nCAEN
Tools for Discovery

Digital Readout Electronics for Fast Neutrons and X-rays: Performance and Perspectives for Fusion Diagnostics

Yuri Venturini (y.venturini@caen.it)

International Conference on Diagnostic for Fusion Reactors

Villa Monastero, Varenna, Italy
September 1 - 5, 2025

Motivation & Context

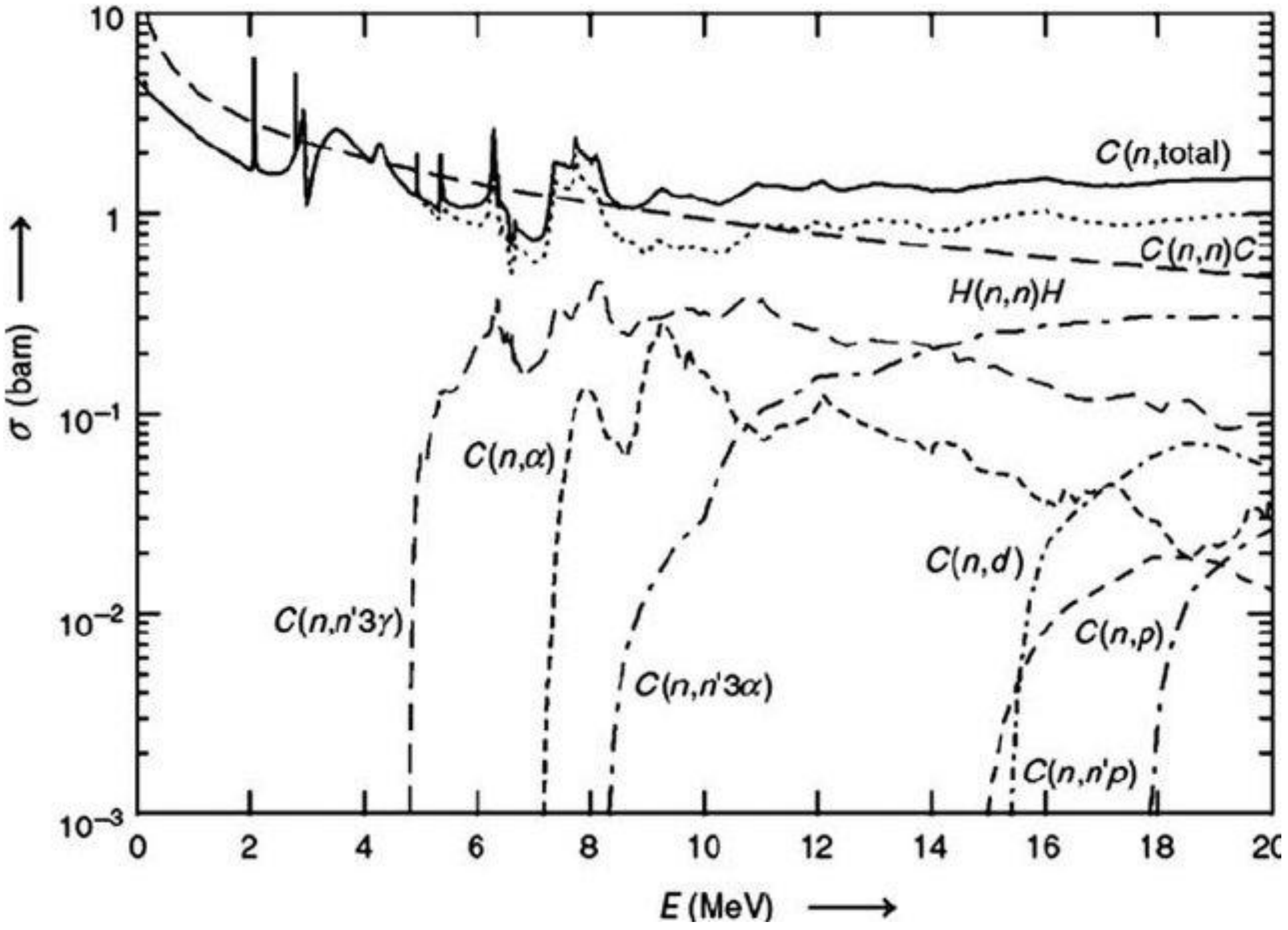
- **Fast neutrons and X-rays** are crucial in **fusion plasma diagnostics**.
  - Fast neutrons carry **direct information on plasma conditions** (temperature, confinement, fuel mix

    H Bryś et al., *Fusion Engineering and Design* 88 (2013) 2205–2208
  - X-rays can probe **fast electrons, impurity radiation, and plasma instabilities**

    E. Joffrin et al., Nucl. Fusion 59 (2019) 112021, doi:10.1088/1741-4326/ab2276
- **Key challenges**
  - **High timing resolution**: ns scale (instabilities, disruptions).
  - **Radiation hardness & compactness**: essential for harsh environments.
  - **Real-time capability**: diagnostics must feed plasma control systems.
- **Technological solutions**
  - **Diamond detectors** → compact, radiation hard, ideal for fast neutron spectroscopy.
  - **Fast scintillators** → large dynamic range, γ/X-rays - A Dal Molin *et al* 2023 *Meas. Sci. Technol.* **34** 085501

