High Event-Rate Discrimination on Mixed Radiation Fields with Machine Learning

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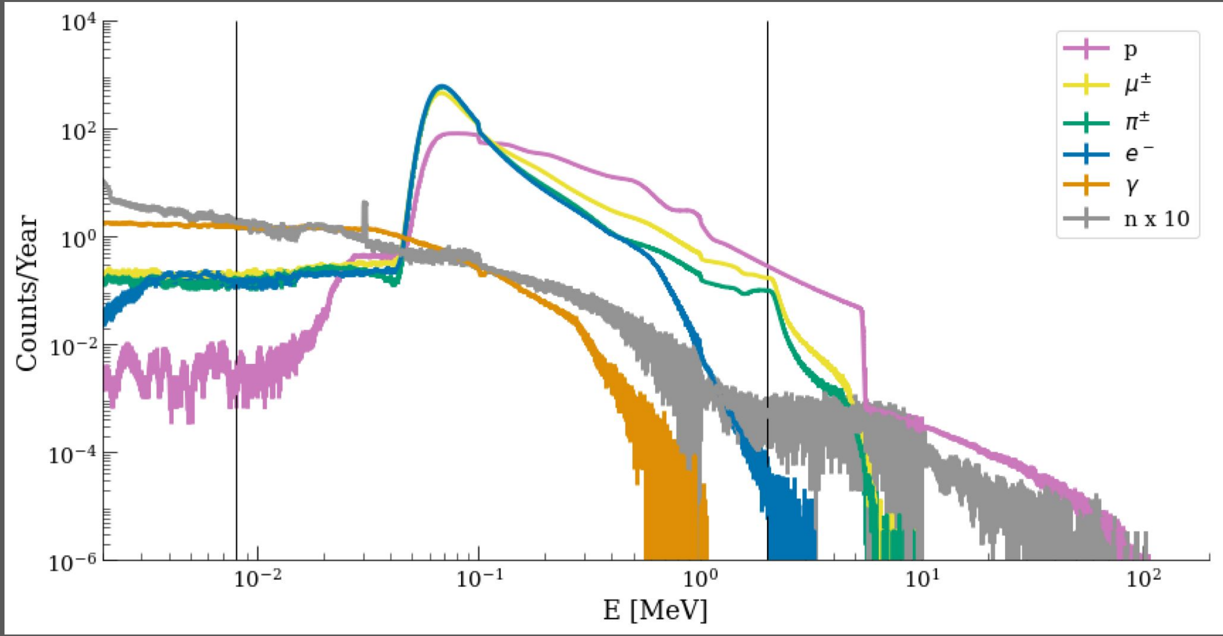
Joint ICTP-IAEA School on Detector Signal Processing and Machine Learning for Scientific Instrumentation and Reconfigurable Computing

Summary

- Mixed radiation fields
- Event detection and discrimination
- High event-rate challenges
- Case study - gamma/neutron
- Hardware setup
- Data collection and analysis
- Real-time event processing with ML
- Results and conclusions

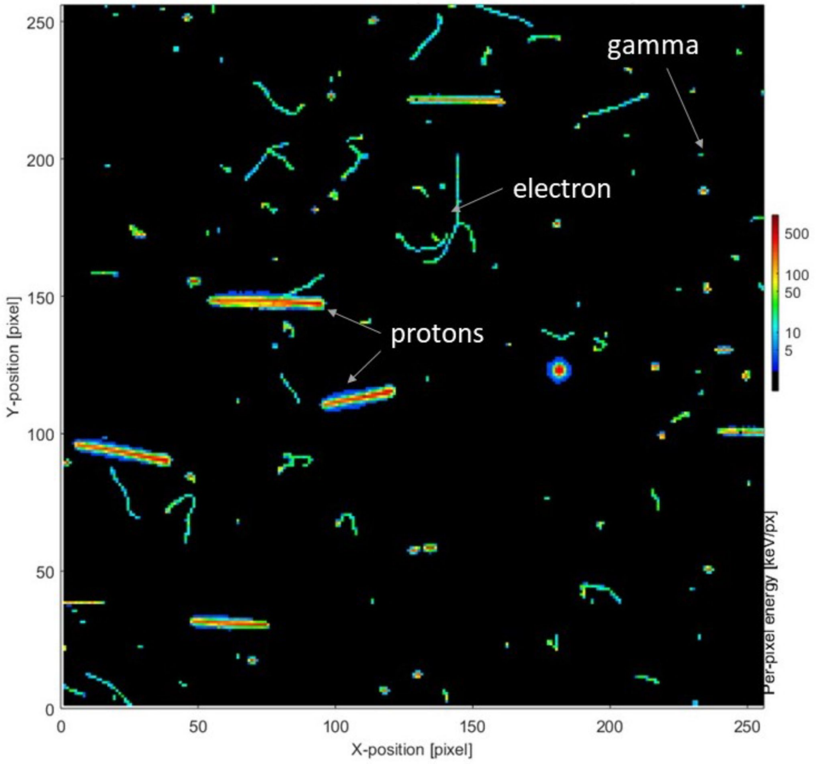
Mixed radiation fields



Distribution of the energy deposited in the active volume of the Timepix3 Radiation Monitor by the particles composing a mixed radiation field at an LHC experiment [1].

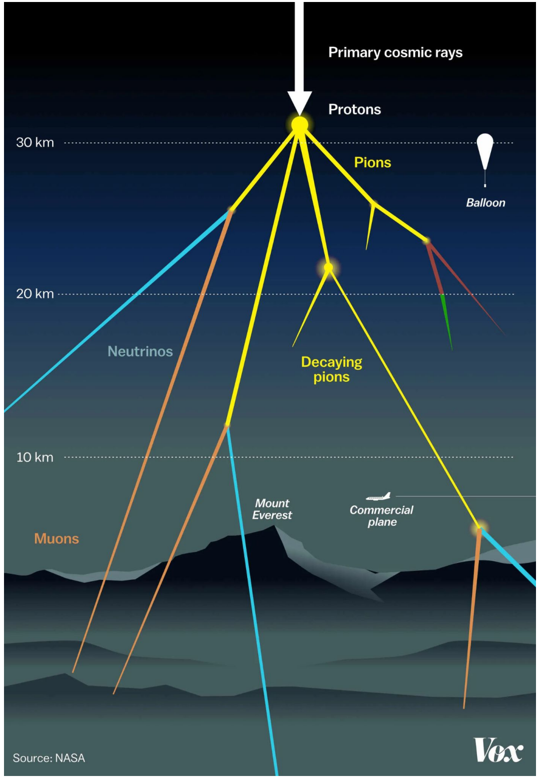
Mixed radiation fields

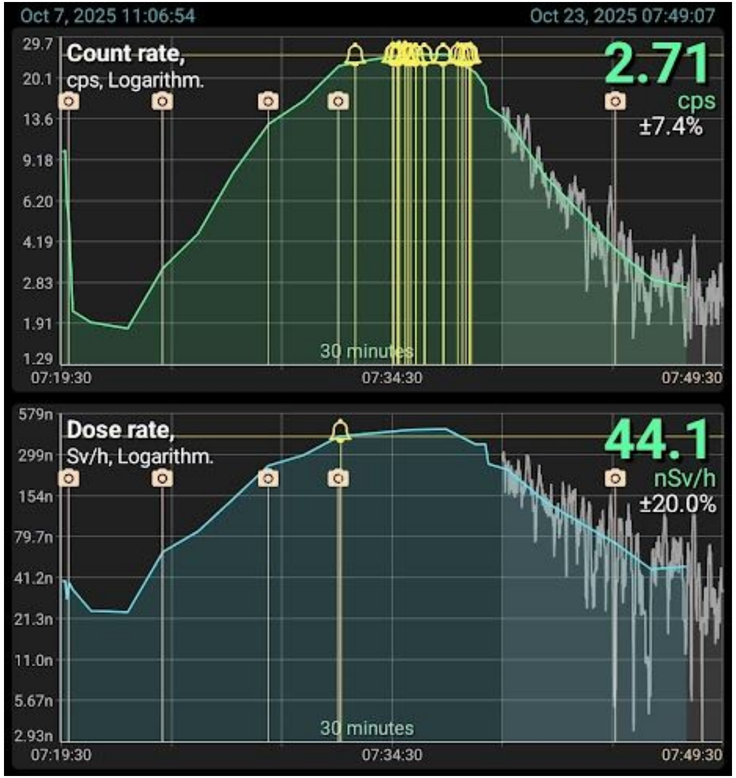
- Ionizing radiation
- Chargeless and charged particles

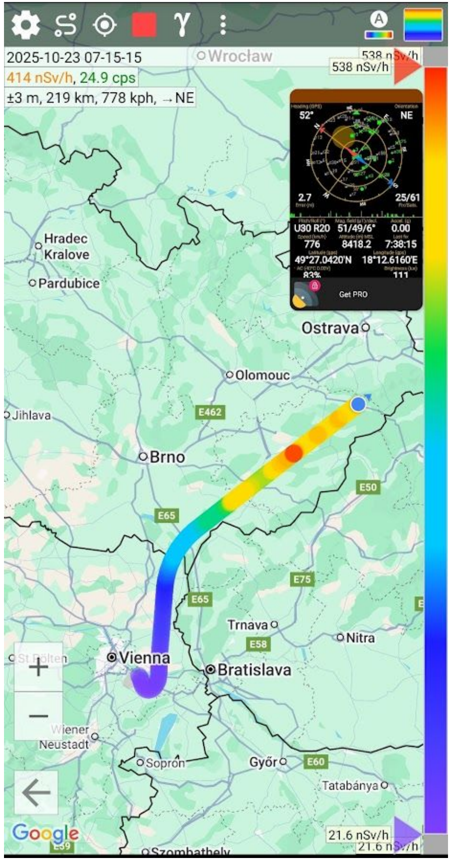


Per-pixel energy deposited by various particles in a mixed radiation field measured using a Minipix Timepix detector with Silicone sensor [2].

Mixed radiation fields - cosmic rays

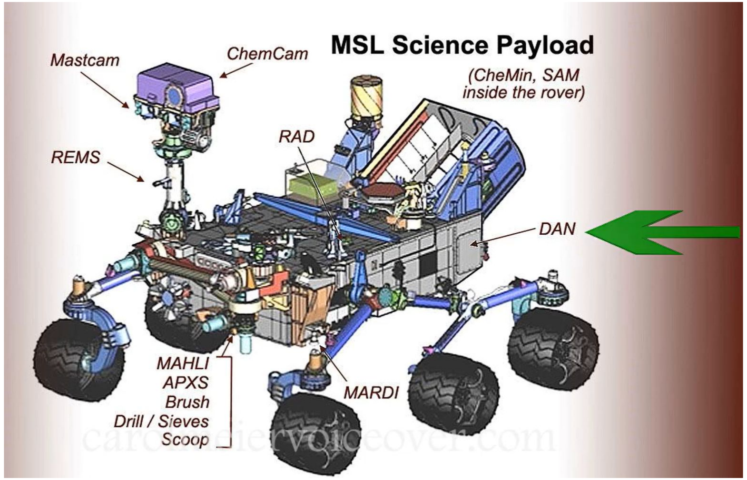






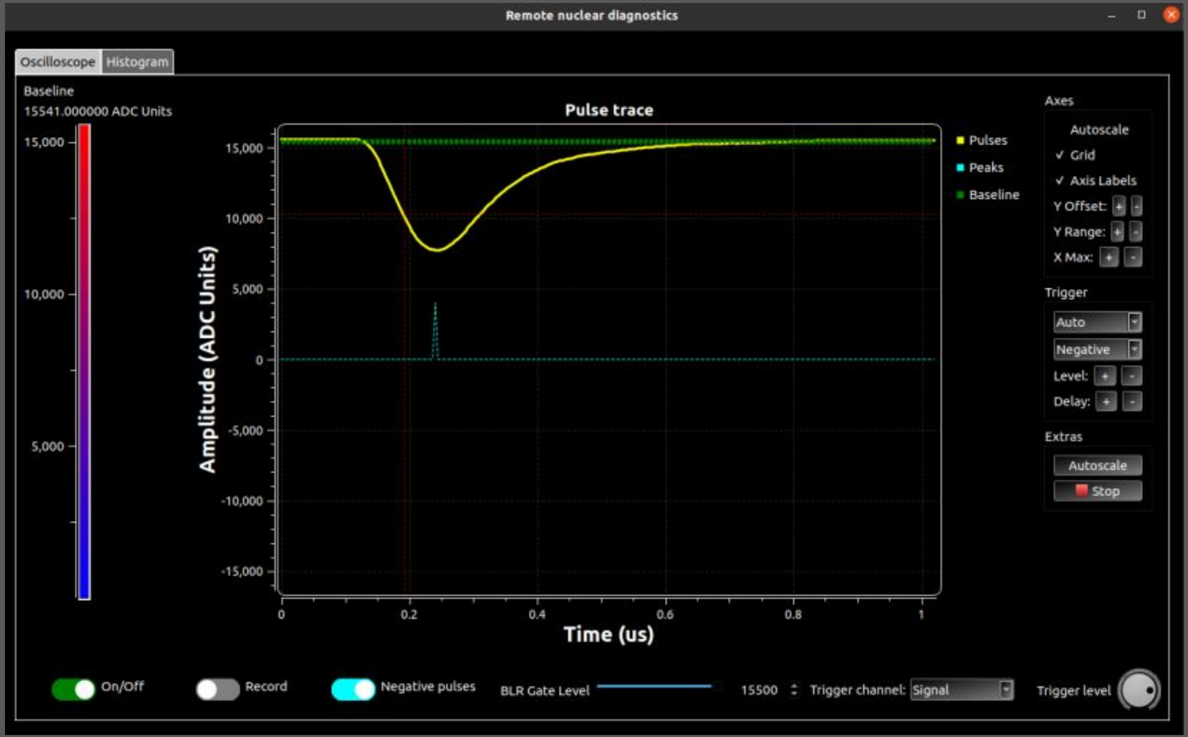
Unmixing mixed radiation fields

- Dosimetry
    - Equivalent dose weighting factor
- Fission reactors
    - Indirect power measurement (^3He)
- HEP and cosmic rays research
    - Study origins of secondary events
- Nuclear medicine
    - Boron capture dose estimation
- Space and planetary exploration
    - Water traces on Moon and Mars



Dynamic Albedo of Neutrons (DAN) instrument on Mars Rover

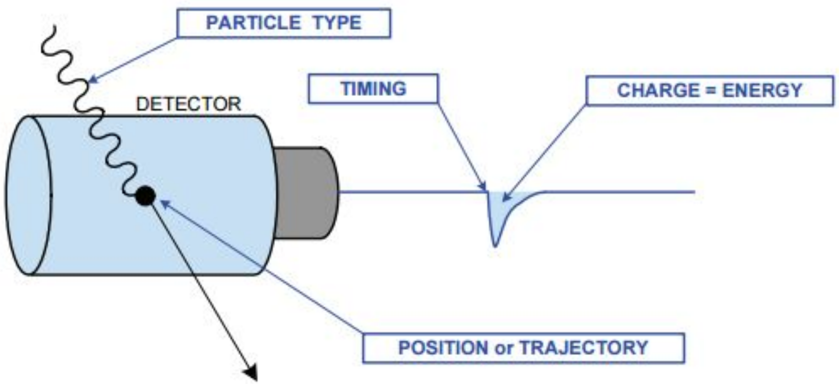
Event detection

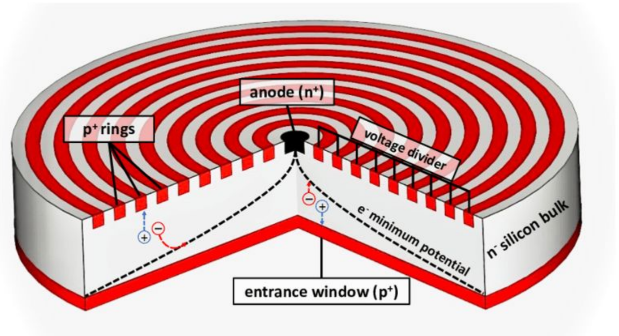


Captured trace from NaI(Tl) detector placed nearby a gamma source [3].

