The UCNA Experiment: Progress Towards a Measurement of the Beta-asymmetry using Ultracold Neutrons

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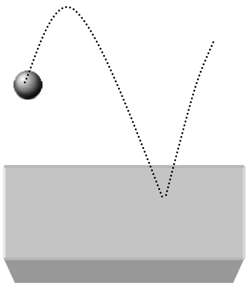
NC State University

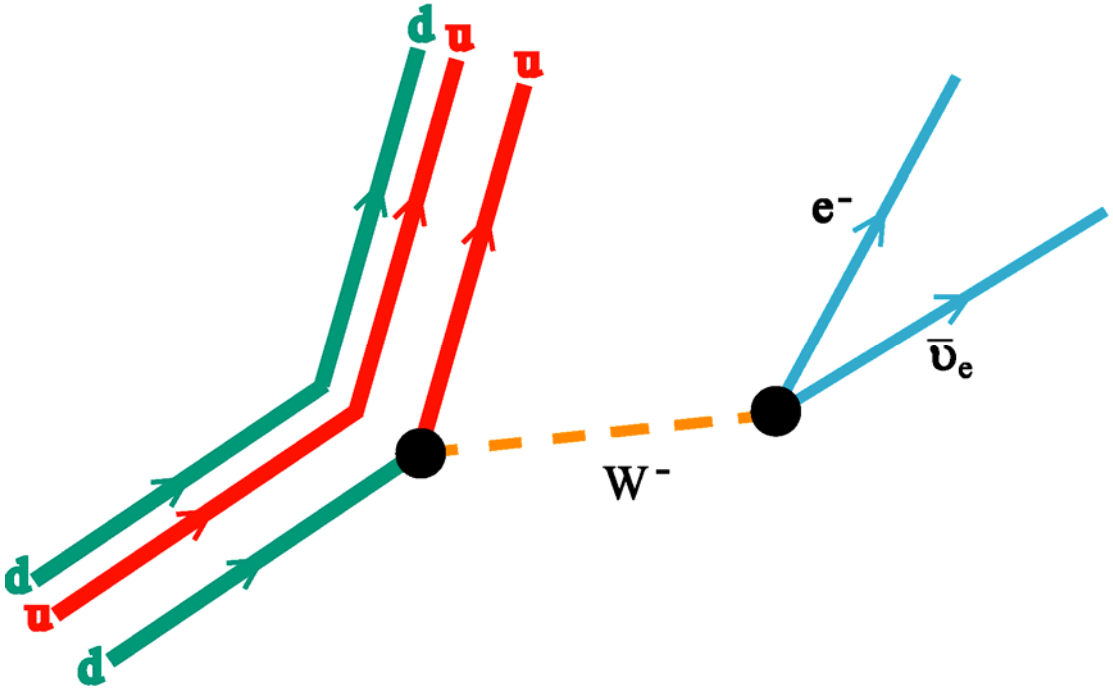


Talk Outline

- Why measure the beta-asymmetry?
- Ultracold neutrons and angular correlations measurements
- The UCNA experiment: the 2007 runs
  - Source and guide development
  - Polarization measurements
  - Beta-decay runs in December, 2007

Neutron β-decay

Straightforward semi-leptonic decay process



“Switch off” the strong interaction:

d quark → u quark + electron + anti-neutrino

(interaction mediated by W^-)

β-decay of quarks (no strong interaction)

$$\left(H_\beta\right)_{eff} = \frac{G_F}{\sqrt{2}} J_\mu^{(quarks)} J^{\mu(leptons)}$$

Semi-leptonic decay
E. Fermi, Z. Phys 88, 161 (1934)

Electroweak Standard Model

Quark current

$$J_\mu^{(quarks)} = (\bar{u}, \bar{c}, \bar{t})\left[\gamma_\mu\left(1-\gamma_5\right)\right] U \begin{pmatrix} d \\ s \\ b \end{pmatrix} + h.c.$$

V-A structure
maximally P-violating

CKM matrix

Lepton current

$$J^{\mu(leptons)} = \overline{\psi_e}\left[\gamma^\mu\left(1-\gamma_5\right)\right]\psi_\nu + h.c.$$

"Switch on" the strong interaction → new form factors induced...

$$d^3\Gamma = \frac{1}{(2\pi)^5 2m_B}\left(\frac{d^3\boldsymbol{p}_p}{2E_p}\frac{d^3\boldsymbol{p}_e}{2E_e}\frac{d^3\boldsymbol{p}_\nu}{2E_\nu}\right)\delta^4(p_n - p_p - p_e - p_\nu)\frac{1}{2}\sum_{spins}|\mathcal{M}|^2$$

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}\langle p(p_p)|J^\mu(0)|\vec{n}(p_n, P)\rangle[\bar{u}_e(p_e)\gamma_\mu(1-\gamma_5)u_\nu(p_\nu)]$$

$$\langle p(p_p)|J^\mu(0)|\vec{n}(p_n, P)\rangle = \bar{u}_p(p_p)\Big(f_1\gamma^\mu - i\frac{f_2}{M_n}\sigma^{\mu\nu}q_\nu + \frac{f_3}{M_n}q^\mu - g_1\gamma^\mu\gamma_5 + i\frac{g_2}{M_n}\sigma^{\mu\nu}\gamma_5 q_\nu - \frac{g_3}{M_n}\gamma_5 q^\mu\Big)u_{\vec{n}}(p_n, P)$$

Note $q = p_n - p_p$ and for baryons with polarization P,
$u_{\vec{n}}(p_n, P) \equiv \left(\frac{1+\gamma_5 \not{P}}{2}\right)u_n(p_n)$

$f_1\,(g_V)$	Fermi or Vector	$g_1\,(g_A)$	Gamow-Teller or Axial Vector
$f_2\,(g_M)$	Weak Magnetism	$g_2\,(g_T)$	Induced Tensor or Weak Electricity
$f_3\,(g_S)$	Induced Scalar	$g_3\,(g_P)$	Induced Pseudoscalar

g_2 and g_3 are two orders of magnitude (or more) below current sensitivity levels and f_3 =0 in the SM

Why Study Neutron Decay

"Clean" extraction of fundamental charged current parameters

All neutron β-decay observables are a function of three form-factors, two of which are specified in the standard model (there are two more which are negligible for our purposes):

$f^V, \; f^{WM}$ Specified by CVC

f^A Must be determined by experiment

Therefore typically two measurements must be performed on the neutron to extract standard model parameters…{lifetime, β-asymmetry, ν-asymmetry, β-ν correl.,etc…} or perform high precision tests of the standard model
For example:

Neutron lifetime & Neutron β-asymmetry ⇒ L/R symmetric models (specific mechanisms for P violation)

Neutron lifetime & Neutron β-asymmetry
+ μ lifetime ⇒ G_F, V_{ud}, f^A
+ masses of p, n, e^-, and μ

+ Weak decay rates for K, B mesons ⇒ Unitarity test of CKM →supersymmetry

2004: 2.5σ discrep.

Neutron β-asymmetry energy dependence ⇒ f^{WM} →CVC, SCC/induced tensor

CKM Matrix

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

Involved in neutron beta-decay (V_{ud})

Matrix elements determined by experiments

Matrix unitary in the SM: $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$

PDG 2004: $\sum V_{ui}^2 = 0.9966 \pm 0.0014$

2003 – 2007 things changed! 2007:

- Experimental values for $f^+(0)V_{us}$: (Leutwyler and Roos form factor)

  $V_{us} = 0.2200 \pm 0.0026 \rightarrow 0.2254 \pm 0.0021$

  $\sum V_{ui}^2 = 0.9991 \pm 0.0012$

- New form factor calculations

  $V_{us} = 0.2254 \pm 0.0021 \rightarrow (0.2208 - 0.2224) \pm 0.0021$

  $\sum V_{ui}^2 = (0.9970 - 0.9977) \pm 0.0012$

- New neutron measurements (experiments not consistent!)

In flux! More neutron measurements needed

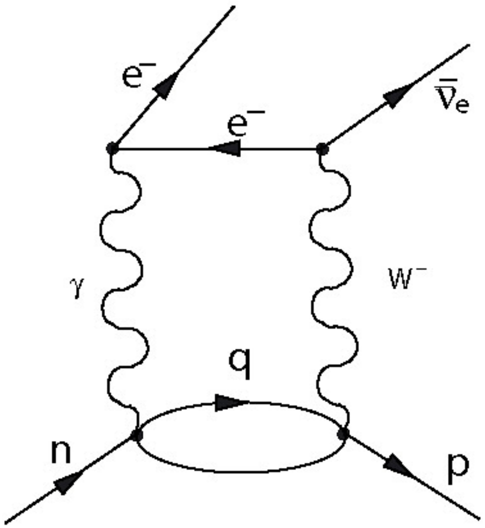
“Loops” are “in”

- Dominant theoretical uncertainty in extracting V_{ud} comes from hadronic loops

Sirlin, Rev. Mod. Phys. **50**, p. 573 (1978).

- At least four groups actively pursuing improvements in this situation:

Marciano and Sirlin, Ramsey-Musolf *et al.*, Gudkov *et al.*, and Ji



Developments 2005-2007:

- First real progress on theoretical radiative corrections in beta-decay

Marciano and Sirlin, Phys. Rev. Lett **96**, 032002 (2006)

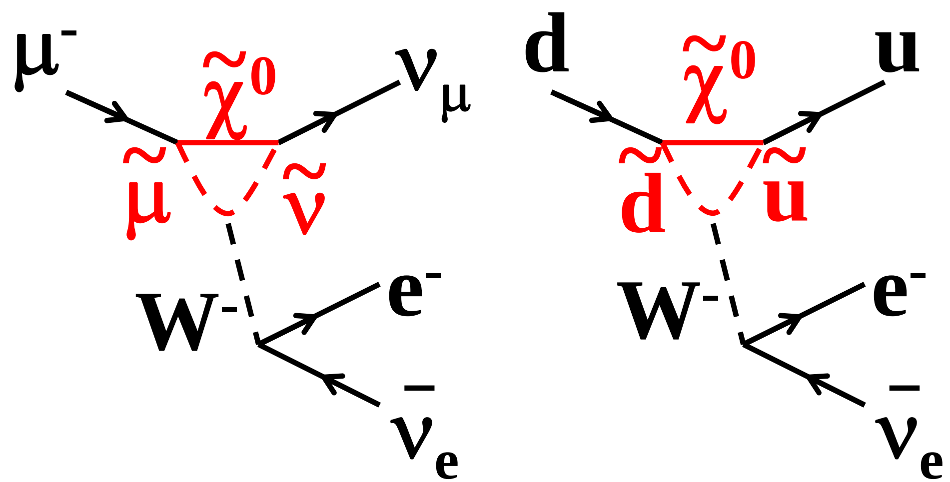
- New calculations of V_{us} involve first competitive high precision results from lattice

Aubin, C. et al (MILC Collaboration), 2004, Phys. Rev. D 70 114501; Bernard, C., 2005, eprint hep-lat/0509137.

More loops!

Supersymmetry

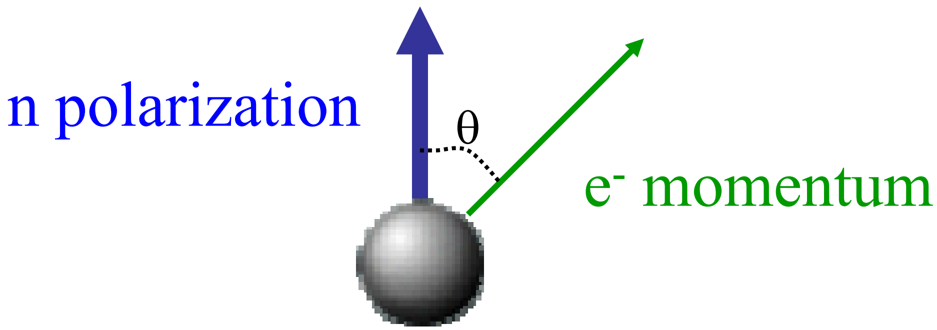
Sensitive to loop corrections
β-decay sensitive to differences in squark/slepton couplings – unitarity tests



Kurylov and Ramsey-Musolf PRL88(2001)076007

Note: Profumo *et al.* suggest the neutrino asymmetry might be very sensitive to supersymmetric effects—measurable phenonemon just below current limits

Beta-Asymmetry



$$R = R_o(1 + (v/c)\,P\,A(E)\cos\theta)$$

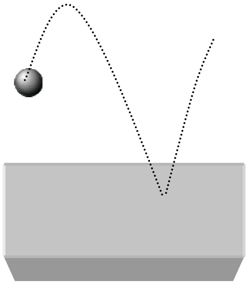
β-asymmetry = A(E) in angular distribution of e^-

