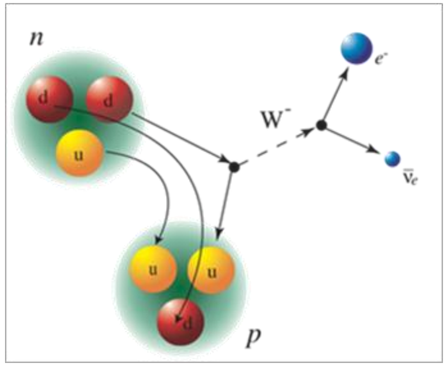
Update on the BL2 in-beam measurement of the neutron lifetime

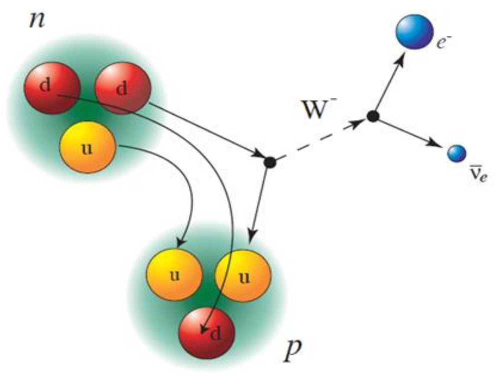


Jimmy Caylor

For the BL2 collaboration

24 Oct 2019 – Physics of Fundamental Symmetries and Interactions (PSI 2019)
Paul Scherrer Institute, Switzerland

Motivation



- CKM Unitarity – Check for beyond the Standard Model physics

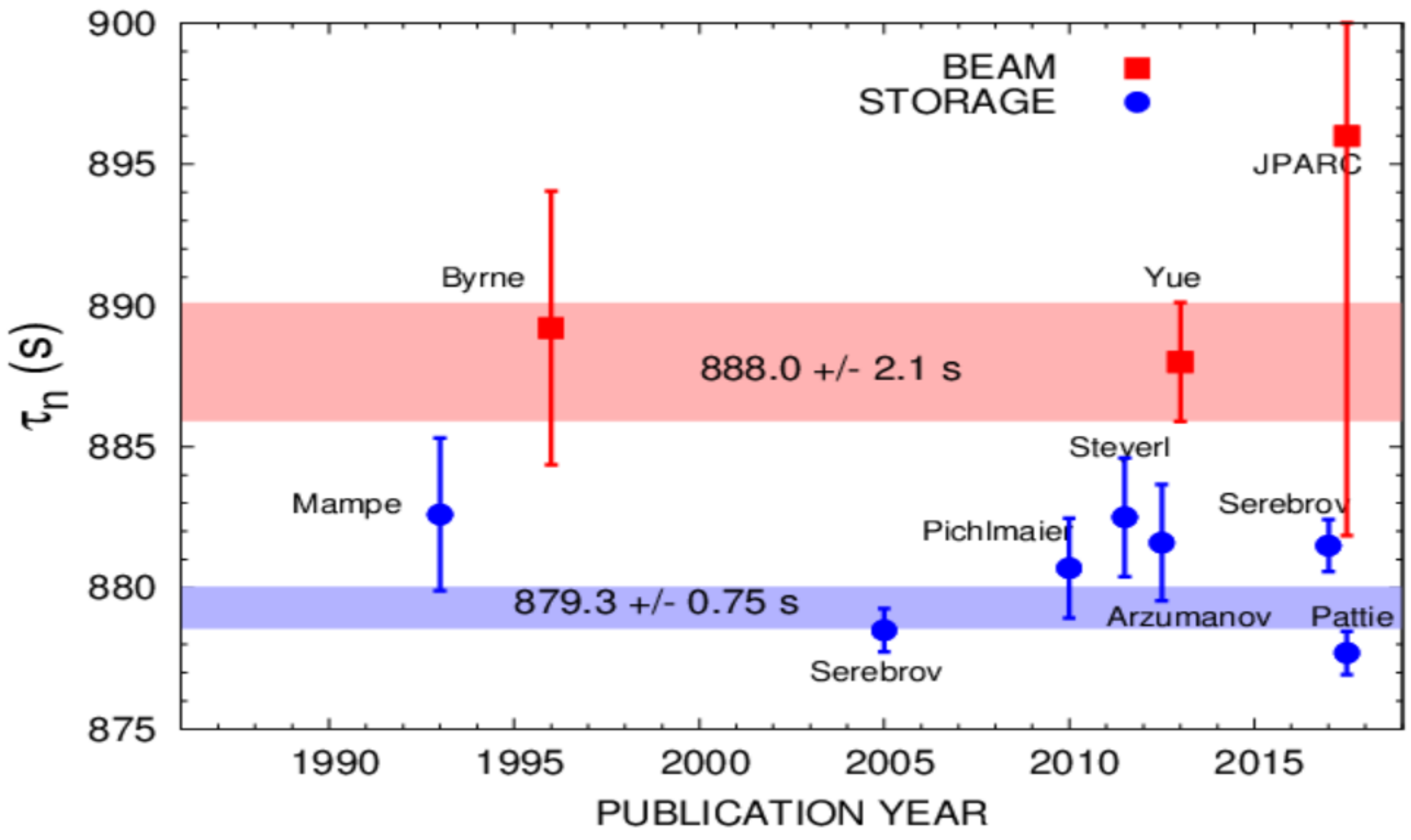
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

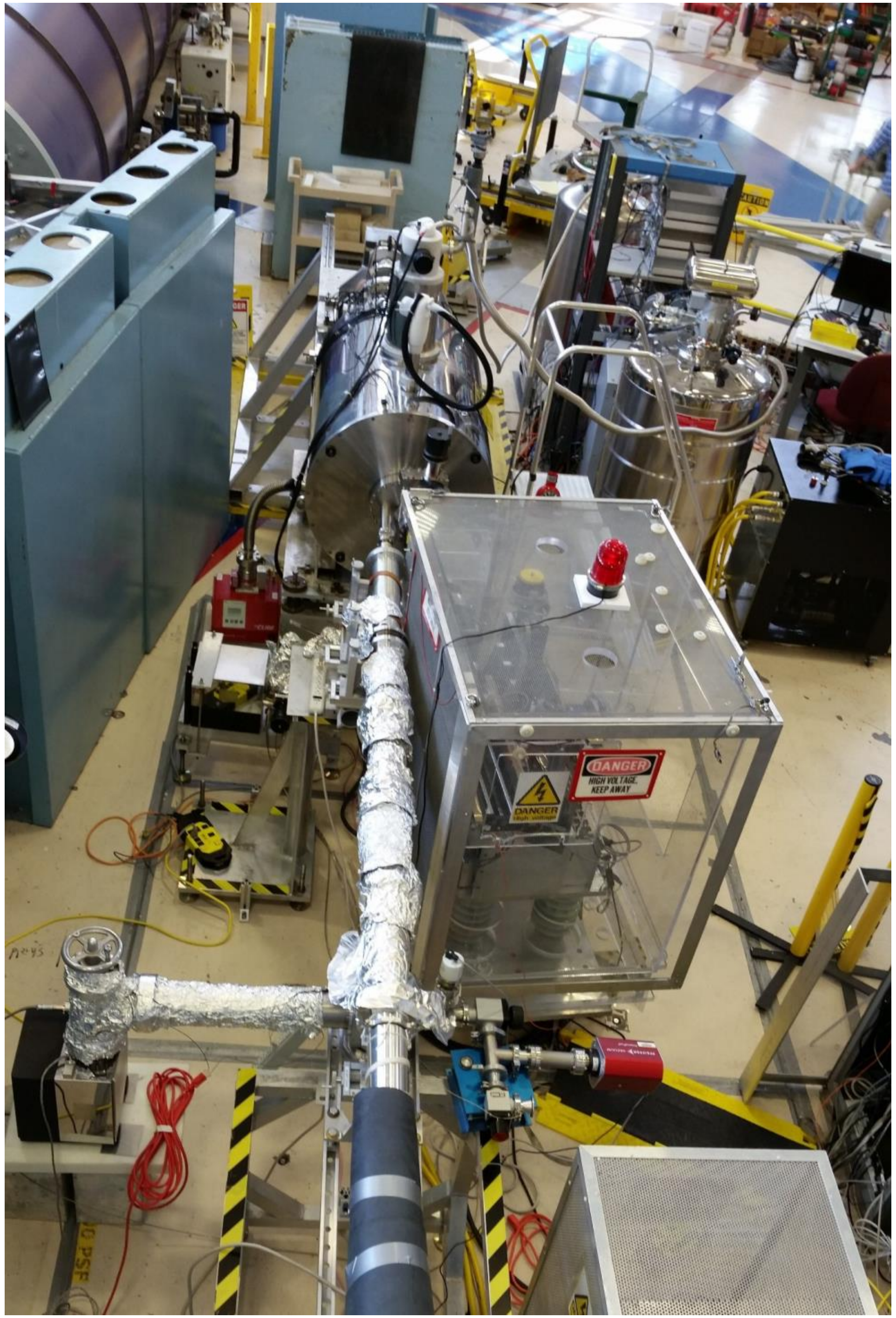
  - V_{ud} from measuring the neutron lifetime, τ_n, and beta decay correlation coefficients.

