Progress toward a new beam measurement of the neutron lifetime

Mike Snow

For the BL2 Collaboration

Indiana University/CEEM
IU Center for Spacetime Symmetries

INT NNbar Workshop

IUCSS

INDIANA UNIVERSITY

Thanks for slides: Shannon Hoogerheide, Nadia Fomin, Eamon Anderson,…

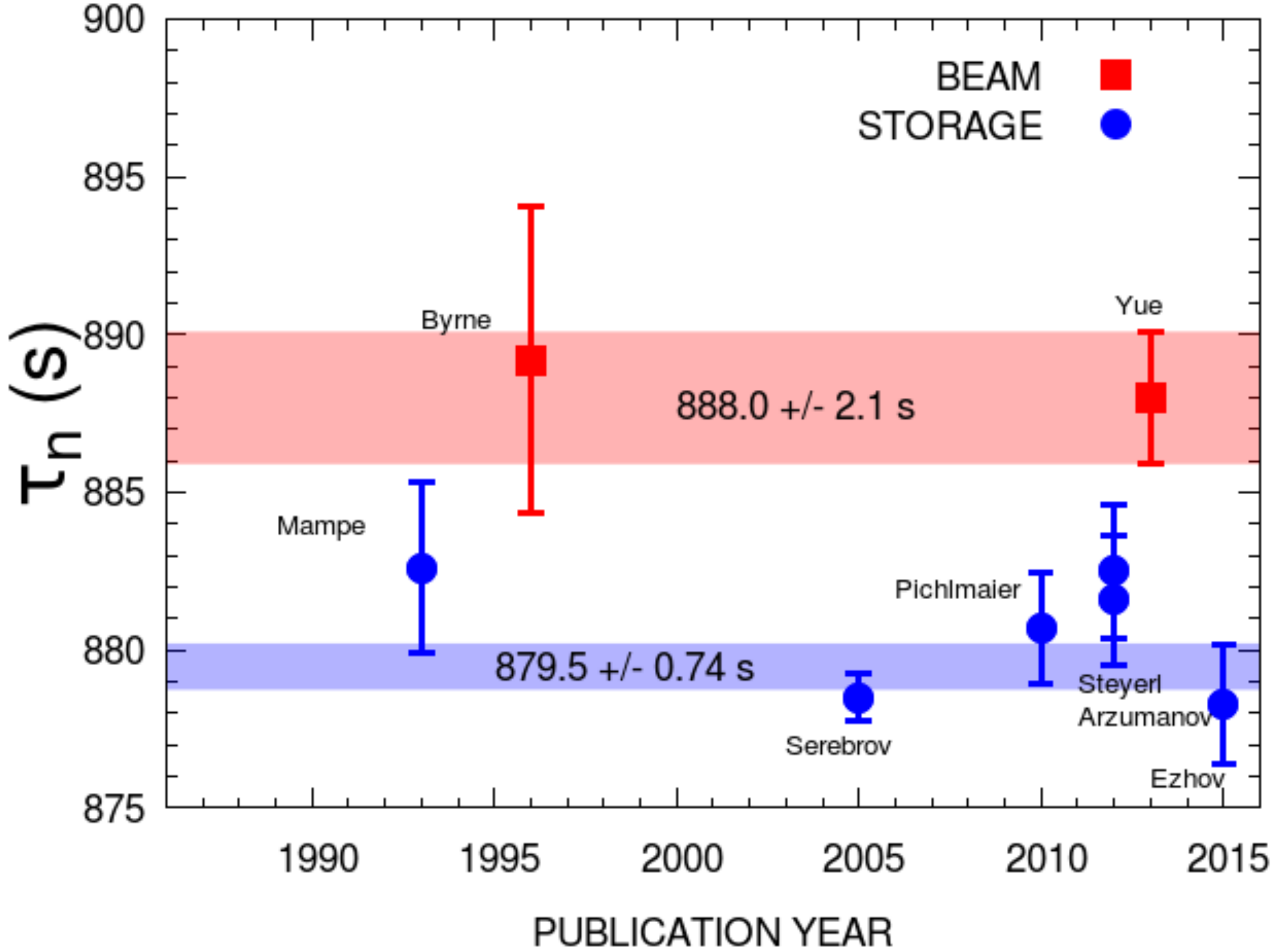
WMS support: NSF and NIST Precision Measurement Grant program

BL2 Collaboration

E. Adamek[1], E. S. Anderson[2], J. Caylor[1], B. Crawford[3], M. S. Dewey[4], N. Fomin[1], D. M. Gilliam[4], K. Grammer[5], G. L. Greene[1,5], R. Haun[6], S. F. Hoogerheide[4], H. P. Mumm[4], J. S. Nico[4], W. M. Snow[2], and F. E. Wietfeldt[6]

1. University of Tennessee
2. Indiana University
3. Gettysburg College
4. National Institute of Standards and Technology
5. Oak Ridge National Laboratory
6. Tulane University

Neutron Lifetime



Measuring τ_n:

$$N = N_0 e^{-t/\tau_n}$$

1. Neutron "bottle": $N(t_1)/N(t_2) = e^{-(t_1-t_2)/\tau_n}$

   Measure **relative** change in population of ultra-cold neutrons (UCN) confined to a storage vessel

2. Direct observation of exponential decay: $\ln(N/N_0) = -t/\tau_n$

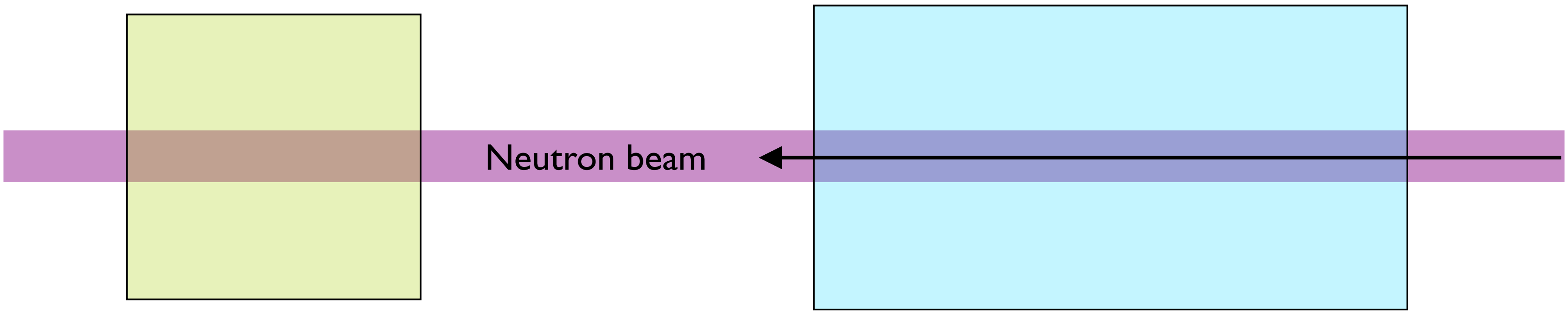
   Measure **relative** decay rate of an ensemble of neutrons as a function of time and measure the slope

3. "In-beam" method: $-\frac{dN}{dt} = N/\tau_n$

   Measure **absolute** neutron decay rate in a well-defined region of a neutron beam of well-measured **absolute** fluence

Cold neutron beam τ_n measurement

$$\tau_n = -\bar{N}_n / \dot{N}_n$$



Beam fluence measurement

$(\bar{N}_n)$

Decay proton counting volume

$(\dot{N}_n)$

ABSOLUTE MEASUREMENT of beam fluence and decay rate

Requires known proton trapping/detection efficiency and known neutron detection efficiency

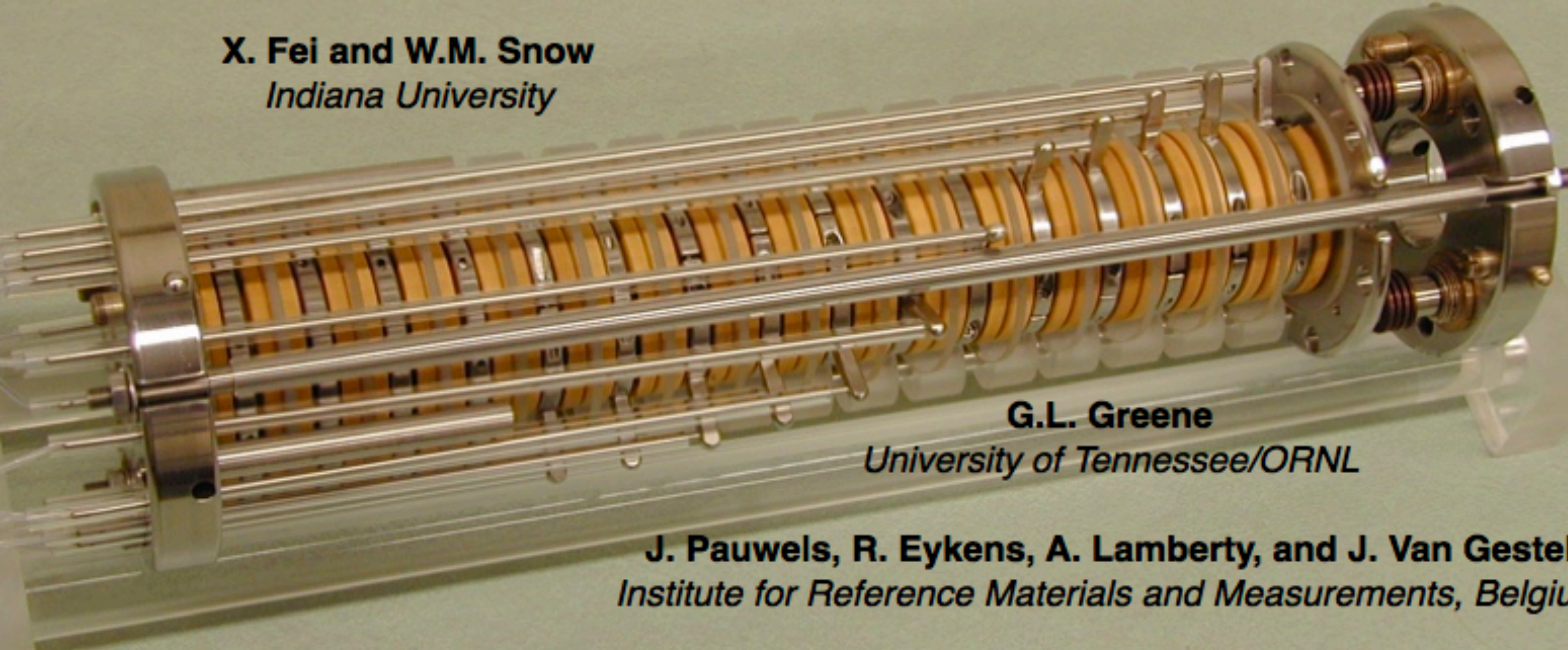
The 2003 Cold Beam Experiment

M. S. Dewey, D.M. Gilliam, and J.S. Nico
National Institute of Standards and Technology

F.E. Wietfeldt
Tulane University

X. Fei and W.M. Snow
Indiana University

M. S. Dewey et al., **Measurement of the Neutron Lifetime Using a Proton Trap**, Phys. Rev. Lett. **91**, 152301 (2003).



G.L. Greene
University of Tennessee/ORNL

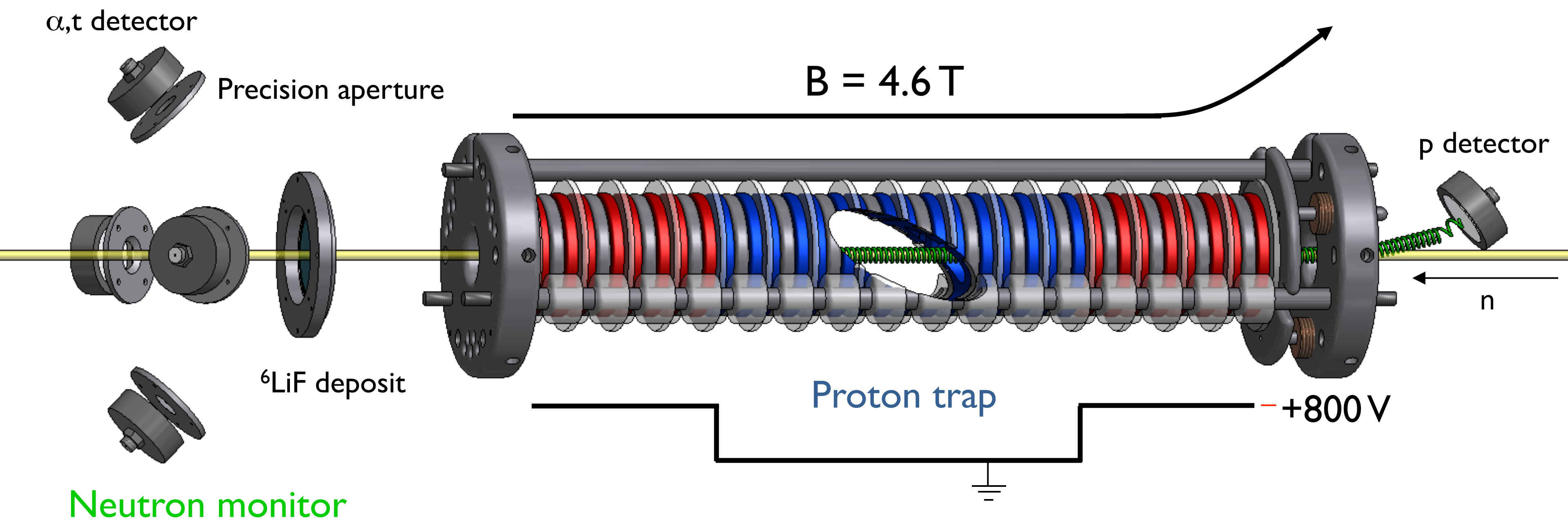
J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
Institute for Reference Materials and Measurements, Belgium

R.D. Scott
Scottish Universities Research and Reactor Centre, U.K.

