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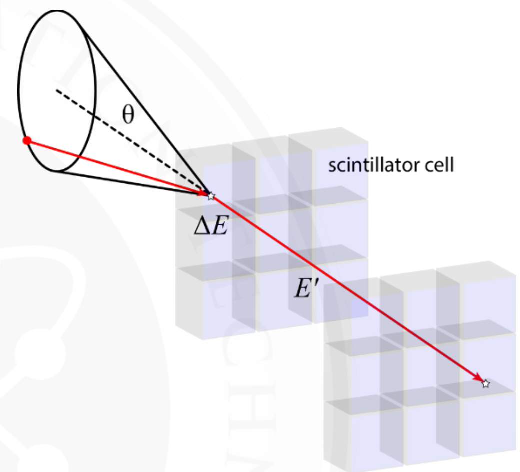
HIGH-THROUGHPUT RADIATION DETECTION SYSTEMS

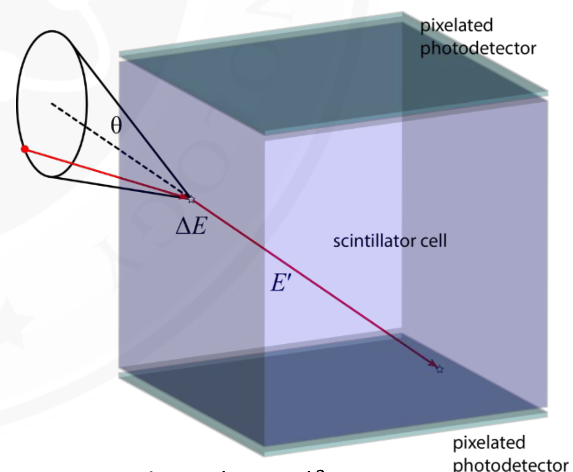
Background

- 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

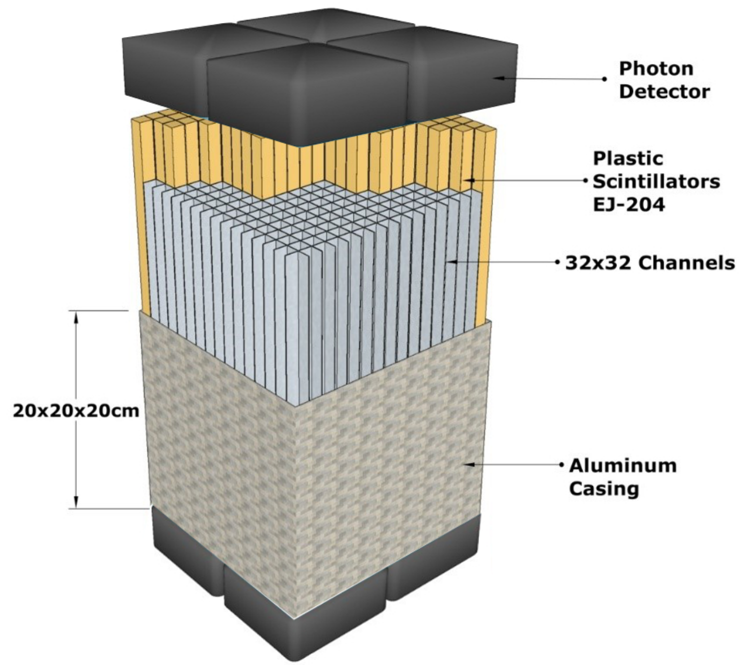




expected size (20 cm)^3

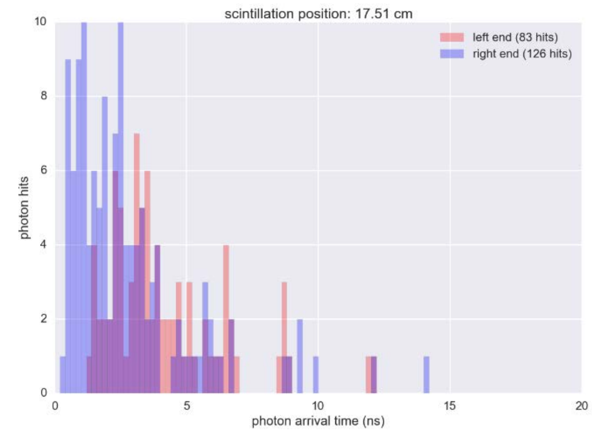
Single-volume scatter camera using pillars of plastic scintillator (SVSC-PiPS)

