High Event-Rate Online Discrimination on Mixed Radiation Fields with ML

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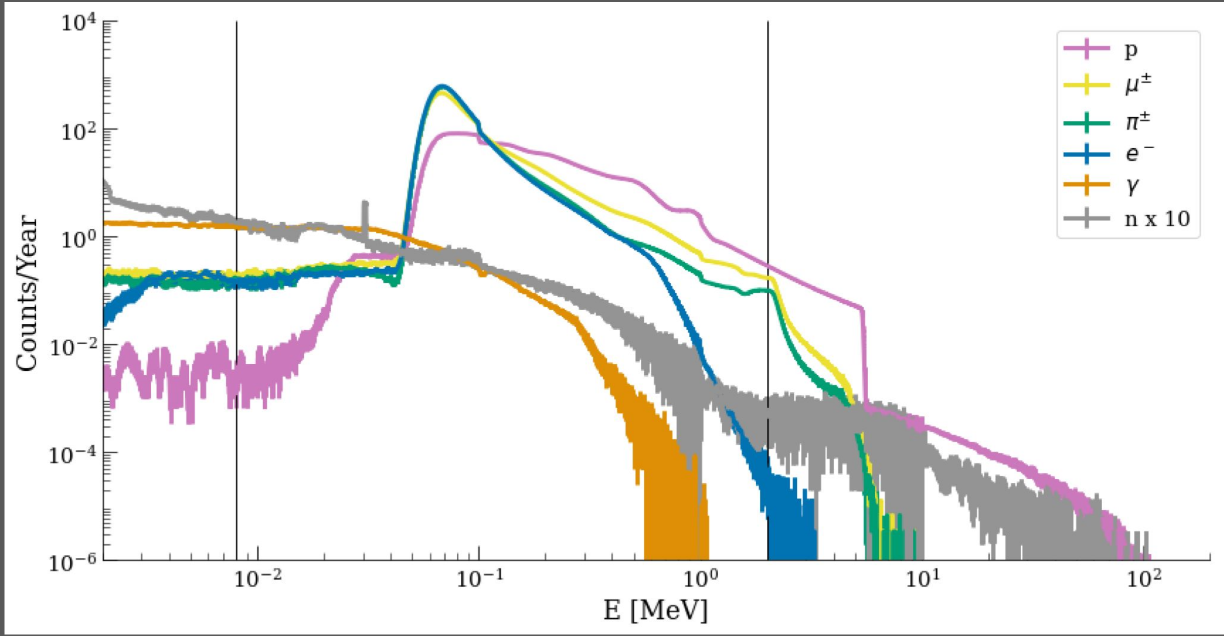
Summary

- 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

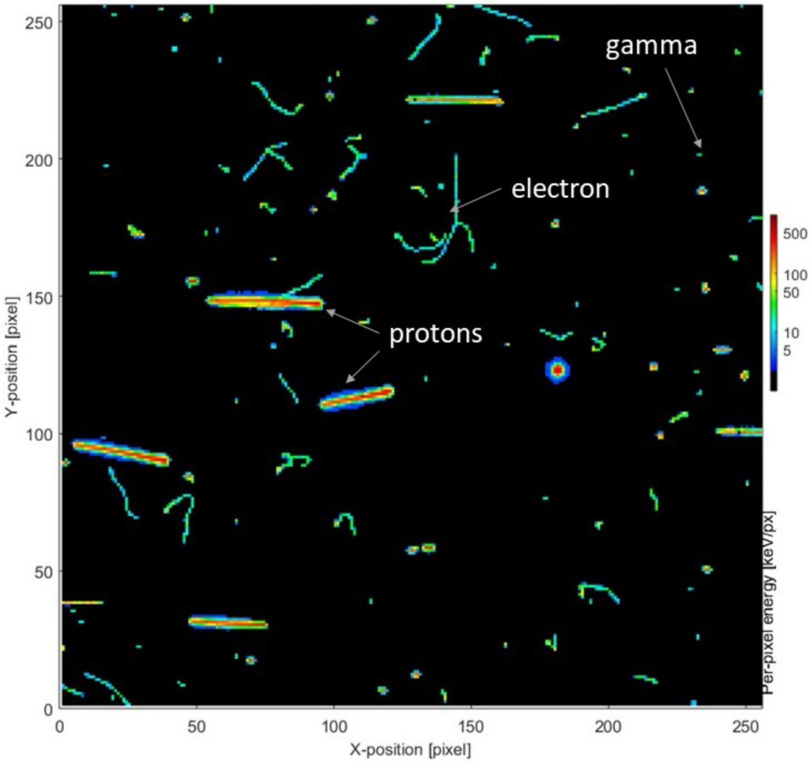
Mixed radiation fields



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].

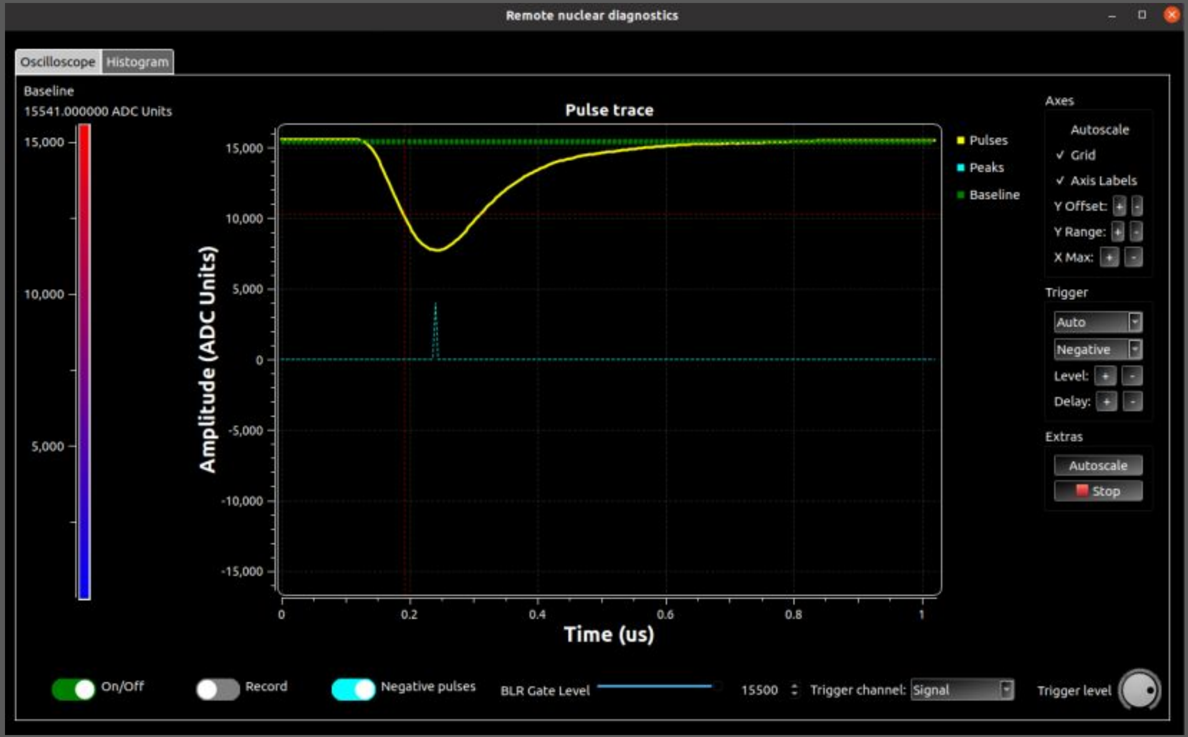
Mixed radiation fields

- 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].

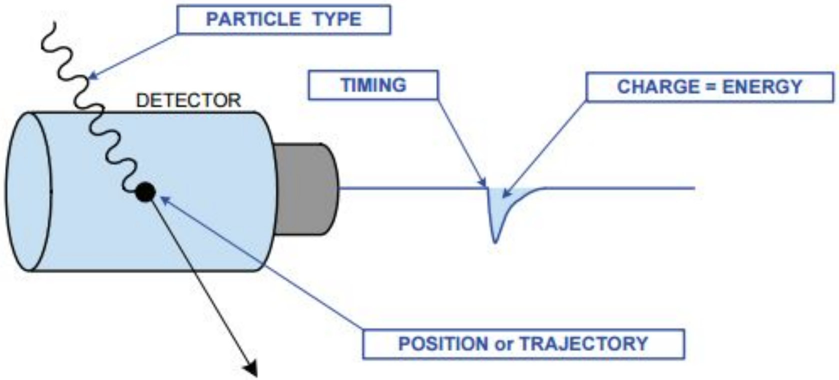
Event detection

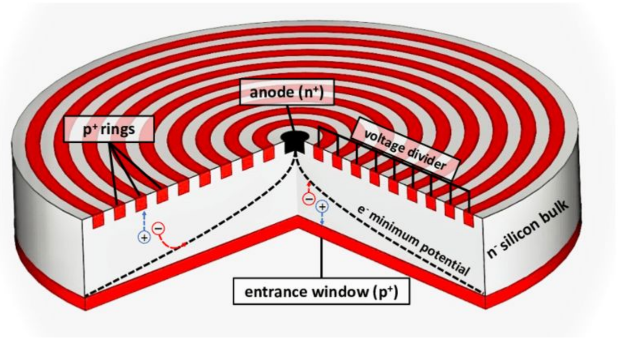


Captured trace from NaI(Tl) detector placed nearby a gamma source [3].

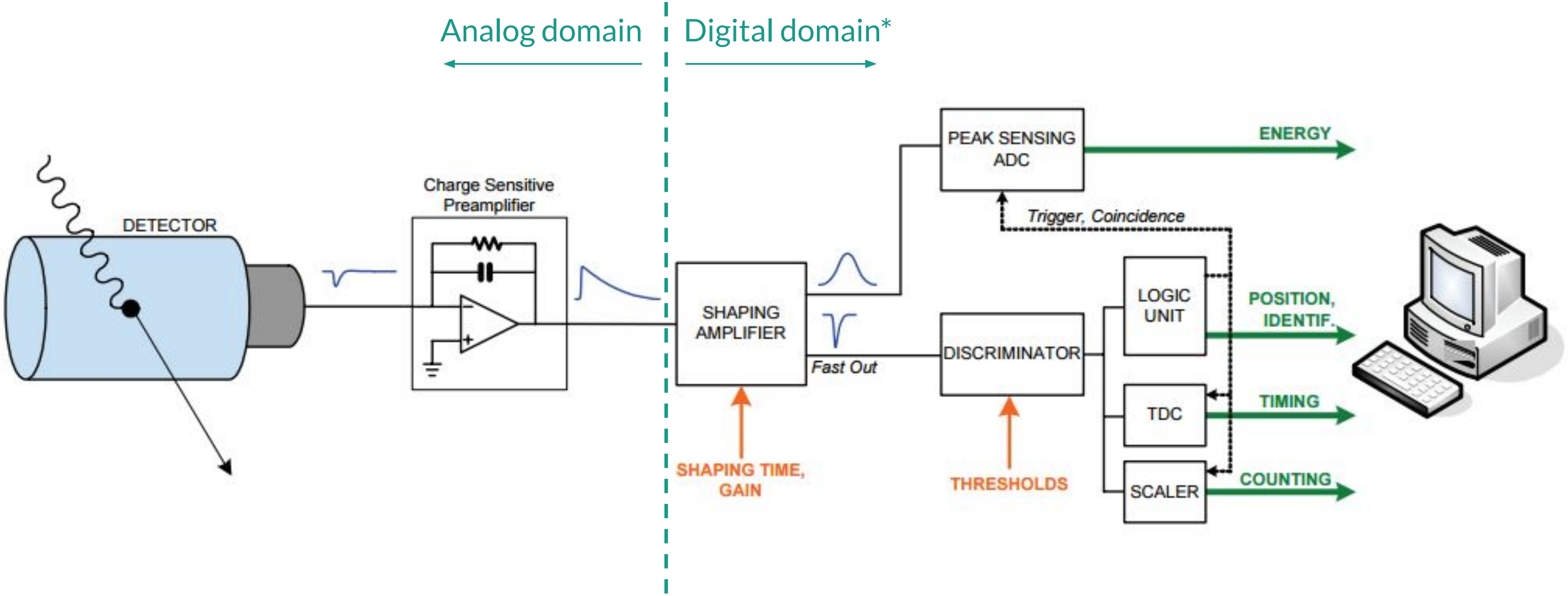
Detector technologies

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





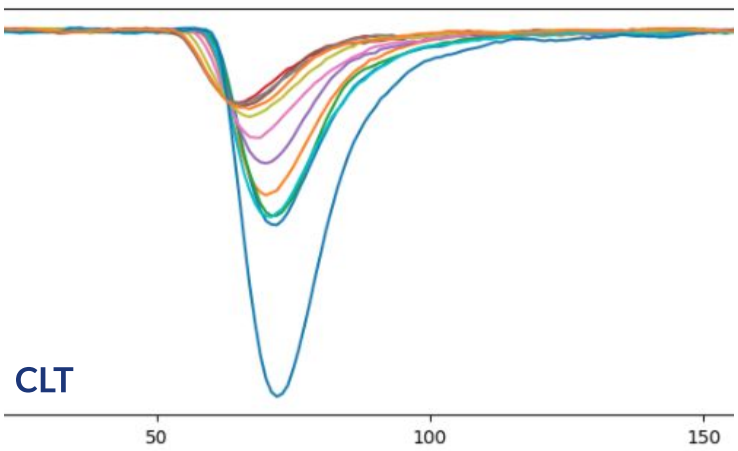
Detection chain



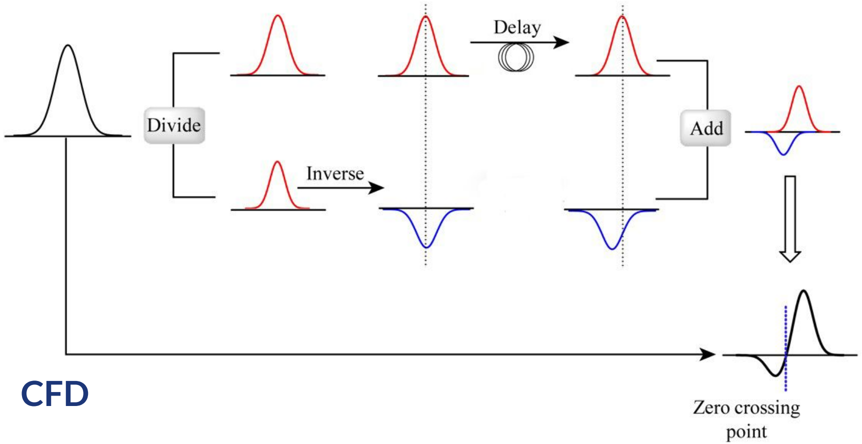
* digital domain starts at this stage in modern digital pulse processing (DPP) systems