To leading order:

$$A = -2\frac{-G_A G_V + G_A^2}{G_V^2 + 3G_A^2}, \qquad t_n = \frac{\text{constant}}{G_V^2 + 3G_A^2}$$

$$G_V = G_F V_{ud} f^V, \qquad G_A = G_F V_{ud} f^A$$

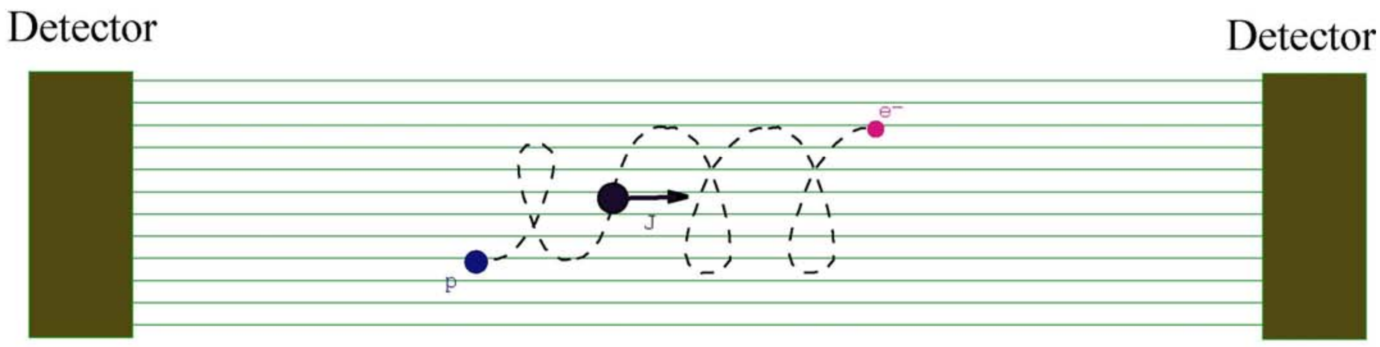
$$f^V = 1 \text{ (CVC)}, \qquad f^A \cong 1.25 \text{ (expt)}$$



Theoretical corrections: RC = 2.40±.08 %, leading recoil order terms ~ 1%/MeV

How to Measure a Beta-Asymmetry

β directional distribution: $1 + P\frac{v}{c}A(E)\cos\theta$
(polarized neutrons)



Magnetic Field
(entrains decay products)

$$A(E) \propto \frac{N_+ - N_-}{N_+ + N_-}$$

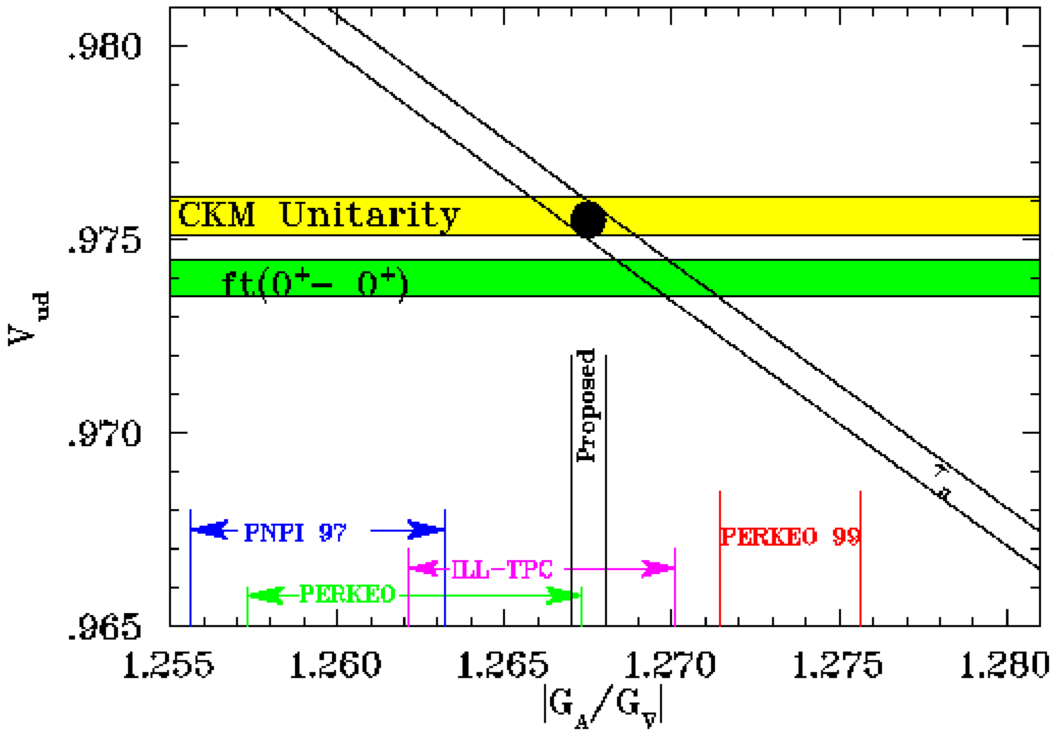
We must determine P (the average neutron polarization), v and E (the β velocity and energy) and cosθ

N_+,N_-,v and E: Signals from the detector arrays → singles backgrounds subtraction critical

cosθ: use magnetic fields to capture all decay products → $\cos\theta = \pm\ 1/2$ (with small corrections)

P: polarize UCN, limit depolarization and measure depolarized UCN fraction

Status of Previous Experiments



Re-evaluation of V_{us} (?),

Shift towards agreement *and* reduce uncertainties in Unitarity range

Experiment		A (Beta-Asymmetry)	Systematic Corrections		
			P	Background	Other
PERKEO	1986	-0.1146 ± 0.0019	2.6%	3%	Mirror: 12%
PNPI	1991	-0.1116 ± 0.0014	27%	small	
ILL-TPC	1995	-0.1160 ± 0.0015	1.9%	3%	Sld ang:15%
PERKEO II	1997	-0.1189 ± 0.0012	1.5%	1.6% (15% "env")	
PNPI* (revised)	1998	-0.1135 ± 0.0014	~27% (adj.)	small	
PERKEO II	2000	-0.1189 ± 0.0007	1.1%	0.5% (15% "env")	

& detector characterization, usually minor correction until now, is growing increasingly important!

PERKEO II recent results — PERKEO III no running

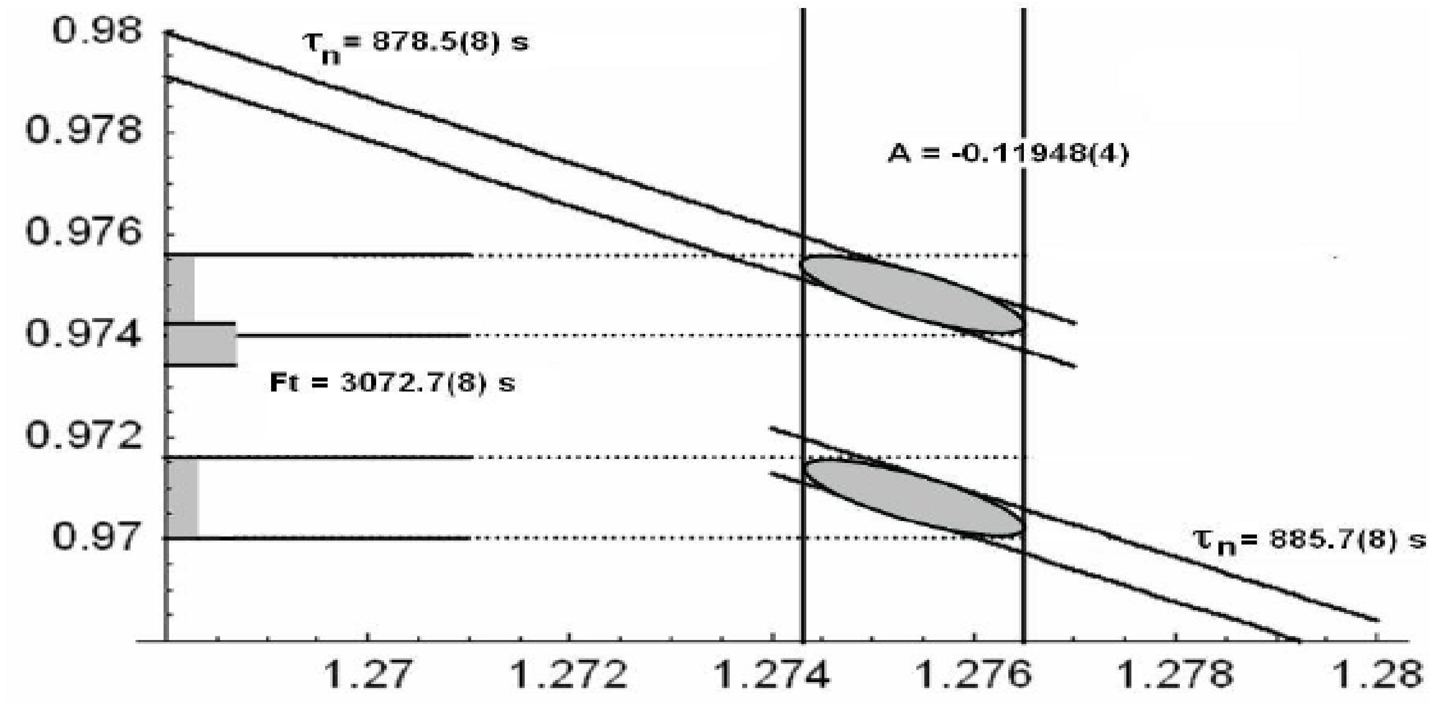
	2002 correction	2002 uncertainty	2006 correction	2006 uncertainty
polarization	1.1 %	0.3 %	0.3 %	0.1 %
flipper efficiency	0.3 %	0.1 %	0.0 %	0.1 %
Statistical error		0.45 %		0.26 %
background	0.5 %	0.25 %	0.1 %	0.1 %
detector function		0.26 %		0.1 %
edge effect	-0.24 %	0.1 %	-0.22 %	0.05 %
time resolution		0.25 %		
mirror effect	0.09 %	0.02 %	0.11 %	0.01 %
backscattering	0.2 %	0.17%	0.003 %	0.001 %
rad. corrections	0.09 %	0.05 %	0.09 %	0.05 %
Sum	2.04 %	0.66 %	0.38 %	0.33 %

2006 preliminary

2002: result: A = -0.1189(8) λ = -1.2739(19)

2006: result: **A = -0.11948(40) λ = -1.2754(11)**

V_{ud} from neutron β decay



Hartmut Abele

What is an Ultracold Neutron (UCN)?

UCN are neutrons with velocities below about 9 m/s

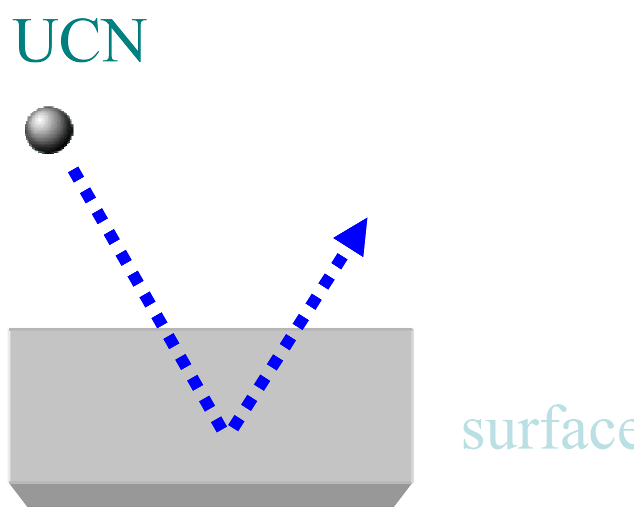
Thermal de Broglie wavelength is greater than 485Å

These long neutron wavelengths result in the classical optics limit for scattering…

$\Downarrow$

reflection and refraction

(much as light reflects and refracts from transparent and metallic surfaces)



The key point is that UCN reflect for any angle of incidence from some material surfaces. You can put them in bottles!

UCN Energy Scales

Energy of UCN moving 8 m/sec: 340 neV (nano-eV)

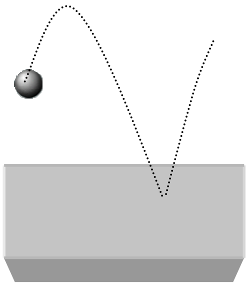
$\approx$ 3.6 mK

Energy of UCN in 1T magnetic field: $\pm$ 60 neV

Energy change associated with a 1 m rise: 104 neV

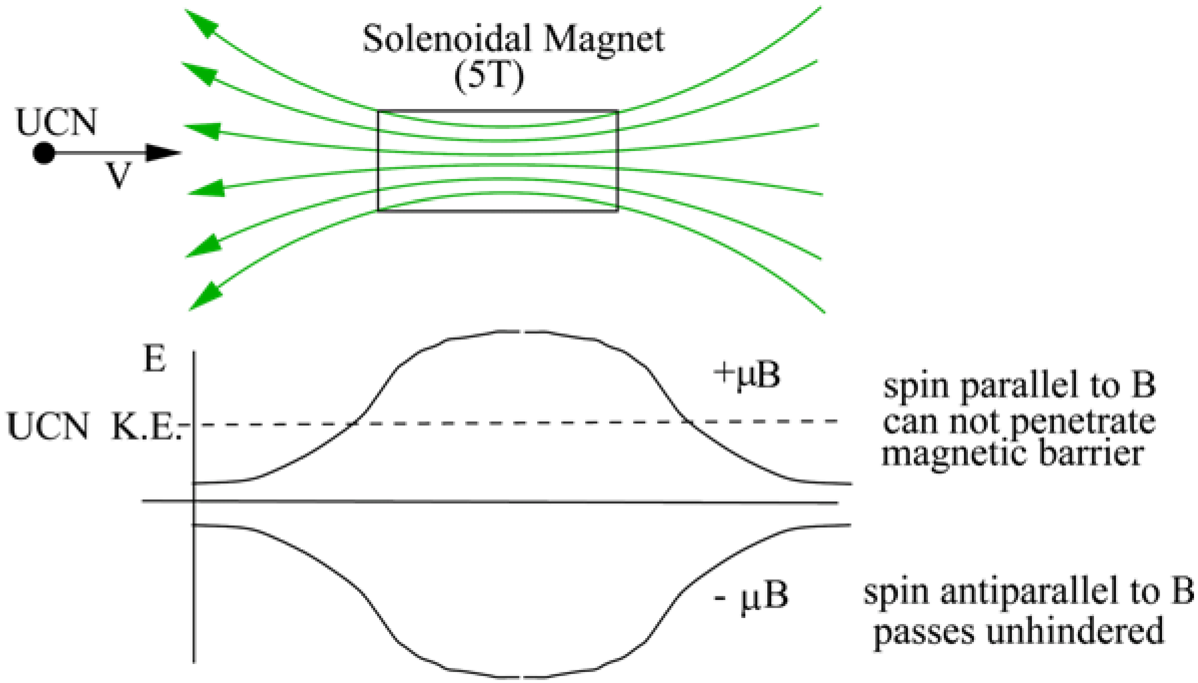
Effective potential barrier (U_{eff}) at a diamond film coating:

