The NPDGamma Experiment

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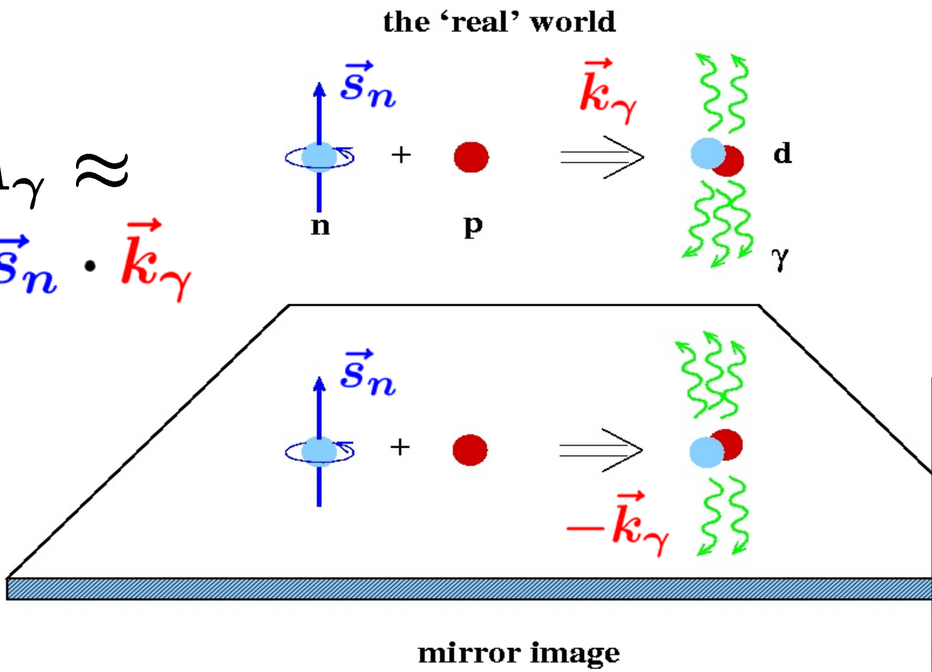
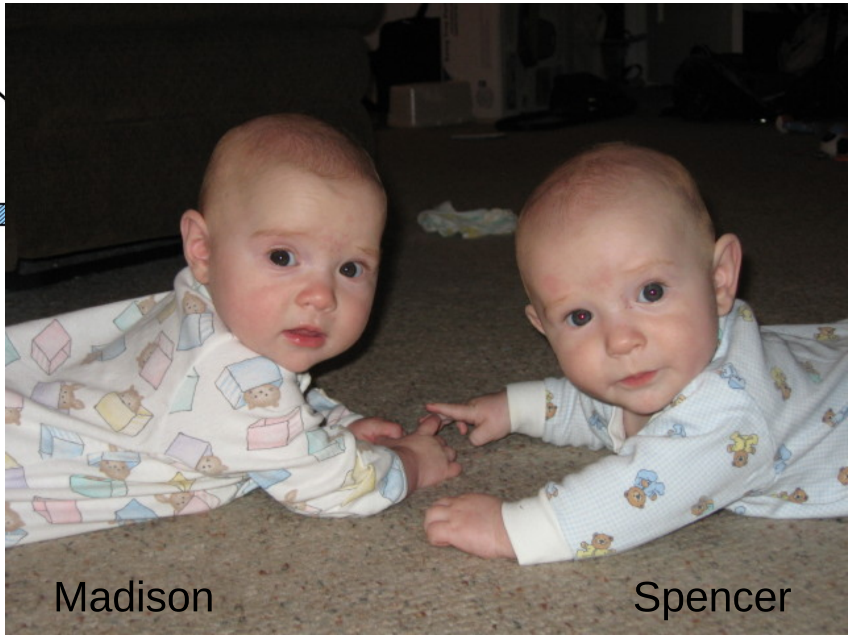
2007-05-30

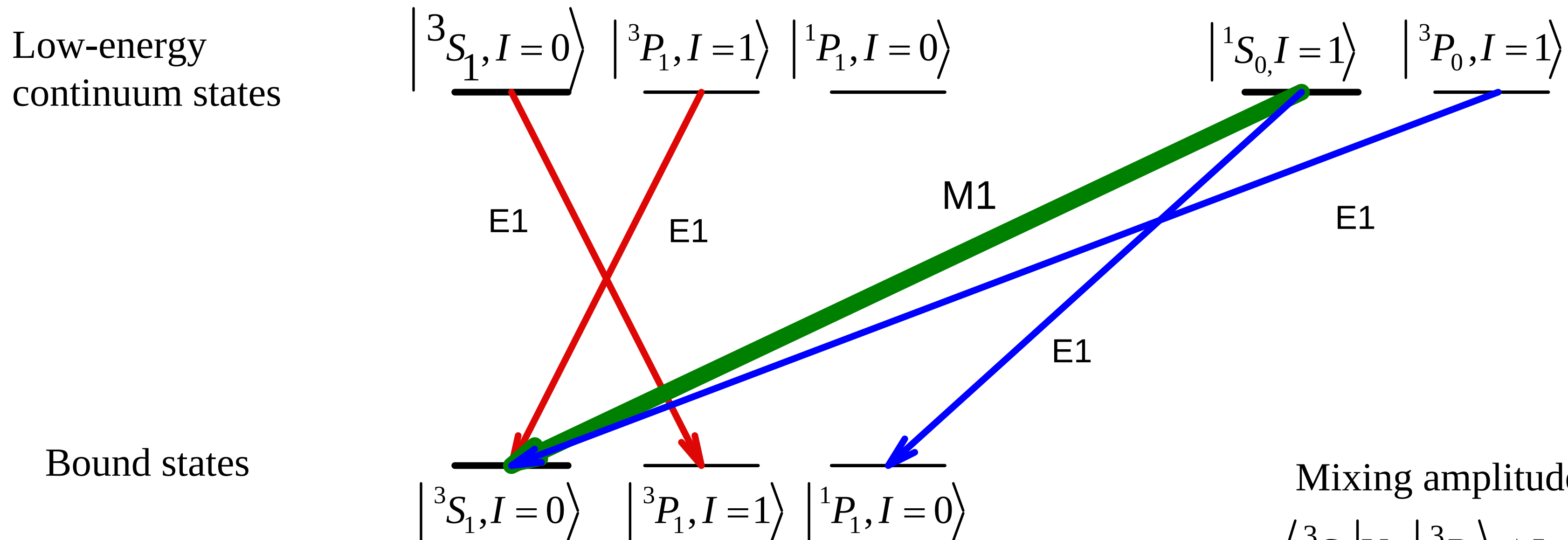
$A_\gamma \approx \vec{s}_n \cdot \vec{k}_\gamma$



- hadronic PV formalism
- experimental setup
- LANSCE) SNS



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



Mixing amplitudes:

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

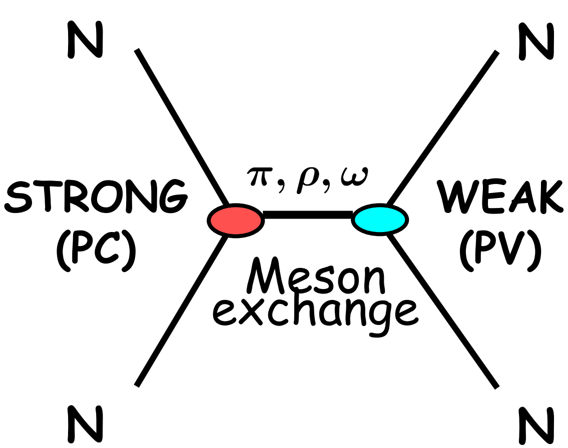
$\left\langle {}^3S_1 \middle| V_W \middle| {}^1P_1 \right\rangle; \Delta I = 0$

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

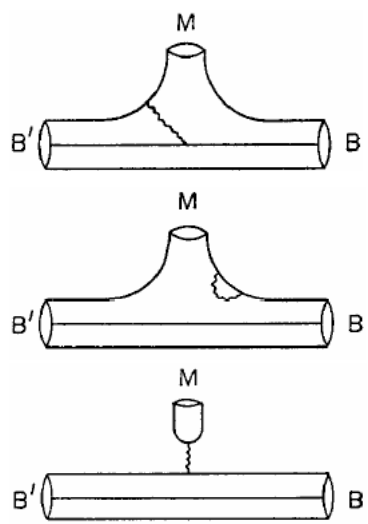
- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is *M*1.
- Parity violation arises from mixing in *P* states and interference of the *E*1 transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference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

Meson exchange model

- DDH formalism:
  - 6+1 meson-nucleon coupling constants
  - pion channel dominated by neutral current (Z^0)
  - PV effects: interference between strong and weak vertex



$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$



Cabibbo model	Reasonable range	"Best" value
f_π	$0 \to 1$	0.5
h_ρ^0	$15 \to -64$	-25
h_ρ^1	$0 \to -0.7$	-0.4
h_ρ^2	-58	-58
h_ω^0	$6 \to -22$	-6
h_ω^1	$0 \to -2$	-1

Amplitudes are in units of $g_\pi = 3.8 \times 10^{-8}$.

Desplanques, Donoghue, Holstein, Ann. Phys. **124** 449 (1980)

EFT approach

$$V^{\mathrm{PV}}_{\mathrm{EFT}}(\boldsymbol{r}) = V^{\mathrm{PV}}_{-1,\mathrm{LR}}(\boldsymbol{r}) + V^{\mathrm{PV}}_{1,\mathrm{MR}}(\boldsymbol{r}) + V^{\mathrm{PV}}_{1,\mathrm{SR}}(\boldsymbol{r})$$

$$V^{\mathrm{PV}}_{-1,\mathrm{LR}}(\boldsymbol{r}) = \frac{2}{\Lambda_\chi^3}\, \widetilde{C}_6^{\pi}\, \tau_\times^z\, \boldsymbol{\sigma}_+ \cdot \boldsymbol{y}_{\pi-}(\boldsymbol{r})$$

$\sim h_\pi^1$

($V^{\mathrm{PV}}_{1,\mathrm{LR}}(\boldsymbol{r})$ redundant)

$$V^{\mathrm{PV}}_{1,\mathrm{MR}}(\boldsymbol{r}) = \frac{2}{\Lambda_\chi^3} \left\{ \widetilde{C}_2^{2\pi}\, \tau_+^z\, \boldsymbol{\sigma}_\times \cdot \boldsymbol{y}^L_{2\pi}(\boldsymbol{r}) + \widetilde{C}_6^{2\pi}\, \tau_\times^z\, \boldsymbol{\sigma}_+ \cdot \left[\left(1 - 1/(3\, g_A^2)\right)\, \boldsymbol{y}^L_{2\pi}(\boldsymbol{r}) - 1/3\, \boldsymbol{y}^H_{2\pi}(\boldsymbol{r}) \right] \right\}$$

$\sim h_\pi^1$ $\quad$ $\sim h_\pi^1$

$$V^{\mathrm{PV}}_{\not\pi}(\boldsymbol{r}) = V^{\mathrm{PV}}_{1,\mathrm{SR}}(\boldsymbol{r}) = \frac{2}{\Lambda_\chi^3} \left\{ \left[C_1 + (C_2 + C_4)\, \tau_+^z + C_3\, \tau. + C_5\, \tau^{zz} \right] \boldsymbol{\sigma}_- \cdot \boldsymbol{y}_{m+}(\boldsymbol{r}) \right.$$

$\sim h_\omega^0$ $\quad h_\omega^1$ $\quad h_\rho^1$ $\quad h_\rho^0$ $\quad h_\rho^2$

$$+ \left[\widetilde{C}_1 + (\widetilde{C}_2 + \widetilde{C}_4)\, \tau_+^z + \widetilde{C}_3\, \tau. + \widetilde{C}_5\, \tau^{zz} \right] \boldsymbol{\sigma}_\times \cdot \boldsymbol{y}_{m-}(\boldsymbol{r})$$

$$\left. + (C_2 - C_4)\, \tau_-^z\, \boldsymbol{\sigma}_+ \cdot \boldsymbol{y}_{m+}(\boldsymbol{r}) + \widetilde{C}_6\, \tau_\times^z\, \boldsymbol{\sigma}_+ \cdot \boldsymbol{y}_{m-}(\boldsymbol{r}) \right\},$$

$\sim h_\rho^{1\prime}$ $\sim h_\pi^1$

Zhu, Maekawa, Holstein, Ramsey-Musolf, van Kolck, Nucl. Phys. **A748**, 435 (2005)

Liu, nucl-th/0609078

Danilov Parameters

PV NN-interaction

$$\Delta L = 1 \qquad \Delta J = 0 \qquad \Delta(S+I) = 1$$

Zero range limit:

$$\begin{array}{rcl}
\lambda_t & \propto & (C_1 - 3C_3) - (\tilde{C}_1 - 3\tilde{C}_3) \\
\lambda_s^0 & \propto & (C_1 + C_3) + (\tilde{C}_1 + \tilde{C}_3) \\
\lambda_s^1 & \propto & (C_2 + C_4) + (\tilde{C}_2 + \tilde{C}_4) \\
\lambda_s^2 & \propto & -\sqrt{8/3}(C_5 + \tilde{C}_5) \\
\rho_t & \propto & \frac{1}{2}(C_2 - C_4) + C_6 \quad .
\end{array}$$

$$^3S_1 \longrightarrow ^1P_1, \quad I = 0$$

$$^1S_0 \longrightarrow ^3P_0, \quad I = 1$$

$$^3S_1 \longrightarrow ^3P_1, \quad I = 1 \rightarrow 0$$

☐Ramsey-Musolf, Page, Ann. Rev. Nucl. Part. Sci. **56**:1-52,2006

Why study hadronic PV?

- probe of atomic, nuclear, and hadronic systems
  - map out coupling constants
  - resolve ^{18}F, ^{133}Cs discrepancy
  - probe nuclear structure effects
  - anapole and qq contributions to PV electron scattering

- probe of QCD in low energy non-perturbative regime
  - confinement, many-body problem
  - sensitive to qq correlations
  - measure QCD modification of qqZ coupling

	np A_γ	nD A_γ	np ϕ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	0.92	-3.12	-0.97		-0.34
h_ρ^0		-0. 50	-0. 23	-0.32	0.08	0.14
h_ρ^1	-0.001	0.10		0.11	0.08	0.05
h_ρ^2		0.05	-0.25		0.03	
h_ω^0		-0. 16	-0. 23	-0.22	0.07	0.06
h_ω^1	-0.003	-0.002		0.22	0.07	0.06

n-capture spin rotation elastic scattering

$$n + p \rightarrow d + \gamma$$

$$A_\gamma = -0.11\ f_\pi + -0.001\ h_\rho^1 + -0.003\ h_\omega^1$$

Bowman

Why study hadronic PV?