- Big Bang Nucleosynthesis
  - τ_n is the largest uncertainty in n/p ratio calculations

Current state of the neutron lifetime:



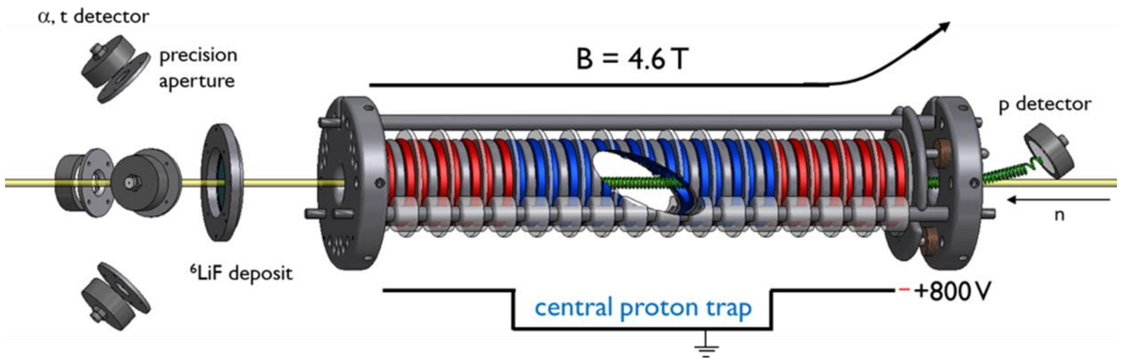
NCNR and experimental apparatus



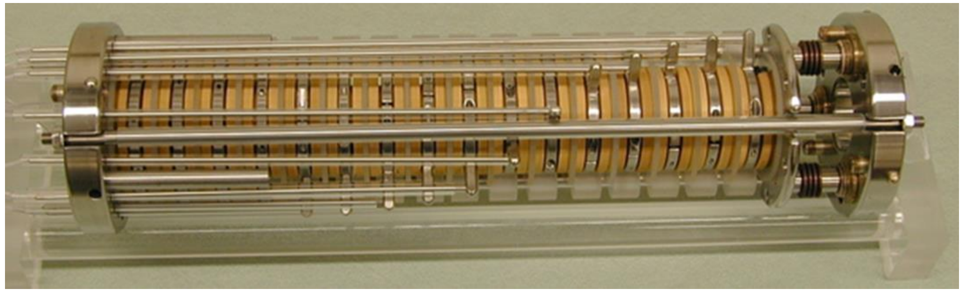
Beam method experiment

$$\frac{\dot{N}_p}{\dot{N}_n} = \tau_n^{-1}\left(\frac{\epsilon_p}{\epsilon_o}\right)(nl + L_{end})$$

- Challenges
  - Low proton rate in the presence of background
  - Must accurately measure the decay volume
  - Measure the neutron density in the trap volume



- Electrode Proton Trap
  - Manufactured of 16 fused quartz electrodes with an evaporated gold coating
  - Measured accuracy of 5µm and change in length ~.01% when cold
  - protons trapped with 100% efficiency in the middle of trap, <100% Trapped in “end region”



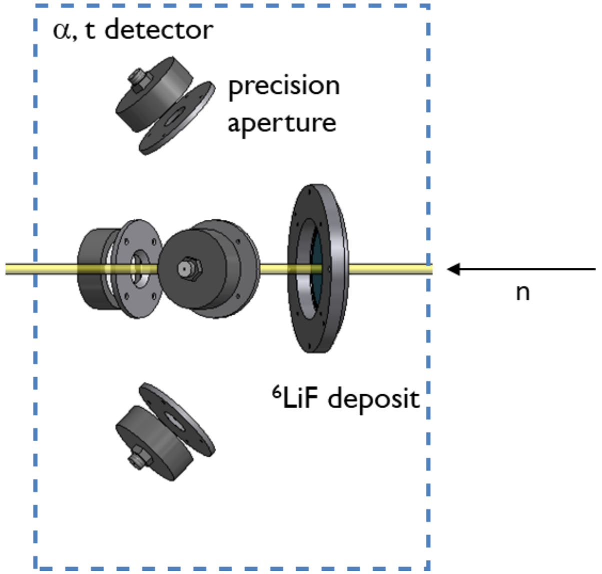
Neutron Flux Monitor

- $^{6}Li(n,t)\ ^{4}He$
  - Neutron capture process
  - Detect a triton and alpha particle for every captured neutron
  - Energies ~few MeV per particle make them easy to detect
- Neutron counting efficiency

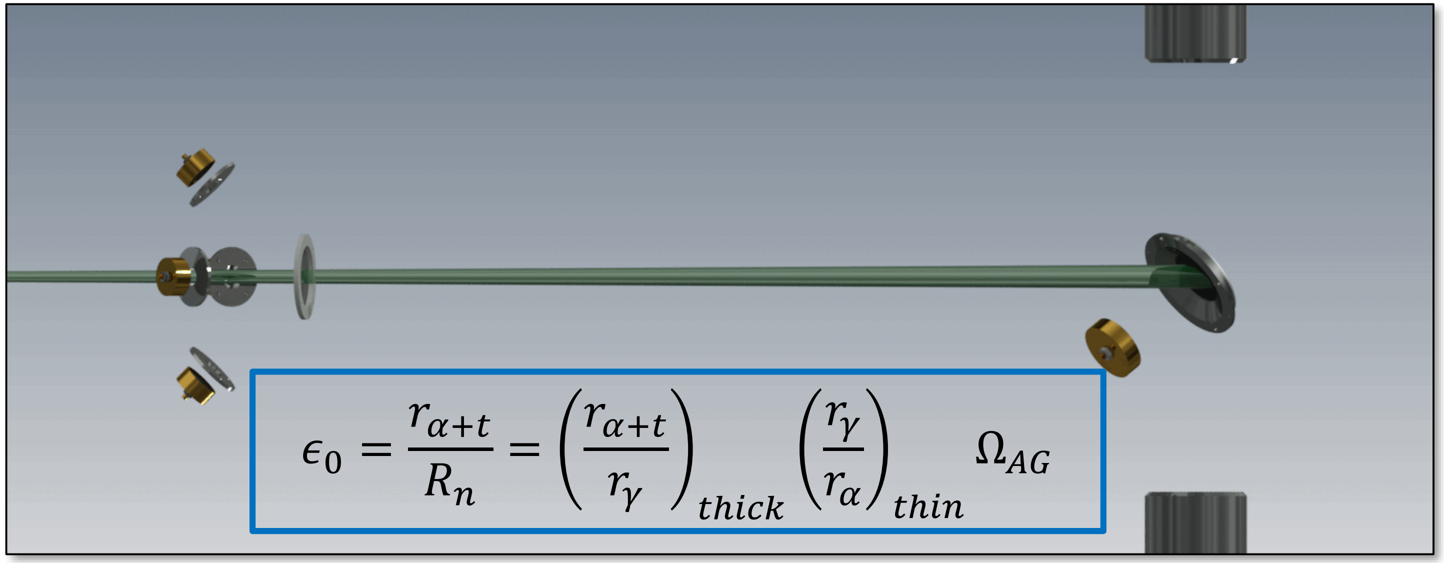
$$\epsilon_o = \frac{2N_A\sigma_o}{4\pi A}\iint \Omega(x,y)\,\rho(x,y)\phi(x,y)dxdy$$

  - Dependent on measuring the neutron capture cross section

1/v neutron monitor



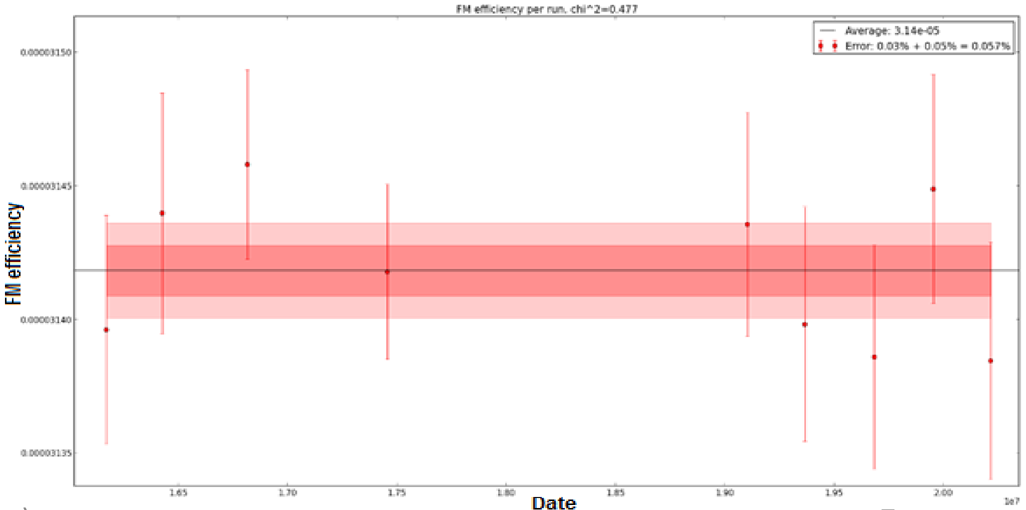
Alpha-Gamma Methodology



$$\epsilon_0 = \frac{r_{\alpha+t}}{R_n} = \left(\frac{r_{\alpha+t}}{r_\gamma}\right)_{thick} \left(\frac{r_\gamma}{r_\alpha}\right)_{thin} \Omega_{AG}$$

Plutonium α Source → α Detector Solid Angle → γ detector efficiency (thin target) → Neutron beam flux (thick target) → Flux monitor Efficiency