Support from NIST
and DoE Nuclear Physics

The NIST beam lifetime experiment

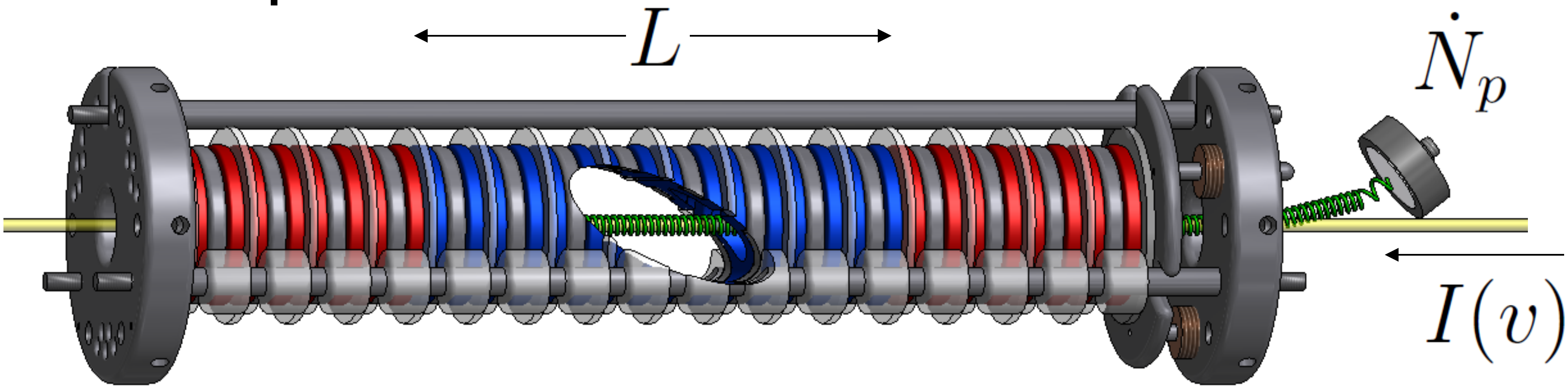
$$\tau_n = -\bar{N}_n / \dot{N}_n$$



- Penning trap electrostatically traps decay protons and directs them to detector via B field

- Neutron fluence monitor measures incident neutron rate via n + ^{6}Li reaction products (α + t)

Proton trap

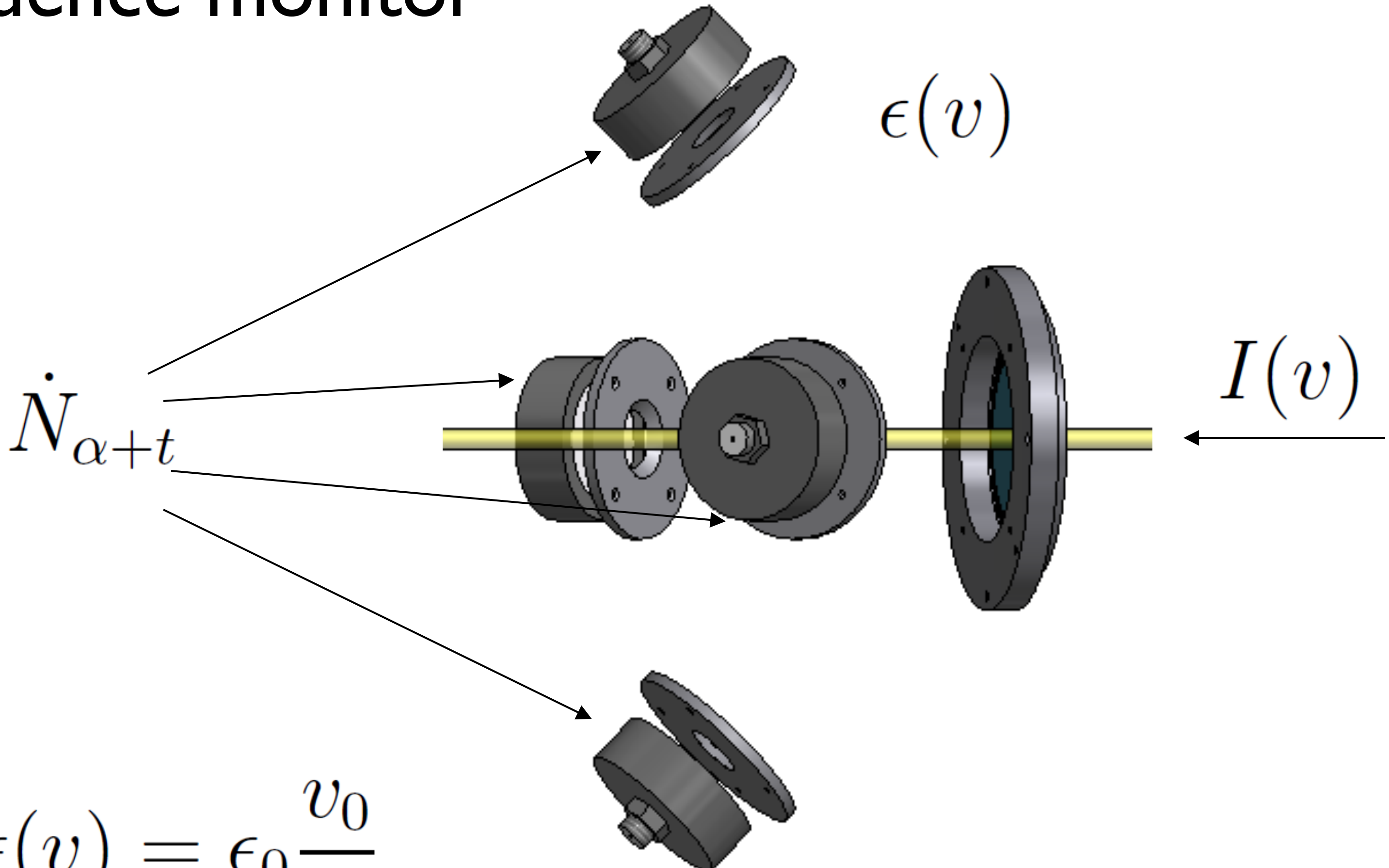


$$N_n = \int_A \int da I(v) \frac{L}{v} dv = L \int_A \int da I(v) \frac{1}{v} dv$$

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

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

Neutron fluence monitor



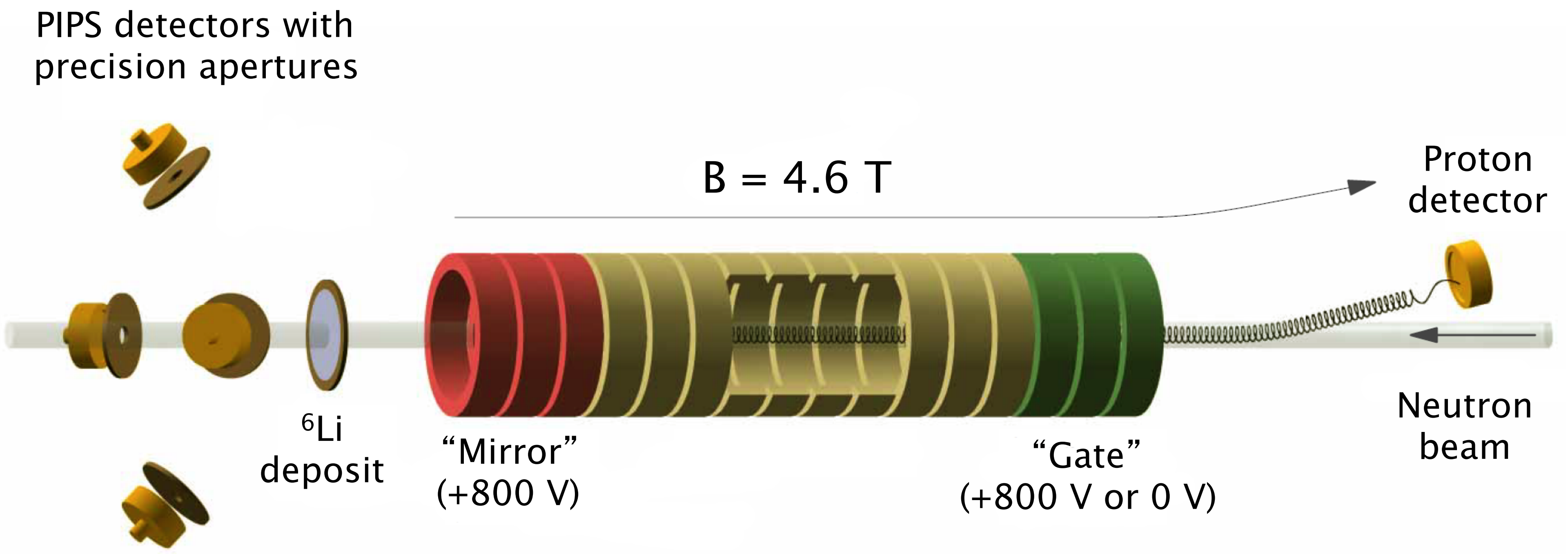
$$\epsilon(v) = \epsilon_0 \frac{v_0}{v}$$

$$\dot{N}_{\alpha+t} = \int_A \int da I(v) \epsilon(v) dv = \epsilon_0 v_0 \boxed{\int_A \int da I(v) \frac{1}{v} dv}$$

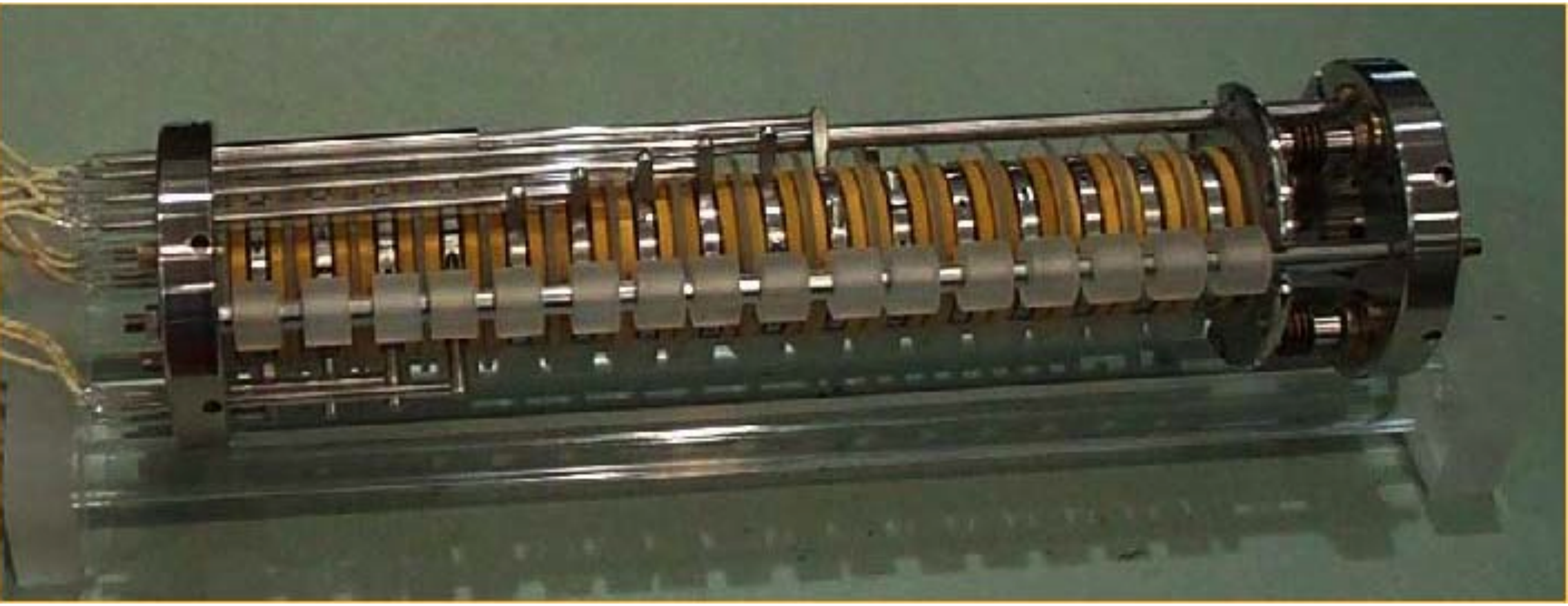
$$\tau_n = -\frac{N_n}{\dot{N}_n} = \left(\epsilon_p \frac{(nl + L_{\mathrm{end}})}{\dot{N}_p}\right)\left(\frac{\dot{N}_{\alpha+\mathrm{t}}}{\epsilon_0 v_0}\right)$$

