NN Weak Interaction Experiments

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What is the weak NN interaction?
Why measure it?
(some) theoretical issues
Constraints from previous experiments
Low energy neutron measurements in progress:
Gamma asymmetry in n+p->D+γ, spin rotation in n+4He
+other possible measurements

Thanks for slides to: C. Bass, A. Micherdzinska, D. Luo, B. Lauss, S. Penttila, G. Greene, D. Bowman,…

SM Lagrangians: QCD vs Electroweak

$L_{QCD}=-1/4\ G^{\mu\nu}G_{\mu\nu}+\bar{q}(i\not{D}-m)q\ (\theta_{QCD}=0)$

Strong Lagrangian

$L_{EW}= L_{V} + L_{F}+ L_{Higgs}+ L_{int}$

$L_{V} = =-1/4\ F^{\mu\nu}F_{\mu\nu}+m_{W}^{2}(W_{+}^{2}+ W_{-}^{2})/2 +m_{Z}^{2}Z^{2}/2$

$L_{F}= \bar{q}(i\not{\partial}-m)q$

$L_{higgs}= \partial_{\mu}\phi\,\partial^{\mu}\phi\ -m_{H}^{2}\phi^{2}$

$L_{int}= L_{VF} + L_{HV}+ L_{HF}+ L_{HH}$

Electroweak Lagrangian

$L_{VF} =g/2(W_{+}^{\mu}J_{+\mu} +W_{-}^{\mu}J_{-\mu}) +e\ A^{\mu}J_{\mu,EM}+g/\cos\theta_{W}Z^{\mu}J_{\mu,neut}$

$L_{HV}=[m_{W}^{2}(W_{+}^{2}+ W_{-}^{2})/2+m_{Z}^{2}Z^{2}/2]\ \phi/\rho(1+ \phi/2\rho)$

$L_{HF}= \bar{q}Mq\ \phi/\rho$

$L_{HH}=- \rho\lambda\phi^{3}/6 - \lambda\phi^{4}/24$

From aesthetic point of view, perhaps QCD is more “fundamental”?

Why is QCD so hard to Understand for light quarks at low energy?

It is nonlinear:gluon-gluon interactions in fundamental Lagrangian

It is strongly interacting:coupling constant grows at large distances

Motion of light quarks in bound states is highly relativistic (m_q~few MeV, M_p~1 GeV)

It is hard to see the gluons directly:no EM charge,no weak charge

It exhibits phenomena similar to many-body condensed matter systems (phase transitions, [chiral] symmetry breaking in the ground state, …)

It exhibits unprecedented phenomena:quark confinement

Weak qq-> Weak NN: what can we learn?

Δs=1 nonleptonic weak interactions [ΔI=1/2 rule, hyperon decays not understood, data not even close to simple estimates from flavor symmetries]

Question: is this problem specific to the strange quark, or is it a general feature in the nonleptonic weak interactions of light quarks? If q-q correlations important answer should be yes.

To answer, we must look at Δs=0 nonleptonic weak interactions (u,d quarks)

Any such process is dominated by strong interaction->must measure ~1E-7 PV effects at low E

Weak NN interaction is one of the few experimentally feasible systems

New Chiral Perturbation Theory Treatment of Weak NN Interaction (Liu)

Recent Development: χ perturbation theory for weak NN interaction [Zhu, Holstein, Ramsey-Musolf, et al,Nucl. Phys. A748 (2005) incorporates chiral symmetry of QCD, Ramsey-Musolf and Page review(hep-ph/0601127): relates coefficients in χ perturbation theory to experimental weak NN observables in NN and few body systems]

Longer-term goal: calculate coefficients of weak NN operators from QCD on lattice [Bean & Savage]

We need measurements of weak NN observables in NN and few body systems

What can low energy neutrons do?

Weak NN: What can be learned with Low Energy Neutrons?

We need to observe processes which can happen by either strong or weak interactions and interfere, then change sign of weak amplitude relative to strong amplitude by exploiting parity violation:

$P_{\pm/-} = |A_S \pm a_W|^2$, asymmetry~ $[P_+ - P_-]/[P_+ + P_-] \sim A_S a_W / |A_S|^2$

Hard to flip spin quickly with low losses for polarized targets (except for 3He!)

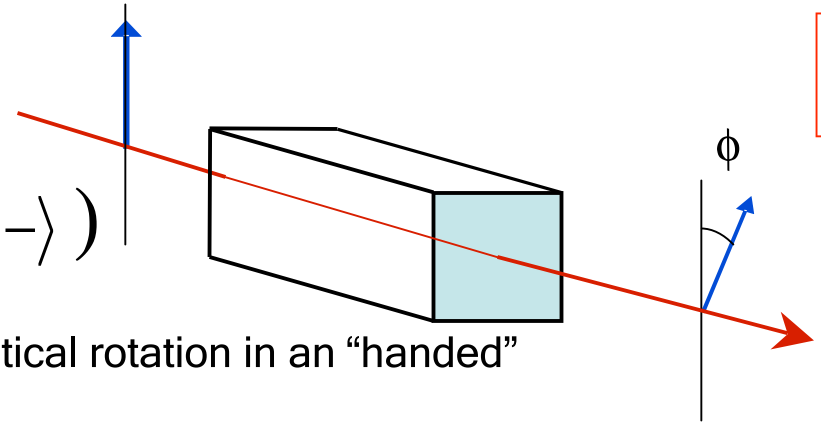
Circular Polarization is tough: MeV gamma polarimeters are inefficient

Easy to flip neutron spin, high polarization possible

-> 2 classes of experiments: PV spin rotation [~Re(f)] and reactions with inelastic channels [gamma capture]

Possible experiments: PV spin rotation in n-p and n-4He (and just maybe n-D?), PV gamma asymmetry in n-p and n-D, PV longitudinal asymmetry in charged particle final state reaction n+3He->3H+p, gamma+D->n+p, …

A Parity-Violating Observable: Neutron Spin Rotation



$$\left|\uparrow\right\rangle_i = \frac{1}{\sqrt{2}}\left(\left|+\right\rangle + \left|-\right\rangle\right)$$

$$\boxed{f(0) = f_{PC} + f_{PV}\left(\vec{\sigma}\cdot\vec{k}\right)}$$

- Analogous to optical rotation in an "handed" medium.
- Transversely-polarized neutrons corkscrew due to the NN weak interaction
- ***PV Spin Angle*** is independent of incident neutron energy in cold neutron regime
- $d\phi_{PV}/dx \sim 10^{-6}$ rad/m based on dimensional analysis
- $d\phi_{PC}/dx$ (due to B field) can be much larger than $d\phi_{PV}/dx$, and is v_n dependent

Refractive index dependent on neutron helicity

$$\frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PV})}\left|z\right\rangle + e^{-i(\phi_{PC}-\phi_{PV})}\left|-z\right\rangle\right)$$

$$\boxed{\phi_{PV} = \varphi_+ - \varphi_- = 2\pi l \rho f_{PV}}$$

Theoretical Expectations for 4He Spin Rotation

$$\phi_{PV}\left(\vec{n},{}^{4}\mathrm{He}\right)=-\left(0.97f_{\pi}+0.22h_{\omega}^{0}-0.22h_{\omega}^{1}+0.32h_{\rho}^{0}-0.11h_{\rho}^{1}-0.02h_{\rho}^{\prime 1}\right)\mathrm{rad/m}$$

Dmitriev *et al*. Phys Lett **125** 1 (1983)

Using “best values” and “reasonable range” values for DDH couplings:

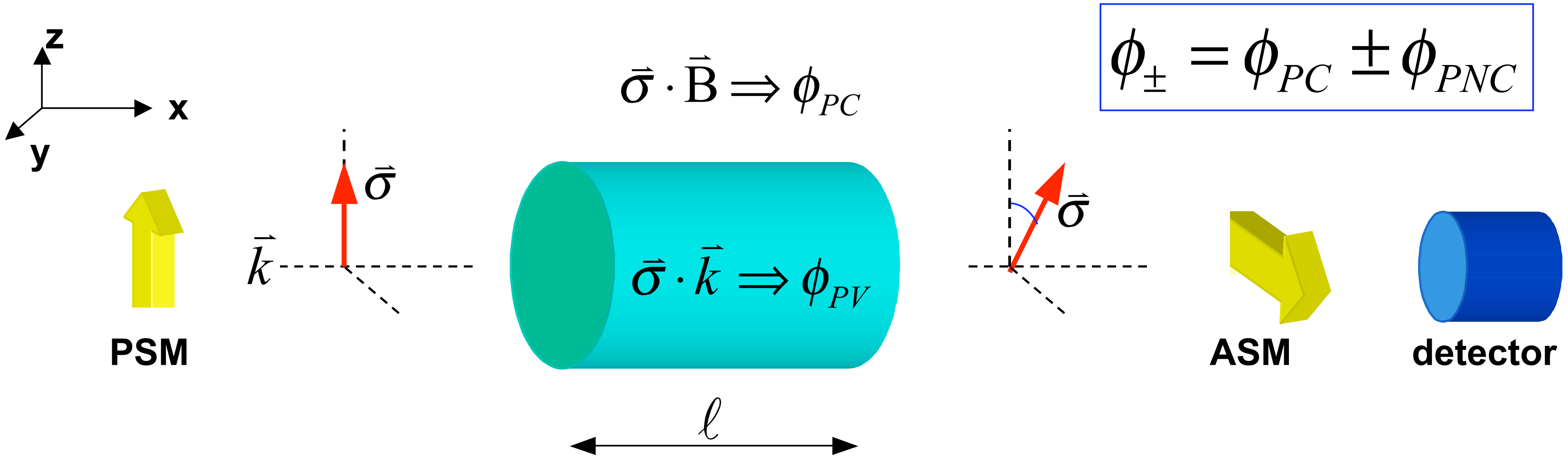
$$\varphi_{PV}\left(\vec{n},{}^{4}\mathrm{He}\right)=-\left(0.1\pm1.5\right)\times10^{-6}\ \mathrm{rad/m}$$

In terms of new EFT couplings Zhu *et al*. Nucl. Phys. A **748** 435-498 (2005)

$$\phi_{\mathrm{PV}}(n\,{}^{4}\mathrm{He})=(1.2\lambda_{s}^{nn}+0.6\lambda_{s}^{np}+1.3\lambda_{t}-2.7\rho_{t})\,m_{n}$$

ϕ = (8 ± 14 (stat) ± 2 (sys)) ´10-7 rad/m is existing (unpublished) experimental limit (D. Markoff, PhD thesis U Washington)

PV Neutron Spin Rotation Measurement



$$\boxed{\phi_{\pm} = \phi_{PC} \pm \phi_{PNC}}$$

$$\vec{\sigma}\cdot\vec{\mathrm{B}} \Rightarrow \phi_{PC}$$

$$\phi_{PNC} = \varphi_{+} - \varphi_{-} = 2\pi\rho z f_{PNC}$$

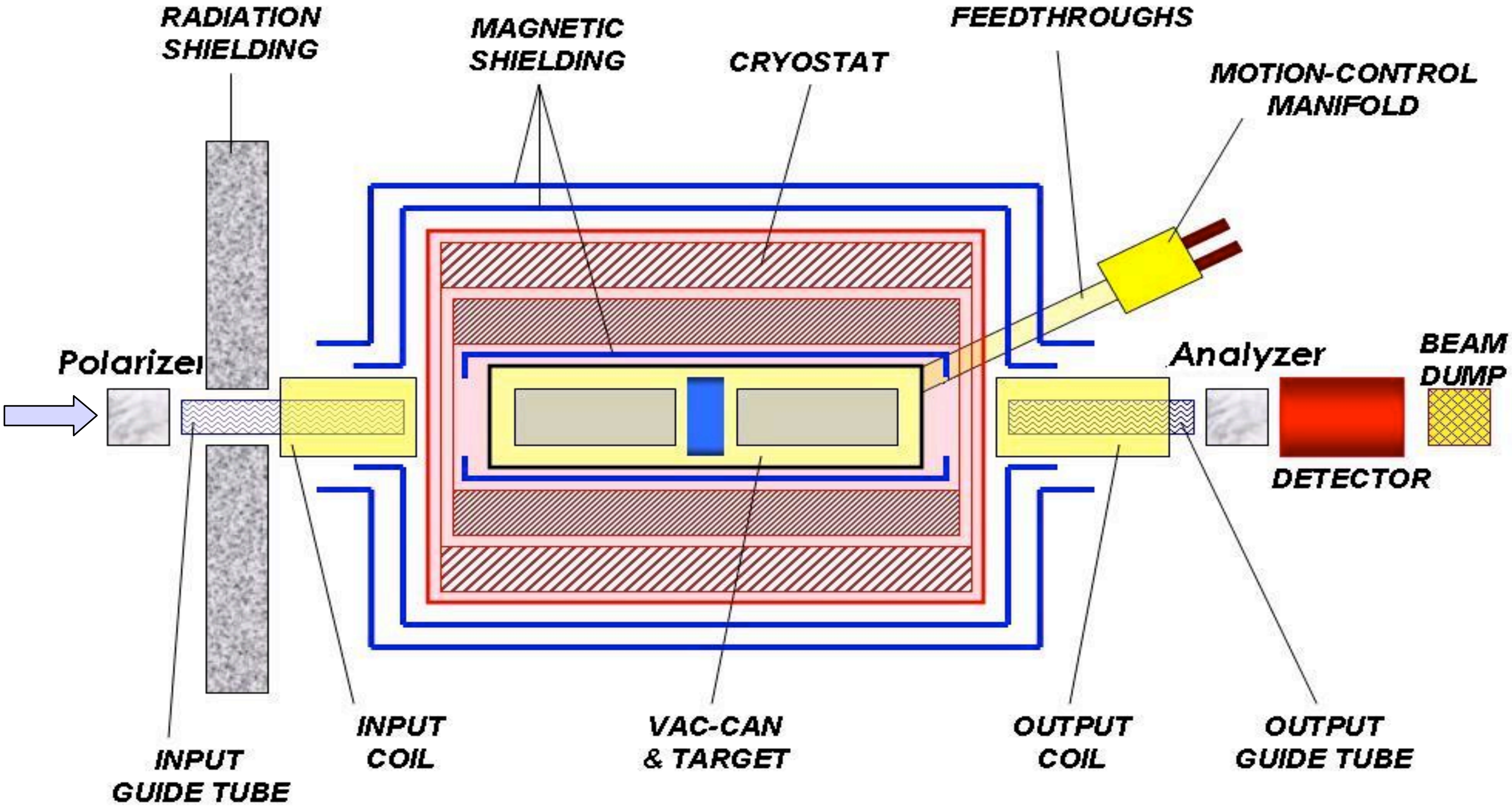
- PV rotation angle / unit length ($d\phi_{PV}/dx$) approaches a finite limit for zero neutron energy:

  $d\phi_{PV}/dx \sim 10^{-6}$ rad/m inlight nuclei (H,D,^{4}He)

- $d\phi_{PC}/dx$ (due to B field) is much larger than $d\phi_{PV}/dx$, and is v_n dependent:

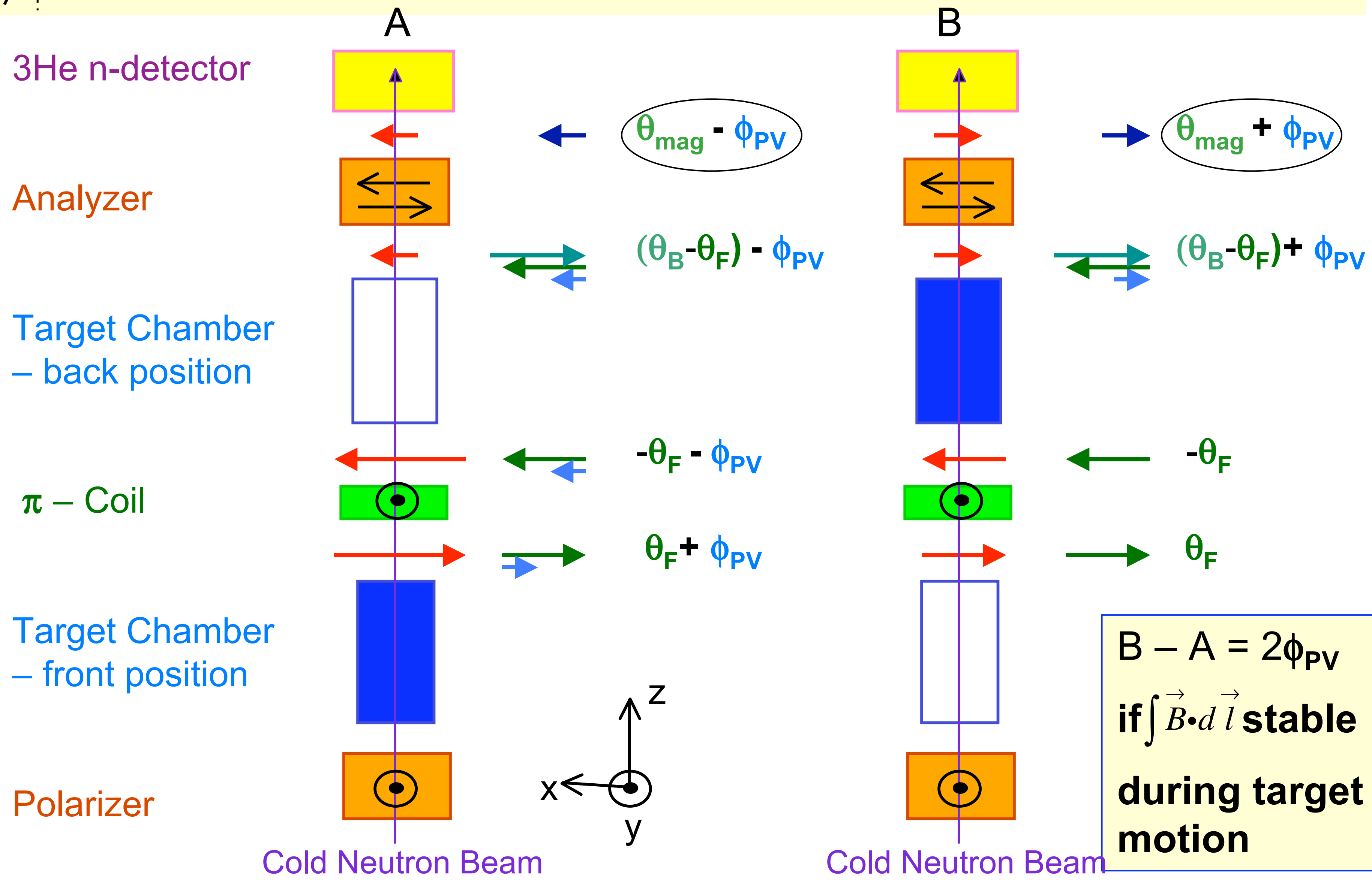
Spin rotation of polarized meV neutrons in B field of Earth is larger than PV rotation by 6 orders of magnitude