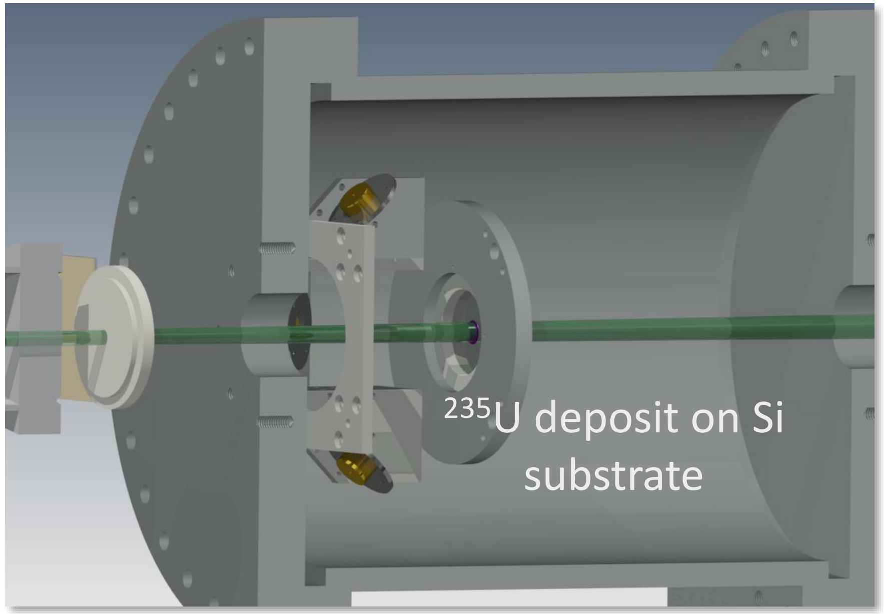
- Uses 239Pu α source to calibrate SBD
- Capture on thin Boron:
  - $n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha + 2.798MeV$
  - (BR=93.7%) transfers calibration to HPGe's
- Gammas from neutron capture on totally absorbing Boron target give beam flux (branching ratio cancels)
- <0.1% precision in ~4 weeks



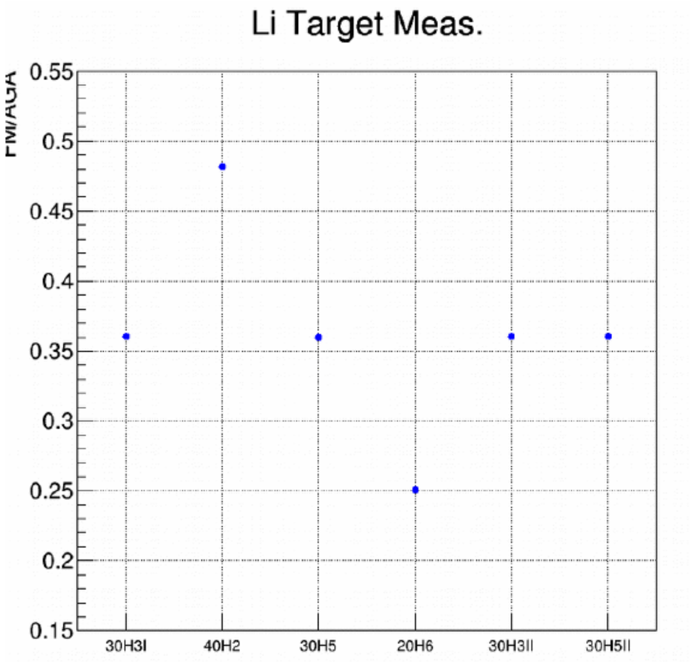
Slide from: E. Adamek

Cross-checks of Alpha-Gamma

- ^{235}U(n,f) cross section precisely known to 0.2%
- Standard ref. material allows us to obtain the mass of ^{235}U deposit
- $\sigma_{U235(n,f)} = \dfrac{r_f}{R_n \rho_U A_{\text{beam}} \Omega_{\text{FM}}}$
- Independent measurement that directly measures systematics



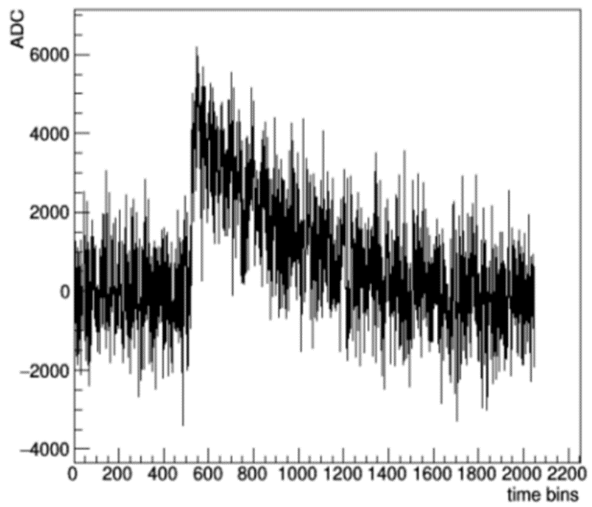
- Measurement campaign directly compares Li target capture rates
- Standard IDMS technique destroys one target to precisely determine Li mass, ^{6}Li/^{7}Li ratio
- Determine cross section from known masses, signal rates of all targets.



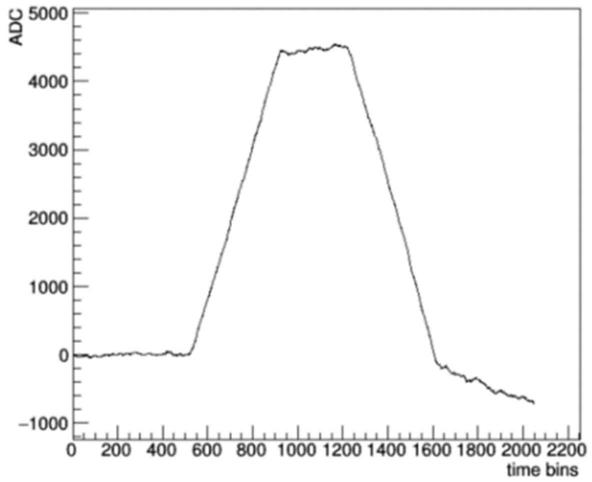
Trapezoid Filter Analysis

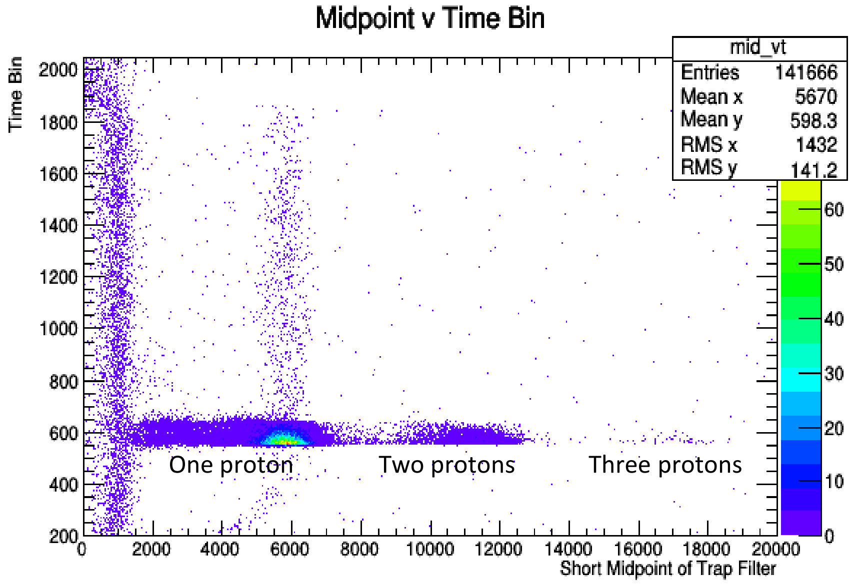
- Uses a convolution for pulse shape discrimination
- Retains information from the original pulse
- Able to identify multiple proton events

