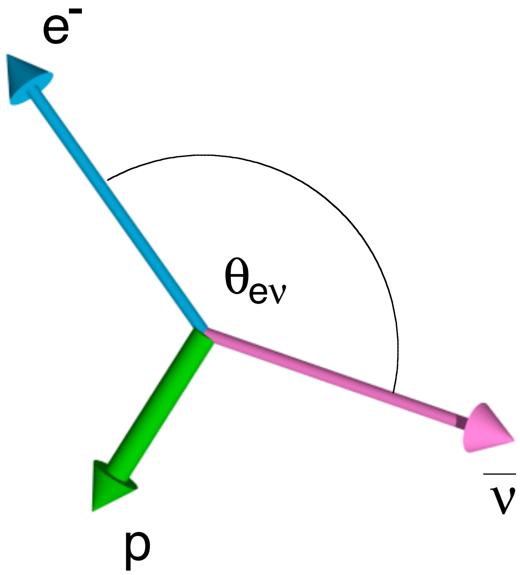
aCORN

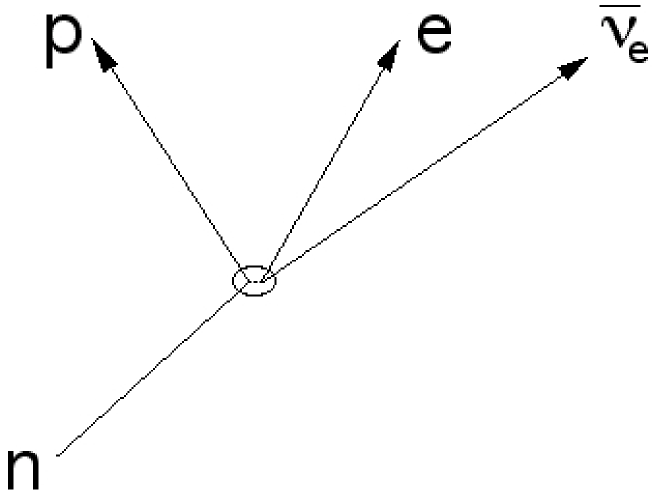
A New Experiment to Measure the Electron-Antineutrino Correlation “a” in Neutron Beta Decay

F. E. Wietfeldt

Physics Department
Tulane University
New Orleans, LA

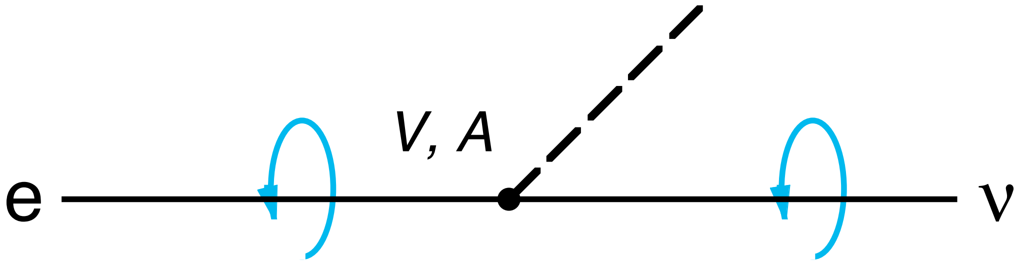


Neutron Beta Decay Hamiltonian

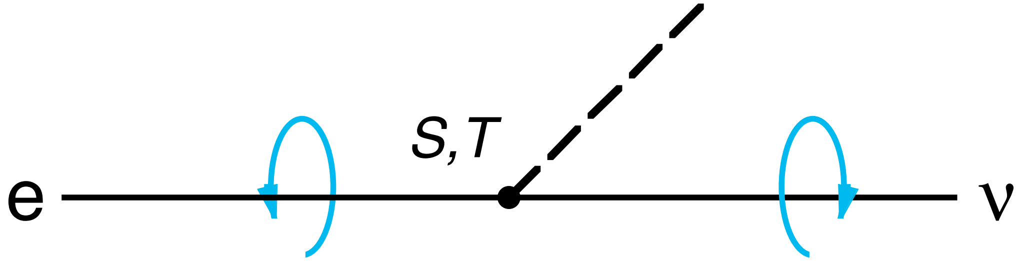


$$\mathcal{H}_{\beta} = \frac{G_F}{\sqrt{2}} \sum_j \int d^3x \left[\bar{\Psi}_p O_j \Psi_n\right]\left[\bar{\Psi}_e O_j (C_j - C'_j \gamma_5) \Psi_\nu\right]$$

scalar:	C_S , C_S'	$O_S = 1$	pseudoscalar:	C_P , C_P'	$O_P = \gamma_5$	(negligible)
vector:	C_V , C_V'	$O_V = \gamma_\mu$	axial vector:	C_A , C_A'	$O_A = \gamma_5 \gamma_\mu$	
tensor:	C_T , C_T'	$O_T = \sigma_{\mu\nu}$				



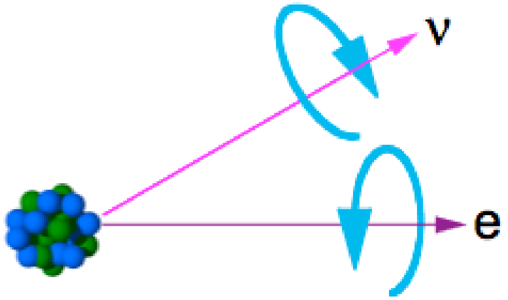
helicity preserving



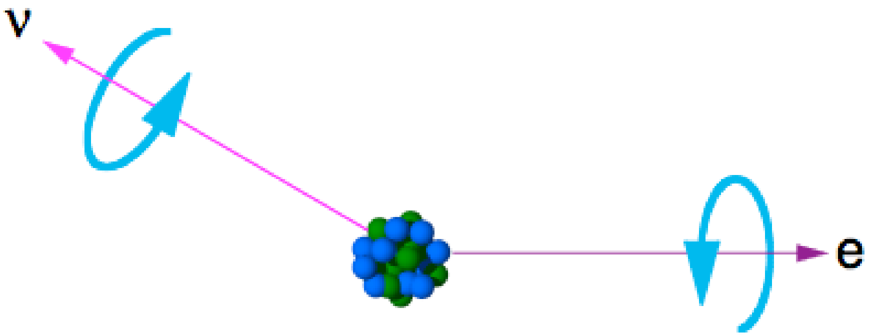
helicity reversing

Look at e-ν correlation in beta decay (Bloch, Møller 1935)

Fermi
(lepton $S = 0$)

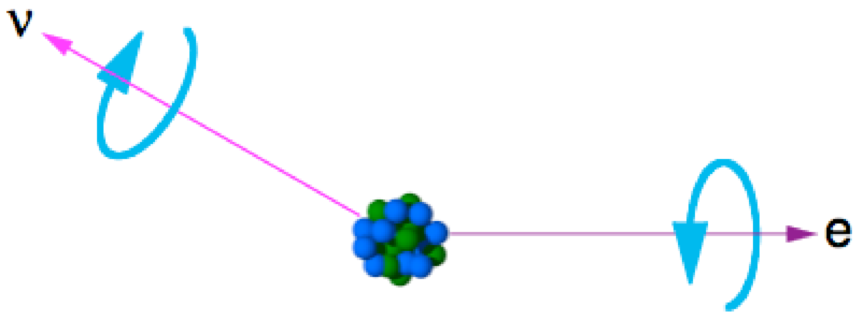


Vector: $a = +1$

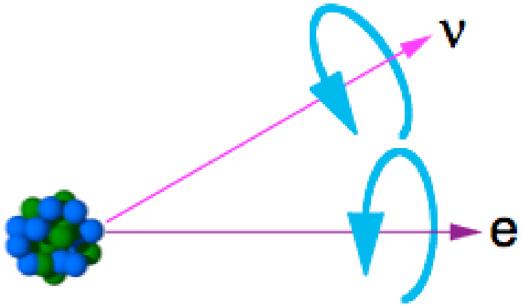


Scalar: $a = -1$

Gamow-Teller
(lepton $S = 1$)



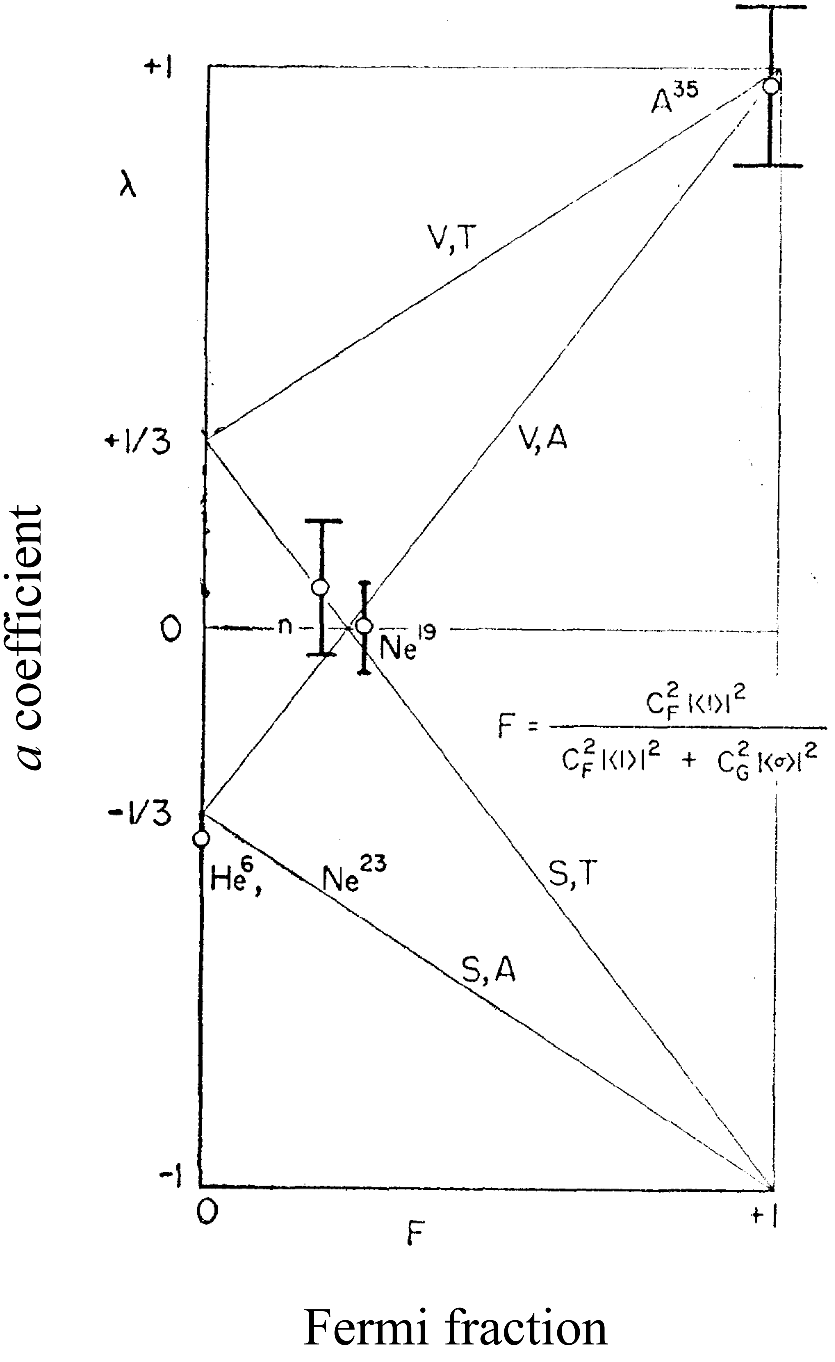
Axial Vector: $a = -1/3$



Tensor: $a = +1/3$

Established the V, A nature of the weak interaction

Allen, *et al.*,
Phys. Rev. 116, 134 (1959)



Experimental evidence from beta decay shows:

(Boothroyd *et al.* 1984, García *et al.* 2000, Hardy and Towner 2005)

$C_V = C'_V$ and $C_A = C'_A$ (within ~1%)

$$\left|\frac{C_S + C'_S}{C_V}\right| < 0.002 \quad \text{and} \quad \left|\frac{C_T + C'_T}{C_A}\right| < 0.01$$

$$\left|\frac{C_S}{C_V}\right|, \left|\frac{C'_S}{C_V}\right| < 0.1 \quad \text{and} \quad \left|\frac{C_T}{C_A}\right|, \left|\frac{C'_T}{C_A}\right| < 0.2$$

This is the basis of the V-A theory of weak interactions, assumed by the Electroweak Standard Model

BUT...

non-standard physics (SUSY, RHC, GUT's, extra Higgs, etc.) could lead to deviations observable in beta decay

Neutron decay: theoretically cleanest nuclear beta decay, mixed Fermi-GT

Neutron Decay Parameters

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

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

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

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

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

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

Present Experimental values*

$\tau = 885.7 \pm 0.8$ s

$A = -0.1173 \pm 0.0013$

$B = 0.981 \pm 0.004$

$a = -0.103 \pm 0.004$

$D = -0.4 \pm 0.6 \times 10^{-3}$

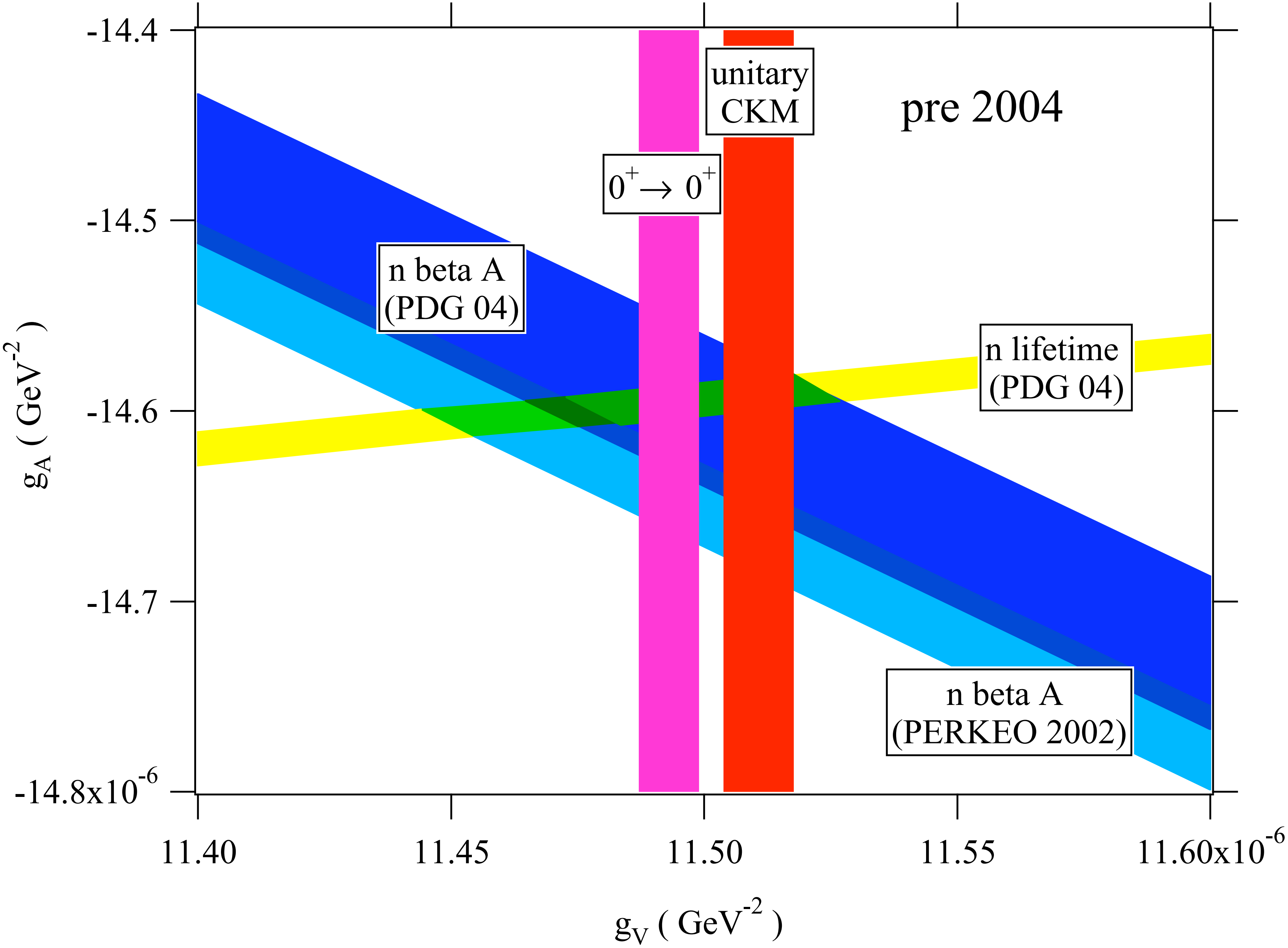
$\lambda = -1.2695 \pm 0.0029$

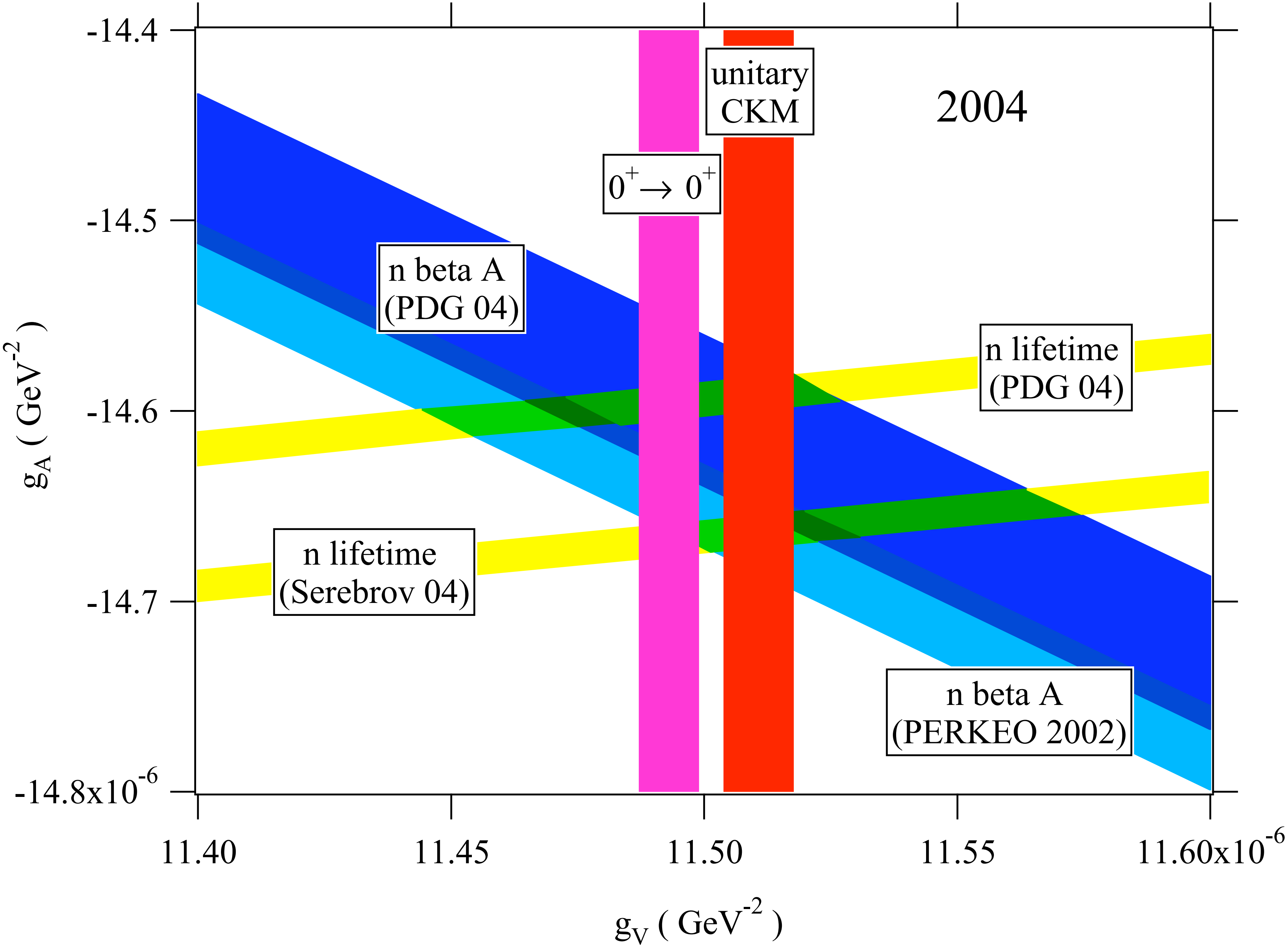
Ultimate objective:

0.1% precision for all parameters:

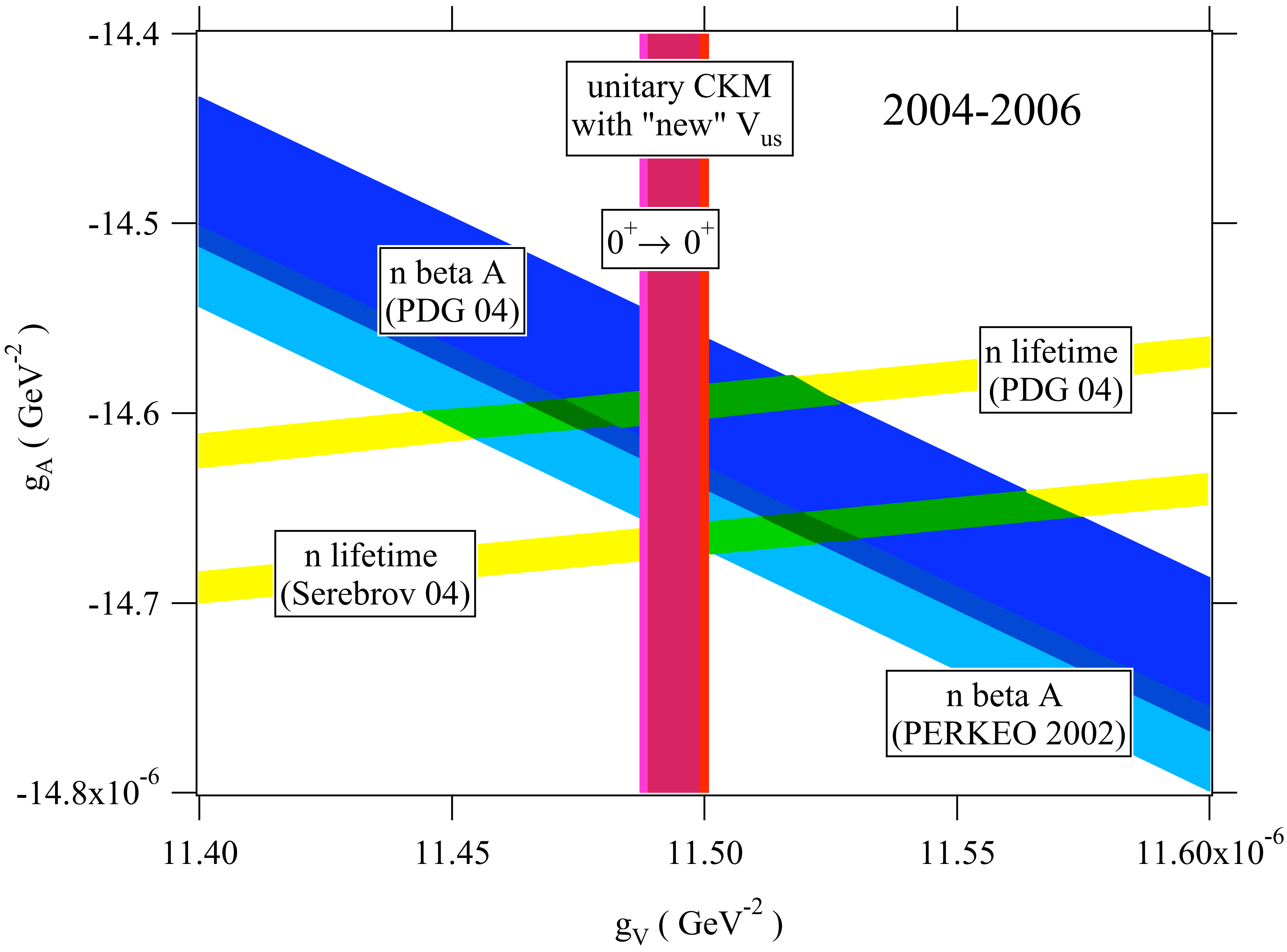
- important limits on S,T currents, RH currents, CVC violation, SCC
- recoil order effects become important

* *Review of Particle Physics*, J. Phys G **33** (2006)

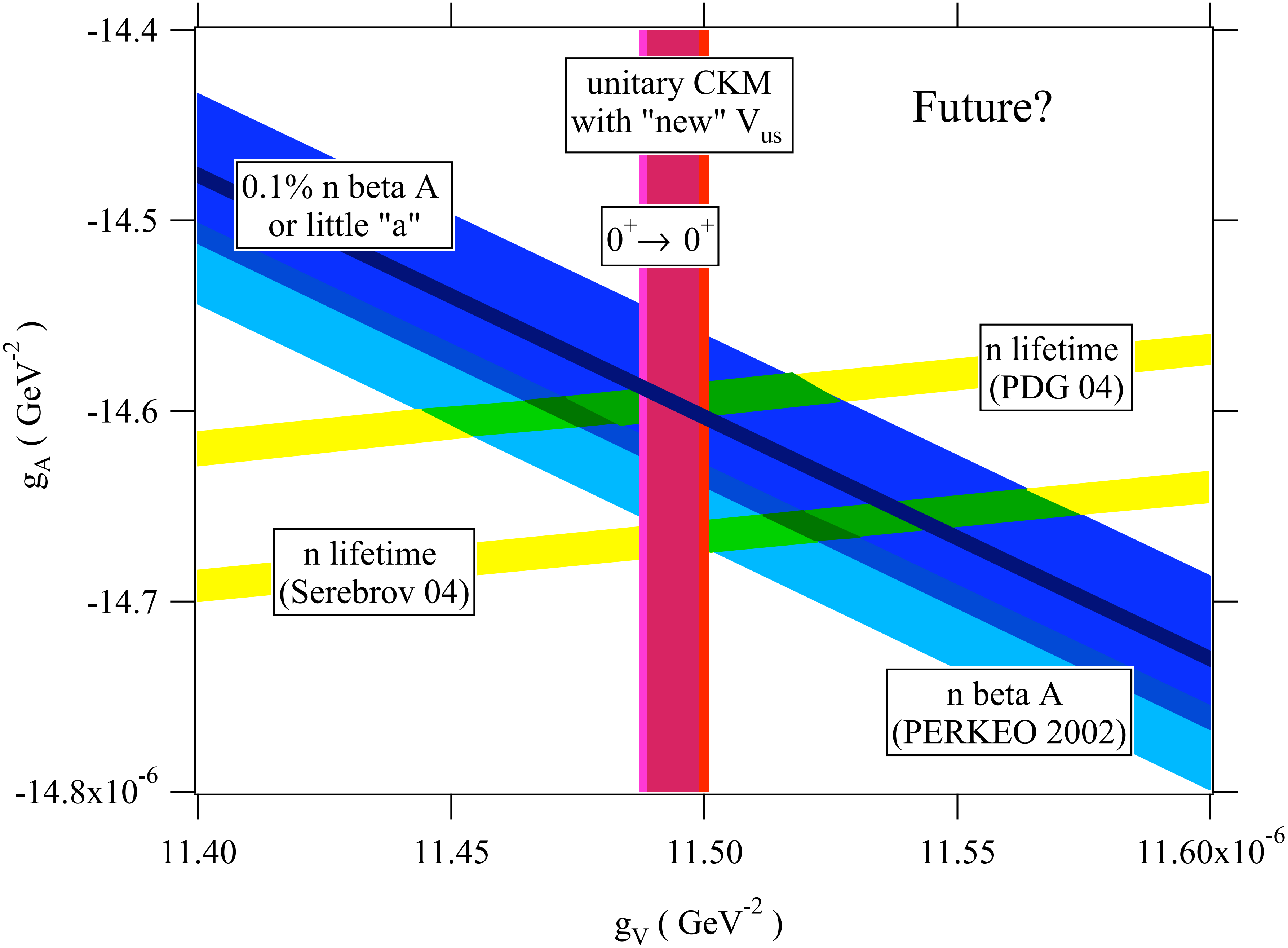

pre 2004
unitary CKM
$0^+ \rightarrow 0^+$
n beta A (PDG 04)
n lifetime (PDG 04)
n beta A (PERKEO 2002)
-14.4
-14.5
-14.6
-14.7
-14.8x10^{-6}
g_A (GeV^{-2})
11.40
11.45
11.50
11.55
11.60x10^{-6}
g_V (GeV^{-2})



2004
unitary CKM
$0^+ \rightarrow 0^+$
n beta A (PDG 04)
n lifetime (PDG 04)
n lifetime (Serebrov 04)
n beta A (PERKEO 2002)
-14.4
-14.5
-14.6
-14.7
-14.8x10^{-6}
11.40
11.45
11.50
11.55
11.60x10^{-6}
g_A (GeV^{-2})
g_V (GeV^{-2})



2004-2006
unitary CKM with "new" V_{us}
$0^+ \rightarrow 0^+$
n beta A (PDG 04)
n lifetime (PDG 04)
n lifetime (Serebrov 04)
n beta A (PERKEO 2002)
-14.4
-14.5
-14.6
-14.7
-14.8×10^{-6}
g_A (GeV^{-2})
11.40
11.45
11.50
11.55
11.60×10^{-6}
g_V (GeV^{-2})



-14.4
-14.5
-14.6
-14.7
-14.8x10^{-6}
g_A (GeV^{-2})
11.40
11.45
11.50
11.55
11.60x10^{-6}
g_V (GeV^{-2})
unitary CKM
with "new" V_{us}
Future?
0.1% n beta A
or little "a"
$0^+ \rightarrow 0^+$
n lifetime
(PDG 04)
n lifetime
(Serebrov 04)
n beta A
(PERKEO 2002)

Reasons to measure "*a*" more precisely

- determines λ (g_A/g_V), with similar sensitivity as *A*, but **without** requiring polarimetry

- helps resolve the CKM unitarity question

- improves tests of self-consistency of the EW Standard Model:

predicted	actual
$F_1 = 1 + A - B - a = 0$	$F_1 = 0.0025 \pm 0.0064$
$F_2 = aB - A - A^2 = 0$	$F_2 = 0.0034 \pm 0.0050$

- *a* and *A* together improve limits on scalar and tensor currents in neutron decay

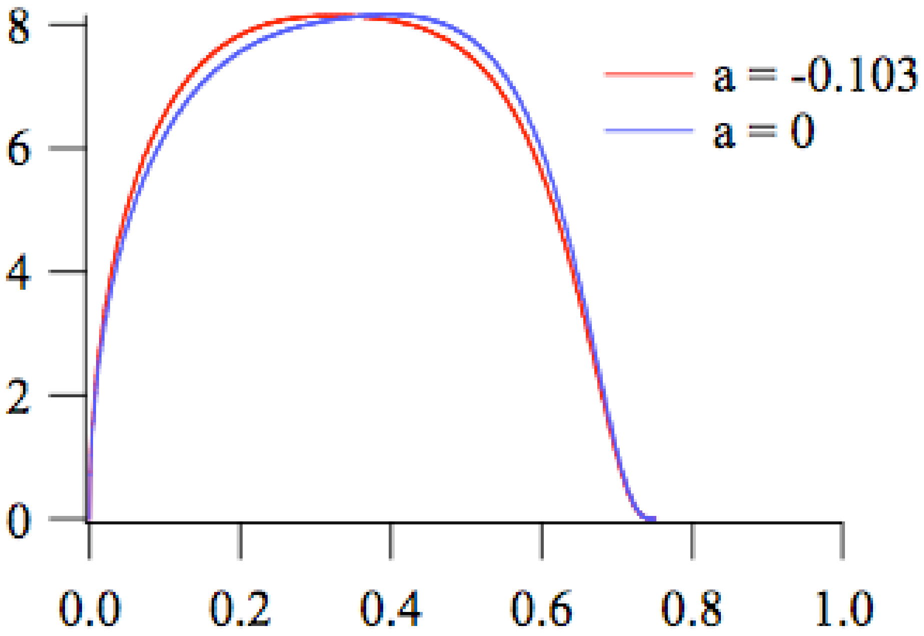
- *a* and *A* together put sharp new limits on CVC violation and SCC (Gardner and Zhang - 2000)

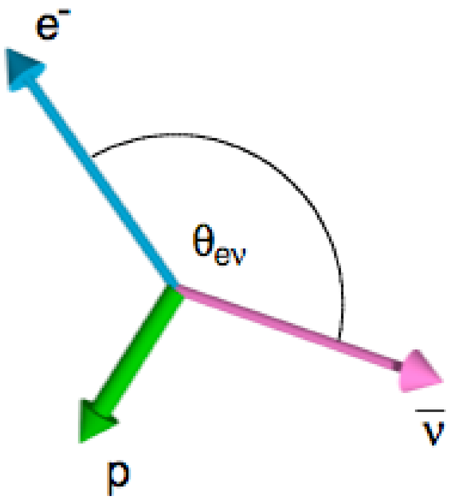
Ultimate goal: *A* and *a* to 0.1%

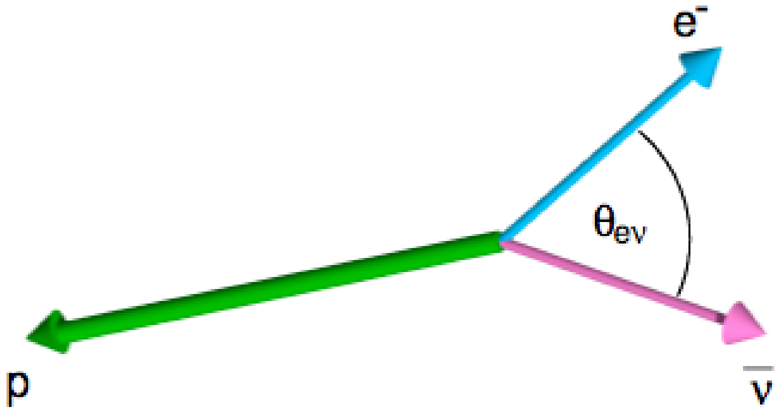
Standard method for measuring the e-ν correlation:

recoil energy spectrum

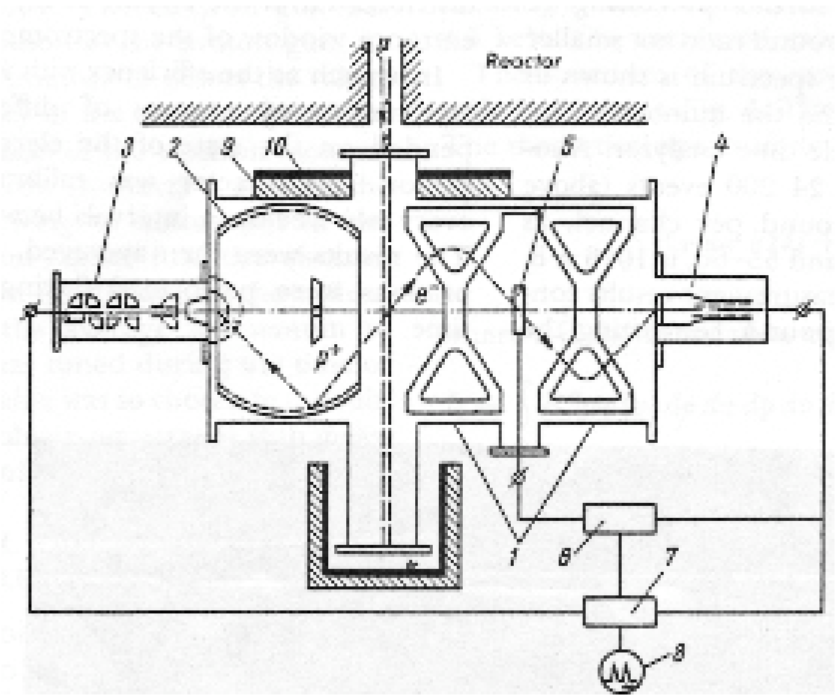
statistically most advantageous



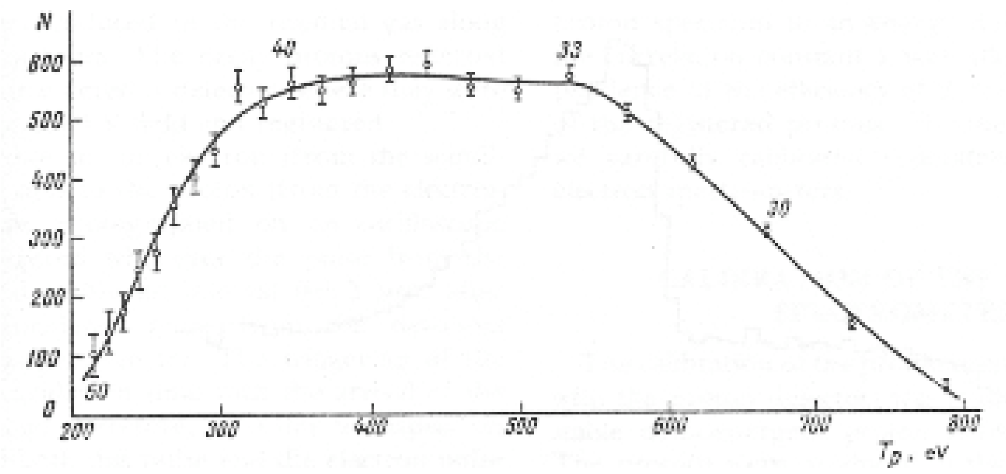




Grigor'ev, *et al.* (1967):



