Characterization of Semiconductor Detectors at the Manitoba Proton Source for Low-Energy Particle Physics

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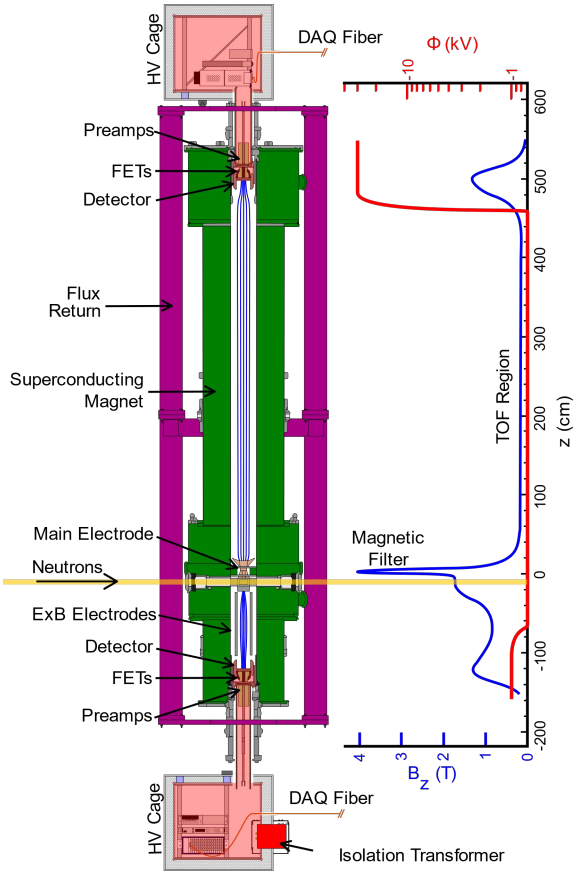
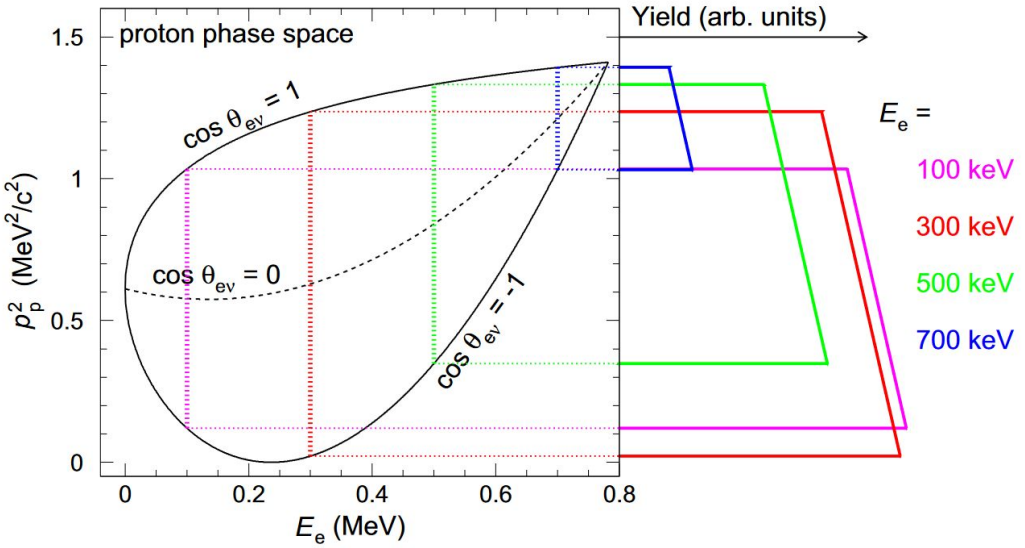
Outline

- Brief introduction to the Neutron-a-b (Nab) experiment
- Detector characterization goals
- Manitoba-II proton source and detector system
- Impurity density study
- Simulation effort