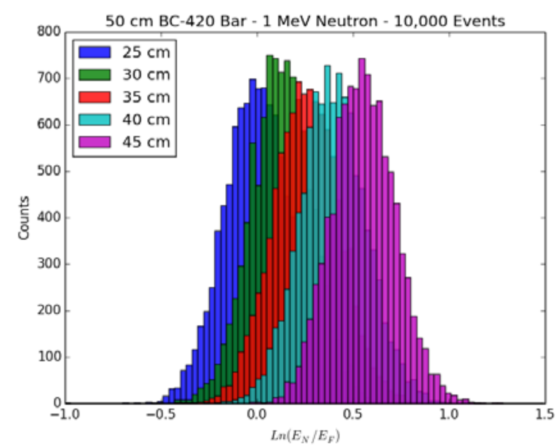
- NCSU is supporting SNL's LDRD by exploring an alternative SVSC design
- The SVSC-PiPS divides the SVSC scintillator cell into a 2D array of optically isolated plastic scintillator channels
- The large number of digitizer channels the SVSC needs can be replaced by an array of discriminators
- Only 2 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

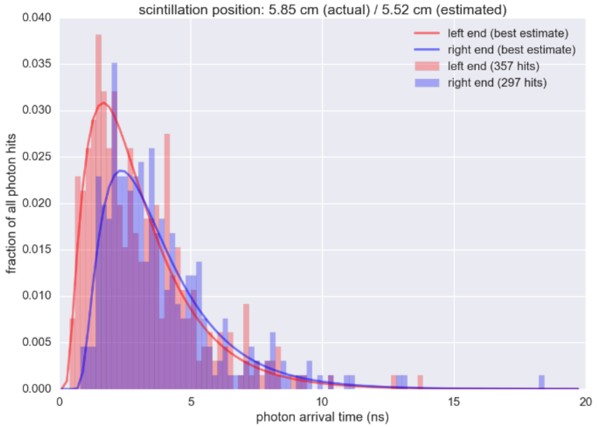
- Only a small number of photons are detected for each neutron scatter
  - Quenching: 1 MeV neutron energy deposition = ~150 keVee
  - Luminosity: 10,000 scintillation photons per MeVee = ~1,500 photons
  - 30% light collection efficiency × 20% photocathode quantum efficiency = ~100 photoelectrons
-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

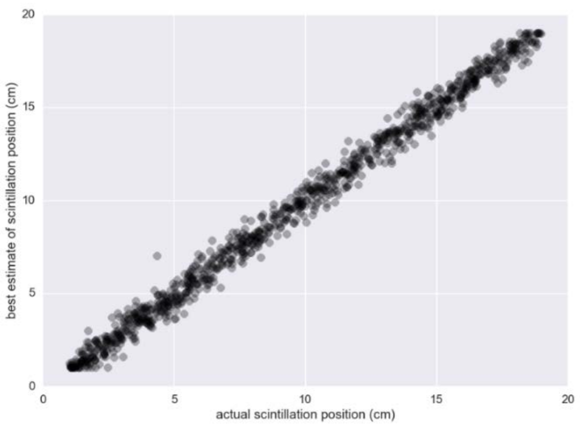




Estimating scintillation position using MLE to fit photoelectron arrival history

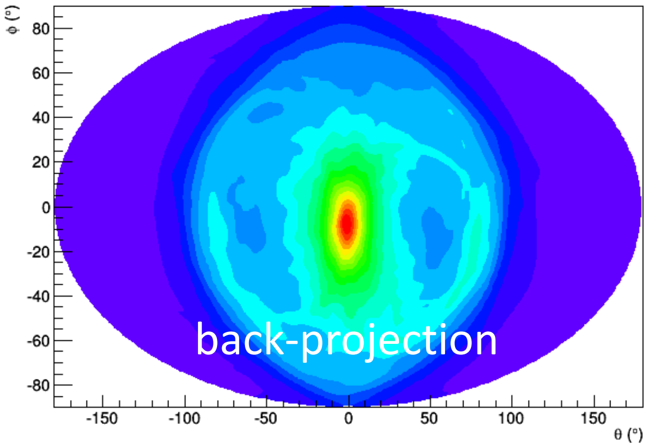
- We used Geant4's model of optical photon transport to construct response functions for the SVSC-PiPS channels vs. scintillation position
- We used MLE to fit the observed photoelectron arrival history with the channel response function
- This analysis produces a much more precise estimate of scintillation position
  - 1 MeV neutron: 9 mm / 80 keV (8%)
  - 2 MeV neutron: 5 mm / 40 keV (2%)