Proton counting

Neutron counting



The Proton Trap

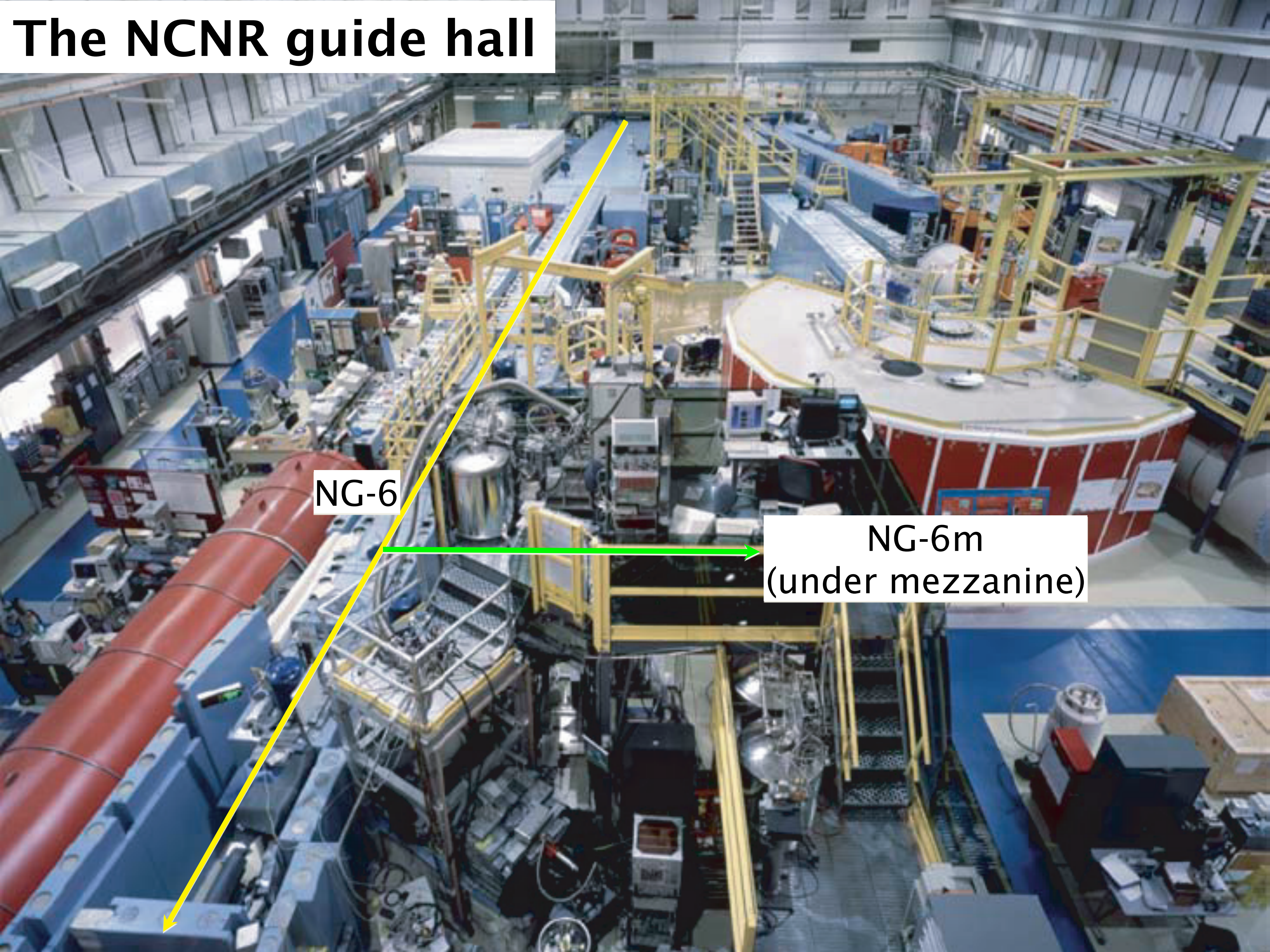


Gold-coated, fused silica segmented electrode structure

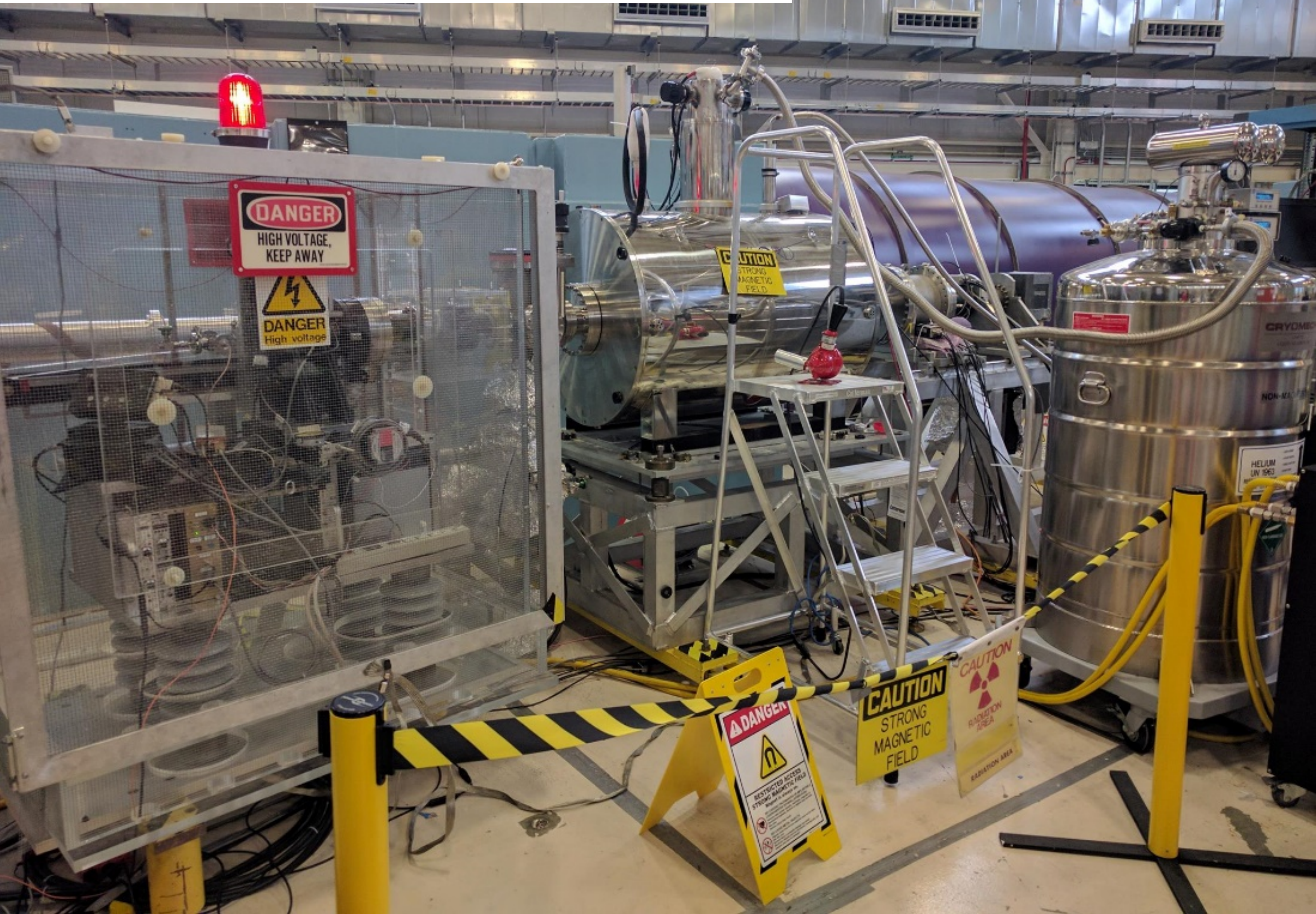
Absolute dimensions from coordinate measuring machine

Nonmagnetic, ~UHV/compatible materials

The NCNR guide hall

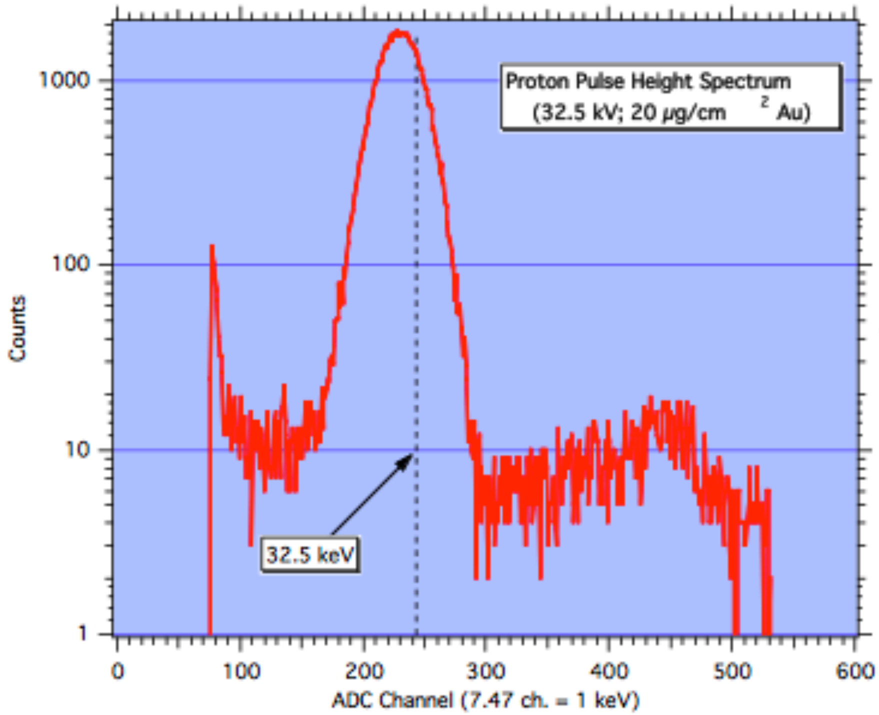


The beam lifetime apparatus

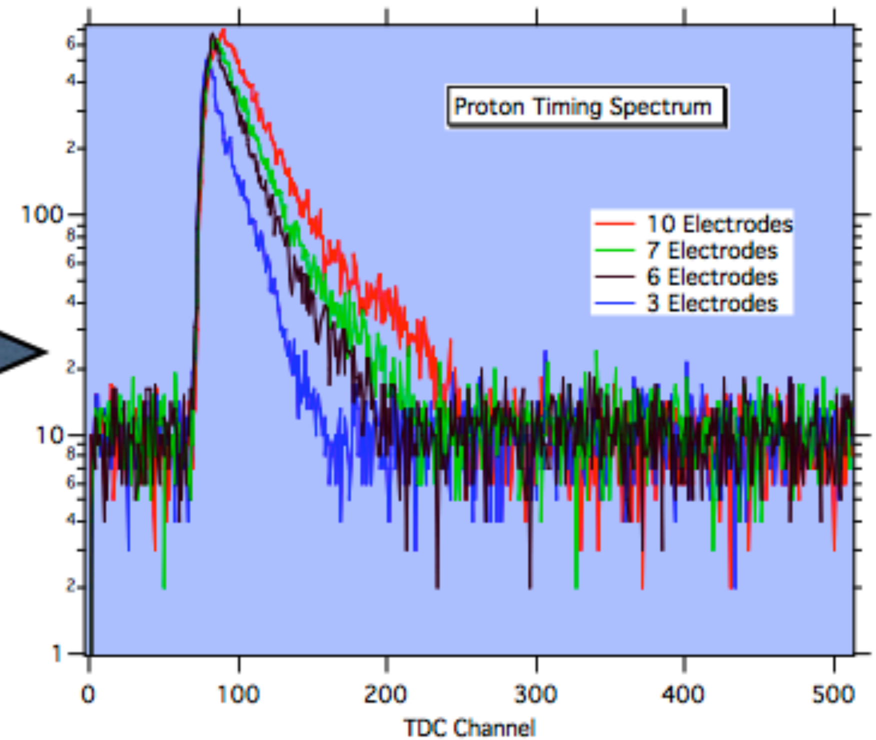


Data: Proton Counting

Energy Spectrum



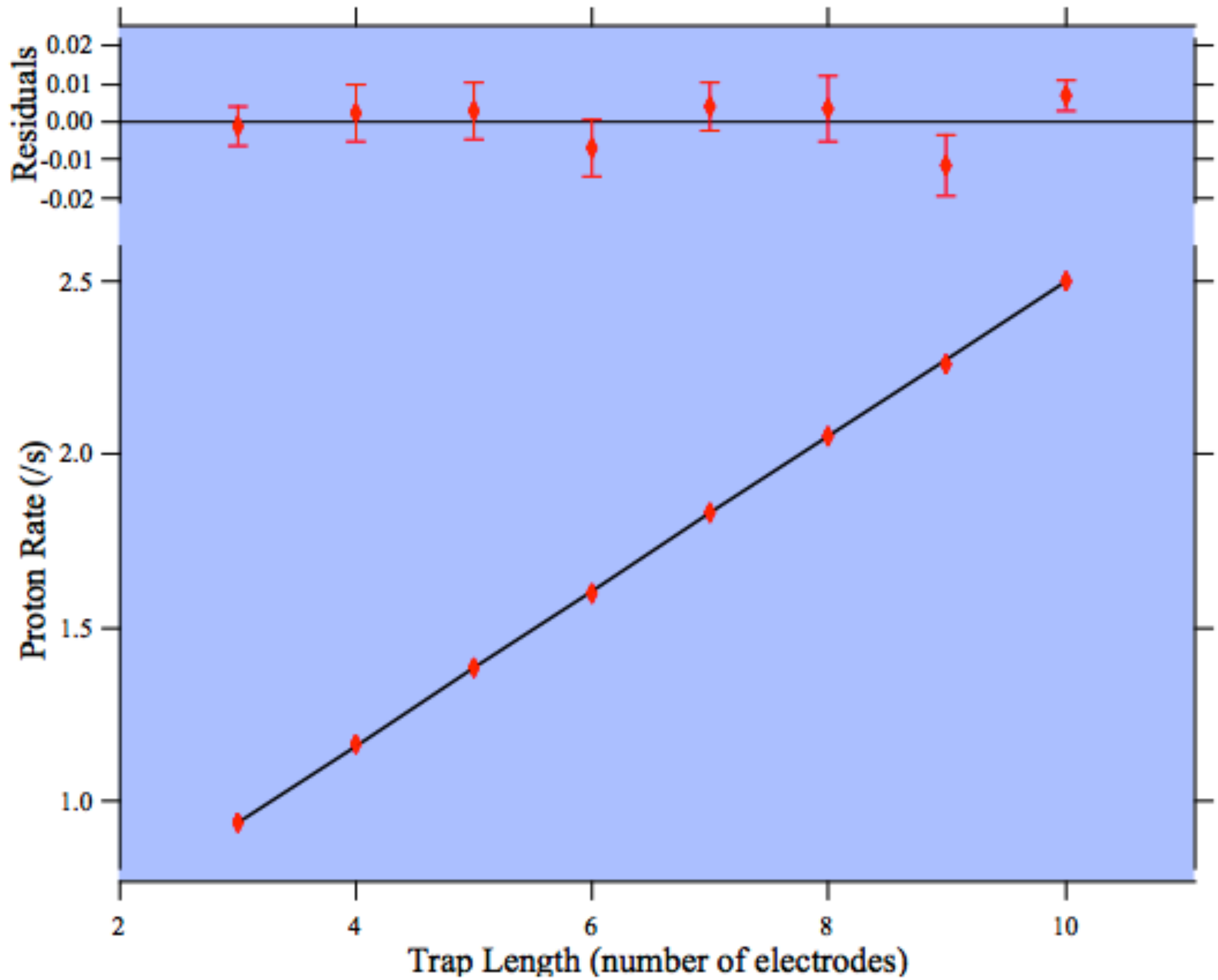
Timing Spectra



- S/N improvement from trapping goes like trapping time/measurement time ≈10 ms/80 μs = 125/1

- 50 V ramp kicks out protons.

