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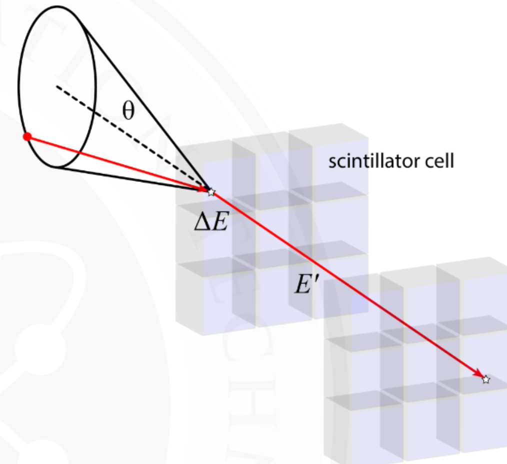
HIGH-THROUGHPUT RADIATION DETECTOR SYSTEMS

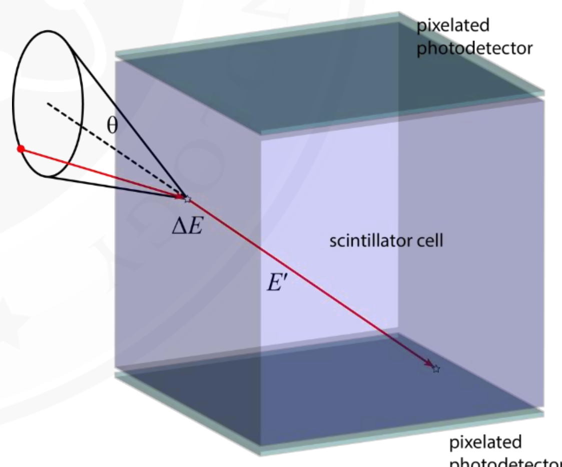
Background

- 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 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

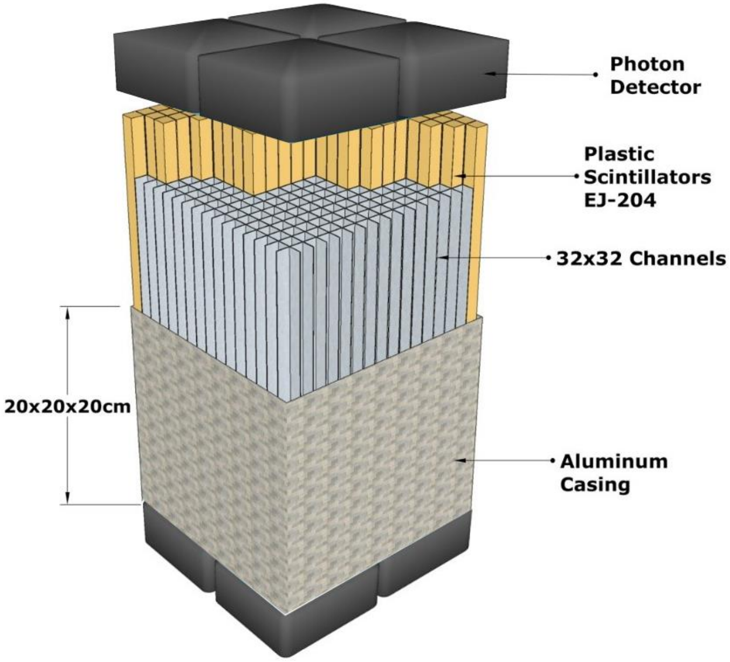




expected size (20 cm)^3

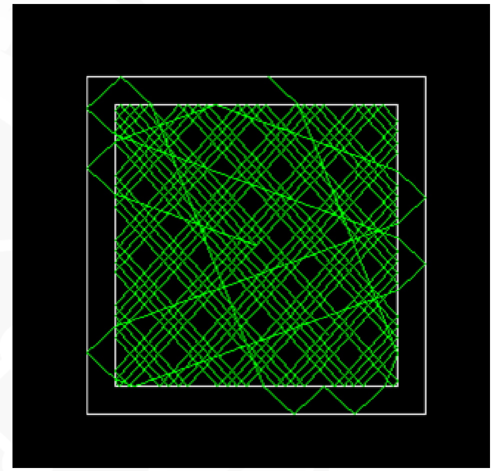
Optically-segmented single-volume scatter camera (OS-SVSC)

