NPDGamma Experiment: from LANSCE to the SNS

Christopher Crawford

University of Kentucky

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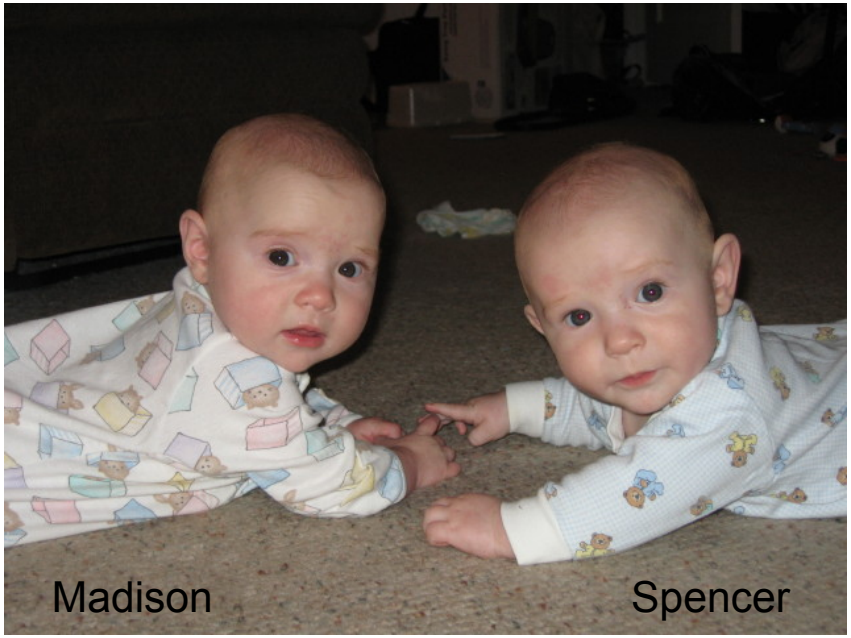
Outline

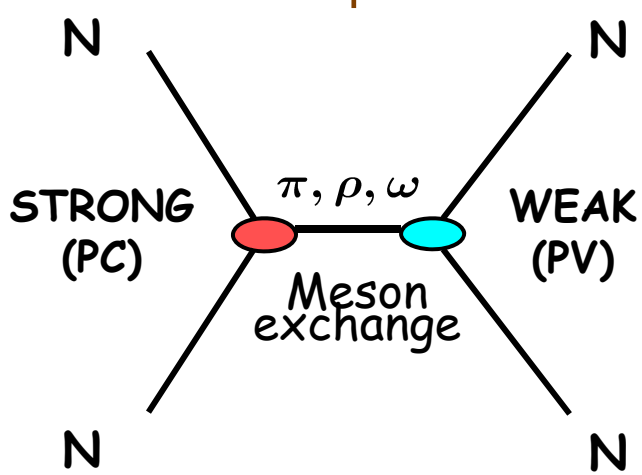
- Hadronic Weak Interaction
  - DDH couplings
  - EFT couplings
  - Danilov parameters
  - existing data
- NPDGamma @ LANSCE
  - experimental setup
  - results
- NPDGamma @ SNS
  - upgrades
  - new sensitivity
- n-^{3}He @ SNS
  - experimental setup
  - R&D at LANSCE
- NDTGamma
  - experimental setup
  - R&D at LANSCE
- Conclusion



Motivation

The Hadronic Weak Interaction is weak, but can be isolated due to parity violation

DDH picture

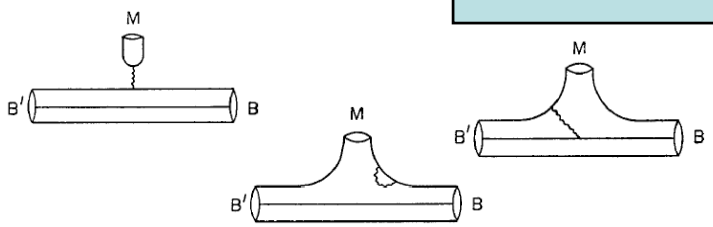


$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

- W,Z range = 0.002 fm – probe short-range quark correlations in QCD nonperturbative regime
- nuclear PV – test of nuclear structure models
- test of EFT in $\Delta S = 0$ sector (ΔI=1/2 rule not understood)
- physics input to PV electron scattering experiments
- $0\nu\beta\beta$ decay – matrix elements of 4-quark operators

DDH Potential

		f_π	$h_\rho'^1$	$h_\rho^{0,1,2}$	$h_\omega^{0,1}$
isospin	$\Delta I = 0$			$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	(1)
	$\Delta I = 1$	$\frac{i}{2}(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)^3$		$\frac{1}{2}(\boldsymbol{\tau}_1 \pm \boldsymbol{\tau}_2)^3$	$\frac{1}{2}(\boldsymbol{\tau}_1 \pm \boldsymbol{\tau}_2)^3$
	$\Delta I = 2$			$\frac{1}{2\sqrt{6}}(3\tau_1^3\tau_2^3 - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	
		$J = 0$		$J = 1$	$J = 1$
range	m_π	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\pi r}}{4\pi r}\right]$			
	$m_\rho = m_\omega$	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$		$i(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$	
				$i(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$	



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

Desplanques, Donoghue, Holstein, Annals of Physics 124, 449 (1980)

EFT approach

$$V_{\rm EFT}^{\rm PV}(\boldsymbol{r}) = V_{-1,\rm LR}^{\rm PV}(\boldsymbol{r}) + V_{1,\rm MR}^{\rm PV}(\boldsymbol{r}) + V_{1,\rm SR}^{\rm PV}(\boldsymbol{r})$$

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

$\sim \boldsymbol{h}_{\boldsymbol{\pi}}^{\mathbf{1}}$

($V_{1,\rm LR}^{\rm PV}(\boldsymbol{r})$ redundant)

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

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

$\sim \boldsymbol{h}_{\boldsymbol{\omega}}^{\mathbf{0}} \quad \boldsymbol{h}_{\boldsymbol{\omega}}^{\mathbf{1}} \quad \boldsymbol{h}_{\boldsymbol{\rho}}^{\mathbf{1}} \quad \boldsymbol{h}_{\boldsymbol{\rho}}^{\mathbf{0}} \quad \boldsymbol{h}_{\boldsymbol{\rho}}^{\mathbf{2}}$

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

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

$\sim \boldsymbol{h}_{\boldsymbol{\rho}}^{\mathbf{1}\prime} \sim \boldsymbol{h}_{\boldsymbol{\pi}}^{\mathbf{1}}$

C.-P. Liu, PRC 75, 065501 (2007)

Zhu, Maekawa, Holstein, Ramsey-Musolf, van Kolck, NP A748, 435 (2005)

Danilov parameters

- elastic NN scattering
- S=1/2+1/2 I=1/2+1/2
- equivalent to EFT in very low energy limit (generally much more complicated)

$$
\begin{array}{ccc}
{}^3P_1(I=0) & {}^3P_0(I=1) & {}^3P_1(I=0) \\
\updownarrow & \updownarrow & \updownarrow \\
{}^3S_1(I=0) & {}^3S_1(I=0) &
\end{array}
$$

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

$$
\begin{aligned}
&{}^3S_1 \longrightarrow {}^1P_1, \quad I = 0 \\
&{}^1S_0 \longrightarrow {}^3P_0, \quad I = 1 \\
&{}^3S_1 \longrightarrow {}^3P_1, \quad I = 1 \rightarrow 0
\end{aligned}
$$

C.-P. Liu, PRC 75, 065501 (2007)

Pion-less EFT Couplings

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

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

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

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

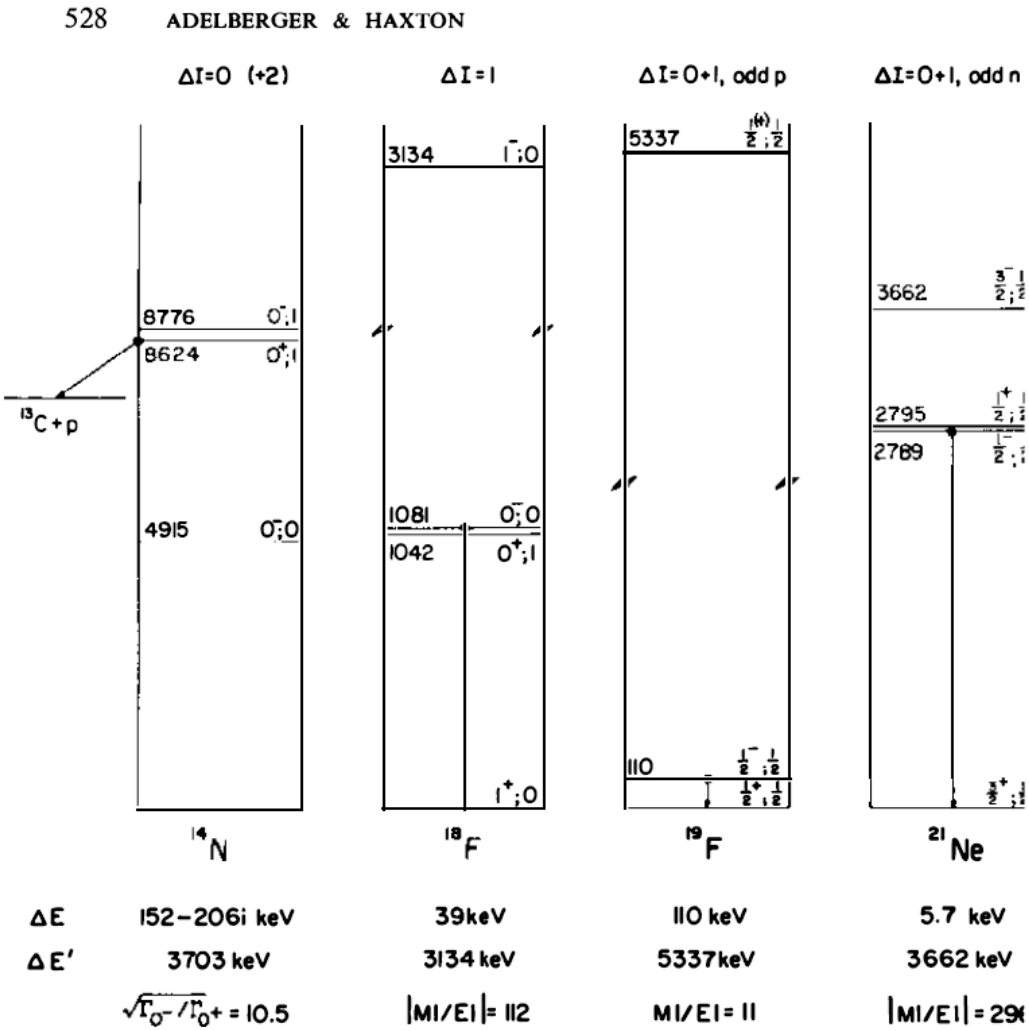
$$P_\gamma^{np}(\mathrm{th.}) \approx -0.16\, m_N \lambda_s^{np} + 0.67\, m_N \lambda_t \approx A_L^{\vec{\gamma}d}(1.32\,\mathrm{keV}+)\,,$$