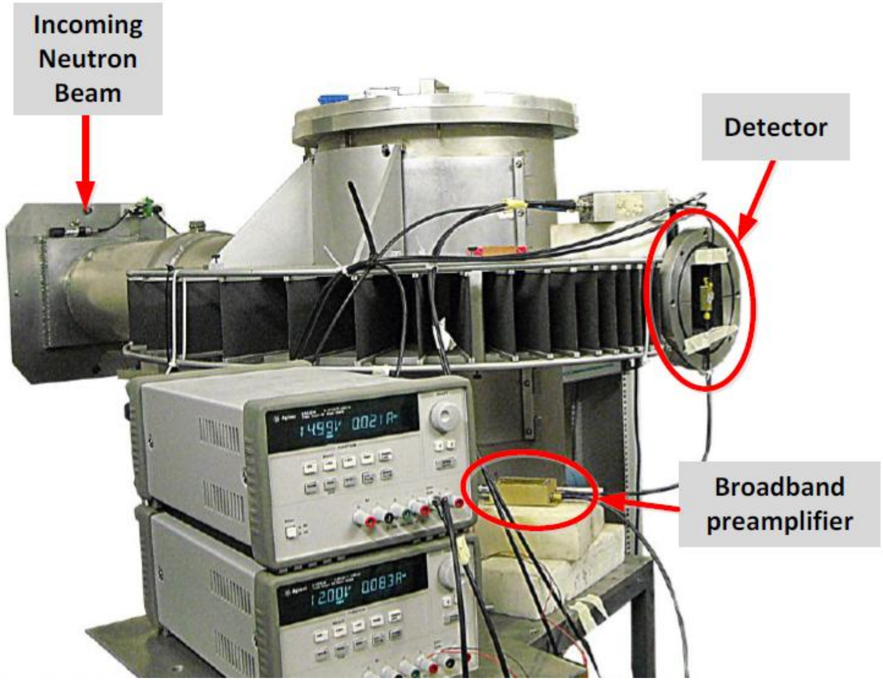
Diamond Detectors & Fusion Relevance

- **Fast signals**: rise times ~100 ps, enabling sub-ns **ToF** measurements.
- Fast neutrons detected via charged particle produced via nuclear reactions
- Neutron interaction mechanisms in diamond (C-12)
    - $C(n,n)C$ - Elastic scattering
    - $C(n,\alpha)$, threshold ~6.2 MeV.
    - $C(n,n'3\alpha)$, threshold ~7.9 MeV.
- Combined channels → sensitivity to fusion neutrons (2.5/14 MeV)



Experimental Campaign @ ISIS

- ROTAX beamline. Beam: 800 MeV protons, 50 Hz, dual-bunch structure (322 ns apart).
- Neutron from spallation: 0–800 MeV (white spectrum) → Collimation to exp. hall
- Goal: full-digital ToF–energy spectroscopy with diamond detector (4.5 x 4.5 mm2 active area single crystal diamond (SCD) by Diamond Detectors Ltd) + CAEN Fast ADC.