Detection mechanisms

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

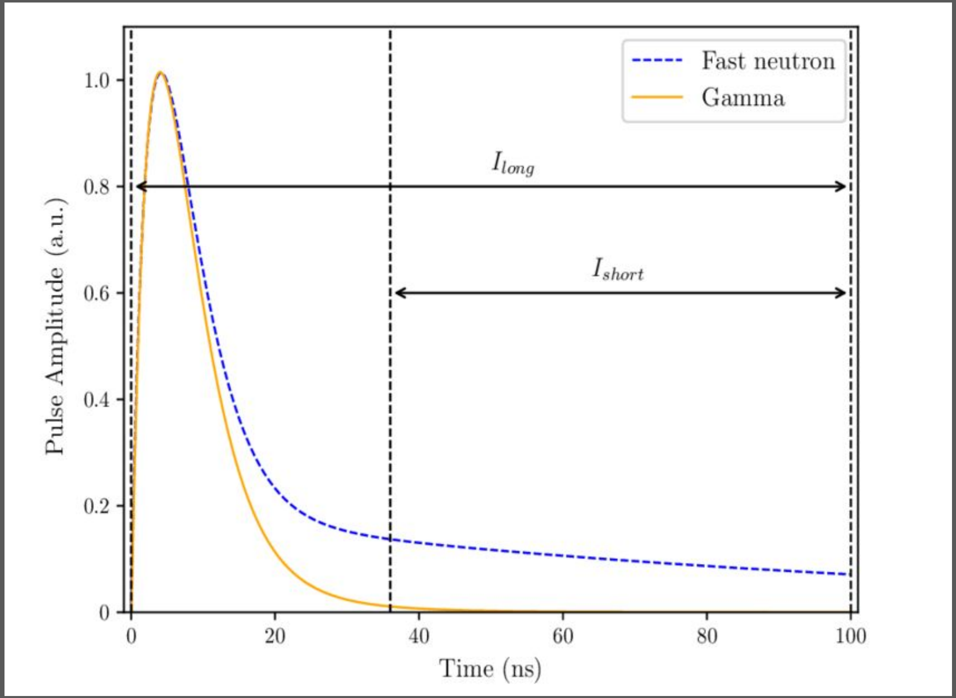


CLT



CFD

Event discrimination

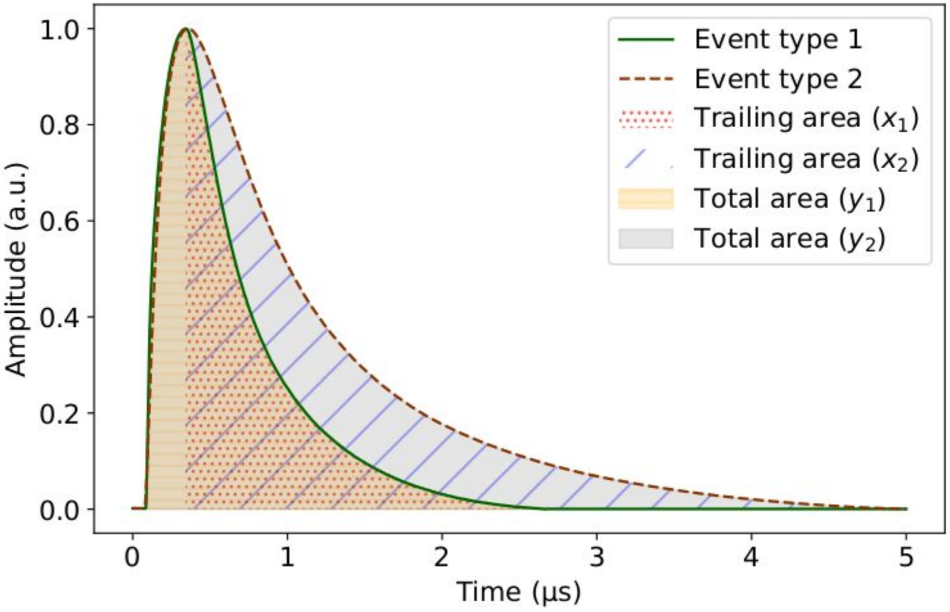


Event discrimination

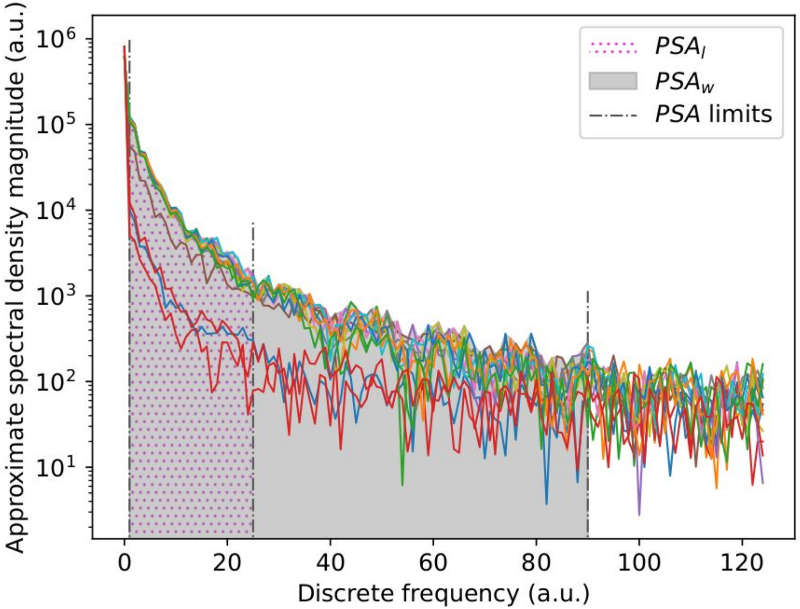
- Different particle interactions -> different pulse shapes
- Real-time hardware deployment

Event discrimination

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



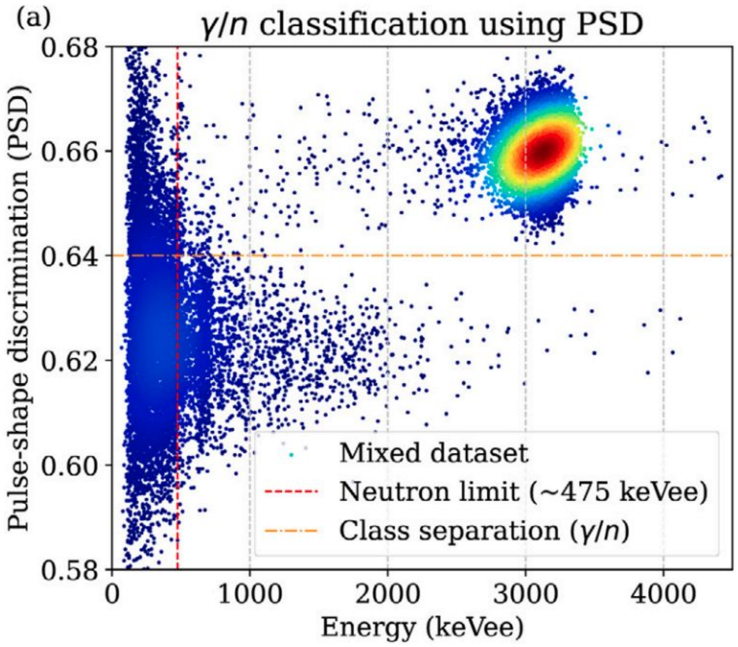
Pulse shape discrimination (PSD) [5]



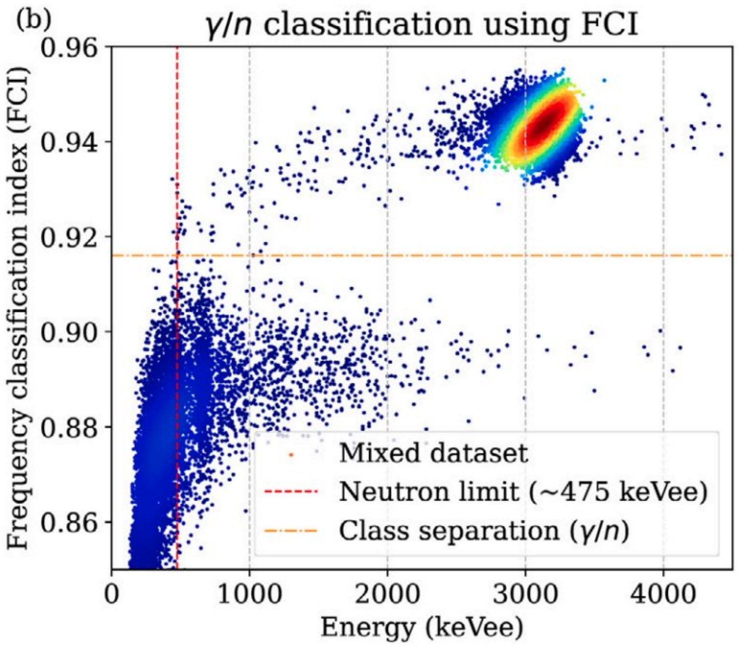
Frequency-based discrimination (FCI) [5]

Event discrimination

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



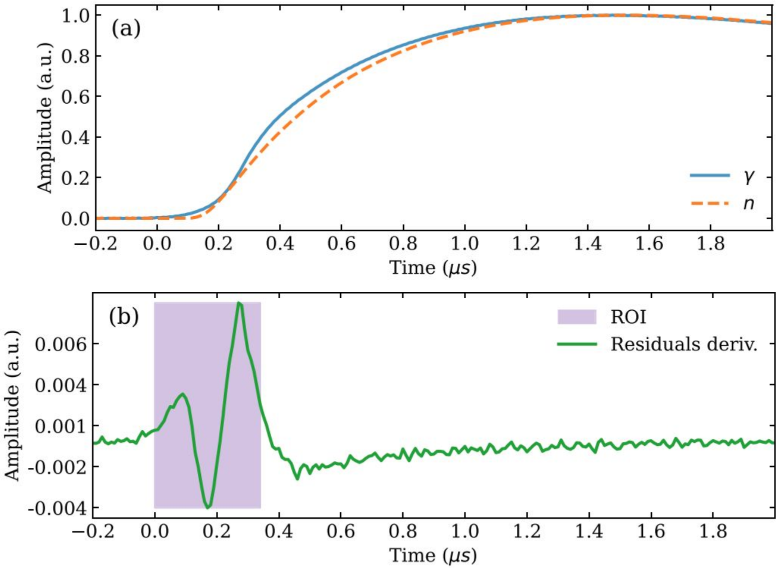
Pulse shape discrimination (PSD) [5]



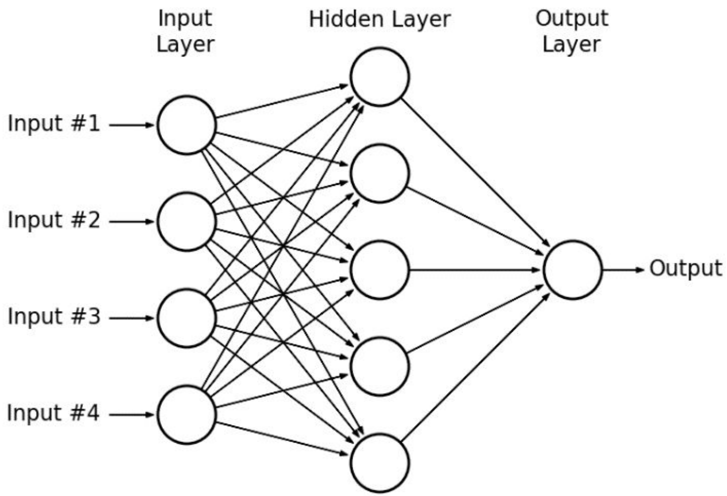
Frequency-based discrimination [5]