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

Liu, PRC 75, 065501 (2007)

Hyun, Ando, Desplanques, nucl-th/0611018

Nuclear PV experiments



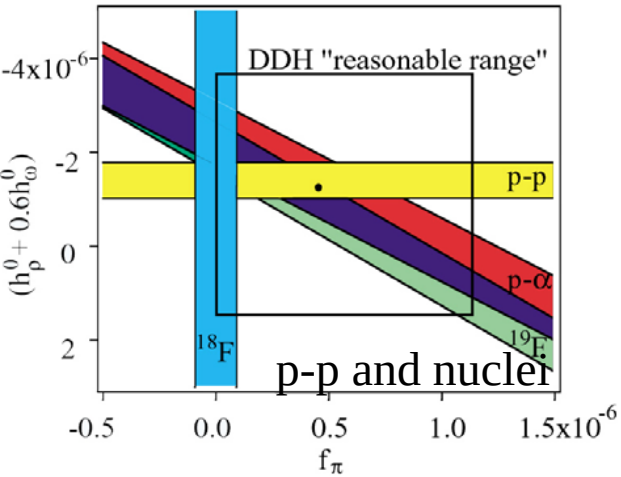
Adelberger, Haxton, Ann. Rev. Nucl. Part. Sci. 35, 501 (1985)

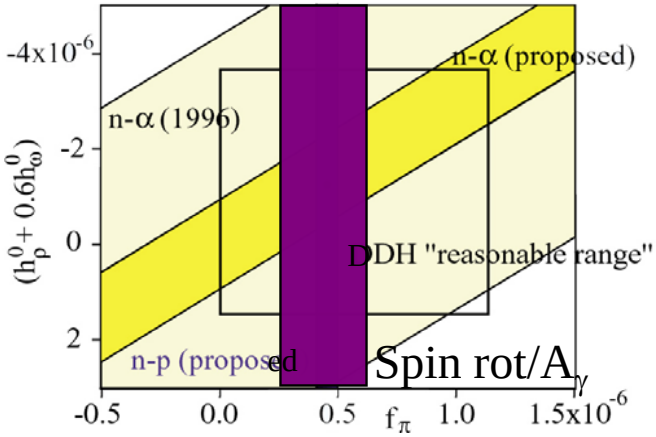
Existing data

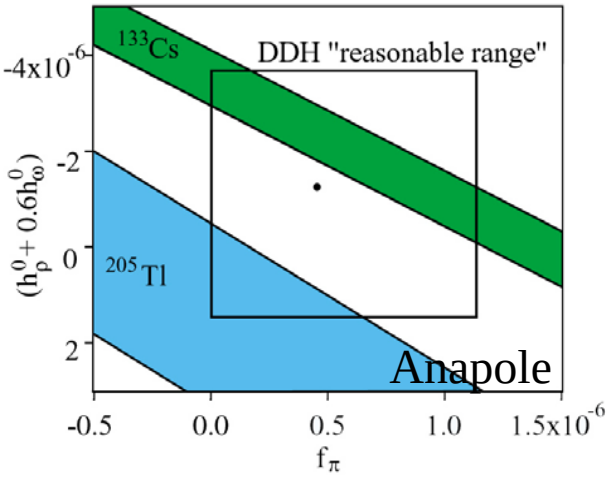
- p-p scat. 15, 45 MeV A_z^{pp}
- p-α scat. 46 MeV A_z^{pp}
- p-p scat. 220 MeV A_z^{pp}
- n+p$\rightarrow$d+γ circ. pol. P_γ^d
- n+p$\rightarrow$d+γ asym. A_γ^d
- n-α spin rot. $d\phi^{n\alpha}/dz$

- ^{18}F asym. $\Delta I = 1$
- ^{19}F, ^{41}K, ^{175}Lu, ^{181}Ta asym.
- ^{133}Cs, ^{205}Tl anapole moment
- ^{21}Ne (even-odd)

GOAL – resolve coupling constants from few-body PV experiments only







NPDGamma Collaboration

R. Alarcon[1], S. Balascuta[1], L. Barron-Palos[2], S. Baeßler[3], D. Bowman[4], J. Calarco ,R. Carlini[5], W. Chen[6], T. Chupp[7], C. Crawford[8], M. Dabaghyan[9], A. Danagoulian[10], M. Dawkins[11], N. Fomin[12], S. Freedman[13], T. Gentile[6], M. Gericke[14] C. Gillis[11], G. Greene[4,12], F. Hersman[9], T. Ino[15], G. Jones[16], B. Lauss[17], W. Lee[18], M. M. Leuschner[11], W. Losowski[11], R. Mahurin[12], Y. Masuda[15], J. Mei[11], G. Mitchell[19], S. Muto[15], H. Nann[11], S. Page[14], D. Pocinic, S. Penttila[4], D. Ramsay[14,20], A. Salas Bacci[10], S. Santra[21], P.-N. Seo[22], E. Sharapov[23], M. Sharma[7], T. Smith[24], W. Snow[11], W. Wilburn[10], V. Yuan[10]

[1]Arizona State University
[2]Universidad Nacional Autonoma de Mexico
[3]University of Virginia
[4]Oak Ridge National Laboratory
[5]Thomas Jefferson National Laboratory
[6]National Institute of Standards and Technology
[7]Univeristy of Michigan, Ann Arbor
[8]University of Kentucky
[9]University of New Hampshire
[10]Los Alamos National Laboratory
[11]Indiana University
[12]University of Tennessee
[13]University of California at Berkeley
[14]University of Manitoba, Canada
[15]High Energy Accelerator Research Organization (KEK), Japan
[16]Hamilton College
[17]Paul Scherer Institute, Switzerland
[18]Spallation Neutron Source
[19]University of California at Davis
[20]TRIUMF, Canada
[21]Bhabha Atomic Research Center, India
[22]Duke University
[23]Joint Institute of Nuclear Research, Dubna, Russia
[24]University of Dayton