Cross section of Spin Rotation Apparatus



Step 1 to isolate PV spin rotation: shielding reduces B by ~10^4

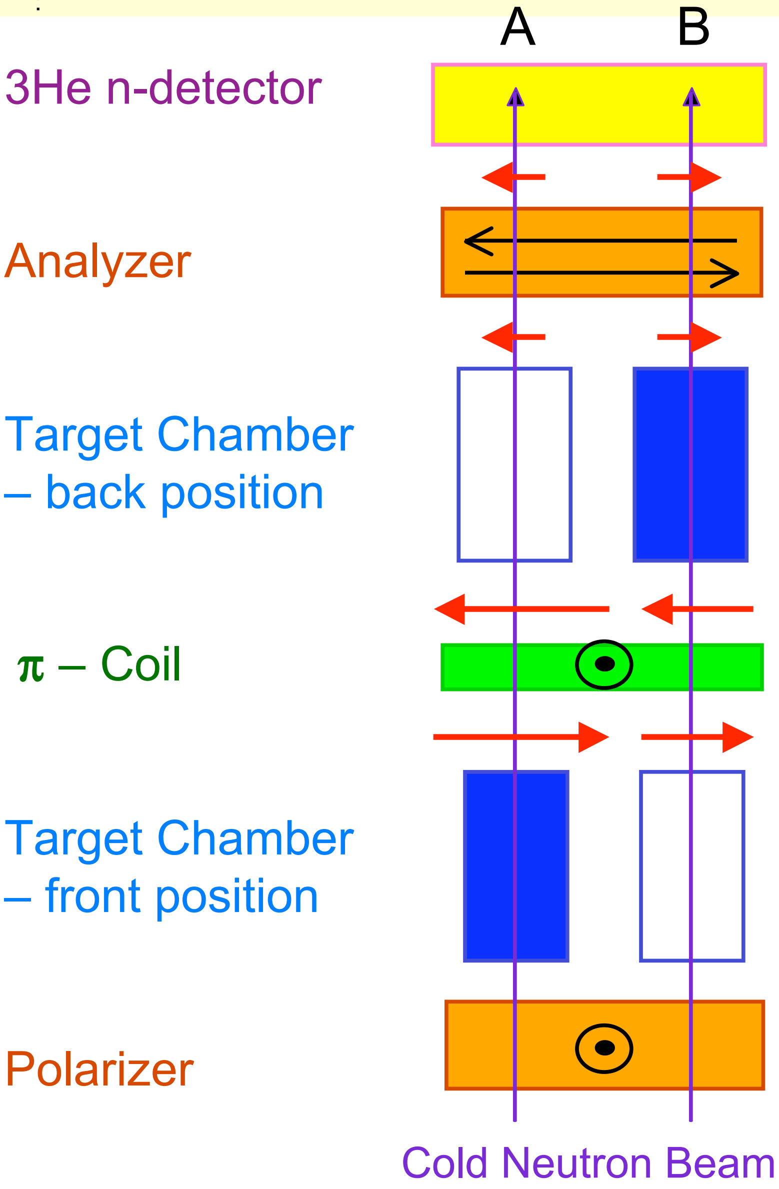
Target design: Oscillation of PV Signal



$B - A = 2\phi_{PV}$

if $\int \vec{B} \cdot d\vec{l}$ stable during target motion

Target design: Beam Noise Suppression



A

B

3He n-detector

Analyzer

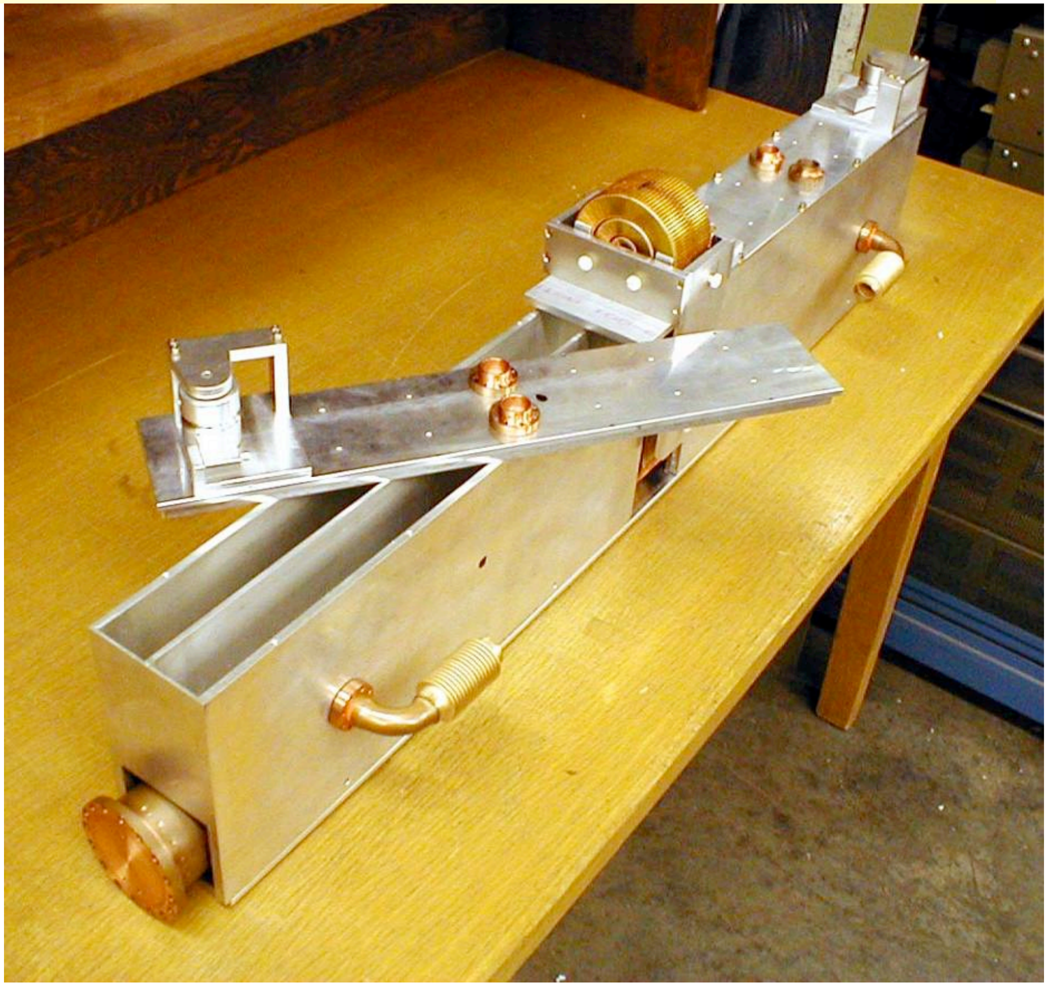
Target Chamber
– back position

π – Coil

Target Chamber
– front position

Polarizer

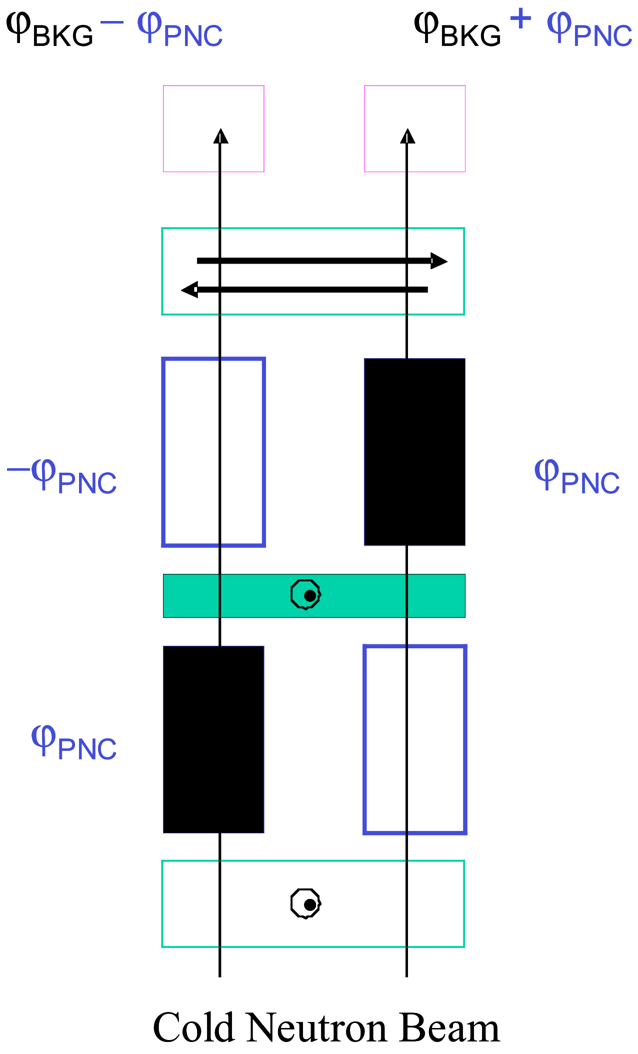
Cold Neutron Beam



$[B - A]_1 - [B - A]_2 = 4\phi_{PV}$ **if** $\int_B [\vec{B}\cdot d\vec{l}\,] - \int_A [\vec{B}\cdot d\vec{l}\,]$

stable during target motion

Signal Modulation/ Noise Suppression



^{3}He *n*-detectors

Analyzer

Target Chamber Back Position

π - Coil

Target Chamber Front Position

Polarizer

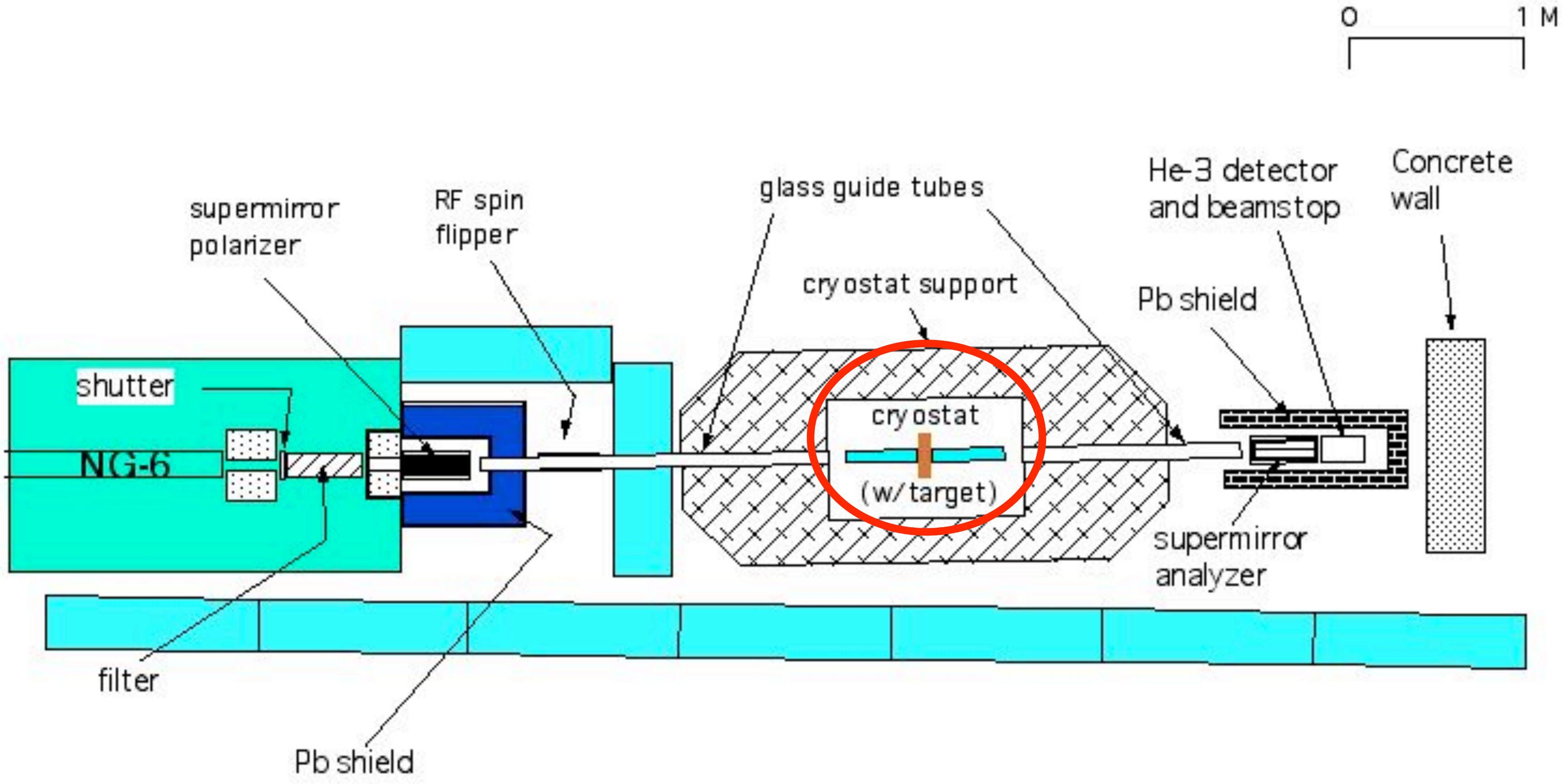
Motion of liquid isolates P-odd signal

Beam split into two parallel beams for common-mode noise reduction

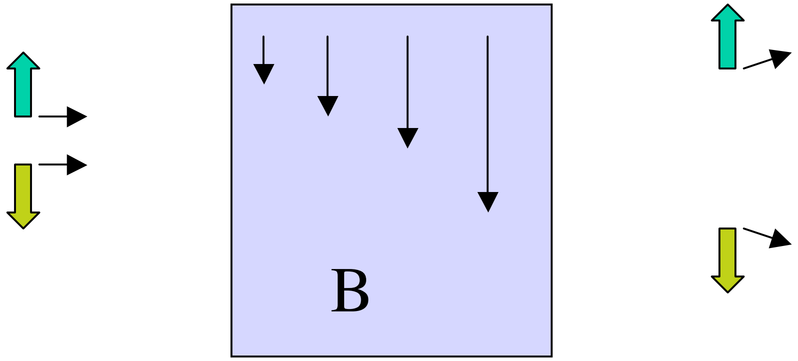
Analyzer direction switched at known frequency

$$\sin\varphi = \frac{N_+ - N_-}{N_+ + N_-}$$

Neutron Spin Rotation apparatus (top view) at NIST

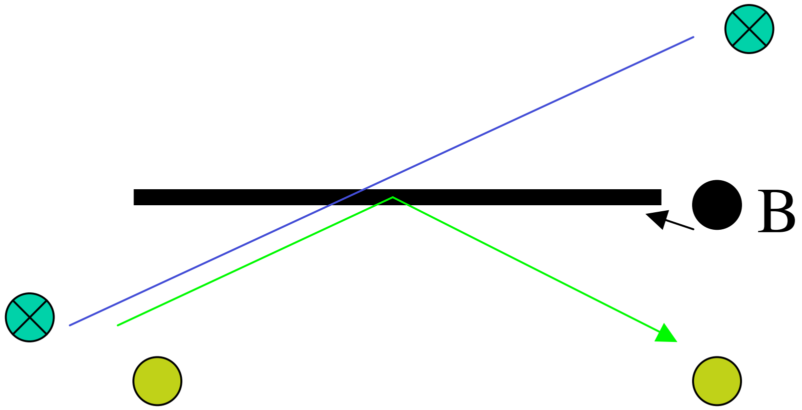


How can neutrons be polarized?



B gradients (Stern-Gerlach, sextupole magnets) electromagnetic

$F=(\mu\bullet\nabla)B$

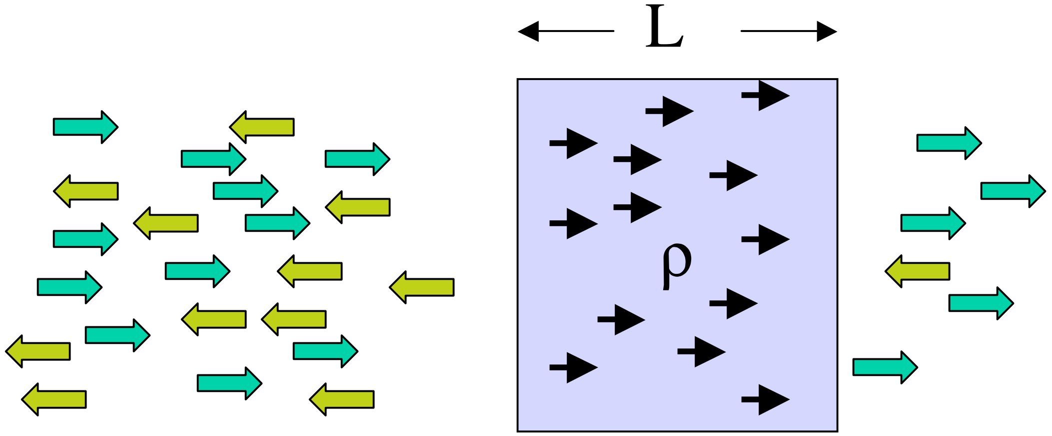


Reflection from magnetic mirror: electromagnetic+ strong

$f\pm=a(\text{strong})\ \ +/-\ \ a(\text{EM})$

with $|\,a(\text{strong})|=|\,a(\text{EM})|$

$\Rightarrow f+=2a,\ f-=0$

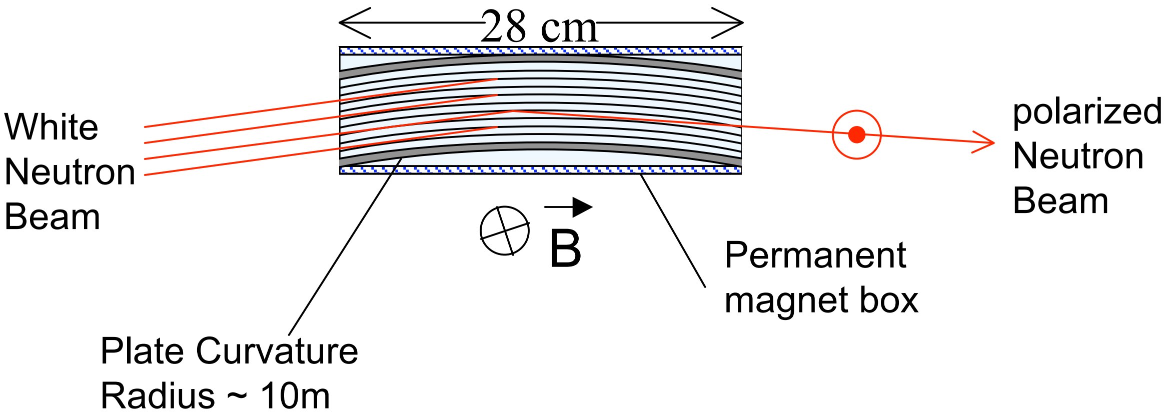


Transmission through polarized nuclei: strong

$\sigma+\neq\ \sigma-\ \Rightarrow\ T+\ \neq\ T-$

Spin Filter: $T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

“Supermirror” Neutron Polarizer

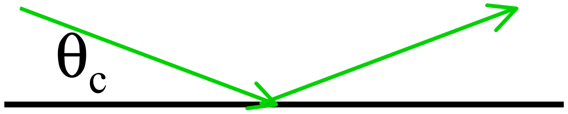


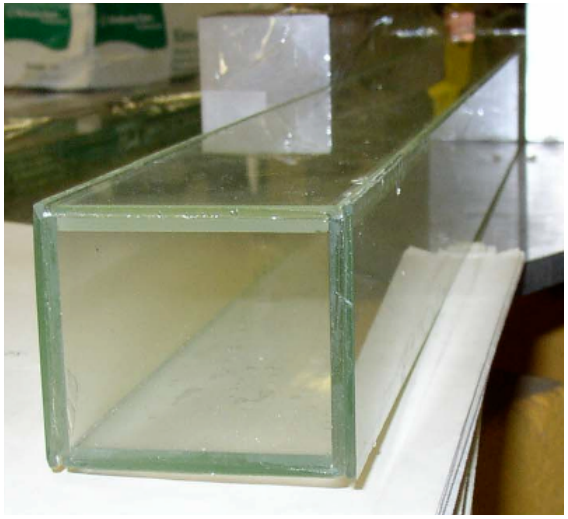
- Neutrons are polarized through
- spin-dependent scattering from
- magnetized mirrors