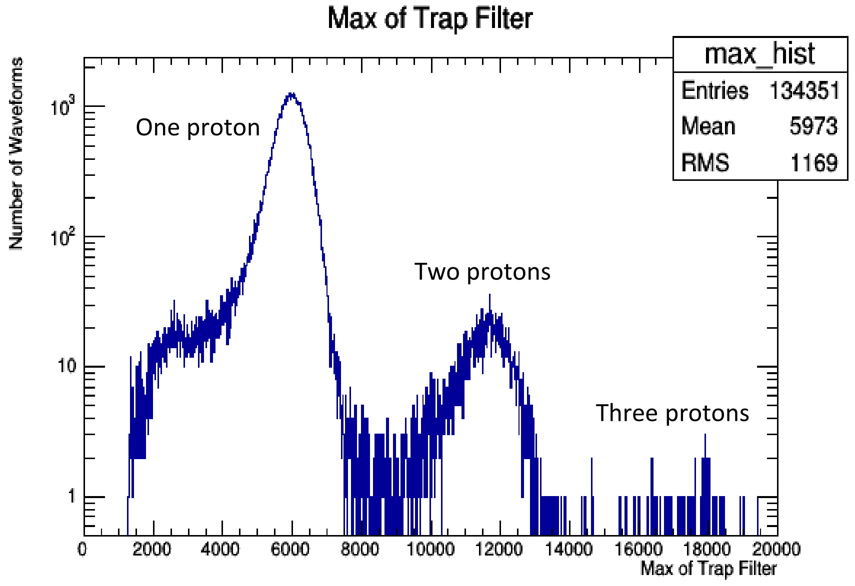
Preamp pulse



Trapezoid filter output

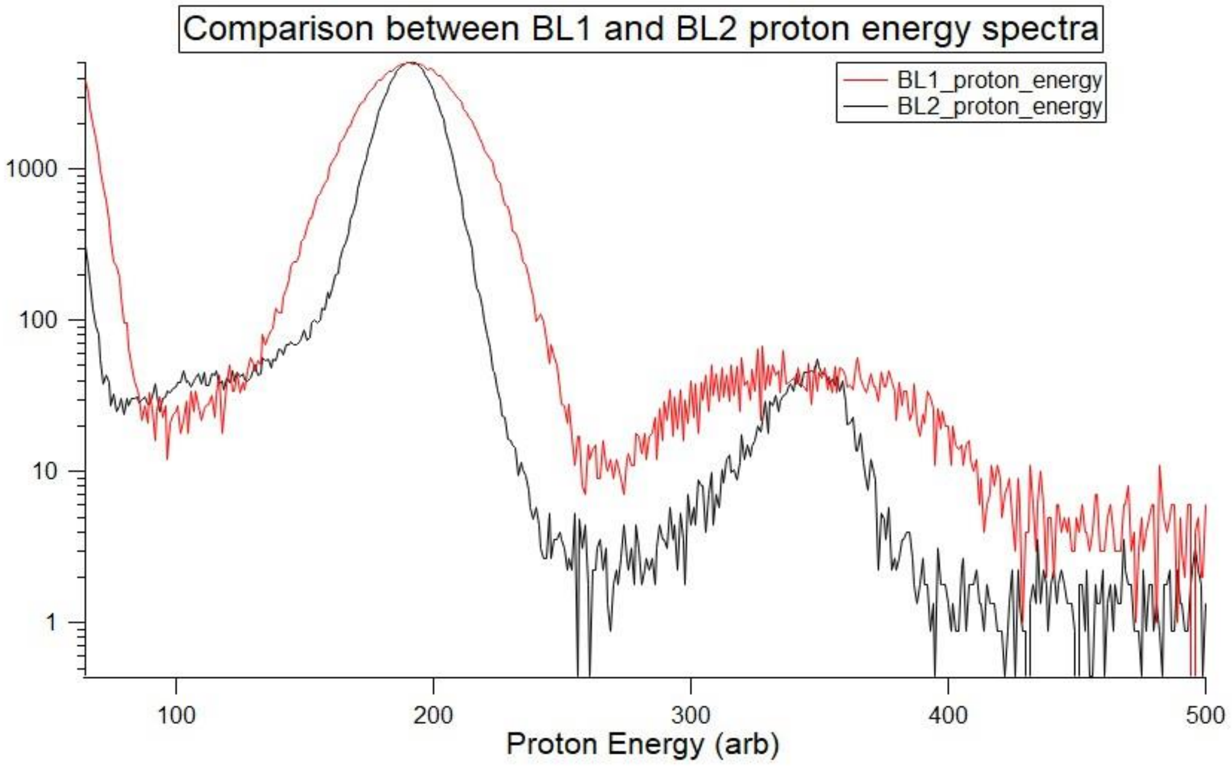


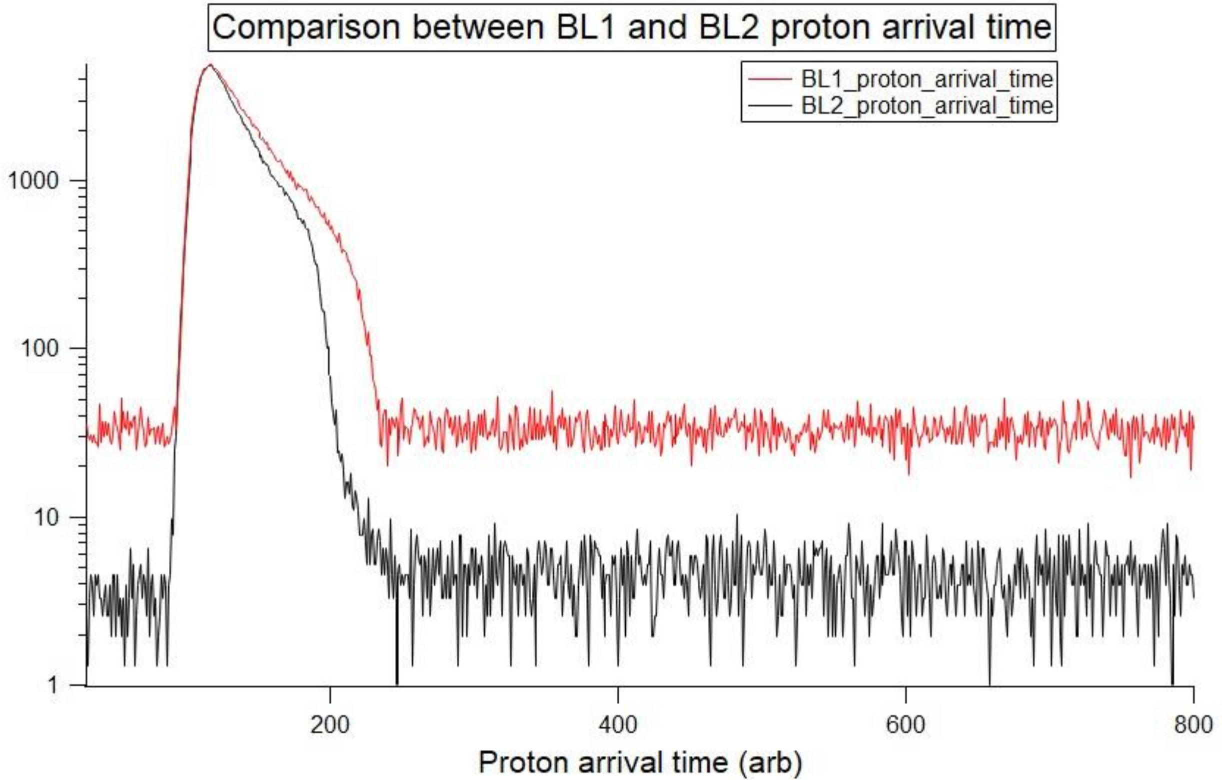




Comparison between BL1 and BL2 data quality

- Better signal to noise
- Better energy and timing resolution





Proton Systematics to check

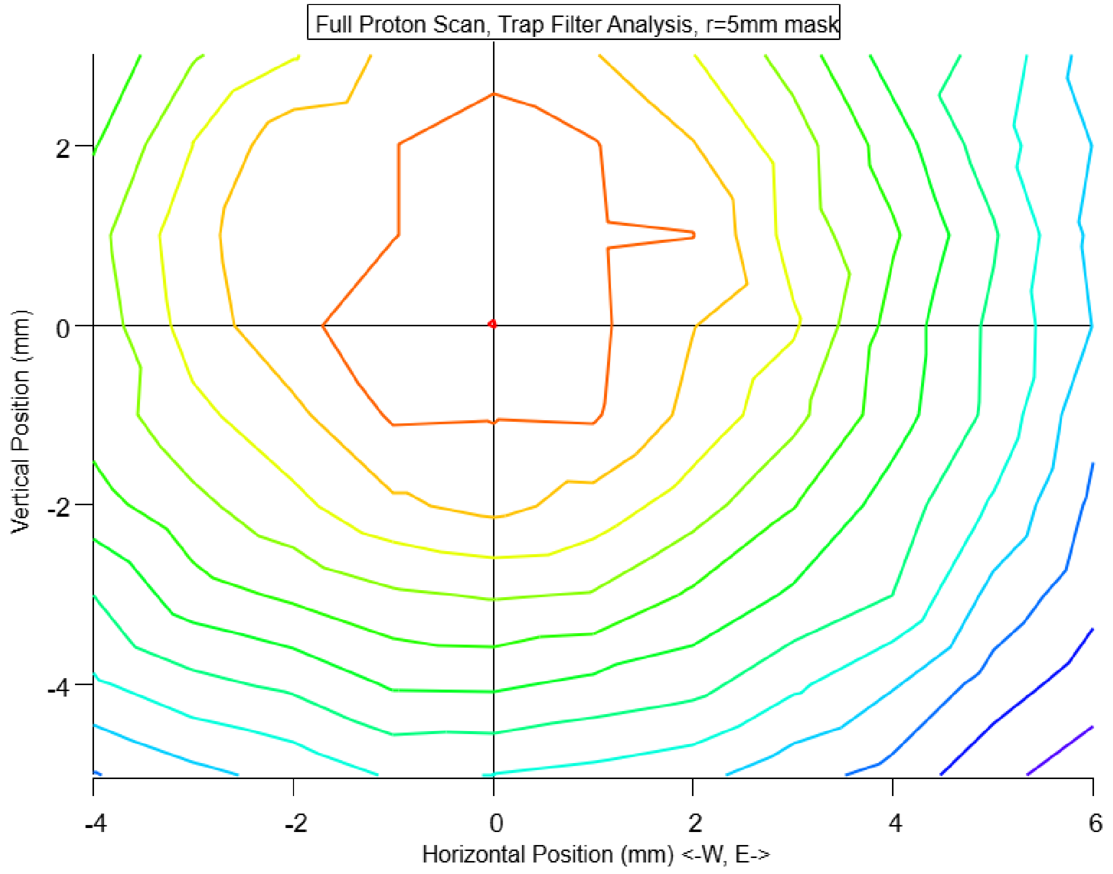
Protons	Test
Different trapping times (3, 5, 10 , 20 and 30+ ms)	Proton loss mechanisms in trap; dead time correction
Run with different B fields	Proton transport; loss of protons in trap
Different beam collimations	Proton transport; sampling of different trap volume
Silicon detector type/manufacturer; acceleration voltage	Backscattering determination
Silicon detector size; neutron beam imaging; detector alignment	Proton loss due to neutron beam halo; proton loss due to misalignments
Different mirror sizes	Demonstrate that 3 is sufficient and understood
Do 3-electrode scan of trap	Uniformity of trap; comparison with calculation
Vary ramp voltage	Efficiency of flushing of trap
Vary door/mirror voltage	Trap efficiency; calculation of protons born in E field
Operate two traps: Mark II and Mark III	Trap-dependent loss
Verify with simulation everything possible	Understanding of particle dynamics (and potential loss)
More sophisticated treatment of proton backscattering	Understanding of backscattering

