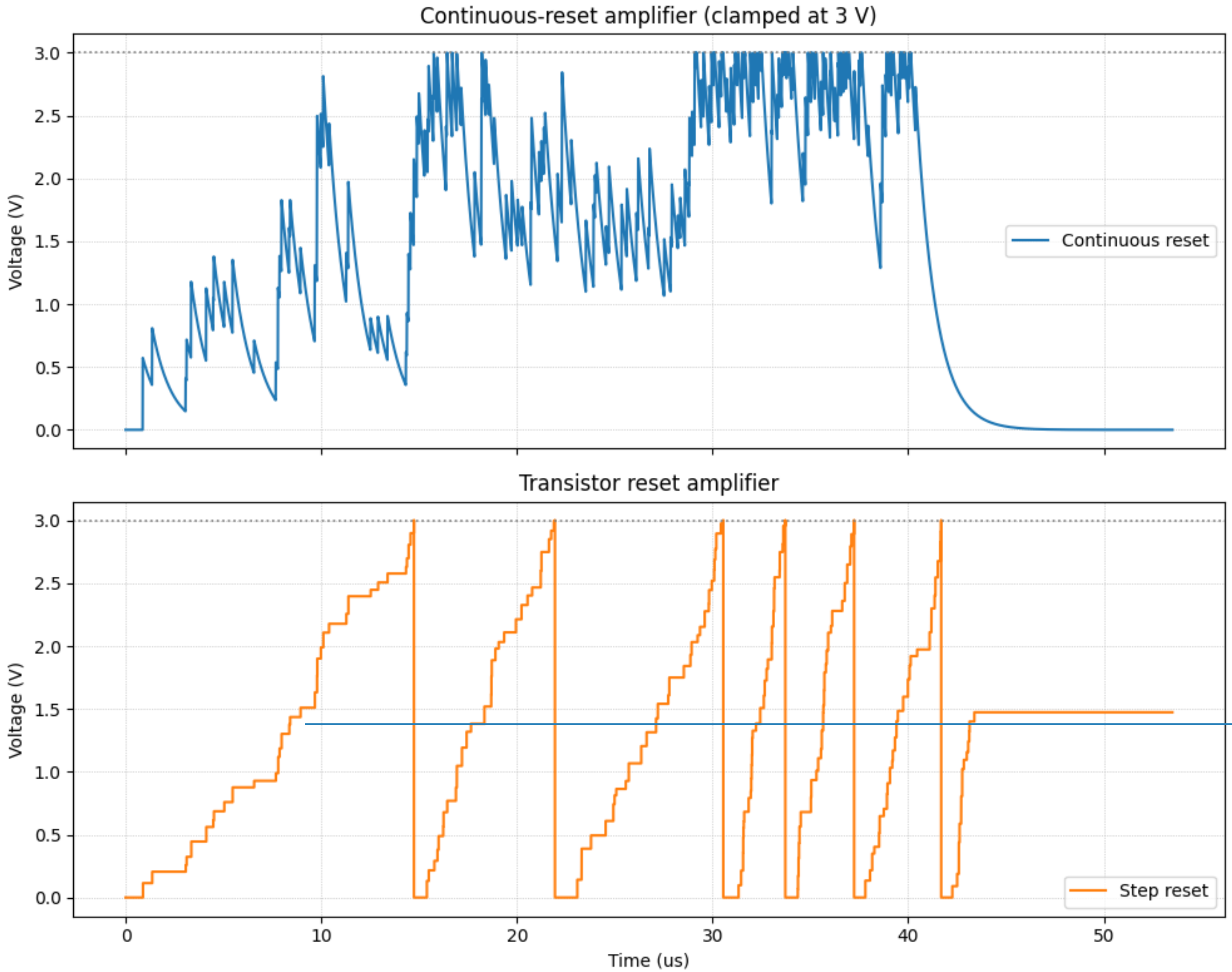
Pileup and saturation on continuous reset amplifier



Pileup and saturation on continuous reset amplifier



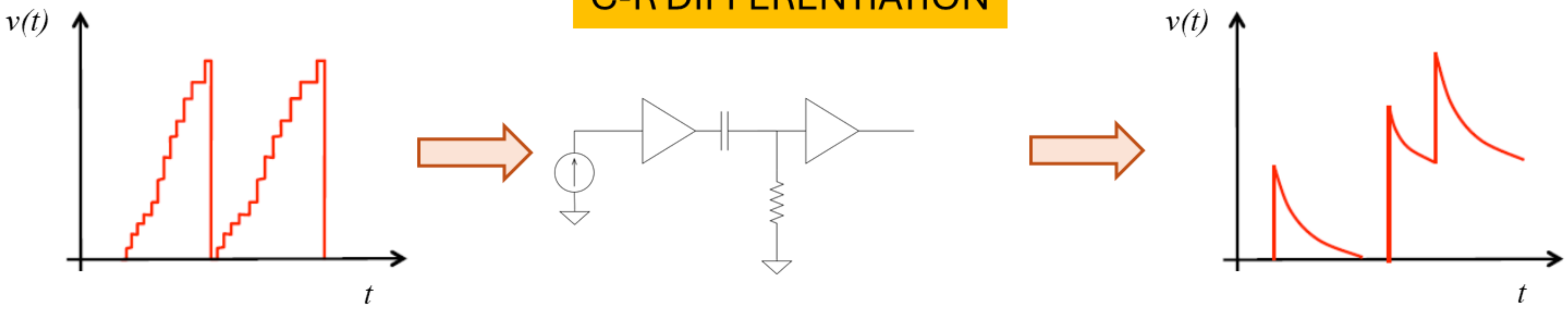
Transistor reset amplifier for high rate detector



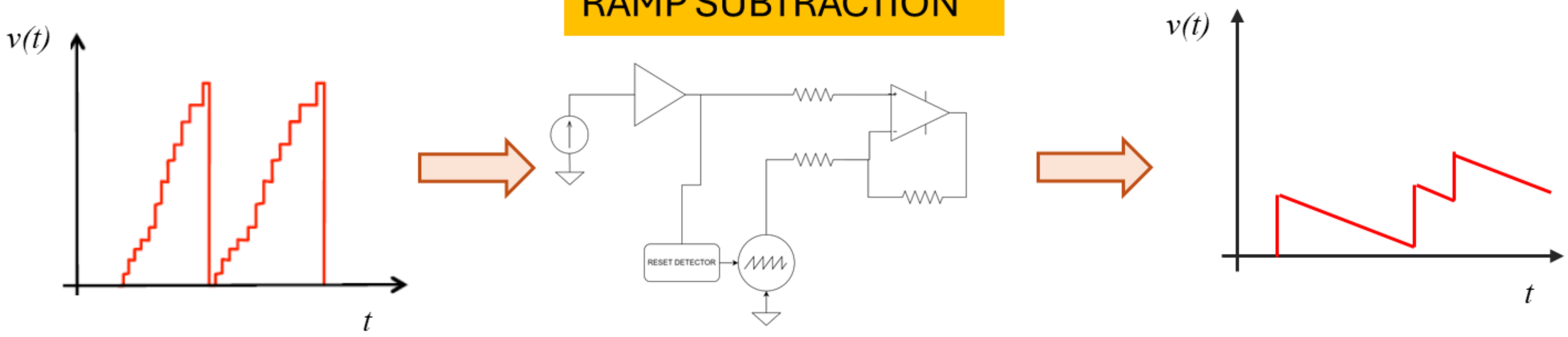
RATE INCREASE

Transistor reset amplifier for high rate detector

C-R DIFFERENTIATION

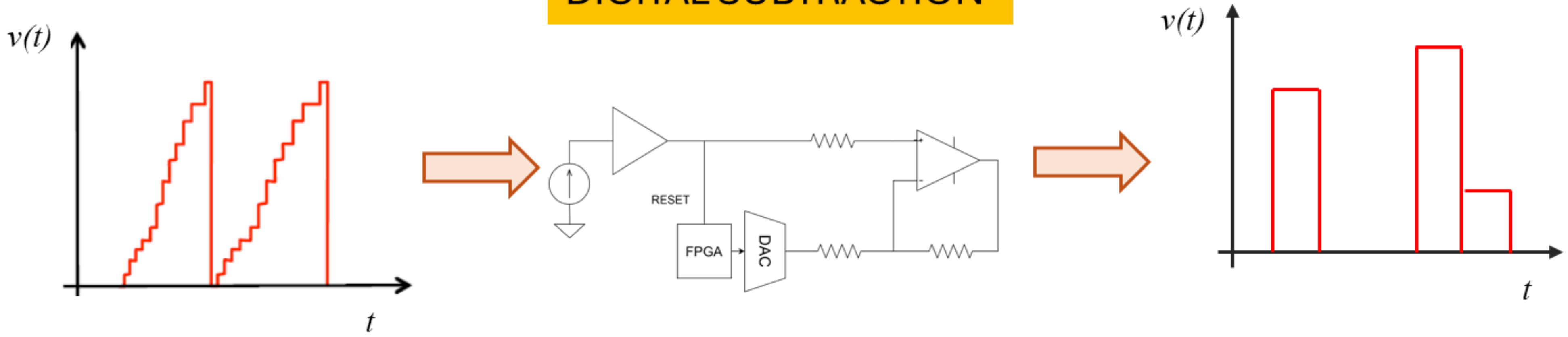


RAMP SUBTRACTION

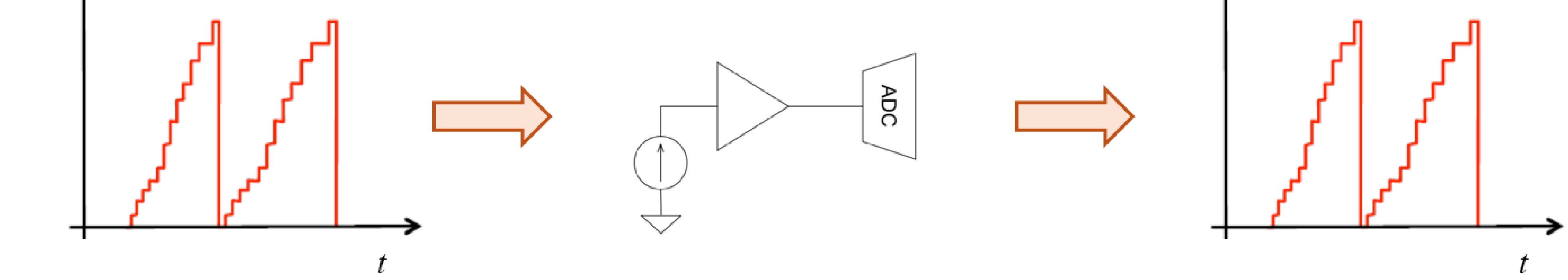


Transistor reset amplifier for high rate detector

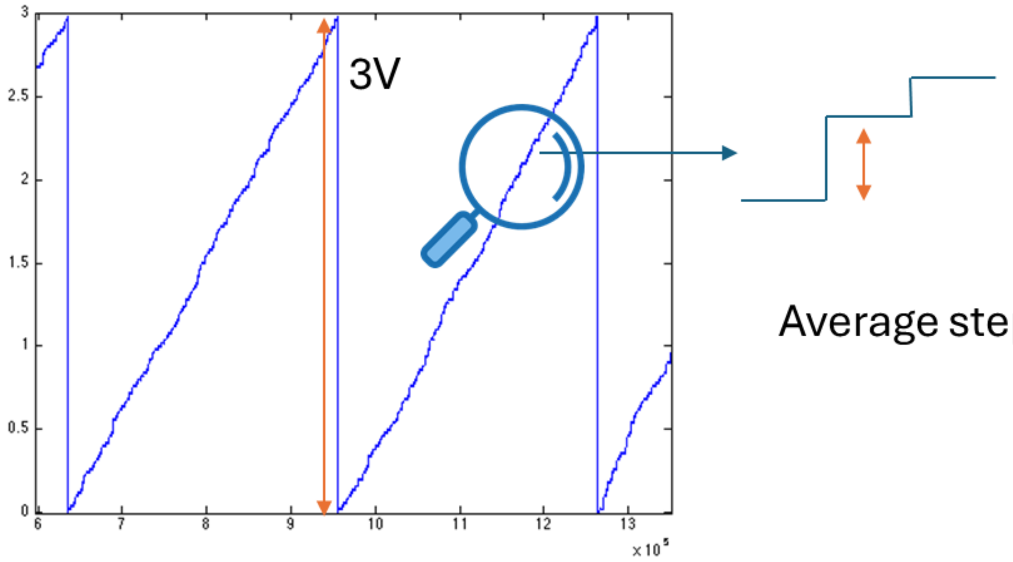
DIGITAL SUBTRACTION



DIRECT SAMPLING



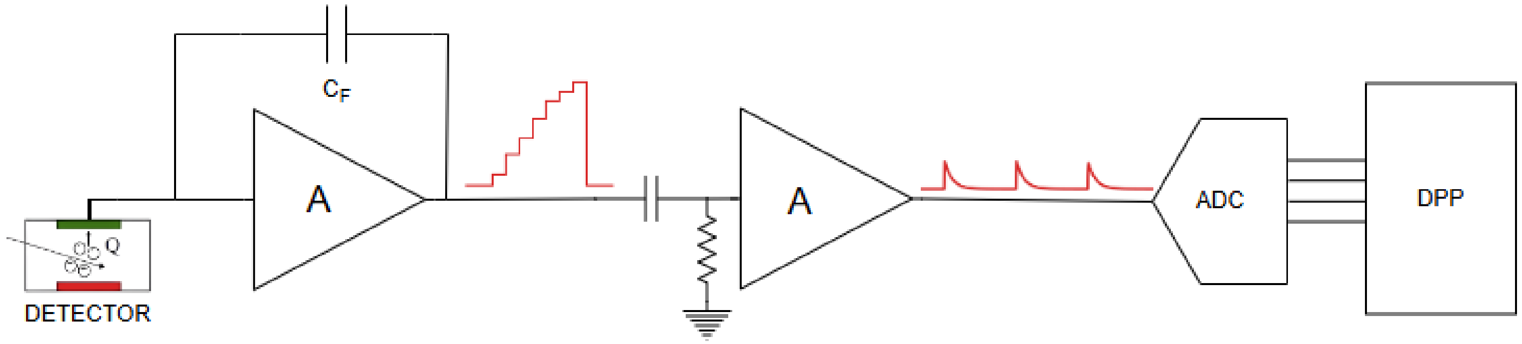
Sampling the transistor reset detector output

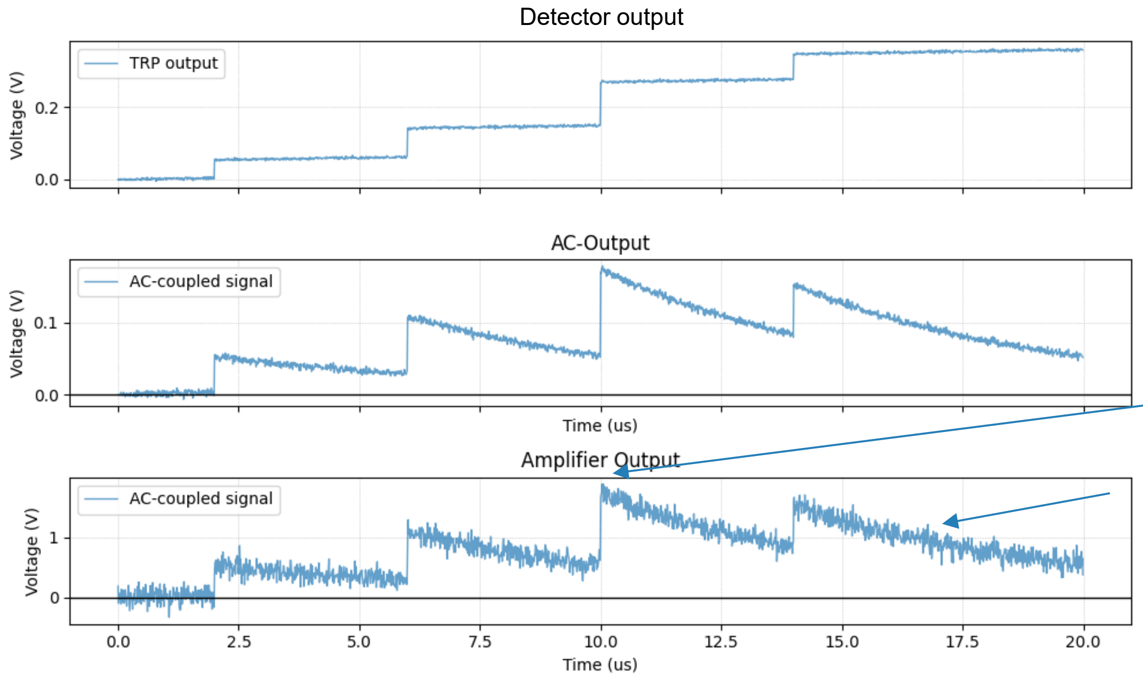


ADC: 16 bit
STEP: 100 ≈ 2^7
BIT PER STEP: 9 bit

Average step amplitude: 30mV

Reshape and amplify TRP output signal

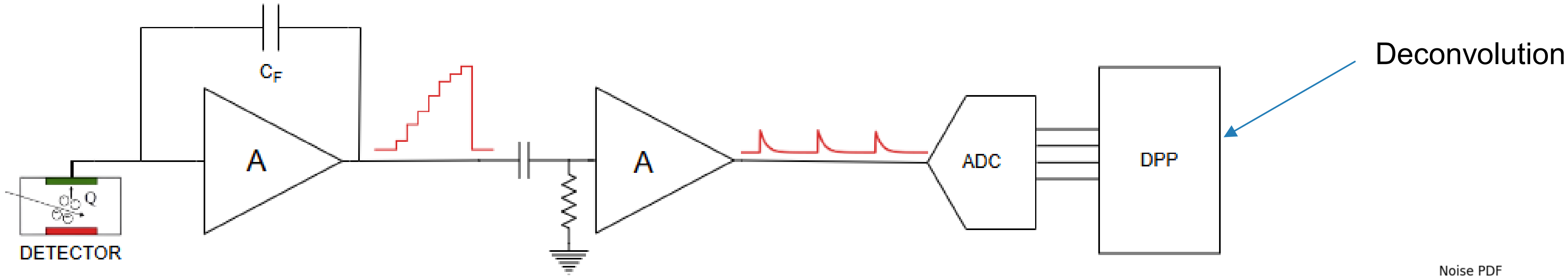


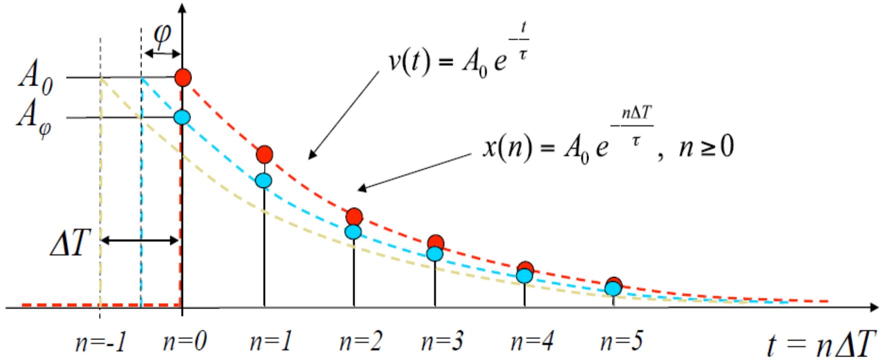


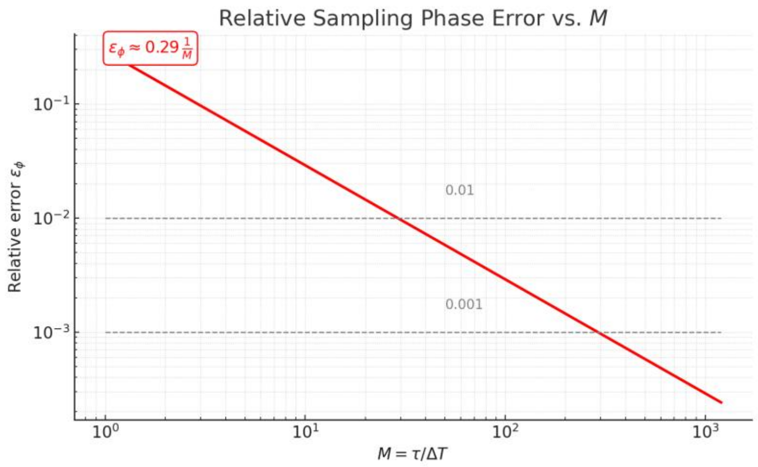
Pileup effect → trade-of between shaping time and gain