- Polarization: ~98%
- transmission: ~25%

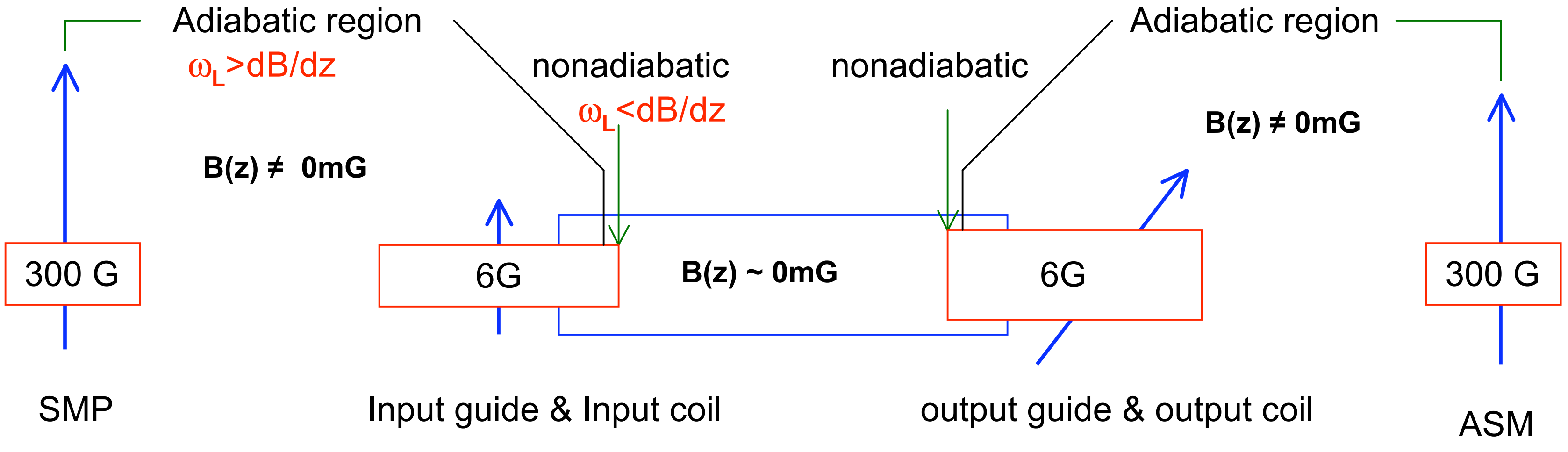
How we transport polarized neutrons – input guide & spin transport

Transport neutrons using float glass guide
(output guide split into 2 parallel beams)





To maintain neutron polarization $\vec{B}$ field pointed in the direction of neutron polarization is needed (spin transport)



Adiabatic region

$\omega_L > dB/dz$

B(z) ≠ 0mG

nonadiabatic

$\omega_L < dB/dz$

nonadiabatic

Adiabatic region

B(z) ≠ 0mG

300 G

6G

B(z) ~ 0mG

6G

300 G

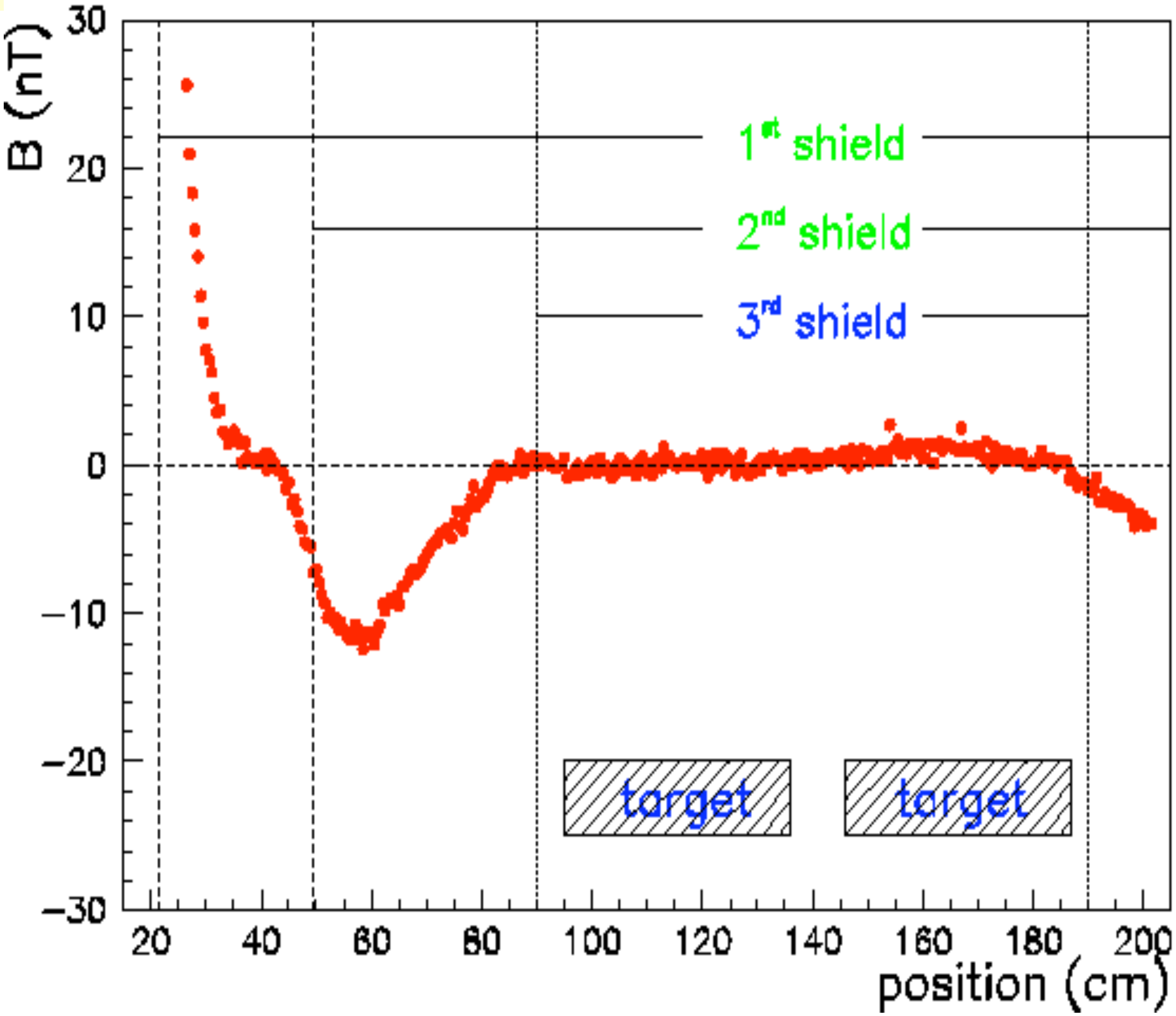
SMP

Input guide & Input coil

output guide & output coil

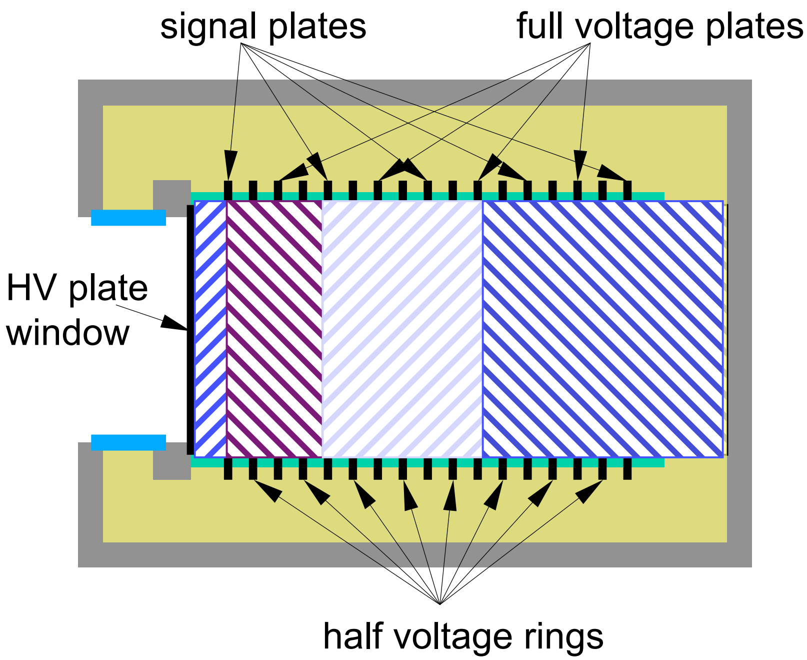
ASM

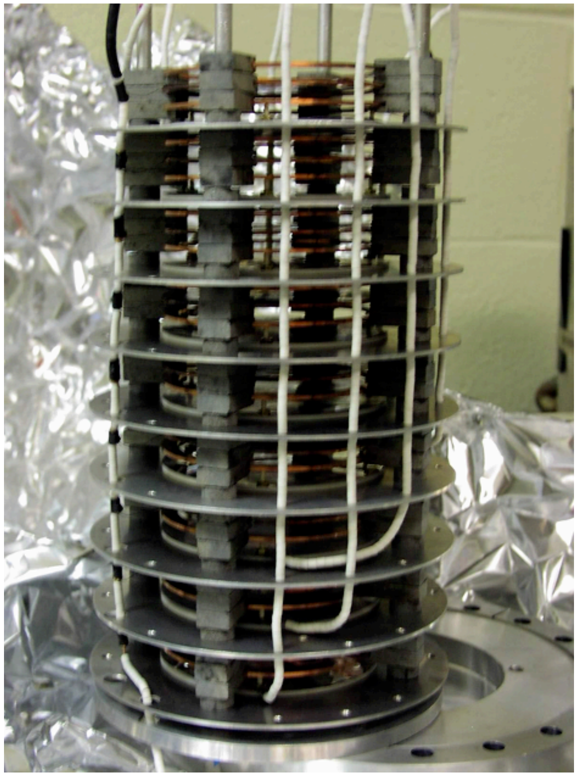
Suppressing the magnetic field

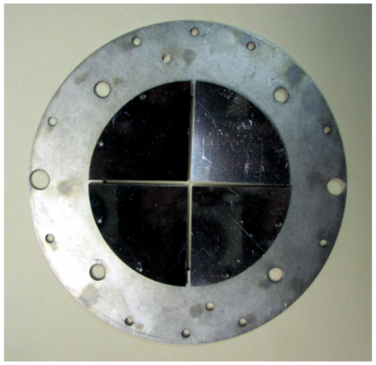


~2nT field in the target region still not good enough (causes rotation ~100 times bigger than ϕ_{pv}), and still need to oscillate PV signal ->Target Design

Segmented ^{3}He ionization chamber





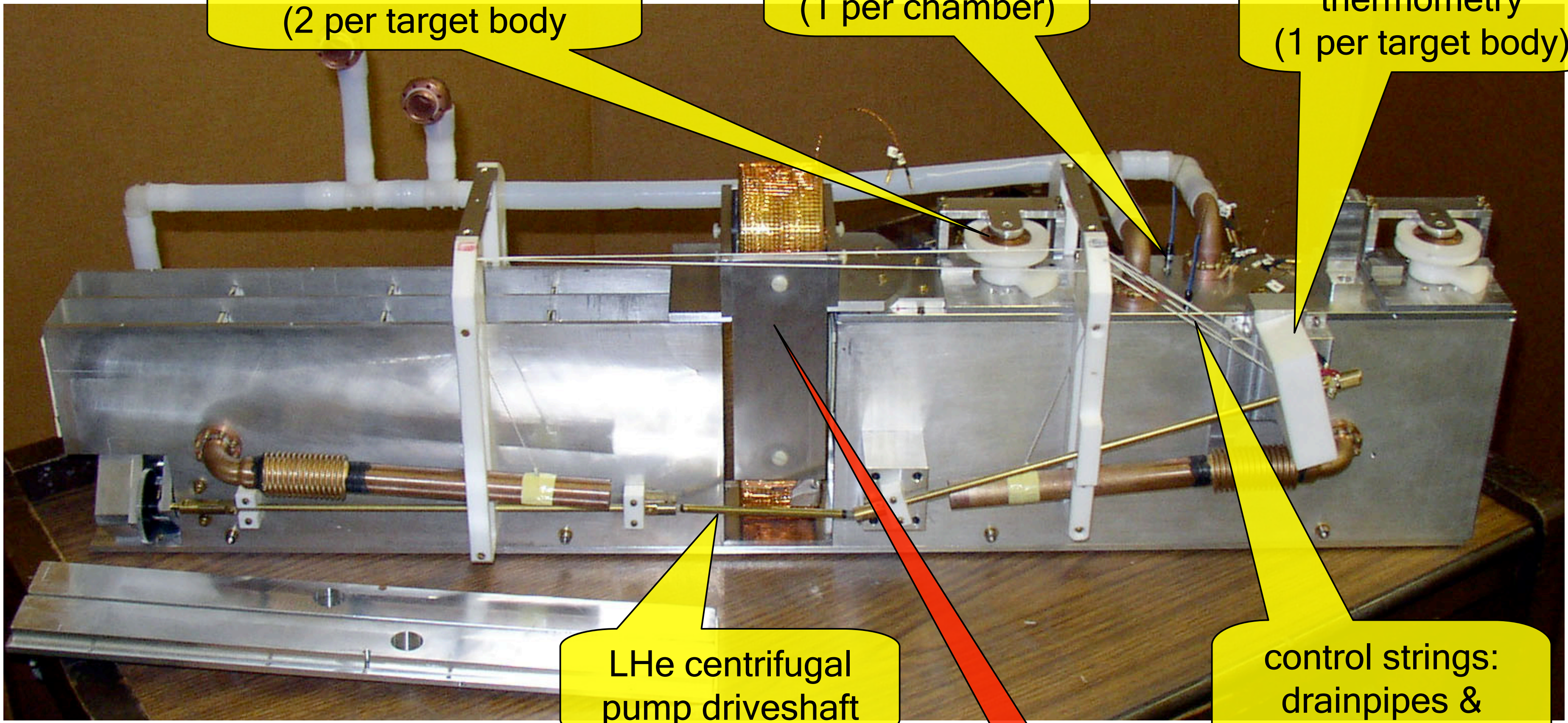


- ^{3}He and Ar gas mixture
- Neutrons detected through $n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{H}$
- High voltage and grounded charge-collecting plates produce a current proportional to the neutron flux
- 4 Detection Regions along beam axis - velocity separation (1/*v* absorption)

S.D.Penn *et al*. [NIM A457 332-37 (2001)]

charge collection plates are divided into 4 quadrants (3" diam) separated L/R and U/D beam

Target Design: Sensors & Motion Control



fluxgate magnetometer
(2 per target body

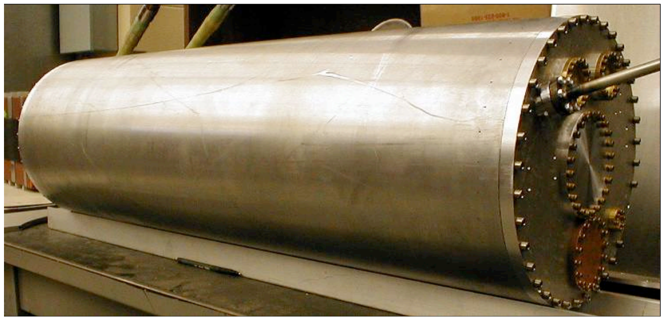
LHe level sensor
(1 per chamber)

thermometry
(1 per target body)

LHe centrifugal
pump driveshaft

pi-coil

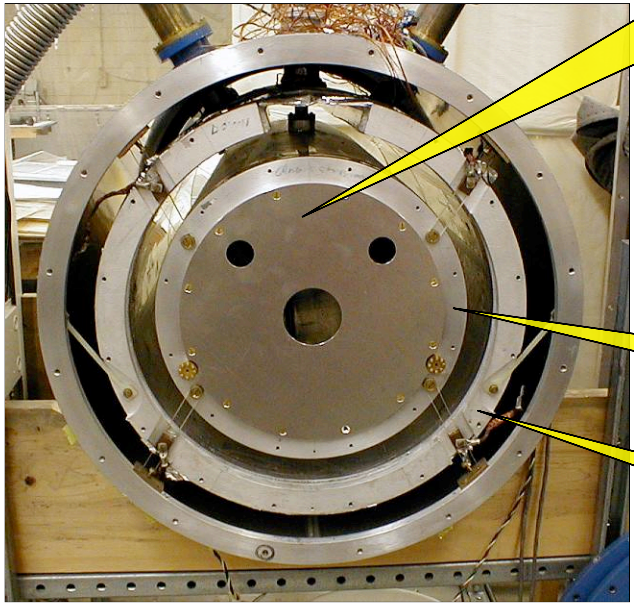
control strings:
drainpipes &
magnetometers



Target/pump immersed in a pool of liquid helium below n beam inside this cylinder