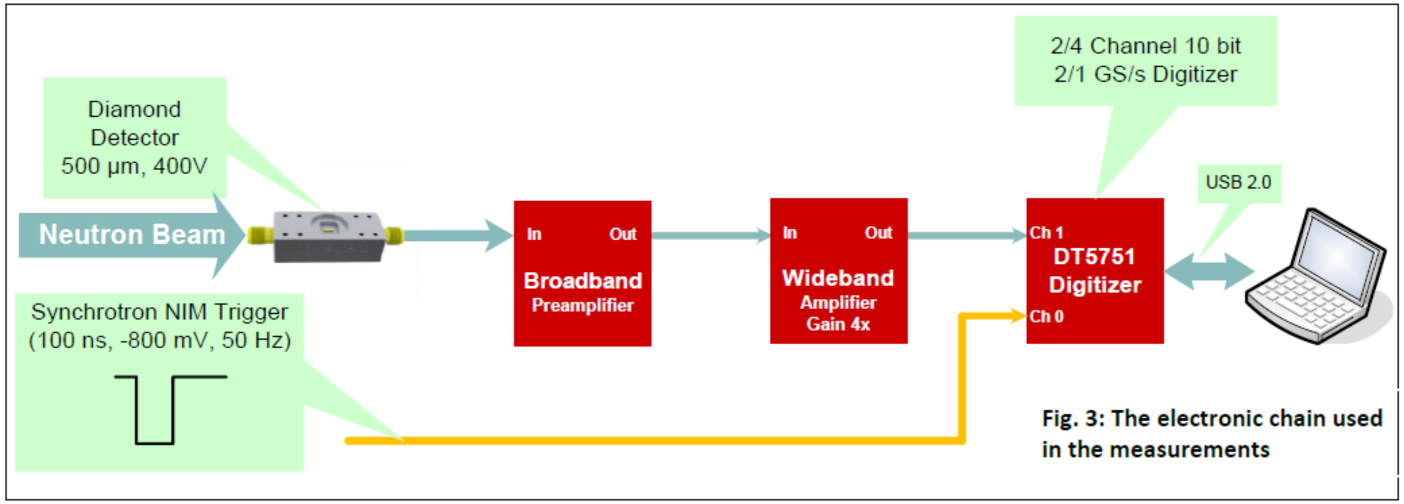
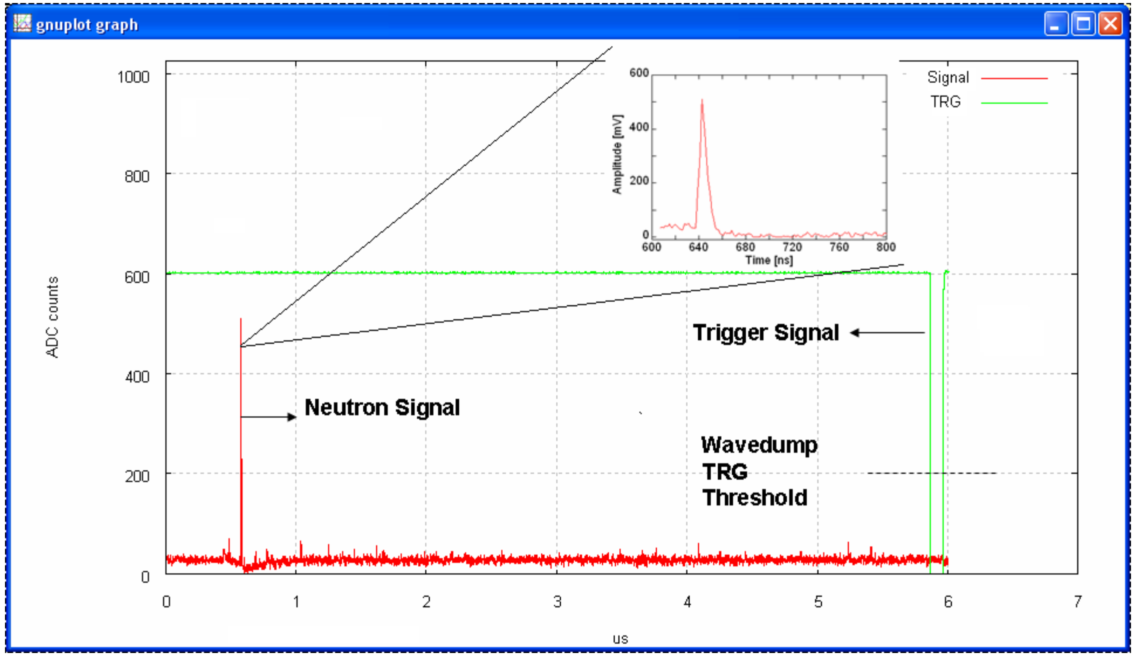