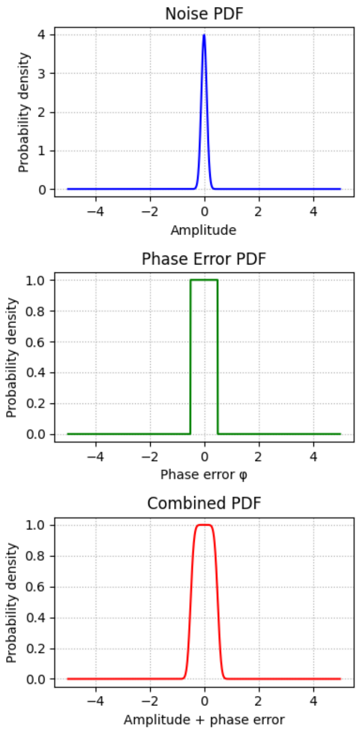
Additional noise introduced by amplifier

Reshape and amplify TRP output signal









$$A_\varphi(\varphi) = A_0 e^{-\frac{\varphi}{\tau}} \quad 0 < \varphi \le \Delta T$$

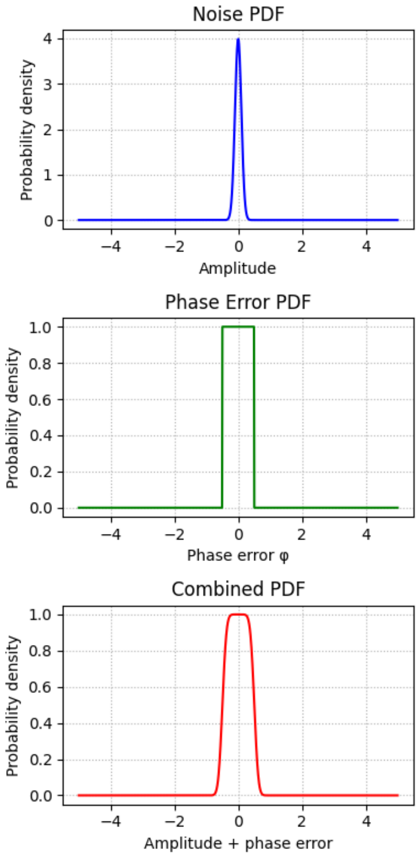
$$e(\varphi) = A_0 - A_\varphi(\varphi) = A_0\left(1 - e^{-\frac{\varphi}{\tau}}\right)$$

$$\text{if } \varphi \ll \tau \rightarrow 1 - e^{-\frac{\varphi}{\tau}} \approx \frac{\varphi}{\tau}$$

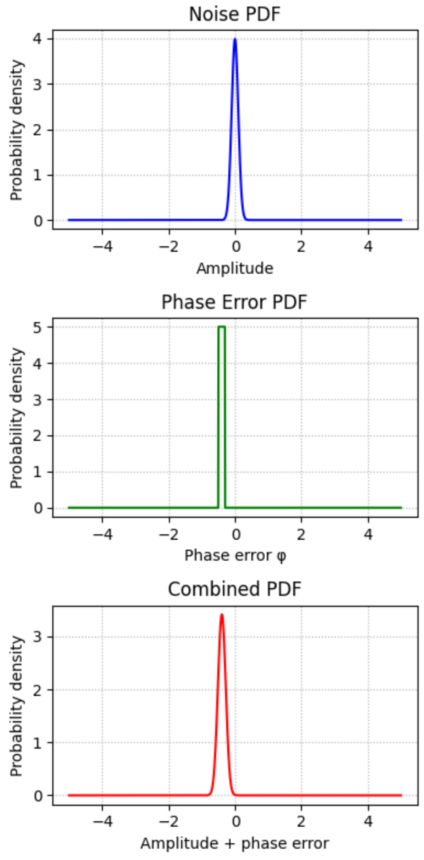
$$e(\varphi) \approx A_0 \frac{\varphi}{\tau}$$

$M=\tau/\Delta T$

Reshape and amplify TRP output signal



Low M=τ/ΔT ratio



High M=τ/ΔT ratio

- To introduce Low sampling error M should be high
- High M means:
  - High sample rate (fast ADC)
  - Long shaping time (pileup)

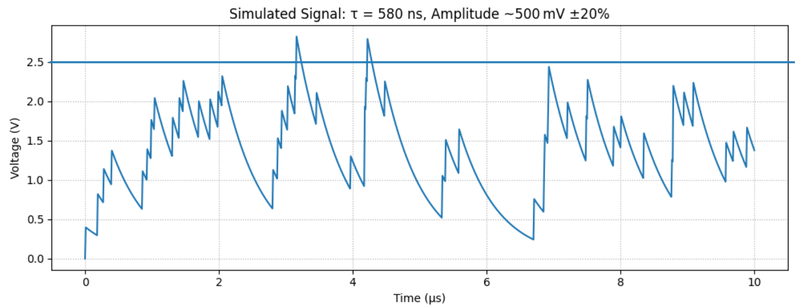
Ts = 10ns → 100Msps

$$\varepsilon_\varphi \approx 0.29\,\frac{1}{M} < 0.005 \quad (0.5\%)$$

(2.2% = 130eV on Fe^{55} $K\alpha$)

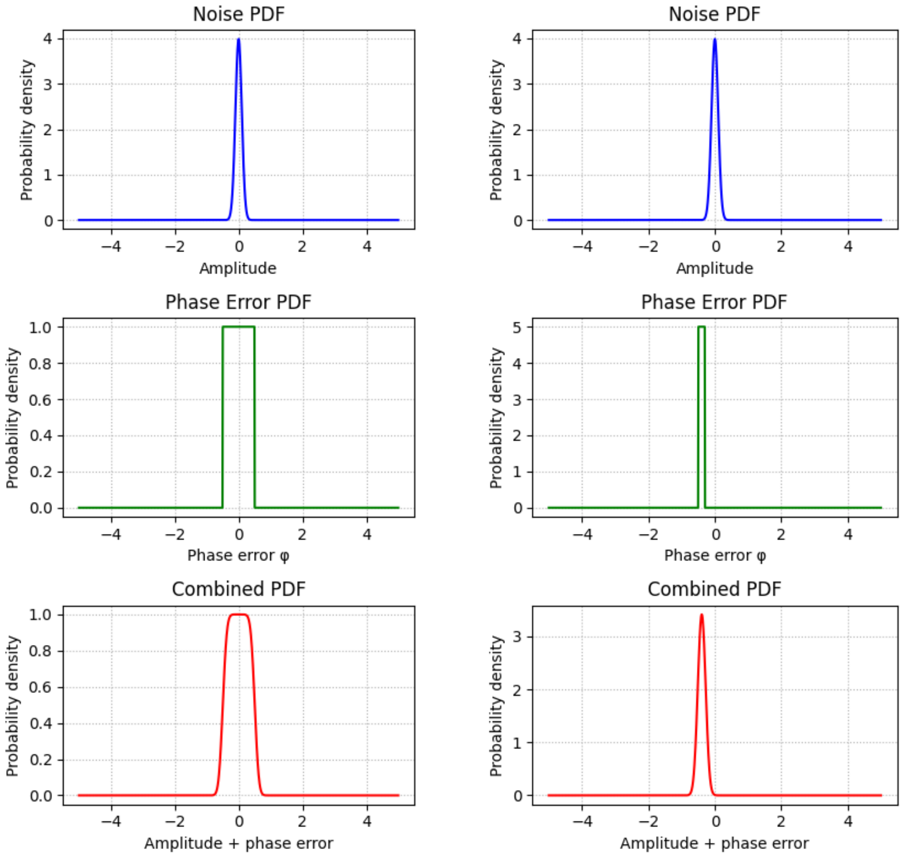
$$0.29/M < 0.005 \implies M > \frac{0.29}{0.005} = 58.$$

$$\tau = M \cdot T_s \approx 58 \times 10\,\text{ns} = 580\,\text{ns}.$$



Simulation 5 Mcps
Fe^{55} $K\alpha$ = 500mV

Reshape and amplify TRP output signal



Low M=τ/ΔT ratio   High M=τ/ΔT ratio

- To introduce Low sampling error M should be high
- High M means:
  - High sample rate (fast ADC)
  - Long shaping time (pileup)

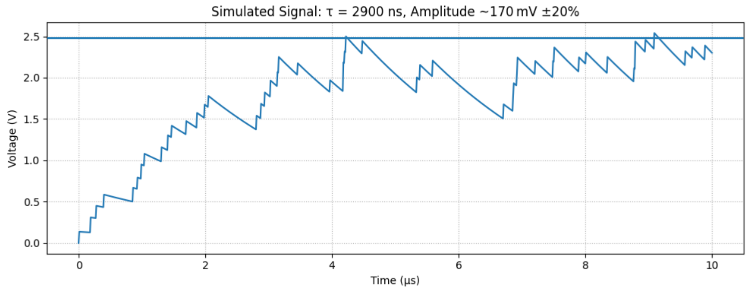
Ts = 10ns → 100Msps

$$\varepsilon_\varphi \approx \frac{0.29}{M} < 0.001 \quad (0.1\%)$$

(2.2% = 130eV on Fe^{55} $K\alpha$)

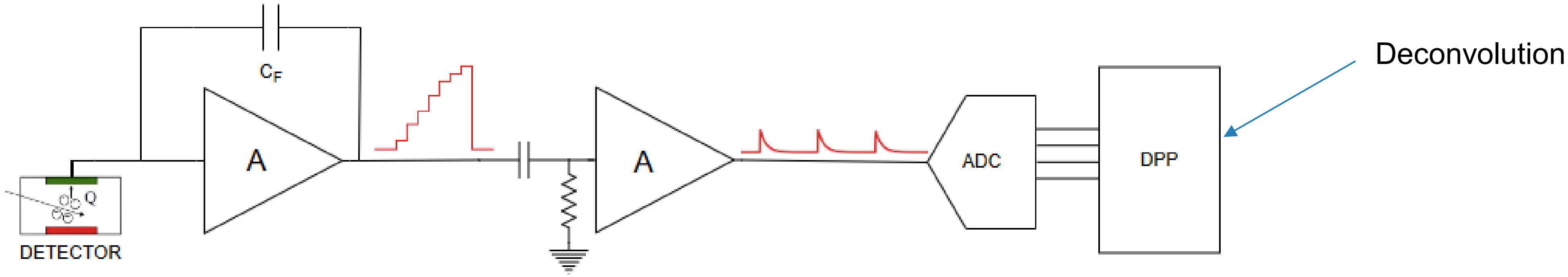
$$M > \frac{0.29}{0.001} = 290.$$

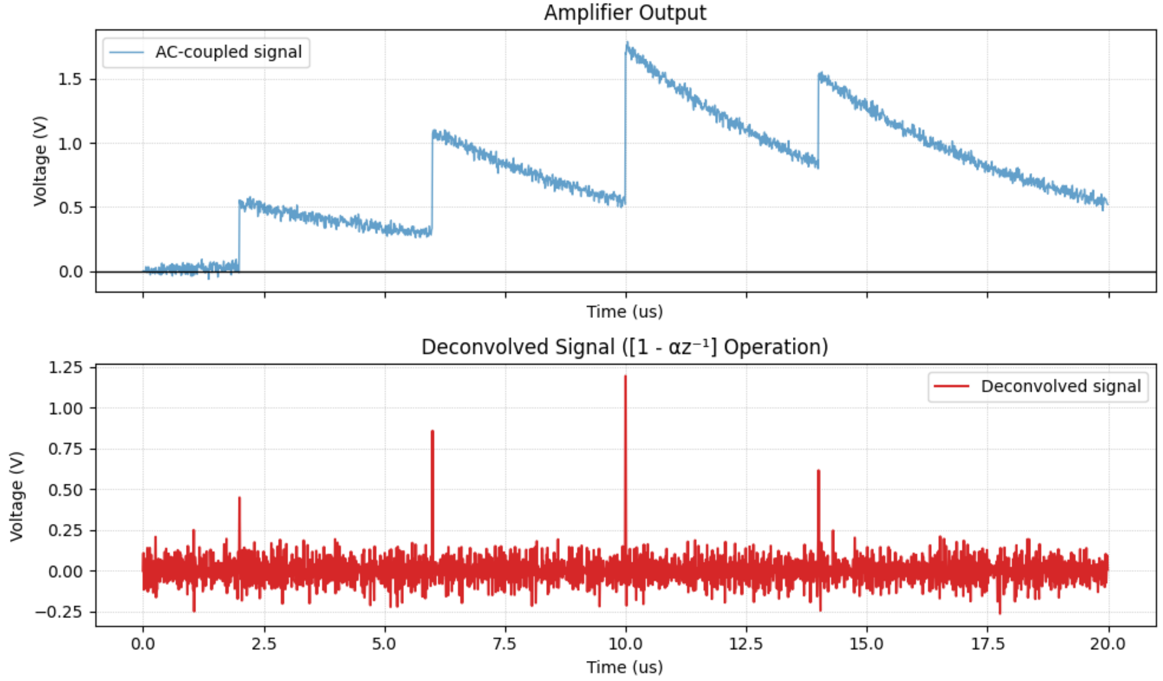
$$\tau = M\,T_s \approx 290 \times 10\,\mathrm{ns} = 2900\,\mathrm{ns} \; = \; 2.9\,\mu\mathrm{s}.$$



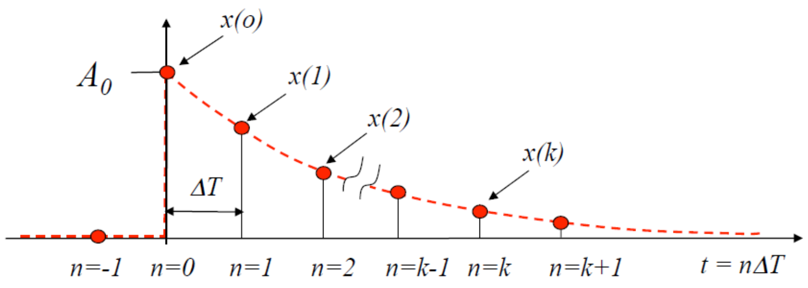
Simulation 5 Mcps
Fe^{55} $K\alpha$ = 170mV

Reshape and amplify TRP output signal





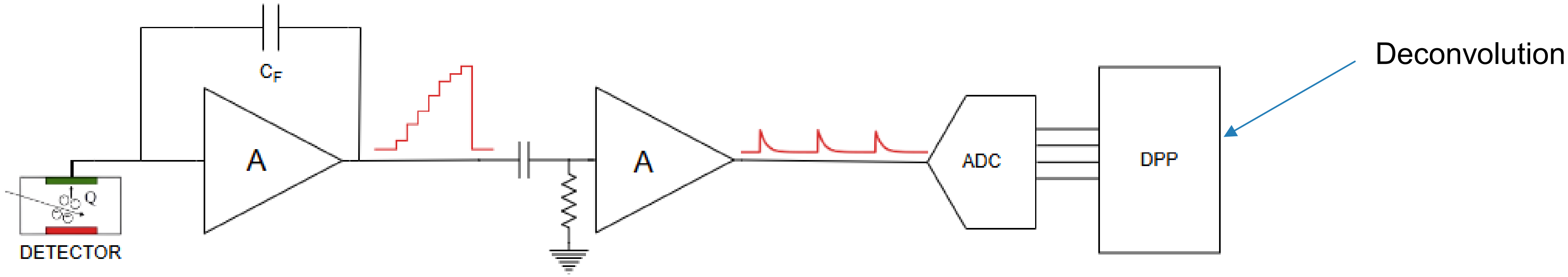
Digital Exponential Pulse Deconvolution

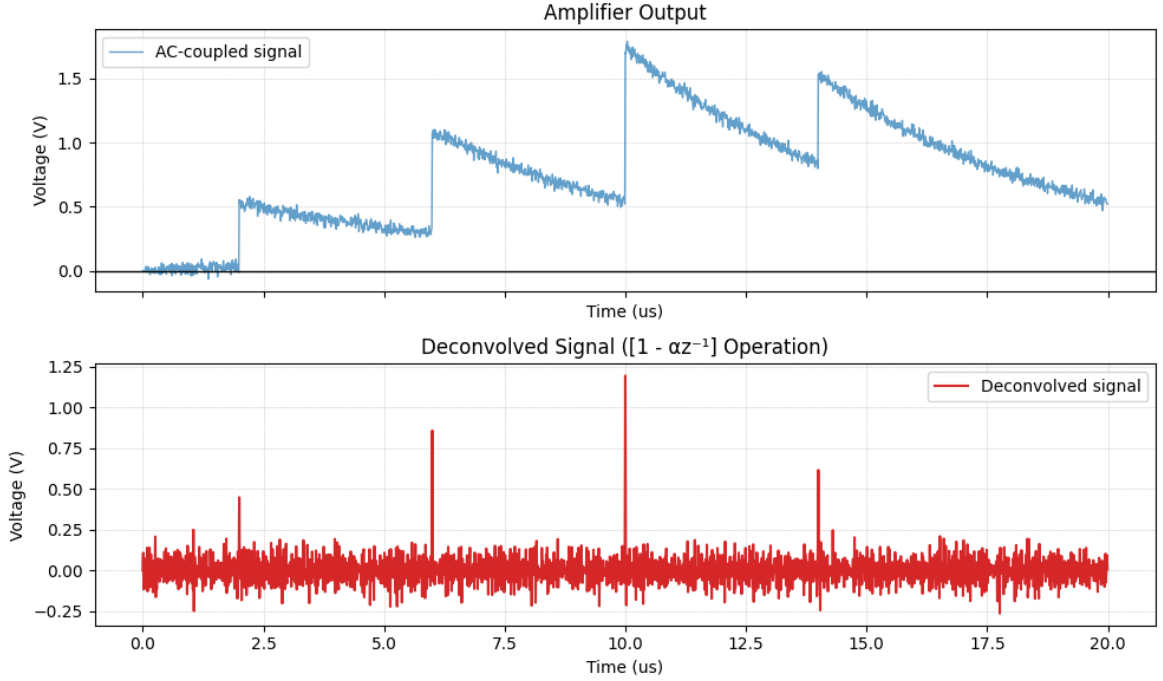


$$x(n) = A_0 e^{-\frac{n\Delta T}{\tau}} \qquad a = e^{-\frac{\Delta T}{\tau}} \qquad x(n) = A_0 a^n$$