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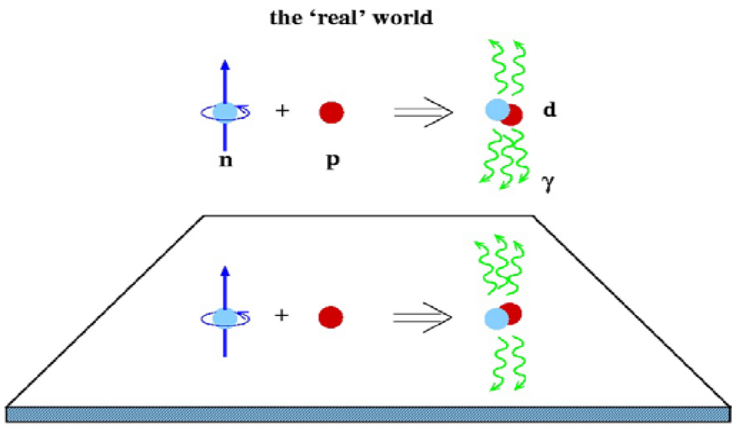
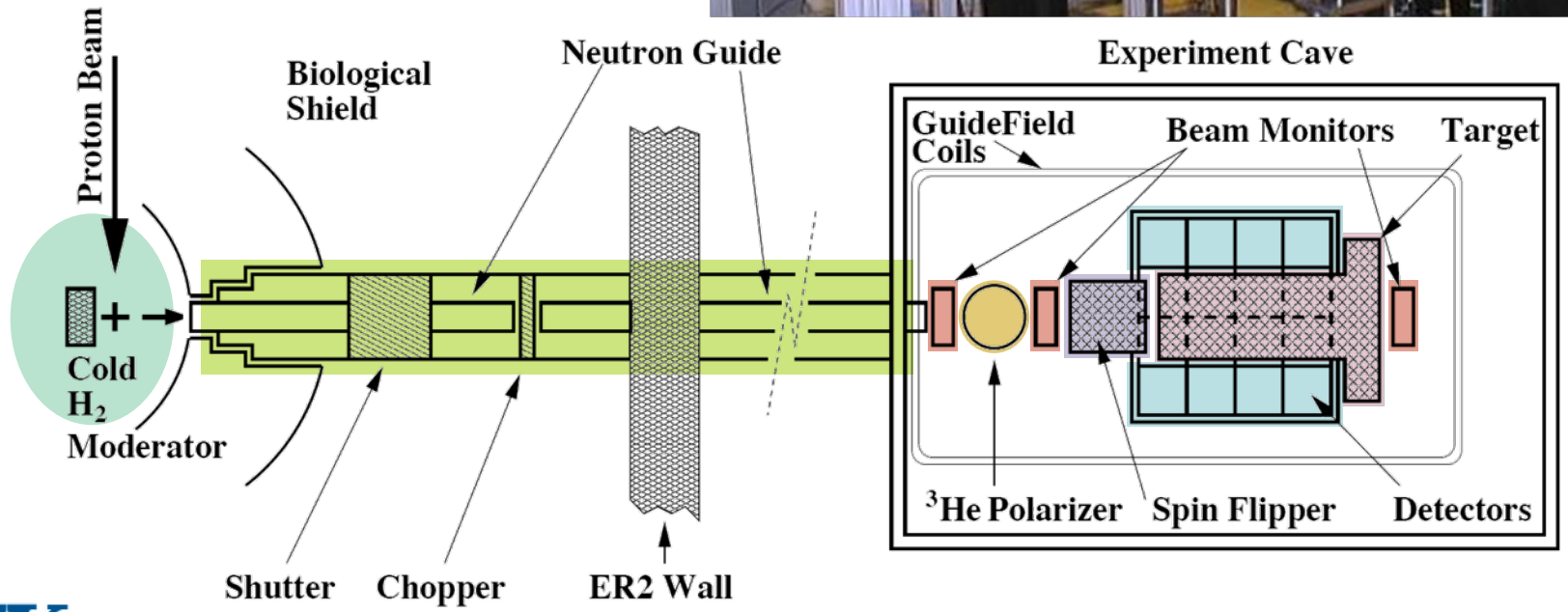
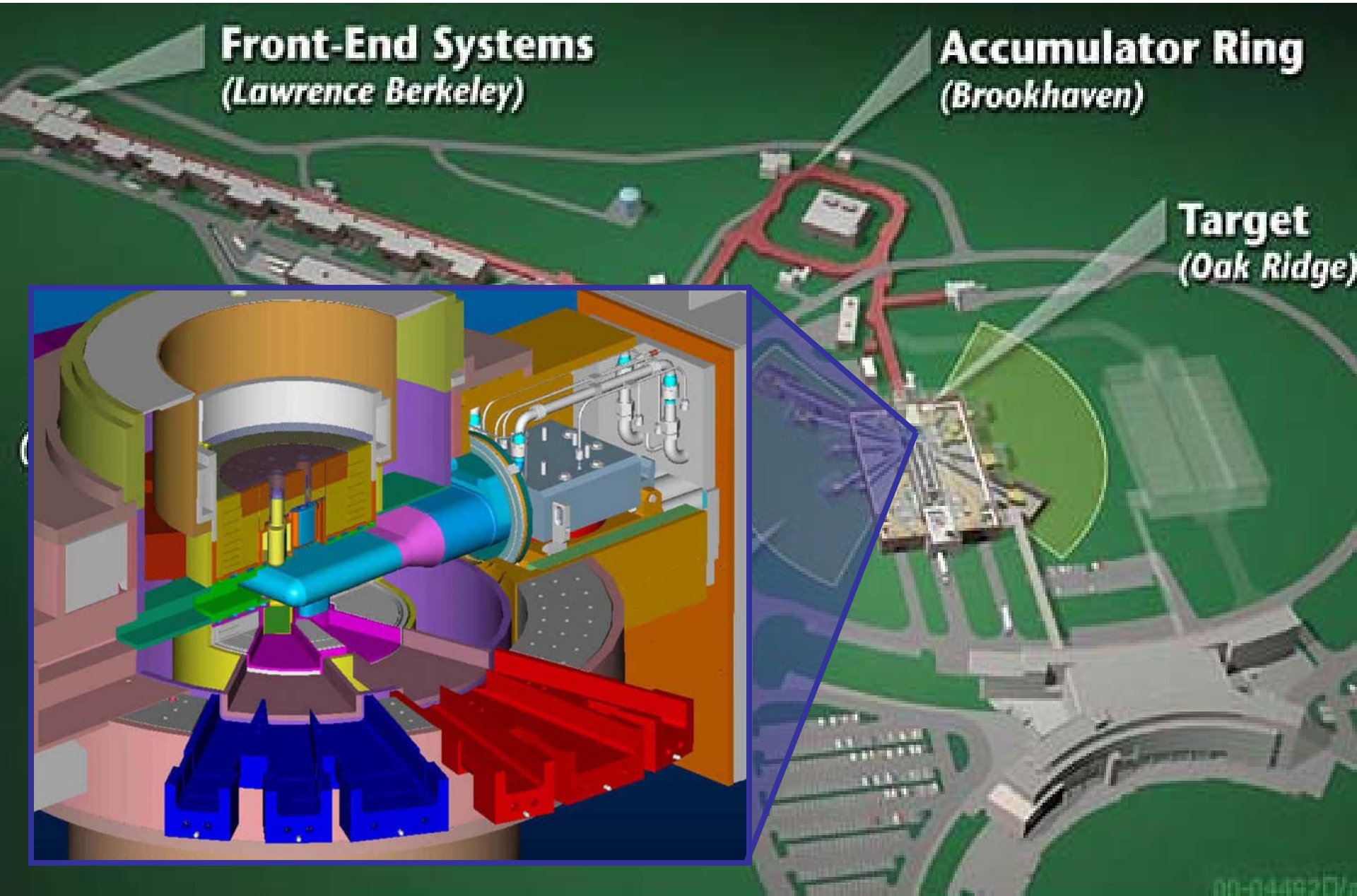
NPDGamma parity-violating observable A_γ

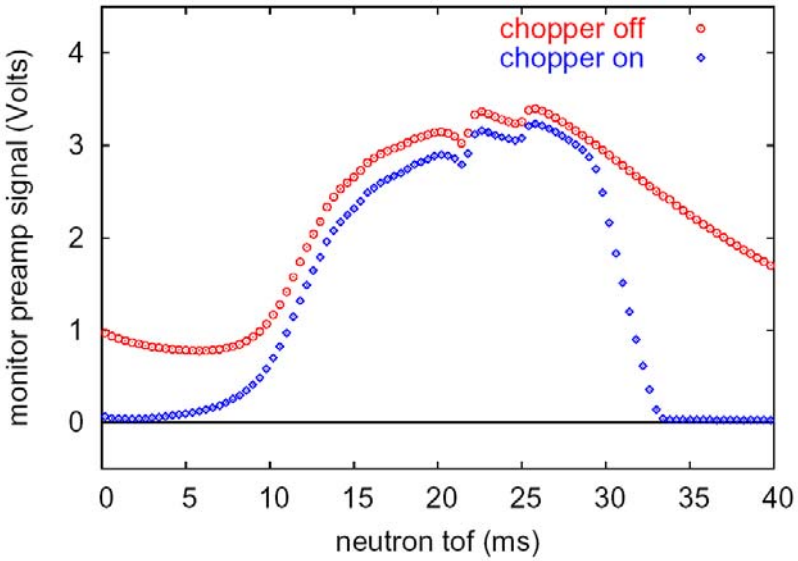




Spallation neutron source – cold moderator



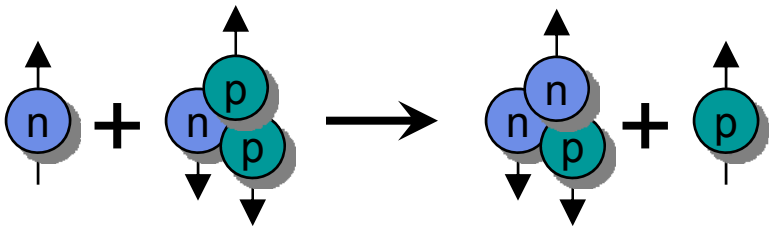
Frame overlap chopper



- Pulsed beam: time-of-flight determines neutron velocity, energy
- PV asymmetry is independent of energy
- Very slow neutrons can overlap with faster neutrons from later pulse
- Chopper rotor coated with Gd_2O_3 absorbs slow neutrons, opens window for faster ones

^{3}He neutron polarizer

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



$\sigma_{J=0}$ = 5333 b λ/λ_0

$\sigma_{J=1}$ ¼ 0

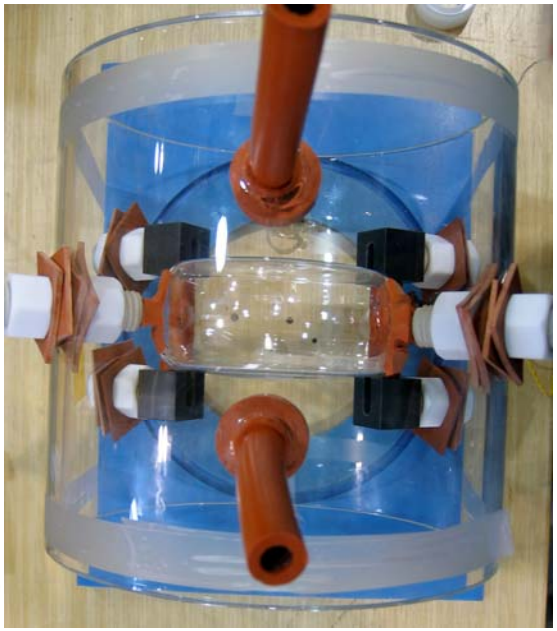
- 10 G holding field determines the polarization angle

