

# Digital Pulse-Processing Electronics for Fusion Diagnostics: Performance and Perspectives across Neutron and Plasma Detectors

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# What fusion diagnostics ask of the read-out

**Fast neutrons and X-rays carry direct information on the plasma:** temperature, confinement, fuel mix, fast electrons, instabilities. Fast, radiation-hard detectors such as diamonds are available: the read-out has to keep up.

1

## Timing

ns-scale resolution  
for time-of-flight  
and pile-up  
rejection

2

## Compactness

Many channels in a  
small footprint

3

## Real-time

On-board FPGA  
processing for real-  
time data  
monitoring

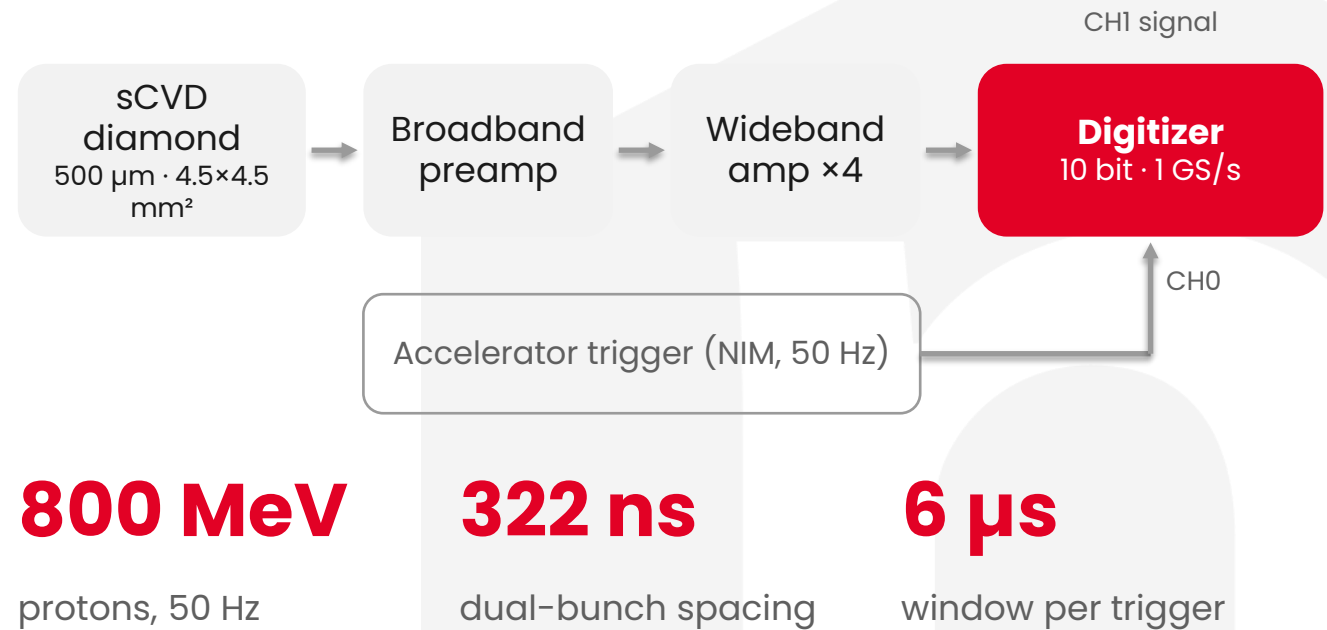
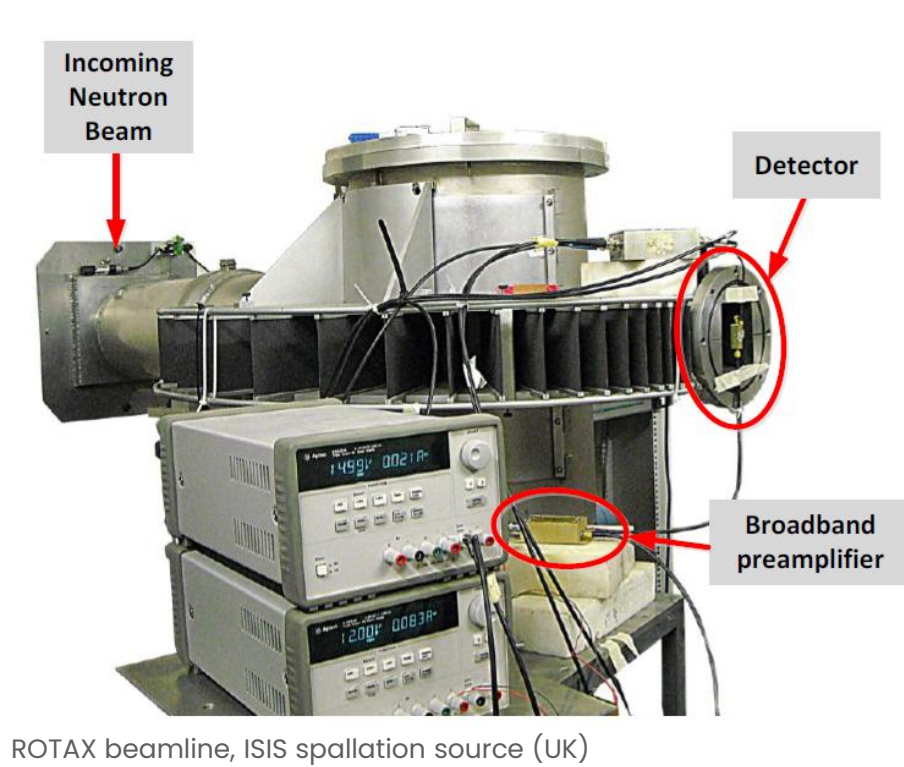
4