$$x(n) = ax(n-1) \; for \; n > 0$$

Reshape and amplify TRP output signal



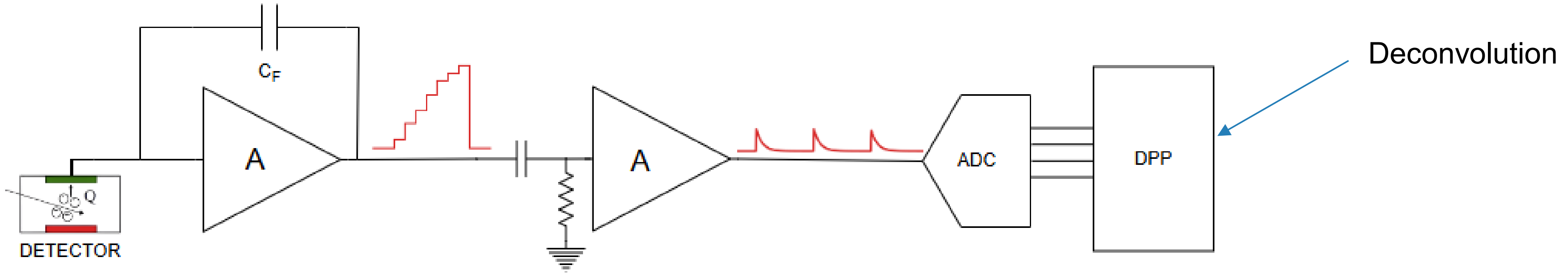


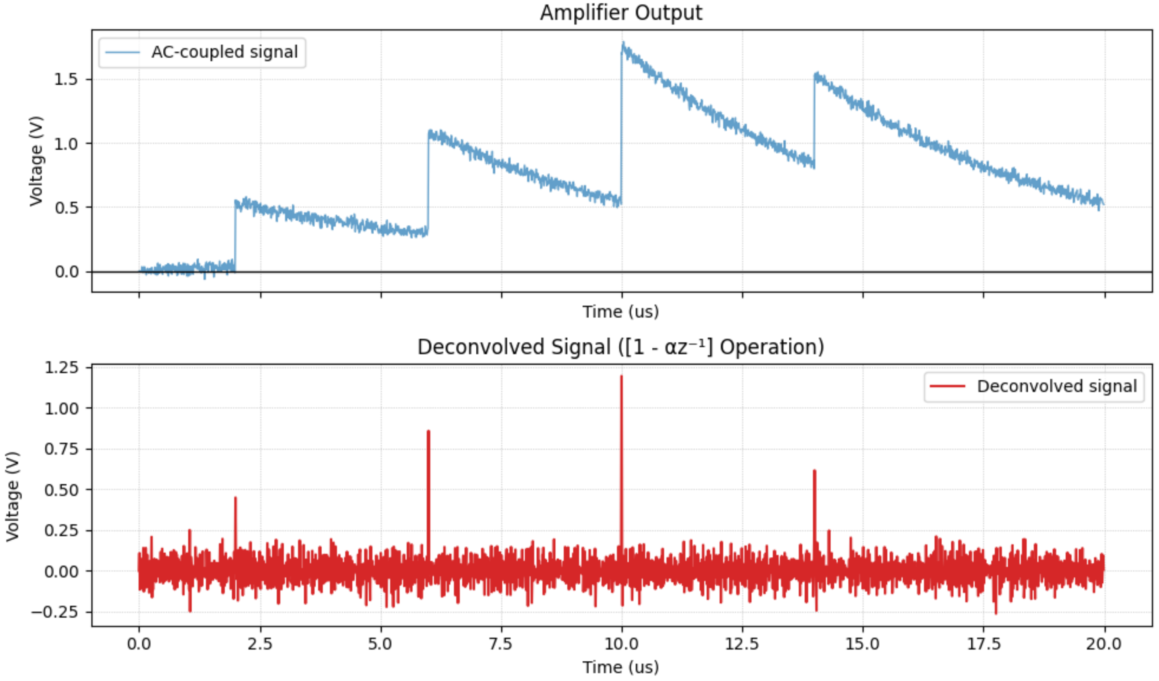
Digital Exponential Pulse Deconvolution

exp. signal set of consecutive samples — shifted and scaled exp. signal = unfolded exp. signal

$$
\begin{bmatrix} x(0)=A_0 \\ x(1)=x(0)a \\ x(2)=x(1)a \\ \bullet \\ \bullet \\ x(k)=x(k-1)a \\ x(k+1)=x(k)a \\ x(k+2)=x(k+1)a \\ \bullet \\ \bullet \end{bmatrix}
-
\begin{bmatrix} x(-1)a=0 \\ x(0)a \\ x(1)a \\ x(2)a \\ \bullet \\ \bullet \\ x(k)a \\ x(k+1)a \\ x(k+2)a \\ \bullet \end{bmatrix}
=
\begin{bmatrix} A_0 \\ 0 \\ 0 \\ 0 \\ \bullet \\ \bullet \\ 0 \\ 0 \\ 0 \\ \bullet \end{bmatrix}
$$

Reshape and amplify TRP output signal





Signal Sharpening

- Converts each exponential decay into short impulse of amplitude ΔI
- Improves temporal resolution and separates overlapping events

High-Pass Action on Noise

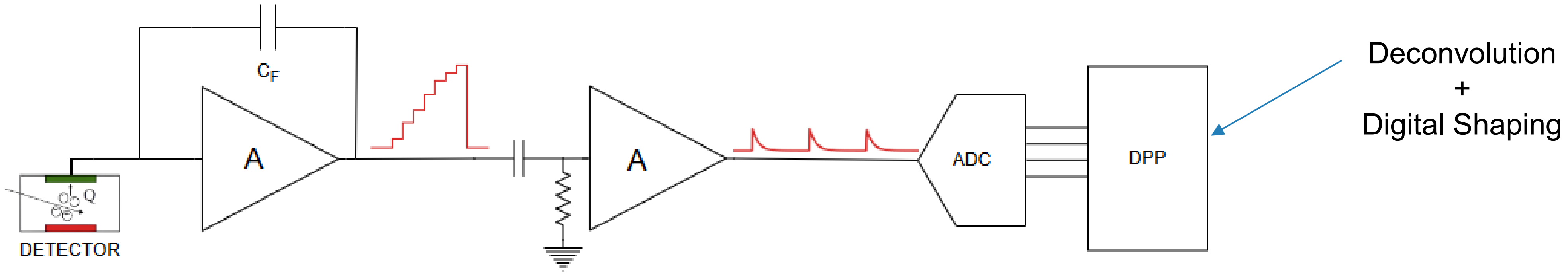
- Acts as a digital high-pass filter: attenuates low-frequency drift but amplifies mid-/high-frequency components
- White noise spectrum becomes “colored,” with increased power at higher frequencies
- Noise Variance Increase If input noise has variance σ^2, output variance ≈ $(1 + \alpha^2)\ \sigma^2$RMS noise grows by factor $\sqrt{(1 + \alpha^2)}$

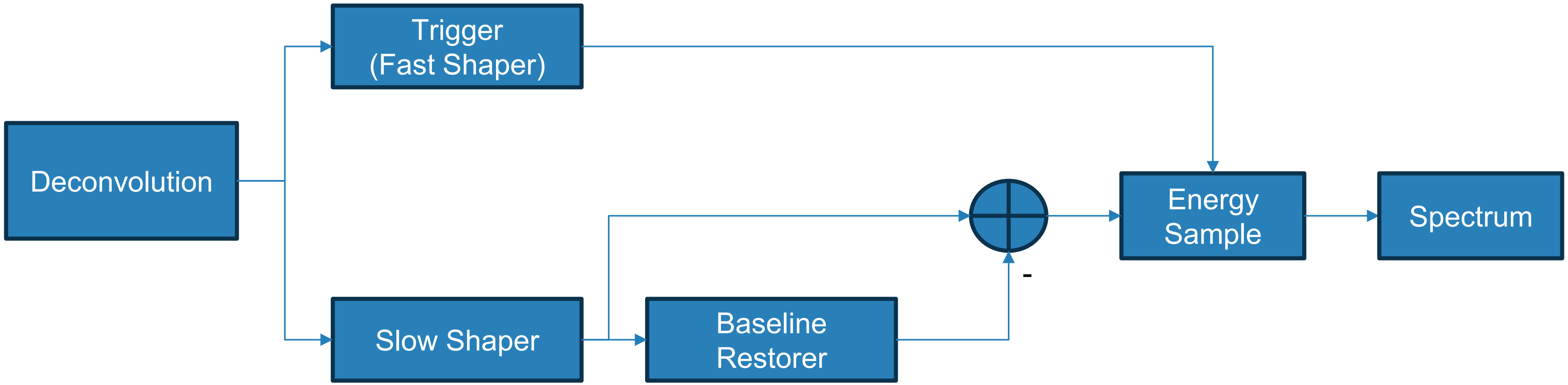
SNR Degradation

Peak amplitude remains ΔI, but noise floor rises resulting

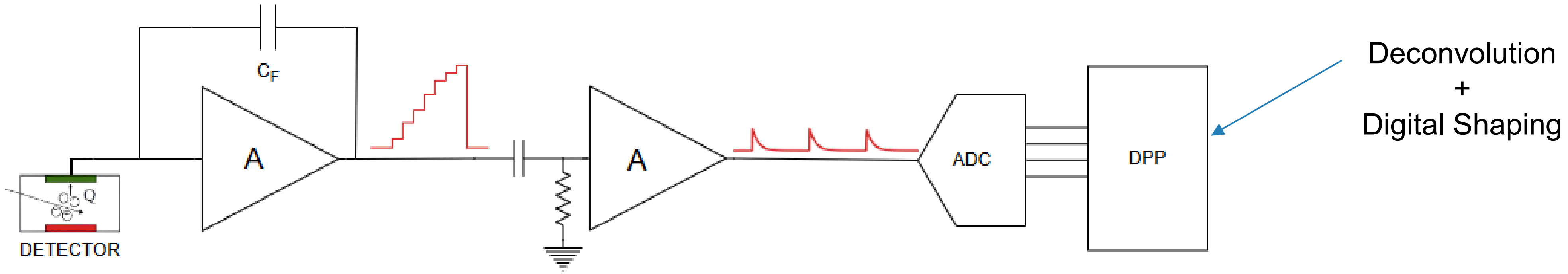
$$\mathrm{SNR}_{\mathrm{deconv}} = \frac{\Delta I}{\sigma\sqrt{1+\alpha^2}} = \frac{\mathrm{SNR}_{\mathrm{raw}}}{\sqrt{1+\alpha^2}} < \mathrm{SNR}_{\mathrm{raw}}.$$