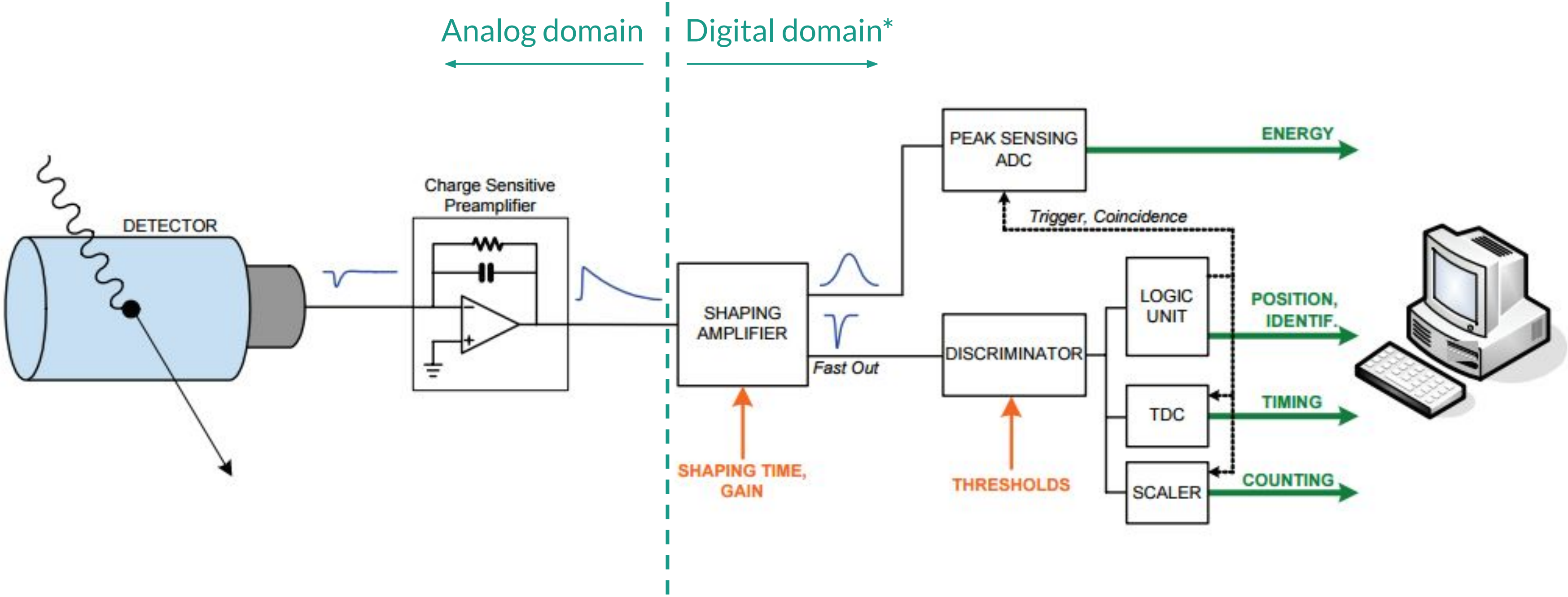
Detector technologies

- Indirect charge collection
- Light detectors (with scintillators)
- Solid-state detectors
- Gas detectors





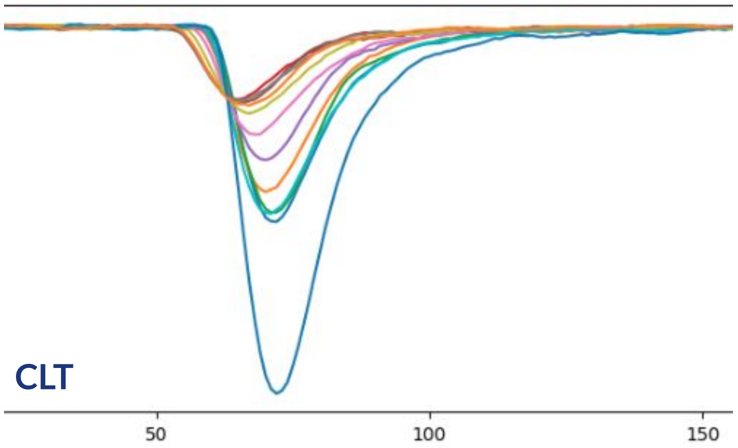
Detection chain



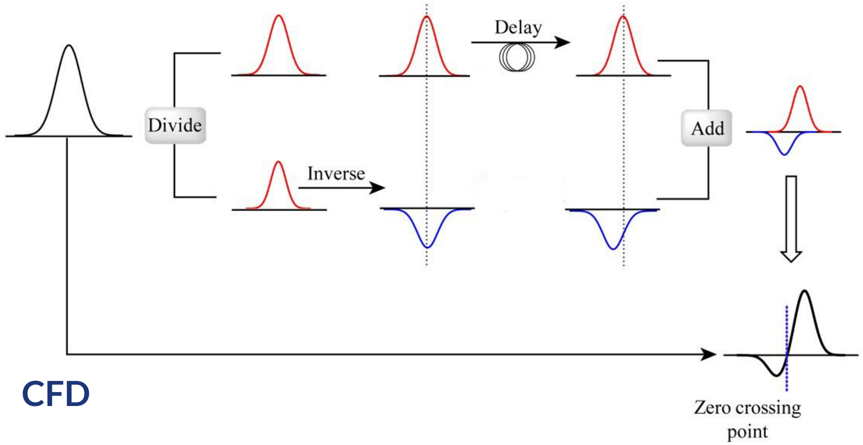
* digital domain starts at this stage in modern digital pulse processing (DPP) systems

Detection mechanisms

- Cross-level trigger (CLT)
- Constant fraction discriminator (CFD)
- Other advanced methods

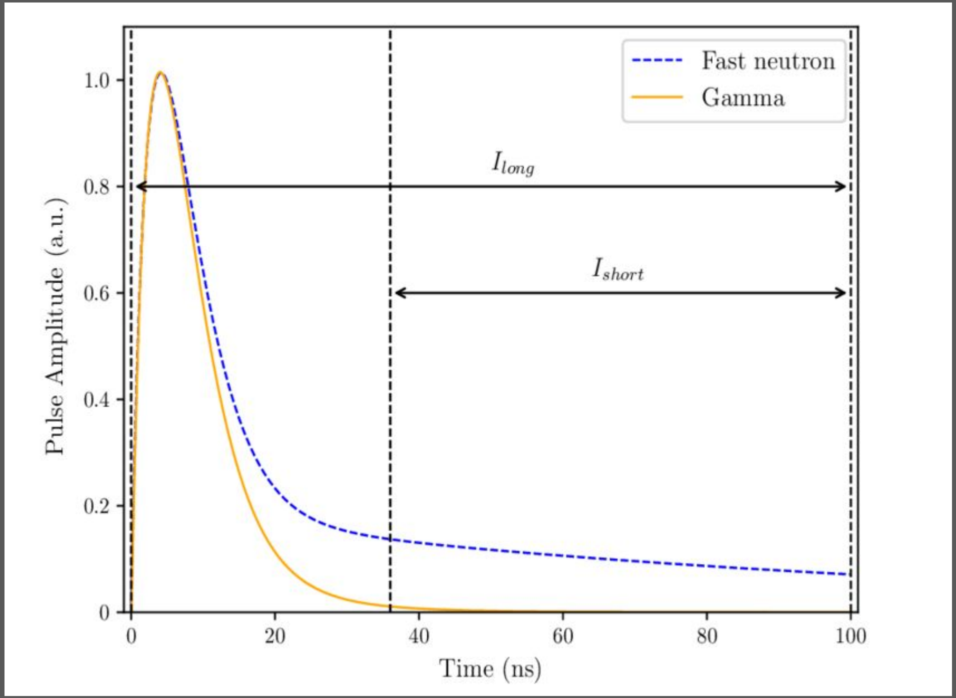


CLT



CFD

Event discrimination

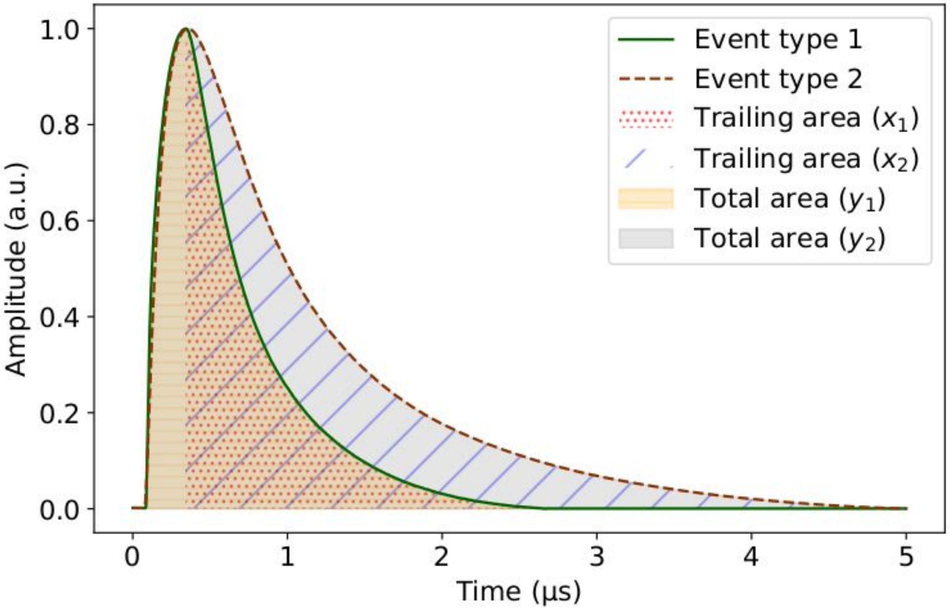


Event discrimination

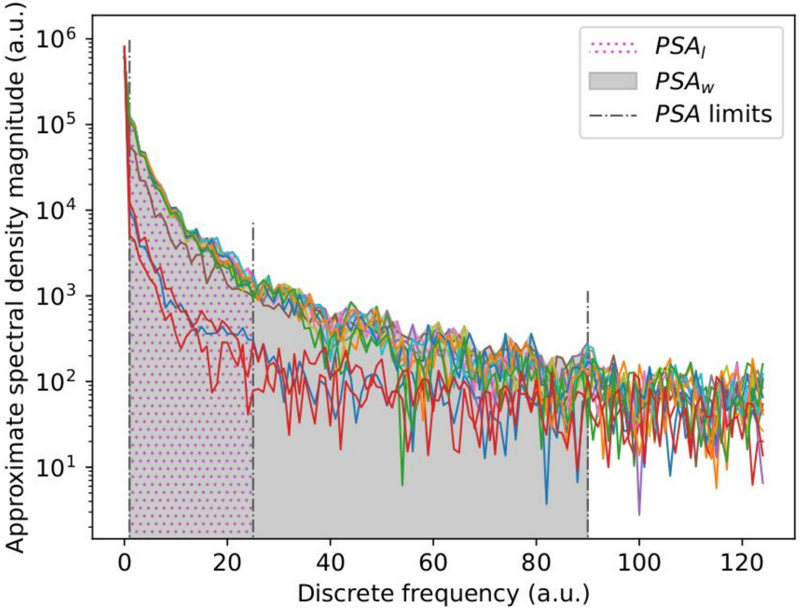
- Different particle interactions -> different pulse shapes
- Real-time hardware deployment

Event discrimination

Pulse shape discrimination (PSD) and frequency-based discrimination (FCI)



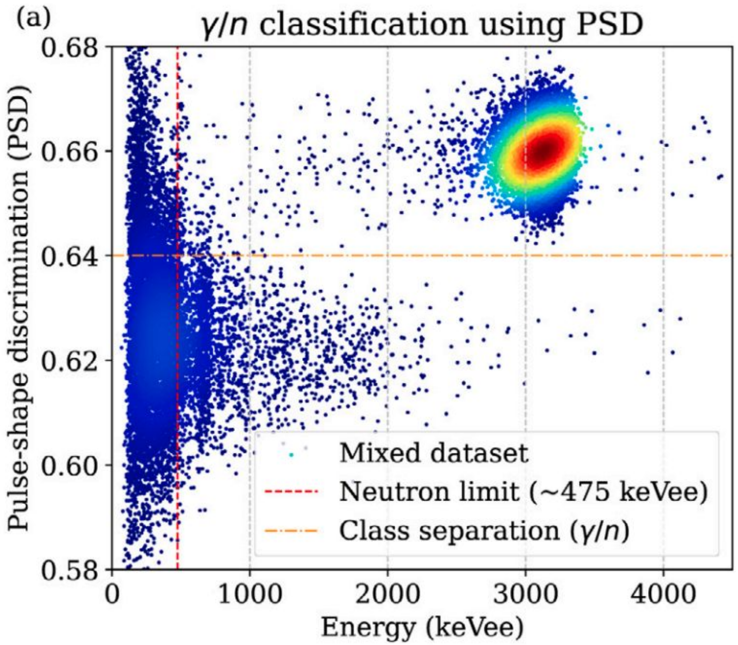
Pulse shape discrimination (PSD) [5]



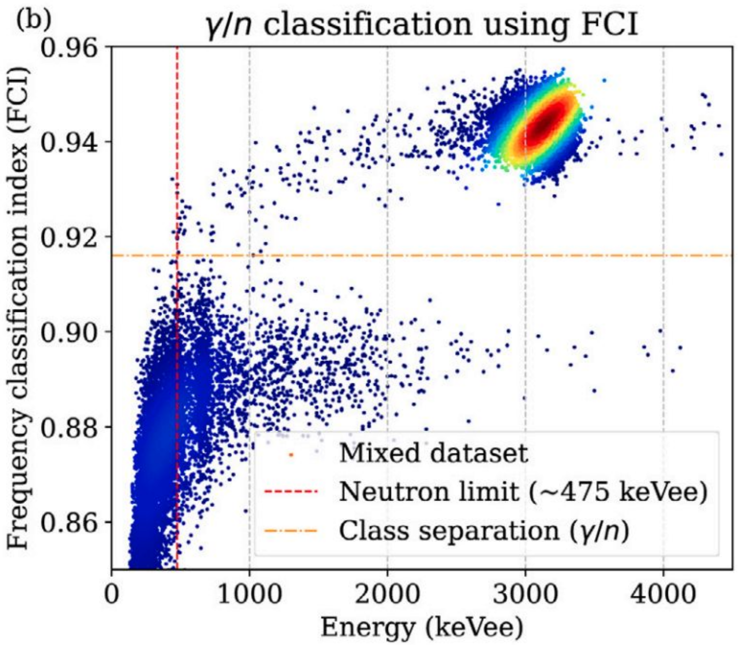
Frequency-based discrimination (FCI) [5]

Event discrimination

Pulse shape discrimination (PSD) and frequency-based discrimination (FCI)



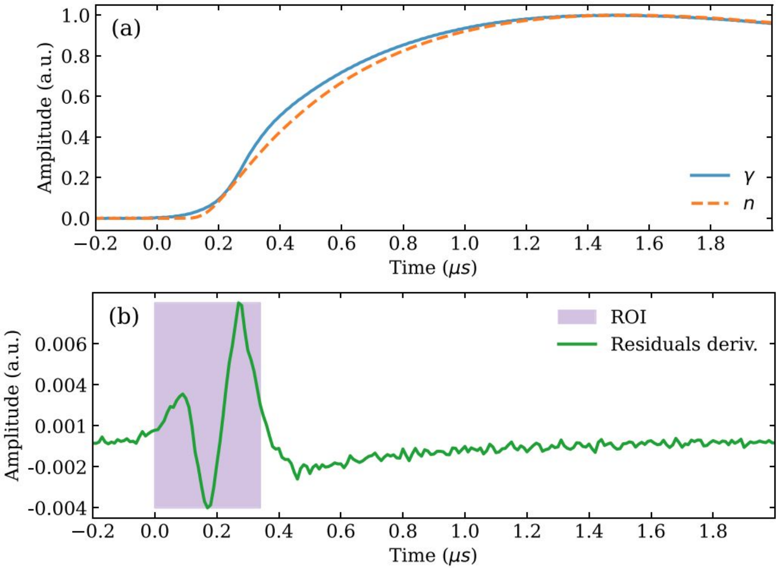
Pulse shape discrimination (PSD) [5]



