Characterization of Segmented Silicon Detectors for Neutron Beta Decay

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April 9th, 2022

Outline

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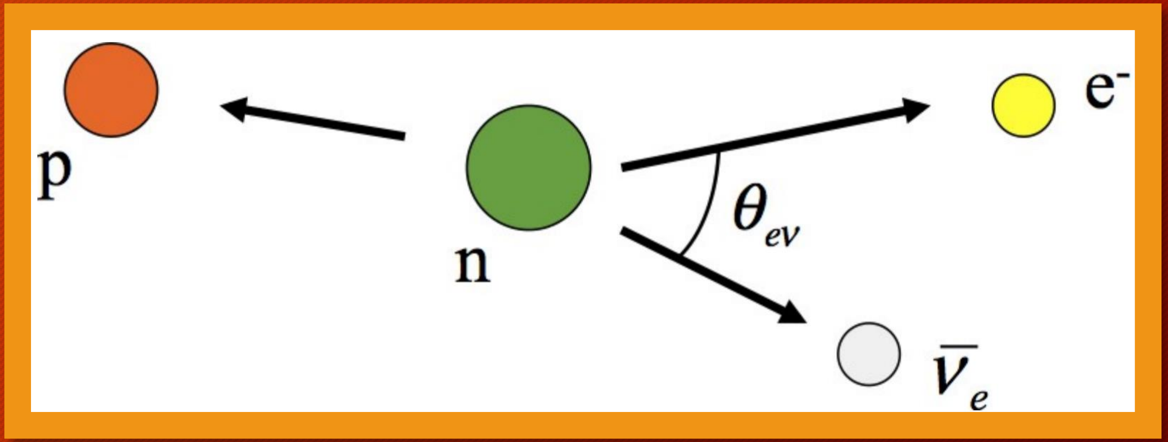
   - Neutron beta decay
   - The CKM matrix

2) Instrumentation
   - The Nab experiment
   - Silicon Diode Detectors
   - Low-energy proton source @ MB

3) Characterization
   - Proton spot size study
   - Detector optimization



Theory - Neutron Beta Decay

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

J. D. Jackson et. al. Phys. Rev. 106 (1957)

- Determine "little-a" from experiment (e-ν momentum correlation)
- Extract λ – the mixing of axial vector to vector coupling in the weak interaction

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

Theory – The CKM Matrix

- λ and τ_n give rise to V_{ud}
- CKM matrix unitarity highly dependent on V_{ud}
- Unitarity of CKM speaks to the number of possible quark generations
- 3σ away from the expected value of 1

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)\ \mathrm{s}}{\tau_n(1+3\lambda^2)}$$