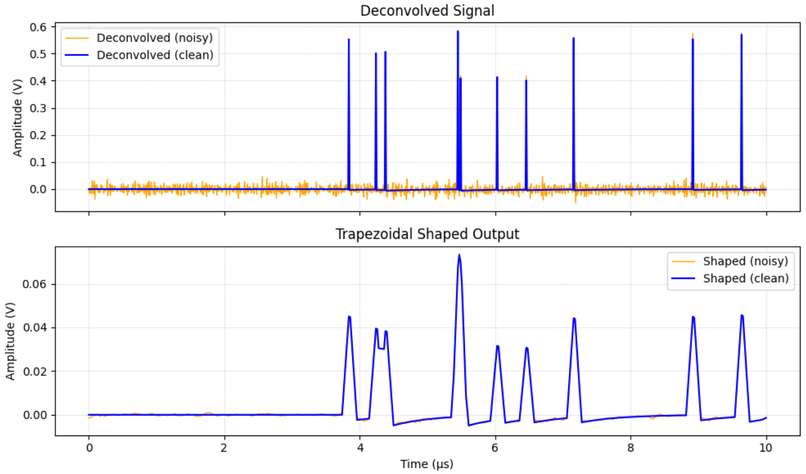
Reshape and amplify TRP output signal



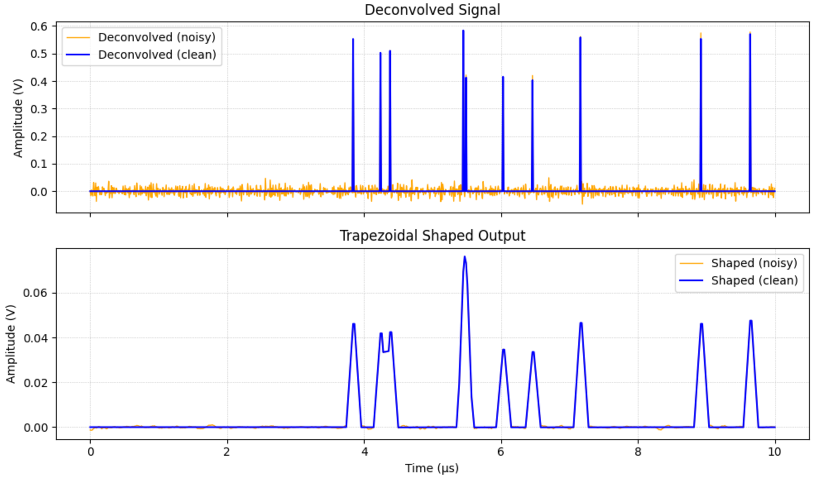


Reshape and amplify TRP output signal

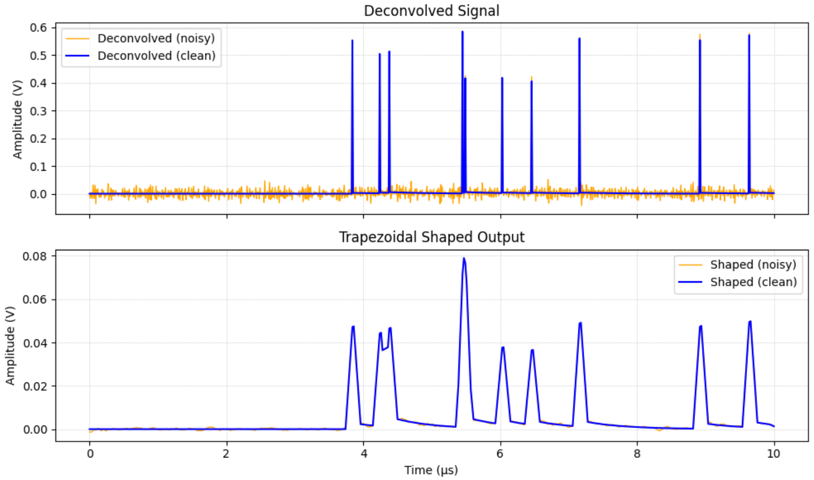




Over Compensated

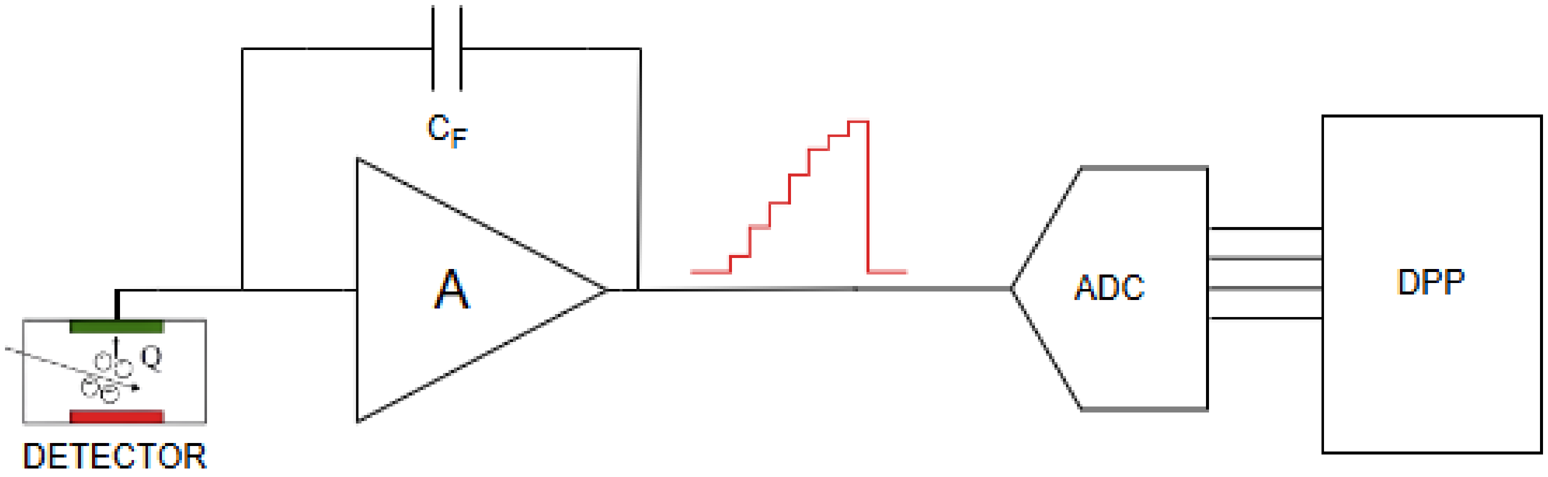


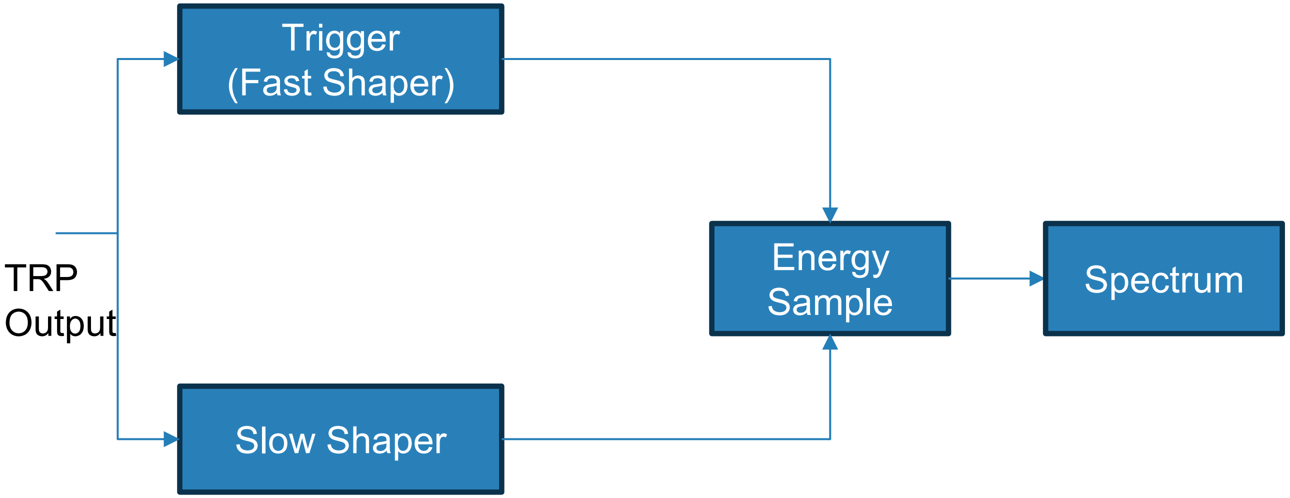
Correctly Compensated

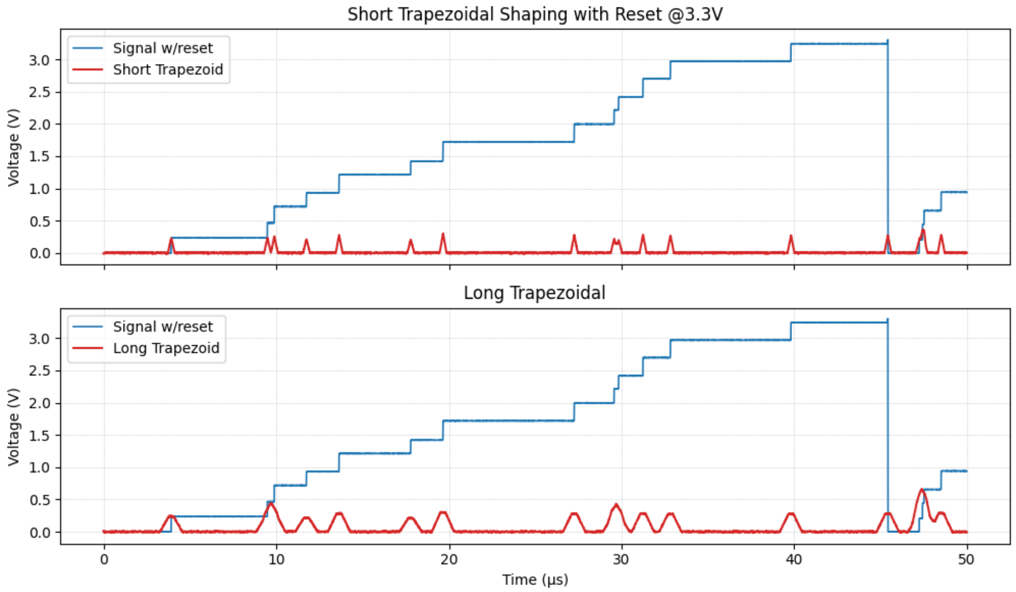


Under Compensated

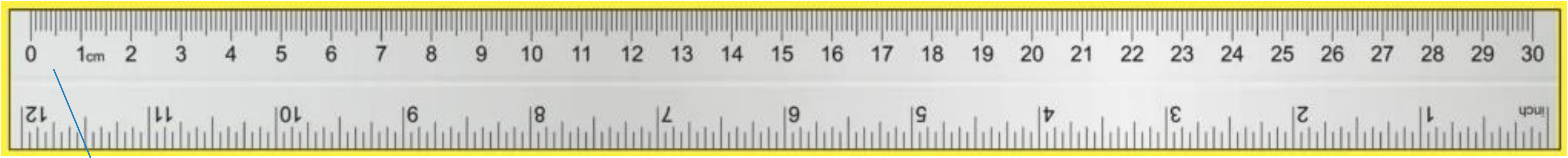
Direct sampling with 20 bit ADC

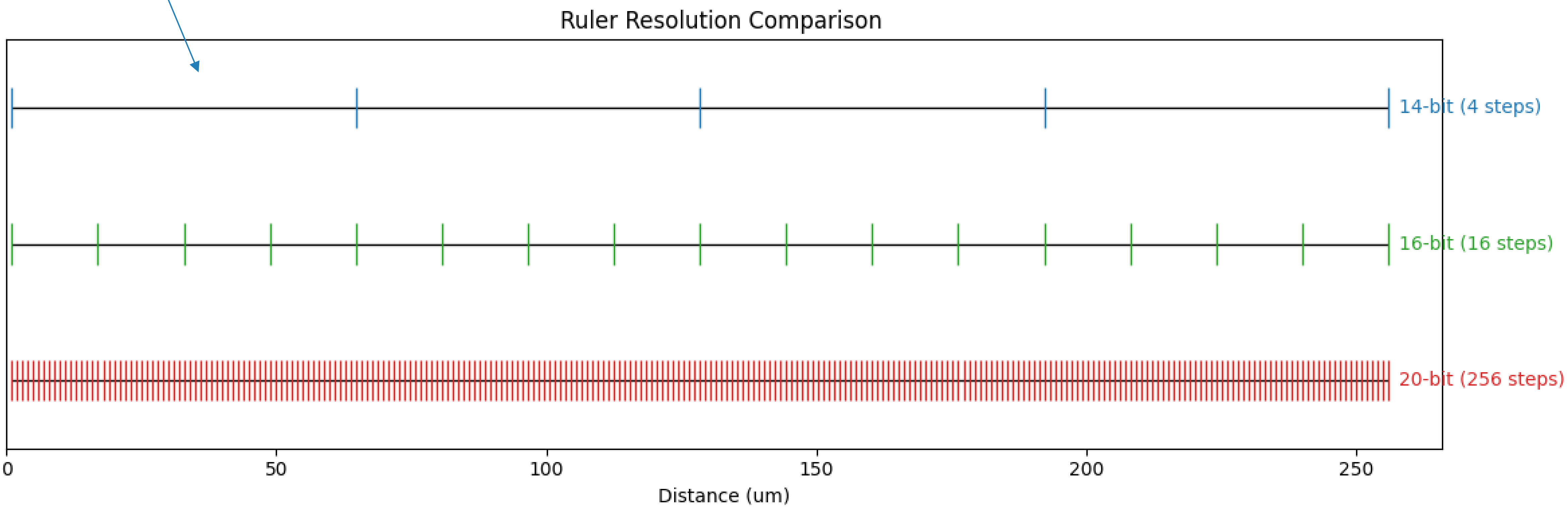




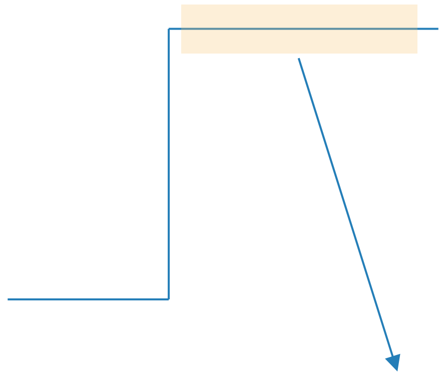


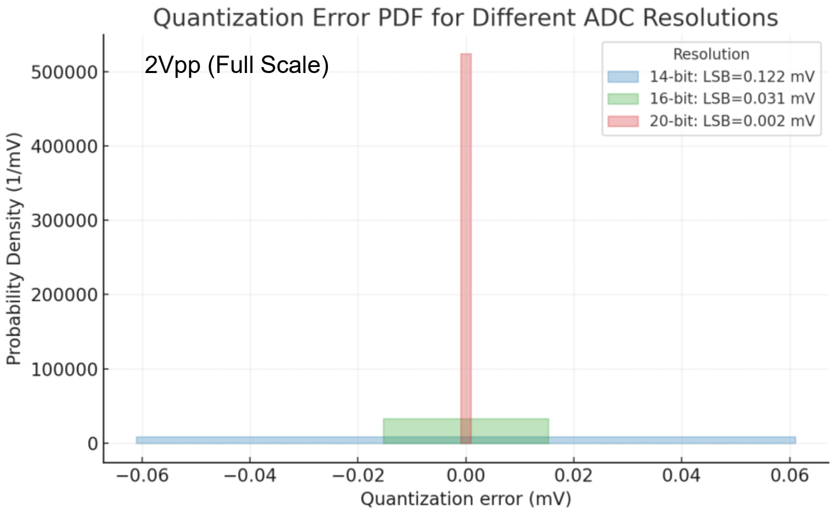
Direct sampling with 20 bit ADC



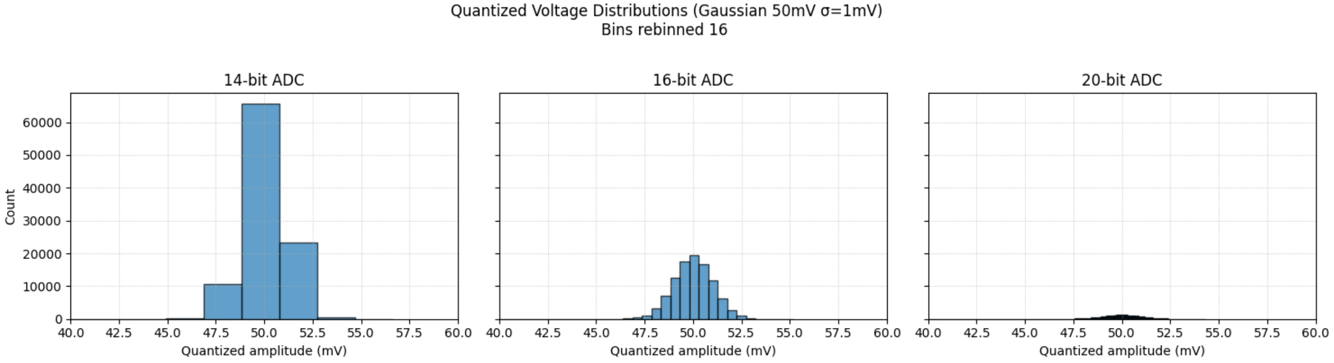


Direct sampling with 20 bit ADC

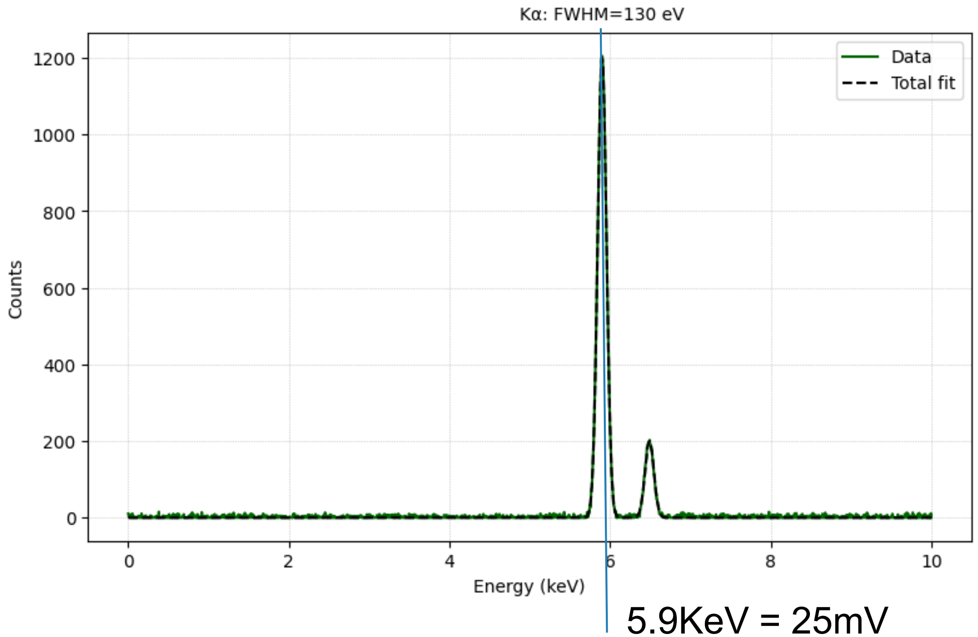


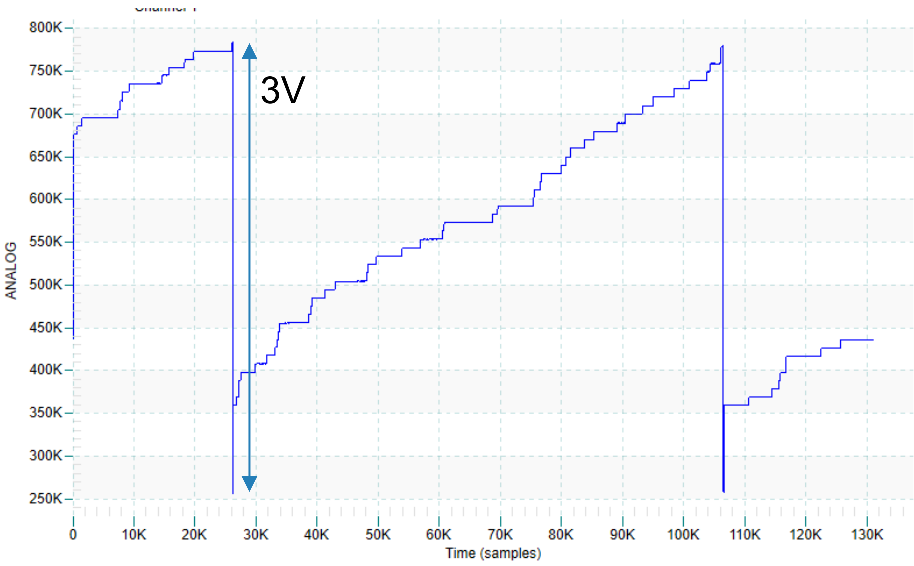


- **14-bit** (LSB ≃0.12 mV → bin ~1.9 mV)
- **16-bit** (LSB ≃0.03 mV → bin ~0.5 mV)
- **20-bit** (LSB ≃0.0019 mV → bin ~0.03 mV)