## Throughput

Deep memory and  
fast links to keep full  
waveforms

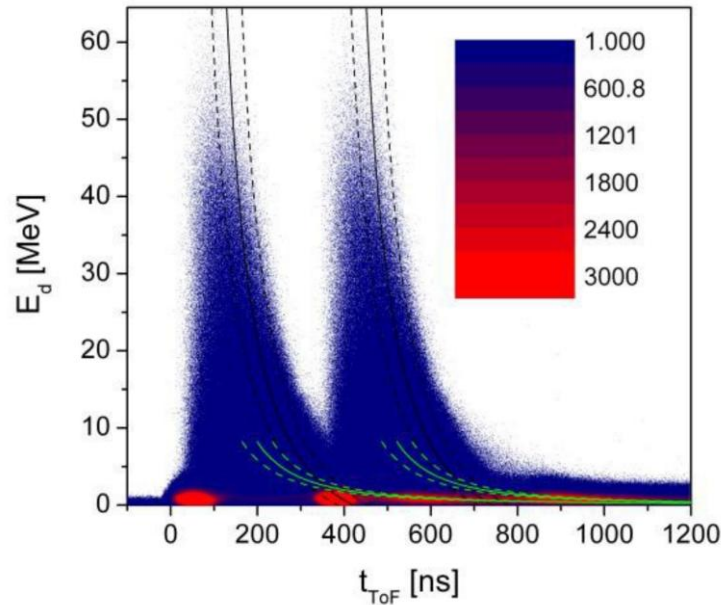
# ISIS test: fast-neutron time-of-flight with a diamond

**Goal:** validate a fully digital read-out chain (diamond + broadband preamp + digitizer) for fast-neutron ToF-energy spectroscopy, with no analog shaping and no external timing modules.