- recoil proton spectrum with constant electron energy
- double toroidal magnetic electron spectrometer



$a = -\,0.091 \pm .039$

$\lambda = 1.22 \pm .08$

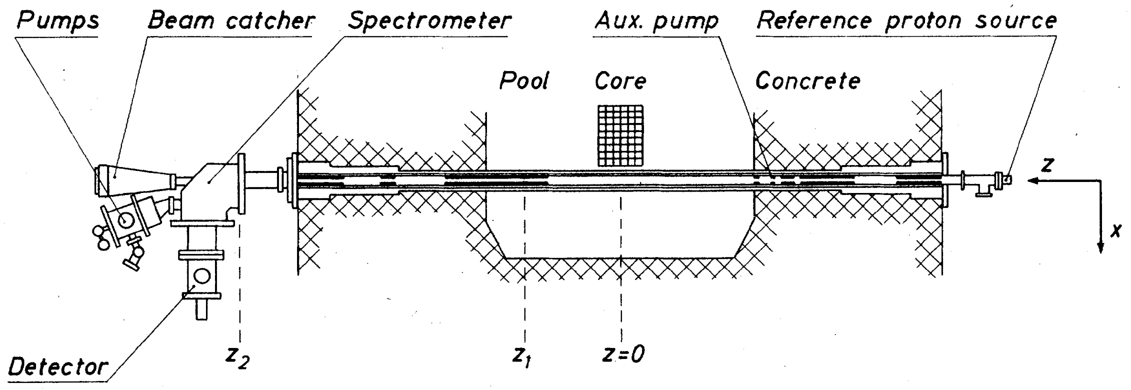
PHYSICAL REVIEW D VOLUME 18, NUMBER 11 1 DECEMBER 1978

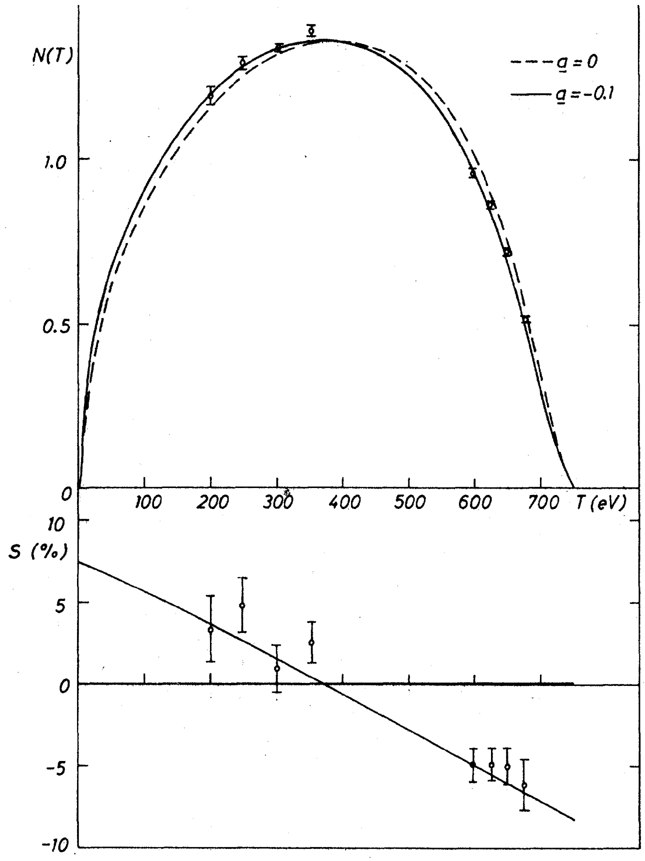
Ratio $|g_A/g_V|$ derived from the proton spectrum in free-neutron decay

Chr. Stratowa, R. Dobrozemsky, and P. Weinzierl
Physics Institute, Research Center Seibersdorf, Österreichische Studiengesellschaft für Atomenergie m.b.H., Lenaugasse 10, A-1082 Vienna, Austria

(Received 11 July 1978)

The electron-neutrino angular-correlation coefficient was determined by measuring the shape of the proton recoil spectrum from free-neutron decay. The protons leaving a highly evacuated tangential reactor beam tube were analyzed by a spherical condenser spectrometer and counted in an ion-electron converter detector. The design of the apparatus, the possible disturbing influences, and the measures to reduce their effects are discussed. The remaining corrections were either calculated or determined by auxiliary measurements and applied to the spectral shape. The sources of systematic errors are considered and included in the final results. We obtained $a = -0.1017 \pm 0.0051$ giving $|g_A/g_V| = 1.259 \pm 0.017$.



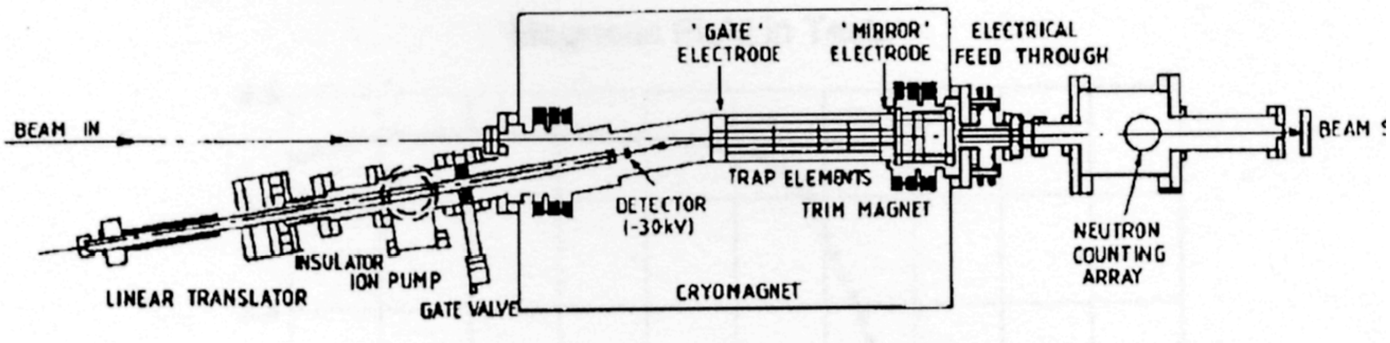


$a = -0.102 \pm 0.005$ (5%)

systematics limited:

- spectrometer calibration
- vacuum correction
- space charge effects

Byrne, et al. (2002):



- Magnetic field expansion to convert 3-D proton energy spectrum into 1 dimension

- Varied electrostatic barrier to obtain integral proton spectrum

a = -0.1054 ± .0055

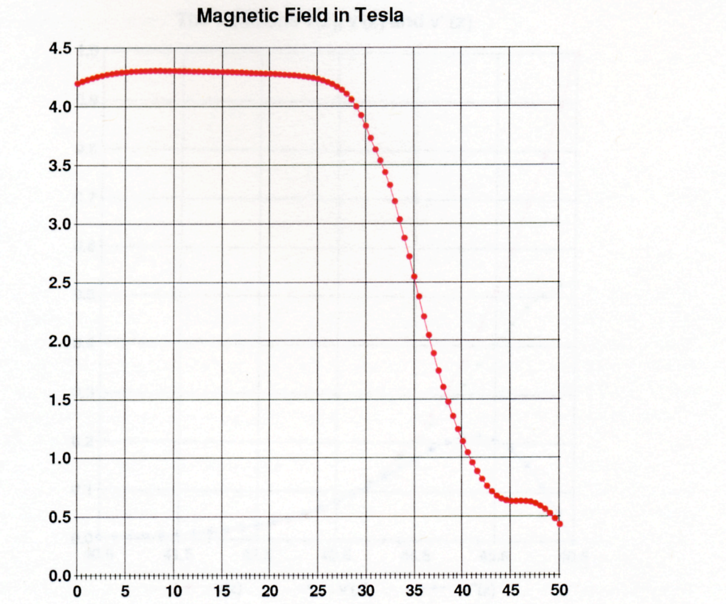


Figure 2. The magnetic field distribution in the trap as a function of axial distance (z) in cm. The beryllium mirror electrode is fixed at $z = 46.5$ cm. The 'long trap' samples the region from the mirror to about $z = 5$ cm, and the 'short trap' from the mirror to about $z = 23.5$ cm.

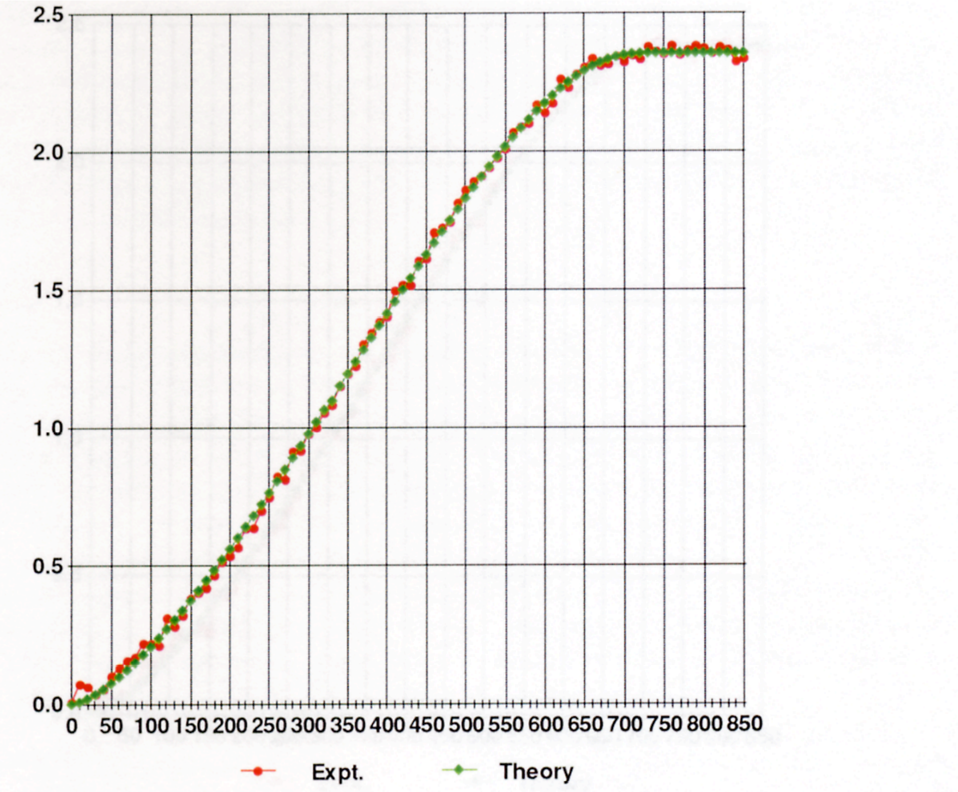
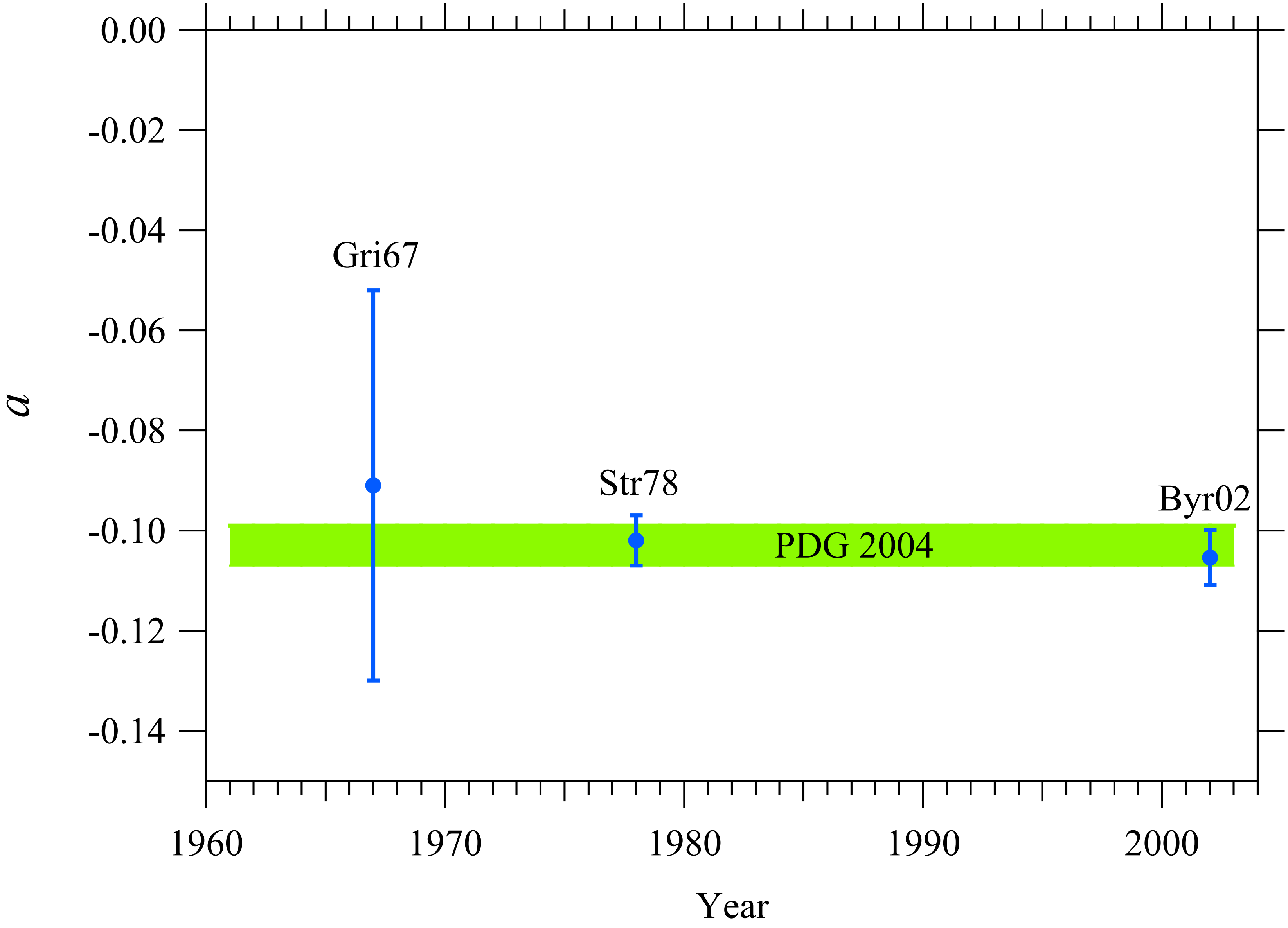


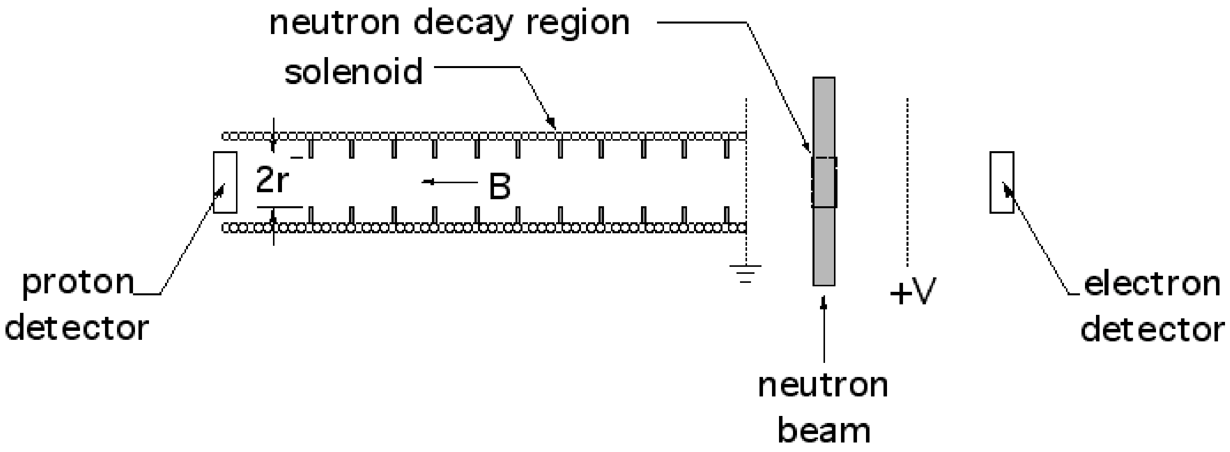
Figure 7. Comparison of experimental data with theory for summed 1 ms runs. The vertical axis shows the integrated counts in arbitrary units and the horizontal axis shows the mirror potential in volts.