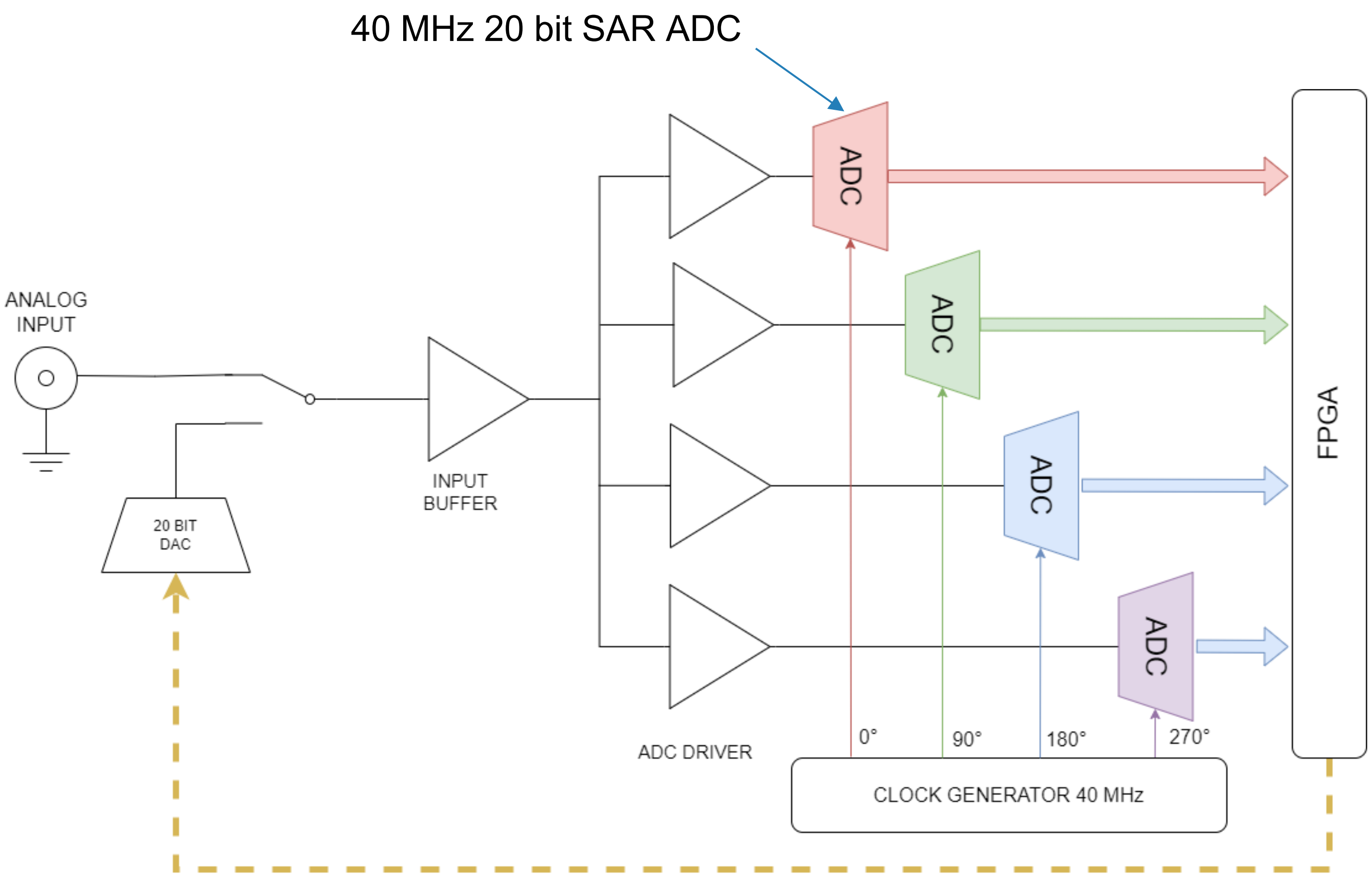
20 bit ADC effective resolution

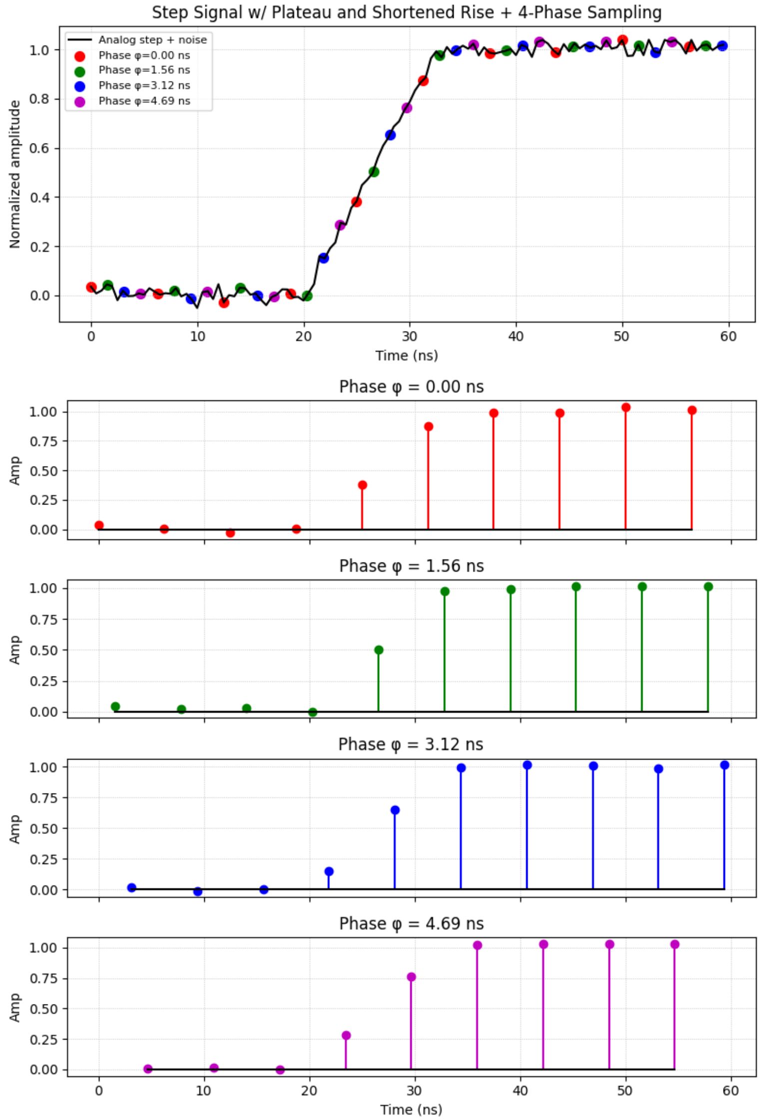




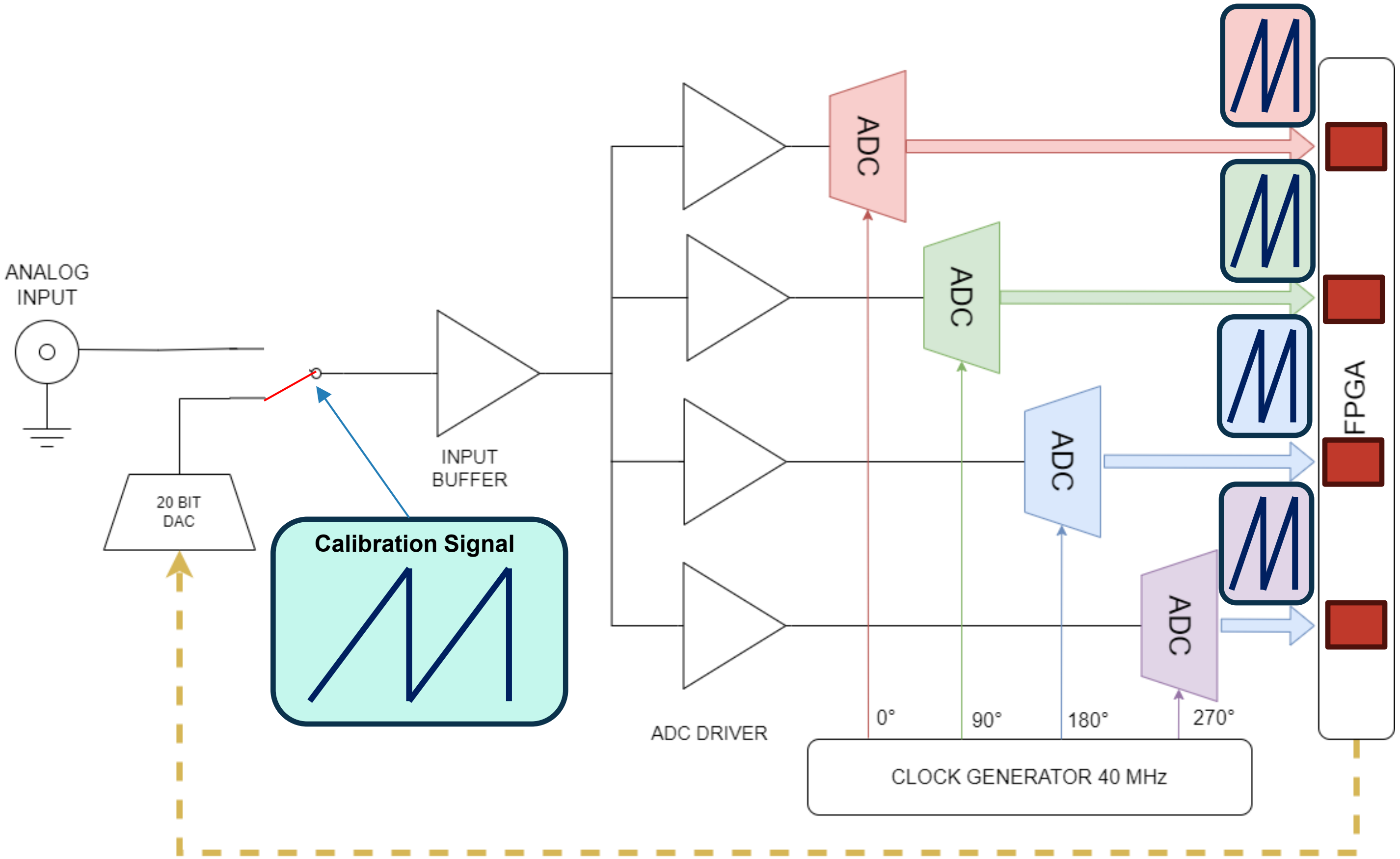
Resolution	LSB (mV)	LSB per keV
14 bit	3 V/2^{14} ≃ 0.1831	4.237 mV/keV / 0.1831 mV/LSB ≃ 23.2 LSB/keV
16 bit	3 V/2^{16} ≃ 0.04578	4.237 / 0.04578 ≃ 92.6 LSB/keV
20 bit	3 V/2^{20} ≃ 0.002861	4.237 / 0.002861 ≃ 1 480 LSB/keV

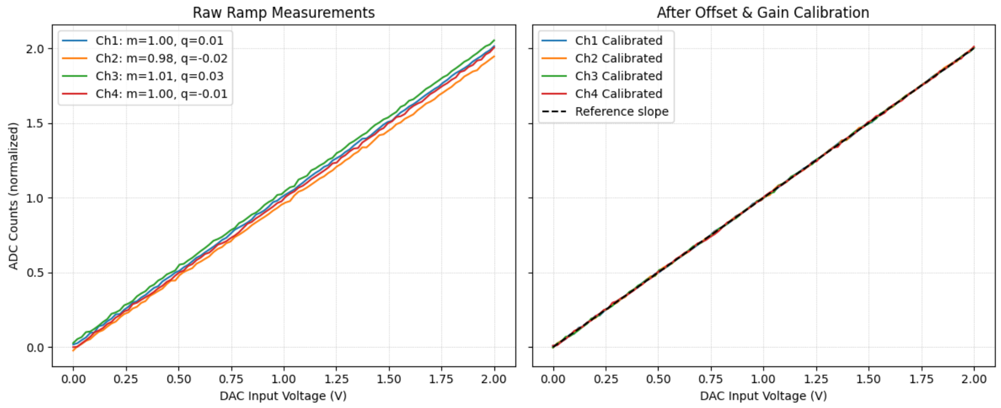
Interleaving 160 MHz 20 bit digitizer using 4x40 MHz SAR ADC





Gain and offset calibration





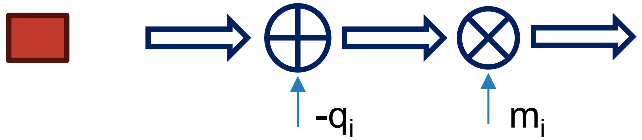
1. **Acquire Calibration Ramps**
   For each ADC channel, apply a precise linear ramp $x(t)$x(t) (e.g. $0 \to V$ over 2 µs) from a 20-bit DAC.

2. **Fit a Straight Line** $y_i = m_i\,x + q_i$

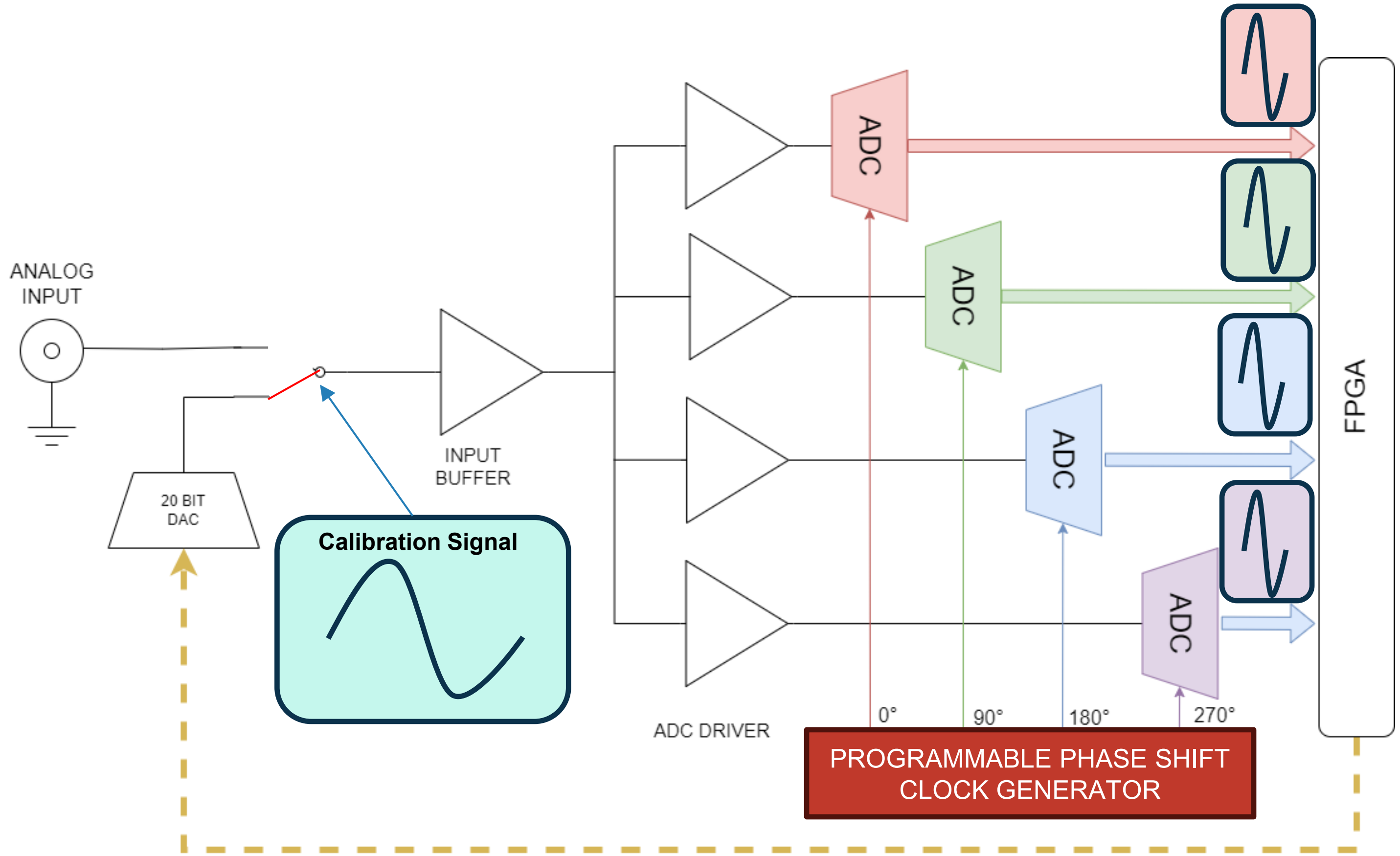
3. **Correct Offsets**
   Subtract each channel's own offset so that each line passes through the origin:
   $$y_i' = y_i - q_i = m_i\,x.$$

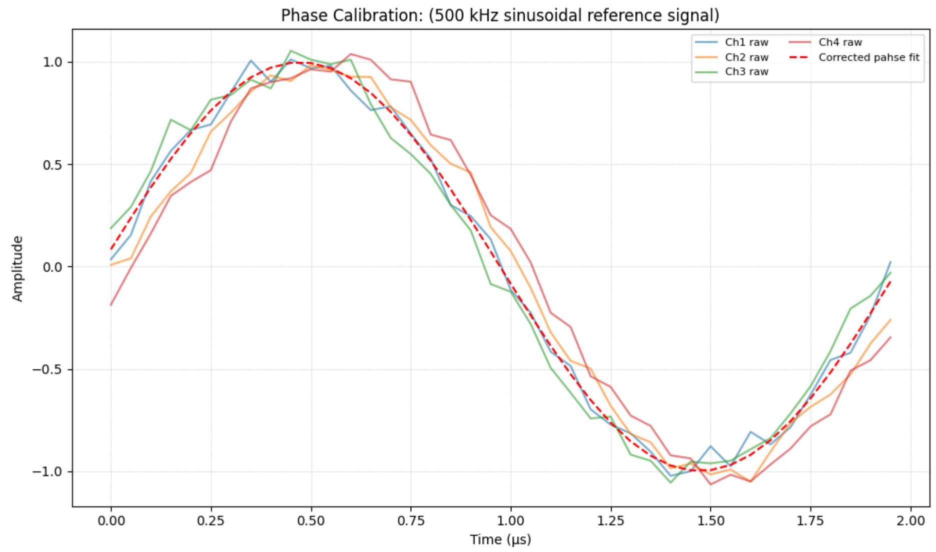
4. **Equalize Gains**
   $$y_i'' = y_i' \times \frac{m_{\text{ref}}}{m_i} = (y_i - q_i)\,\frac{m_1}{m_i} \longrightarrow y_i'' = m_1\,x.$$