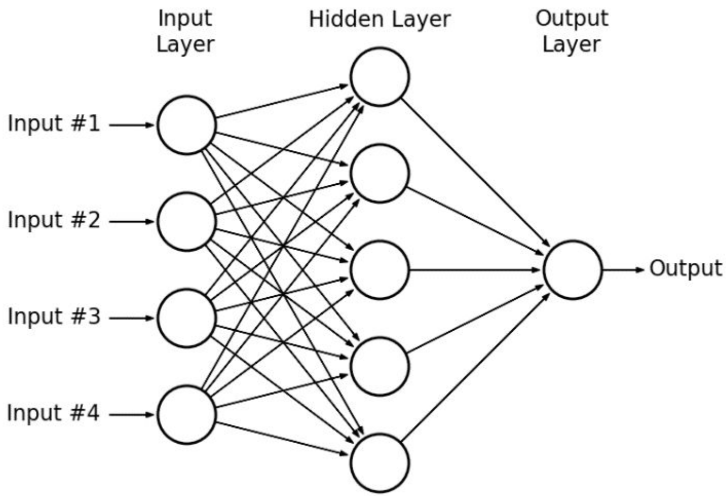
Frequency-based discrimination [5]

Event discrimination

Feature extraction + machine learning

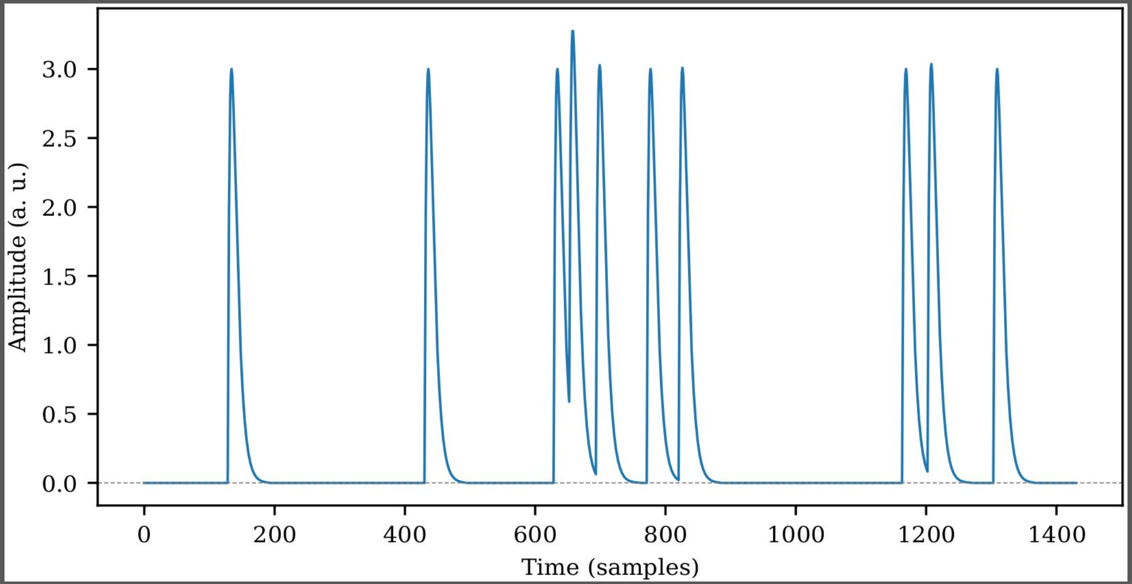


Feature extraction [6]



Example architecture of ML model

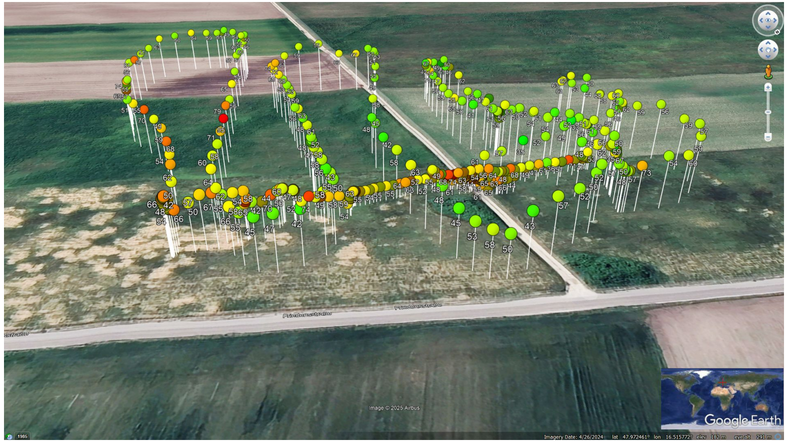
High-event rate challenges



Simulated pile-up events at high SNR

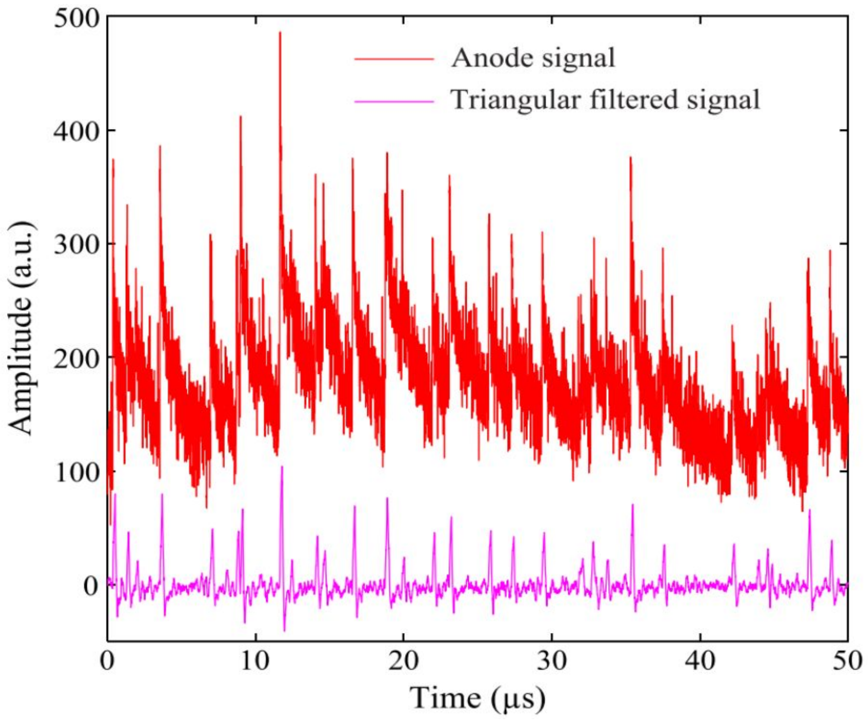
High-event rate scenarios

- Radiation monitoring/surveying
- Space exploration
- Cosmic ray observatories
- Large dynamic range in count-rate



High-event rate challenges

- Pile-up distortion
- Baseline shifting
- Pulse shape for PSD or FCI distorted

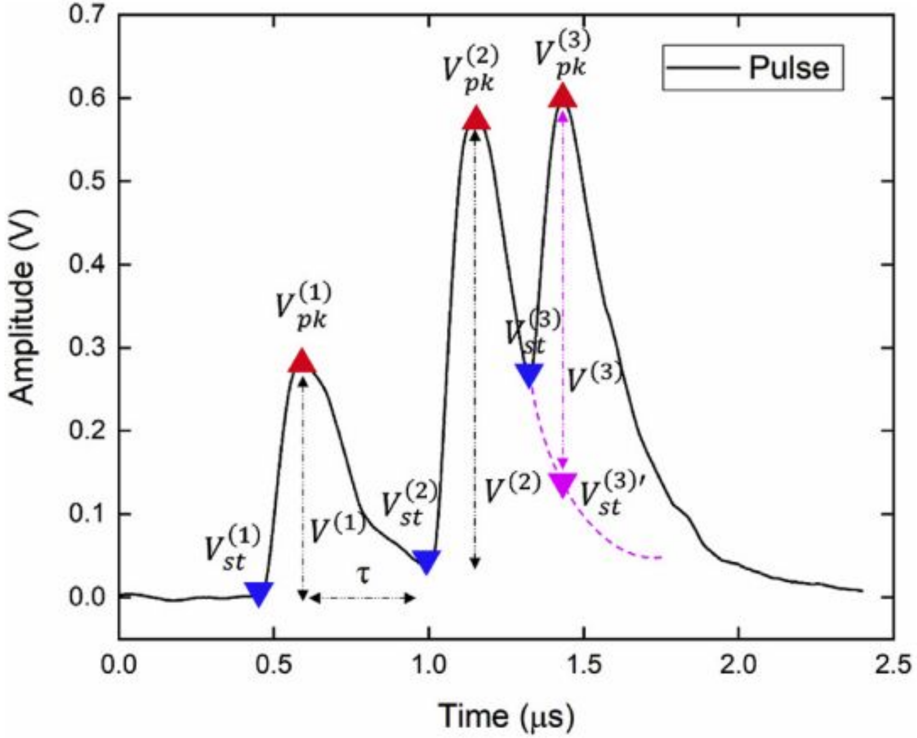


Severe pile-up distortion and shifted baseline [5]

Pile-up rejection

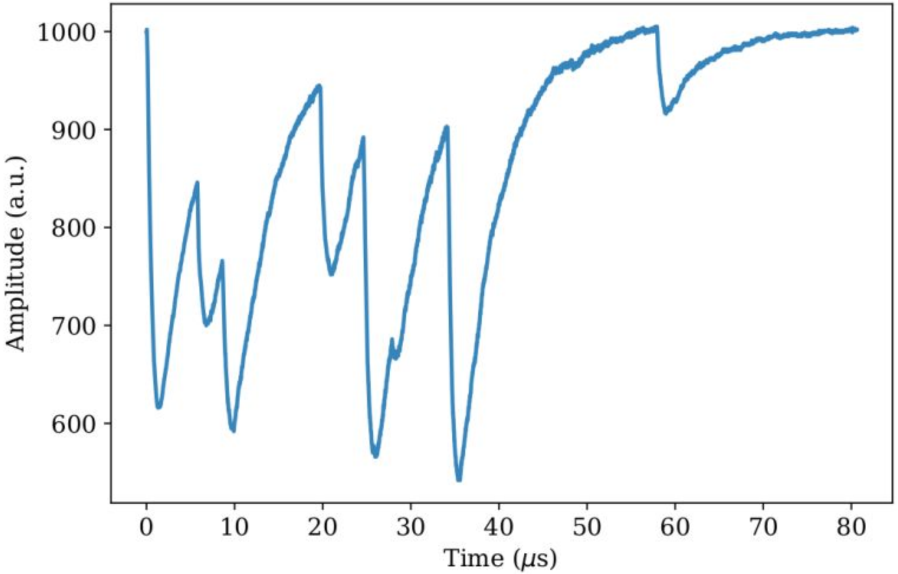
- Severe pile-up:
  - Events discarded
  - Live-time reduced
- Detectors on current mode:
  - No discrimination

Reduced pulse count efficiency



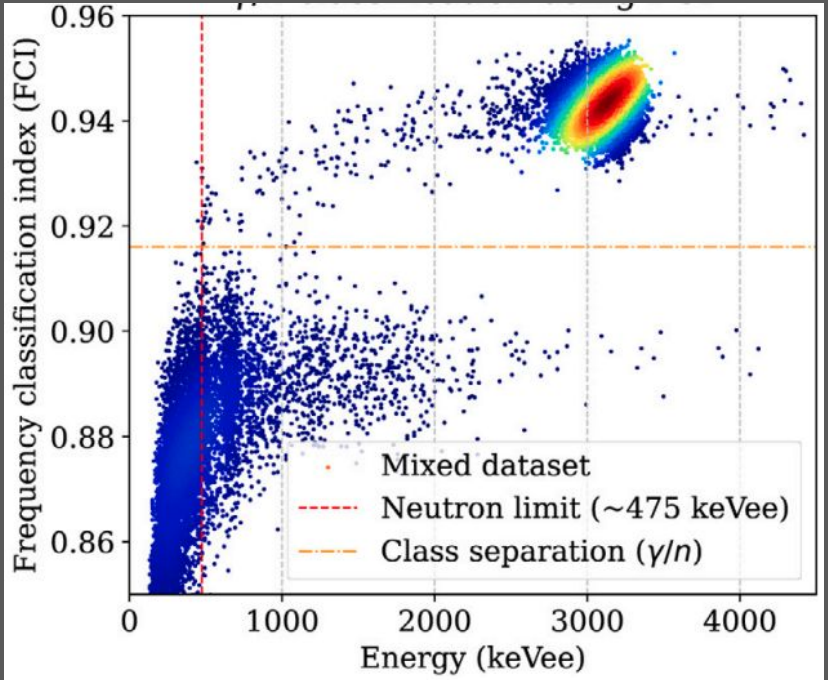
High-event rate + event discrimination

- Pulse shape analysis
- Feature extraction
- Machine learning model
- ML model compression
- Real-time deployment in hardware



Eight piled-up events from gamma/neutron detector [5]

Case study: γ/n discrimination

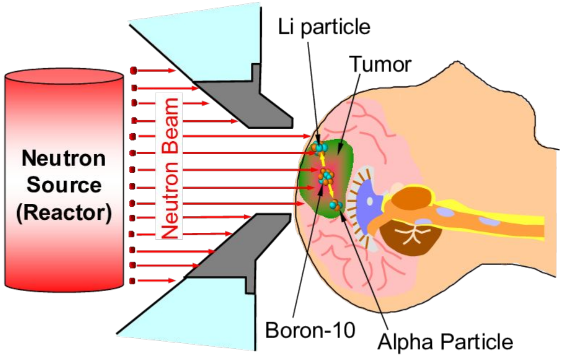


Gamma/neutron discrimination featuring novel frequency-based approach [8].

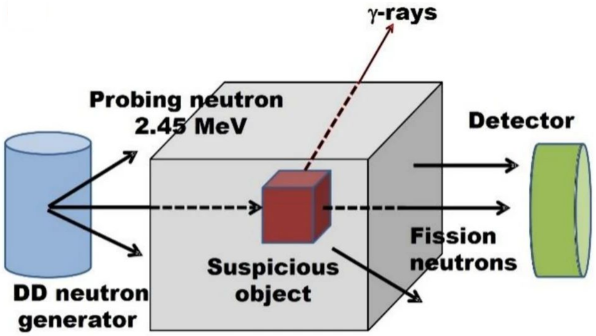
Why γ/n discrimination?

- Gamma radiation associated to neutron presence
- Several neutron applications in industry, medicine, energy, security, etc.