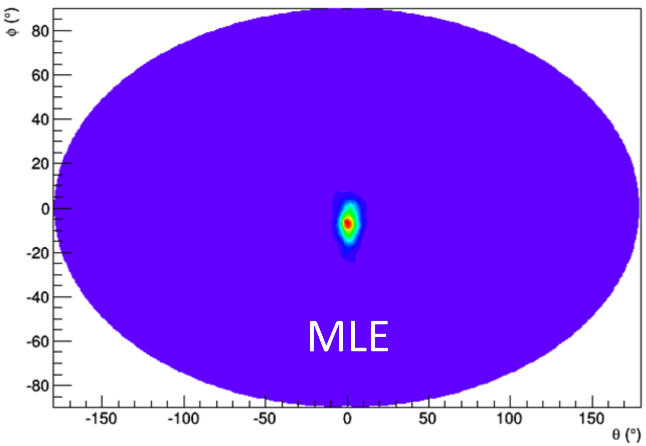




SVSC-PiPS point source location

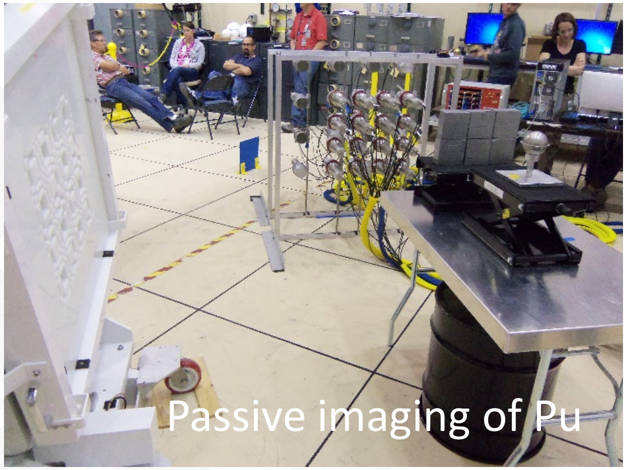
- We used MCNPX-PoliMi to simulate the SVSC-PiPS response to a point source of fission neutrons
- The photoelectron arrival time history was analyzed by fitting the photoelectron arrival history to estimate the z-location of each scintillation
- The incoming neutron direction was estimated using back-projection and MLE
- These simulations predict that the SVSC-PiPS can precisely identify incoming neutron direction

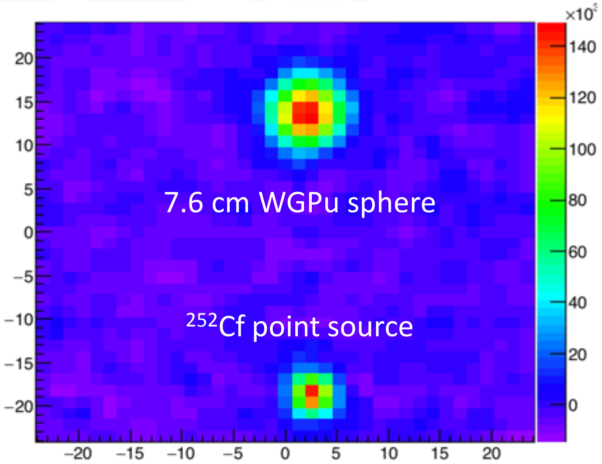




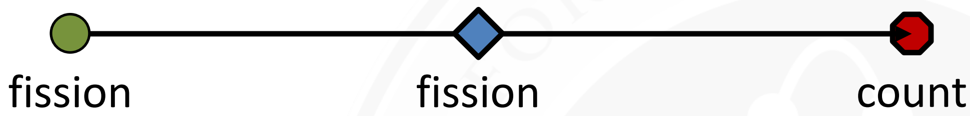
Nevada Test Site experiments with ORNL/SNL neutron coded aperture imager (NCAI)