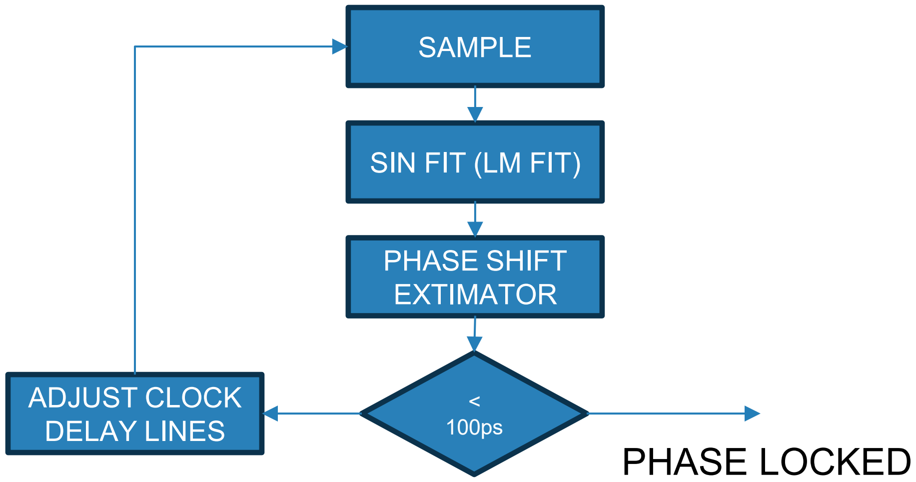
   m_{ref} is channel 1



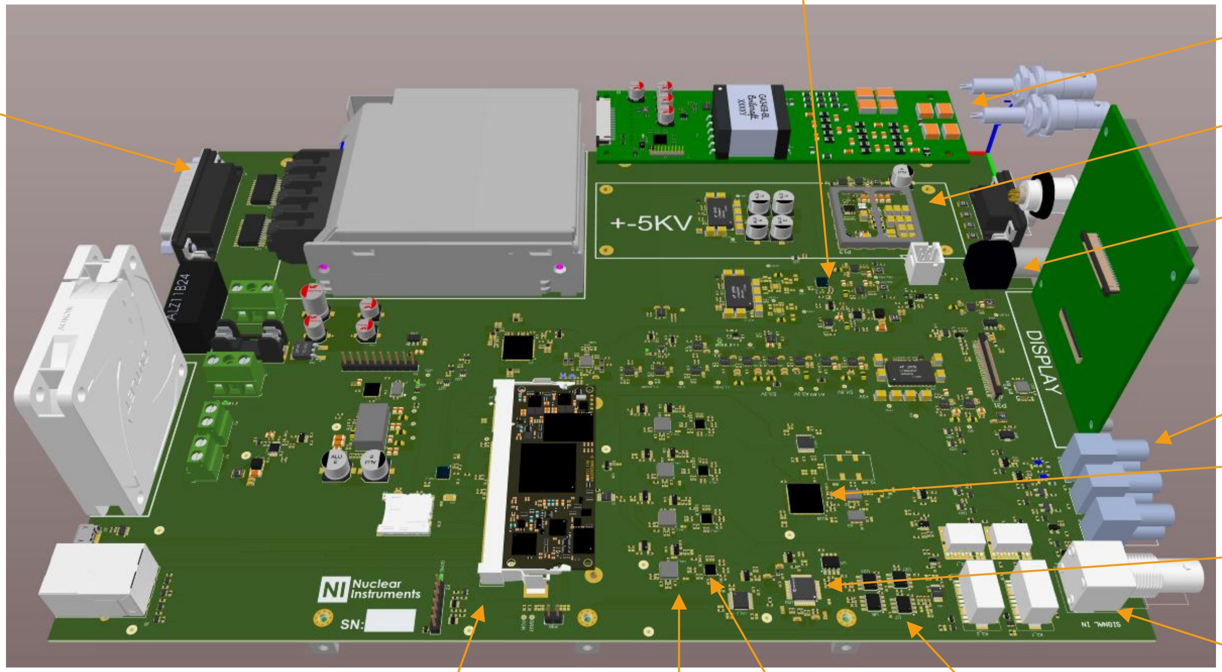
Gain and offset calibration



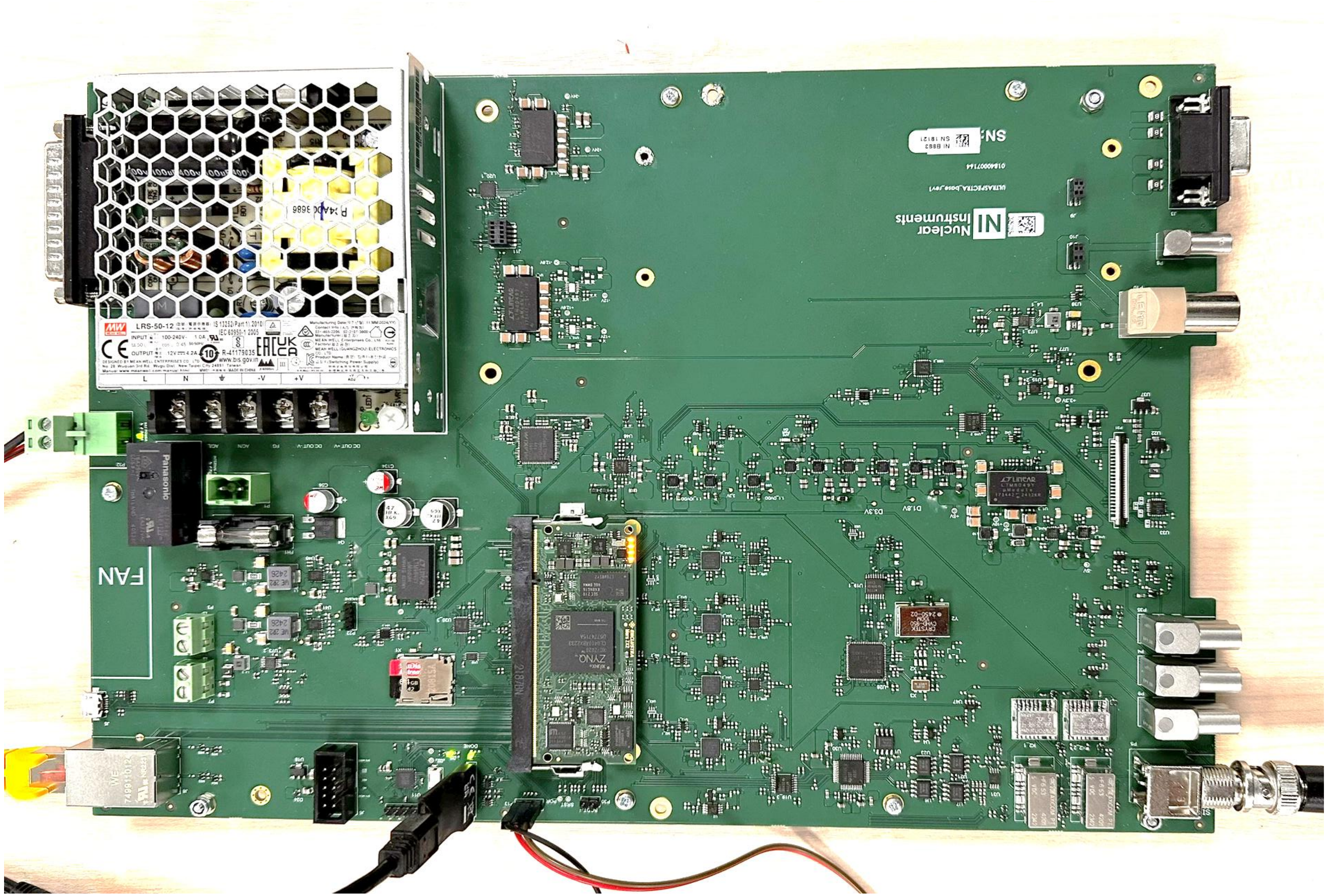




System overview



System overview



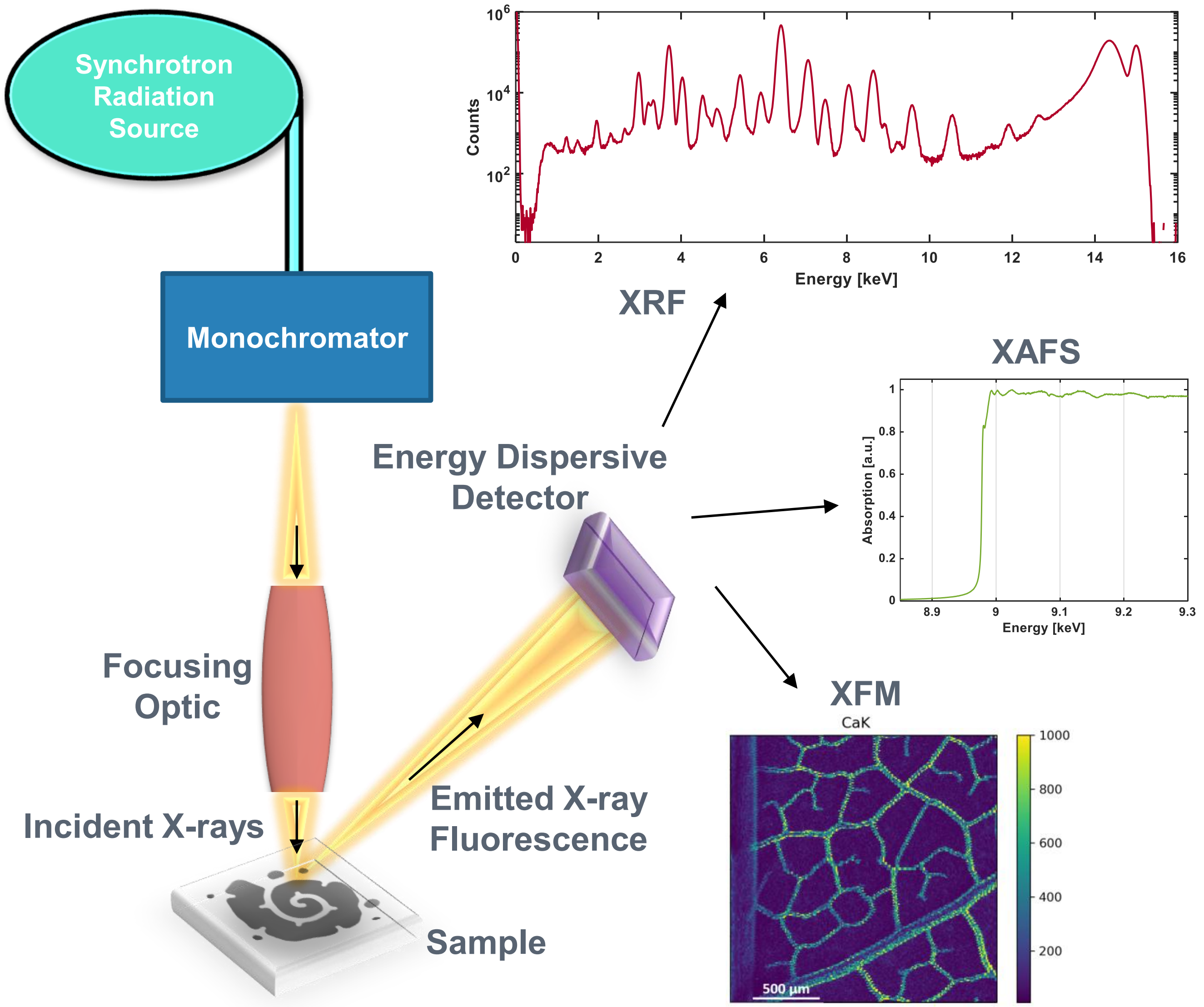
Ardesia Project
ARray of DEtectors for Synchrotron radlation Applications

RadLab POLITECNICO MILANO 1863

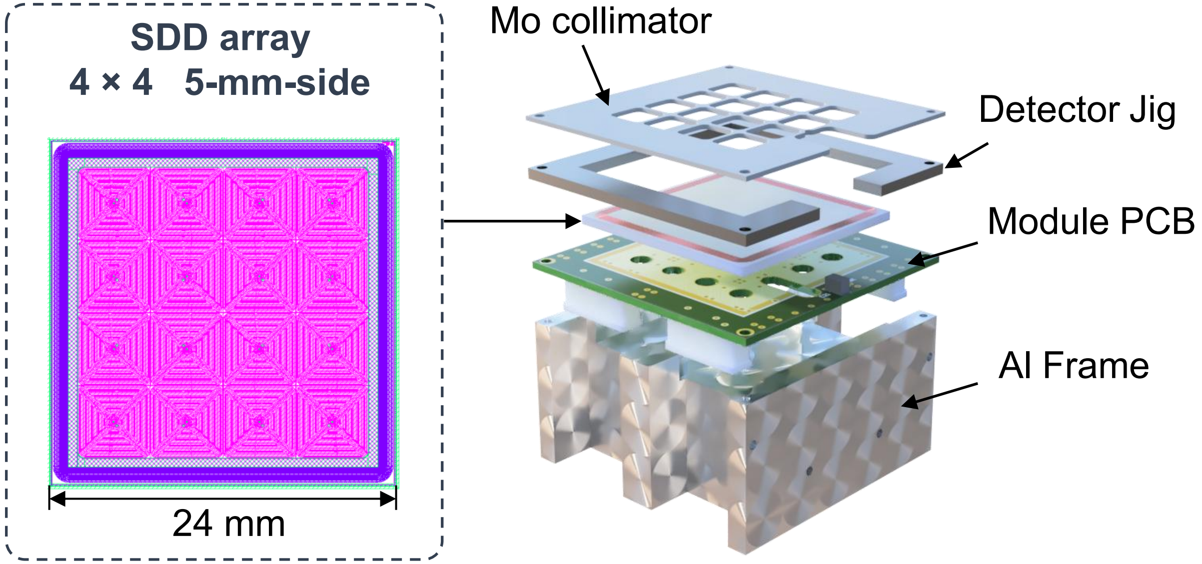
Motivation :
Develop a low-noise and versatile detector based on monolithic arrays of **Silicon Drift Detectors** for high-rate synchrotron applications
(mainly XRF, XAFS, and XFM)

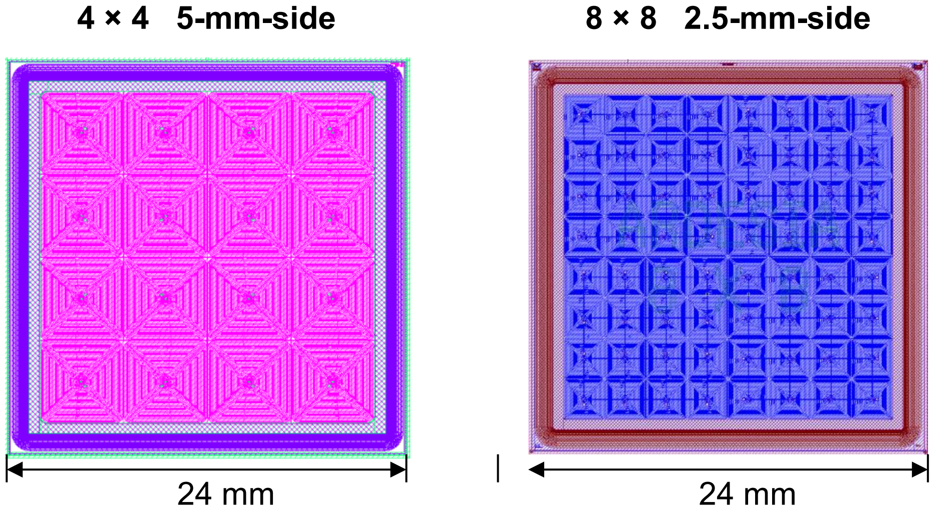
Detector requirements:

- ❑ X-ray energy range**: 0.2 keV – 20 keV** (Si detection region)
- ❑ **Target energy resolution** (~**125 eV** of FHWM Mn-Kα) at optimum shaping time and low rate, **good resolution** (**≤ 200 eV**) at short shaping time and **high throughput** (**> 1 Mcps/ch.**)
- ❑ **Modular** and **scalable** design, to easily increase sensitive area and adapt to different experiment configurations



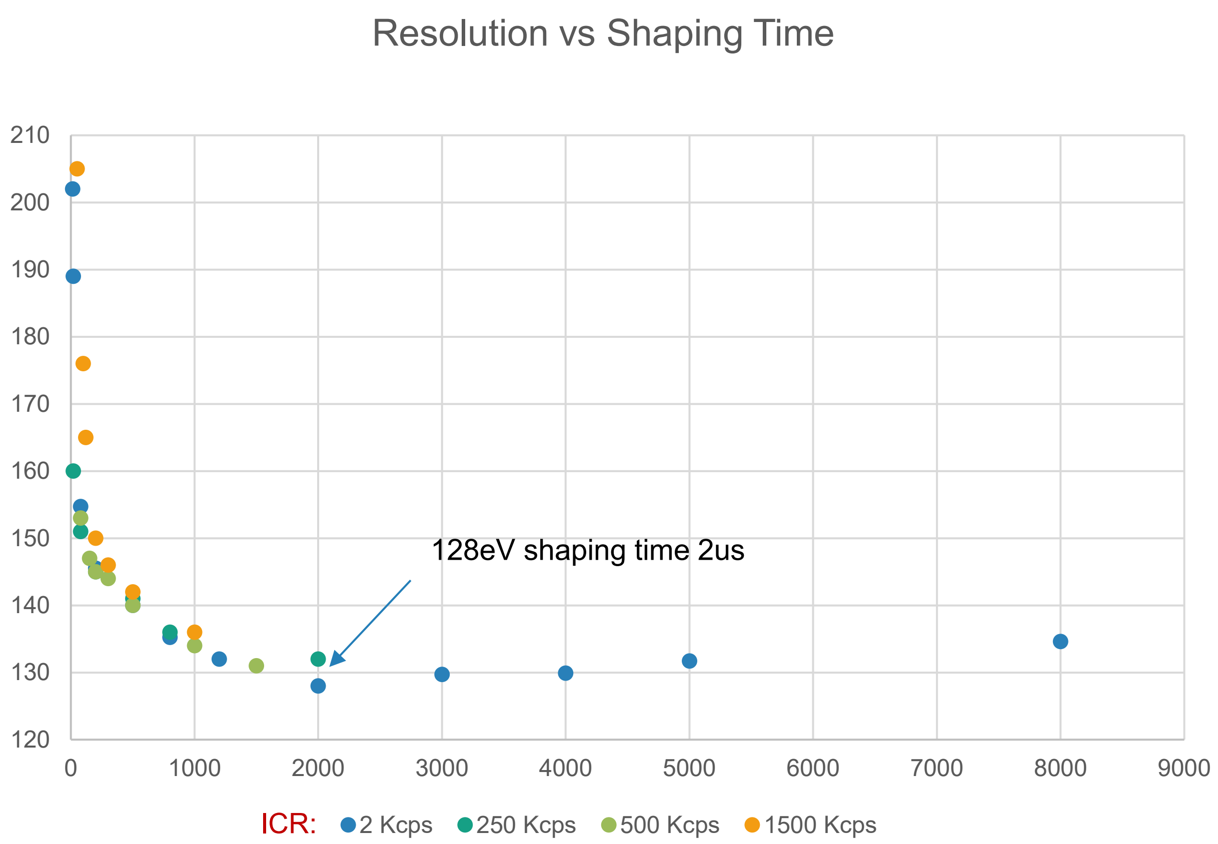
Increase high-rate capability of SDD-based X-ray spectrometers

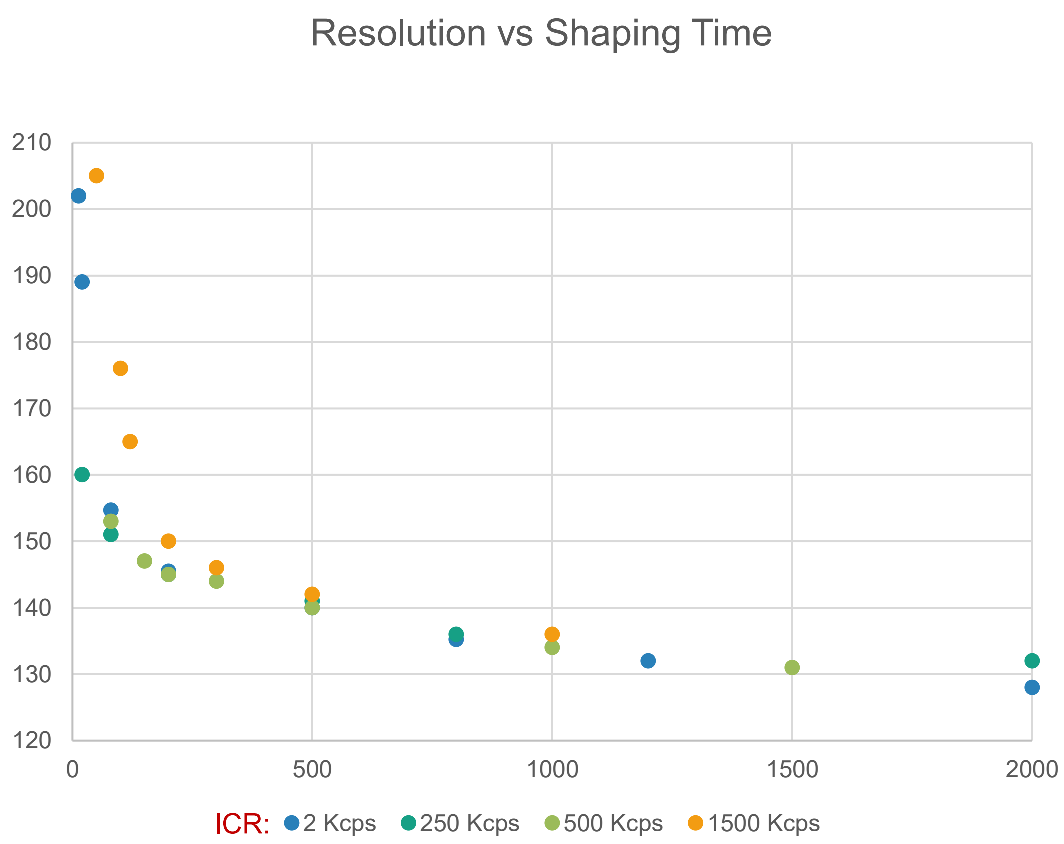




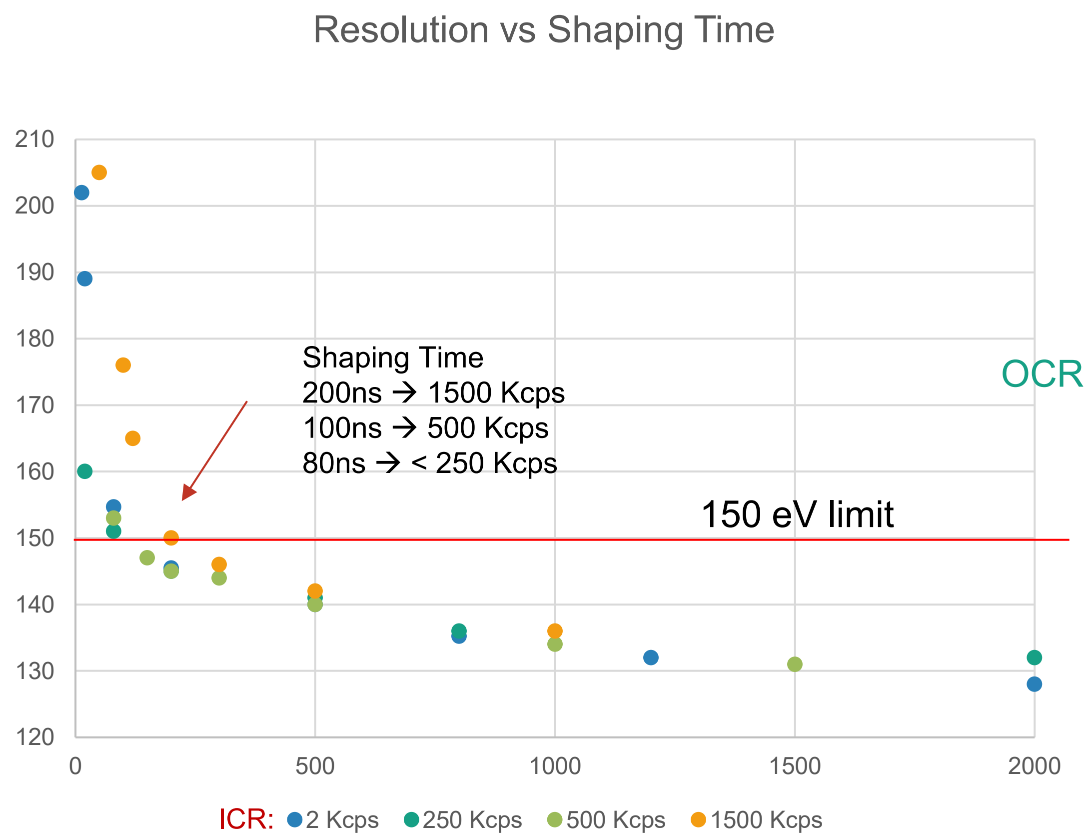
- ❑ Hosts the **16/64 channel Monolithic SDD array** (450 μs, 80 μm, or 1 mm thicknesses)
- ❑ 500 μm thick **Molybdenum Mask** to prevent charge sharing
- ❑ Active area after collimation: **324 mm²** (81% of window)
- ❑ Four custom-designed 4-channel **CUBE Preamplifiers**
- ❑ Preamplifiers and Detector are glued to a **High-density PCB**