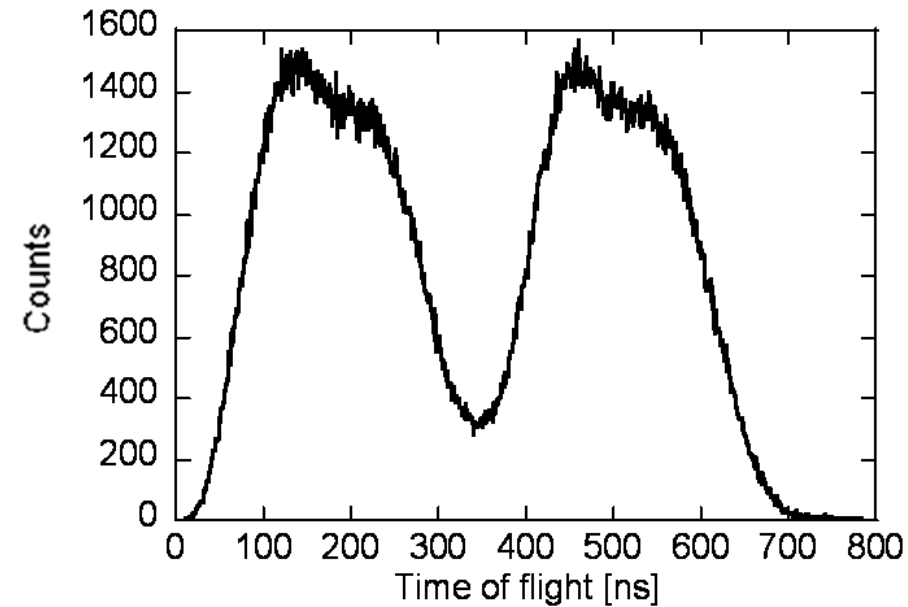


**After the preamplifier everything is digital:** ToF and pulse integral from the same samples.

# Biparametric ToF-energy spectrum



(a) ToF vs deposited energy —  $3 \times 10^7$  events, 65 h



(b) Projection on the ToF axis, deposited energy  $> 5$  MeV

**1**

## Two bunches, one trigger

The same pattern repeats 322 ns later, each with its own prompt  $\gamma$ -flash.

**2**

## Kinematic limits on $^{12}\text{C}$

Maximum deposited energy vs ToF: elastic (green),  $(n, \alpha)$  (black).

**3**

## ToF alone is ambiguous

Slow neutrons of bunch 1 overlap fast ones of bunch 2: the deposited energy separates them.

# From 2012 to today: what the read-out can now do

| Specification         | Digitizer 1.0                                           | Digitizer 2.0                                                                       |
|-----------------------|---------------------------------------------------------|-------------------------------------------------------------------------------------|
| Maximum record length | A few ms of waveform per channel                        | ≈ 84 ms per channel at full sampling rate                                           |
| Readout bandwidth     | <b>USB 2.0:</b> 30 MB/s<br><b>Optical Link:</b> 80 MB/s | <b>USB 3.0:</b> 280 MB/s<br><b>1 GbE:</b> 110 MB/s<br><b>10 GbE UDP*:</b> 1100 MB/s |
| On-board processing   | Fixed firmware algorithms                               | Open FPGA: user-defined algorithms                                                  |
| Input gain            | Fixed or selectable gain                                | Variable Gain Amplifier                                                             |