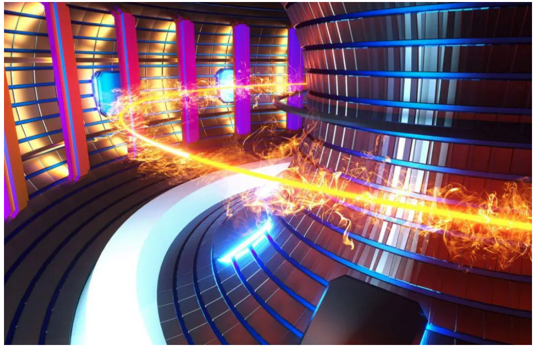
Fission power plants



Boron capture neutron therapy

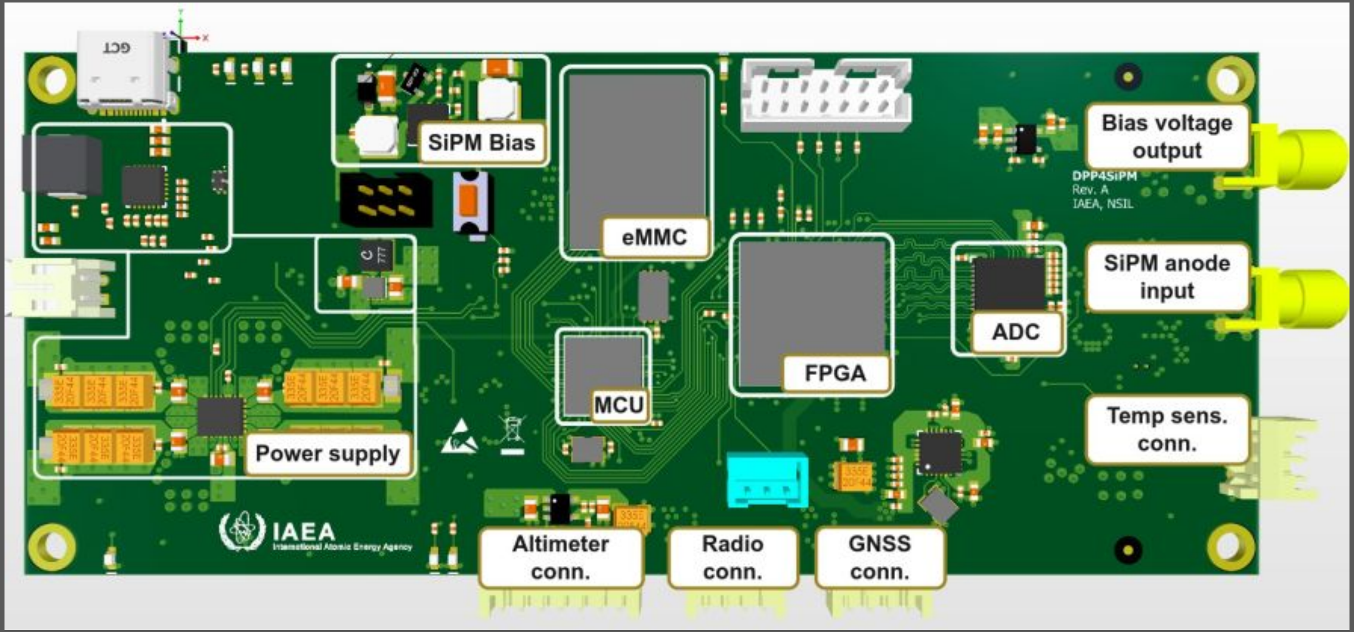


Active neutron interrogation



Experimental fusion reactors

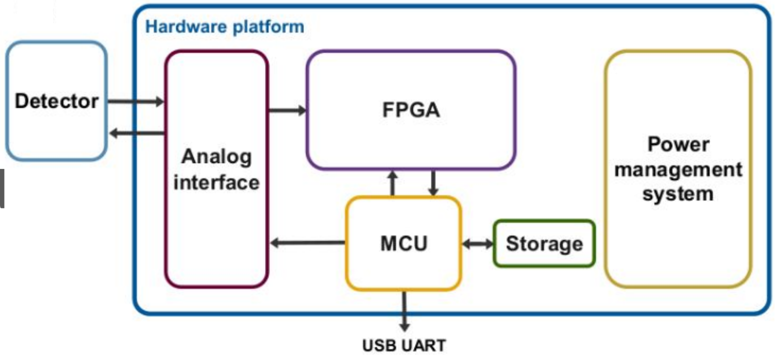
Hardware setup

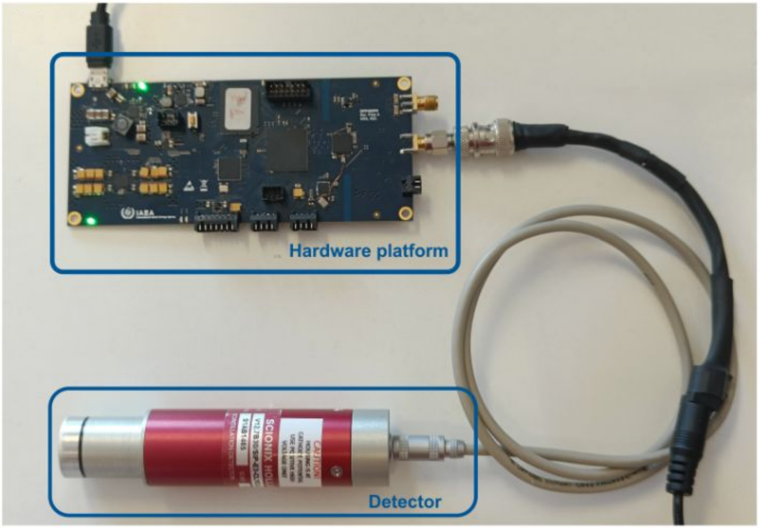


Render of custom DAQ board for low-SWaP radiation monitoring system

Hardware setup

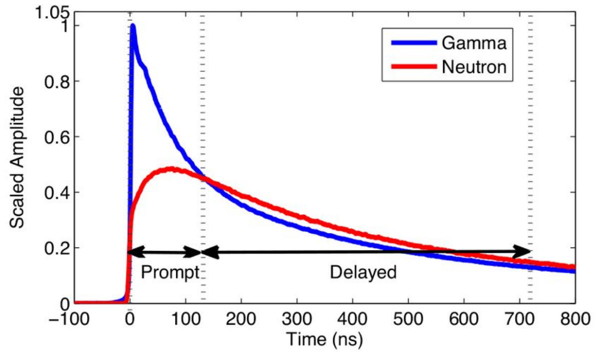
- IAEA/NSIL low-SWaP DAQ board
- Off-the-shelf CLYC detector

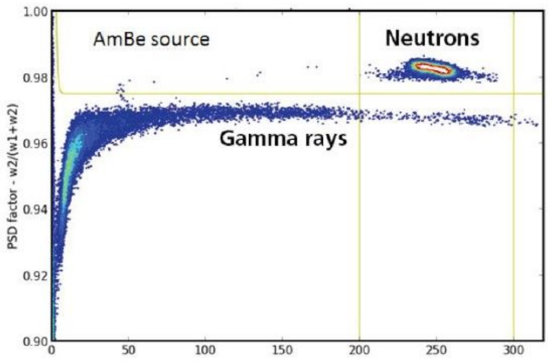




CLYC scintillator

- Triple-mode scintillator
  - Gamma spectroscopy
    - Better resolution than NaI(Tl)
    - Similar sensitivity to NaI(Tl)
  - Thermal neutron detection
    - Enriched with Li-6 (neutron capture)
  - Fast neutron spectroscopy
    - Cl-35 neutron scattering
- Optimized for gamma/neutron discrimination

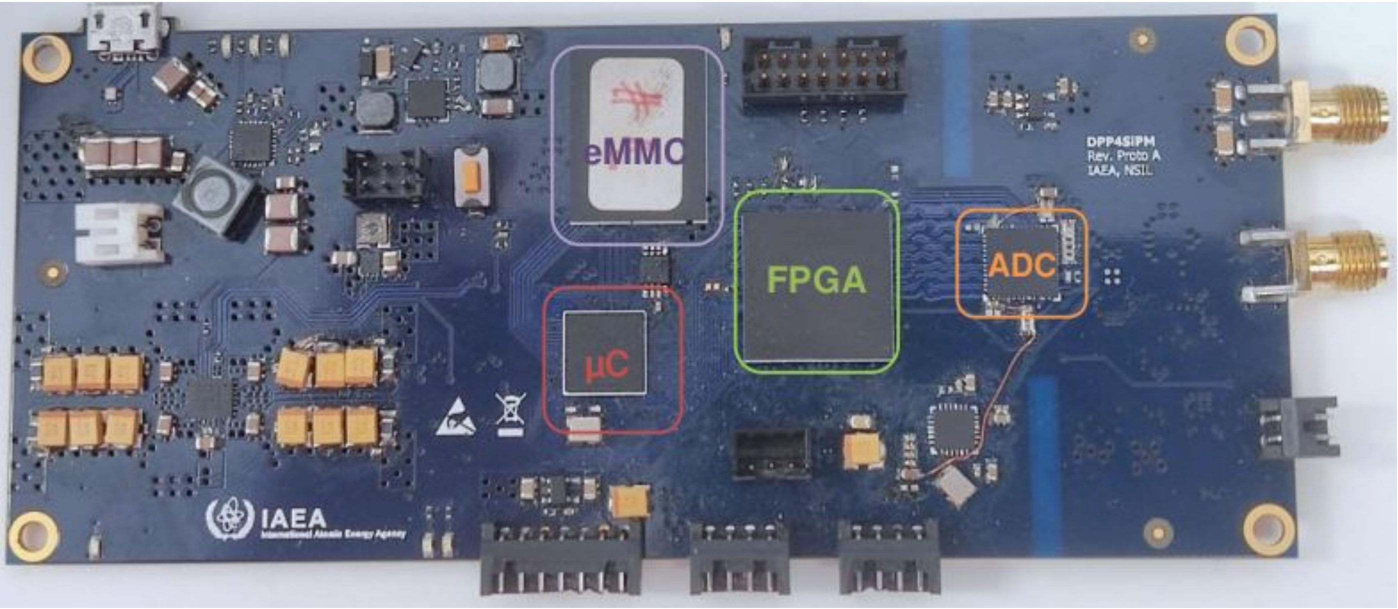




Mixed radiation detector based on CLYC

- Integrated detector: compensated bias, output preamplifier
- CLYC crystal: gamma rays, thermal neutrons, fast neutrons
- SiPM sensor array: low SWaP (size, weight, power), magnetic field tolerance, robustness
- Higher output capacitance: challenging signal processing
- Reduced SNR and higher dead-time
    - Pulse length/duration: ~ 30 µs

Custom DAQ board

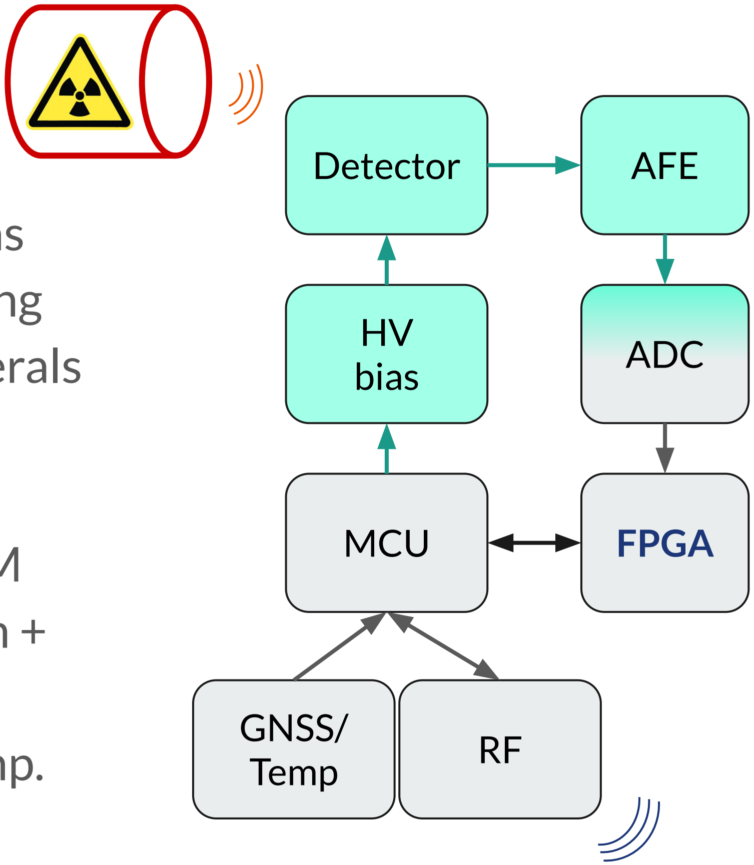


HV bias supply

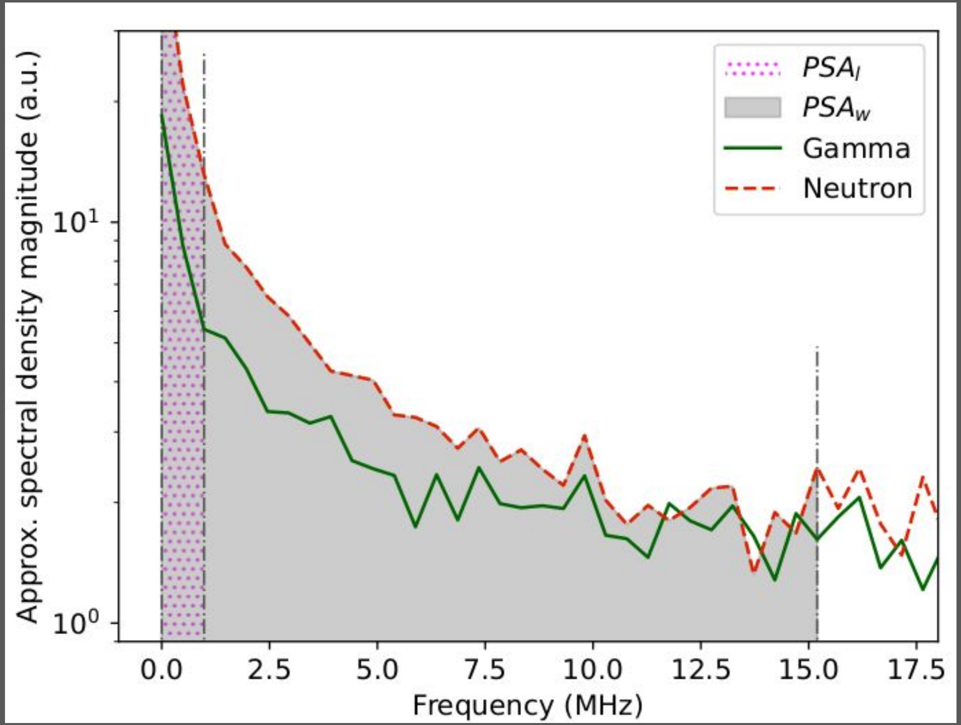
SiPM input

Custom DAQ board

- Low SWaP for portable applications
- FPGA for real-time signal processing
- Microcontroller (MCU) for peripherals
- 14-bit ADC @ 250 Msps
- Analog front-end (AFE)
- Programmable bias supply for SiPM
- Non-volatile flash: FPGA bitstream + detector data
- GNSS/GPS, RF interface, SiPM temp.



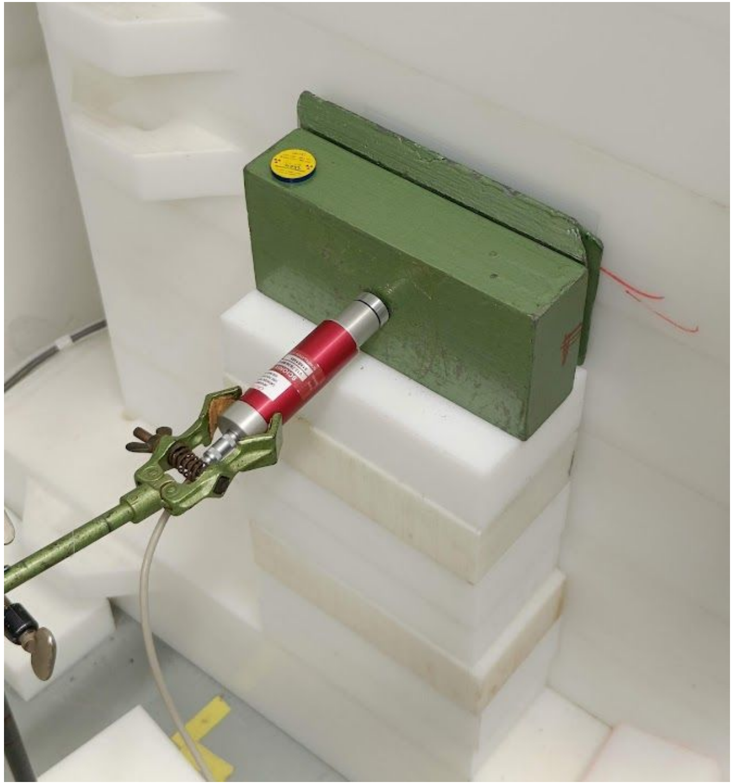
Data collection and analysis



Simulation of gamma/neutron discrimination using FFT with plastic scintillator [5].