Event discrimination

Feature extraction + machine learning

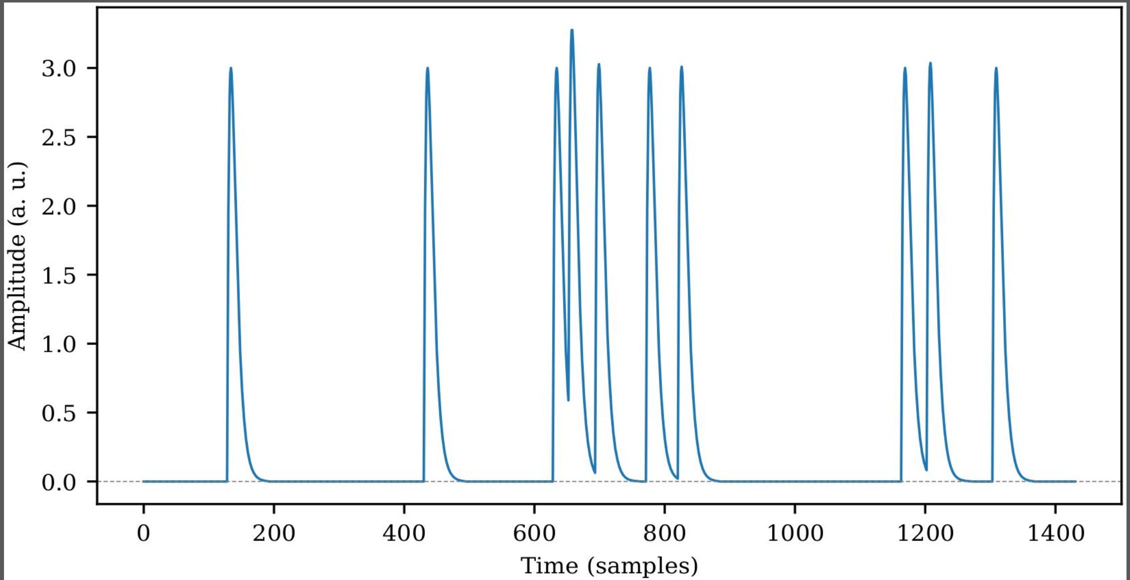


Feature extraction [6]



Example architecture of ML model

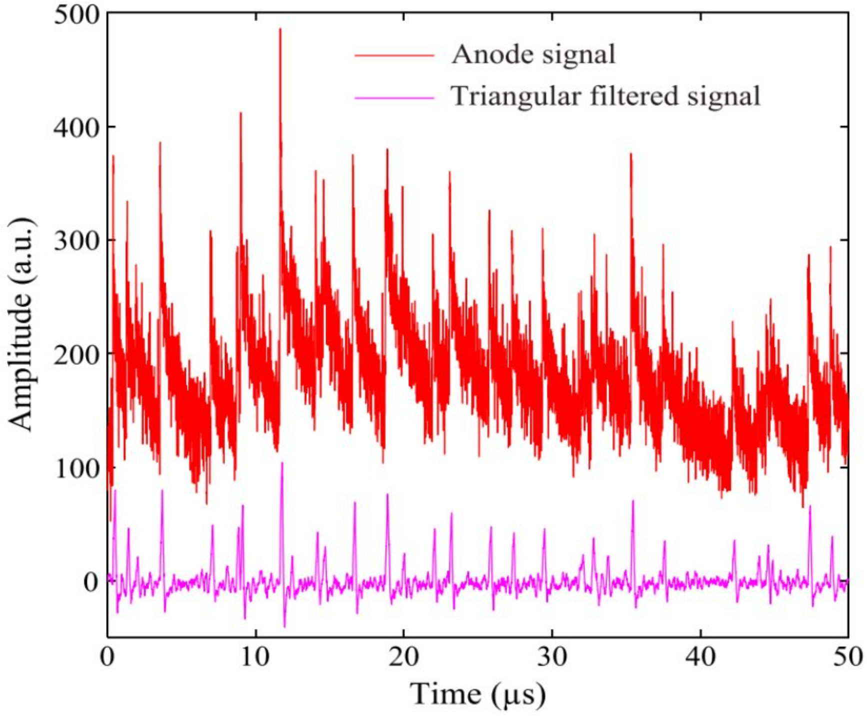
High-event rate challenges



Simulated pile-up events at high SNR

High-event rate challenges

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

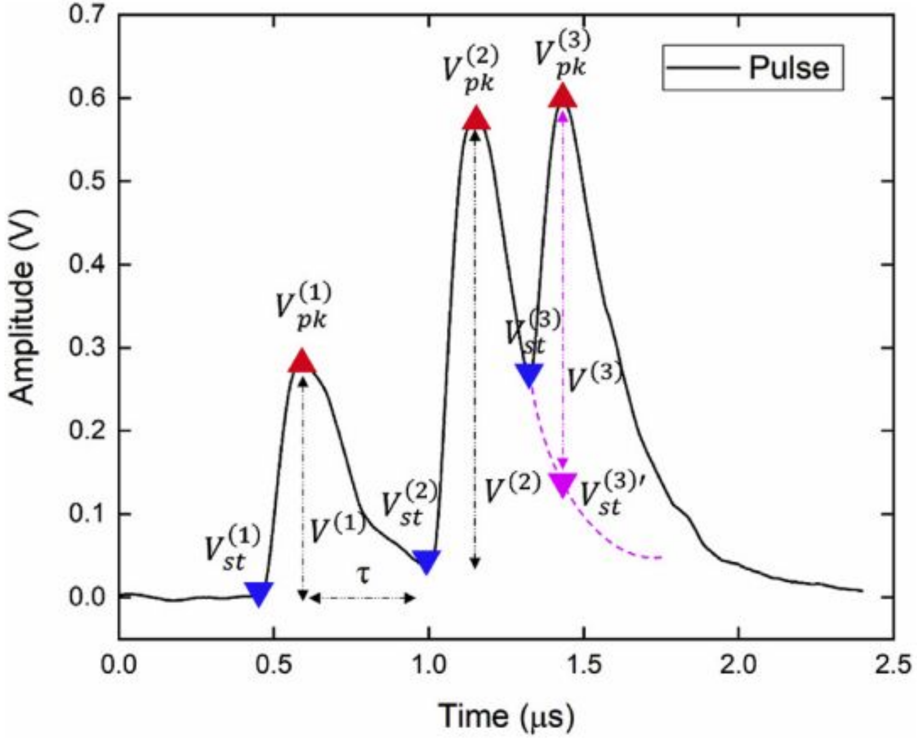


Severe pile-up distortion and shifted baseline [5]

Pile-up rejection

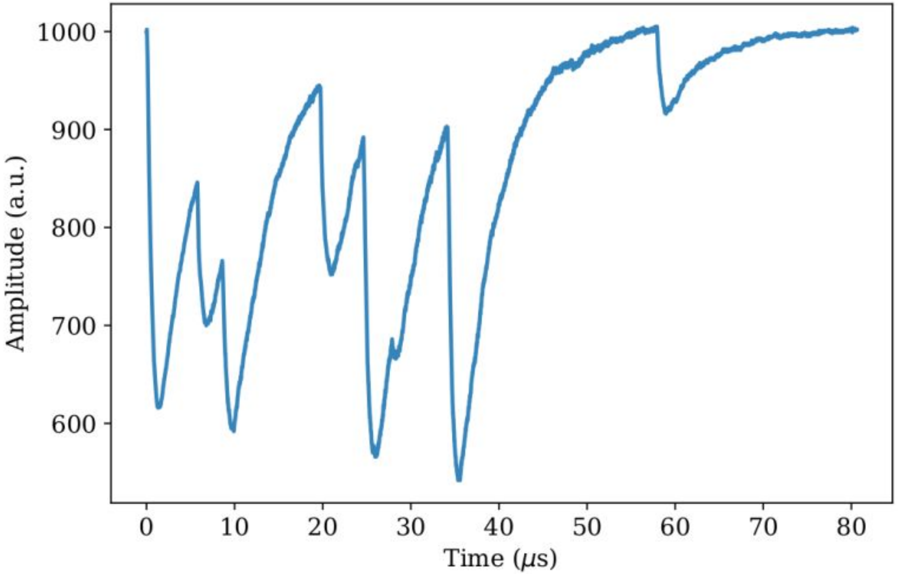
- Severe pile-up:
  - Events discarded
  - Live-time reduced

- Detectors on current mode:
  - No discrimination



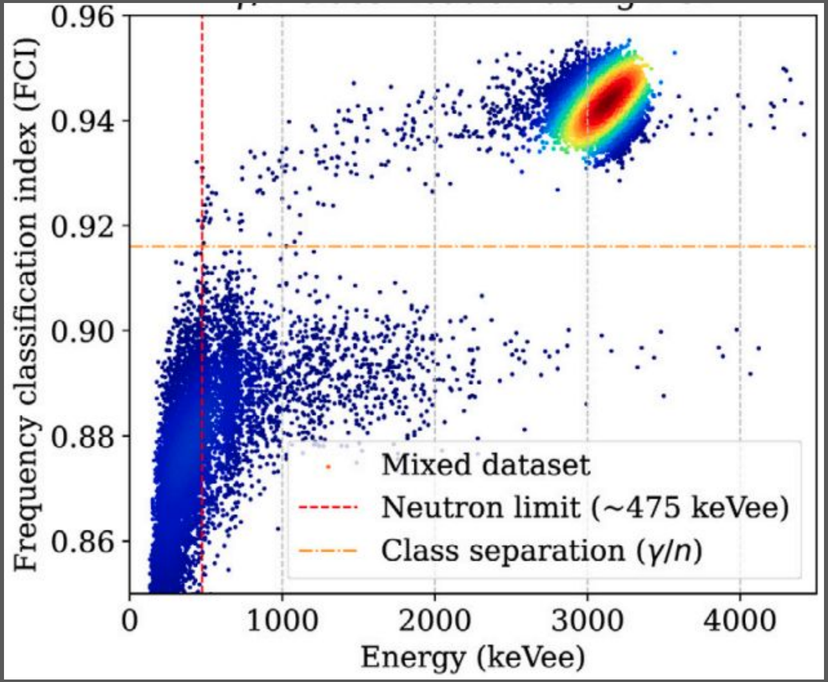
High-event rate + event discrimination

- 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]

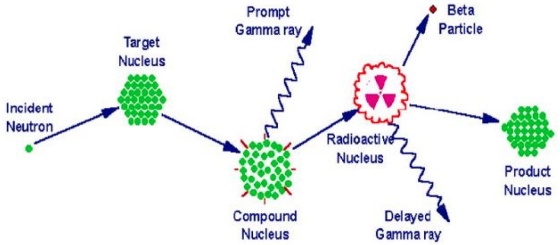
Case study: γ/n discrimination

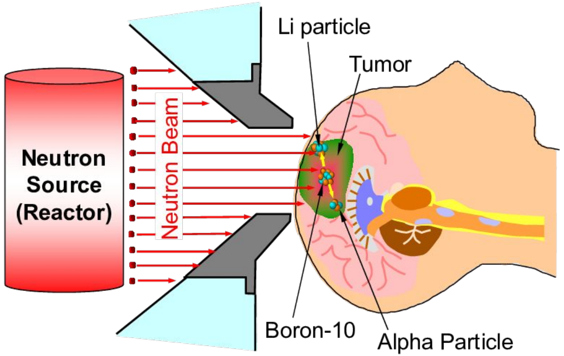


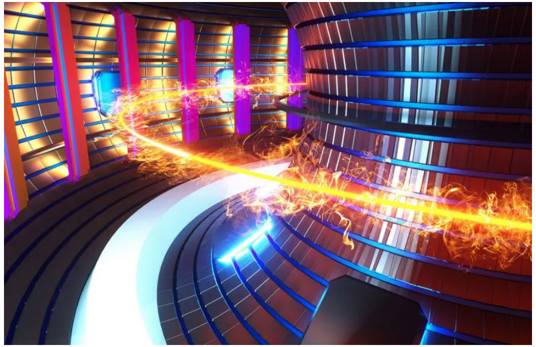
Gamma/neutron discrimination featuring novel frequency-based approach [8].

Why γ/n discrimination?