- 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

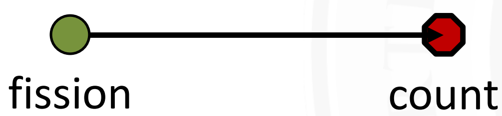




Exploiting fission chain-reaction dynamics to passively image fissile material



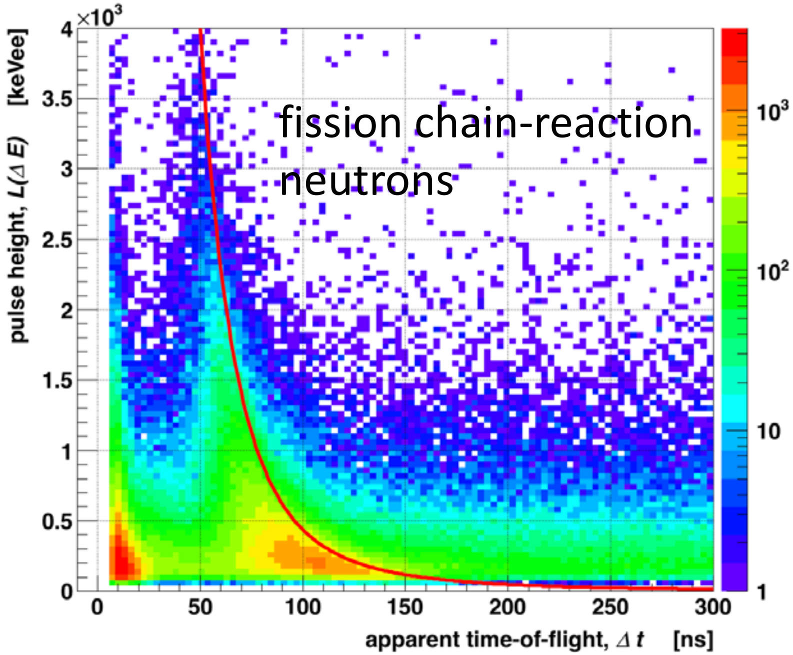
$$E_p > \frac{1}{2} m_n \left(\frac{d}{\Delta t} \right)^2$$ (sometimes)

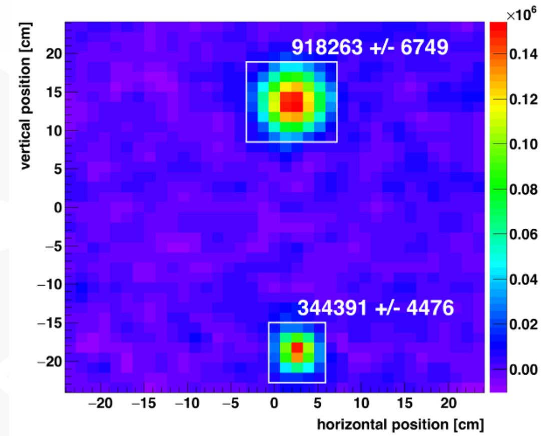


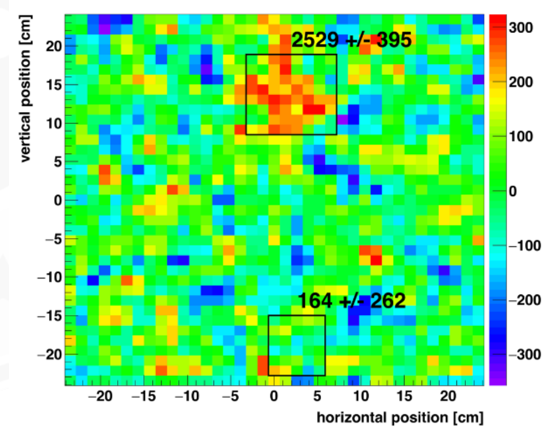
$$E_p \leq \frac{1}{2} m_n \left(\frac{d}{\Delta t} \right)^2$$