Nonmagnetic Cryostat

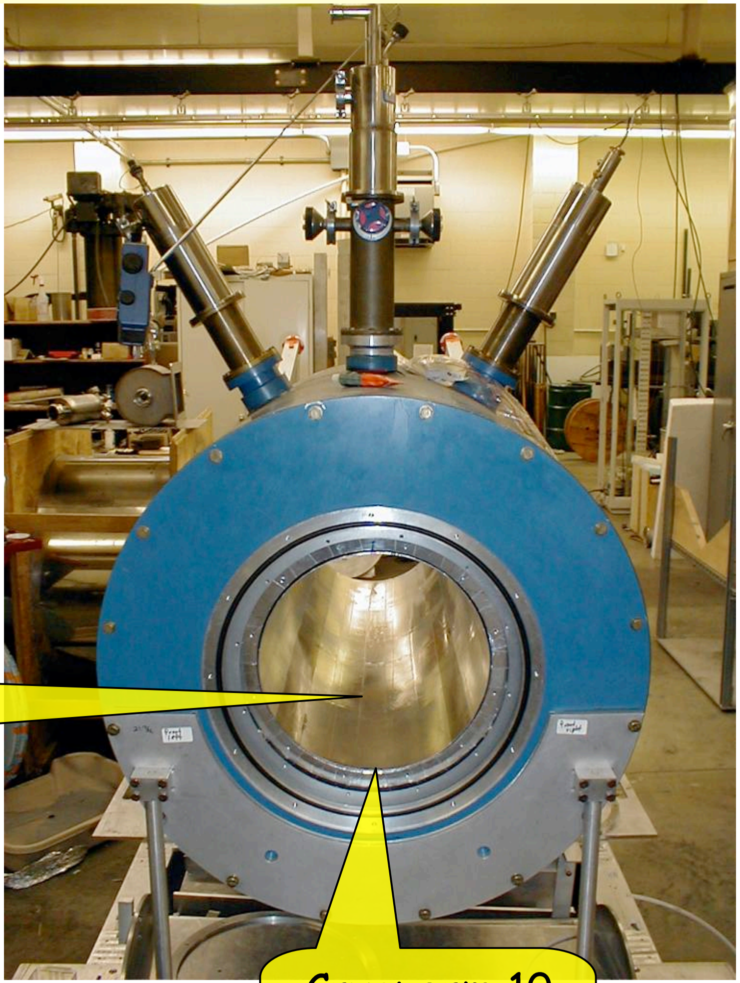
- Oxford horizontal, cold-bore cryostat
  - built from ***non-magnetic*** materials
  - consists of two coaxial annular vessels housed within a cylindrical main vacuum vessel



4K thermal shield

LHe volume: 30L

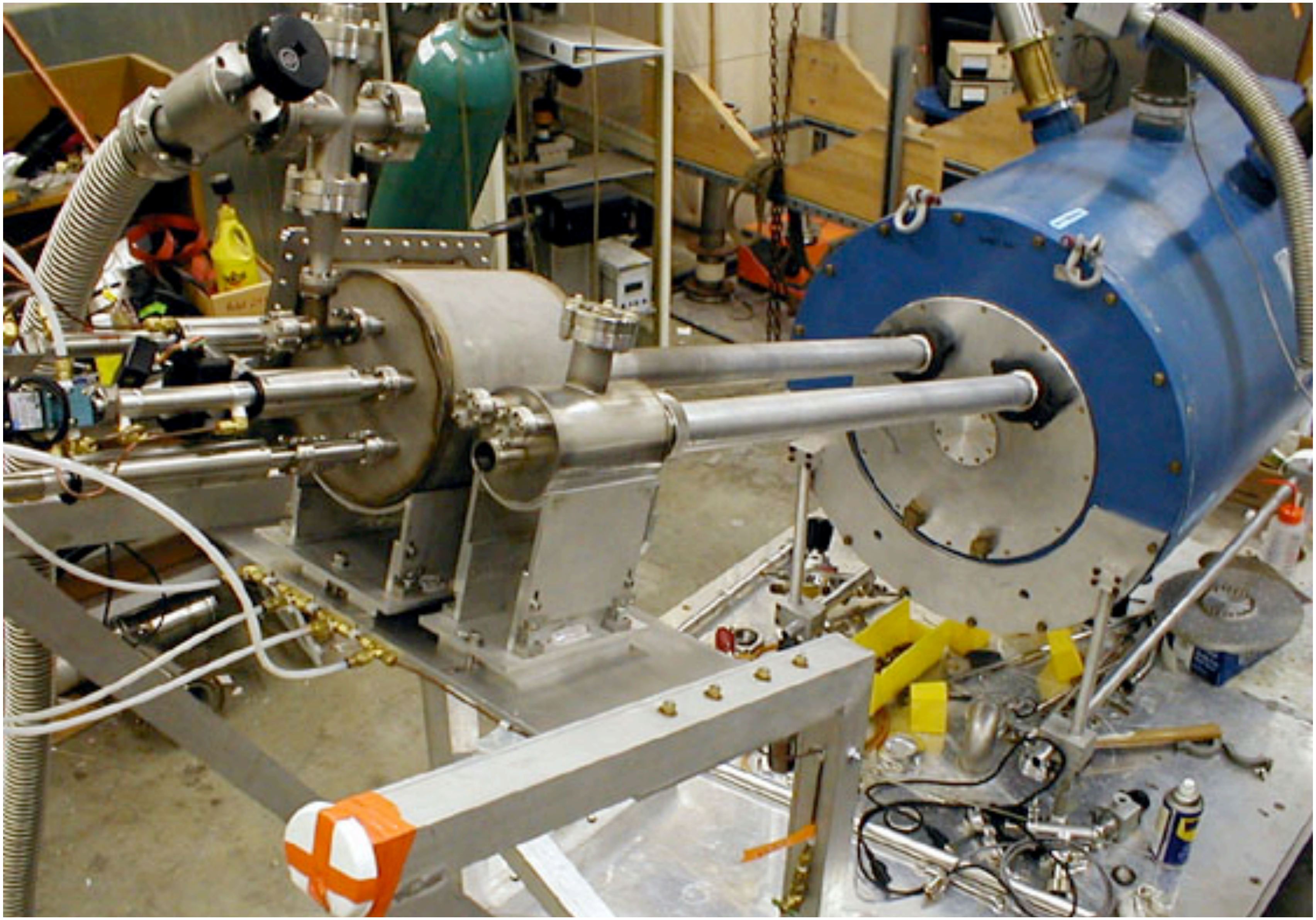
LN2 volume: 50L



cold bore:
30.5 cm dia
100 cm long

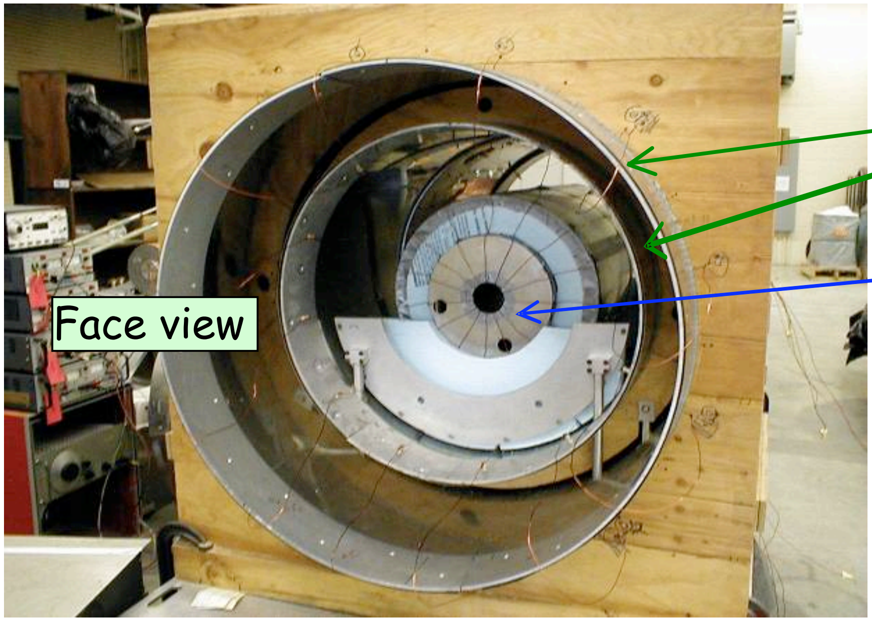
Cryoperm 10 cylinder lines coldbore

Liquid Helium Motion Control System



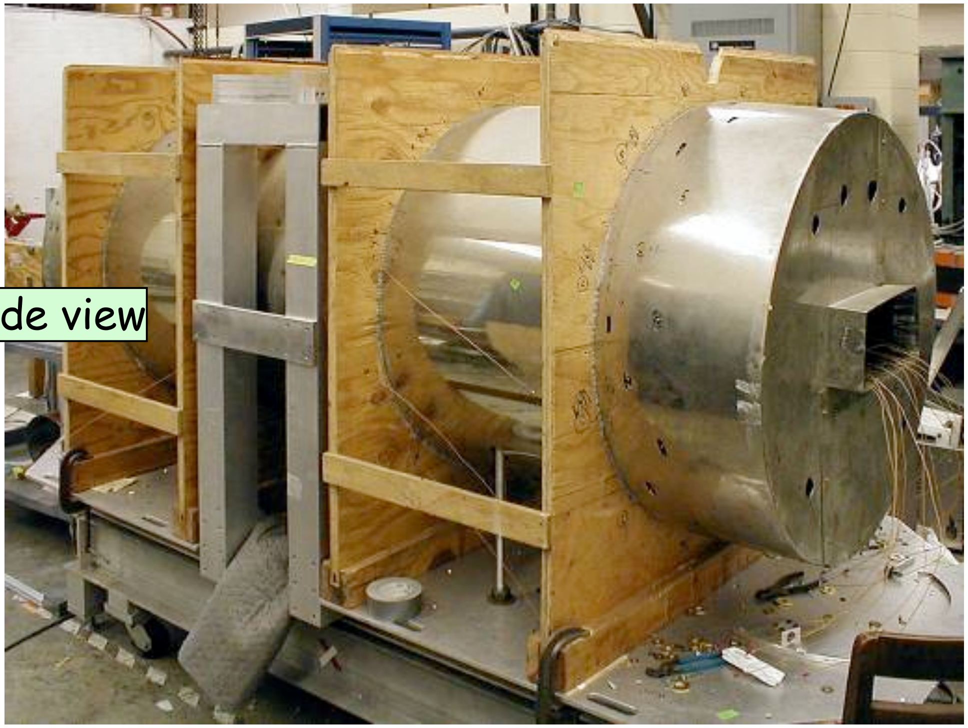
Nonmagnetic cryostat: target feedthroughs and liquid motion control system