Fig. 3: The electronic chain used in the measurements

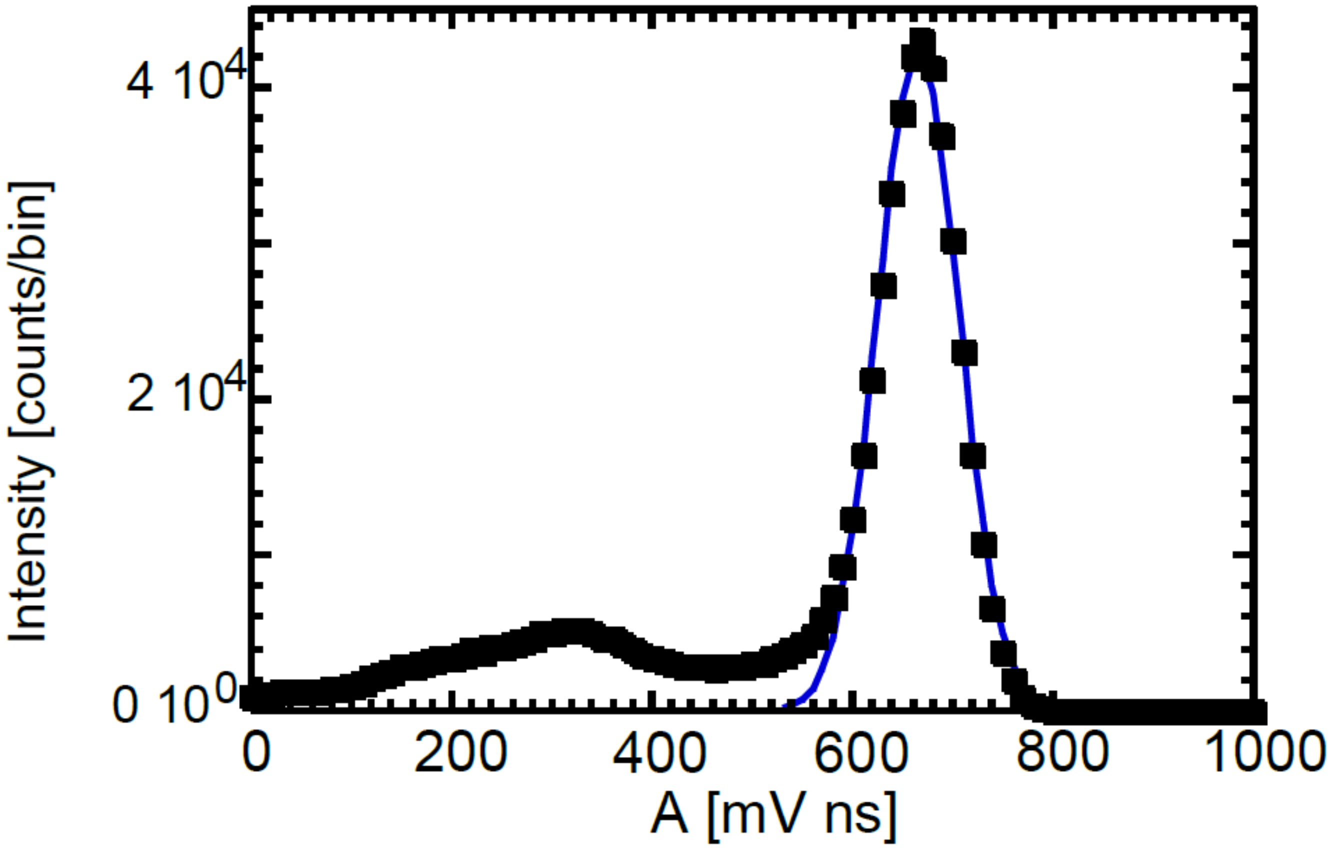
Measurements

- Waveforms: slightly shaped signal with a rise time of 2 ns and a width of 10 ns, 10-100s mV
- Fast Flash ADC –> CAEN DT5751 1-2 GS/s
- DT5751 common trigger firmware
  - Channel 0: synchrotron trigger (NIM)
  - Channel 1: diamond detector signal.
  - Acquisition window: 6 μs, 1% post-trigger
  - "Look-back" mode allows storing detector pulses occurring before trigger arrival
  - Timing resolution: 1 ns at 1 GS/s, 500 ps at 2 GS/s.

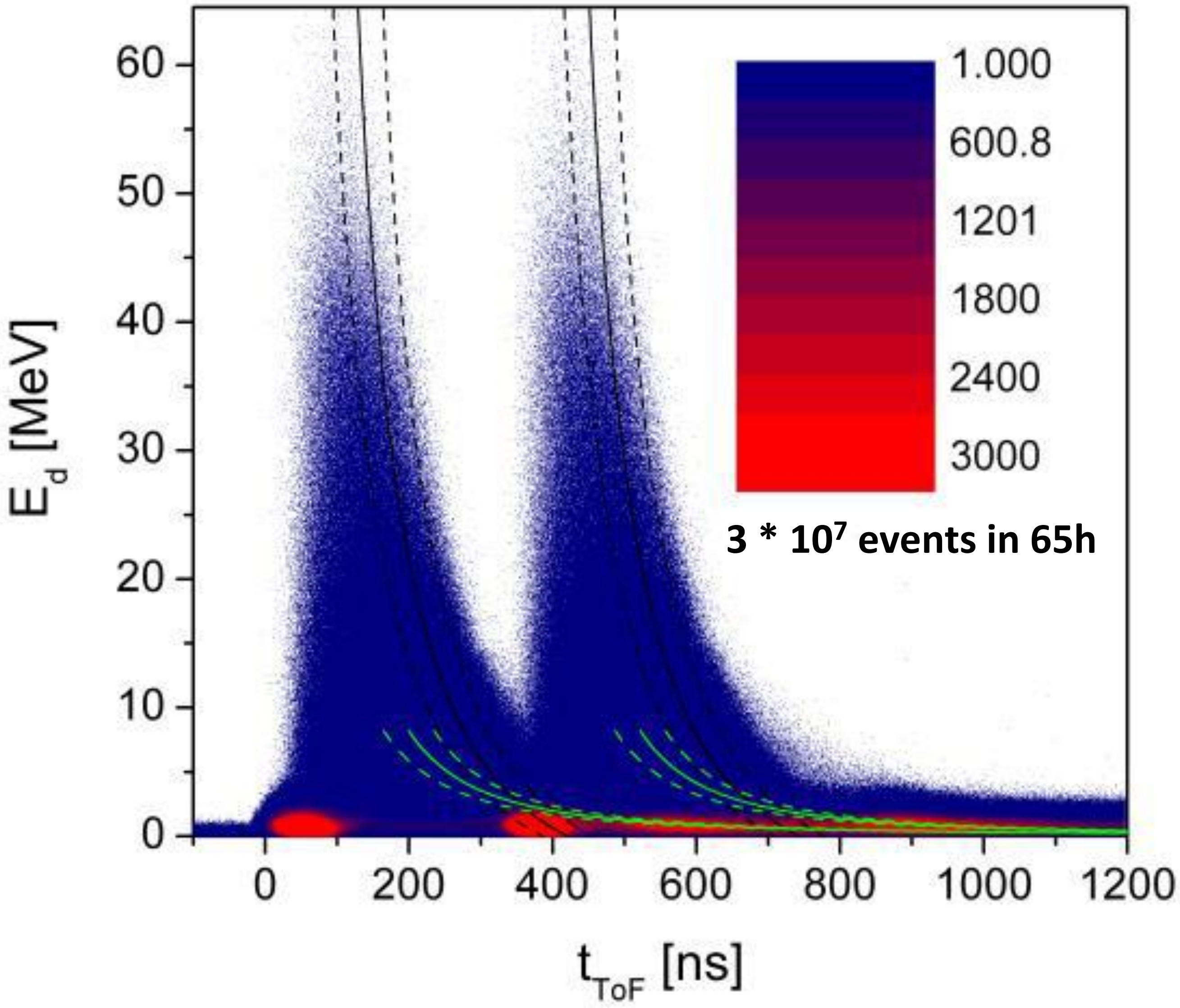


Calibration

- Correlation between pulse integral and deposited energy
- 241Am alpha source (5.5 MeV) positioned in front of diamond
- DT5751 Digitzer in self-trigger mode
- Gaussian peak, FWHM ~96 mV ns.correlation between pulse integral and deposited energy.