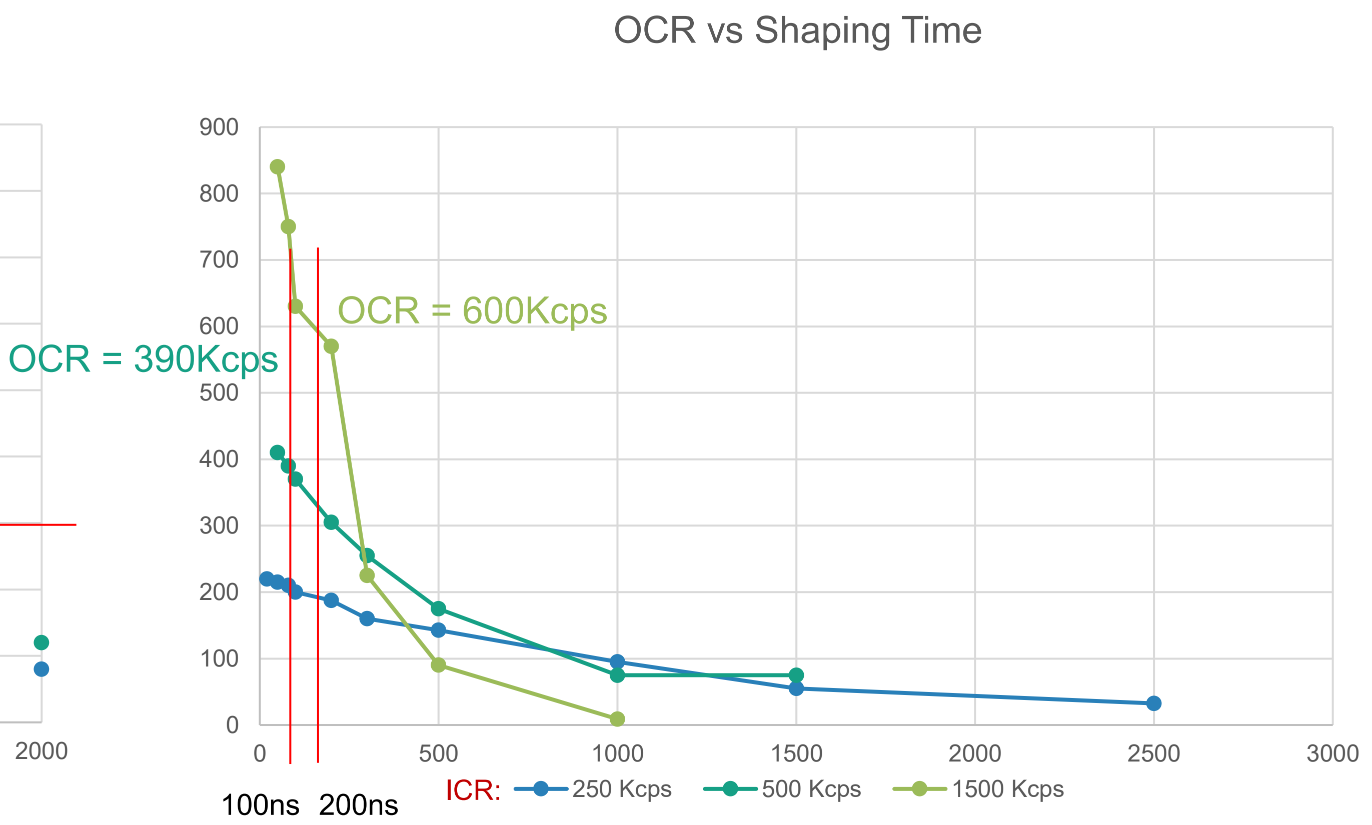
Resolution vs Shaping Time measuring Adesia Detector





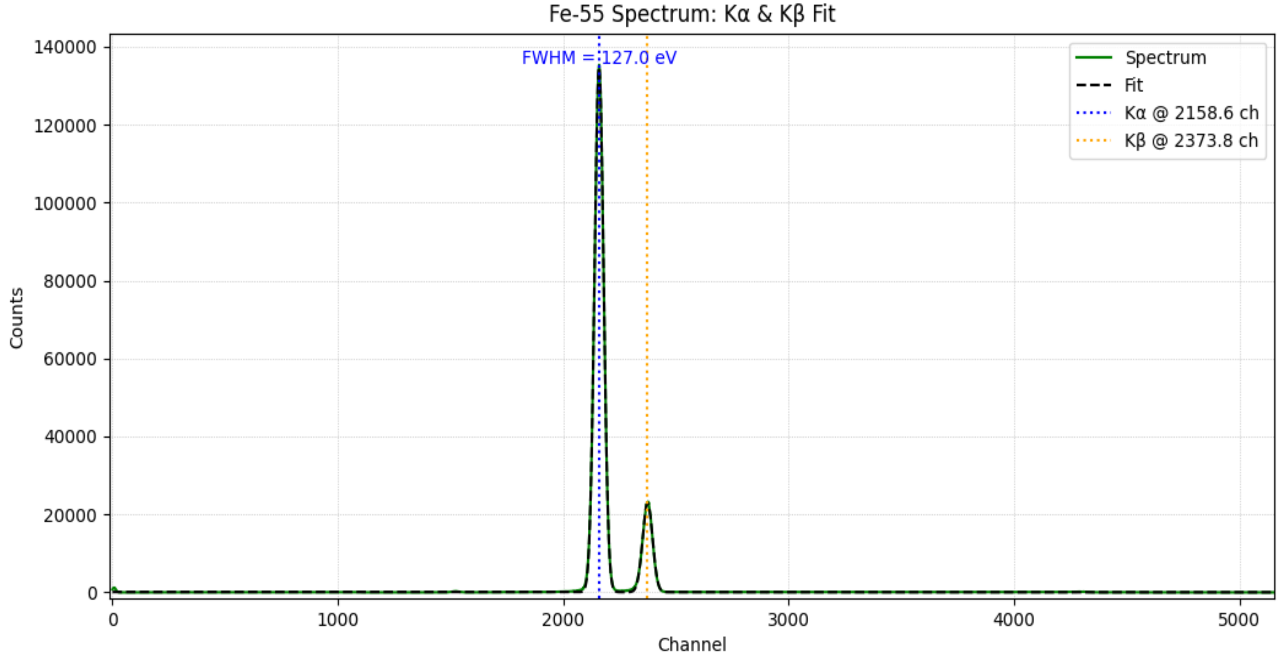
OCR vs Shaping Time measuring Ardesia Detector