Data: Extrapolation in Electrode Length



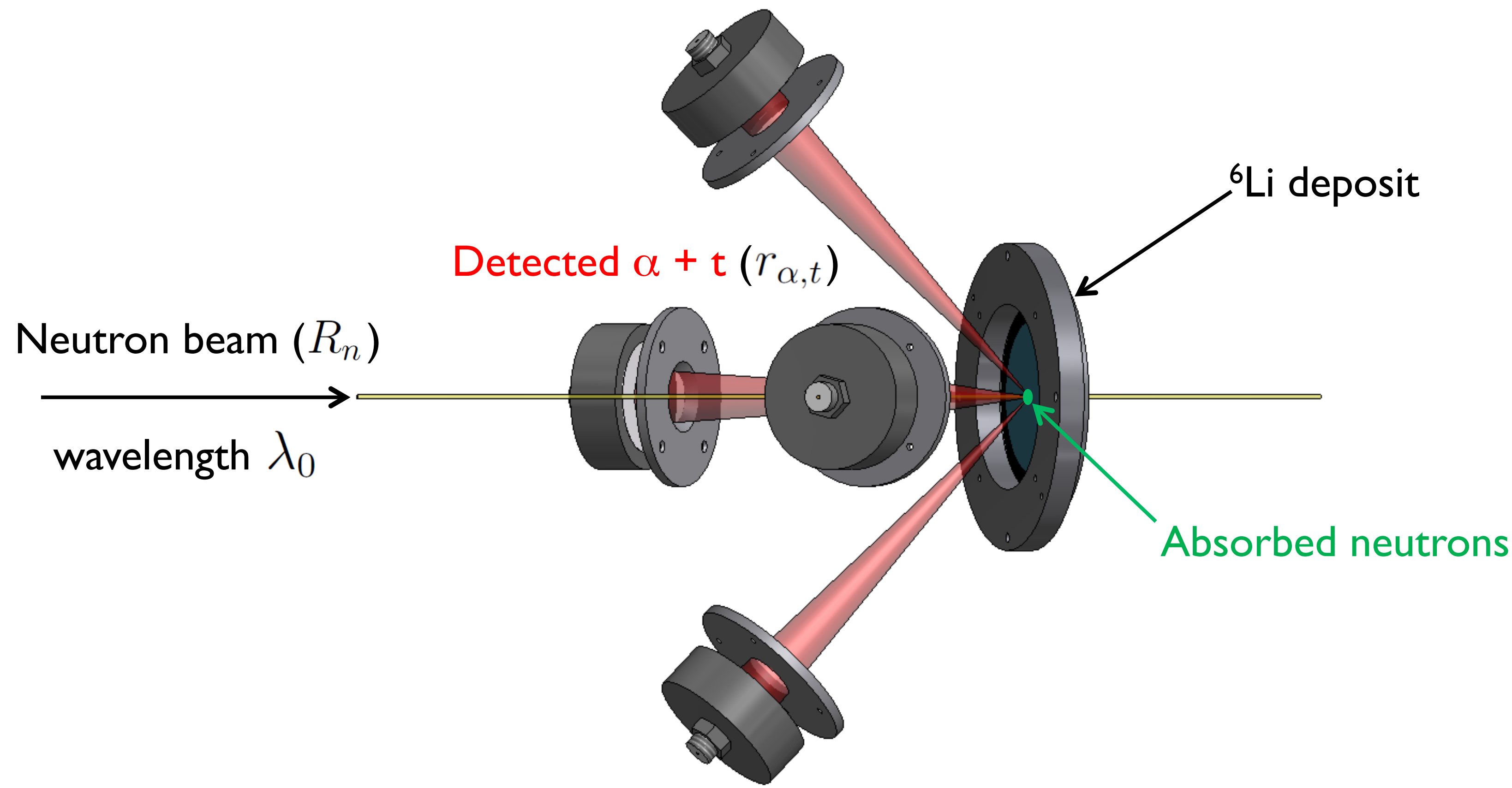
$\tau_n = 886.3(1.2)_{stat}(3.2)_{sys}$

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

2.7s

J. S. Nico et al, Phys. Rev. C 71, 055502 (2005).

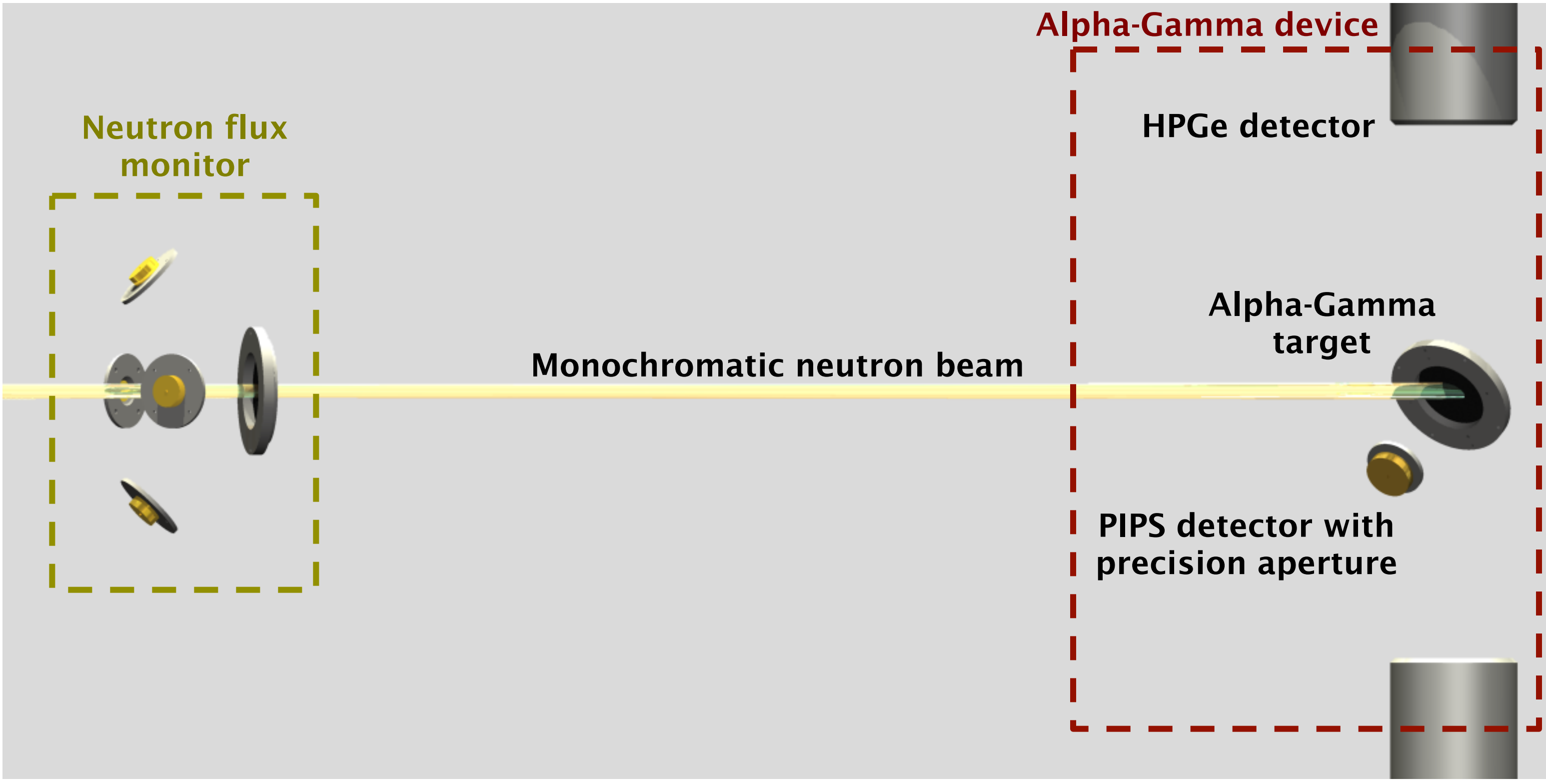
Definition of fluence monitor (FM) ϵ_0



$$\epsilon_0 = \left[\frac{N_A}{A}\rho\left(0,0\right)\sigma_0\right] \times \left[2 \cdot \Omega_{\mathrm{FM}}\left(0,0\right)\right]$$

Neutron absorption probability α, t detection probability

Measuring ϵ_0 directly with Alpha-Gamma



A new ϵ_0:

Allows for re-evaluation of τ_n without running experiment again

Enables a re-run of the experiment for higher accuracy

Makes result insensitive to absolute cross sections

Calibration of Alpha-Gamma as an absolute neutron flux monitor

1. Measure the absolute activity of an alpha source

2. Use this source to determine solid angle of alpha detector

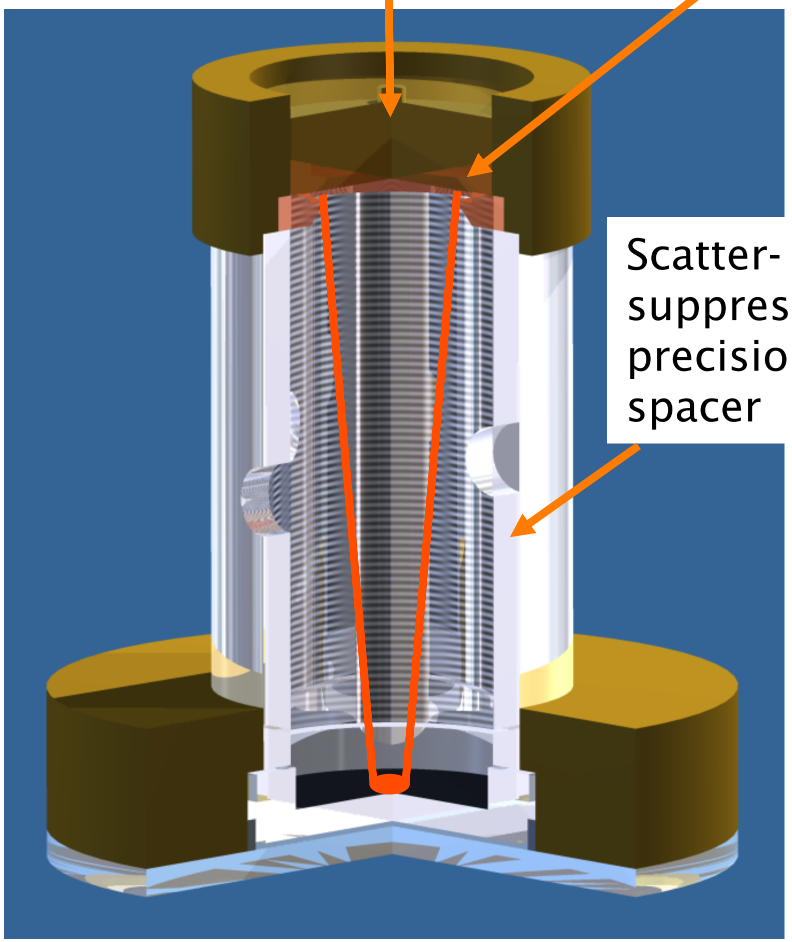
3. Use an (n,$\alpha\gamma$) reaction to transfer the calibration to the gamma detectors

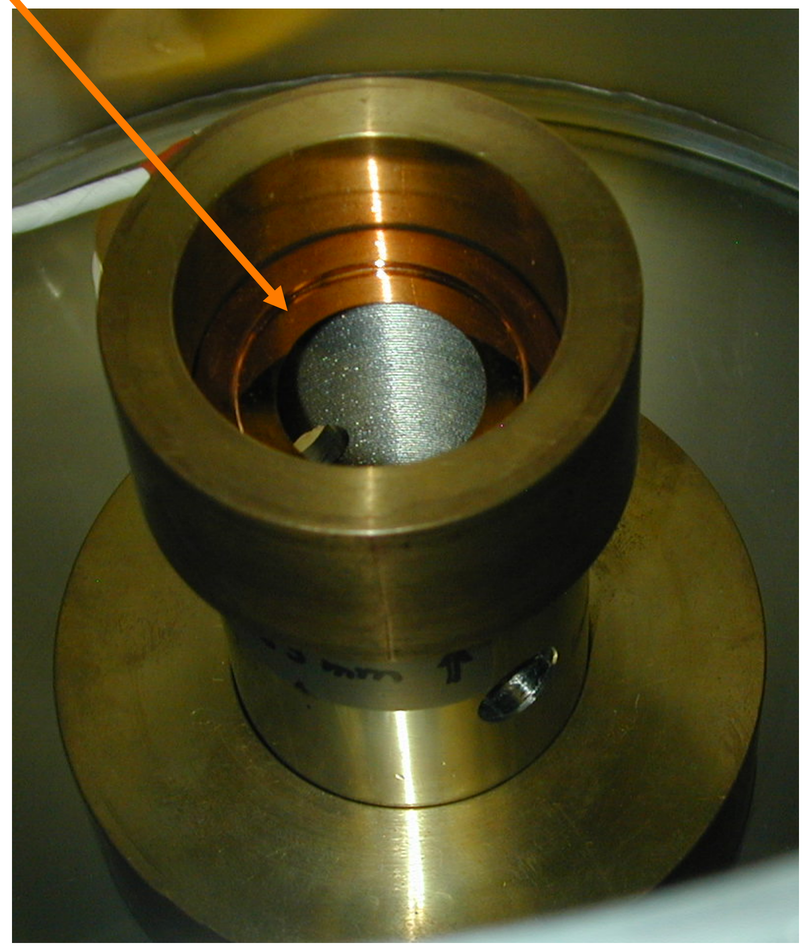
Alpha source (^{239}Pu) disintegration rate measured in simple geometry with metrologically determined solid angle

PIPS detector

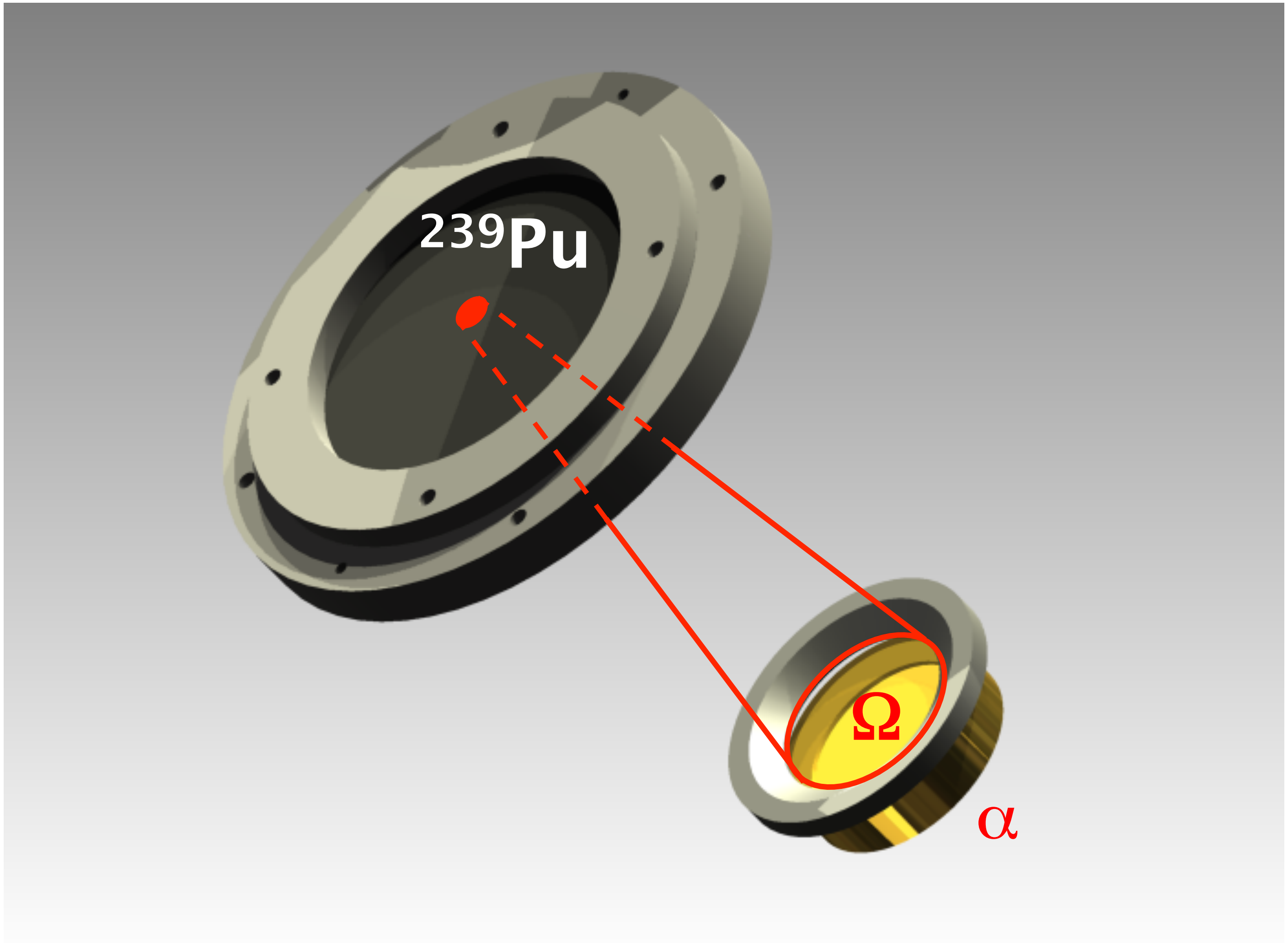
Diamond-turned Cu aperture

Scatter-suppressing precision spacer





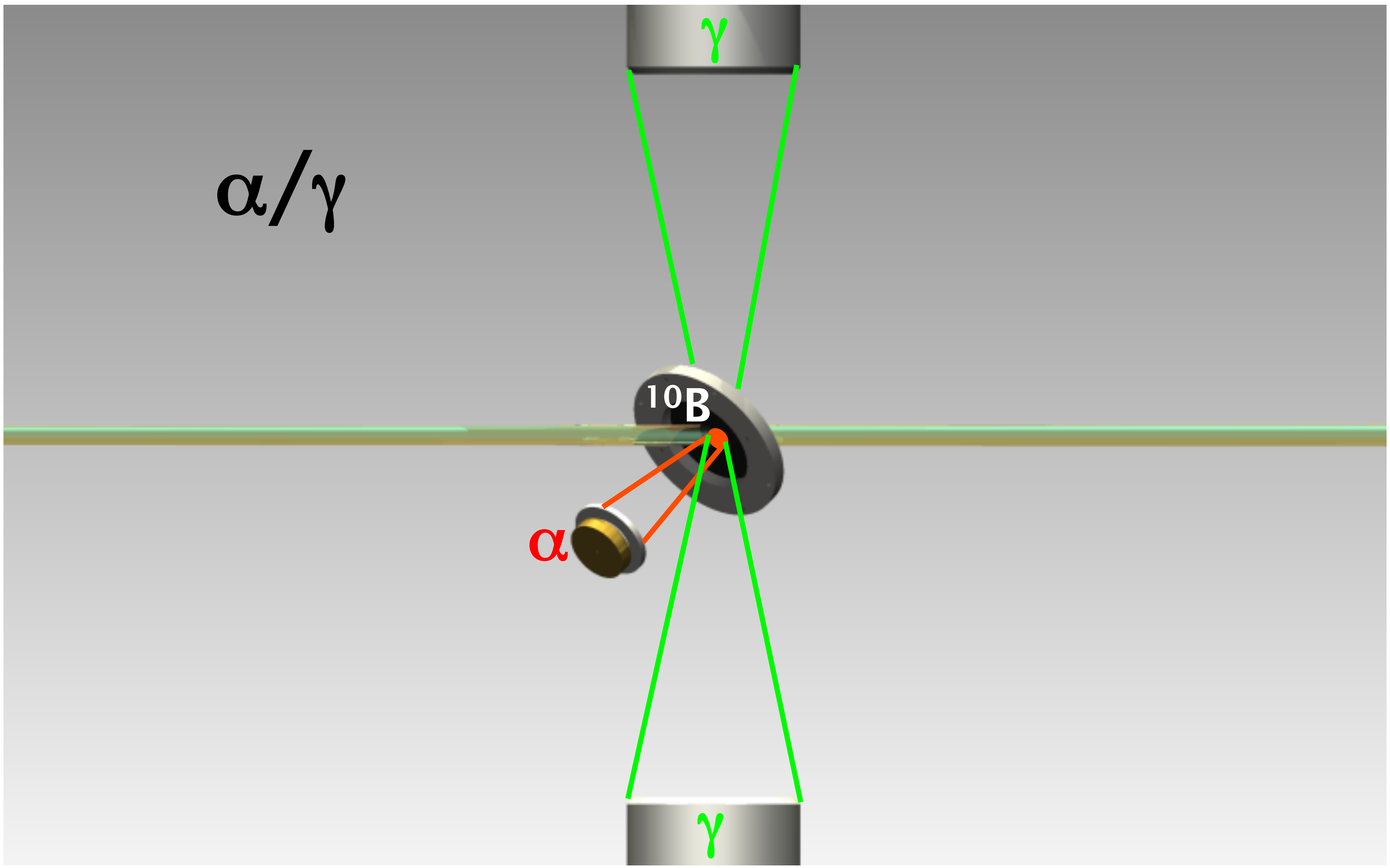
2 Source loaded into vacuum chamber and counted