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

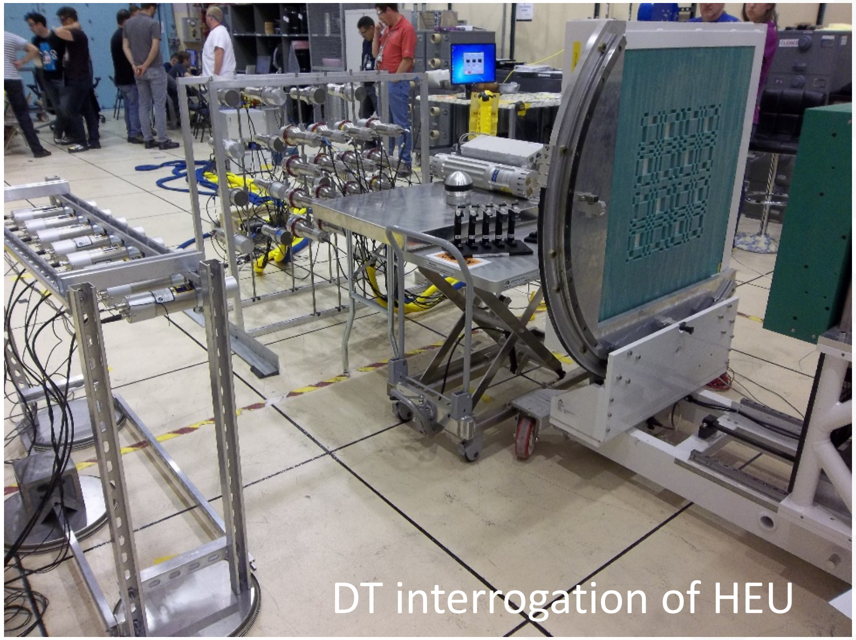
Passive imaging of fission chain-reaction neutrons

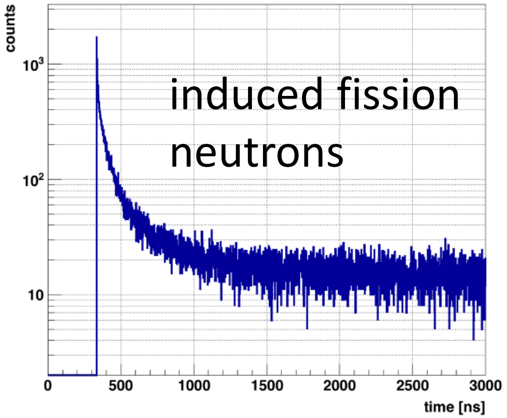


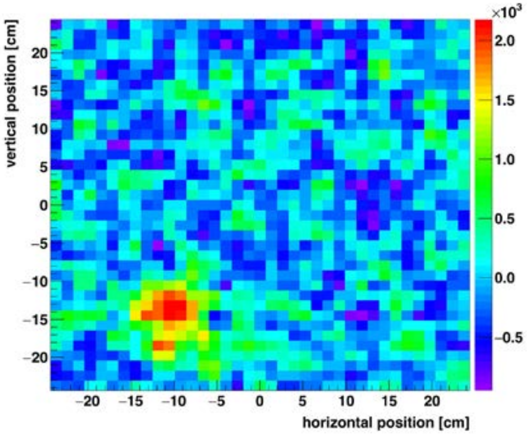




Active imaging of induced fission neutrons







Kinematic reconstruction of proton-recoil energy (KREPRE) experiment

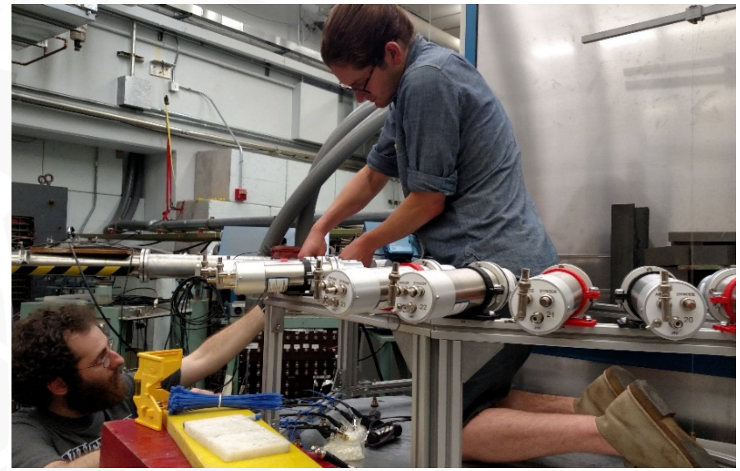
- We worked with the Triangle Universities Nuclear Lab (TUNL) to conduct an experiment to precisely measure anisotropy in crystalline organic scintillator light output