Magnetic shielding

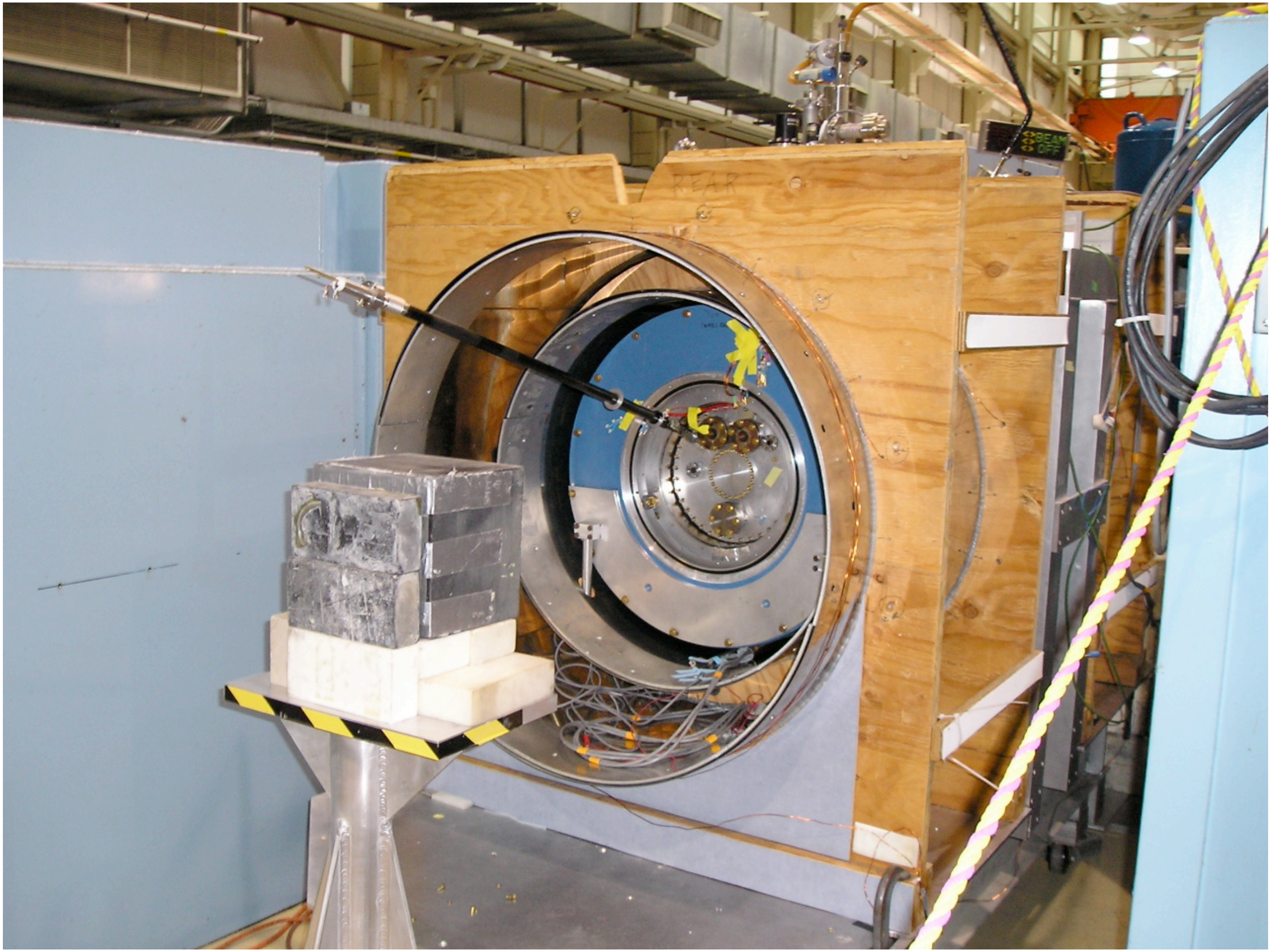


2 outer
CO-NETIC AA shield

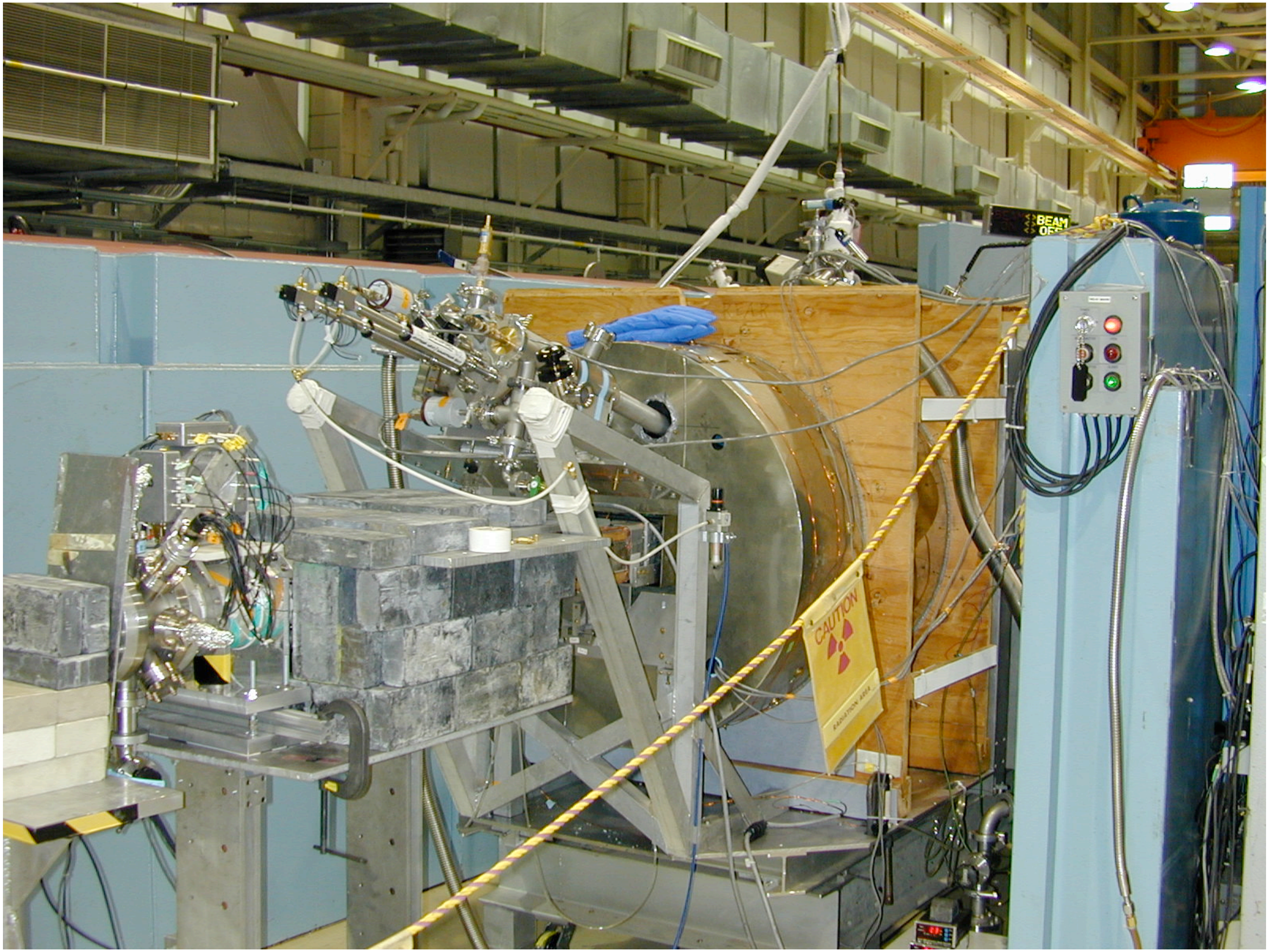
1 inner
CRYOPERM-10 shield



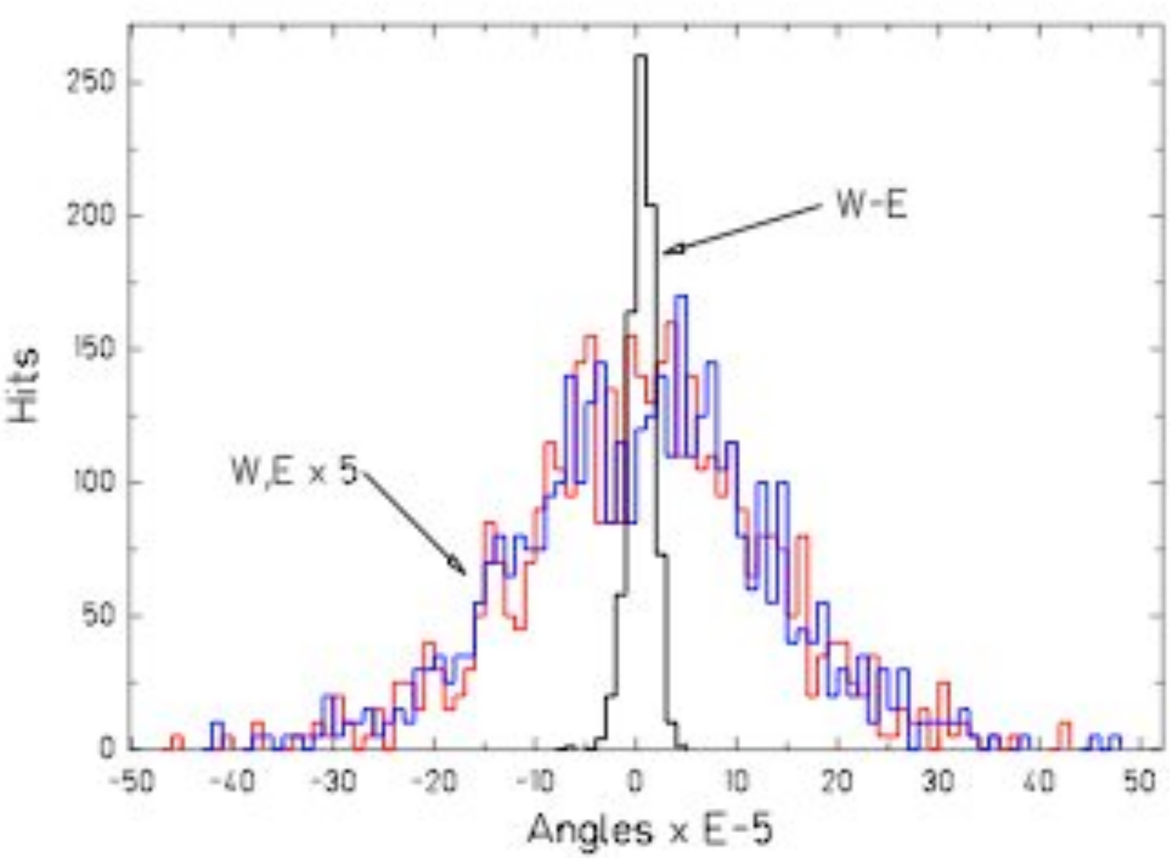
Cryostat and Target in B Shielding on Beamline



N-4He Spin Rotation Apparatus at NIST

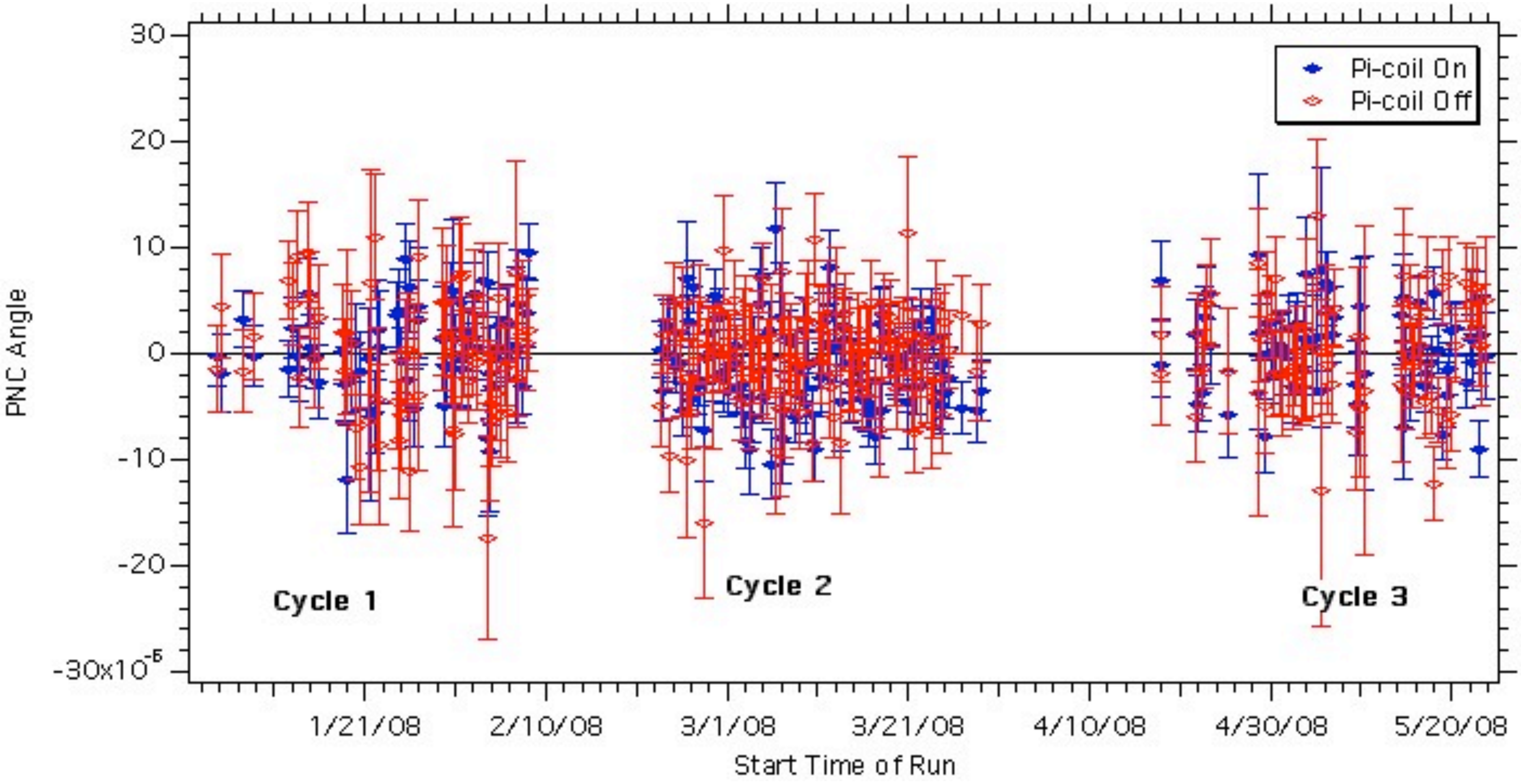


Reduction of Common Mode Noise from Reactor Fluctuations: 4He Target

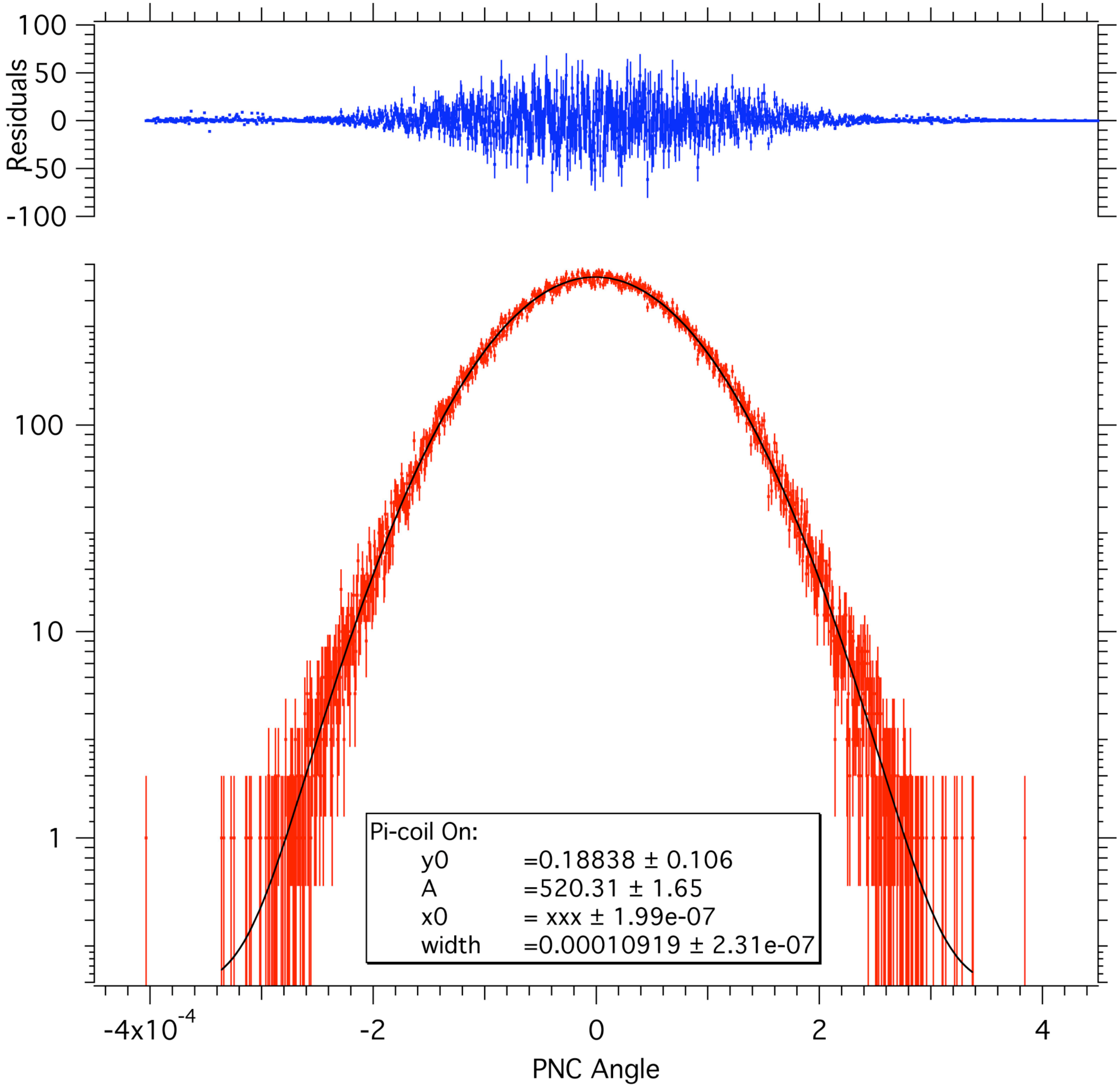


Large noise from beam intensity fluctuations is suppressed
Width of W-E difference of spin rotation angles is $\sim\sqrt{N}$

4He Spin Rotation data from NIST vs cycle

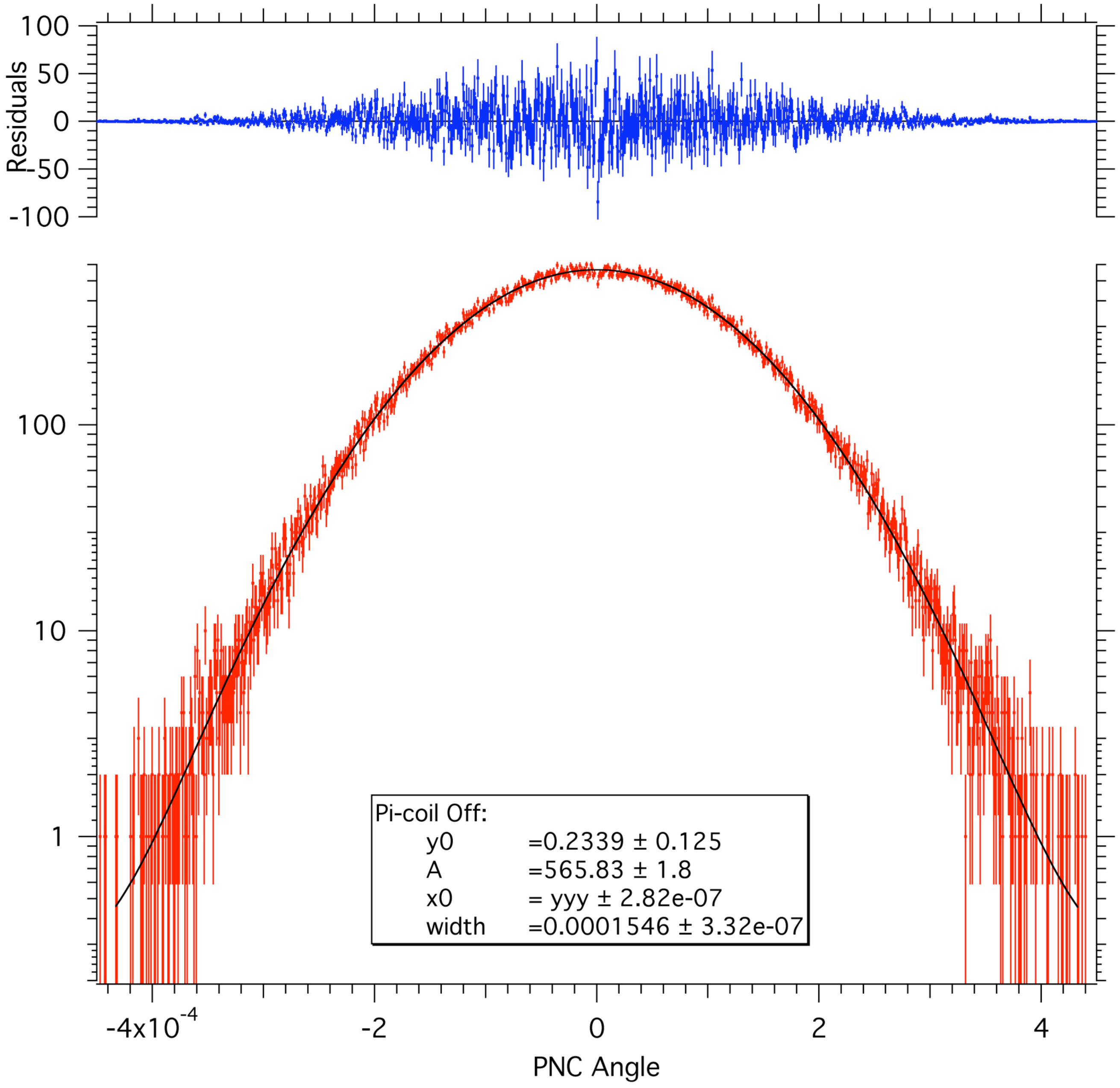


Distribution of Raw Asymmetries, pi-coil on



Pi-coil On:
y0 =0.18838 ± 0.106
A =520.31 ± 1.65
x0 = xxx ± 1.99e-07
width =0.00010919 ± 2.31e-07

Distribution of Raw Asymmetries, Pi-coil off



For pi-coil off, no oscillation of PV signal, asymmetry should be zero

Width larger by factor of sqrt(2) as expected from +,-,0 pi-coil sequence

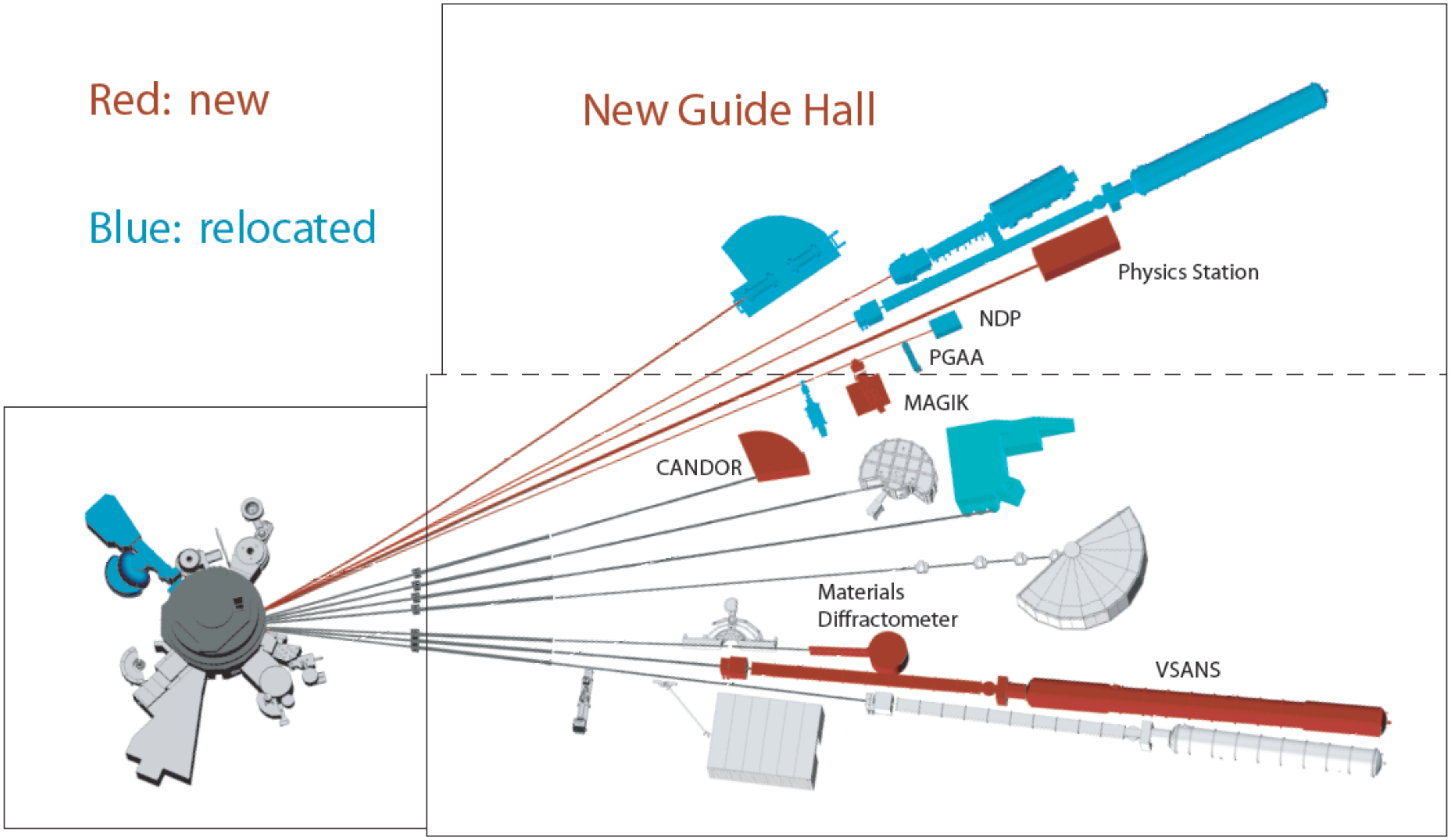
Upper Bounds on 4He Systematic Effects

Background rotations cancel if liquid motion does not change spin rotation from internal B fields