The Neutron-a-b Experiment

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1+3\lambda^2}{(4\pi)^5\hbar}|V_{ud}|^2 g_v^2 \left(\frac{g_w}{M_w}\right)^4 p_e E_e (E_0 - E_e)^2 \times \left(1 + a\frac{\vec{p}_\nu \cdot \vec{p}_e}{E_\nu E_e} + b\frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu}\right) + \ldots\right)$$





Other sections with Nab-related talks:

- D05.00003 The Nab Experiment: Present Status
- F04 Neutron Beta Decay - for various subsystem discussion.
- L11.00003: From the Detector Characterization to the Analysis of Commissioning Data of the Nab Experiment

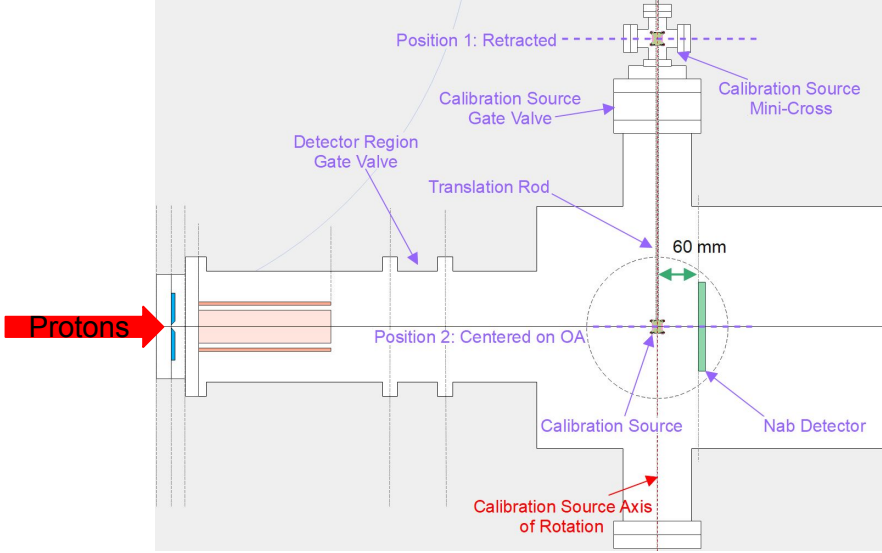
Image credits: J.D. Jackson et. al. (1958) (top), The Nab Collaboration (left, center)