Observable	$m_N\rho_t$	$m_n\lambda_t$	$m_N\lambda_s^0$	$m_N\lambda_s^1$	$m_N\lambda_s^2/\sqrt{6}$	Expt. (10^{-7})	Ref.
$A_z^{pp}(k)$	0	0	$4k/m_N$	$4k/m_N$	$4k/m_N$	-0.93 ± 0.21 -1.50 ± 0.22	(52) (53)
$A_z^{p\alpha}$	-1.07	-0.54	-0.72	-0.48	0	-3.3 ± 0.9	(96)
P_γ	0	0.63	-0.16	0	0.32	1.8 ± 1.8	(63)
A_γ^d	-0.107	0	0	0	0	0.6 ± 2.1	(65)
$d\phi^{n\alpha}/dz$	-2.68	1.34	1.8	-1.2	0	8 ± 14	(76)
A_γ^t	-3.56	-1.39	-0.95	-0.24	1.18	42 ± 38	(97)

☐Ramsey-Musolf, Page, Ann. Rev. Nucl. Part. Sci. **56**:1-52,2006

$$A_L^{\vec{p}p}(13.6\,\mathrm{MeV}) \approx -0.45\, m_N \lambda_s^{pp}\,,$$

$$A_L^{\vec{p}p}(45\,\mathrm{MeV}) \approx -0.78\, m_N \lambda_s^{pp}\,,$$

$$\frac{d}{d\,z}\,\phi_n^{\vec{n}p}(\mathrm{th.})|_{\mathrm{rad/m}} \approx 0.30\,\widetilde{C}_6^\pi + 2.50\, m_N \lambda_s^{np} - 0.57\, m_N \lambda_t + 1.41\, m_N \rho_t\,,$$

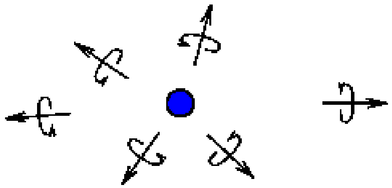
$$P_\gamma^{np}(\mathrm{th.}) \approx -0.16\, m_N \lambda_s^{np} + 0.67\, m_N \lambda_t \approx A_L^{\vec{\gamma}d}(1.32\,\mathrm{keV}+)\,,$$

$$A_\gamma^{\vec{n}p}(\mathrm{th.}) \approx -0.27\,\widetilde{C}_6^\pi - 0.093\, m_N \rho_t\,.$$

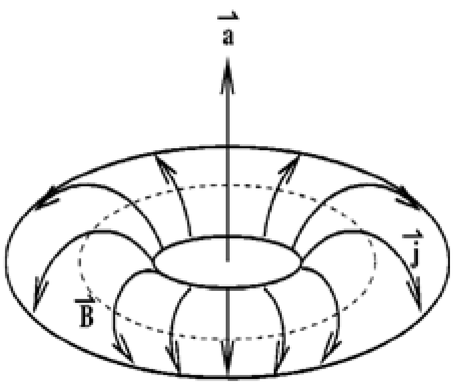
Liu, nucl-th/0609078

Existing measurements

Light nuclei gamma transitions
(circular polarized gammas)

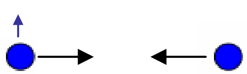


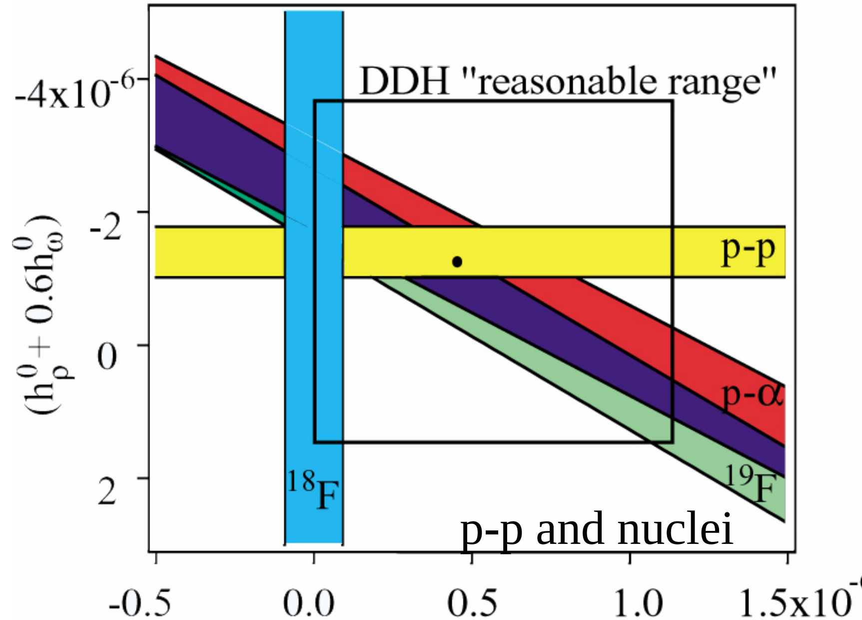
Nuclear anapole moment
(from laser spectroscopy)

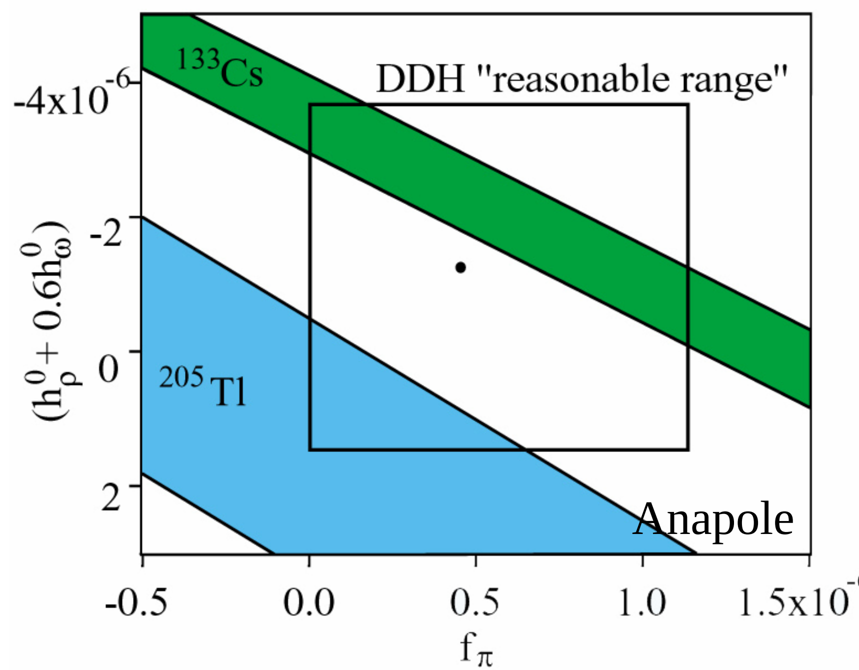


$$\vec{a} = -\int d^3r \; r^2 \vec{j}(r)$$

Polarized proton scattering asymmetries

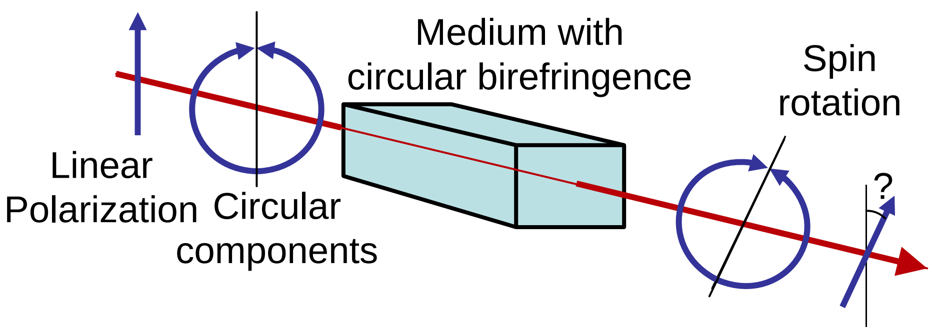


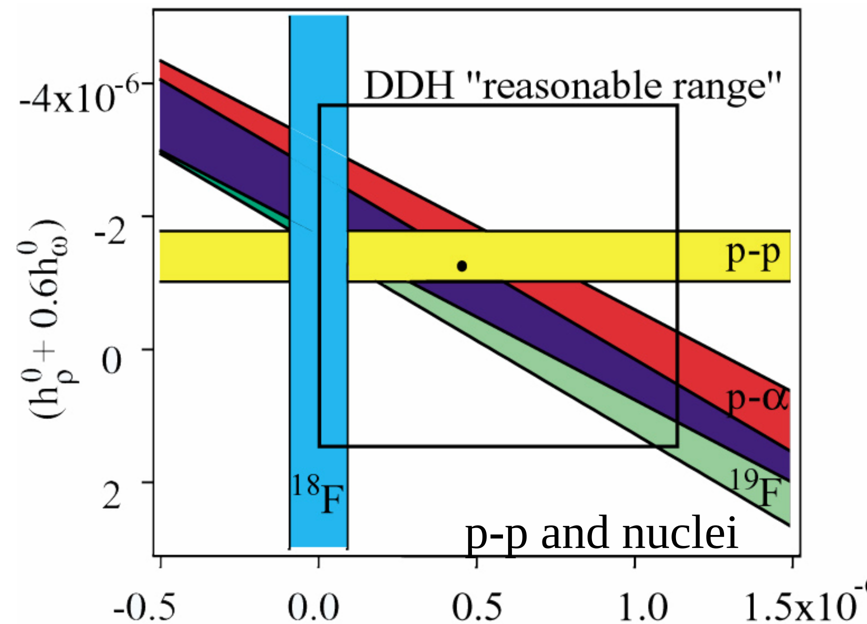


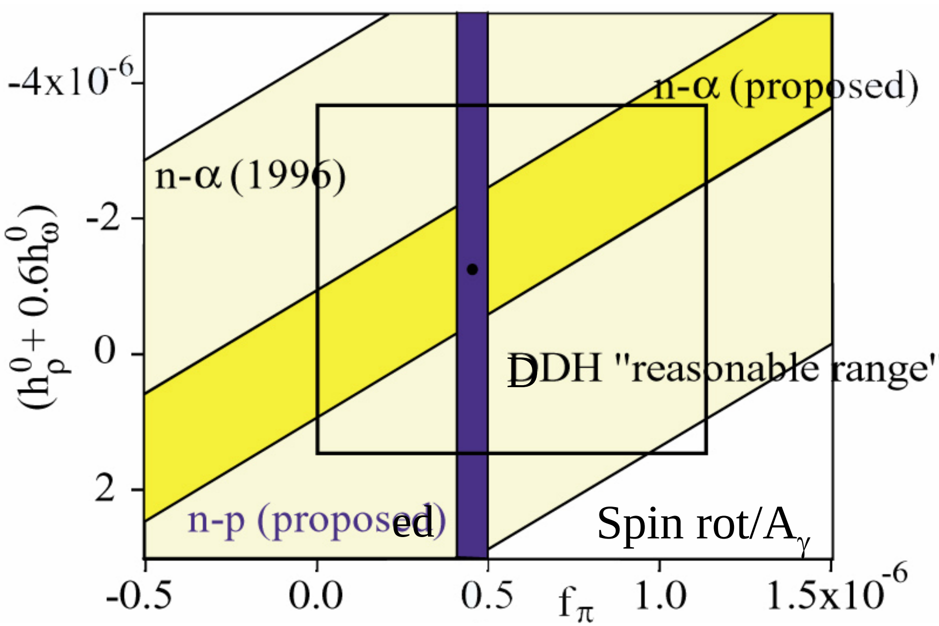


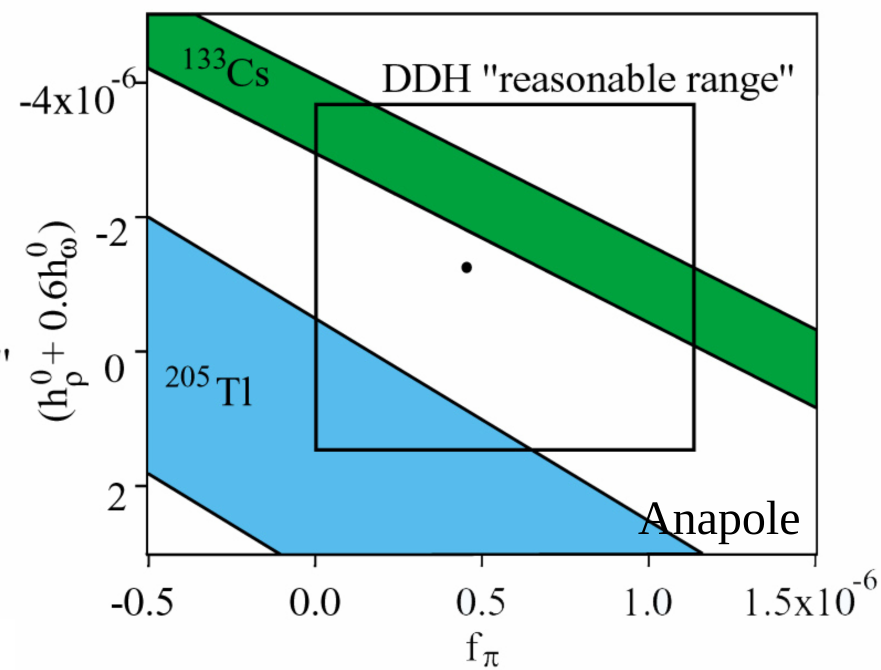
Existing measurements

Neutron spin rotation









Measurement of the Parity - Violating Gamma Asymmetry A_γ in the Capture of Polarized Cold Neutrons by Para-Hydrogen