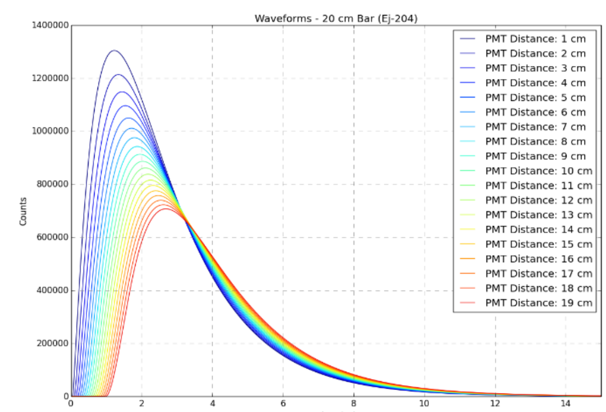
- NCSU is supporting SNL's LDRD by exploring an alternative SVSC design
- The OS-SVSC divides the SVSC scintillator cell into a 2D array of optically isolated channels
- The large number of digitizers needed by the SVSC is replaced by an array of discriminators
- The (x, y)-location of each interaction 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

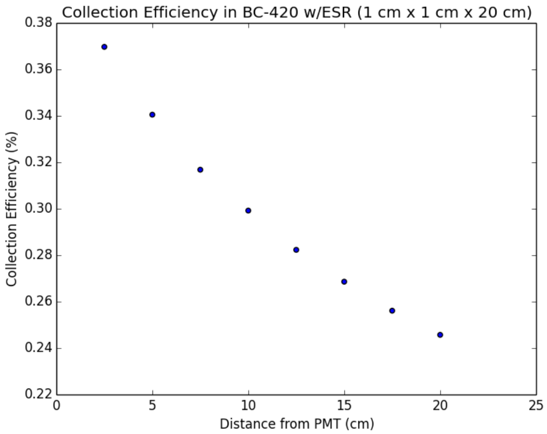




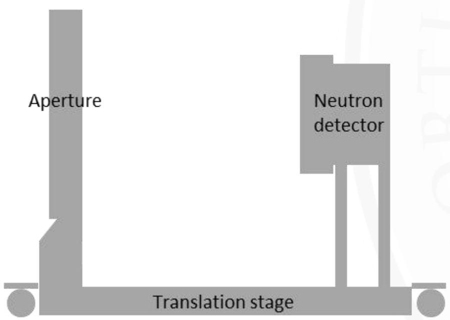
Experimental characterization of OS-SVSC

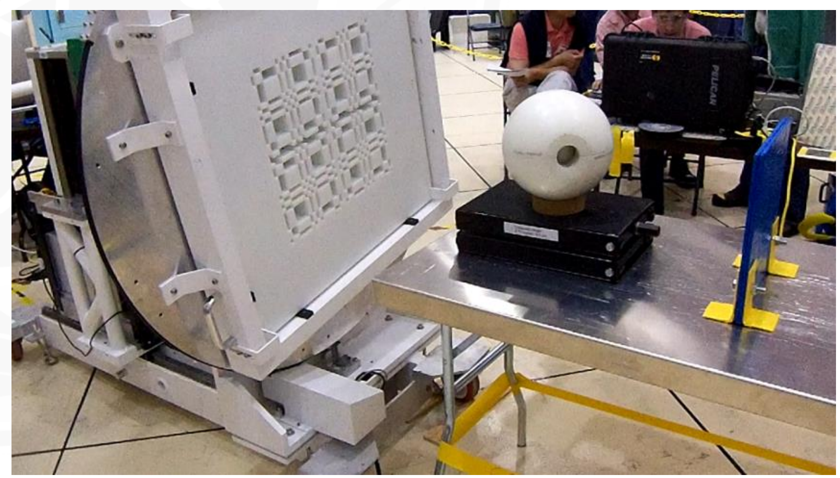
- We're also conducting a small scale experiment with a single 1 cm × 1 cm × 20 cm channel of EJ-204 with fast photomultipliers on both ends