Known source activity gives us detector Ω without direct metrology

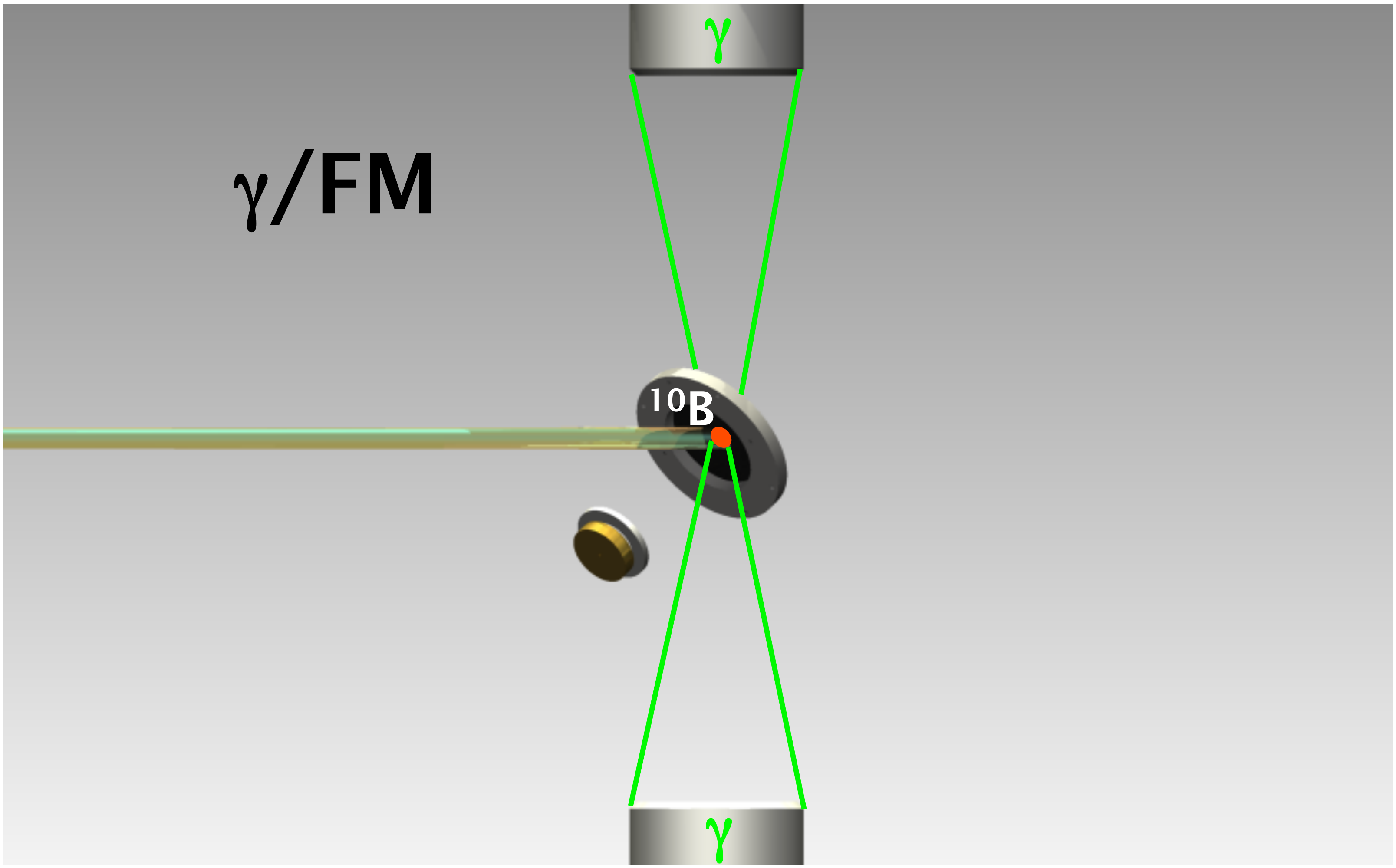
3 ^{239}Pu replaced with thin ^{10}B foil, beam on

- n + $^{10}B \rightarrow {}^{7}Li + \alpha + \gamma$
- Observed alpha and gamma rates calibrate gamma detectors

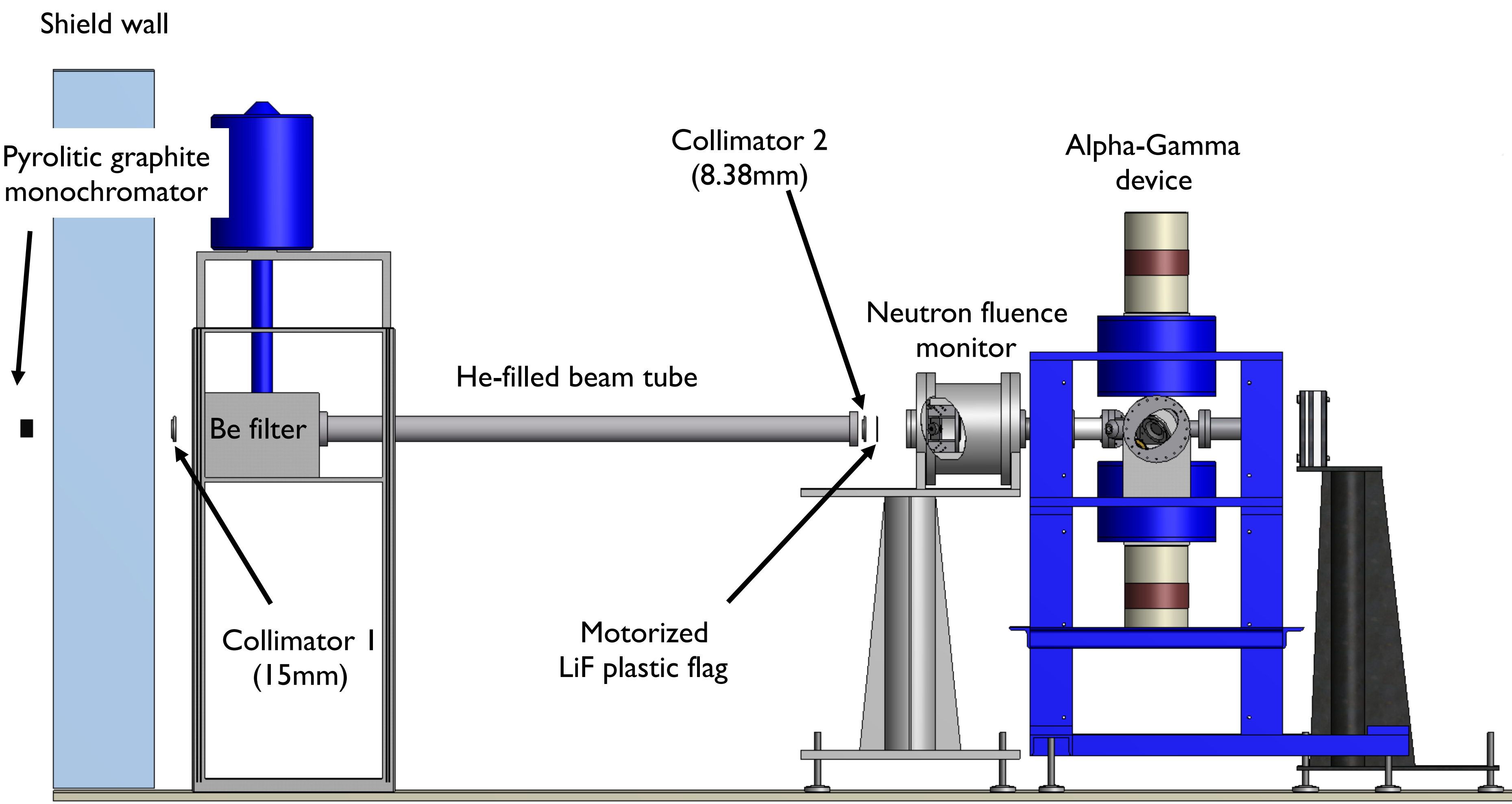


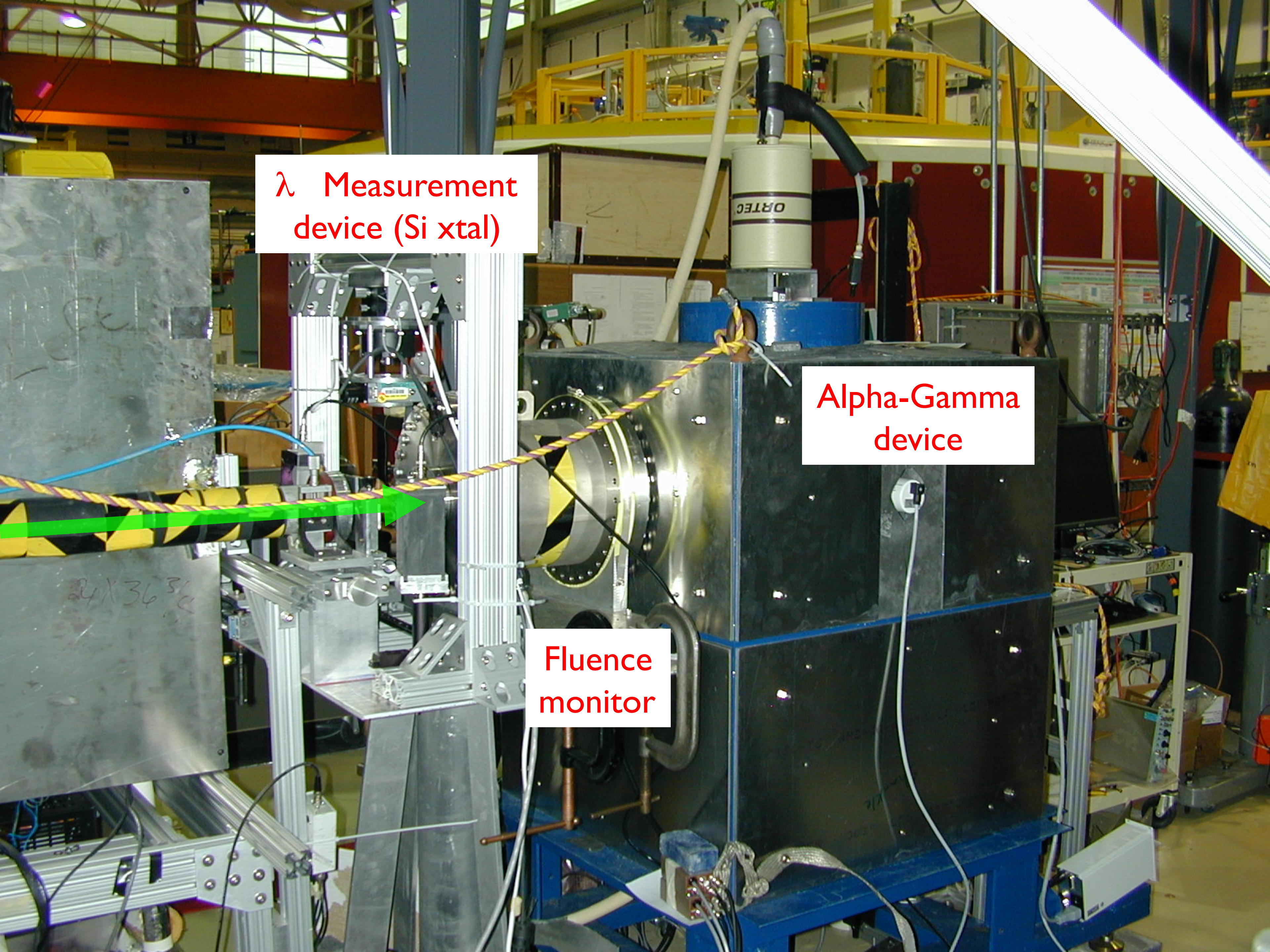
4 Thin foil replaced with thick (totally absorbing) ^{10}B foil

- -Every neutron participates in n + ^{10}B reaction
- -Gamma efficiency gives incident neutron rate



Experiment ran on NCNR beamline NG-6m




λ Measurement device (Si xtal)
Alpha-Gamma device
Fluence monitor
ORTEC

Uncertainty budget: factor of 5 Improvement!

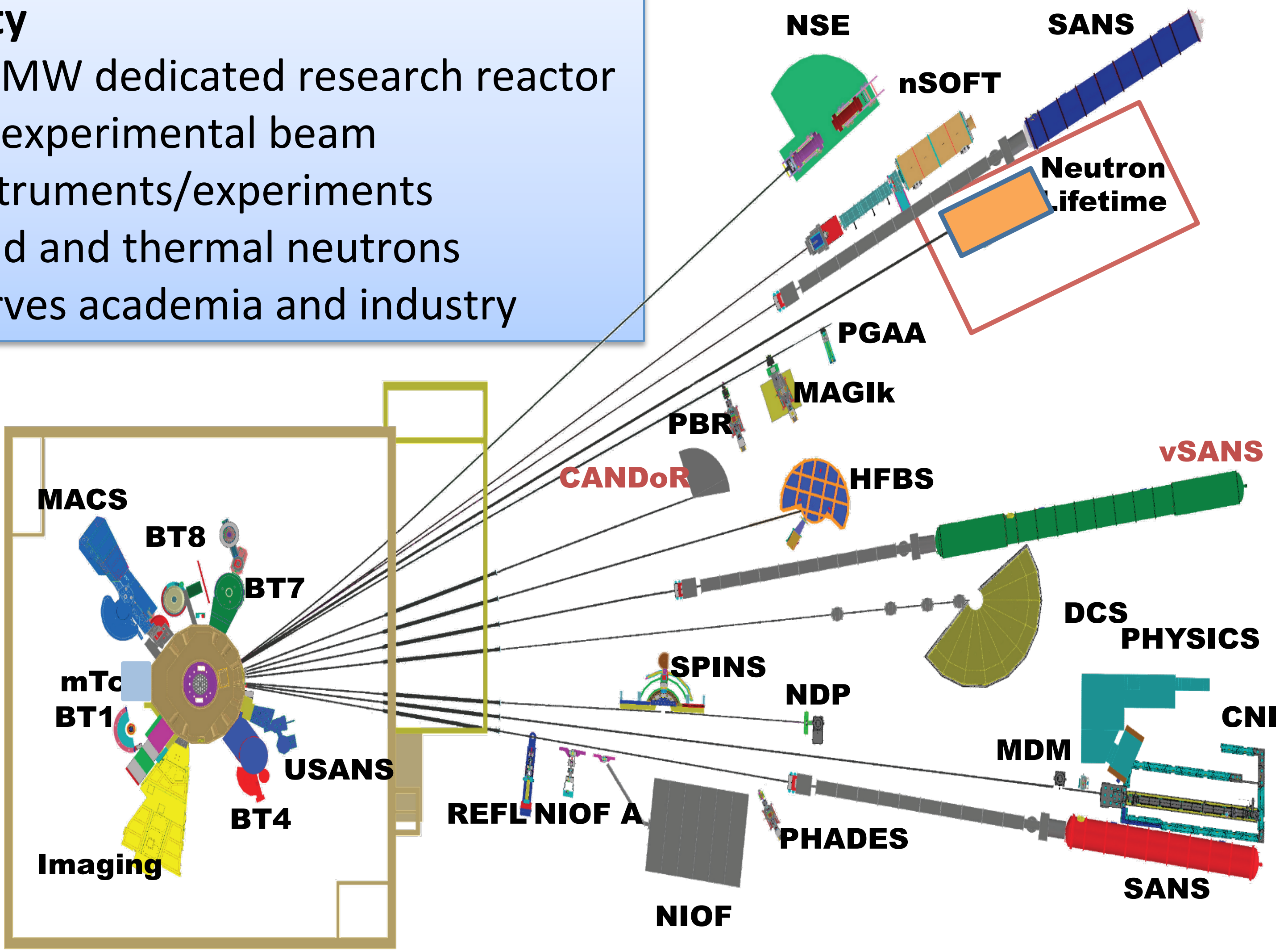
Source of uncertainty	Fractional uncertainty
α-source calibration of AG α-detector	3.1×10^{-4}
Neutron beam wavelength	2.4×10^{-4}
γ attenuation in B_4C target	2.3×10^{-4}
Correction to AG α-detector efficiency for beam spot	1.5×10^{-4}
γ attenuation in thin ^{10}B target	1.2×10^{-4}
Correction to FM solid angle for beam spot	9.0×10^{-5}
Neutron backscatter in FM substrate	4.0×10^{-5}
γ detection dead time	2.9×10^{-5}
Neutron loss in Si substrate	1.8×10^{-5}
Neutron absorption by ^{6}Li	1.2×10^{-5}
FM misalignment	6.1×10^{-6}
Self-shielding of ^{6}Li deposit	6.1×10^{-6}
γ production in thin ^{10}B target Si subtrate	3.3×10^{-6}
Neutron scattering from B_4C	3.5×10^{-7}
Neutron counting statistics	3.2×10^{-4}
Total	6.0×10^{-4}