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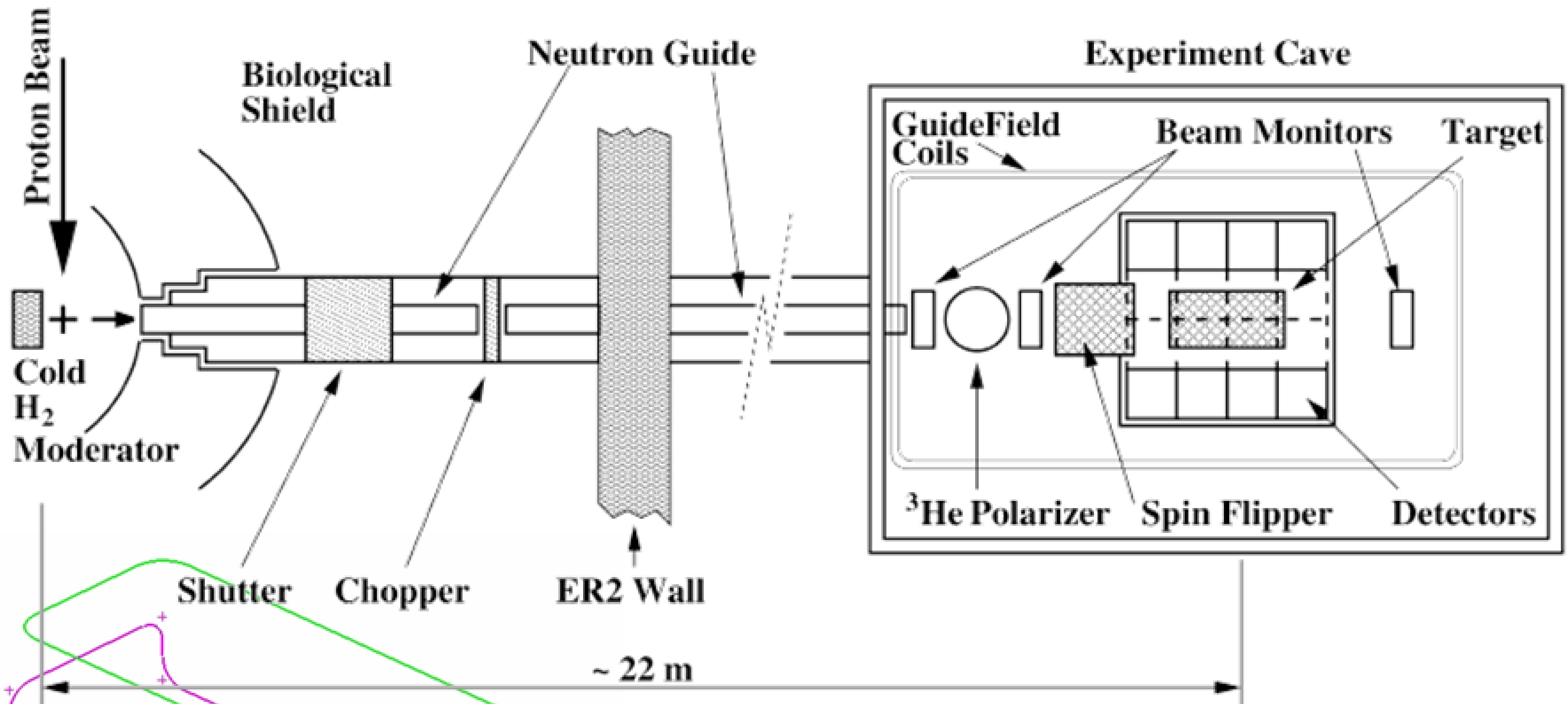
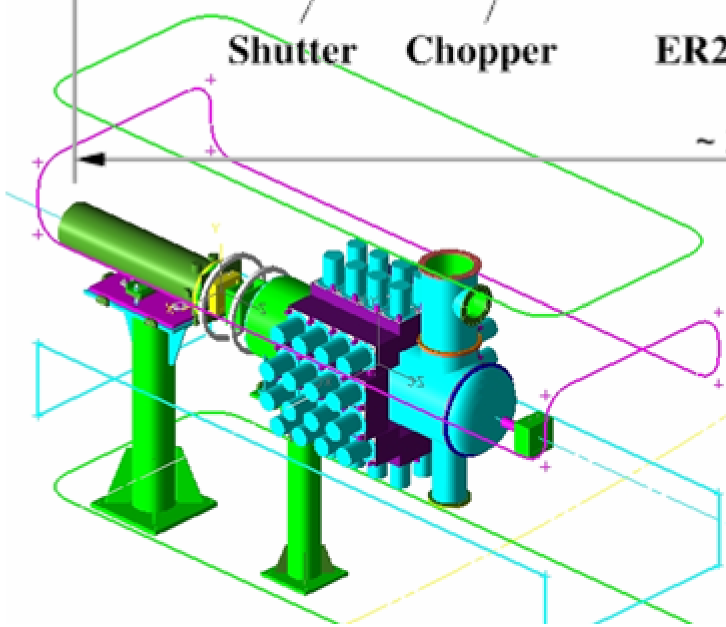
Overview of NPDG experiment





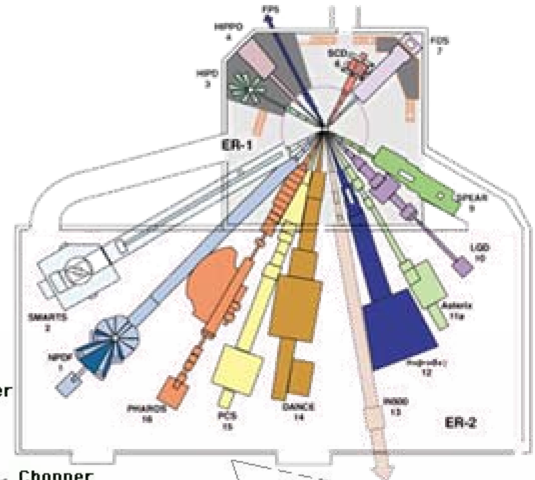
A_γ = -0.11 f_π ¼ 5 £ 10^{-8}

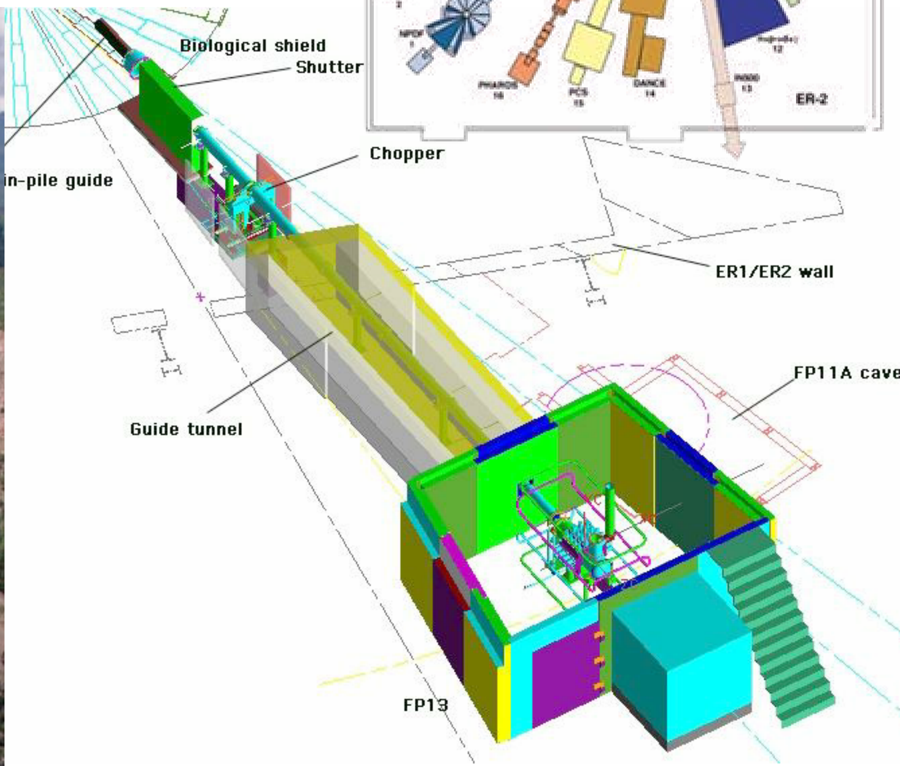
$d\sigma$ / 1 + P_n A_γ cos θ + P_n A_{PC} sin θ

δA = 1 £ 10^{-8} for N ¼ 3 £ 10^{16} events

Overview of NPDG experiment

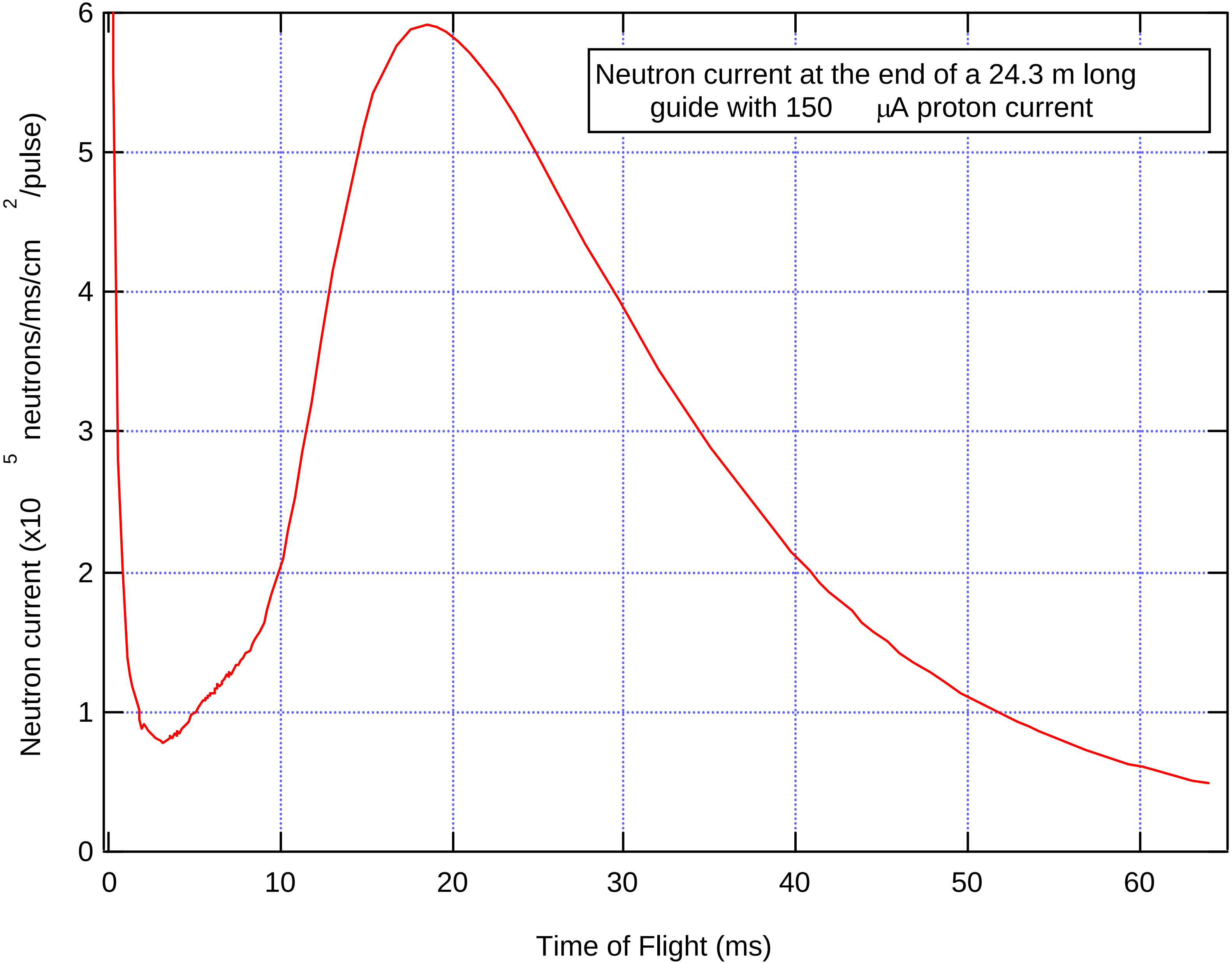
Pulsed neutron beam



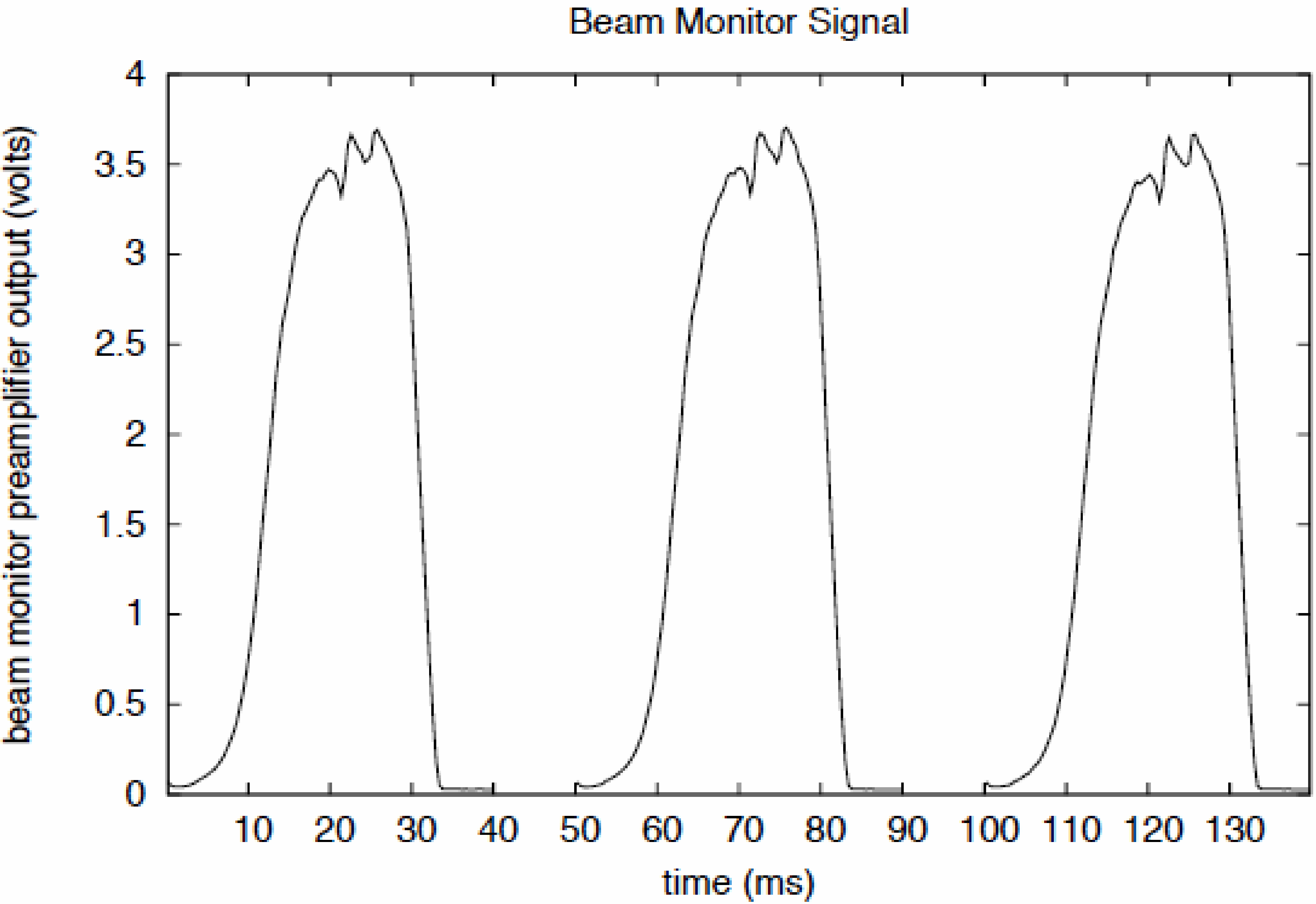


~6x10^{8} cold neutrons per 20 Hz pulse at the end of the 20 m supermirror guide (largest pulsed neutron flux)