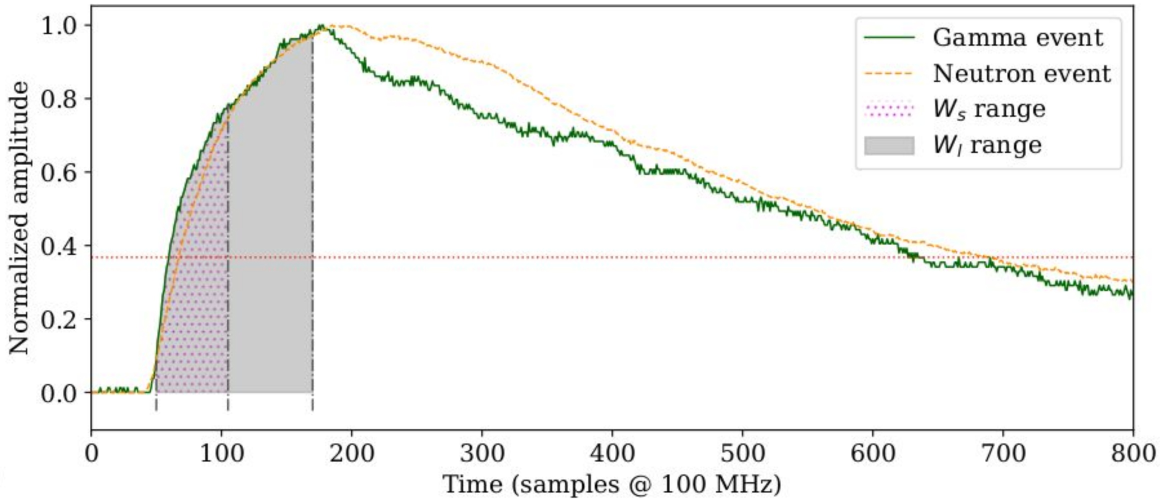
Data collection

- Aiming to train supervised ML model
- Data recorded at NSF, IAEA with CLYC detector.
    - AmBe source
    - Deuterium-deuterium gen.
- ~10^6 individual events recorded



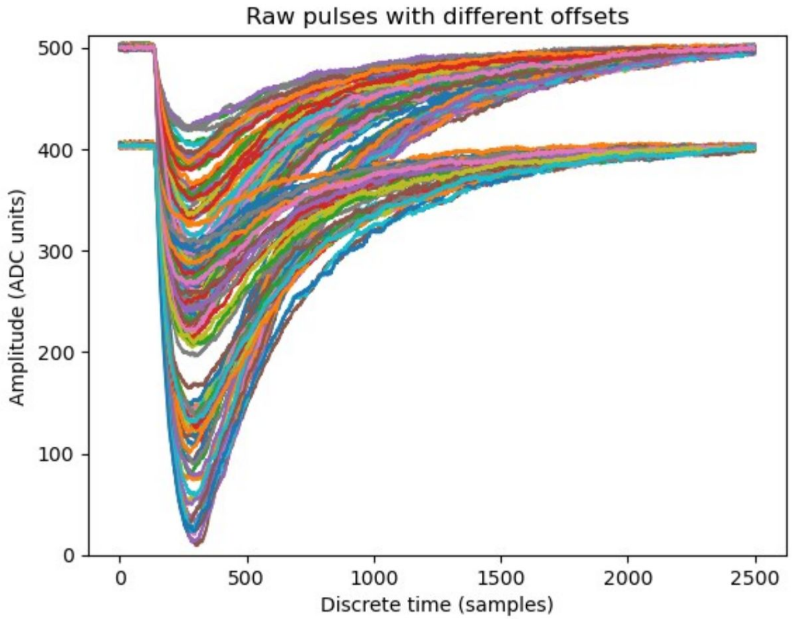
Data wrangling

- Data curation with simplified correlation [8].
- Removed piled-up pulses
- Identified low-energy events



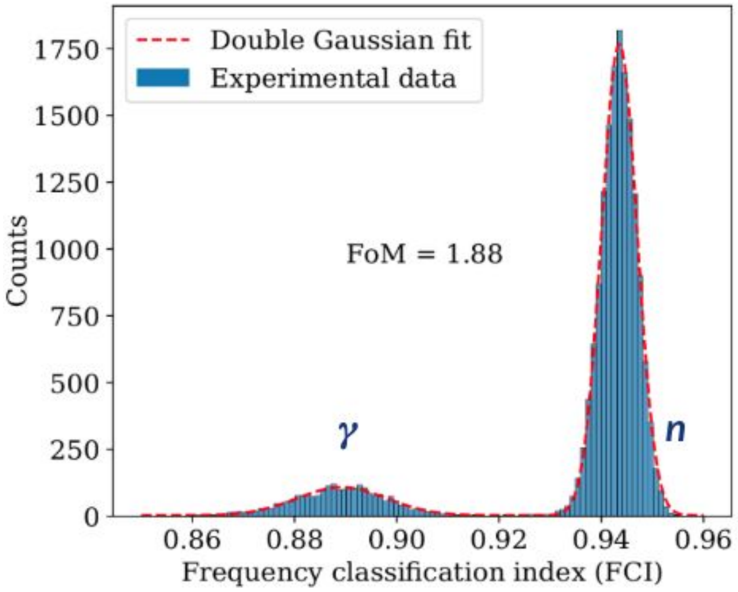
Data features after wrangling

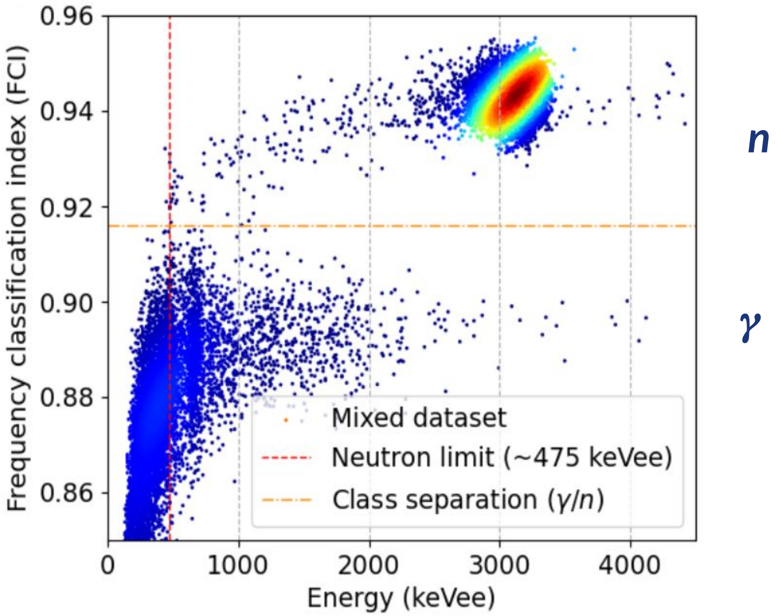
- Slight pulse shape differences between gamma/neutron
- Diverse baseline shifts
- Sampled at 4 Gsps
    - Further downsampled for real-time processing to 100 Msps
- No pile-up distortion



Data labeling

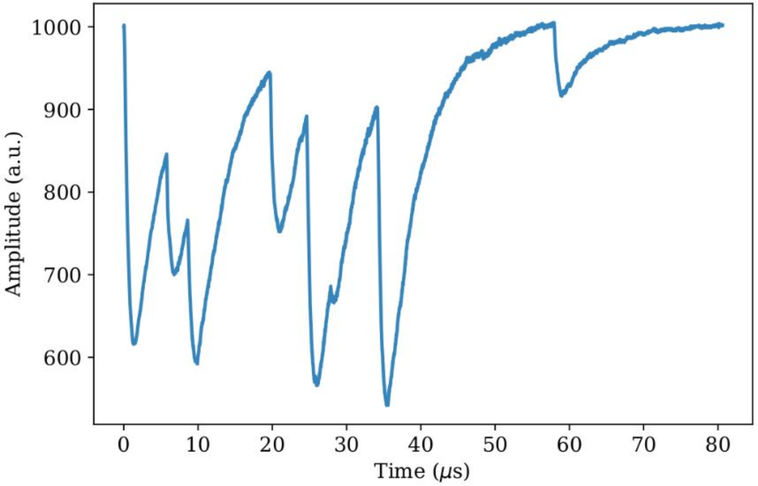
- Frequency-based event discrimination [9].
- Two labels: gamma/neutron

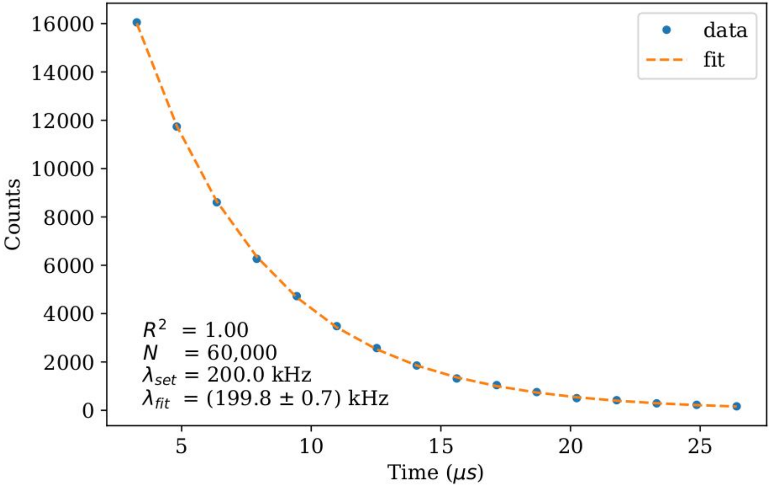




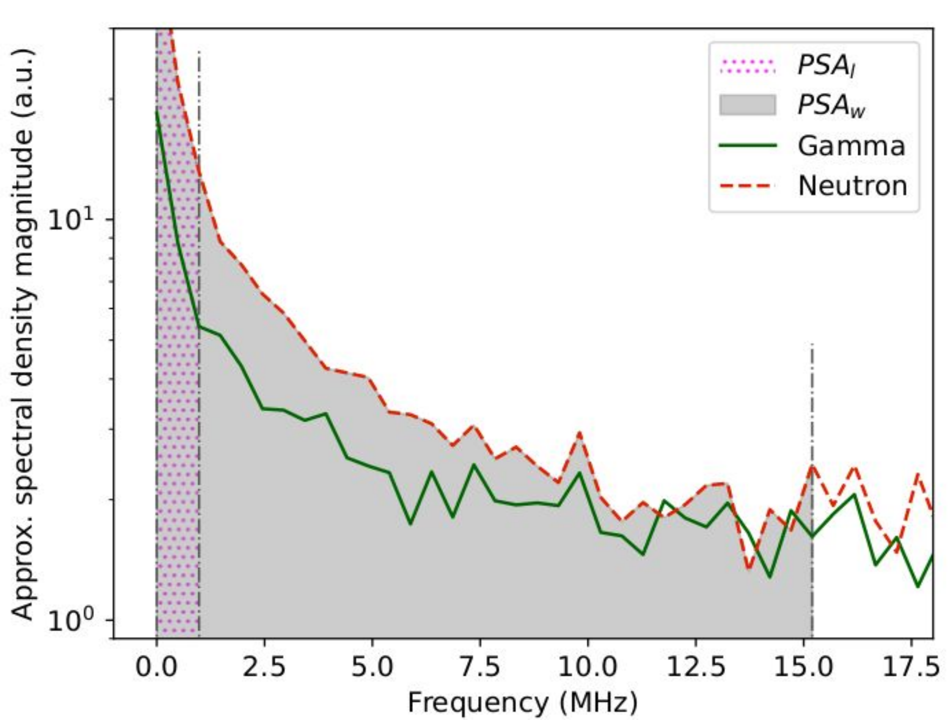
Pile-up synthesis for ML training

- Exponential distribution of “clean” piled-up pulses
- Event rate at 200 kHz (max 400 kHz)
- Validated event time distance with $R^2 \sim 1.00$





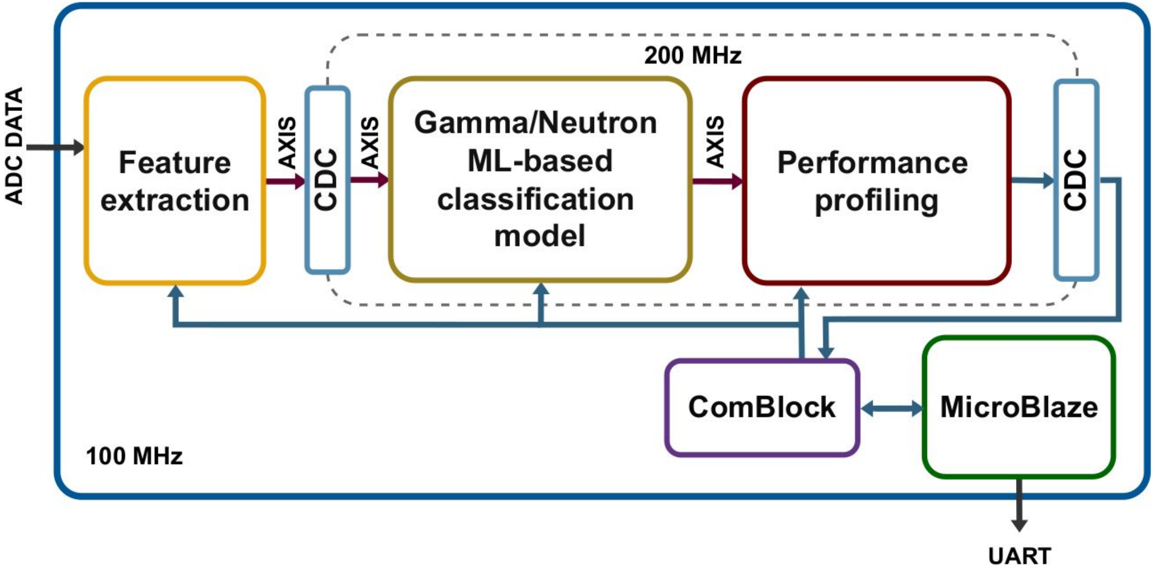
Real-time event processing with ML



Simulation of gamma/neutron discrimination using FFT with plastic scintillator [5].

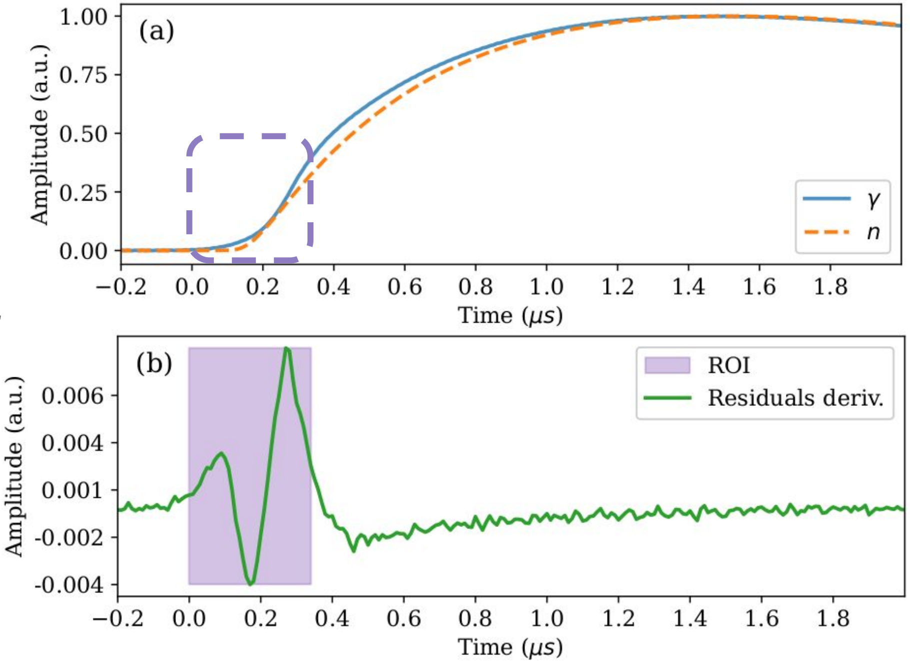
FPGA system architecture

- Low/high-power domains: 100/200 MHz
- Real-time processing pipeline: II = 995 ns, latency < 2.5 μs