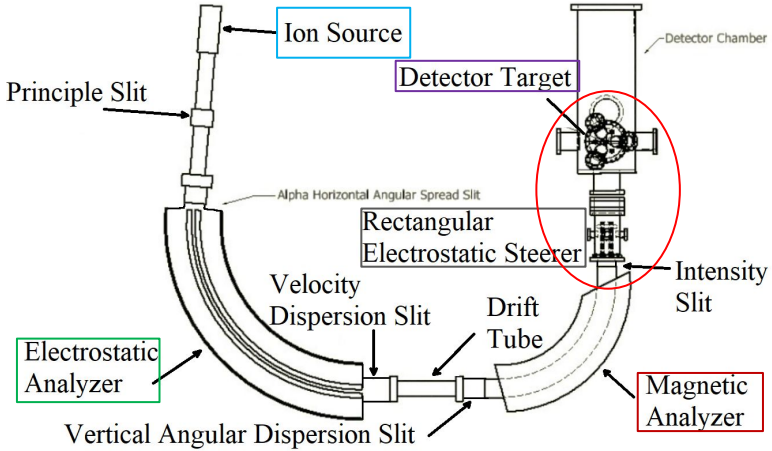
Characterization Goals

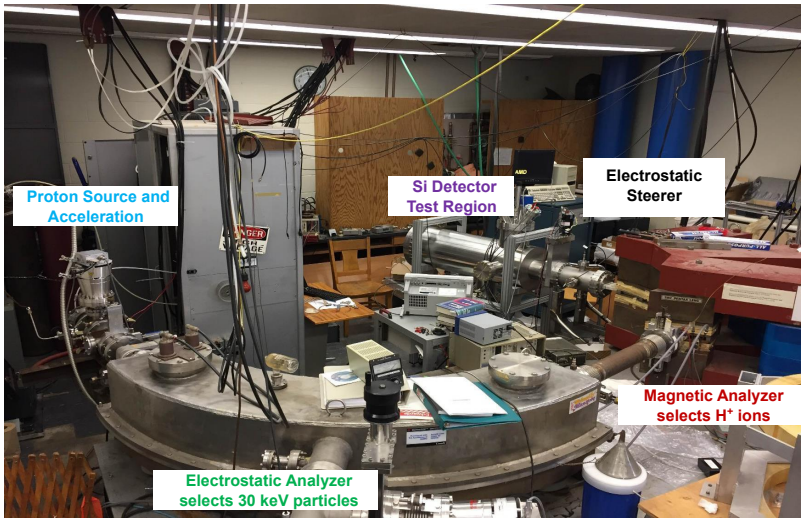
- Quantify full silicon detector system performance in particular for proton detection
  - Effective ionization signals for protons (including dead layer effects as a function of position)
  - Complete library of pulse-shapes for protons, as function of position (both intra- and inter-pixel position), detector bias, operating temperature
  - Signal stability with respect to temperature, bias voltage, event location
- **Derived quantities include a map of impurity density across detector face (in particular, as a function of radial position on detector)**
- Impact on Nab:
  - Assessment of calibration for electrons, X-rays and protons
  - Assessment of expected to signal to noise
  - Assessment of rise-time variations as a function position → feeds into expected timing bias for proton TOF measurements

Manitoba-II Proton Source

- Simulate beta decay protons accelerated to 30 keV
- Penning Ion Generator (PIG)
- Combined analyzers: 1% momentum resolution
- Electrostatic Beam Steering
- ~1mm pencil beam