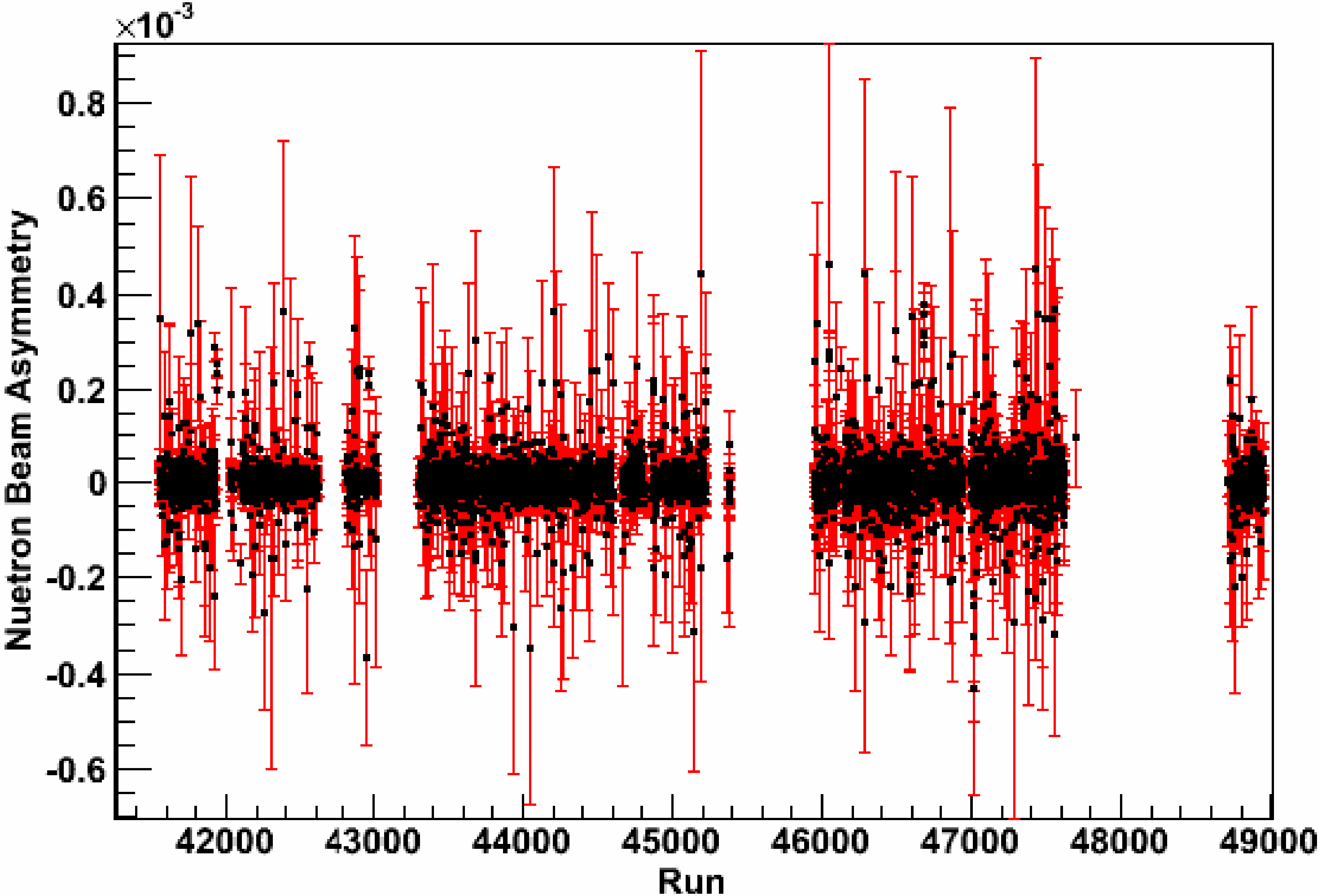
Time-of-flight beam profile



Time-of-flight beam profile

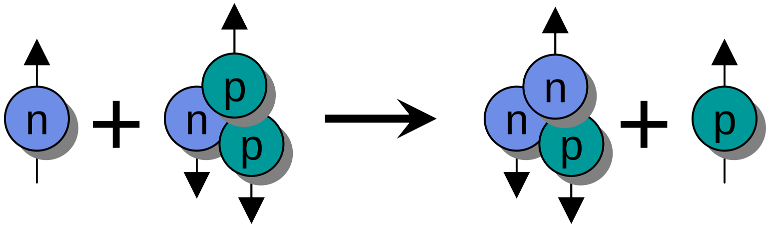


Beam stability



^{3}He neutron polarizer

- $n + {}^3He \rightarrow {}^3H + p$ cross section is highly spin-dependent



$\sigma_{J=0}$ = 5333 b λ/λ_0

$\sigma_{J=1}$ ¼ 0

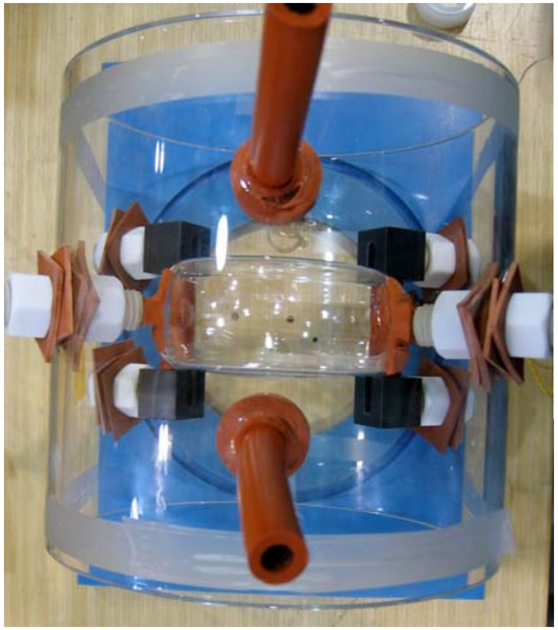
- 10 G holding field determines the polarization angle

  rG < 1 mG/cm to avoid Stern-Gerlach steering

P_3 = 57 %

Steps to polarize neutrons:

1. Optically pump Rb vapor with circular polarized laser
2. Polarize ^{3}He atoms via spin-exchange collisions
3. Polarize ^{3}He nuclei via the hyperfine interaction
4. Polarize neutrons by spin-dependent transmission



Neutron Beam Monitors

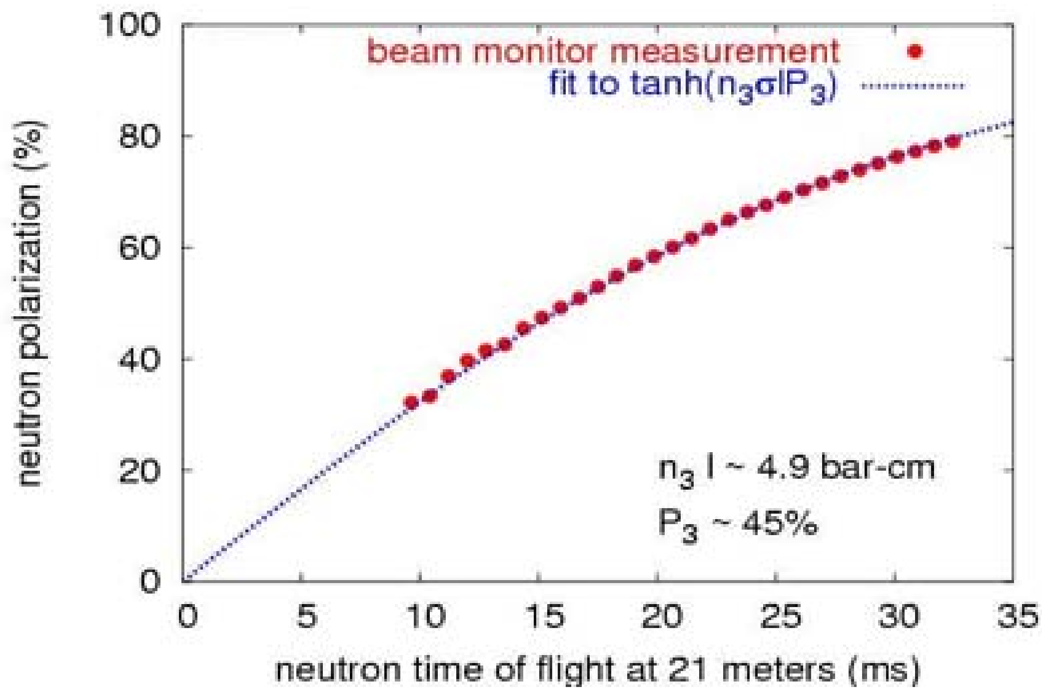
- ^{3}He ion chambers
- measure transmission through ^{3}He polarizer

$$T_\pm = e^{-nl\sigma(1\mp P_3)} \qquad T_0 = e^{-nl\sigma}$$

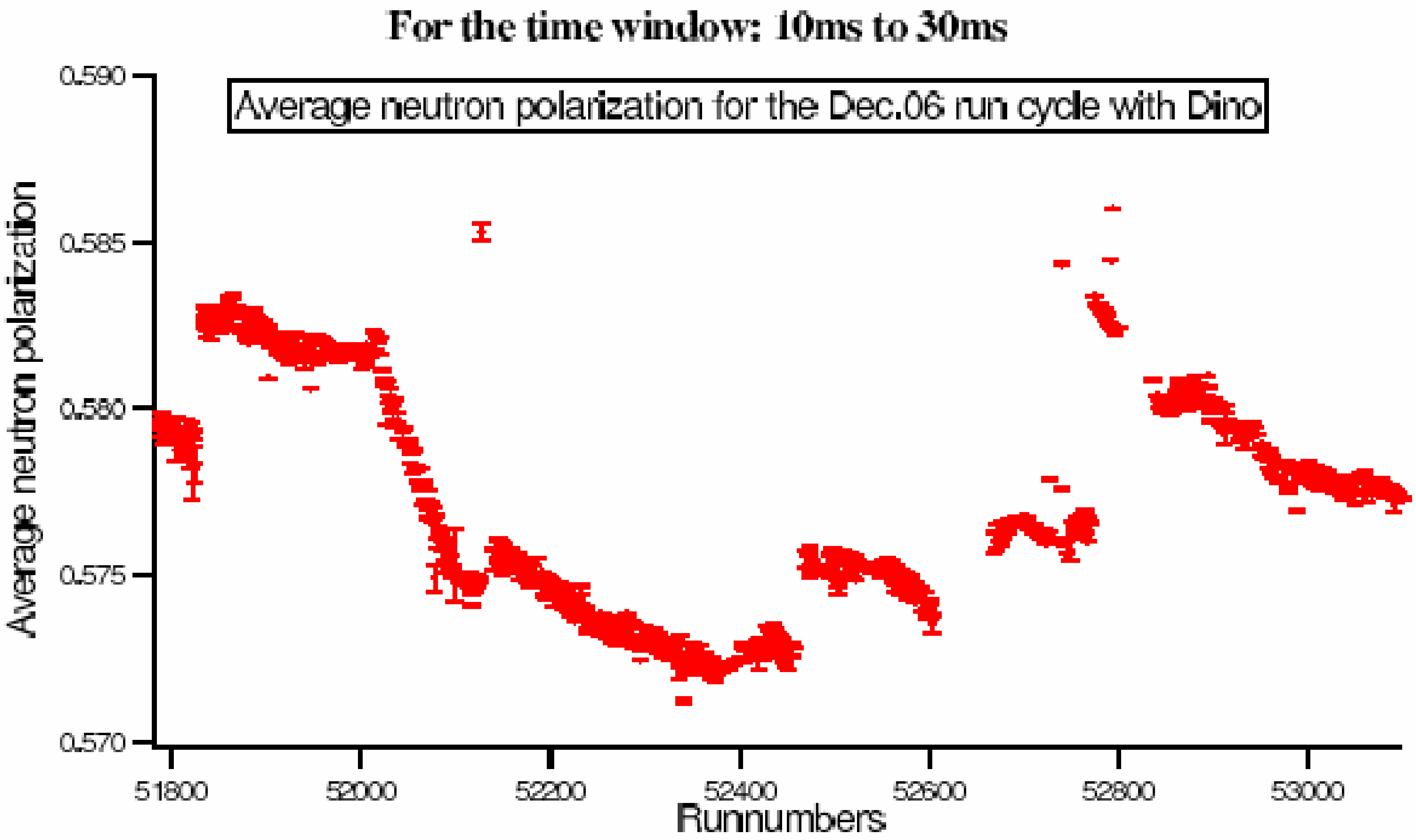
$$T \equiv \tfrac{1}{2}(T_+ + T_-) = T_0 \cosh(nl\sigma P_3)$$

$$P \equiv \frac{(T_+ - T_-)}{(T_+ + T_-)} = \tanh(nl\sigma P_3)$$

$$= \sqrt{1 - T_0^2/T^2}$$

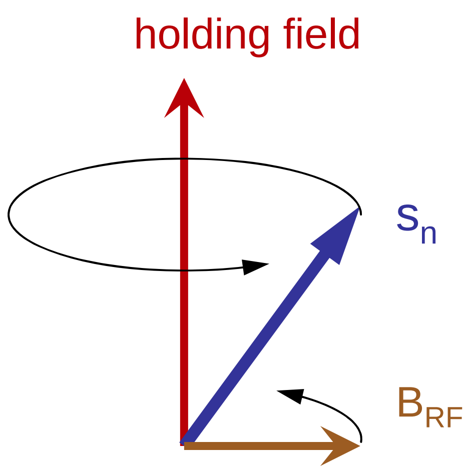


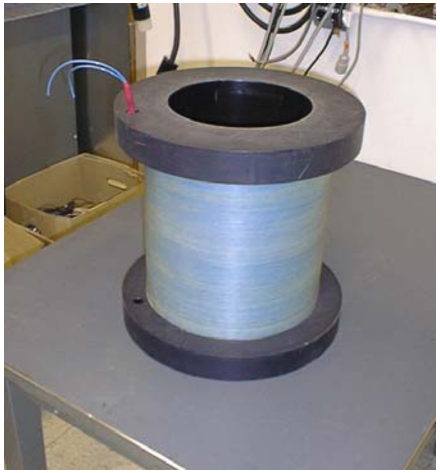
Beam Polarization



RF Spin Rotator

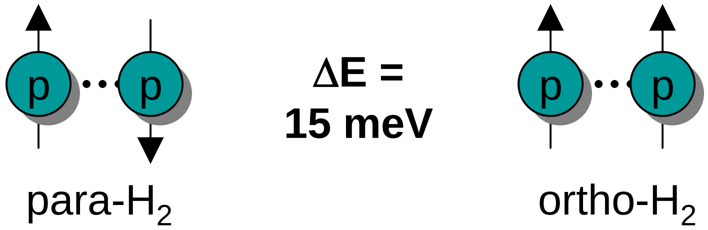
- essential to reduce instrumental systematics
    - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd order
    - danger: must isolate fields from detector
    - false asymmetries: additive & multiplicave
- works by the same principle as NMR
    - RF field resonant with Larmor frequency rotates spin
    - time dependent amplitude tuned to all energies
    - compact, no static field gradients