  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



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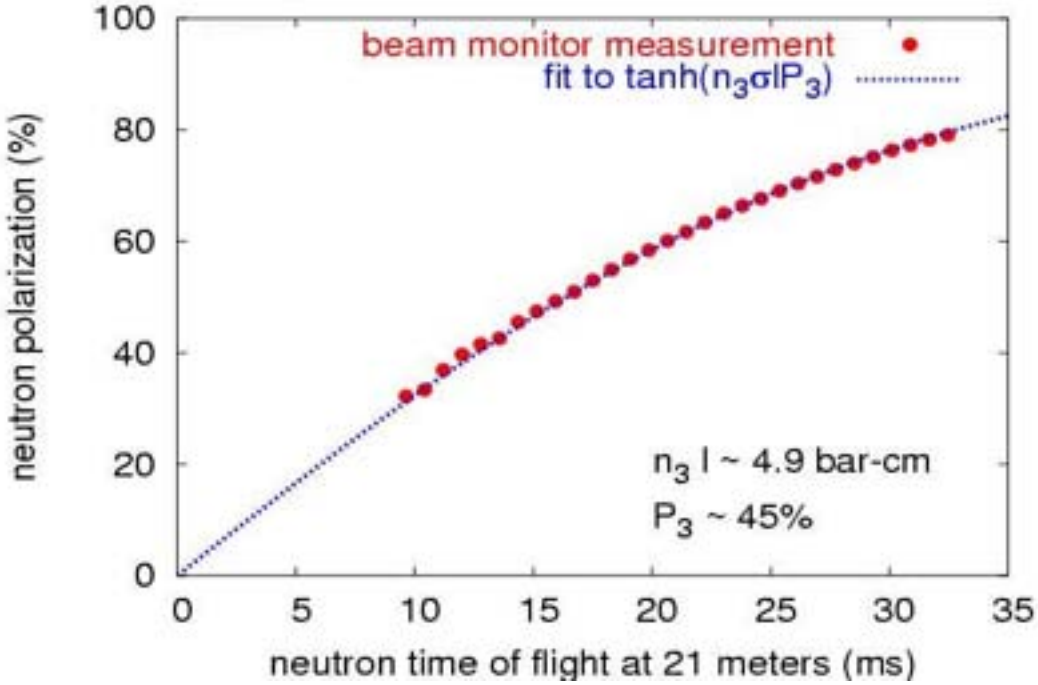
Neutron Beam Monitors

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

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

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

$$\boldsymbol{P} \equiv \frac{(T_+ - T_-)}{(T_+ + T_-)} = \tanh(nl\sigma P_3) = \sqrt{1 - T_0^2/T^2}$$



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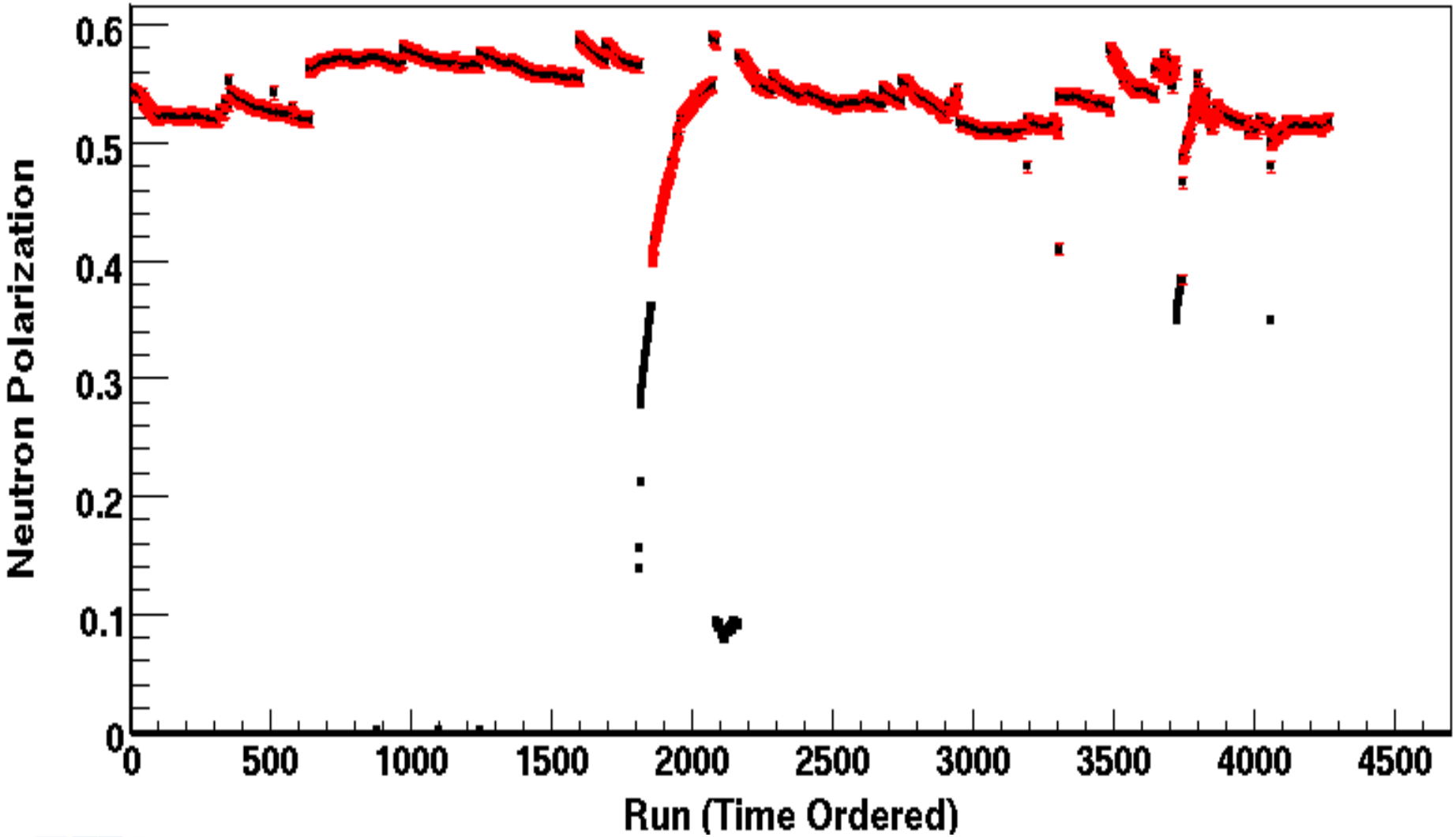
Neutron Polarization



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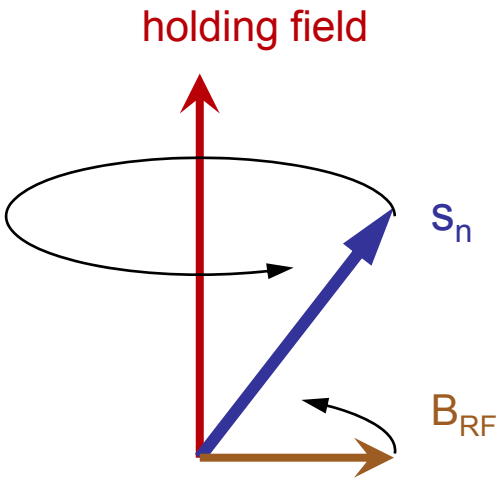
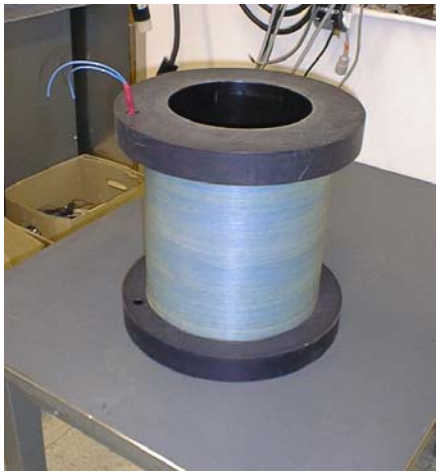
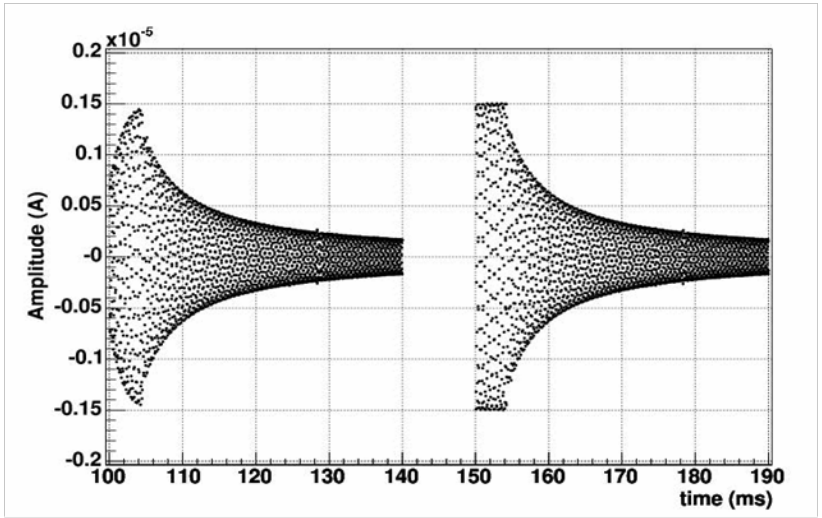
RF spin rotator