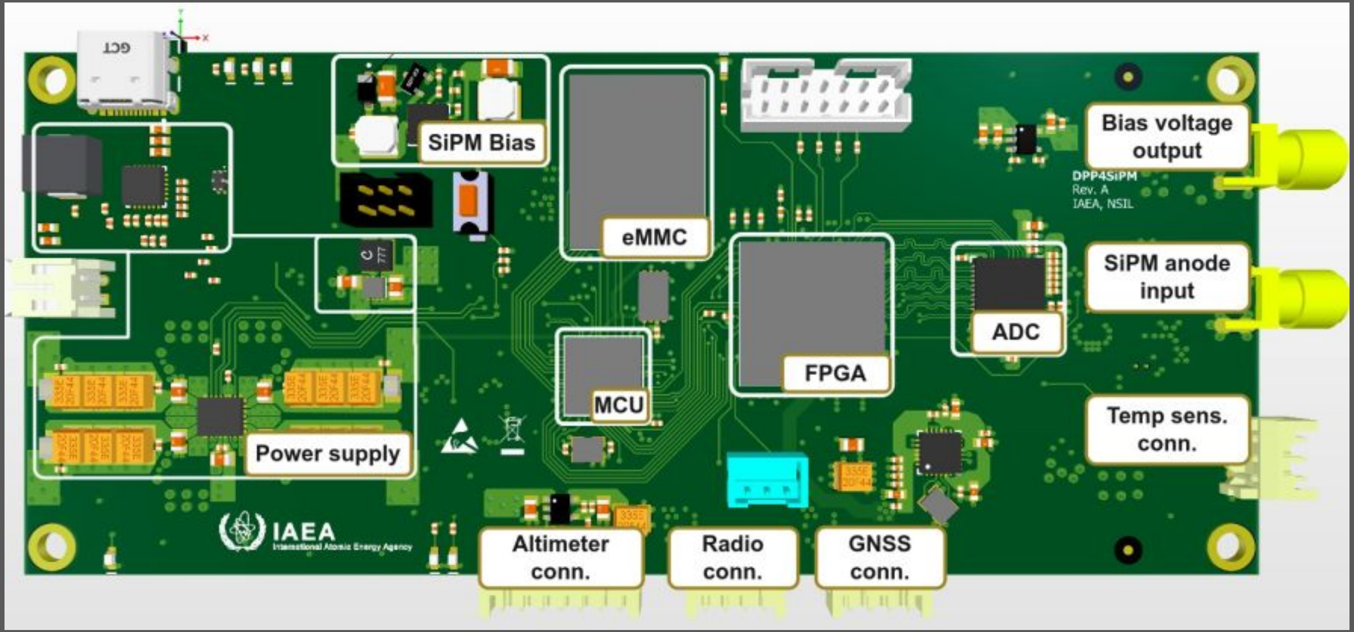
- Gamma radiation associated to neutron presence
- Several neutron applications in industry, medicine, energy, security, etc.







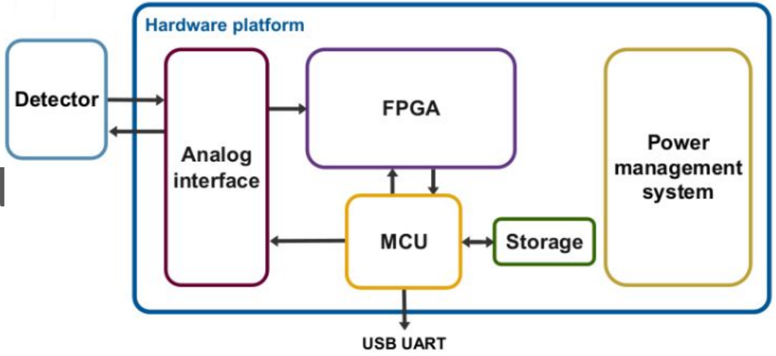
Hardware setup

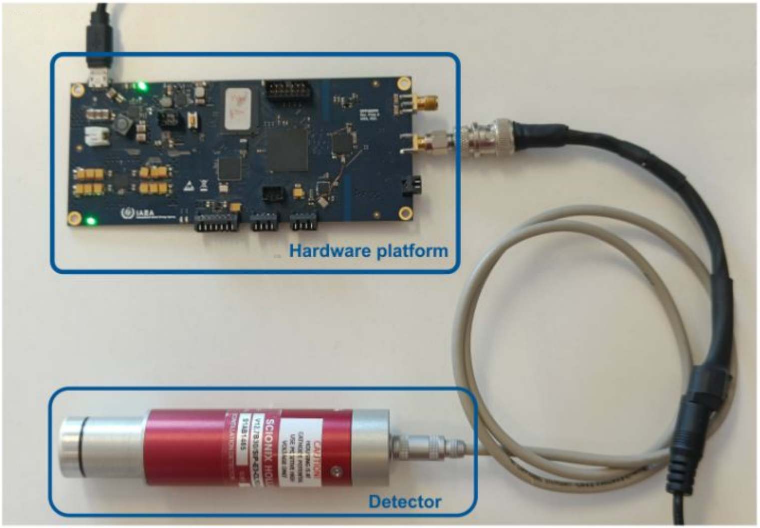


Render of custom DAQ board for low-SWaP radiation monitoring system

Hardware setup

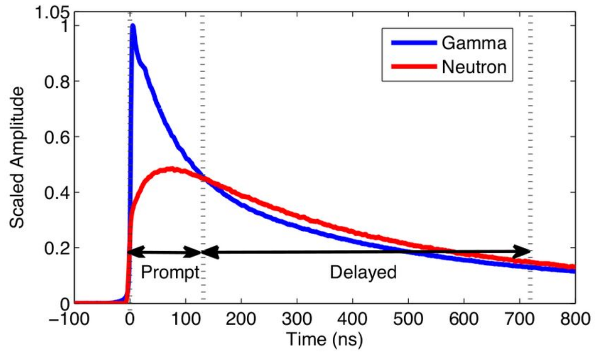
- IAEA/NSIL low-SWaP DAQ board
- Off-the-shelf CLYC detector

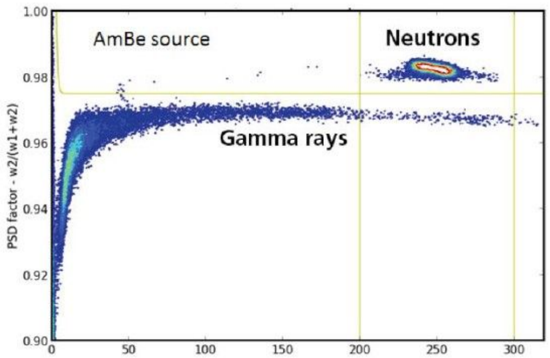




CLYC scintillator

- 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

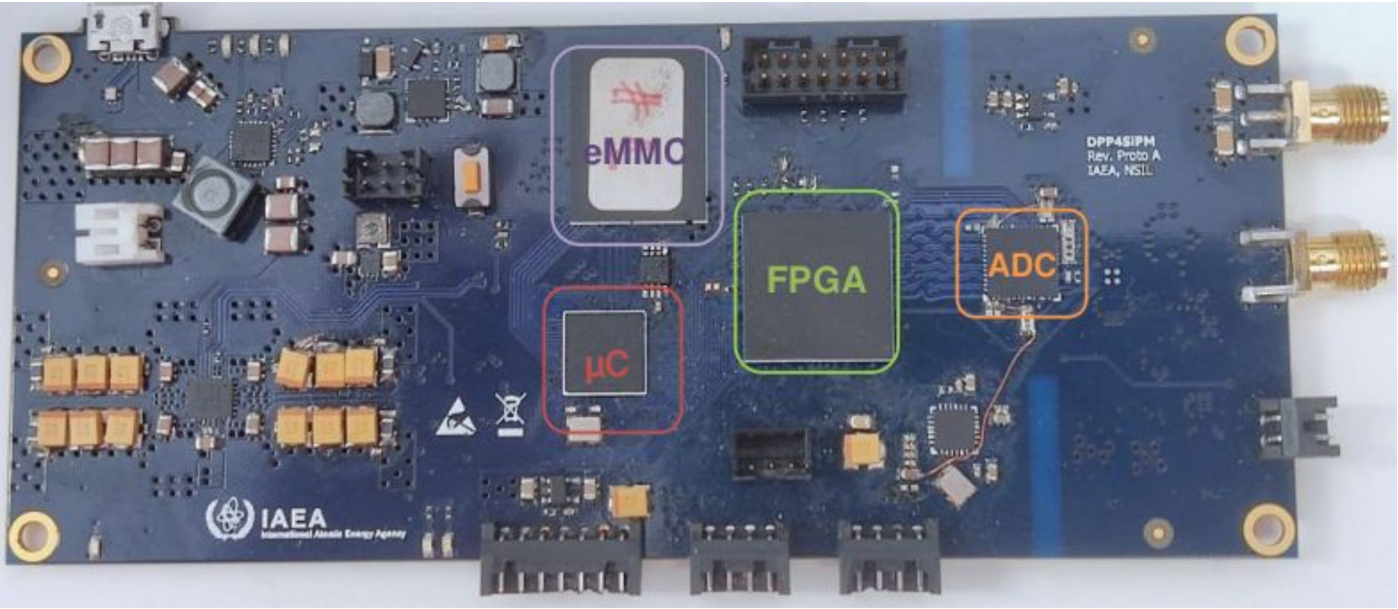




Mixed radiation detector based on CLYC

- 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

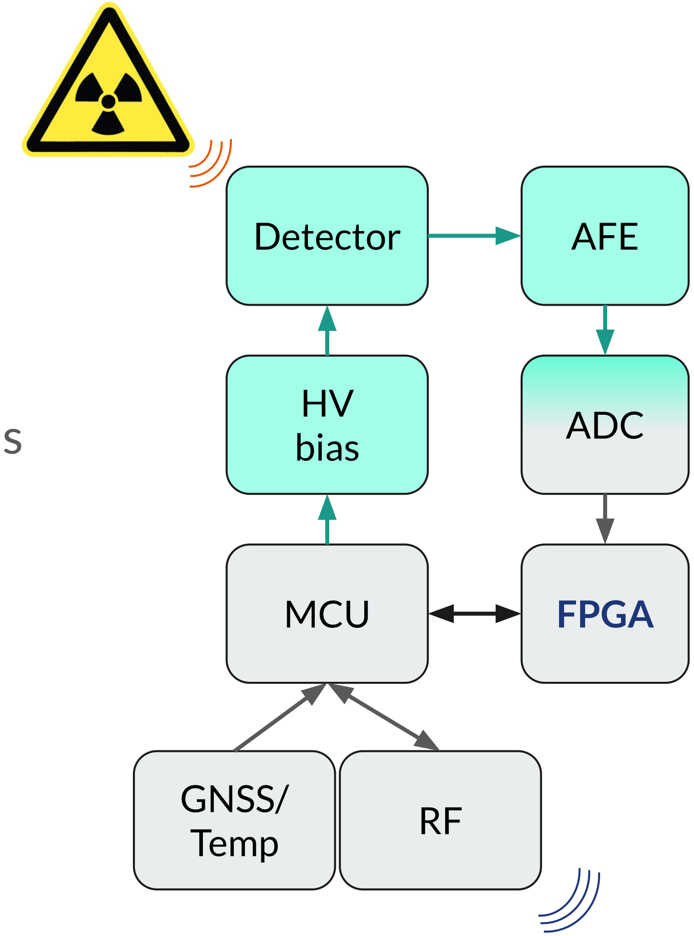


HV bias supply

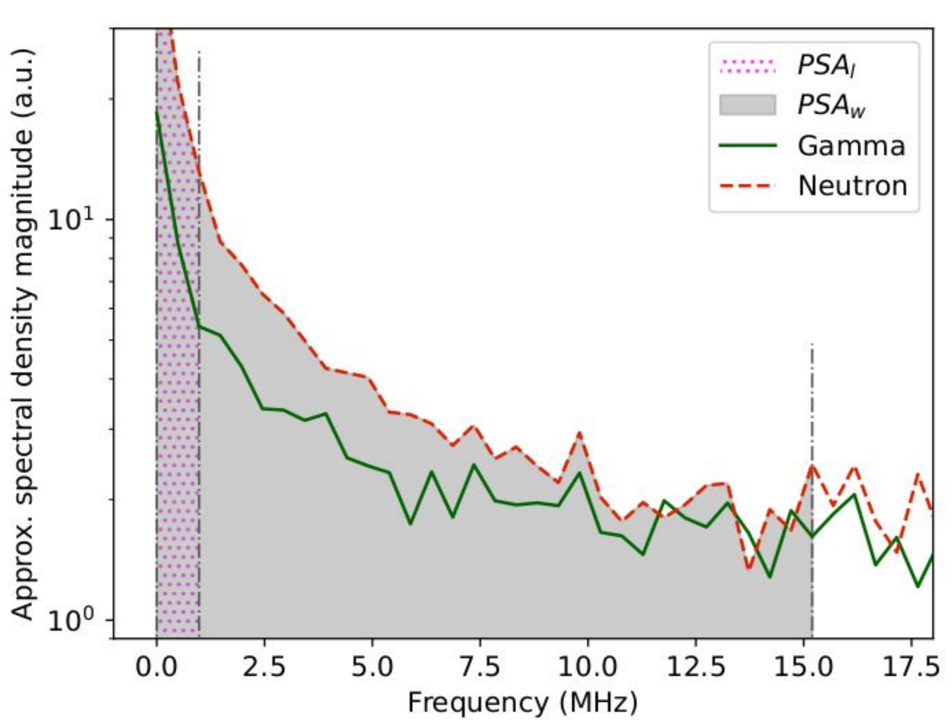
SiPM input

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.