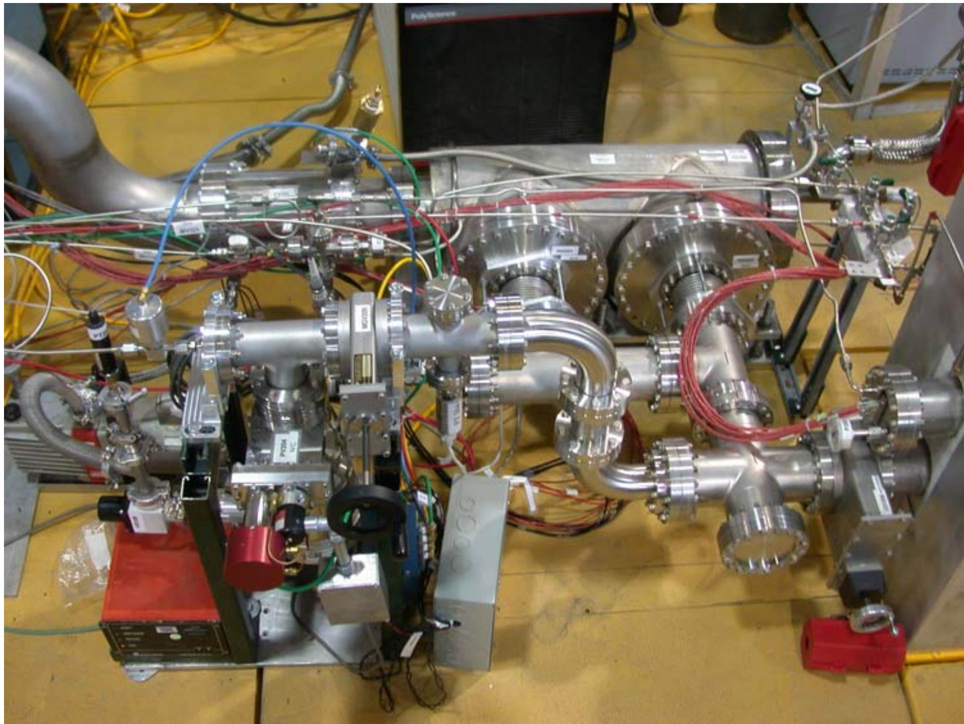




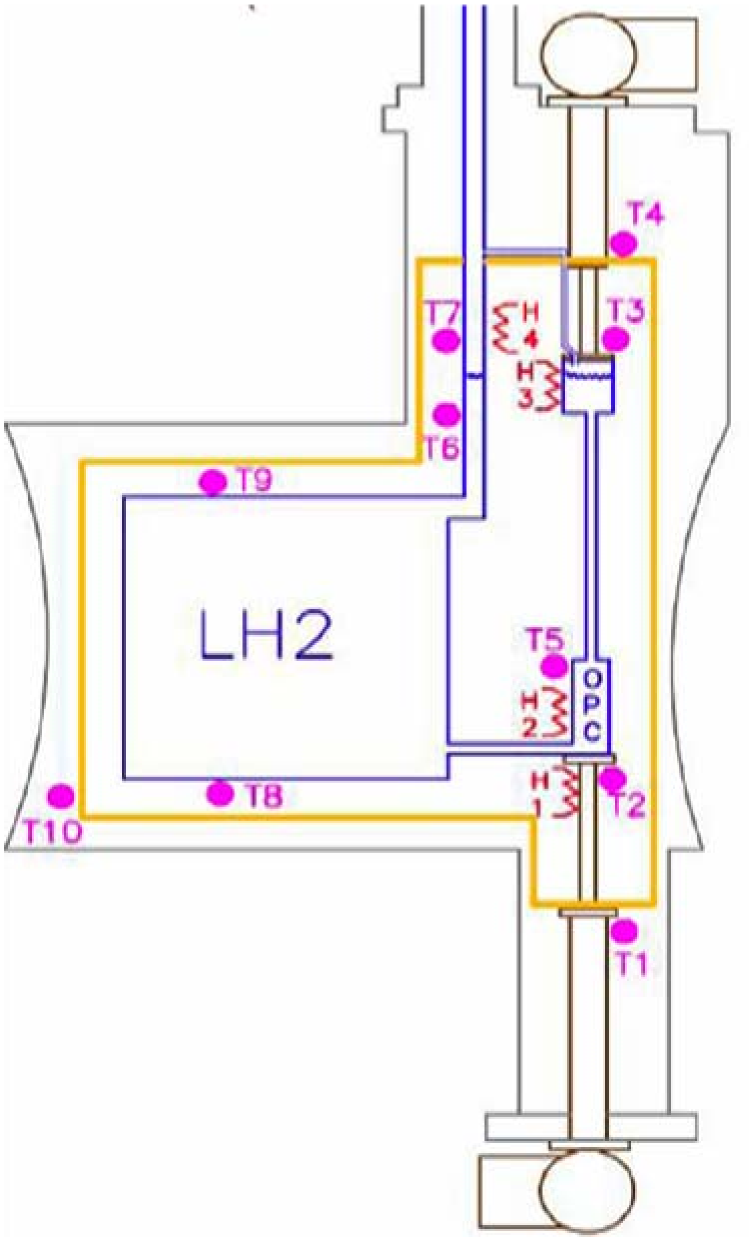
16L liquid para-hydrogen target

- 30 cm long $\rightarrow$ 1 interaction length
- 99.97% para $\rightarrow$ 1% depolarization
- pressurized to reduce bubbles
- SAFETY !!