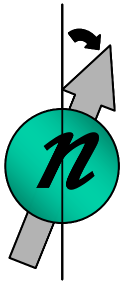
- Measurement noise above $\sqrt{N}$
  - reactor noise (use right-left chambers to suppress common-mode noise)
  - *ion chamber current-mode measurement method*

- Systematics associated with residual B-fields (100 μG level)
  - Diamagnetism of liquid helium → $\Delta B/B \approx 6E\text{-}8$ → 2E-9 rad/m
  - Optical potential of liquid helium → ~ 10 neV → 2E-8 rad/m
  - Shift in neutron energy spectrum → $\Delta L \approx 0.01$ mm → 4E-8 rad/m
  - *Small angle scattering* → <5E-8 rad/m
  - *Change in neutron paths due to refraction* → <5E-8 rad/m
  - *Change in neutron phase space from target reflections* → <5E-8 rad/m
  - *Phase space non-uniformity in analyzing power of ASM* → <4E-8 rad/m
  - *Time-dependence of internal magnetic field IN PROGRESS*
  - *Time-dependence of density fluctuations IN PROGRESS*

More neutrons soon: NIST Guide Hall Expansion Project



X20 increase in polarized slow neutron flux(!) done~late 2010?
Spin rotation statistical precision of 1E-7 rad/5 week cycle possible



Neutron Spin Rotation in Few-Body Systems: Expected size of Effects

$\varphi(n\alpha)$ ***liquid helium***

DDH range gives ~± 1.5E-6 rad/m L~0.5m-><u>7E-7 rad</u>

$\varphi(np)$ ***parahydrogen***

calculations in DDH framework (Schiavilla et al) gives ~5E-7 rad/m for DDH best values. L~20 cm -><u>1E-7 rad</u>

$\varphi(nD)$ ***orthodeuterium***

calculations in DDH framework(Schiavilla et al) give ~5E-6 rad/m for the DDH best value, larger than n-p by an order of magnitude, dominated by weak pion exchange. L~5 cm -><u>2.5E-7 rad</u>

The NPDγ Collaboration

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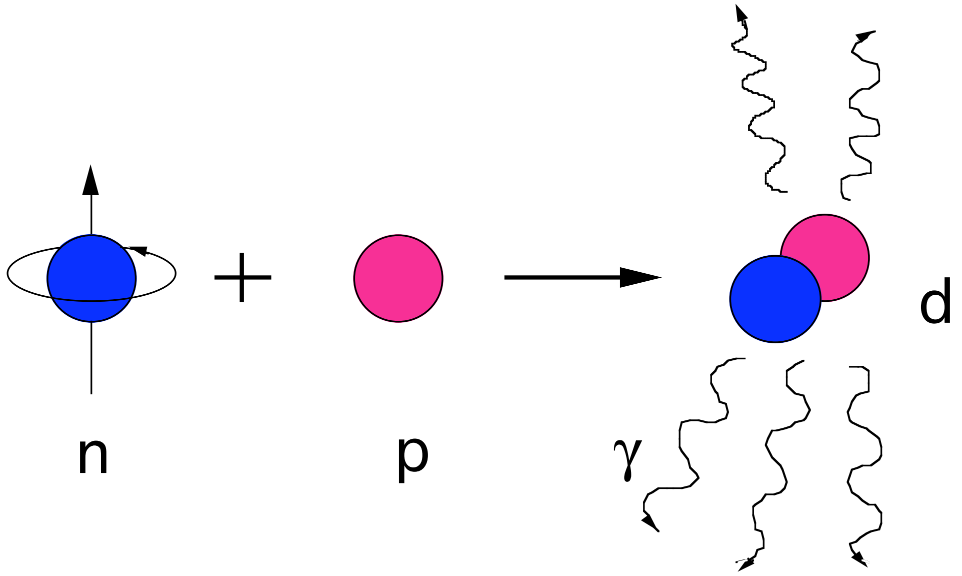
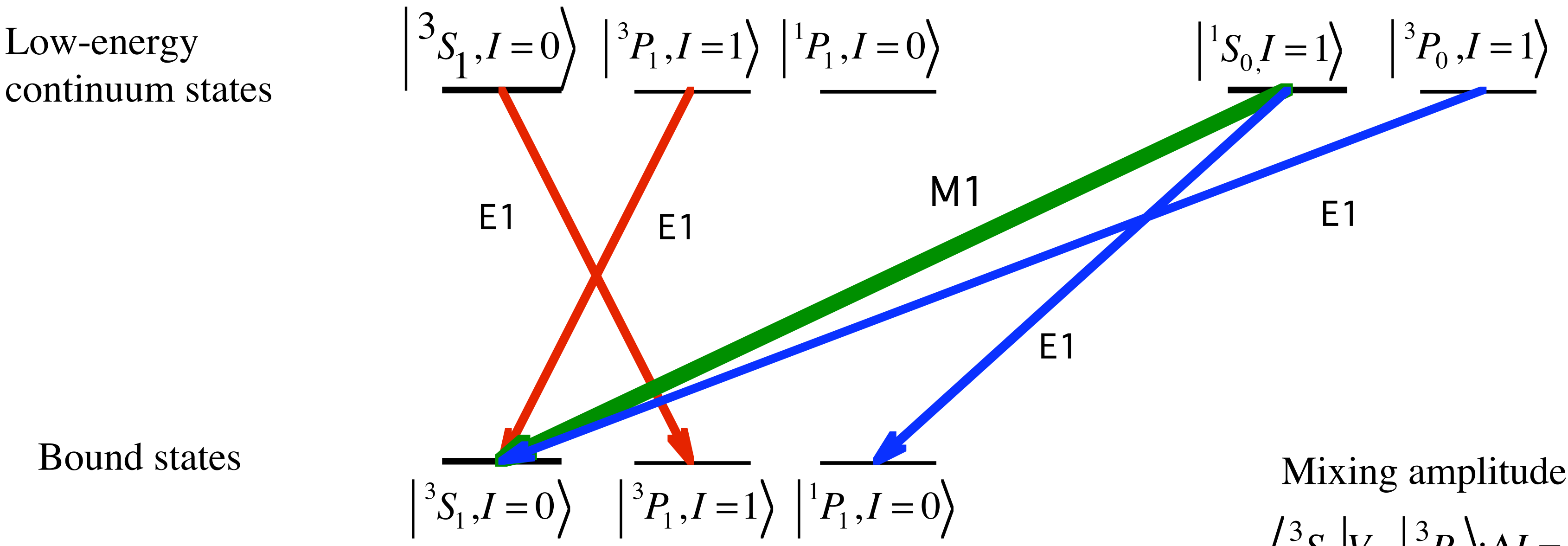
PV Gamma Asymmetry in Polarized Neutron Capture



- Asymmetry A_γ of gamma angular distribution upon polarized neutron capture due to weak NN interaction [from $s_n \bullet p\gamma$]
- Goals: 1×10^{-8} at SNS/7000 MW-hours
- Asymmetry depends mainly on the weak pion coupling f_π for n-p
- PV gamma asymmetry in n+D->3H+γ also possible (SNS letter of intent)

Simple Level Diagram of *n-p* System; $\vec{n}+p\rightarrow d+\gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction



- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of *E*1-*M*1 transitions - $\Delta I = 1$ channel.

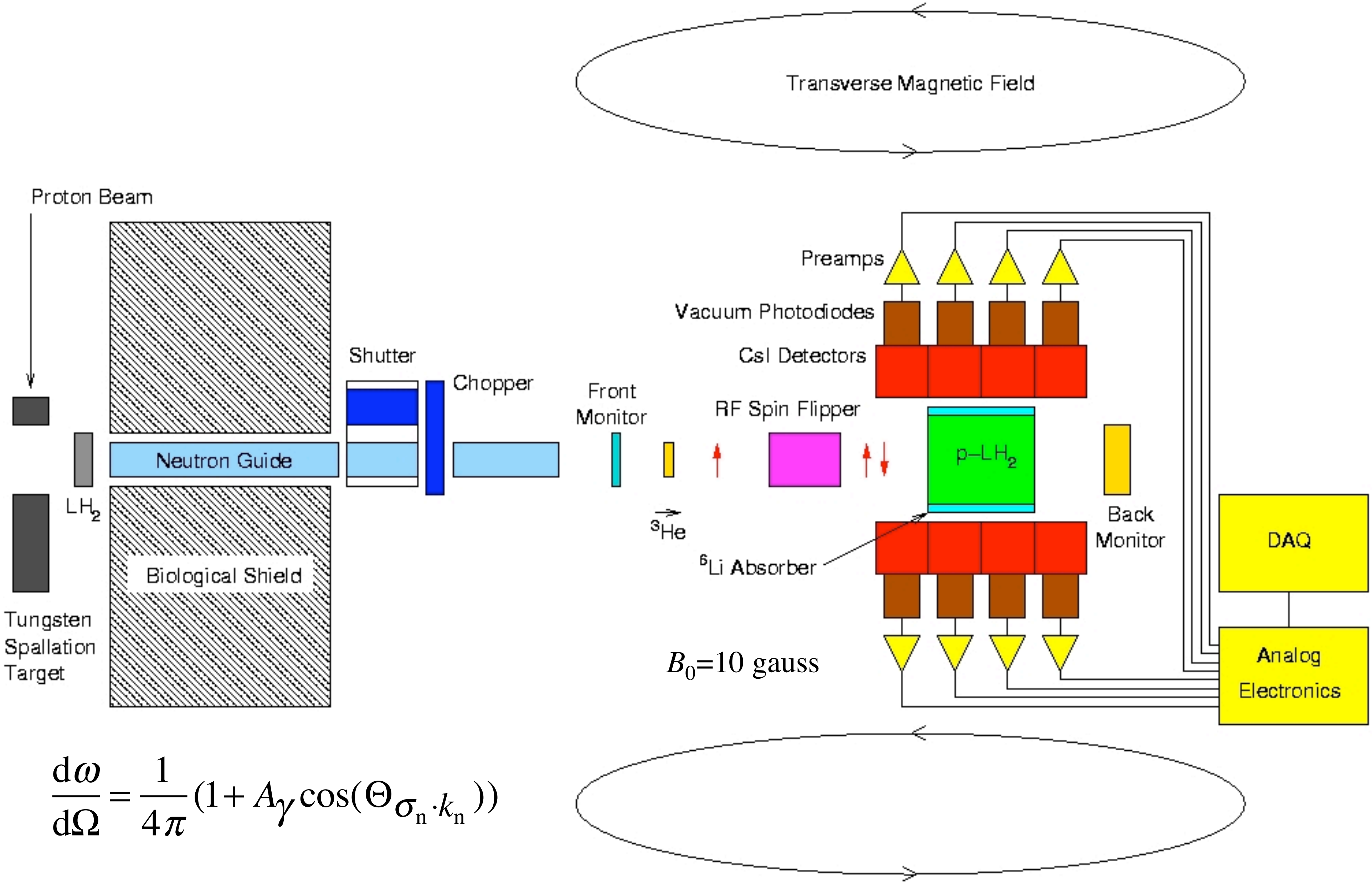
Mixing amplitudes:

$\langle {}^3S_1 | V_W | {}^3P_1 \rangle; \Delta I = 1$

$\langle {}^3S_1 | V_W | {}^1P_1 \rangle; \Delta I = 0$

$\langle {}^1S_0 | V_W | {}^3P_0 \rangle; \Delta I = 2$

NPDGamma Experimental Setup at Los Alamos (LANSCE)

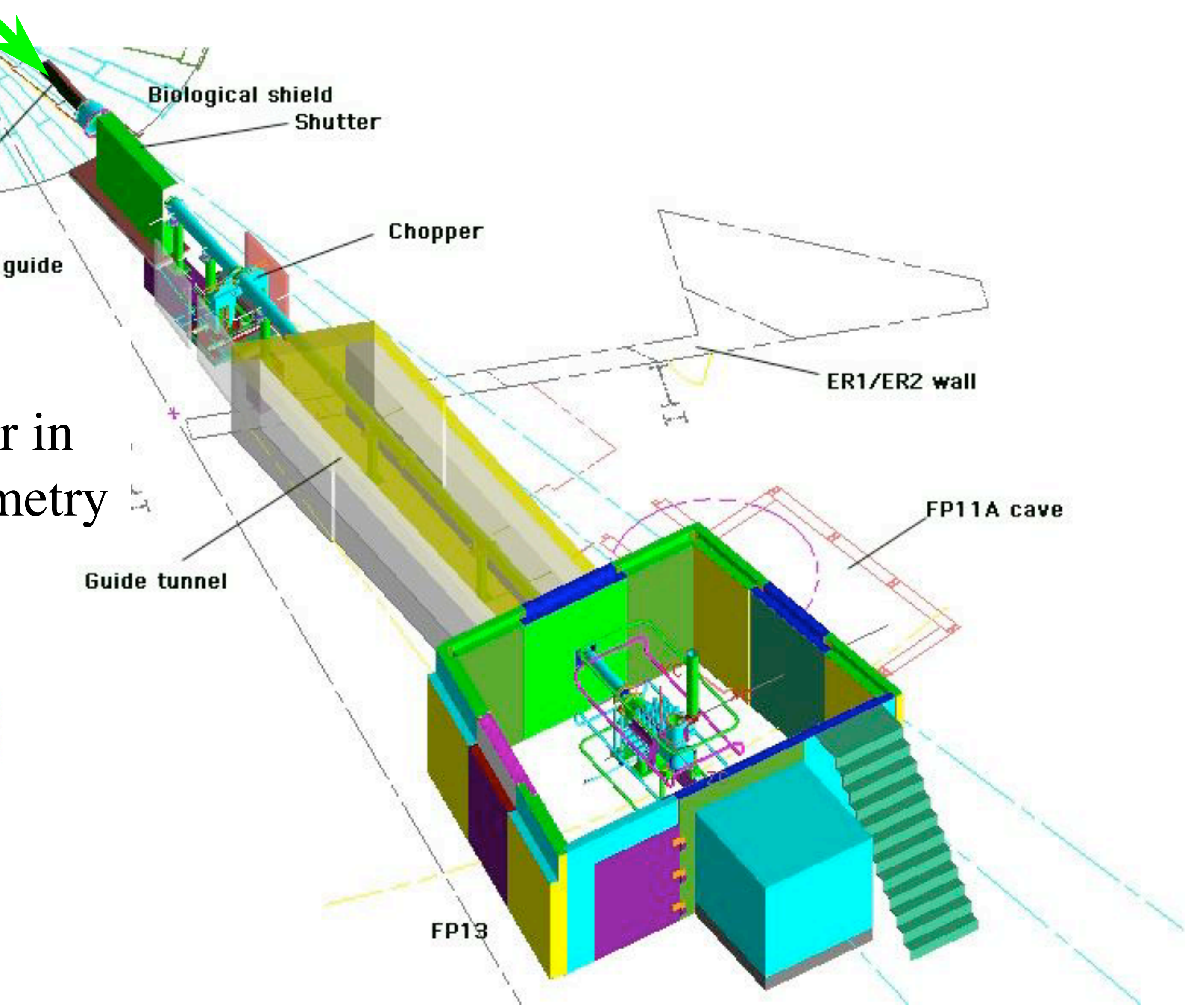


$$\frac{d\omega}{d\Omega} = \frac{1}{4\pi}(1 + A_\gamma \cos(\Theta_{\sigma_n \cdot k_n}))$$

NPDGamma Setup on FP12

20 Hz pulsed neutron beam

FP12 views a cold hydrogen moderator in backscattering geometry



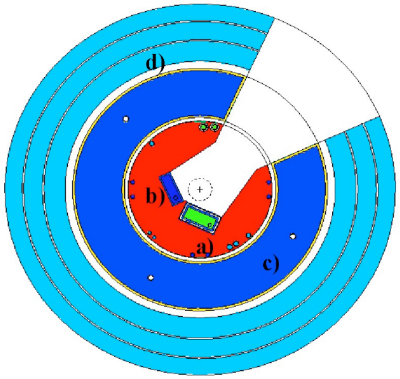
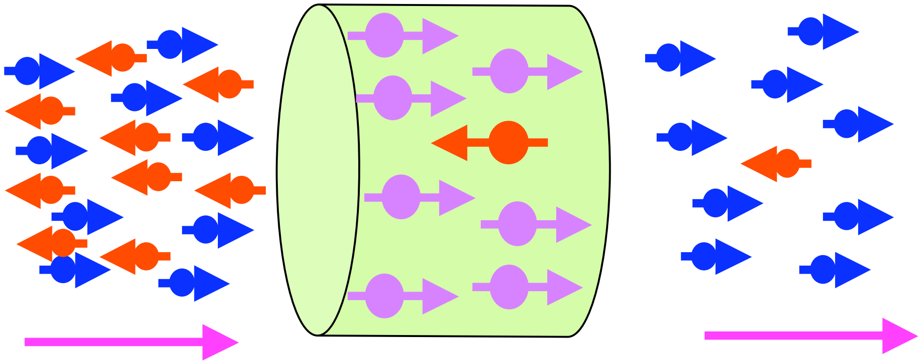


Figure 1. The scheme of the liquid H_2 coupled moderator layout at LANSCE: a) liquid H_2 coupled moderator; b) H_2O partially coupled moderator; c) Be-reflector, d) Pb-reflector

Polarized ^{3}He as Neutron Spin Filter

- strongly spin-dependent neutron absorption cross section.