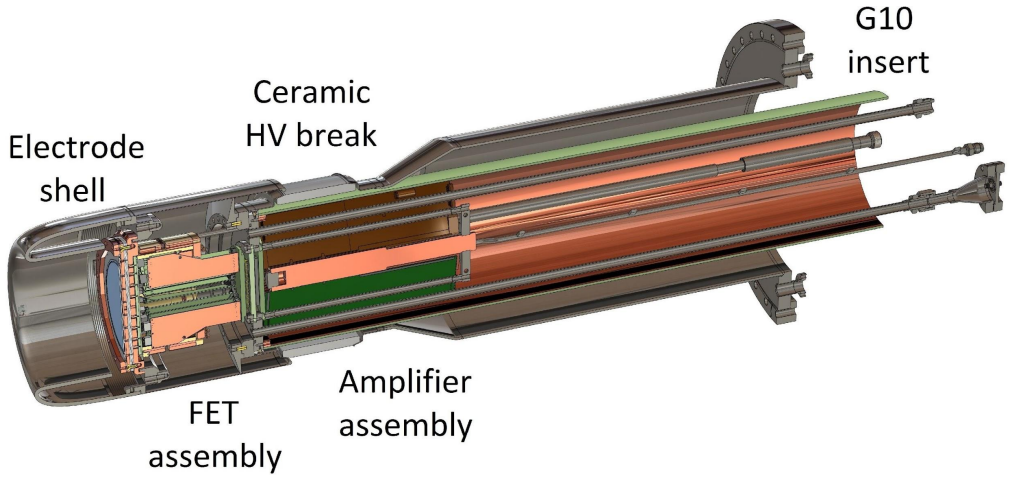


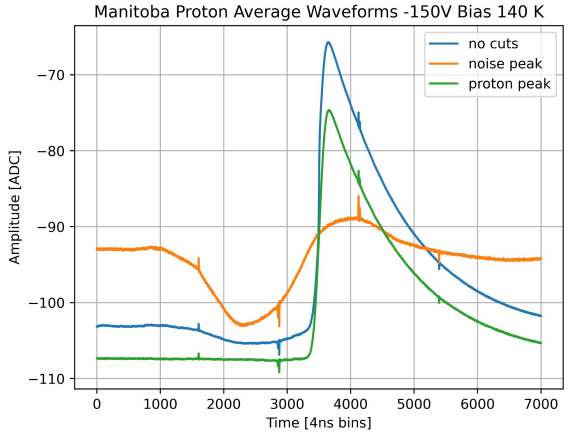


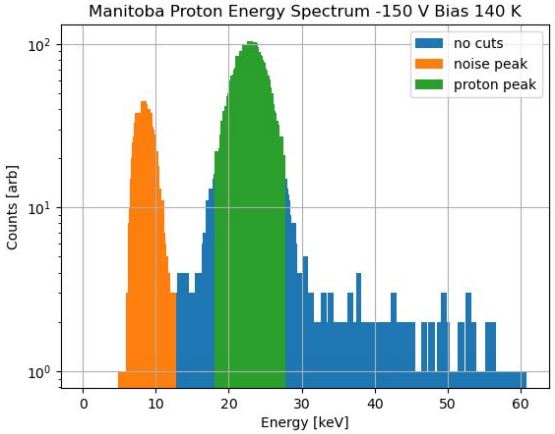


Detector System

- Silicon detector → preamplifier → DAQ
  - Large-area, highly segmented
  - Run over-depleted
  - Digitize linear-tail pulse waveforms
- L11.00003: *From the Detector Characterization to the Analysis of Commissioning Data of the Nab Experiment*

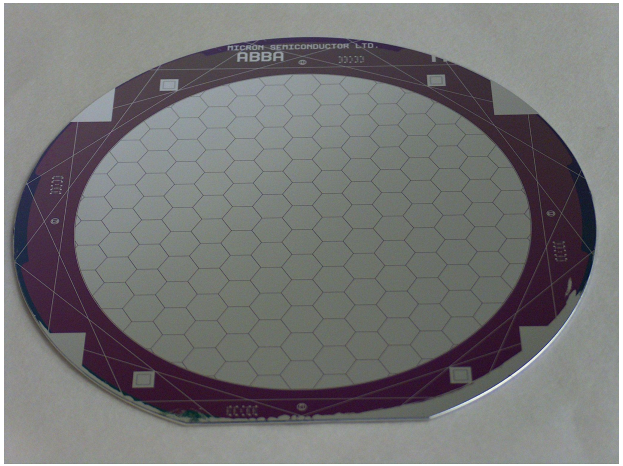






Nab Silicon Detectors

- 1.5 mm or 2 mm thick 117 mm diameter
- 127 segments
- N-doped bulk with boron p^+ dopant implanted via P-SPRAY or P-STOP methods
- Radiation incident on the p^+ junction window (~100 nm dead layer)