Data analysis

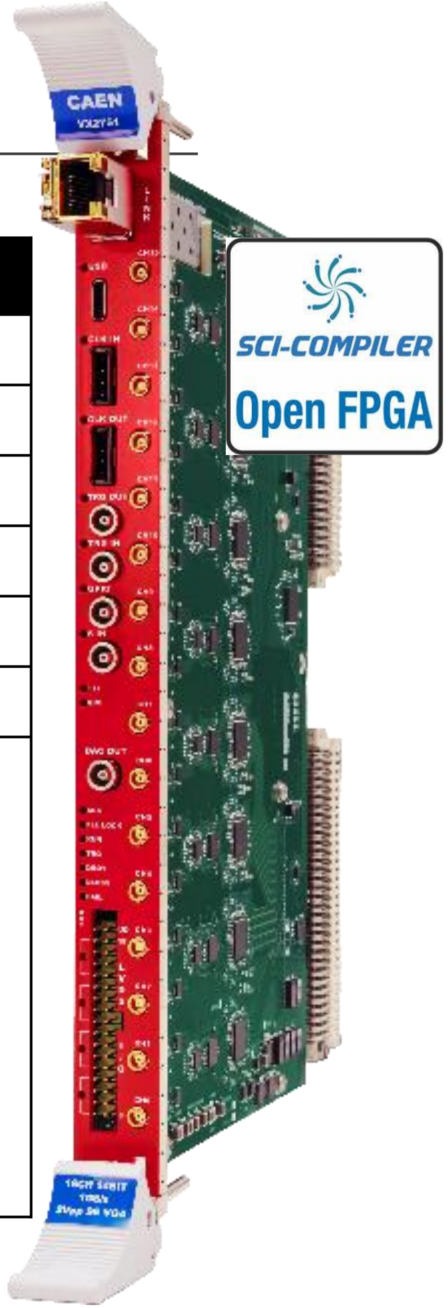


- Waveform acquisition and offline analysis
- Biparametric (ToF vs deposited energy) plot:
  - Dual-bunch structure (322 ns separation) clearly visible.
  - Gamma flash at ~49 ns and 320 ns later
  - Broader peaks at 600 and 900 ns → elastic scattering of less energetic neutrons (few energy deposited)
- Black line: maximum possible energy deposit for (n,alpha) reactions
- Green line: maximum possible energy deposit for elastic scattering

M. Rebai et al., 2012, JINST 7 C05015

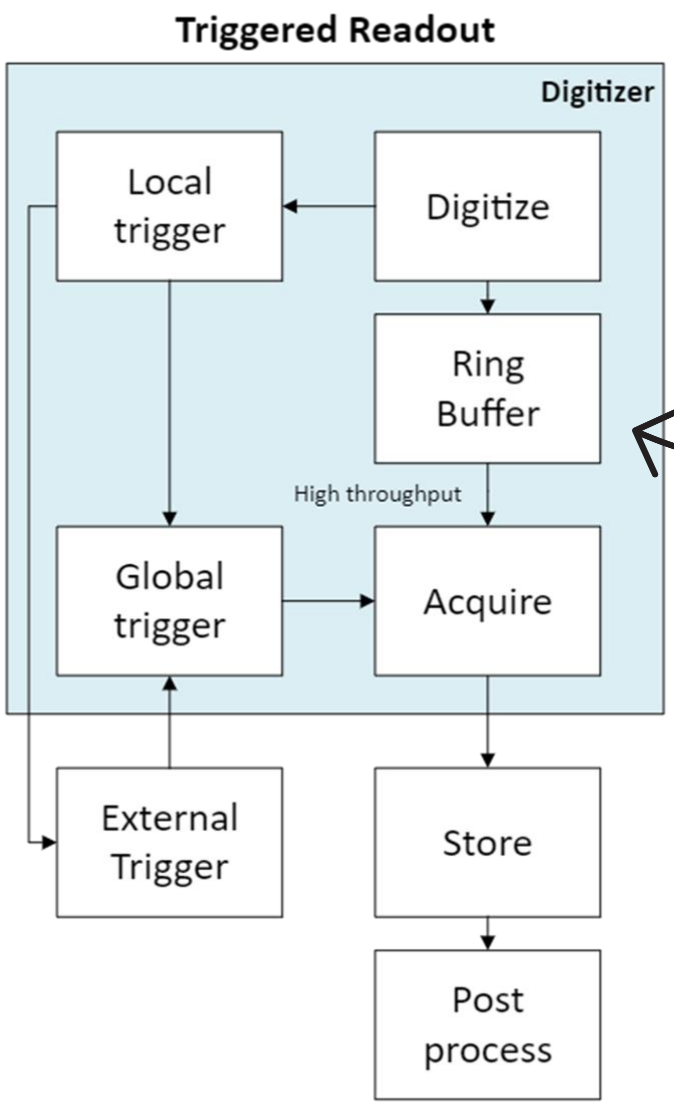
State-of-the art electronics

Digitizers 2.0	2740/2745	2730	2751
Channels	64	32	**16**
Sampling	125 MS/s @ 16 bit	500 MS/s @ 14 bit	**1 GS/s @ 14 bit**
Variable Gain Amplifier	x100 *(2745 only)*	x20	**x10**
Max record length	**84 ms per channel *(extendable by disabling channels)***		
Max. readout bandwidth	**10 GbE UDP @ ~800 MB/s**		
Acquisition Modes	**Waveform recording, DPP, Custom firmware**		
Applications	• PMT with slow scintillators (e.g. NaI) • Spectroscopy with segmented Si and HPGe • Dark Matter and Neutrino experiments	• High Resolution Timing • Fast detector readout (PMT, SiPM, etc…) • Pulse Shape Discrimination with liquid and plastic scintillators (n/γ discrimination) • Multi parametric acquisition (Energy + Time + PSD)	



8

Triggered and Streaming Readout



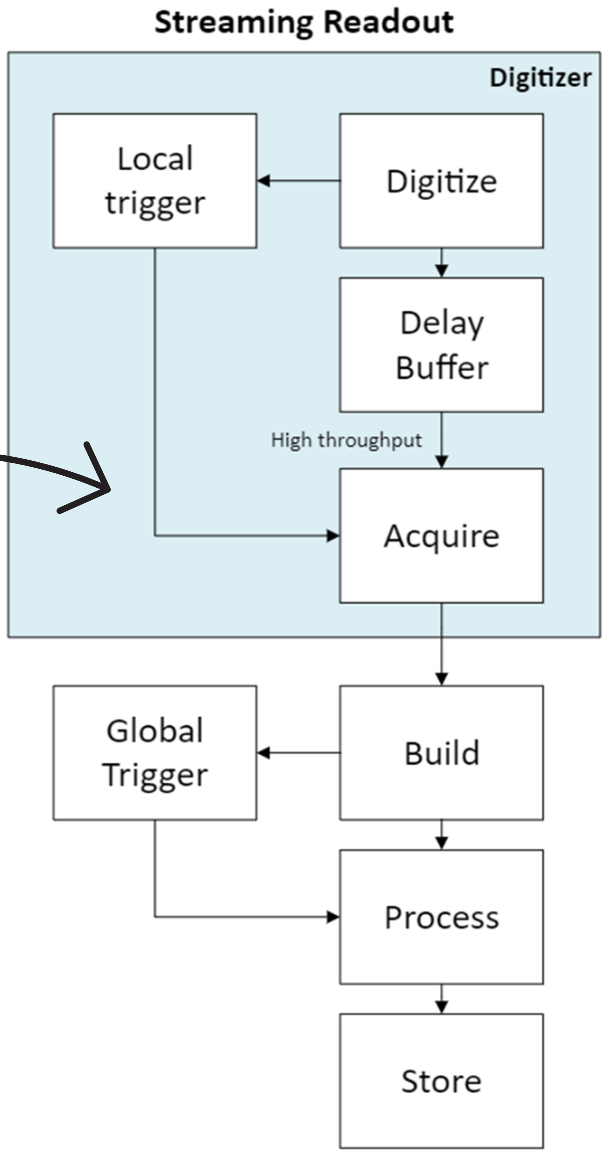
Two firmware families:

Waveform recording (a.k.a. Scope)

- Common trigger (an event contains the waveforms of all channels)
- Big events (24 + 2 bytes per sample):
  - Timestamp
  - Waveforms

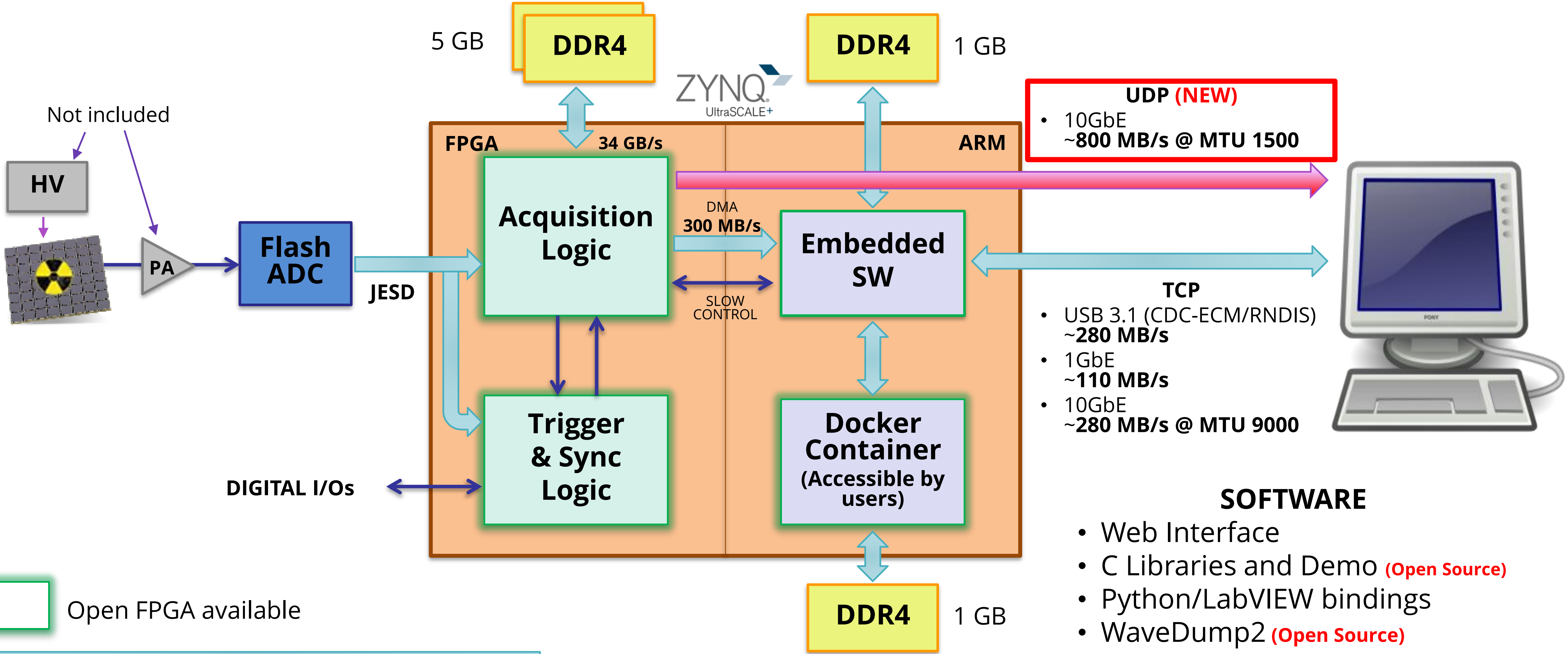
Digital Pulse Processing (DPP)