Goal of BL2: 0.1% Accuracy

Source of uncertainty	past BL1 [s]	present BL2 projected [s]
Neutron flux monitor efficiency	2.7	0.5
Absorption of neutrons by ^{6}Li	0.8	0.1
Neutron beam profile and detector solid angle	0.1	0.1
Neutron beam profile and ^{6}Li deposit shape	0.1	0.1
Neutron beam halo	1.0	0.1
Absorption of neutrons by Si substrate	0.1	0.1
Scattering of neutrons by Si substrate	0.5	0.1
Trap nonlinearity	0.8	0.2
Proton backscatter calculation	0.4	0.4
Neutron counting dead time	0.1	0.1
Proton counting statistics	1.2	0.6
Neutron counting statistics	0.1	0.1
Total	3.4	1

NIST Center for Neutron Research (NCNR)

Facility
- 20 MW dedicated research reactor
- 28 experimental beam instruments/experiments
- Cold and thermal neutrons
- Serves academia and industry



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
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Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

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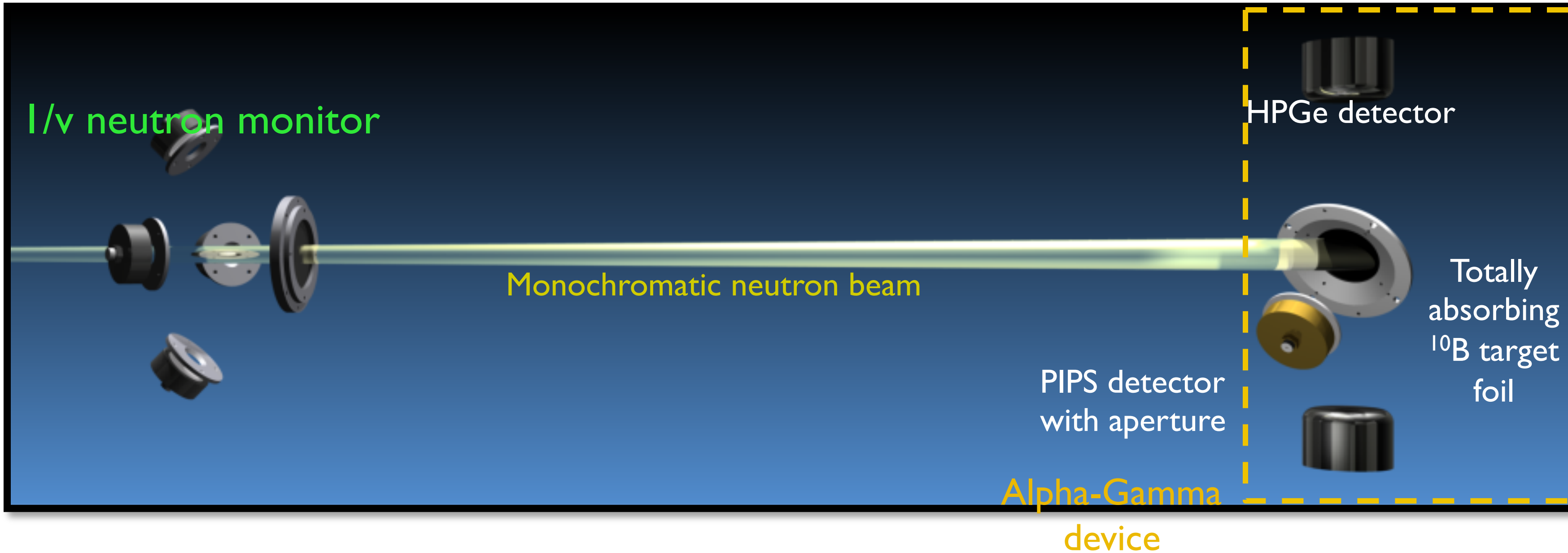
Neutron counting statistics		0.1
Total	−0.4	3.4

Alpha-Gamma Device



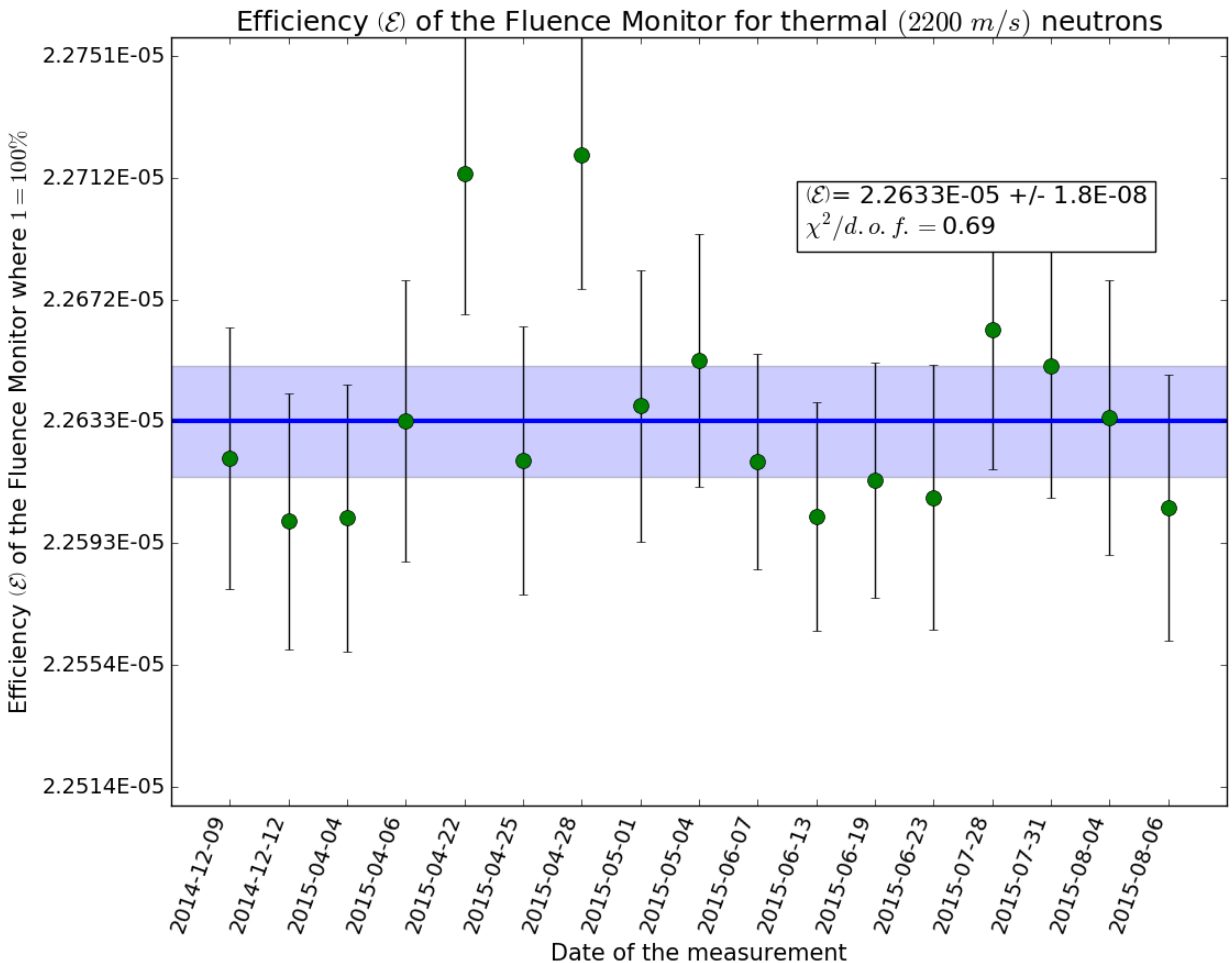
Reduces neutron counting efficiency uncertainty: 2.7 s → 0.5 s

Retroactively update the 2005 measurement (Yue, *et.al.*, PRL **111** 222501 (2013))

$$\tau_n = 886.3(1.2)_{stat}(3.2)_{sys} \rightarrow \tau_n = 887.7(1.2)_{stat}(1.9)_{sys}$$

For BL2: Operate simultaneously with 1/v neutron monitor & lifetime measurement

For the IRMM 30-H3 ^{6}Li deposit



Uncertainty Budget Projection

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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

0.5 s

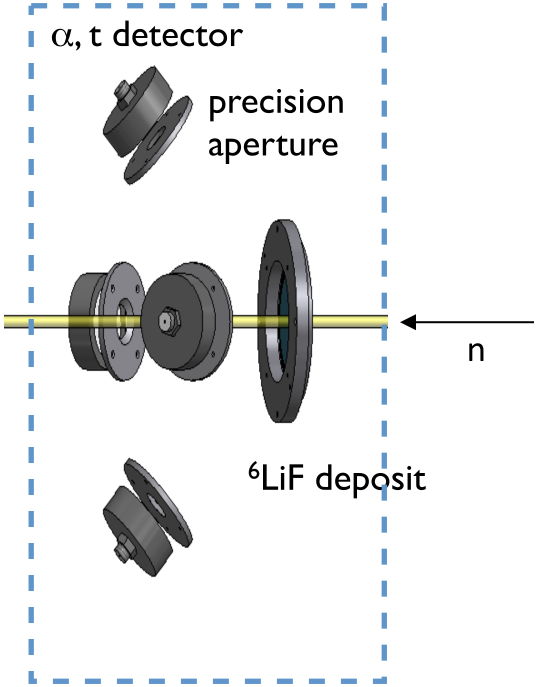
Absorption of neutrons by ^{6}Li

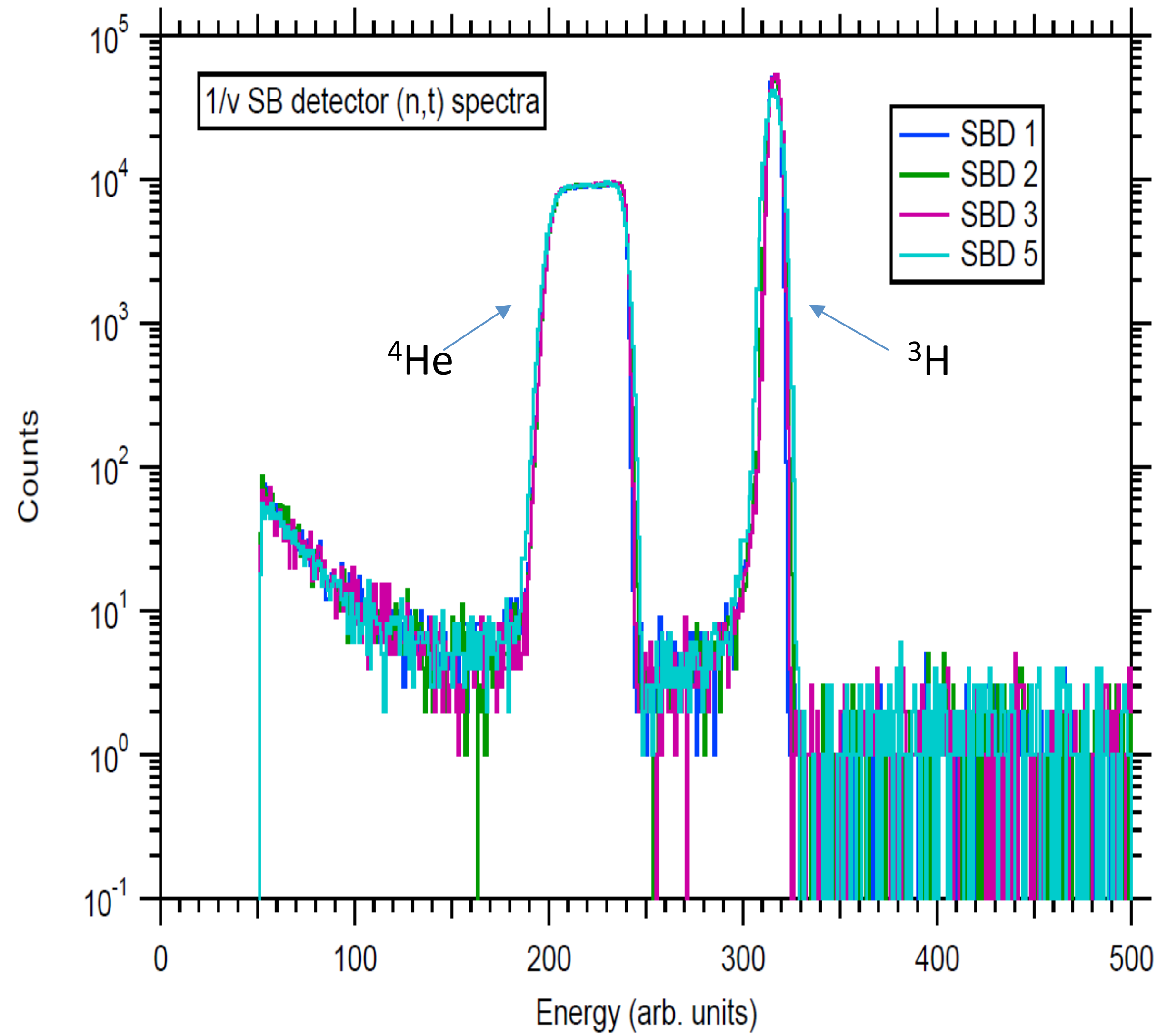
- Perform wavelength measurement of NG-C beamline
  - Test measurement already performed on NG-6
- Operate with multiple, thinner ^{6}Li deposits in neutron monitor
  - 20, 30, and 40 μg/cm^2 nominal Li deposits already characterized
- Operate with B deposit(s) in neutron monitor
  - Multiple deposits available but not yet characterized

