Data Compression and Analysis Methods for High-Throughput Radiation Detector Systems

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Introduction

- The capabilities of analog-to-digital (A/D) conversion instruments are rapidly advancing
  - High resolution (10-bit [1:1024] to 14-bit [1:16,384])
  - High sampling rates (100 MS/s to 5 GS/s)
  - High channel density (8 channels to 64 channels)
  - Low dead time (nearly zero to 10s of μsec)
  - Low cost ($100 to $10,000)

- Our ability to ***acquire*** radiation detector signals is rapidly surpassing our ability to ***analyze*** them in real-time

High-output vs. high-throughput

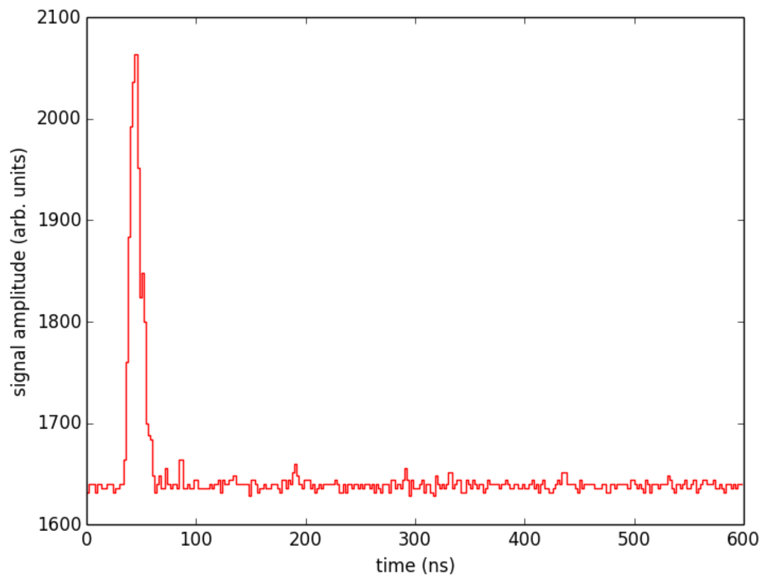
- There are many multi-modal radiation detector systems currently under development:
  - Gamma and neutron time-of-arrival, energy, and multiplicity systems
  - Fast neutron imagers
  - Spectroscopic gamma imagers

- Some of these systems can output 100s of gigabytes of digitally sampled radiation detector signals from a single measurement

- We need to develop methods to compress and analyze the signals they acquire in near real-time

Digital data acquisition

- Waveform digitizers sample the detector's analog output at regular intervals to create a digital record of the signal amplitude vs. time
- In some applications, only a few specific parameters need to be extracted from each pulse
  - Time-of-arrival
  - Energy deposited
  - Particle type
- However, in other applications, the entire digitized pulse is needed
- In still other applications, only specific patterns of pulses are needed



Waveform digitization

- CAEN VX1730:
  - Flash ADC VME module
  - Moderate sampling rate (500 MS/s)
  - High resolution (14 bits)
  - Channel density: 16 channels/module
  - High per-unit cost (~$20,000)
- PSI DRS-4:
  - Switched capacitor array
  - Moderate resolution (11 - 12 bits)
  - High sampling rate (700 MS/s to 5 GS/s)
  - Channel density: 8 channels/chip
  - Low per-unit cost (< $100 per chip in large quantities)
  - Requires several additional components for digitization (clock, ADC, FPGA); PSI offers an evaluation board
  - Large dead-time for readout

CAEN VX1730

Data analysis and compression

- A single waveform record is typically on the order of 1 to 2 kilobytes
- Detector systems that employ a large number of channels can rapidly acquire gigabytes to terabytes of data
- Analysis to extract arrival time, energy, and particle type can reduce the record to a few bytes
- In applications where the digitized pulse is required, there are methods to compress the record
  - Retain only the portion of the record above the baseline
  - Decimate the trace into a smaller number of samples representing the integral over specific portions of the pulse
- In some applications, only specific patterns of pulses need to be recorded
- In all 3 cases, there are tradeoffs between throughput and fidelity of the measurement – and what constitutes "fidelity" is highly application-specific