- Individual trigger (an event contains only one channel)
- Many flavors (PHA, QDC, PSD, CFD, ZLE, DAW, Open DPP)
- Small events (16 or 8 bytes):
  - Channel
  - Timestamp
  - Energy and PSD
  - Flags
  - *Waveforms (optional)*



9

Digitizers 2.0 architecture



SOFTWARE
- Web Interface
- C Libraries and Demo **(Open Source)**
- Python/LabVIEW bindings
- WaveDump2 **(Open Source)**
- CoMPASS

Open FPGA available

Talk by Andrea Abba, Nuclear Instruments

10

High Readout Bandwidth

TCP bottleneck	Mitigation
Computationally expensive on ARM	Increasing MTU from 1500 to 9000, but not standard and eventually limited to 280 MB/s
DMA readout rate	Currently hard to go faster than 300 MB/s

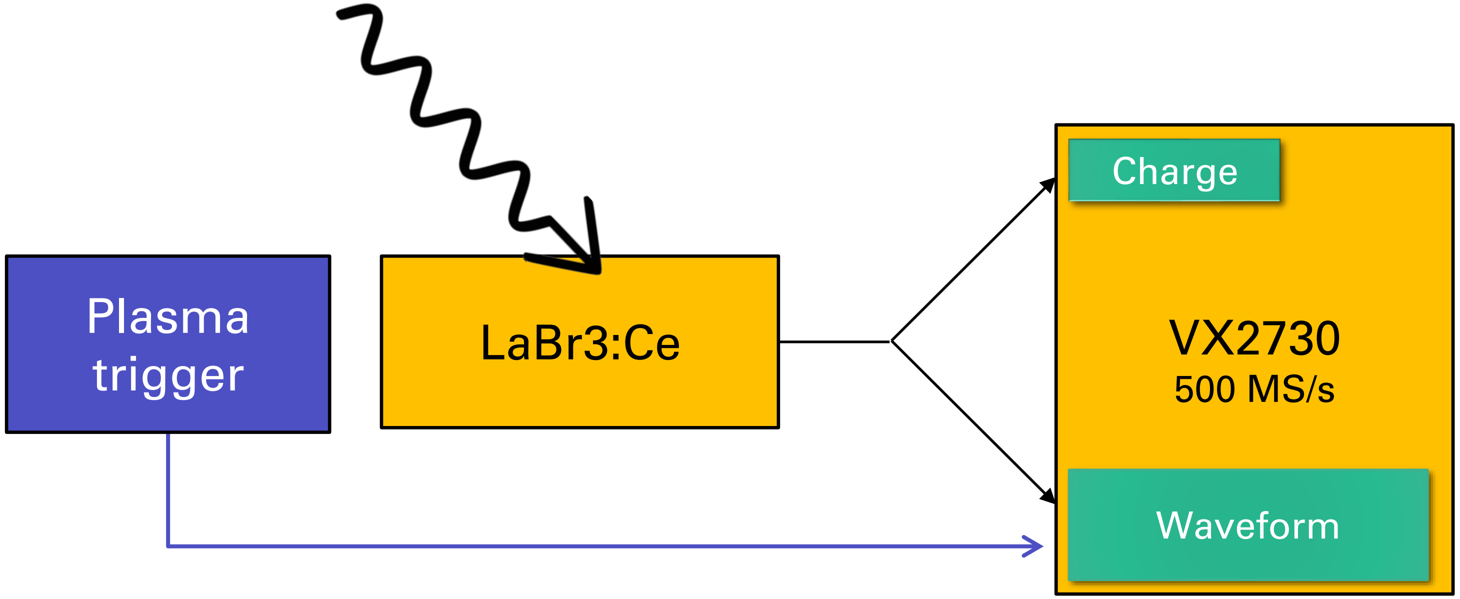
	Connection	MTU	Max. readout rate	Max. trigger rate	
				Scope *(2)*	DPP *(3)*
TCP	USB 3.1	15000	~280 MB/s *(1)*	~140 kcps	~18 Mcps
	1GbE	1500	~110 MB/s	~56 kcps	~7 Mcps
	10GbE	1500	~200 MB/s	~100 kcps	~13 Mcps
		9000	~280 MB/s	~140 kcps	~18 Mcps
UDP	10GbE	1500	**~800 MB/s**	**~410 kcps**	**~52 Mcps**

