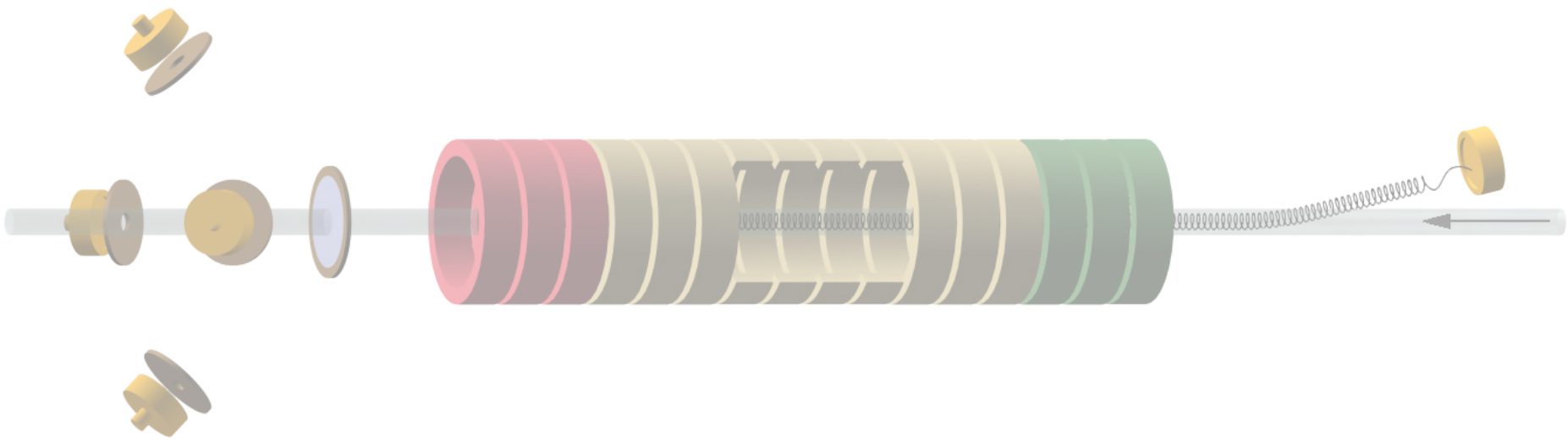
The Next Generation Beam Neutron Lifetime Experiment



F. E. Wietfeldt
Tulane University

Our Plan

Based on Sussex-ILL-NIST beam neutron lifetime program using quasi-Penning proton trap.

More than 30 years experience with this program; many systematics thoroughly studied and understood.

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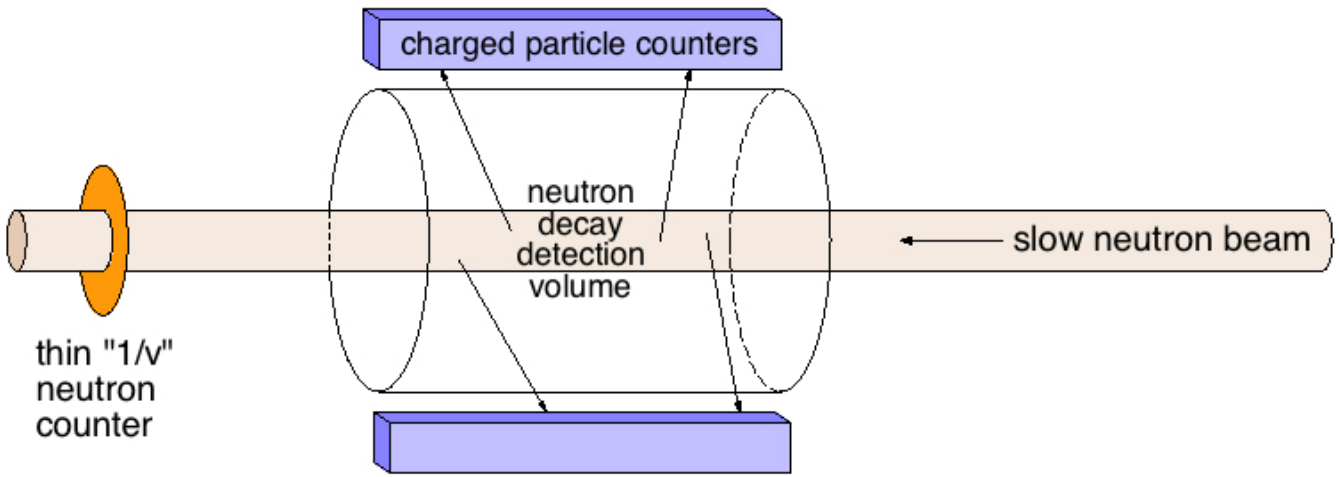
Goal #1: Further explore, cross check, and reduce all systematic uncertainties to the 10^{-4} level

Goal #2: Reduce the neutron lifetime uncertainty, using the beam method, to < 0.2 s

Brief Review of the 2005 NIST Beam Neutron Lifetime Experiment and 2013 Update



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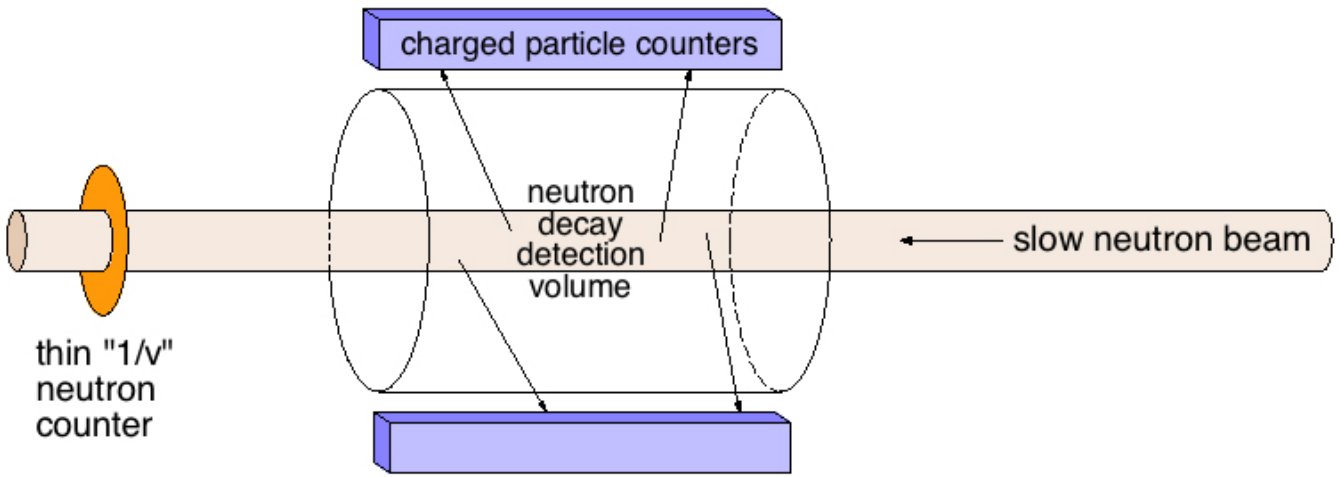

proton counting rate: $R_p = \varepsilon_p \frac{A_{\rm beam} L_{\rm det}}{\tau_n} \int \frac{\phi(v)}{v} dv$

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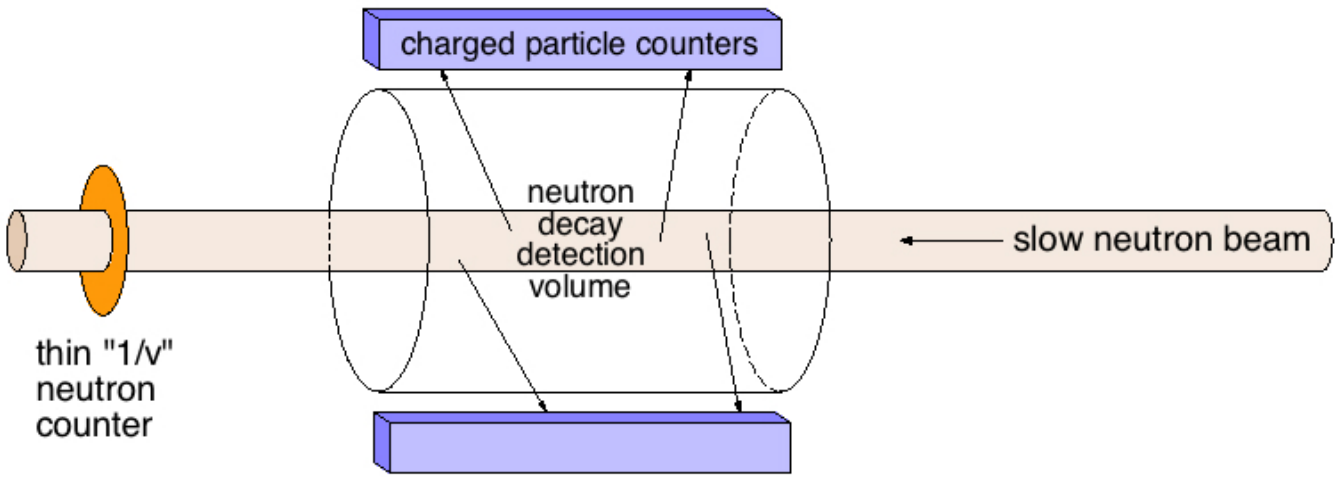

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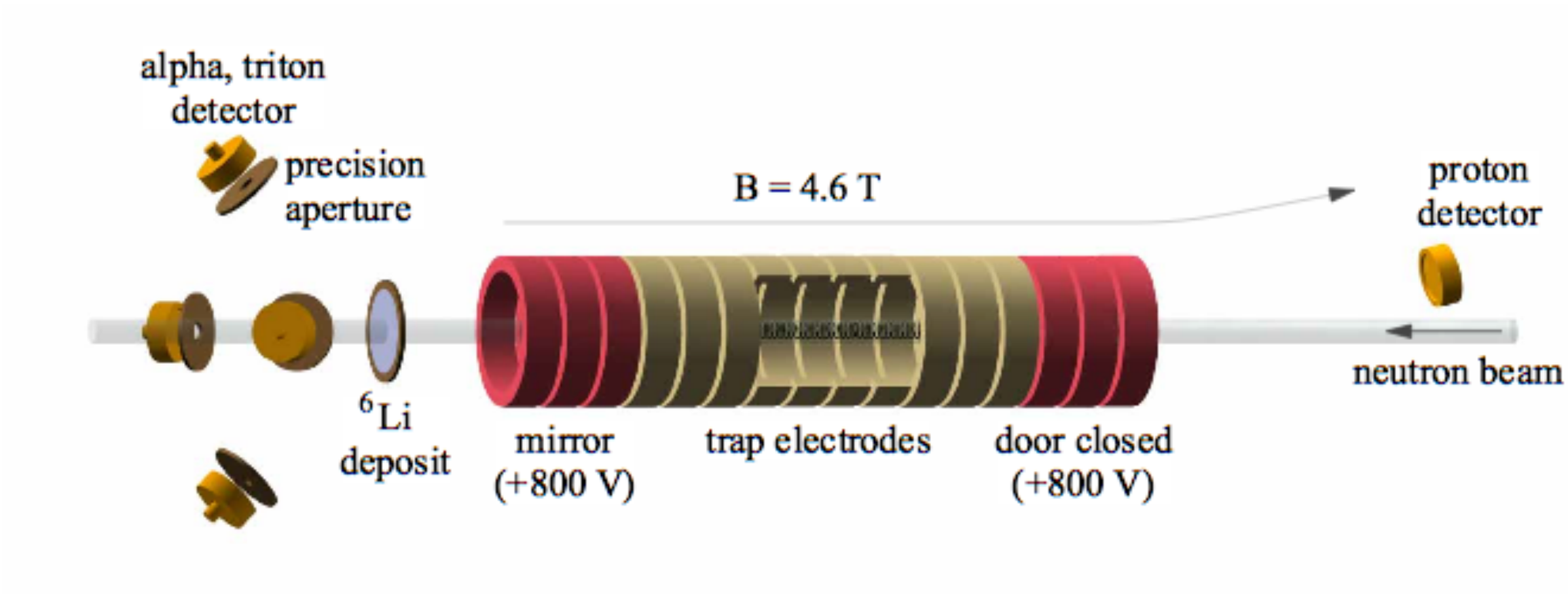
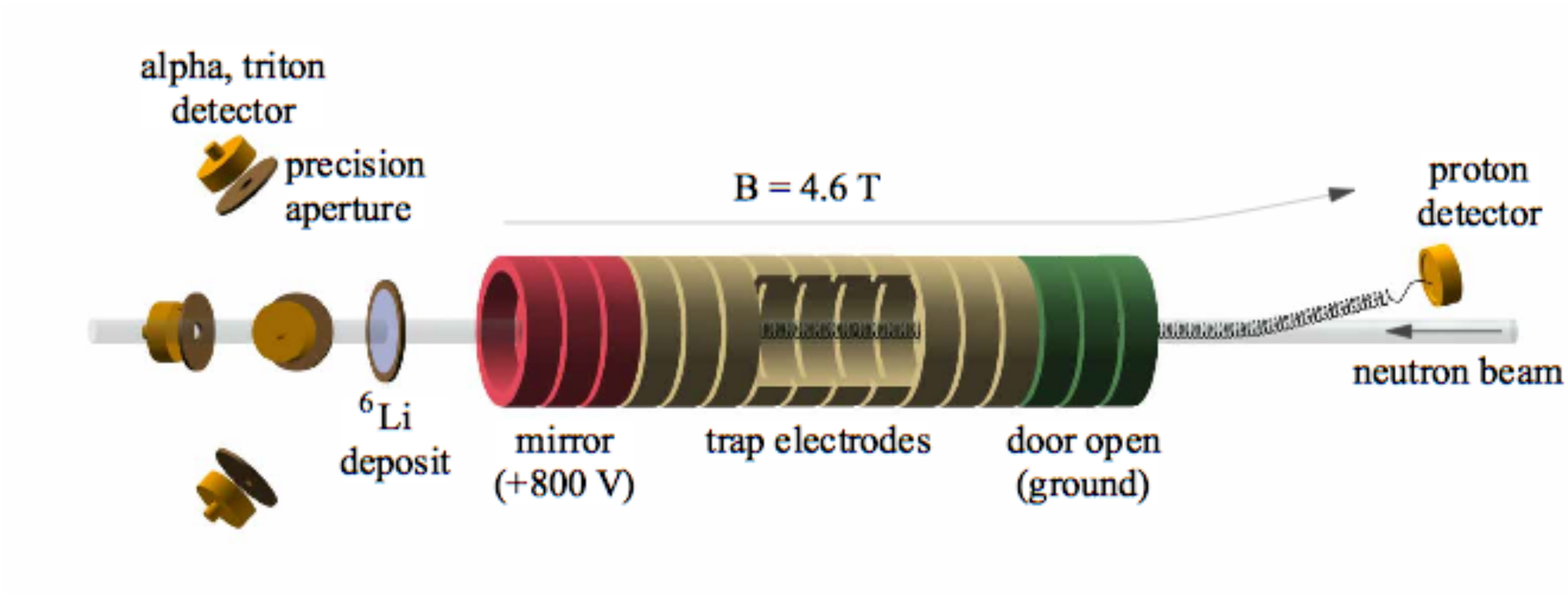
$$\tau_n = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} v_{th}}$$


alpha, triton
detector
precision
aperture
B = 4.6 T
proton
detector
neutron beam
^{6}Li
deposit
mirror
(+800 V)
trap electrodes
door closed
(+800 V)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detector
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proton
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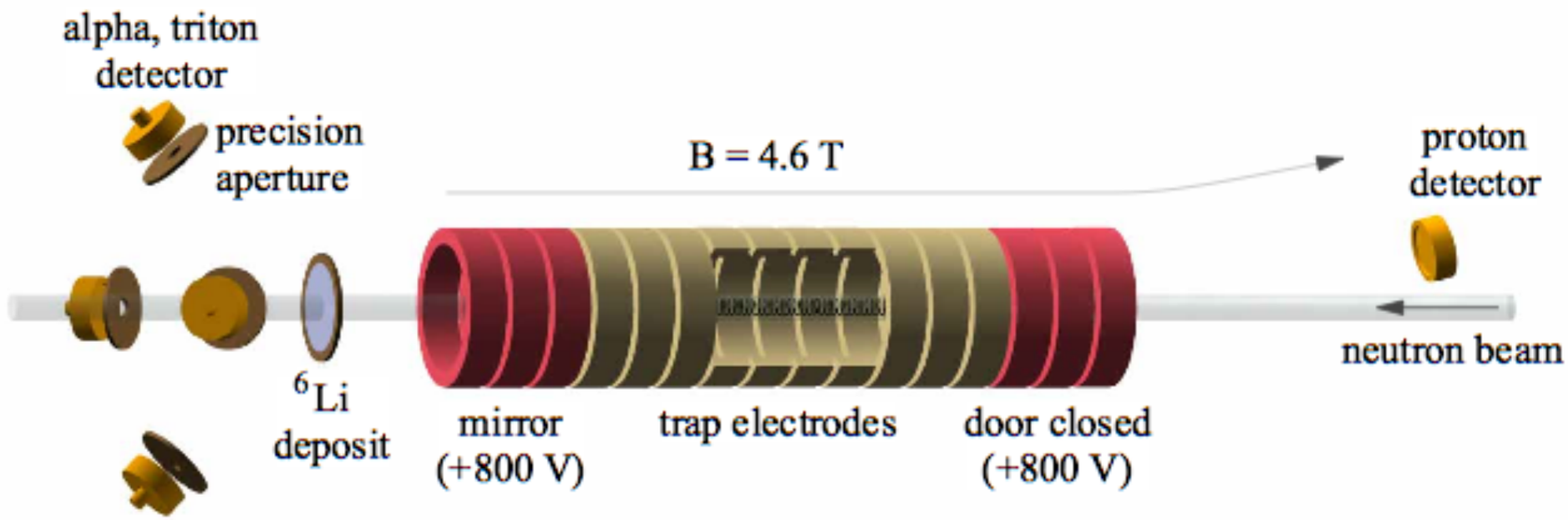
neutron beam
^{6}Li
deposit
mirror
(+800 V)
trap electrodes
door open
(ground)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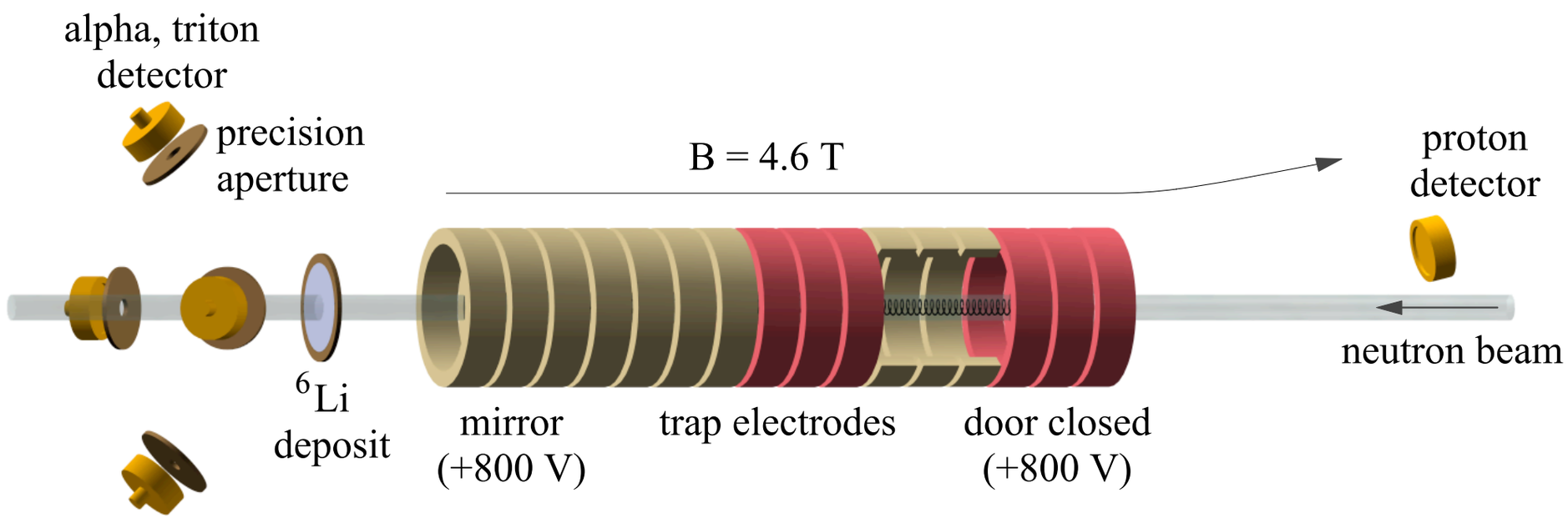
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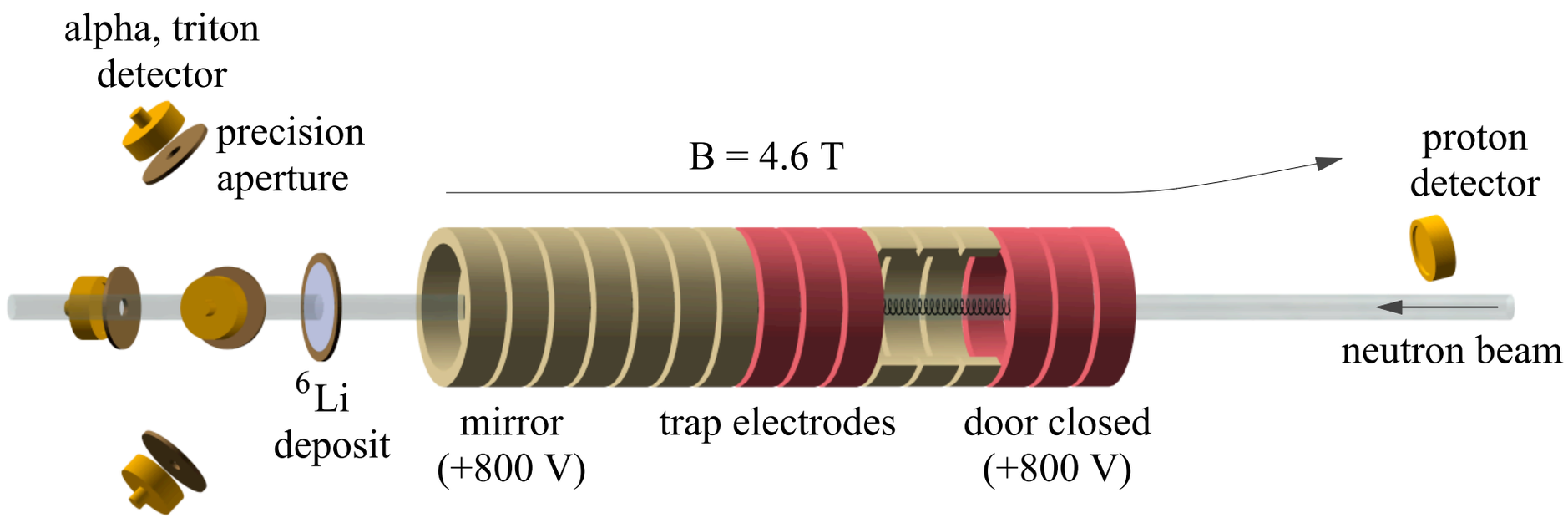
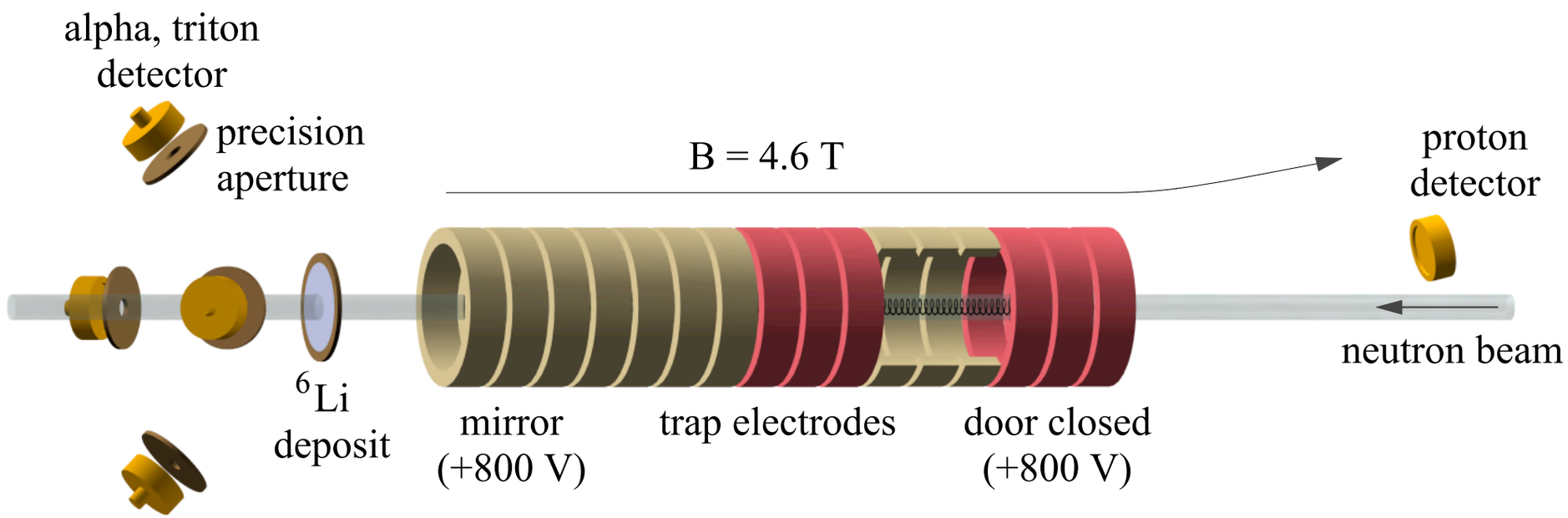


$$\tau = \frac{R_n \varepsilon_p L_{\mathrm{det}}}{R_p \varepsilon_{th} v_{th}}$$



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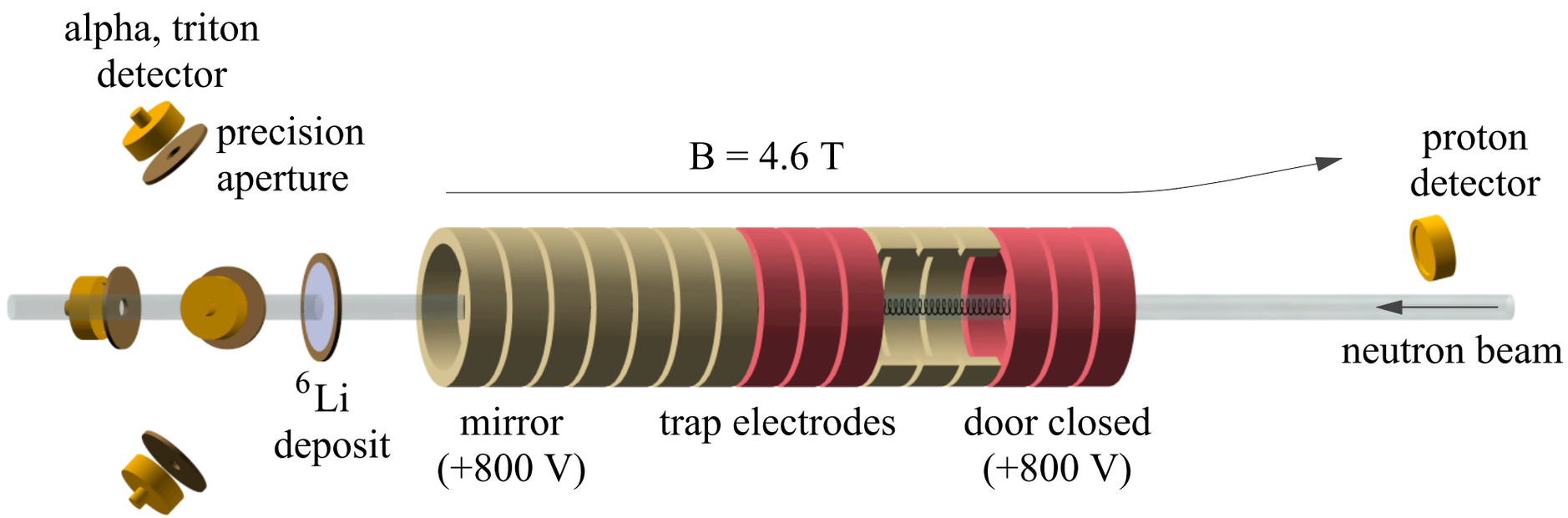

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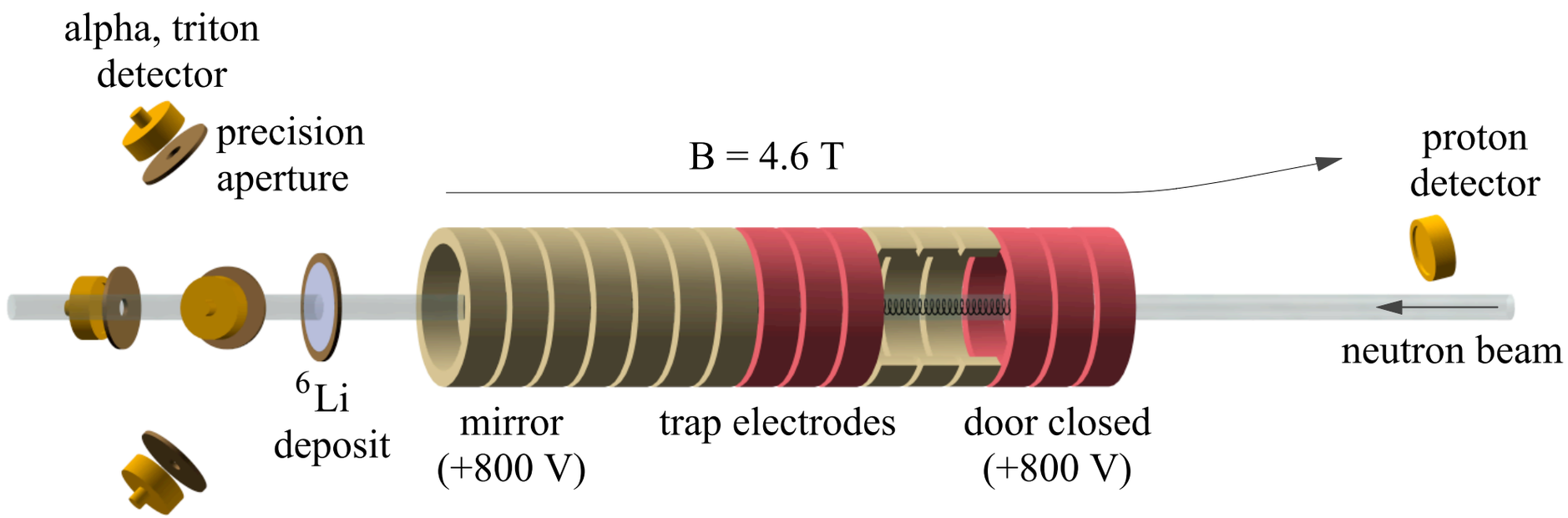

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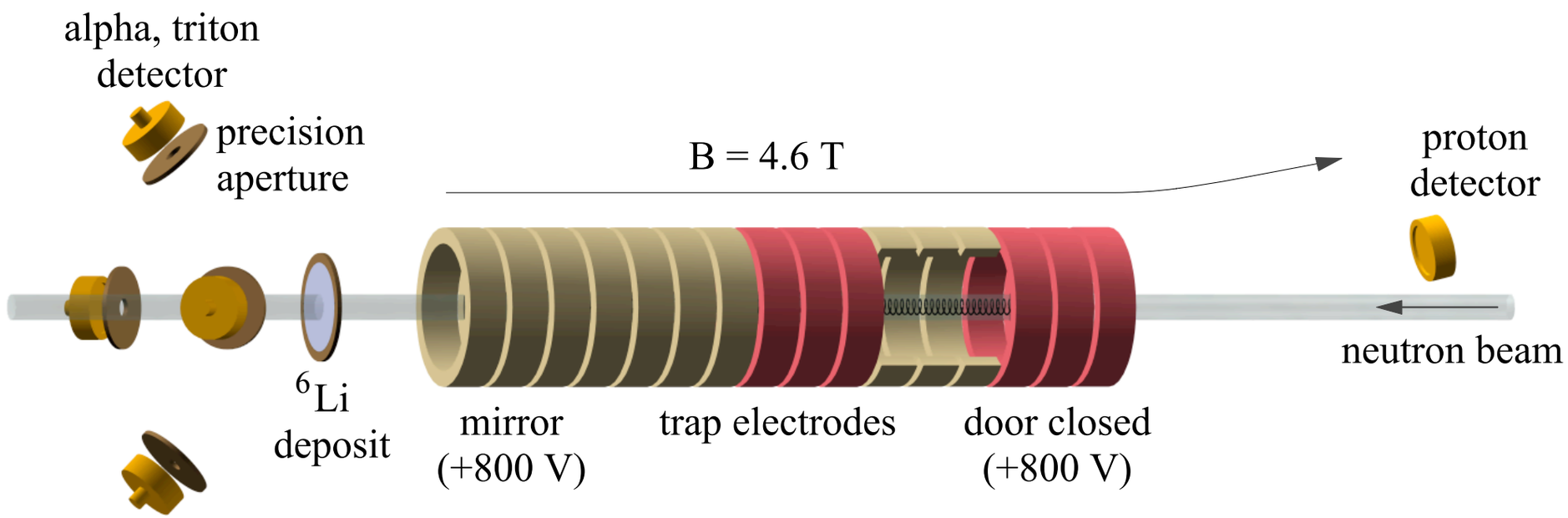
trap electrodes

length of
electrode + spacer



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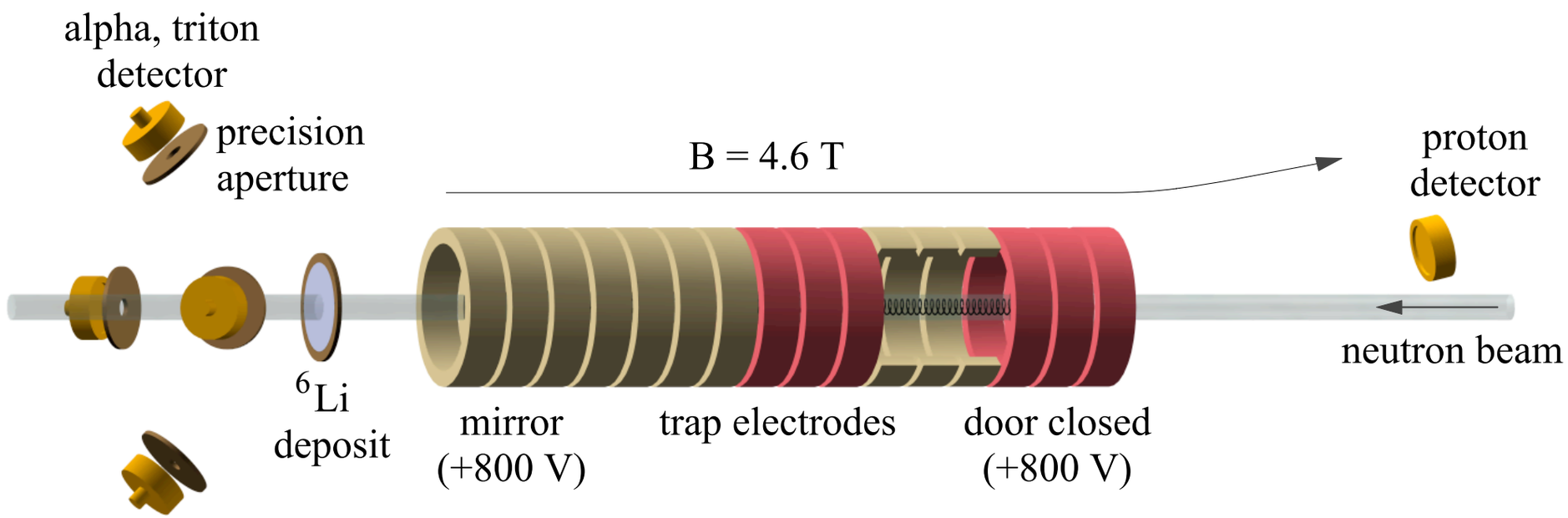
total *effective*
end region length



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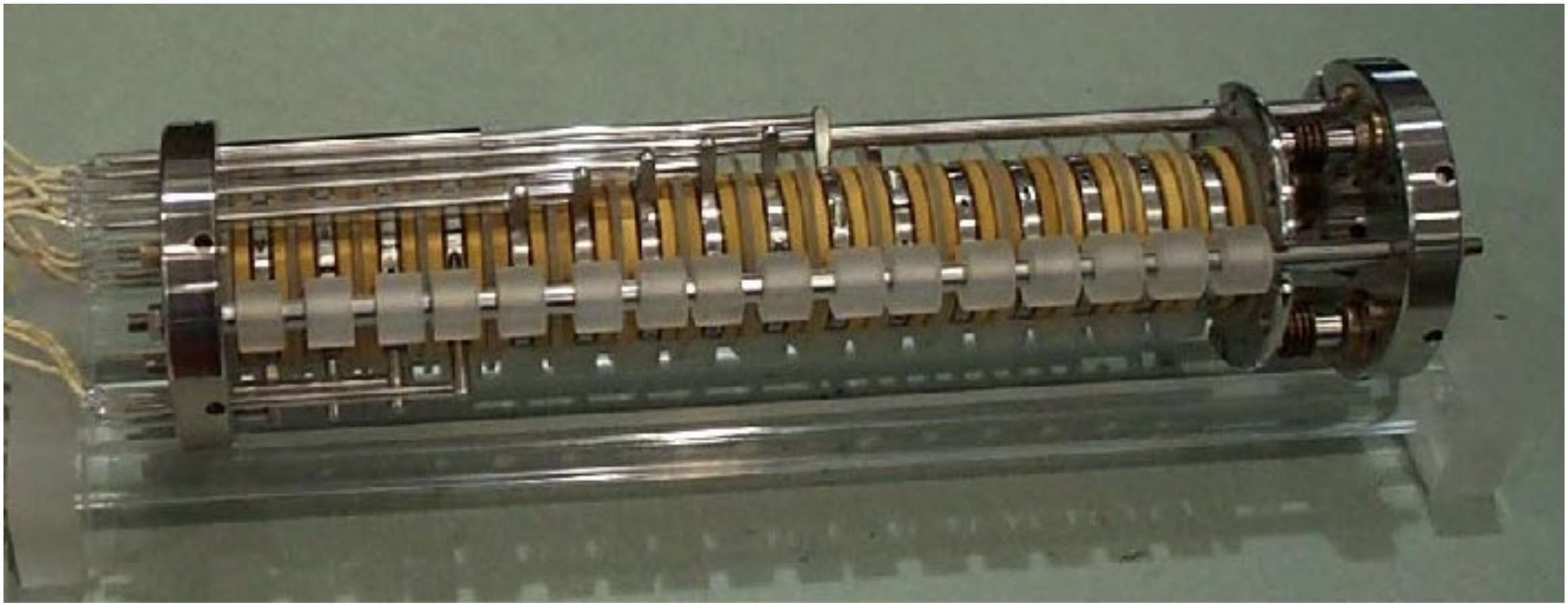
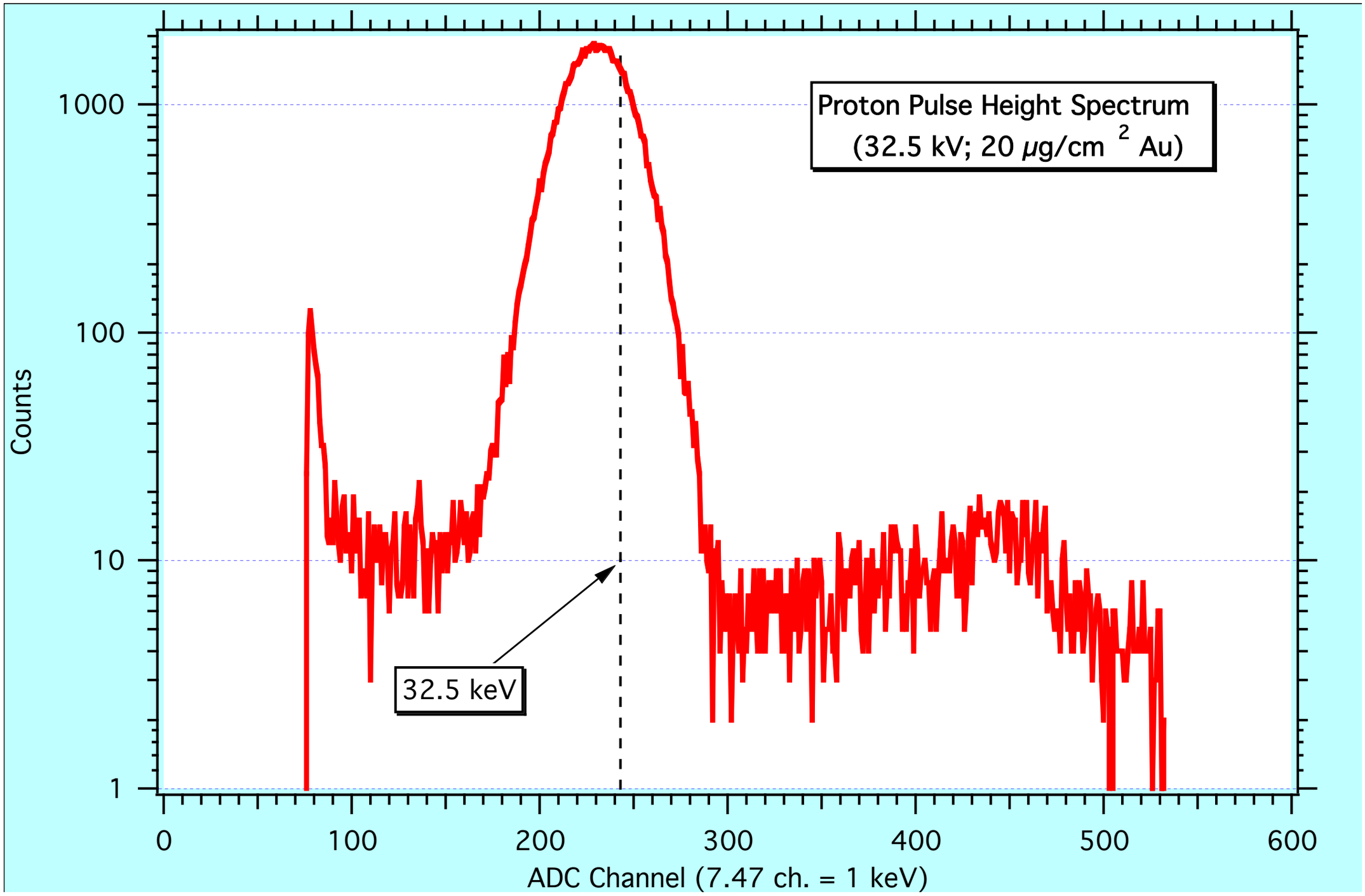
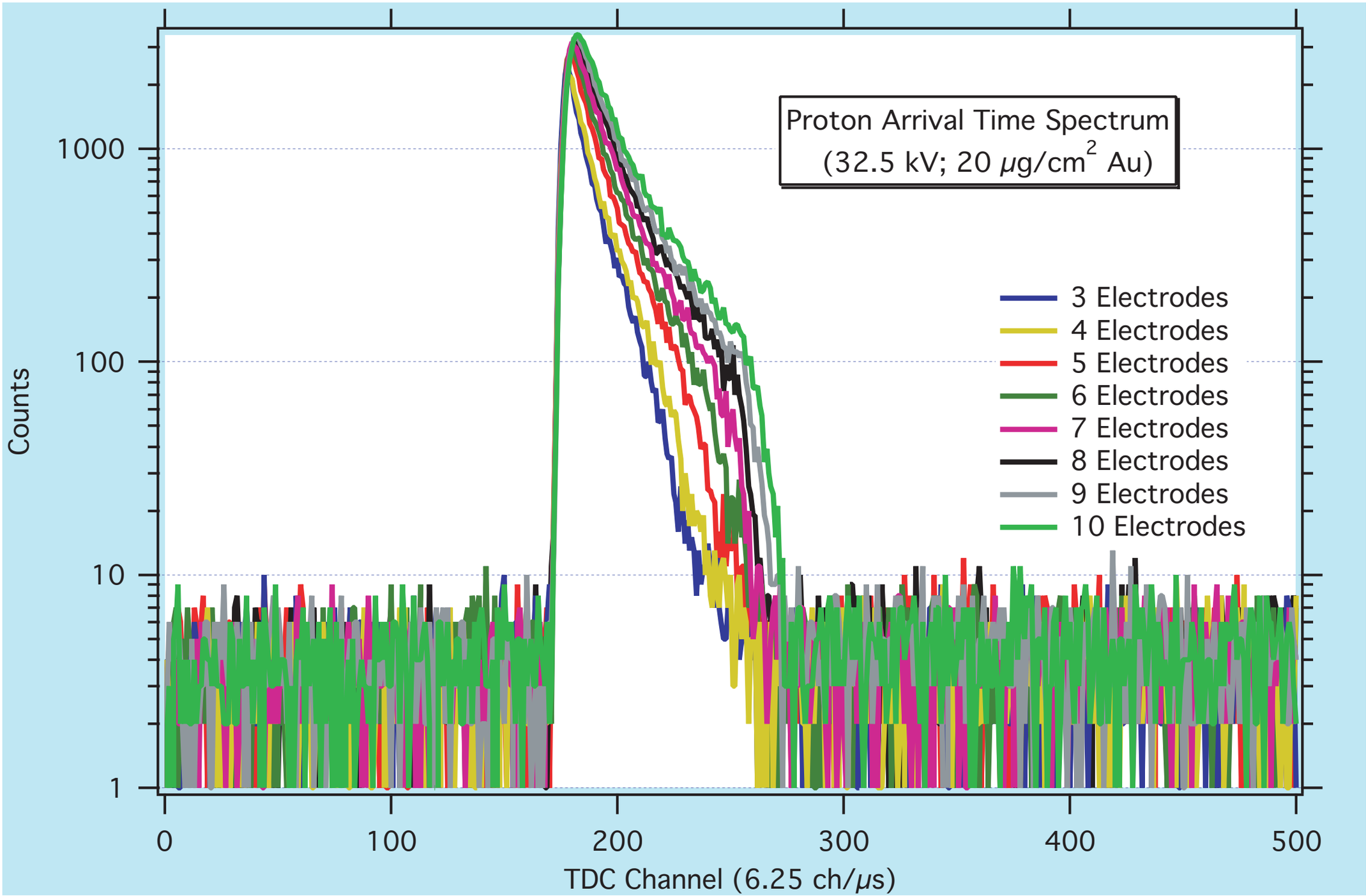
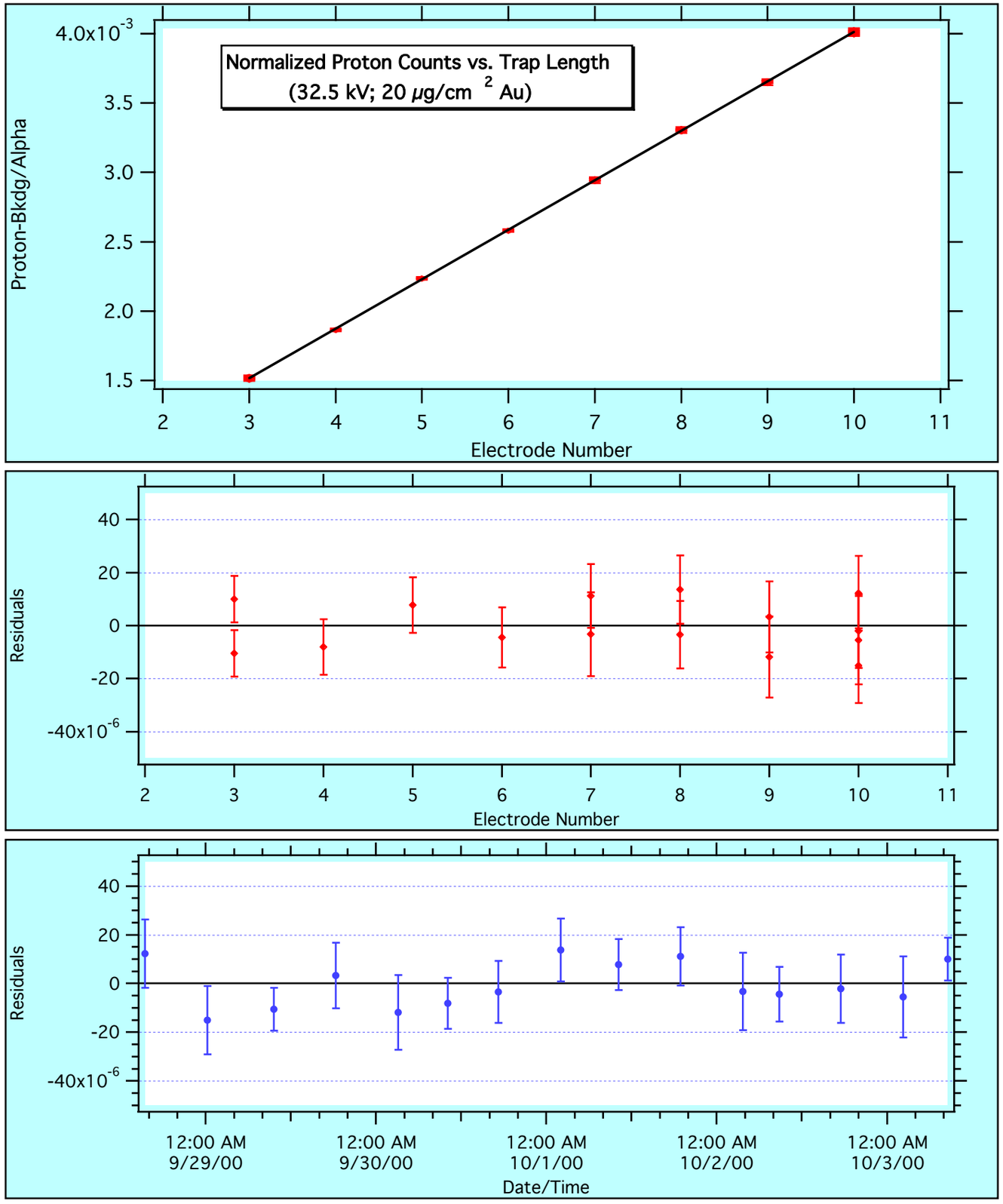
$$\boxed{\frac{R_p}{R_n} = \tau^{-1}\left(\frac{\varepsilon_p}{\varepsilon_{th} v_{th}}\right)\left(nl + L_{\text{end}}\right)}$$

Proton Trap



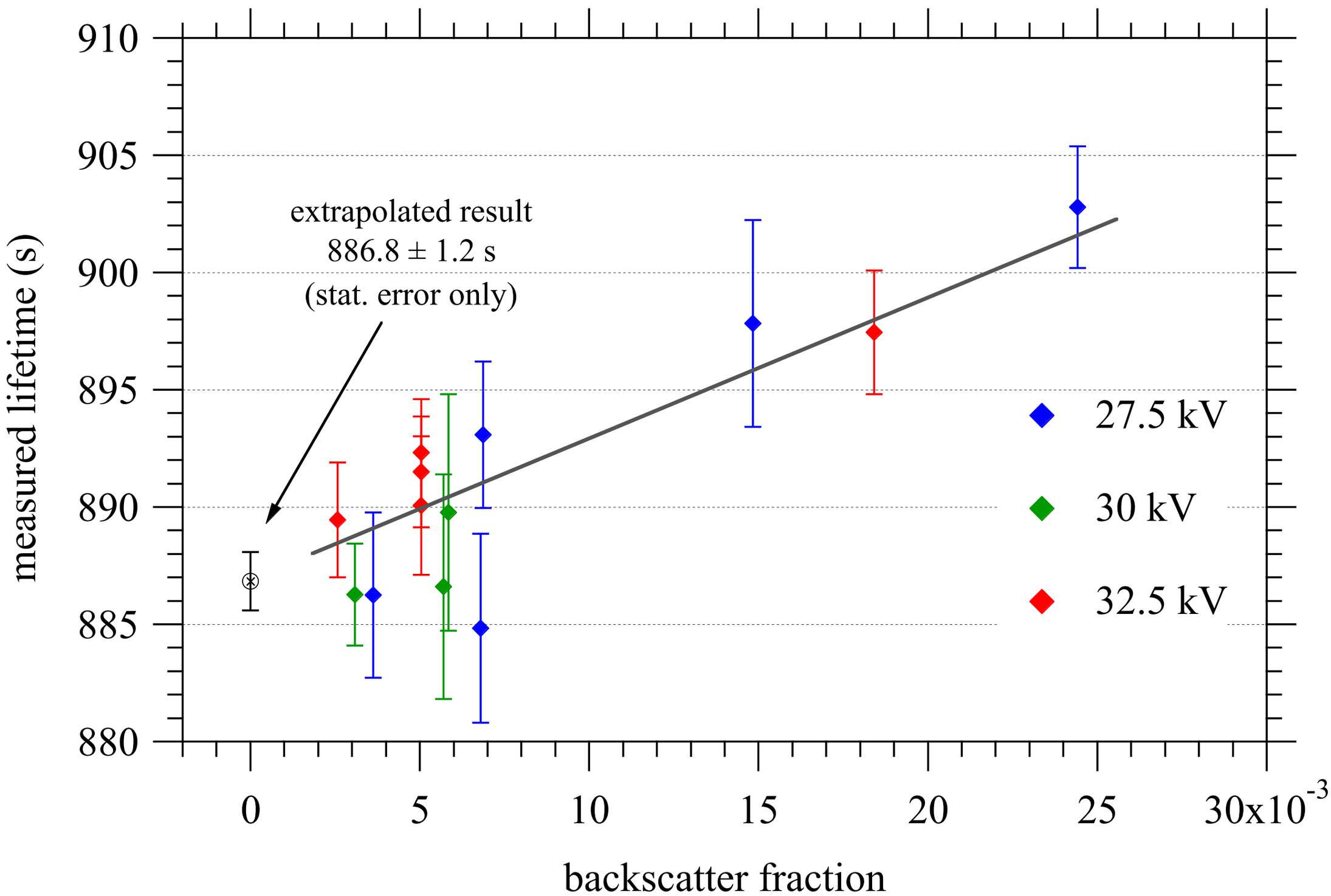

Proton Pulse Height Spectrum
(32.5 kV; 20 μg/cm 2 Au)
32.5 keV
Counts
1000
100
10
1
0
100
200
300
400
500
600
ADC Channel (7.47 ch. = 1 keV)


Proton Arrival Time Spectrum
(32.5 kV; 20 μg/cm² Au)
3 Electrodes
4 Electrodes
5 Electrodes
6 Electrodes
7 Electrodes
8 Electrodes
9 Electrodes
10 Electrodes
Counts
1000
100
10
1
0
100
200
300
400
500
TDC Channel (6.25 ch/μs)

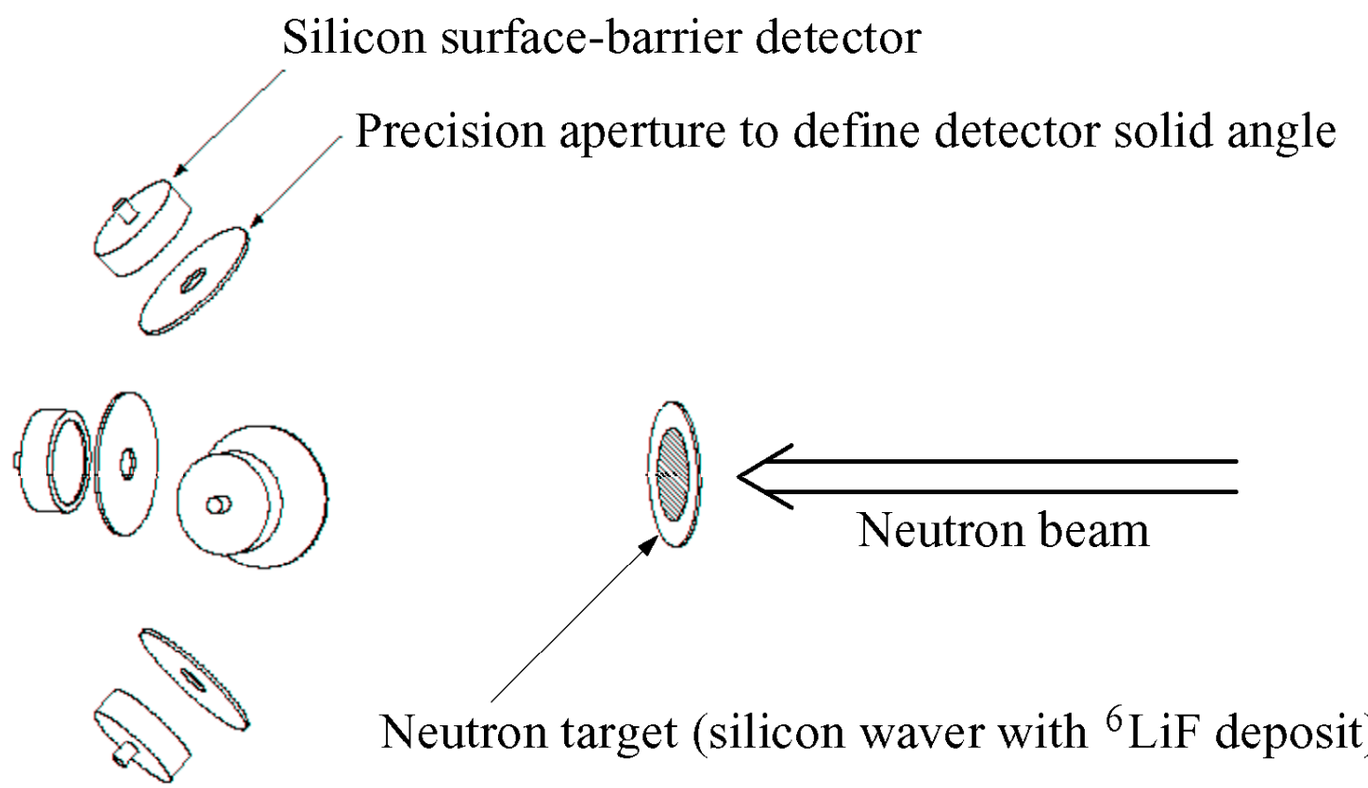


Fit of $\frac{R_p}{R_n}$ *vs.* number trap electrodes

Lifetime vs. Backscatter



1/v neutron counter



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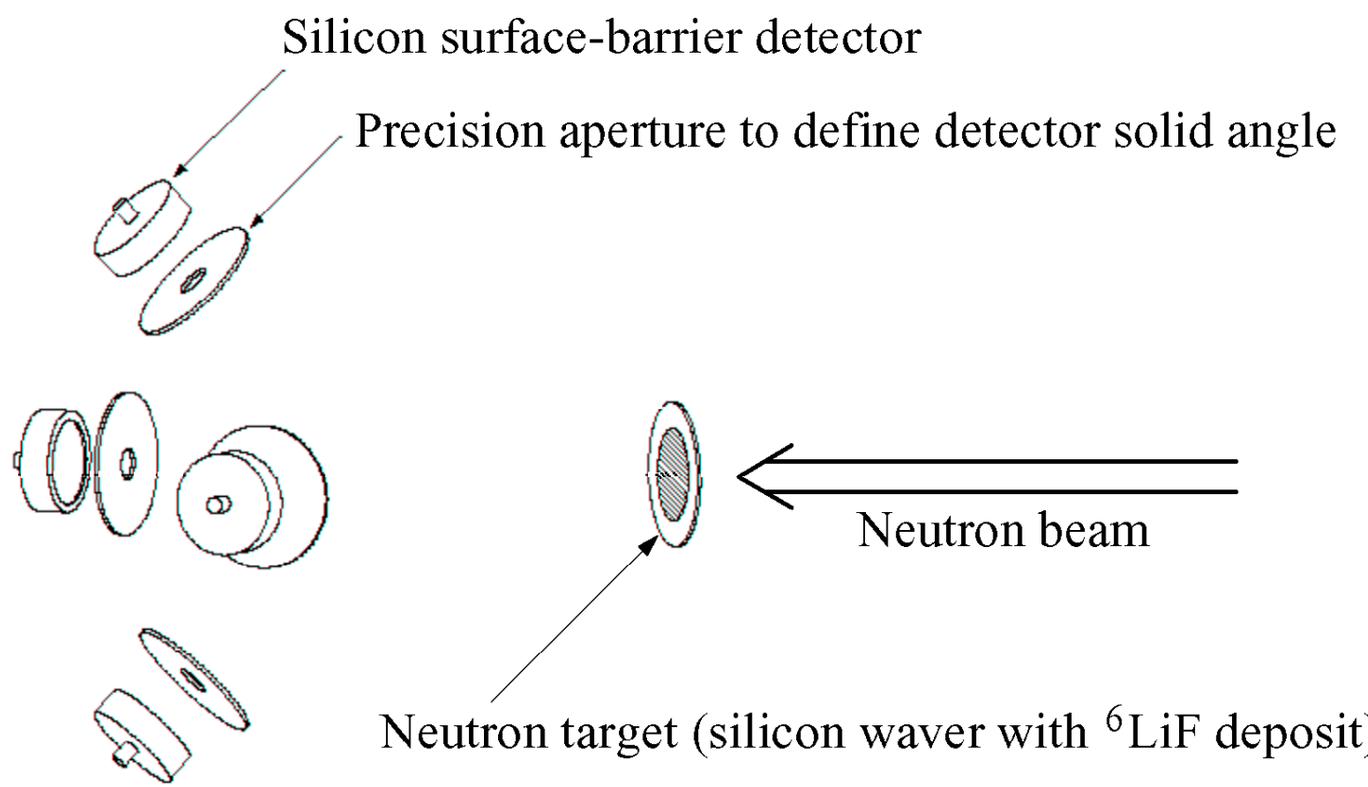

neutron detection efficiency: $\varepsilon_{th} = \frac{\sigma_{th}}{4\pi} \int\int \Omega(x,y)\rho(x,y)\theta(x,y)\,dxdy$

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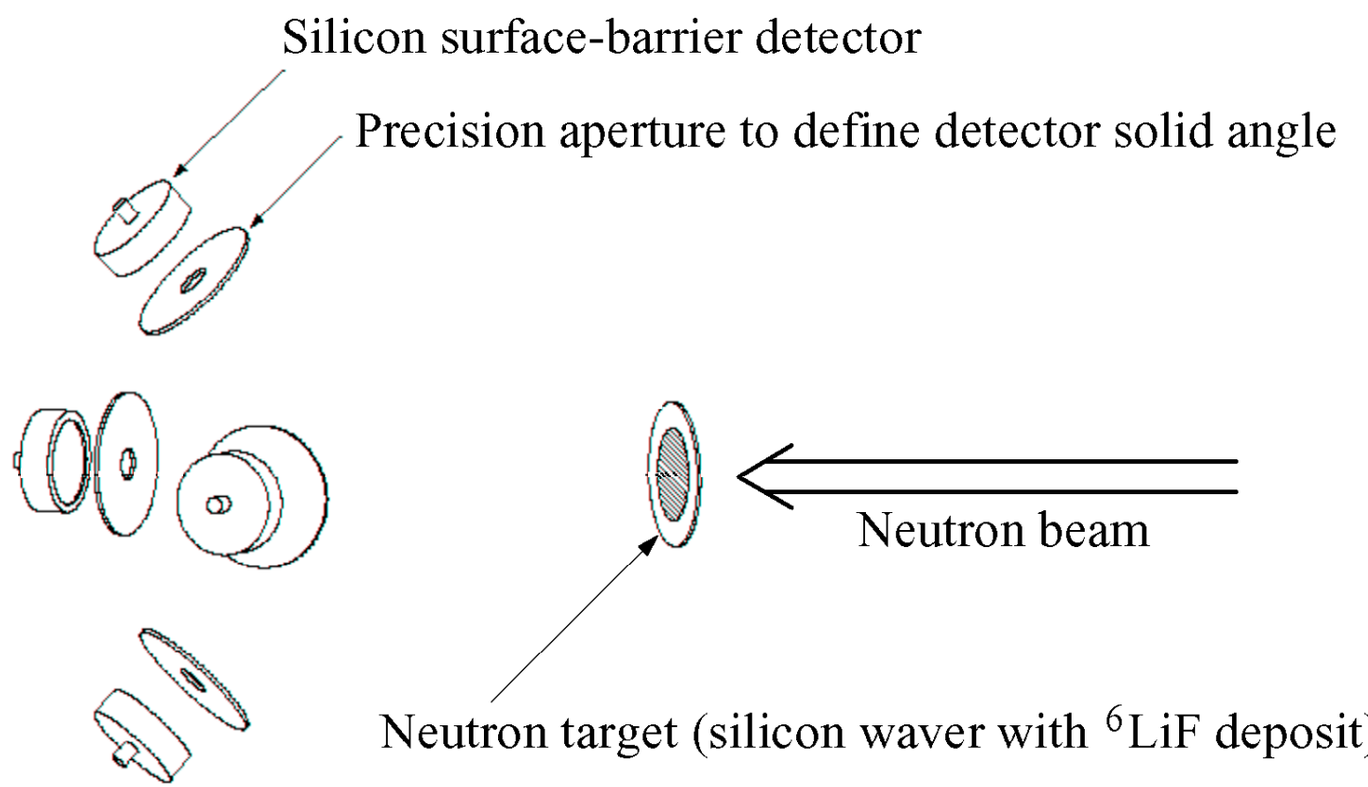

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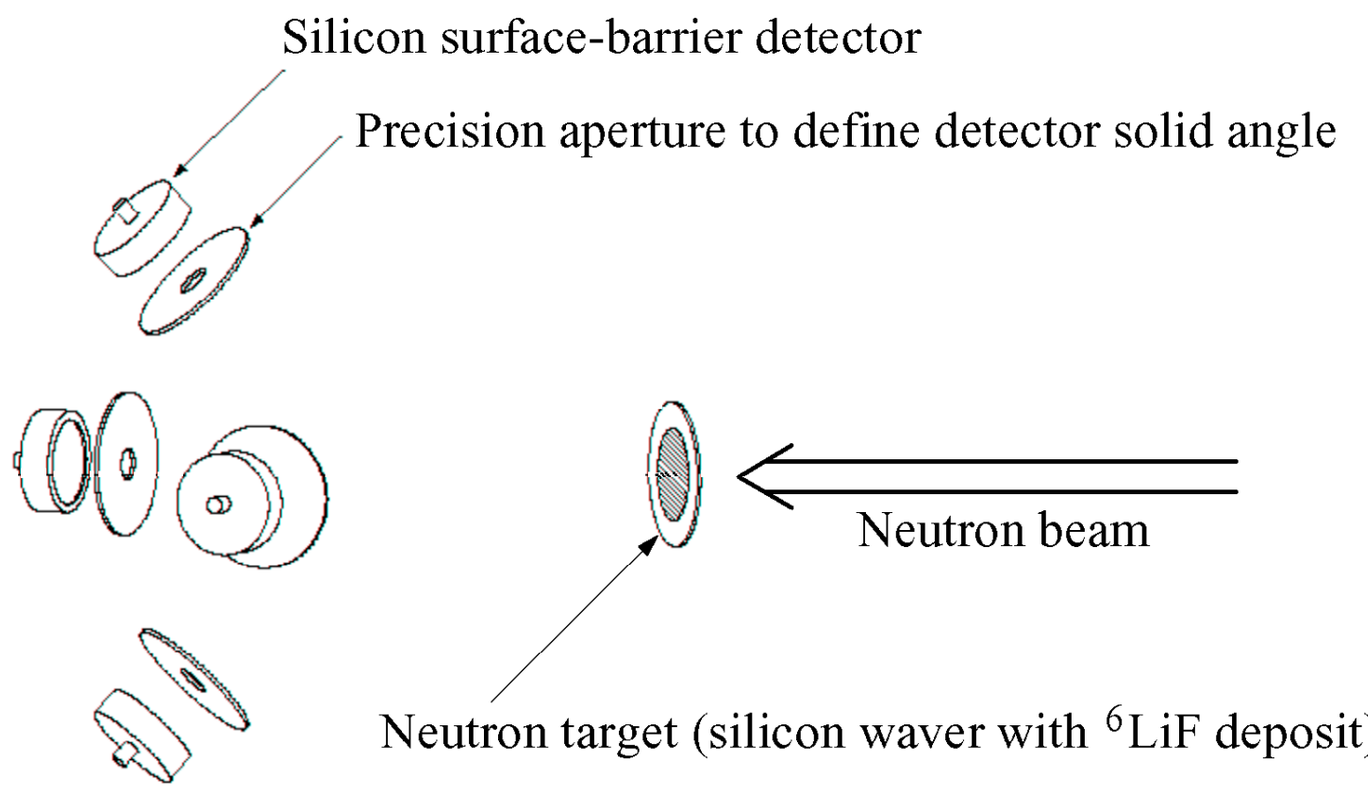

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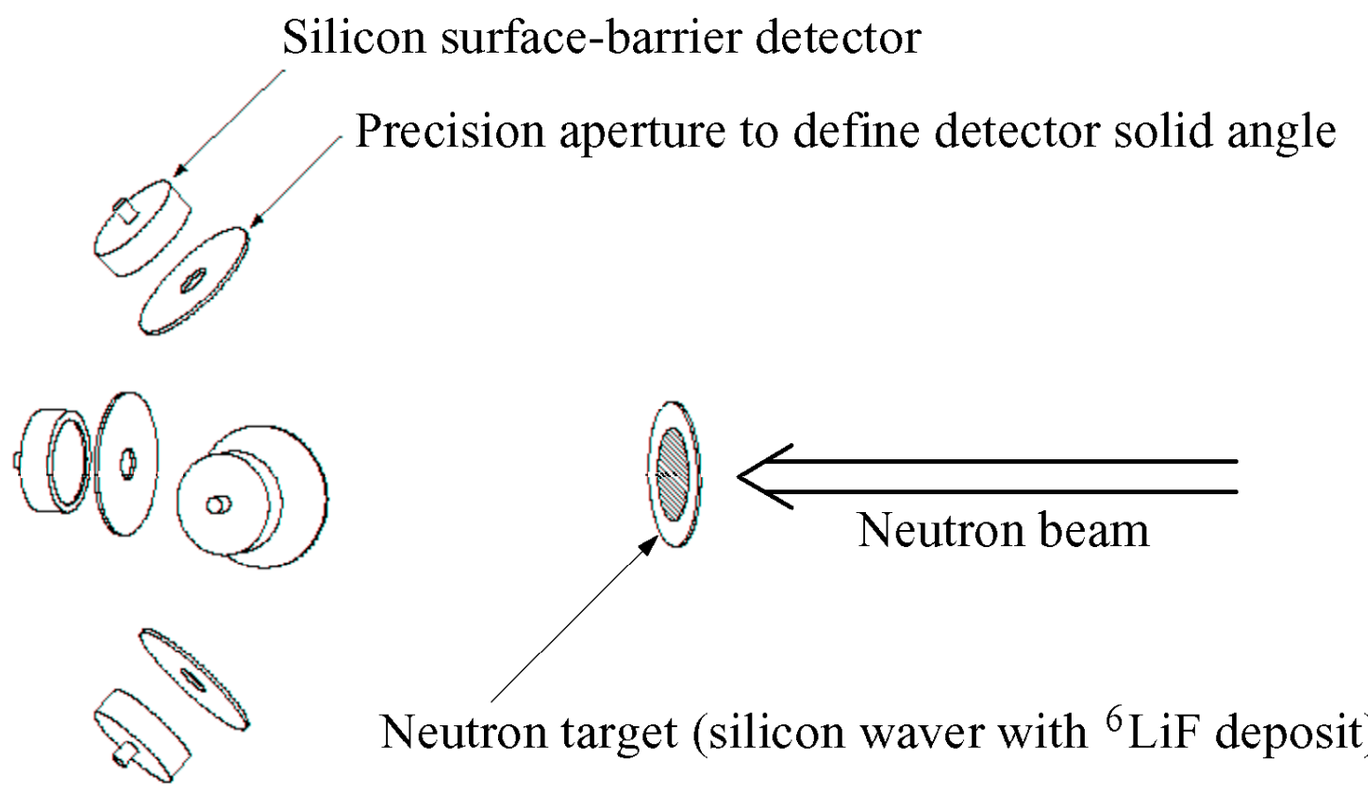

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neutron beam density

Error 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

2005: $\tau_n = 886.3 \pm 3.4$ s

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can be significantly reduced by an absolute calibration of the 1/v neutron counter

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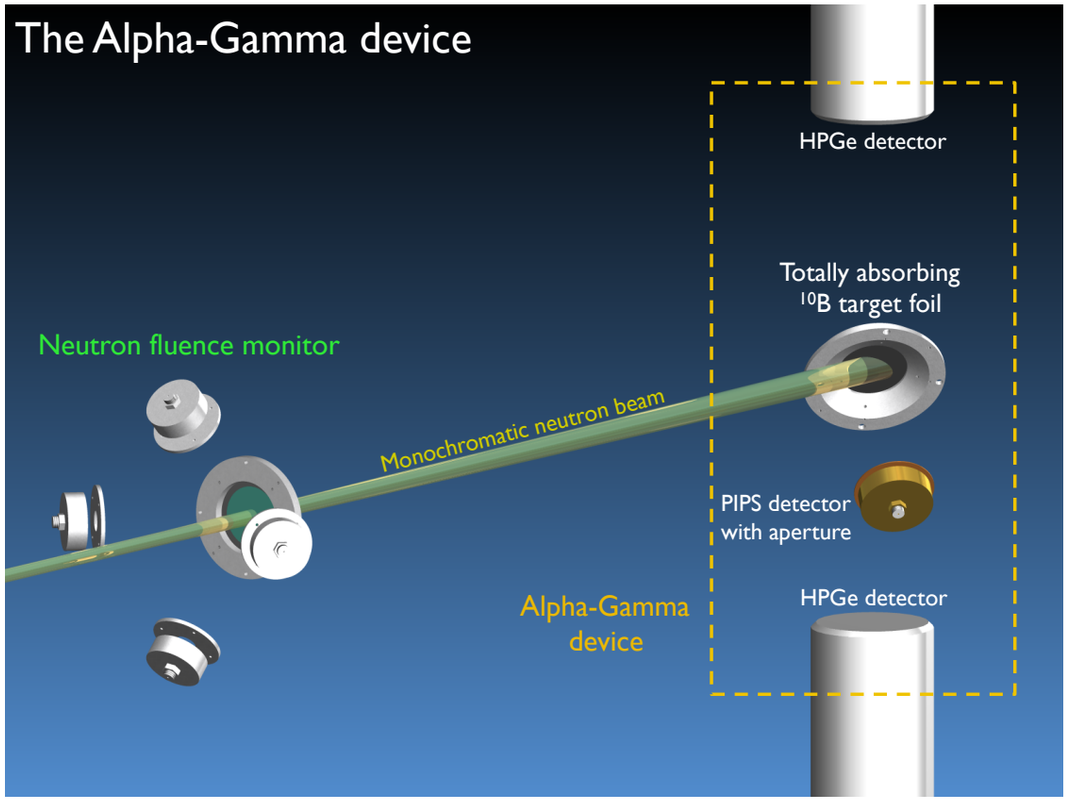
Absolute neutron flux measurement to < 0.1% precision

- ^{10}B alpha-gamma device
  now working at NIST
  0.06% precision recently achieved!
  (Andrew Yue, NIST)



- ^{3}He gas scintillation chamber (Tulane, NIST) - in construction/testing

- neutron radiometer (Indiana, Michigan) - under development

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  2013 improved result:
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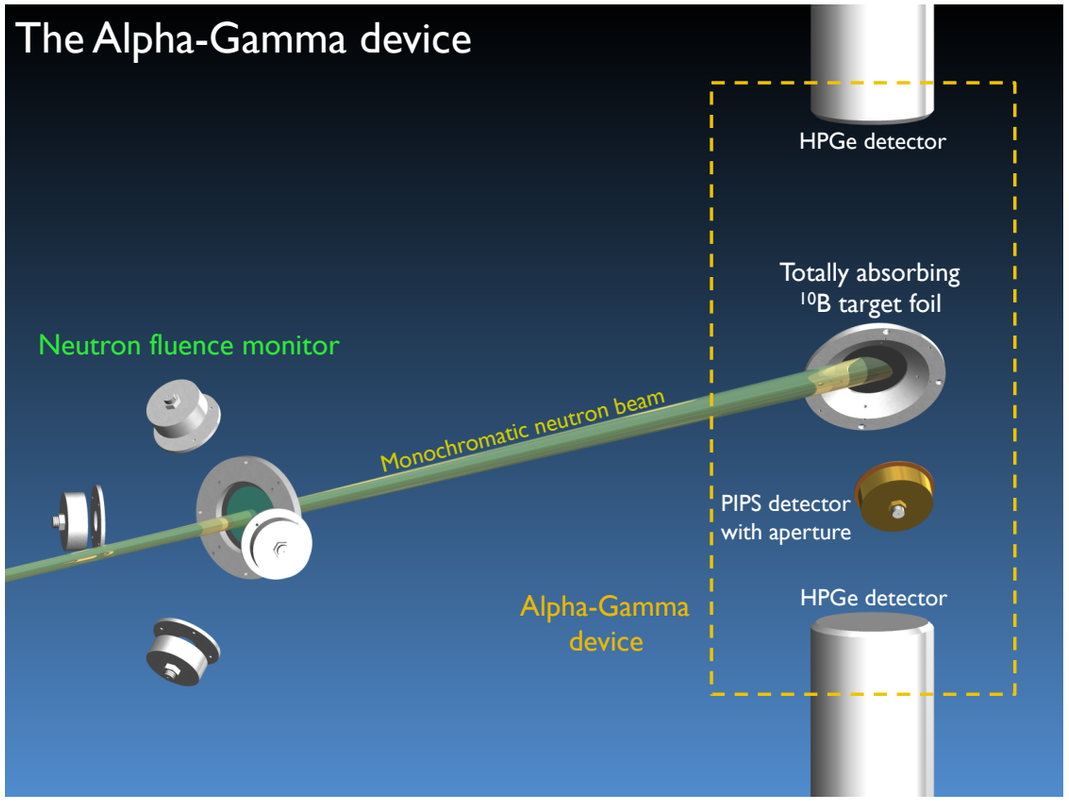

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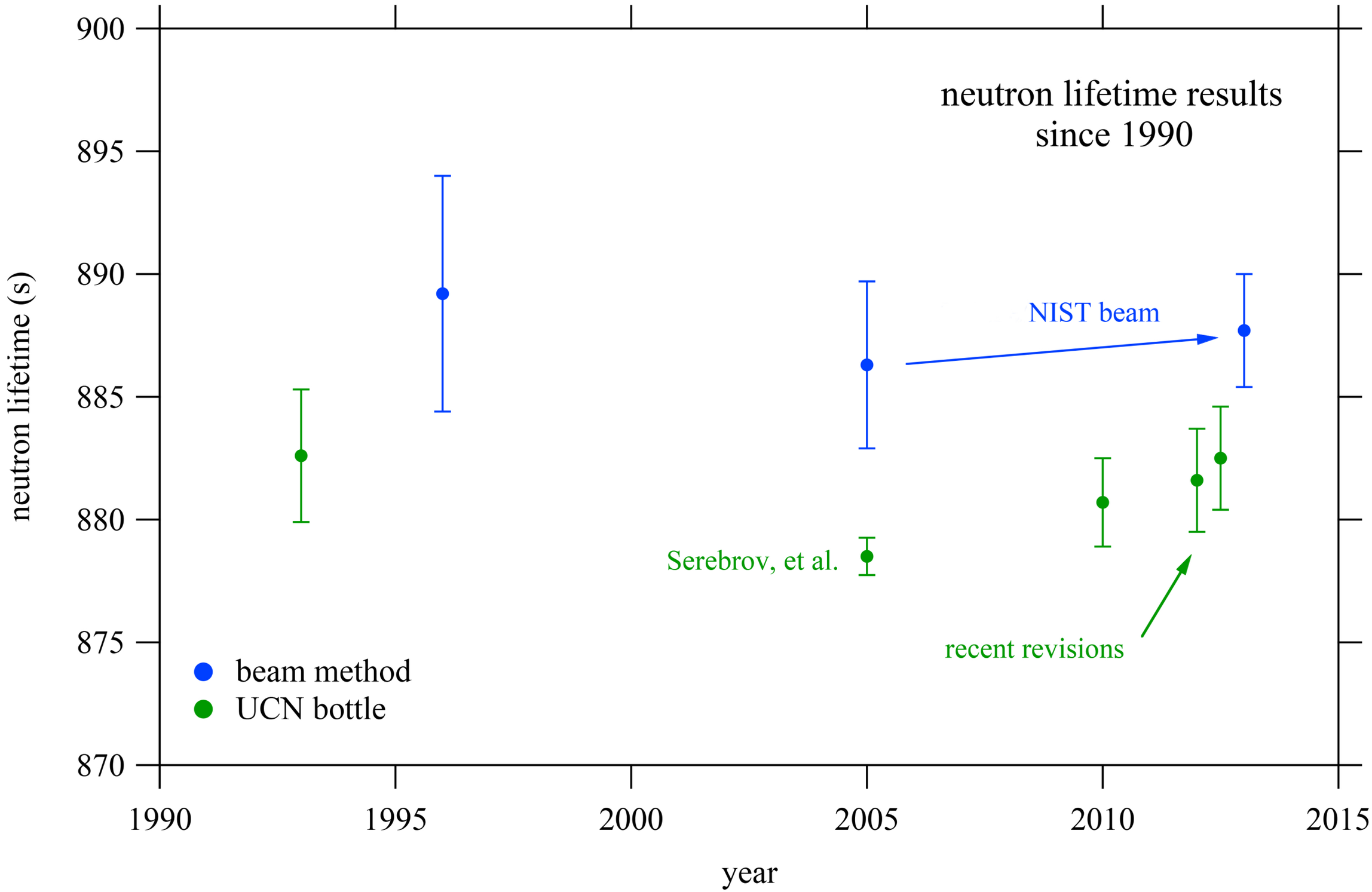
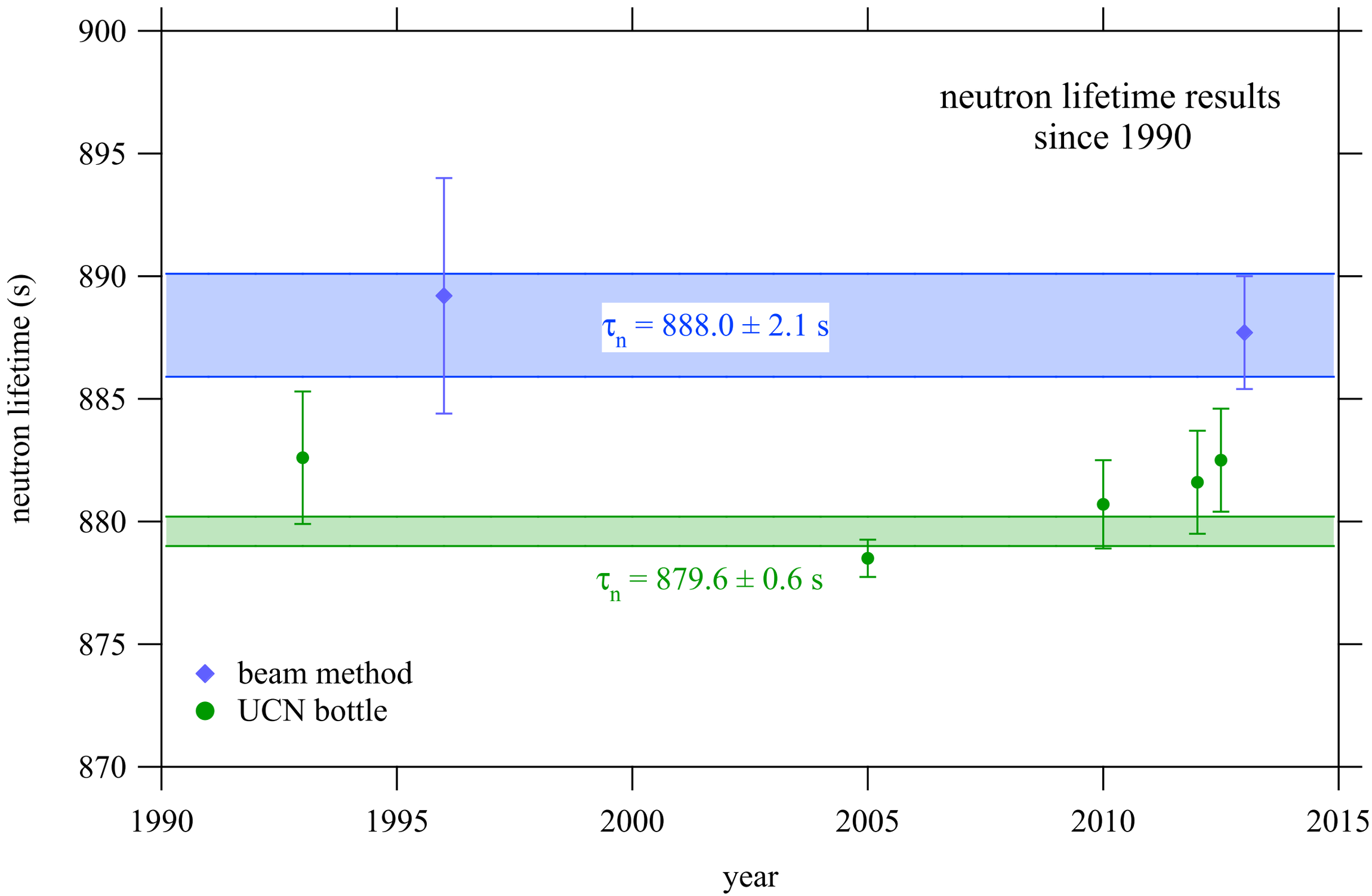

neutron lifetime results
since 1990
NIST beam
Serebrov, et al.
recent revisions
beam method
UCN bottle
neutron lifetime (s)
900
895
890
885
880
875
870
1990
1995
2000
2005
2010
2015
year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BEAM NEUTRON LIFETIME
THE NEXT GENERATION

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Proton Counting Statistics

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Want 200x increase in proton trapping rate

Bigger, longer trap and magnet, larger neutron beam

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	2005 NIST	BL3	factor
beam diameter	7 mm	35 mm	25
effective trap length	300 mm	600 mm	2
relative neutron flux*	1	4	4

Net: 200

*based on MCNP calculation using optimized collimation at NIST NG-C end position

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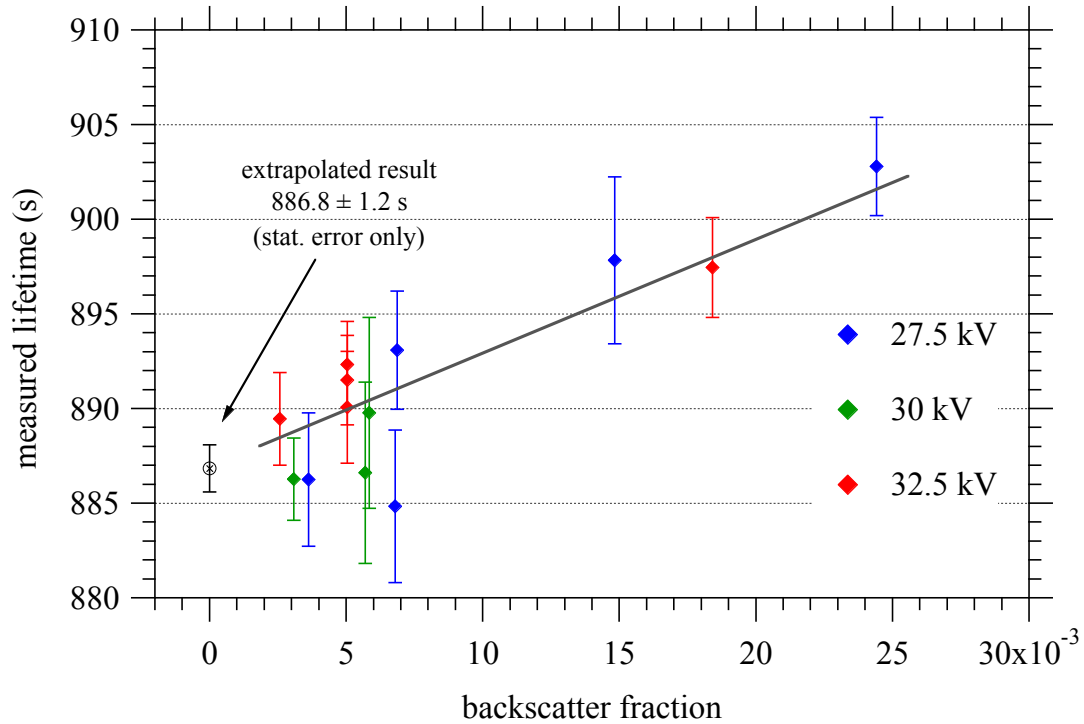
Proton Backscatter Extrapolation

Proton Backscatter Extrapolation

2005 NIST:



Proton Backscatter Extrapolation

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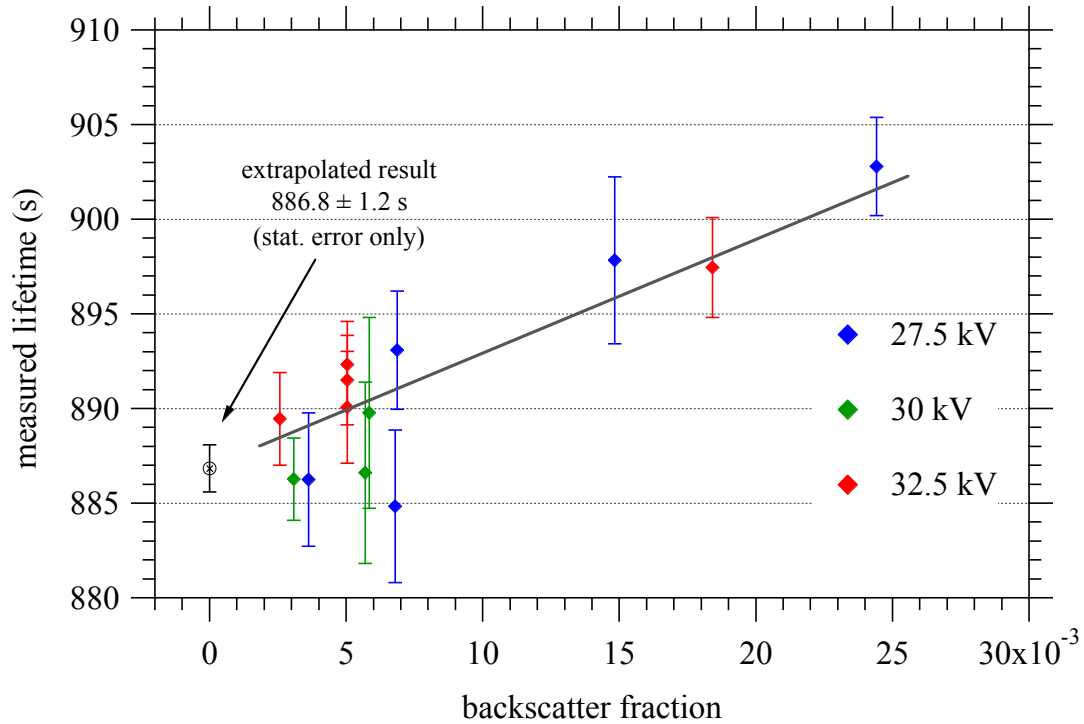


BL3:

Larger detector, variable field expansion eliminate this effect (Monte Carlo)

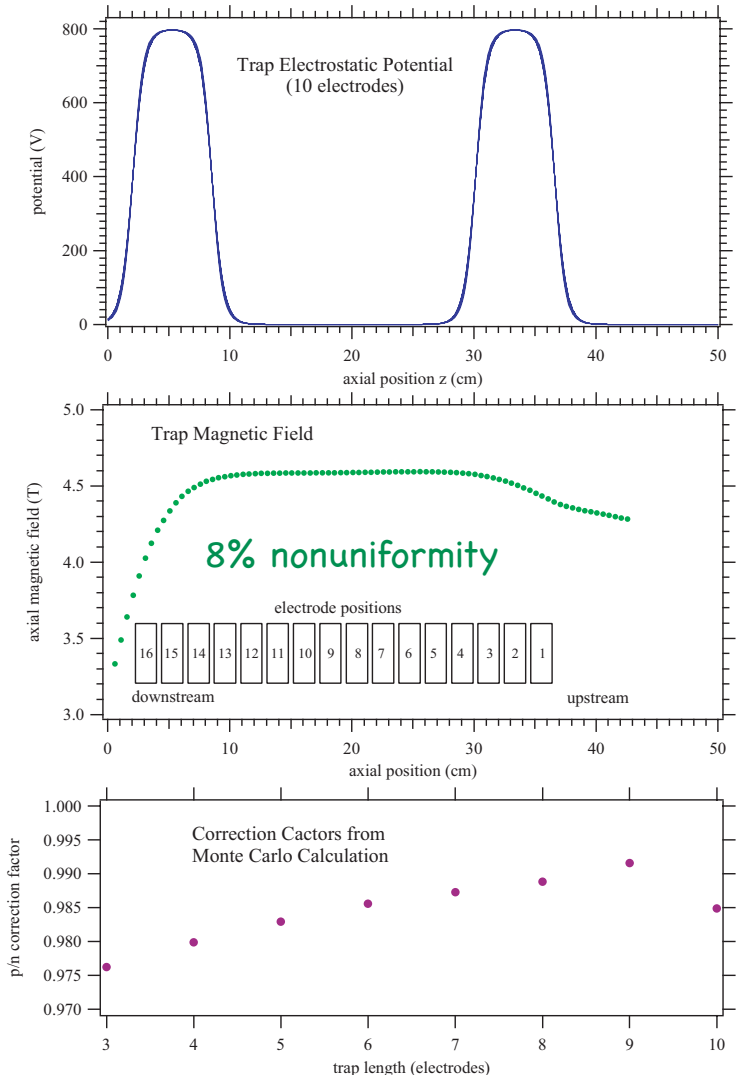
2005 Error Budget

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

Proton Trap Nonlinearity

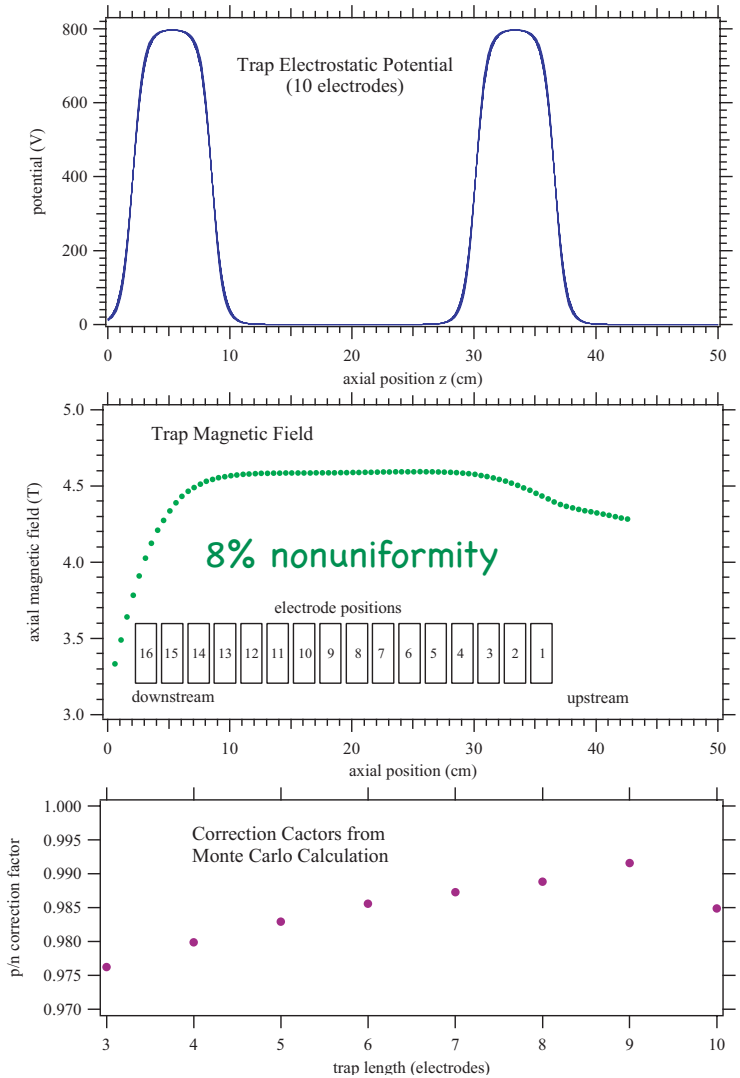
Proton Trap Nonlinearity

2005 NIST



Proton Trap Nonlinearity

2005 NIST

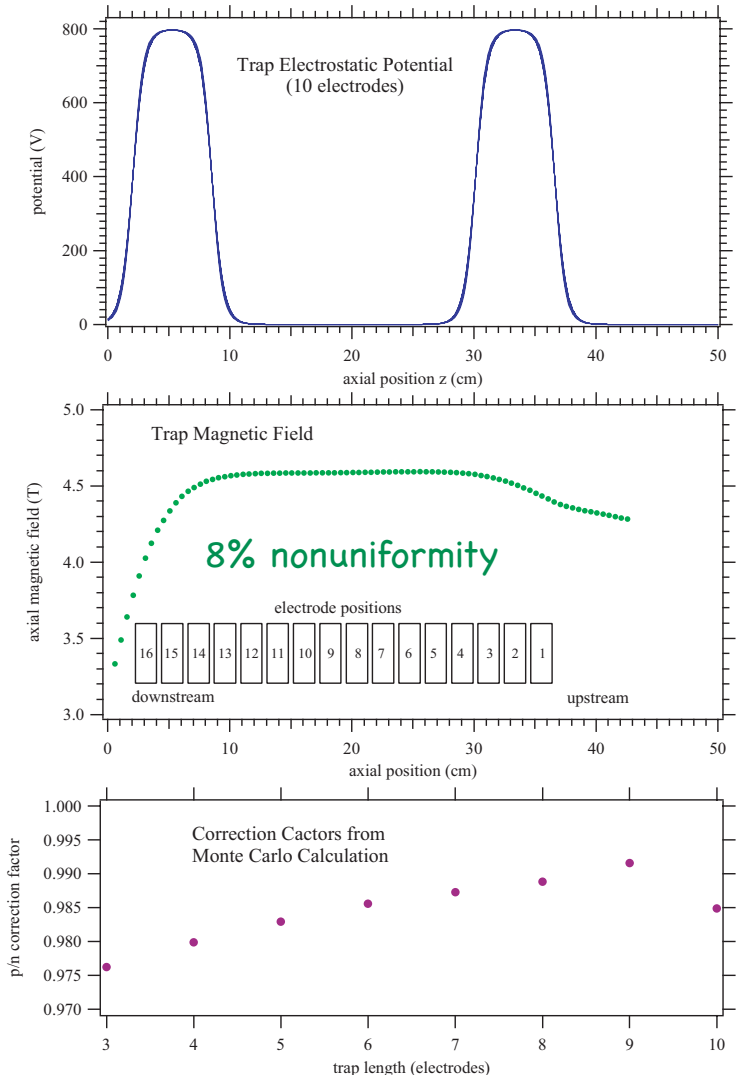


BL3

$\Delta B/B < .001$ over 60 cm proton trapping region

Proton Trap Nonlinearity

2005 NIST



BL3

$\Delta B/B < .001$ over 60 cm proton trapping region

Other contributions:

- trap metrology
- beam divergence

are small, < 0.1 s

2005 Error Budget

Source of correction	Correction (s)	Uncertainty (s)	
^{6}LiF deposit areal density		2.2	neutron counting
^{6}Li cross section		1.2	
Neutron detector solid angle		1.0	
Absorption of neutrons by ^{6}Li	+5.2	0.8	
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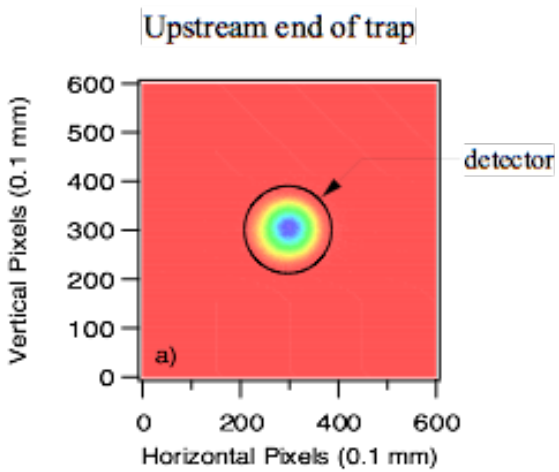
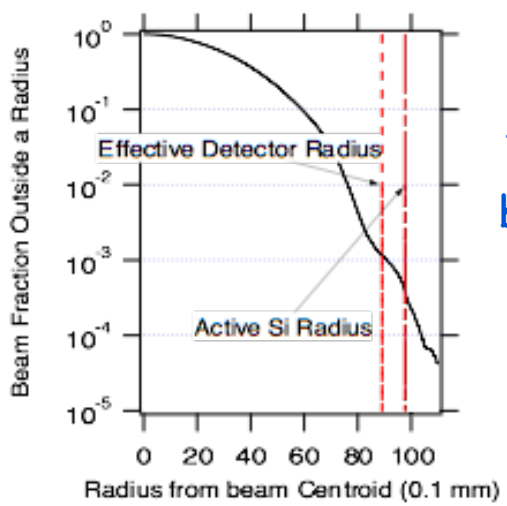
Total	−0.4	3.4	

Neutron Beam Halo

Neutron Beam Halo

2005 NIST

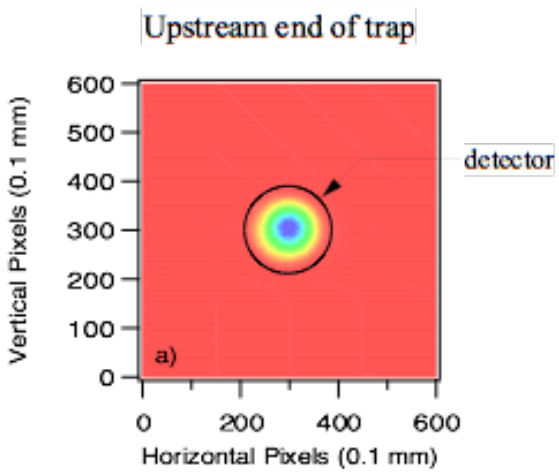


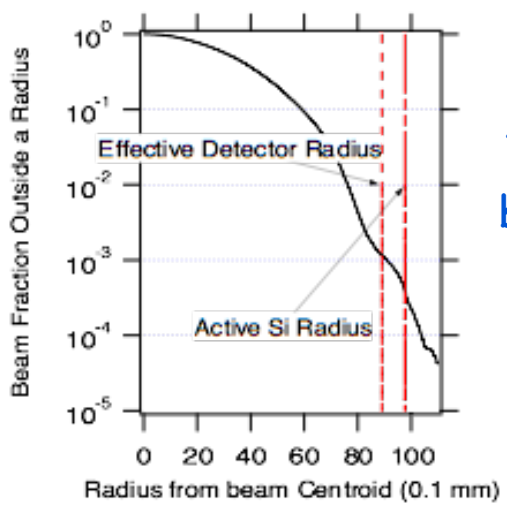


Due to neutron beam + readout hysteresis

Neutron Beam Halo

2005 NIST





Due to neutron beam + readout hysteresis

BL3

Recent studies: readout hysteresis >90% of effect

So with much larger (10 cm dia.) proton detector this will be negligible

2005 Error Budget

Source of correction	Correction (s)	Uncertainty (s)	
^{6}LiF deposit areal density	independent	2.2	
^{6}Li cross section	of neutron	1.2	
Neutron detector solid angle	spectrum	1.0	neutron counting
Absorption of neutrons by ^{6}Li	+5.2	0.8	
Neutron beam profile and detector solid angle	+1.3		
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Total	−0.4	3.4	

Absolute Neutron Fluence Measurement

Absolute Neutron Fluence Measurement

Alpha-Gamma Method:

2013 result error budget

Source of uncertainty	Fractional uncertainty
Neutron counting statistics	3.1×10^{-4}
α-source calibration of AG α-detector	2.7×10^{-4}
γ attenuation in B_4C target	2.5×10^{-4}
Neutron beam wavelength	2.4×10^{-4}
γ attenuation in thin ^{10}B target	1.3×10^{-4}
$\frac{\lambda_{\mathrm{mono}}}{2}$ contamination of beam	1.0×10^{-4}
Neutron backscatter in monitor substrate	3.9×10^{-5}
AG α solid angle for beam spot	2.7×10^{-5}
Detector dead time	2.4×10^{-5}
Neutron loss in Si substrate	1.8×10^{-5}
Neutron absorption by ^{6}Li	1.2×10^{-5}
Self-shielding of ^{6}Li deposit	6.0×10^{-6}
Neutron monitor solid angle for beam spot	4.5×10^{-6}
γ production in thin ^{10}B target Si subtrate	3.2×10^{-6}
Monitor misalignment w.r.t. beam	2.0×10^{-6}
Neutron scattering from B_4C	3.3×10^{-7}
Total	5.7×10^{-4}

counting statistics

reduced using new geometry

can be done better

<0.01% achieved previously at NIST

Absolute Neutron Fluence Measurement

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Total	5.7×10^{-4}

counting statistics

reduced using new geometry

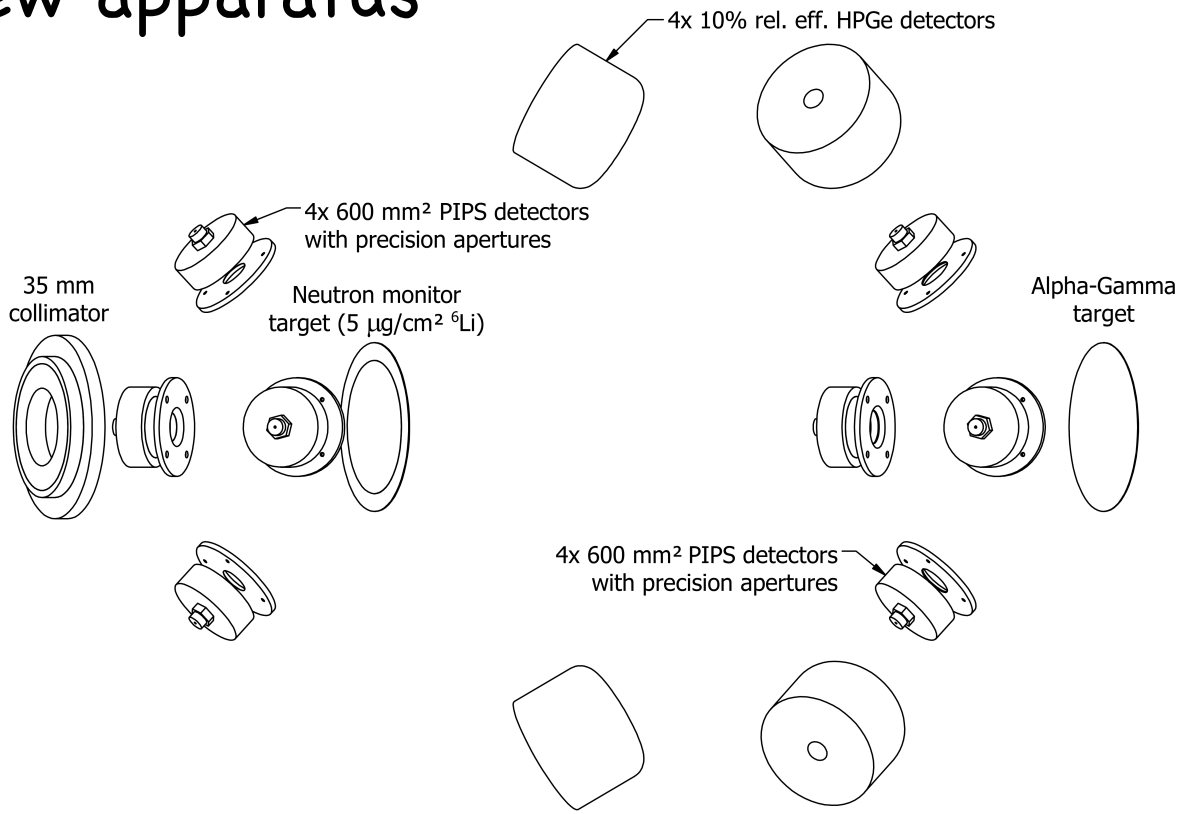
can be done better
<0.01% achieved previously at NIST

need a factor of 6
better for BL3

Absolute Neutron Fluence Measurement

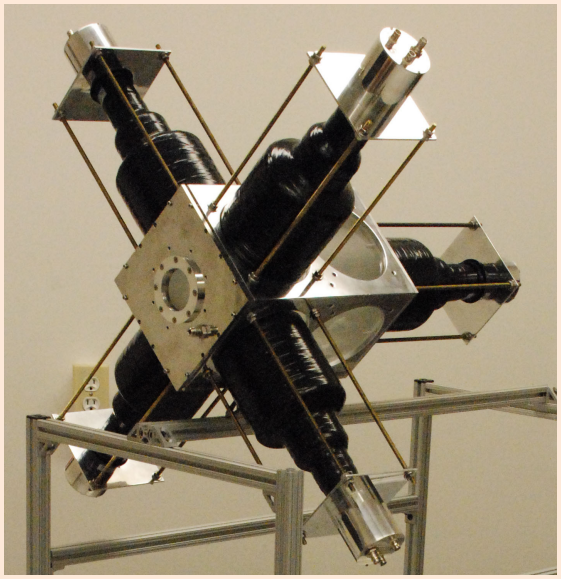
Alpha-Gamma Method:

new apparatus

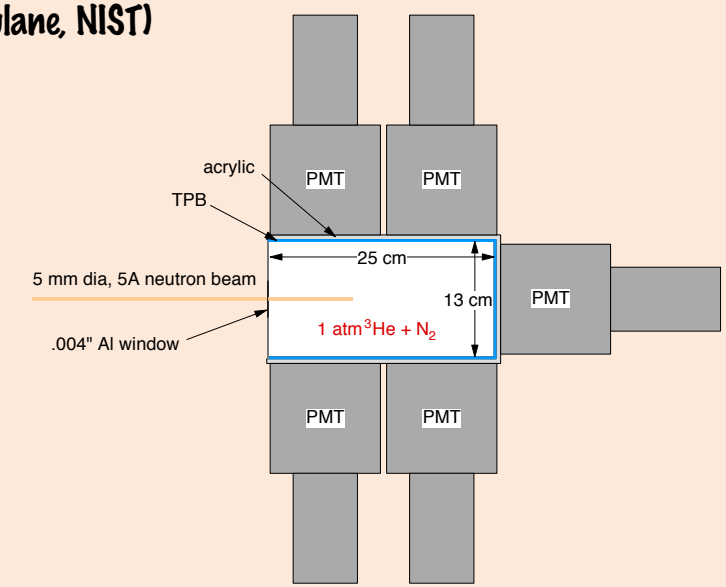


Absolute Neutron Fluence Measurement

A ^{3}He gas scintillation absolute neutron counter



(Tulane, NIST)



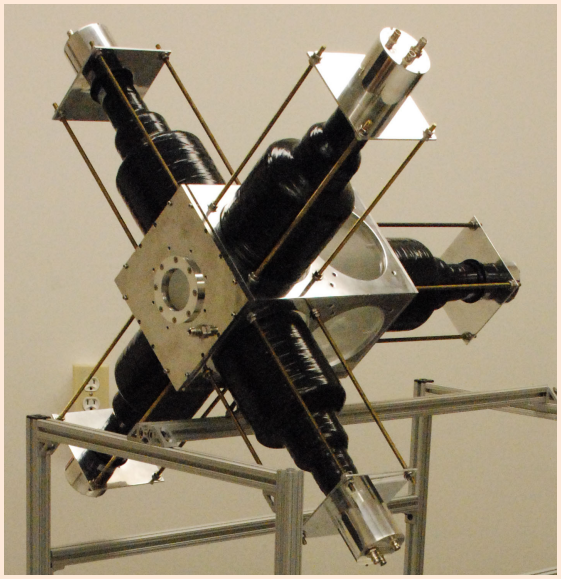
Design features:

- absolute neutron counting to 99.95%
- >50 kHz pulse counting rate
- >30 photoelectrons/neutron capture
- ^{3}He gas scintillates in XUV (70-90 nm)
- XUV downshifted to visible by TPB
- 1-10 torr N_2 quenches long-lived triplet dimers

construction / testing now in progress

Absolute Neutron Fluence Measurement

A ^{3}He gas scintillation absolute neutron counter



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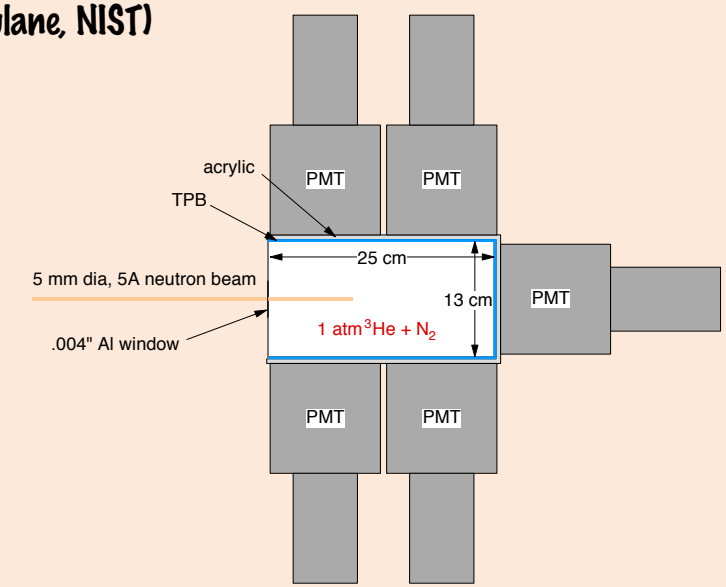

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- XUV downshifted to visible by TPB
- 1-10 torr N_2 quenches long-lived triplet dimers

construction / testing now in progress

current goal is < 0.05% precision

2005 Error 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
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Neutron counting dead time	+0.1	
Proton counting statistics		1.2
Neutron counting statistics		
Total	−0.4	3.4

neutron counting

depend on neutron spectrum

proton counting

Need a precise measurement of the in situ neutron velocity spectrum

Need a precise measurement of the in situ neutron velocity spectrum

Dedicated time-of-flight spectrometer

2005 Error Budget

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	
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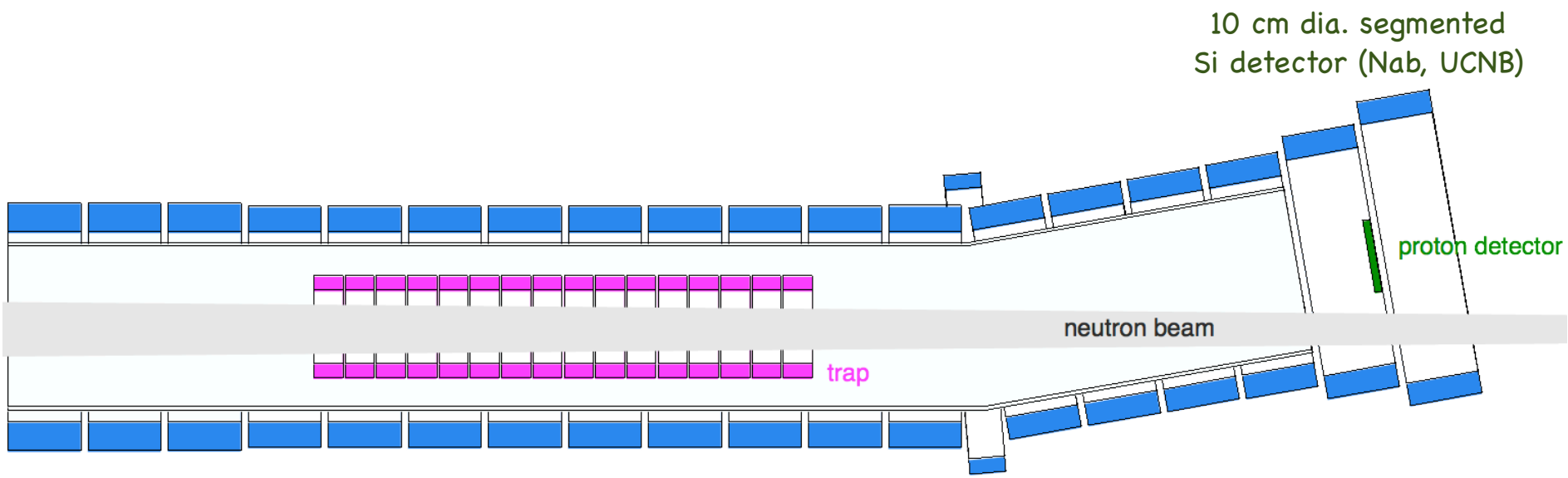
Trap nonlinearity	−5.3	0.8	
Proton backscatter calculation		0.4	
Neutron counting dead time	+0.1	0.1	
Proton counting statistics		1.2	
Neutron counting statistics		0.1	
Total	−0.4	3.4	

BL3

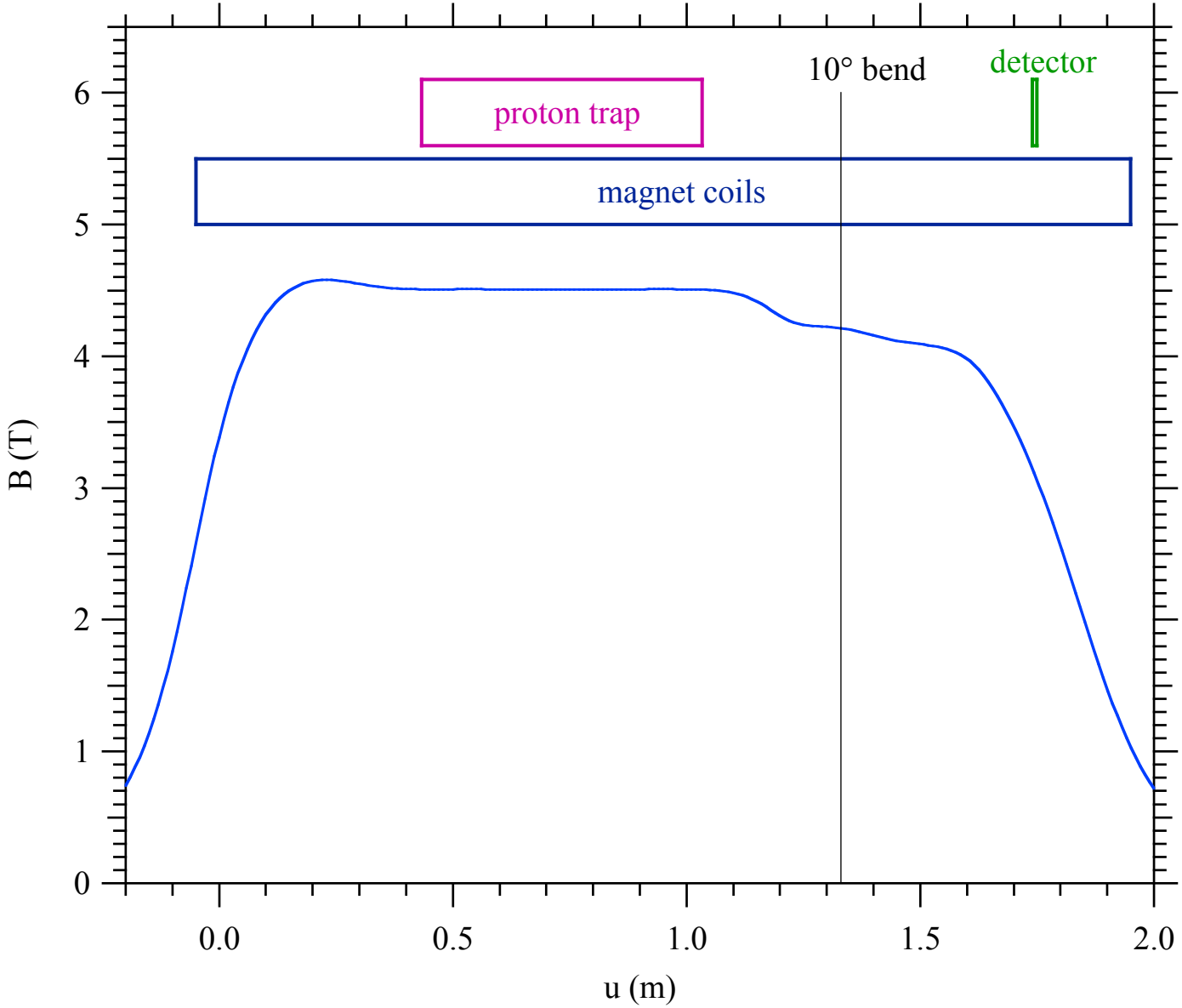
A Next Generation Beam Neutron Lifetime Experiment

Goals:

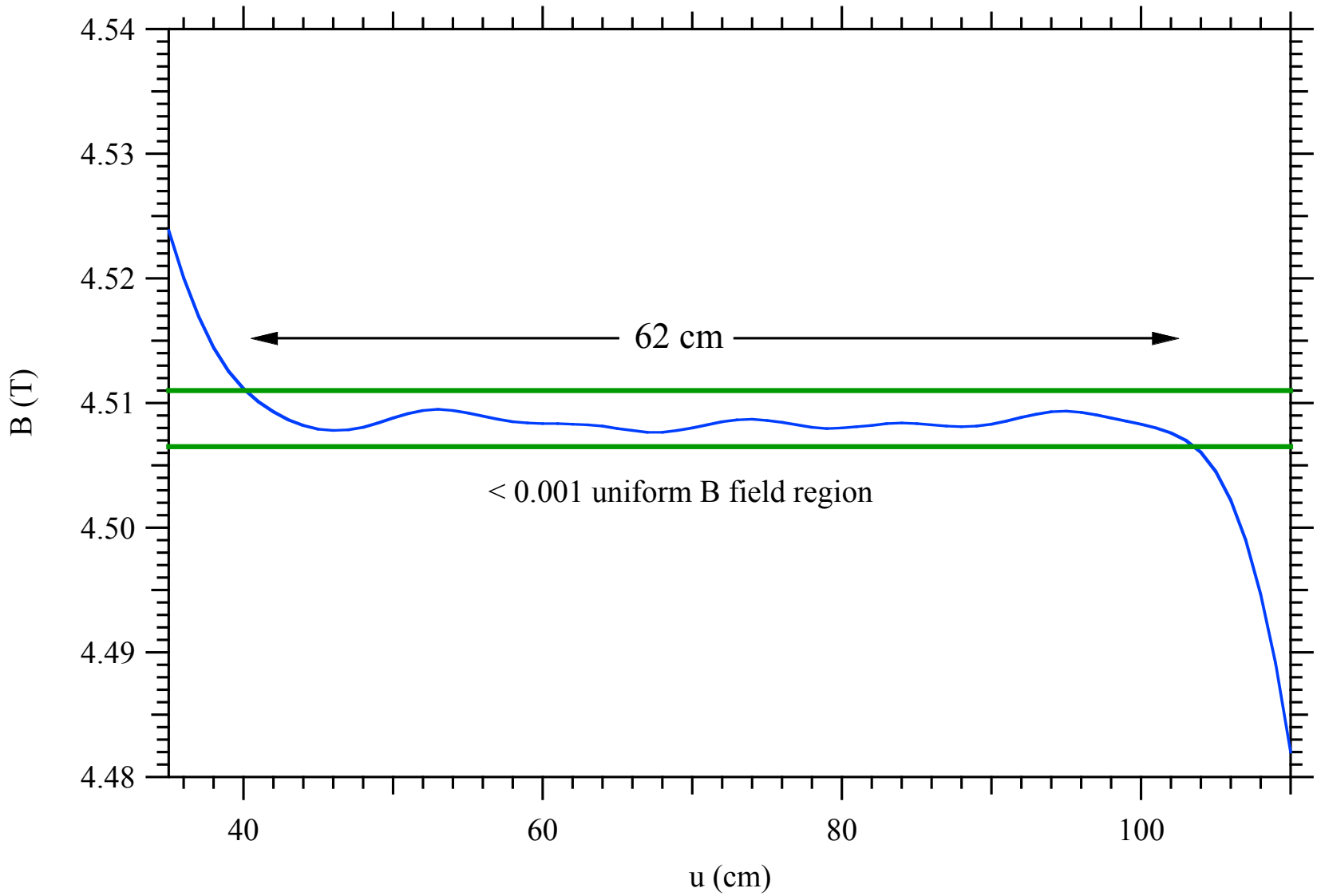
1) Control and reduce all systematics at the <0.1 s level
2) Reduce the beam neutron lifetime uncertainty to < 0.2 s



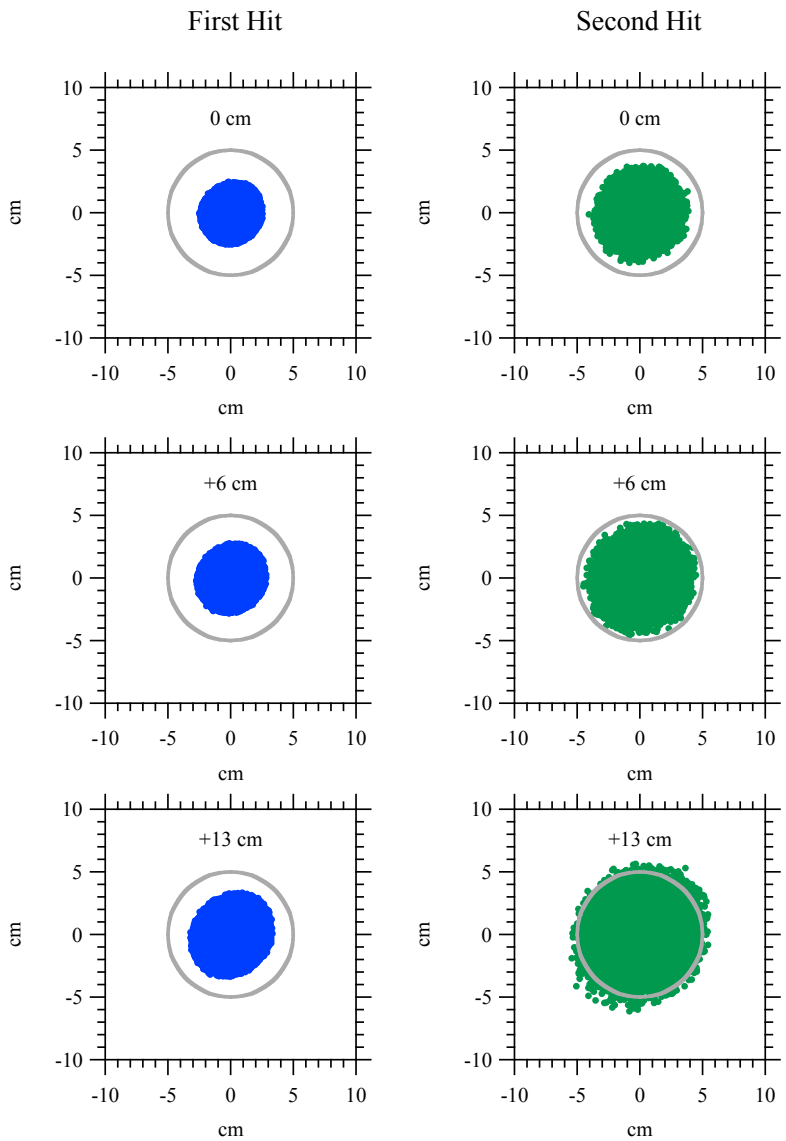
BL3

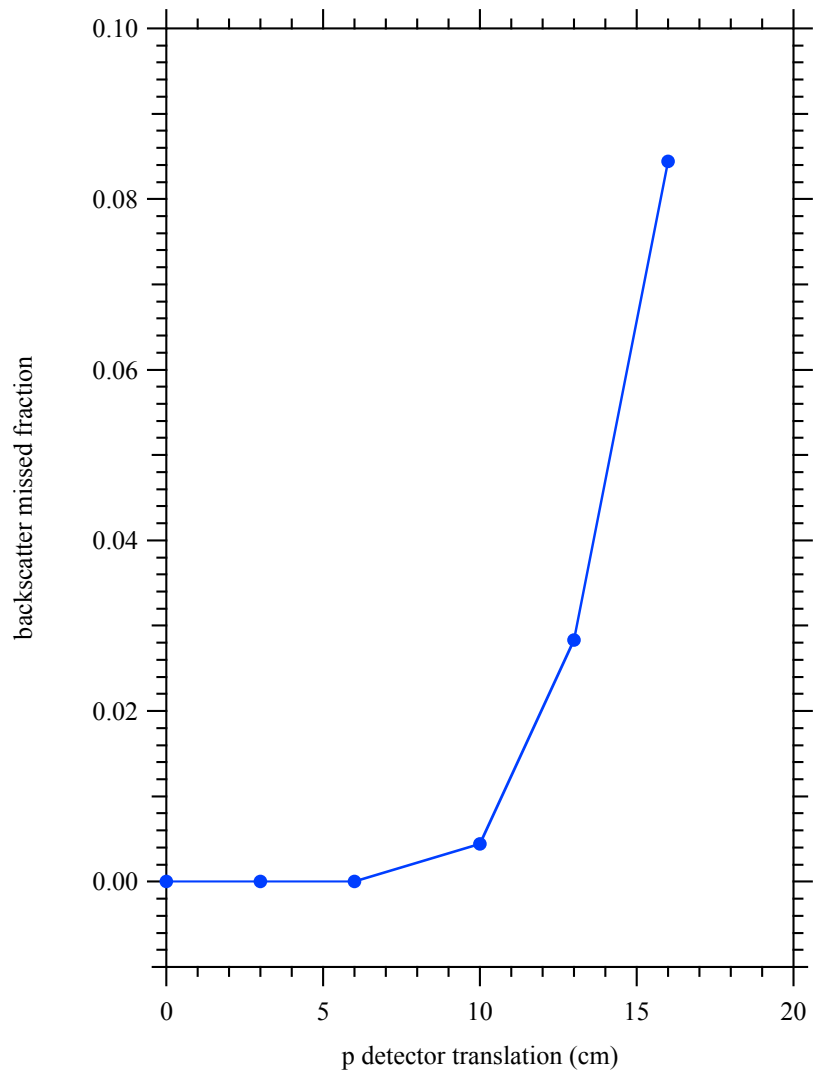

10° bend
detector
proton trap
magnet coils
B (T)
u (m)
0
1
2
3
4
5
6
0.0
0.5
1.0
1.5
2.0

BL3


4.54
4.53
4.52
4.51
4.50
4.49
4.48
B (T)
62 cm
< 0.001 uniform B field region
40
60
80
100
u (cm)

Proton Backscatter





BL3 Systematic Improvements

Proton Counting:

- larger detector area (30x)
- pixellated detector
- variable field expansion by detector translation (backscatter correction)
- <0.01% magnetic field uniformity in trap region
- trim coils to test variations in field uniformity

Neutron Counting:

- precision neutron spectral flux measurement
- improved alpha-gamma geometry
- multiple independent absolute flux calibrations

Summary

- >30 years experience with the Sussex-ILL-NIST beam neutron lifetime program.

- With a larger beam, magnet, and trap of design similar to the existing apparatus, proton counting statistics can achieve < 0.1 s uncertainty

- With achievable technical improvements (no high-risk R&D), known systematic effects can be reduced to < 0.1 s.

- As before, neutron counting systematics are the most challenging part.

- Estimated capital cost is approx. $2M (DOE + NSF)

- Timetable: 2015: proposal
  2016-2017: funding
  2017-2020: design/construction
  2020+ commissioning at NIST.