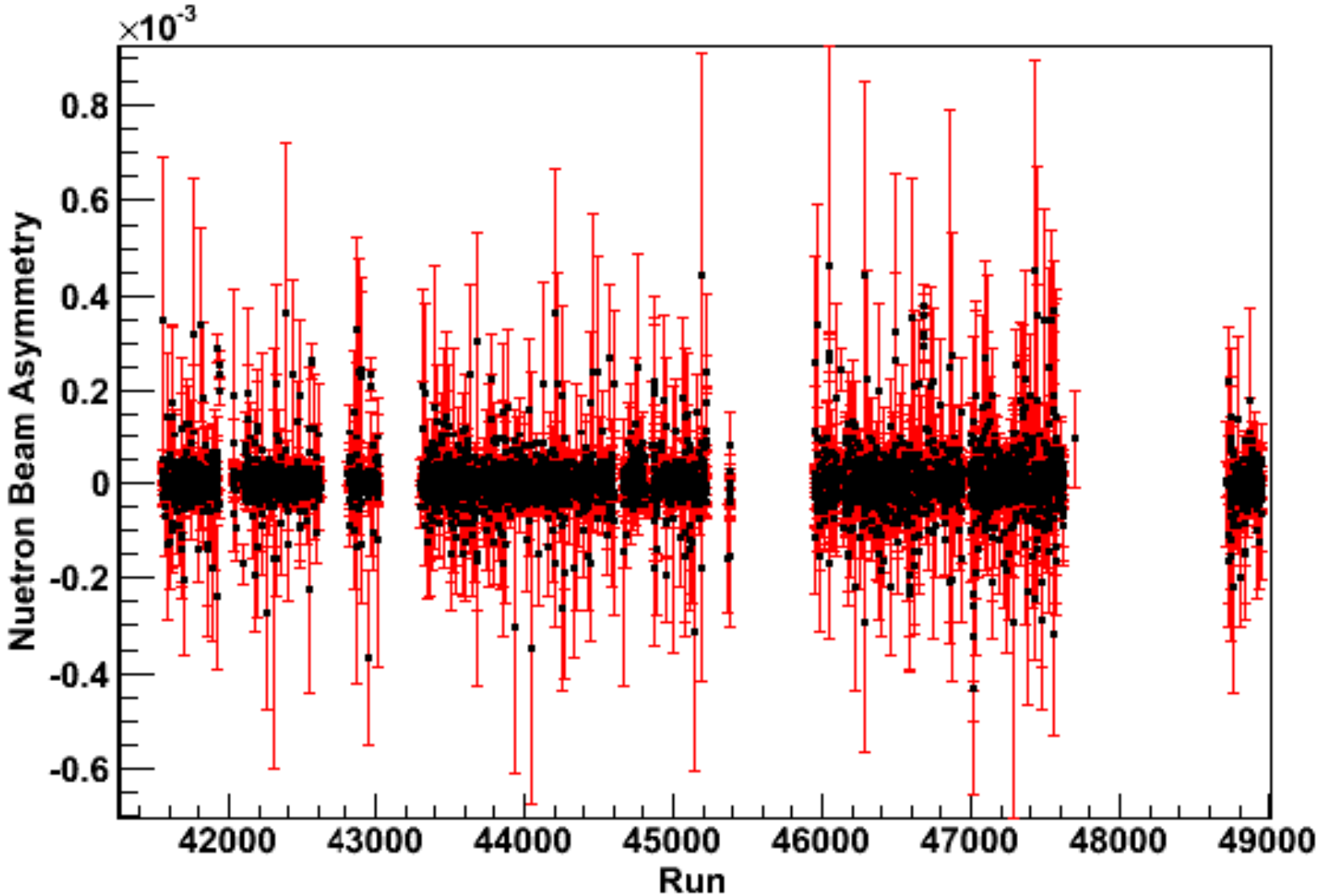
- essential to reduce instrumental systematics
  - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd order
  - danger: must isolate fields from detector
  - false asymmetries: additive & multiplicave
- works by the same principle as NMR
  - RF field resonant with Larmor frequency rotates spin
  - time dependent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