260 neV



Advantages of using UCN for Beta-Asymmetry measurement

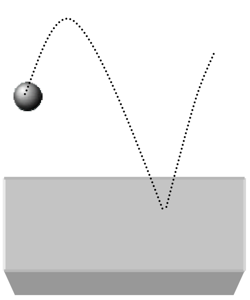
UCN can be essentially 100 percent polarized



First time UCN used for angular correlations measurements…

(note: neutron magnetic moment is negative)

Beta-decay measurements performed with UCNs produced at a spallation source may have an order of magnitude or more improvement in backgrounds (targets: > 100 Hz decay rate, <0.5 Hz total background rate)



UCNA Collaboration

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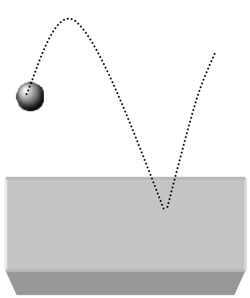
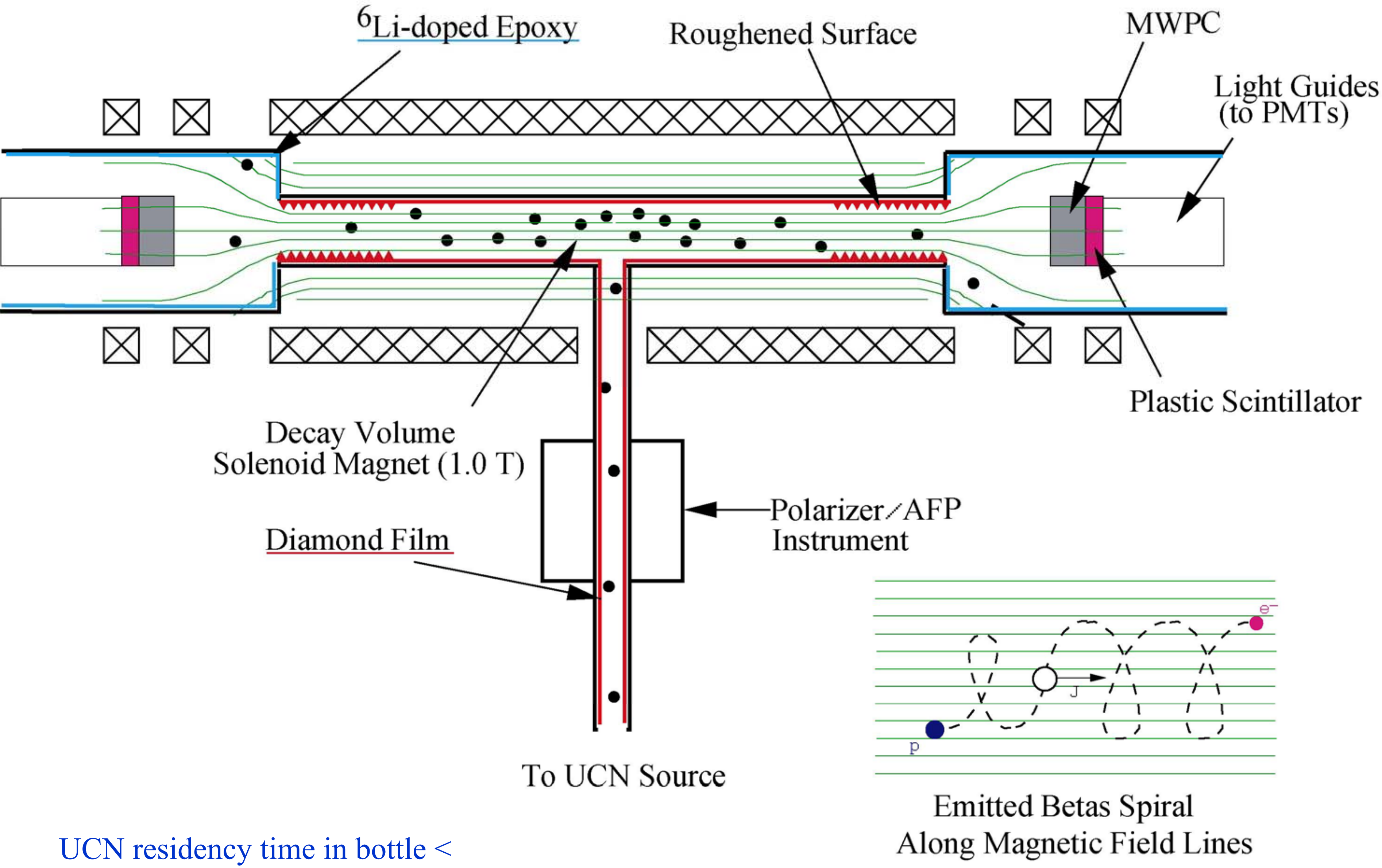




UCN residency time in bottle <
5s to limit depolarization…

Systematic Uncertainty Budget

Original Goal: measure A to precision of 0.2% or better

for a decay rate of 116 Hz in our bottle

UCN density ~6 UCN/cm^3

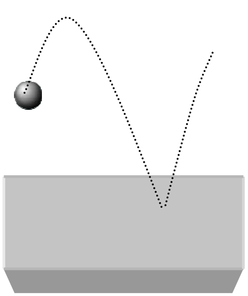
requires 45 days of beam time + 45 days to explore systematics

Dominant systematic corrections

Systematic Effect	Size of correction	Uncertainty
UCN Pol/spin-flip eff.	1×10^{-3}	1×10^{-4}
Wall depolarization	9×10^{-4}	1×10^{-4}
Backscattering	2×10^{-3}	4×10^{-4}
Field non-uniformity	7×10^{-4}	7×10^{-5}
Detector response	3×10^{-4}	3×10^{-4}
Detector linearity	6×10^{-5}	6×10^{-5}
Total background	.5 Hz	.1 Hz
Total	2.5×10^{-3}	1.0×10^{-3}

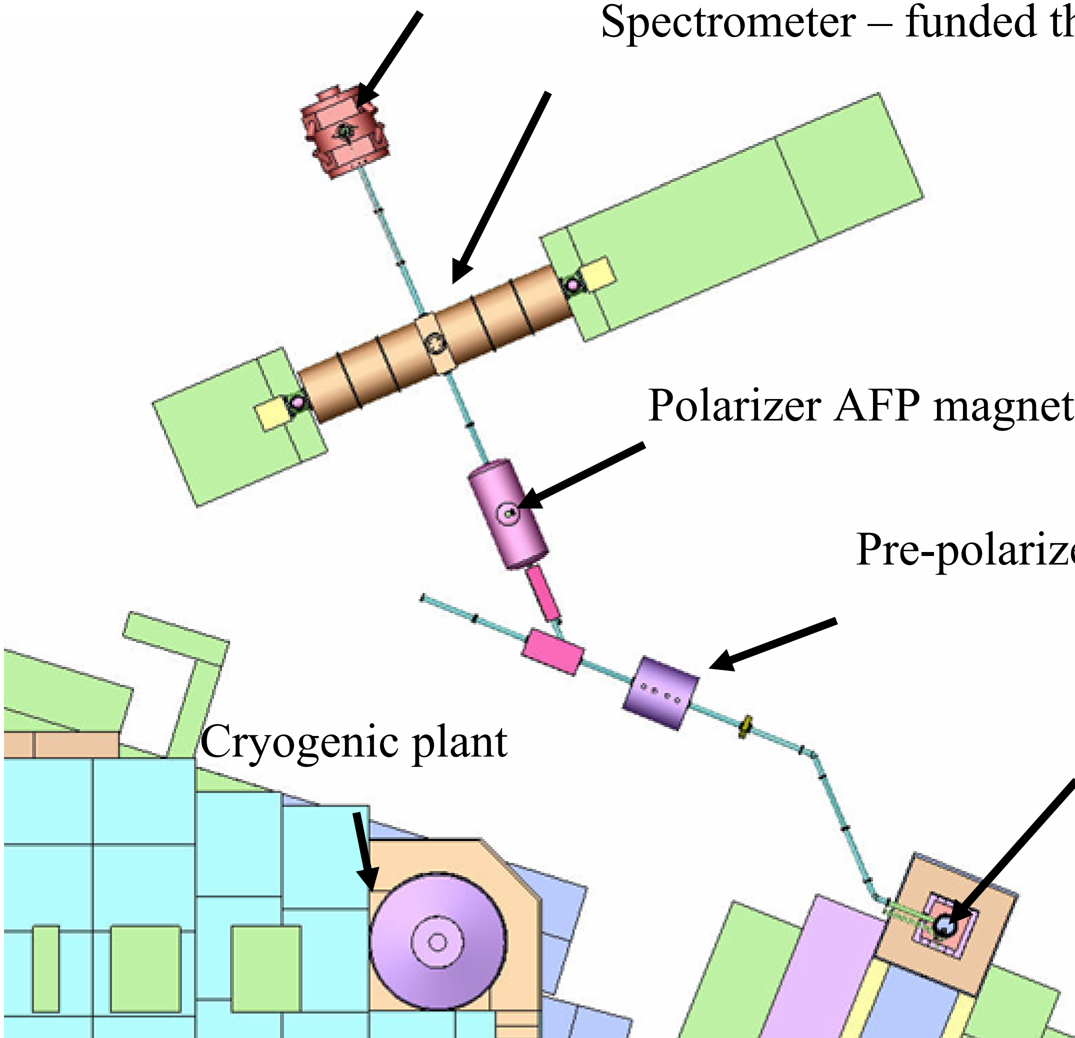
Leading corrections roughly order of mag smaller than prev experiments

Need *in situ* measurement with UCN!

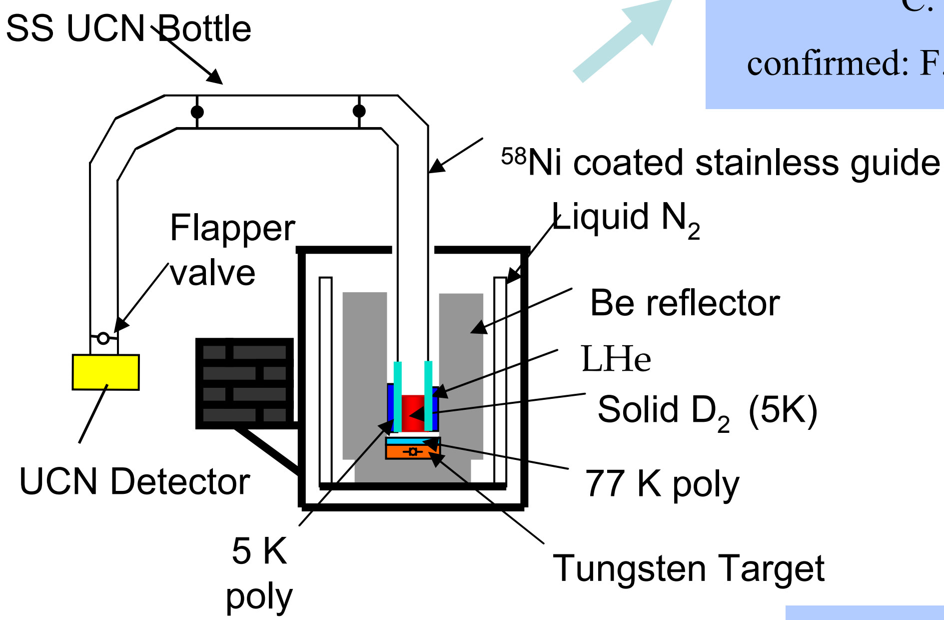


The UCNA Experiment

Major-System Status: operational



Key UCNA Prototype Results



$$\tau_{para} = 1.2 \pm .14\ (\text{stat}) \pm .20\ (\text{syst})\ \text{ms}$$

C. L. Morris *et al.*, Phys. Rev. Lett. **89**, 272501 (2002)

confirmed: F. Atchison et al., Phys. Rev. Lett. **95**, 182502 (2005)