- 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

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

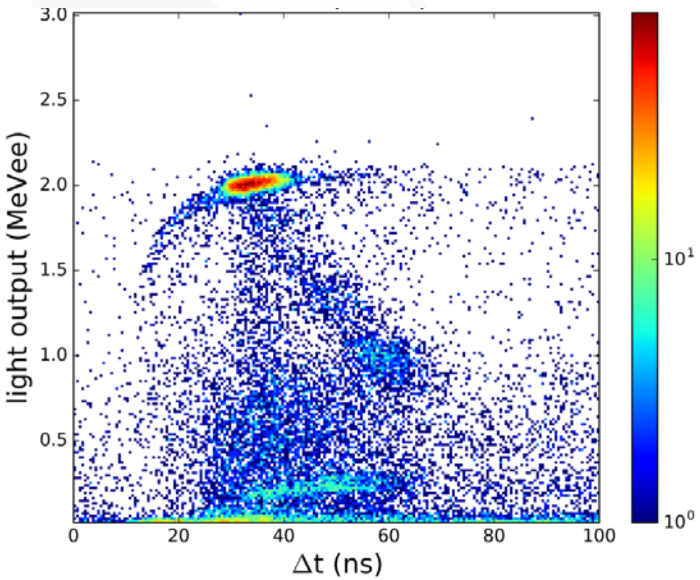
- We characterized anisotropy in the light output of stilbene over proton recoil energies between 500 keV and 10 MeV



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

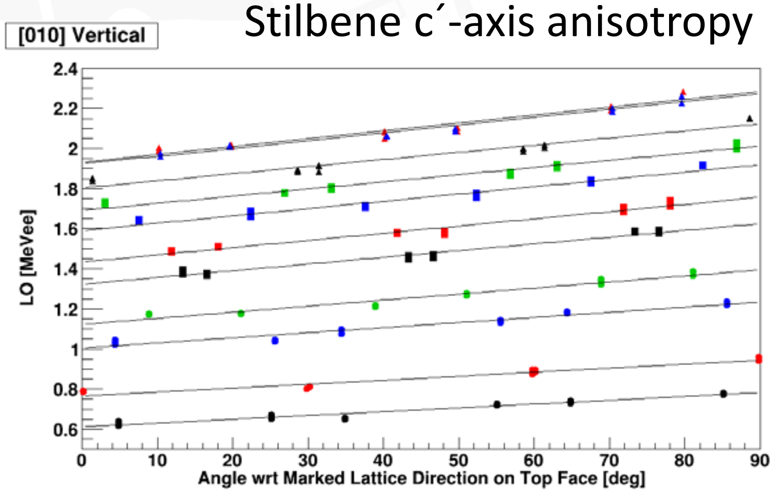
70° backing detector



Anisotropy of stilbene light output

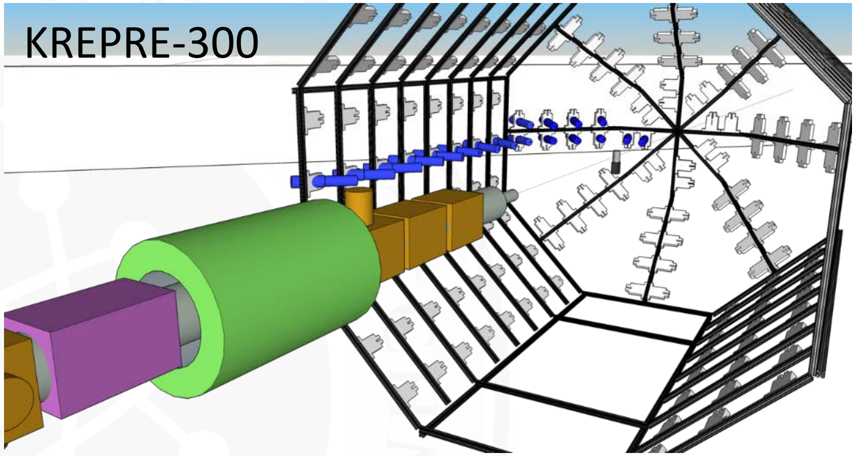
- We measured stilbene light output at > 10 proton recoil energies vs. angle w.r.t. the c´-axis
- Stilbene exhibited minimum light output when the proton recoil direction was parallel to the c´-axis
- We also characterized the light output anisotropy w.r.t. the a- and b-axes
- The experiments took only a few days of beam-time
- We have started analyzing the anisotropy in pulse shape