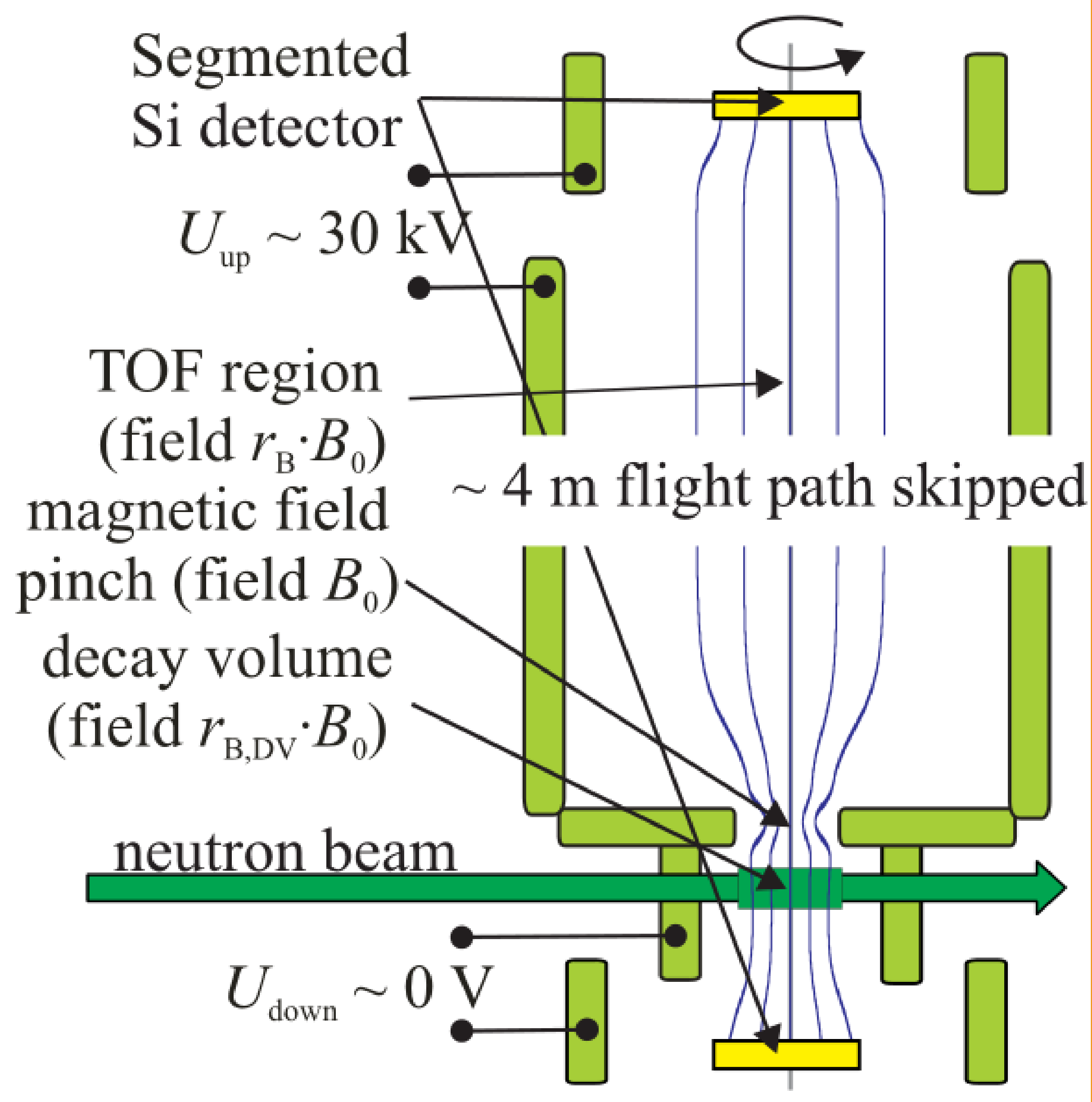
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ideally:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

The Nab Experiment

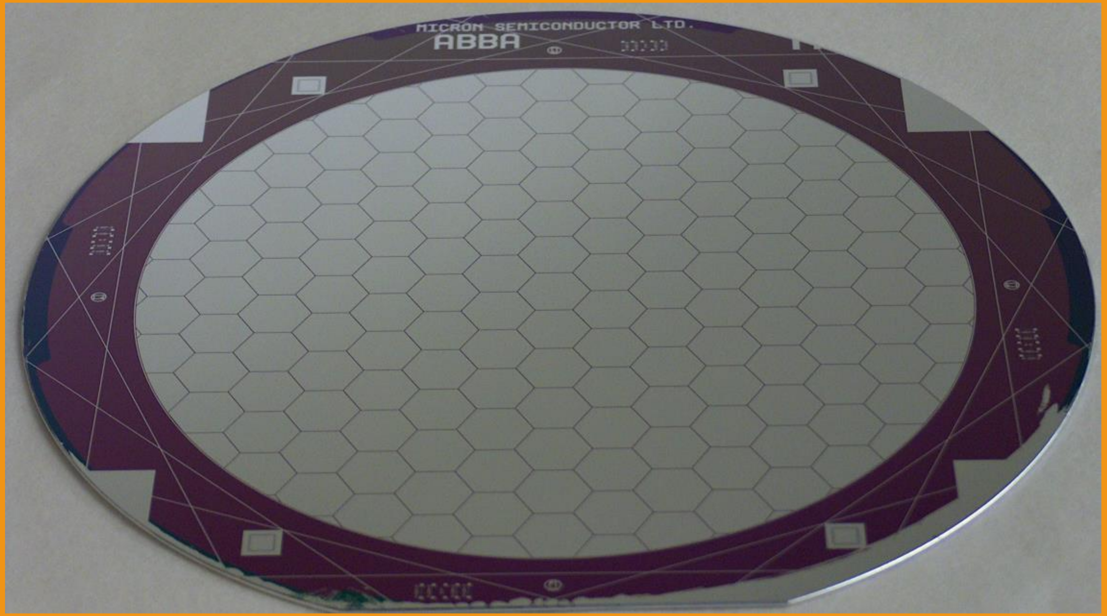
- Spalled neutrons spontaneously decay
- Time-of-Flight Spectrometer
- Measure a and b via electron energy and proton momentum
- Uses well-characterized silicon diode detectors