→ Reduce correction and uncertainty by ~ factor of 2

Counting Neutrons: 1/v Flux Monitor

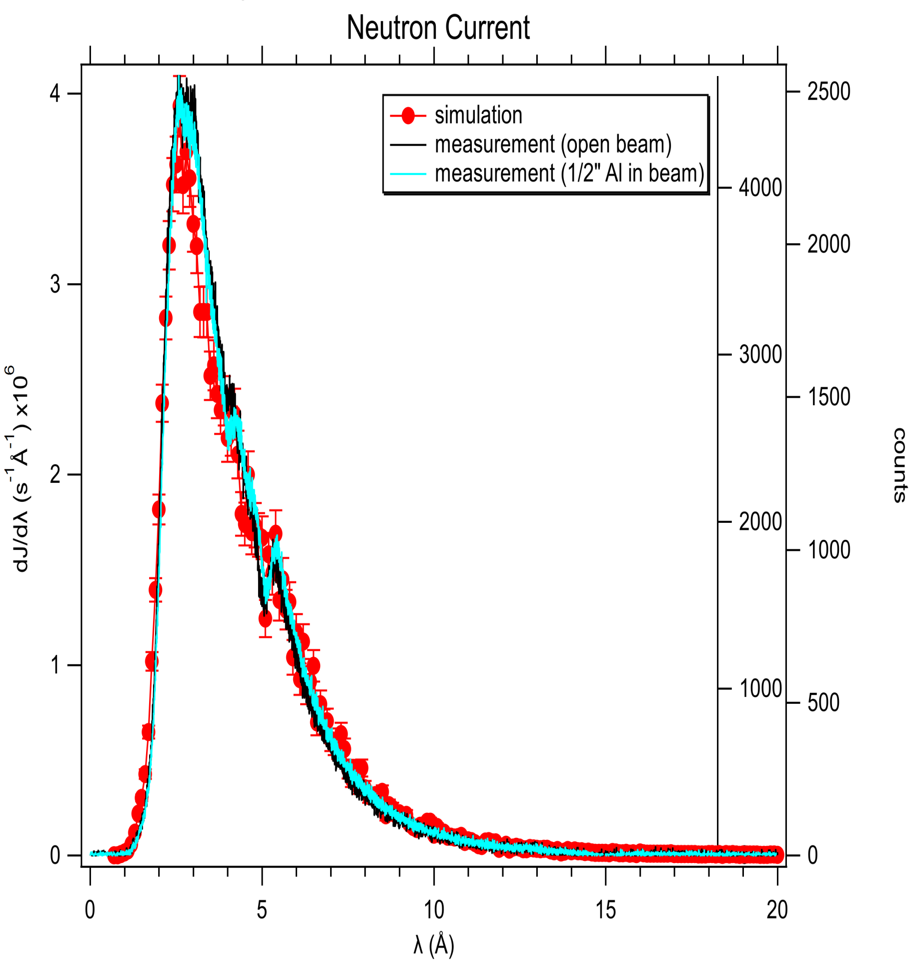
1/v neutron monitor



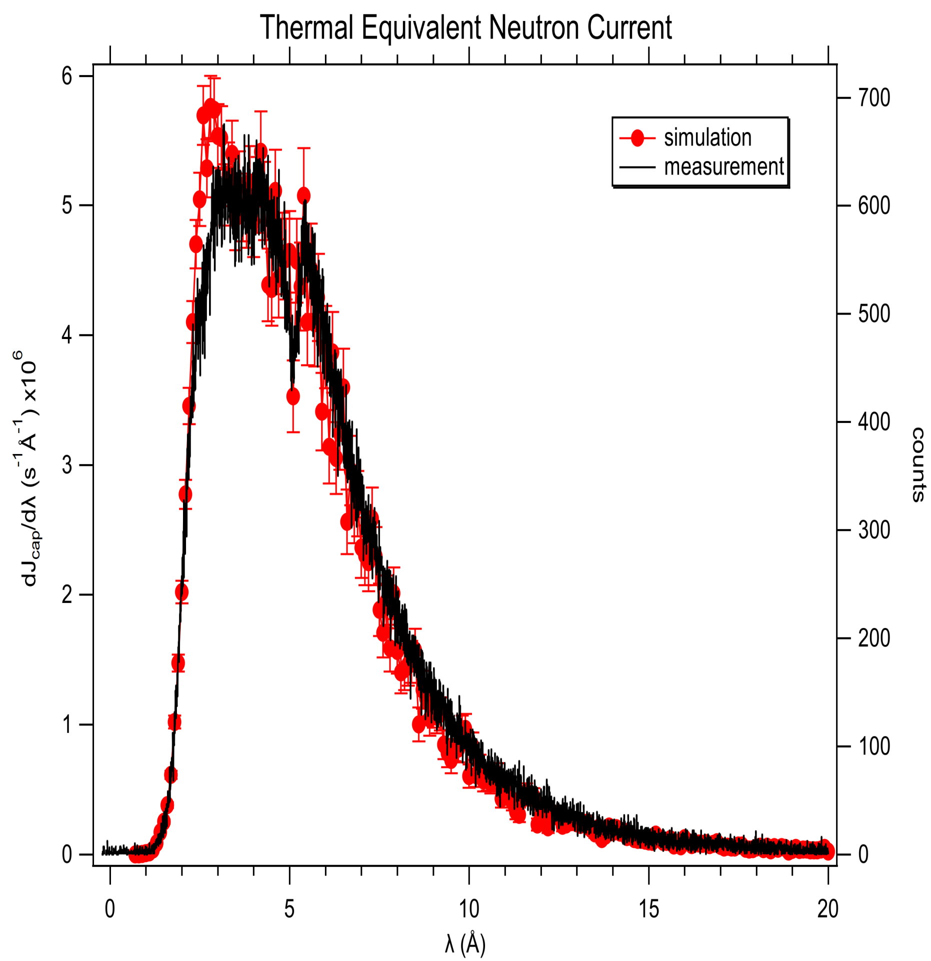


NG-C Wavelength Measurement

Nearly “black” ^{6}Li in PMT



Fission Chamber



Uncertainty Budget Projection

Source of correction	Correction (s)	Uncertainty (s)
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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

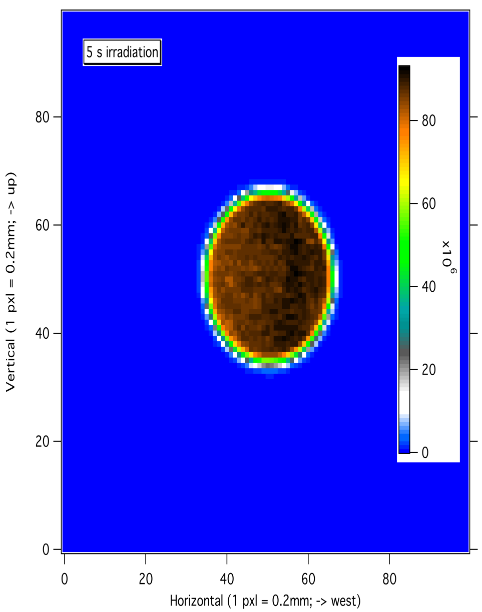
0.5 s

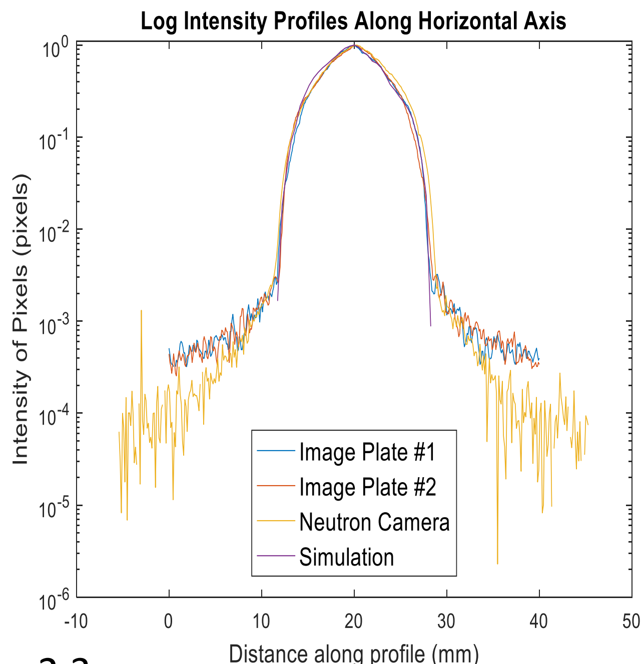
0.4 s

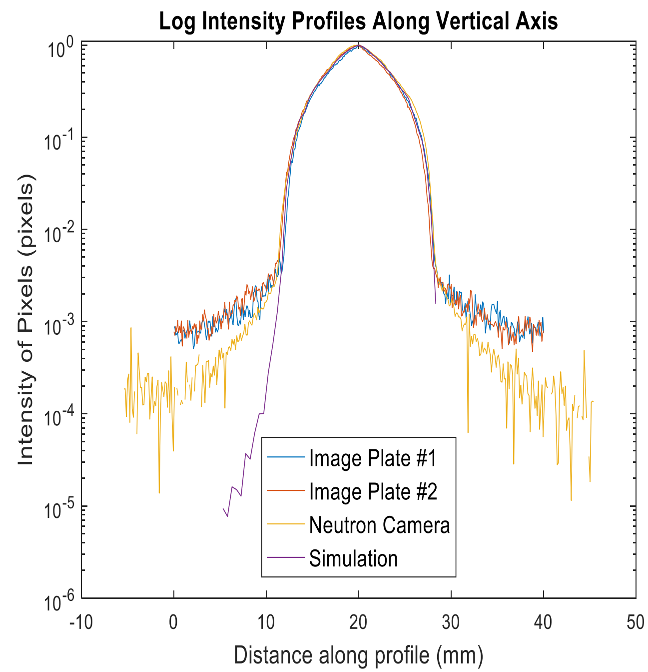
Beam Halo

1 s uncertainty in 2005 measurement

- More recent measurements suggest this uncertainty was overestimated
- 3 imaging methods plus simulation will be used to measure beam profile and constrain halo
- 2 sizes of proton detector will be used to minimize this uncertainty (300 mm^2 and 600 mm^2)



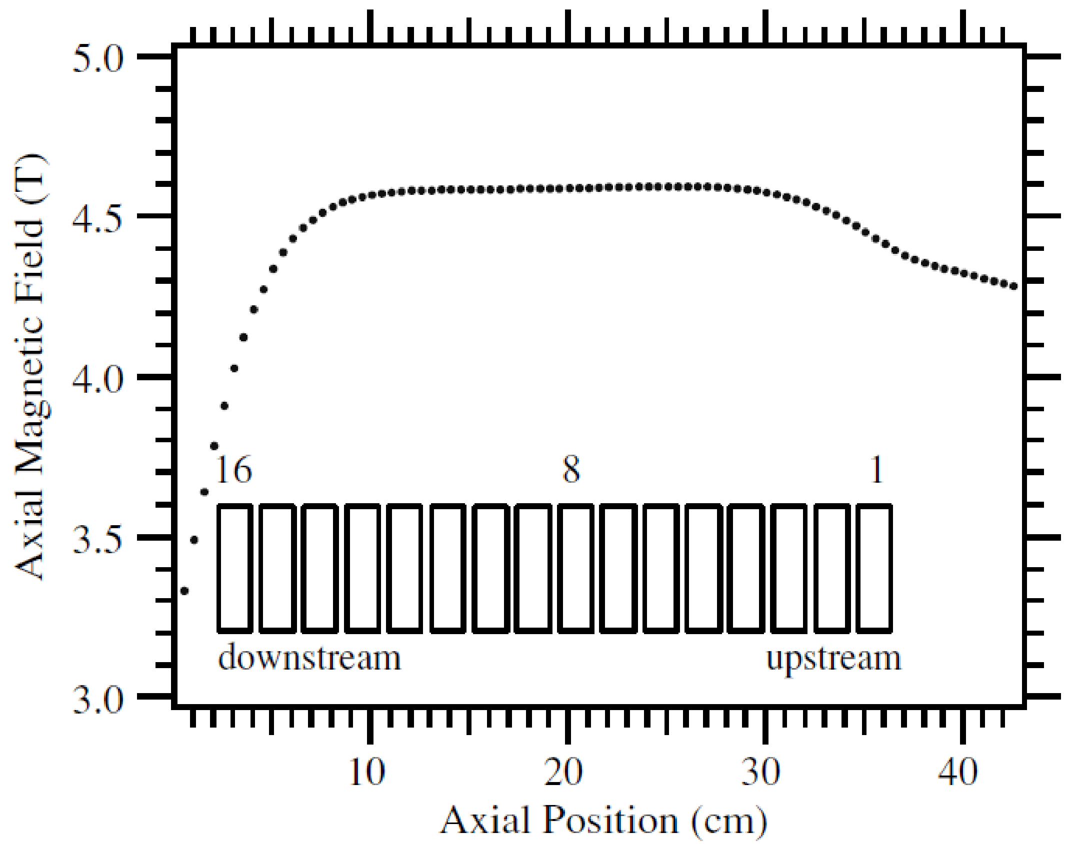




Measured Neutron Capture Flux = 2.3 x 10^7 /s

Trap Non-linearity

- Trap Non-linearity
  - 5.3 ± 0.8 s correction from large magnetic field gradient at longest trap length (10 electrodes)
  - Run with shorter traps to reduce correction and minimize uncertainty



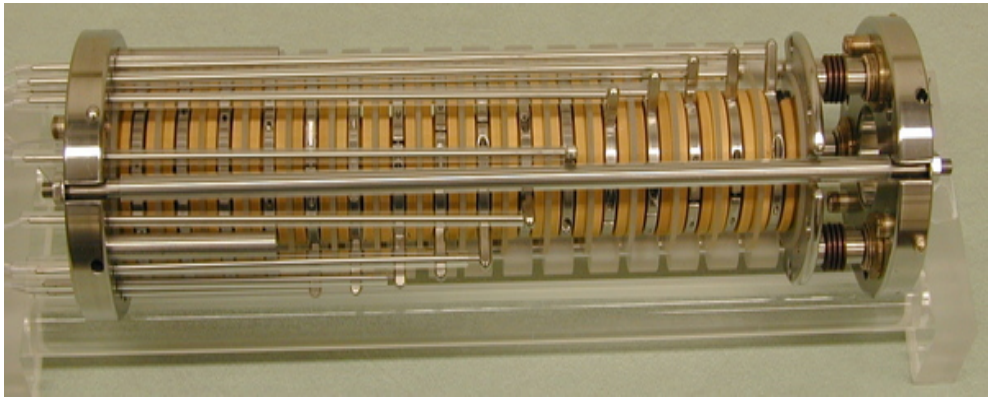
Uncertainty Budget Projection

Source of correction	Correction (s)	Uncertainty (s)	
^{6}LiF deposit areal density		2.2	
^{6}Li cross section		1.2	0.5 s
Neutron detector solid angle		1.0	
Absorption of neutrons by ^{6}Li	+5.2	0.8	0.4 s
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	0.1 s
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	0.2 s
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	