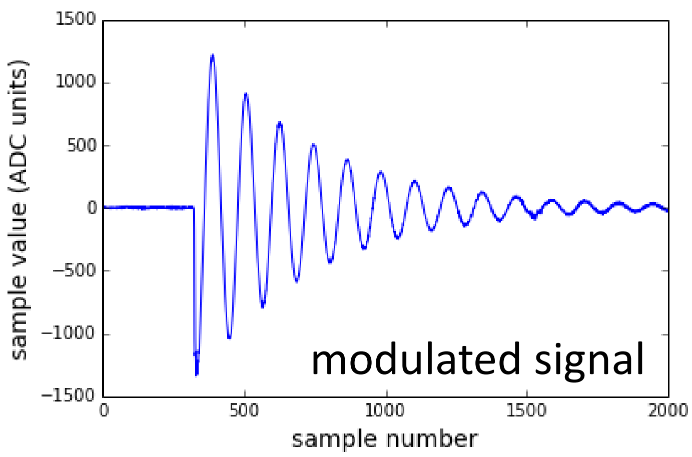
Stilbene c´-axis anisotropy



Frequency-domain multiplexing (FDM)

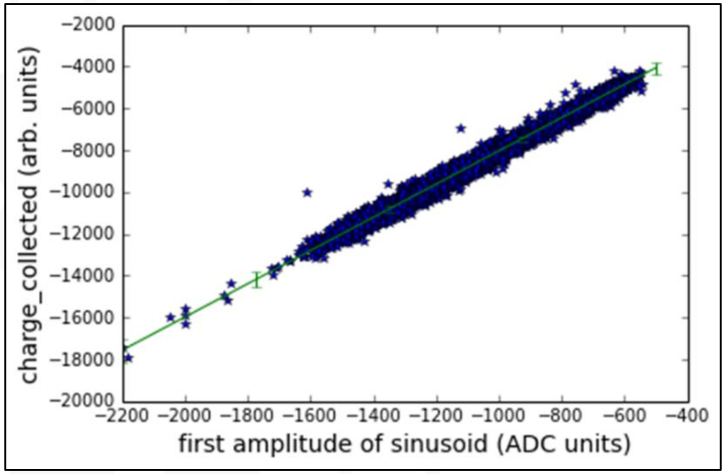
- TUNL has a cache of ~300 plastic scintillators and PMTs
- We are working to expand the KREPRE experiment to use 300 backing detectors
- We have developed a method to multiplex multiple backing detectors to a single digitizer channel
- Each backing detector signal will be modulated at a specific frequency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

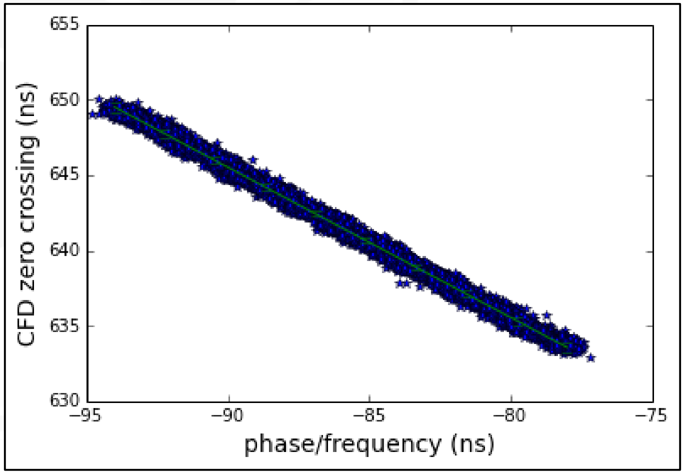




Estimating energy deposition and arrival time from FDM-modulated signals

- 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
  - KREPRE: 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

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Dr. Jonathan Mueller
Post-doctoral fellow

Kyle Weinfurther
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Rob Weldon
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- Jason Newby (ORNL)
- Paul Hausladen (ORNL)
- Phil Barbeau (Duke)
- Jesson Hutchinson (LANL)