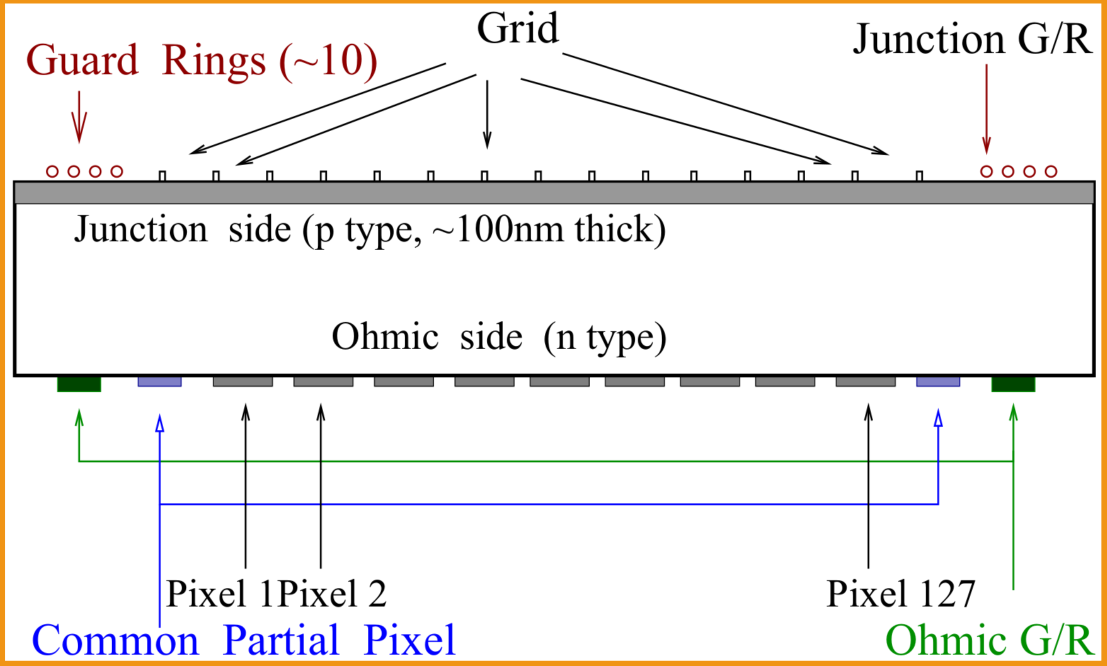
Salas-Bacci et. al., Nuclear Instruments and Methods (2014)

Silicon Diode Detectors

- Layered silicon semiconductor
- Dopants added to increase/decrease charge carriers
- Reverse DC Bias applied across the junction
- Charged particle lodges in the depleted region