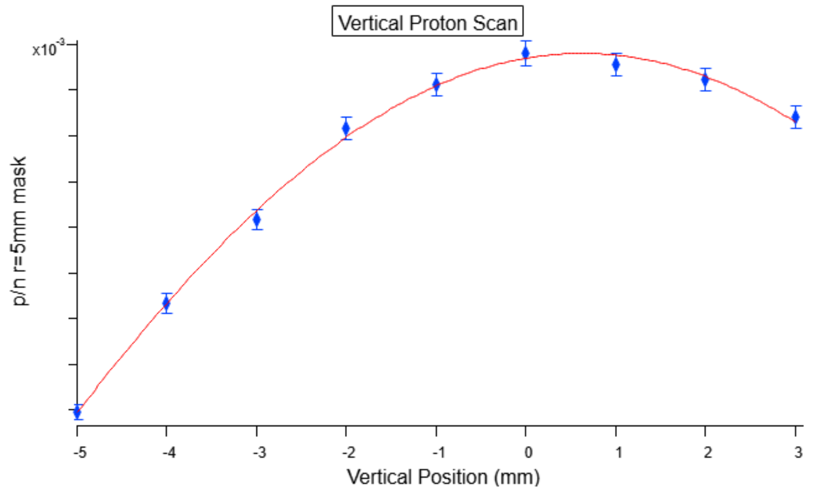
Neutron Systematics to check

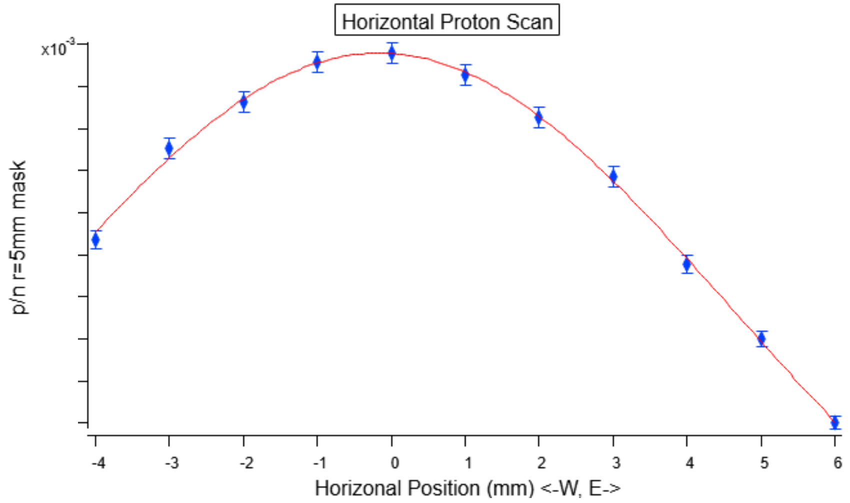
Neutrons	Test
With and without Si wafer in beam	Test Si corrections
Measure wavelength and intensity distributions	Improved determination of absorption correction
Vary 1/v configuration (deposit orientation)	Test neutron counting and corrections
Run with different Li deposits	Test deposit/mass specific corrections; rate effects
Run with B deposit(s)	Test mass specific corrections

Proton detector alignment

- 1 and 2D detector scans to check alignment with trapped protons

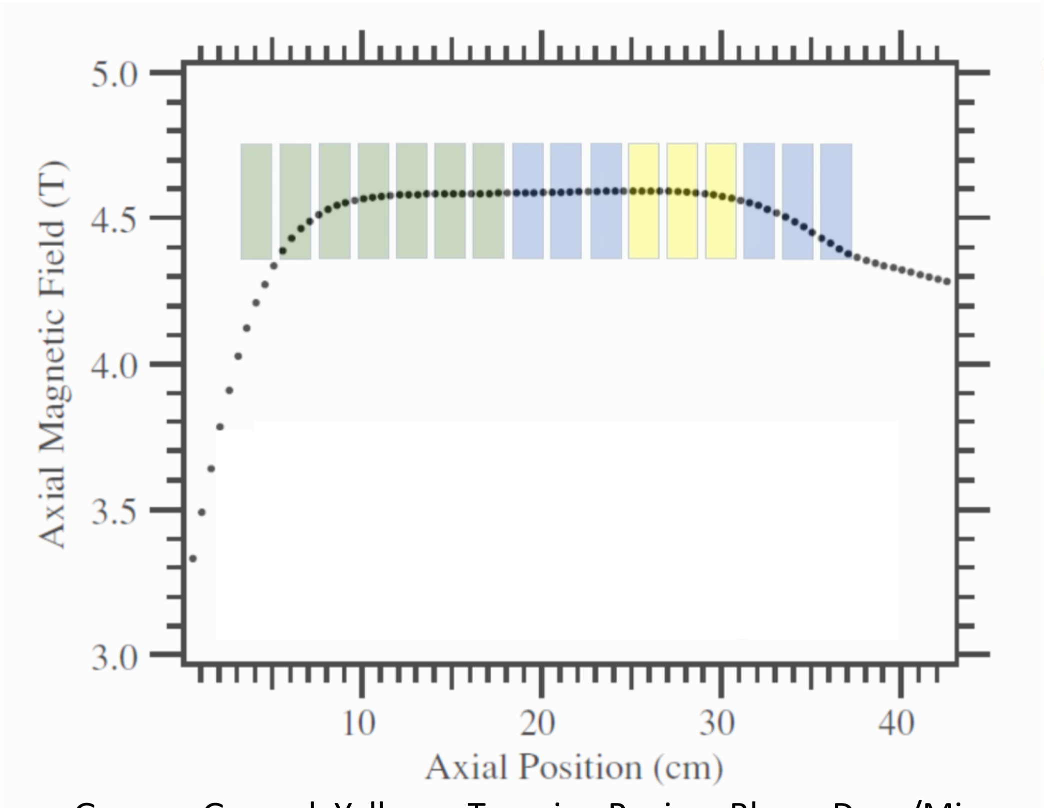




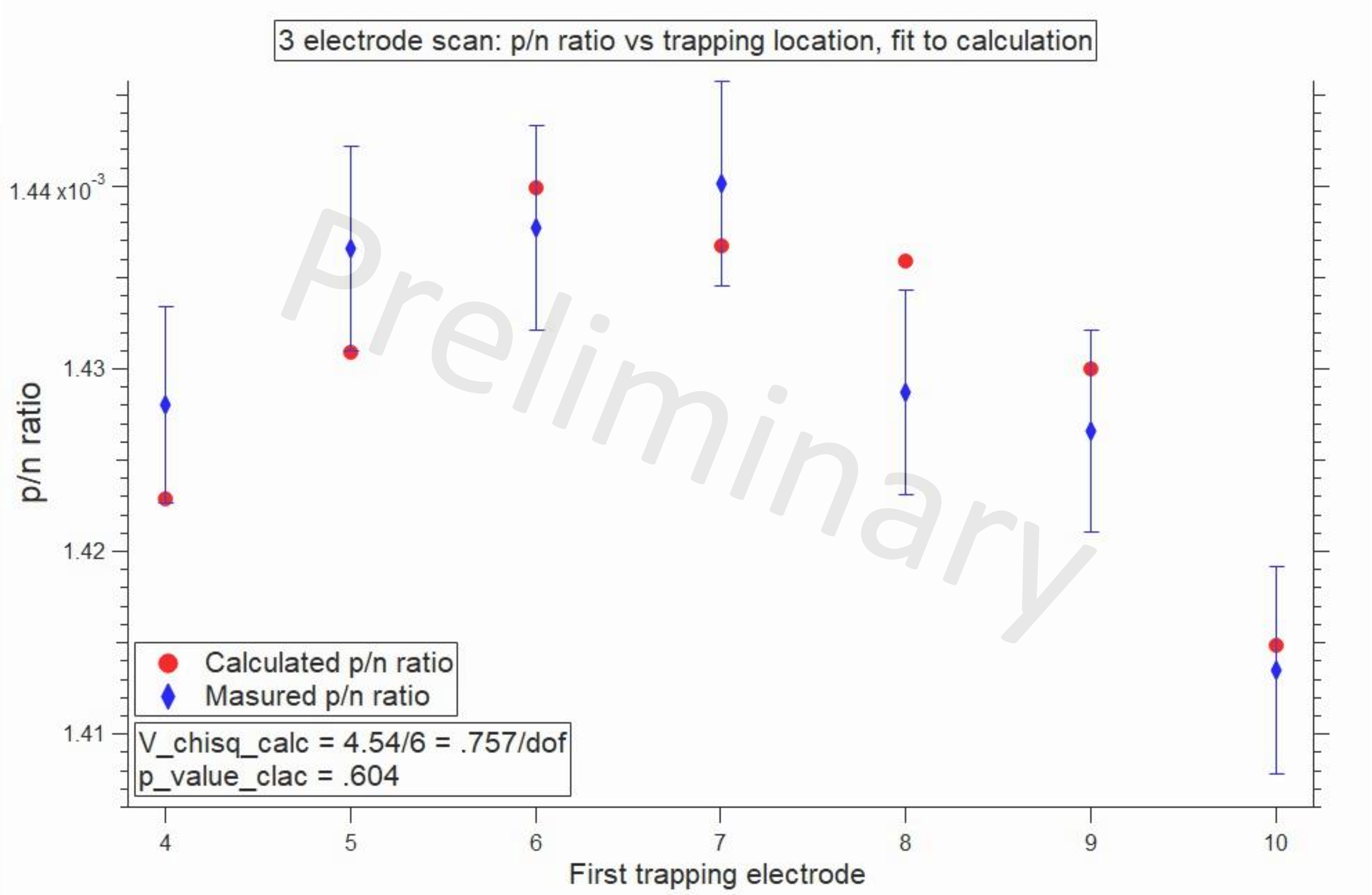


3-electrode scan of trap

- Checks uniformity of trapping region
  - Depends on trapping length and magnetic field shape
- Able to compare to calculation