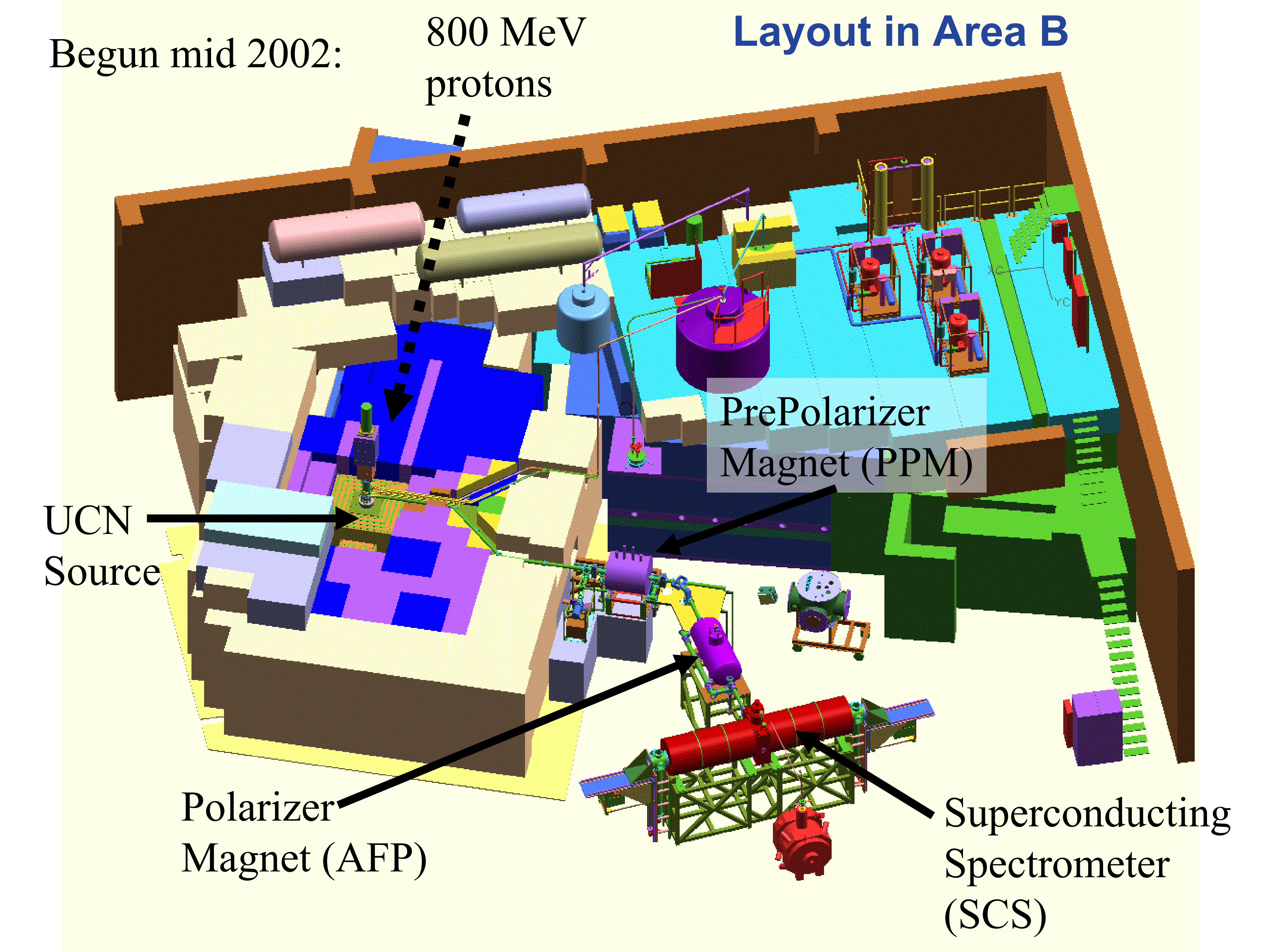
$$\rho_{UCN} \rightarrow 145 \pm 7\ \text{UCN/cm}^3$$

A. Saunders *et al.*, Phys. Lett. B **593**, 55 (2004)

confirmed: F. Atchison et al., Phys. Rev. C. **71**, 054601 (2005)

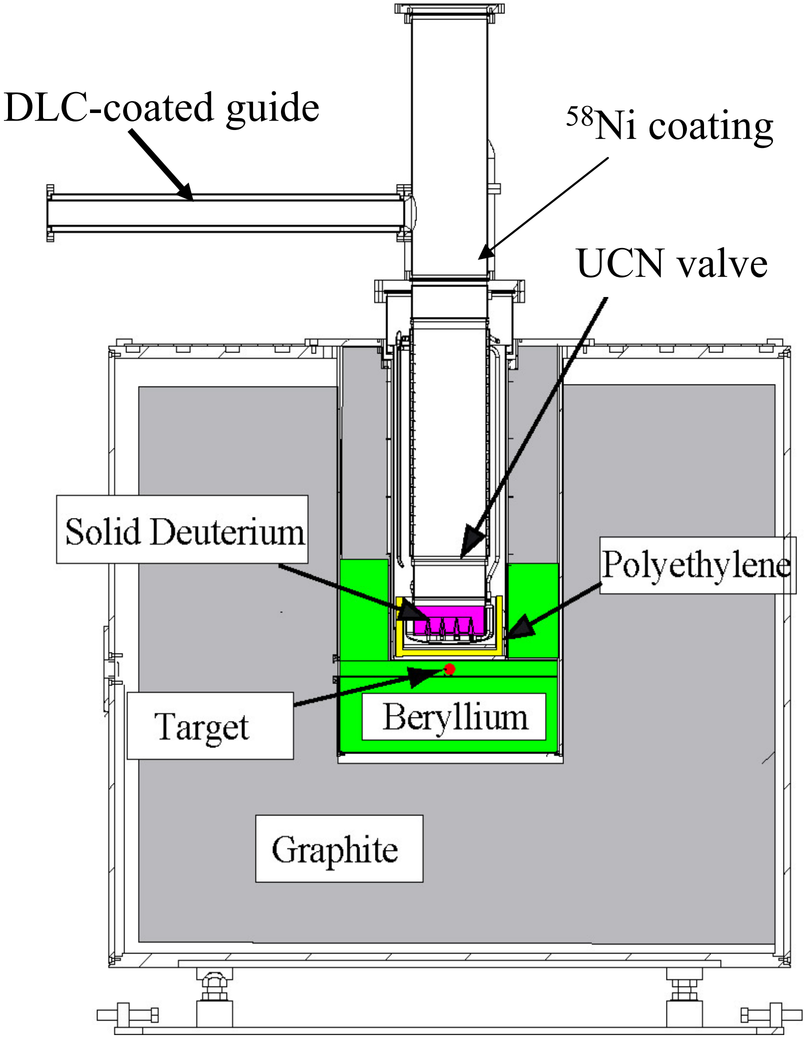
PhD Thesis: Chen-Yu Liu

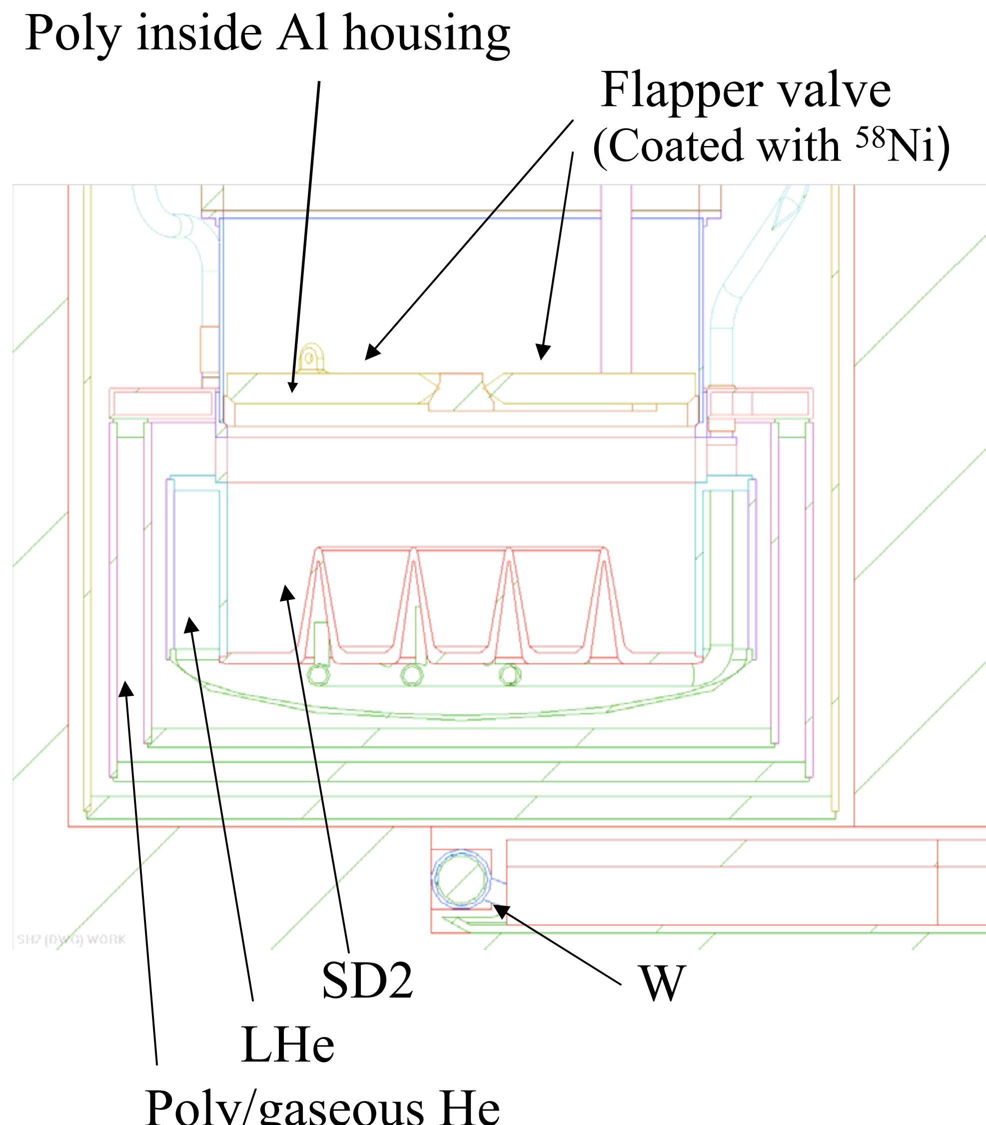
Recent work on multiphonon production: F. Atchison *et al.*, Phys. Rev. Lett. **99**, 262502 (2007).


Layout in Area B
Begun mid 2002:
800 MeV protons
PrePolarizer Magnet (PPM)
UCN Source
Polarizer Magnet (AFP)
Superconducting Spectrometer (SCS)

Area B Source (2004)

Max. cooling power at 4K: ~75W (100 liter/hr LHe)





Thermal conductivity of SD_2 limits acceptible beam currents….

2007 Source and Guide Upgrades

.07 UCN/cm^3 in SCS running at 2 μA in 2006…

- A new ^{58}Ni coated stainless steel insert and ucn valve installed.

  Gain x2-3 observed, τ ~30s

- Some additional warm polyethylene added under the source, this should increase thermal, cold and ultracold neutron production.

  Modest gain probably observed

- More proton beamline diagnostics and a beam position monitor

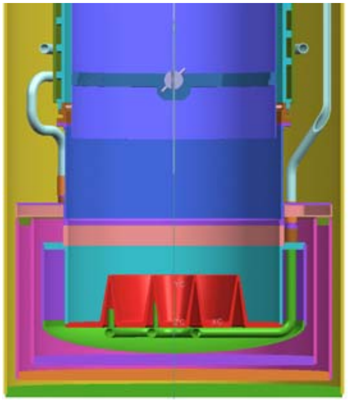
  Continuing refinement, improvements expected

- Electropolished Cu (V_F=168 neV) for guides & decay trap beyond switcher

  Gain x2-3 observed

Source Performance in 2007

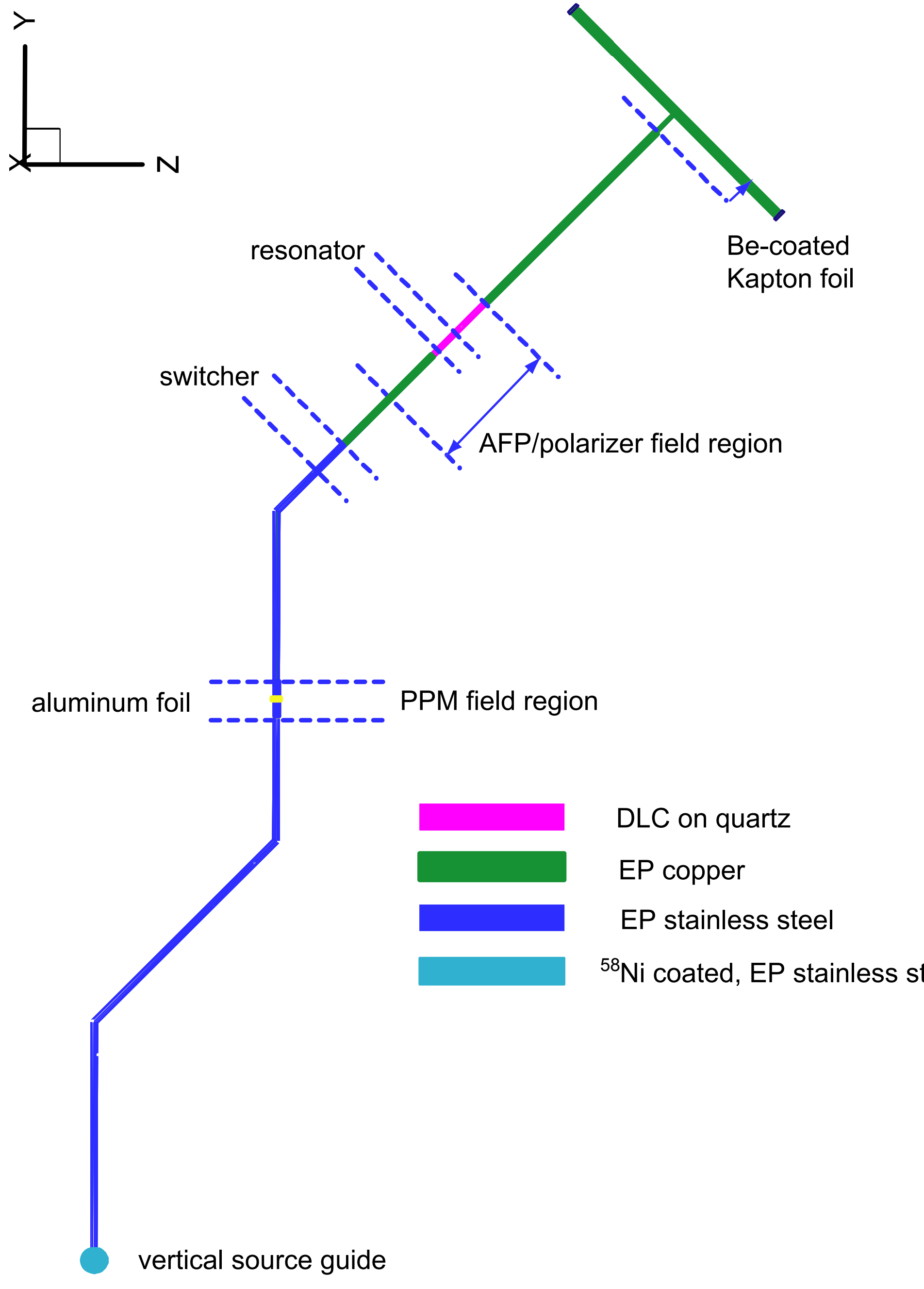
- 1.6 μA
- Approximately 2 liters SD_2 w/ P/O ratio below 3.1% (P/O ratio falls continuously with time under irradiation, typically well below 2%)
- maximum density (from UCN decay rate in SCS at 0.5 T) ~ 0.78 UCN/cm^3 – order of magnitude improvement…
- Average density during runs (SCS at 1.0 T) ~0.23 UCN/cm^3



Guide System

- Transport: 58Ni-coated vertical section
- EP SS to switcher
- Polarization-preserving guide
  - EP Cu beyond switcher (2-3 Ra µinch mechanical polish + EP)
  - DLC-coated quartz in resonator region

Note: switched to Cu because of time constraints on producing DLC-coated guide



UCN Guide Fabrication Improvements

• UCNA collaboration developed (2002) diamond-like carbon coatings for cylindrical guides using pulsed-laser deposition (quartz tubing substrates)

• 95% transmission per meter – comparable to best guides to date, Fermi potential 260 neV, depolarization less than 3×10^{-6}/bounce.

• In 2006 we introduced *in situ* ion energy monitors, thickness monitors and profilometry scans of multiple witness plates ensure coating quality

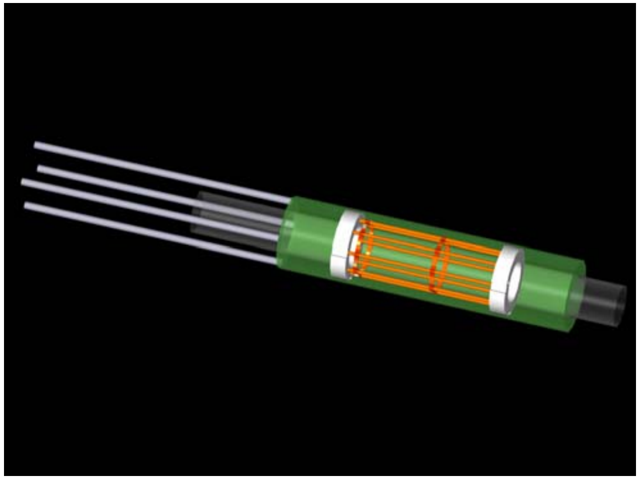
• Adequate Fermi potential and thickness confirmed via measurement of transport properties using UCN "Guide evaluation box"

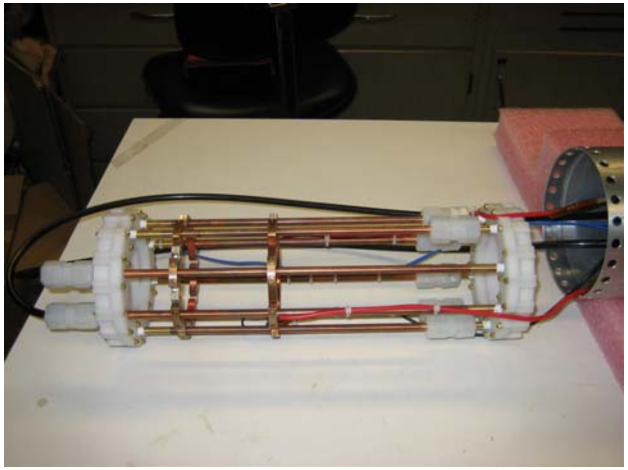
150 x 70 mm ID coated tube

Polarization Measurements

- Crossed polarizer-analyzer measurements (not directing UCN into the β-spectrometer)
- *Ex situ* measurements of depolarization and transport time constants (draining times) using geometry with β-spectrometer
- *In situ* measurements during run cycle (1hr of data, 10min of depol)
- Rf-tuning accomplished using Fe-foil polarimeter between AFP/polarizer and β-spectrometer

AFP Resonator (A. T. Holley)

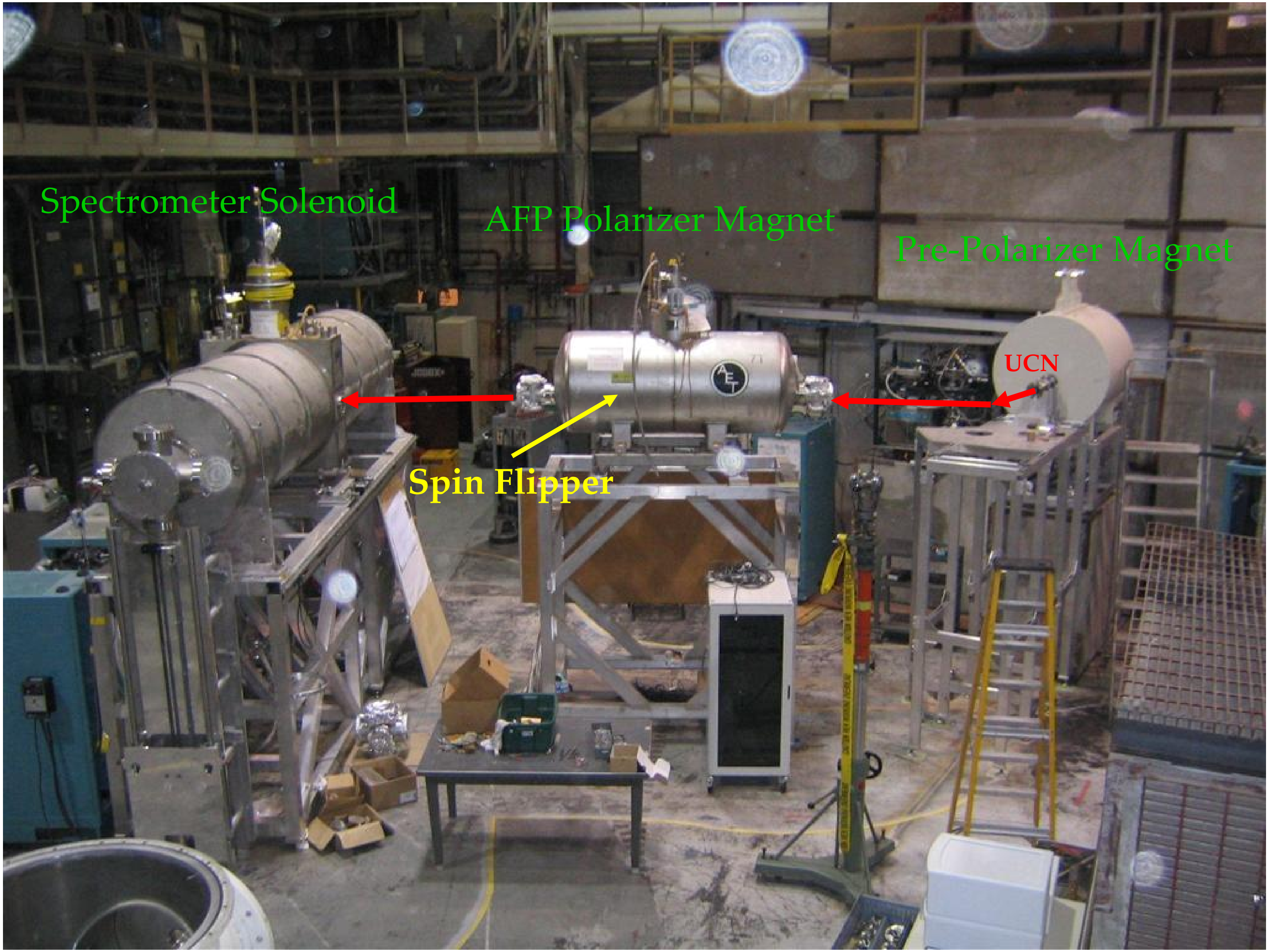




Final version for 2007 run

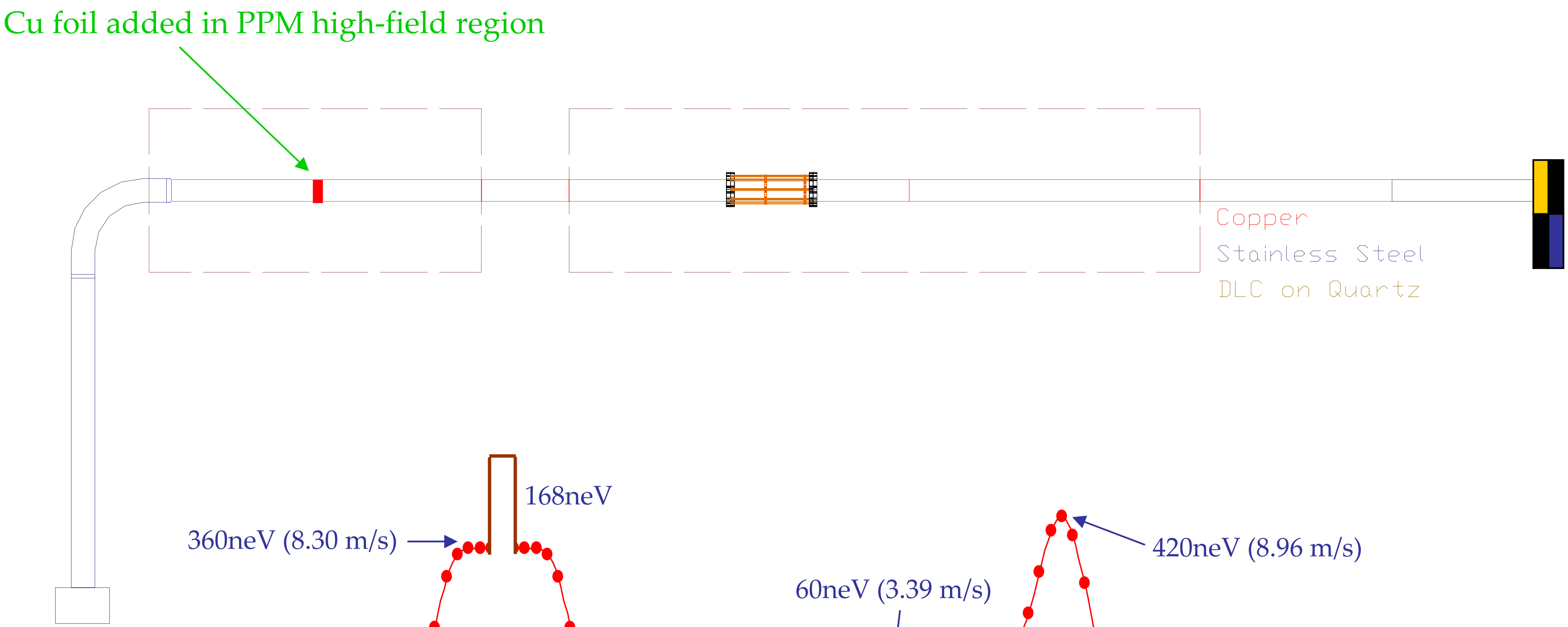
1. Designed to produce uniform rf field up to 5G at 30 MHz (nominal minimum spin-flipping efficiency .999) – 500 W input rf!
2. Additional tailoring of gradient field possible (currently about .6 G/cm, can improve by factor 10)
3. No backgrounds observed during operation of rf in detector arrays

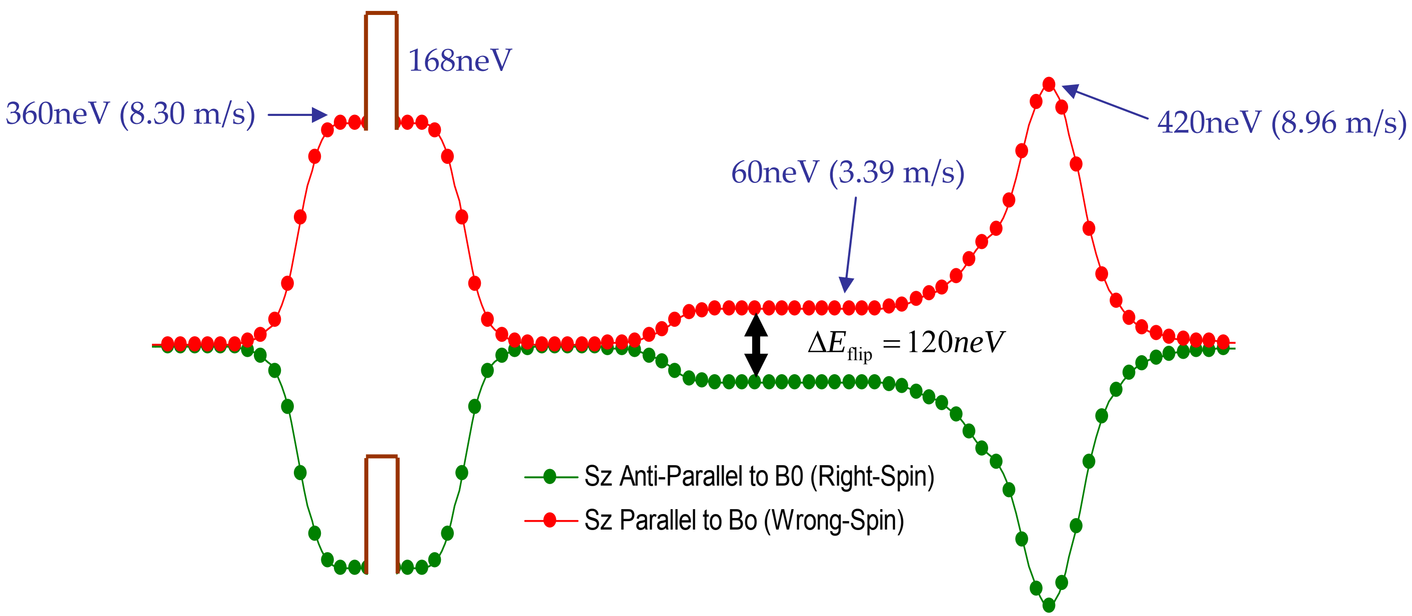
The UCNA Experiment



Cross Polarizer Analyzer

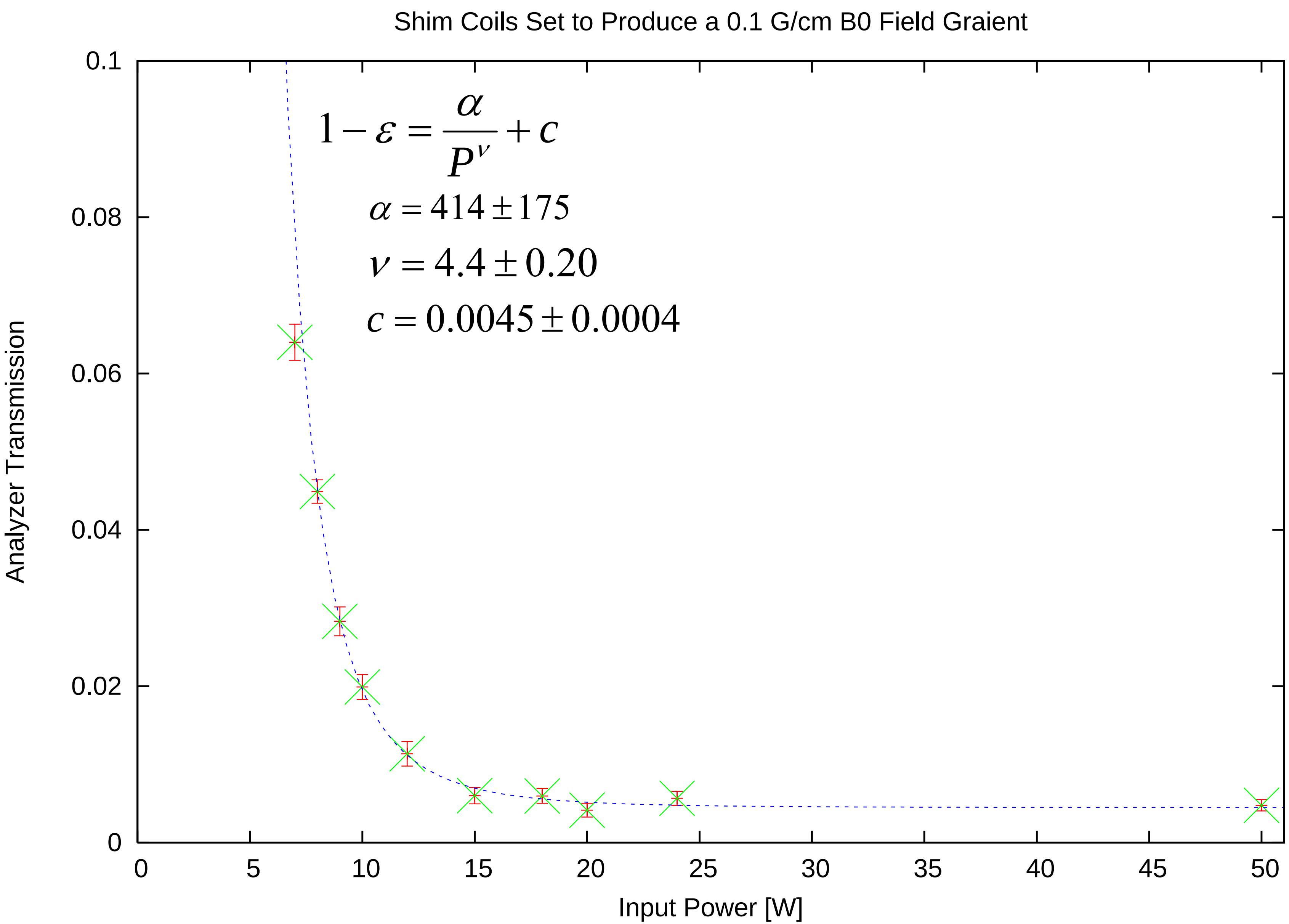
Cross Polarizer Analyzer: Increase Analyzing Power





$200+120 \sim V_{\text{wrong}}$

Cross Polarizer Analyzer: Power Scan

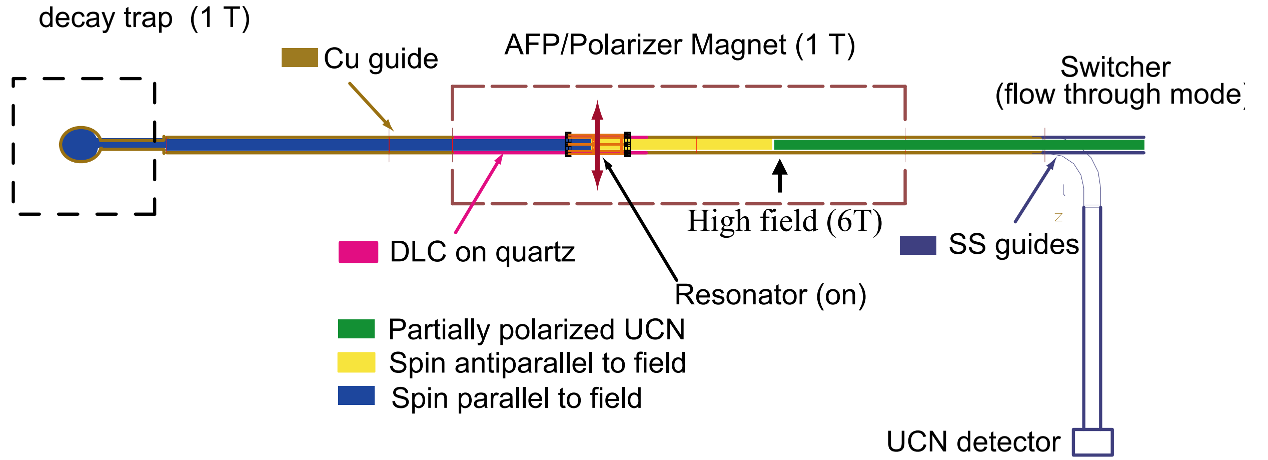


Polarization Measurements During Runs

- Field geometry automatically “traps” depolarized neutrons
- Use switcher to direct UCN accumulated in trap to UCN detector to monitor cleaning and draining of trap of right spin neutrons
- Change state of rf to monitor remaining depolarized neutrons

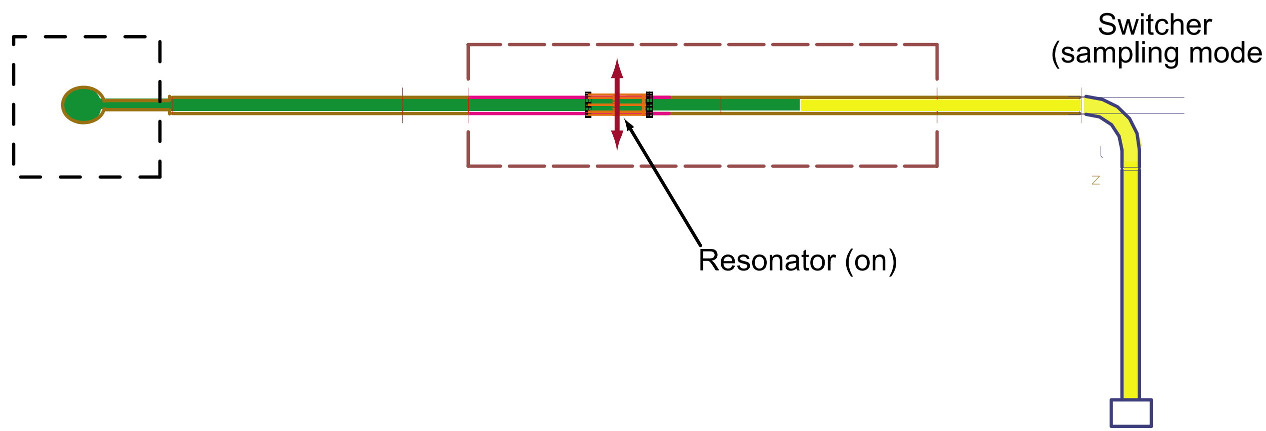
Loading:

Spins are fully polarized in high field region, flipped, and loaded (parallel to field – “blue”) into trap during run



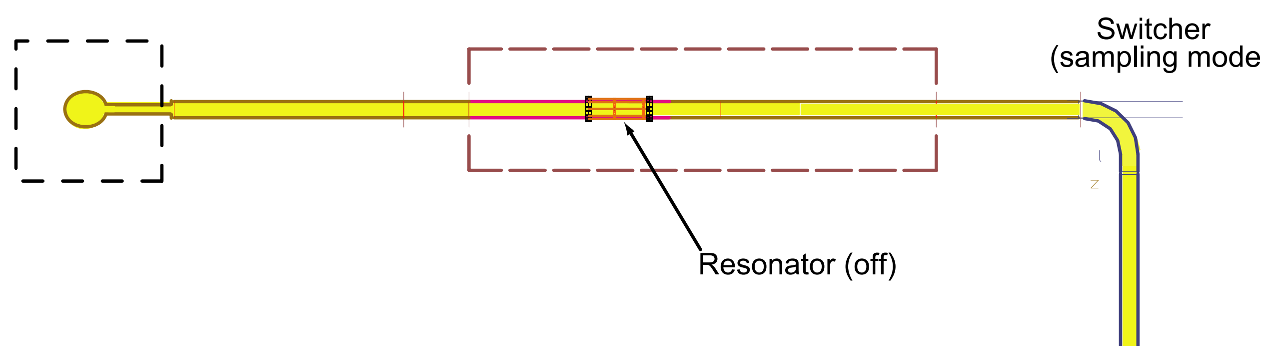
Cleaning:

Depolarized neutrons (“yellow”) accumulate during run. Run is stopped and right spin neutrons drained



Measuring:

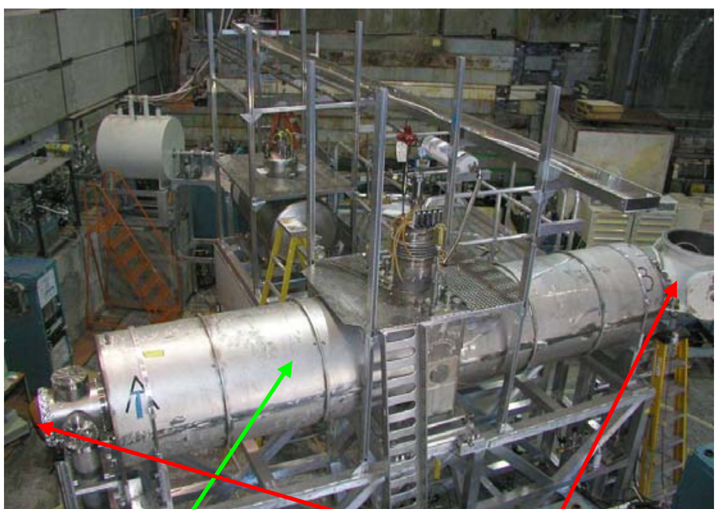
Spin flipper is turned off, permitting depolarized neutrons to reach detector



Analysis of these data by A. T. Holley is proceeding

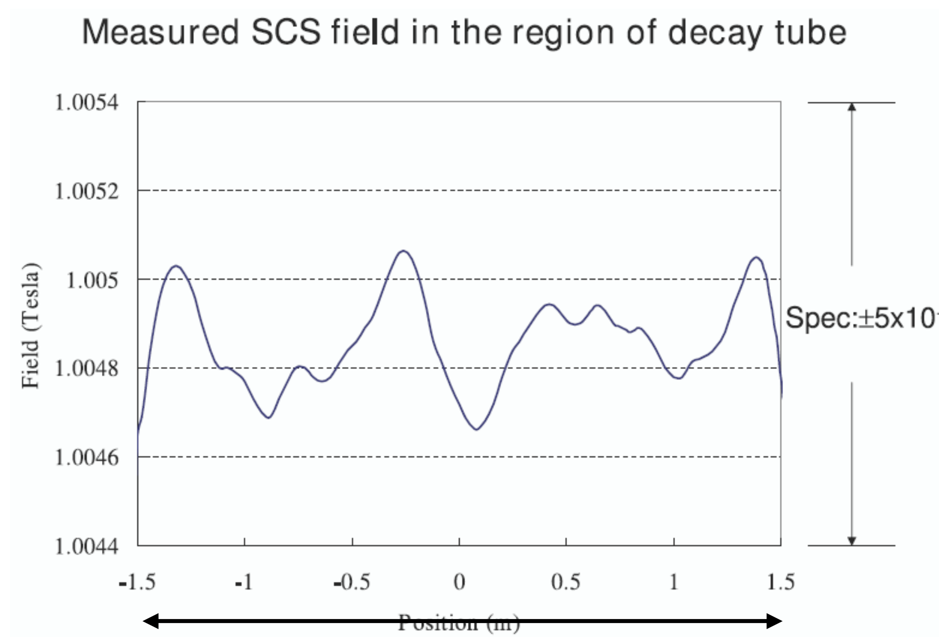
Spectrometer and β-decay Studies

- 1.0-Tesla solenoidal spectrometer with field uniformity of ~ ± 2 × 10^{-4} over decay trap volume
- UCN decay trap (3-m long) oriented along spectrometer axis
  - radius of 5.0-cm
    - → projects to radius of ($5.0/\sqrt{0.6}$) ~ 6.5-cm in field-expansion region



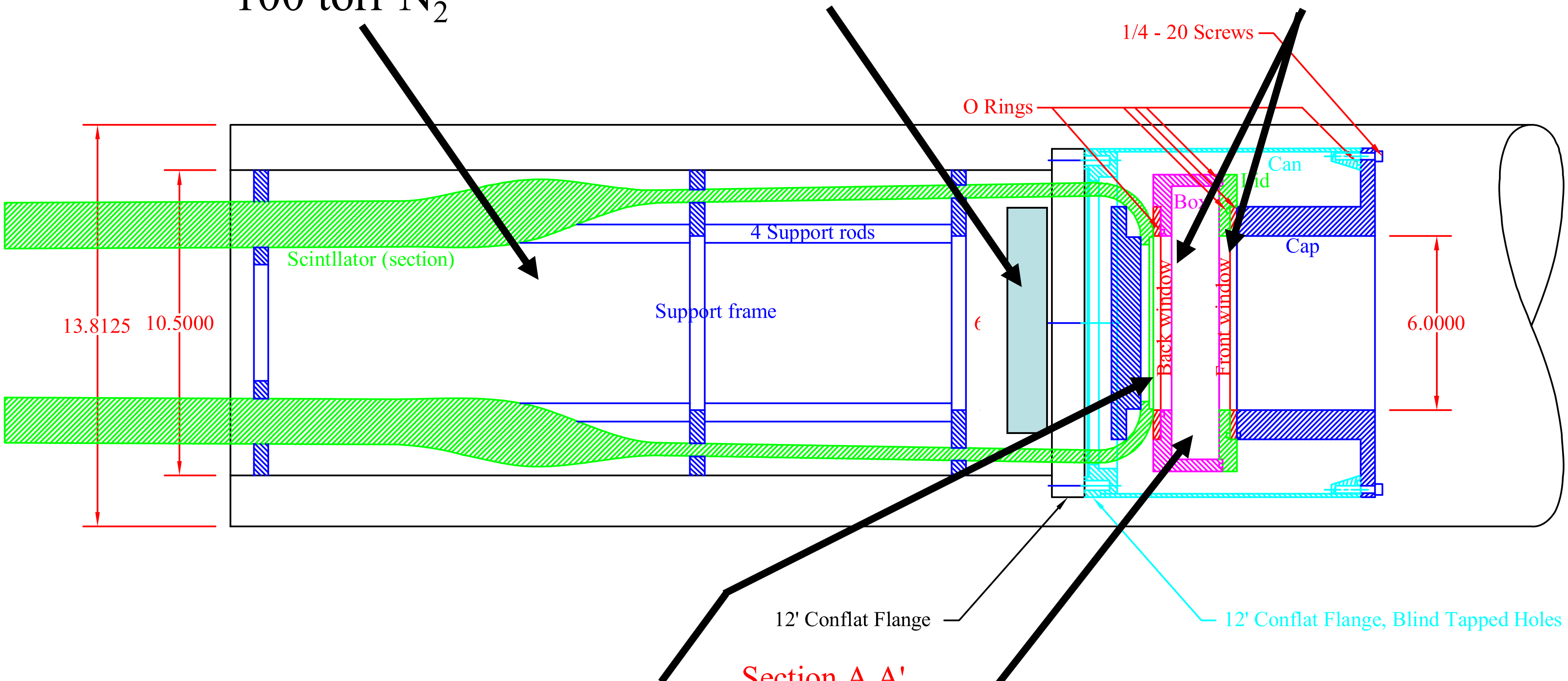
1-Tesla solenoidal spectrometer

β-detector mount points



3-meters

β-detector array



plastic scintillator 15cm diam, .35cm thick, coupled on all edges (4 PMTS)

MWPC (100 torr neopentane)

β-detector package

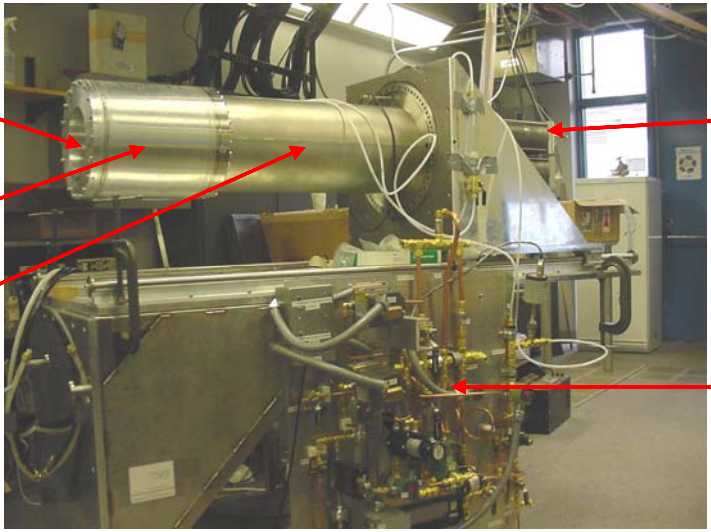
- MWPC: position information, low sensitivity to gamma-rays, and low threshold for identification of backscattering
  - (163 × 163) mm^2 active area
  - 100 Torr neopentane gas
- Plastic scintillator: energy and timing information
  - 7.5-cm radius
  - 3.5-mm thickness [range of (end-point) 782 keV electrons = 3.1-mm]

T.M. Ito *et al.*, in preparation for NIMA

MWPC entrance window (25-micron) facing decay trap

MWPC

100 Torr nitrogen vacuum housing for scintillator and light guides



4 PMTs with magnetic shields (~300 Gauss)

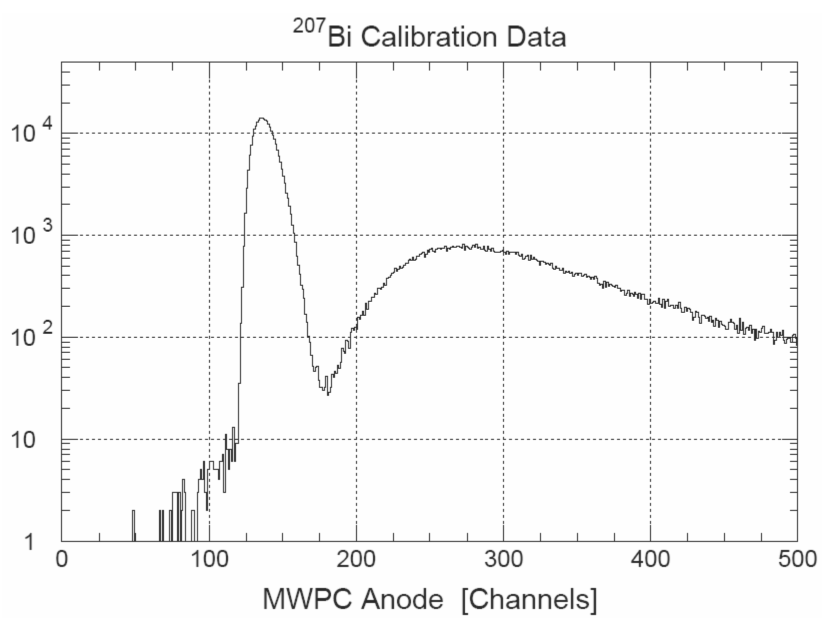
neopentane and nitrogen gas-handling system

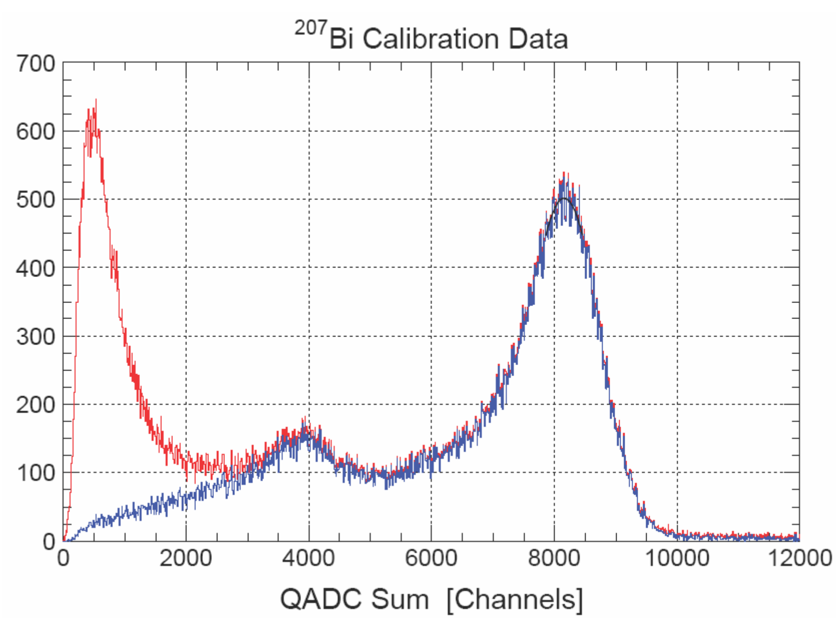
On-line performance tests

- Conducted with conversion line sources during January 2006
  - ^{113}Sn: 364 keV
  - ^{207}Bi: 481 keV, 975/1047 keV

neutron β-decay end-point = 782 keV

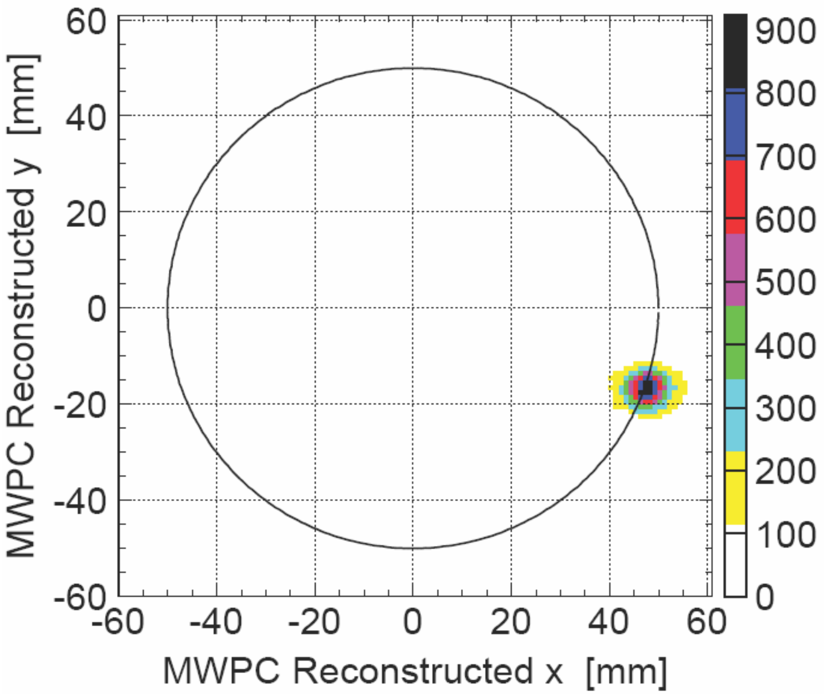
- Spectrometer energized to full 1.0-Tesla field
- Vacuum feedthrough used to move sources into/out of decay-trap region

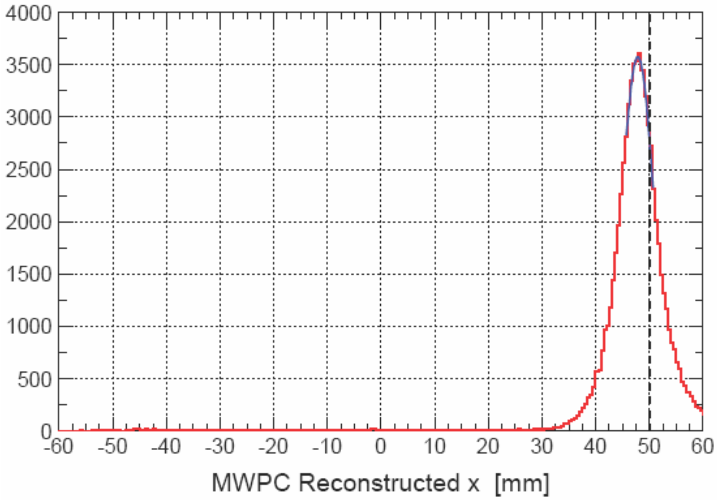


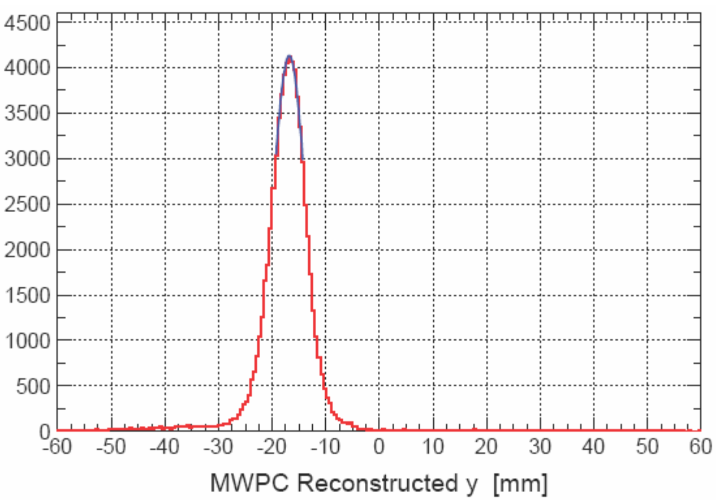


MWPC position reconstruction

- Reconstruction with source near edge of fiducial volume





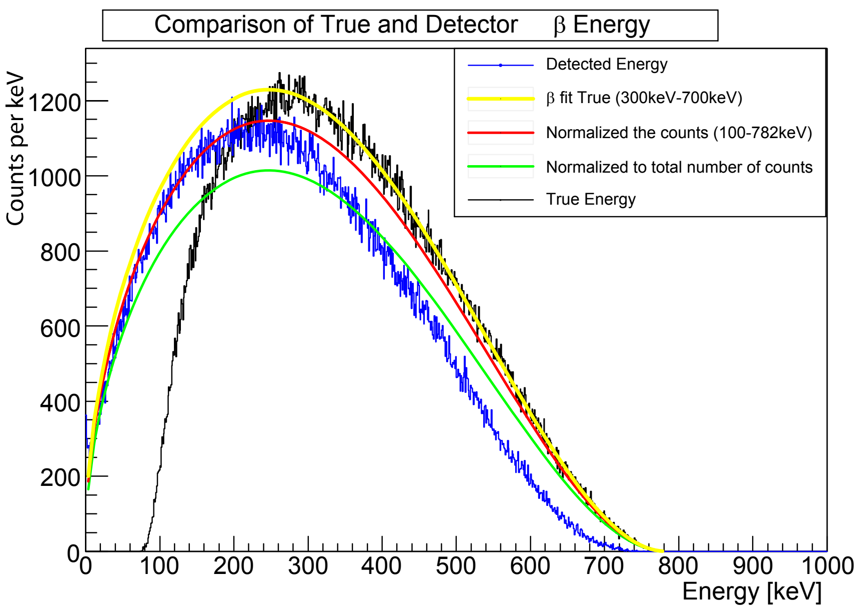


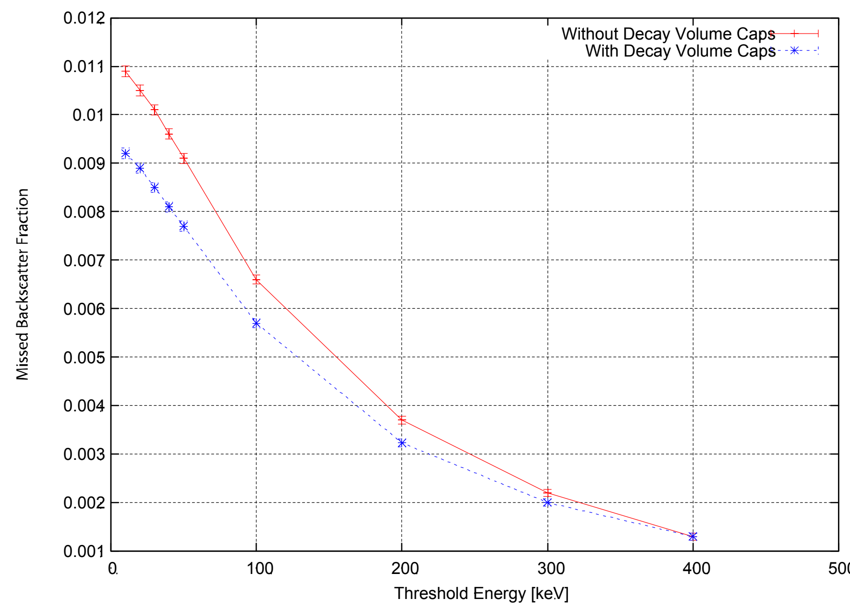
2006 β-decay Runs: Analysis and Implications (R. W. Pattie)

Backgrounds meet expectations! (Total non-vetoed bkg < 0.2 Hz)

- ``New Measurements and Quantitative Analysis of Electron Backscattering at Energies Relevant to Neutron β-Decay,'' J. W. Martin, M. J. Betancourt, B. W. Filippone, S. A. Hoedl, T. M. Ito, B. Plaster, A. R. Young and J. Yuan, Phys Rev. C **73**, 015501 (2006).
- ``Measurement of Electron Backscattering in the Energy Range of Neutron β-Decay,'' J. W. Martin, J. Yuan, S. A. Hoedl, B. W. Filippone, D. Fong, T. M. Ito, E. Lin, B. Tipton and A. R. Young, Phys. Rev. C **68**, 055503 (2003).

+ ^{113}Sn calibration runs →we understand our spectrometer response!



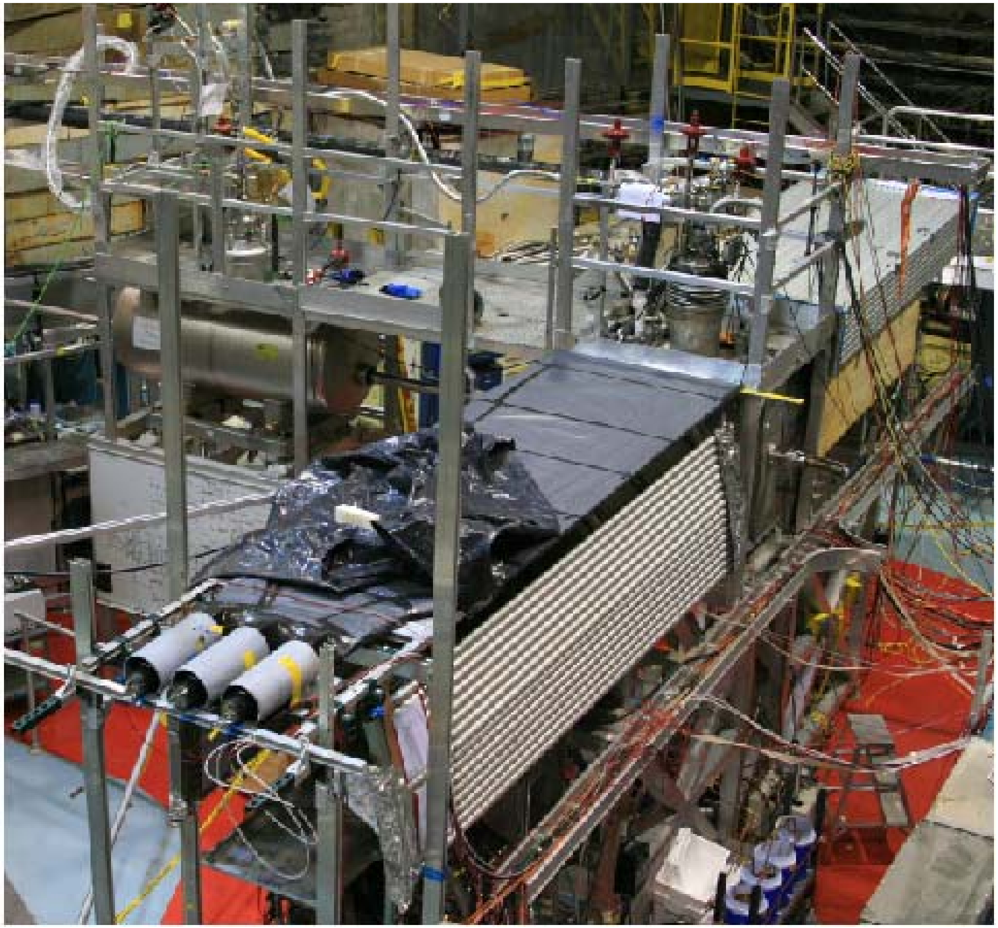


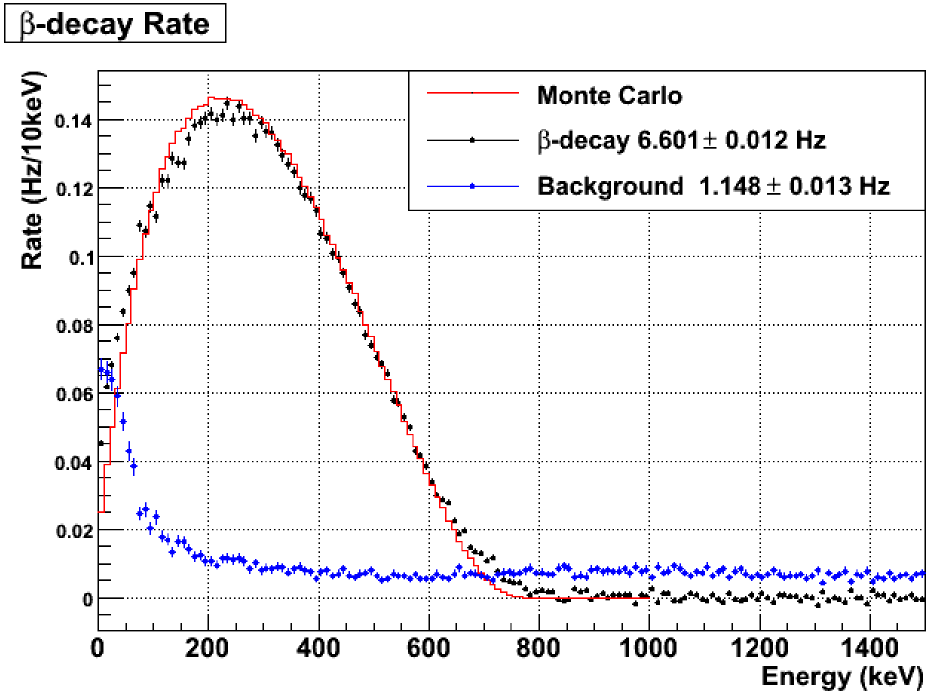
β-spectrum in excellent agreement with expectations (PENELOPE sims)

Preliminary analysis of scattering corrections promising

Beta-decay Results: 2007

- 2007 Run cycle from June until December
- Max. rate = 22 Hz (0.5 T)
- 34 hours of β-decay data at 1 T
- ~300,000 cts after cuts
- Run cycle:
  - 1hr β-decay
  - 10 minutes of background and depol.
  - Change flipper state
  - repeat





- Full β-decay runs w/ average rate of 6.5 Hz (at 1.0 T), signal to background better than 10 to 1 in the analysis window.
- Cuts:
  - Scintillator and MWPC must be above threshold
  - Fiducial volume (r < 4 cm), max = 5.7cm
  - 300 keV < E_β < 600 keV
  - No top, side or backing veto signal

- 791,618 events w/ energy below 800 keV and ~300,000 events after cuts

-Analysis proceeding…statistical errors less than 4% for these cuts, numerous systematic errors to investigate…

Summary and Outlook

- We have established adequate count rates for a 1% measurement of the beta-asymmetry, and we can still
  - implement DLC guides in horizontal guide system
  - increase current on target
  - improve purity and increase volume (a bit) of D_2
  - improve beam tune (new BPM and no diffuser)
  - continue to find and close small gaps in system

  } x4 seems reasonable (first two items)

- A significant effort is currently going into analysis of the runs, this effort has already uncovered areas we can improve:
  - reduce foil thicknesses on windows
  - improve drift-tube veto efficiency
  - improve stability of PMT gains
  - add shutter between spectrometer and AFP/polarizer magnet

- Goal for 2008: sub 1% measurement of the beta-asymmetry