\* 10 GbE available on request

# Digitizer 2.0: matching the digitizer to the detector

◀ Channel density

Sampling speed ▶

## x2740 / x2745

**64/8 ch · 16 bit · 125 MS/s**

2.5 GB on-board memory

x2745: gain up to  $\times 100$

Detectors: Si / HPGe with CSP,  
scintillators + PMT, photodiode  
arrays

## x2730

**32/8 ch · 14 bit · 500 MS/s**

5 GB on-board memory

Programmable gain  $\times 1 - \times 20$

Detectors: liquid and inorganic  
scintillators + PMT / SiPM

Fast timing, n/ $\gamma$  pulse-shape  
discrimination

## x2751

**16/4 ch · 14 bit · 1 GS/s**

5 GB on-board memory

Programmable gain  $\times 1 - \times 10$

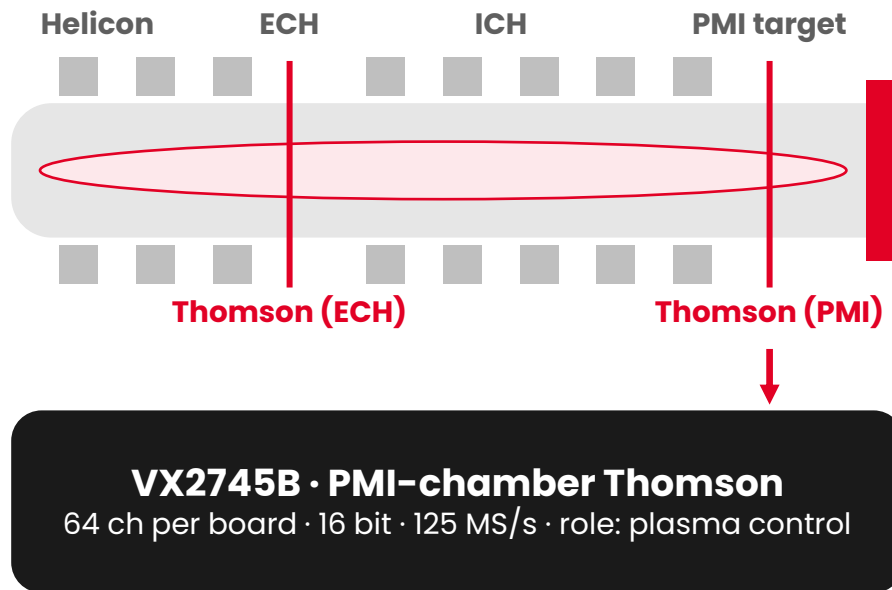
Detectors: diamonds, fast  
scintillators + PMT / SiPM

ns time-of-flight

# MPEX: digitizing the Thomson scattering diagnostic

Steady-state linear plasma device (ORNL) for plasma-material interaction under divertor conditions — under construction, operations from 2027

## Where the digitizer sits



## Physics requirement

**Many volumes × spectral bands**

**Every channel on the same laser shot**

**Weak scattered light on plasma background**

**Steady-state plasma, continuous laser shots**

## Read-out choice

→ Tens of channels per system:  
64 per board

→ External trigger from the laser: all  
channels acquired together

→ Analog gain and high ADC resolution

→ Continuous readout on high-bandwidth  
links, on-board data reduction

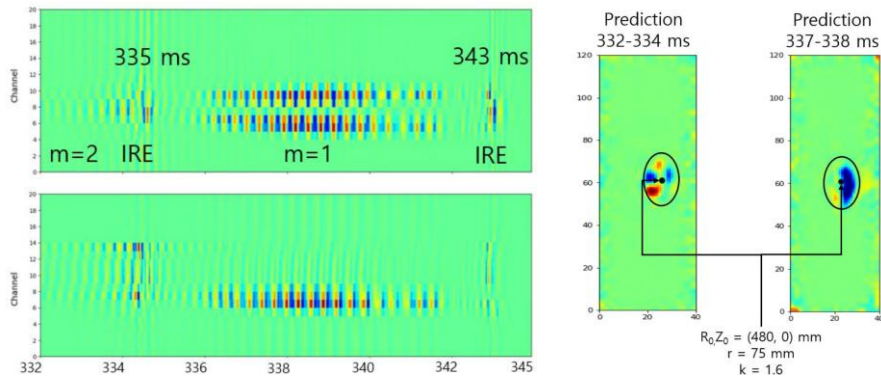
MPEX diagnostics: T.M. Biewer, X.-Y. Yu et al., 3rd MPEX Users Research Forum, ORNL (2026) · Proto-MPEX TS: Rev. Sci. Instrum. 89 (2018) 10C107

MPEX basis: C. Lau, T.M. Biewer et al., Nucl. Fusion 63 (2023) 056009 · VX2745B for the PMI-chamber TS: private communication (ORNL)

# VEST: soft X-ray diagnostic for MHD instabilities

Spherical tokamak at Seoul National University — two 20-channel AXUV cameras, vertical and horizontal views

## What the SXR cameras reveal



#41657 (VEST clock, plasma  $\approx 0.32$ – $0.35$  s):  $m = 2 \rightarrow \text{IRE} \rightarrow m = 1$ ; deep-learning tomograms of the island