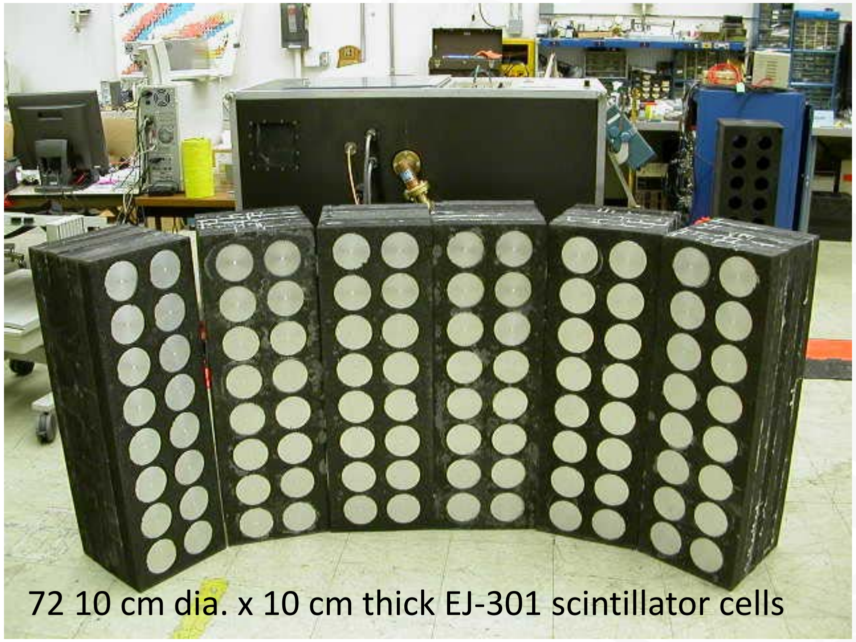
Strategy for research

- We plan to conduct research in data analysis and compression in 3 related areas
  - Mine existing data acquired by high output detector systems to extract useful signatures of SNM corresponding to specific pulse patterns
  - Apply optimization to pulse compression to study tradeoffs between throughput and fidelity
  - Develop data acquisition logic to reduce the "data velocity" at the front-end of different detector systems

- We've identified 3 detector systems that can serve as test-beds for the research
  - LLNL liquid scintillator array
  - ORNL/SNL fast neutron coded aperture camera
  - SNL fast neutron single volume scatter camera

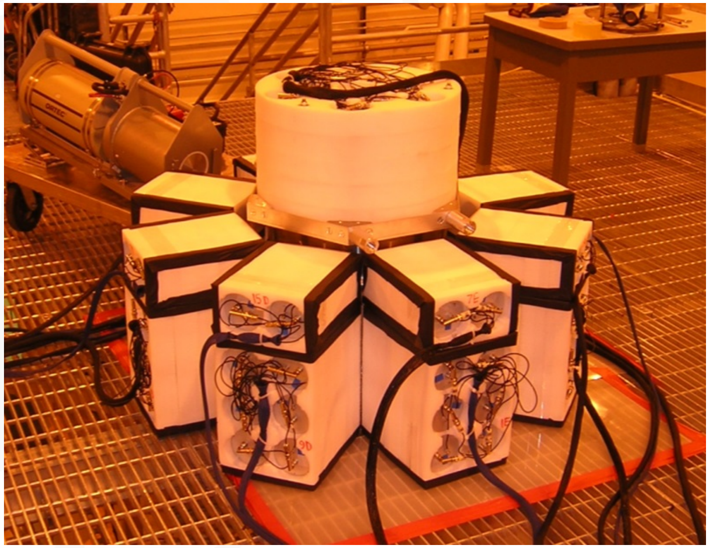
LLNL liquid scintillator array

Original configuration



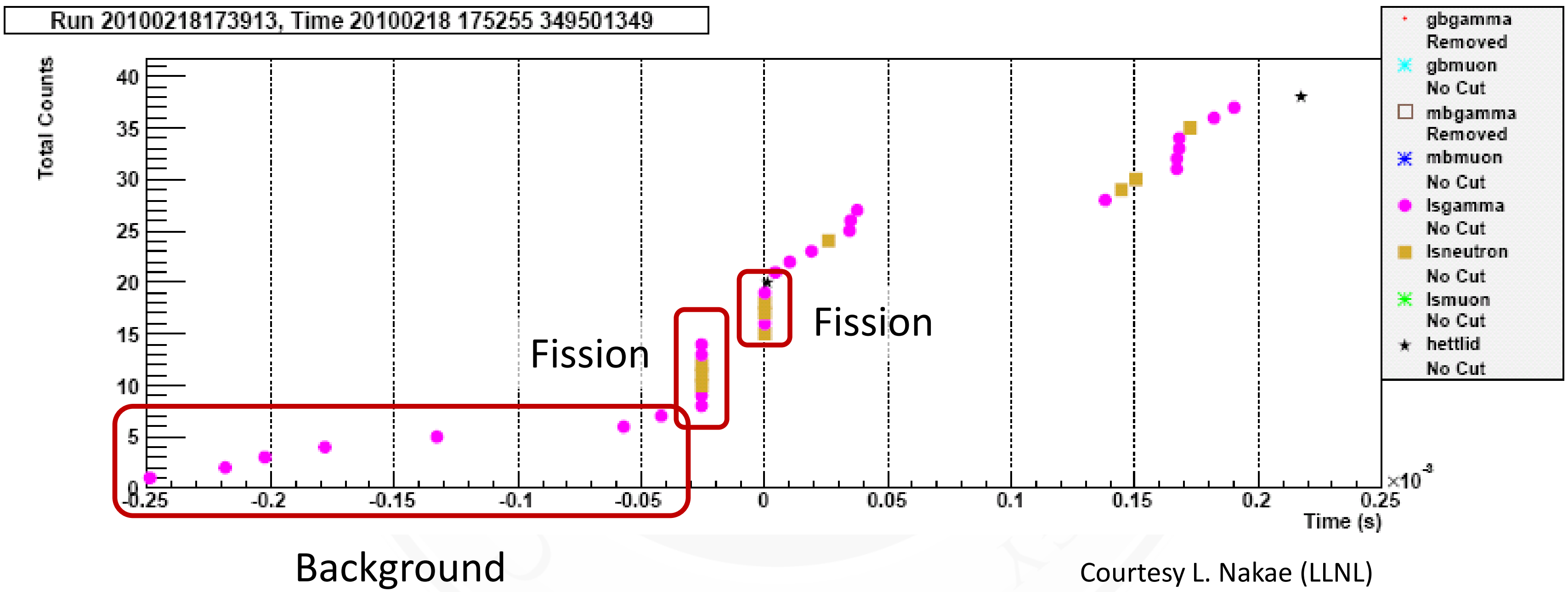
72 10 cm dia. x 10 cm thick EJ-301 scintillator cells