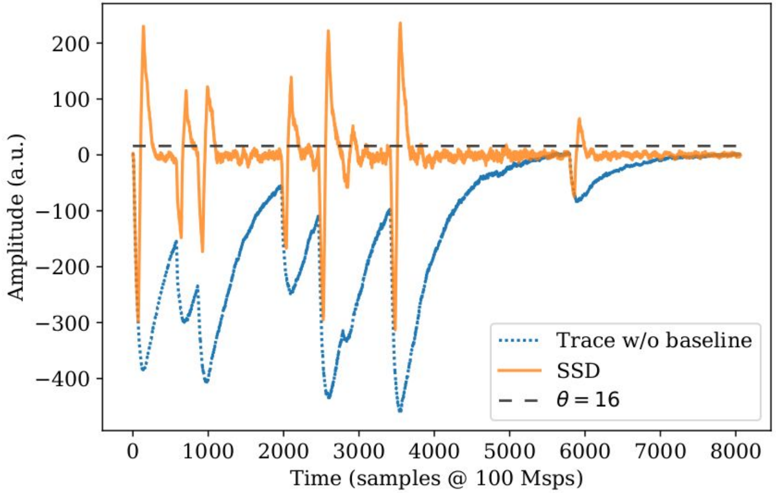


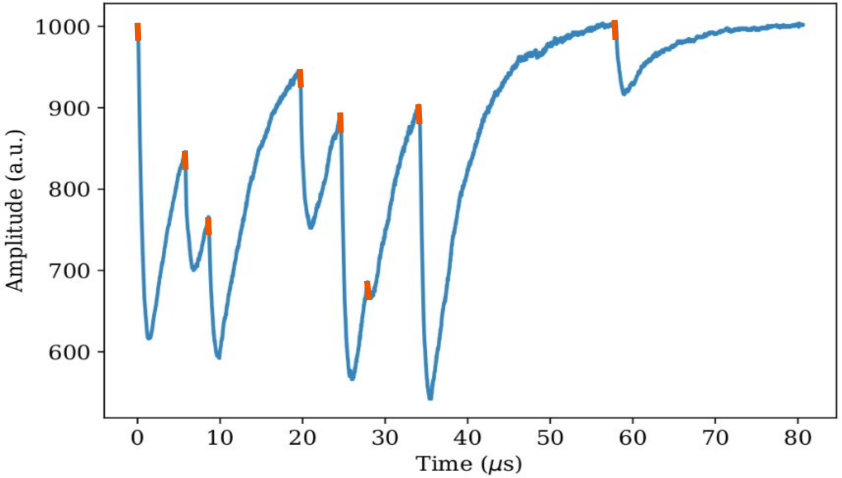
Real-time feature extraction

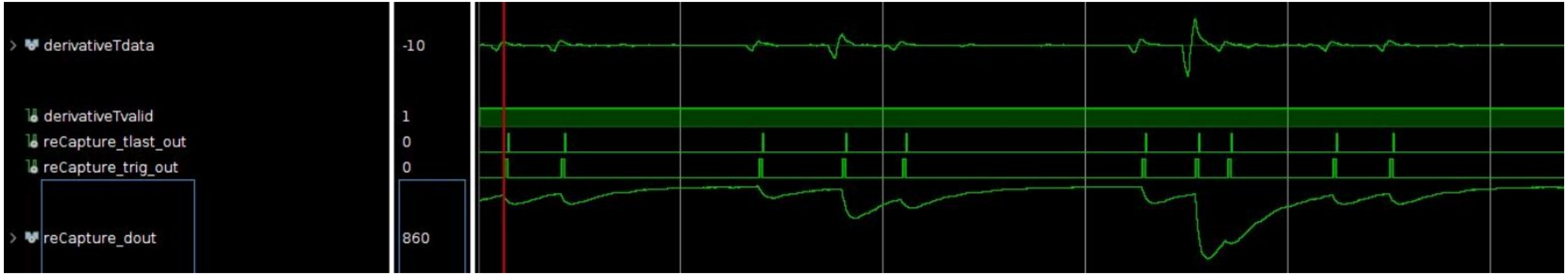
- Pulse leading edge
- First 350 ns (pulse 30 μs)
- No time alignment required
- 2nd derivative trigger (SSD)
  - IIR bandpass differentiator
- Python model
- VHDL real-time module



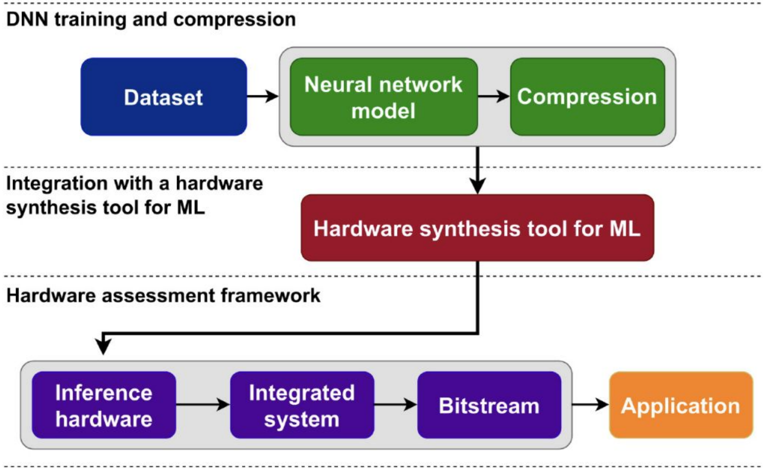
Real-time feature extraction

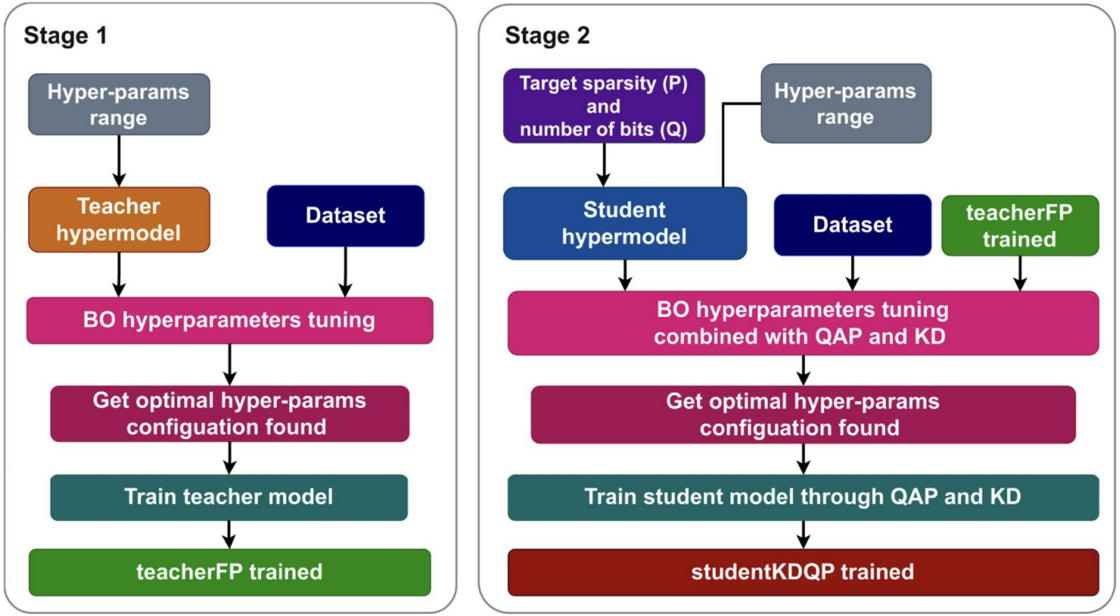






Machine learning workflow

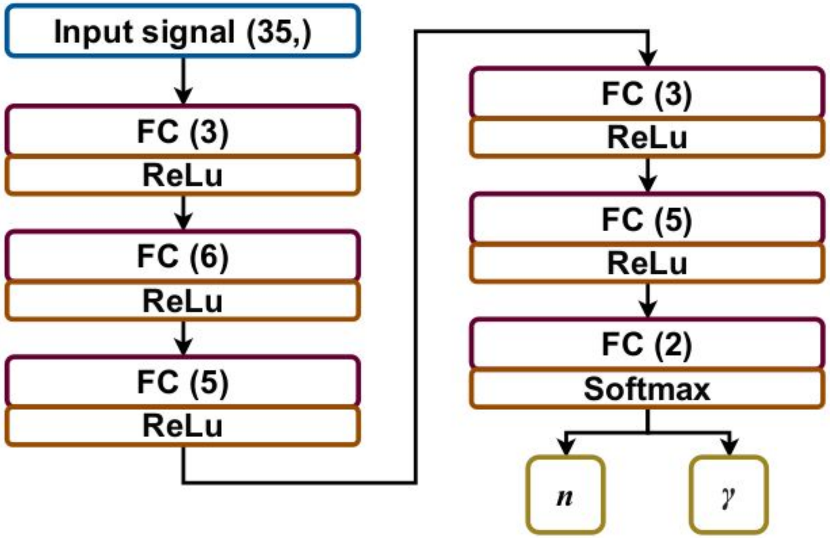




Machine learning workflow for efficient DNN deployment on FPGA [10]

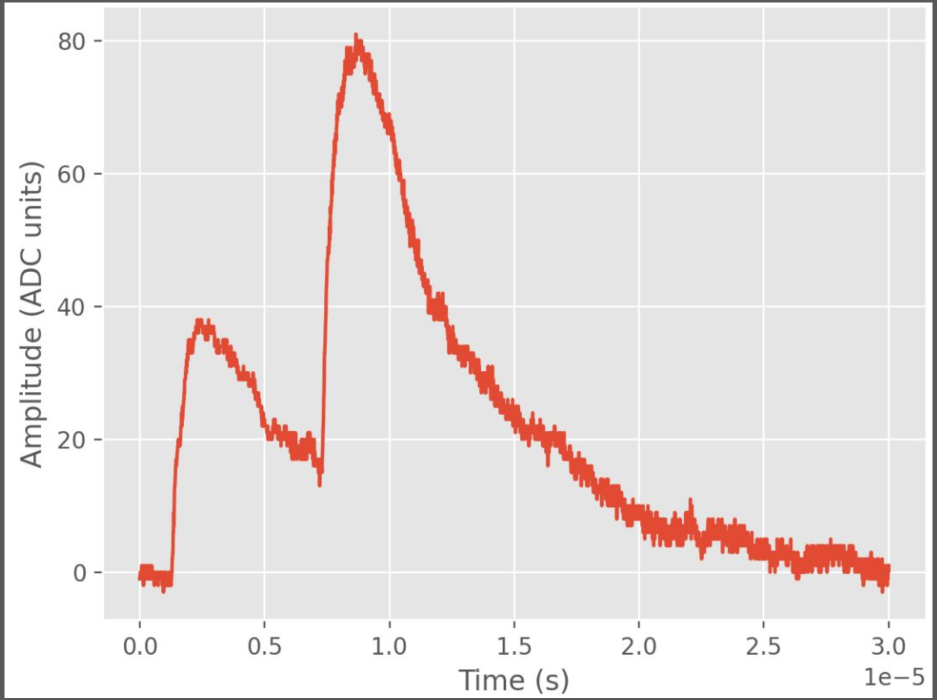
Online machine learning classification

- Multilayer perceptron (MLP): binary classifier.
- Compression workflow from [9].
- Distillation + quantization-aware pruning
- 8-bit FP quantization with 30% sparsity.
- 217 parameters in 6 hidden layers.
- Overall accuracy 98.2%.



Distilled (student) compressed MLP model

Results

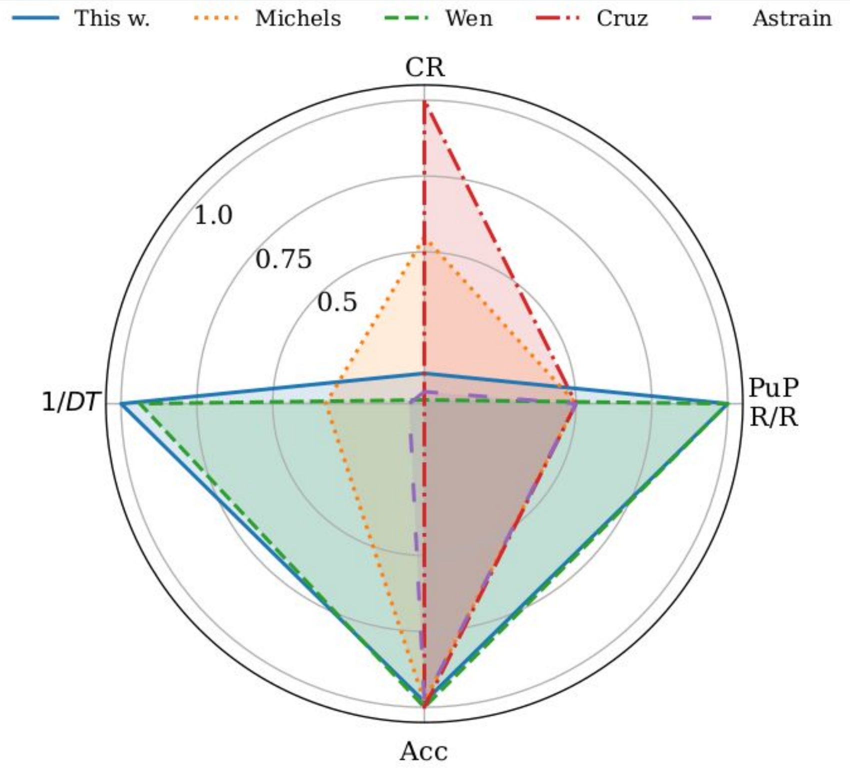


Piled-up neutron and gamma pulses

Results: performance

- Count-rate (CR)
- Inverse of dead-time (1/DT)
- Pile-up recovery/rejection (PuP)
- Accuracy (Acc)

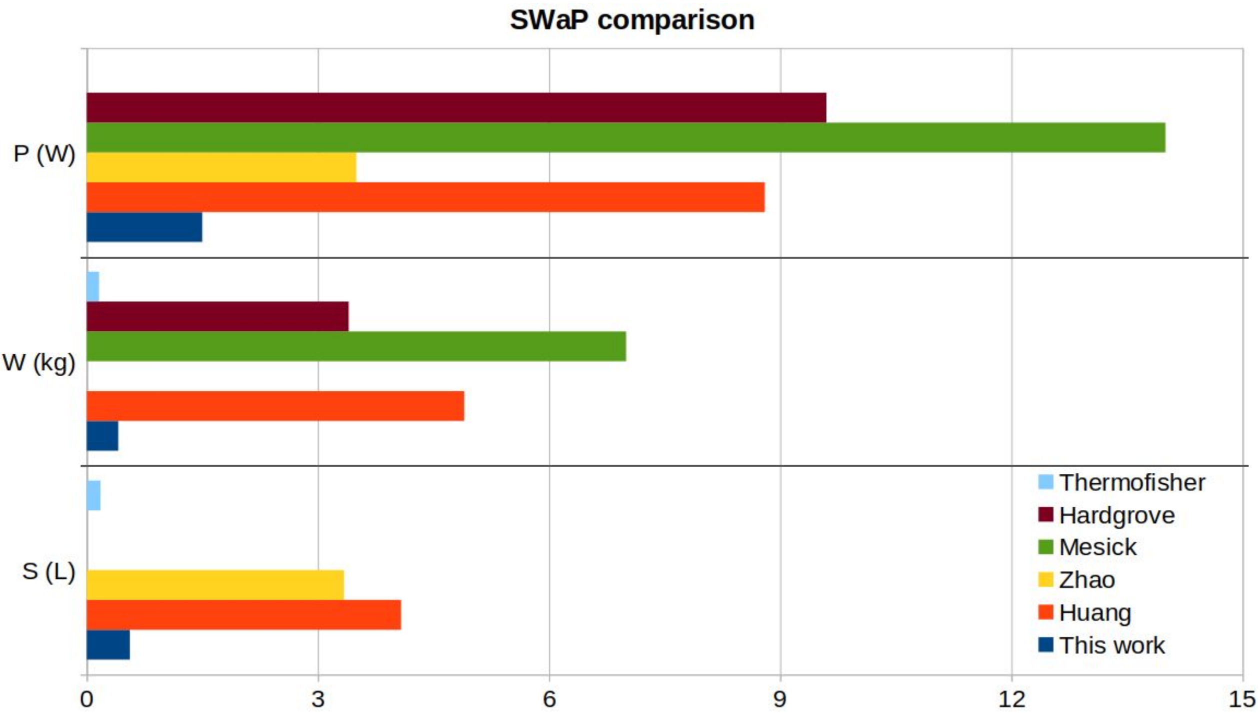
Work	Overall perf.
This work	1.0
Michels et al.	0.89
Wen et al.	0.12
Cruz et al.	0.01
Astrain et al.	0.01



Michels et al. doi:10.1109/ACCESS.2023.3298208
Wen et al. doi:10.1016/j.nima.2017.06.007
Cruz et al. doi:10.1109/TNS.2019.2907056
Astrain et al. doi:10.1109/TNS.2021.3090670

Highest values are the best

Results: low SWaP



Lowest values are the best

Thermo Fisher Scientific
https://www.thermofisher.com/order/catalog/product/4250631