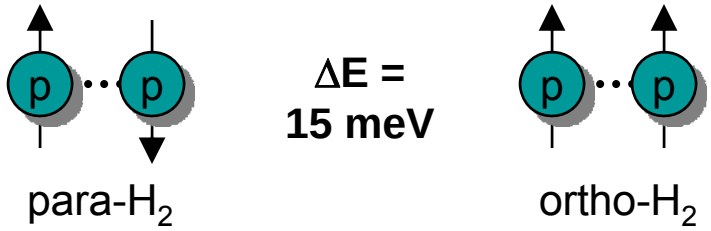


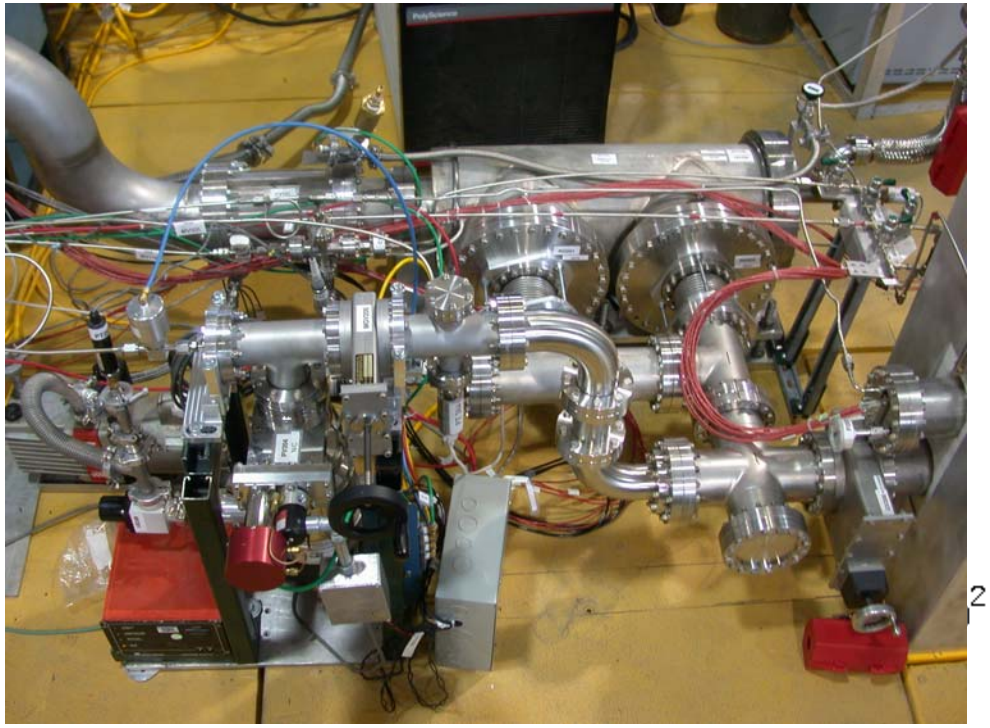
Beam stability



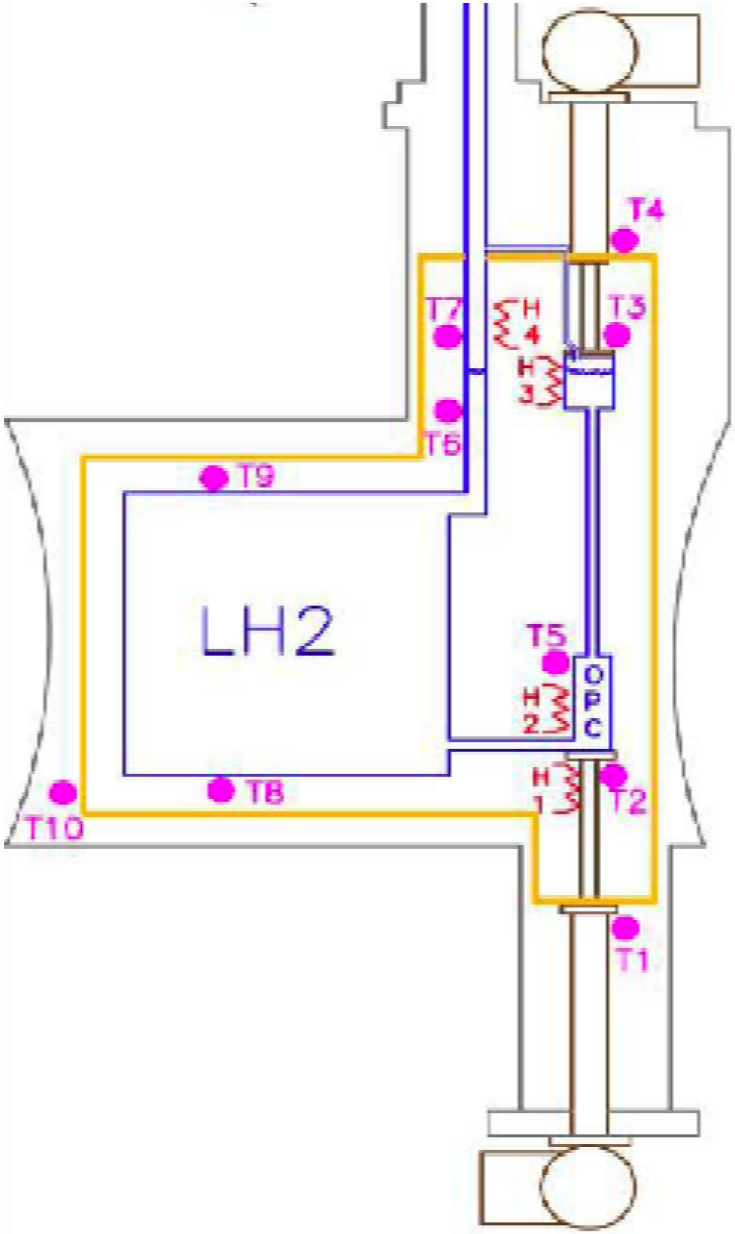
16L liquid para-hydrogen target

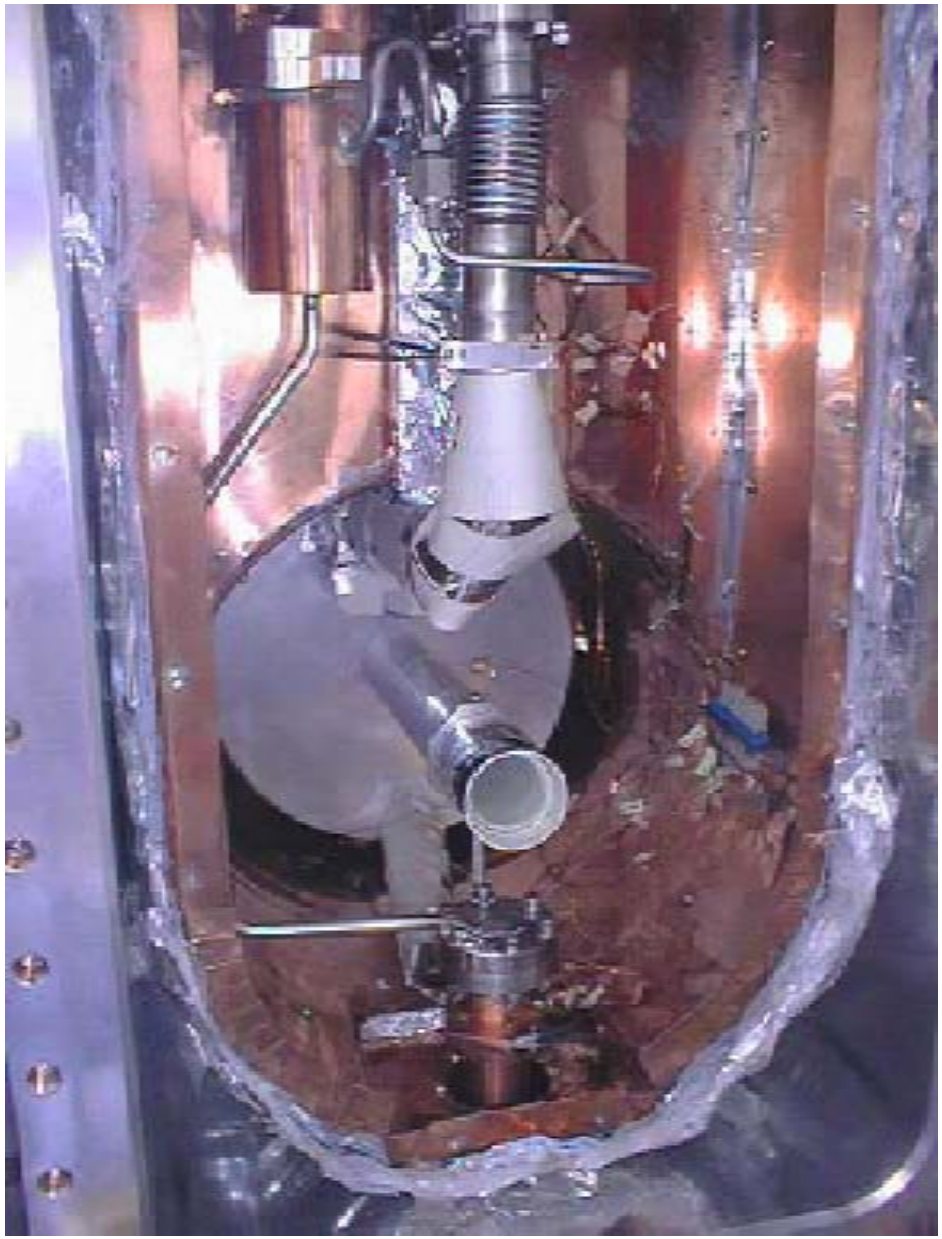
- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- super-cooled to reduce bubbles
- SAFETY !!





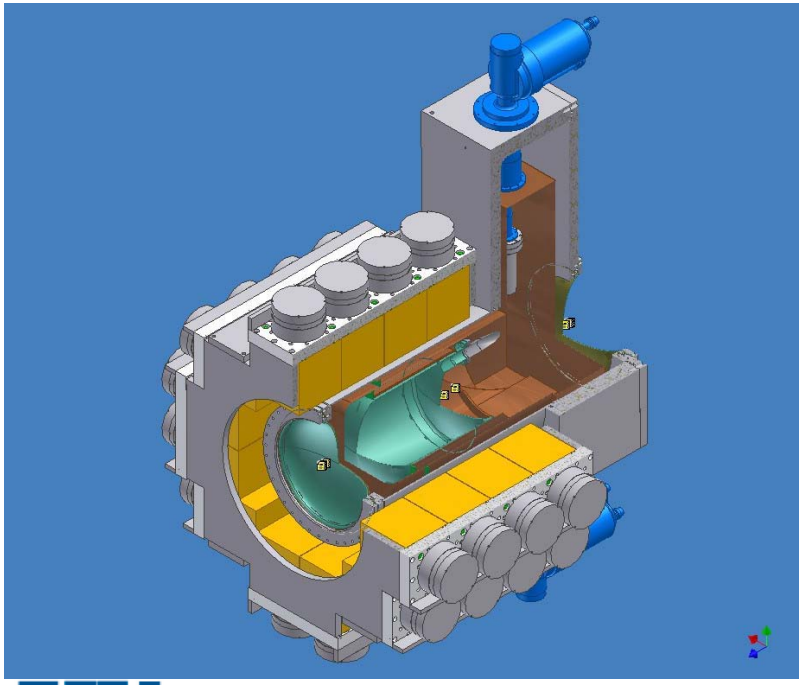
16L liquid para-hydrogen target

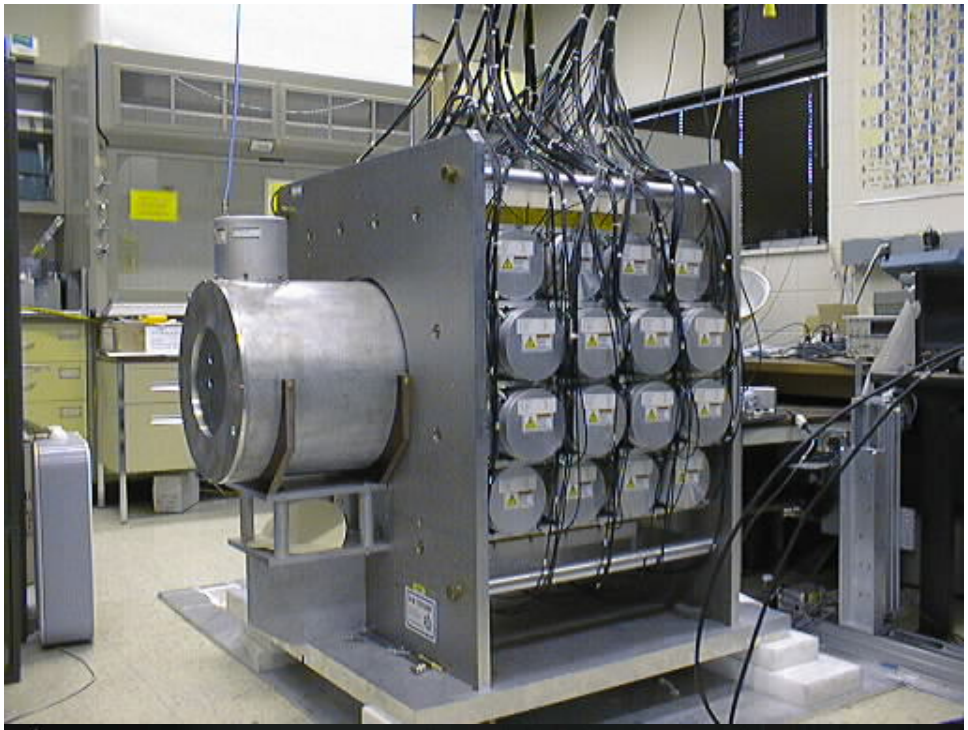


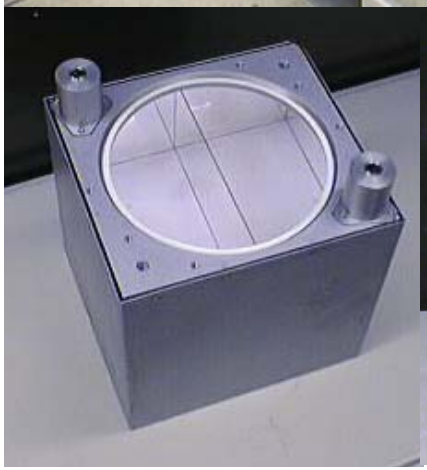


CsI(Tl) Detector Array

- 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







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Asymmetry analysis

yield (det,spin)

P.C. asym

background asym

P.V. asym

geometry factor

raw, beam, inst asym

RFSF eff.

neutron pol.