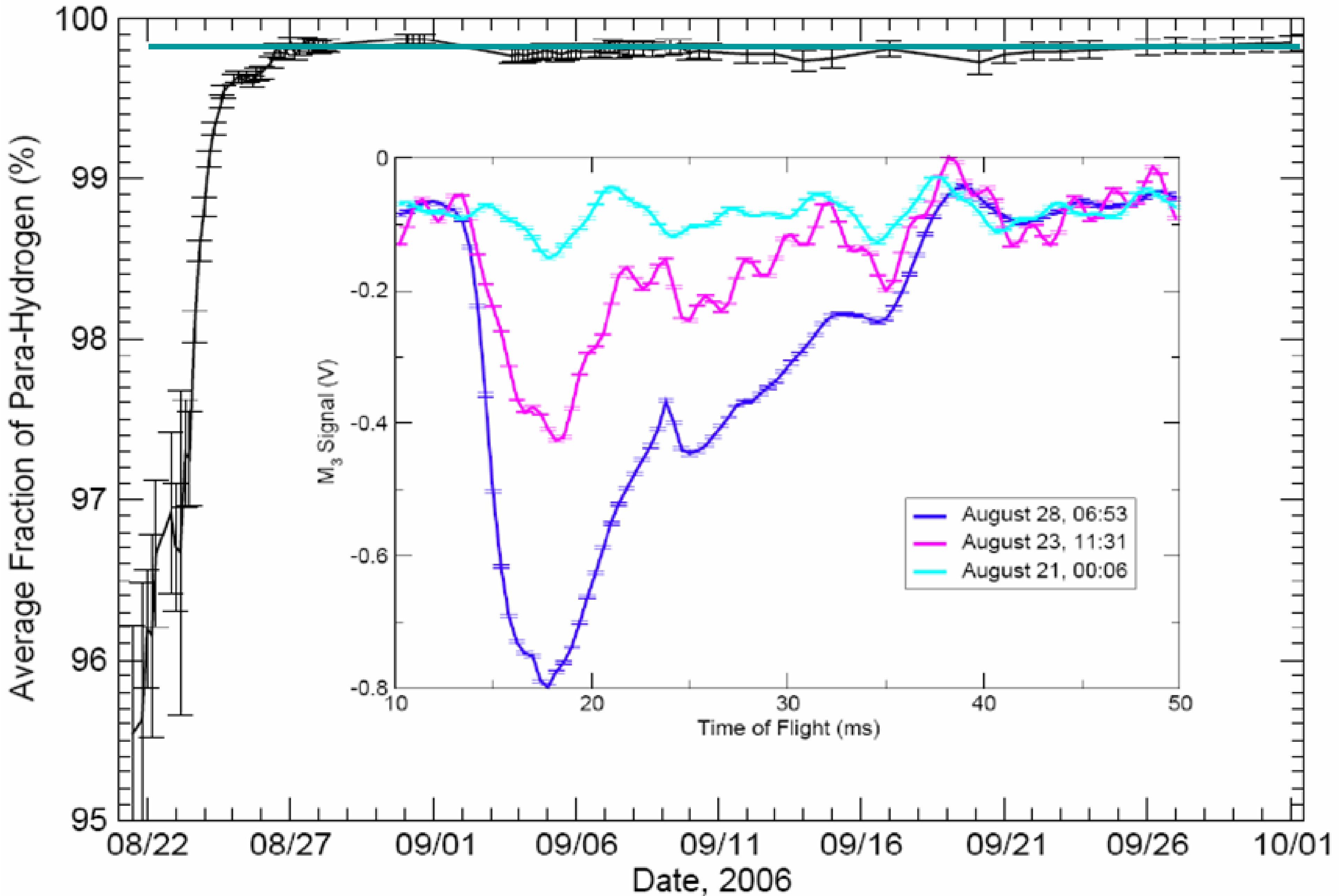




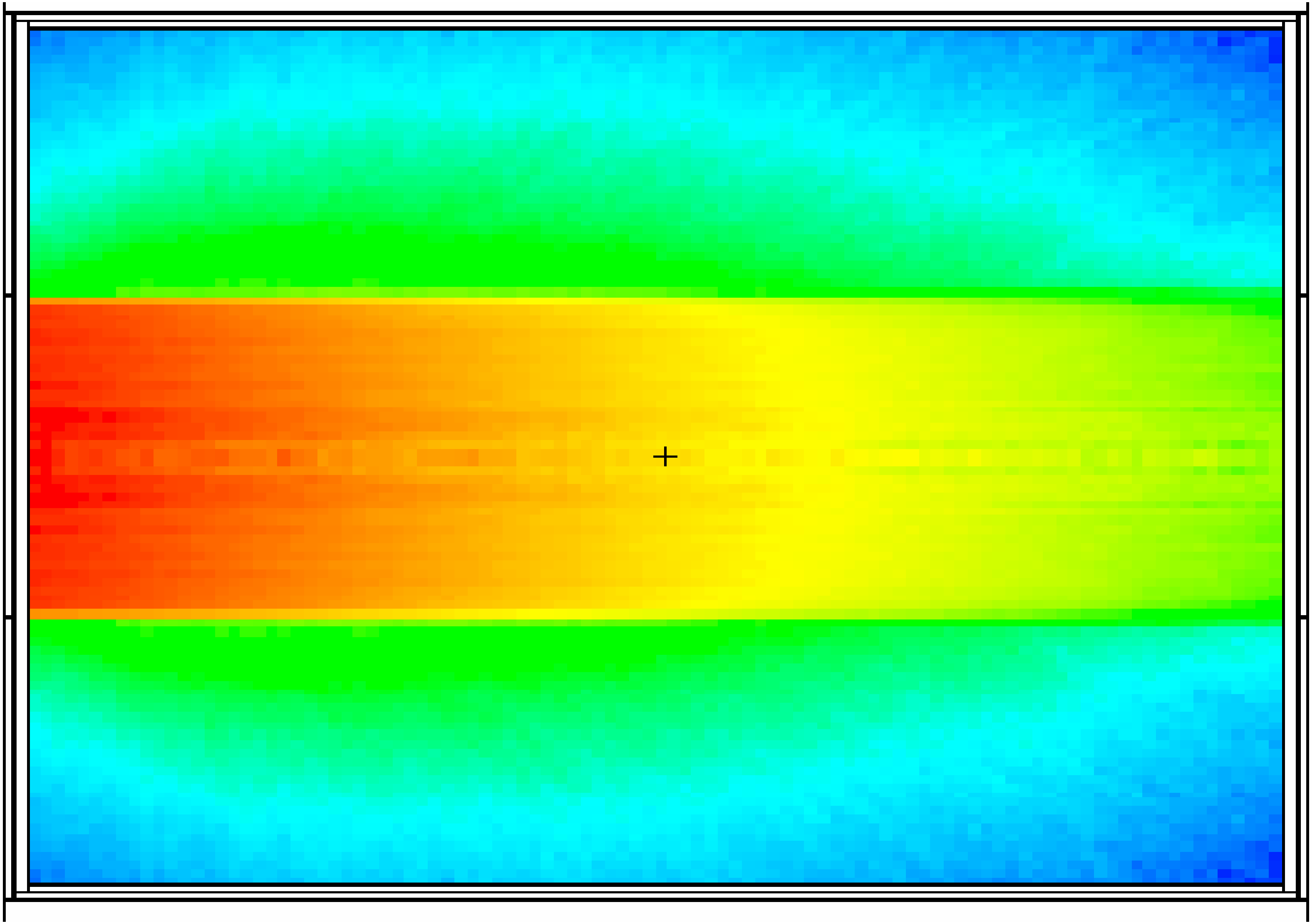
Ortho-Para Conversion Cycle



O/P Equilibrium Fraction

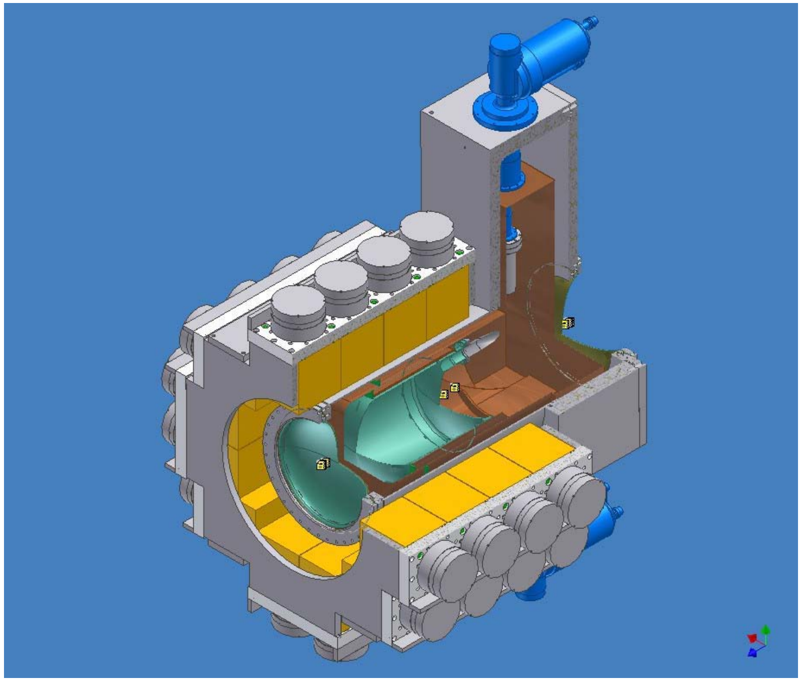


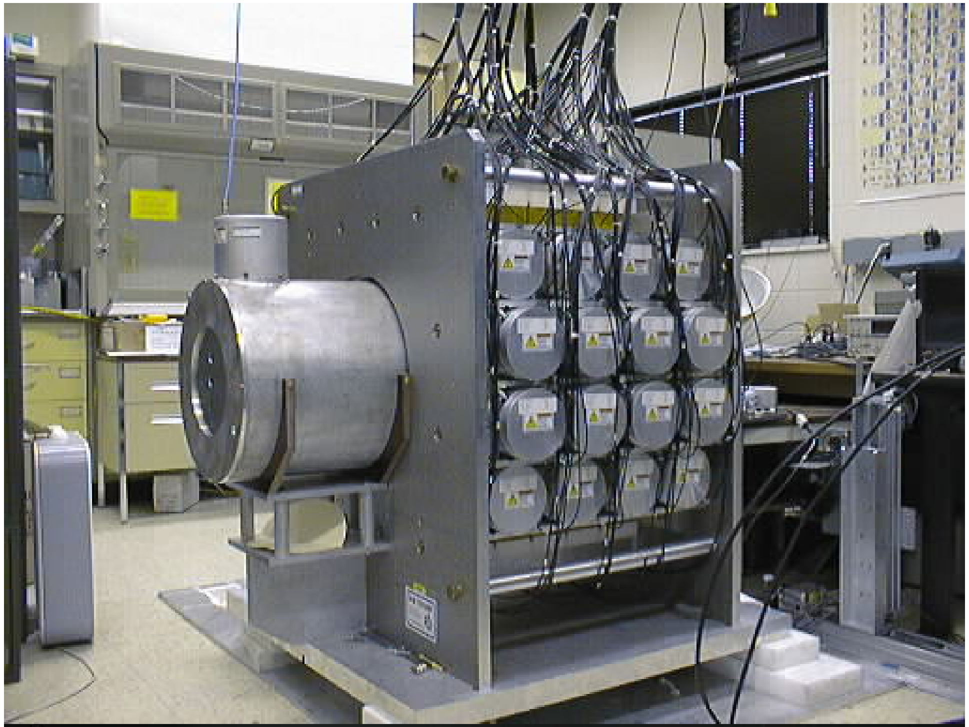
Neutron Intensity on Target

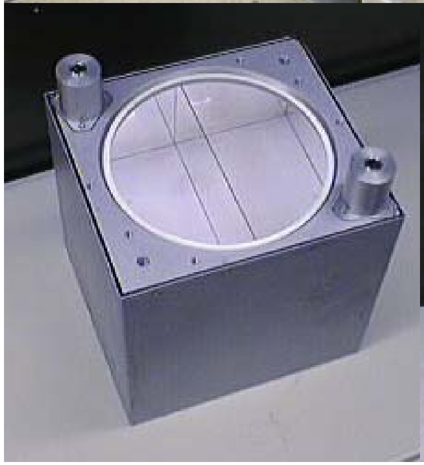


CsI(Tl) Detector Array

- 4 rings of 12 detectors each
  - 15 x 15 x 15 cm^3 each
- VPD's insensitive to B field
- detection efficiency: 95%
- current-mode operation
  - 5 x 10^7 gammas/pulse
  - counting statistics limited
  - optimized for asymmetry







Asymmetry Analysis

yield (det,spin)

$$A_{raw,p}(t_i) = \frac{\mathcal{Y}_{A_p,\uparrow}(t_i) - \mathcal{Y}_{B_p,\uparrow}(t_i) - \mathcal{Y}_{A_p,\downarrow}(t_i) + \mathcal{Y}_{B_p,\downarrow}(t_i)}{\mathcal{Y}_{A_p,\uparrow}(t_i) + \mathcal{Y}_{B_p,\uparrow}(t_i) + \mathcal{Y}_{A_p,\downarrow}(t_i) + \mathcal{Y}_{B_p,\downarrow}(t_i)}$$

P.C. asym

background asym

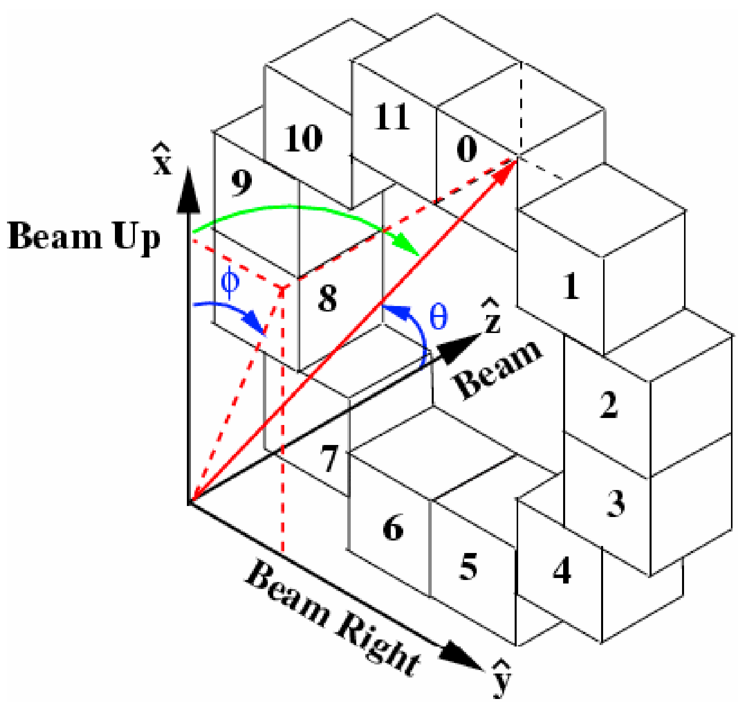
P.V. asym

$$\left(A^{j,p}_{UD}(t_i) + \beta A^{j,p}_{UD,b}(t_i)\right)\langle G_{UD}(t_i)\rangle + \left(A^{j,p}_{LR}(t_i) + \beta A^{j,p}_{LR,b}(t_i)\right)\langle G_{LR}(t_i)\rangle = \frac{\left(A^{j,p}_{raw} - A^{p}_{g} A_f(t_i) - A^{p}_{noise}\right)}{E(t_i) P_n(t_i) S(t_i)}$$

geometry factor

raw, beam, inst asym

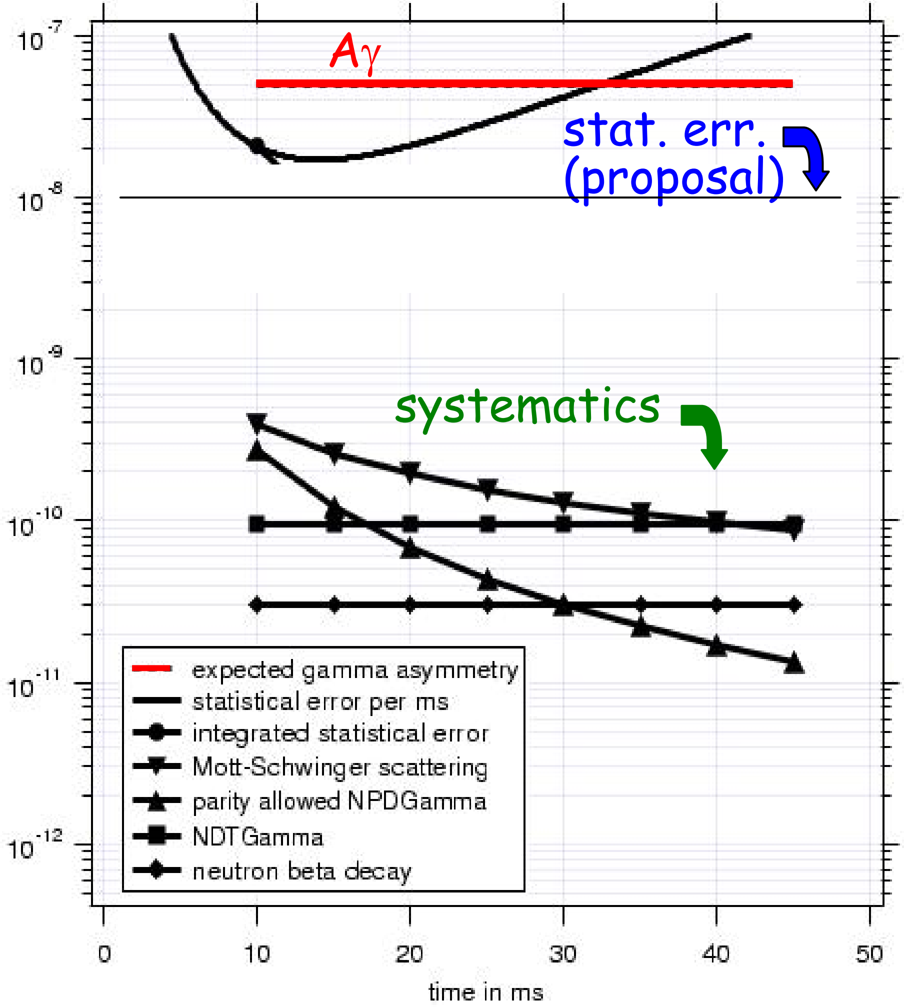
RFSF eff. neutron pol. target depol.



$$\langle G_{UD}\rangle = \langle \cos\theta \rangle$$

Systematic Uncertainties

Statistical and Systematic Errors



slide courtesy Mike Snow

Systematics, e.g:

- activation of materials,
  e.g. cryostat windows
- Stern-Gerlach steering
  in magnetic field gradients
- L-R asymmetries leaking into
  U-D angular distribution
  (np elastic, Mott-Schwinger...)
- scattering of circularly polarized
  gammas from magnetized iron
  (cave walls, floor...)

→ estimated and expected to be negligible (expt. design)

Left-Right Asymmetries

- Parity conserving: $\boldsymbol{s_n \cdot k_n \times k_\gamma}$
- Three processes lead to LR-asymmetry
  - P.C. $\boldsymbol{n+p \longrightarrow d+\gamma}$ asymmetry — 0.23×10^{-8}
    - Csoto, Gibson, and Payne, PRC **56**, 631 (1997)
  - elastic $\boldsymbol{n+p \longrightarrow n+p}$ scattering — 2×10^{-8}
    - beam steered by analyzing power of LH_2
    - eg. ^{12}C used in p,n polarimetry at higher energies
    - P-wave contribution vanishes as k^3 at low energy
  - Mott-Schwinger scattering — $\sim 10^{-8}$ at 2 MeV
    - interaction of neutron spin with Coulomb field of nucleus
    - electromagnetic ☐spin-orbit interaction
    - analyzing power: 10^{-7} at 45 deg

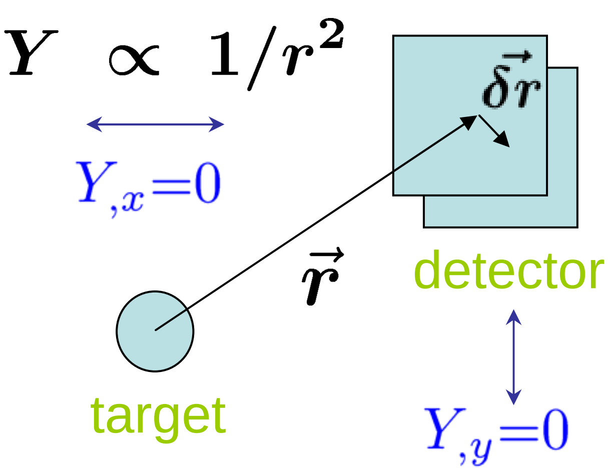
$$\begin{aligned} H'_{em} &= \vec{\mu} \cdot \vec{B} = g \vec{s}_n \cdot (\vec{E} \times \vec{v}_n) \\ &= -\frac{1}{m} V(r) \vec{L} \cdot \vec{s}_n \end{aligned}$$