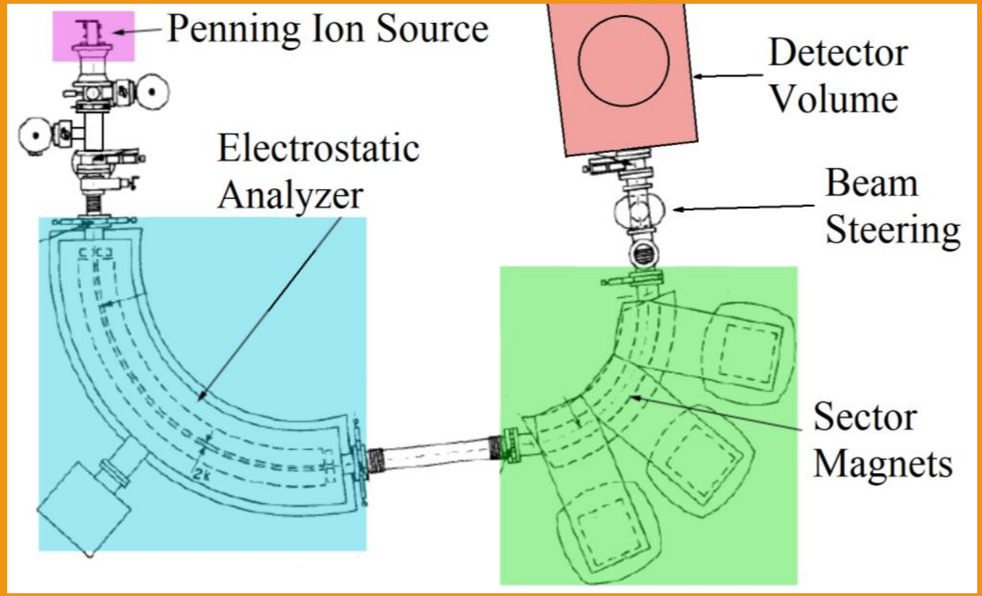
Courtesy of the Nab collaboration



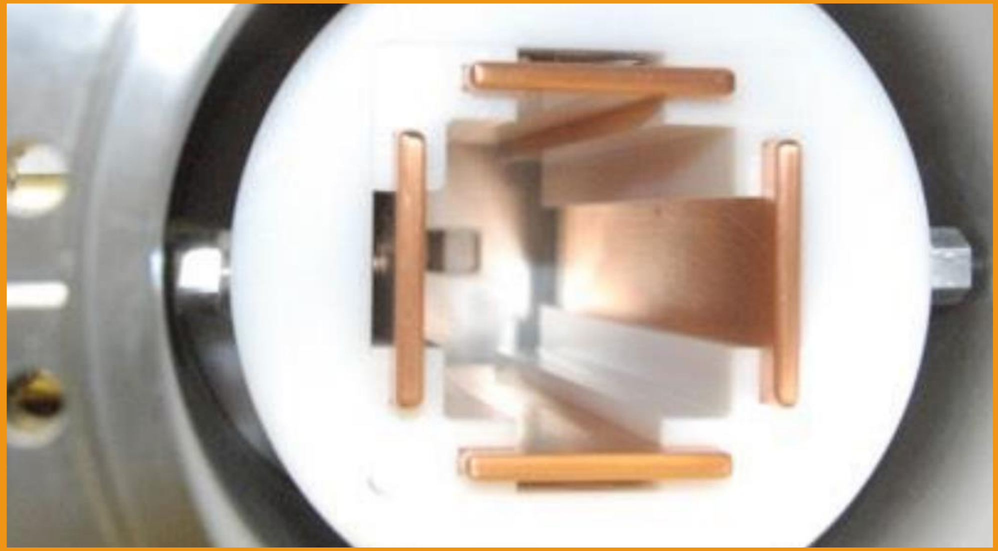
Salas-Bacci et. al., Nuclear Instruments and Methods (2013)

Experimental Setup

- Manitoba II proton source (ex-mass spec)
- Consists of:
  - Penning Ion Source (H-Ar)
  - Energy filtering (ESA)
  - Momentum filtering (Sector Magnets)
  - Beam steering apparatus