Hardgrove et al.
doi:10.1109/MAES.2019.2950747

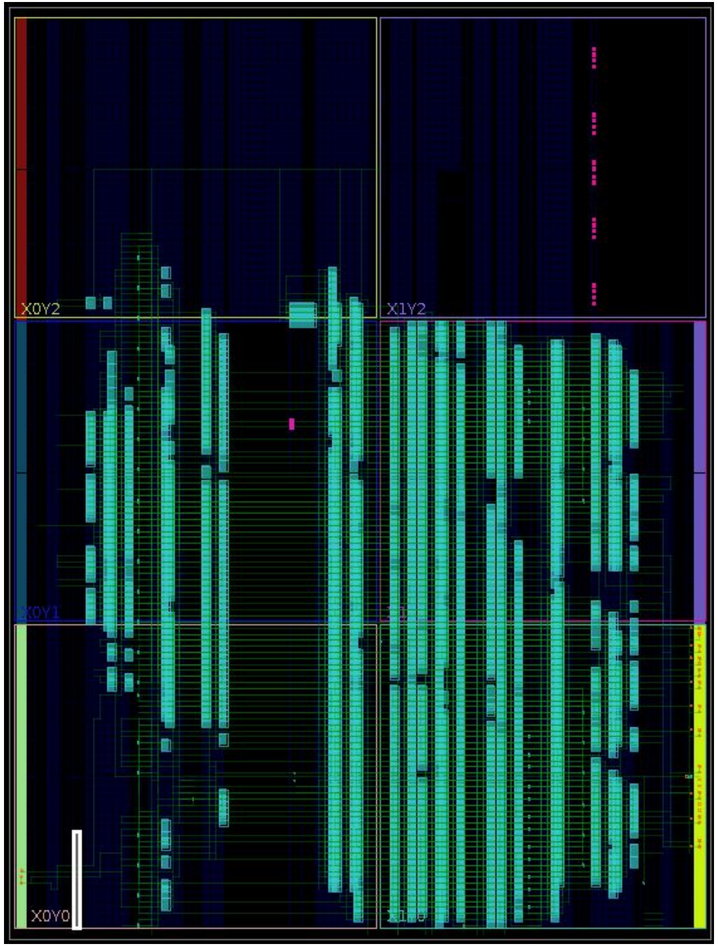
Mesick et al.
https://digitalcommons.usu.edu/smallsat/2020/all2020/118/

Zhao et al.
doi:10.1088/1748-0221/18/09/P09043

Huang et al.
doi:10.2139/ssrn.4717223

Results: FPGA utilization

- Low-end Artix-7 35T FPGA
  - LUT: 30.4%
  - Registers: 17.4%
  - BRAMs: 24.0%
  - DSPs: 17.8%

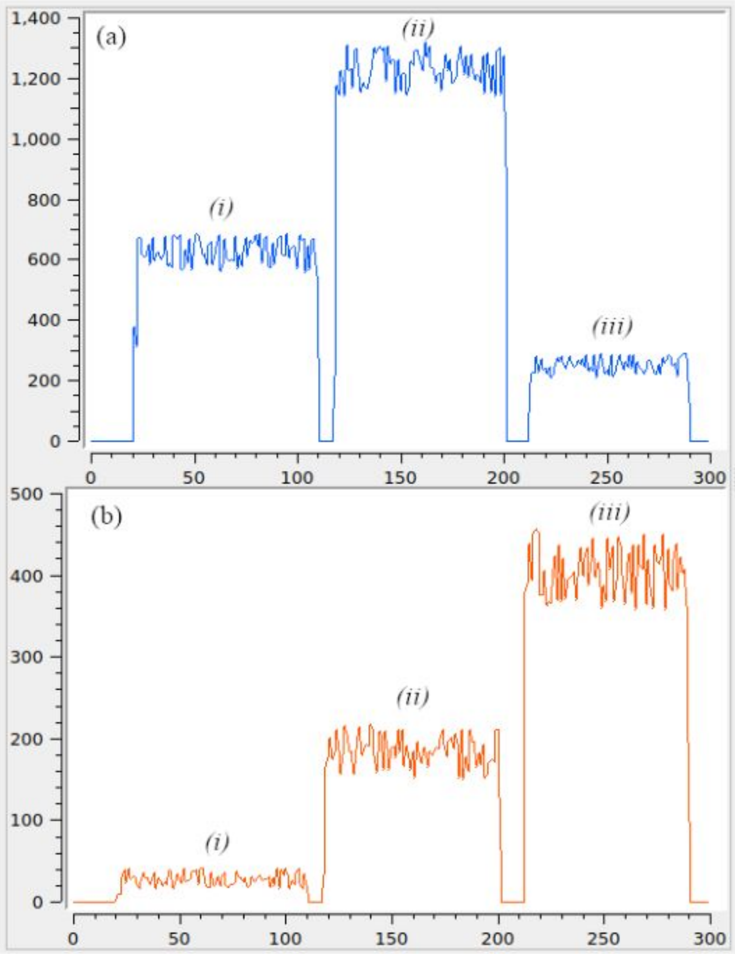


Validation with γ+n events

- Recorded pulses from CLYC plugged into AFE
  - (a) Gamma events
  - (b) Neutron events

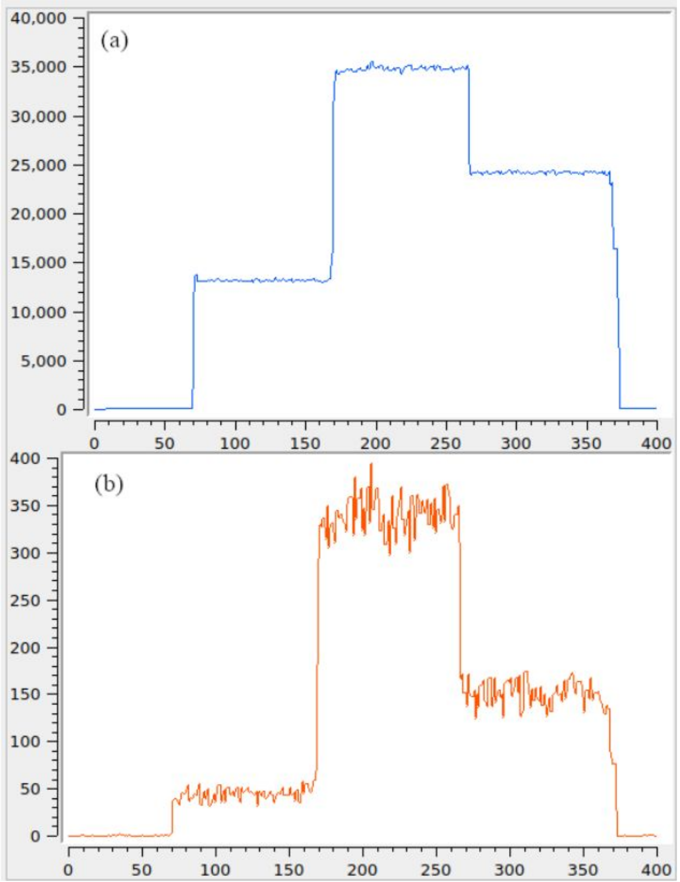
- Runs
  - (i) Gamma-only events
  - (ii) AmBe + Cs-137 sources
  - (iii) DD neutron gen. + Cs-137

- Neutron false alarms <2.5%
- Accuracy: 98.2%

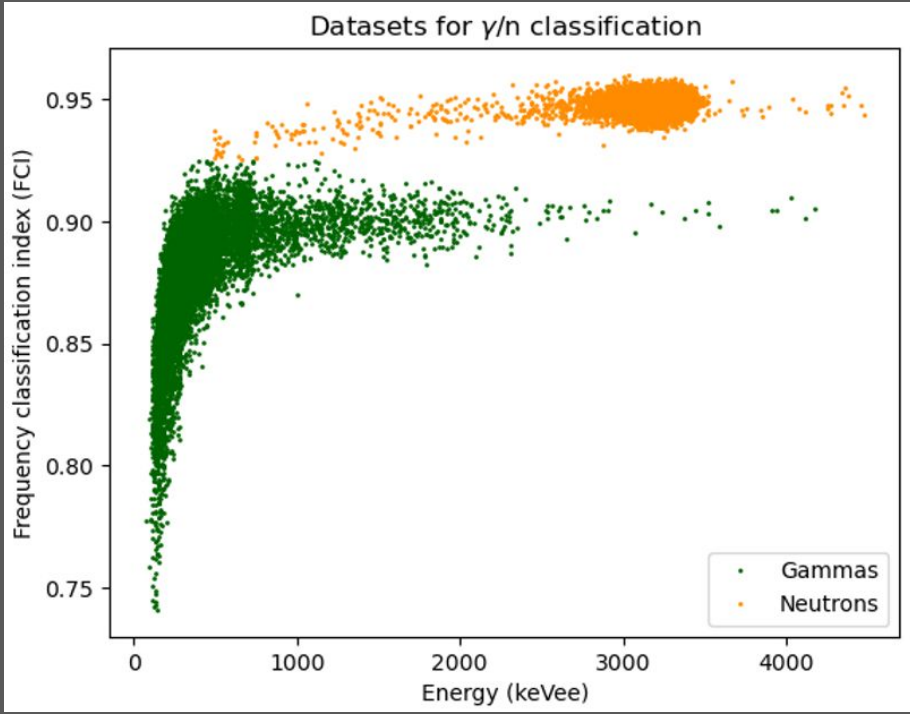


Validation with other detectors

- NaI(Tl) detector sensing γ events from Co-60 source
  - Accuracy 99.1%
- Synthetic γ events of fast plastic scintillator
  - Absolute max. countrate: **~1.01 Mcps**
  - Lowest deadtime: 995 ns
  - 129 ppm (missing events)



Conclusions



Experimental gamma/neutron dataset after discrimination with frequency-based analysis for ML training

Conclusions and FW

- FPGA enables a flexible mixed-radiation detection and measurement platform
- Reliable event discrimination under pile-up distortion on mixed radiation fields has been achieved
- Low-SWaP instrument with benchtop performance enabled by ML
- Multi-detector systems might be deployed leveraging existing system architecture
- Targets include portable instruments in nuclear security, radiation monitoring, and HEP experiments.

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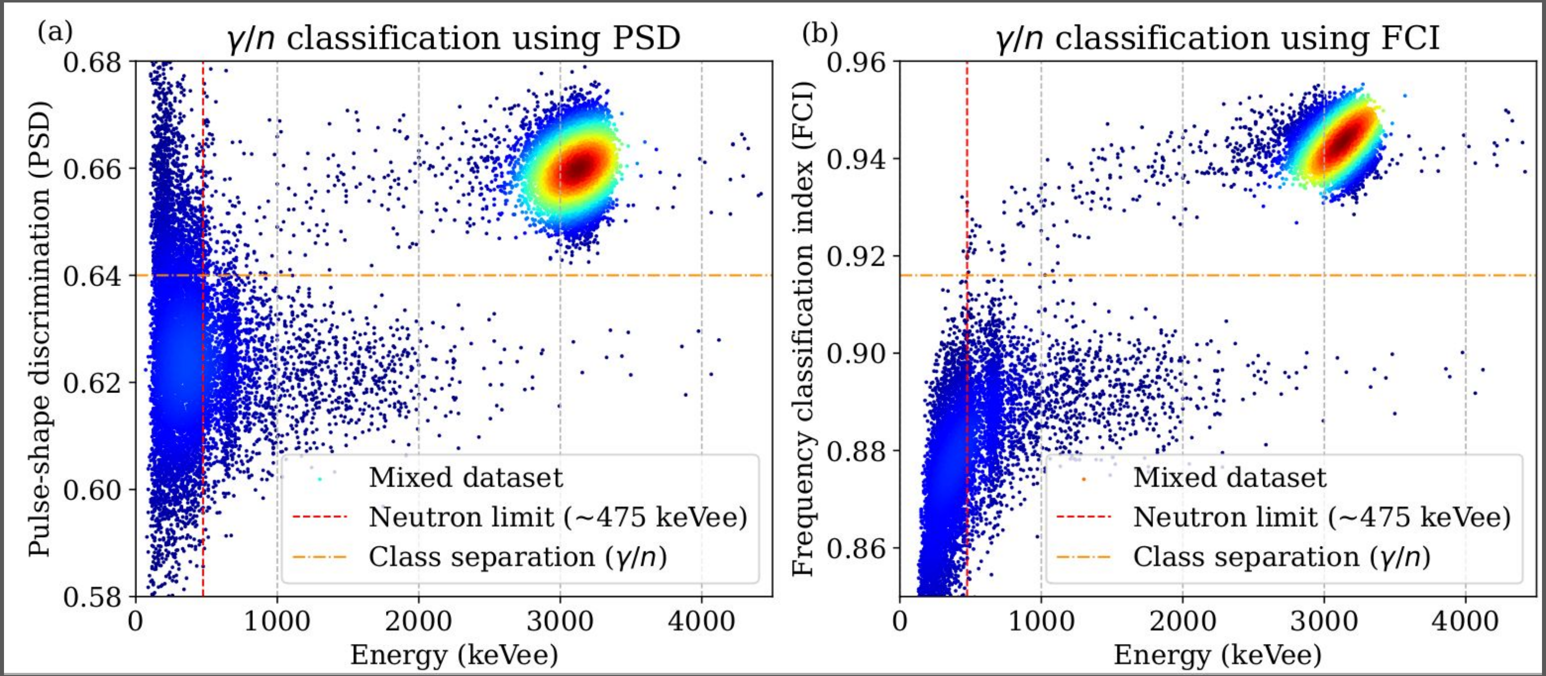
Thanks for your attention

Backup slides



SWaP comparison

Work	S (L)	W (kg)	P (W)	SaW	WaP
This work	0.56	0.41	1.5	0.13	1.00
Huang [153]	4.08	4.9	8.8	0.00	0.01
Zhao [18]	3.34	-	3.5	-	-
[1]Mesick [221]	-	7.0	14	-	0.01
[1]Hardgrove [106]	-	3.4	9.6	-	0.02
Thermofischer [105]	0.18	0.16	-	1.00	-