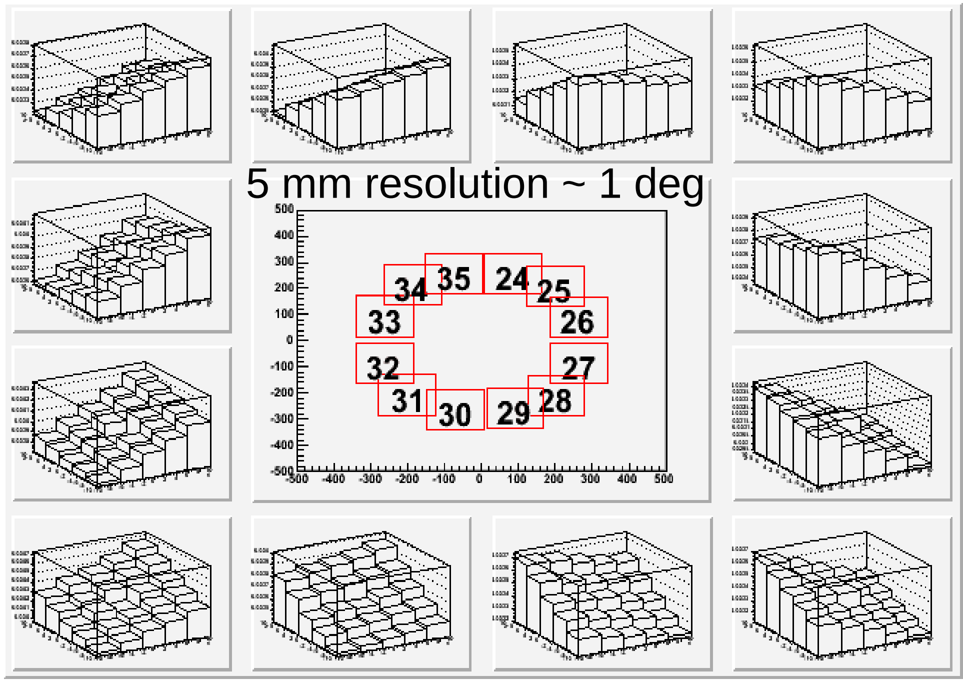
Detector position scans

$$Y \propto 1 + A_\gamma^{PV} \cos\theta + A_\gamma^{PC} \sin\theta$$

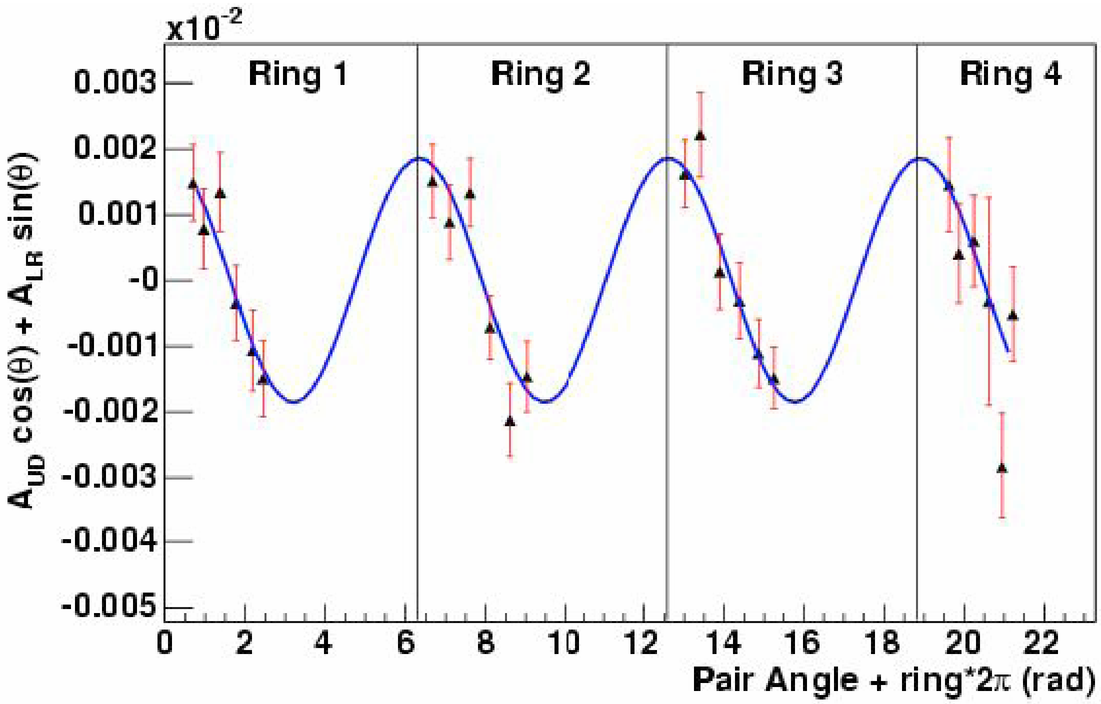
UP-DOWN LEFT-RIGHT

$$s_n \cdot k_\gamma \qquad s_n \cdot k_n \times k_\gamma$$

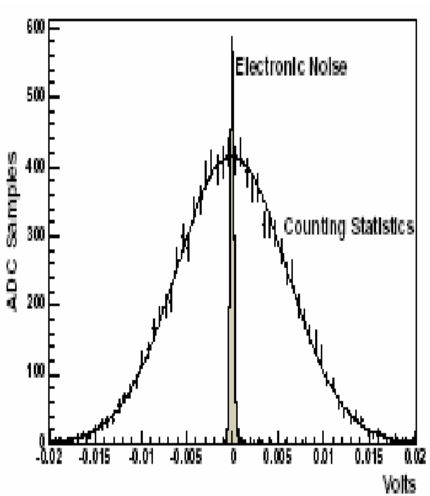


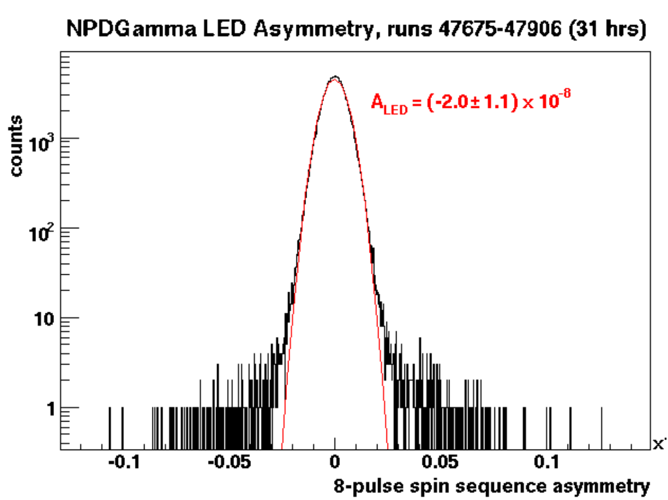


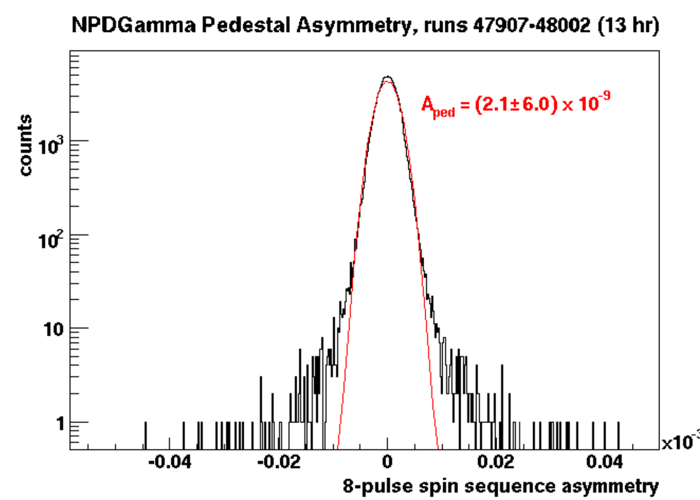
Engineering Runs



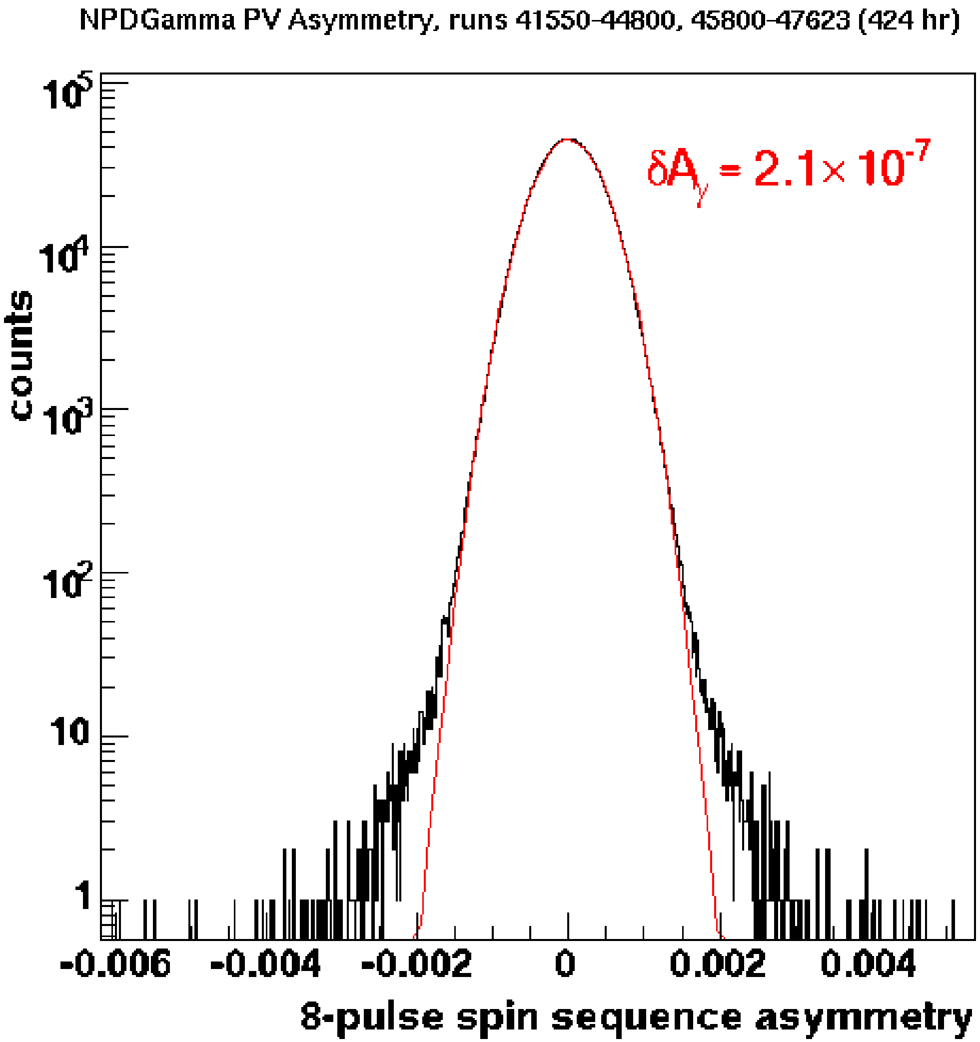
Material	# runs	A_γ ($\times 10^{-6}$)	
Engineering:			
Cl	53	−21.	± 1.6
Cu	17	−1.	± 3.
B_4C	11	−1.	± 2.
Al	1057	−0.00	± 0.30
In	716	−0.68	± 0.30
LEDs	2864	−0.0477	± 0.0603
Noise		∼ 0.001	
Physics:			
Mn	529	0.53	± 0.78
V	2313	0.24	± 0.45
Ti	2864	0.41	± 0.36
Co	744	0.61	± 0.31
Sc	2179	−1.04	± 0.25

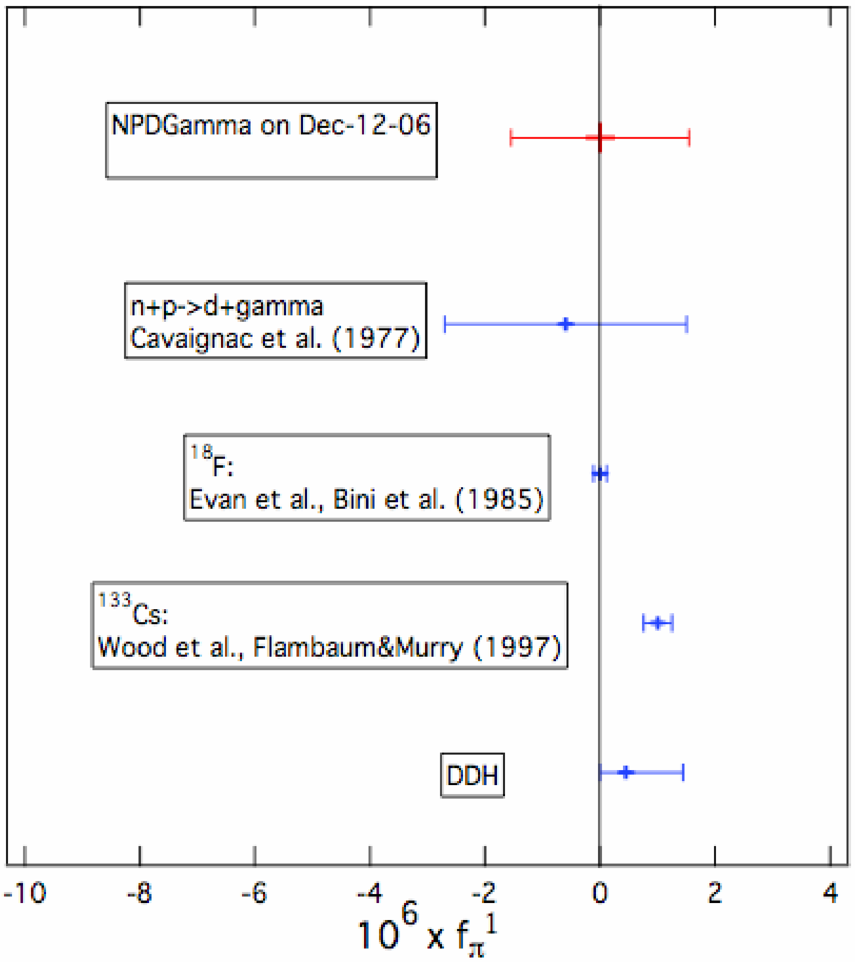




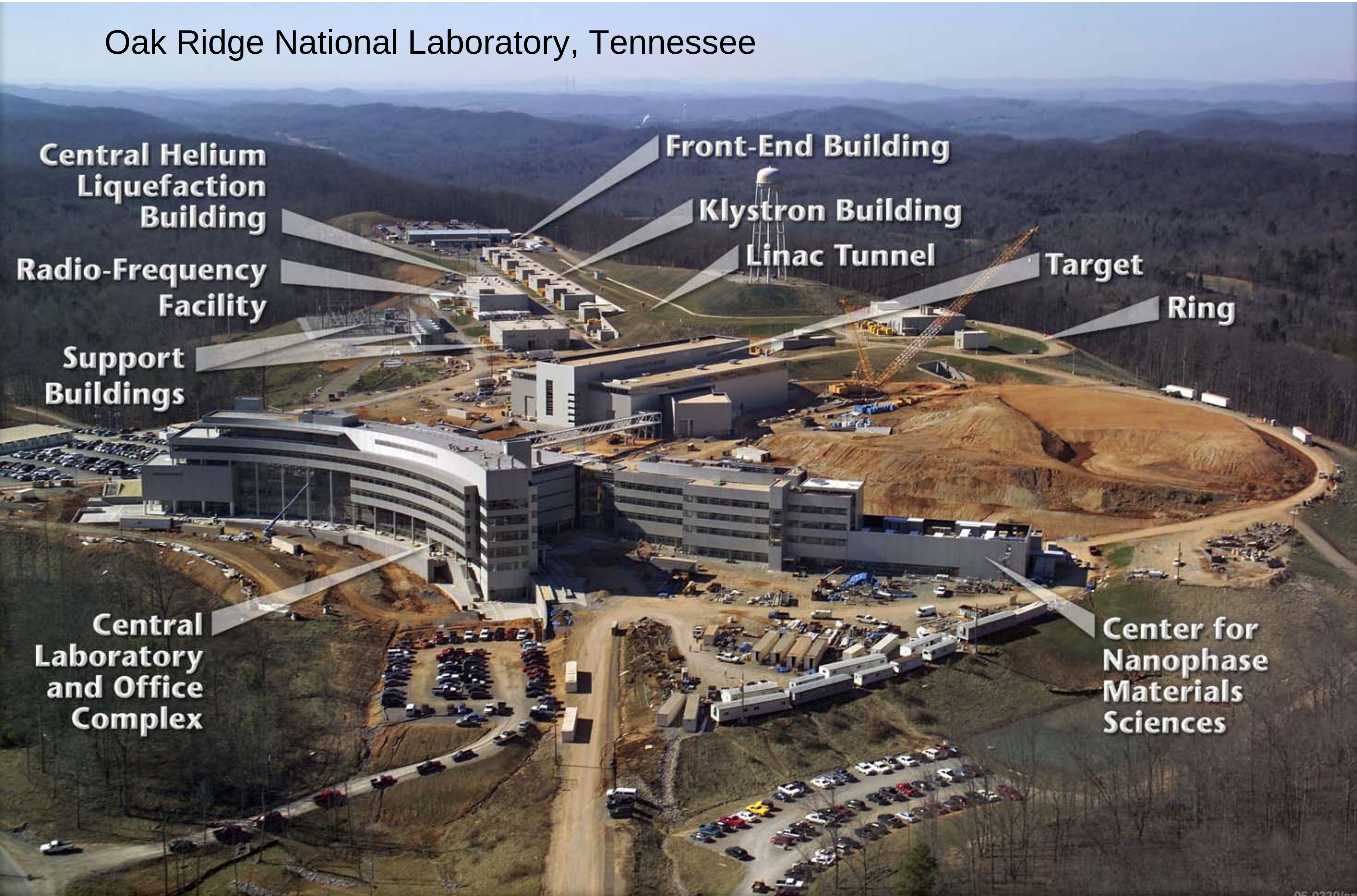


NPDG Asymmetry (Stat. Error)