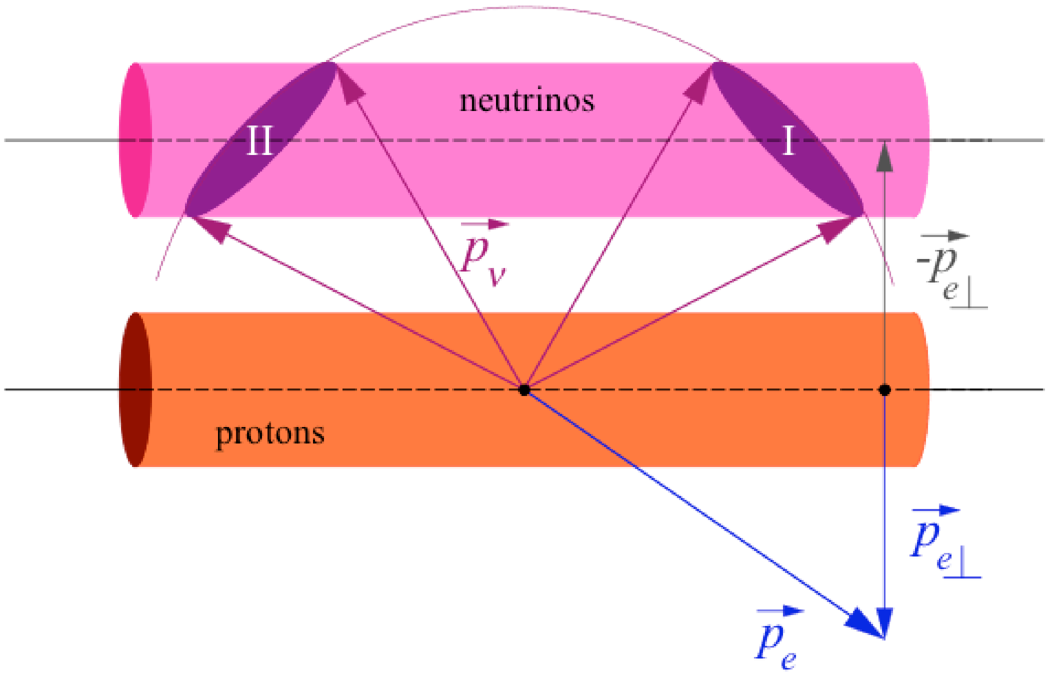
Summary of neutron decay "a" measurements



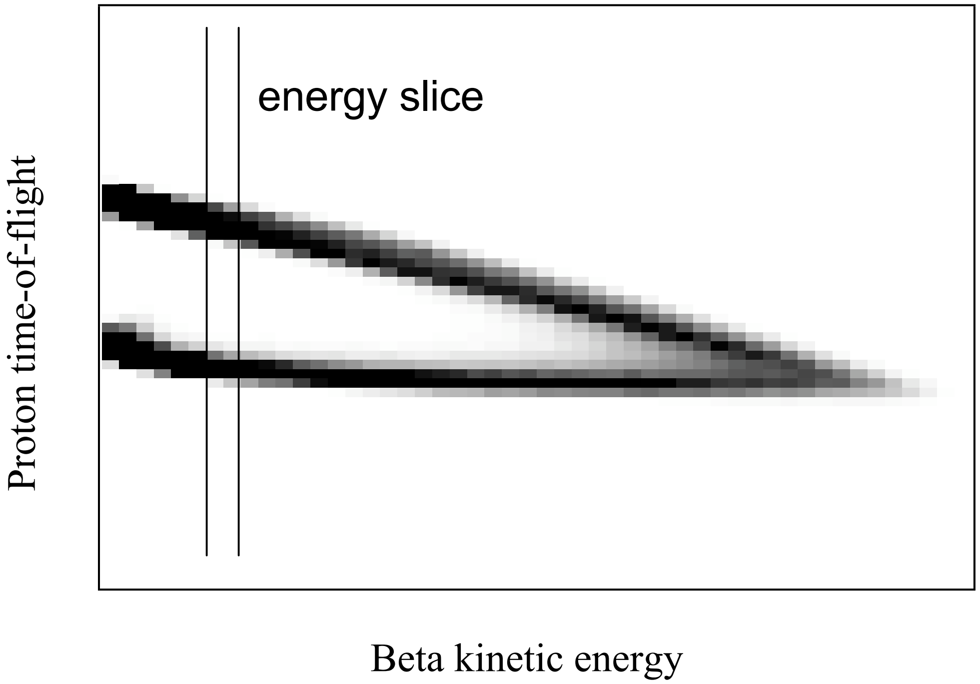
A Novel Method to Measure *a*

(Yerozolimsky and Mostovoy, 1996)





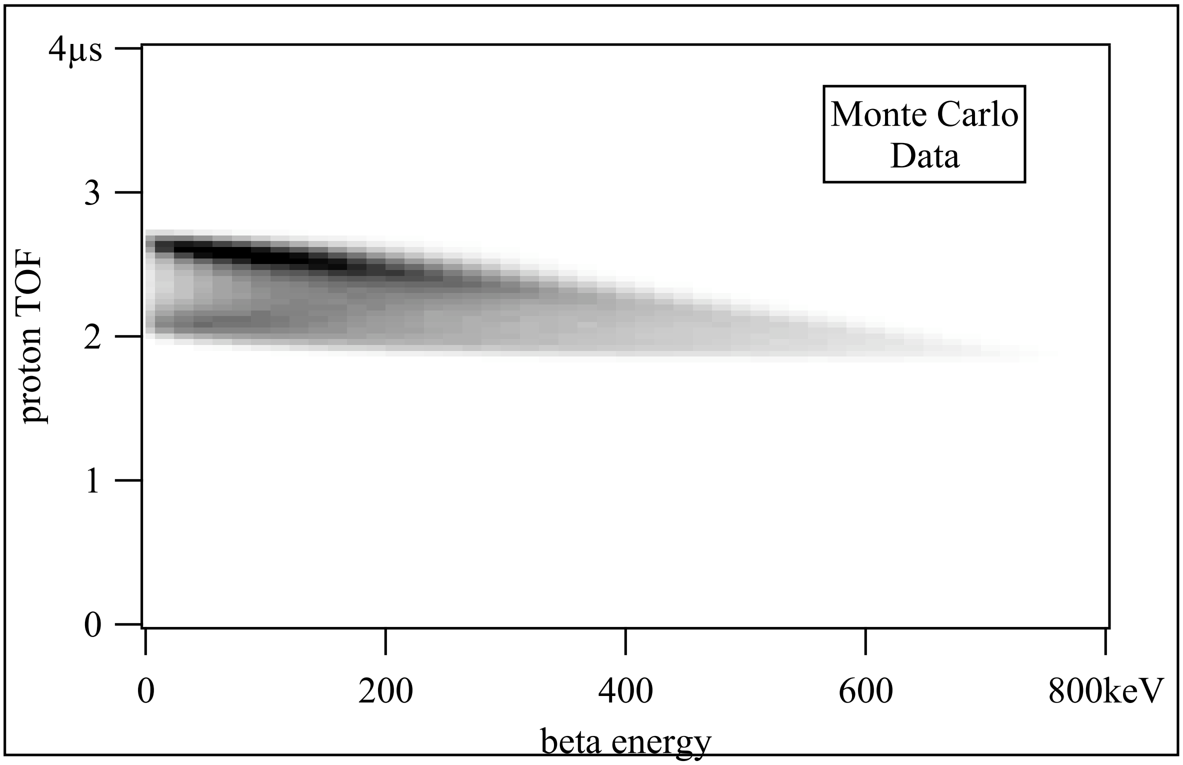
We separate groups I and II by the beta energy and time-of-flight between beta and proton detection.



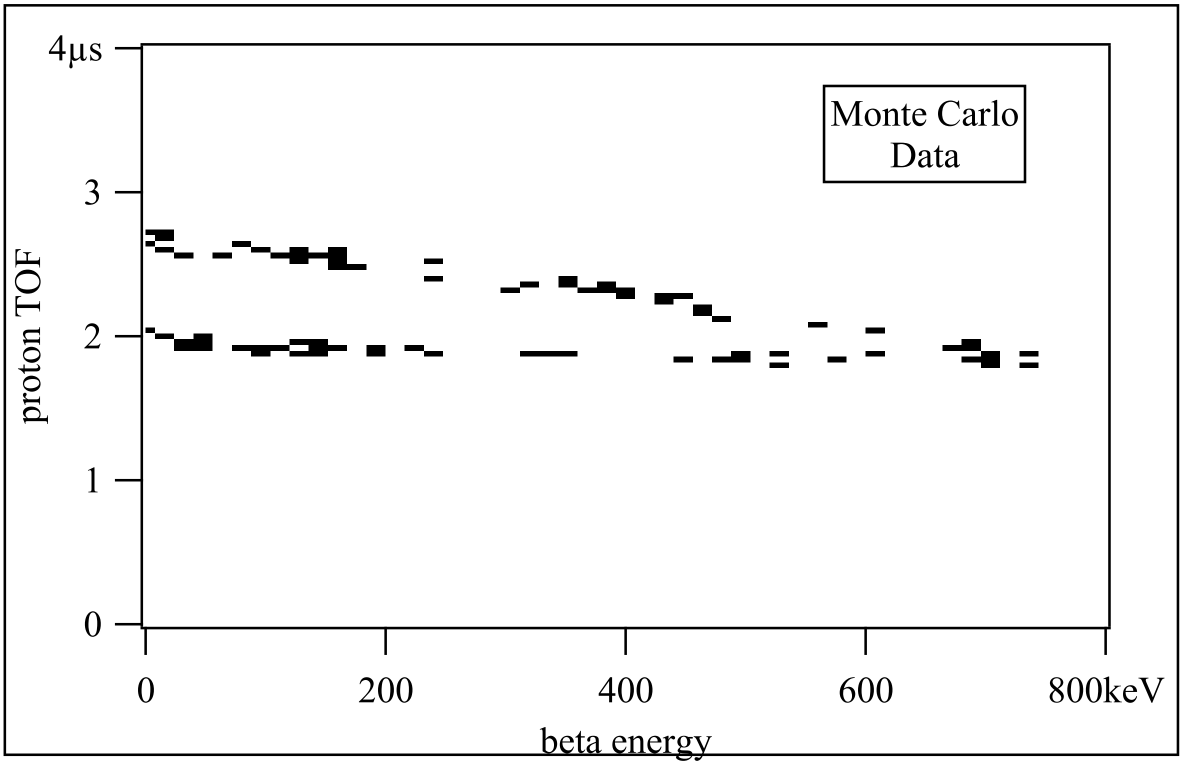
$$a(E_\beta) = \frac{1}{v_\beta} K(E_\beta) \left(\frac{N_I - N_{II}}{N_I + N_{II}} \right)$$

Our goal is a 0.5% measurement
(10x improvement)

Too much transverse momentum accepted:



Too little transverse momentum accepted:



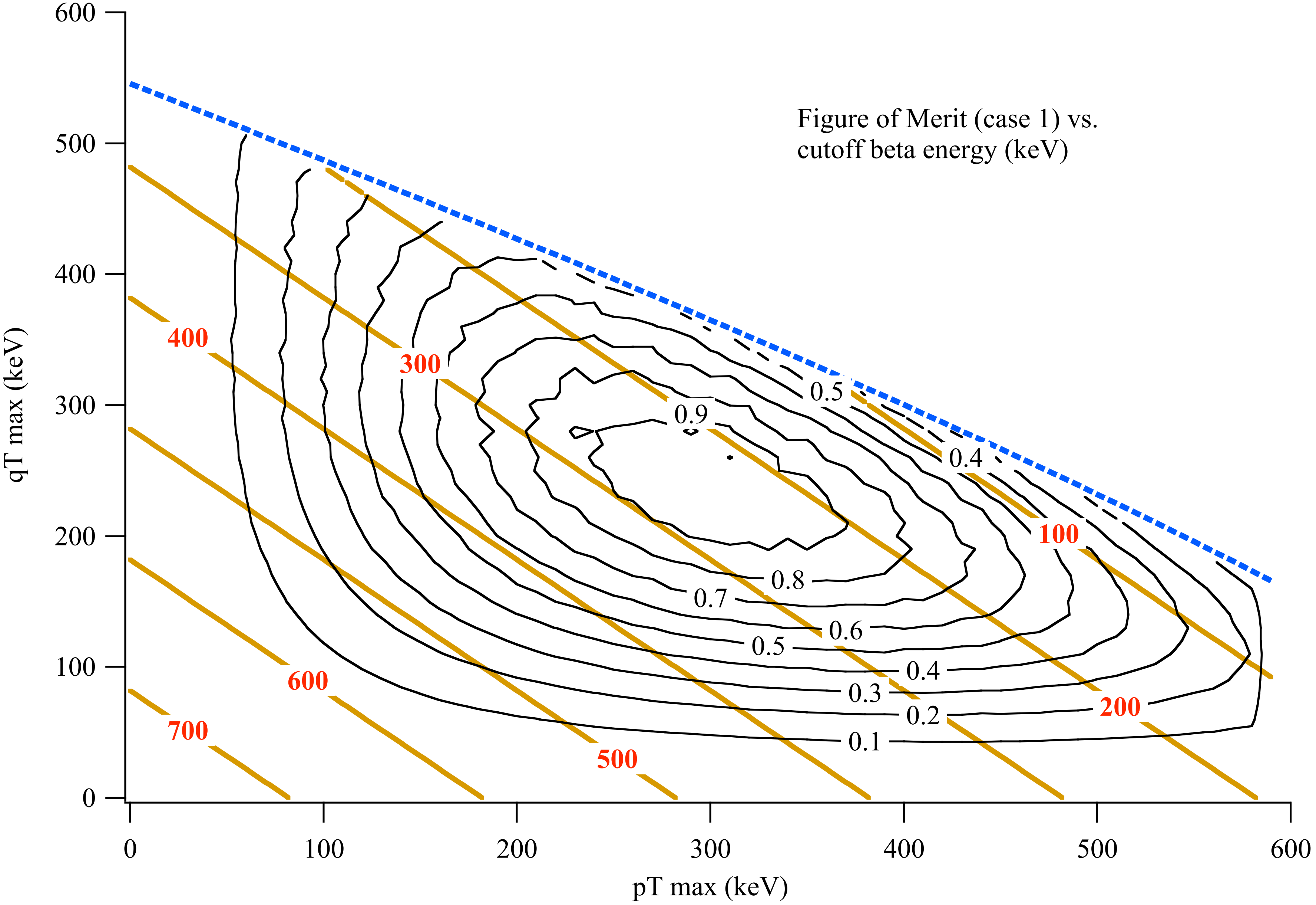
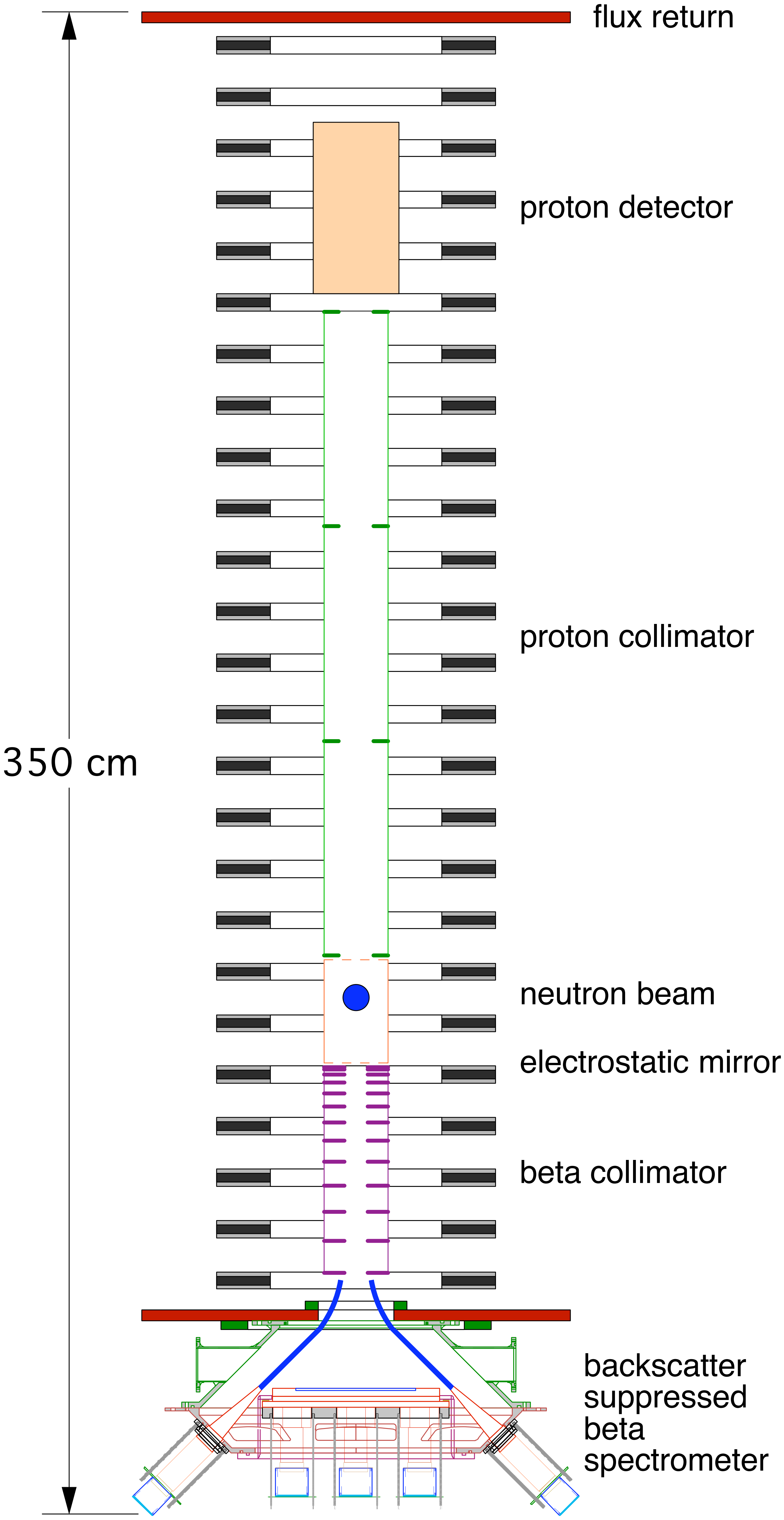
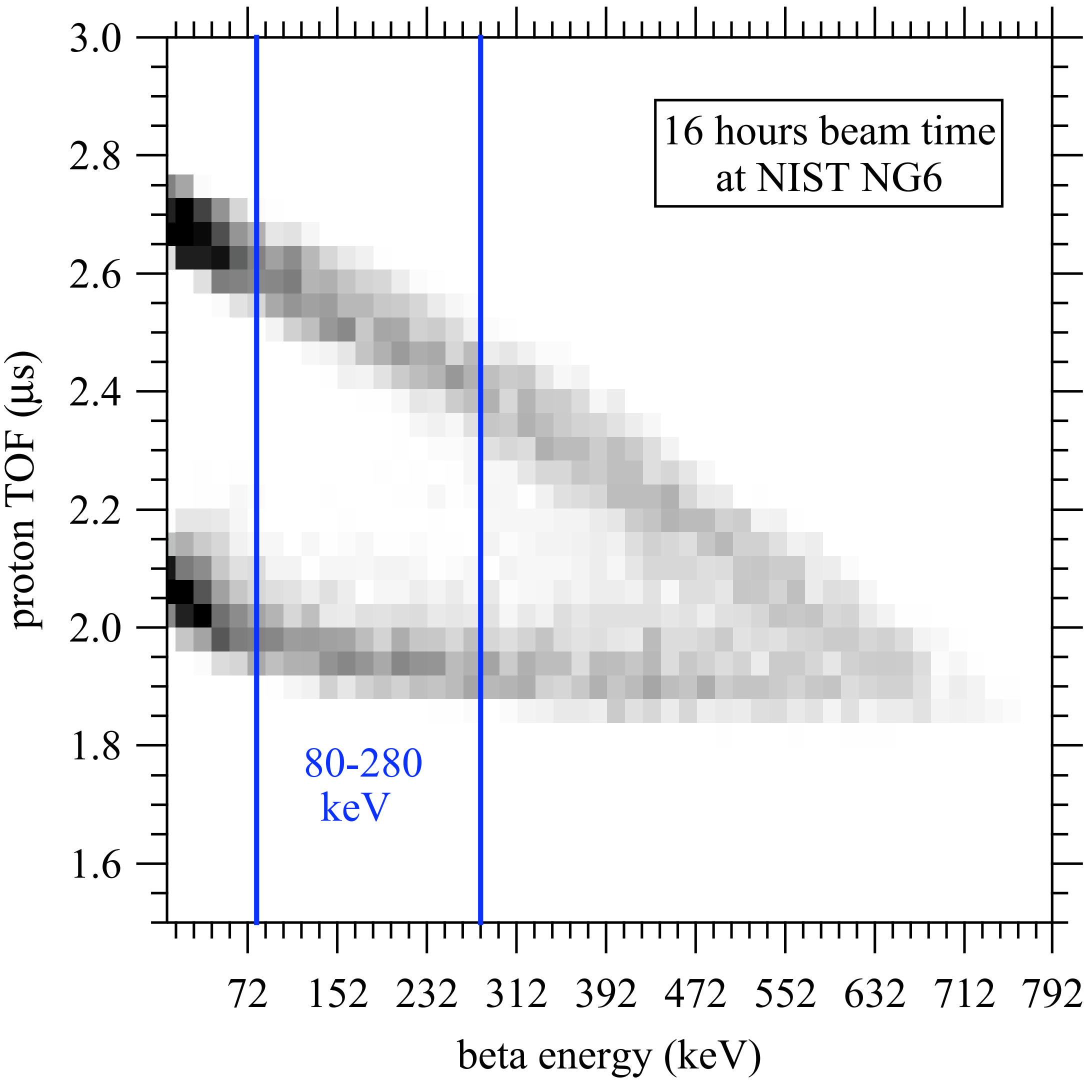