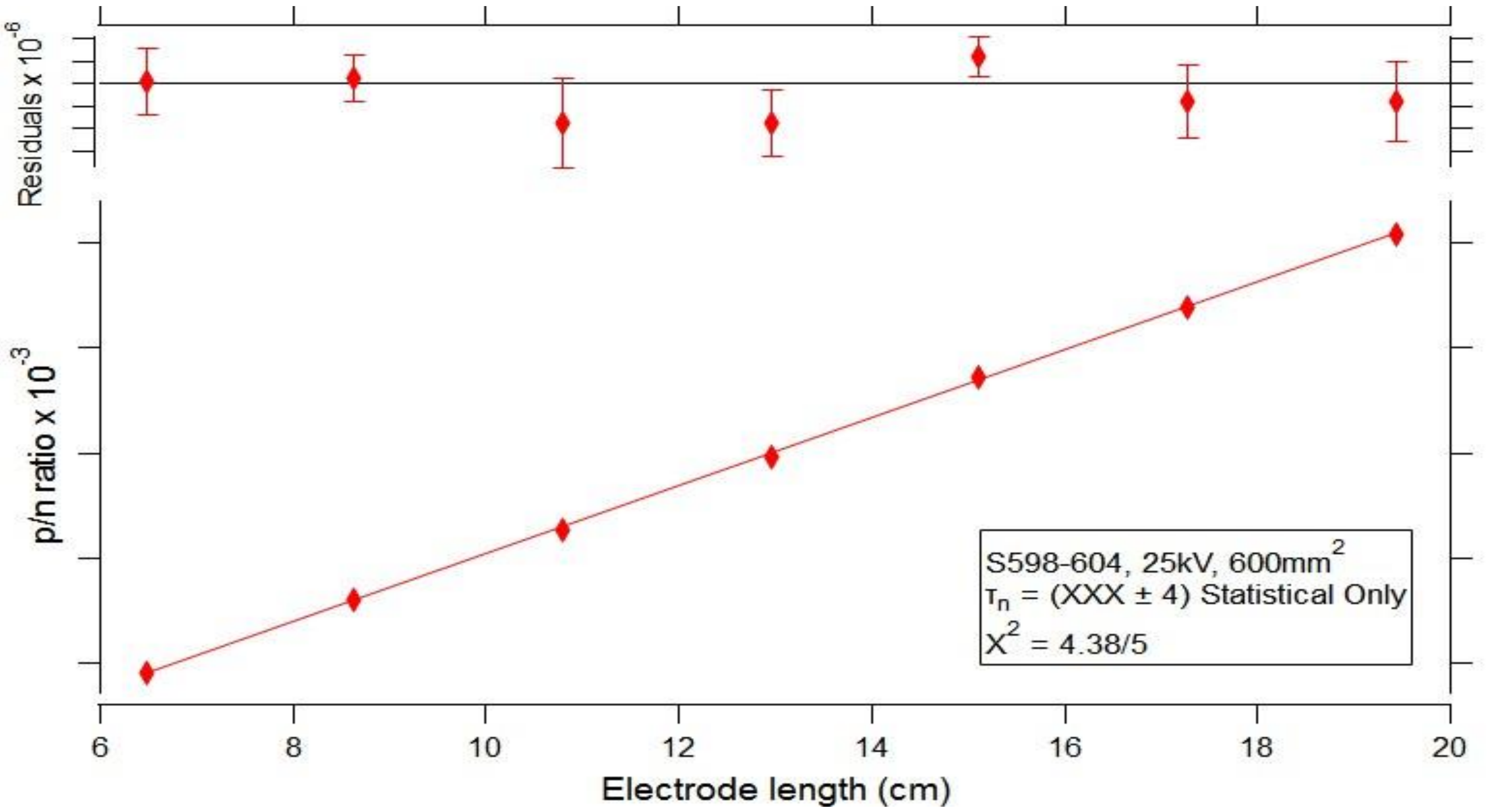


Green = Ground, Yellow = Trapping Region, Blue = Door/Mirror



Lifetime fit example

$$\frac{\dot{N}_p}{\dot{N}_n} = \tau_n^{-1}\left(\frac{\epsilon_p}{\epsilon_o}\right)(nl + L_{end})$$



Summary

- Neutron lifetime is needed for tests of CKM Unitarity
- Neutron lifetime is an important input parameter to Big Bang nucleosynthesis calculations
- Finished commissioning experiment in 2018
- Currently taking production data and making systematic checks
- Continue running through (at least) 2020

BL2 Collaboration

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2. Indiana University
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4. National Institute of Standards and Technology
5. Oak Ridge National Laboratory
6. Tulane University

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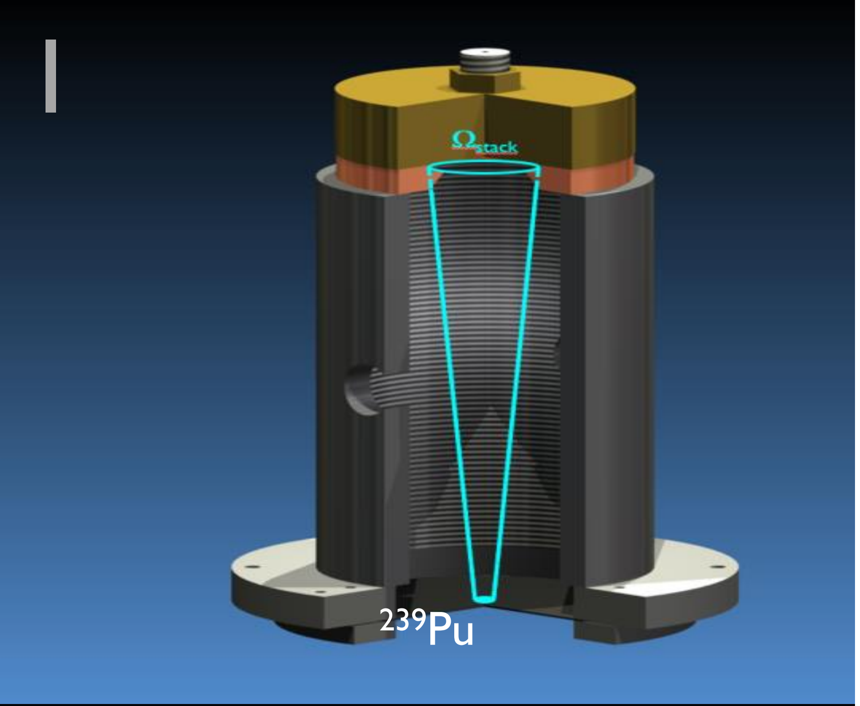
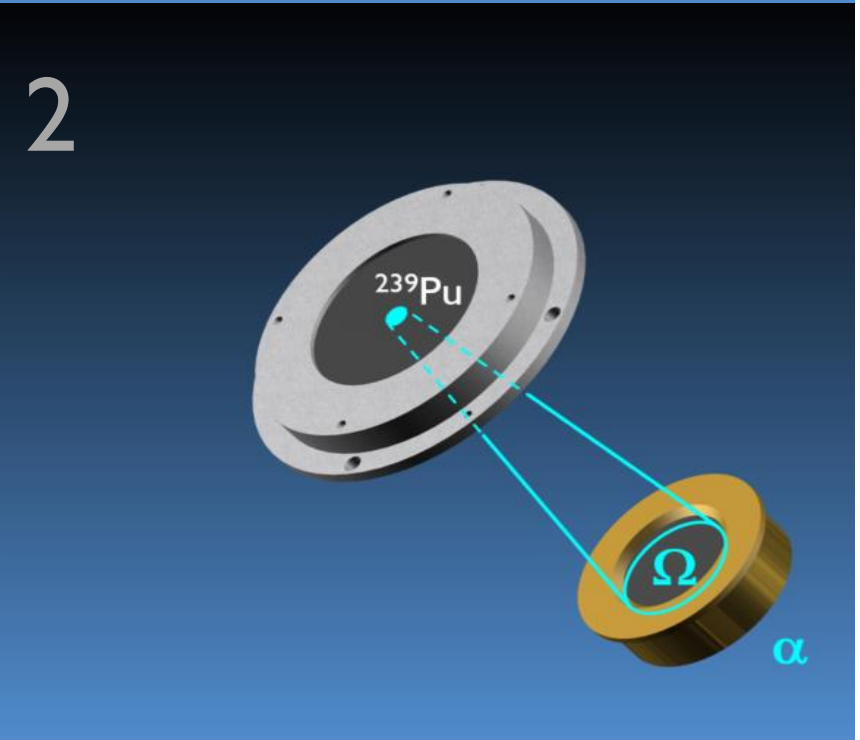
Backup Slides

2005 Measurement Uncertainty Budget

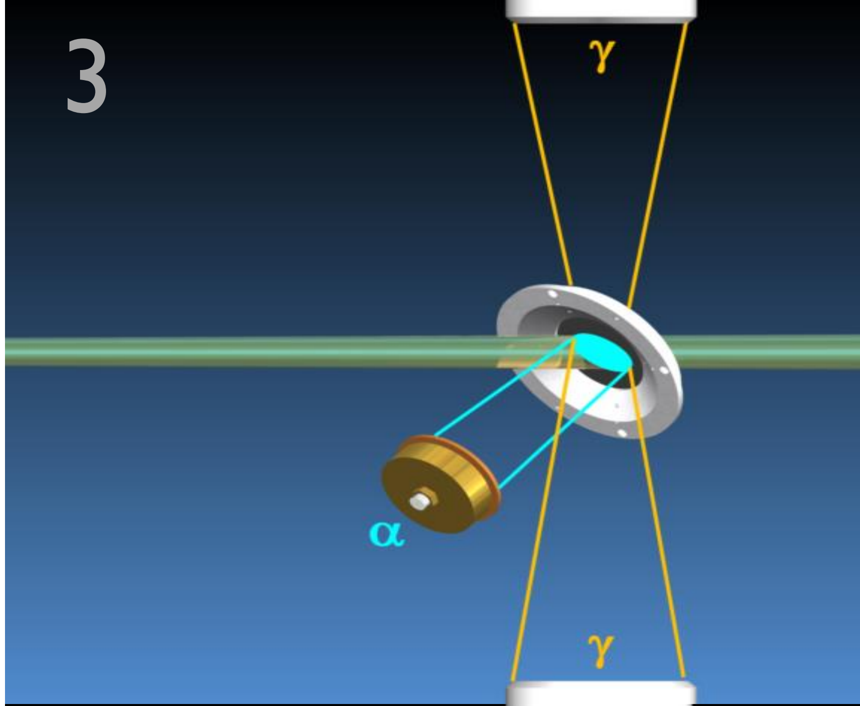
Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