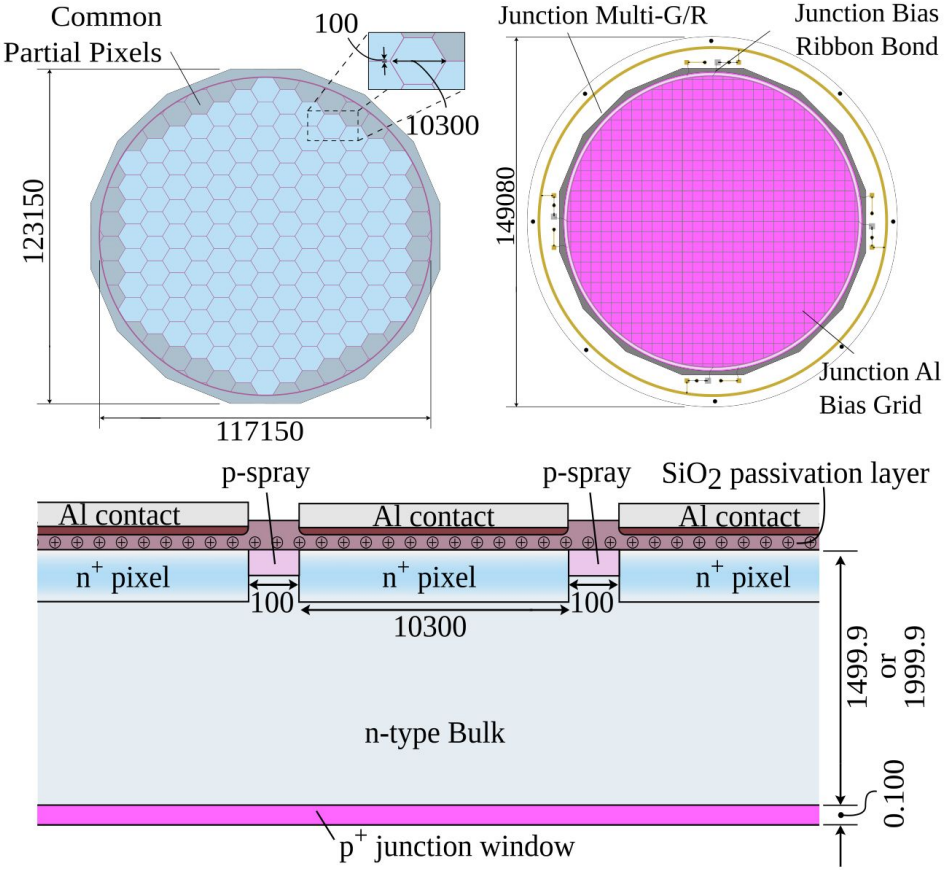
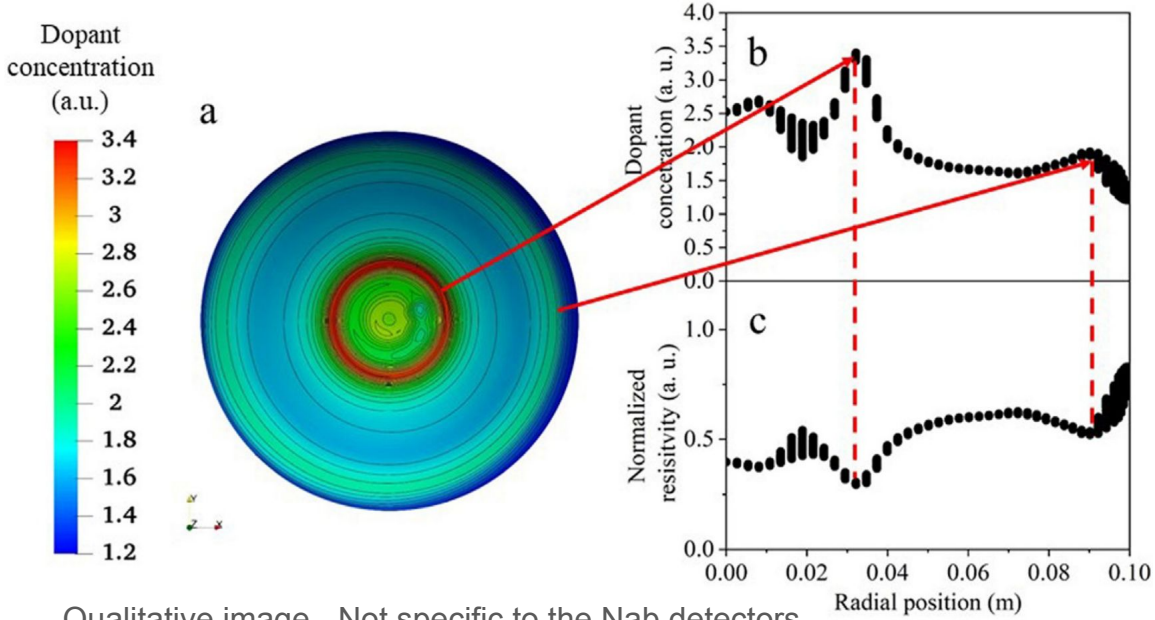


Image sources: Scott Wilburn (left)
https://link.aps.org/doi/10.1103/PhysRevC.107.065503 (above)