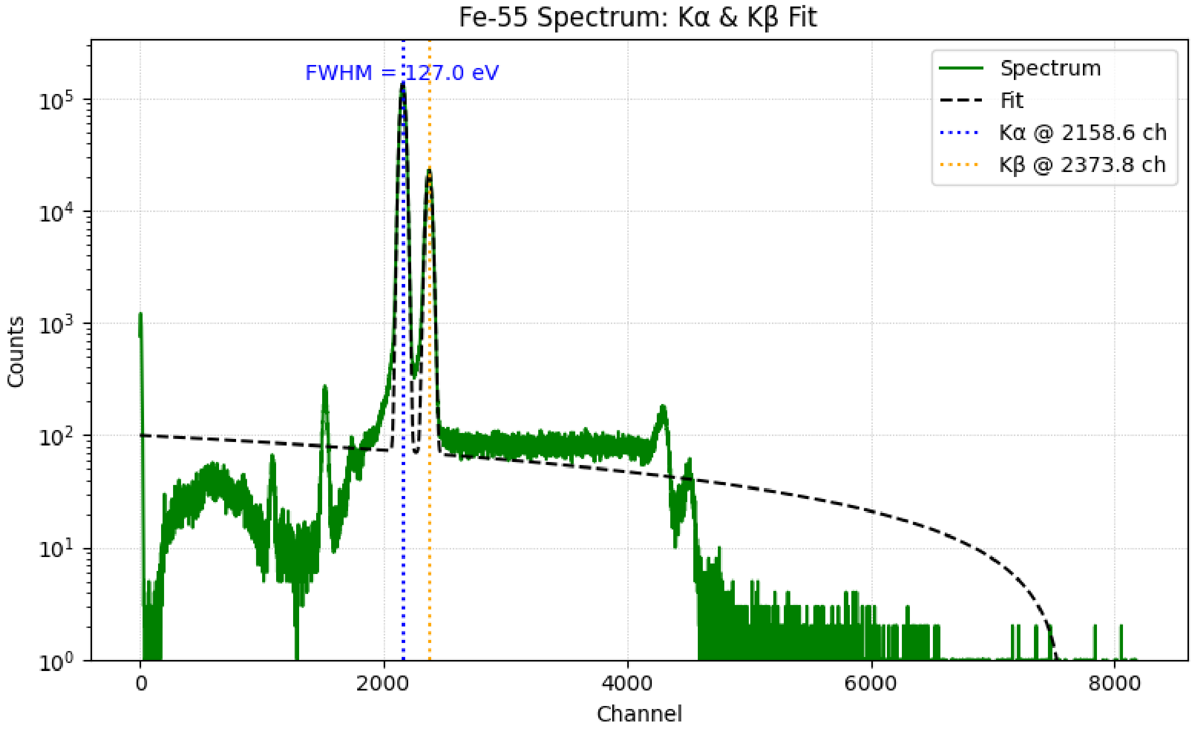




Ardesia Detector measured spectrum

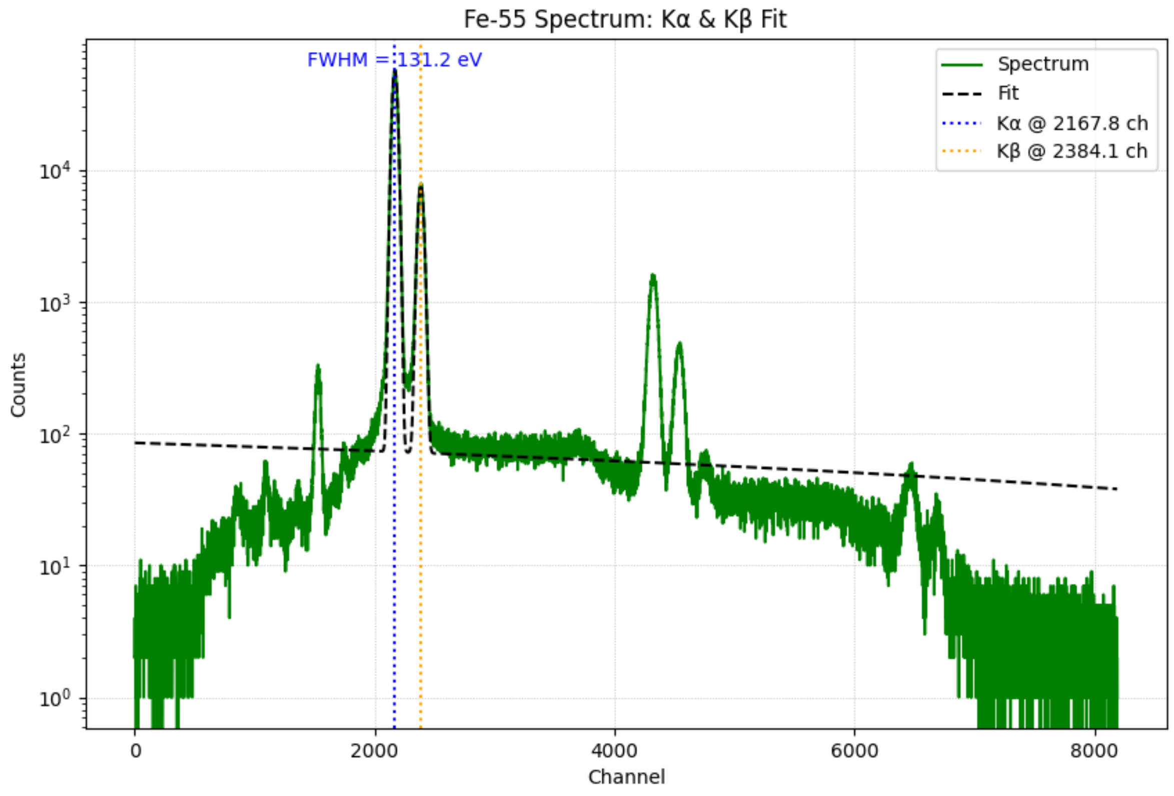
ICR 5 kcps 2us shaping time



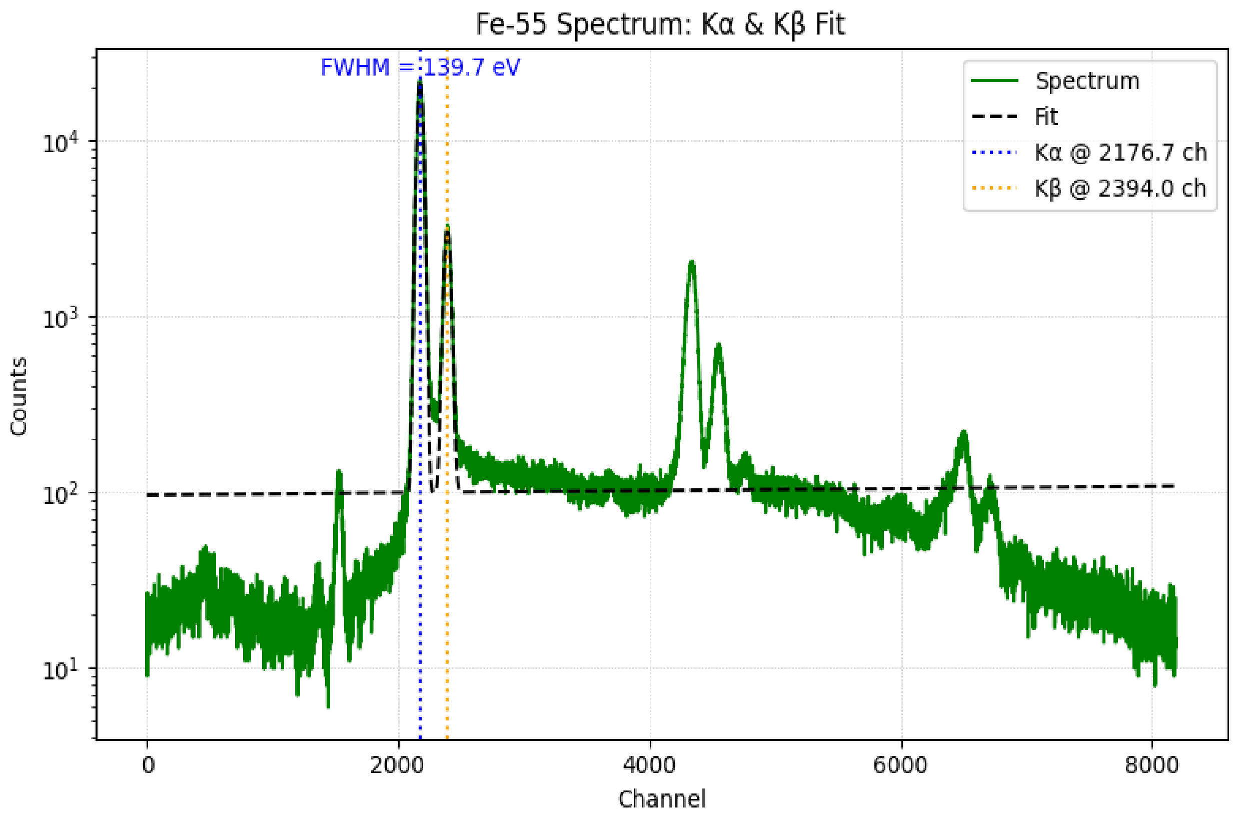


Ardesia Detector measured spectrum

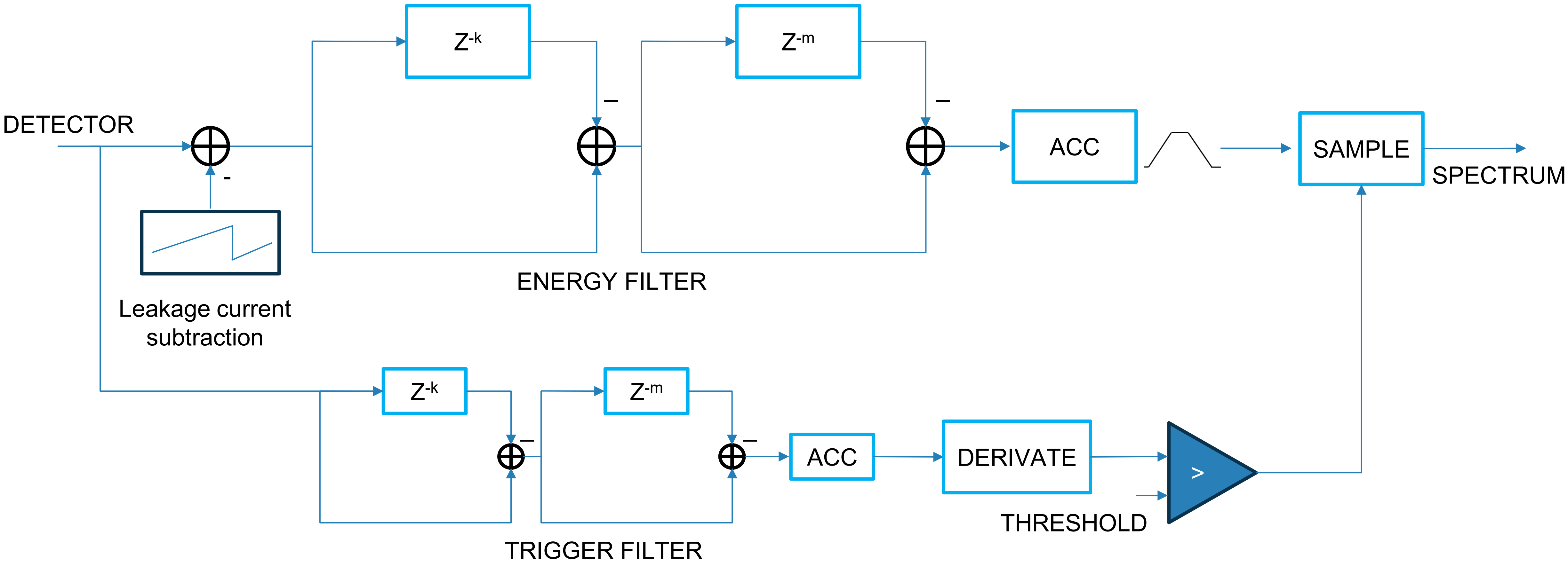
ICR 250 kcps 1 us shaping time



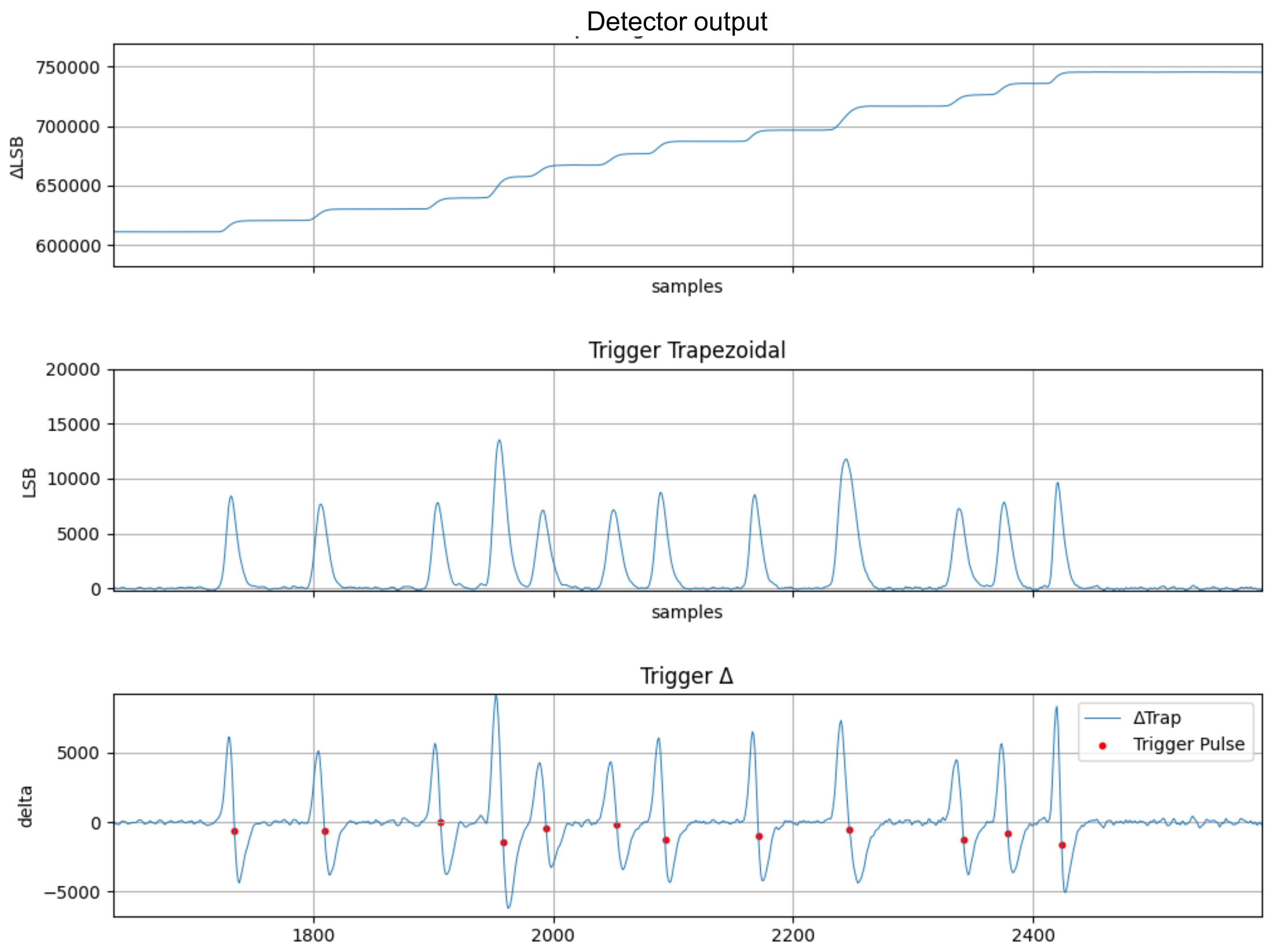
ICR 1500 kcps 500 ns shaping time



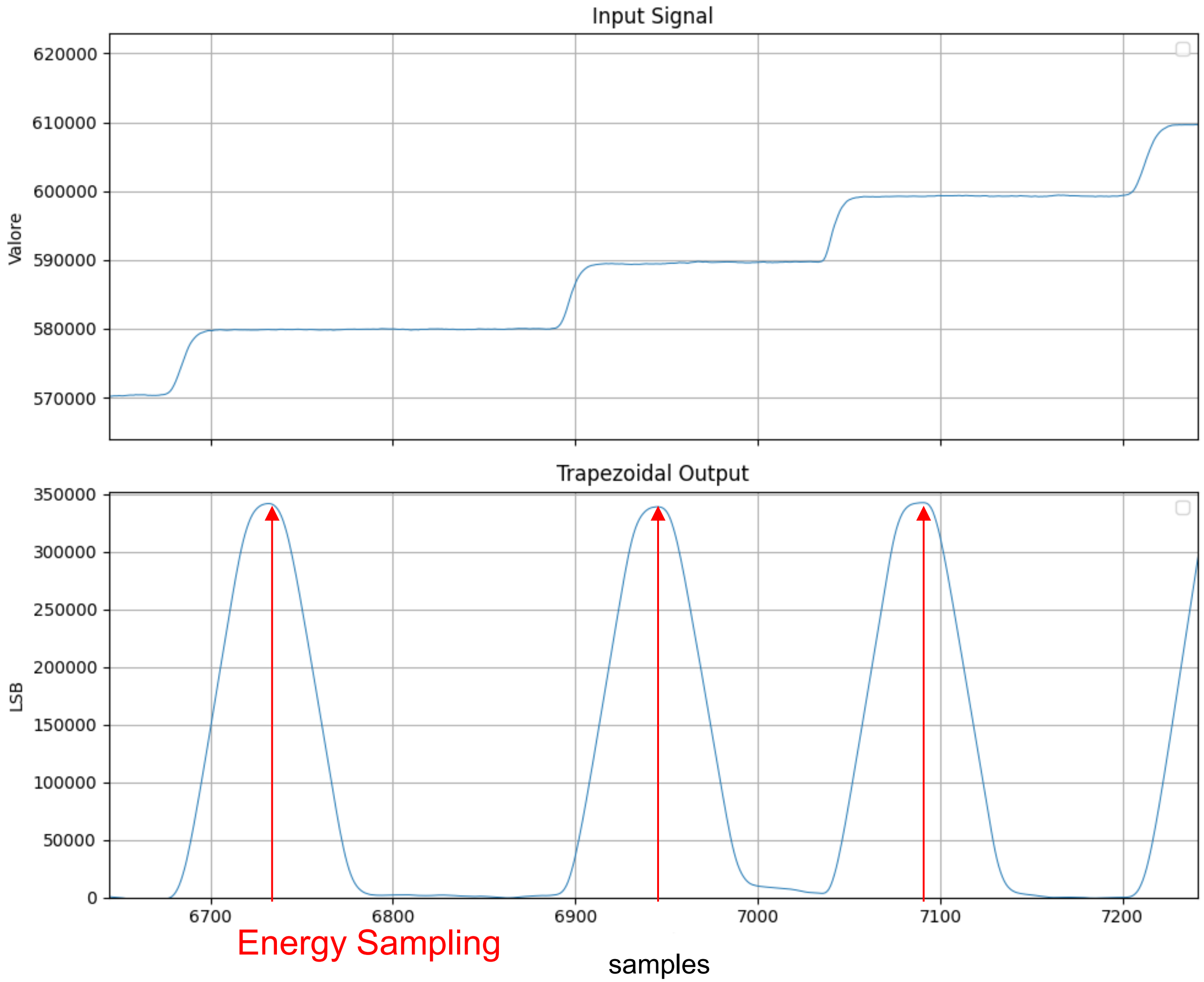
Realtime MCA processing algorithm



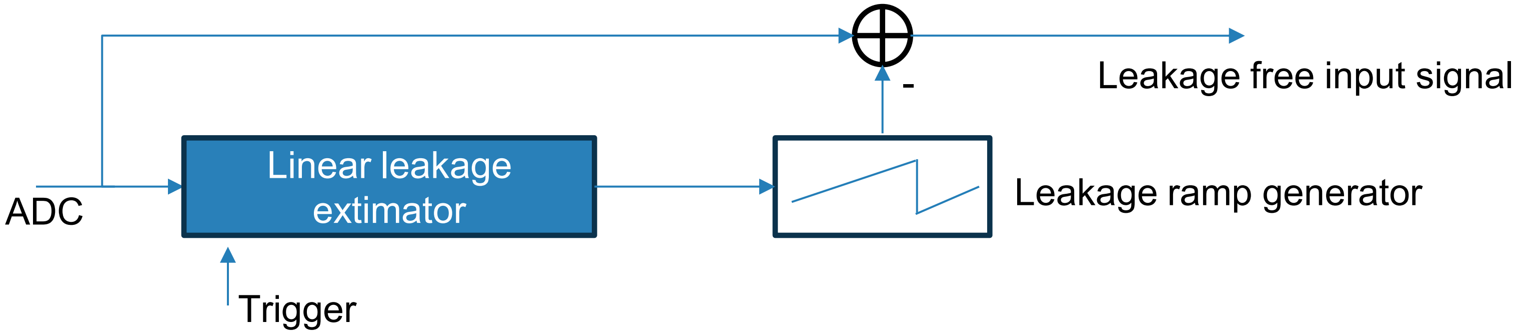
Trigger algorithm signals

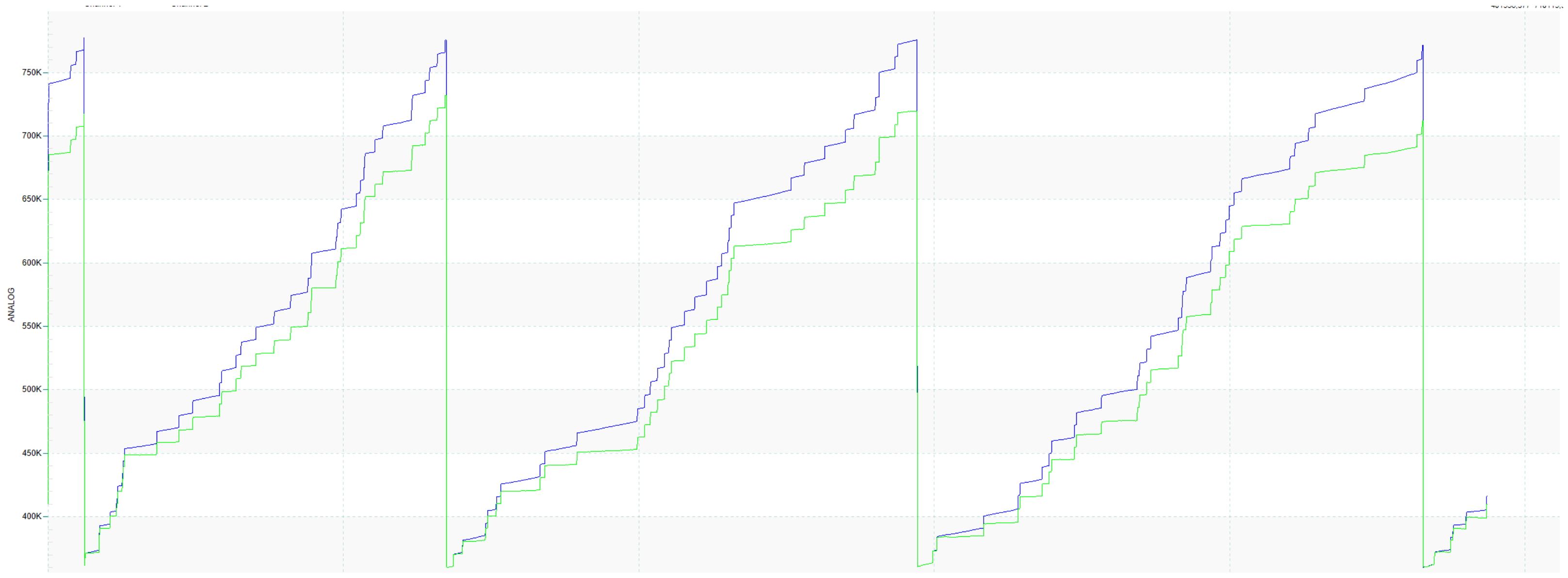


Energy Filter

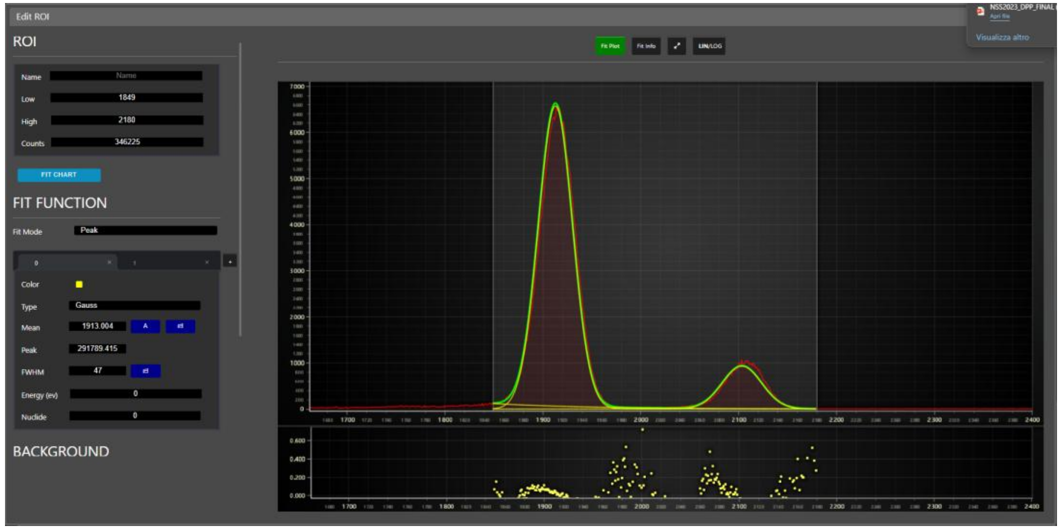


Leakage current compensation





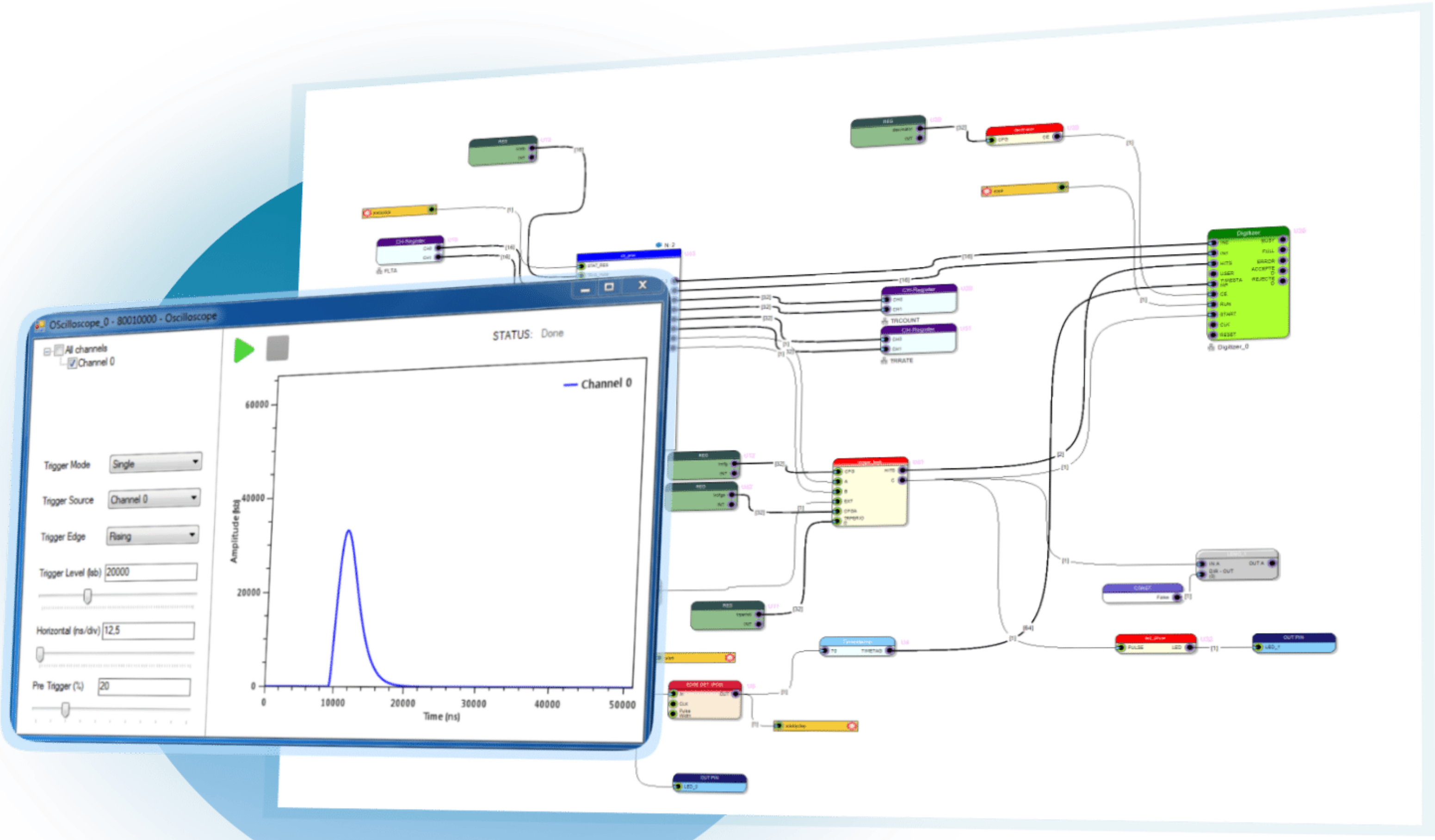
Ultraspectra & Web Interface



- 1 channels 160 Msps, 20 bit digitizer
- Realtime TRP optimized trapezoidal filter with leakage current compensation algorithm
- Up to 32 million point memory for waveform digitalization
- SmartMCA web based software with realtime fitting and calibration
- C/C++/C#/Python/Java/NodeJS/Labview … SDK and REST API for slow control and readout
- Onboard ARM CPU with Ubuntu Linux
- Easy integration in SCADA system (TANGO and EPICS integration is ongoing). Onboard Grafana connector.
- Fully supported in Sci-Compiler

Firmware customization

SCI-COMPILER



•Allows for customizing the firmware of digitizers and logic units.

•Simple and intuitive graphical programming language to learn.

•Nearly 200 IP cores designed for nuclear physics applications.

•Enables any researcher to develop their own acquisition and processing setup without FPGA knowledge.

•Firmware portability across different hardware.

•Extends the system's lifecycle by maintaining firmware compatibility with future hardware.

Open source SDK compatible with all Nuclear Instruments and CAEN OpenFPGA Digitizer

Available open source on GitHUB

GitHub

https://github.com/NuclearInstruments/SCISDK

Works on: Windows, Linux
Compatible with Raspberry PI

SCI-SDK

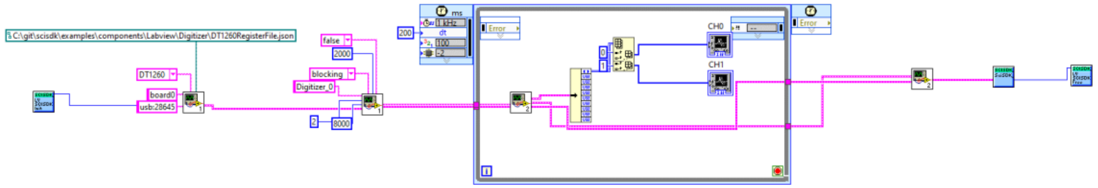
Available on: PIP, NPM, and APT (for Ubuntu) and ANT (java)

Works inside Jupyter Lab, pre installed on new instruments

Documentation and examples available here:
https://nuclearinstruments.github.io/SCISDK/

```
int main()
{
    SCISDK_OSCILLOSCOPE *osc_data;

    sdk.AddNewDevice("usb:0006", "dt1260", "SCIDKTester.json", "board0");
    sdk.StrobeRegister("Registers/res", "pos");

    sdk.SetParameter("Oscilloscope_0/decimator", 10);
    sdk.SetParameter("Oscilloscope_0/trigger", "ext");
    sdk.SetParameter("Oscilloscope_0/acq_mode", "blocking");
    sdk.SetParameter("Oscilloscope_0/data_processing", "decode");

    sdk.ExecuteCommand("Oscilloscope_0", "start");

    sdk.AllocateBuffer("Oscilloscope_0", "decoded_buffer", (void **) &osc_data);

    for (int i = 0; i < 10; i++) {
        sdk.ReadData("Oscilloscope_0", osc_data);
        dump_to_file(osc_data);
    }

    return 0;
```

python™ LabVIEW VB.NET Java ROOT Data Analysis Framework



Multichannel solution for matrix detectors

- 128 channels, independent gain (up to x100) and AC shaping (300ns, 3 us, 10us)
- 125 Msps 14 bits
- 4 FPGA Zynq 7035
- Up to 80 Gbps connectivity on optical link, 4 Gbps on ethernet

Future Development

Multichannel (16 channels) 20 bit 160 Msps digitizer