Figure of Merit (case 1) vs.
cutoff beta energy (keV)
qT max (keV)
pT max (keV)
0
100
200
300
400
500
600
0
100
200
300
400
500
600
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.5
0.4
100
200
300
400
500
600
700

aCORN


flux return
proton detector
proton collimator
350 cm
neutron beam
electrostatic mirror
beta collimator
backscatter
suppressed
beta
spectrometer

aCORN Monte Carlo



$\sigma_a/a = 2\%$
in 120 beam days on NG6

Ultimate goal is
$\sigma_a/a = 0.5\%$

Important Systematic Effects

1. Electron backscattering from beta spectrometer
   - fills in gap between proton groups

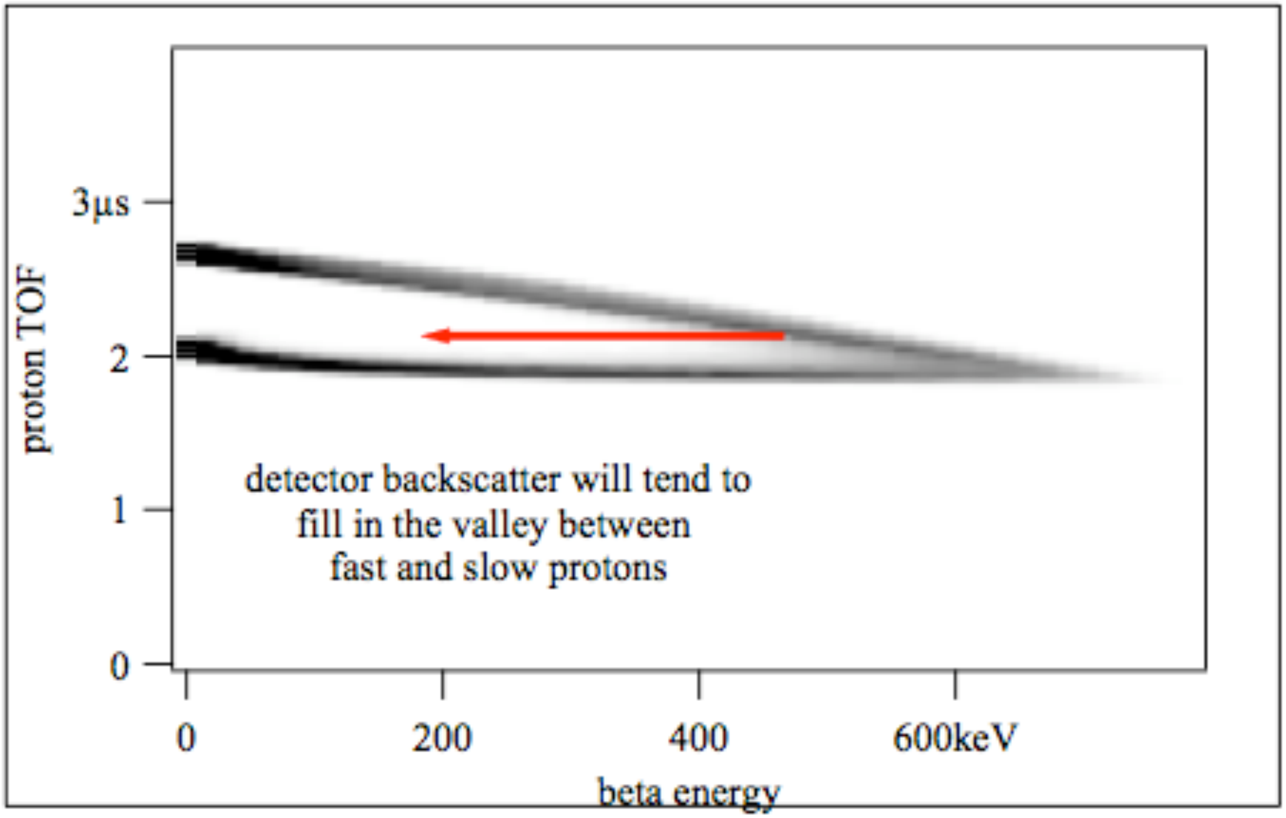
2. Electron scattering from beta collimator
   - similar effect

3. Transverse magnetic and electric fields
   - creates false asymmetry, false "*a*"

4. Wrong-way electrons scattering from proton end

All will be controlled at the level of 0.5% of "*a*"

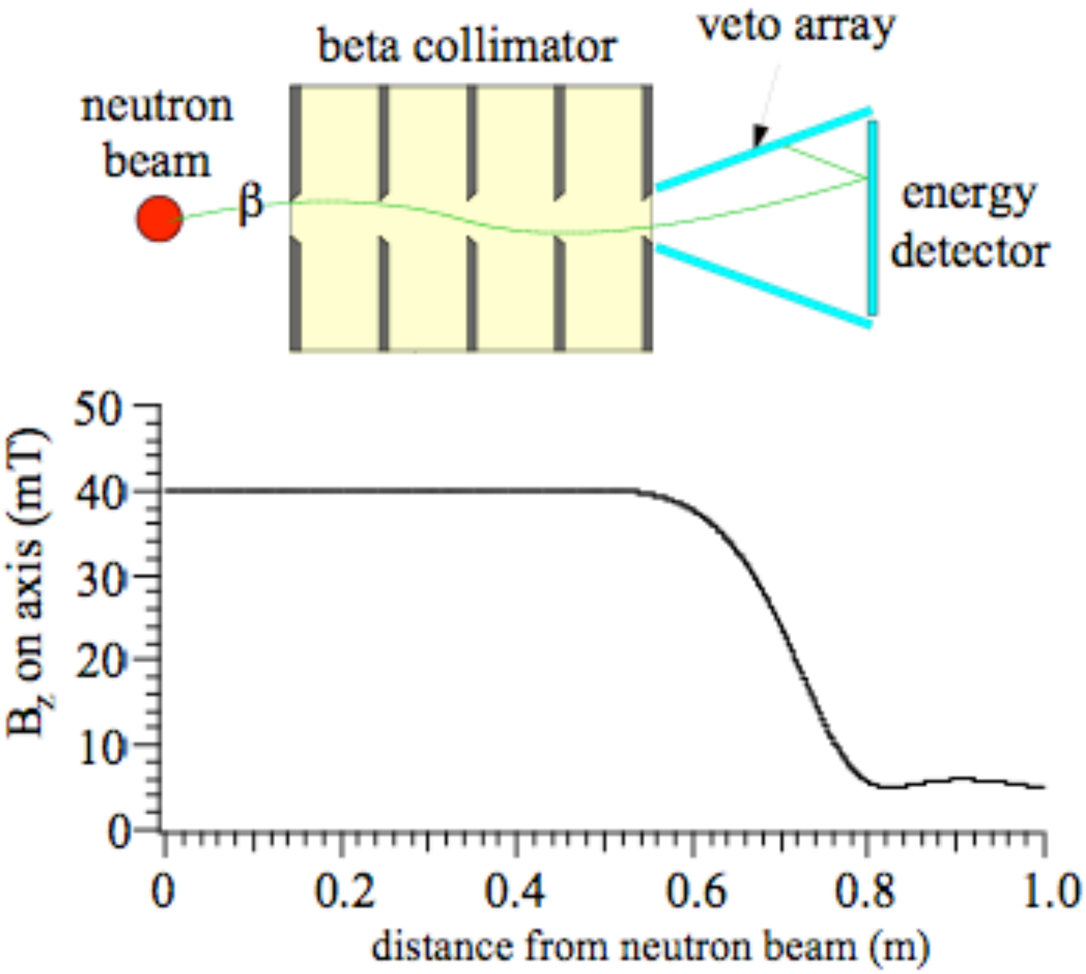
Backscatter From Beta Spectrometer



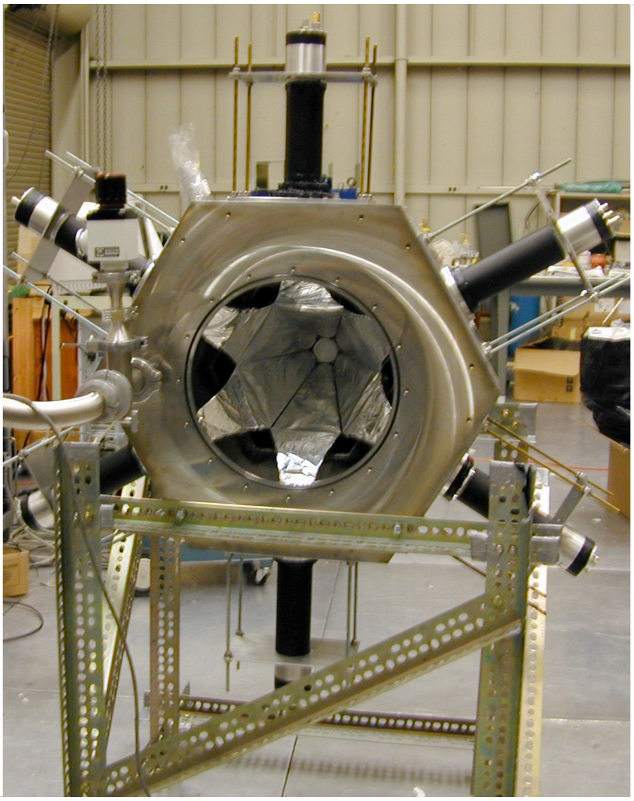
This can cause as much as a 16% error in "*a*"

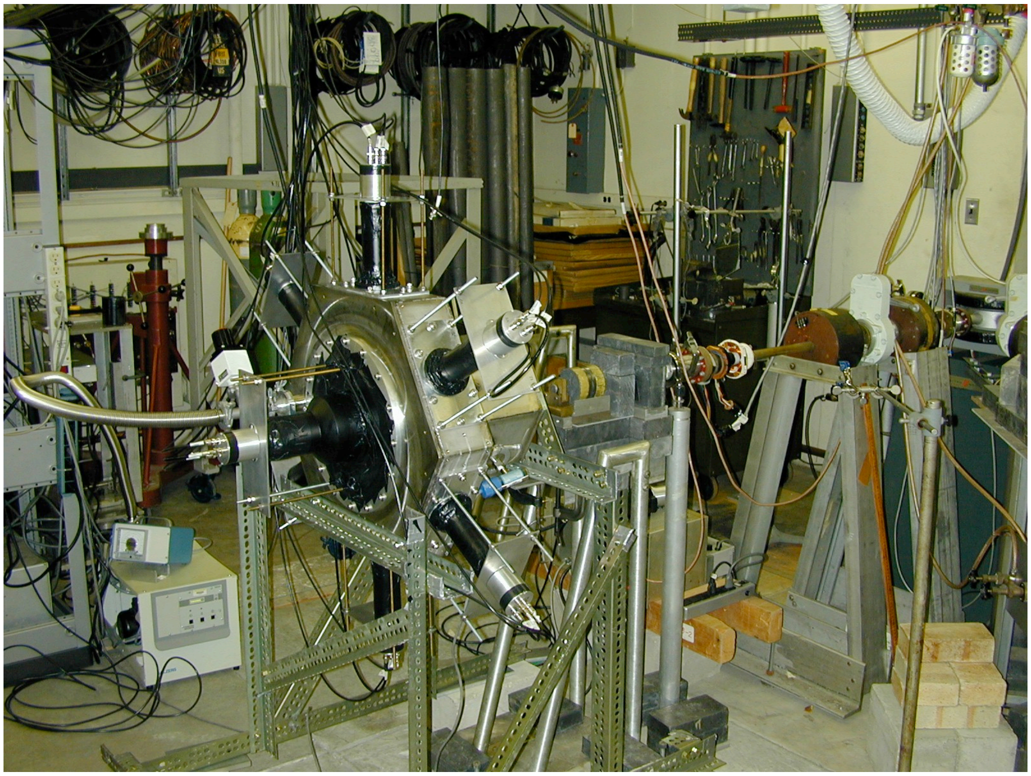
We want to suppress backscatter by at least a factor of 10

Backscatter Suppressed Beta Spectrometer

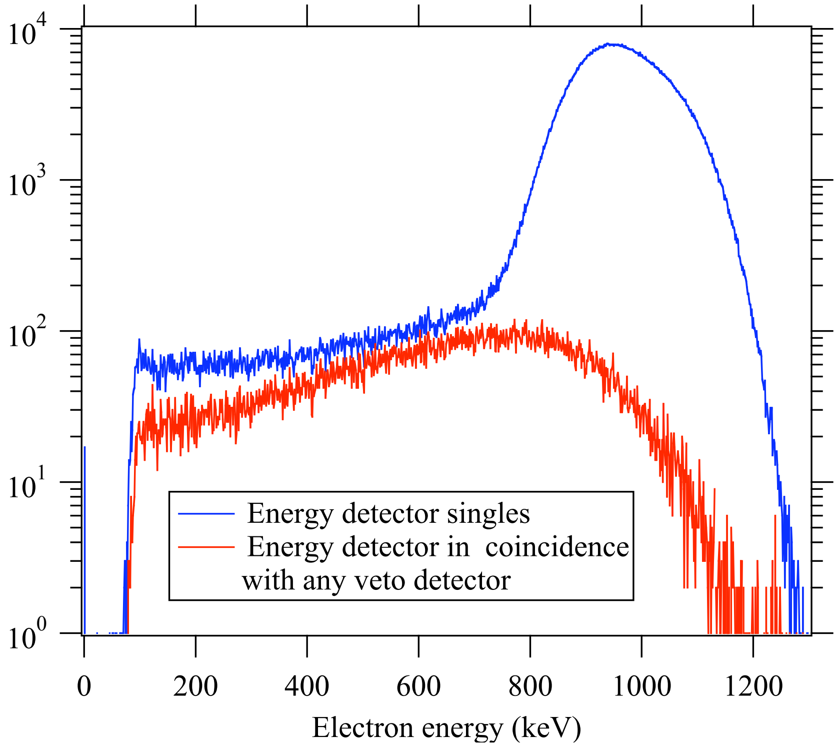


Prototype Backscatter-Suppressed Electron Spectrometer

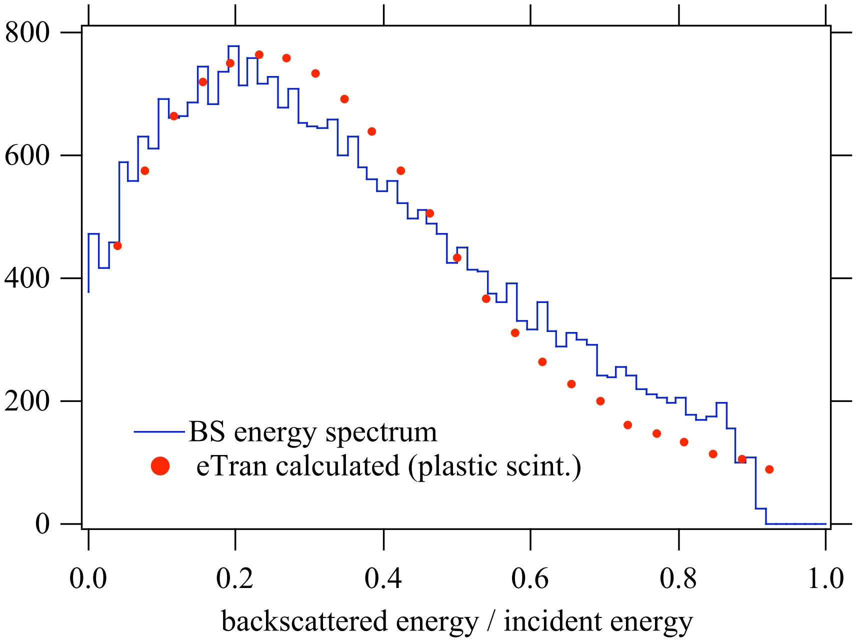




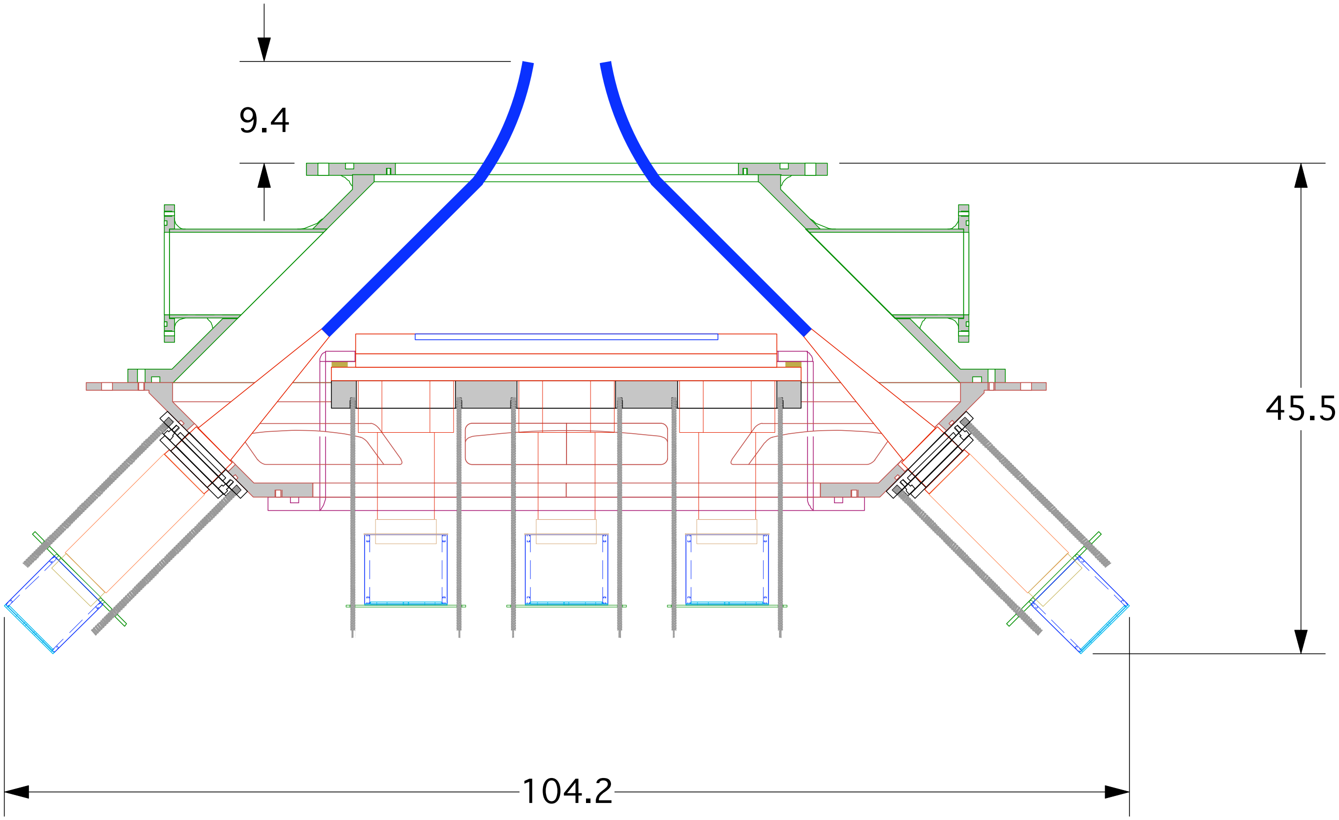
Prototype Backscatter-Suppressed Electron Spectrometer