- We'll use the experiments to validate the light pulse shape predicted by Geant4

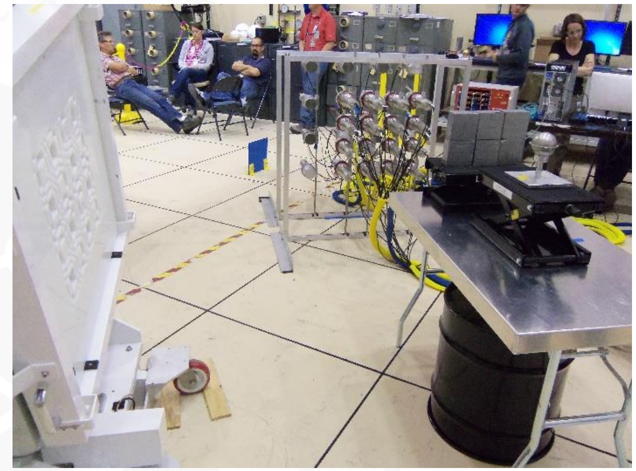


ORNL/SNL neutron coded aperture imager (NCAI)

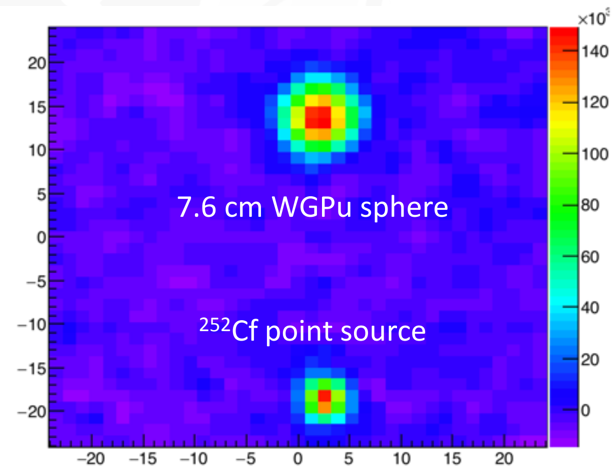




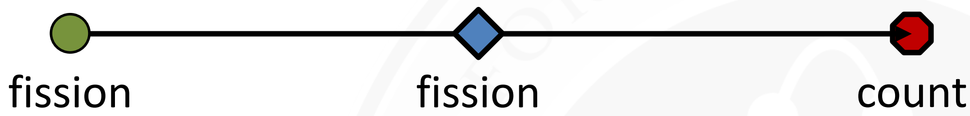
Nevada Test Site experiments with NCAI



- 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