Silicon Boule Formation

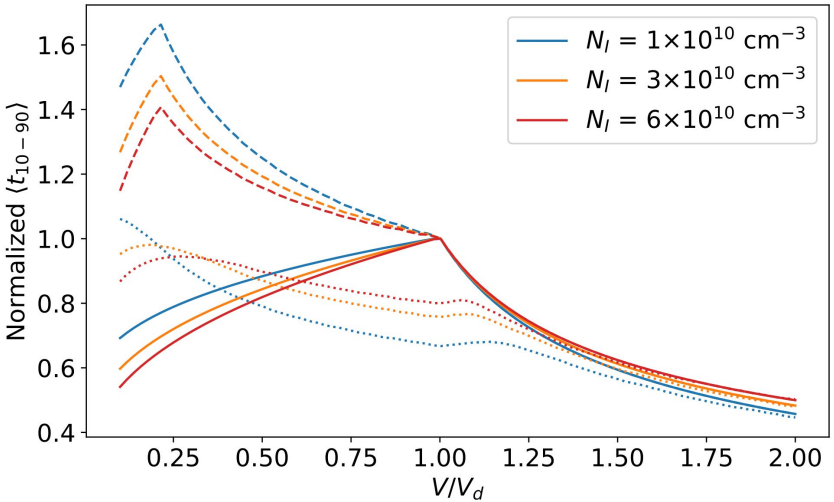
- Expect impurity variation between 10-40%
- **Affects charge collection time and pixel depletion voltage**

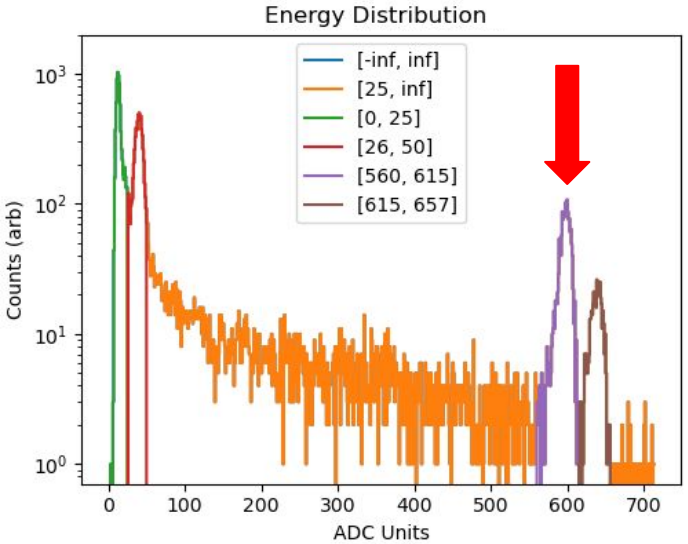


Qualitative image - Not specific to the Nab detectors
Image source:doi.org/0.1016/j.jcrysgro.2020.125752

Study of Event Rise Time vs Displacement

- Study waveform rise time (after amplification) as a function of position
- Initial analysis shows consistency with radially decreasing impurity density.





