aCORN

A Precision Measurement of the Electron-Antineutrino Correlation "*a*" in Neutron Beta Decay

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Neutron Decay Parameters

Phenomenological (J = 1/2 → J = 1/2) beta decay formula [Jackson, Treiman, Wyld, 1957] :

$$dW \propto \frac{1}{\tau} F(E_e)\left[1 + \boxed{a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu}} + b\frac{m_e}{E_e} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + D\frac{\vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)}{E_e E_\nu}\right]$$

For allowed beta decay, neglecting recoil order terms, the standard electroweak model (Weinberg, Glashow, Salam, et al.) predicts:

$$\boxed{a = \frac{1-\lambda^2}{1+3\lambda^2}} \qquad b = 0 \qquad A = -2\frac{\lambda^2 + \mathrm{Re}(\lambda)}{1+3\lambda^2} \qquad B = 2\frac{\lambda^2 - \mathrm{Re}(\lambda)}{1+3\lambda^2}$$

$$D = 2\frac{\mathrm{Im}(\lambda)}{1+3\lambda^2} \approx 0 \qquad \tau \propto \frac{1}{g_\nu^2 + 3g_A^2}$$

where $\lambda \equiv \frac{g_A}{g_V}$

aCORN Collaboration

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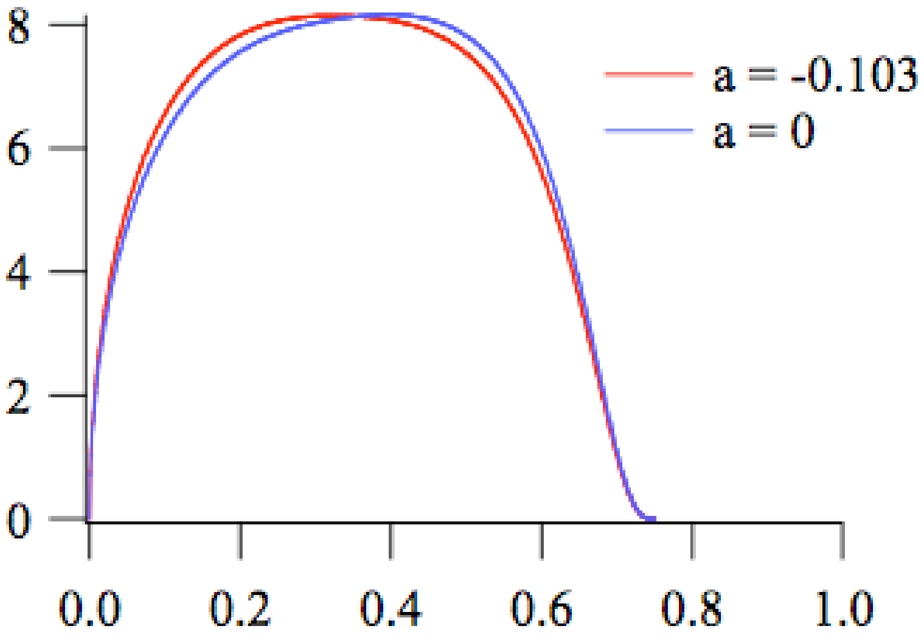
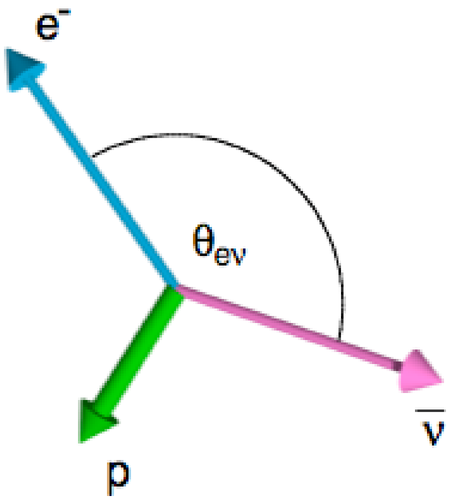
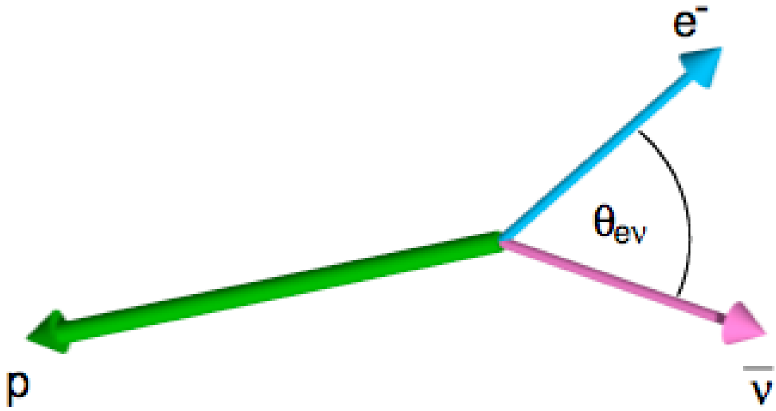
Standard method for measuring the e-ν correlation:

recoil energy spectrum

statistically most advantageous

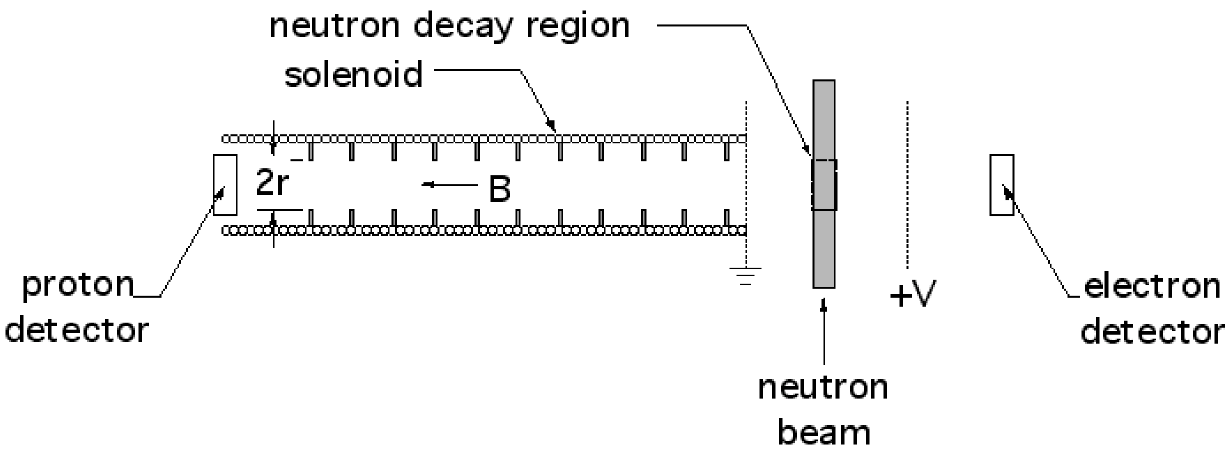


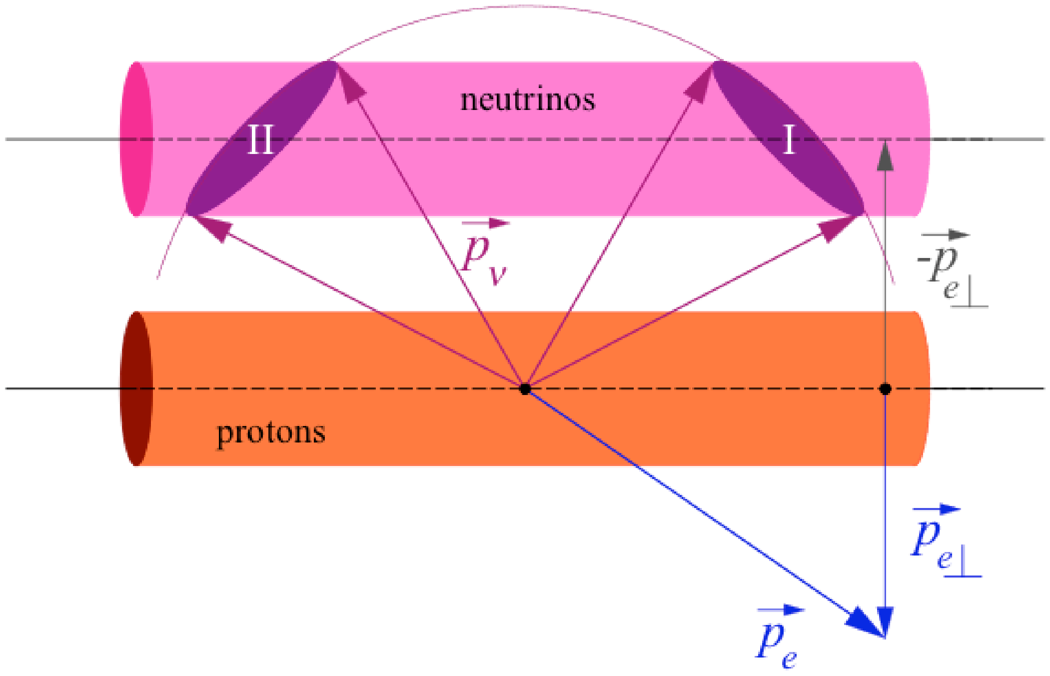




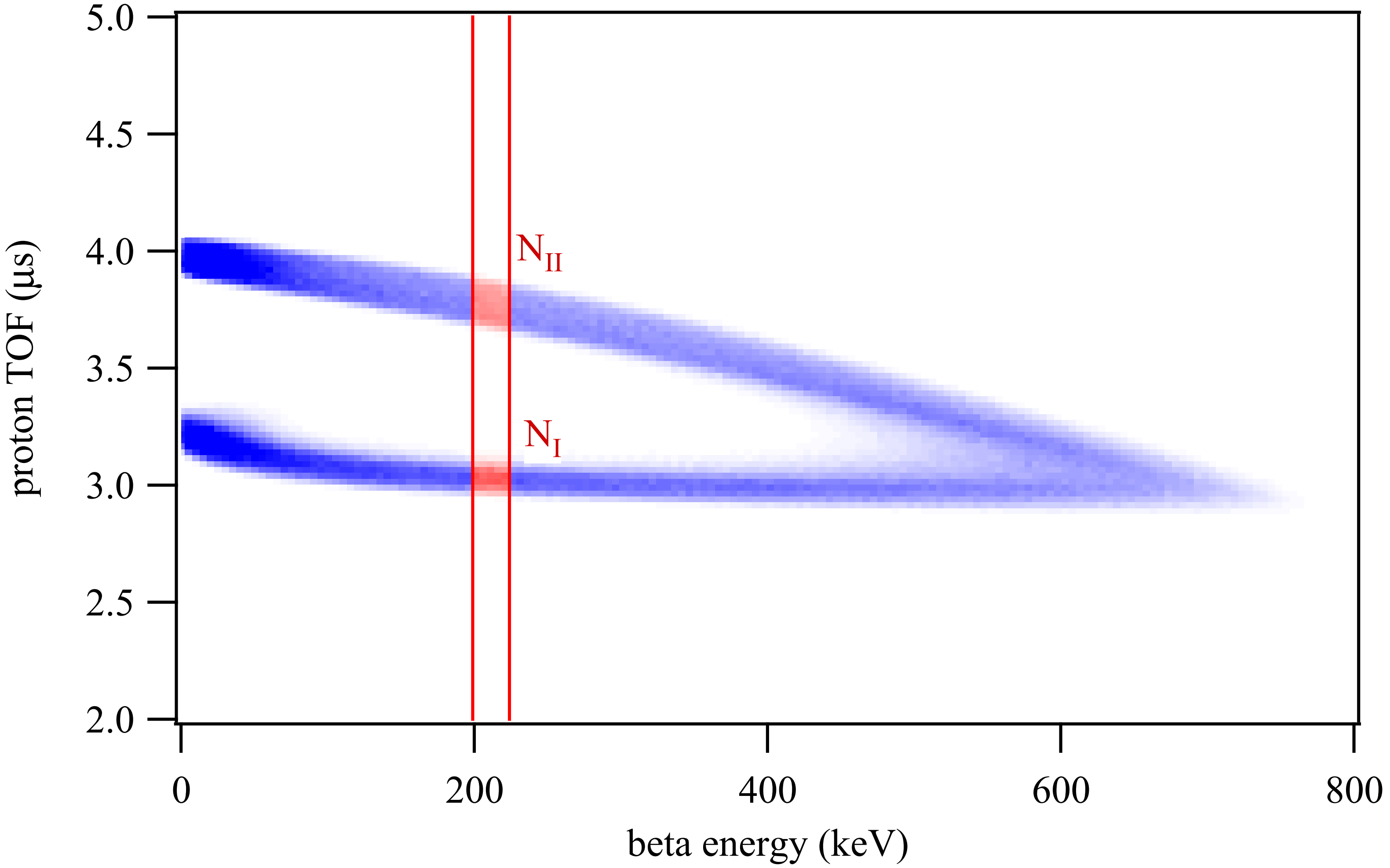
A Novel Method to Measure *a*

(Yerozolimsky and Mostovoy, 1996)





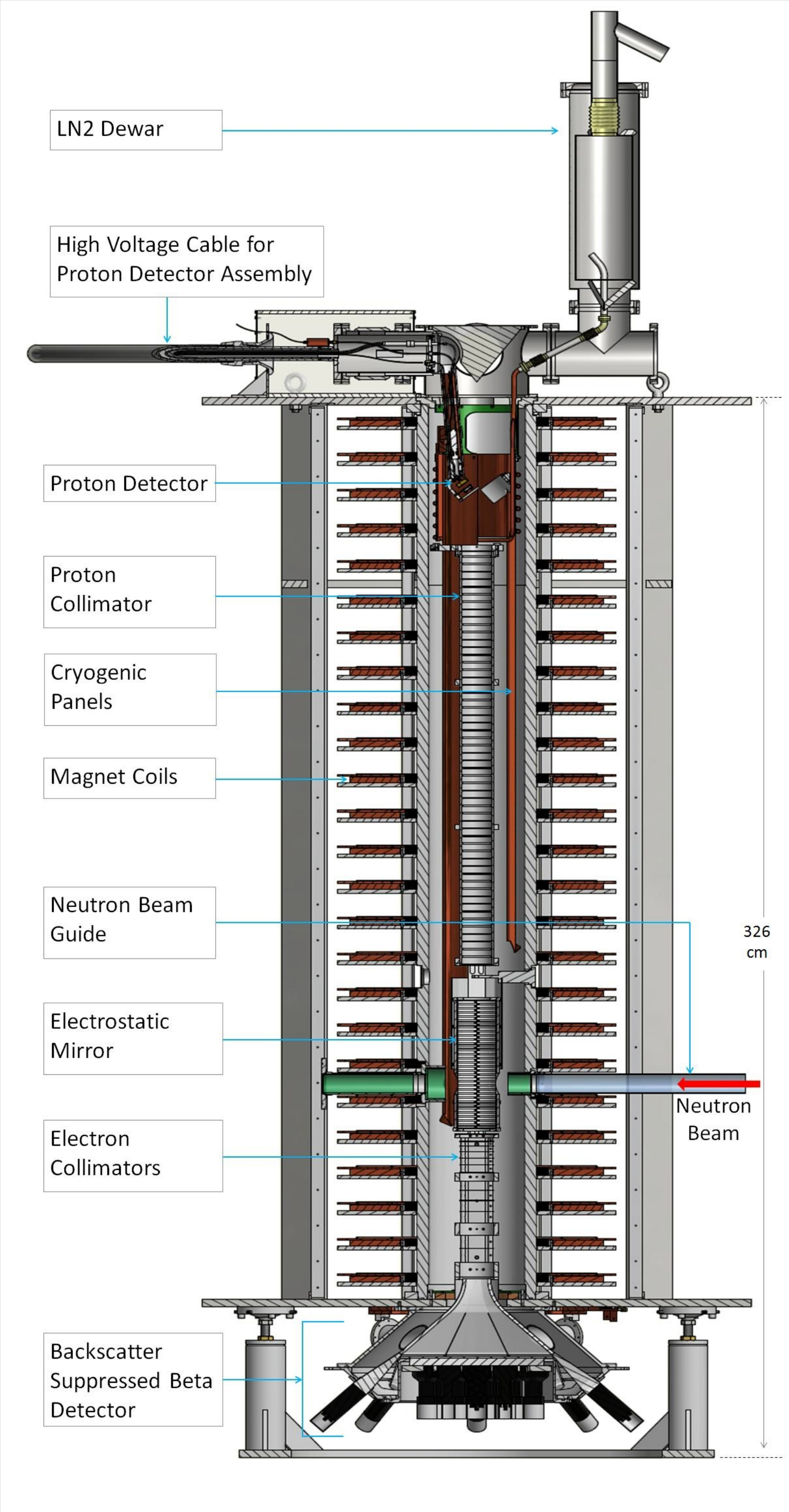
We separate groups I and II by beta energy and proton time-of-flight (TOF)



$$X(E) = \frac{N_I - N_{II}}{N_I - N_{II}} = a\, f_a(E)$$

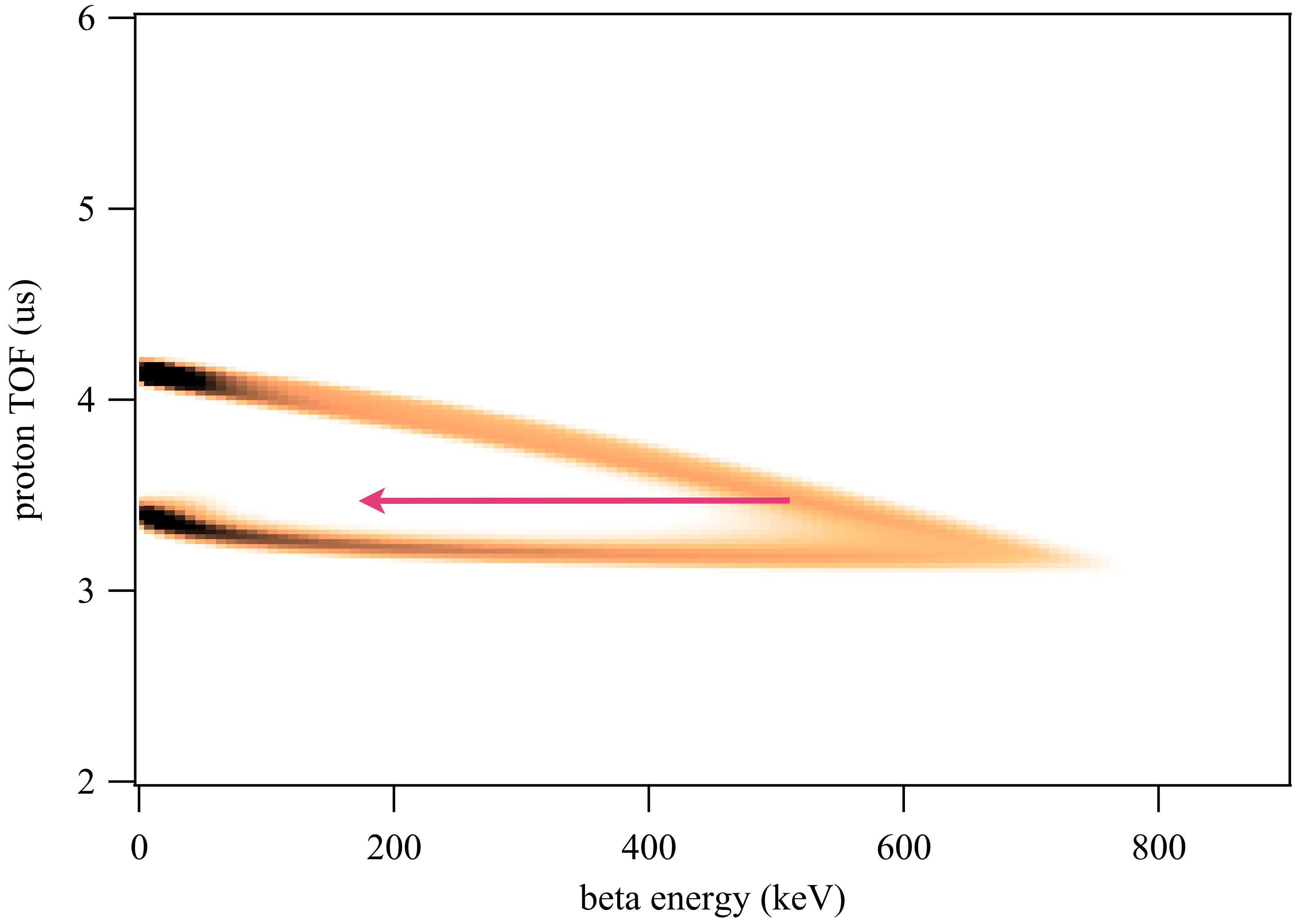
wishbone
asymmetry

geometric
function


LN2 Dewar
High Voltage Cable for Proton Detector Assembly
Proton Detector
Proton Collimator
Cryogenic Panels
Magnet Coils
Neutron Beam Guide
Electrostatic Mirror
Electron Collimators
Backscatter Suppressed Beta Detector
326 cm
Neutron Beam

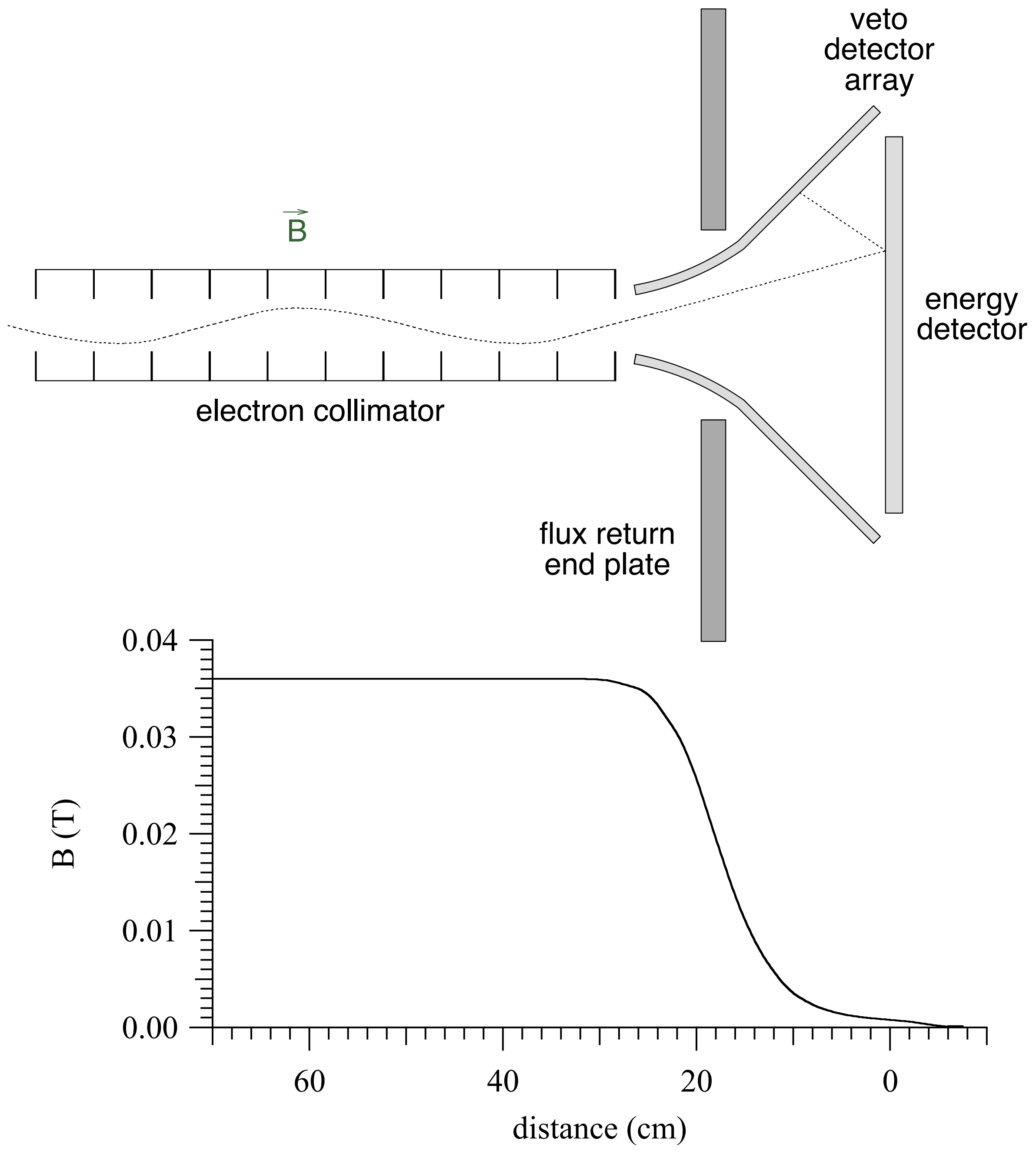
aCORN

Electron backscatter

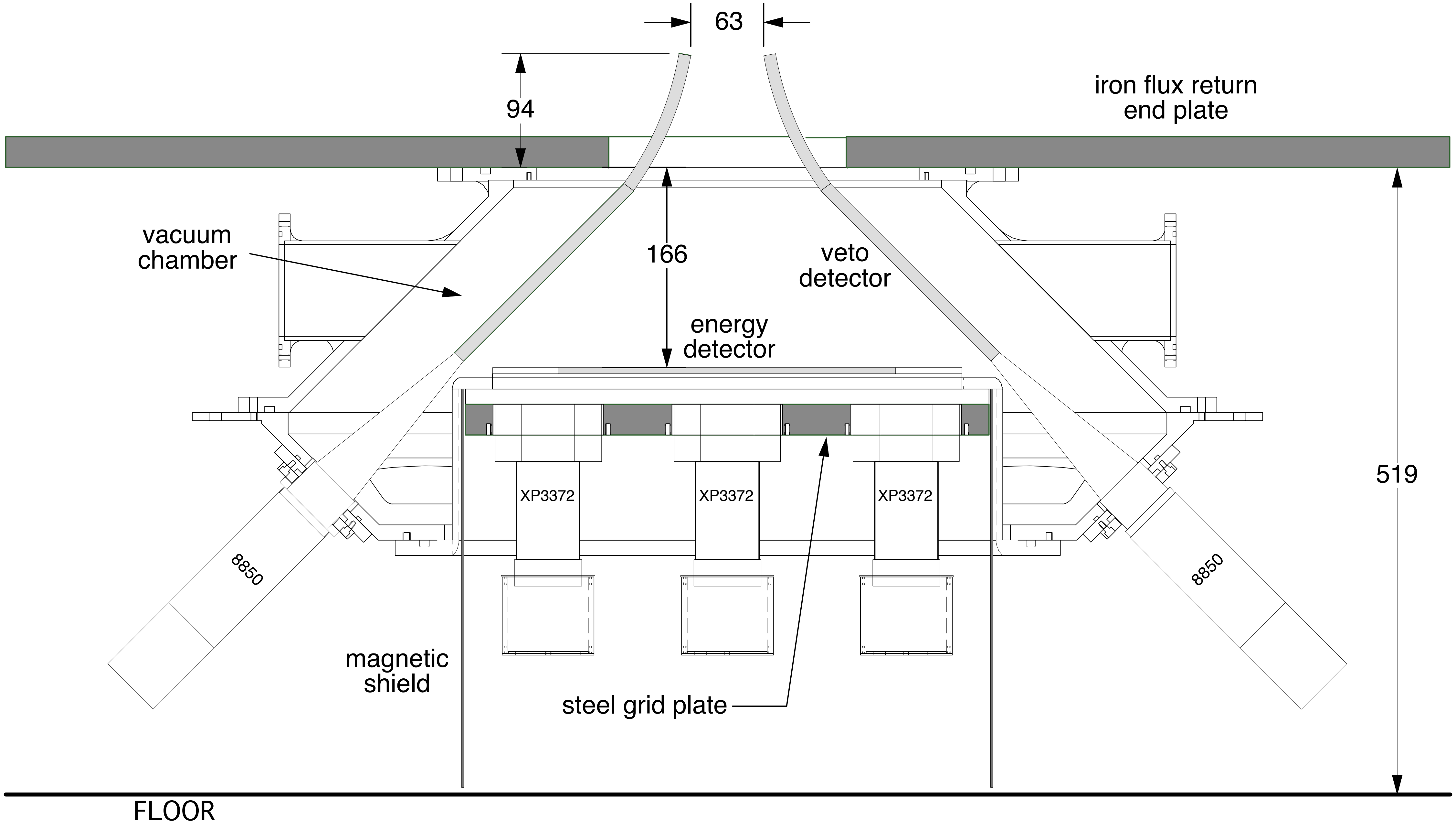


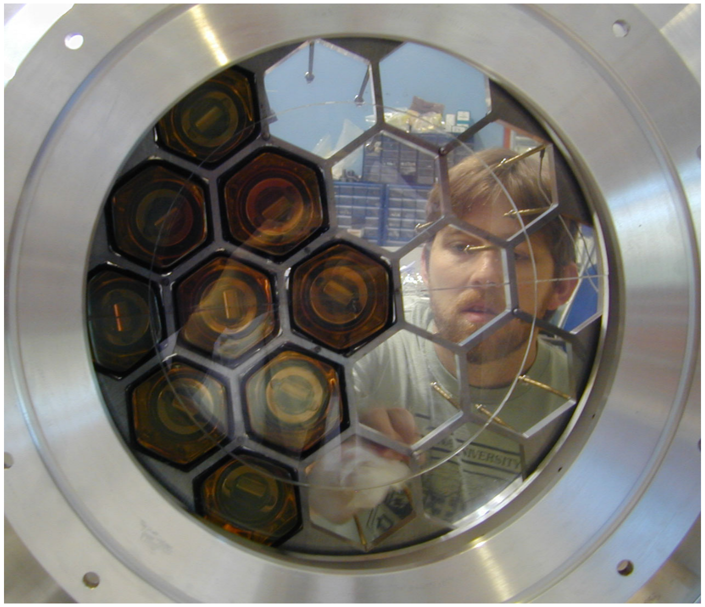
Electron backscatter will cause electrons to appear at a lower, incorrect energy, filling in the gap between the branches.

Backscatter Suppressed Beta Spectrometer

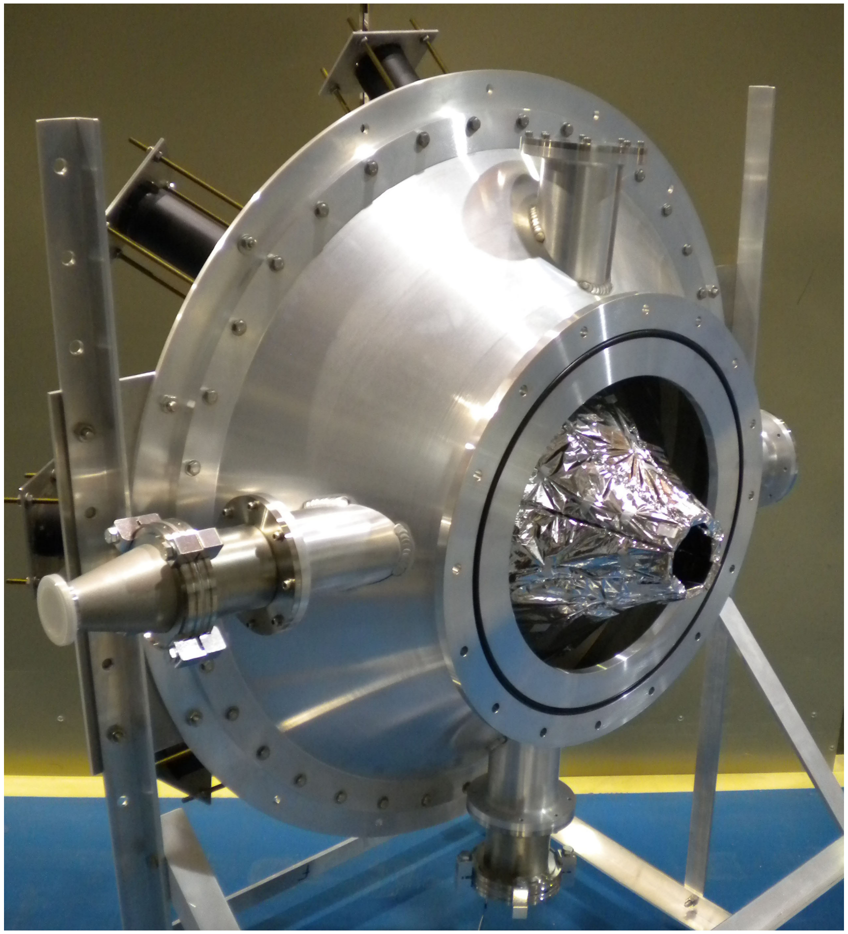


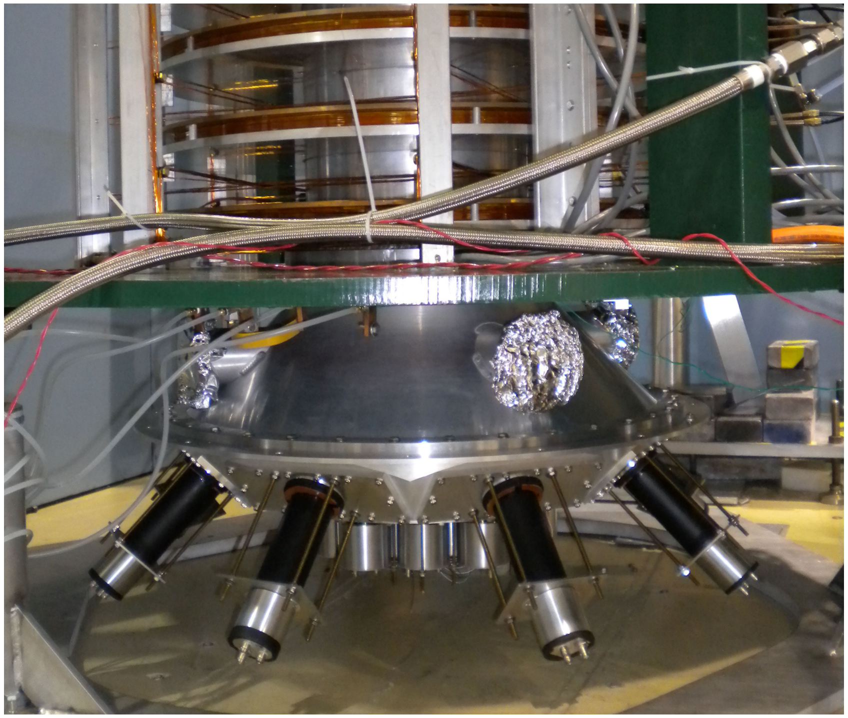
aCORN backscatter suppressed beta spectrometer

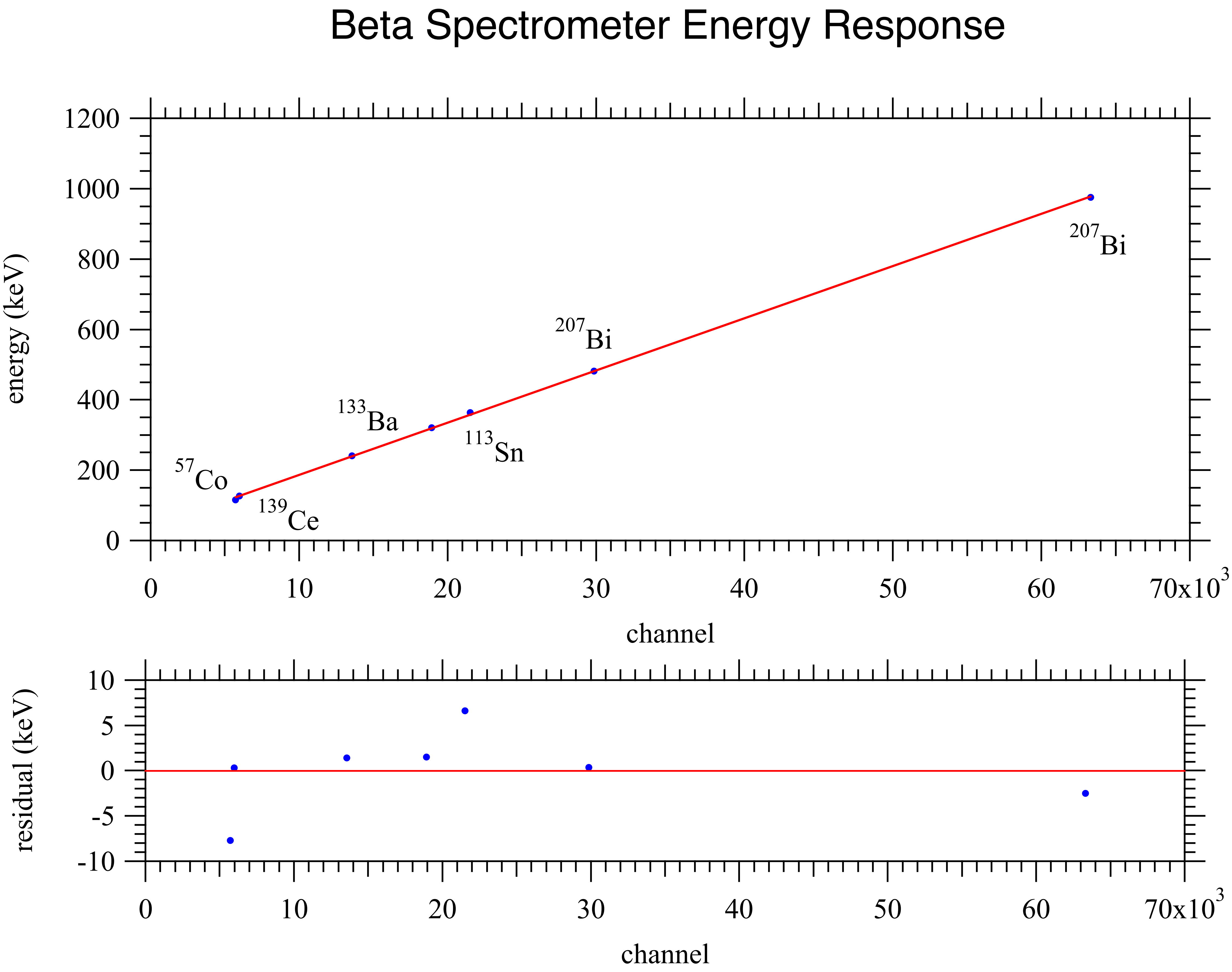


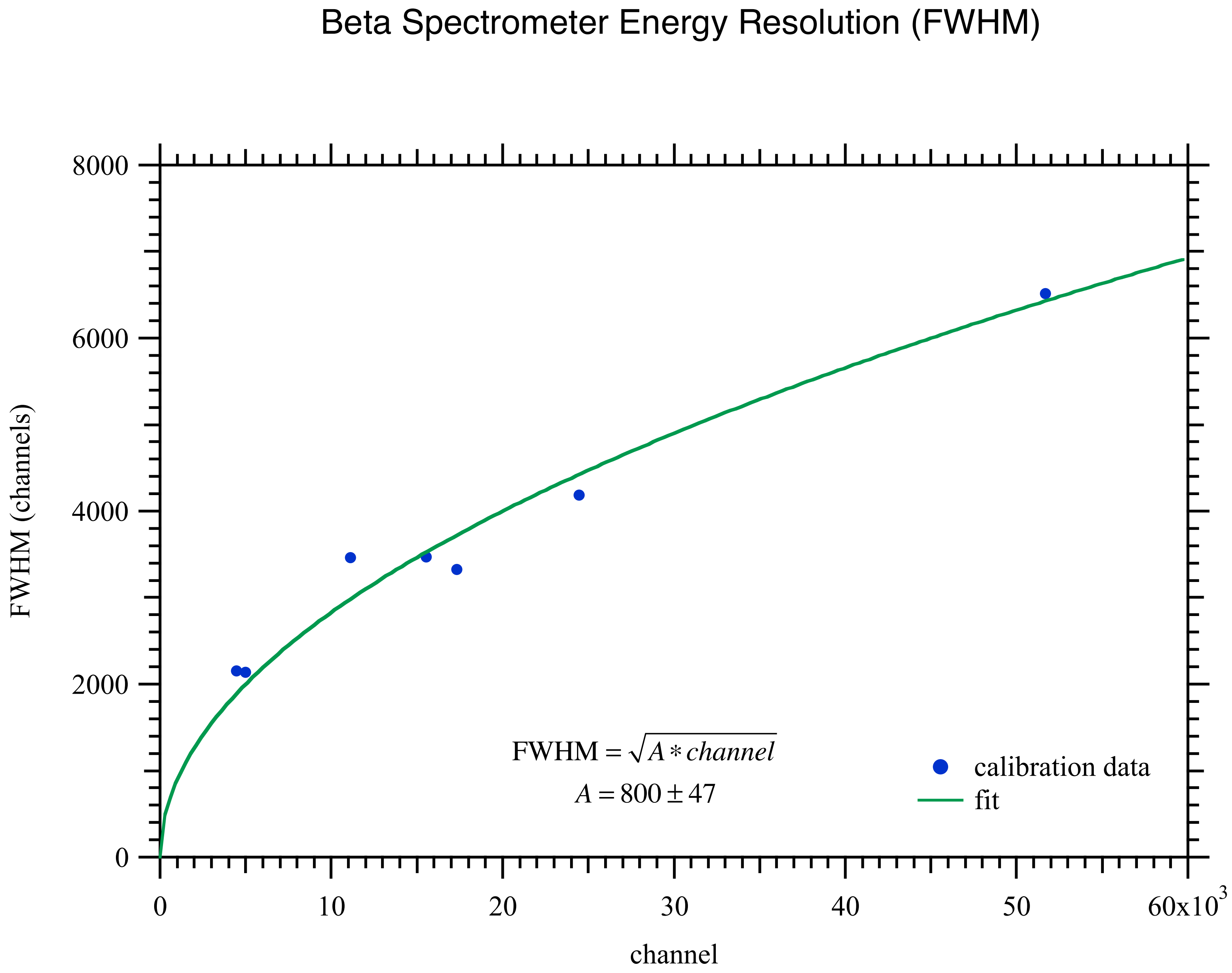


aCORN Beta Spectrometer

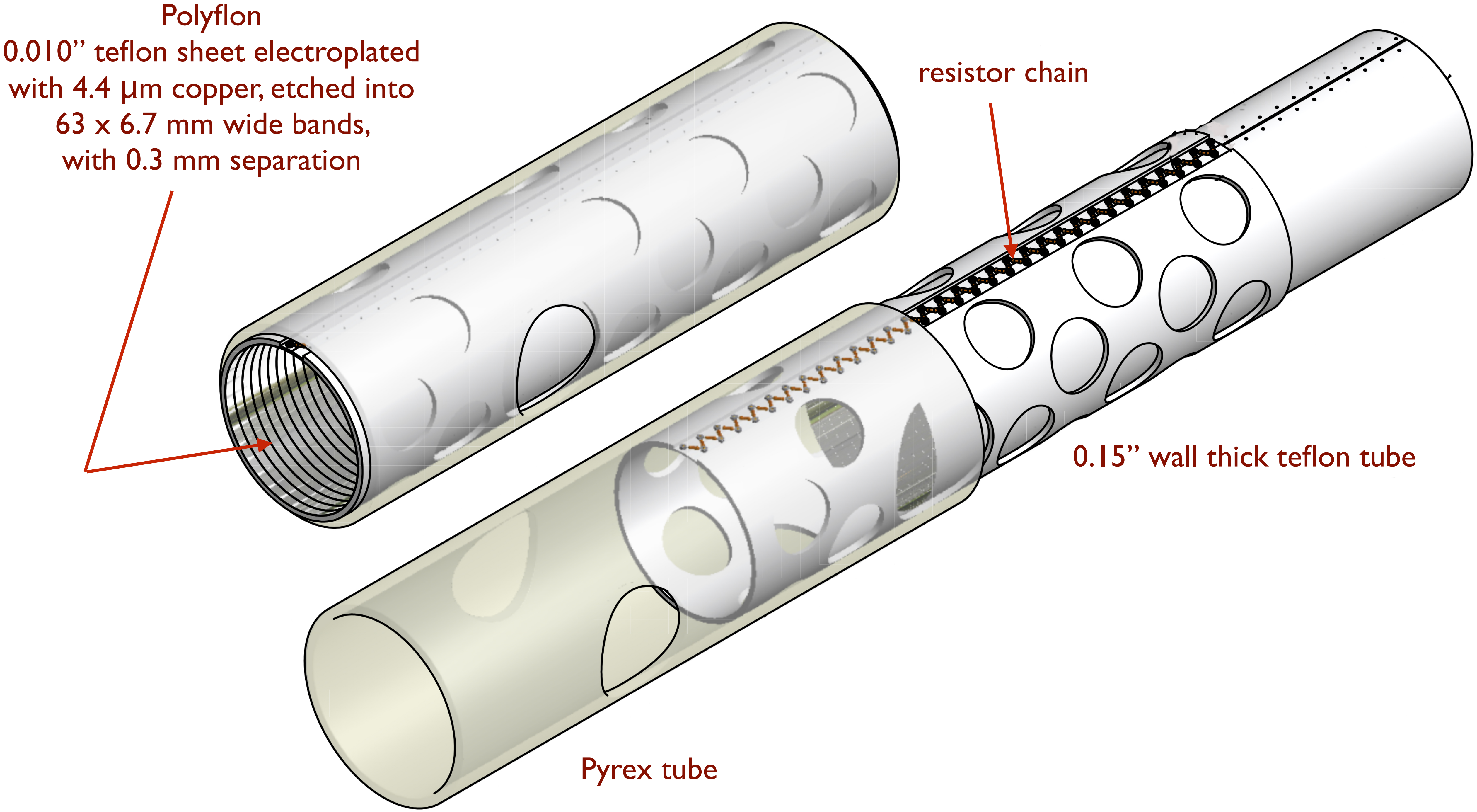





Beta Spectrometer Energy Response
energy (keV)
1200
1000
800
600
400
200
0
^{207}Bi
^{207}Bi
^{133}Ba
^{113}Sn
^{57}Co
^{139}Ce
0
10
20
30
40
50
60
70x10^{3}
channel
residual (keV)
10
5
0
-5
-10
0
10
20
30
40
50
60
70x10^{3}
channel


Beta Spectrometer Energy Resolution (FWHM)
FWHM (channels)
8000
6000
4000
2000
0
0
10
20
30
40
50
60x10^3
channel
FWHM = $\sqrt{A * channel}$
$A = 800 \pm 47$
● calibration data
fit

Electrostatic mirror



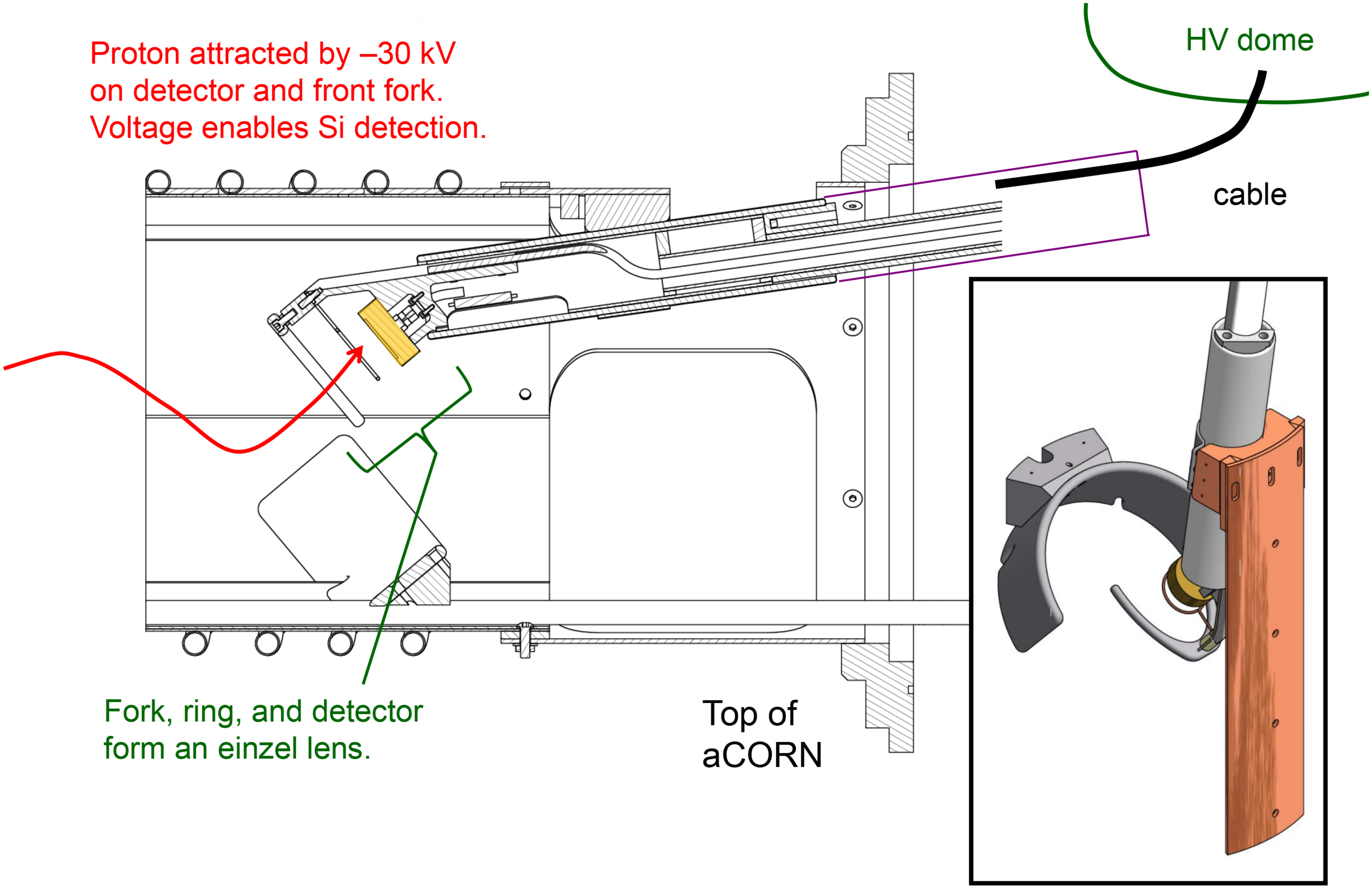
Polyflon
0.010” teflon sheet electroplated
with 4.4 µm copper, etched into
63 x 6.7 mm wide bands,
with 0.3 mm separation

resistor chain

0.15” wall thick teflon tube

Pyrex tube

Proton detector



Proton attracted by –30 kV
on detector and front fork.
Voltage enables Si detection.

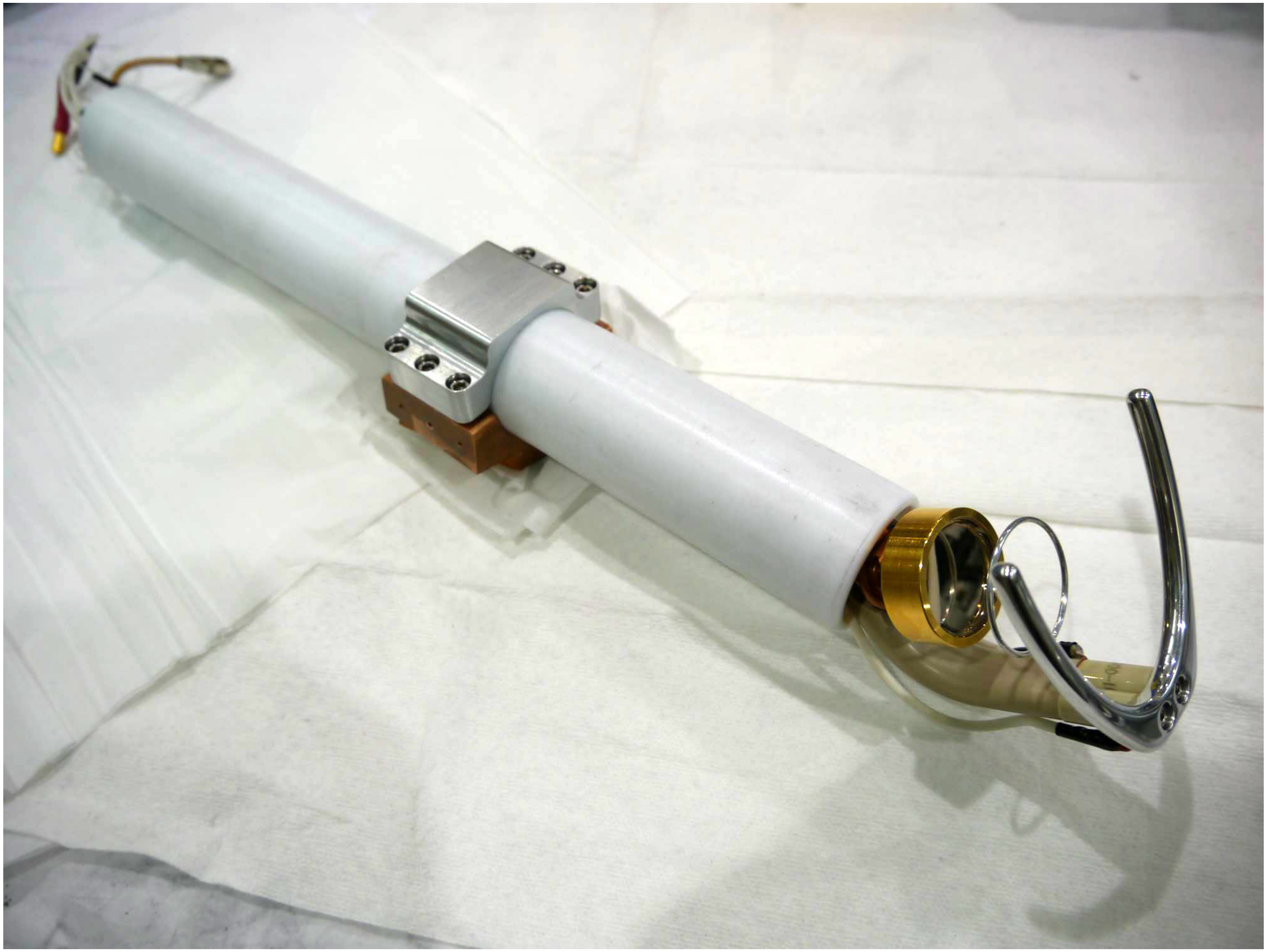
HV dome

cable

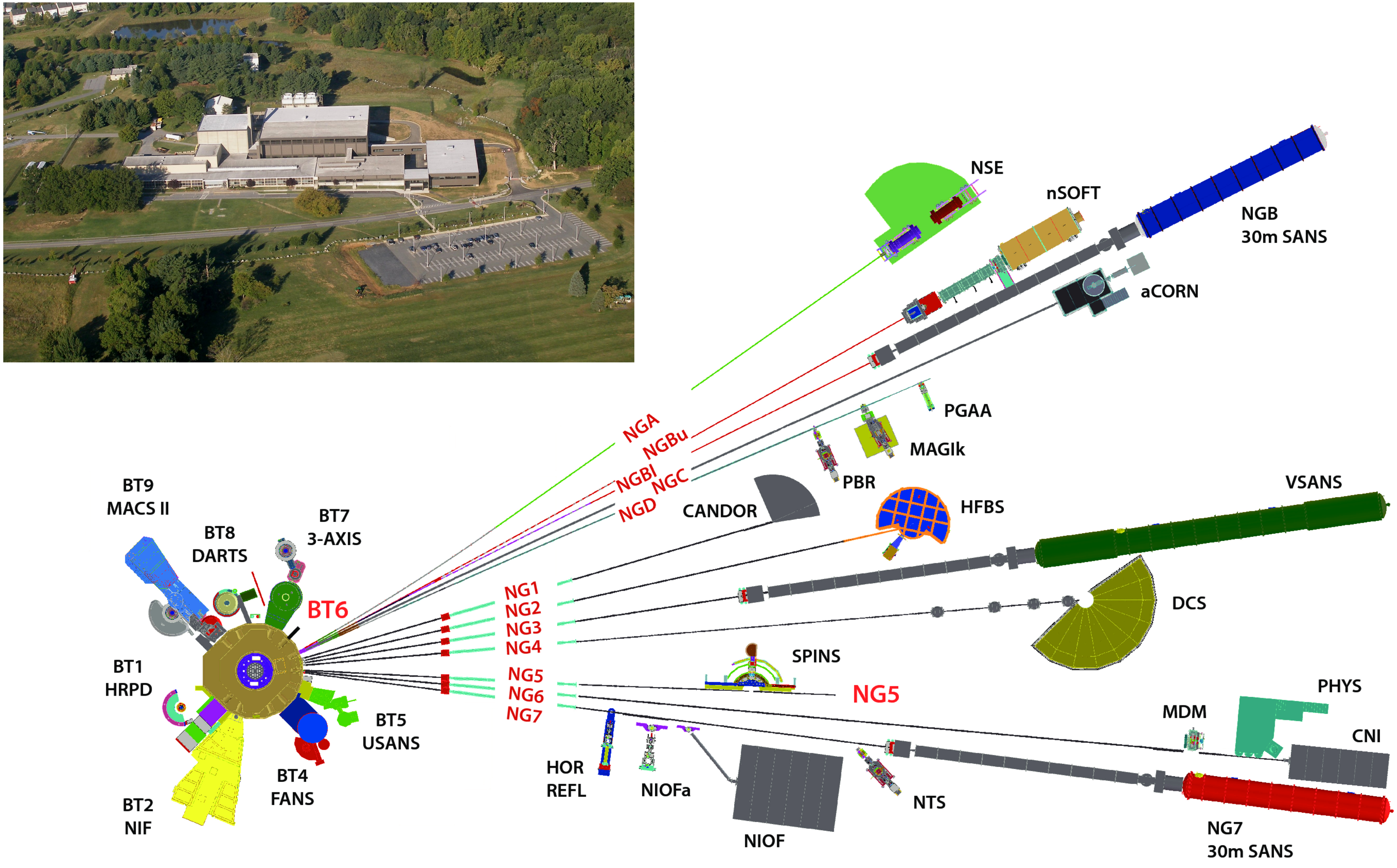
Fork, ring, and detector
form an einzel lens.

Top of
aCORN

aCORN proton detector

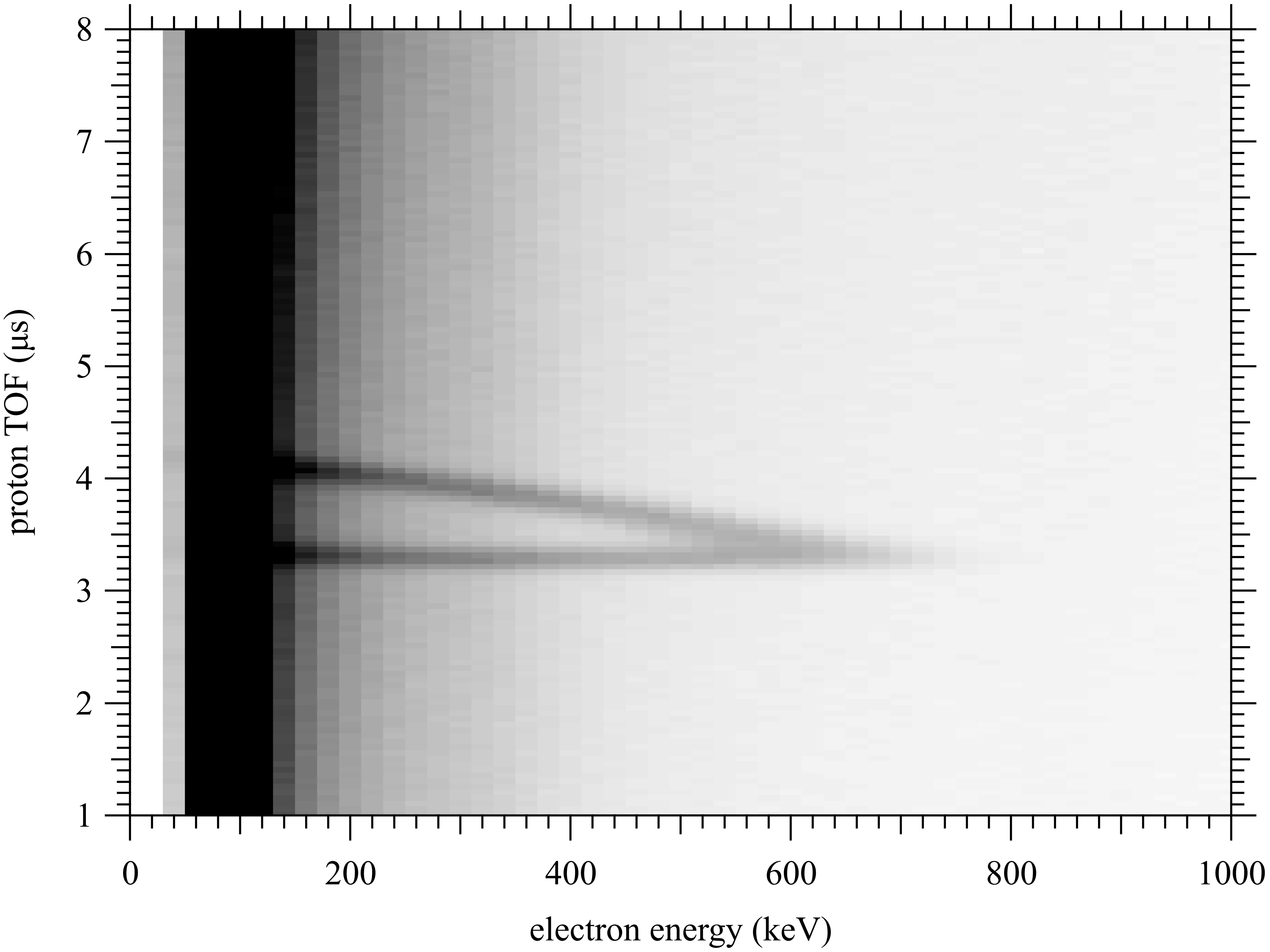


NIST Center for Neutron Research

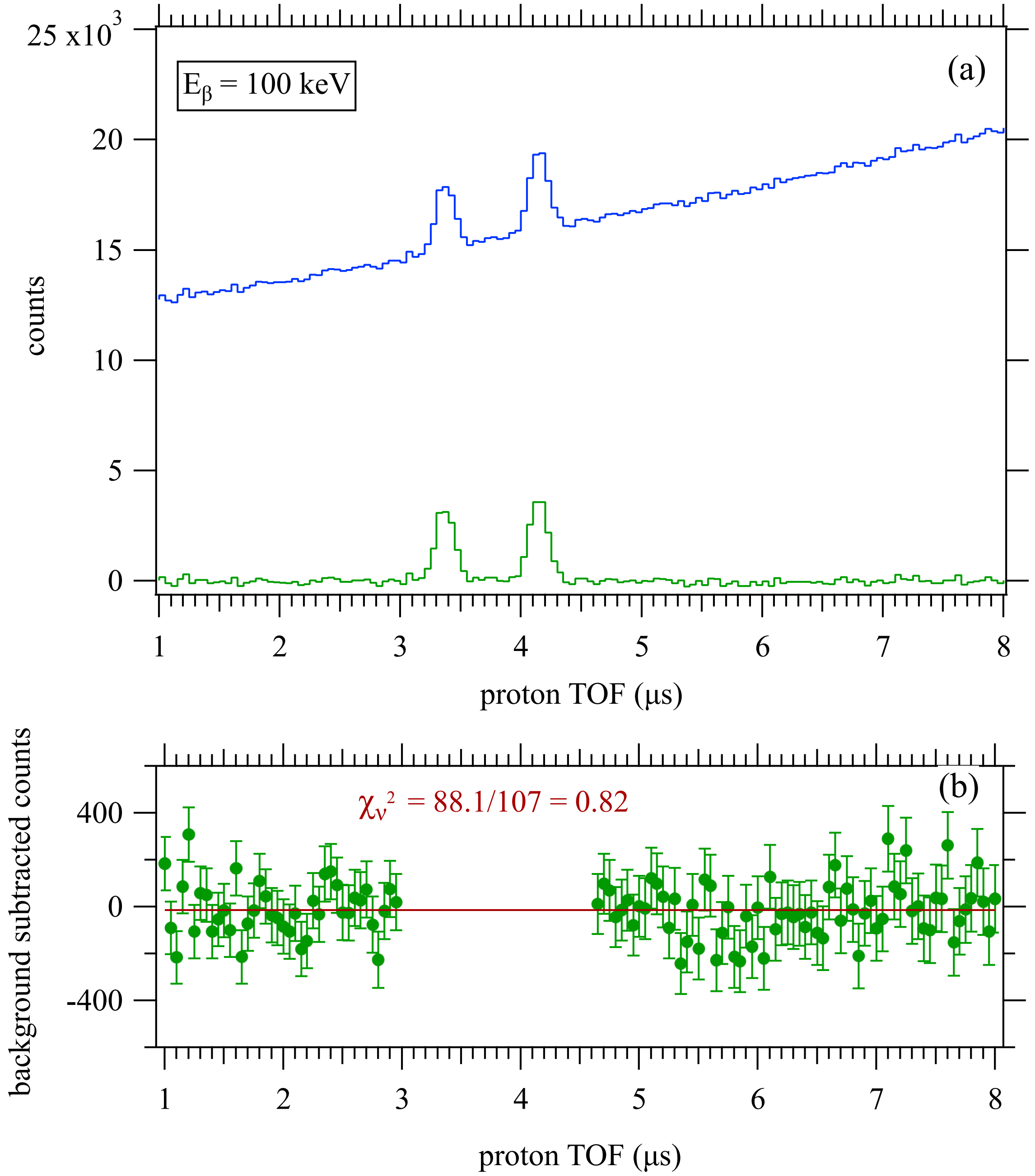


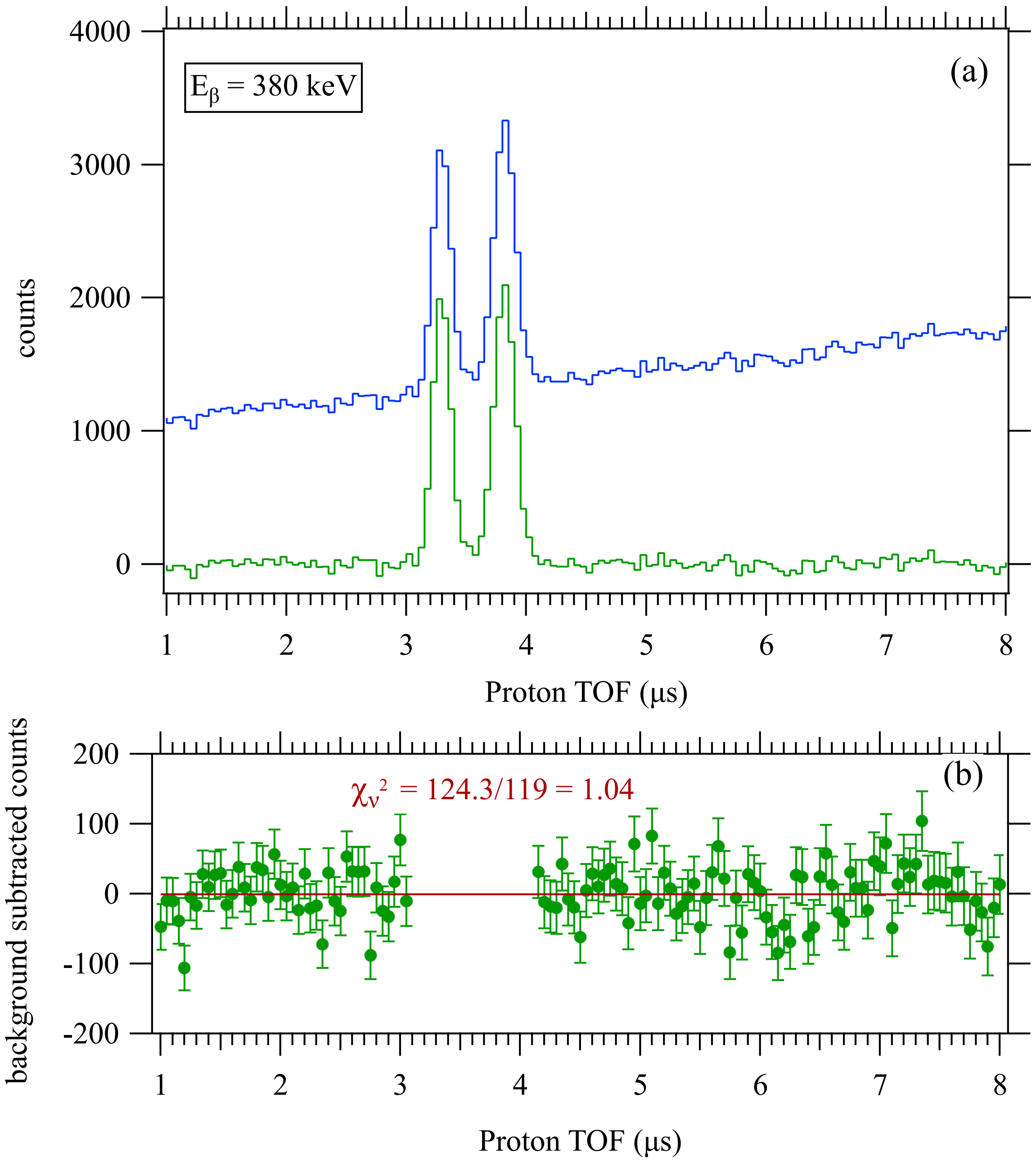

NIST

aCORN NG-C Raw Wishbone

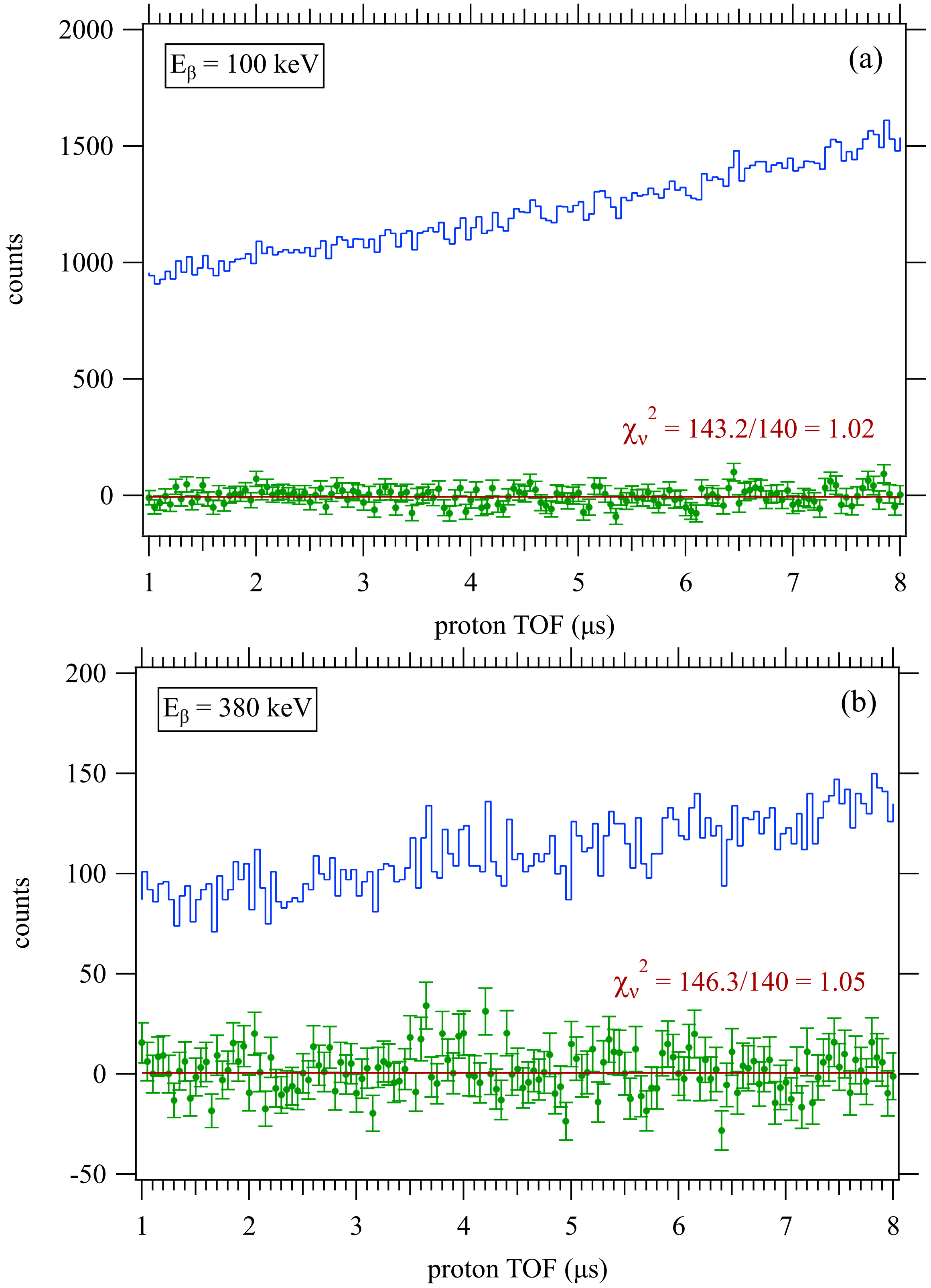


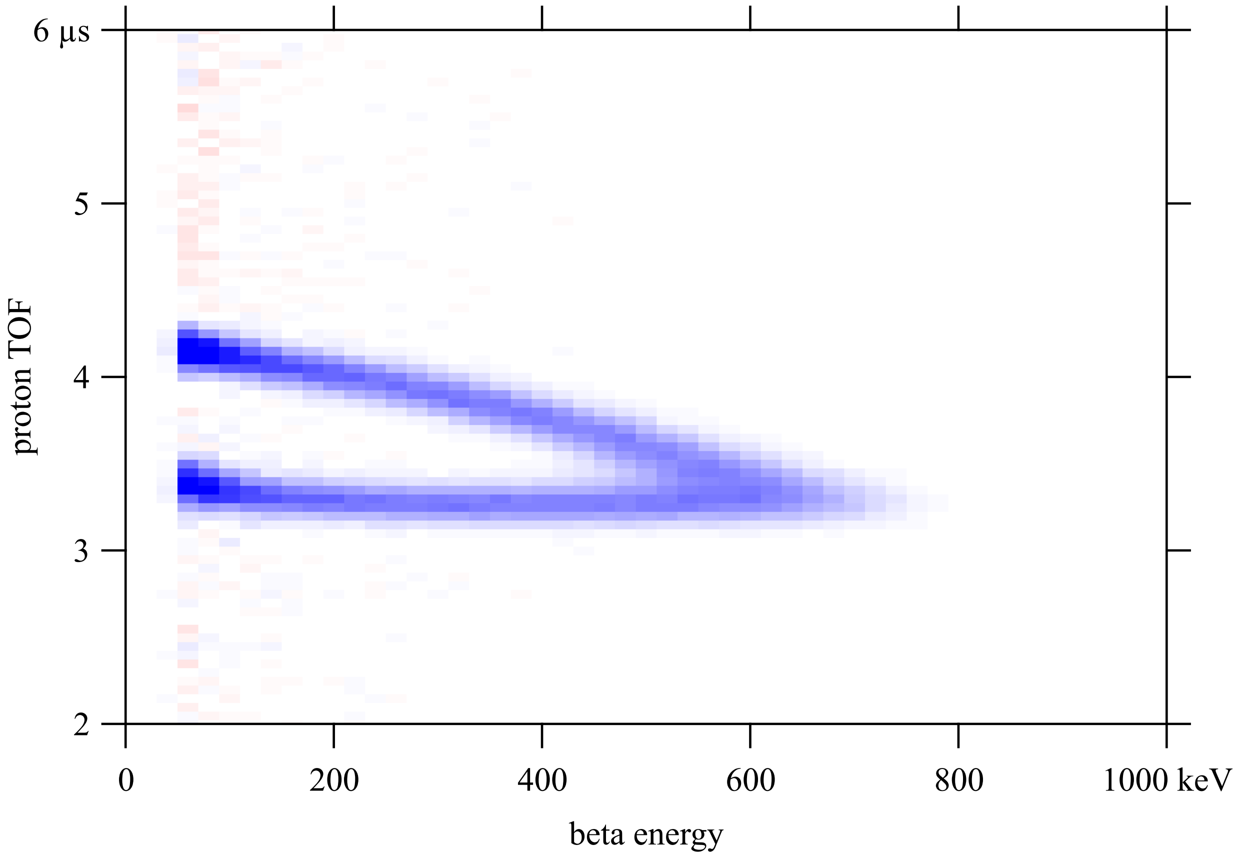
aCORN Wishbone Energy Slices



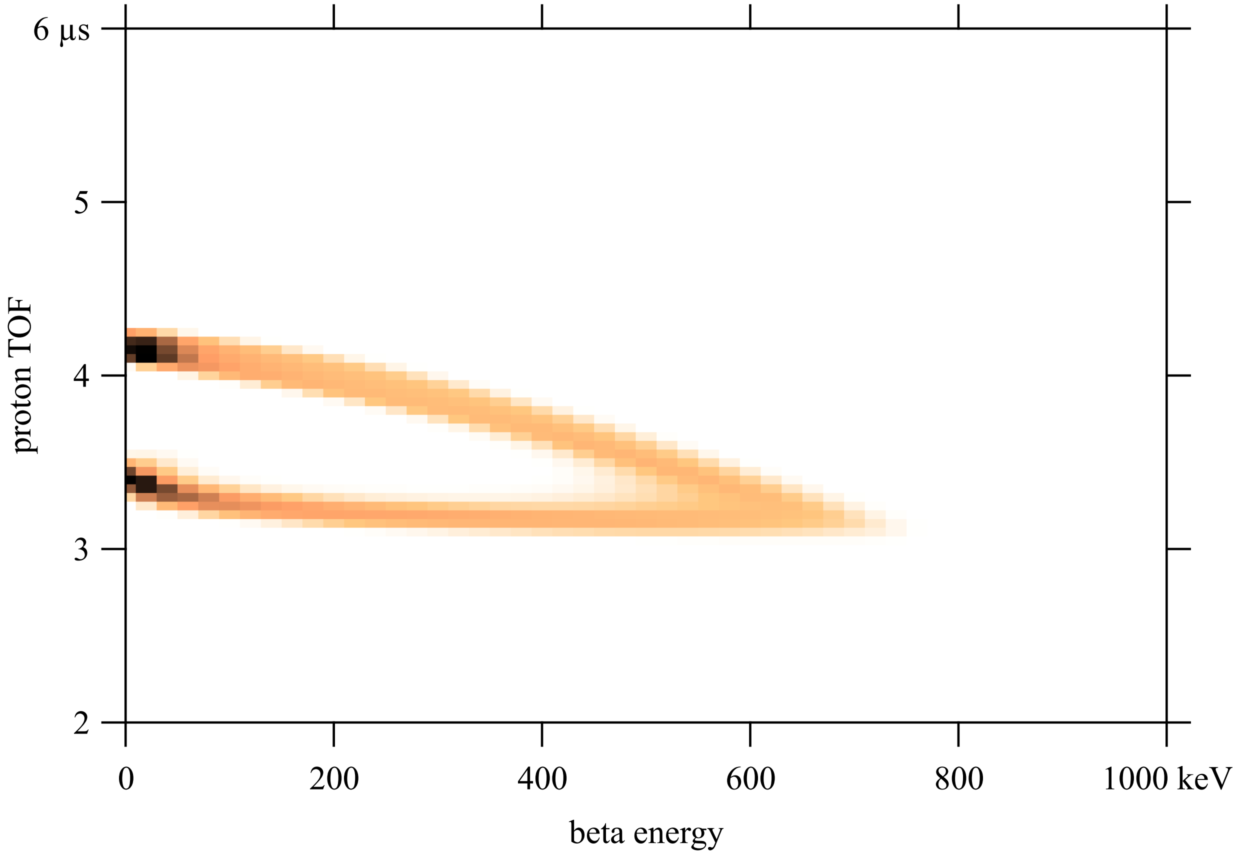


aCORN Wishbone Reversed Mirror





Background-Subtracted
Wishbone Data



aCORN Monte Carlo

The geometric function f_a(E)

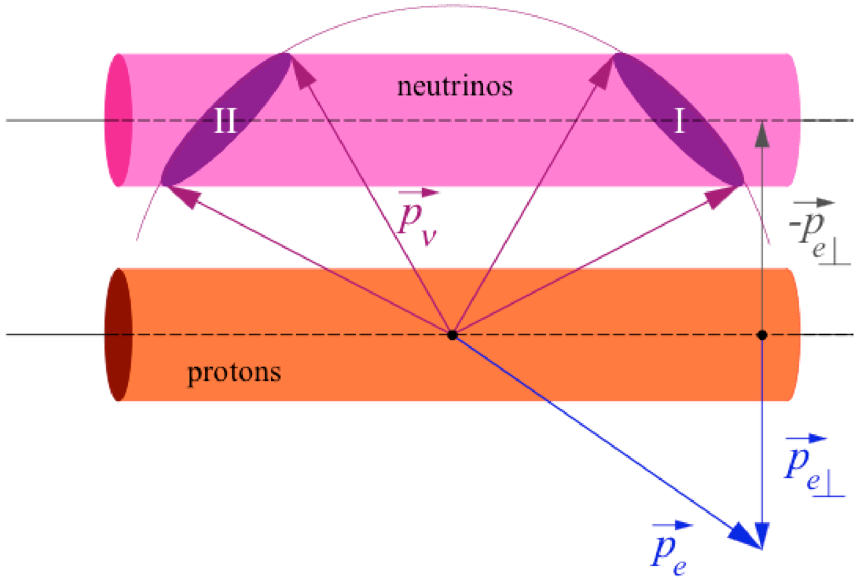
wishbone asymmetry: $X(E) = a\, f_a(E)$

$$f_a(E) = \frac{1}{2} v\left(\phi^I(E) - \phi^{II}(E)\right)$$

$\phi^I(E), \phi^{II}(E)$ are the average angle between electron and antineutrino momentum vectors for all momenta within the aCORN acceptance, independent of the beta decay distributions.

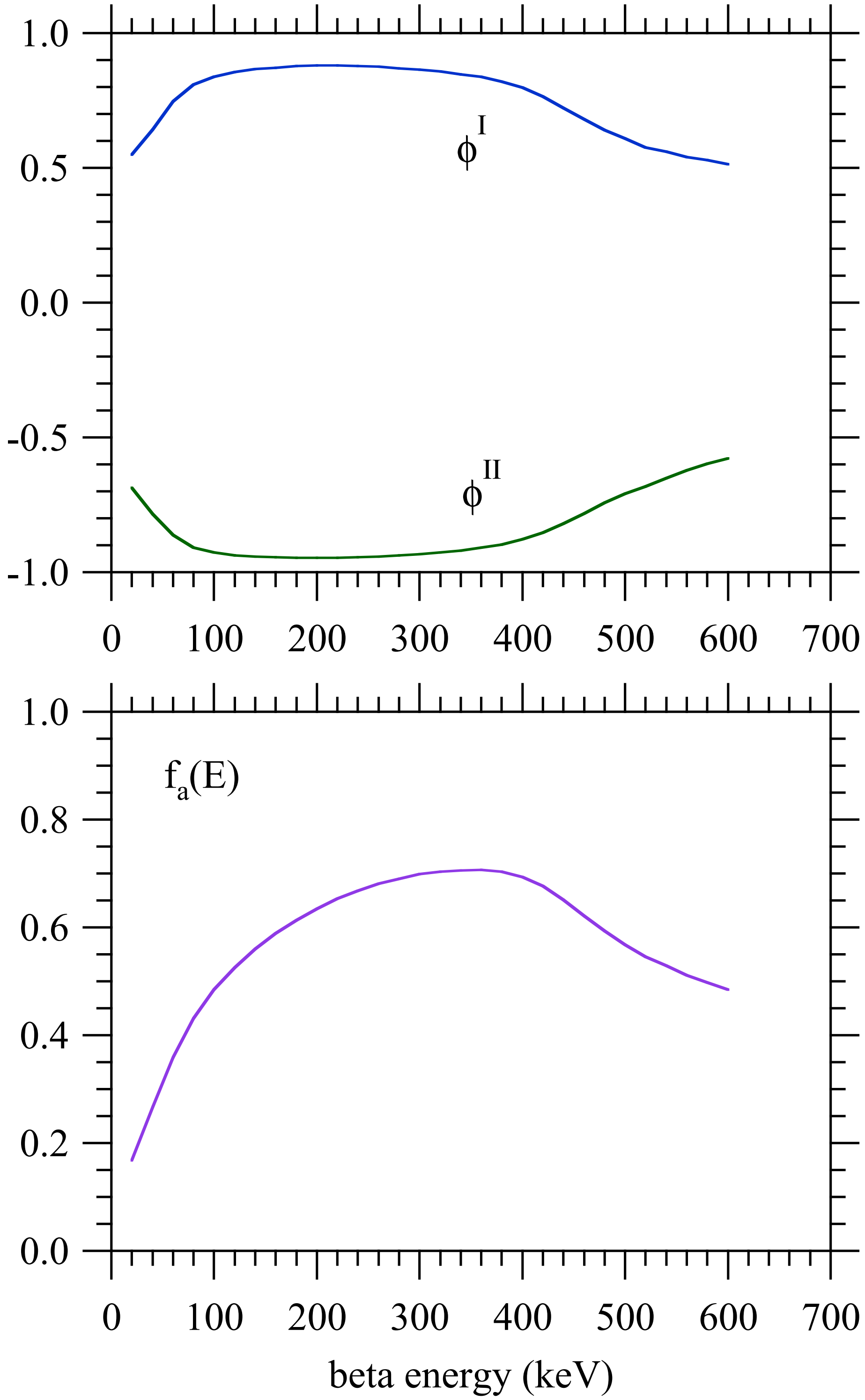
f_a(E) depends ONLY on:

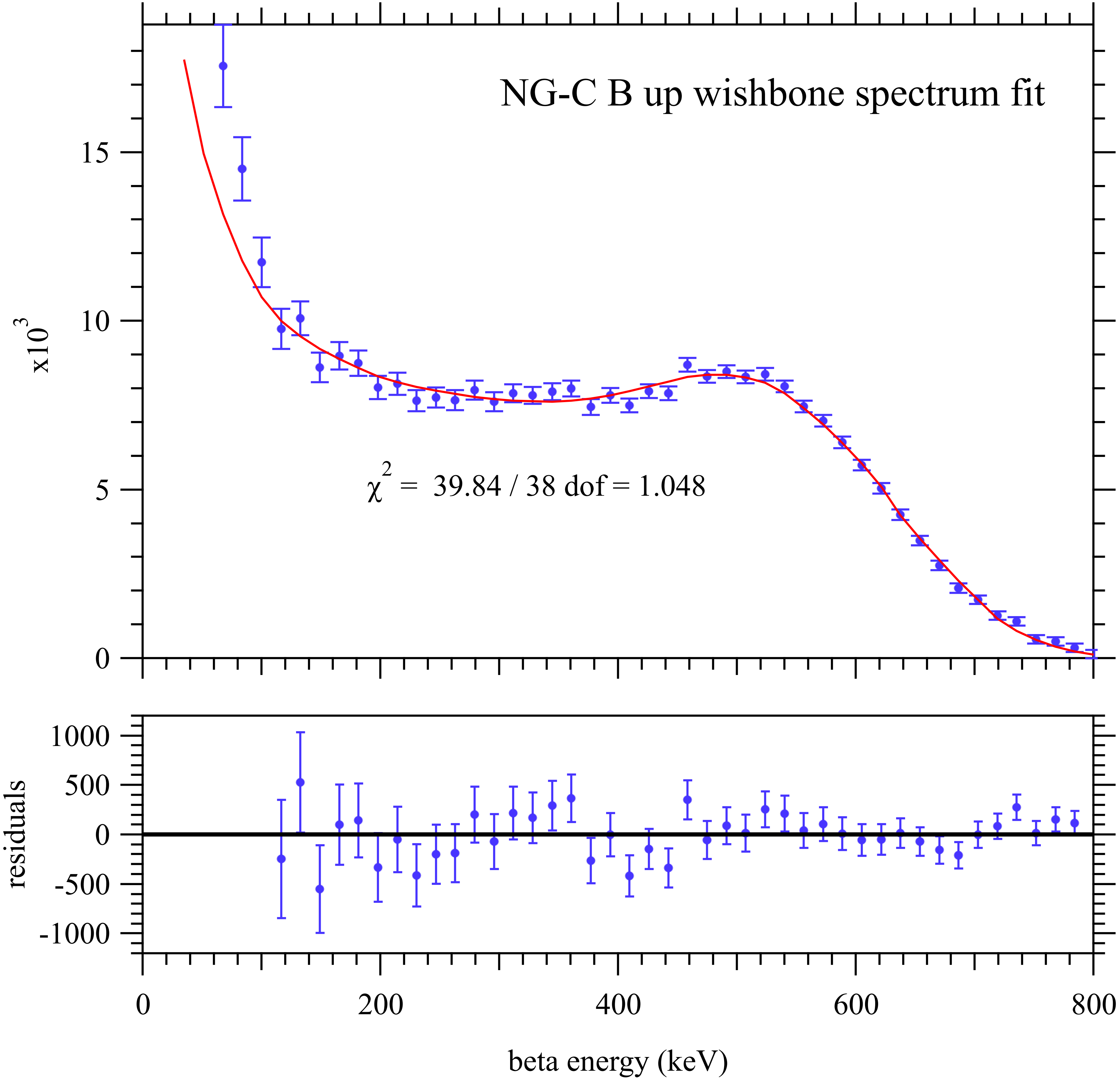
- magnetic field strength
- collimator geometry
- neutron beam density distribution (weakly)



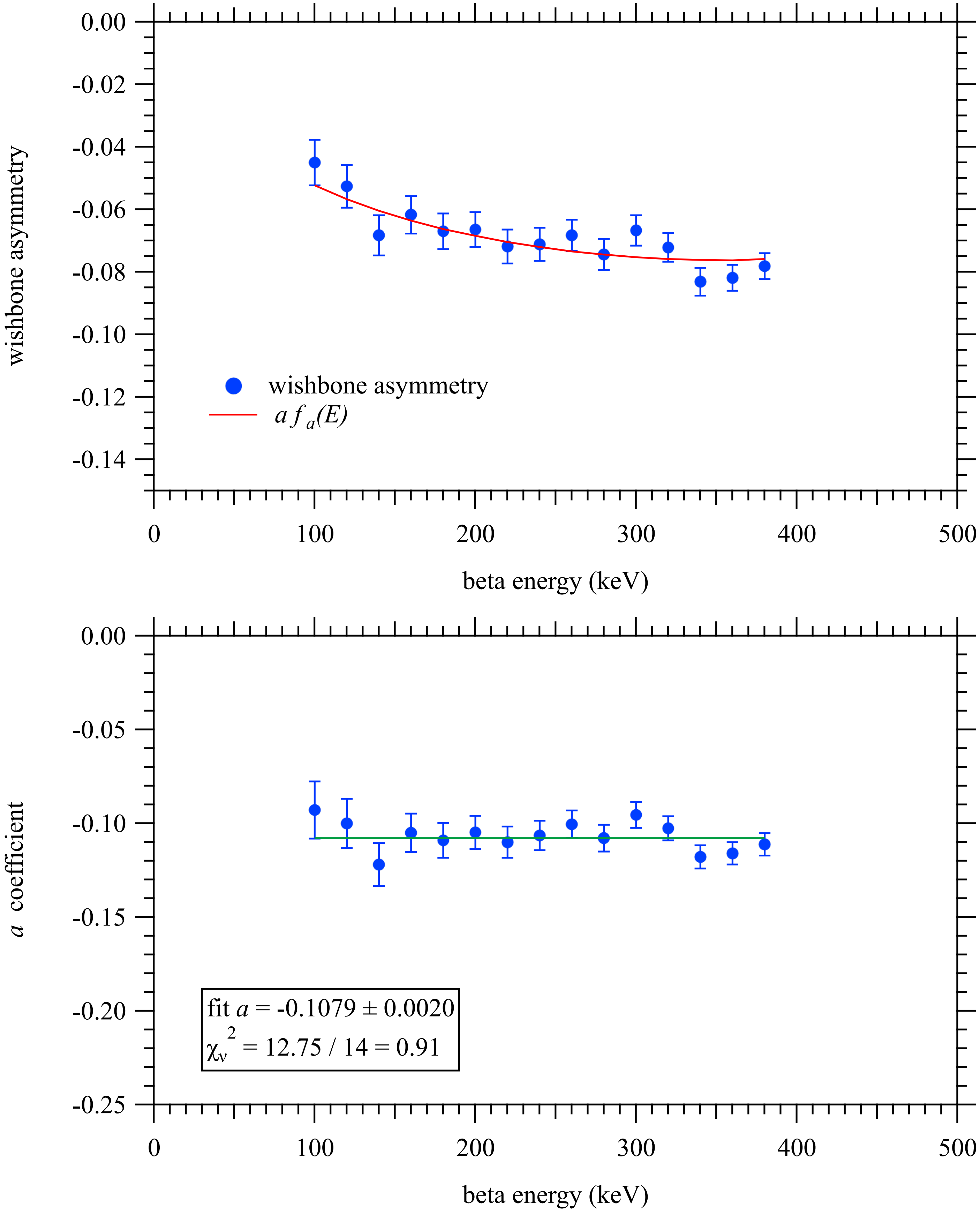
$$\phi^{\mathrm{I}}(E) = \frac{\int d\Omega_e \int_{\mathrm{I}} d\Omega_\nu \cos\theta_{e\nu}}{\Omega_e \Omega_\nu^{\mathrm{I}}}$$

$$\phi^{\mathrm{II}}(E) = \frac{\int d\Omega_e \int_{\mathrm{II}} d\Omega_\nu \cos\theta_{e\nu}}{\Omega_e \Omega_\nu^{\mathrm{II}}}$$




NG-C B up wishbone spectrum fit
χ^2 = 39.84 / 38 dof = 1.048
x10^3
0
5
10
15
residuals
1000
500
0
-500
-1000
0
200
400
600
800
beta energy (keV)

NG-C B up combined

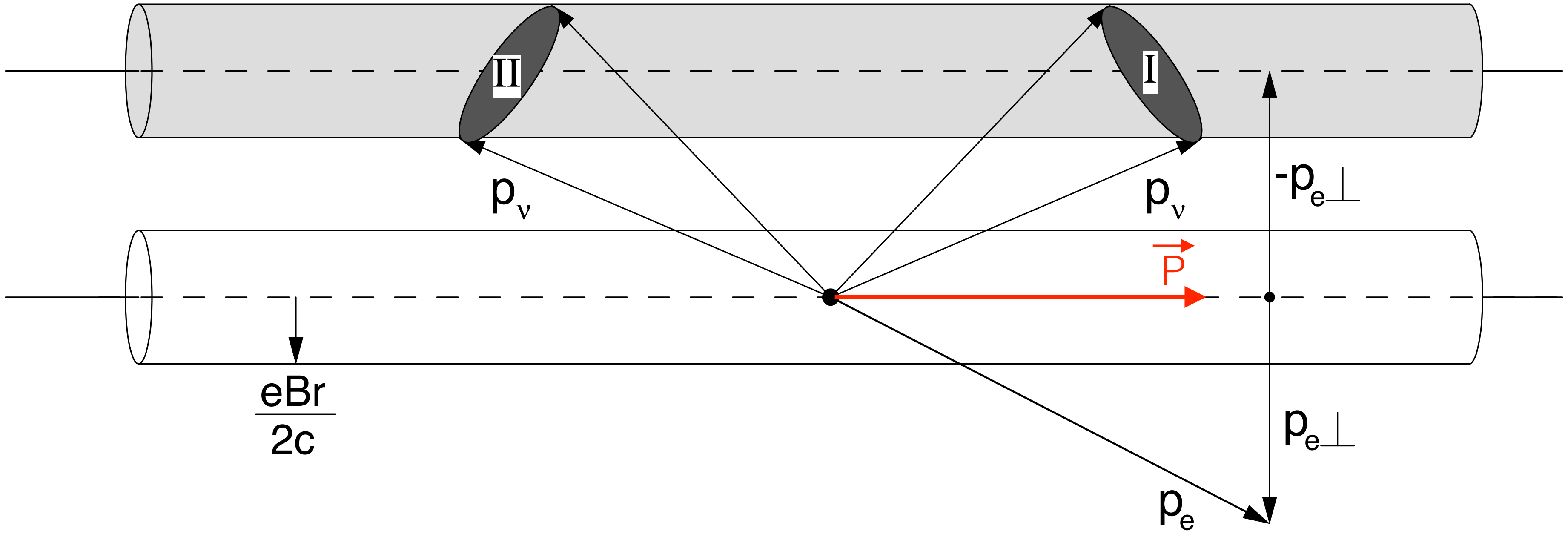


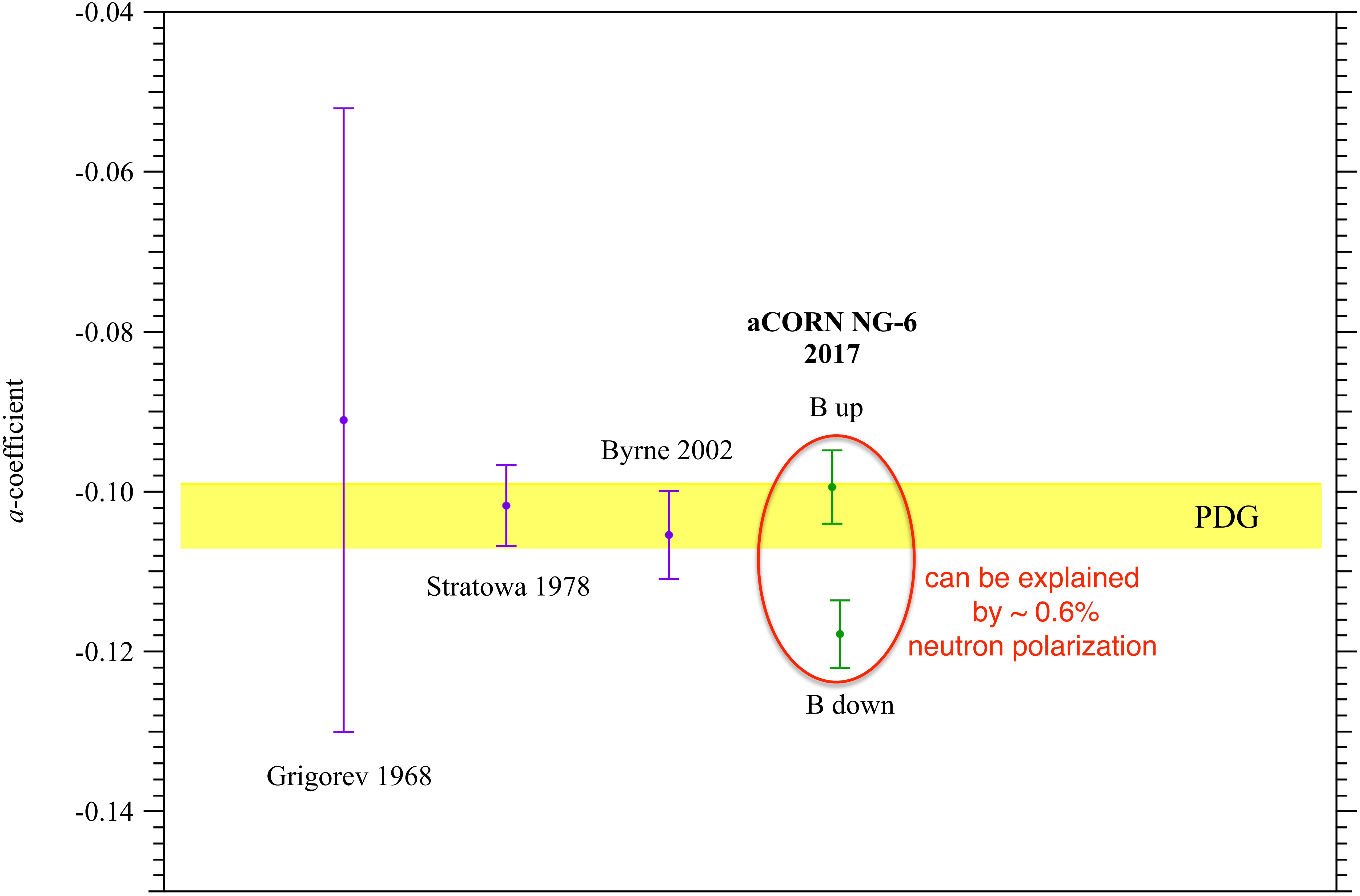
Beam Polarization

With a polarized neutron beam:

$$\text{wishbone asymmetry } A_{wb} = af_a(E_\beta) + PBf_B(E_\beta)$$

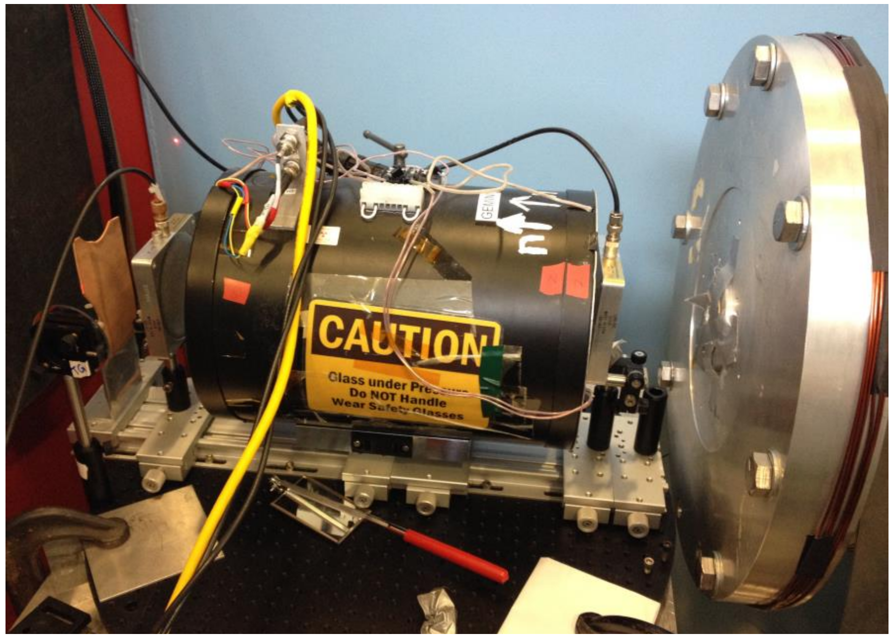
$$\frac{Bf_B(E_\beta)}{af_a(E_\beta)} \approx 14$$



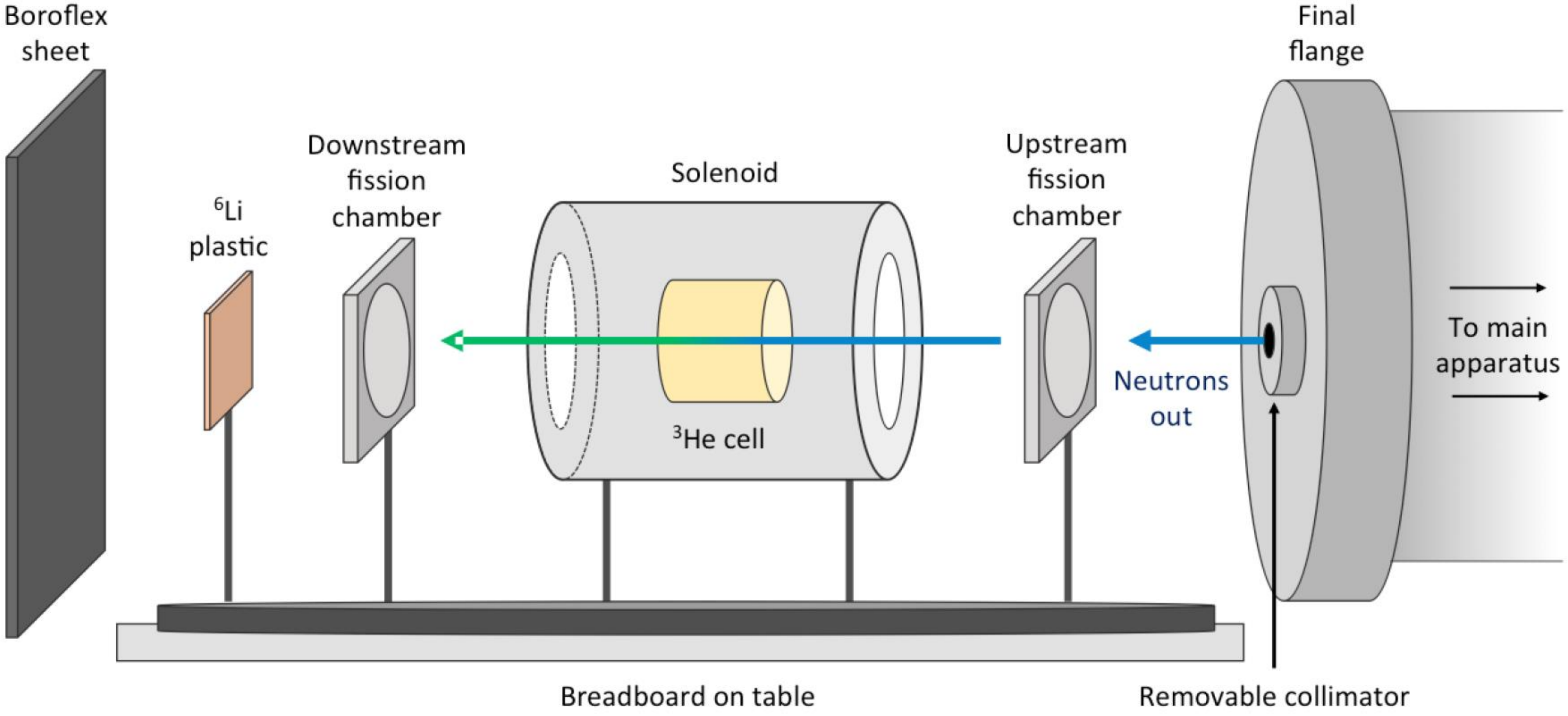


can be explained
by ~ 0.6%
neutron polarization

Neutron Polarimetry with Polarized ^{3}He (SEOP)



$$P_n = \frac{T_n^{\uparrow} - T_n^{\downarrow}}{2T_0 \sinh(\sigma_n N_{\mathrm{He}} P_{\mathrm{He}} L)}$$



Neutron Polarimetry with Polarized ^{3}He (SEOP)

Blind Analysis Strategy:

1. aCORN physics data collected on NG-C:
   B up: Aug. — Dec. 2015
   B down: Feb. — Jul. 2016
   B up: Aug. — Sep. 2016

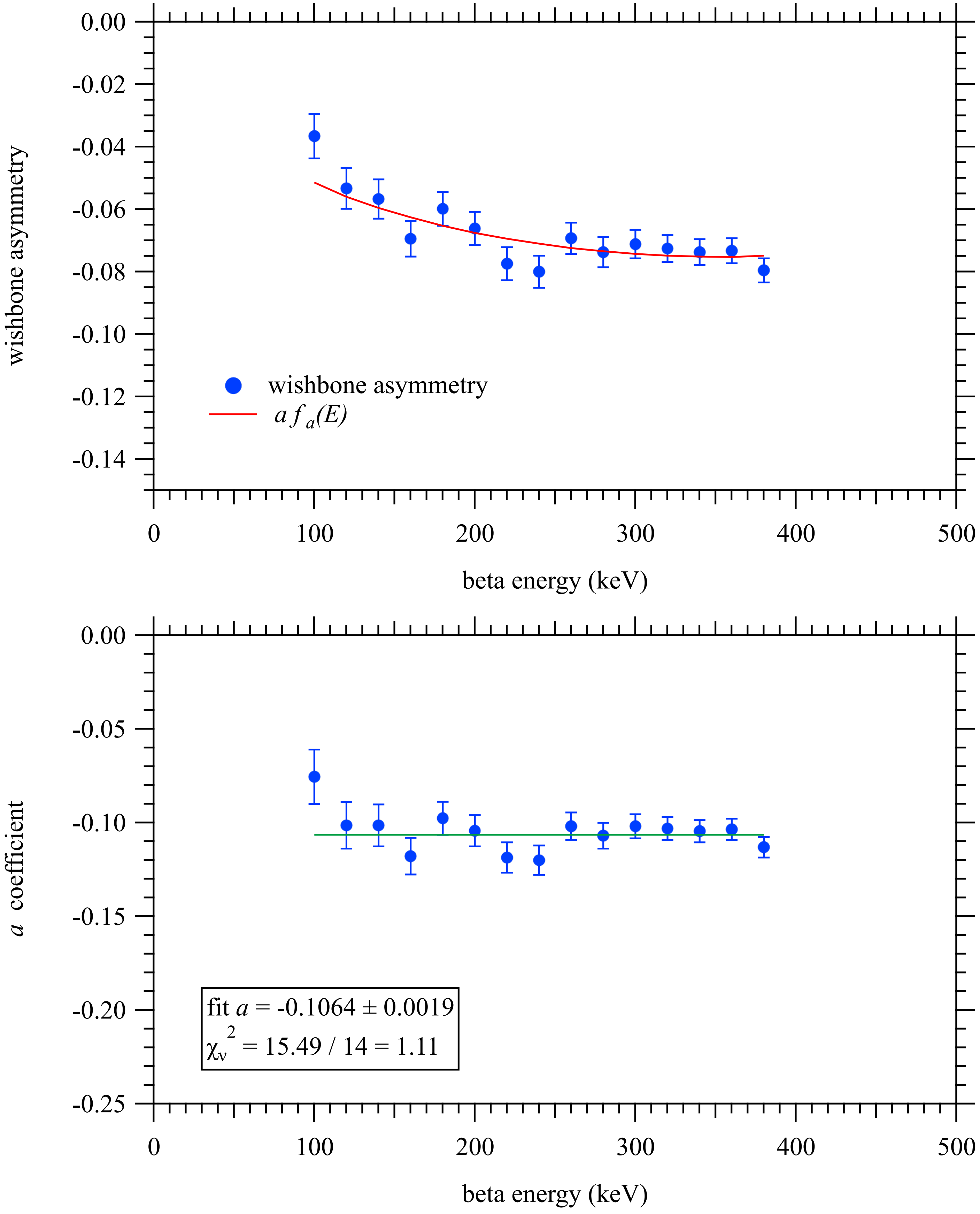
2. Neutron polarization on NG-C measured in summer 2016 and result embargoed (the blind).

3. All B up data analyzed and systematics evaluated and vetted by the collaboration. A B up result is obtained.

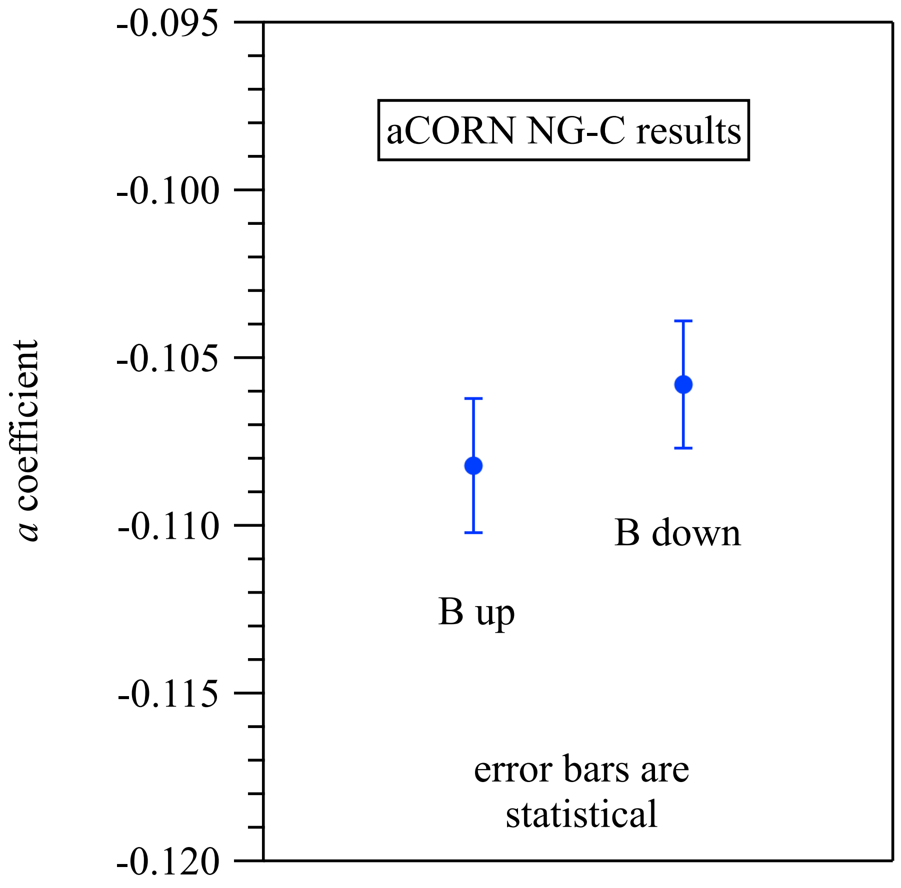
4. All B down data analyzed using the same fixed methods and routines. A B down result is obtained and compared to the B up.

5. "Box opened" on measured neutron polarization.

NG-C B down combined



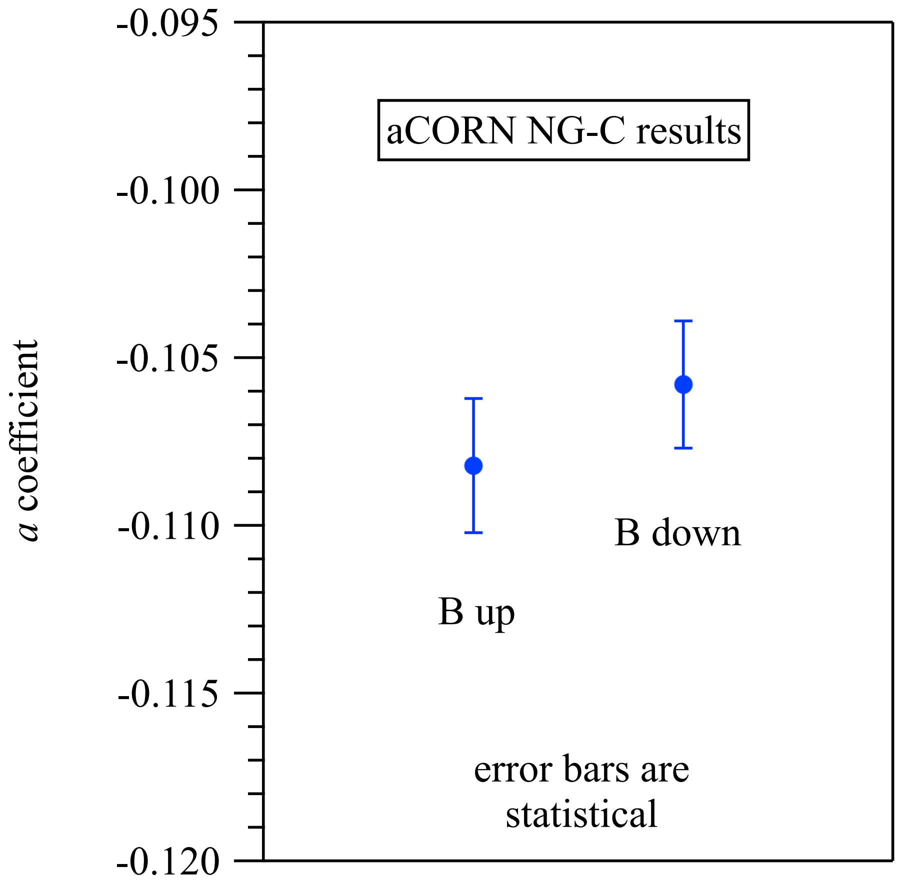
aCORN NG-C Preliminary Result



The difference implies

$$P_n = 0.8 \pm 1.0 \times 10^{-3}$$

aCORN NG-C Preliminary Result

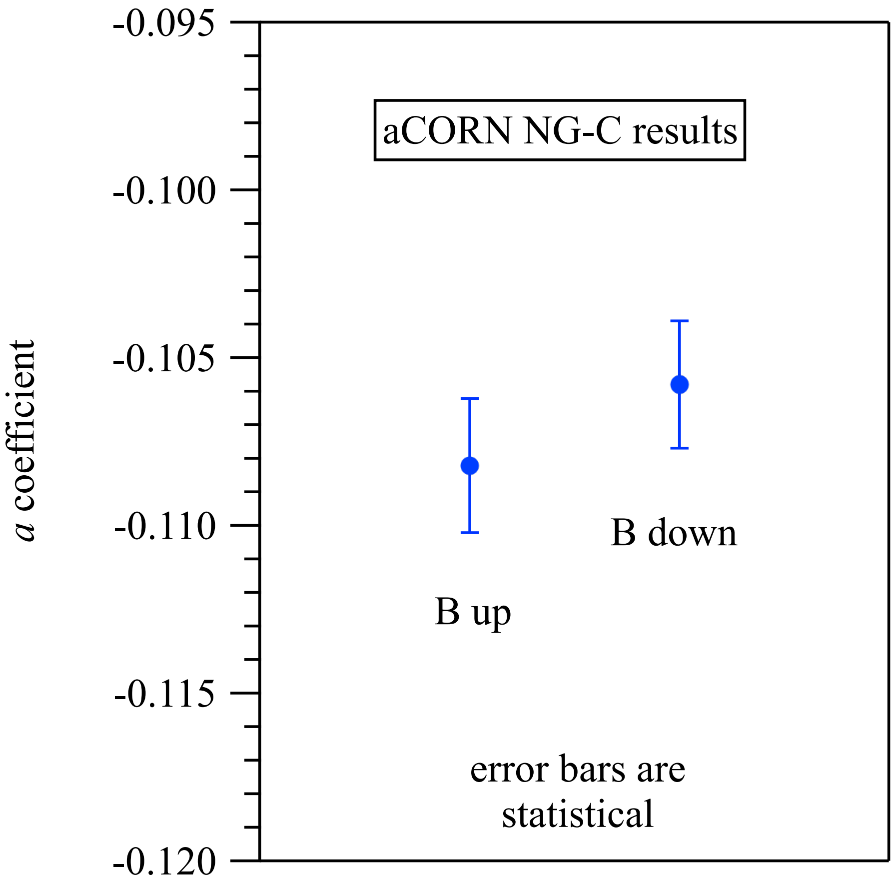


Polarimetry “box” opened
on Wed. April 10, 2019

The difference implies

$$P_n = 0.8 \pm 1.0 \times 10^{-3}$$

aCORN NG-C Preliminary Result



The difference implies

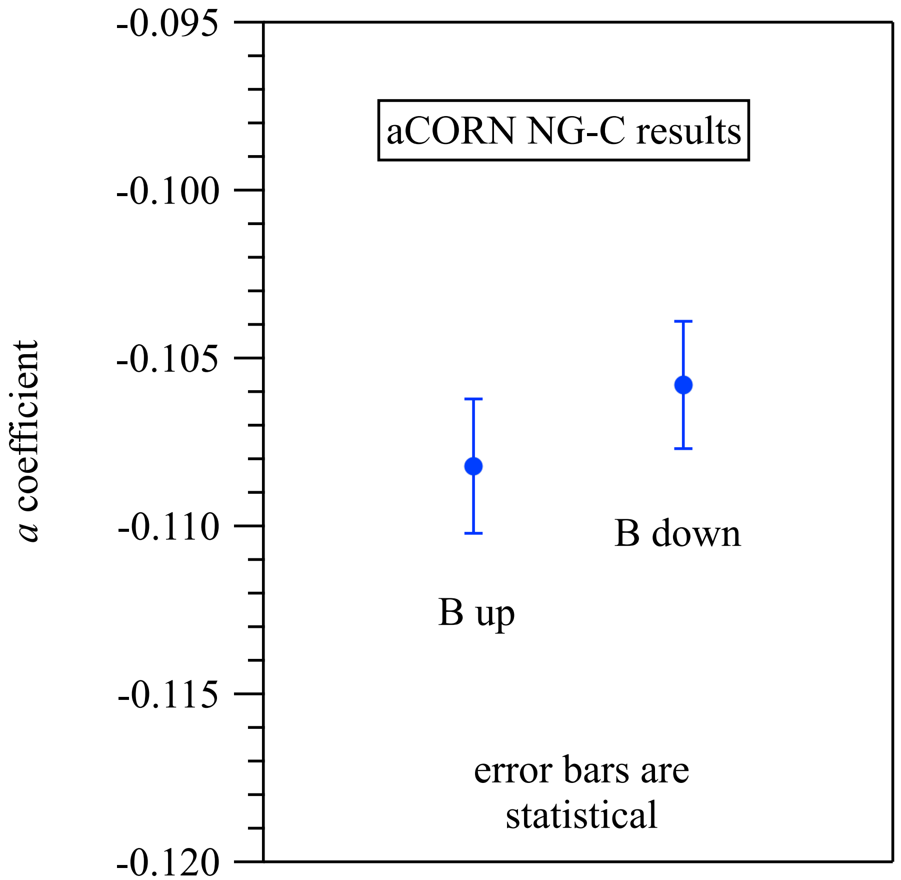
$$P_n = 0.8 \pm 1.0 \times 10^{-3}$$

Polarimetry “box” opened on Wed. April 10, 2019

$$\boxed{P_n = 7 \pm 9 \times 10^{-5}}$$

most precise ever using polarized ^{3}He!

aCORN NG-C Preliminary Result



The difference implies

$$P_n = 0.8 \pm 1.0 \times 10^{-3}$$

Polarimetry "box" opened
on Wed. April 10, 2019

$$\boxed{P_n = 7 \pm 9 \times 10^{-5}}$$

most precise ever
using polarized ^{3}He!

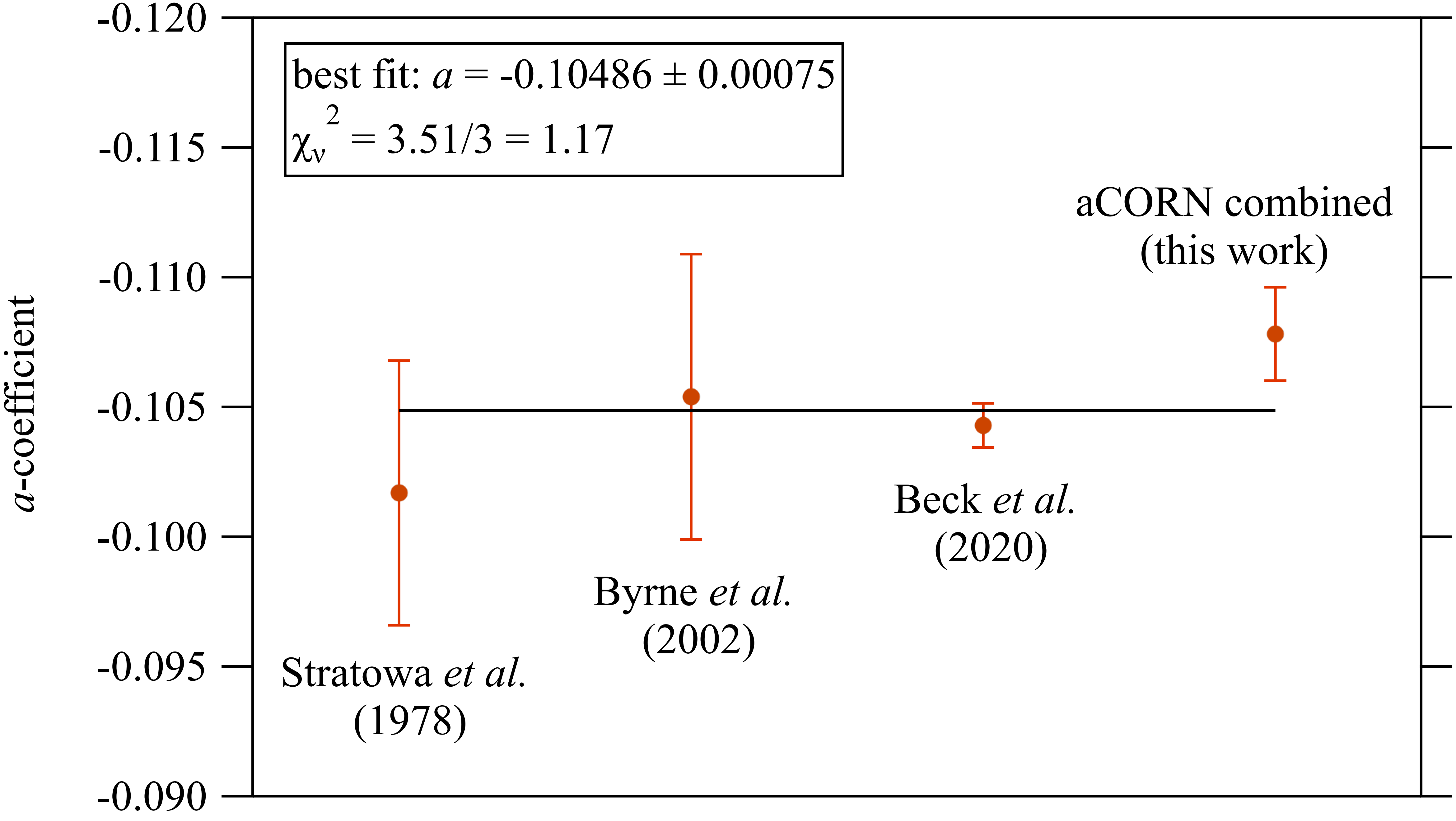
Agreement!

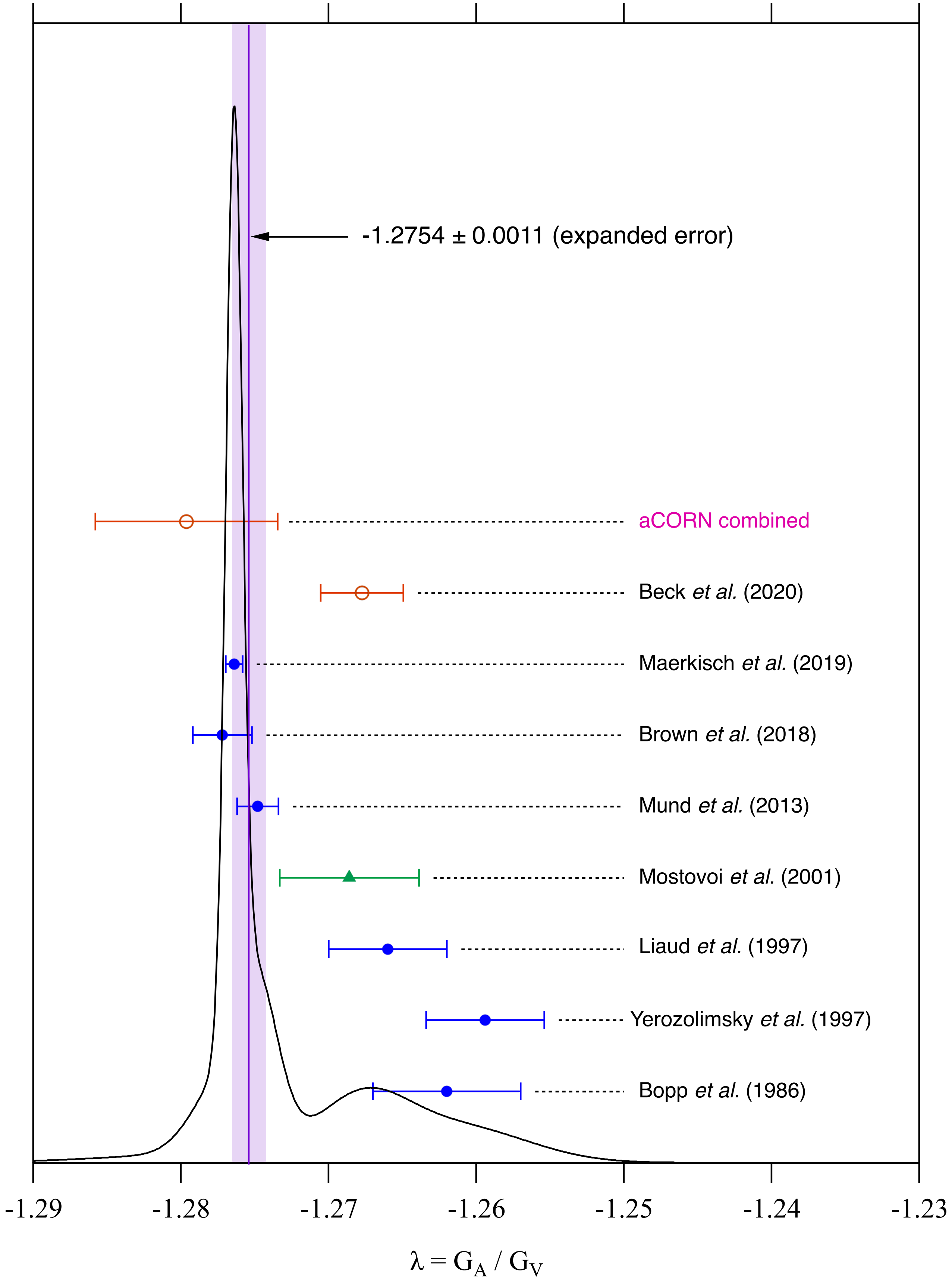
aCORN NG-C Result

systematic	correction	1σ uncertainty	relative uncertainty
e scattering	-0.00083	0.00083	0.0077
wishbone asymmetry		0.00064	0.0060
residual gas		0.00048	0.0045
proton scattering		0.00038	0.0035
beta energy calibration		0.00030	0.0028
electrostatic mirror	0.00161	0.00032	0.0030
absolute magnetic field	0.00023	0.00023	0.0022
energy loss in grid	-0.00111	0.00022	0.0020
proton collimator alignment	0.00046	0.00020	0.0019
magnetic field shape	0.00018	0.00011	0.0010
electrostatic mirror alignment	0.00025	0.00009	0.0008
neutron beam density	-0.00045	0.00009	0.0008
proton focusing	0.00036	0.00055	0.0051
total systematic	0.00070	0.00148	0.0137
statistical		0.00136	0.0126
combined uncertainty		0.00201	0.0186

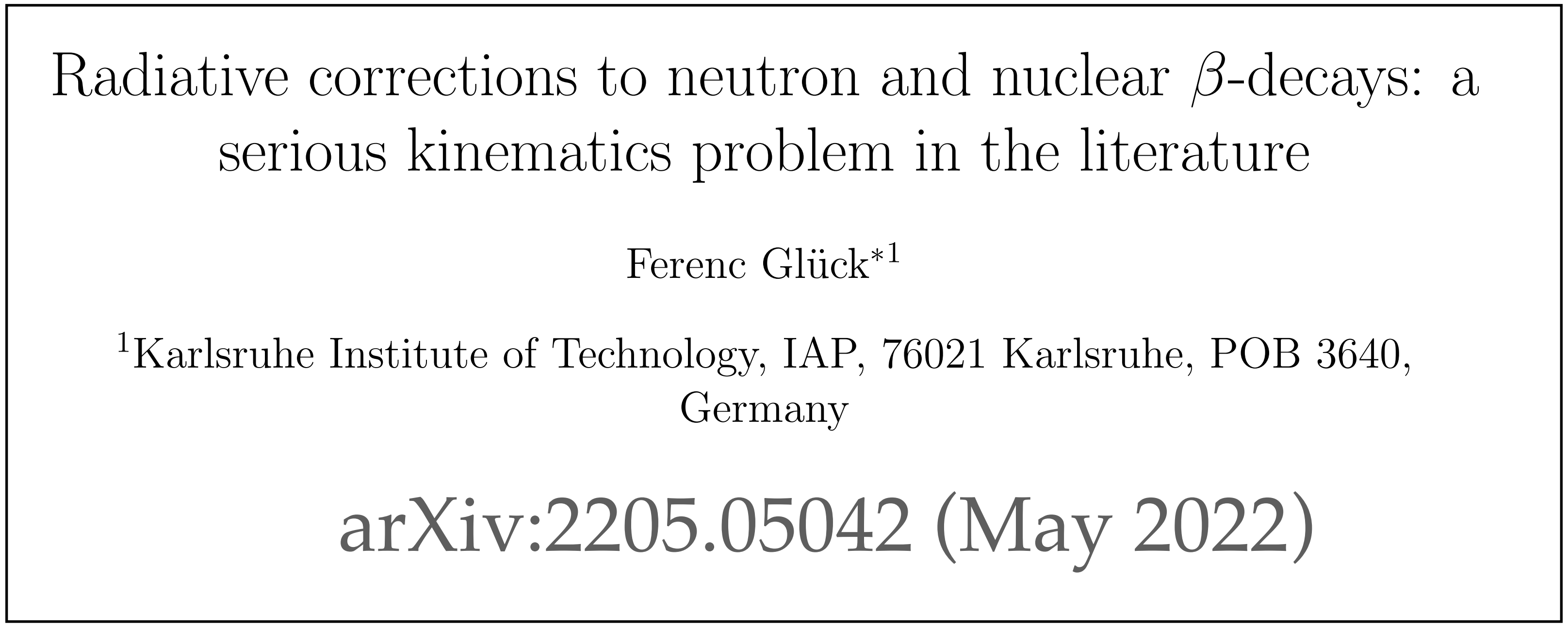
a = -0.1076 ± 0.0014 (stat) ± 0.0015 (sys); 1.9%

Hassan, *et al*. Phys. Rev. C **103**, 045502 (2021)


best fit: a = -0.10486 ± 0.00075
χν² = 3.51/3 = 1.17
a-coefficient
-0.120
-0.115
-0.110
-0.105
-0.100
-0.095
-0.090
Stratowa et al. (1978)
Byrne et al. (2002)
Beck et al. (2020)
aCORN combined (this work)


-1.2754 ± 0.0011 (expanded error)
aCORN combined
Beck et al. (2020)
Maerkisch et al. (2019)
Brown et al. (2018)
Mund et al. (2013)
Mostovoi et al. (2001)
Liaud et al. (1997)
Yerozolimsky et al. (1997)
Bopp et al. (1986)
-1.29
-1.28
-1.27
-1.26
-1.25
-1.24
-1.23
λ = G_A / G_V

4-body radiative correction

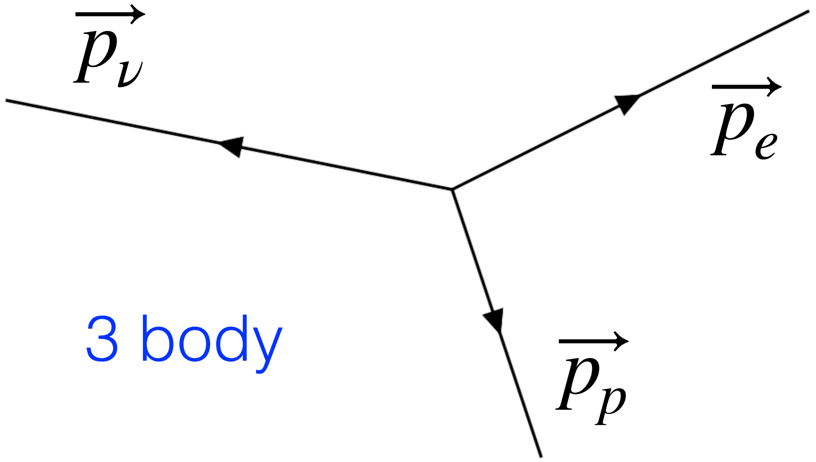


Radiative corrections to neutron and nuclear β-decays: a serious kinematics problem in the literature

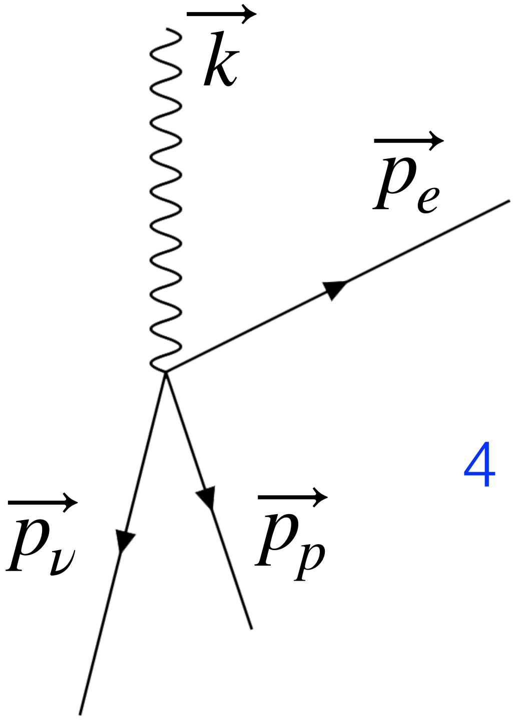
Ferenc Glück*[1]

[1]Karlsruhe Institute of Technology, IAP, 76021 Karlsruhe, POB 3640,
Germany

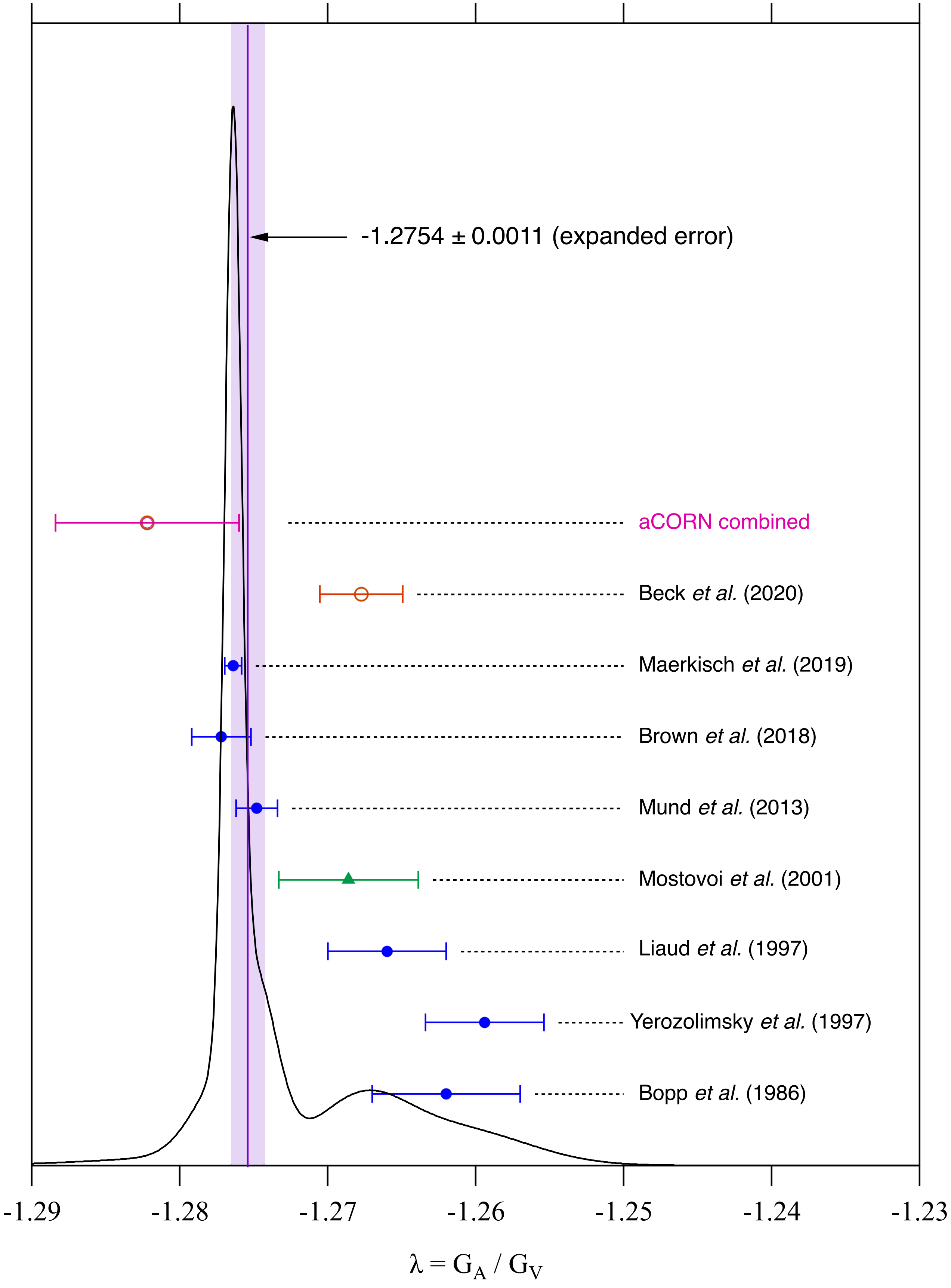
arXiv:2205.05042 (May 2022)



3 body



4 body



including the
calculated order-α 4-body
radiative correction

F. Glück,
Phys. Rev. D **47**, 47 (1993);
arXiV:2205.05042 (2022)

-0.7% shift!
(preliminary)

aCORN B

A precision measurement of the neutrino asymmetry (B-coefficient) in free neutron decay

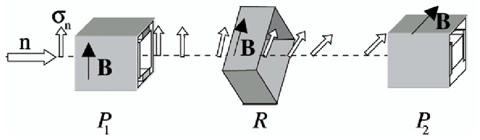
$$dW \propto \frac{1}{\tau}F(E_e)\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + A\frac{\vec{\sigma}_n\cdot\vec{p}_e}{E_e} + \boxed{B\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu}} + D\frac{\vec{\sigma}_n\cdot\left(\vec{p}_e\times\vec{p}_\nu\right)}{E_eE_\nu}\right]$$

Polarization and Polarimetry

assume the PERKEO II crossed supermirror polarizer (XSM) scheme
[Mund, et al., PRL 110, 172502 (2013)]

achieved: $P = 0.997 \pm .001$

$s = 0.998 \pm .001$

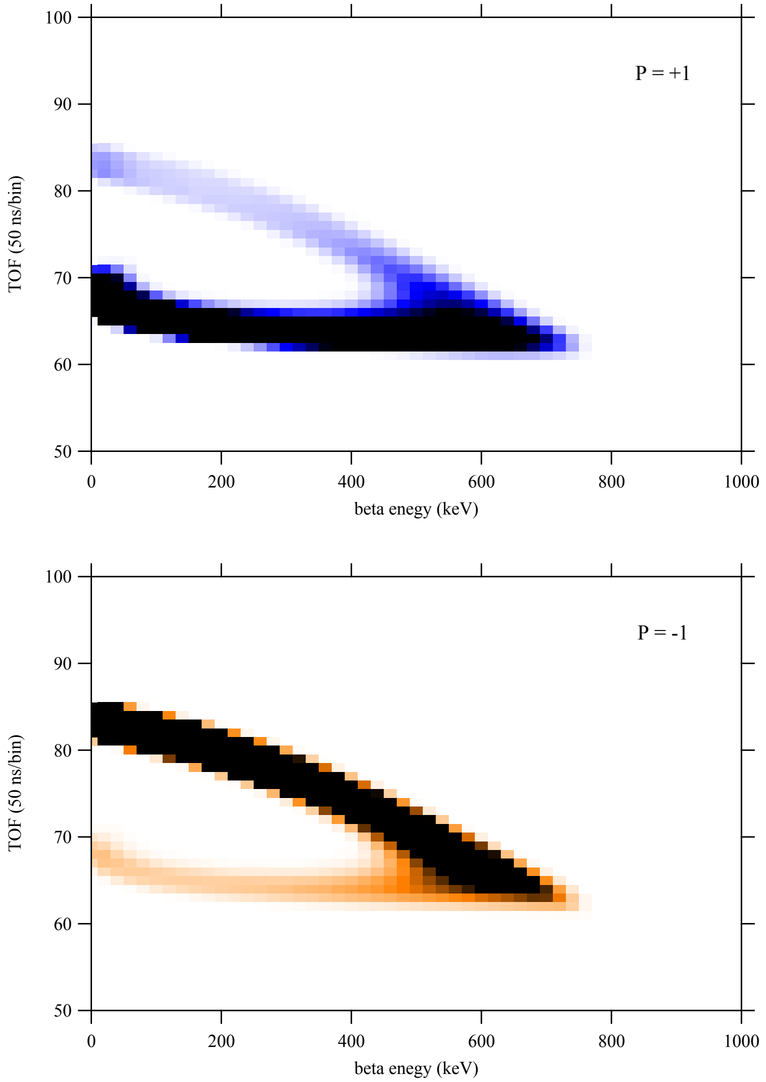


Systematics

	correction	σ
electrostatic mirror	0.0058	0.0012
absolute B field	-0.0001	0.0005
B field shape	0.0003	0.0008
proton soft threshold	-0.0031	0.0007
residual gas	0.0005	0.0005
e scattering	-0.0015	0.0015
beta spect. energy cal.		0.00031
proton collimator alignment	0.00041	0.0005
p scattering		0.00050
wishbone asymmetry calc.		0.0008
total systematic	0.0023	0.0026

all but two are strongly cancelled by the spin flip

goal: $\frac{\sigma_B}{B} < 0.003\ \text{(sys)}$



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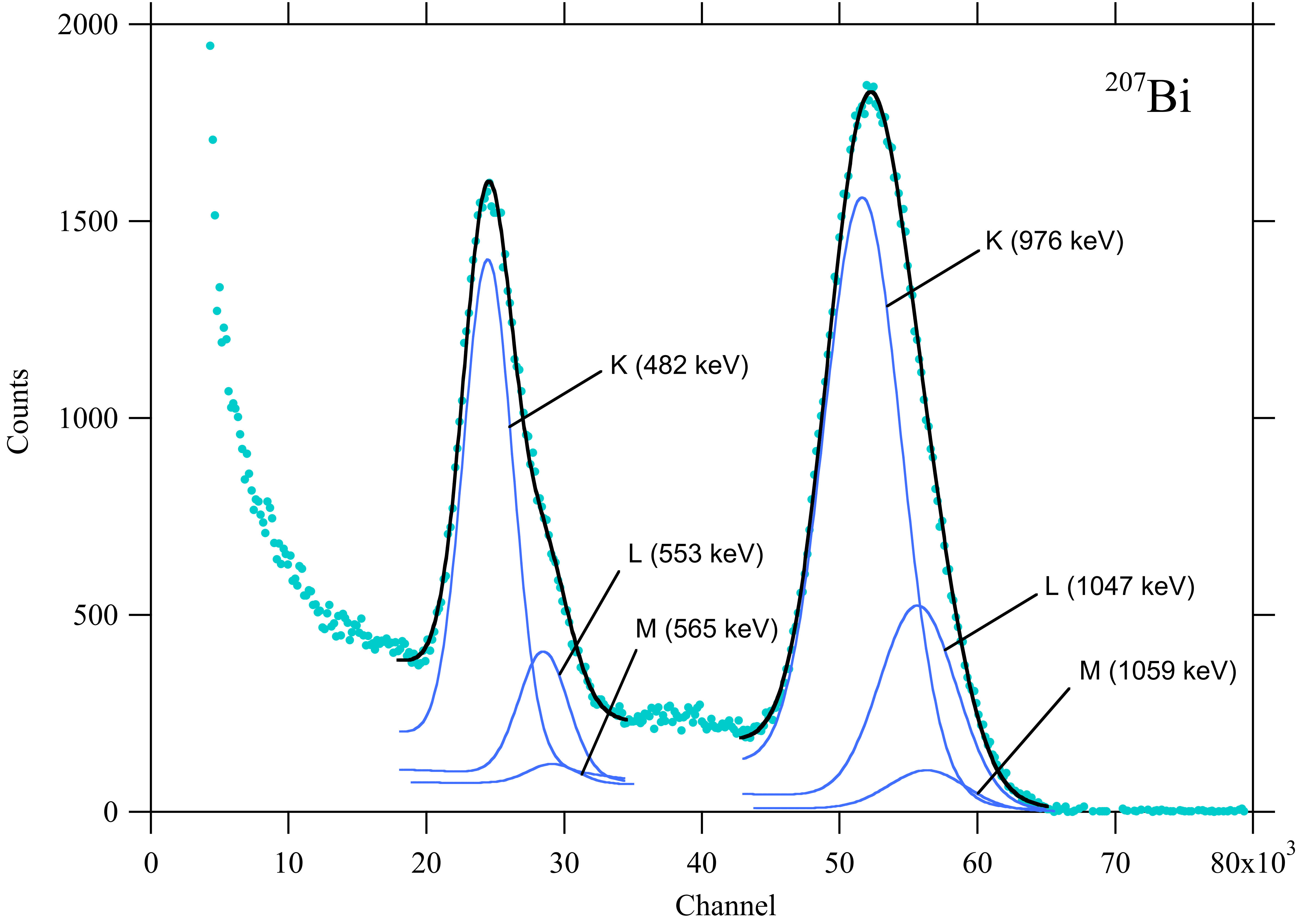
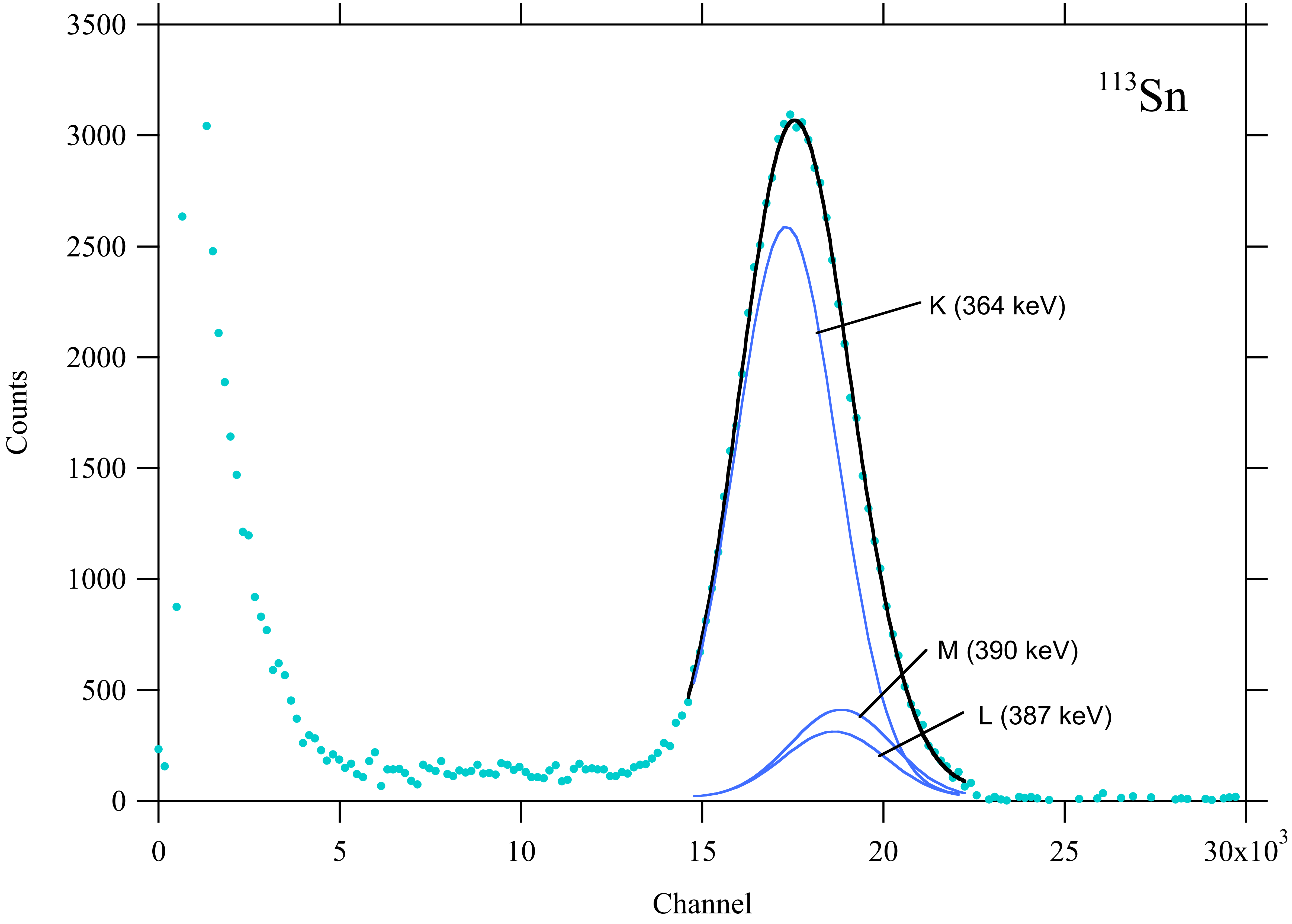
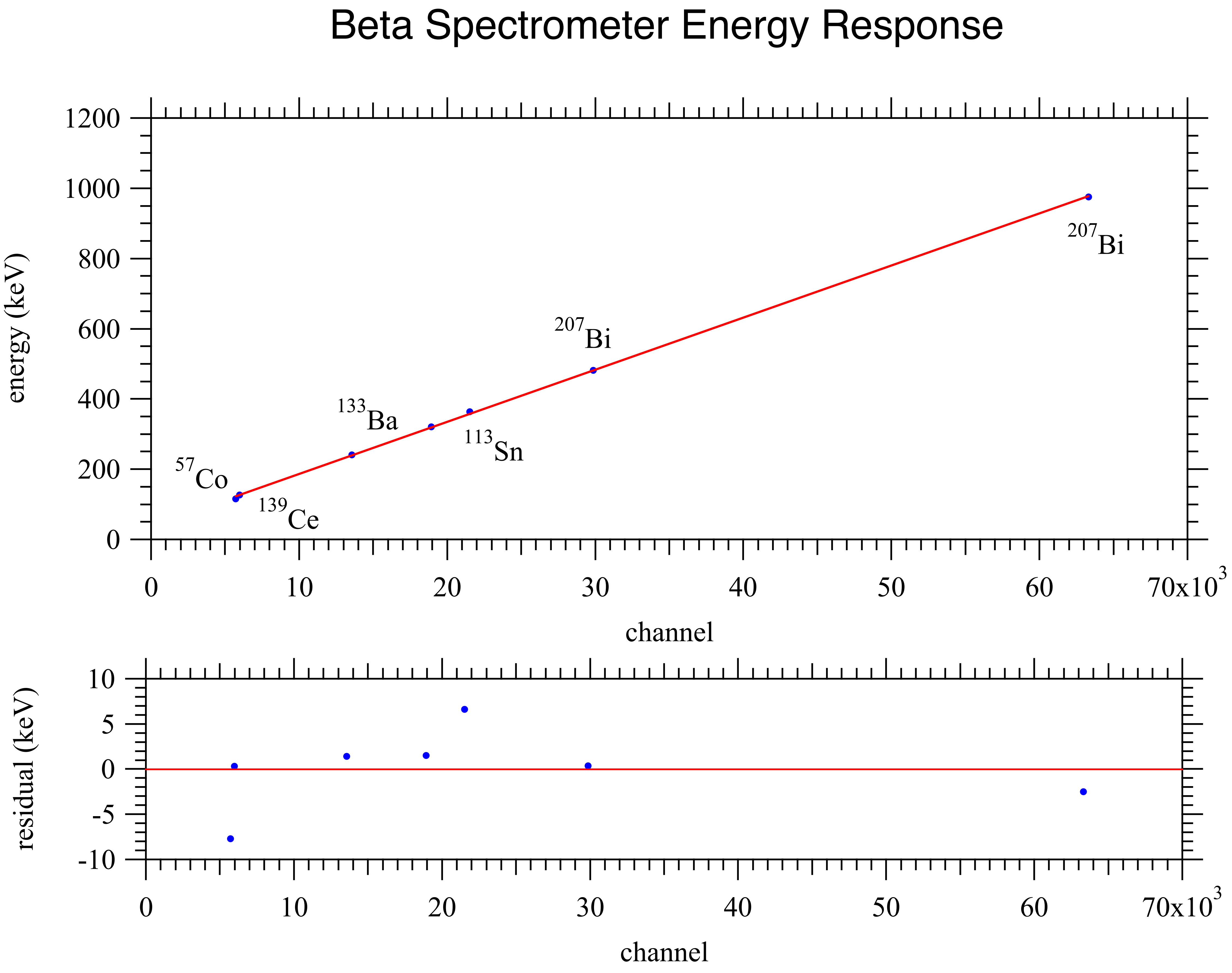
NIST, U.S. Dept. of Commerce

U.S. Dept. of Energy Office of Science

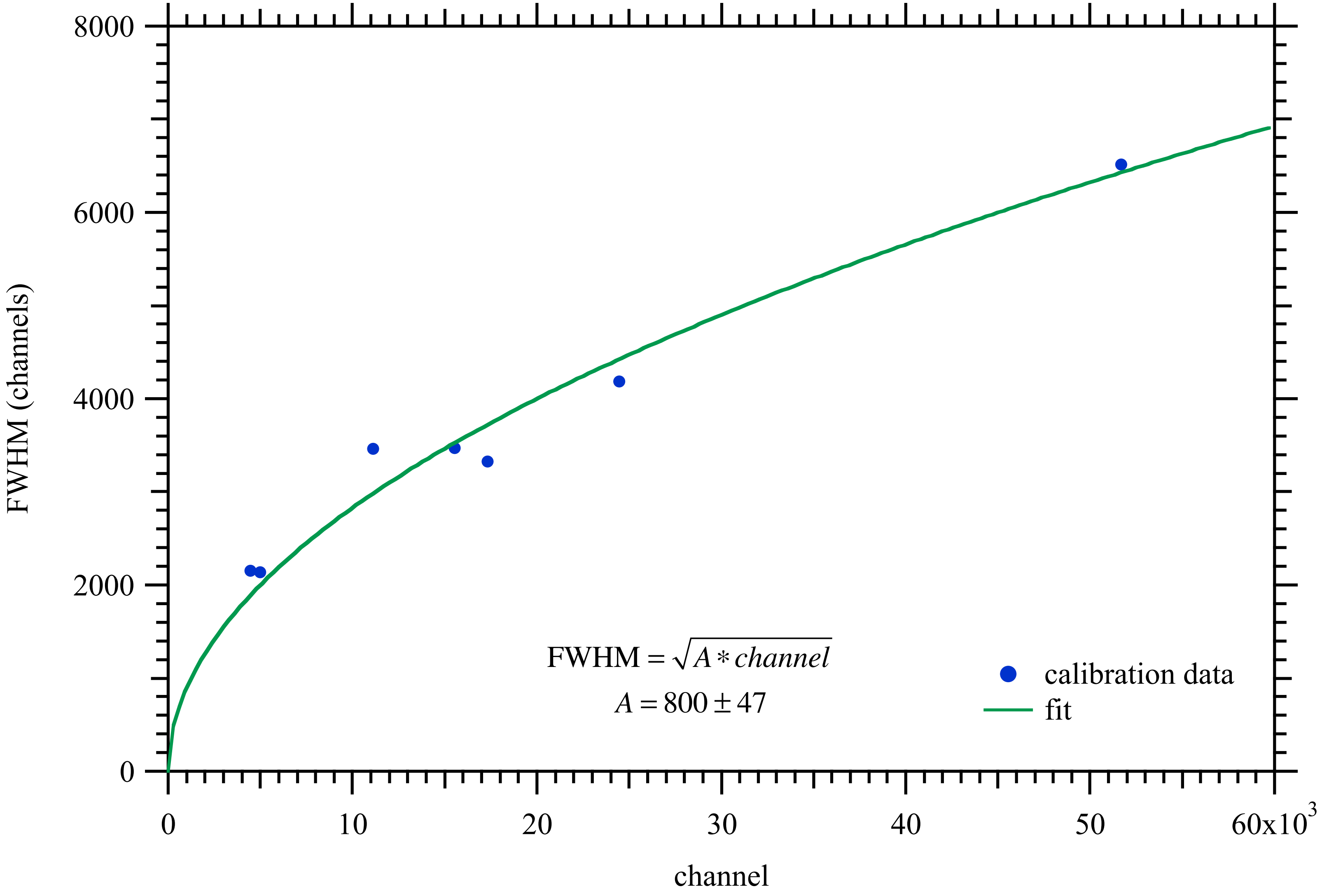
Thank you!


^{207}Bi
K (482 keV)
L (553 keV)
M (565 keV)
K (976 keV)
L (1047 keV)
M (1059 keV)
Counts
2000
1500
1000
500
0
0
10
20
30
40
50
60
70
80x10^3
Channel


^{113}Sn
K (364 keV)
M (390 keV)
L (387 keV)
Counts
Channel
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30x10^3


Beta Spectrometer Energy Response
energy (keV)
1200
1000
800
600
400
200
0
^{207}Bi
^{207}Bi
^{133}Ba
^{113}Sn
^{57}Co
^{139}Ce
0
10
20
30
40
50
60
70x10^3
channel
residual (keV)
10
5
0
-5
-10
0
10
20
30
40
50
60
70x10^3
channel

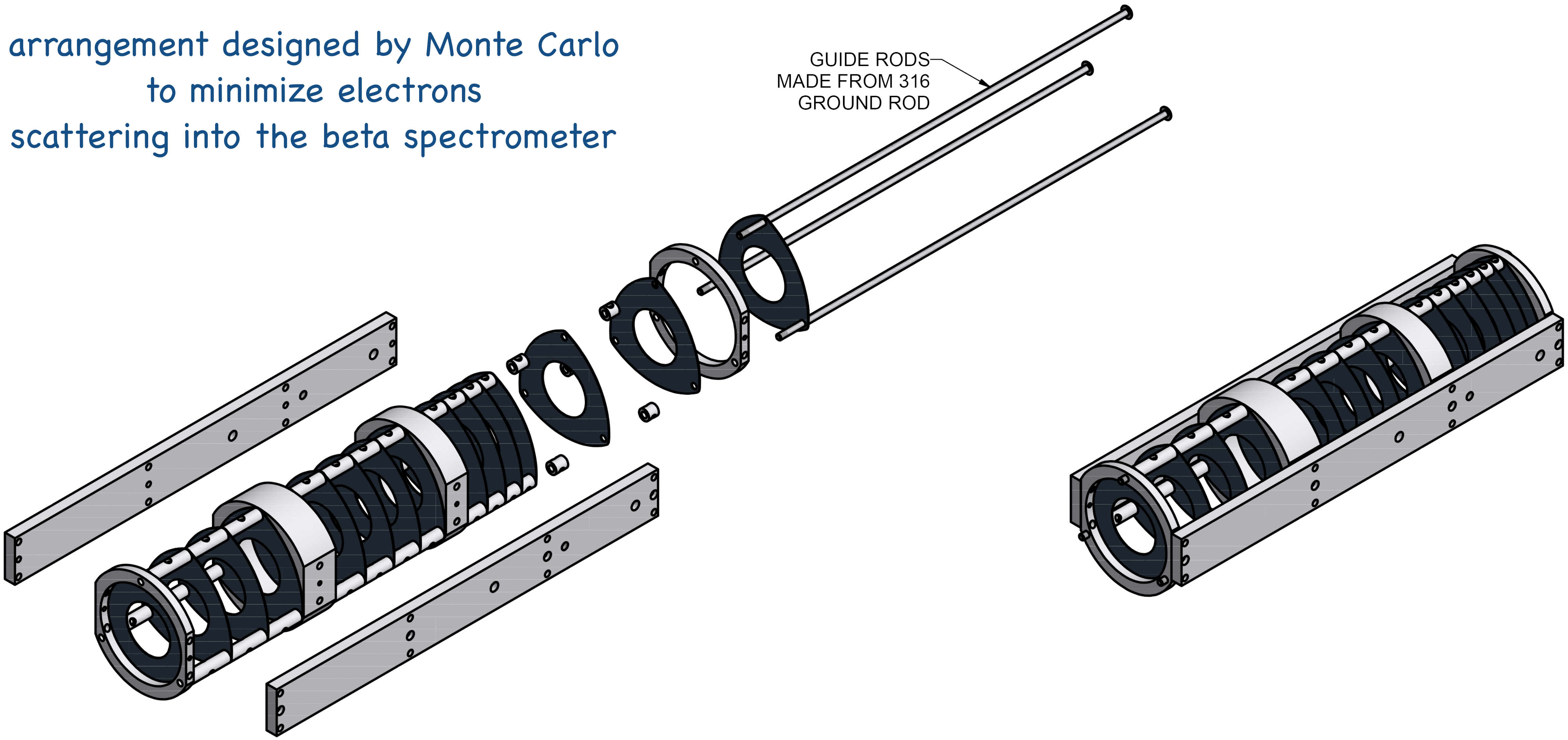
Beta Spectrometer Energy Resolution (FWHM)



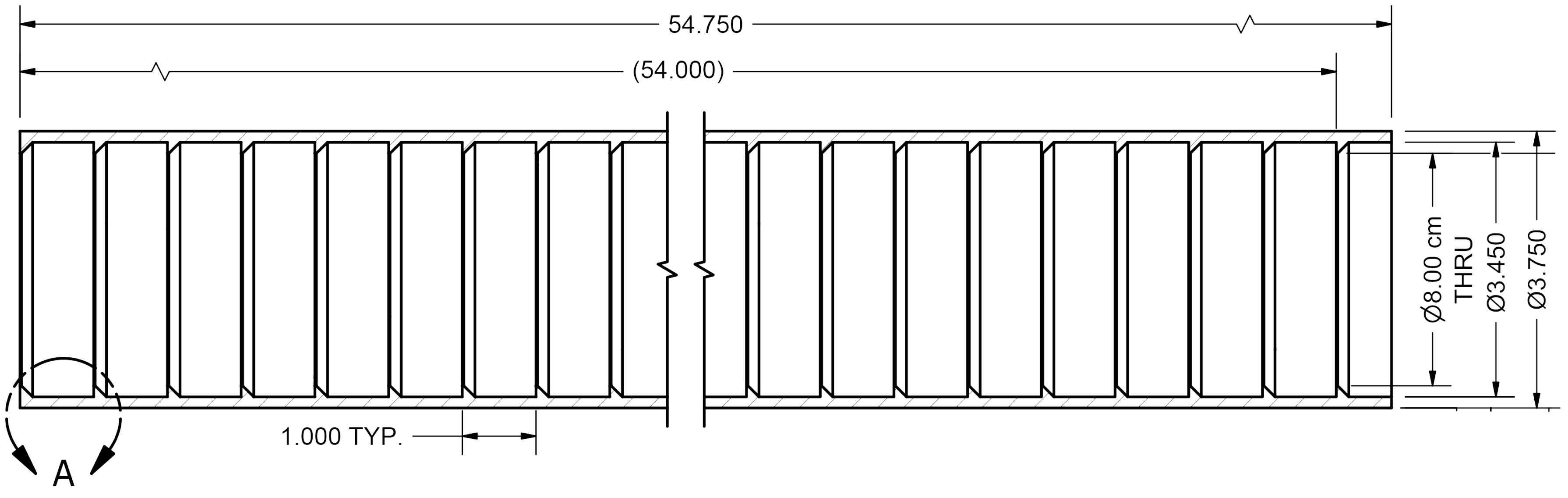
Beta Collimator

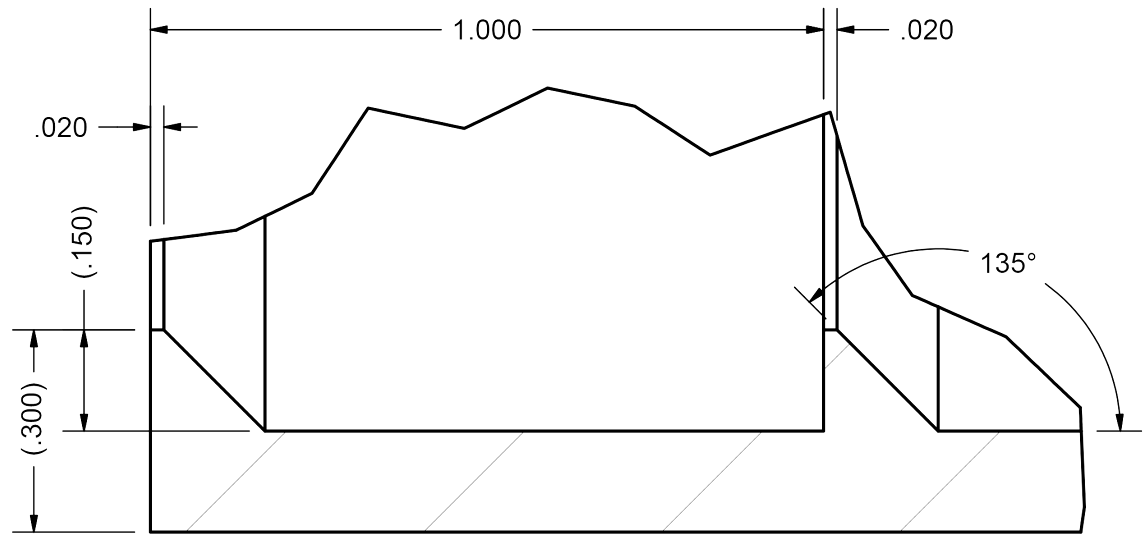
17 x 0.5 mm precision cut
tungsten collimation elements
with graded spacing
axes aligned to 0.005”

arrangement designed by Monte Carlo
to minimize electrons
scattering into the beta spectrometer



Proton collimator

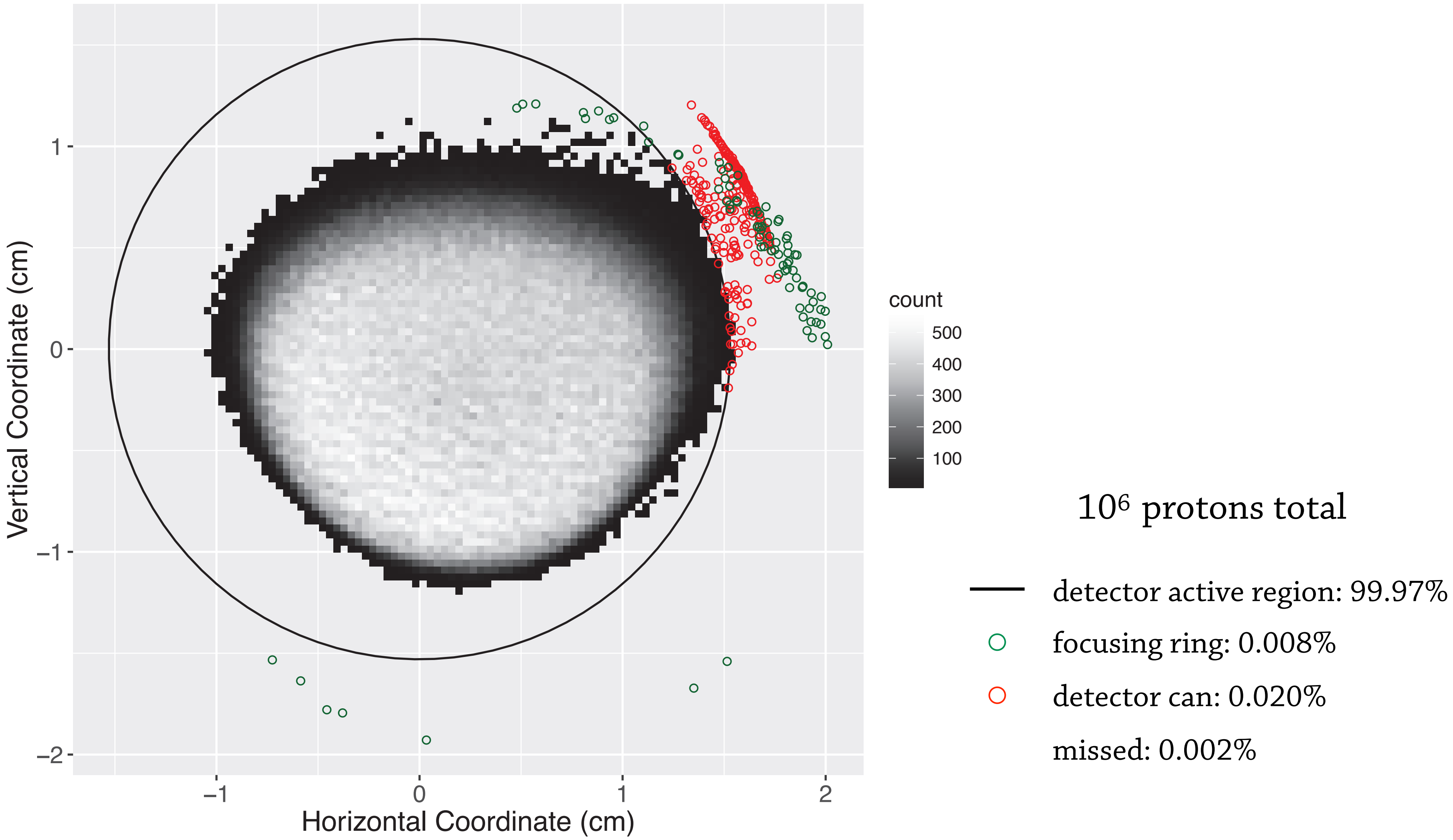




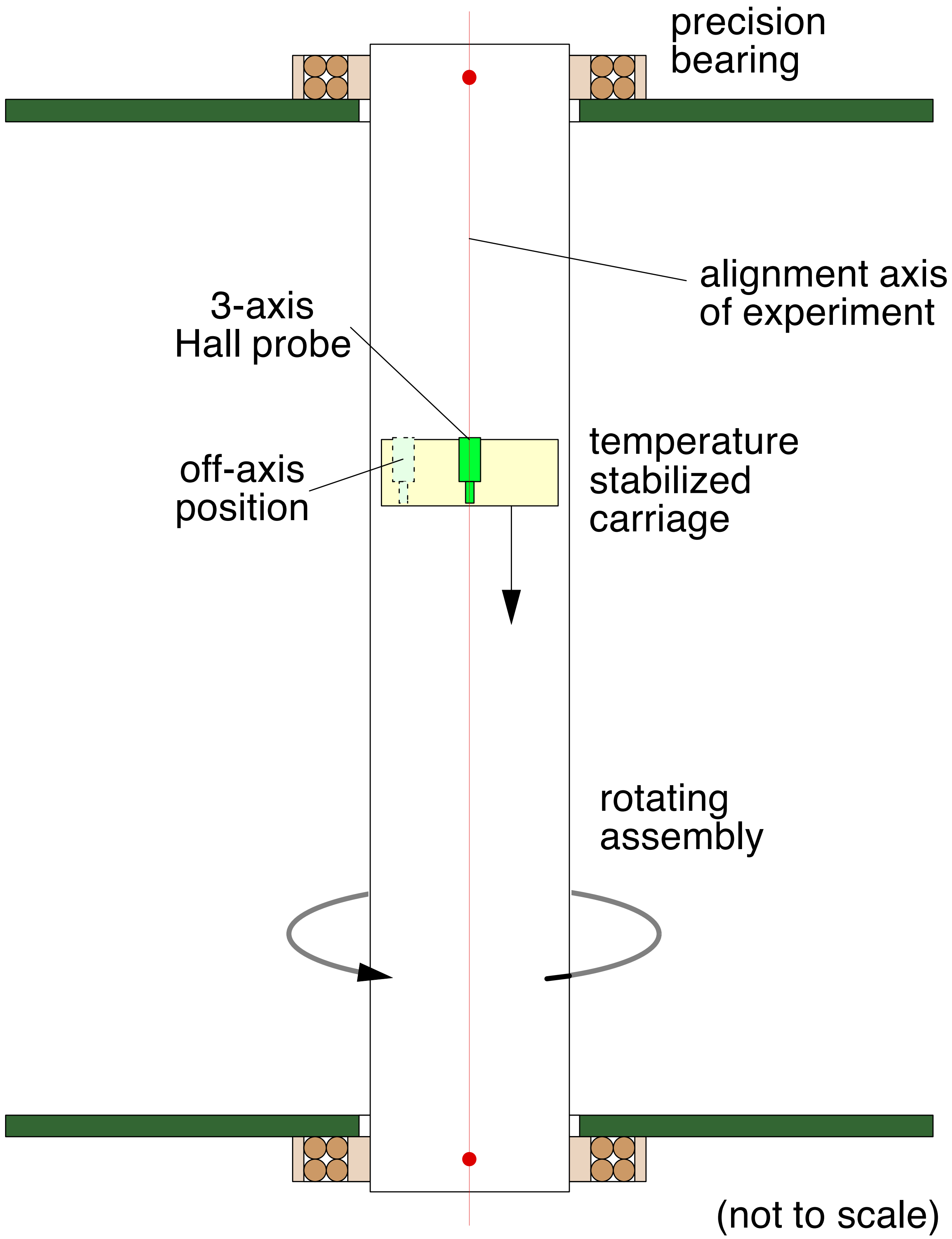
DETAIL A, TYP. 55 PLACES

140 cm long monolithic Al tube with 55 precision-turned collimation elements

Proton Focusing Simulation



aCORN magnetic field mapper



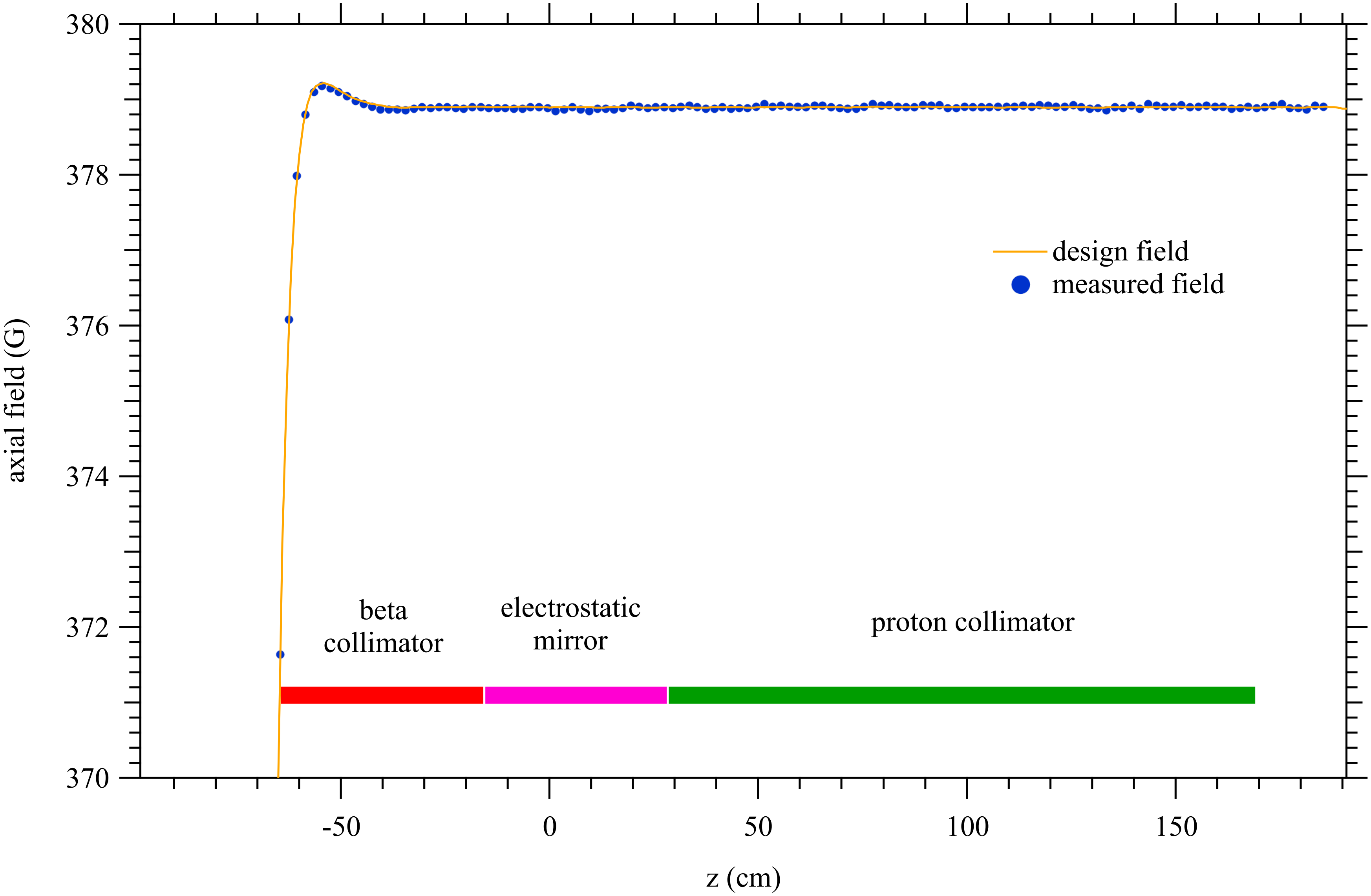
Precision bearings at top and bottom define a precise alignment axis.

Computer-controlled servo motors rotate and translate the mapper to separate axial and transverse field components.

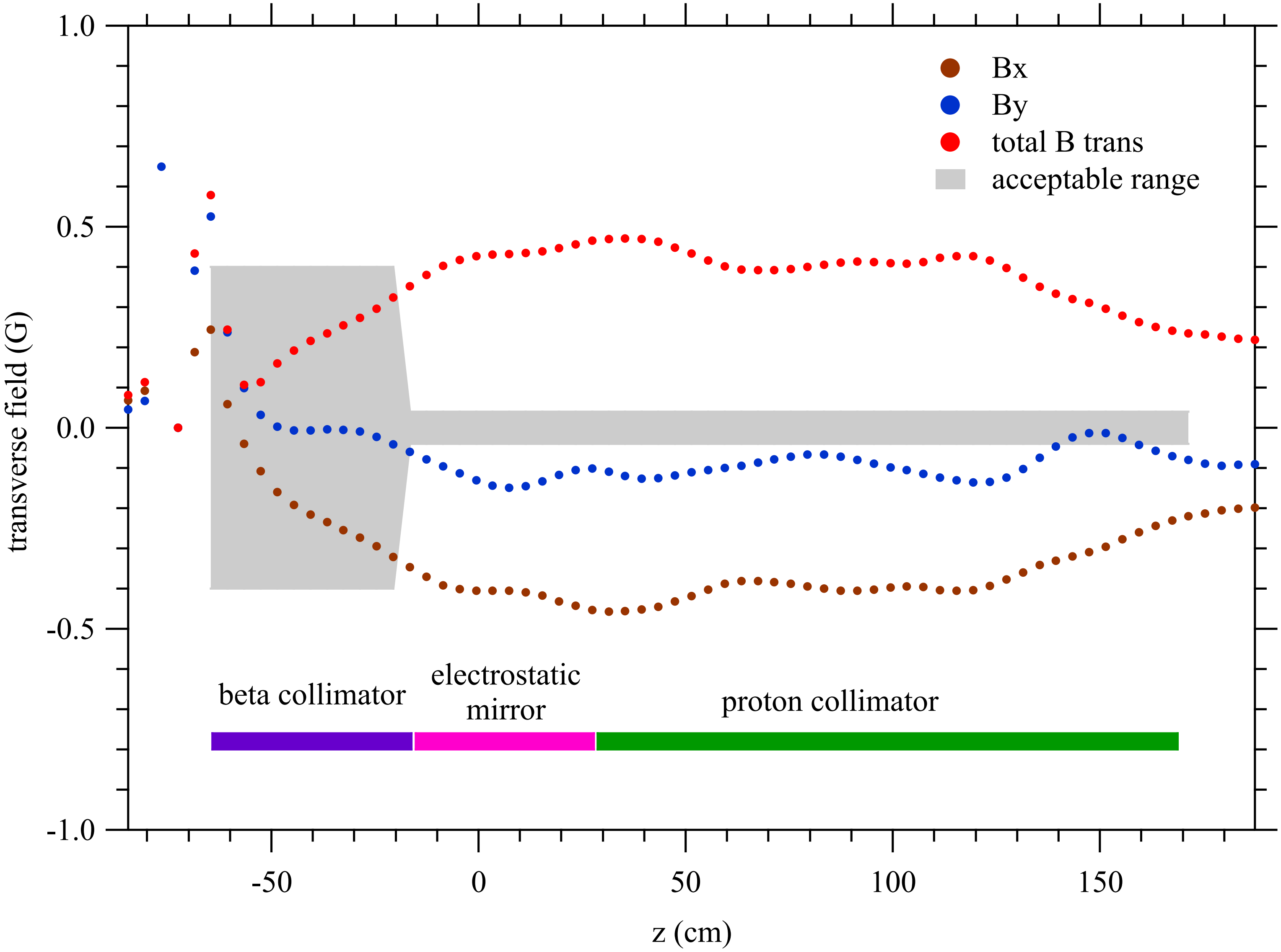
The off-axis Hall probe measures field gradients.

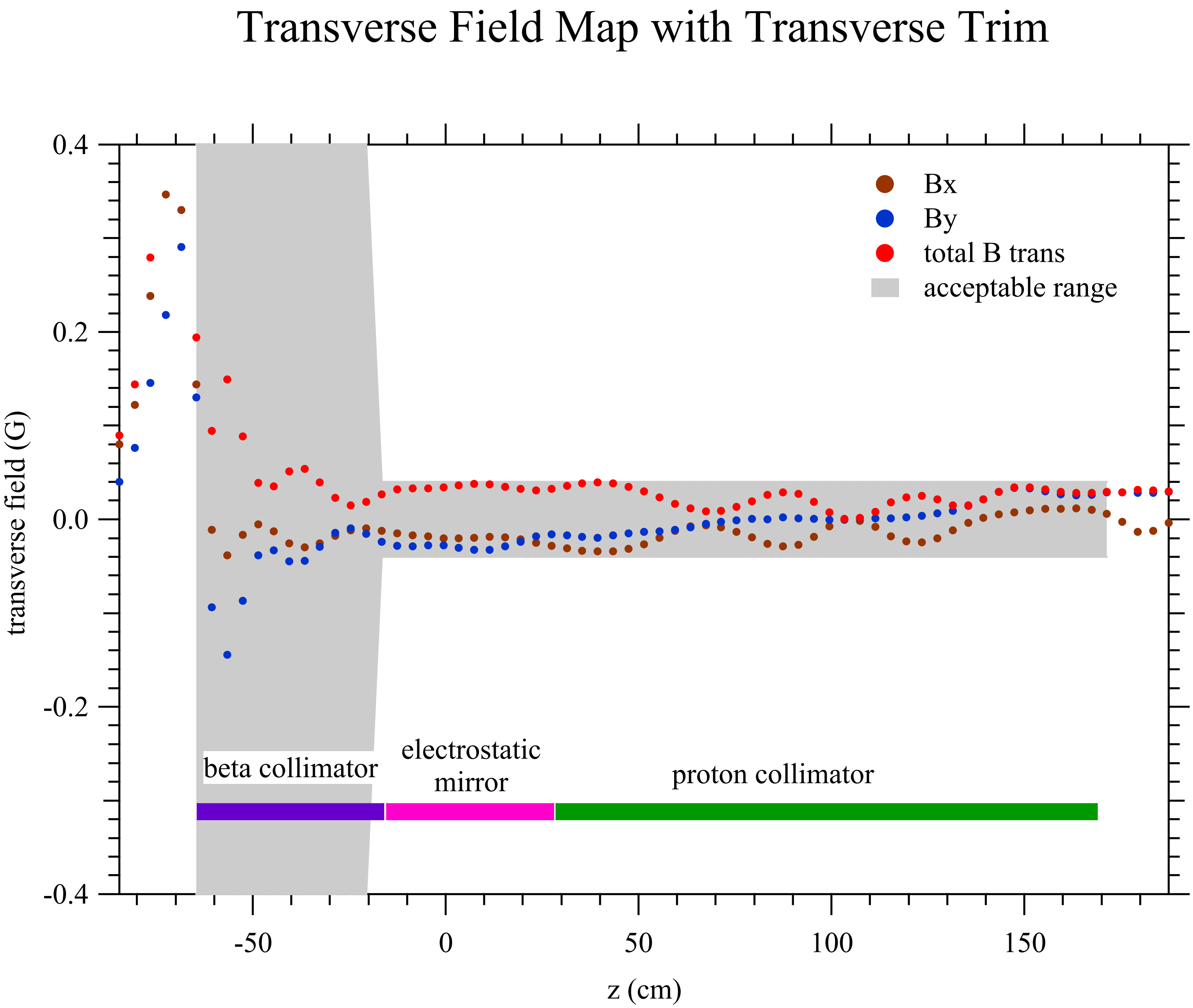
The collimation insert is later optically aligned to the bearing centers.

aCORN Axial Magnetic Field



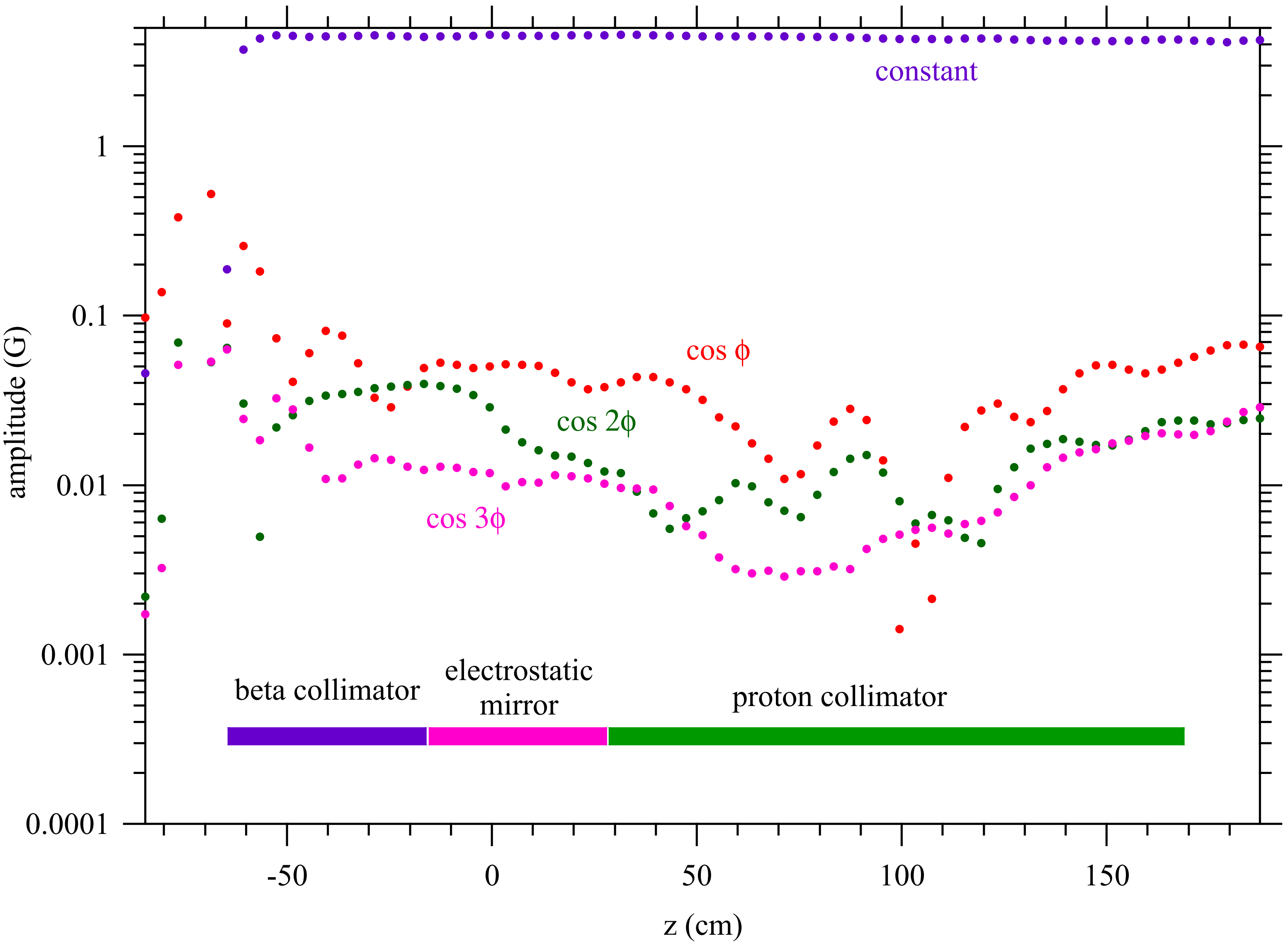
Transverse Field Map with No Transverse Trim



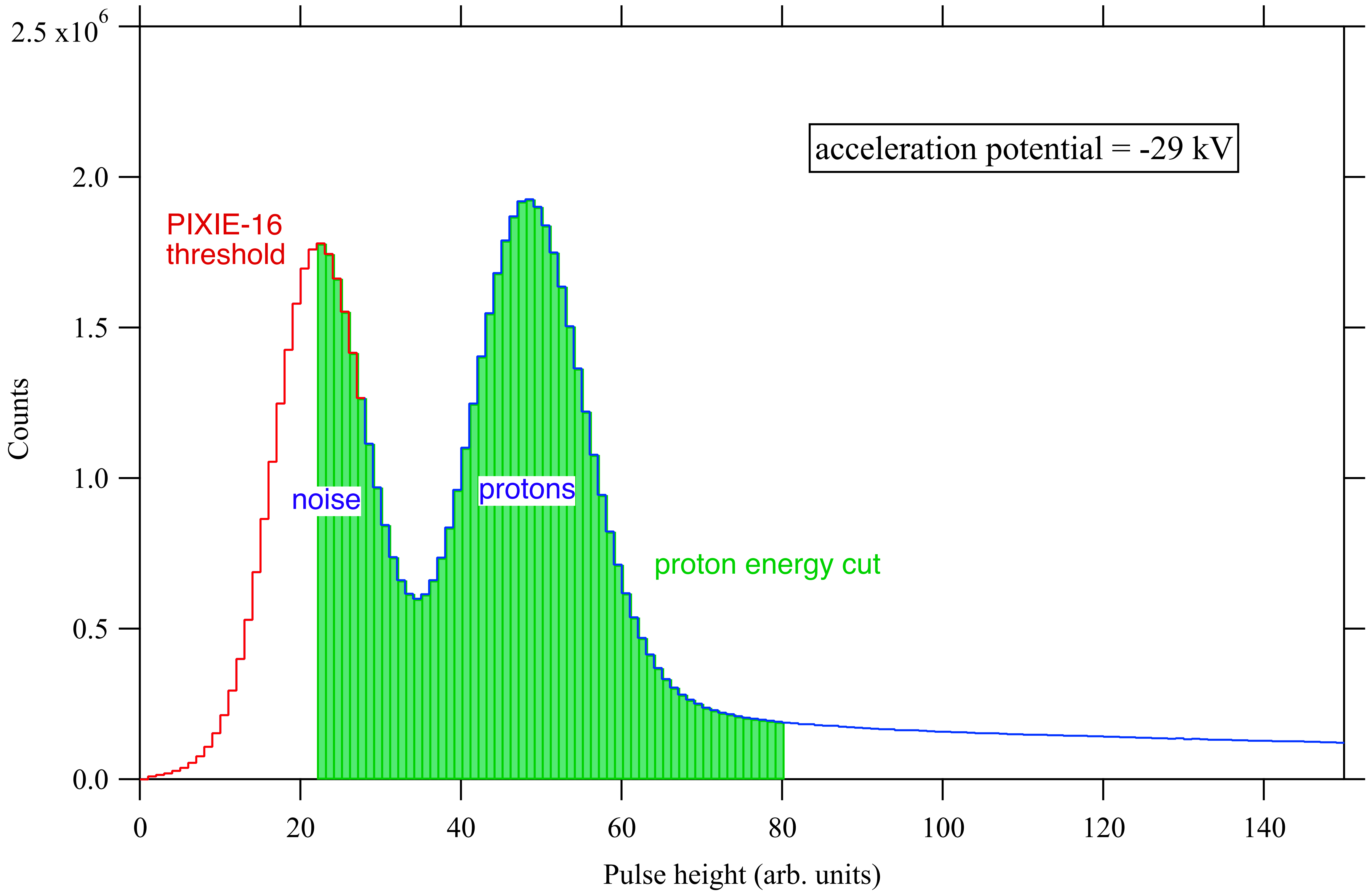


Transverse Field Map with Transverse Trim

Transverse Decomposition, With Transverse Trim, V Probe



Proton Energy Spectrum



Electrostatic mirror correction

detailed 3D COMSOL model of NG-6 mirror

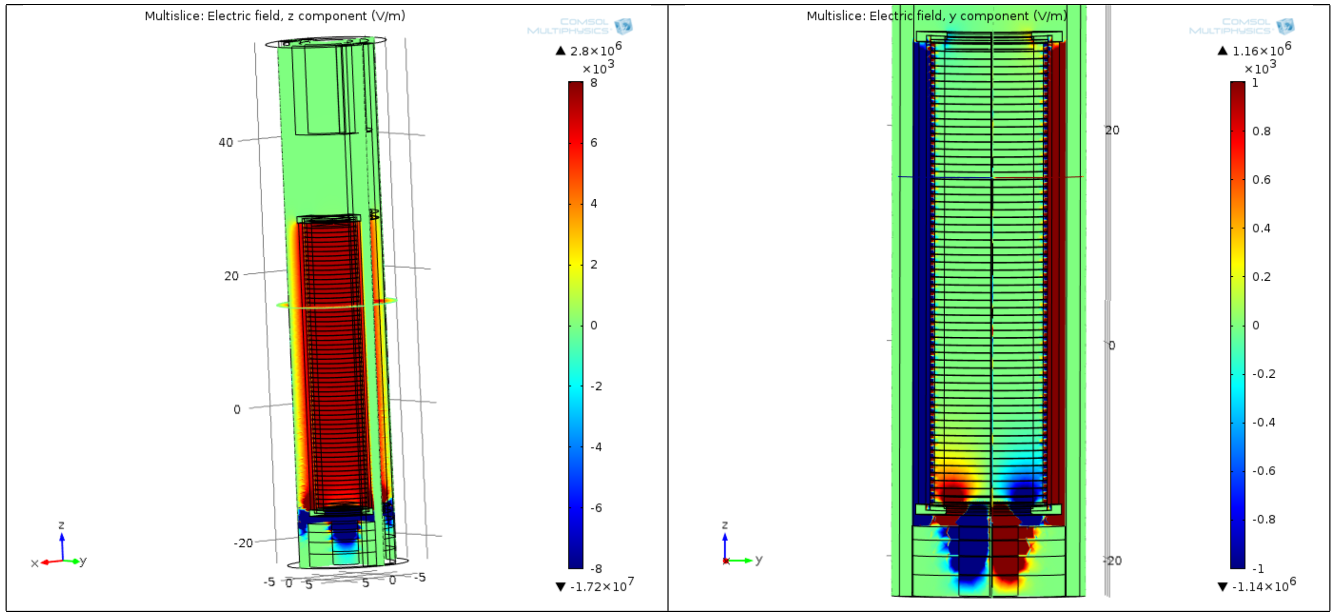
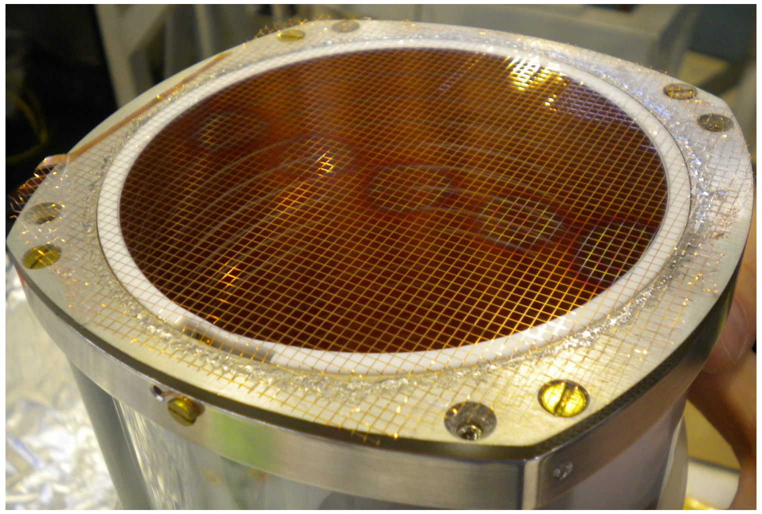
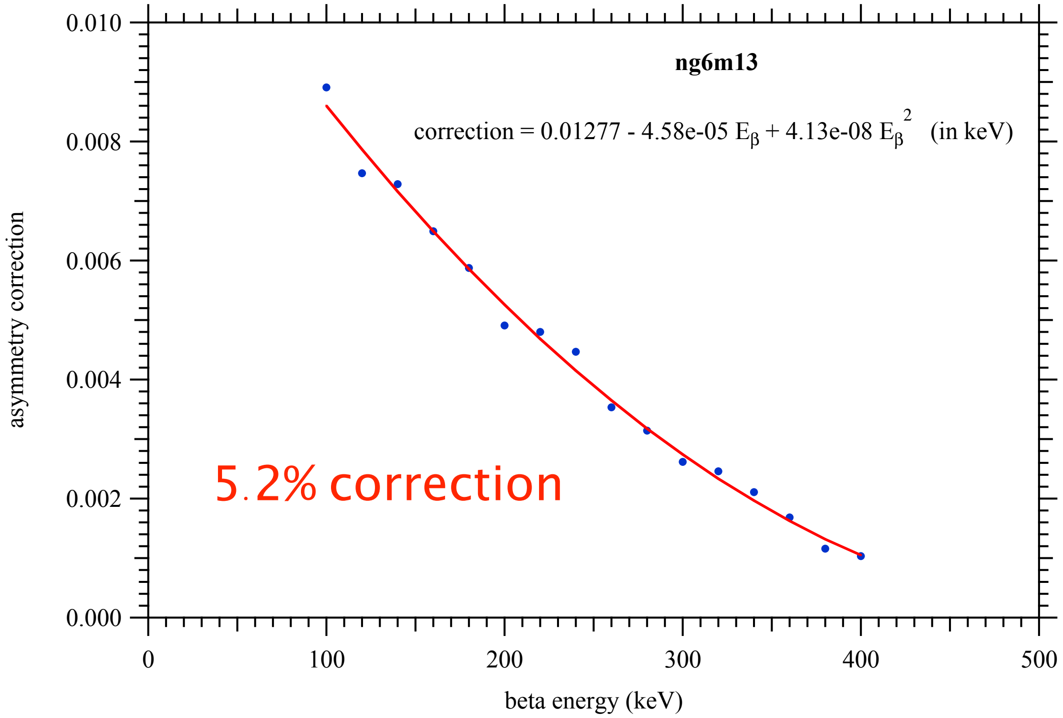


Figure 2: Axial (l) and Transverse (r) Electric fields in NG6Mirror13

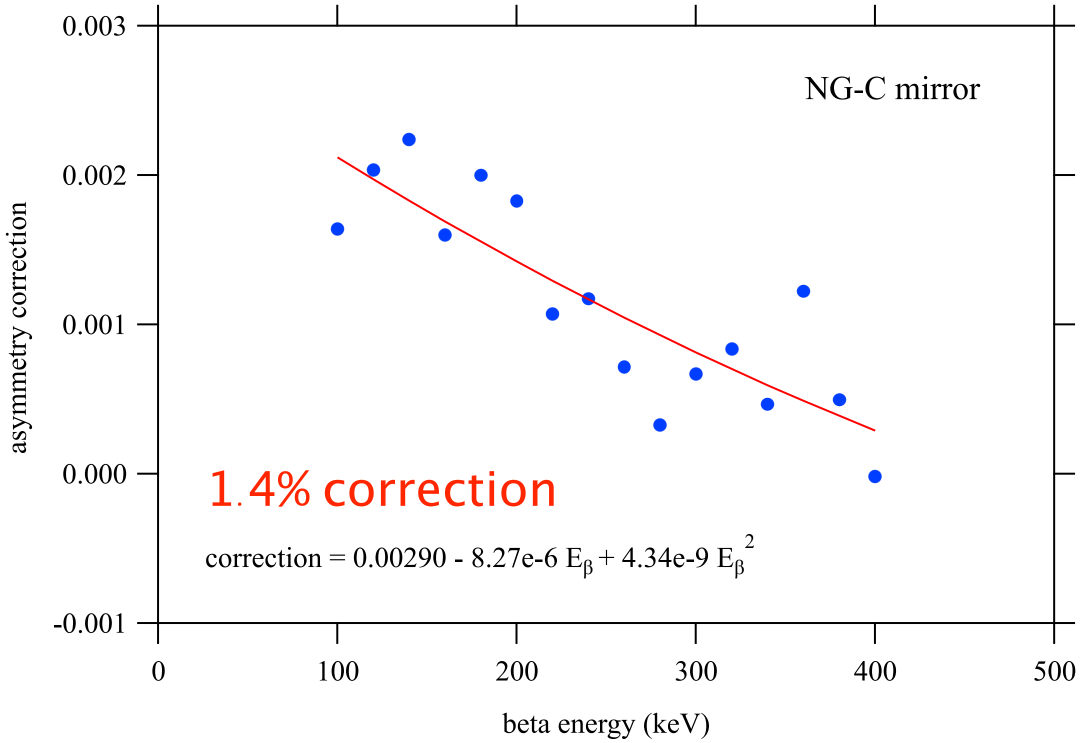
crossed wire top grid (NG-C)



4th order RK p transport simulation



5.2% correction



1.4% correction

Beta backscatter systematic correction