Unpolarized
Incoming
Neutrons

Polarized
^{3}He

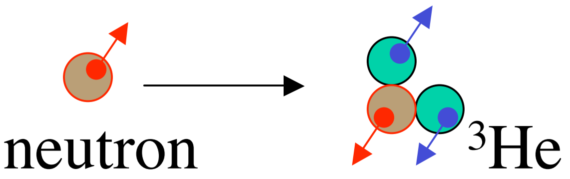
Polarized
Outgoing
Neutrons

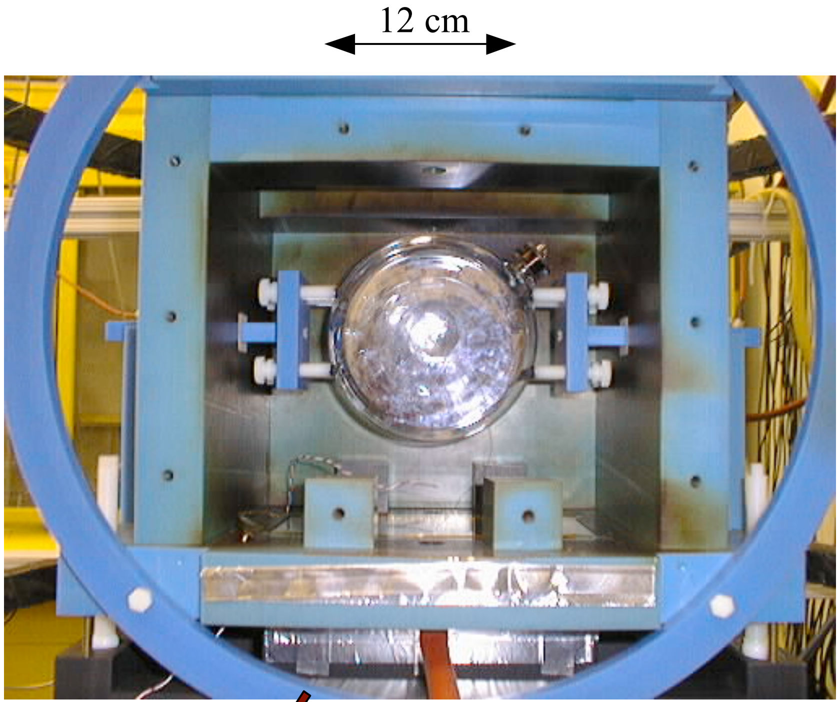
$$P_n = \frac{T^+ - T^-}{T^+ + T^-} = \tanh[\sigma(\lambda) N_{He} L P_{He}]$$

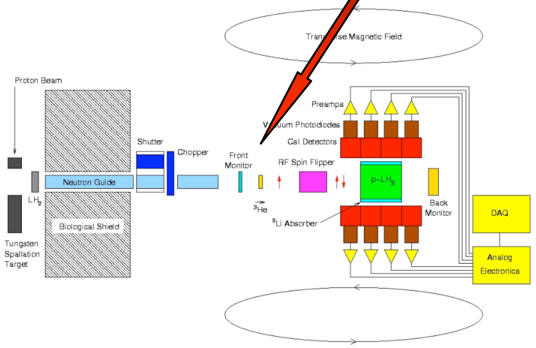
$$T_n = T_E \exp(-\sigma N_{He} L) \cosh(\sigma N_{He} L P_{He})$$

$$= \sqrt{1 - \left(\frac{T_0}{T_n}\right)^2}$$

Neutrons are polarized by Optically-Polarized ^{3}He Spin Filter



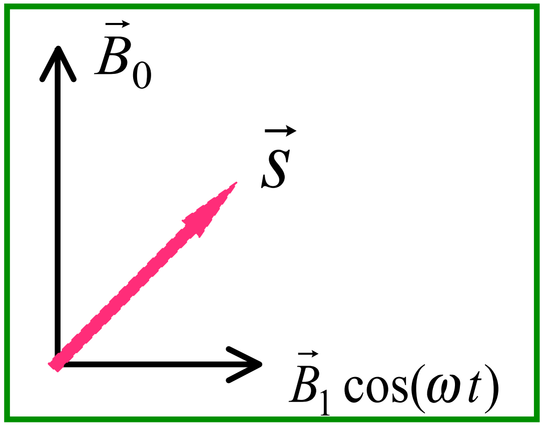




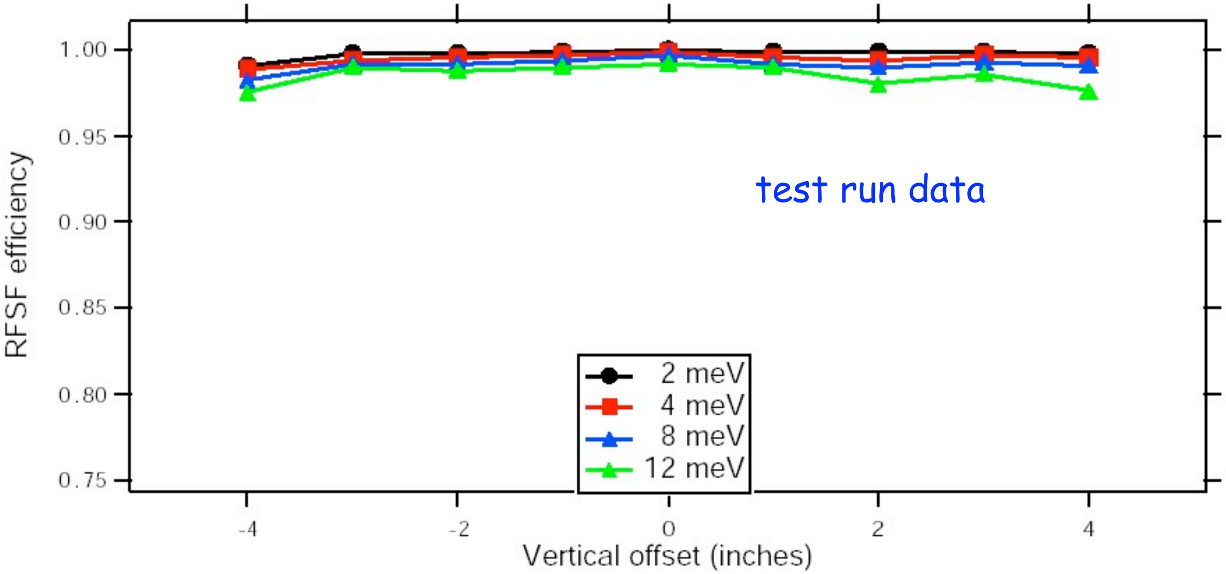
^{3}He neutron spin filter:

- In a ^{3}He cell Rb atoms are polarized by laser light. Through spin exchange, ^{3}He gas is nuclear polarized.
- neutron capture cross section of the ^{3}He singlet state is much larger than the triplet state. (10^4 difference)
- Therefore, neutrons with spin antiparallel with ^{3}He spins are absorbed and neutrons with spin parallel with ^{3}He spins are transmitted → neutron spin filter

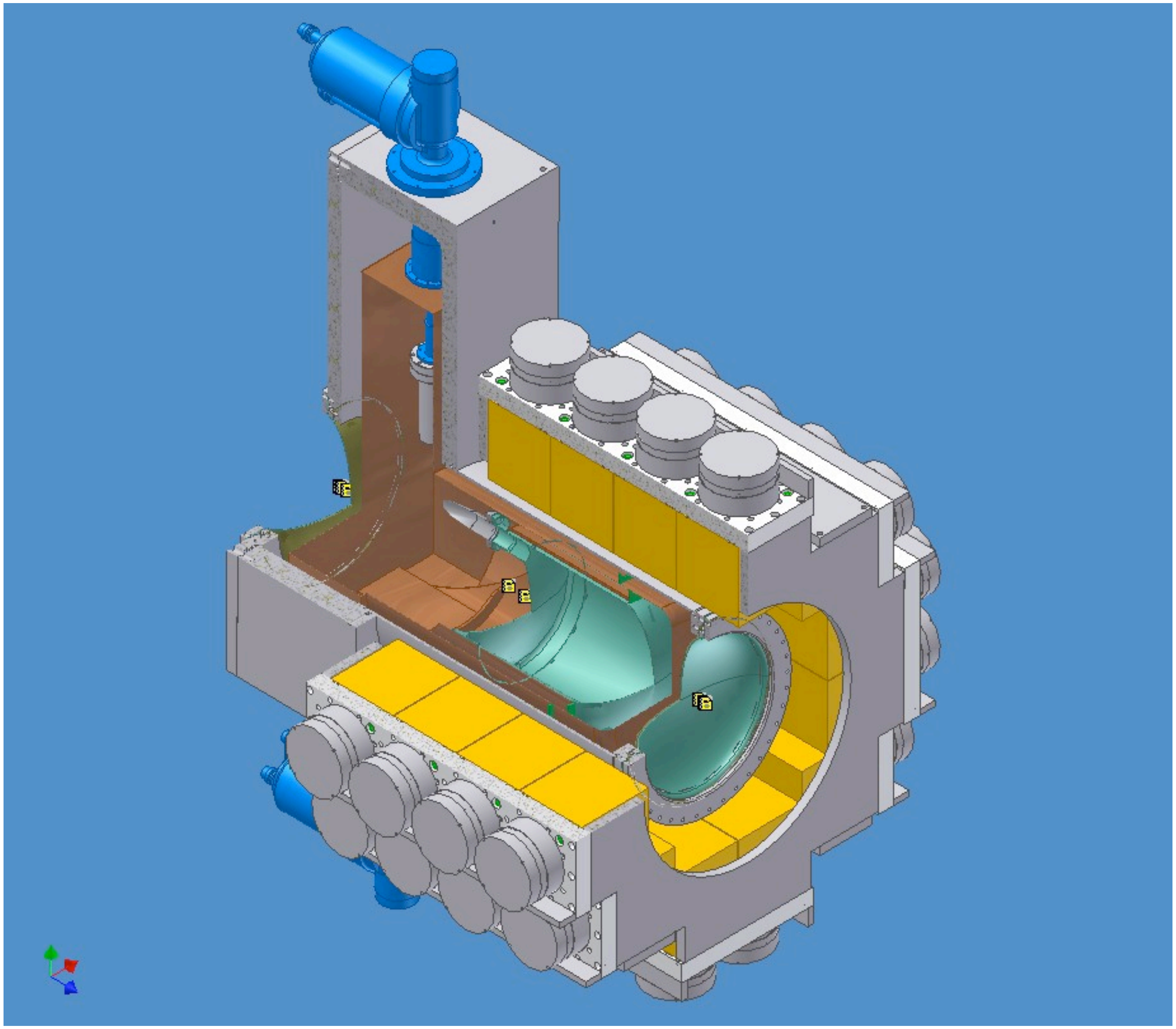
RF Resonance Neutron Spin Flipper



- uniform vertical guide field B_o = 10 G
- oscillating RF solenoidal field B_1
- resonant condition: spins precess around RF field if $\omega = \gamma\ B_o$
- B_o must be uniform and stable to 6 mG across the spin flipper volume
- 1/(tof) RF amplitude flips spin for all energies



LH2 Target and CsI Array

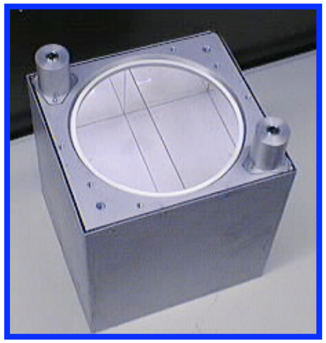


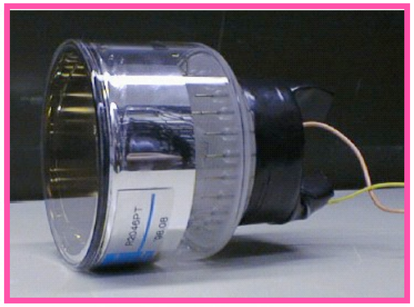
48 element CsI(Tl) detector array, 15x 15x15 cm xtals+ vacuum photodiodes, current mode for 2.2 MeV gammas, move-able w.r.t.beam

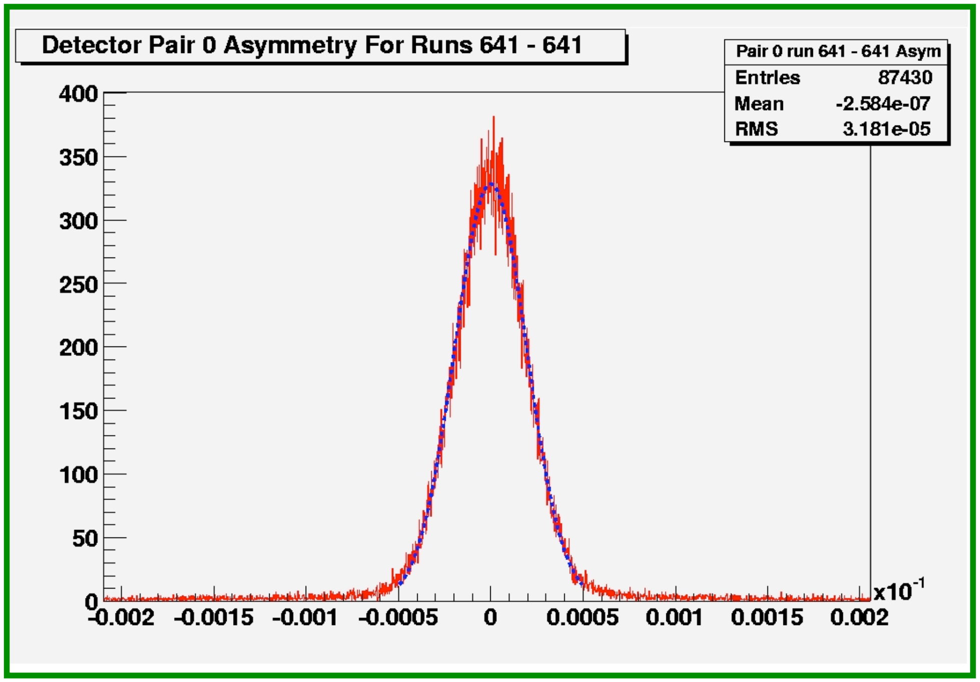
16 liter liquid parahydrogen target, 2 mechanical refrigerators+ ortho/para converter

CsI Detector Array (IU)

- 48, (15 x 15 x 15) cm^3 CsI (Tl) crystals surrounding the LH_2 target
- coupled to 3" vacuum photodiodes (KEK)
- current mode readout via low noise I-V amplifiers



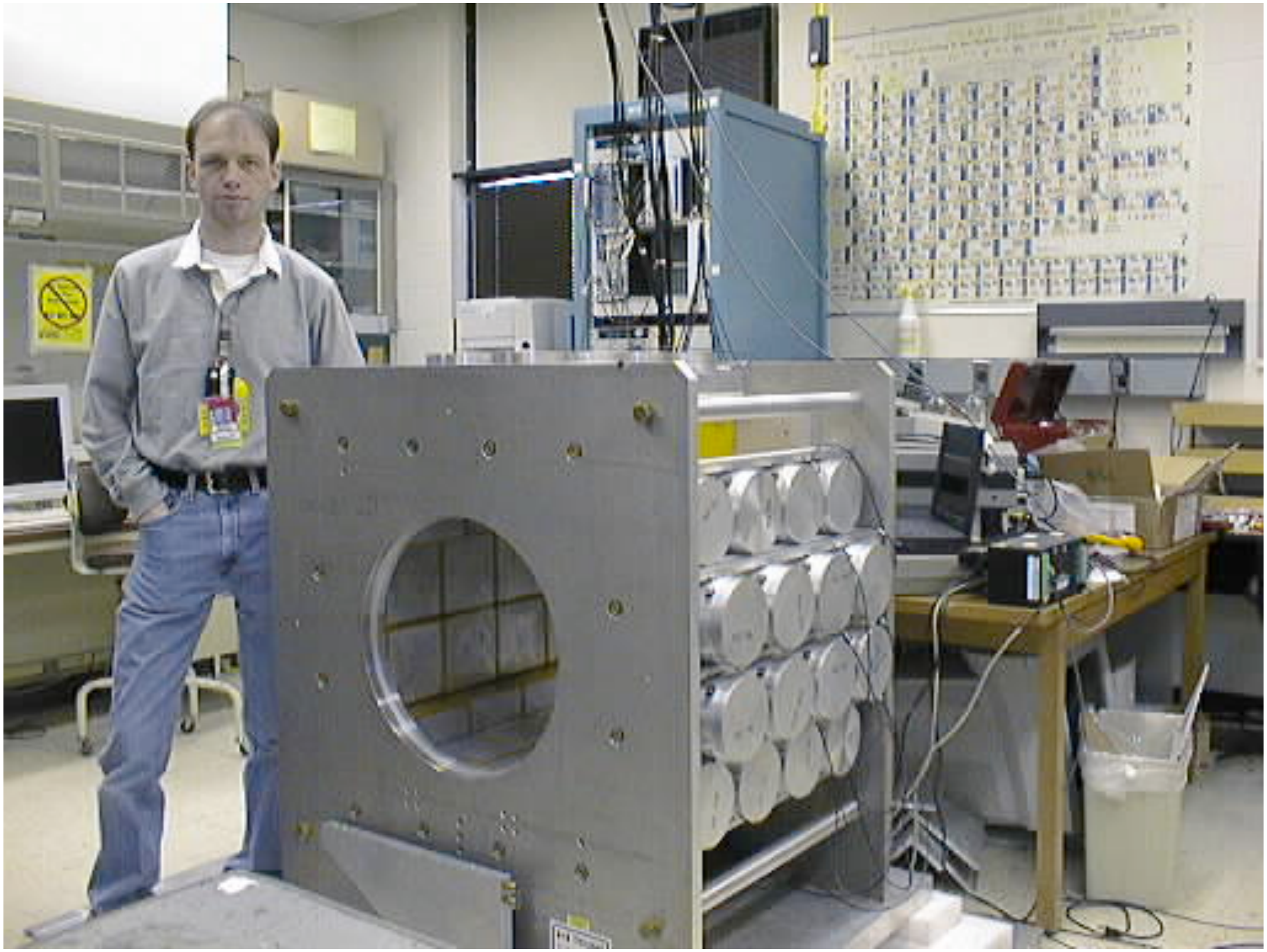




Electronic Asymmetry Test

- RFSF pulsed as in expt.
- zero false asymmetry
- 5×10^{-9} sensitivity in 2 hr
- non-Gaussian tails: cosmic rays!

CsI(Tl) Gamma Detector

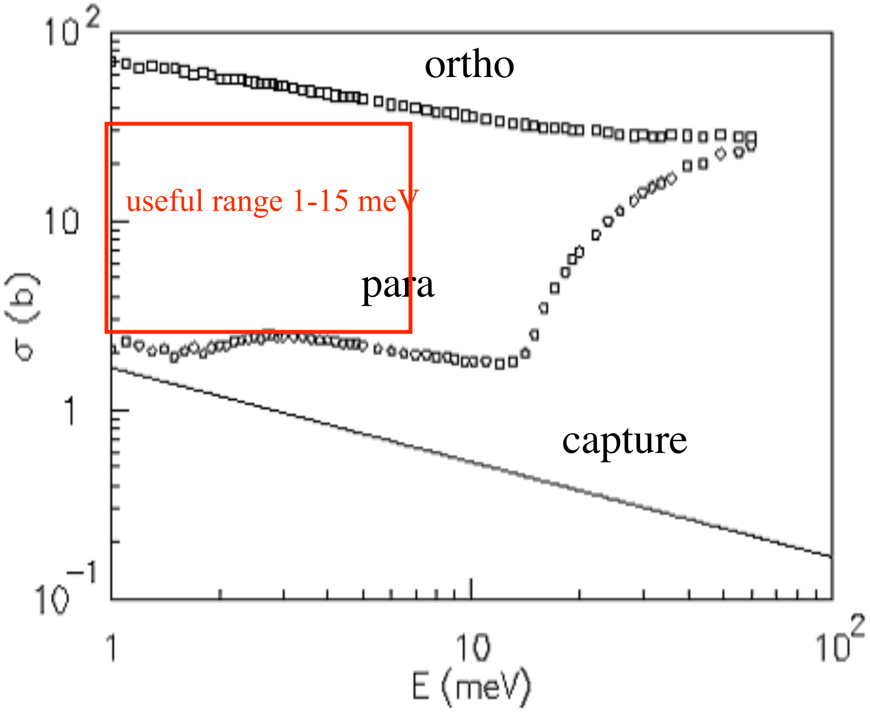


Detector solid angle is ≈ 3π.