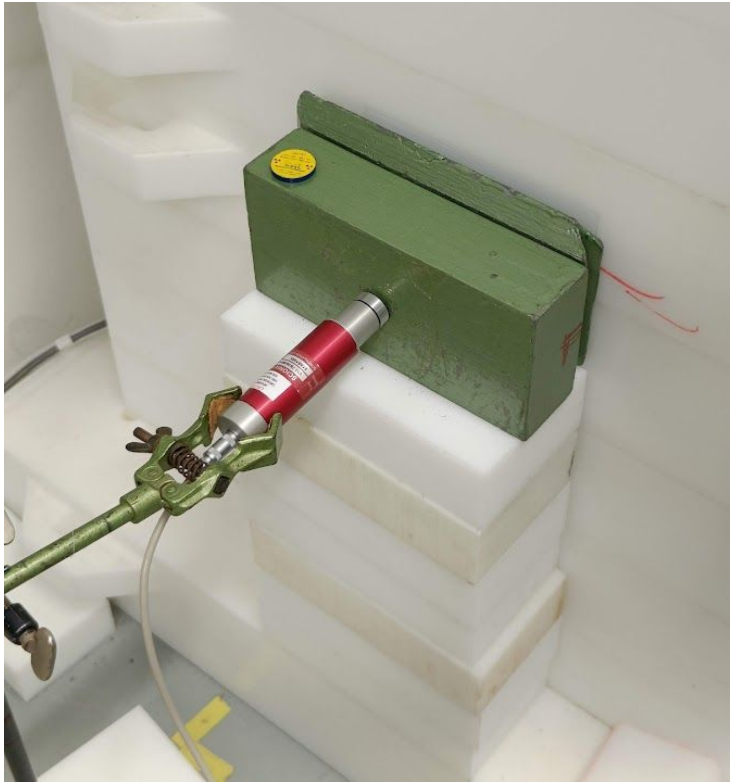
Data collection and analysis



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

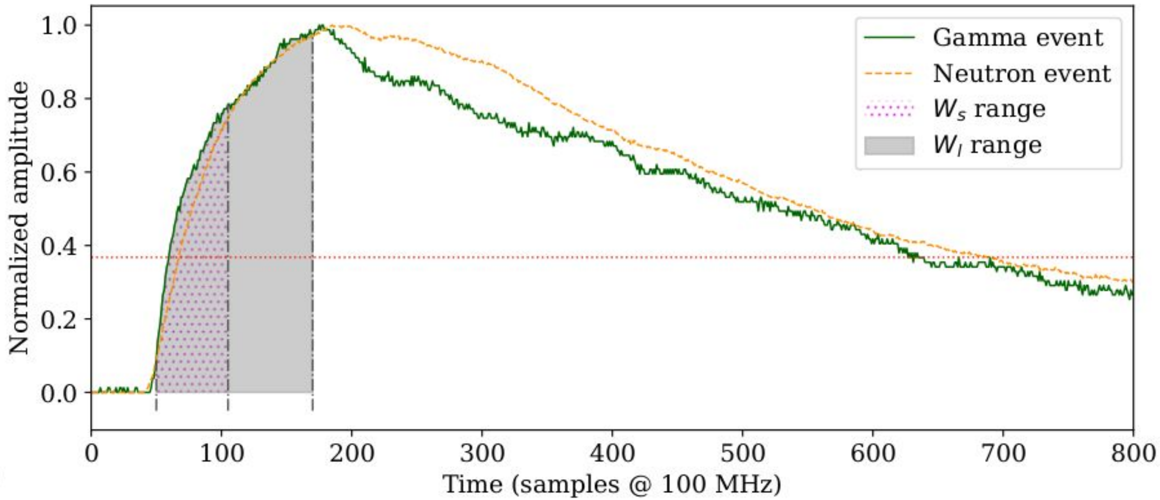
Data collection

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



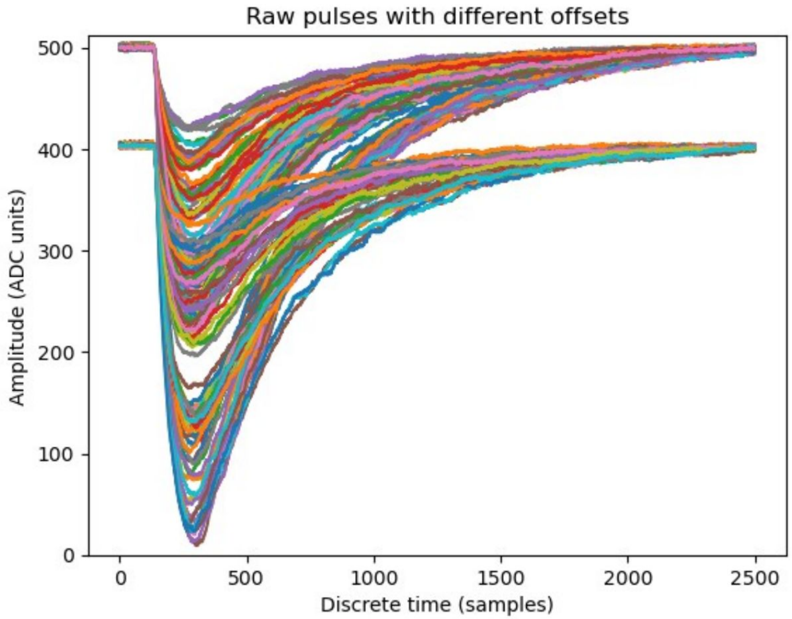
Data wrangling

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



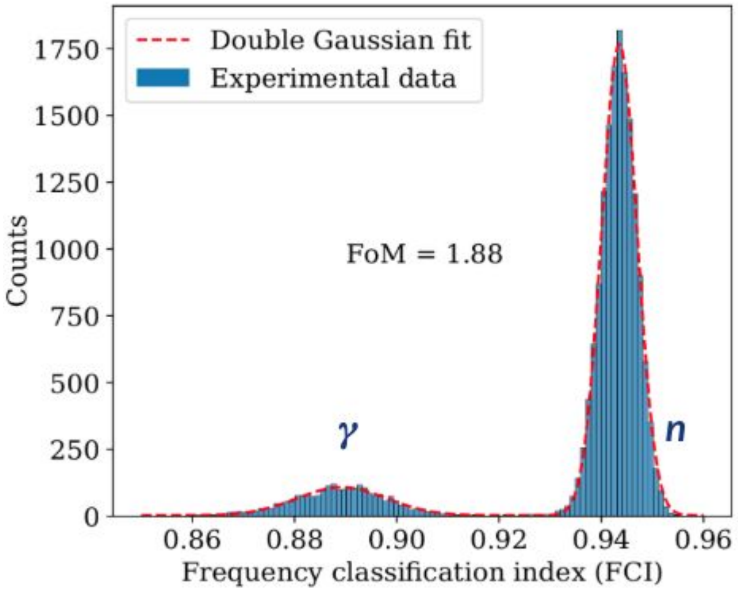
Data features after wrangling

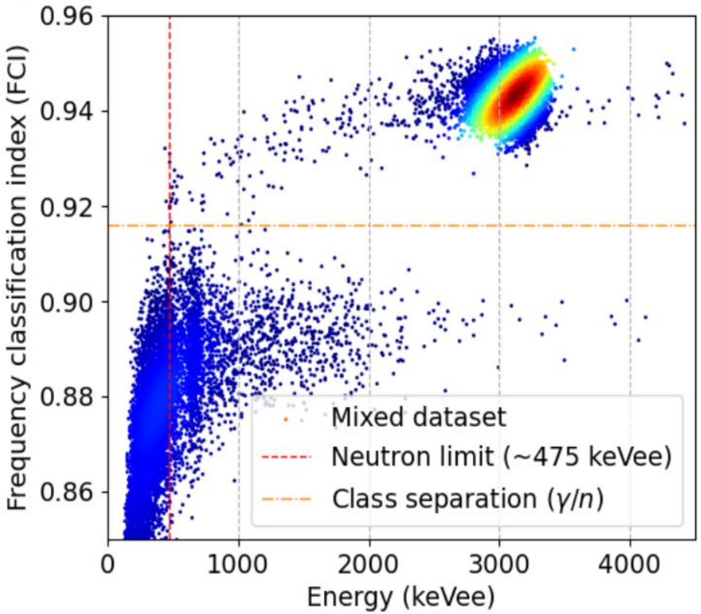
- Slight pulse shape differences between gamma/neutron
- Diverse baseline shifts
- Sampled at 4 Gsps
    - Further downsampled for real-time processing
- No pile-up distortion