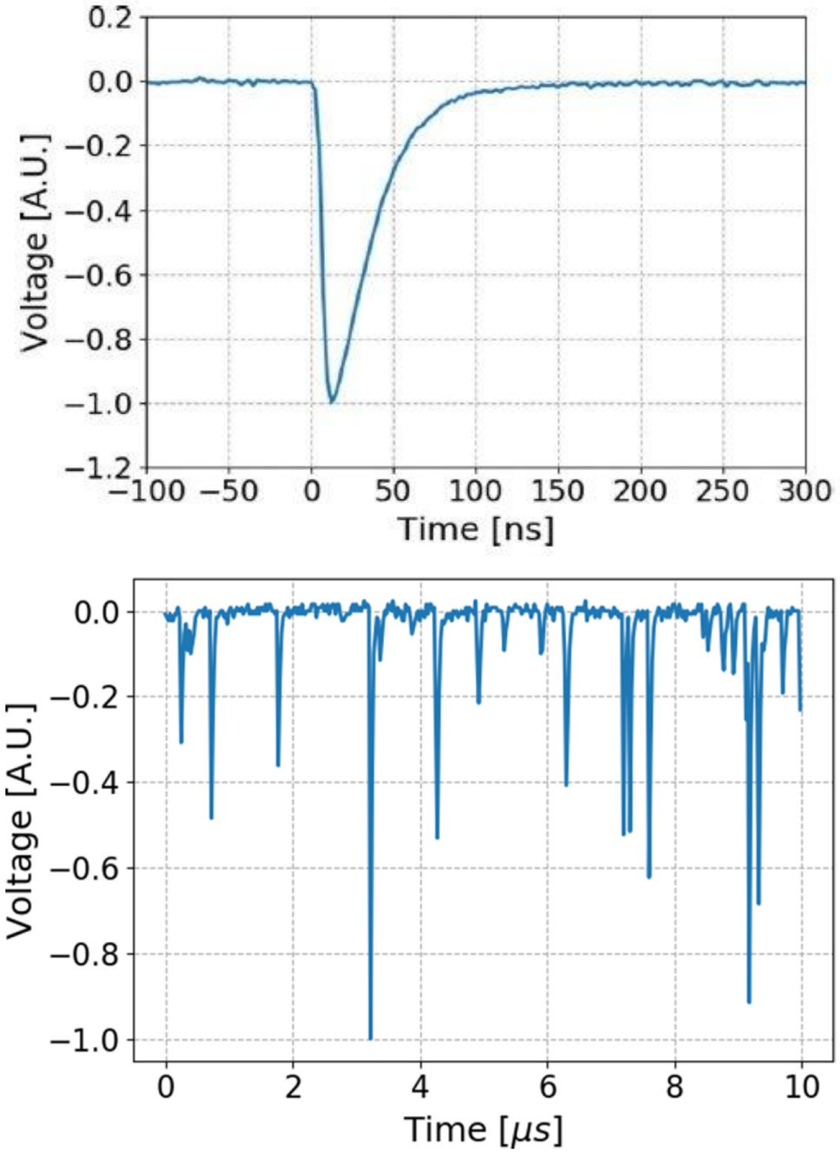
Notes:
(1) Drops to 250 MB/s with 3 boards and to 185 MB/s with 4 boards due to client CPU overload
(2) Scope firmware, record length of 1024 samples per channel (8192 ns on a VX2740)
(3) DPP firmware, reduced event format disabled (16 bytes per event)

11

Application: SPARC HXR Monitor (1)

HXR from bremsstrahlung radiation
of electrons interacting with plasma





A Dal Molin et al., 2023 Meas. Sci. Technol. 34 085501

Application: SPARC HXR Monitor (2)

Sampling speed

0.5/1 GS/s suitable for fast detectors

Onboard memory

Acquiring waveforms for 1s, with a recording window of 75us every 100 us

Readout Bandwidth

10,000 pulses @ 10 kHz → **10 GbE UDP** → 1,050 events before going busy

Customization

Online analysis, data reduction/selection

Conclusions

- Plasma diagnostics requires radiation-hard detectors and fast digital electronics for neutrons, gammas, and X-rays.
- Fully digital acquisition chains (DT5751) demonstrated compact, precise, and robust performance without analog modules.
- Next generation digitizers (DT2751 family) provide:
- Multi-channel (16), 14-bit, 1 GS/s capability.
- Open FPGA → real-time algorithms (ToF–energy analysis, pile-up rejection)
- Applications ahead:
  - Fusion experiments (JET, ITER, ...) → neutron and gamma spectroscopy for plasma control.
  - Spallation sources (ISIS, ESS) → real-time beam monitoring.
  - Broader high-rate radiation diagnostics in harsh environments.

Thank you for your attention

Backup slides