Latest configuration



Courtesy L. Nakae (LLNL)

Fission chain-reaction dynamics

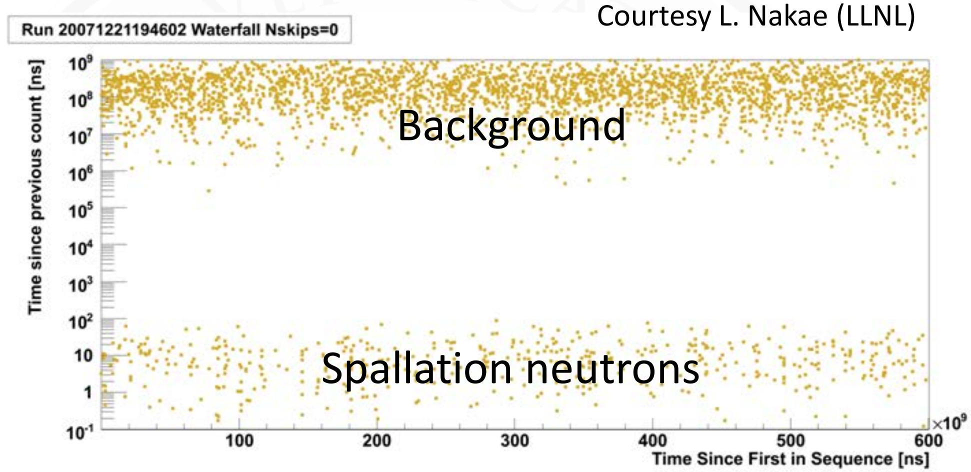


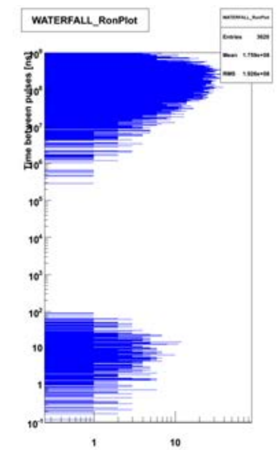
Courtesy L. Nakae (LLNL)

Fission chain-reaction dynamics

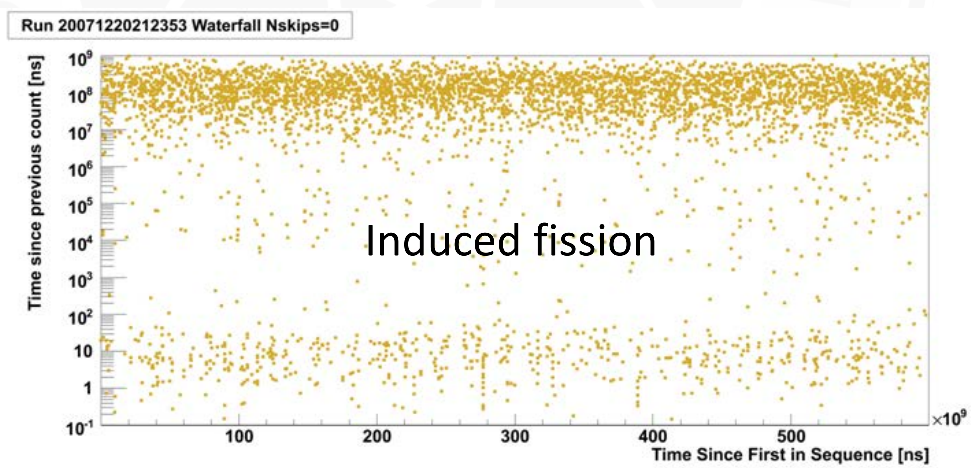
Courtesy L. Nakae (LLNL)

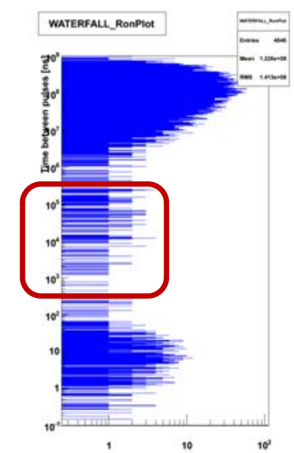
1 ton of lead



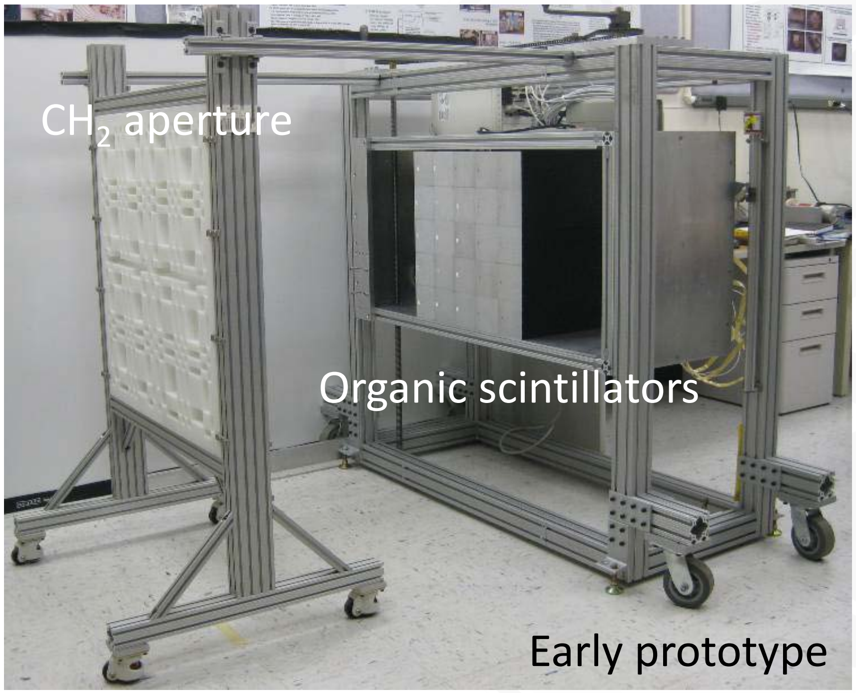


1 ton of lead +
HEU metal
(multiplication 2.5 to 3)

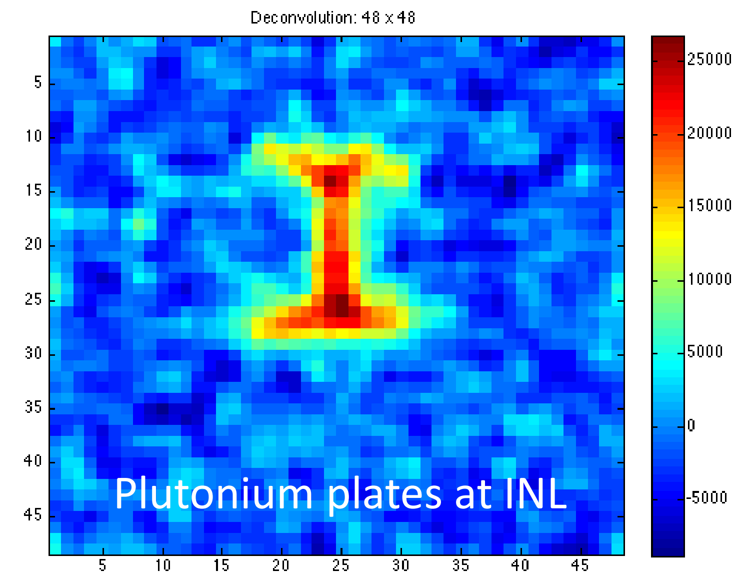




ORNL/SNL fast neutron coded-aperture imager



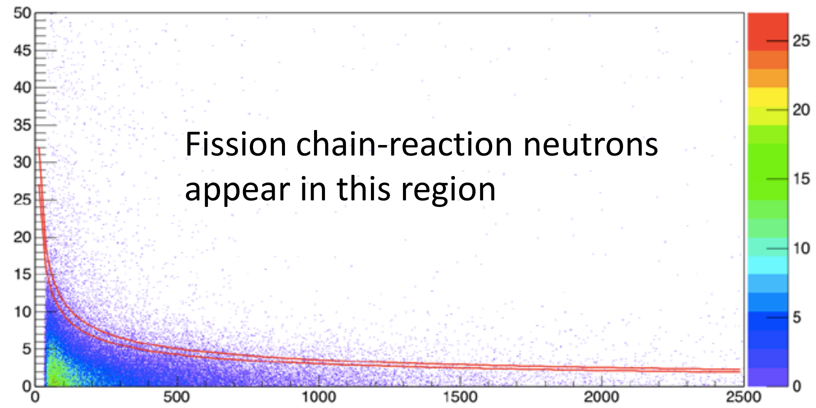
P. Marleau (SNL), et al., INMM 2011

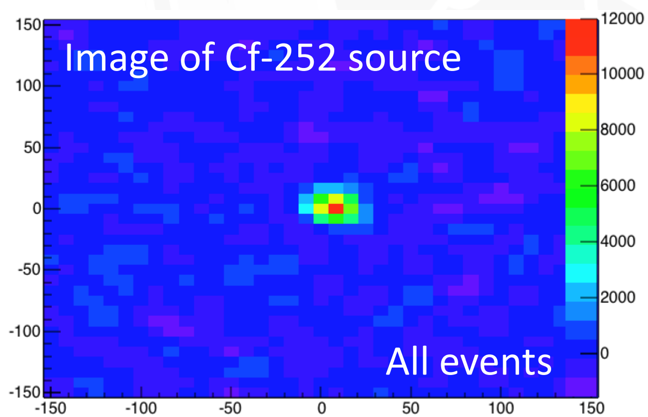


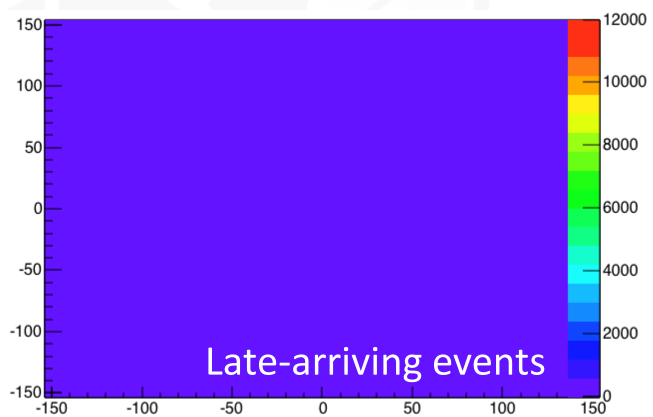
M. Blackston (ORNL), et al., INMM 2012

"Filtering" fast neutron images for fission chain-reactions

Neutron time since preceding gamma vs. energy

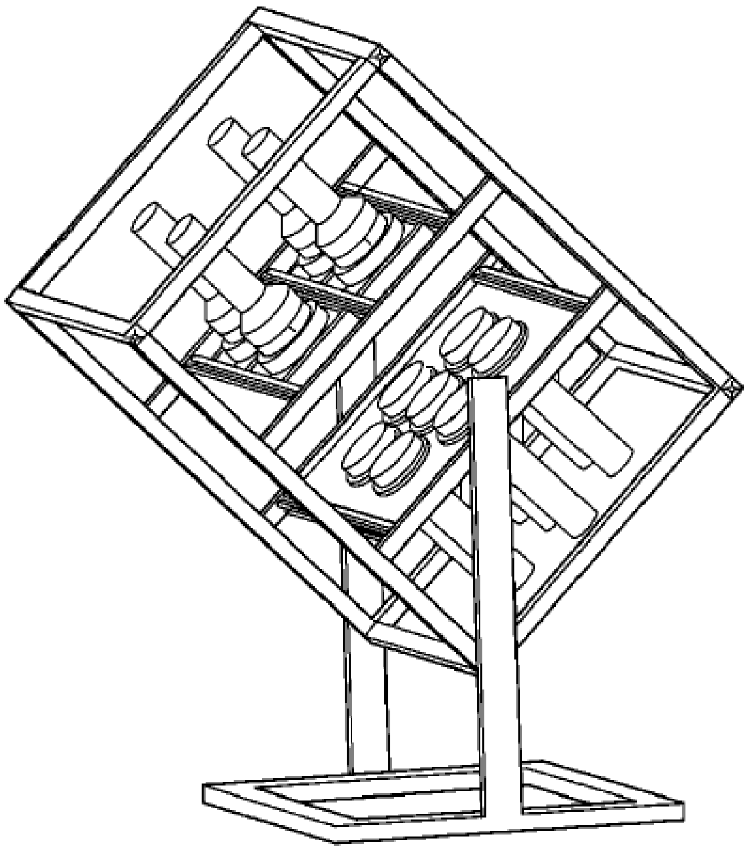






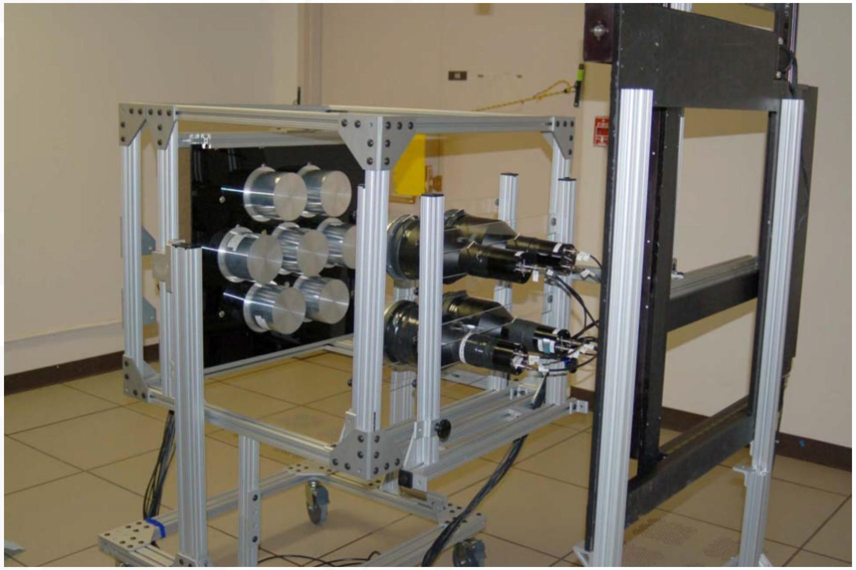
J. Linkous (NCSU)

SNL multi-volume scatter camera



SNL patent US 7741613 B1

Original 11-cell version

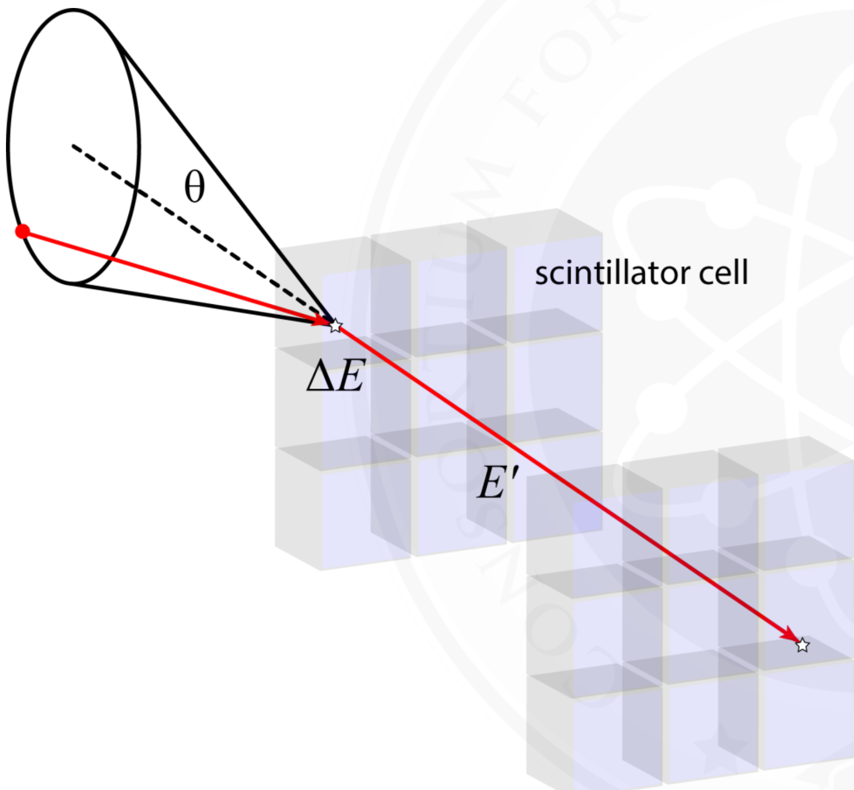


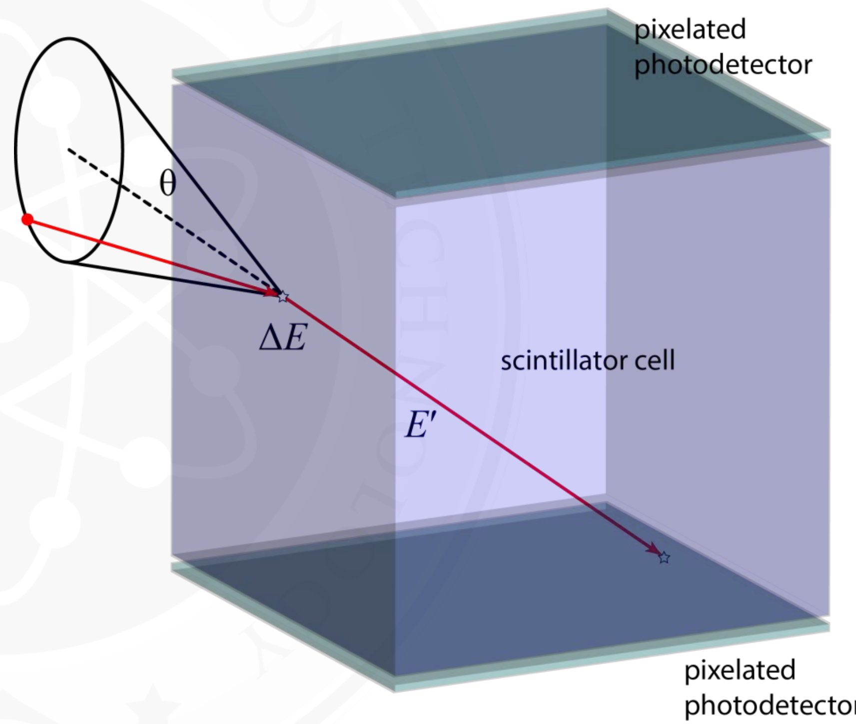
P. Marleau (SNL), et al., IEEE NSS 2007

The current version uses 32 organic scintillators

SNL single-volume scatter camera (SVSC)

Multi-volume camera | **Single-volume camera**

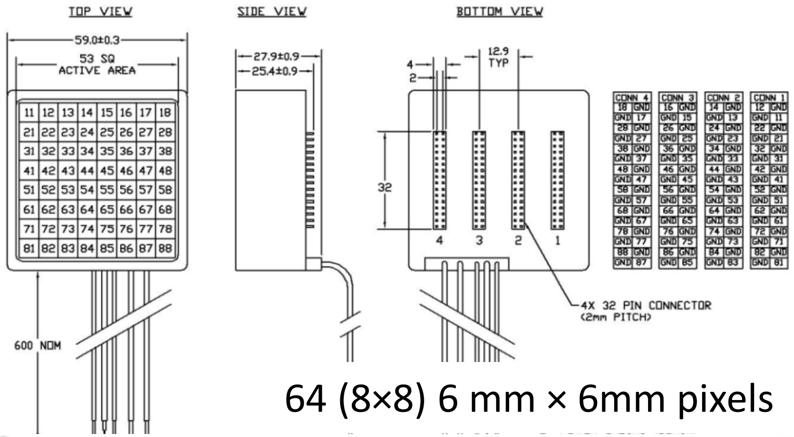




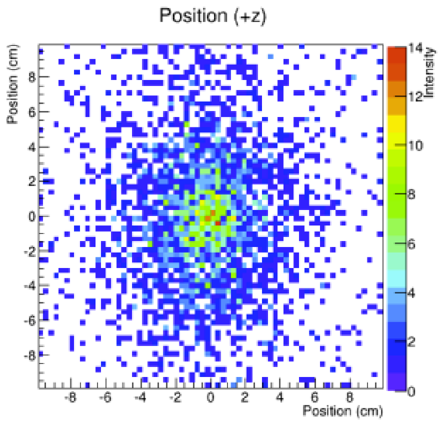
not to scale
nominally 20× 20× 20 cm^3 volume

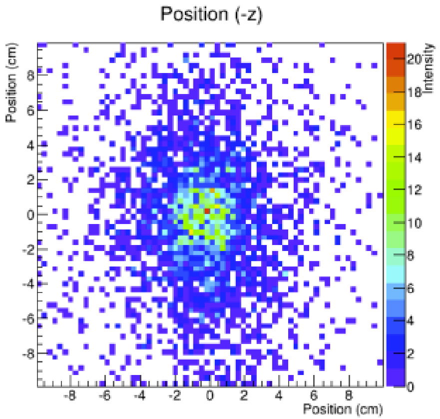
Scintillation position reconstruction

Photonis pixelated MCP photomultiplier



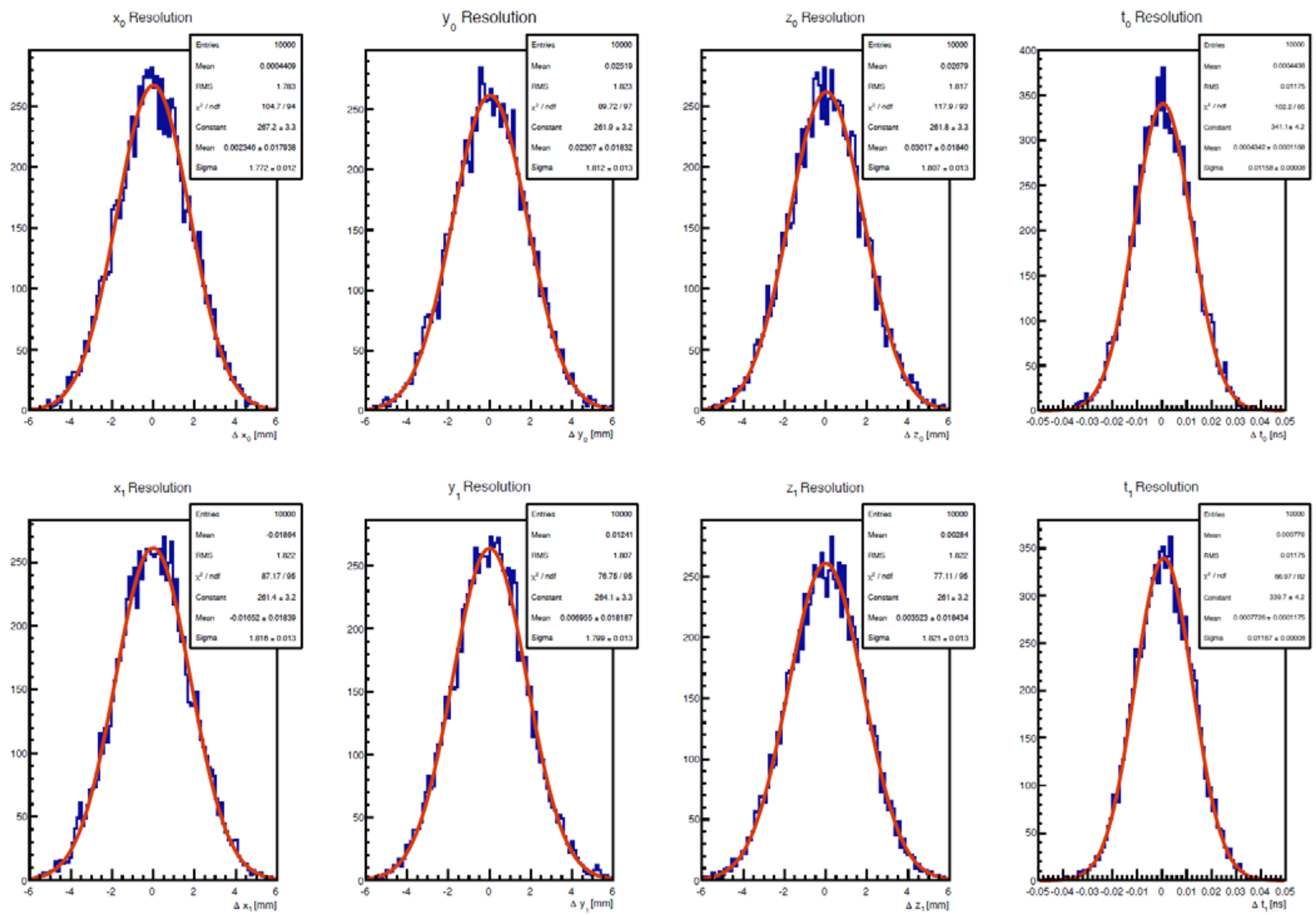
Scintillation event at origin (simulation)





K. Weinfurther (NCSU)

Double-scintillation event reconstruction using direct likelihood maximization



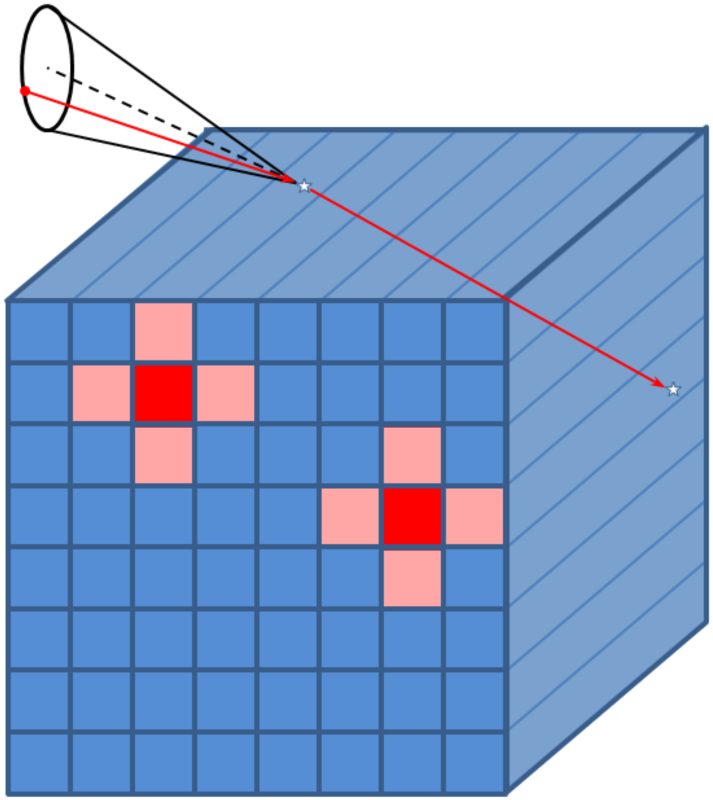
Courtesy E. Woods (SNL)

Optically-segmented SVSC

- Event reconstruction that uses the entire "data cube" containing the response of ~2048 pixels recorded at ~1024 intervals of 200 ps is not practical (that's 4 megabytes acquired in 250 ns for one event)

- SVSC's current long-term strategy for analysis is to implement data acquisition logic that retains only useful samples (i.e., only retain samples where photons were detected)

- NCSU and SNL are investigating a second alternative design that optically segments the scintillator to reduce the number of channels

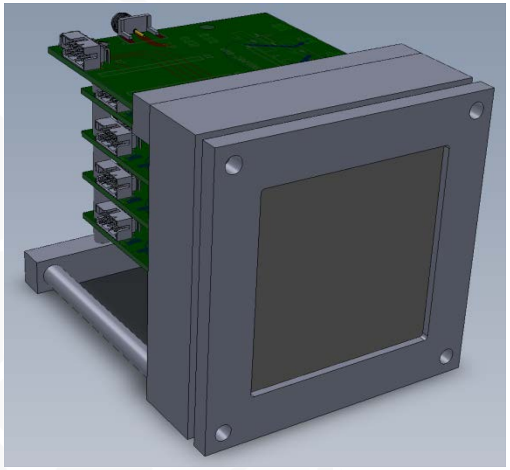


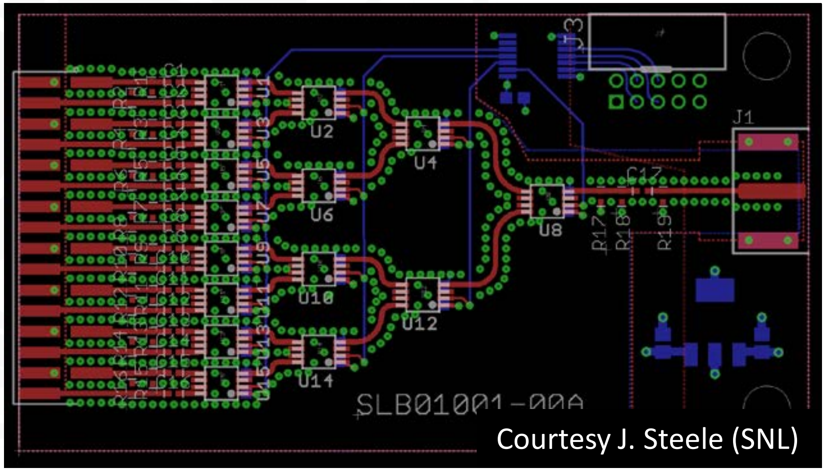
Data acquisition logic

- Using an optically segmented design, it may be possible to reduce the number of channels that need to be digitized to 20
  20 channels =
  (brightest cell + 4 nearest neighbors) ×
  (2 scintillation centers) ×
  (2 photodetectors)

- However, it will require a network of switches to “route” the correct channels to the digitizers

- It will also require an array of low-cost discriminators to trigger the switches and delay components to time the digitization correctly





Courtesy J. Steele (SNL)

Summary

- There are numerous alternative approaches to data analysis and compression for “high data velocity” detector systems

- We plan to research 3 main areas:
  - Identify specific pulse patterns that are signatures of SNM by mining existing data
  - Study tradeoffs between throughput and fidelity by applying optimization to pulse compression
  - Reduce the “data velocity” at the front-end of different detector systems using data acquisition logic

- There are 3 existing detector systems that are good candidates for study:
  - LLNL liquid scintillator array
  - ORNL/SNL fast neutron coded aperture camera
  - SNL fast neutron single volume scatter camera

SUPPLEMENTAL SLIDES

Onboard data compression

- Struck Innovative Systeme (SIS) :
  - Moderate sampling rates
  - Moderate to high resolution
  - Moderate channel density
  - Some SIS digitizers provide onboard compression of digitized signal into user-defined gate integrals

http://www.struck.de/sis3316.html

Particle type discrimination using gate integrals

- Compressing the digitized waveform into a small number of gate integrals substantially increases throughput in high event rate applications

- However, it can also degrade particle type discrimination

- Gamma misclassification (i.e., as a neutron) can occur when multiple pulses occur in the same record