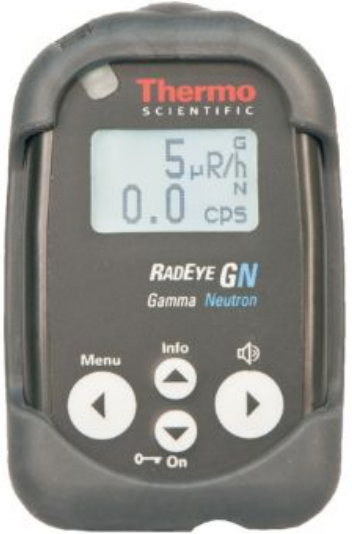
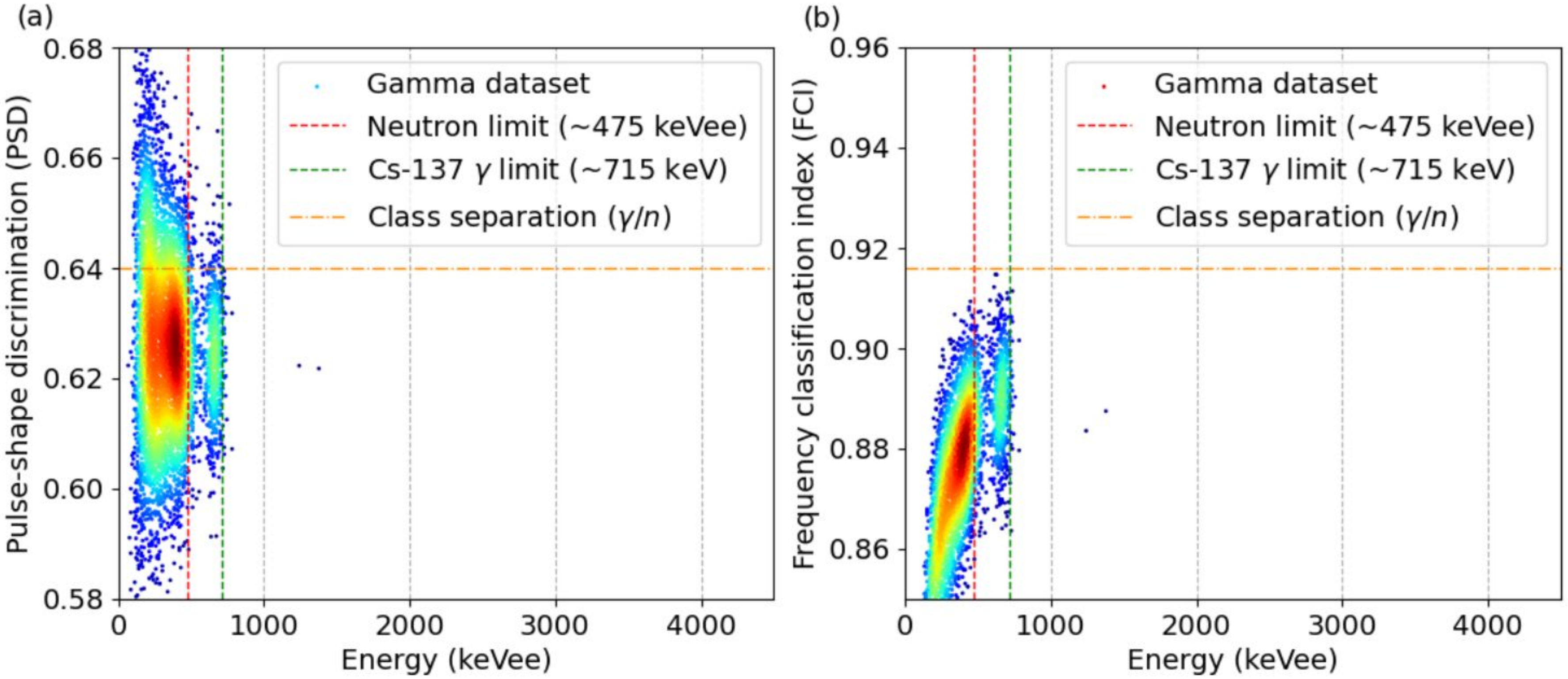
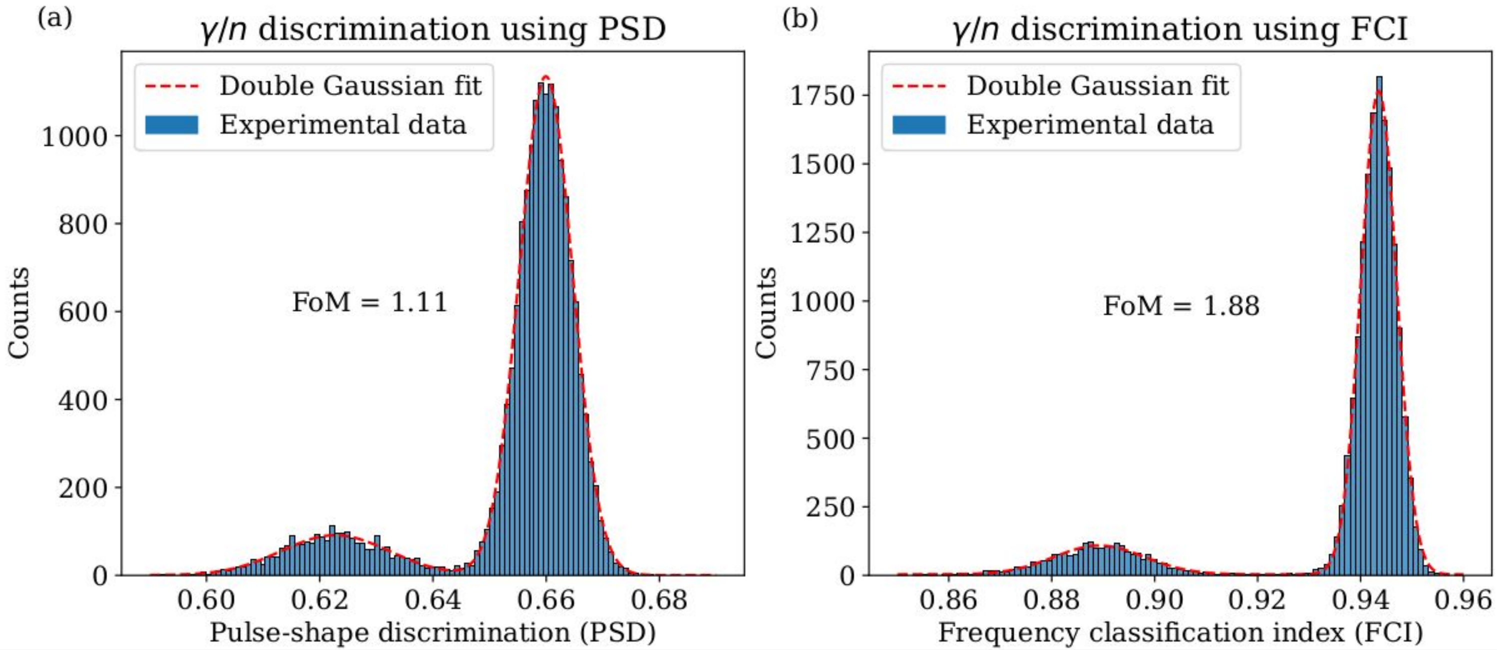


Table 5.2: SWaP comparison of recent CLYC-based γ/n discrimination systems, including SaW and WaP scores

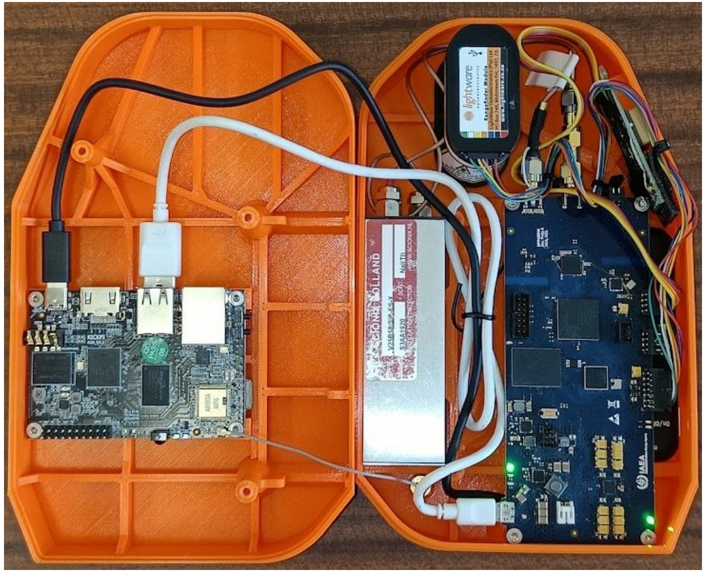
PSD vs FCI: gamma-only dataset

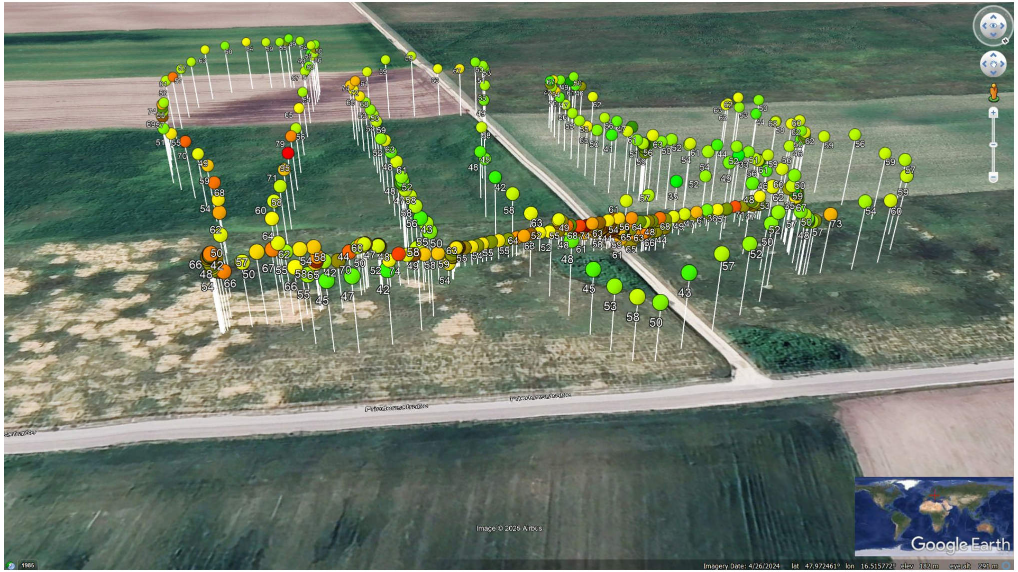


Dataset FOM for ML training

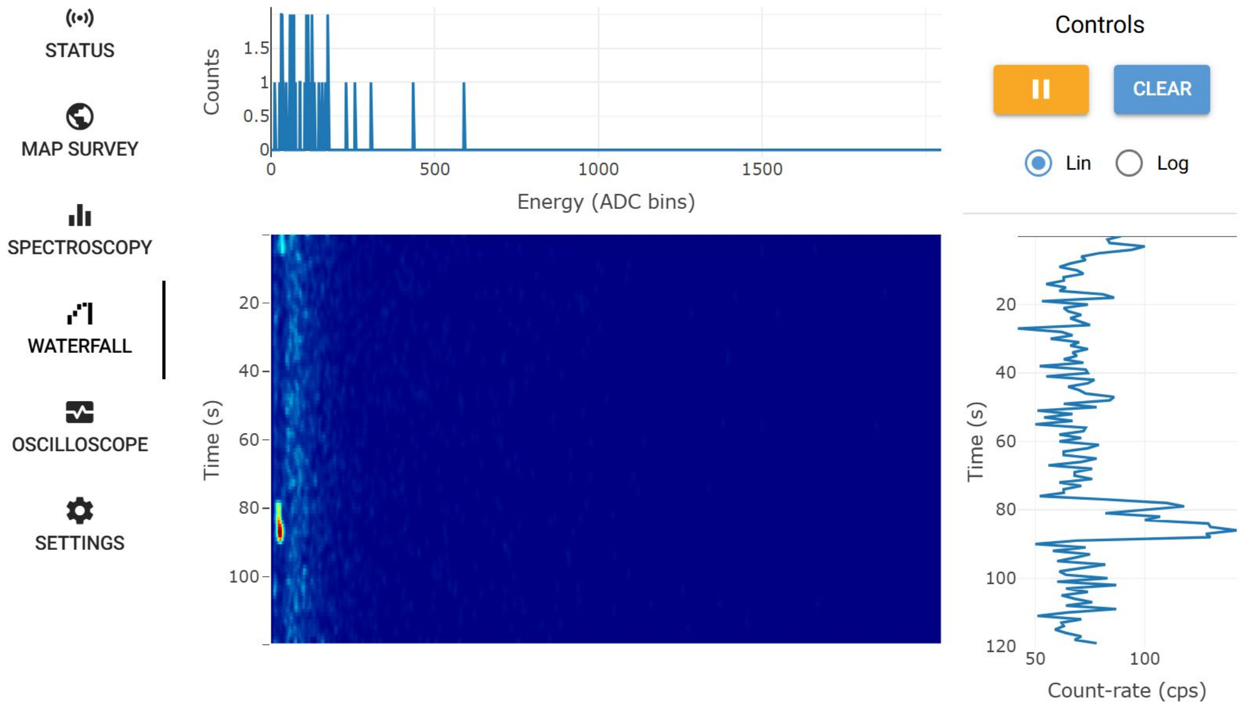


Related applications

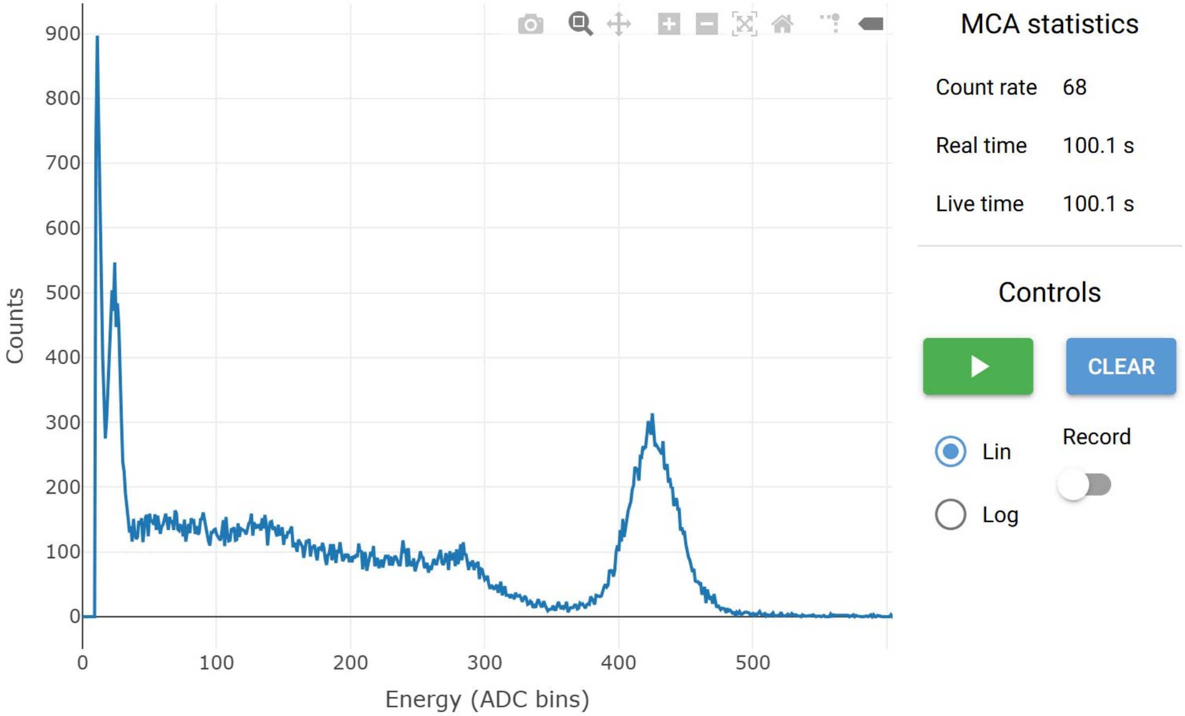




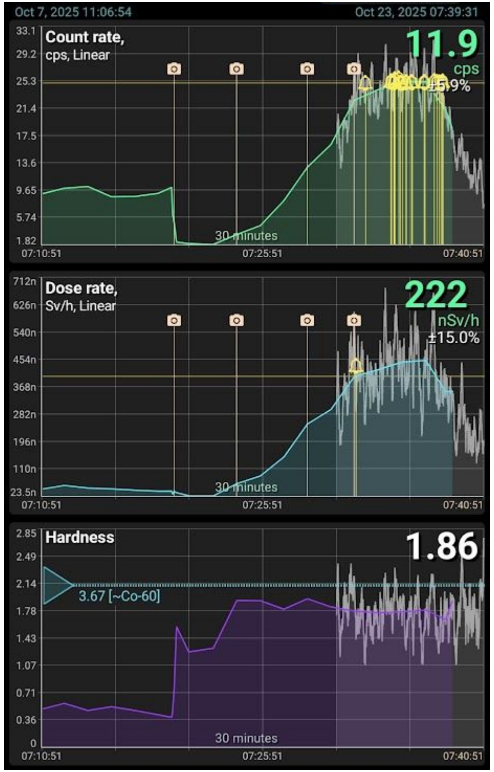
Remote radiation monitoring platform

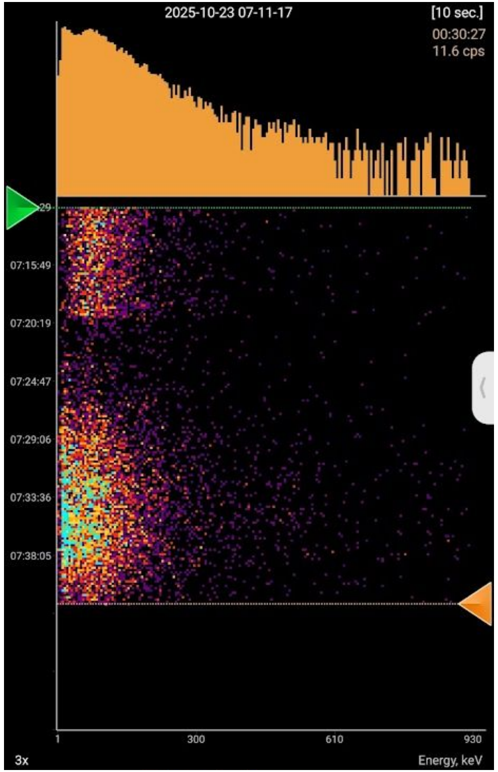


Remote radiation monitoring platform



Flight data from dosimeter/spectroscopy





Radiation dose limits

0.01–0.03 mSv per image	Typical dose range for an X-ray of the thorax
up to 0.1 mSv per flight	Dose due to cosmic radiation during a flight from Munich to Japan
1 mSv per year	Limit value (maximum permissible dose) for annual radiation exposure of members of the general public (e.g. resulting from the release of radioactive substances from nuclear facilities)
1–3 mSv per image	Typical dose range for a cranial CT (head CT)
10–20 mSv per image	Typical dose range for a whole-body CT of an adult
20 mSv per year	Limit value (maximum permissible dose) for annual radiation exposure of occupationally exposed persons in Germany

https://www.bfs.de/EN/topics/ion/radiation-protection/limit-values/limit-values_node.html
https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1785_web.pdf