BS suppression efficiency = 94 ± 2 %

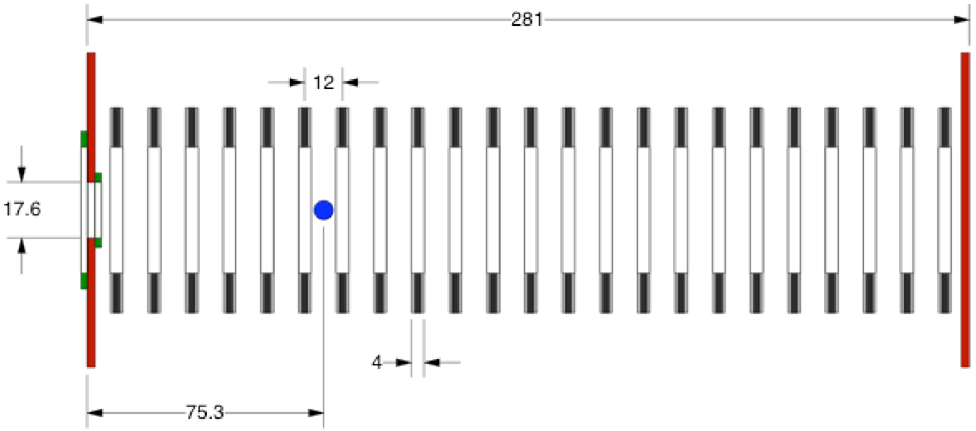


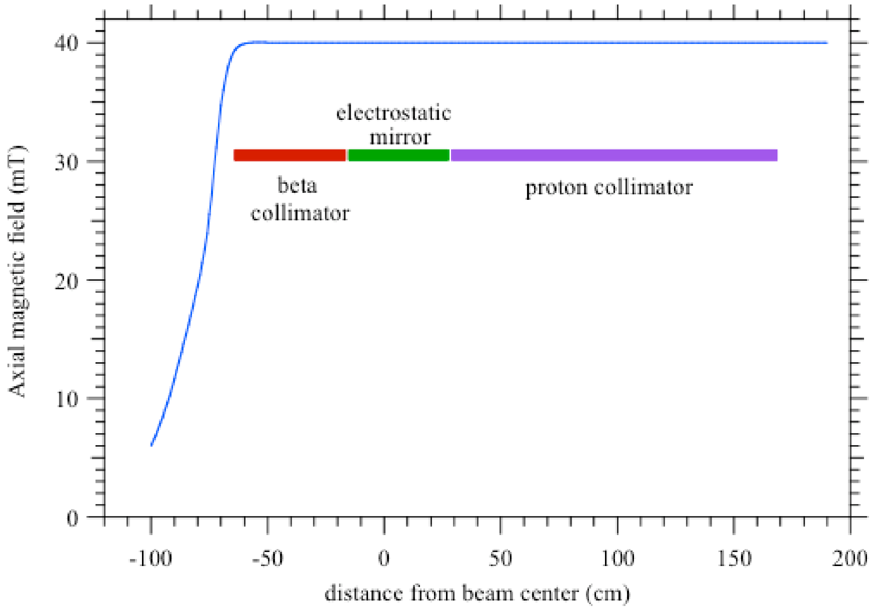
aCORN Beta Spectrometer

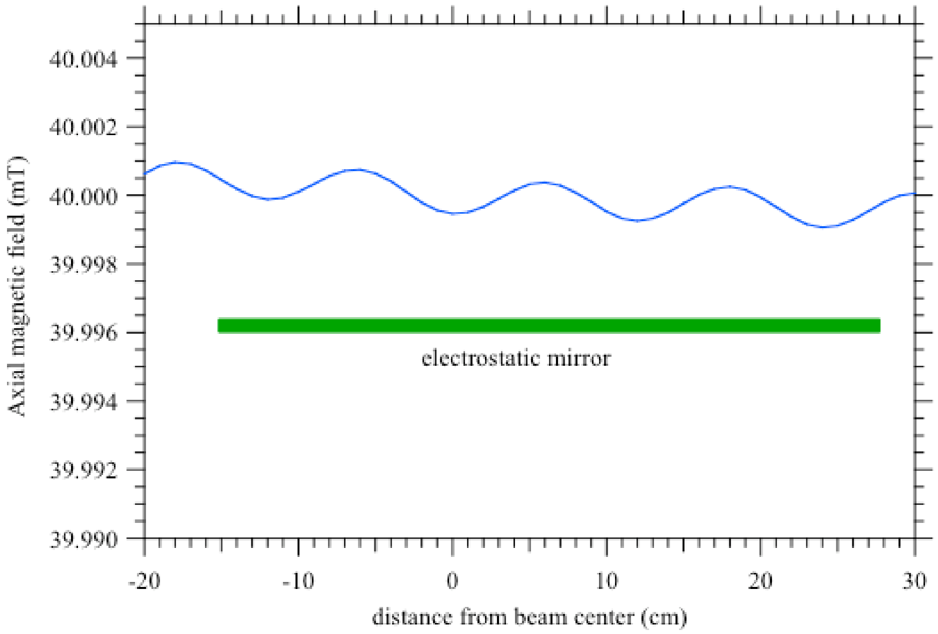


units in cm

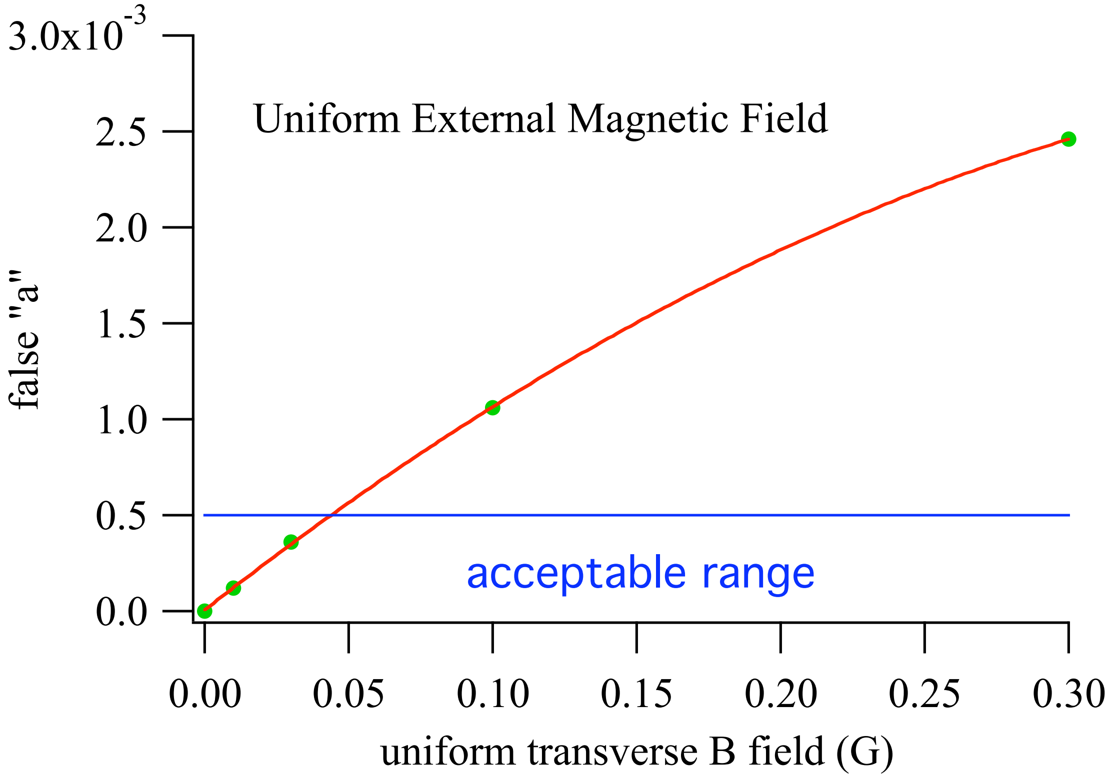
aCORN Main Magnet



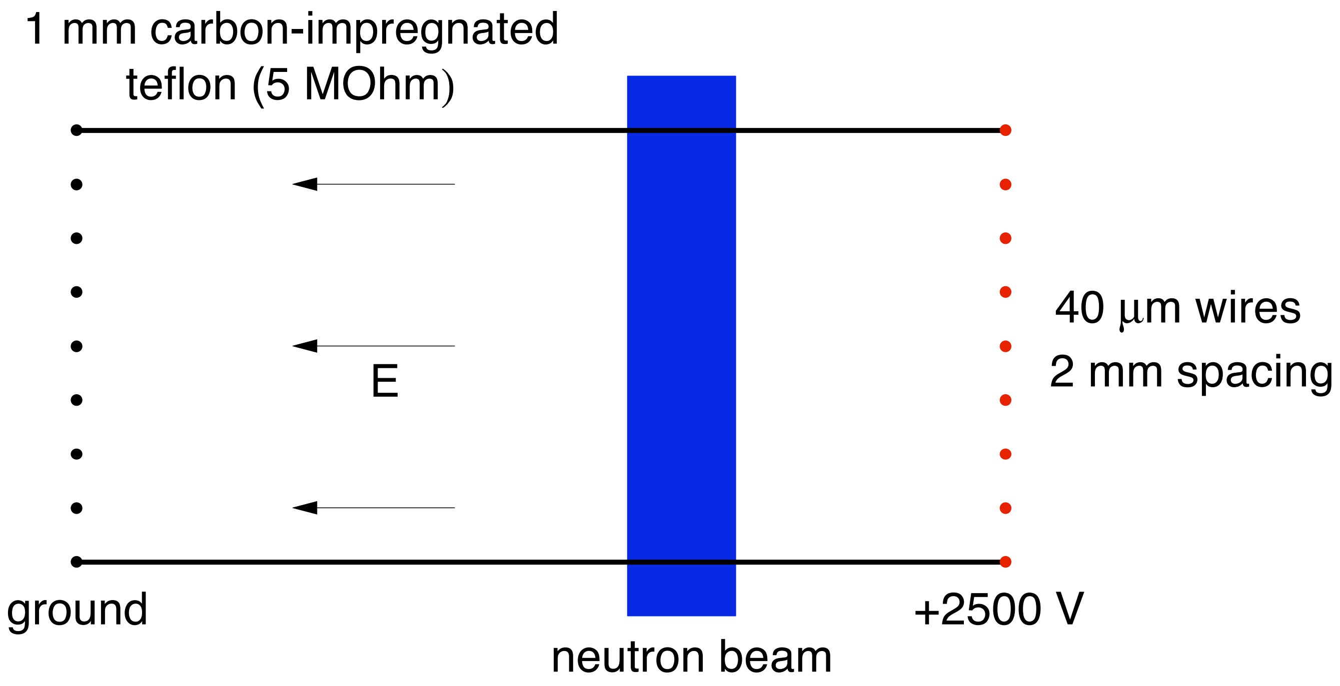




Transverse External Magnetic Field Sensitivity



Electrostatic Mirror



1 mm carbon-impregnated
teflon (5 MOhm)

40 μm wires
2 mm spacing

E

ground

+2500 V

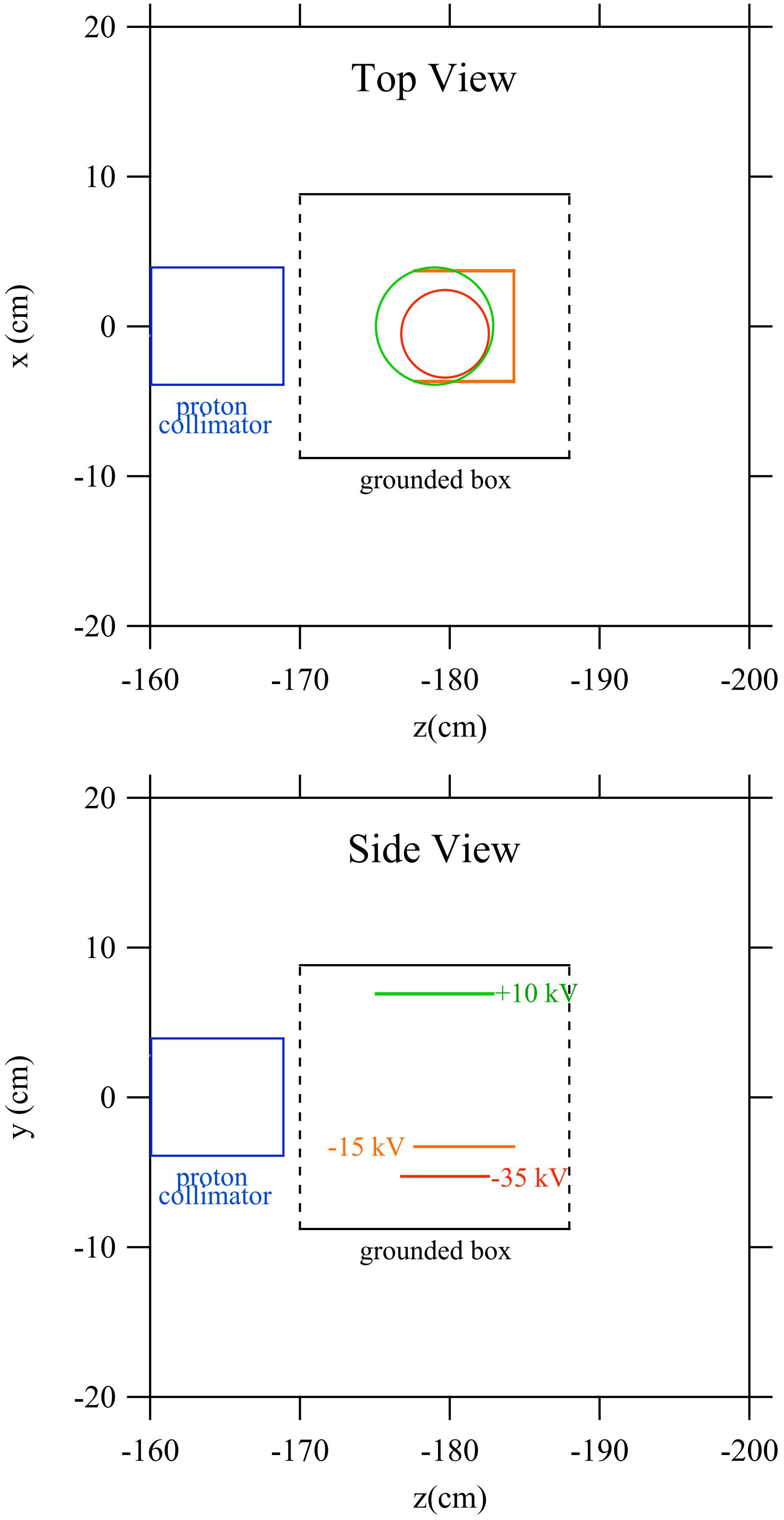
neutron beam

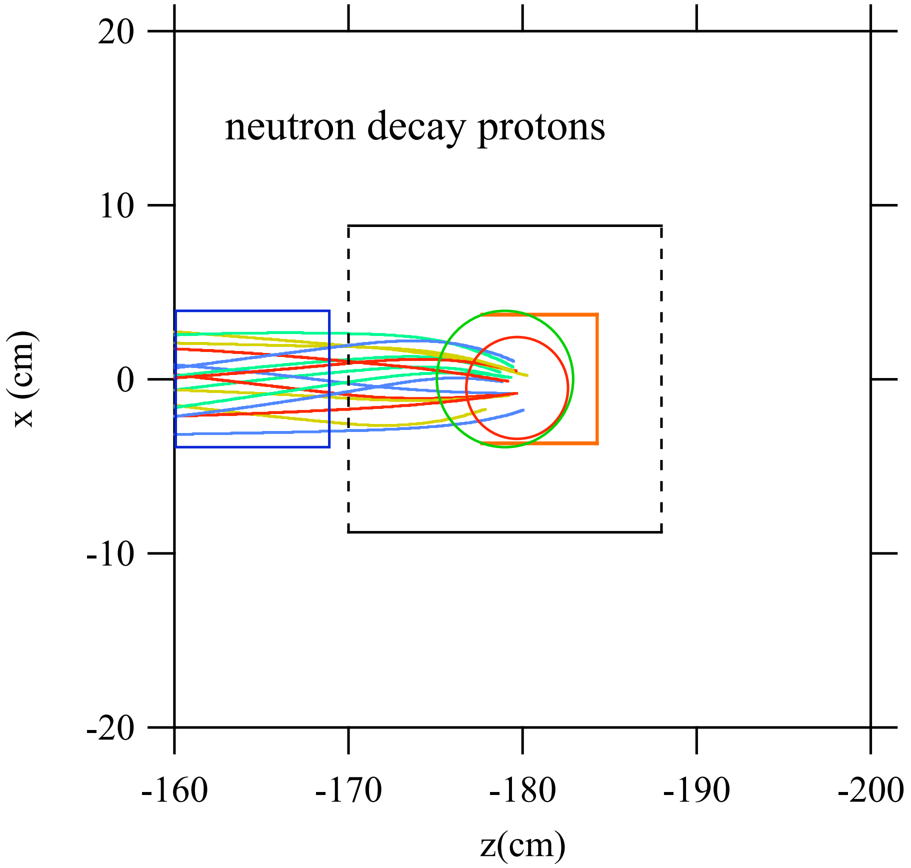
Monte Carlo:

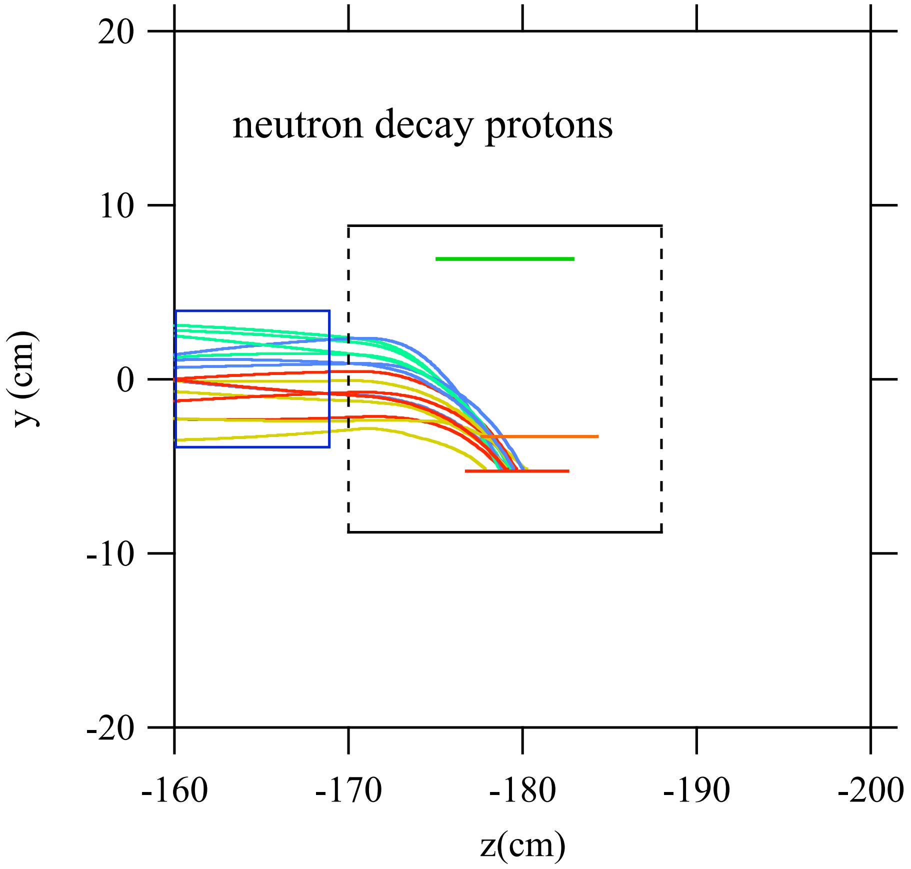
False asymmetry due to transverse deflection
of protons = 1.1 ± 0.5 x 10^{-5}

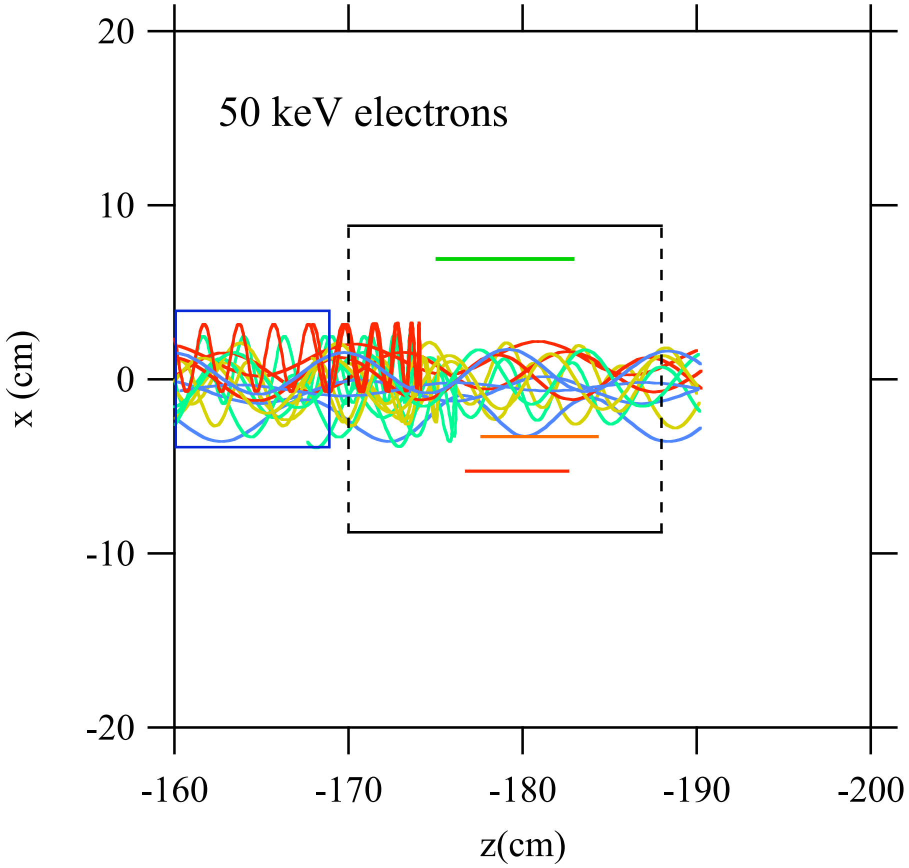
= 0.2% of "a"

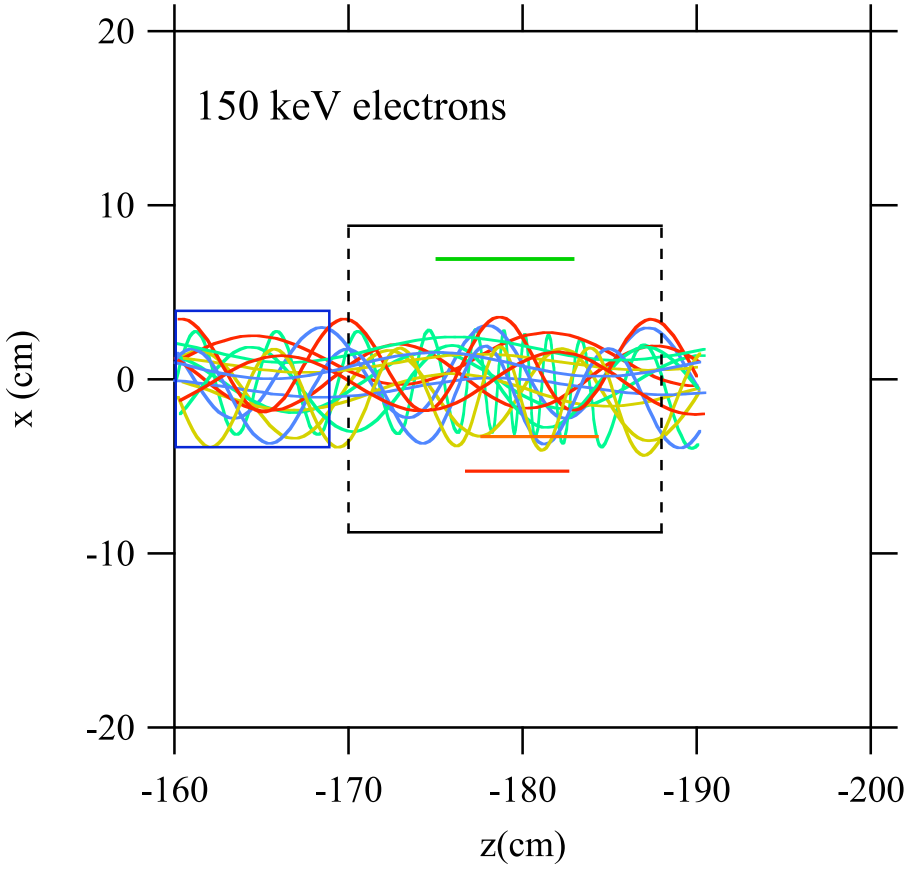
aCORN Proton Detector



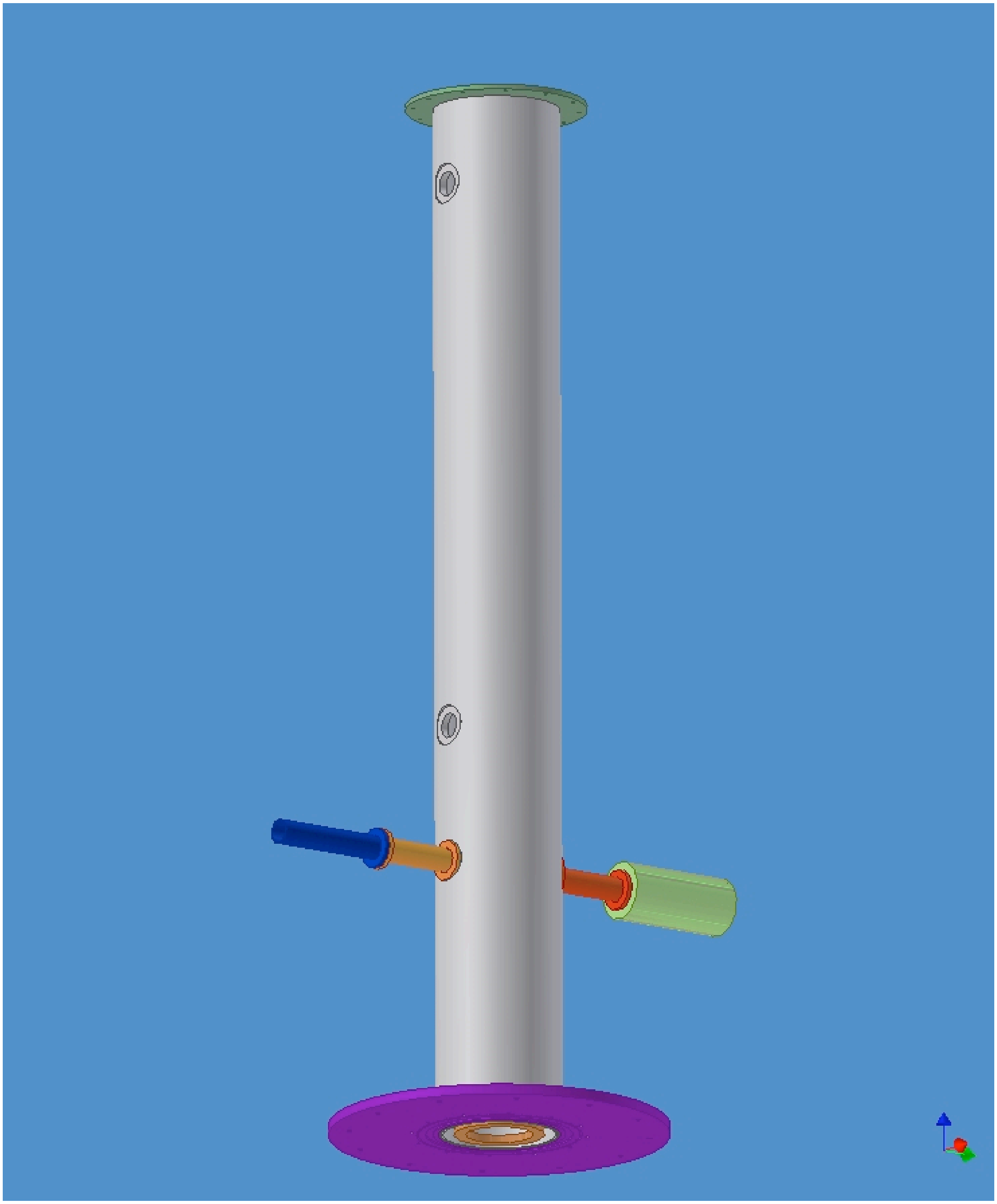

neutron decay protons
x (cm)
20
10
0
-10
-20
-160
-170
-180
-190
-200
z(cm)

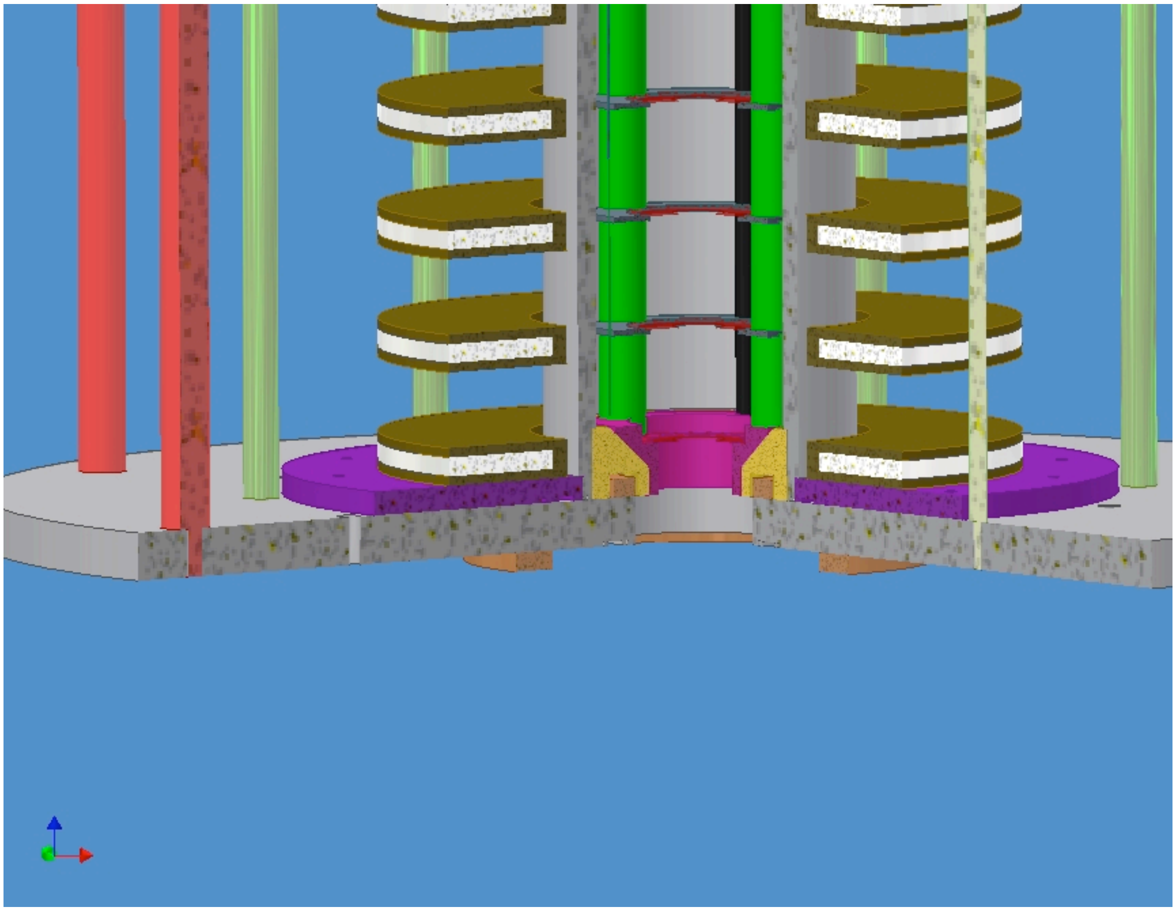

neutron decay protons
y (cm)
20
10
0
-10
-20
-160
-170
-180
-190
-200
z(cm)

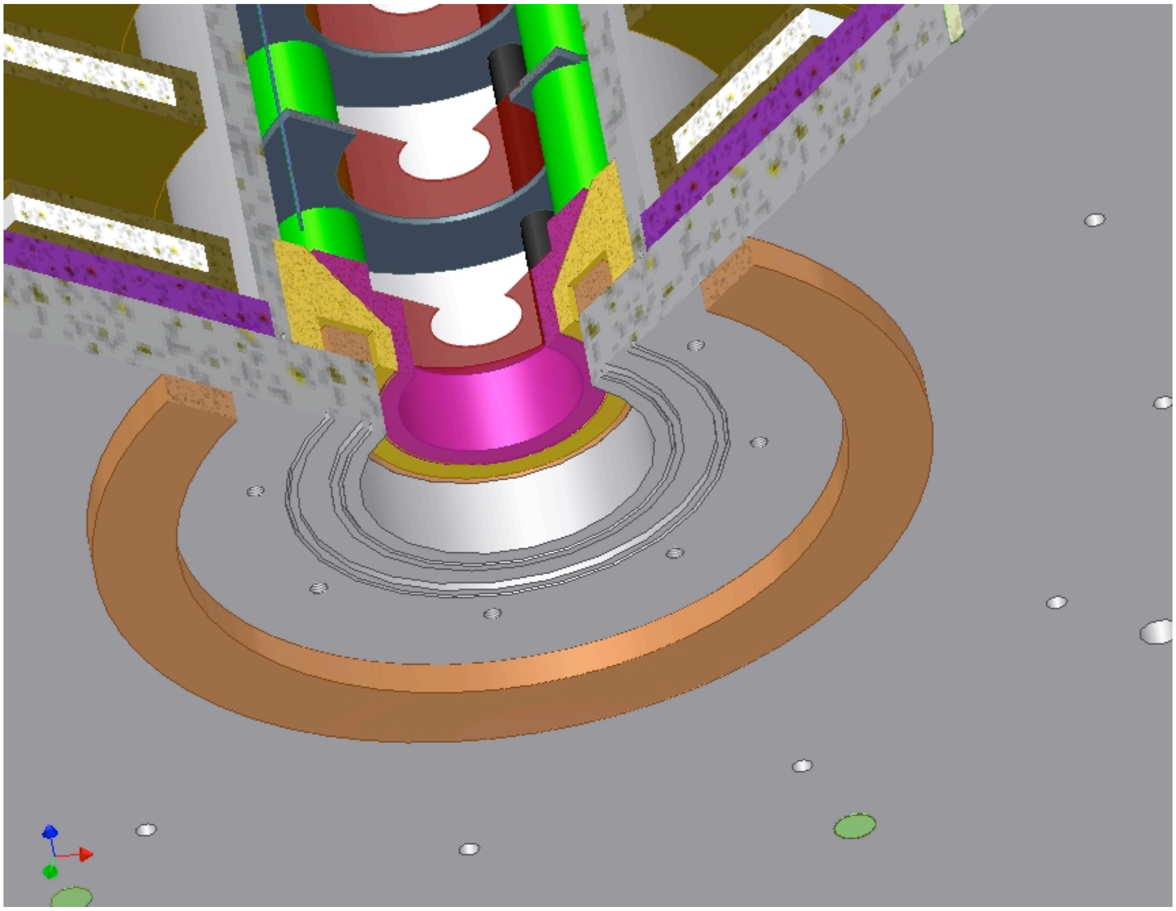

50 keV electrons
20
10
0
-10
-20
x (cm)
-160
-170
-180
-190
-200
z(cm)