Data tagging

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



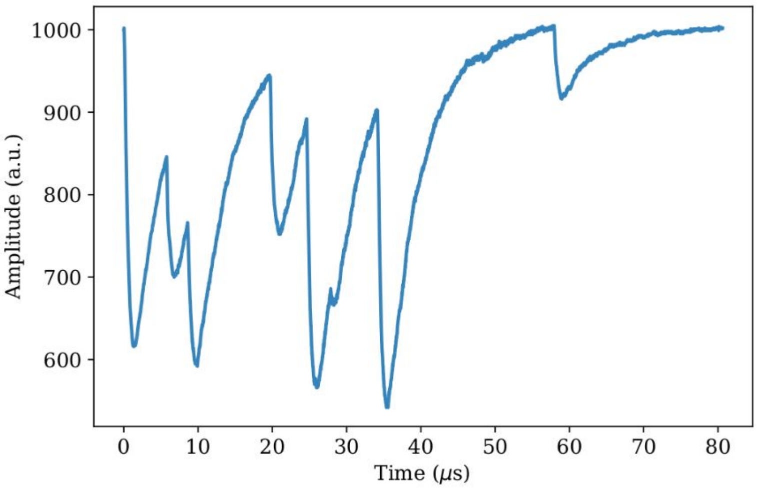


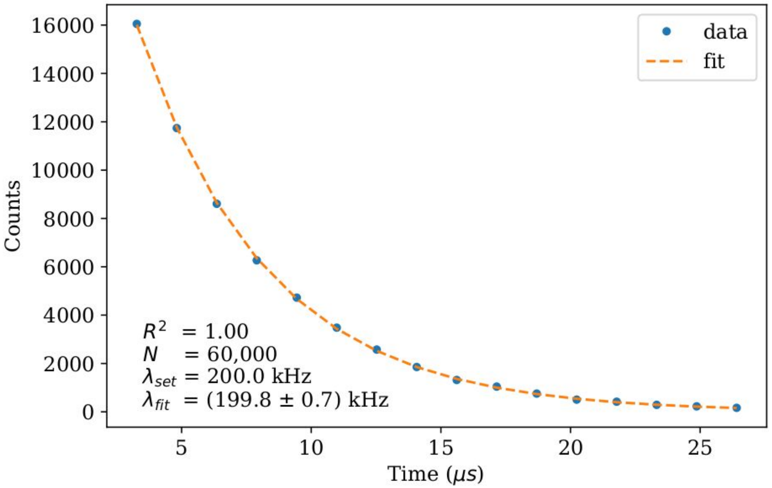
n

γ

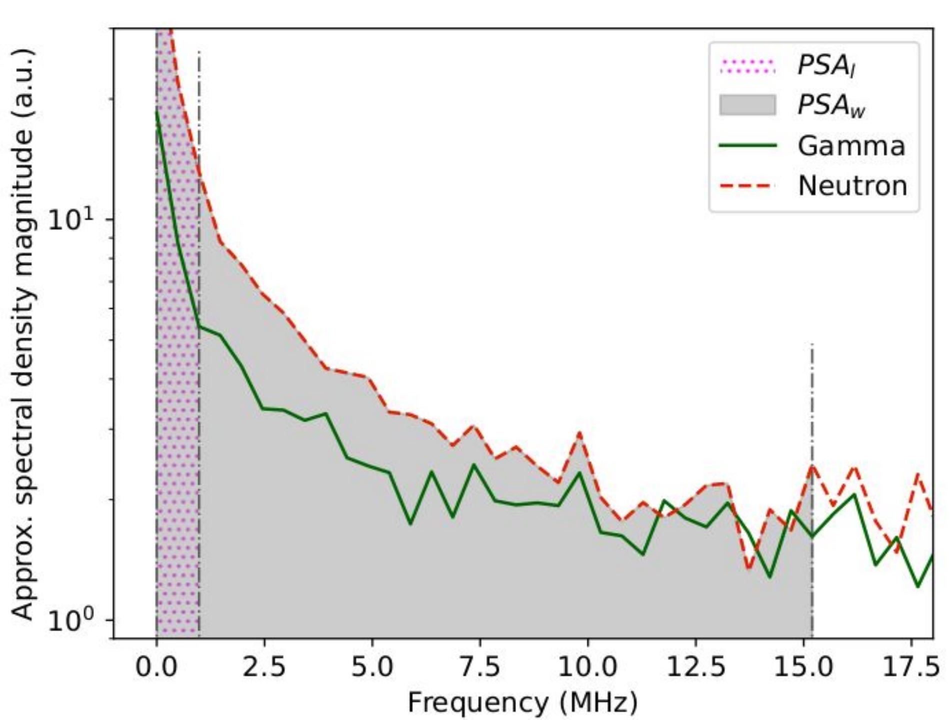
Pile-up synthesis for ML training

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





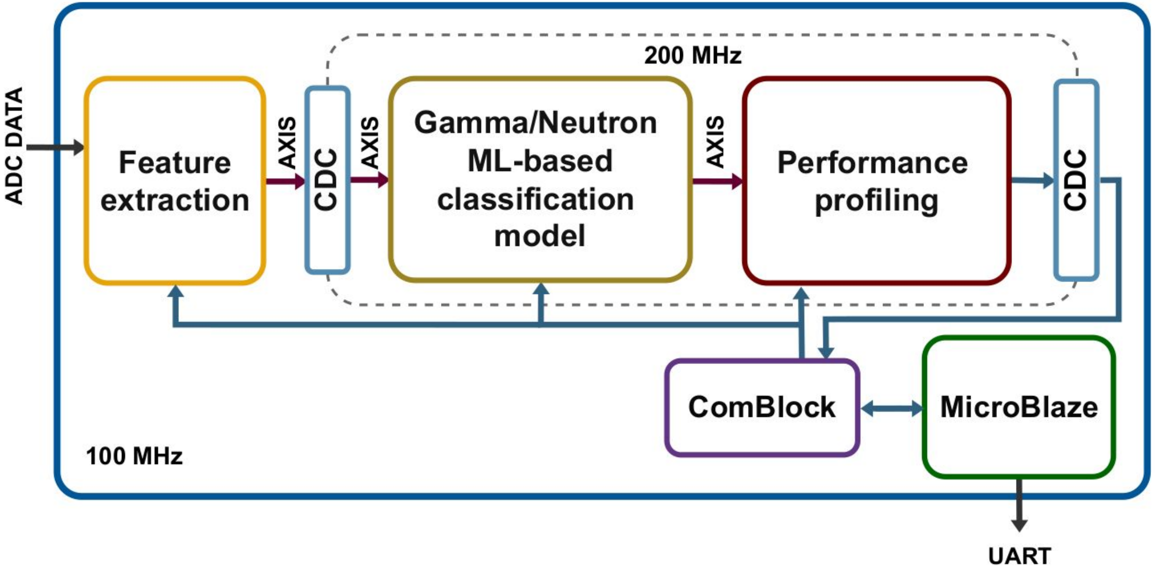
Real-time event processing with ML



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

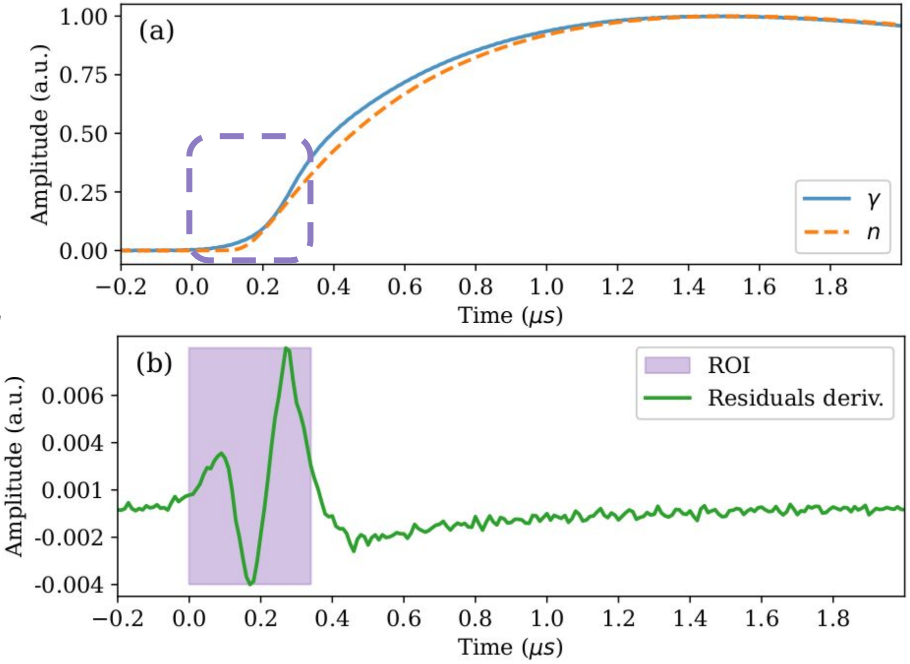
FPGA system architecture

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

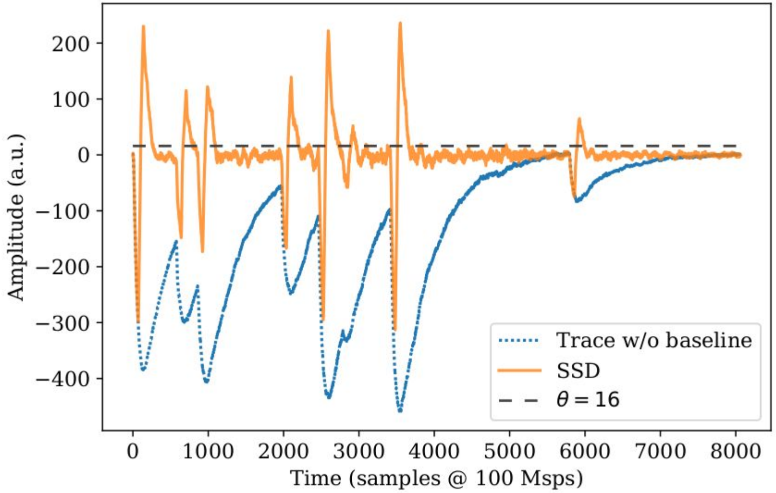


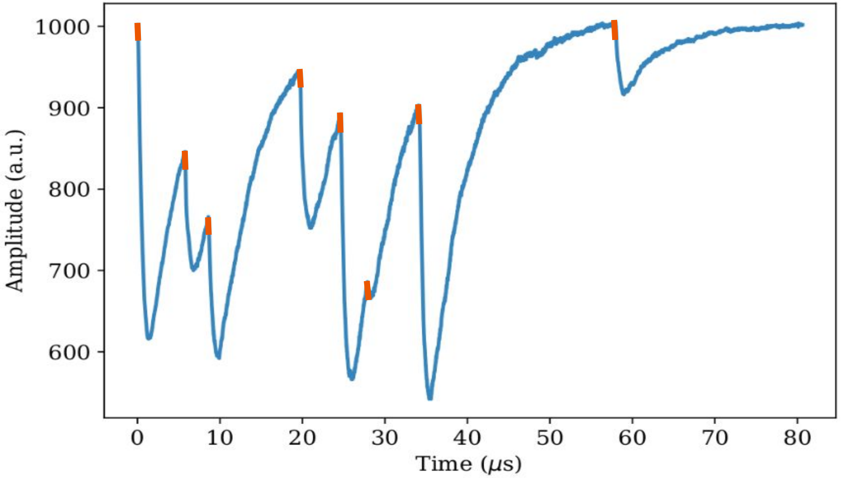
Real-time feature extraction

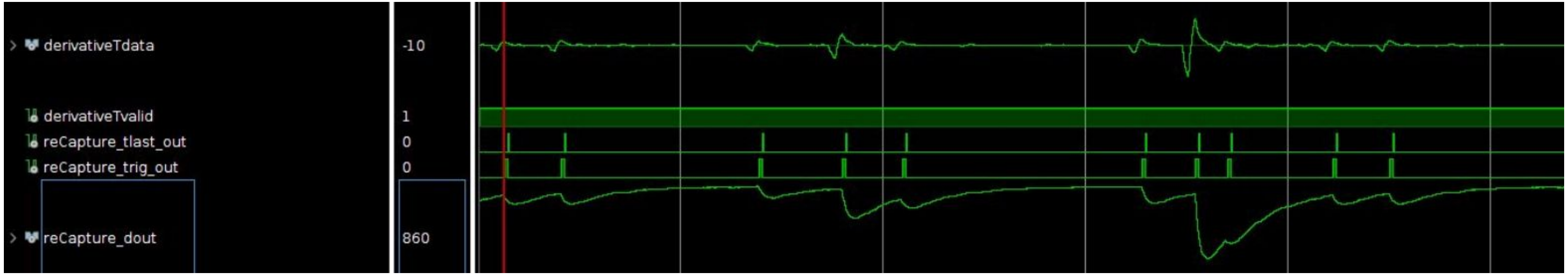
- Pulse leading edge
- First 350 ns (pulse 30 μs)
- No time alignment required
- 2nd derivative trigger (SSD)
  - IIR bandpass differentiator
- Python model
- VHDL real-time module



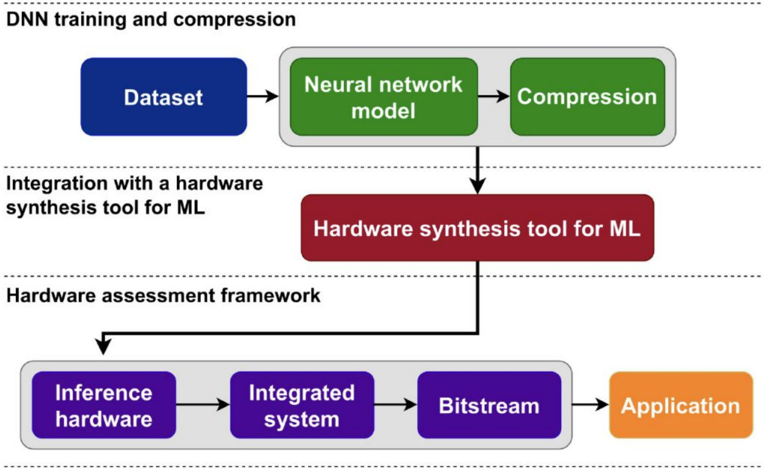
Real-time feature extraction





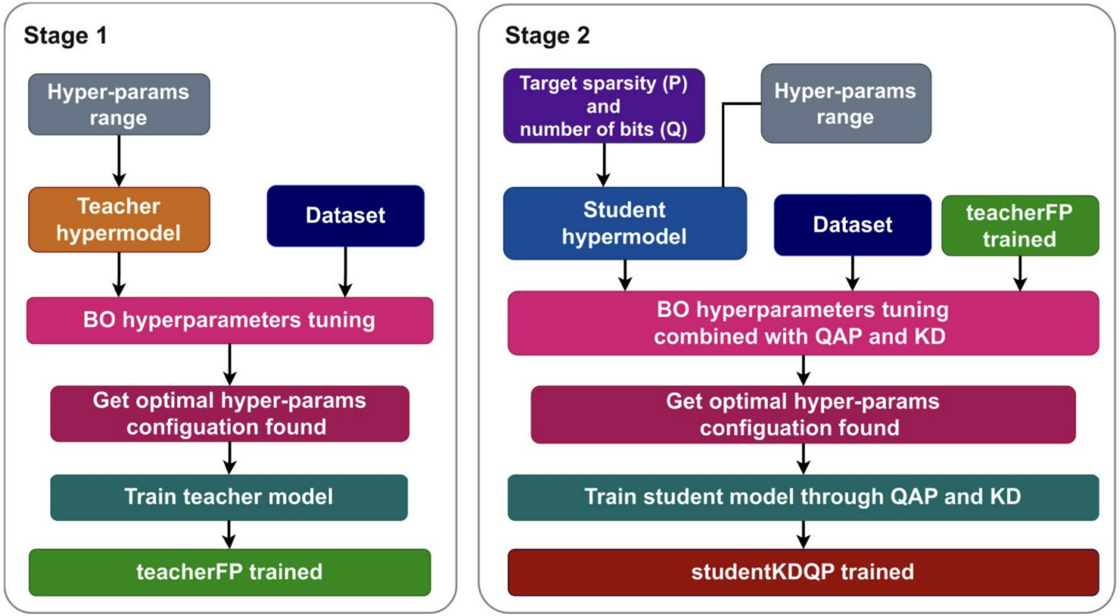


Machine learning workflow



QKeras

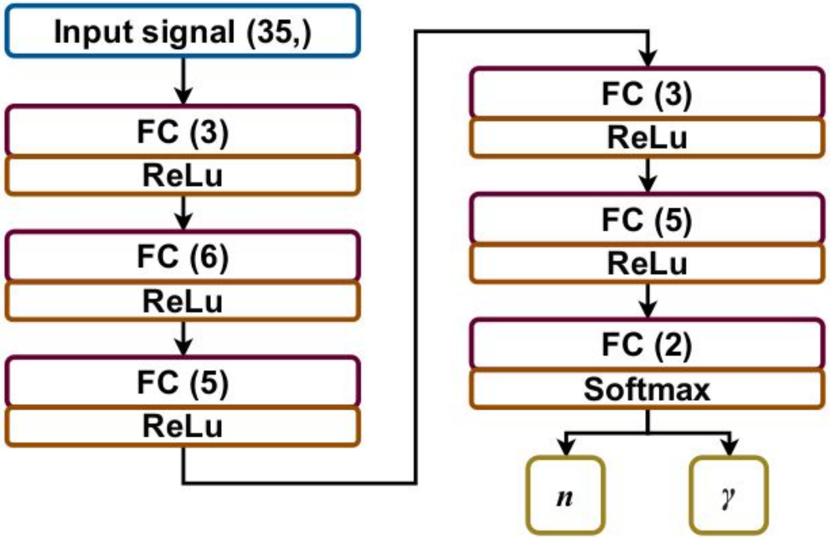
hls4ml



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%.

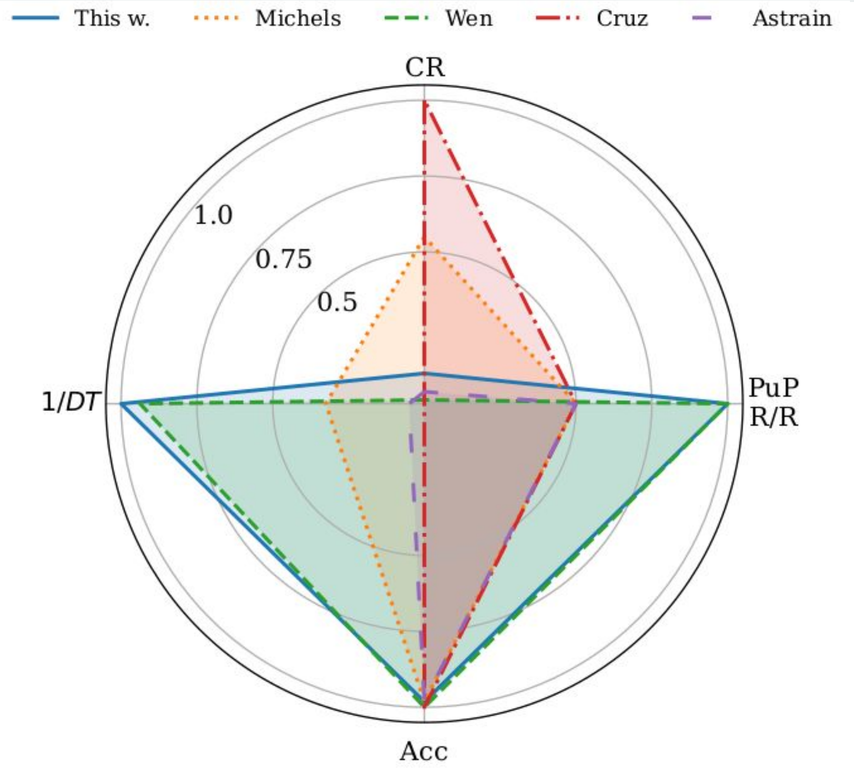


Results

Results: performance

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

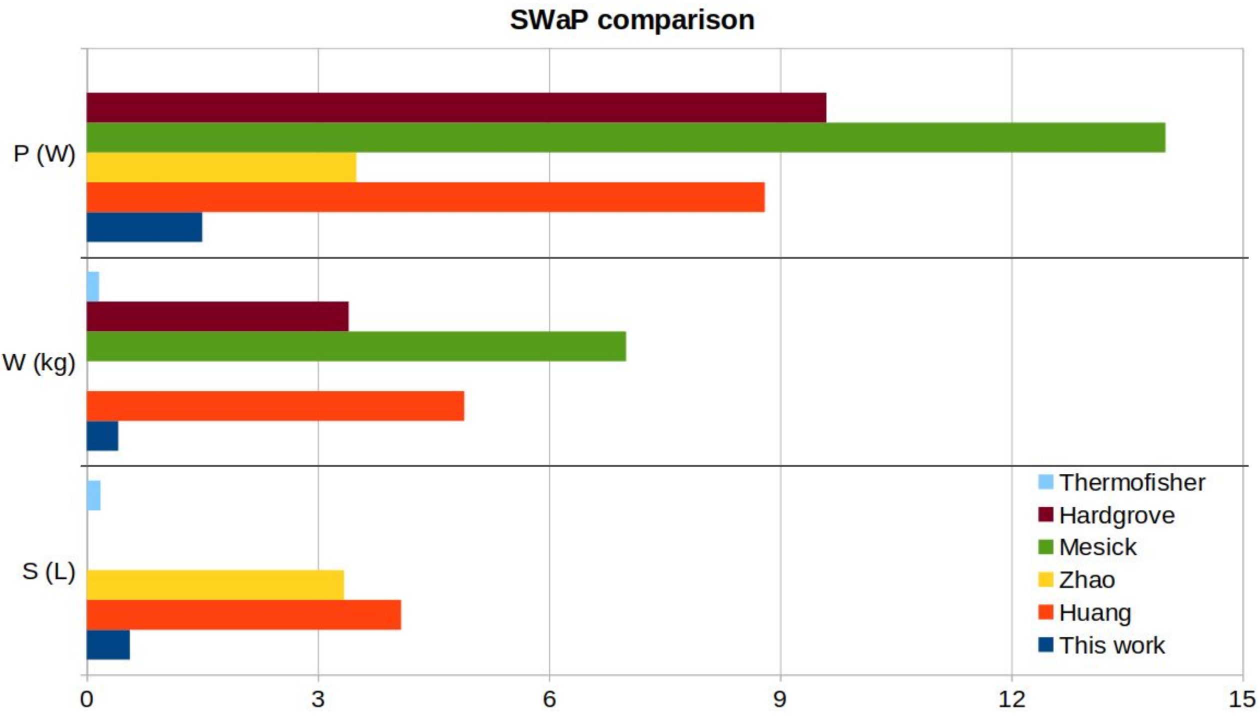
Work	Overall perf.
This work	1.0
Michels et al.	0.89
Wen et al.	0.12
Cruz et al.	0.01
Astrain et al.	0.01



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

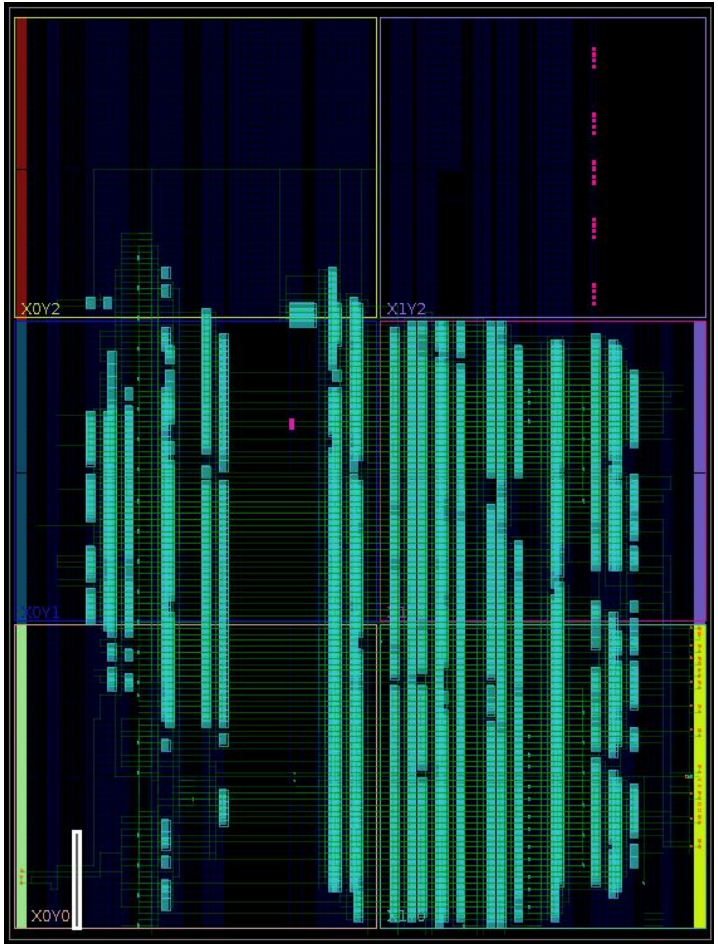
Mesick et al.
https://digitalcommons.usu.edu/smallsat/2020/all2020/118/

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%

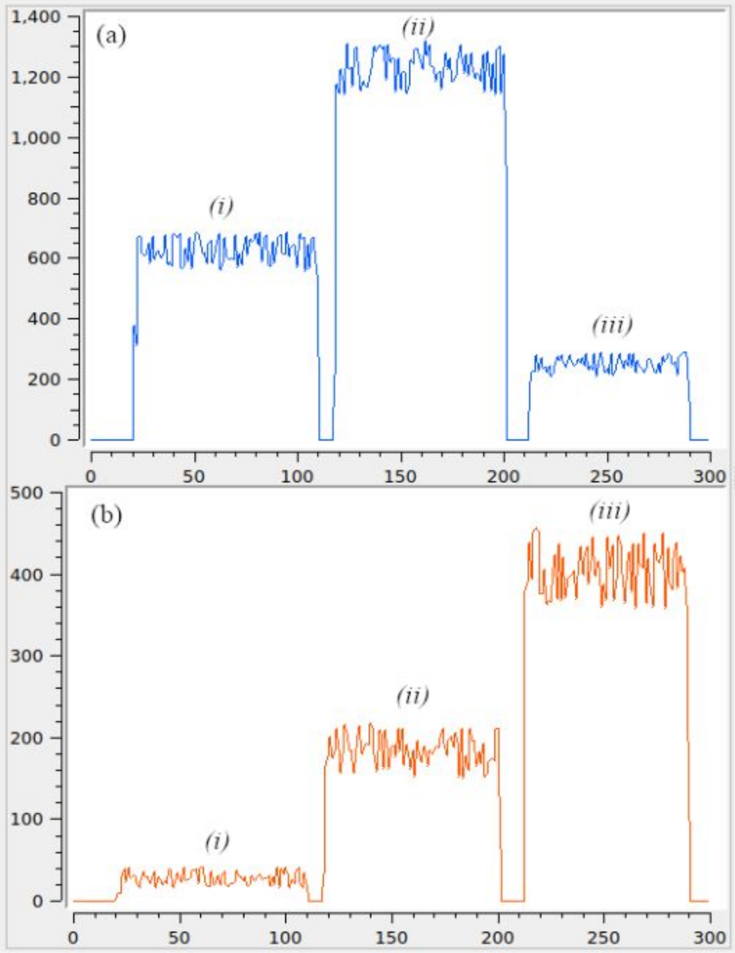


Validation with γ+n events

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

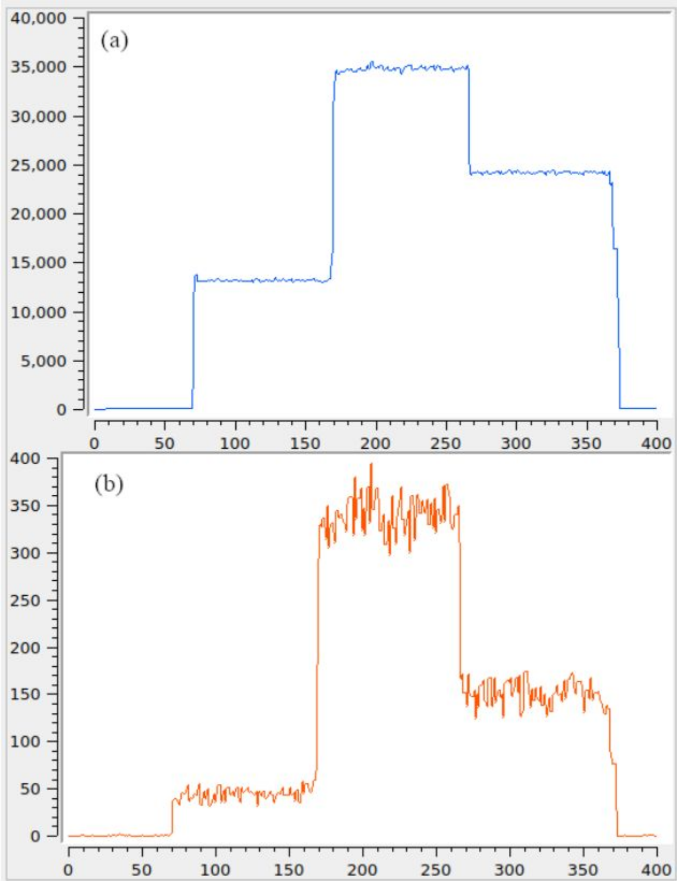
- Runs
    - (i) Gamma-only events
    - (ii) AmBe + Cs-137 sources
    - (iii) DD neutron gen. + Cs-137

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

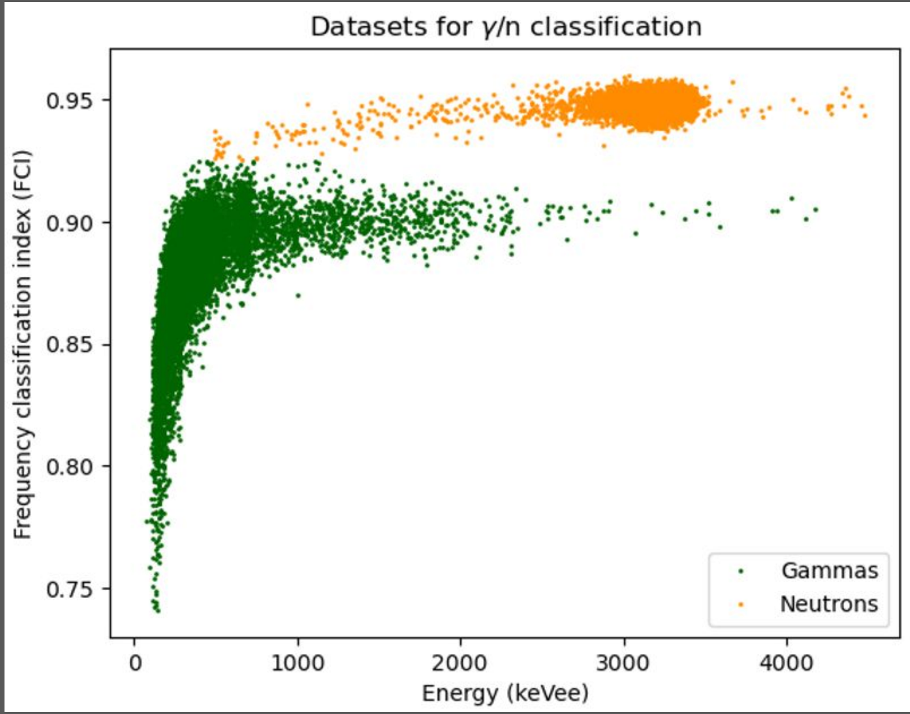


Validation with other detectors

- 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.

References

[1] Homola, P., Beznosko, D., Bhatta, G., Bibrzycki, Ł., Borczyńska, M., Bratek, Ł., ... & Woźniak, K. W. (2020). Cosmic-ray extremely distributed observatory. *Symmetry*, *12*(11), 1835. https://doi.org/10.3390/sym12111835
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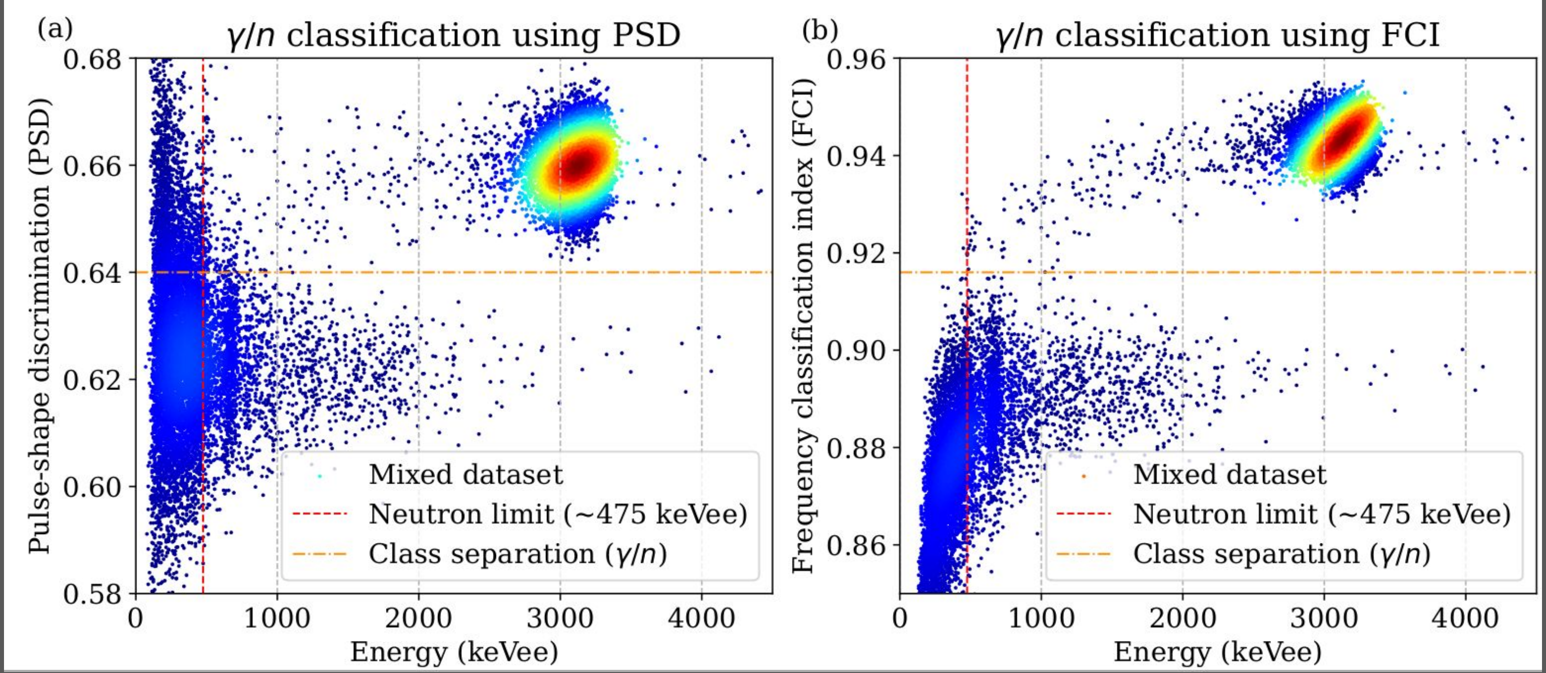
Thanks for your attention

MLab, ICTP (Italy)

ECFM, USAC (Guatemala)

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	-

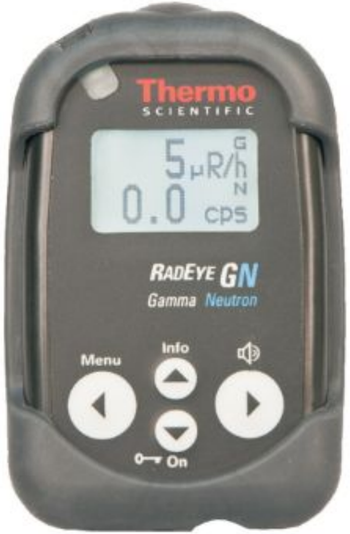
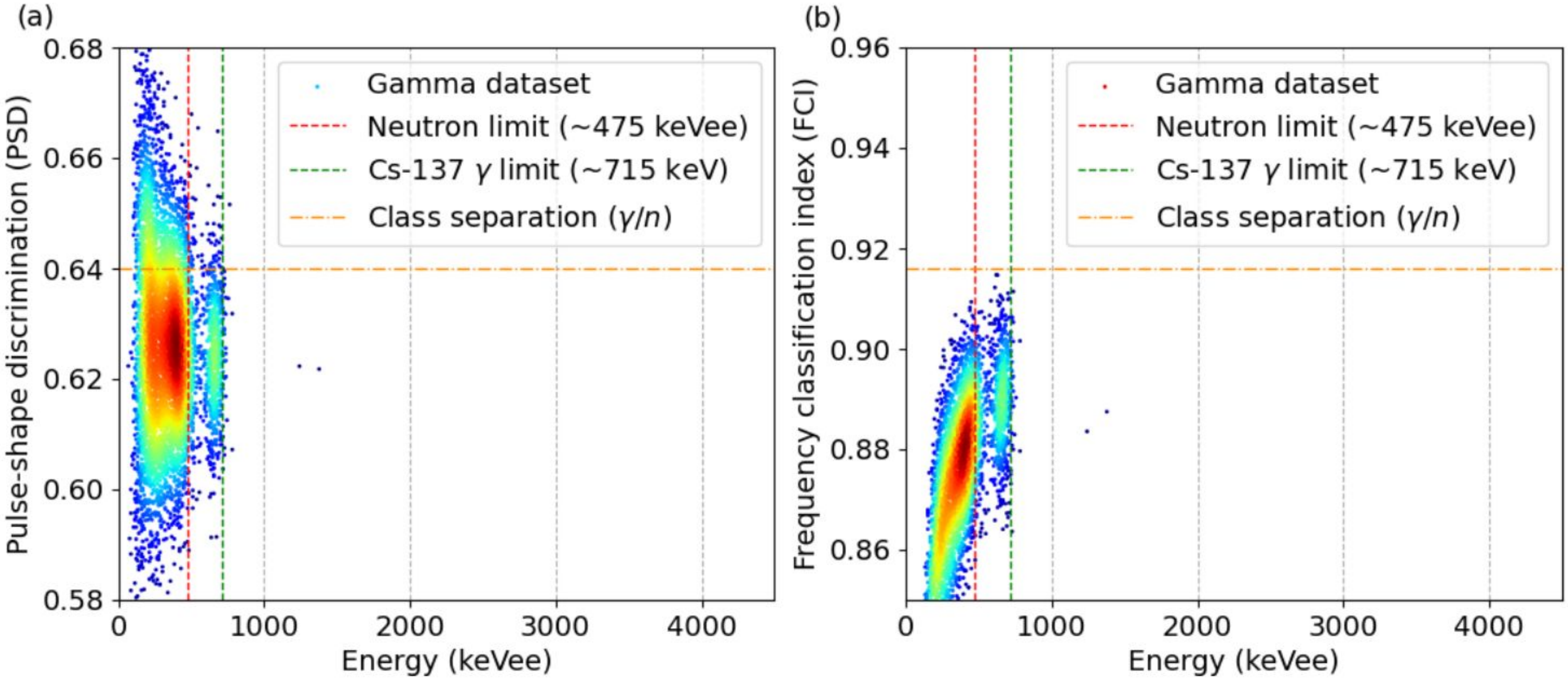
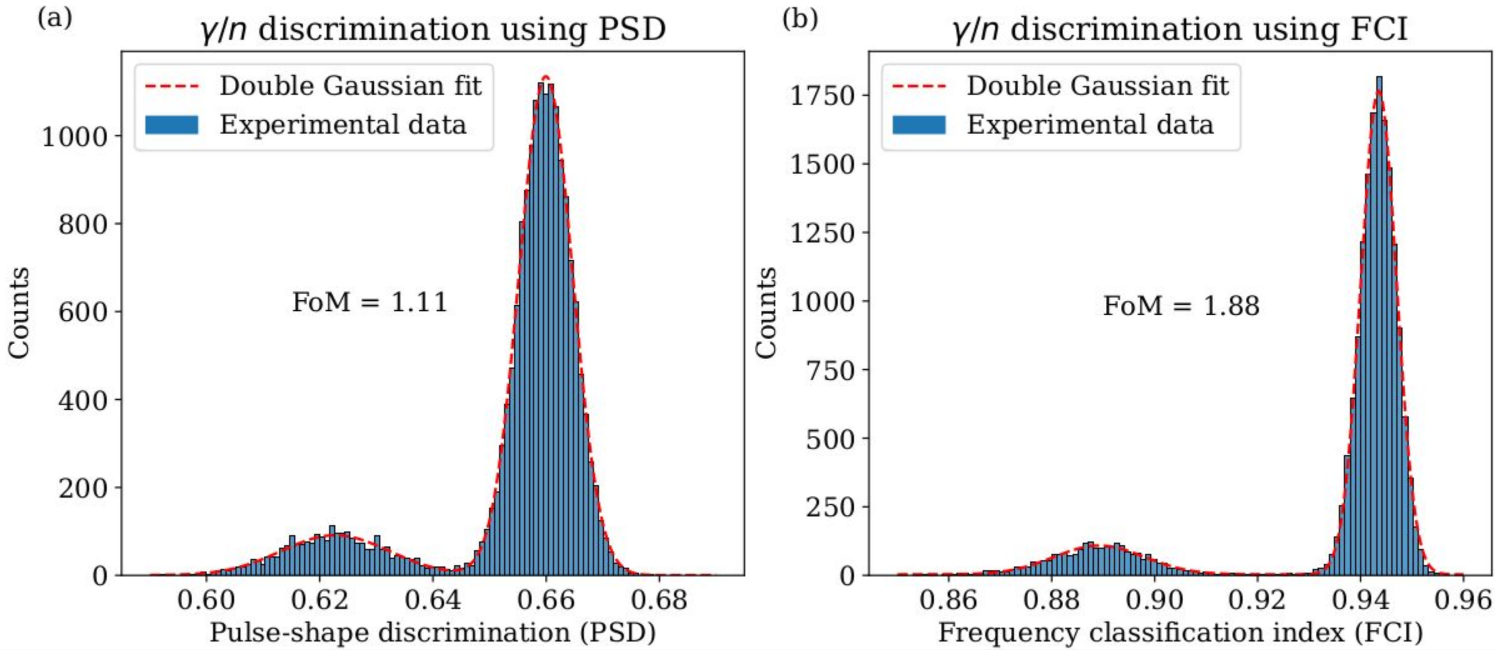


Table 5.2: SWaP comparison of recent CLYC-based γ/n discrimination systems, including SaW and WaP scores

PSD vs FCI: gamma-only dataset



Dataset FOM for ML training



Related applications

Remote diagnostics