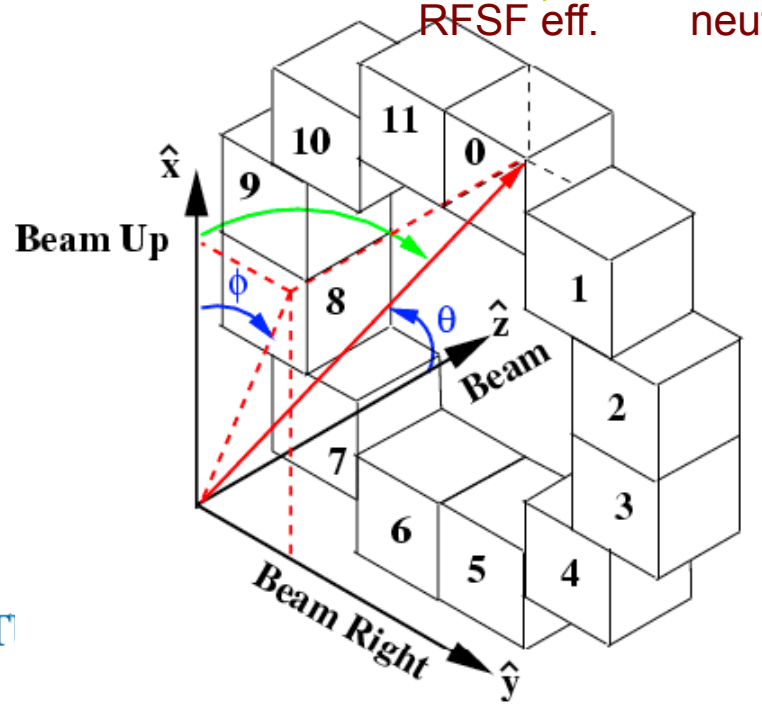
target depol.

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

$$\left(A^{j,p}_{UD}(t_i) + \beta A^{j,p}_{UD,b}(t_i)\right)\langle G_{UD}(t_i)\rangle + \left(A^{j,p}_{LR}(t_i) + \beta A^{j,p}_{LR,b}(t_i)\right)\langle G_{LR}(t_i)\rangle$$

$$= \frac{\left(A^{j,p}_{raw} - A^p_g A_f(t_i) - A^p_{noise}\right)}{E(t_i)P_n(t_i)S(t_i)}$$

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



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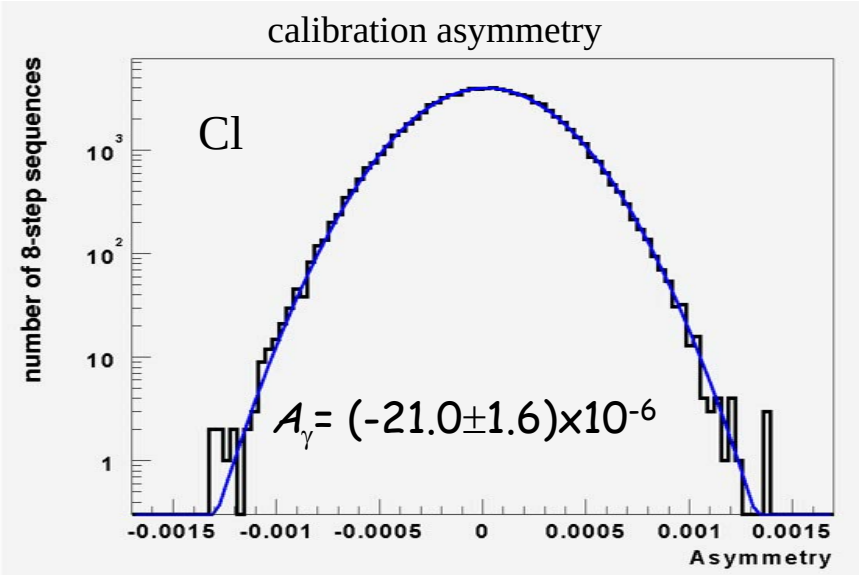
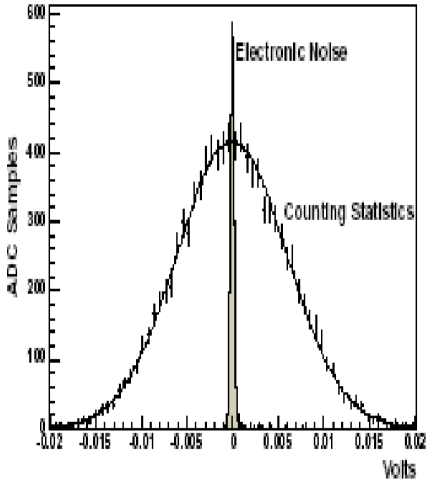
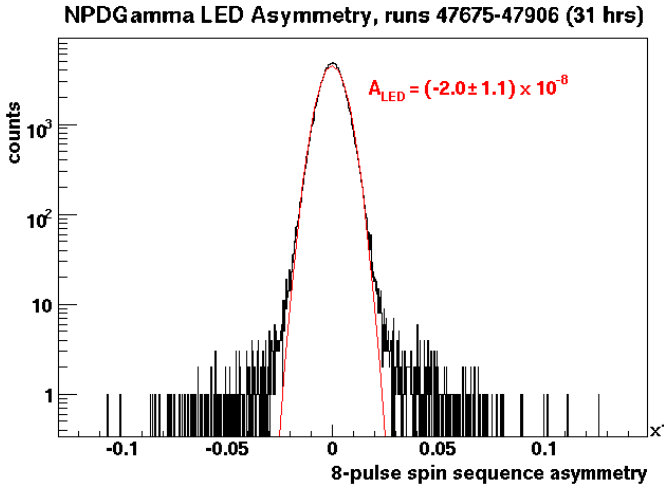
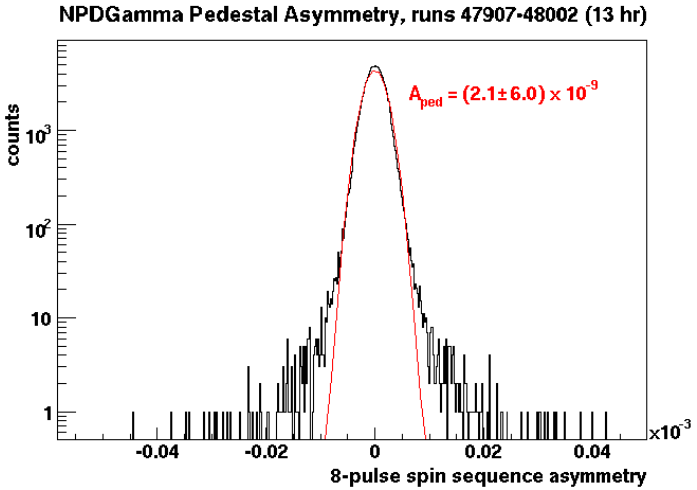
Engineering Runs