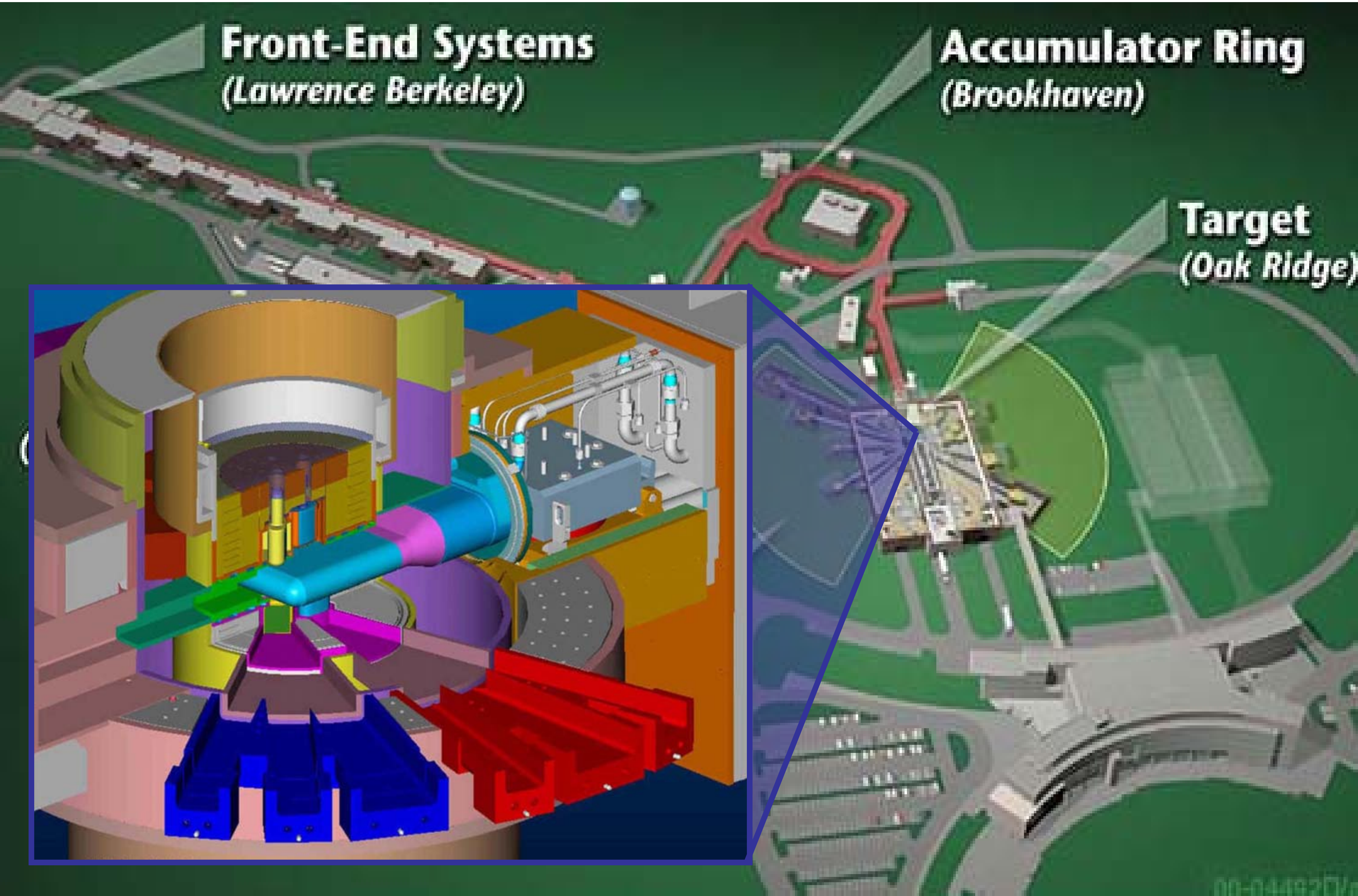




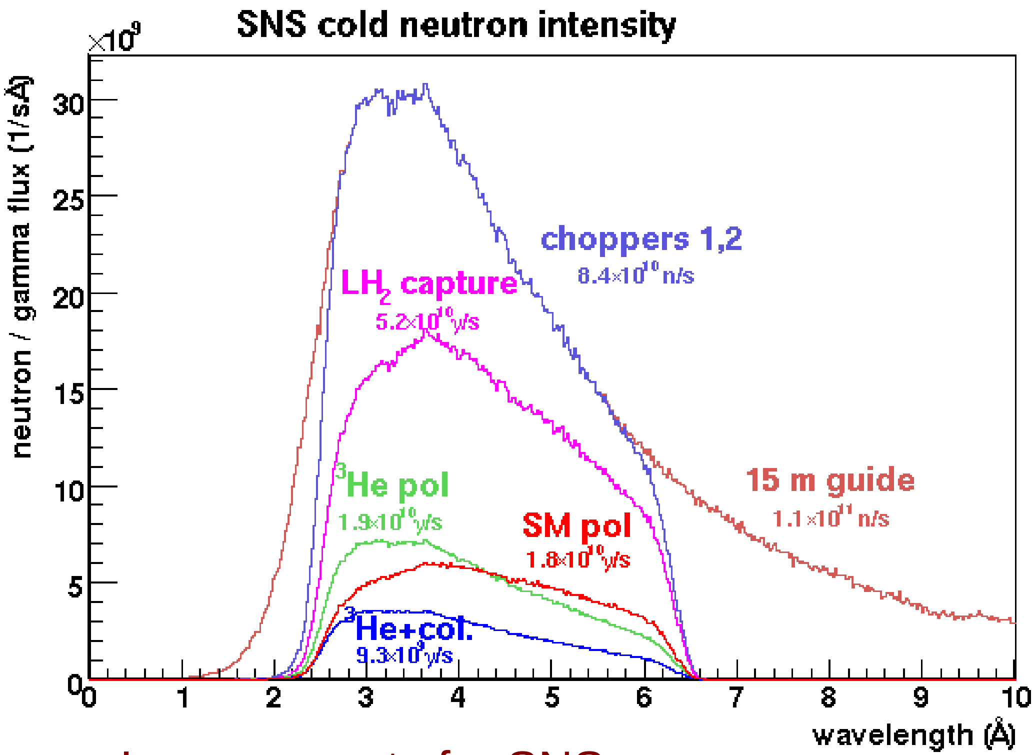
Spallation Neutron Source (SNS)

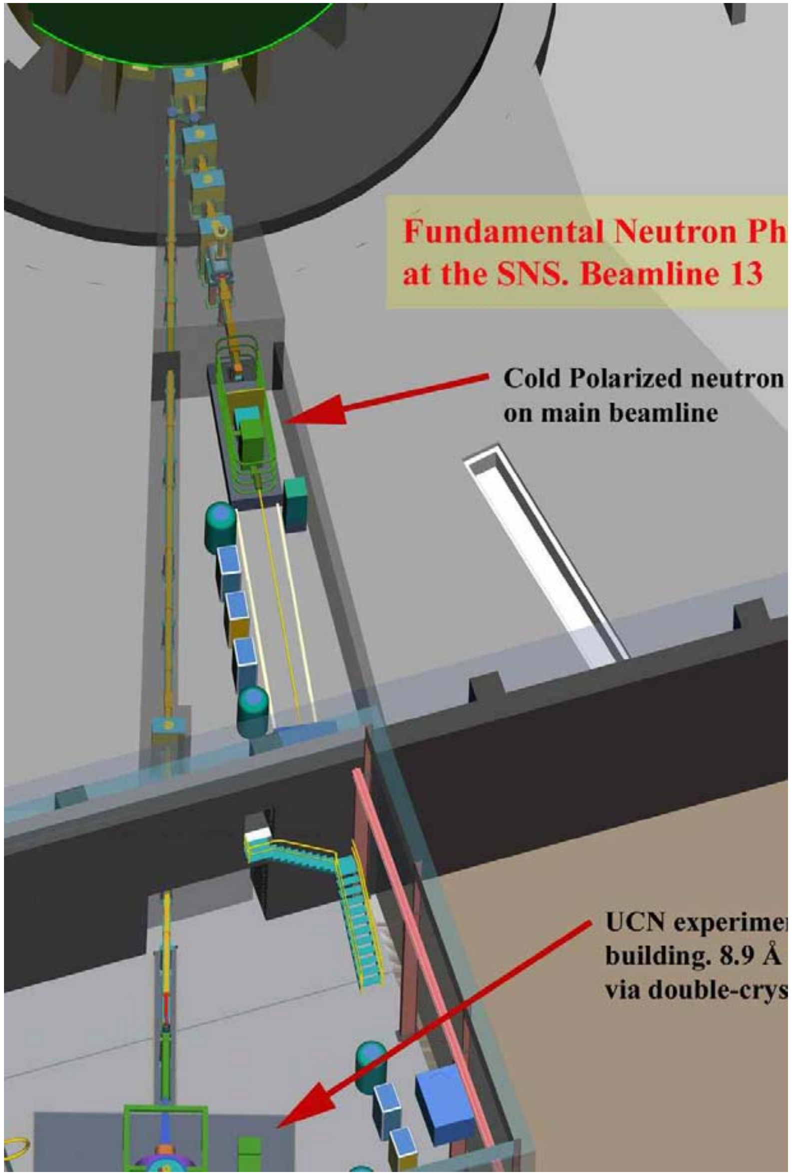


Spallation Neutron Source (SNS)



FnPB Cold Neutron Beamline



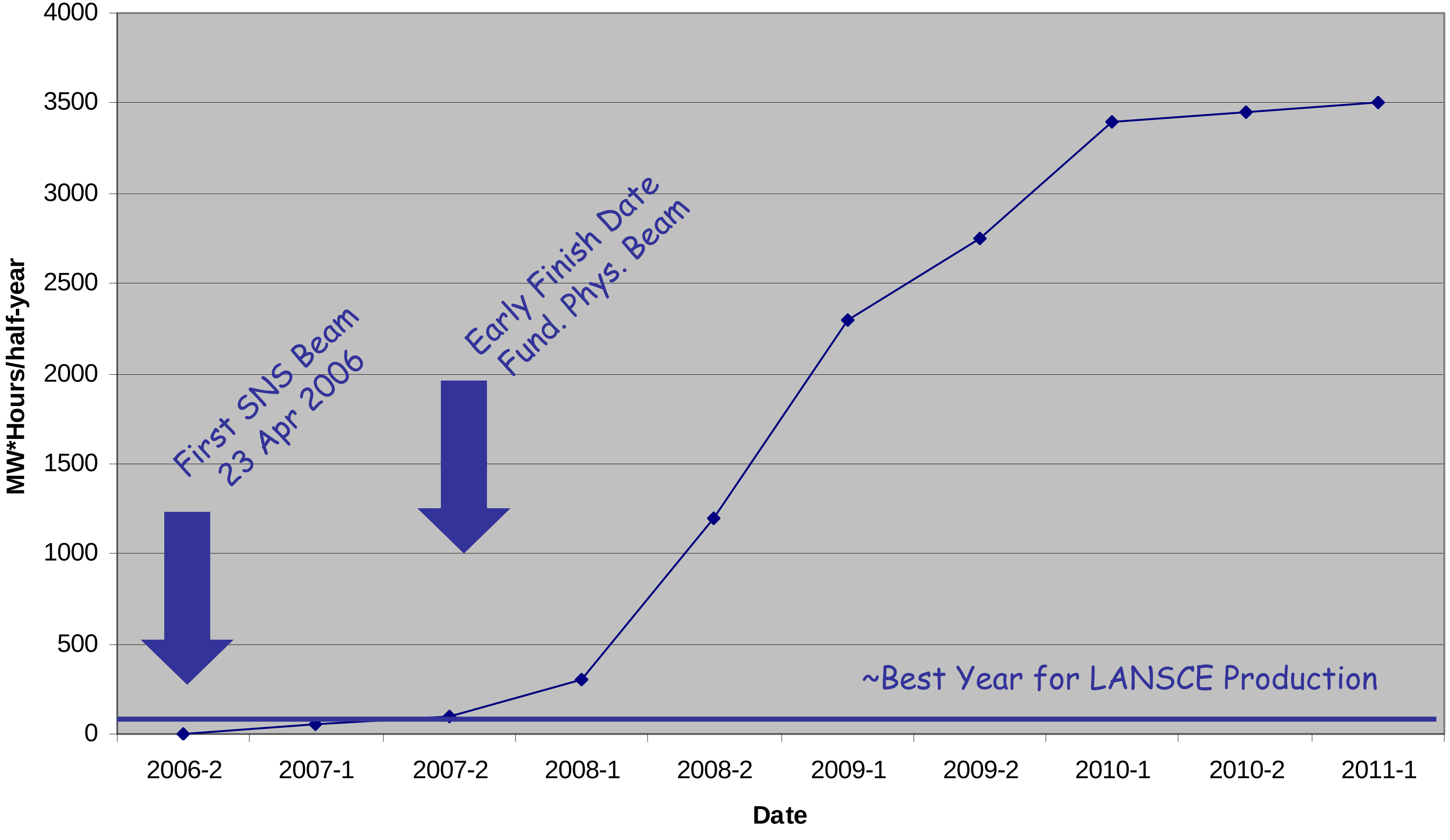


Improvements for SNS:

- curved beamline
- 2 choppers (+ 2 unused)
- new shielding hut
- SM bender polarizer
- new LH_2 vent line
- 60 Hz DAQ system

Timeline

- move NPDG to the SNS to achieve goal of $\delta A_\gamma = 1 \times 10^{-8}$
- possible follow-up experiment: $n + d \rightarrow t + \gamma$



Conclusion

- the NPDG experiment had a successful first phase at LANSCE
- project to determine A_γ to 1£10^{-8} at the SNS
  - possible follow-up experiment: $n + d \rightarrow t + \gamma$
- hadronic parity violation is a unique probe of short-distance nuclear interactions and QCD
  - neutron capture is an important key to mapping the long-range component of the hadronic weak interaction