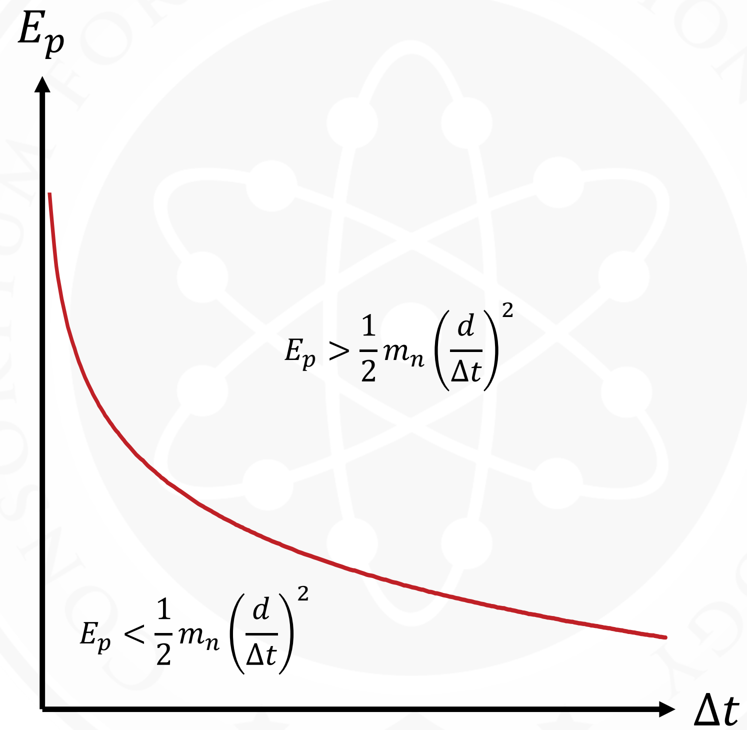


$$E_p > \frac{1}{2} m_n \left(\frac{d}{\Delta t}\right)^2 \quad \text{(sometimes)}$$

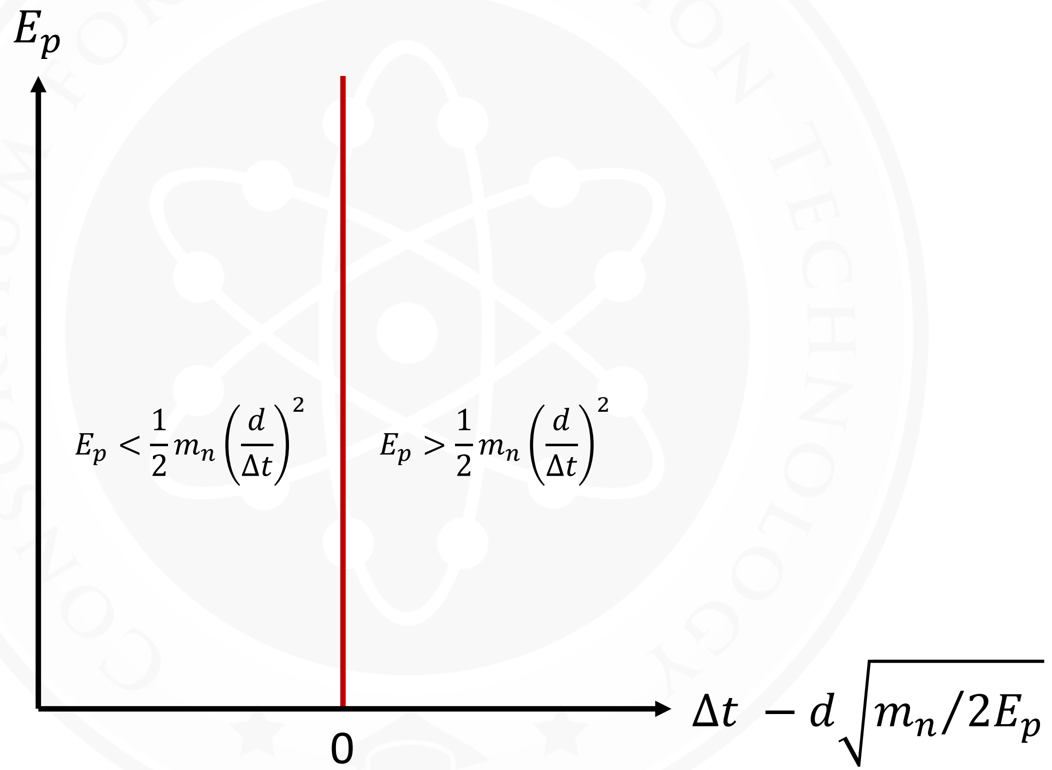
$$E_p \leq \frac{1}{2} m_n \left(\frac{d}{\Delta t}\right)^2$$

$$t_\gamma - \frac{d}{c} \longrightarrow \Delta t = t_n - \left(t_\gamma - \frac{d}{c}\right)$$