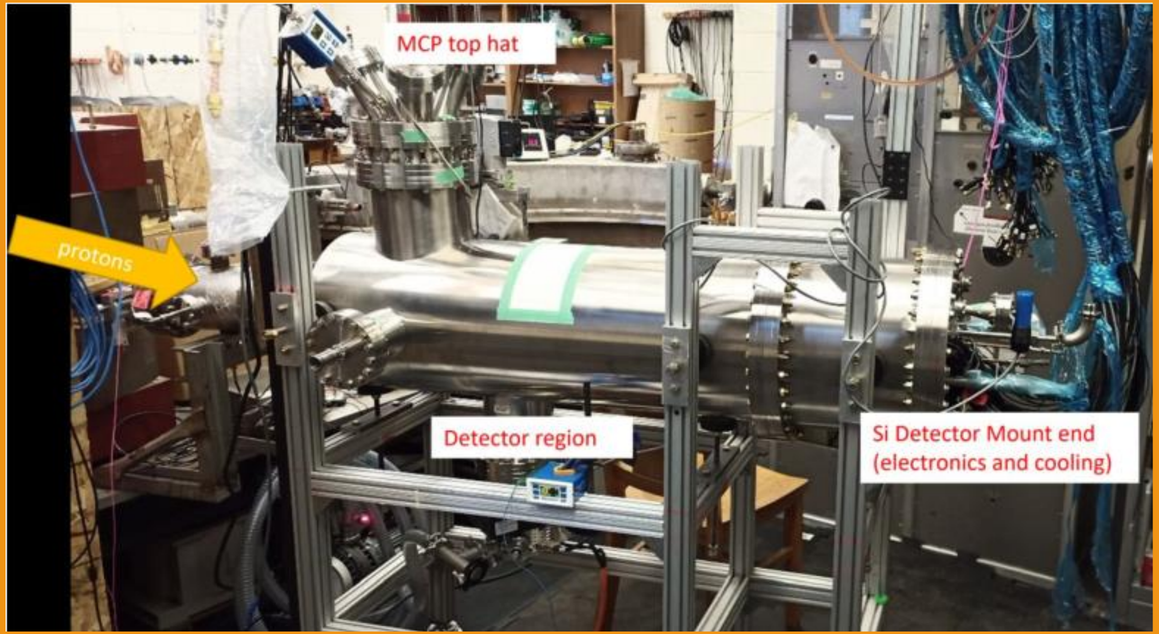


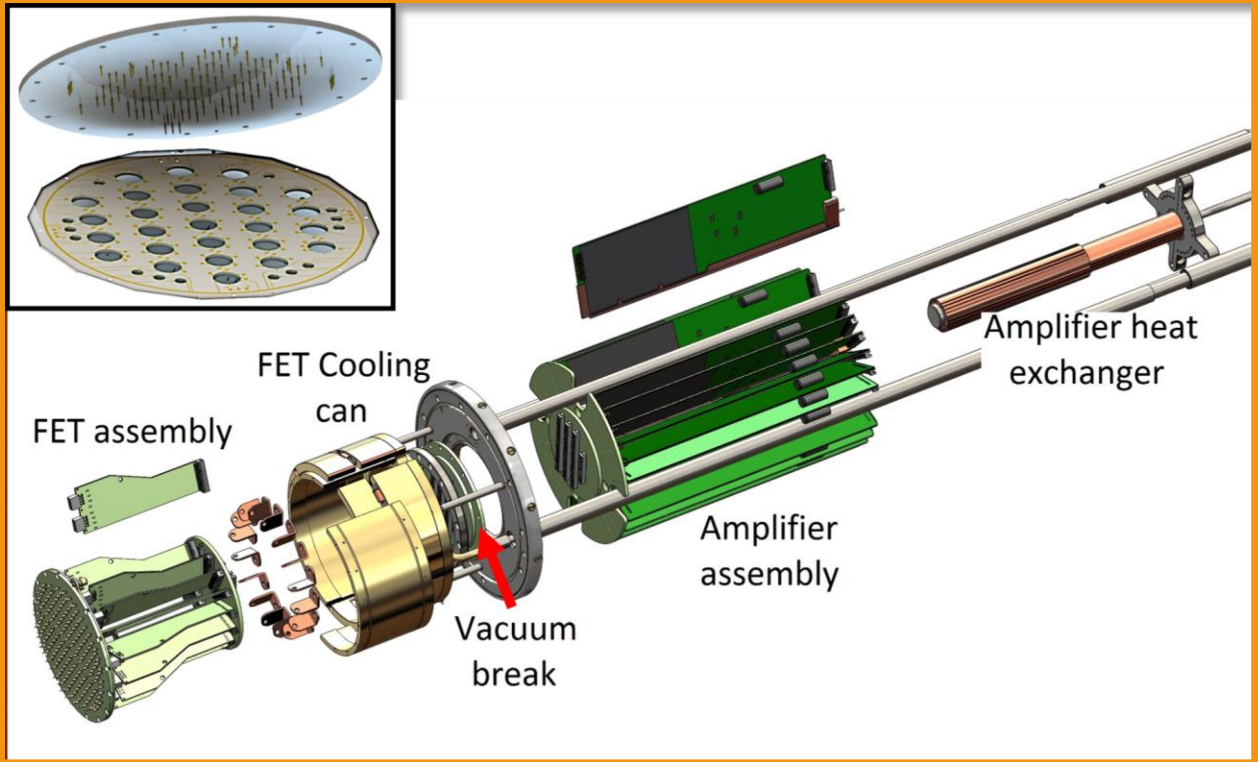
D. Harrison M.Sc Thesis (2013) modified



Courtesy of R. Mammei

The Detector Mount

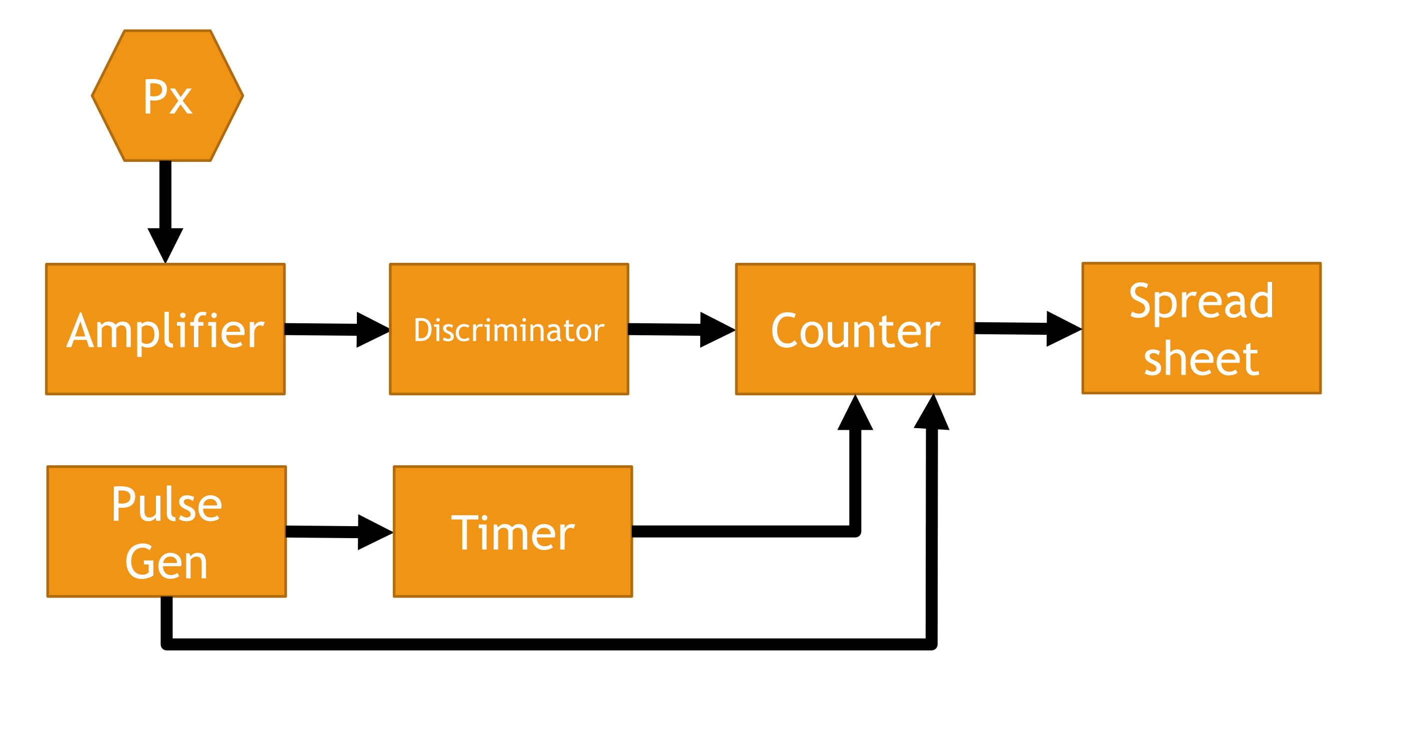




Courtesy of R. Mammei   Courtesy of the Nab collaboration

Proton Spot Size Study

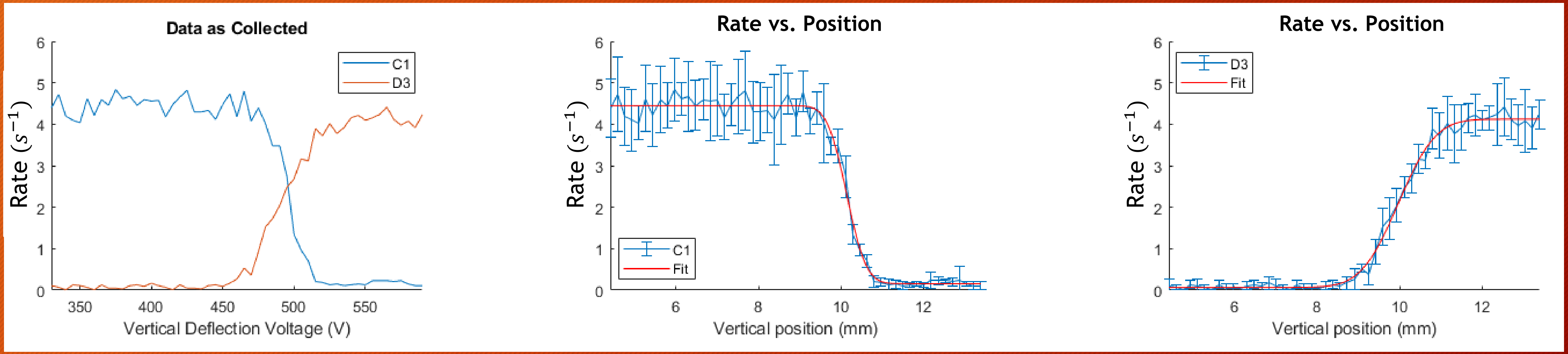
- Use edge of pixel to determine beam diameter (1 ± 0.2mm)
- Erf fit in terms of position
- Two Methods
  - NIM Counter
  - Dedicated DAQ software
- Position information extremely relevant