**A1442B charge sens preamp + V2740 digitizer**  
40 SXR channels · whole discharge

## Physics requirement

**40 lines of sight**

**Tiny photodiode charge, noisy environment**

**MHD modes at 5–10 kHz**

**Every channel over the whole discharge**

## Read-out choice

One 64-channel board reads all 40

Charge-sensitive preamps at the port, differential lines to the DAQ

125 MS/s decimated to 1–4 MS/s

On-board memory: 40–50 ms record per channel

S. Lim, Ph.D. thesis, Seoul National University (2024) · read-out: CAEN A1442B preamplifiers + V2740 digitizer

# Conclusions and perspectives

1

## Neutrons: the physics is in the waveform

ToF and deposited energy from each diamond pulse resolve the bunch structure, the prompt  $\gamma$ -flash and the  $^{12}\text{C}$  reaction channels.

2

## Thomson scattering: many channels per laser shot

In the MPEX PMI chamber, many scattering volumes and spectral channels are digitized in parallel: channel density sets the reach.

3

## Plasma: sampling matched to the physics

At VEST, 40 SXR channels over the whole discharge, at MHz sampling, reveal 5–10 kHz MHD modes, the island structure and m-number.

## Outlook

Waveform-based ToF–energy spectroscopy with diamond detectors in fusion neutron fields:

ns timing and energy extracted on board, at high rate, scalable to multichannel arrays.