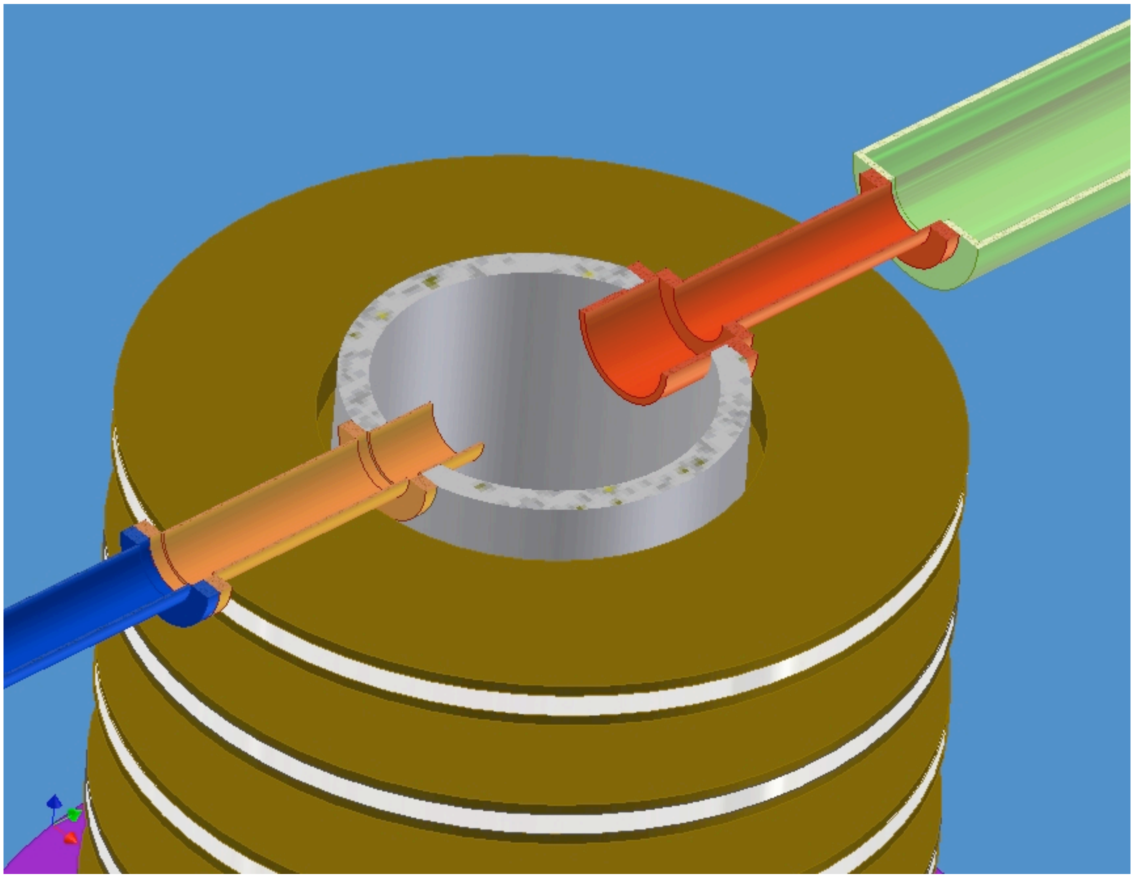

150 keV electrons
20
10
0
-10
-20
x (cm)
-160
-170
-180
-190
-200
z(cm)

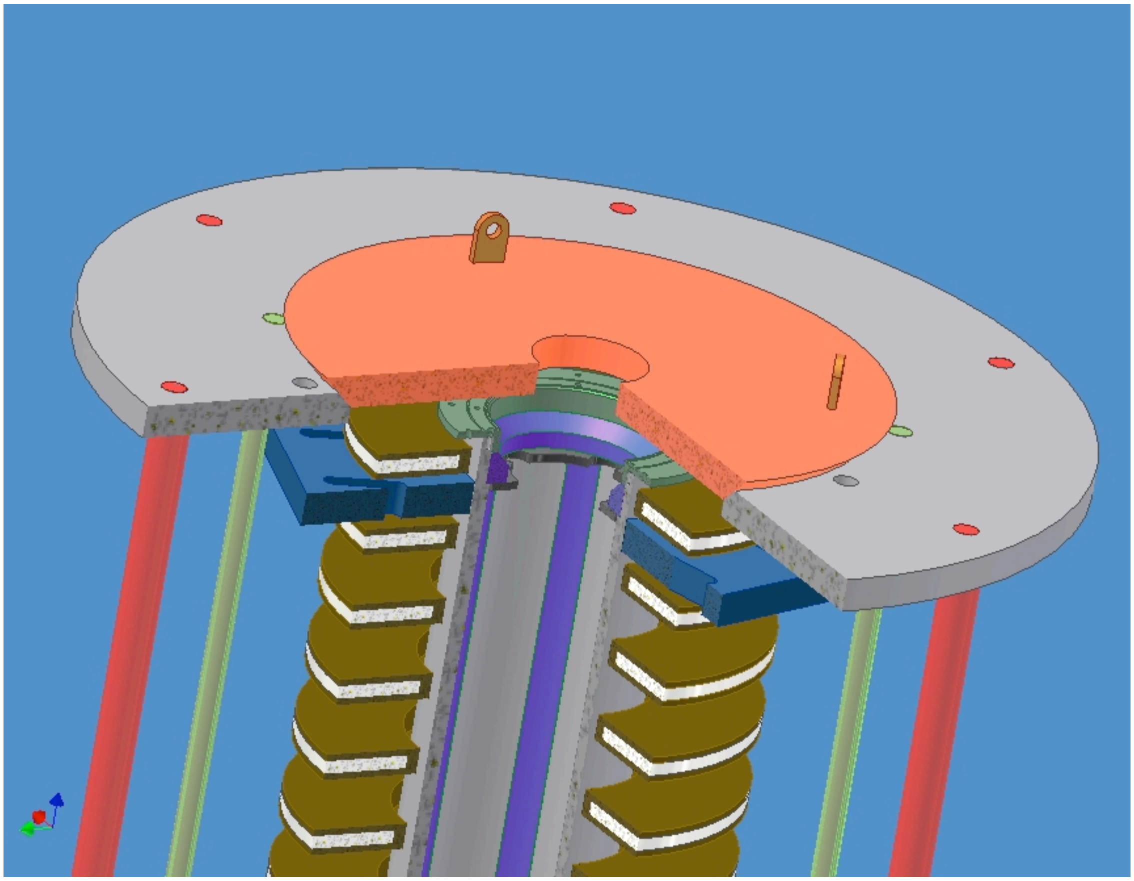
aCORN

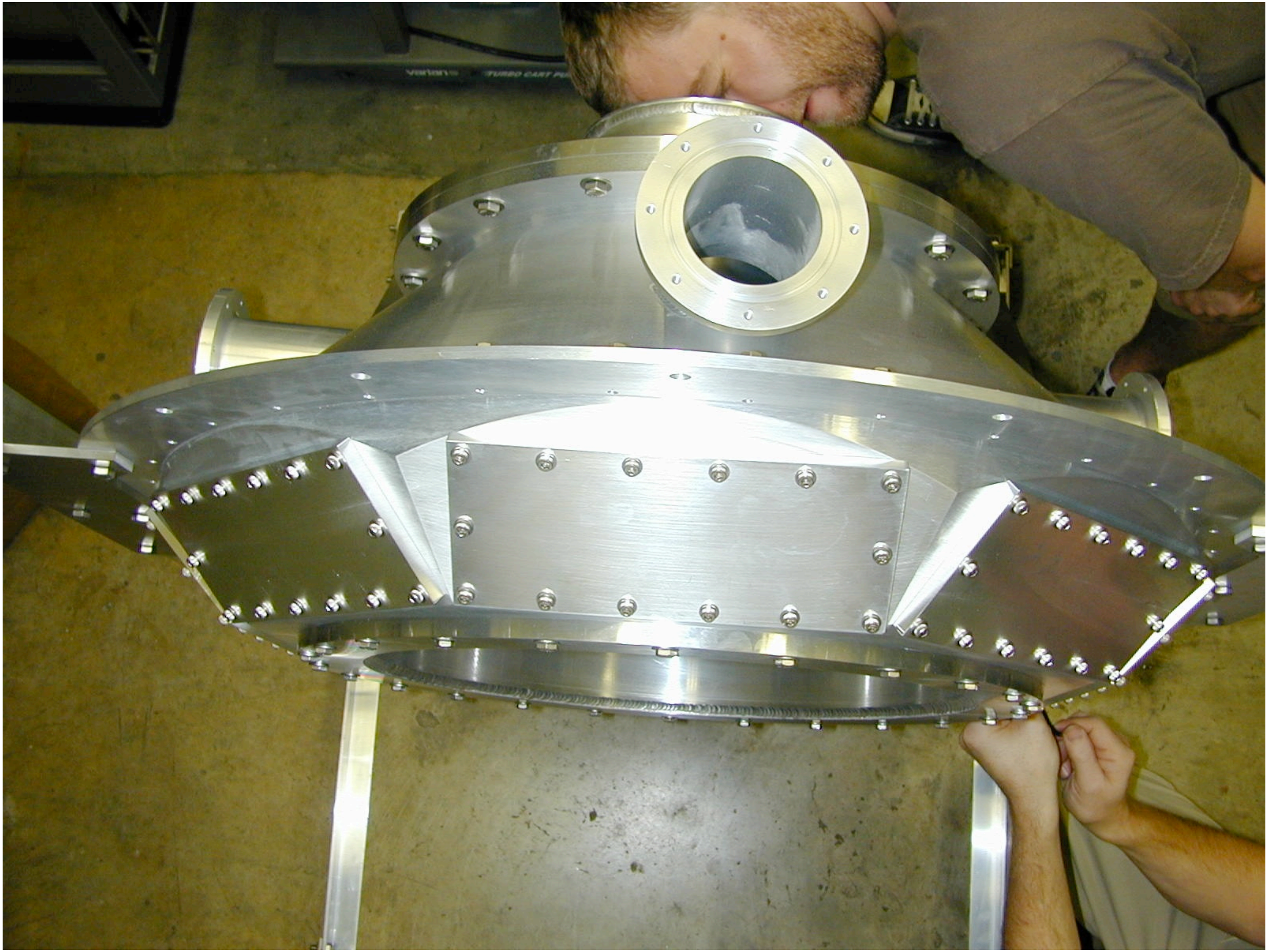


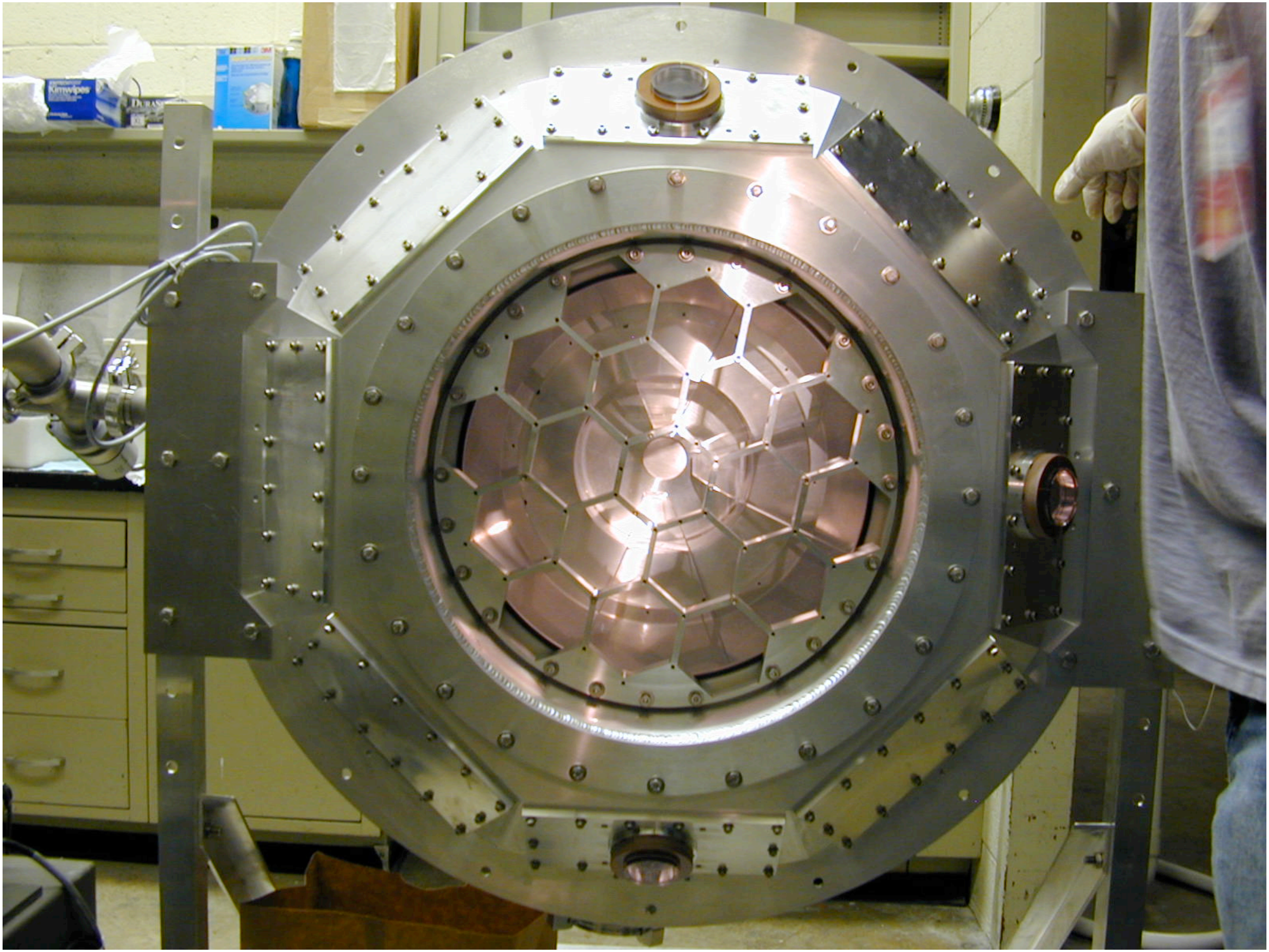











Kimwipes
3M


30677
30641

aCORN

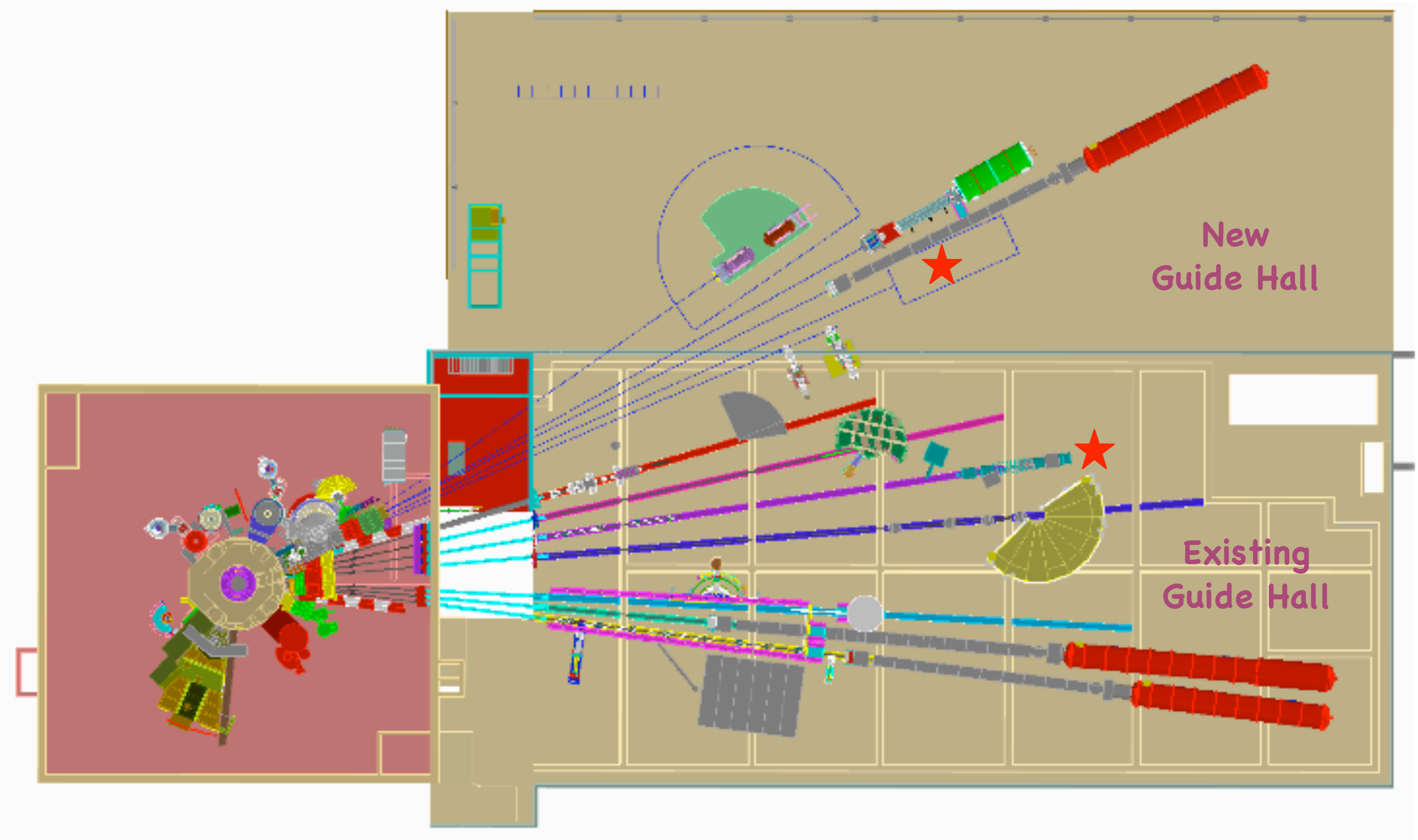
Responsibilities:

Main vacuum chamber	Indiana
Mechanical support structure	Indiana
Magnet system	Hamilton
Magnet alignment system	Hamilton
Beta spectrometer	Tulane/NIST
Electrostatic mirror	Tulane
Proton detector	DePauw
Collimator system	DePauw
Neutron transport	NIST
DAQ	NIST/Tulane

Schedule:

final design and component construction	Jan-Dec 2007
integration of apparatus at IUCF	Jul 2007 - Jun 2008
shakedown/test run at LENS?	summer 2008
begin physics run at NIST	fall 2008

$100M NCNR Expansion Project Funded in FY07



★ Fundamental Neutron Physics End Position

Other experiments proposed or in progress to measure the electron-antineutrino correlation (*a*) in neutron decay:

- aSPECT: ILL, Munich - complete run in 2005
- abBA/Nab: LANL, UT/Oak Ridge, UVA
- UCN A (*a*): LANL, NC State, Caltech, UW