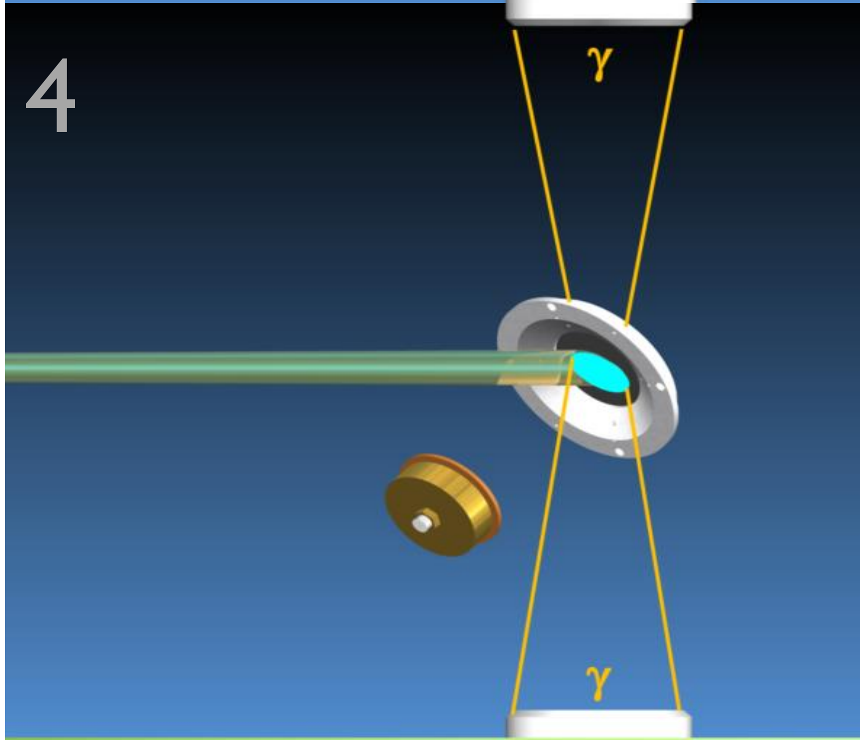




Alpha-Gamma Process

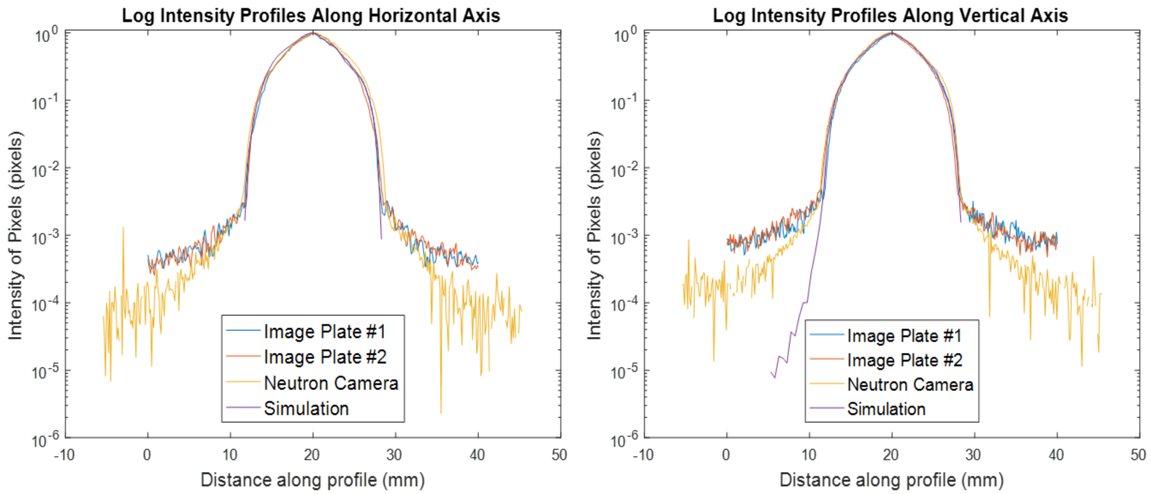
1. Calibrate ^{239}Pu source
2. Insert Pu source in Alpha-Gamma and measure alpha detector solid angle
3. Insert thin Boron foil and calibrate gamma detector efficiency
4. Insert thick Boron foil to stop and count every neutron





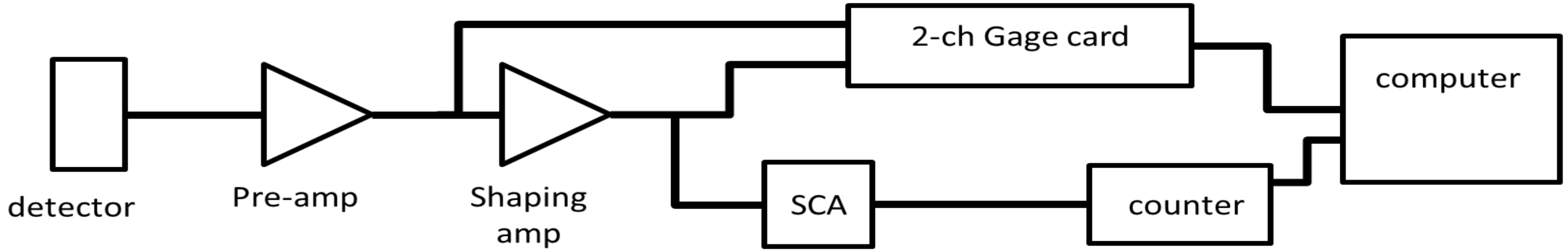
Neutron beam halo and neutron absorption

- Neutron Absorption in ^{6}Li
  - Use multiple, thinner ^{6}Li deposits
  - Measured wavelength spectrum on new beamline
  - Better able to make $\frac{1}{v}$ correction
- Neutron Beam Halo
  - Artifact of previous measurement technique
  - Unnecessarily added uncertainty to the previous result
  - Larger proton detector and better imaging techniques



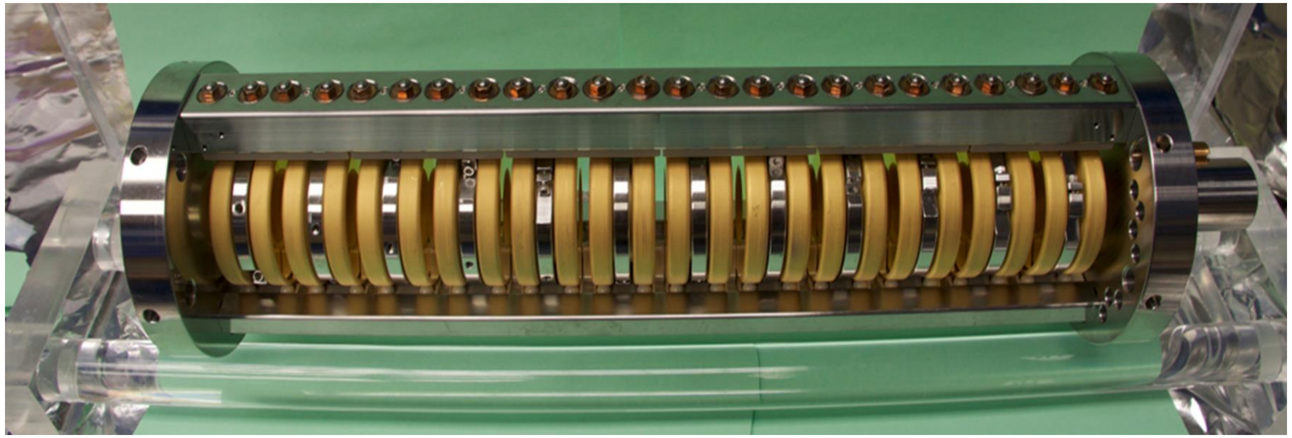
DAQ digitization and Beamline Upgrades

- DAQ
  - Previous analysis method did not save any proton waveforms
  - New DAQ digitizes both preamp and specamp waveforms for every threshold passing
  - Allows for more detailed offline analysis
- Beamline
  - Previous experiment ran on NG-6 at NIST
  - New experiment running on NG-C and has greater neutron flux
  - Curved guide -> less background, no direct sight to reactor

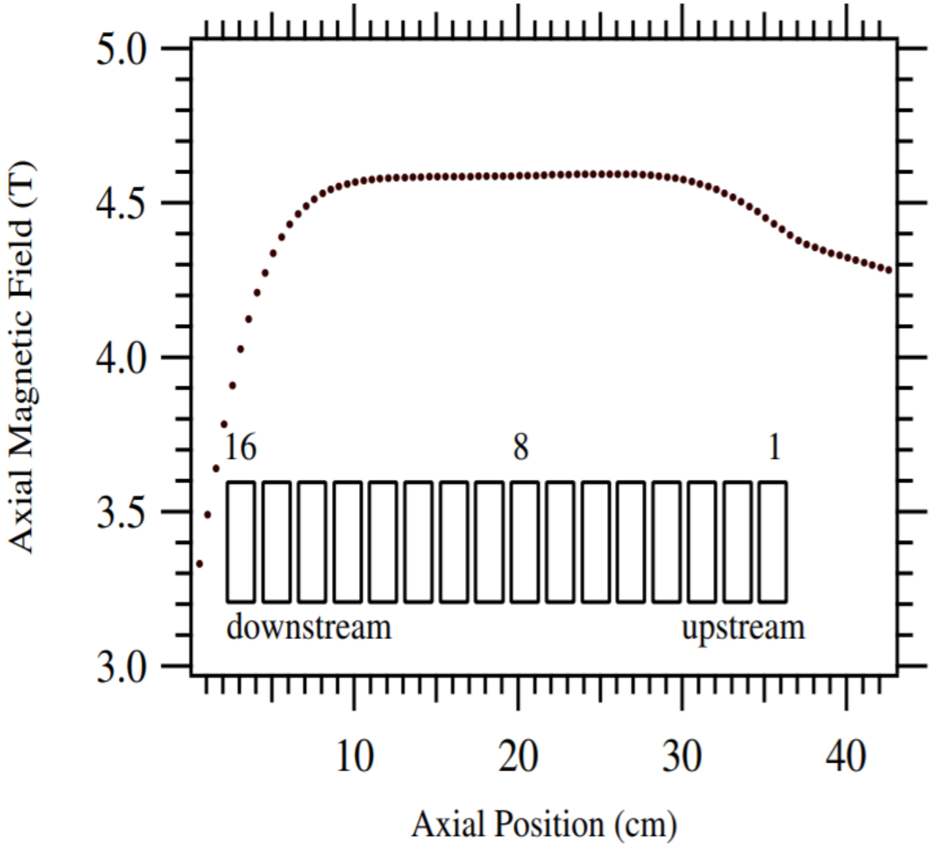


Electrode Trap Nonlinearity

- Previous measurement took a significant amount of data at 10 central electrodes
  - Largest correction to the 2005 result (-5.3s)
- New measurement will not use trap lengths that exceed 9 trap lengths