Proton Counting Improvements

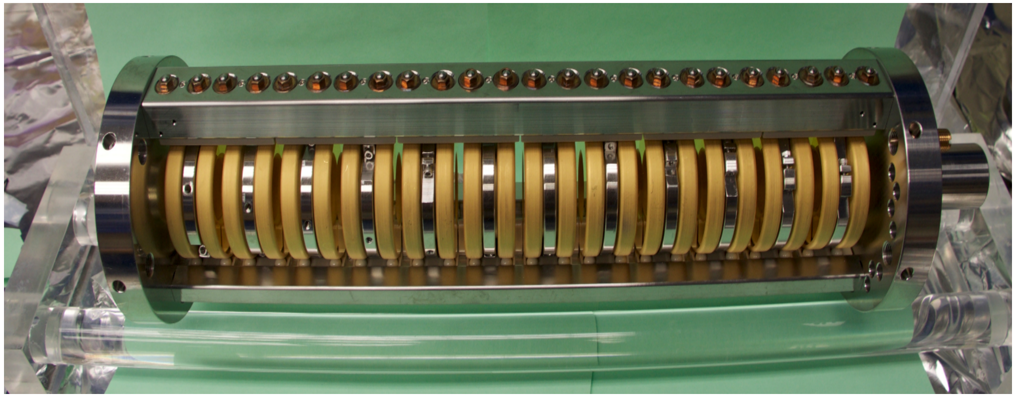
- Extensive modeling of the apparatus (MCNP and GEANT)
- NCNR Cold source upgrade -> 50% more neutrons
- New low-noise pre-amp
  - Allows operation at lower proton acceleration voltages, reducing backscatter uncertainties & improving stability
- Two parallel data acquisition systems
  - Digitization of all proton waveforms, enabling detailed study of multiple-proton events and background events
  - Consistency check
- Extensive off-line testing of the proton trap and detector
  - Trap instability was a major issue during the previous run of the experiment
- New version of the proton trap

Two versions of the proton trap



Mark II trap:

- Used in 2005 measurement
- Well characterized
- Offline testing shows stable operation under a wide range of conditions

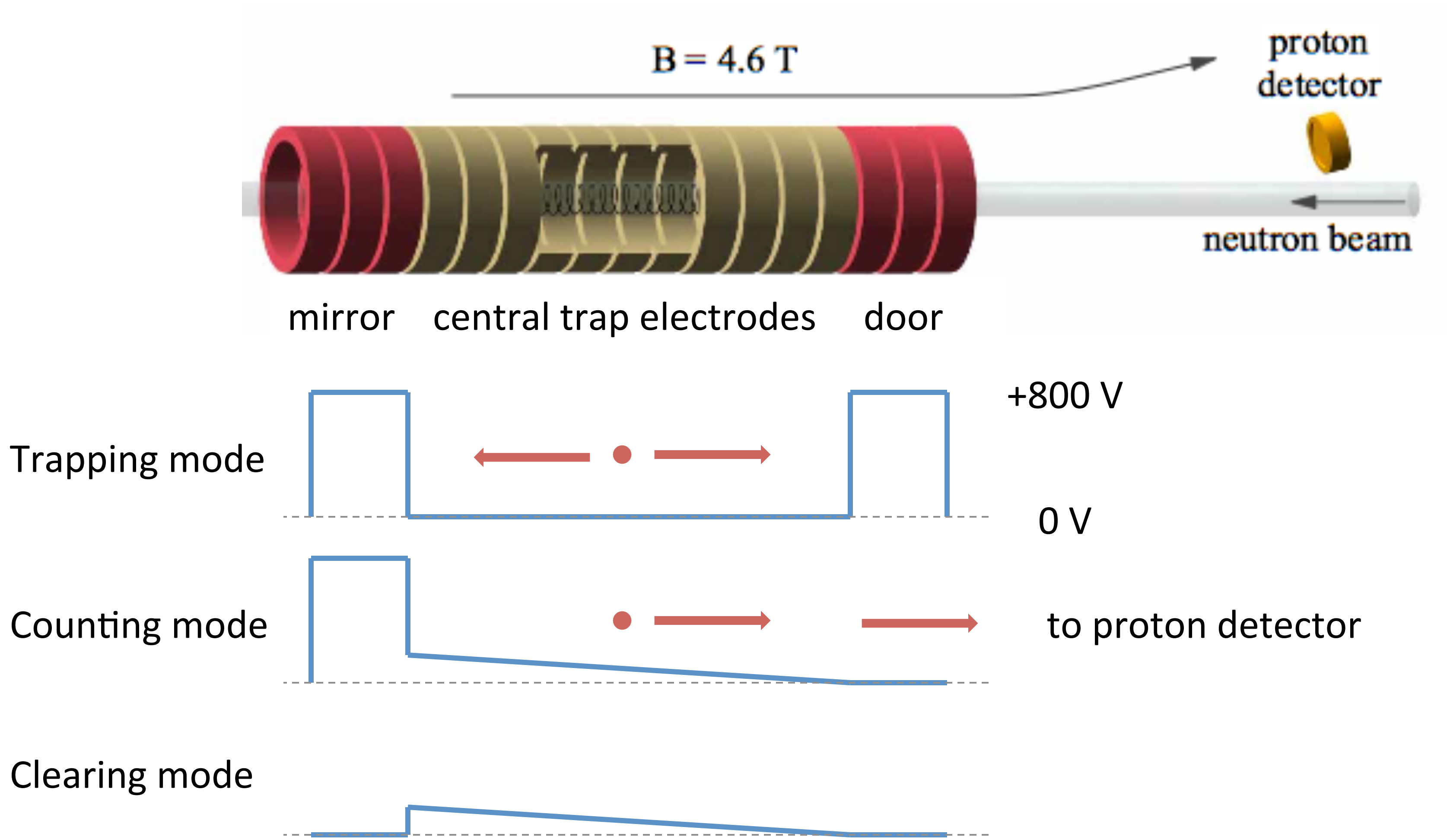


Mark III trap:

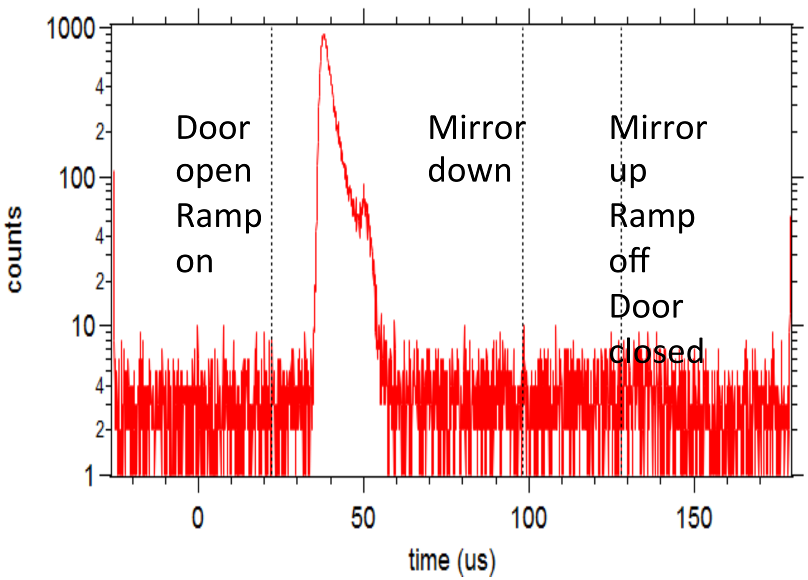
- Better pumping of trap volume
- Better metrology of relevant electrode edges
- Offline testing shows stable operation under a wide range of conditions

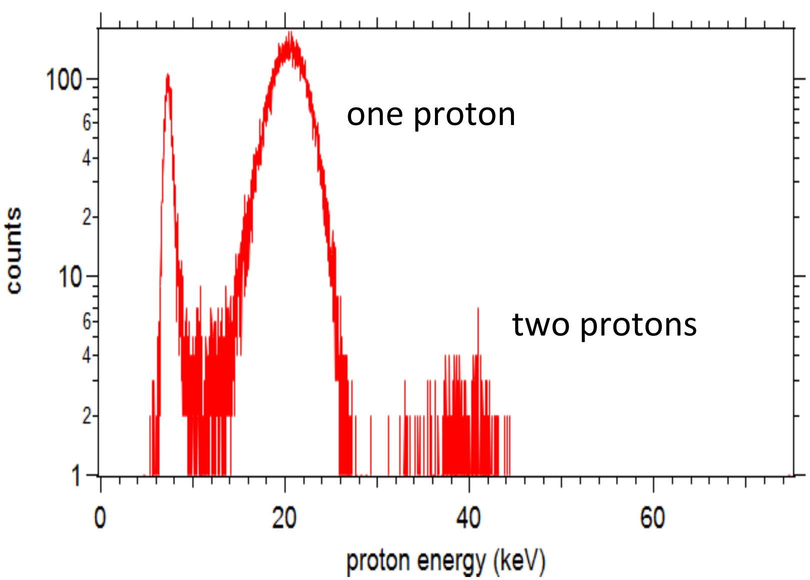
Two traps will allow for a wider range of systematic tests

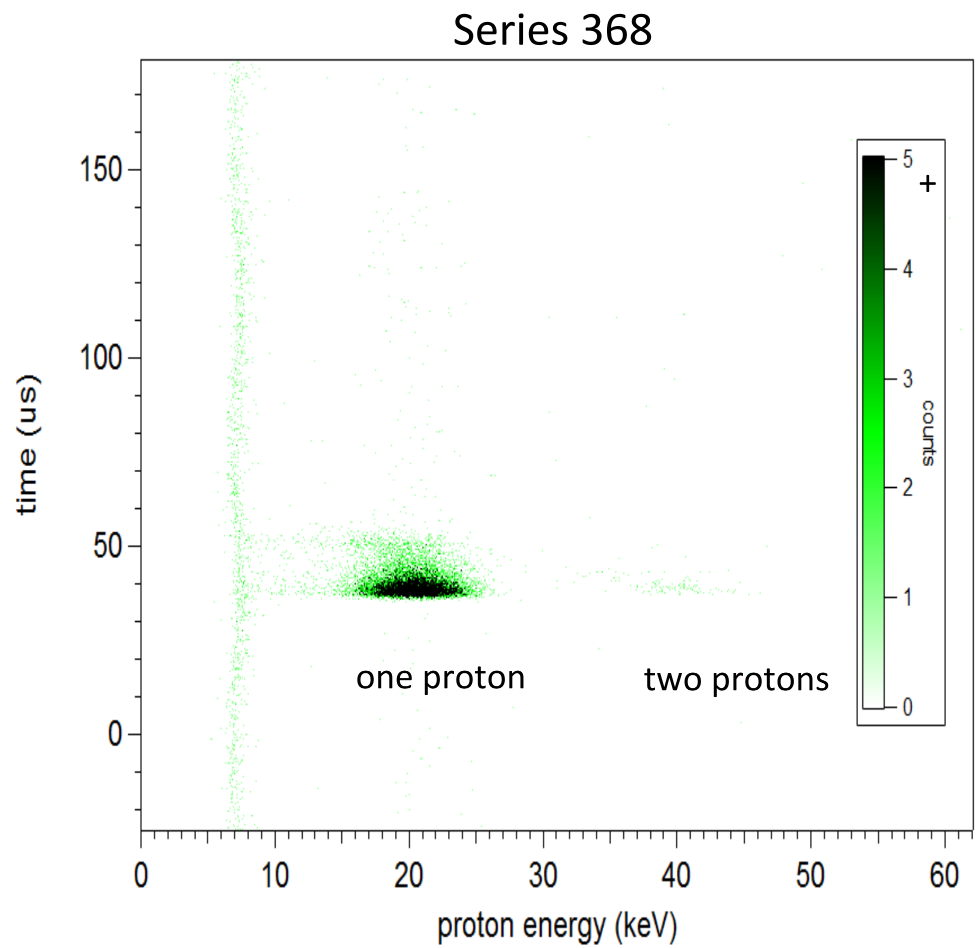
Proton Trapping Cycle



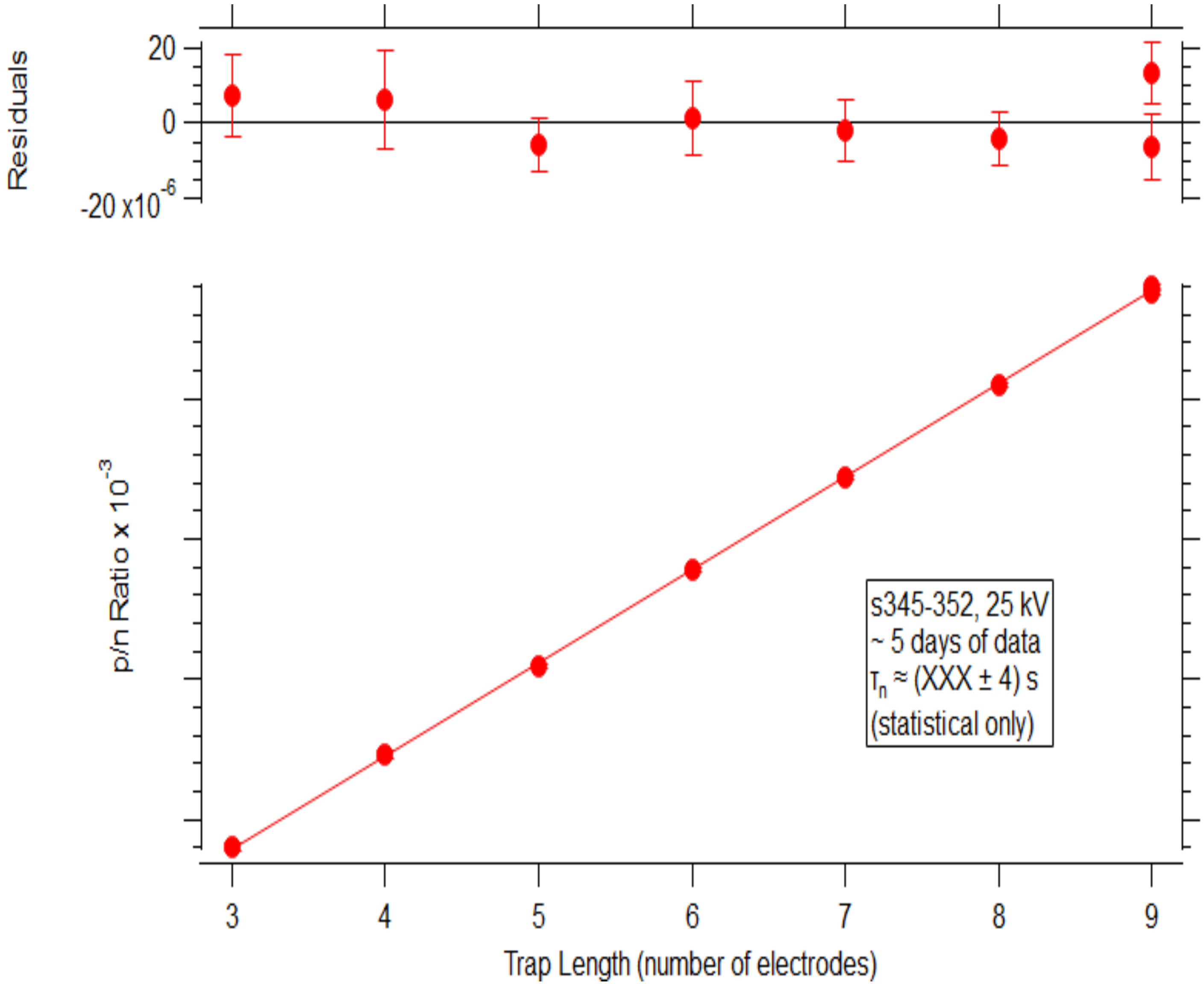
Proton timing and energy spectra







Lifetime fit example



BL2 Experiment Status

- Running on NG-C
- 2 cycles of initial data and testing
  - 2 types of detector
  - Multiple trap lengths
  - Multiple trapping times
  - Multiple proton acceleration voltages
- Currently in 4 month long reactor shutdown
  - Data analysis
  - Equipment repairs and upgrades
  - DAQ improvements
  - Additional testing