John Mattingly
North Carolina State University

HIGH-THROUGHPUT RADIATION DETECTION SYSTEMS
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 SNL, ORNL, and Duke to develop alternative methods for data compression and analysis in high-throughput radiation detection systems.
SNL single-volume scatter camera (SVSC)

- Relative to a multi-volume scatter camera, an SVSC can potentially have 10× higher efficiency.
- The camera has to be able to resolve pairs of sequential neutron scatters separated by 1 to 2 cm to attain such high efficiency.
- The microchannel plate (MCP) photodetectors’ \((x, y, t)\)-dependent waveforms have to be fully digitized to resolve such closely spaced events.
- That is one of the most significant challenges to designing a functioning SVSC.
Single-volume scatter camera using pillars of plastic scintillator (SVSC-PiPS)

- NCSU is supporting SNL’s LDRD by exploring an alternative SVSC design
- The SVSC-PiPS divides the SVSC scintillator cell into a 2D array of optically isolated plastic scintillator channels
- The large number of digitizer channels the SVSC needs can be replaced by an array of discriminators
- Only 2 photodetector channels would need to be digitized for each interaction
- The \((x, y)\)-location of each interaction can be determined from the channel that registered a light pulse
- The \(z\)-location can be determined by fitting the light pulse shape
Estimating scintillation position in the SVSC-PiPS

- Only a small number of photons are detected for each neutron scatter
  - Quenching: 1 MeV neutron energy deposition = ~150 keVee
  - Luminosity: 10,000 scintillation photons per MeVee = ~1,500 photons
  - 30% light collection efficiency × 20% photocathode quantum efficiency = ~100 photoelectrons

- The uncertainty in the number of scintillation photons detected on either end of the channel is large (~10%) on a per-event basis

- The uncertainty in the ratio of photons counted on either end is very large (~14%) on a per-event basis

- Scintillation position can only be estimated to about 5 cm using the ratio of photons counted on either end
Estimating scintillation position using MLE to fit photoelectron arrival history

- We used Geant4’s model of optical photon transport to construct response functions for the SVSC-PiPS channels vs. scintillation position.

- We used MLE to fit the observed photoelectron arrival history with the channel response function.

- This analysis produces a much more precise estimate of scintillation position:
  - 1 MeV neutron: 9 mm / 80 keV (8%)
  - 2 MeV neutron: 5 mm / 40 keV (2%)
SVSC-PiPS point source location

- We used MCNPX-PoliMi to simulate the SVSC-PiPS response to a point source of fission neutrons.

- The photoelectron arrival time history was analyzed by fitting the photoelectron arrival history to estimate the $z$-location of each scintillation.

- The incoming neutron direction was estimated using back-projection and MLE.

- These simulations predict that the SVSC-PiPS can precisely identify incoming neutron direction.
Nevada Test Site experiments with ORNL/SNL
neutron coded aperture imager (NCAI)

- We worked with ORNL and SNL to deploy the NCAI during the 2015 and 2016 CVT experiment campaigns at NTS

- The NCAI uses 1,600 physical pixels composed of EJ299-33 plastic scintillator

- We conducted imaging measurements of weapons-grade plutonium and highly enriched uranium metal
  - Plutonium: passive imaging
  - Uranium: active imaging

- We developed methods to reconstruct images of fissile material
Exploiting fission chain-reaction dynamics to passively image fissile material

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

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

\[ \Delta t = t_n - \left( t_\gamma - \frac{d}{c} \right) \]
Passive imaging of fission chain-reaction neutrons
Active imaging of induced fission neutrons

DT interrogation of HEU

induced fission neutrons
We worked with the Triangle Universities Nuclear Lab (TUNL) to conduct an experiment to precisely measure anisotropy in crystalline organic scintillator light output.

We used the TUNL tandem Van de Graaf accelerator to generate tunable, monoenergetic neutron beams from the d(d, n) reaction.

We used kinematics to estimate recoil proton energy from neutron-hydrogen scattering:

$$E_p = E_n \sin^2 \psi$$

We characterized anisotropy in the light output of stilbene over proton recoil energies between 500 keV and 10 MeV.
Light output vs. recoil proton energy

- We know the neutron beam energy within a few percent.

- We also know the scatter angle (from the backing detector that triggered) within a few percent.

- The mean recoil proton energy was estimated to better than one percent in less than 24 hours of beam-time.

- Nuisance events (e.g., multiple hydrogen scatter) were discriminated out using time-of-flight.
Anisotropy of stilbene light output

- We measured stilbene light output at > 10 proton recoil energies vs. angle w.r.t. the c’-axis

- Stilbene exhibited minimum light output when the proton recoil direction was parallel to the c’-axis

- We also characterized the light output anisotropy w.r.t. the a- and b-axes

- The experiments took only a few days of beam-time

- We have started analyzing the anisotropy in pulse shape
Frequency-domain multiplexing (FDM)

- TUNL has a cache of ~300 plastic scintillators and PMTs
- We are working to expand the KREPRE experiment to use 300 backing detectors
- We have developed a method to multiplex multiple backing detectors to a single digitizer channel
- Each backing detector signal will be modulated at a specific frequency using a series RLC-circuit
- The backing detector that triggered will be identified by its modulation frequency
Estimating energy deposition and arrival time from FDM-modulated signals

- The energy deposition and arrival time of the detector anode pulse are encoded in the FDM-modulated signal.
- FDM signal amplitude is proportional to anode signal amplitude.
- FDM signal phase is inversely proportional to anode pulse trigger time.
- We can precisely estimate energy deposition and arrival time from FDM-modulated signals.
Summary

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

• We’re working to reduce the “data velocity” of different detector systems using alternative data acquisition/processing logic
  – SVSC-PiPS: reduce number of channels that have to be digitized by a factor of 512:2
  – NCAI: reconstruct images from induced fission and fission chain-reaction neutrons
  – KREPPE: measure proton recoil energy using coincidence logic
  – FDM: multiplex multiple detectors to a single digitizer channel
  – We are also working with Struck Innovative Systeme (SIS) to implement event rejection based on particle ID using the SIS3316 onboard FPGA
CVT fellows, associates, and partners

Pete Chapman
Graduate associate

Mudit Mishra
Graduate associate

Dr. Jonathan Mueller
Post-doctoral fellow

Kyle Weinfurther
Graduate fellow

Rob Weldon
Graduate fellow

Partners:
- Erik Brubaker (SNL)
- Jason Newby (ORNL)
- Paul Hausladen (ORNL)
- Phil Barbeau (Duke)
- Jesson Hutchinson (LANL)