Detecting fission chain-reaction neutrons



Fission chain-reaction neutron discrimination



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

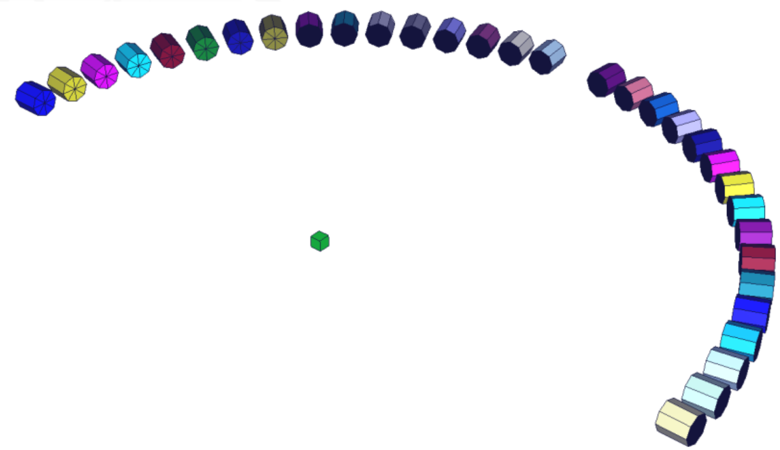
- It is possible to reconstruct the image by selectively using only late-arriving, high-energy neutrons
  - The resulting image would show only *multiplying* material
  - Jack Linkous will present this analysis tomorrow

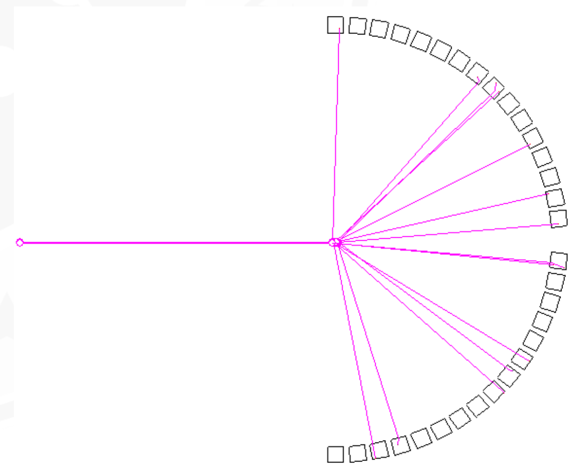
High-precision measurements of organic scintillator neutron response at TUNL

- 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
  - $^{7}Li(p,n)$ reaction for neutrons below 500 keV
  - $^{2}H(^{2}H,n)$ 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