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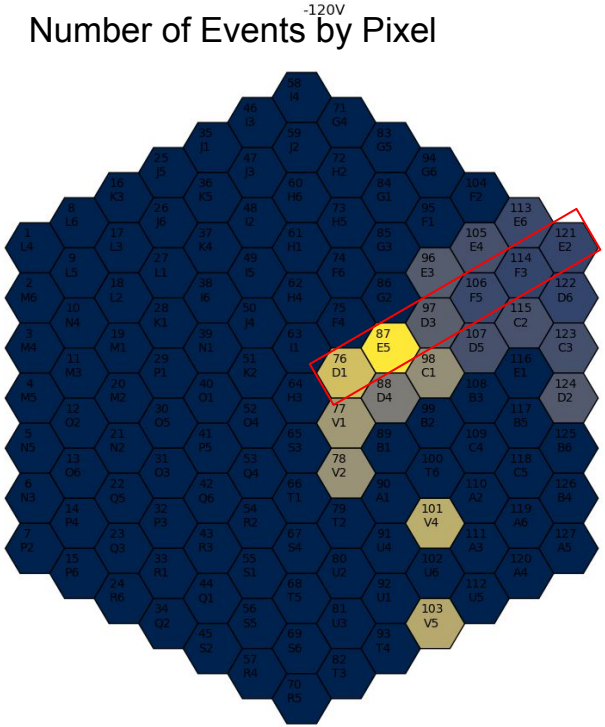
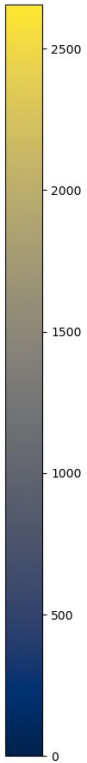
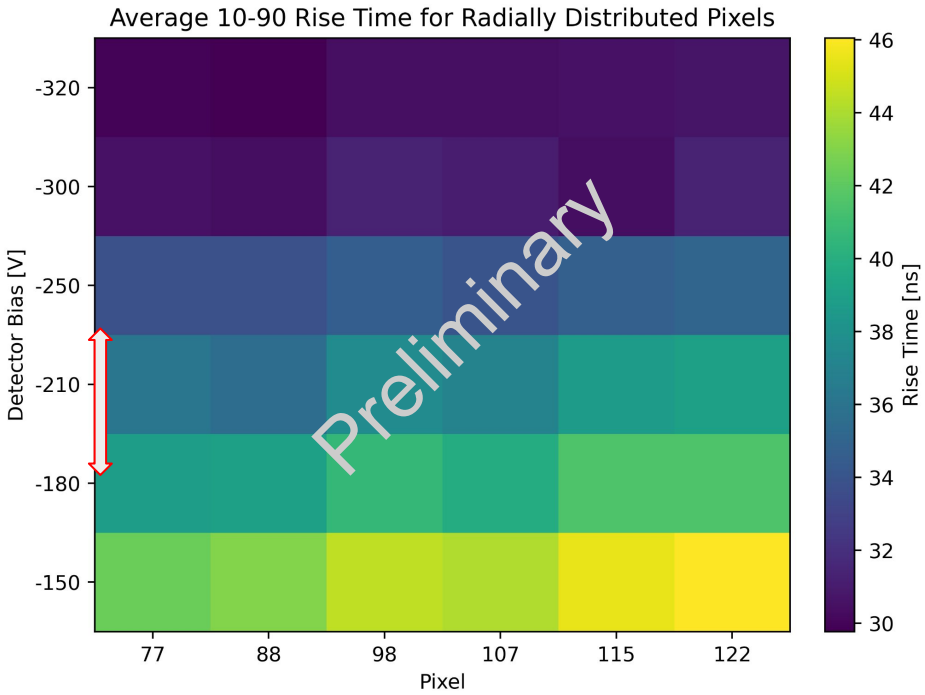
Study of Event Rise Time vs Displacement





^{113}Sn conversion electron data



-180 to -240 target over-depletion at present

Detector Modelling/Simulation

- Nab Event Shape Simulation Effort (NESSE)
- Takes GEANT4/SRIM/custom energy deposits as input
- Considers weighting fields, doping etc.
- Simulates charge collection in Si detector and front-end amplification
- https://link.aps.org/doi/10.1103/PhysRevC.107.065503

Precision pulse shape simulation for proton detection at the Nab experiment

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MB analysis team: Leendert Hayen, RJ Taylor, Jin Ha Choi, WIlliam McCray, Dustin Combs

Recap

- Proton pixel scans and source data collected
- Preliminary study of waveform rise time vs position
- Analysis shows radial impurity density variation
- Further study underway
- Currently working in lockstep on data analysis and simulation

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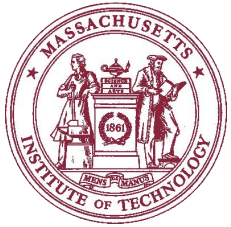
The Nab Collaboration



Main project funding: