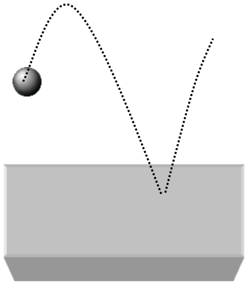
Progress at Los Alamos: the Current Status of UCN and CN Beta-decay Studies

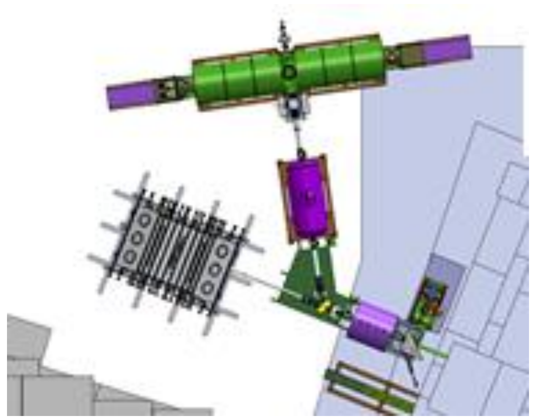
A. R. Young



Outline

- UCNA/UCNB
- Nab
- UCNτ
- One slide on ^{19}Ne

UCNA, UCNB

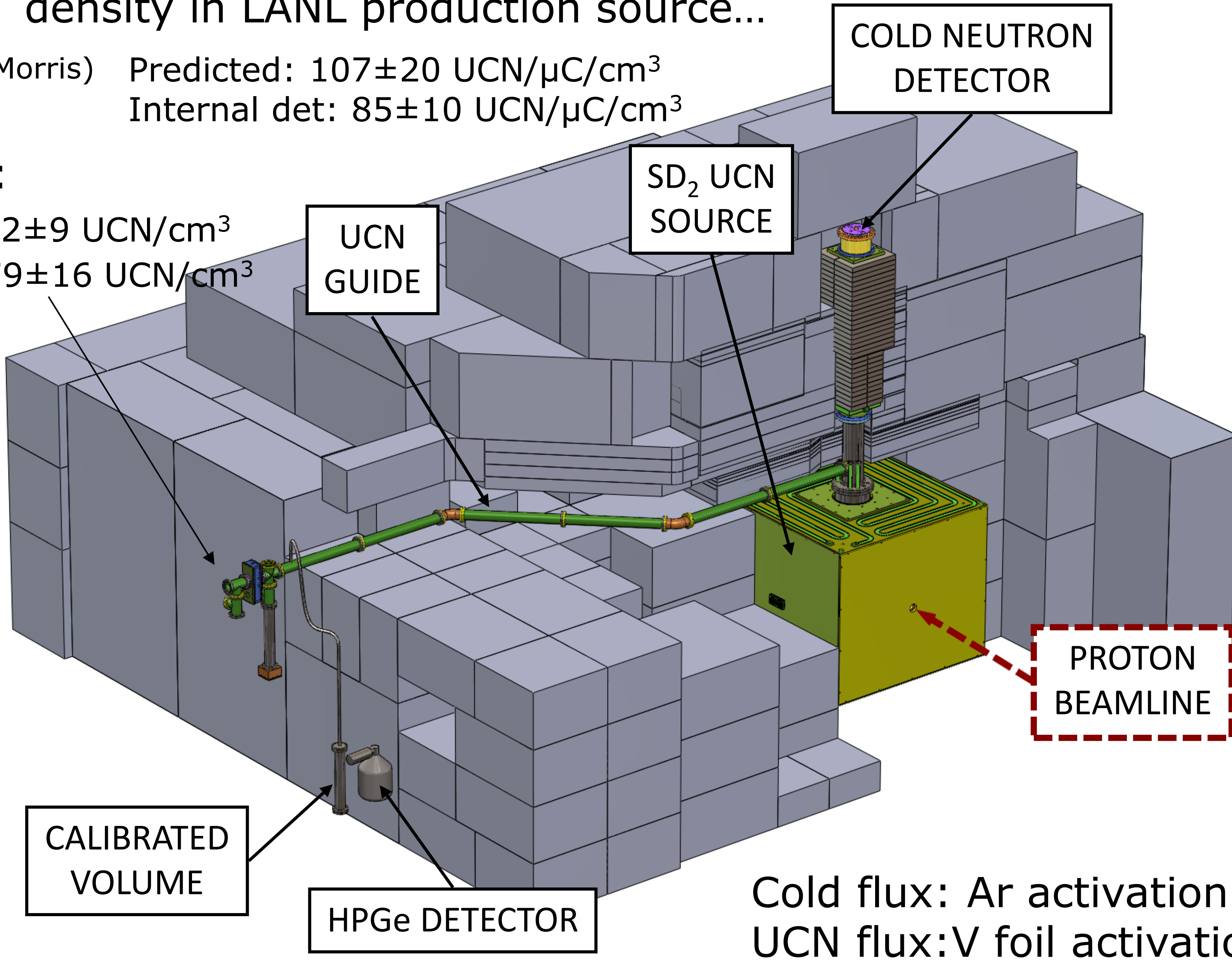


Consistent interpretation of extracted UCN density in LANL production source…

(C. Morris) Predicted: 107±20 UCN/μC/cm^3
Internal det: 85±10 UCN/μC/cm^3

2010:

V: 52±9 UCN/cm^3
Mon: 79±16 UCN/cm^3



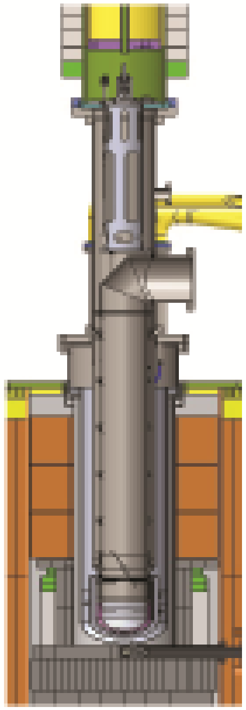
Cold flux: Ar activation
UCN flux:V foil activation

Planned LANL UCN source improvements

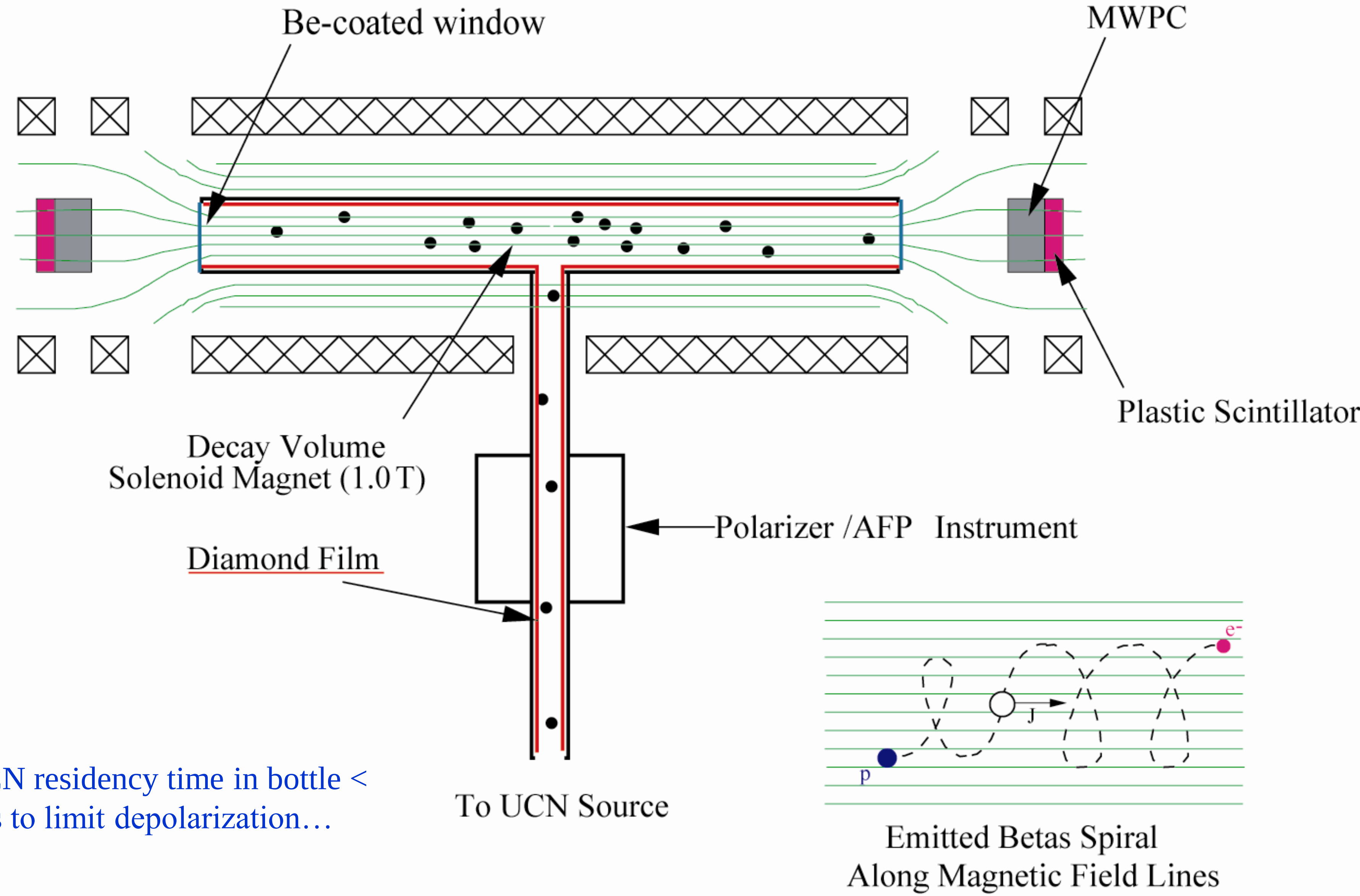
• Feb. 2014 production tests establish capability to increase proton current 6 →10 uA, Beam timing also can be optimized to reduce losses (up to another factor 1.8 gain)

• LDRD source upgrade, planned increase of at least a factor of 3 in production (T. Ito)

• Without upgrade, UCNA baseline roughly 50 Hz, UCNτ roughly 10^5 n/load

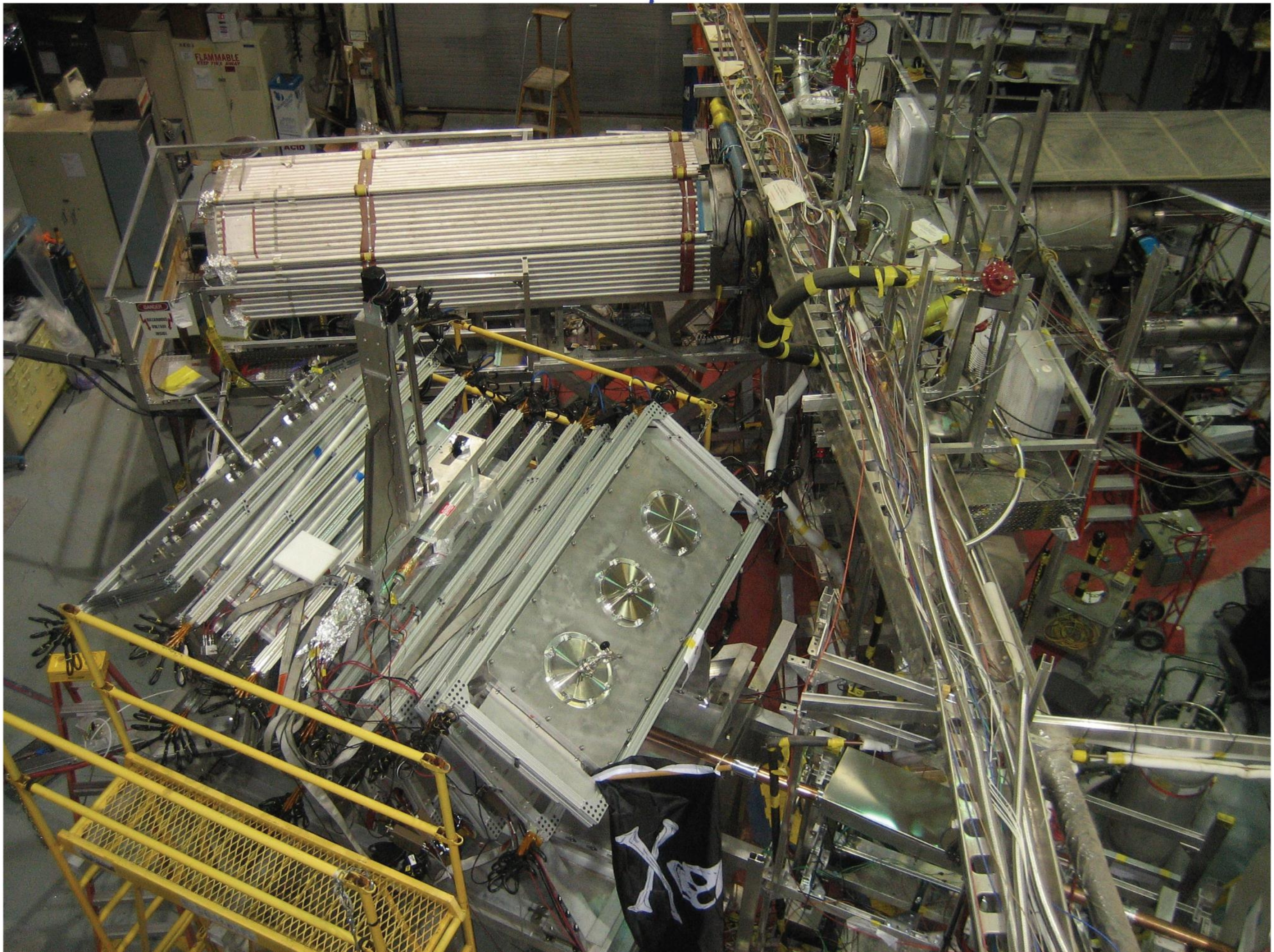


$$A \propto \frac{\sqrt{R}-1}{\sqrt{R}+1}, \text{ where } R = \frac{N_1^+ N_2^-}{N_2^+ N_1^-} \text{ is a "super-ratio"}$$



UCN residency time in bottle < 20s to limit depolarization…

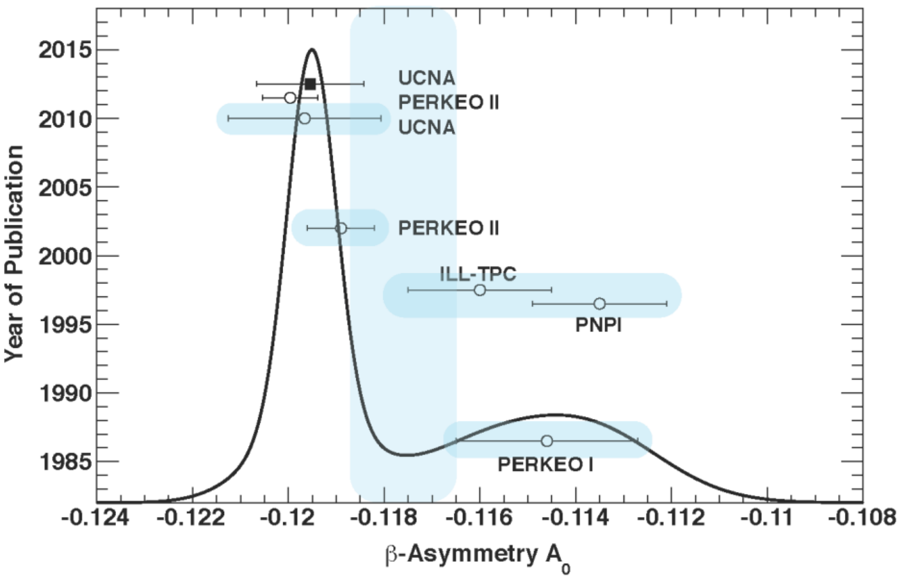
The UCNA and UCNτ Experiments at Los Alamos

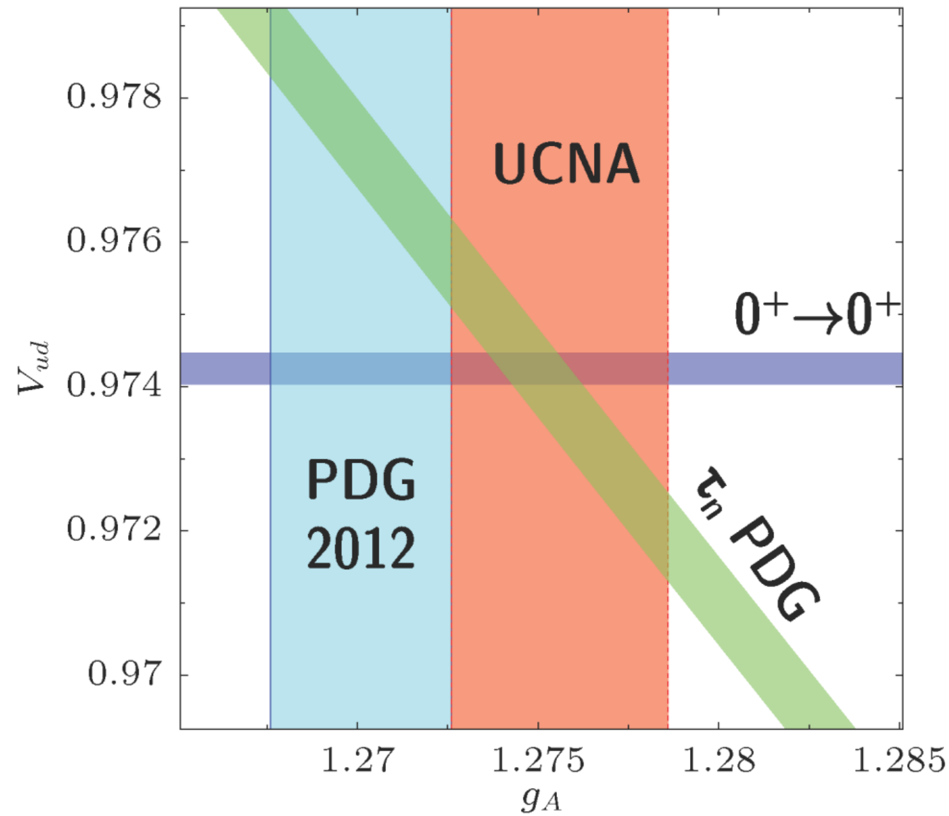


$$A_0 = 0.11972(55)_{stat}(98)_{syst}$$

M. P. Mendenhall *et al.*, Phys. Rev. C **87**, 032501 (2013)

Systematic	corr. (%)	unc. (%)
Polarization	+0.67	±0.56
$\Delta_{\text{backscattering}}$	+1.36	±0.34
Δ_{angle}	−1.21	±0.30
Energy reconstruction		±0.31
Gain fluctuation		±0.18
Field non-uniformity	+0.06	±0.10
ϵ_{MWPC}	+0.12	±0.08
Muon veto efficiency		±0.03
UCN-induced background	+0.01	±0.02
$\sigma_{\text{statistics}}$		±0.46
Theory contributions		
Recoil order [19–21]	−1.71	
Radiative [22]	−0.10	





Pushing Down the Limits: 2014 and beyond…

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Polarimetry

2010 method calibrated, but required MC corrections:
add shutter, remove MC corrections

Scattering corrections

Backscattering limited by foils:
reduce areal density

Energy Reconstruction

Add more conversion sources, Xe position-dependent gain maps, LED pulser

2011/2012: 57 M decays -- targeting better than 0.6% precision
2014: improving rate for final UCNA in this configuration

Projected UCNA Error Budget

Preliminary estimates…

Uncertainty (%)	Mendenhall (2013)	In analysis (TBS 8/14)	Next Step	Source of improvement
Statistics	+/- 0.46	+/- 0.40	+/- 0.28	Decay rate!
Depolarization	+0.67 +/- 0.56	+0.7 +/- 0.1	+0.7 +/- 0.1	Shutter+ ex situ
Backscatter	+1.36 +/- 0.34	+0.56 +/- 0.15	+0.56 +/- 0.15	Thin windows
Angle effect	-1.21 +/- 0.30	-0.8 +/- 0.2	-0.8 +/- 0.1	Windows+APD
Energy Reconstruction	+/- 0.31	+/- 0.08	+/- 0.08	Xenon + LED
Total Sys.	+/- 0.82	+/- 0.28	+/- 0.22	
Total	+/- 0.94	+/- 0.5	+/- 0.35	

Statistics: 0.28% requires 150x10^6 raw decays
@100 Hz, 50% duty factor, requires 13 weekends, or ~one full run cycle
(But could be split over multiple cycles)

Path Forward for UCNA

Fall 2014:

- Complete analysis of 2011/2013 data (target of end of year for unblinding)
- Install replacement guide
- Investigate impact of switcher to share beam with UCNτ
- **Conduct rate test to confirm gains**

Take first opportunity for “final data run” once statistics are available…

The UCNA Collaboration

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Virginia Polytechnic Institute and State University
X. Ding, M. L. Pitt, R. B. Vogelaar

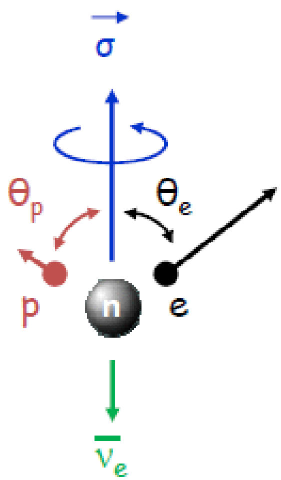
UCNB: Accessing b and b_ν

$$\frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

spectrum

[U.S., Nab exp't ~0.003]

[UCNB, B ~10^{-3}]



Measure e-p coincidences w/ polarized neutrons

"Classic" Method for B :

$$B_{\text{exp}}(E_e) = \frac{Q_{--}(E_e) - Q_{++}(E_e)}{Q_{--}(E_e) + Q_{++}(E_e)}$$

$$\propto B_0 + \frac{m_e}{E_e} \left[\underbrace{\frac{1+3\lambda^2}{2\lambda(1+\lambda)} b_\nu^{\text{BSM}} - b^{\text{BSM}}}_{\approx b_\nu^{\text{BSM}} - b^{\text{BSM}}} \right]$$

$Q_{\pm\pm}$

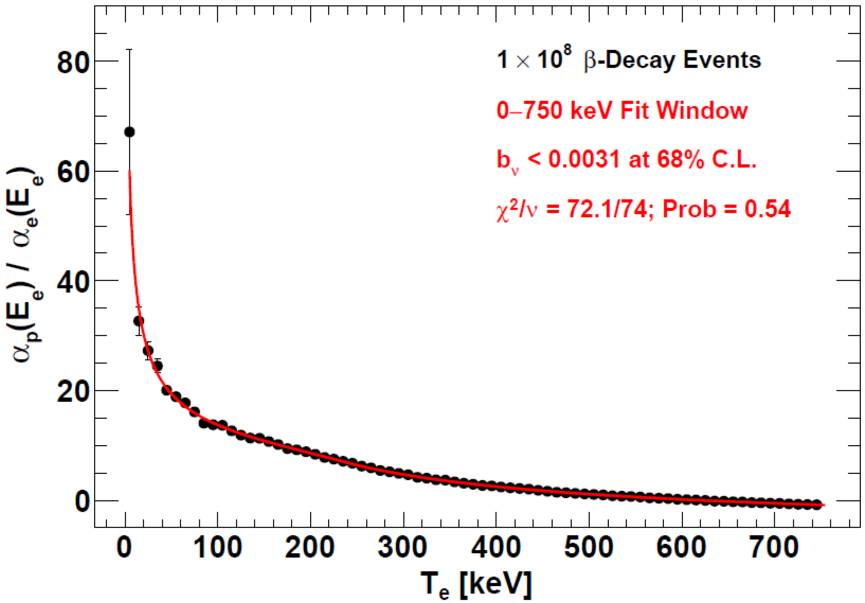
e p

T. Bhattacharya et al., PRD 85, 054512 (2012)

Analysis: How to directly measure b_ν

Measure $\dfrac{\text{proton asymmetry}}{\text{electron asymmetry}}$

Differential Analysis:

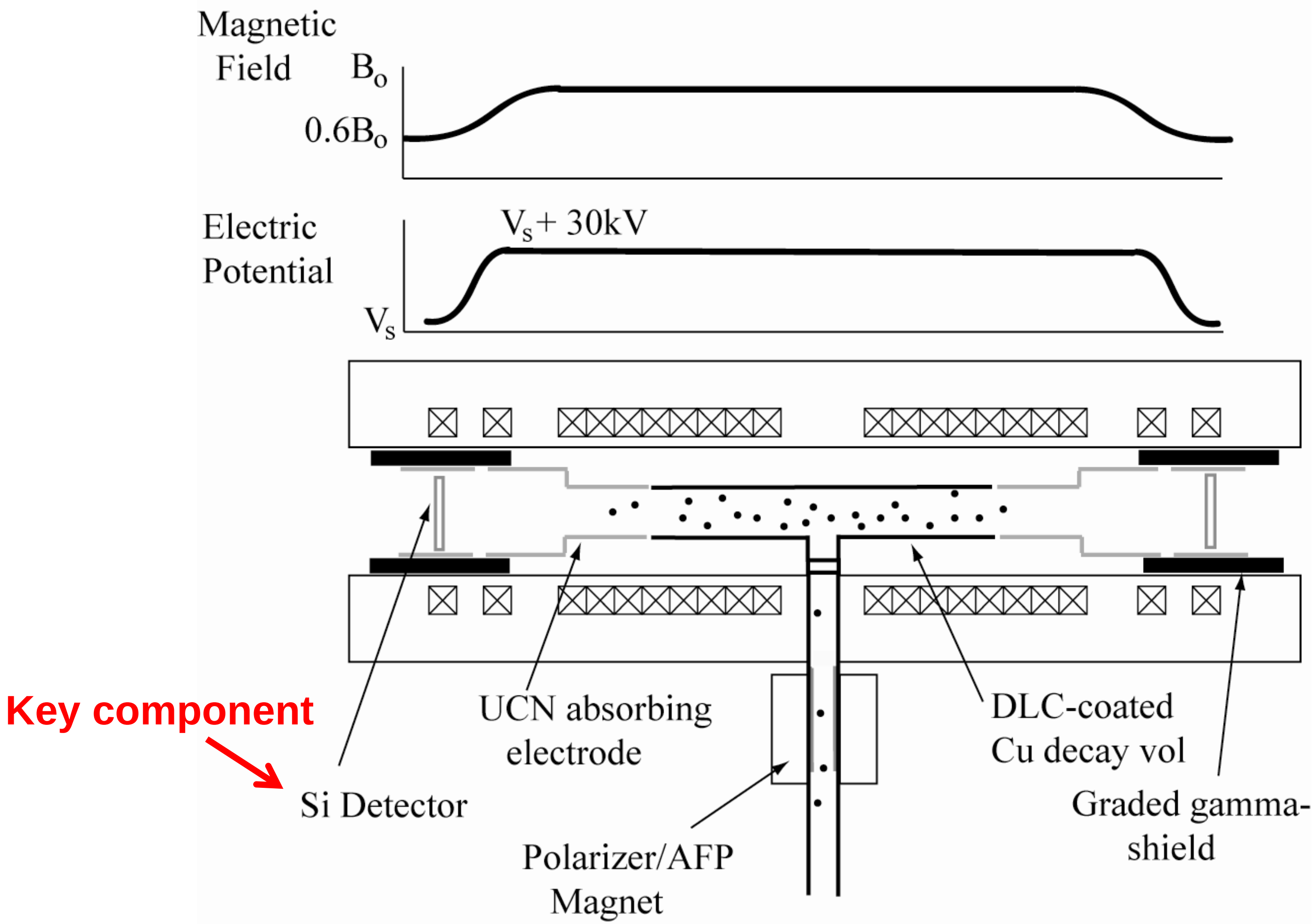


Integral Analysis:

$$\dfrac{\langle \alpha_p \rangle = \dfrac{\int dE_e\, w_s(E_e)\,(Q_-^p) - \int dE_e\, w_s(E_e)\,(Q_+^p)}{\int dE_e\, w_s(E_e)\,(Q_-^p) + \int dE_e\, w_s(E_e)\,(Q_+^p)}}{\langle \alpha_e \rangle = \dfrac{\int dE_e\, w_s(E_e)\,(Q_-^e) - \int dE_e\, w_s(E_e)\,(Q_+^e)}{\int dE_e\, w_s(E_e)\,(Q_-^e) + \int dE_e\, w_s(E_e)\,(Q_+^e)}}$$

$\sim 0.3\sigma$ sensitivity to $b_\nu = 10^{-3}$
with $N = 1 \times 10^8$

Additional advantage: removes leading order dependence on polarization and detector efficiency (Mostovoi et al, Phys. Atomic Nucl. 64, 1955 (2001)).– **need to integrate with other e-p coincidence and spectrum measurements for best sensitivity**!



Experimental strategy is similar to that carried out by PERKEO II, measure same-hemisphere electron-proton coincidences:

$$B_{\exp} = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}$$

(use super-ratio)

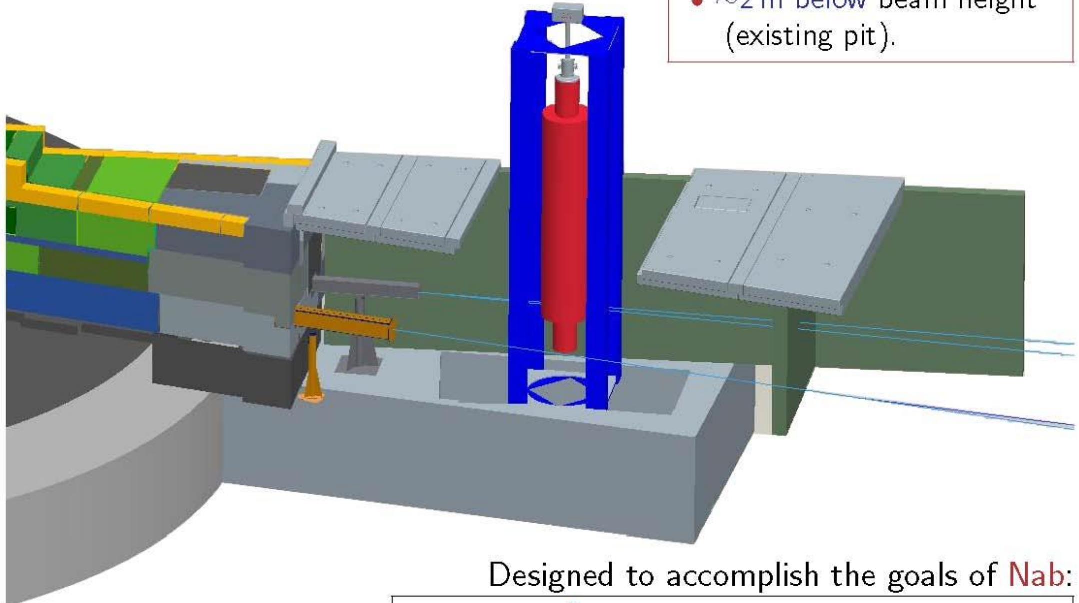
UCNB Current status

- Detector development integrated into Nab R&D
- Decay trap and electrode development ongoing -- updated error budget under development
- Fall 2014: Configure two full detectors with pixels “ganged” nominally in groups of 6
- Investigate running modes and full error budget for specific goal of high precision beta-spectroscopy as soon as possible (potentially this run cycle)

Nab

Nab apparatus in FnPB

Apparatus extends:
- ~6 m above beam height,
- ~2 m below beam height (existing pit).



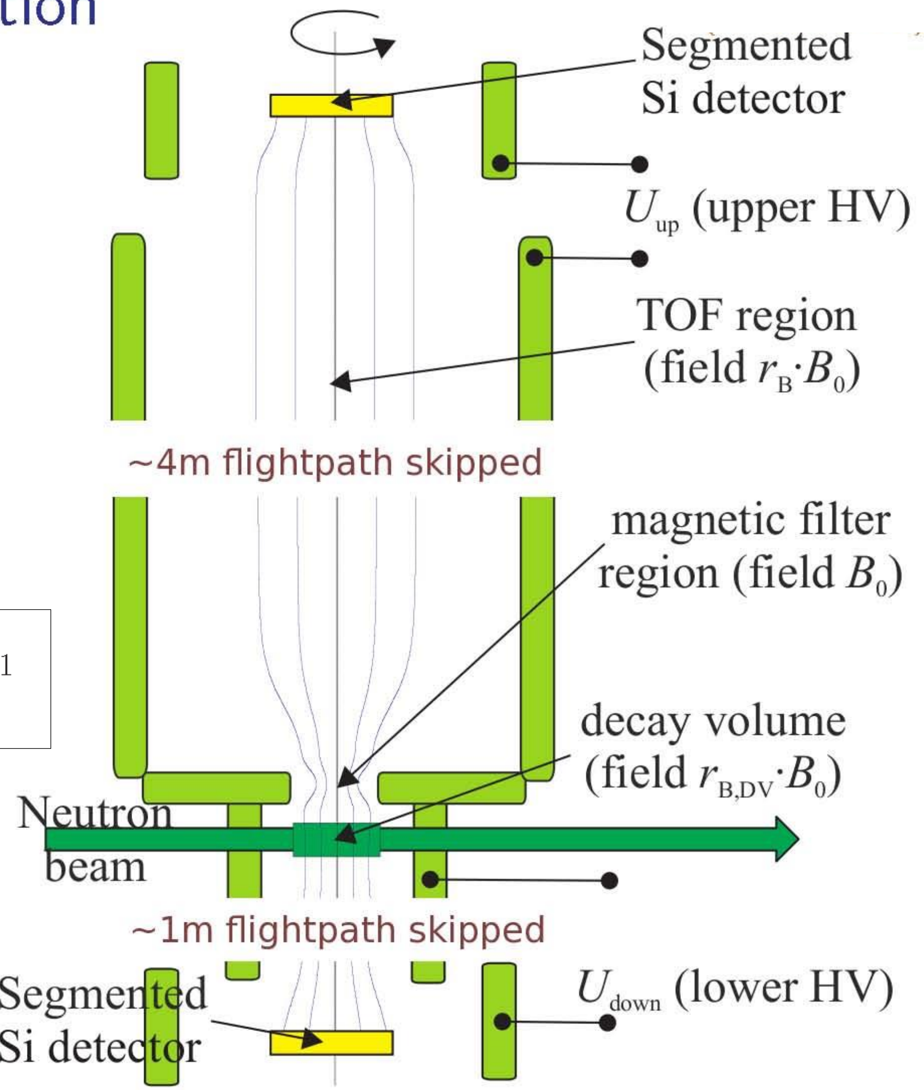
Designed to accomplish the goals of Nab:

Measure: $\frac{\Delta a}{a} \simeq 10^{-3}$ and $\Delta b \simeq 3 \times 10^{-3}$.

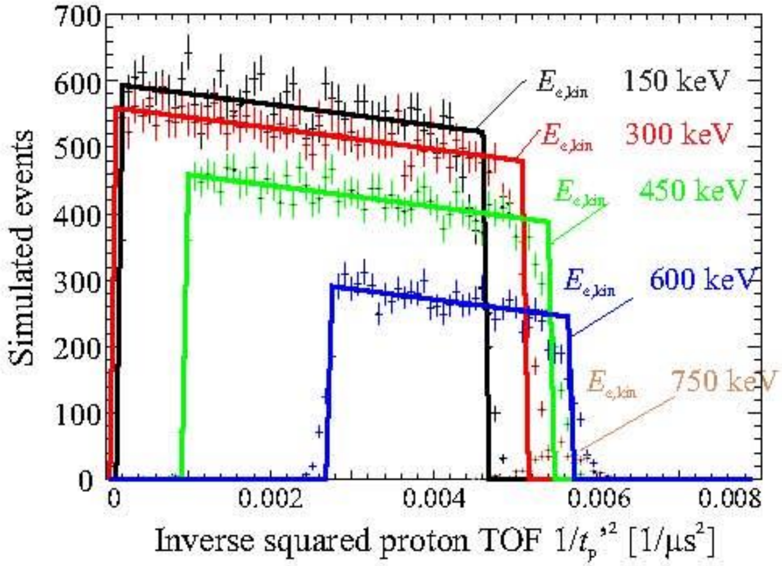
Nab principles of operation

- Collect and detect **both** electron and proton from **n decay**.
- Measure E_e and TOF_p and reconstruct decay kinematics

$$P_p(p_p^2) = \begin{cases} 1 + a\beta \frac{p_p^2 - p_e^2 - p_\nu^2}{2 p_e p_\nu} & \text{where } \left| \frac{p_p^2 - p_e^2 - p_\nu^2}{2 p_e p_\nu} \right| < 1 \\ 0 & \text{otherwise} \end{cases}$$



Analysis strategy



Proportional to p_p^2

- Use edges to determine and verify shape of detection function $\Phi(1/t_\mathrm{p}^2, p_\mathrm{p}^2)$;
- Use central part of $P_t(1/t_p^2)$ ($\sim$ 70%) to extract **a**.

Electron-neutrino asymmetry error budget

>500 Hz expected, necessary statistics (0.07%) available in less than 2 mo.

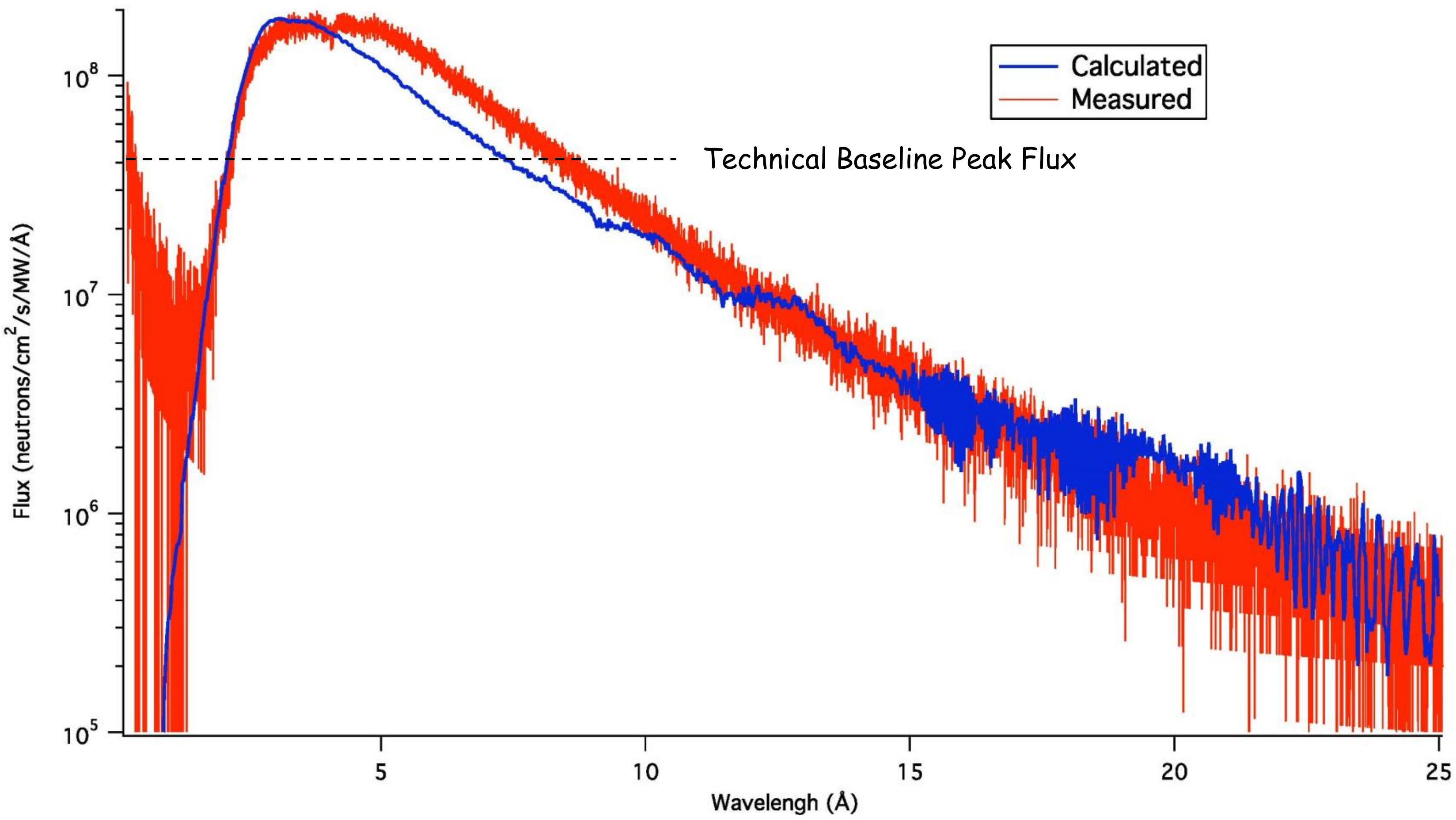
Nab systematic uncertainties: Method B

Experimental parameter		$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	5×10^{-4}
	ratio $r_B = B_{\mathrm{TOF}}/B_0$	2.5×10^{-4}
	ratio $r_{B,\mathrm{DV}} = B_{\mathrm{DV}}/B_0$	3×10^{-4}
L_{TOF}, length of TOF region		(*)
U inhomogeneity:	in decay / filter region	5×10^{-4}
	in TOF region	1×10^{-4}
Neutron beam:	position	4×10^{-5}
	width	2.5×10^{-4}
	Doppler effect	small
	unwanted beam polarization	small
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_e calibration	(*)
	E_e resolution	5×10^{-4}
	Proton trigger efficiency	2.5×10^{-4}
Accidental coinc's	(will subtract out of time coinc)	small
Residual gas	ongoing parametric studies	small
Background	ongoing parametric studies	small
Overall sum		1×10^{-3}

(*) Free fit parameter

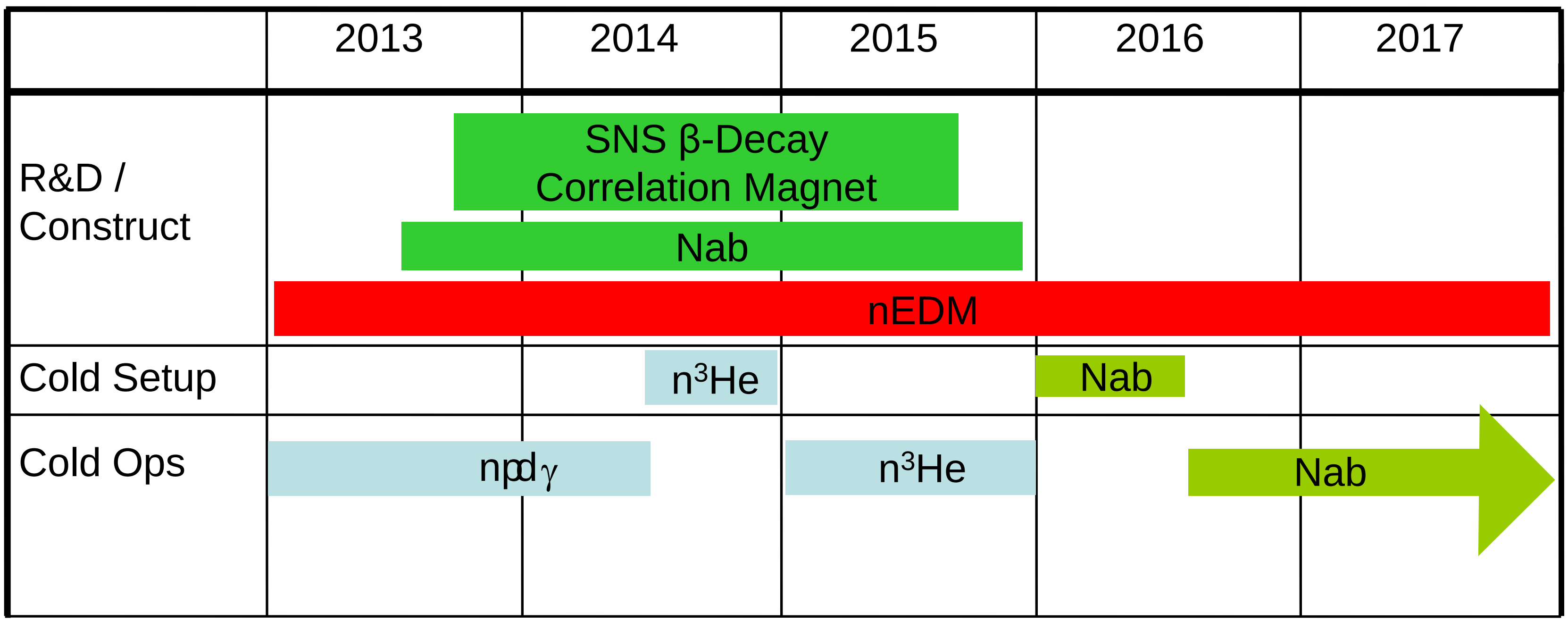
“b” error budget under development, anticipate less than 0.3% uncertainty

FNPB flux is well understood



Notional FNPB Experimental Program

(as presented Aug, 2013)



Nab/UCNB Development

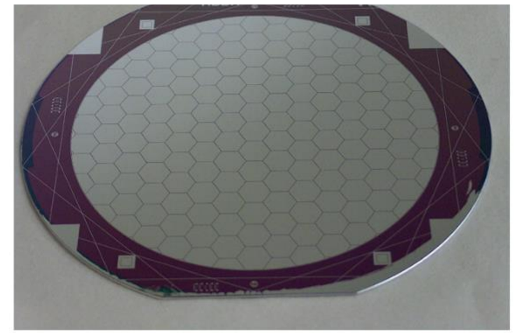
- Large area Si detectors the key to high precision β-spectroscopy and proton detection: 2mm thick, 127 pixels, ~15 cm diam

- Development program underway at LANL

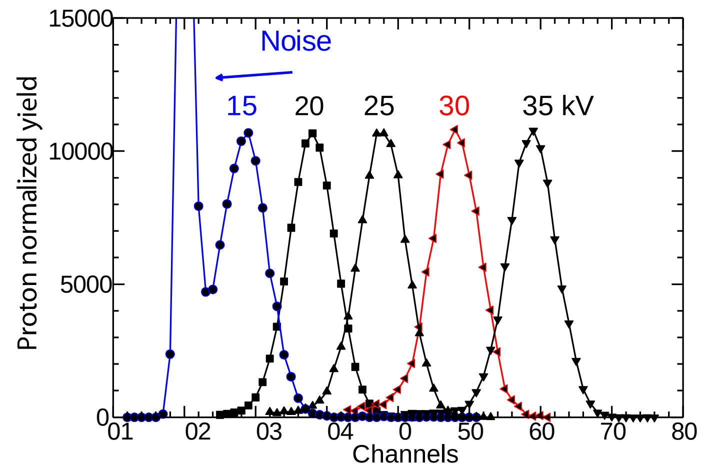
- Used TUNL, low energy proton beam for first evaluation of proton detection sensitivity (A. Salas-Bacci *et al*., Nuclear Instruments and Methods in Physics Research A 735 (2014) 408–415)

- Si detector response function studies (determine energy-angle response from point sources – S. Sjue *et al*, submitted)

Prototype Si detector

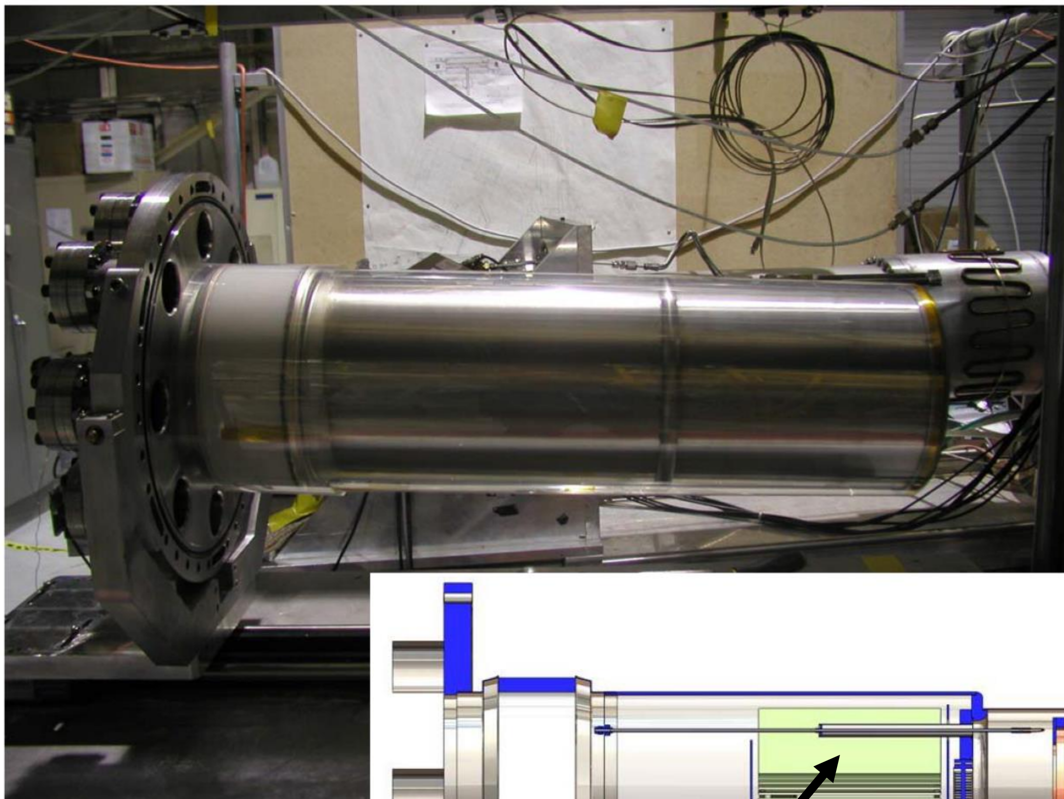


6″ wafer, 0.5 mm thick (now 1.0 mm), 127 full pixels

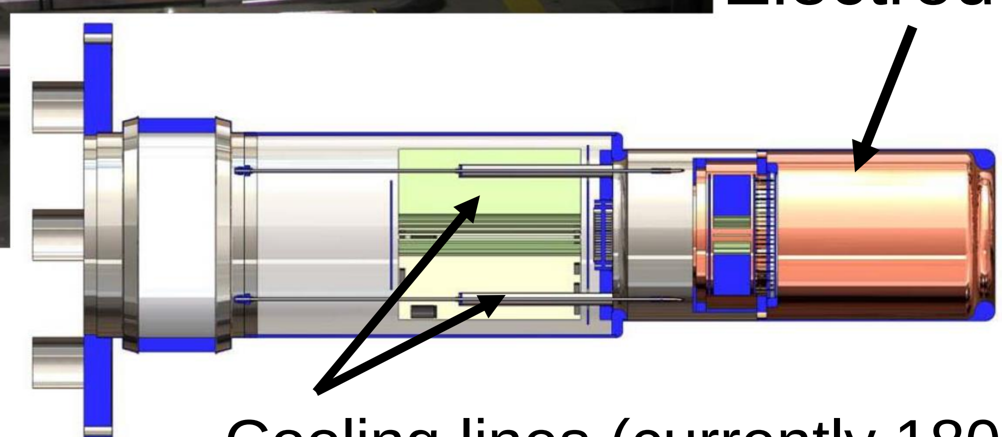


Detected proton energy deposition in Nab/UCNB Si detector

Research and Development: Detector Mount for Cooling and Acceleration Bias



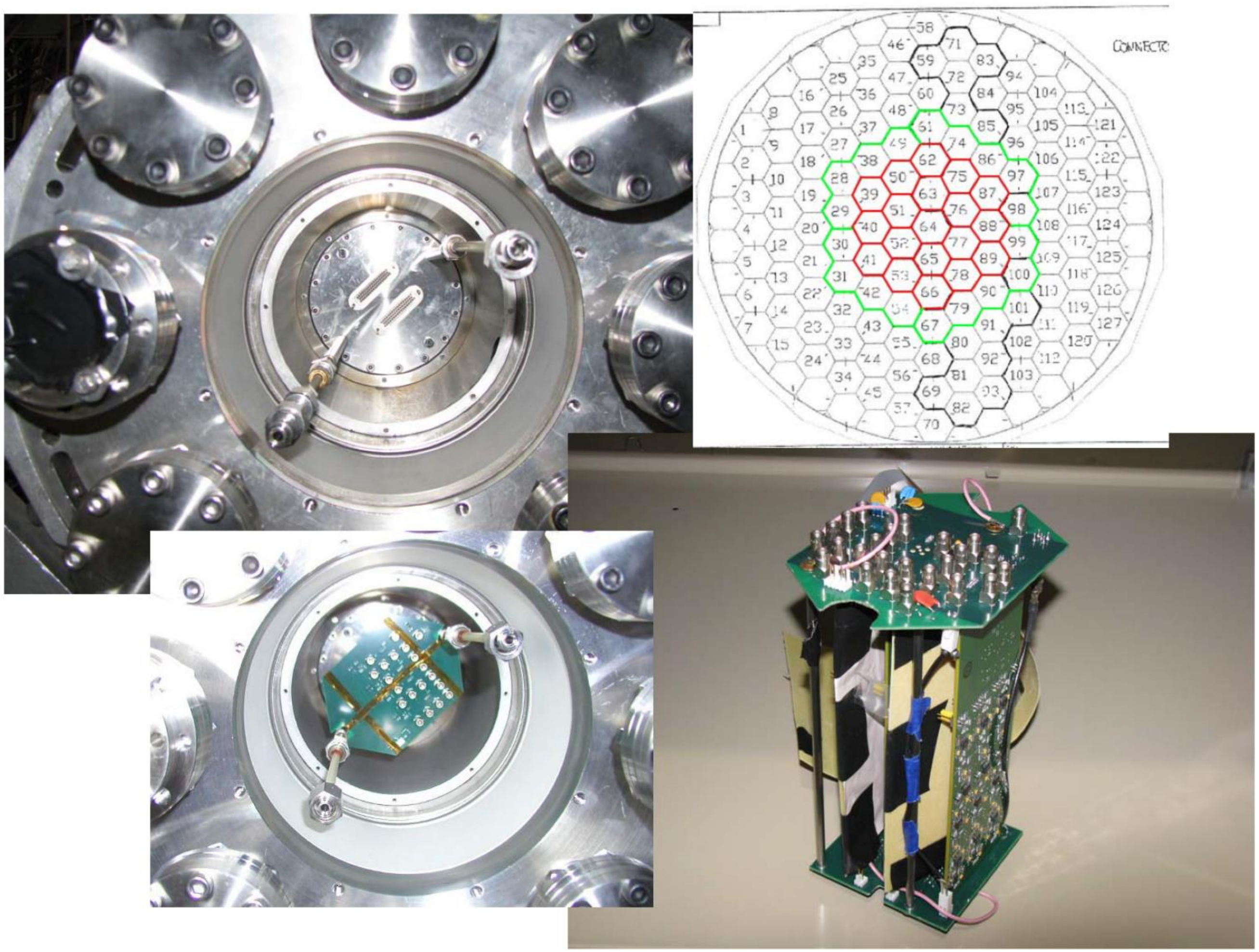
Acceleration Electrode: -30 kV



Cooling lines (currently 180K)

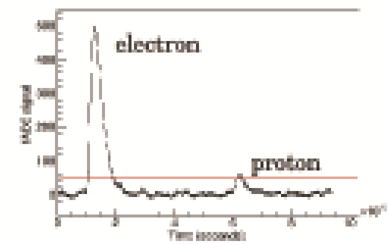
Research and Development: 2013 Running

(24 channels Instrumented)



Status: 2014

Detectors



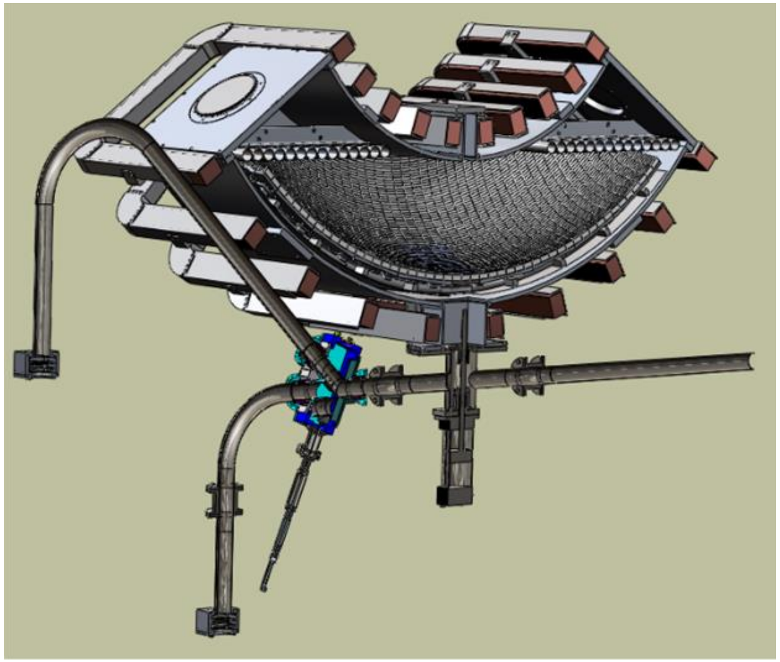
Runs in October 2013 and January 2014

- 24 channels instrumented
- Intermittent LN2 cooling used
- Example of thresholds for properly working channel: ~15 keV
- Example of resolution for properly working channel: ~2.5 keV
- Proton-electron coincidences detected (analysis ongoing)
- Pogo-pin tests complete

Nab construction

- Full Nab DAQ ordered, NI PXIe-5171R: 254 chans of 250 Ms/s, 14 bit fADC (with low-level trigger filter capability)
- Magnet ordered

UCNτ



Analysis: Lifetime consistency check

- Compare measured and predicted n lifetime (using $0^+ \rightarrow 0^+$ vector coupling and λ from angular correlations)

Bhattacharya *et al*., Phys. Rev. D 85, 054512 (2012) & A. N. Ivanov *et al*., arXiv:1212.0332 (2012).

- Indep. of (V,A) extensions, do not need to fit for λ
- Errata required for publication (thanks to K. Vos at RUG)

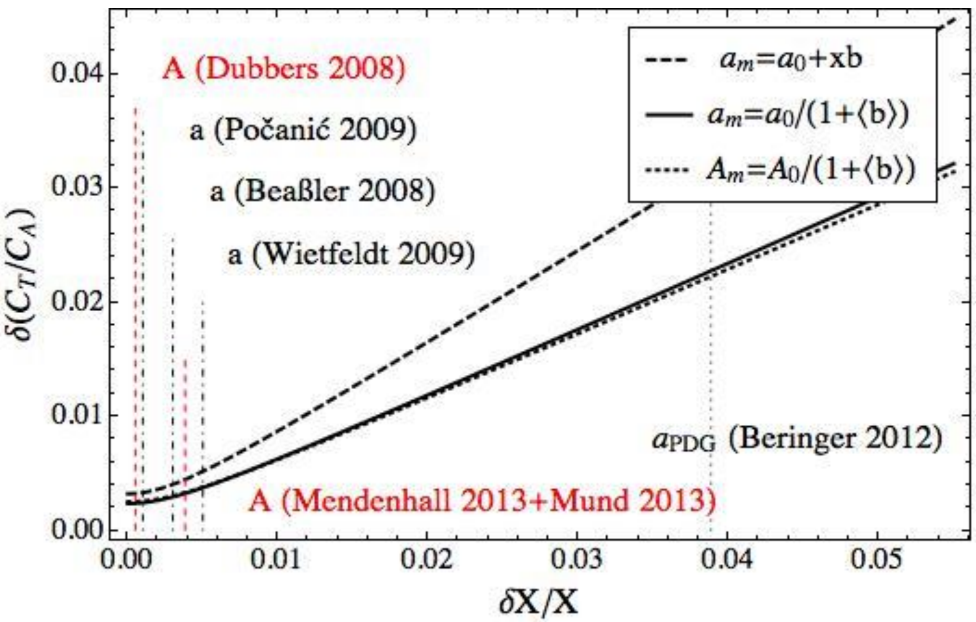
Depends on $\langle b_{0+} \rangle$

$$1/\tau_n - 1/\tau_{0+} = 1/\tau_n - K(G_F V_{ud})_m^2 (1+3\lambda_m^2) f_n (1+\Delta_r) = \kappa b_n - \alpha b_{0+}$$

Measured n decay rate

Predicted n decay rate using $0^+ \rightarrow 0^+$ for $(G_F V_{ud})$

λ extracted from angular corr meas (depends on b_n)



Difference comes only from non-zero Fierz terms!

Use limits for g_S, Solve for g_T:

$$-4.0\times10^{-3} < C_T/C_A < 2.6\times10^{-3}$$

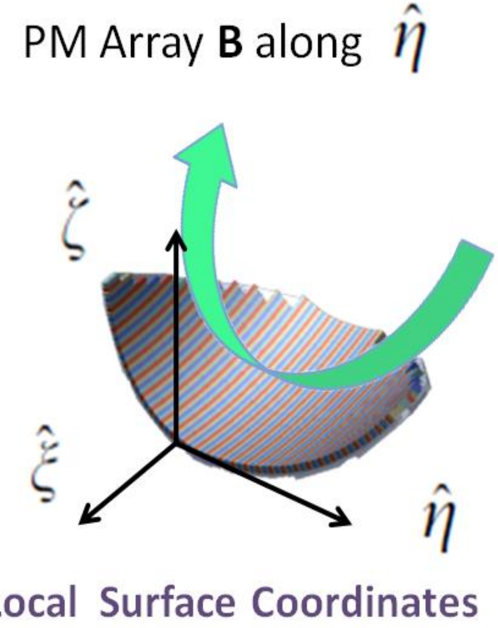
(limited at present by unc in λ)

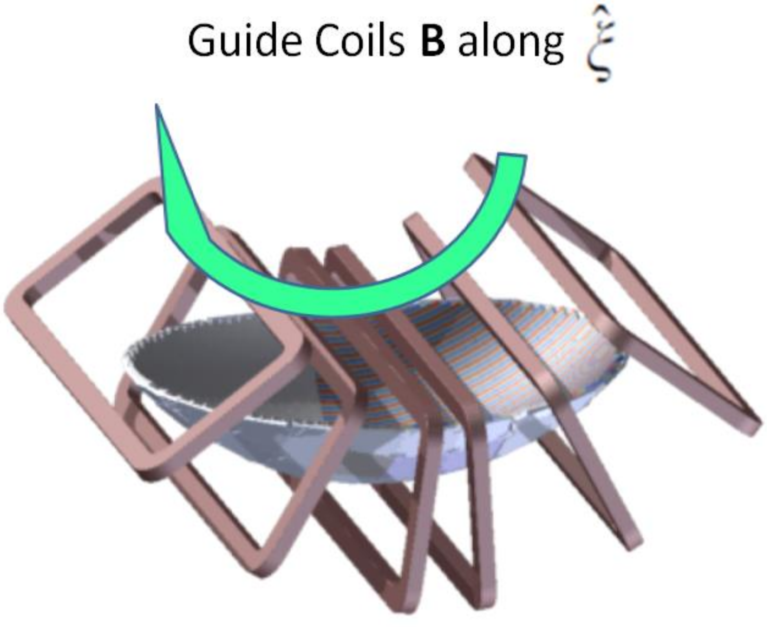
Pattie *et al*, Phys. Rev. C **88**, 048501 (2013)

UCNτ: Magneto-Gravitational Trap

- **Avoid material loss (magnetic trap)**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).





UCNτ: Unique Features

- Low symmetry construction permits very rapid spectral cleaning
- Populations monitored by conventional analysis through UCN guides and also by V absorber

Asymmetric Trap induces Phase Space Mixing

Low symmetry, together with **field ripples**, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

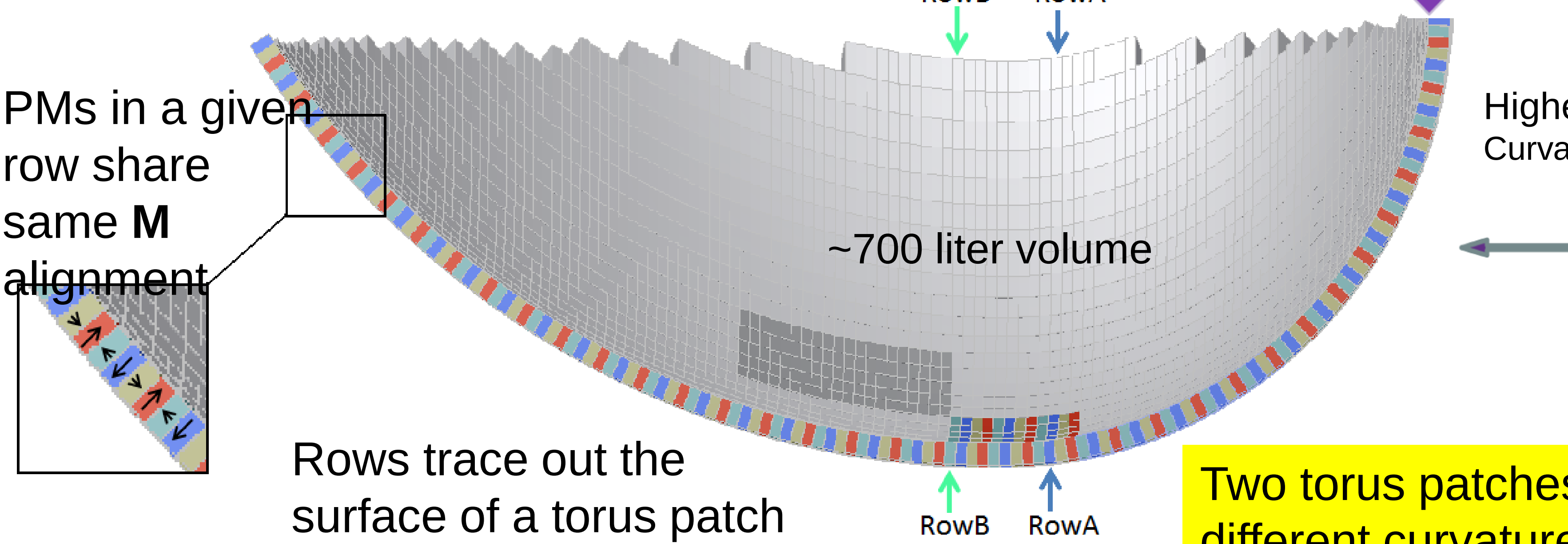
→ **quick cleaning** (~ 10s of seconds) of the ‘quasi-bound’ UCN with large tangential velocities.

Adjacent Magnetization $\pi/2$ out of

• Rows: 141

• PMs: 5310

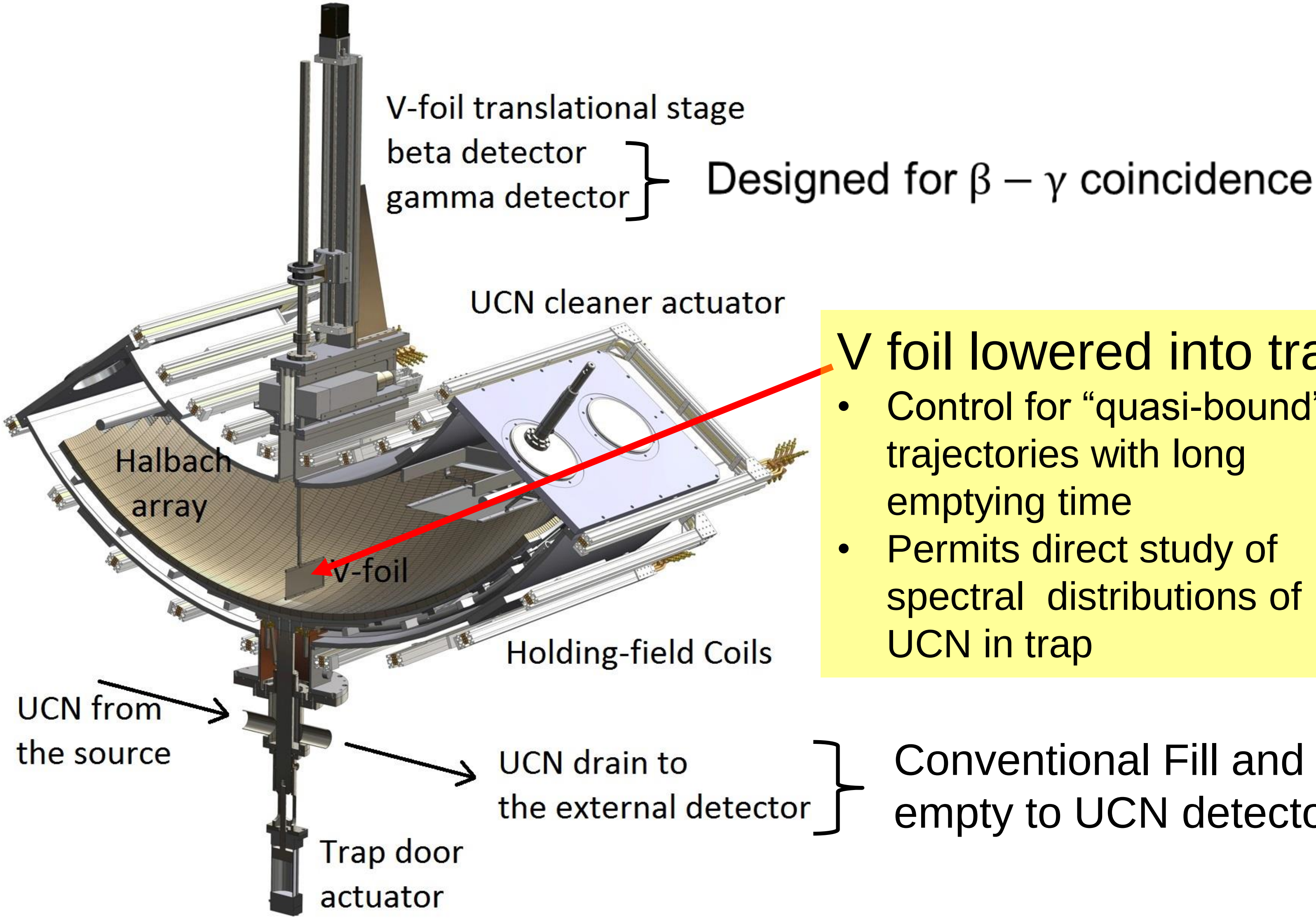
PMs in a given row share same **M** alignment



Rows trace out the surface of a torus patch (circumferentially)

Two torus patches of different curvatures join along middle row

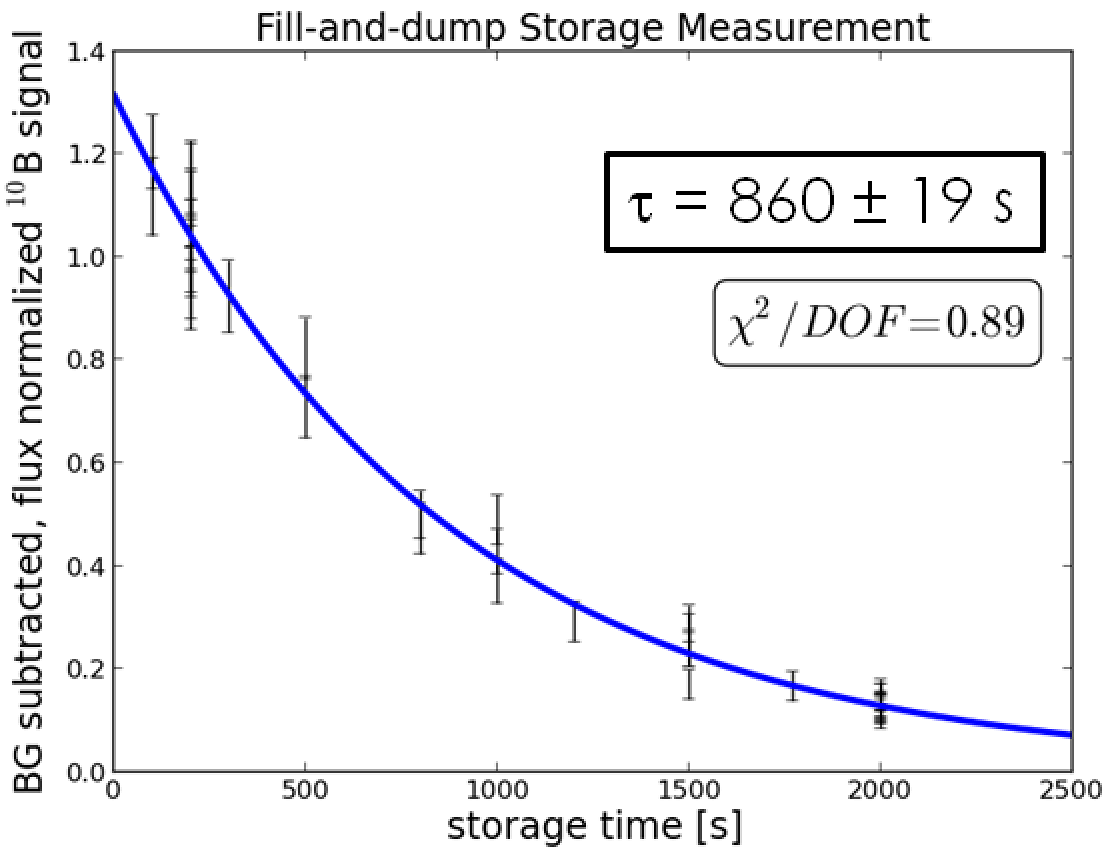
UCN Population Monitoring



V foil lowered into trap

- Control for “quasi-bound” trajectories with long emptying time
- Permits direct study of spectral distributions of UCN in trap

UCN Storage Time Measurement: 2013

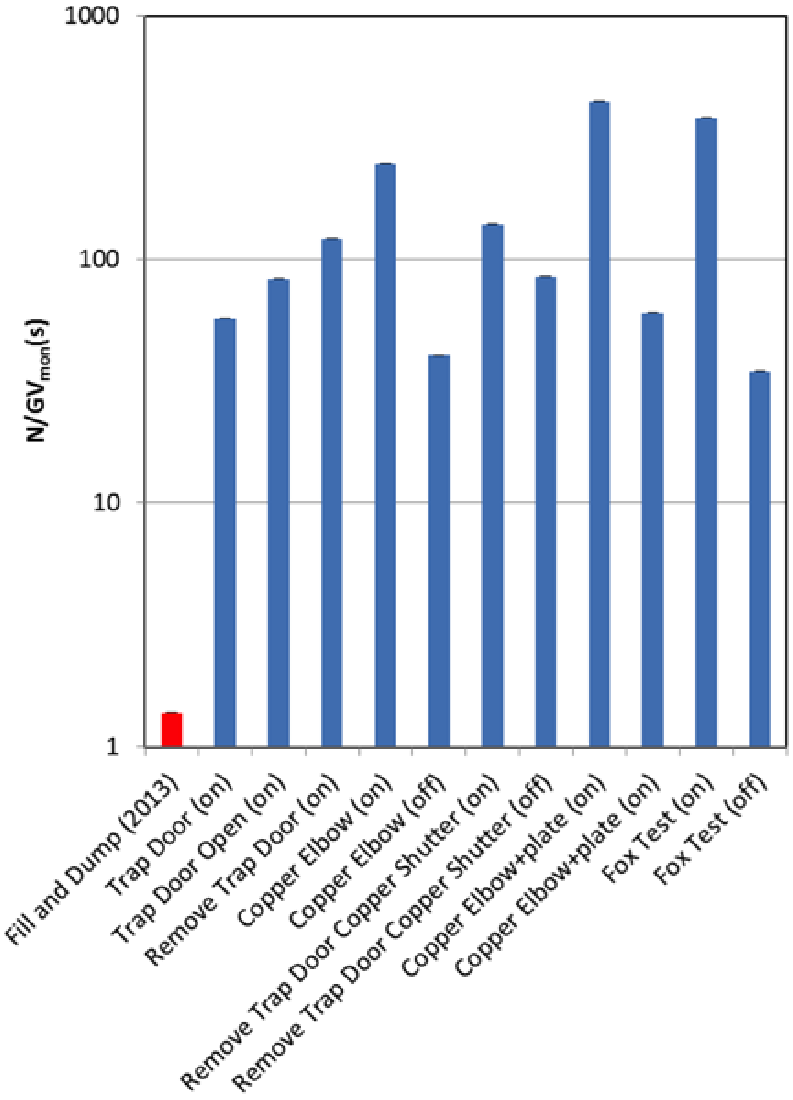


Conventional load, store and empty to external UCN detector measurement (between 10k and 20k UCN loaded per fill): accepted for PRC

UCNτ progress

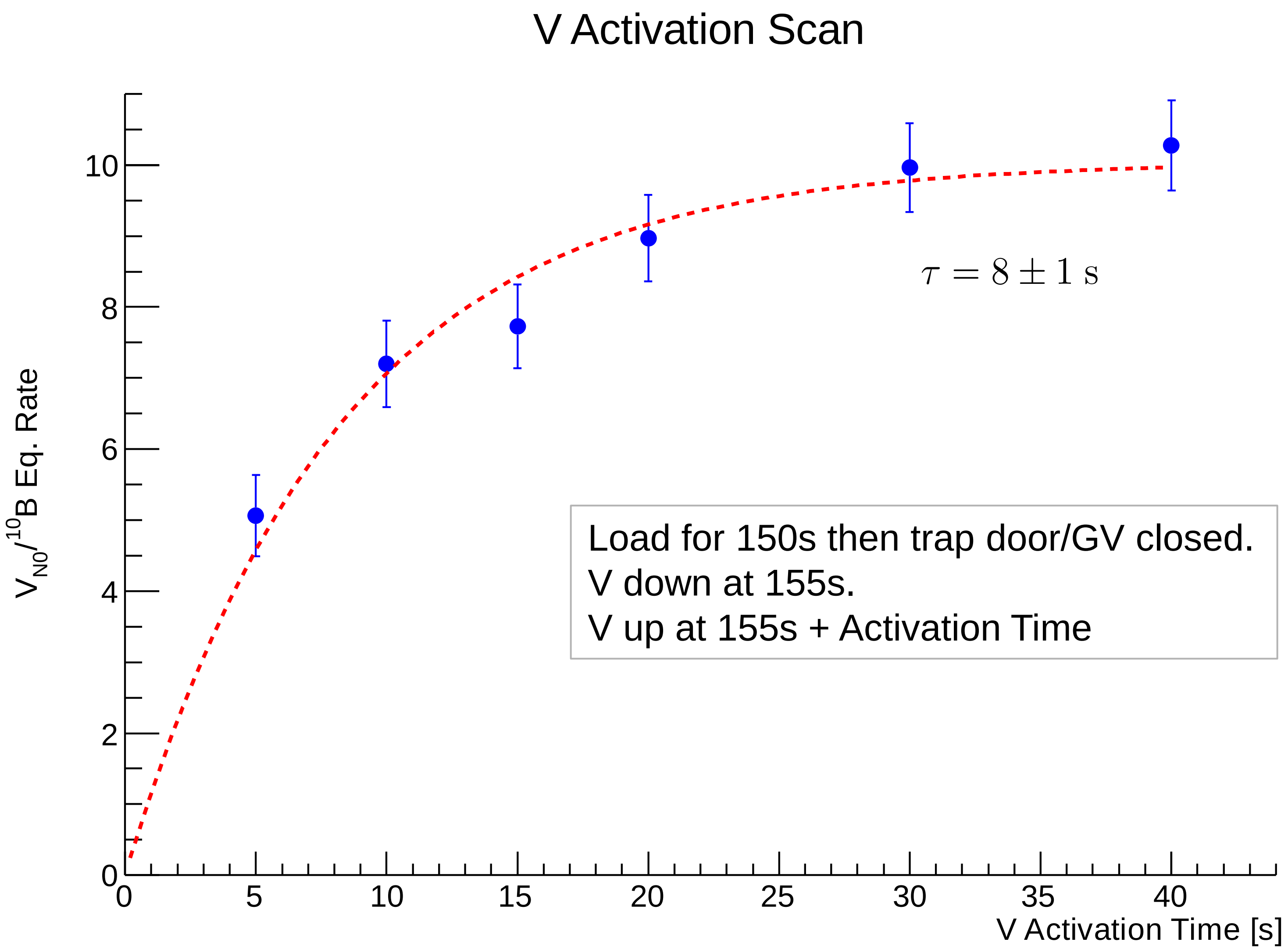
End of 2013, experimented with "mock-up" of replacement trap-door assembly:

- Obtained well over order of magnitude improvement in loaded population
- Observed appropriate impact for spin-flipper
- Concluded depol. losses very large in 2013 geometry—new fill system being installed now



Loading Study Dec 2013

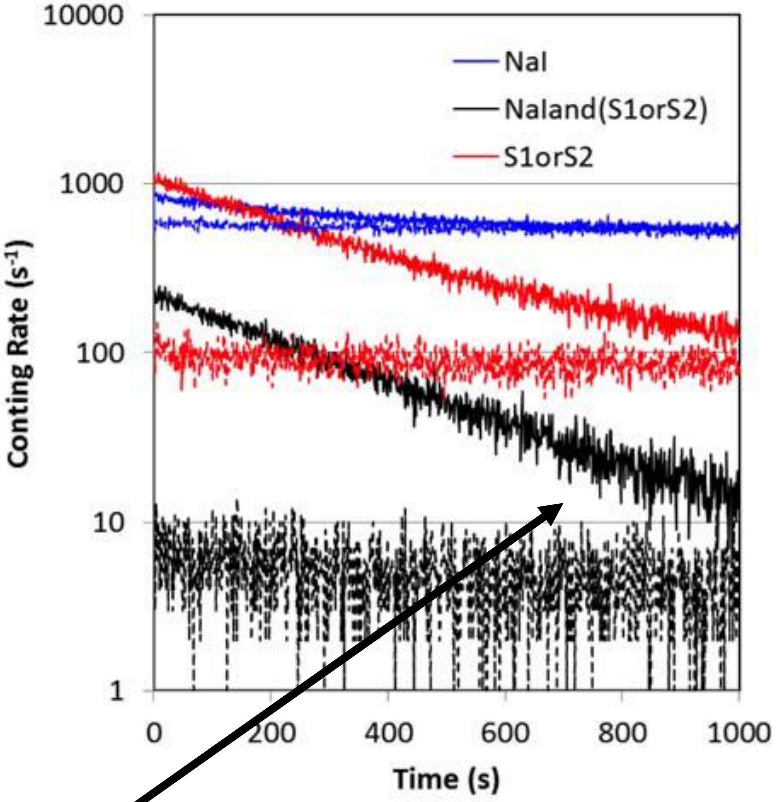
Very short time measured to absorb UCN!



V detector progress

2013:

- Added lead shielding
- Increased number of NaI detectors
- Achieved about 19% counting efficiency (90% from plastic alone)
- More efficiency and background improvements in works



V detector now yielding clean activation decay curves with S/B > 10

The Neutron Lifetime Experiment at LANL

Steven Clayton for the UCNτ collaboration

S. Clayton, M. Makela, C. Morris, J. Ramsey, A. Saunders, S. Seestrom, P. Walstrom, Z. Wang (LANL)

D. Bowman, S. Penttila (ORNL)

E. Adamek, W. Fox, A. Holley, M. Hozo, C.-Y. Liu, N. Callahan, D. Salvat, J. Vanderwerp, B. Slaughter, K. Solberg, M. Snow (Indiana U.)

B. Vogelaar (V. Tech)

K. Hickerson (UCLA)

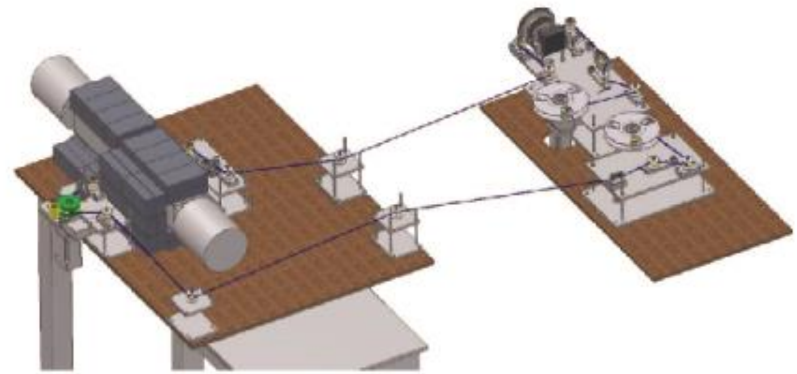
A. R. Young, B. VornDick, E. B. Dees, C. Cude (NCSU)

PSI2013

^{19}Ne

- Lifetime:

Broussard *et al*., PRL **112**, 212301 (2014)
Collaboration between KVI/RUG and TUNL

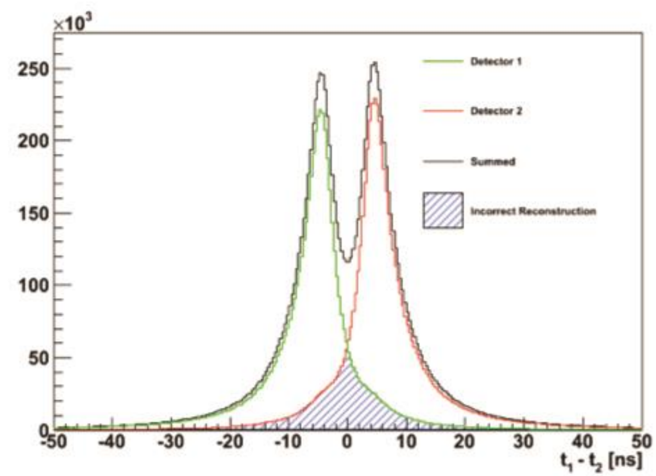


$T_{1/2}$ =17.2832 ± 0.0051 ± 0.0066 s

→ $\langle T_{1/2} \rangle$= 17.2604 ± 0.0034 s

Careful dedicated systematic studies – rate dependence, diffusion and contaminants

- Asymmetry



D. Combs at NCSU completed analysis of thesis data for Princeton student, G. Jones (1995). -- precision close to the thesis analysis…

Conclusions!

- UCNA is making good progress towards analysis of 2011-2013 data, and unblinding this year, confirming readiness for high statistics running

- Nab and UCNB achieved major milestones towards fully instrumented detectors, and orders for the Nab DAQ and magnet are placed

- UCNτ should be ready for high statistics running this fall, and detailed assessment of systematic error budget