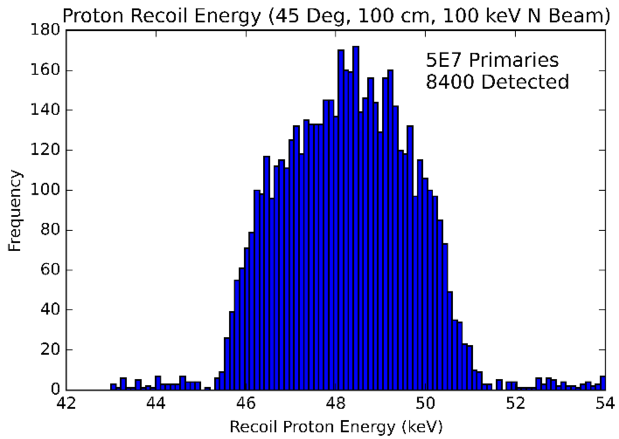


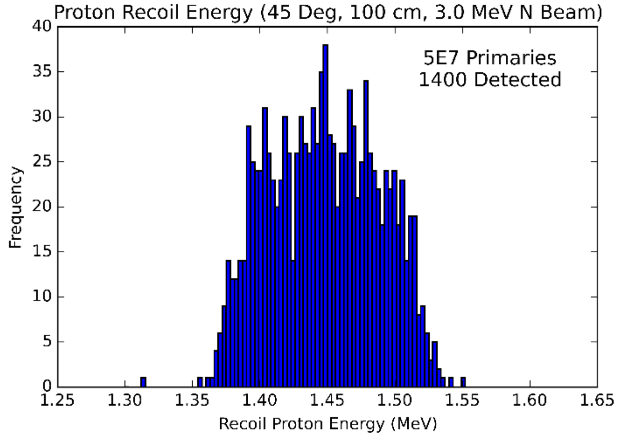
Measuring organic scintillator neutron response function

- 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:

$$R = \frac{\sigma_{\overline{E_p}}}{\overline{E_p}} = \frac{\sigma_{E_p}}{\overline{E_p} \cdot \sqrt{N}}$$

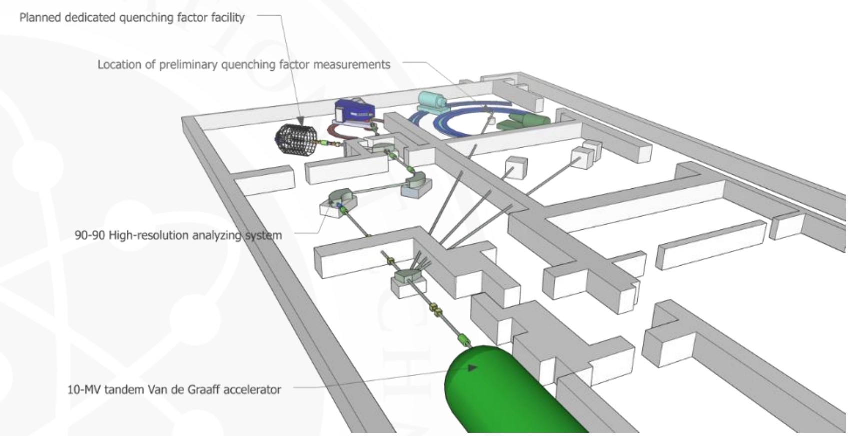
- Initial estimates of resolution using Geant4 and MCNPX-PoliMi (for ~24 h beam time):
  - 100 keV neutron beam: < 0.05%
  - 3 MeV neutron beam: < 0.5%
- These estimates don't (yet) account for
  - Spread in neutron beam energy
  - Uncertainty in backing detector placement

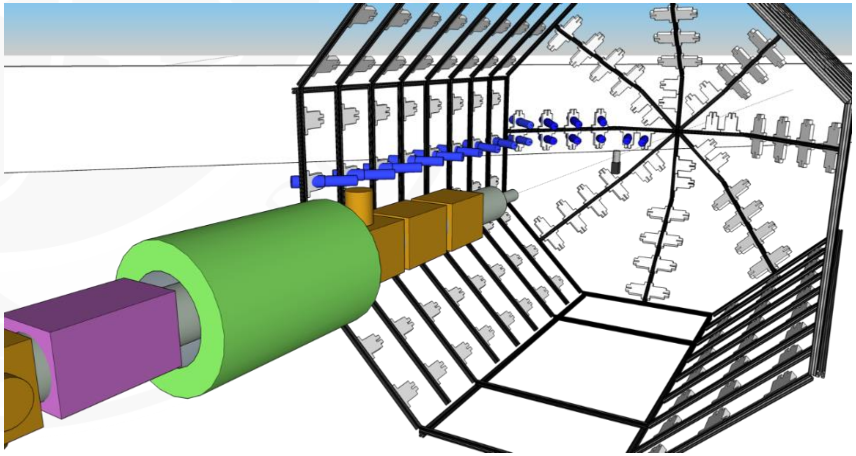




High channel-density proton-recoil measurements

- 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

CVT fellows, associates, and partners

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Post-doctoral fellow

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Rob Weldon
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Partners:

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