**Common thread:** sample as fast as the physics needs, record long enough, process where the detector needs it.



**Thank you!**

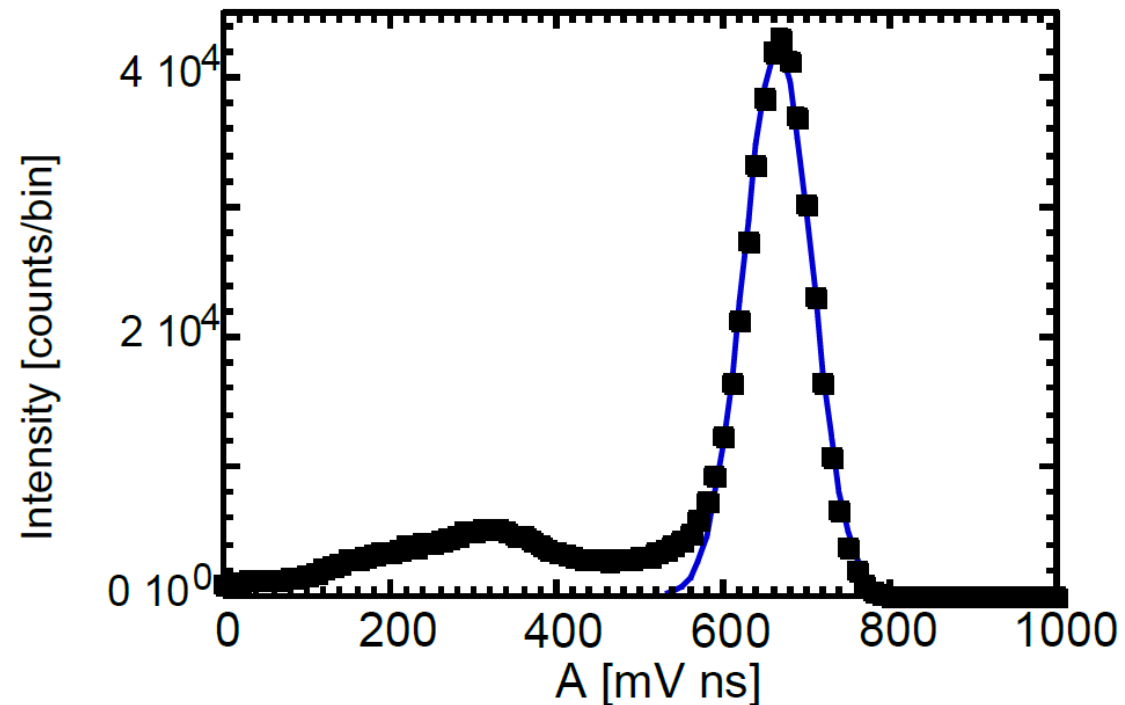




# Backup slides

- ◆ **Calibration**
- ◆ **Raw waveforms**
- ◆ **Acquisition modes**

# Backup — Energy calibration



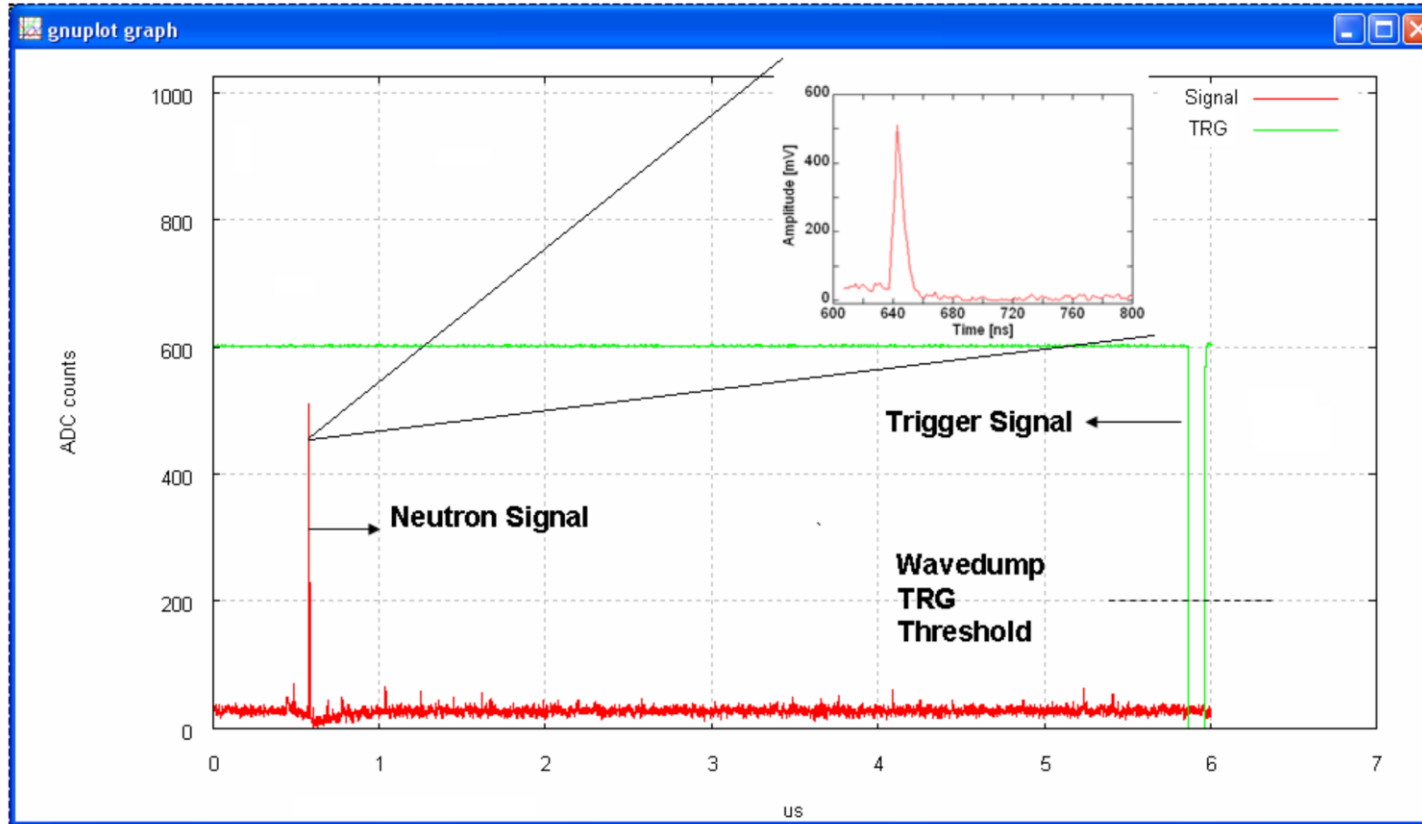
**$^{241}\text{Am}$   $\alpha$  source** (5.5 MeV) in front of the diamond