Experimental Apparatus w/o LH2

16-liter Liquid Para-Hydrogen Target

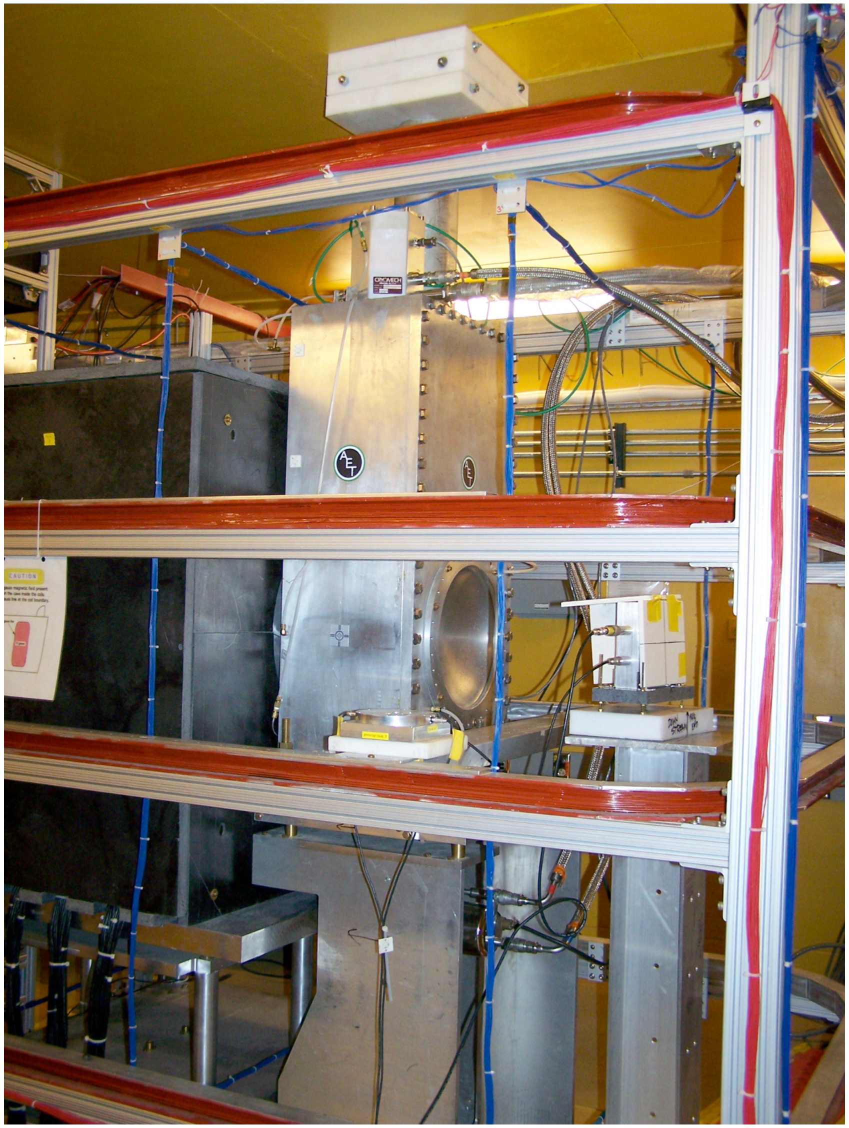
- To maintain neutron spin in scattering a para- hydrogen target is required.
- The 30 cm in diameter and 30 cm long target captures 60% of incident neutrons.
- At 17 K only 0.05% of LH_2 is in ortho state → 1% of incident neutrons will be depolarized.
- Target cryostat materials selected so that false asymmetries $< 10^{-10}$.



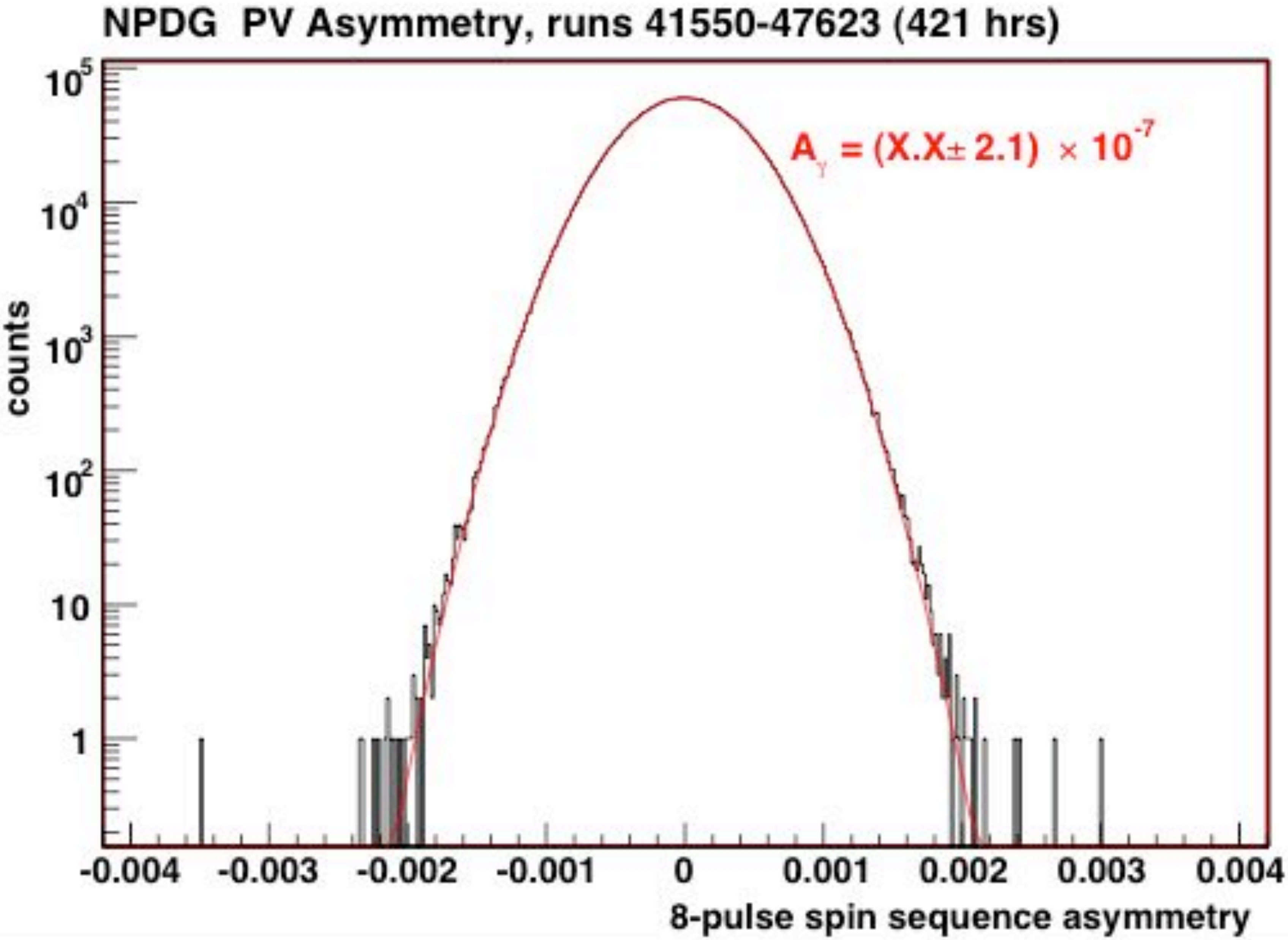
Neutron mean free paths at 4 meV in
- ortho-hydrogen is $\lambda = 2$ cm,
- para-hydrogen is $\lambda = 20$ cm
- for a *n-p* capture is $\lambda = 50$ cm.

NPDGamma Liquid Hydrogen Target

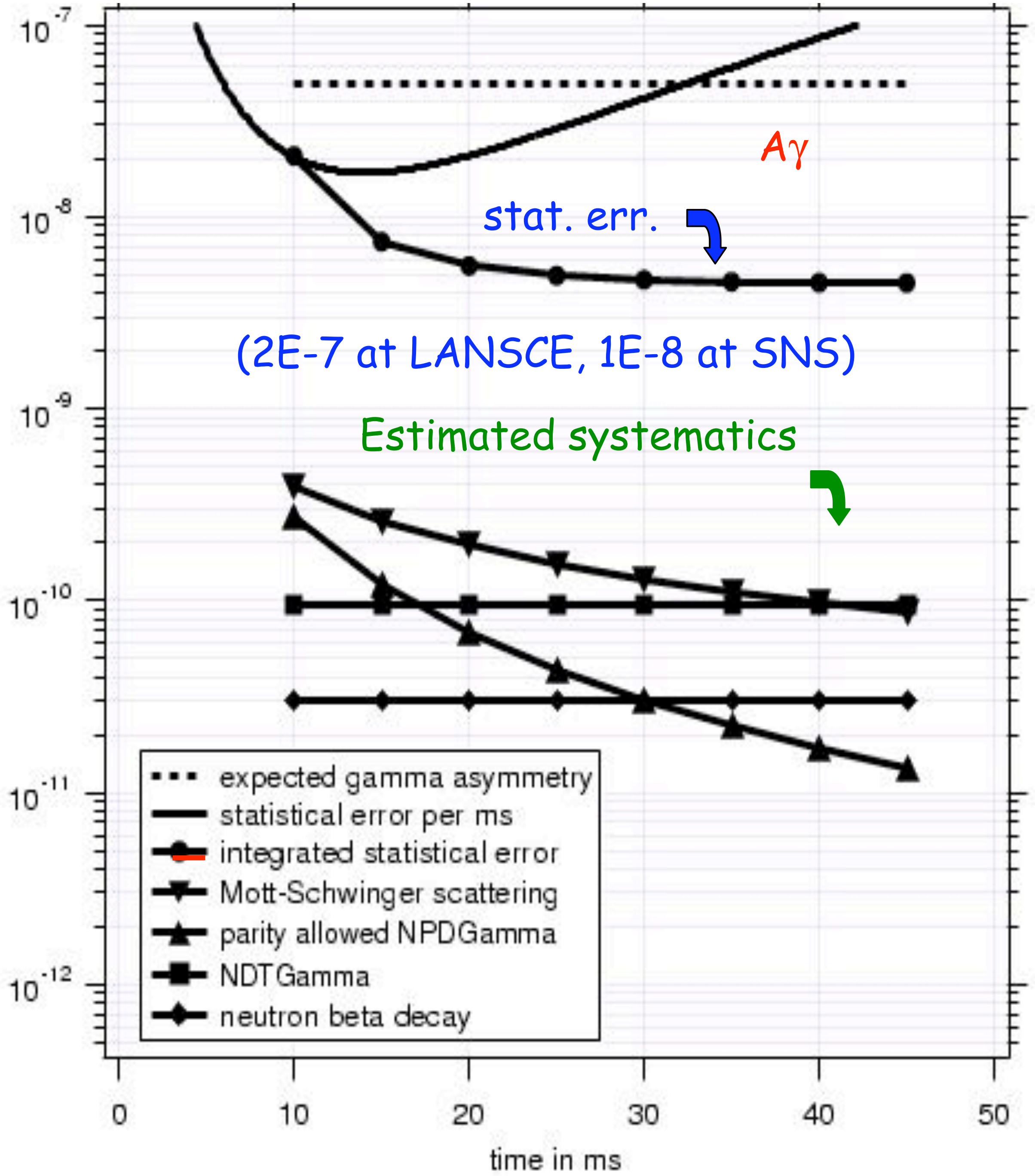
The target is an aluminum vessel containing 16 liters of LH_2 held at ~17 K. At this temperature, the equilibrium fraction of para-hydrogen is 99.97%.



Parity Violating Asymmetry in n+p at LANSCE



Statistical and Systematic Errors



Aγ

stat. err.

(2E-7 at LANSCE, 1E-8 at SNS)

Estimated systematics

Neutron time-of-flight from pulsed source (msec, $E_n \propto 1/t^2$)

How can (many) systematic effects be so small?

(1) Neutron is easy to polarize, flip spin

(2) No electric charge -> no change of beam on spin flip

(3) meV energy -> strong interaction spin asymmetries small

Possible Targets for Gamma Capture

H (in form of liquid parahydrogen)

First approved experiment for SNS

Dominated by f_pi in DDH picture

Target requires serious LH2 safety infrastructure

D (in form of D2O ice or perhaps liquid/solid orthodeuterium)

Letter of intent for SNS as potential follow-on to n-p

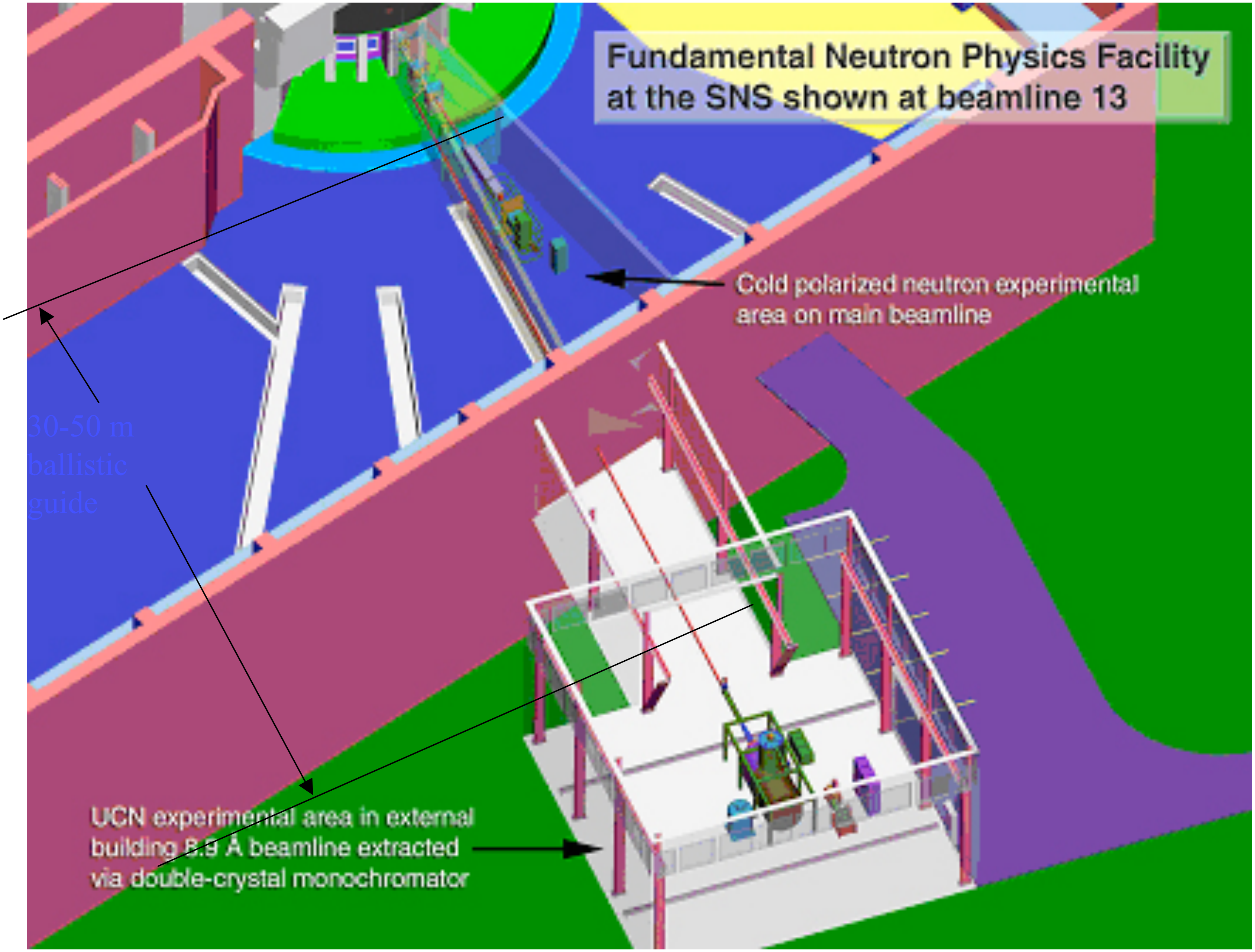
Very small (~mb) absorption cross section>background/depolarization issues, depolarization in target needs to be measured

The Spallation Neutron Source at ORNL

SNS Site Overlay

- $1.4B--1GeV protons at 2MW, ready now.
- Short (~1 usec) proton pulse– mainly for high TOF resolution
- Will be brightest spallation neutron source with JSNS@JPARC

SNS Fundamental Neutron Physics Beam



Fundamental Neutron Physics Facility at the SNS shown at beamline 13

Cold polarized neutron experimental area on main beamline

30-50 m ballistic guide

UCN experimental area in external building 8.9 Å beamline extracted via double-crystal monochromator

Conclusion?

EFT coupling (partial wave mixing)	np A_γ	np P_γ	nD A_γ	nα ϕ	np ϕ	pp A_z	pα A_z
$m\rho_t\,({}^3S_1\text{-}\,{}^3P_1)$	-0.09	0	1.4	-2.7	1.4	0	-1.07
$m\lambda_t\,({}^3S_1\text{-}\,{}^1P_1)$	0	0.7	1.2	1.3	-0.6	0	-0.54
$m\lambda_s^{nn}\,({}^1S_0\text{-}\,{}^3P_0)$	0	0	0.6	1.2	0	0	-0.48
$m\lambda_s^{np}\,({}^1S_0\text{-}\,{}^3P_0)$	0	-0.16	0.5	0.6	2.5	0	-0.24
$m\lambda_s^{pp}\,({}^1S_0\text{-}\,{}^3P_0)$	0	0	0	0	0	-0.45, -0.78	0
$C^\pi\,({}^3S_1\text{-}\,{}^3P_1)[\sim f_\pi]$	-0.3	0	0	0	0.3	0	0
experiment (10^{-7})	0.6 ±2.1	1.8 ±1.8	42 ±38	8 ±14		-0.93, -1.57 ±0.2	-3.3 ±0.9

Theorists: EFT calculations of PV in few body systems (NN done, others in progress)
Experimentalists: put some more accurate numbers on the board.