HIGH-THROUGHPUT RADIATION DETECTOR SYSTEMS

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Background

• Analog-to-digital (A/D) conversion instruments are advancing rapidly in terms of resolution, sampling rate, channel density, and cost

• Our ability to acquire radiation detector signals is surpassing our ability to analyze them in real time

• There are many multi-modal radiation detector systems currently under development by NNSA and other government agencies to support future arms reduction initiatives:
  – 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 to terabytes of digitally sampled radiation detector signals from a single measurement

• We are working with ORNL, SNL, and Duke to develop alternative methods for data compression and analysis in high-throughput radiation detector systems
SNL single-volume scatter camera (SVSC)

- Relative to a multi-volume scatter camera, an SVSC can potentially have 10× higher efficiency.
- In order to attain such high efficiency, the camera has to be able to resolve sequential neutron scatters separated by 1 – 2 cm.
- To resolve such closely-spaced interactions, the photodetectors’ \((x, y, t)\)-dependent waveforms have to be fully digitized.
- That is one of the most significant challenges to designing a functioning SVSC.

Expected size \((20 \text{ cm})^3\)
Optically-segmented single-volume scatter camera (OS-SVSC)

- NCSU is supporting SNL’s LDRD by exploring an alternative SVSC design
- The OS-SVSC divides the SVSC scintillator cell into a 2D array of optically isolated channels
- The large number of digitizers needed by the SVSC is replaced by an array of discriminators
- The \((x, y)\)-location of each interaction would be determined from the channel that registered a light pulse
- The number of photons detected and their arrival time history depends on the \(z\)-location of the scintillation
- The \(z\)-location would be determined by fitting the light pulse shape (acquired at each end of the channel)
- Only 2 photodetector channels would need to be digitized for each interaction
Estimating scintillation position in the OS-SVSC

- Only a few hundred photons are collected in a typical neutron scatter interaction with hydrogen.
- In order to estimate the \((z, t)\)-location of the scintillation, we need to analyze the entire photodetector pulse waveform.
- We’re using the Geant4 to develop a model of light pulse shape that can be fit to measured photodetector pulses.
Experimental characterization of OS-SVSC

• We’re also conducting a small scale experiment with a single 1 cm × 1 cm × 20 cm channel of EJ-204 with fast photomultipliers on both ends

• We’ll use the experiments to validate the light pulse shape predicted by Geant4
ORNL/SNL neutron coded aperture imager (NCAI)
Nevada Test Site experiments with NCAI

- NCSU worked with ORNL and SNL to field the NCAI during the CVT experiment campaign at NTS
- We conducted imaging measurements of weapons-grade plutonium and highly enriched uranium metal
- The measurements also used polyethylene, steel, and tungsten reflectors/shields
- The NCAI uses Anger camera interpolation to estimate \((x, y)\)-interaction position in
  - 1600 logical channels from
  - 64 PMTs attached to
  - 16 plastic scintillators
- Scintillator responses are measured using 4 16-channel 250 MS/s Struck digitizers
  - The Struck digitizers can acquire user-programmable gate integrals using internal FPGAs
  - They can also acquire full waveforms
- The digitized waveforms (compressed or uncompressed) can be used to estimate
  - Arrival time
  - Energy deposition
  - Particle type
Exploiting fission chain-reaction dynamics

\[ E_p > \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \] (sometimes)

\[ E_p \leq \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ \Delta t = t_n - \left( t_\gamma - \frac{d}{c} \right) \]
Detecting fission chain-reaction neutrons

\[ E_p > \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ E_p < \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]
Fission chain-reaction neutron discrimination

\[ E_p < \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ E_p > \frac{1}{2} m_n \left( \frac{d}{\Delta t} \right)^2 \]

\[ \Delta t = d \sqrt{\frac{m_n}{2E_p}} \]
Coded aperture image reconstruction using fission chain-reaction neutrons

• The coded aperture imager records all detection events in list mode
  – Compressed: trigger time, charge collected, pulse shape (for particle ID)
  – Uncompressed: fully digitized waveforms

• It is possible to reconstruct the image by selectively using only late-arriving, high-energy neutrons
  – The resulting image would show only multiplying material
  – Jack Linkous will present this analysis tomorrow
High-precision measurements of organic scintillator neutron response at TUNL

- We’re working with Triangle Universities Nuclear Lab (TUNL) to construct an experiment to precisely measure scintillator light output (and anisotropy)

- The TUNL tandem Van de Graaf accelerator will be used to generate pulsed, tunable, monoenergetic neutron beams
  - \(^7\text{Li}(p,n)\) reaction for neutrons below 500 keV
  - \(^2\text{H}(^2\text{H},n)\) reaction for neutrons above 500 keV

- The experiment will use a single “target” organic scintillator surrounded by an array of “backing” scintillators

- Recoil proton energy from neutron-hydrogen scattering will be estimated from kinematics

\[ E_p = E_n \sin^2 \psi \]

- We’ll use the experiment to characterize light output vs. recoil proton energy, including anisotropy in crystalline organic scintillators
Measuring organic scintillator neutron response function

- Detection events coincident between the target and backing detectors can be used to estimate recoil proton energy
- Multiple scatter and carbon scatter events can be discriminated using time-of-flight
- Resolution of recoil proton energy:
  \[ R = \frac{\sigma_{Ep}}{E_p} = \frac{\sigma_{Ep}}{E_p \cdot \sqrt{N}} \]
- Initial estimates of resolution using Geant4 and MCNPX-PoliMi (for ~24 h beam time):
  - 100 keV neutron beam: < 0.05%
  - 3 MeV neutron beam: < 0.5%
- These estimates don’t (yet) account for
  - Spread in neutron beam energy
  - Uncertainty in backing detector placement
High channel-density proton-recoil measurements

• TUNL has a cache of plastic scintillator and PMTs sufficient to construct 300 backing detectors

• The measurement of proton recoil energy doesn’t require waveform digitization – only discriminator time-tagging is necessary

• We are exploring methods to time-tag each detector channel without using 300 independent discriminators

• For example, it may be possible to tag each detector by “tuning” it to ring at a unique frequency
Summary

• We’re working with ORNL, SNL, and Duke in 3 main areas to develop alternative approaches to data analysis and compression for “high data velocity” detector systems

• Studying tradeoffs between throughput and fidelity – e.g., pileup correction vs. rejection to improve particle ID

• Reducing the “data velocity” at the front-end of different detector systems using alternative data acquisition logic – e.g. eliminating/minimizing the need for digitization by altering the instrument/experiment design

• Identifying specific pulse patterns that are signatures of SNM – e.g., fission chain-reaction image reconstruction
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