- Pixel Charge-Sharing Study
  - Much the same as above – now looking at detector with beam



Schematic of the spot size determination using hardware

Statistics for the Counter Method

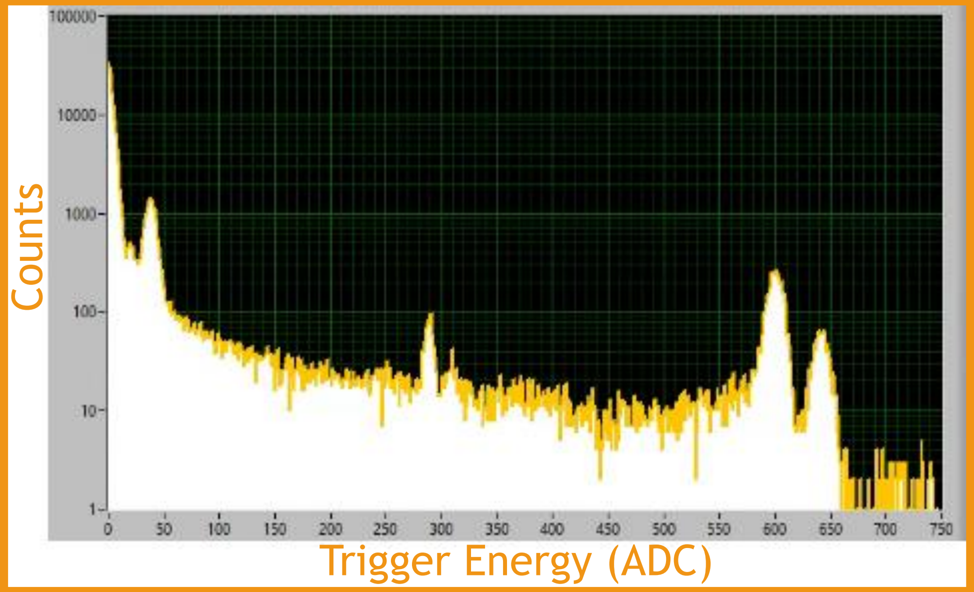
- Created a MATLAB script to fit a cumulative distribution
- Assumed displacement was center-to-center distance
- Extracted 2*HWHM
- $F(x) = \frac{a}{2}\left[b \pm \operatorname{erf}\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)\right]$
- $2 * HWHM = 2\sqrt{2\ln 2}\,\sigma$
- Corresponds to beam cross-section



Running Parameter Optimization

- Two kinds of detectors:

  P-spray and P-stop
- Intend to characterize both with 30KeV protons and radiation sources (Cd^{109} and Sn^{113})



- Want to reduce typical noise contributions
  - Thermal (Johnson) noise $\propto I_L$
    - Temperature and bias are coupled
    - $I_L \propto T^2 \exp\left(-\frac{E_g}{2kT}\right)$
    - Use of LN_2 to achieve temperatures of 120°K
  - Shot noise – FET amplifier
  - $1/f$ ("pink") noise
- Analysis is in-progress

Thank you!