**DT5751 in self-trigger mode**

**Gaussian fit:** FWHM  $\approx 96$  mV·ns

Linear relation between pulse integral and deposited energy

# Backup — Recorded waveforms



**CH0:** accelerator trigger (NIM)

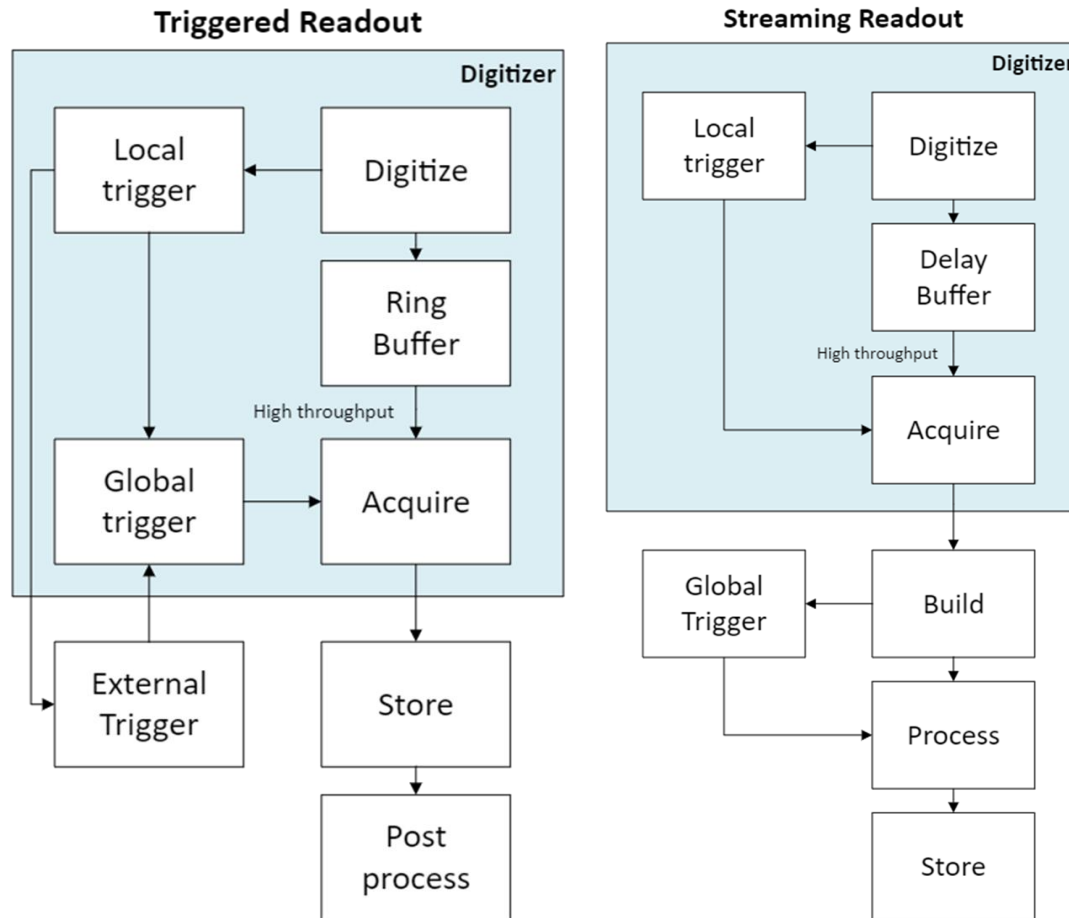
**CH1:** diamond signal, ~2 ns rise, ~10 ns width

**Window:** 6  $\mu$ s, 1 % post-trigger

**Look-back:** pulses before the trigger are kept

**Timing:** 1 ns at 1 GS/s (500 ps at 2 GS/s)

# Backup — Triggered and DPP readout



## Waveform recording (Scope)

Common trigger: one event holds the waveforms of all channels

## Digital Pulse Processing (DPP)

Individual trigger per channel; compact events (timestamp, energy, PSD, flags, optional waveform)

Flavours: PHA, QDC, PSD, CFD, ZLE, DAW, Open DPP