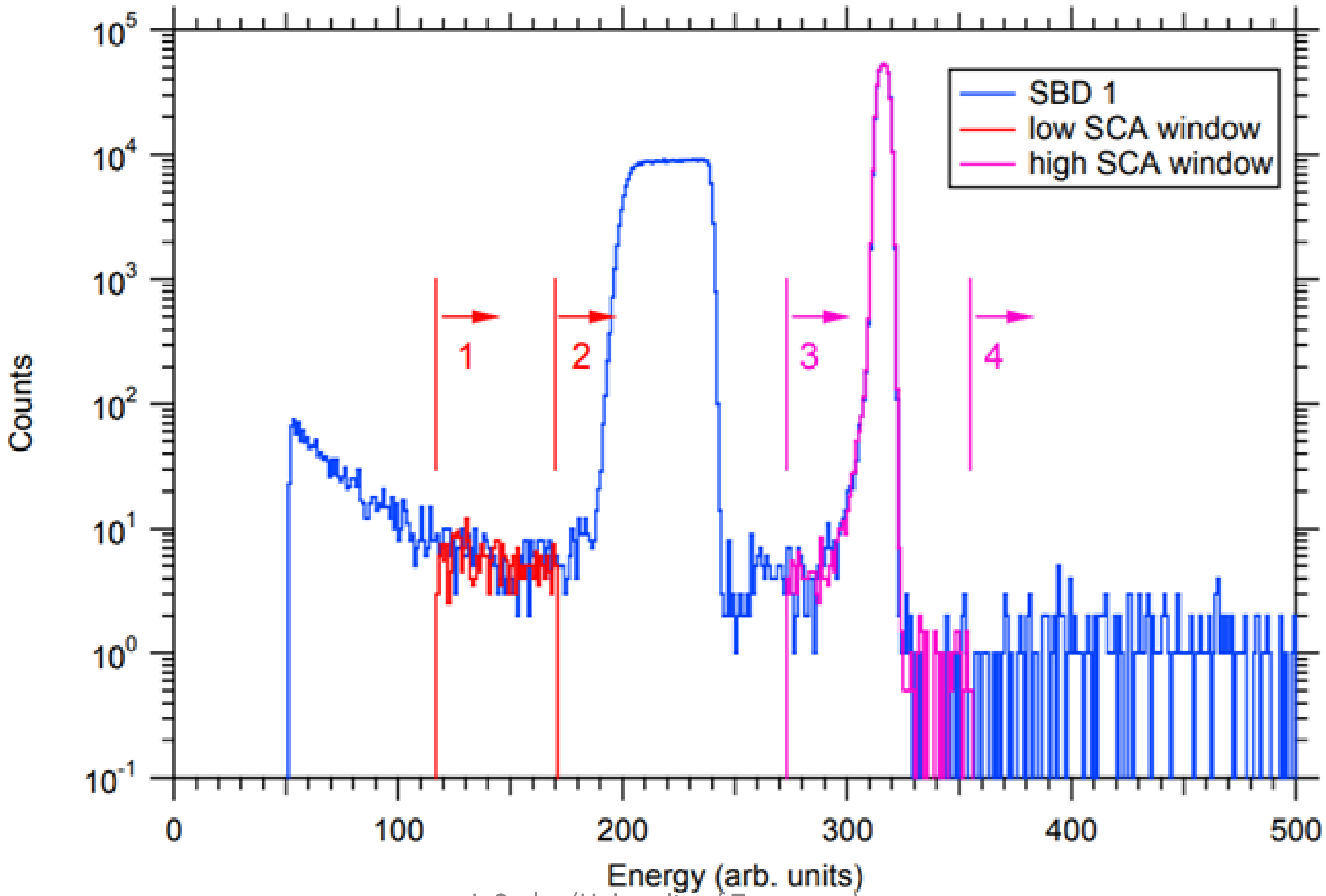
Mark 3 Trap



Sequence of Trapping Cycle

- One cycle lasts 10,000μs
  - 0μs the detector is turned on, in trapping mode
  - 22μs counting mode is engaged
  - 98μs cleaning mode engaged
  - 128μs returns to trapping mode for remainder of cycle
  - 160μs detector is turned off
- Only have the detector turned on when we are expecting trapped protons to arrive reduces the backgrounds

Alpha and Triton Peaks



- Measure proton rate

$$\dot{N}_p = \tau_n^{-1} \epsilon_p L \int_A da \int I(v) \frac{1}{v} dv$$

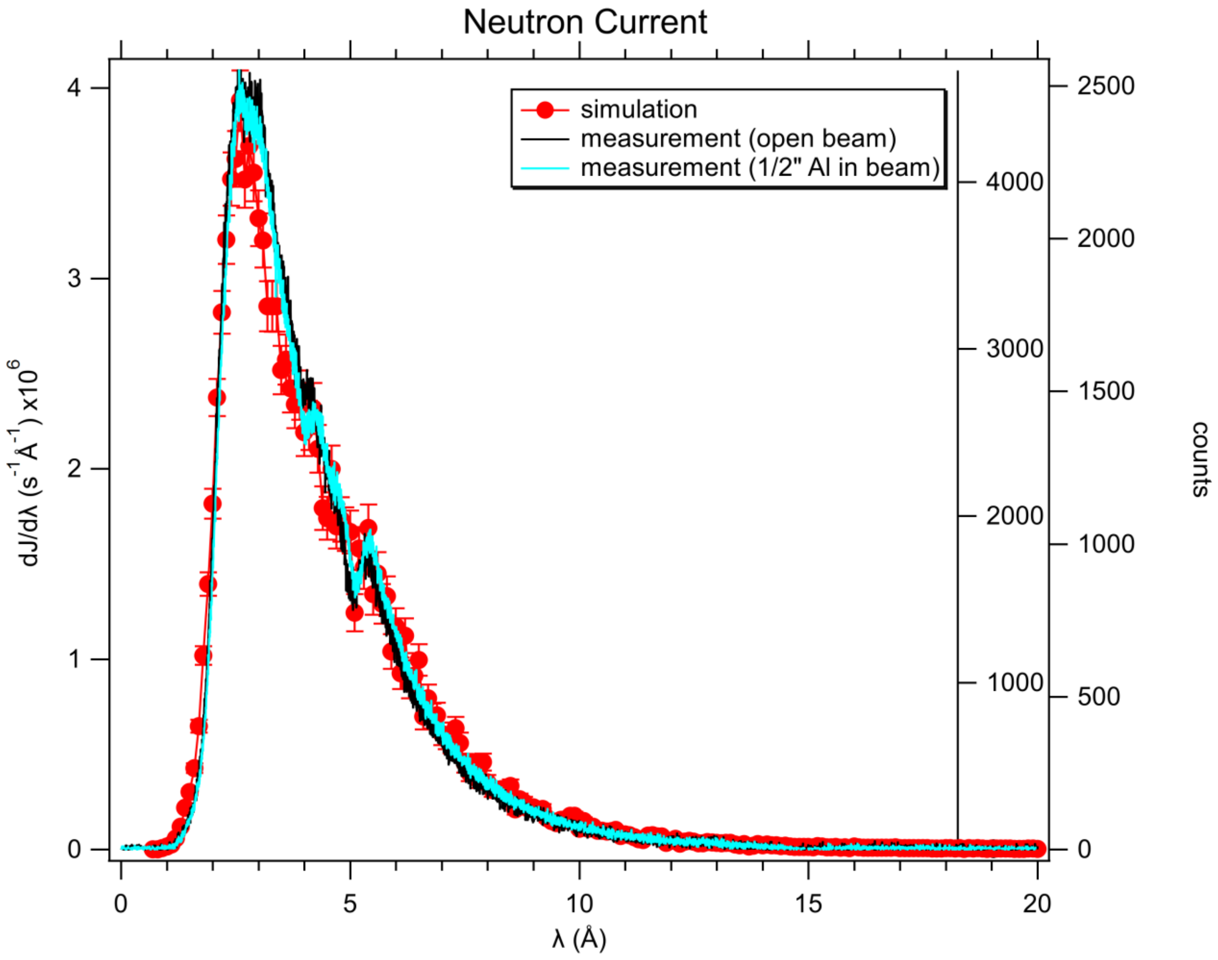
- Measure neutron rate

$$\dot{N}_n = v_o \epsilon_o \int_A da \int I(v) \frac{1}{v} dv$$

$$\epsilon_o = \frac{2 N_A \sigma_o}{4\pi A} \iint \Omega(x, y)\, \rho(x, y) \phi(x, y) dx dy$$

NG-C Wavelength Measurement

Nearly "black" ^{6}Li in PMT



Fission Chamber