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

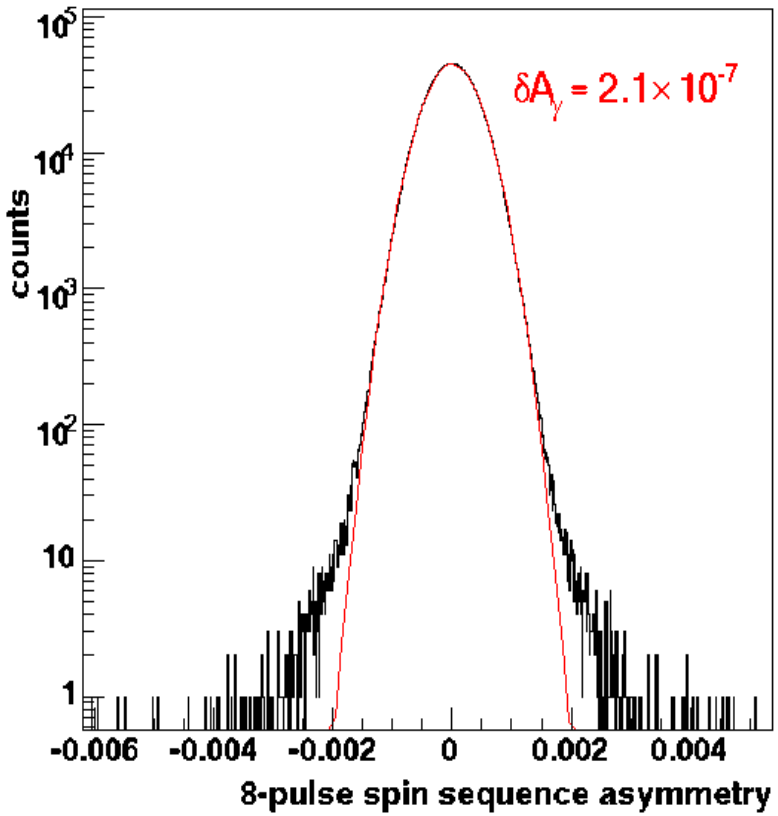


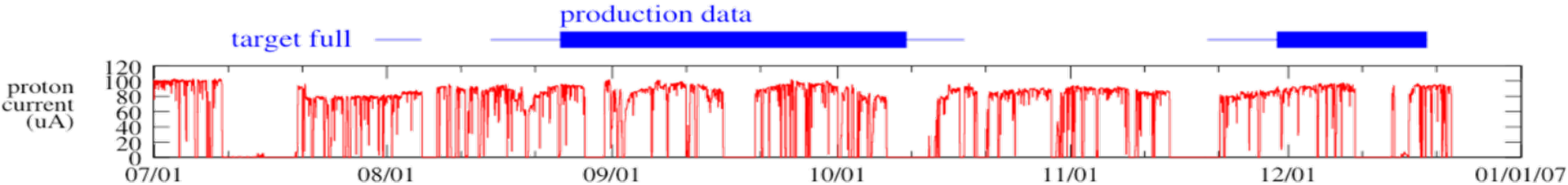




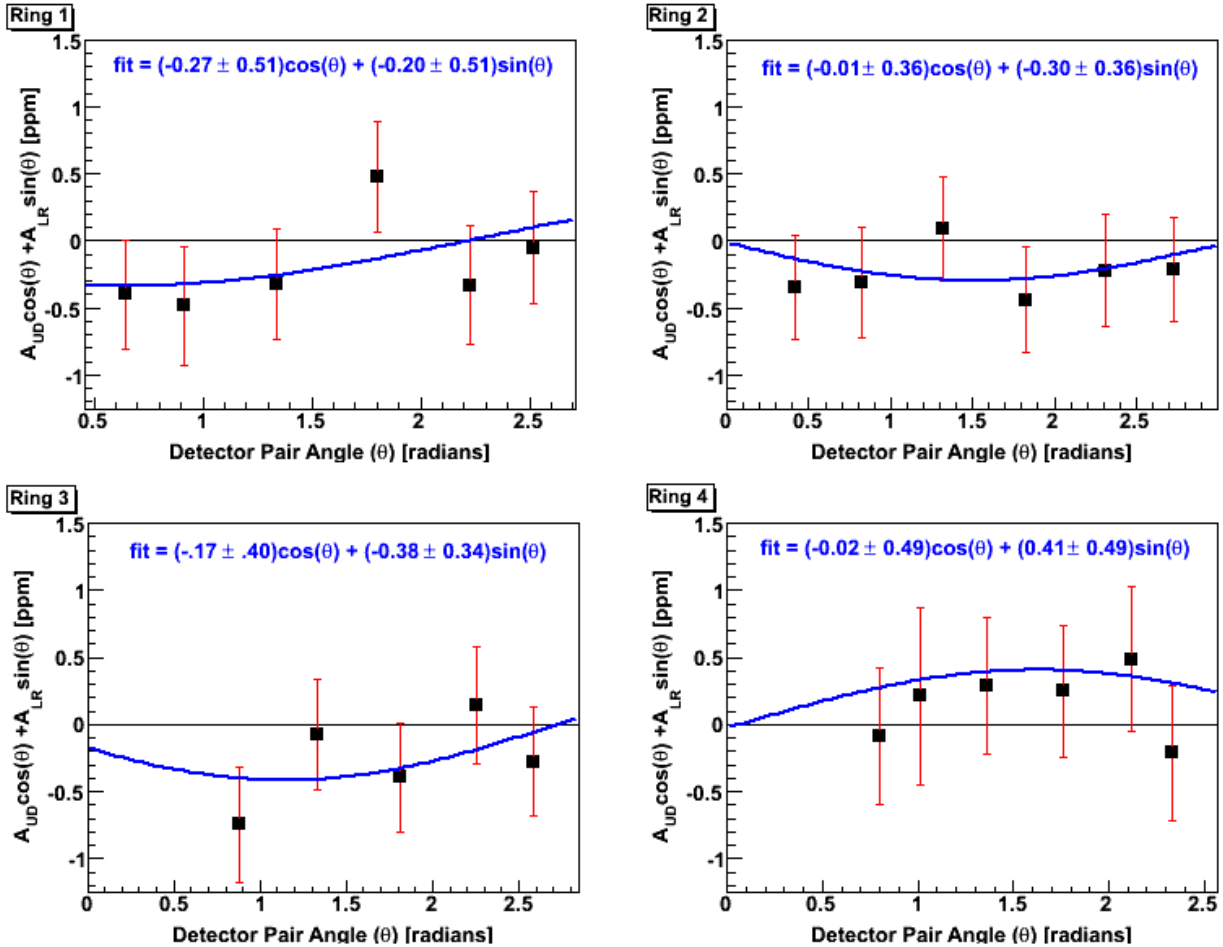
LH_2 run – Fall 2006

- Number of good runs
  5401 / 750 h
- Average delivered proton current
  89 A at 80 kW
- Average beam pol. (3He spin filter)
  55 +/- 7.5 %
- Spin-flip efficiency
  98 +/- 0.8%
- Para-hydrogen fraction in LH2 target
  99.98 %
- Beam depolarization in target
  2 %
- Data loss (cuts, bad events)
  ~1 %





Preliminary results



Total statistical error: $A_{\gamma,UD} = (-1.1 \pm 2.1) \times 10^{-7}$ $A_{\gamma,LR} = (-1.9 \pm 2.0) \times 10^{-7}$

Total systematic error: a (very) conservative 10% mostly due to polarization

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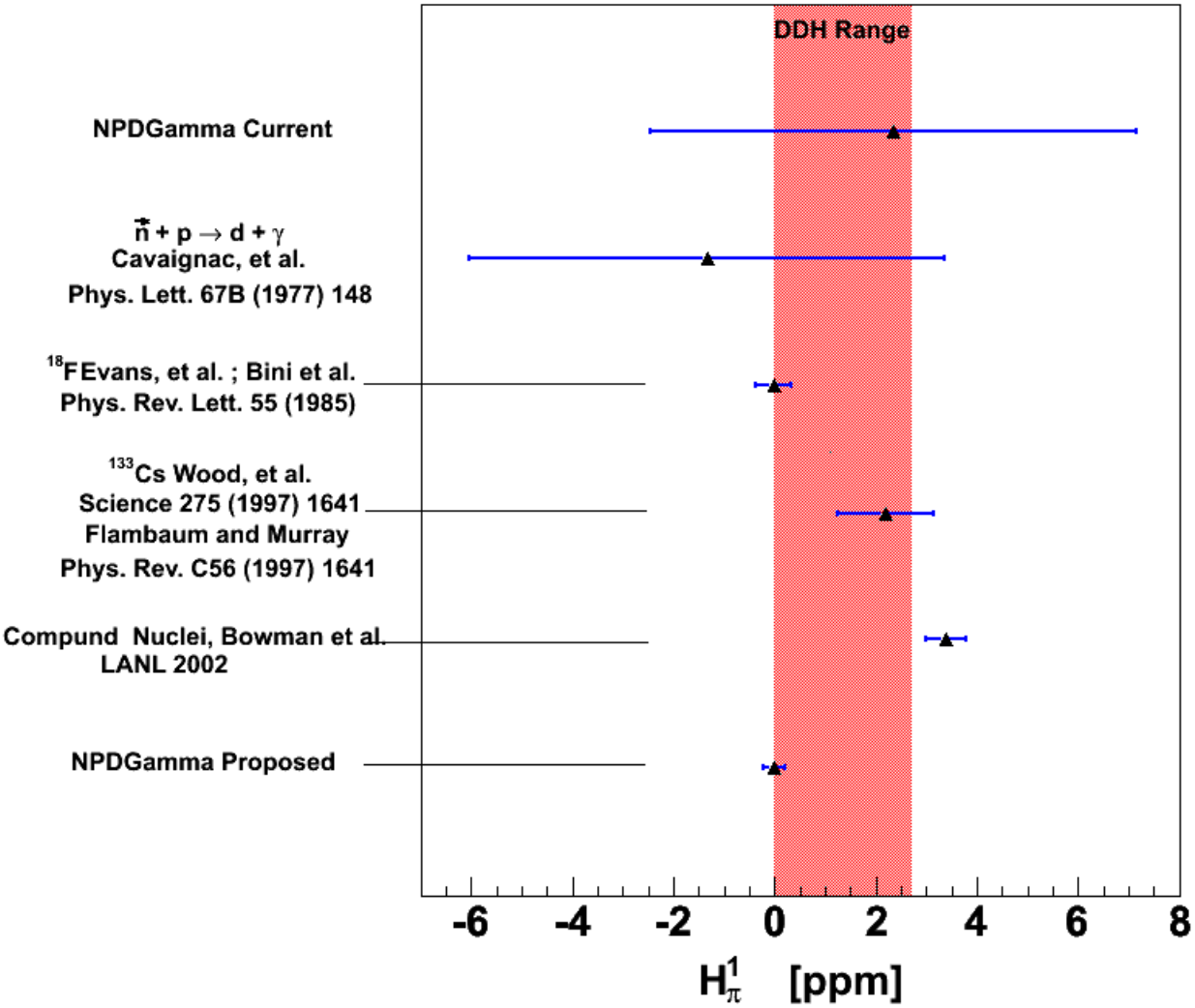
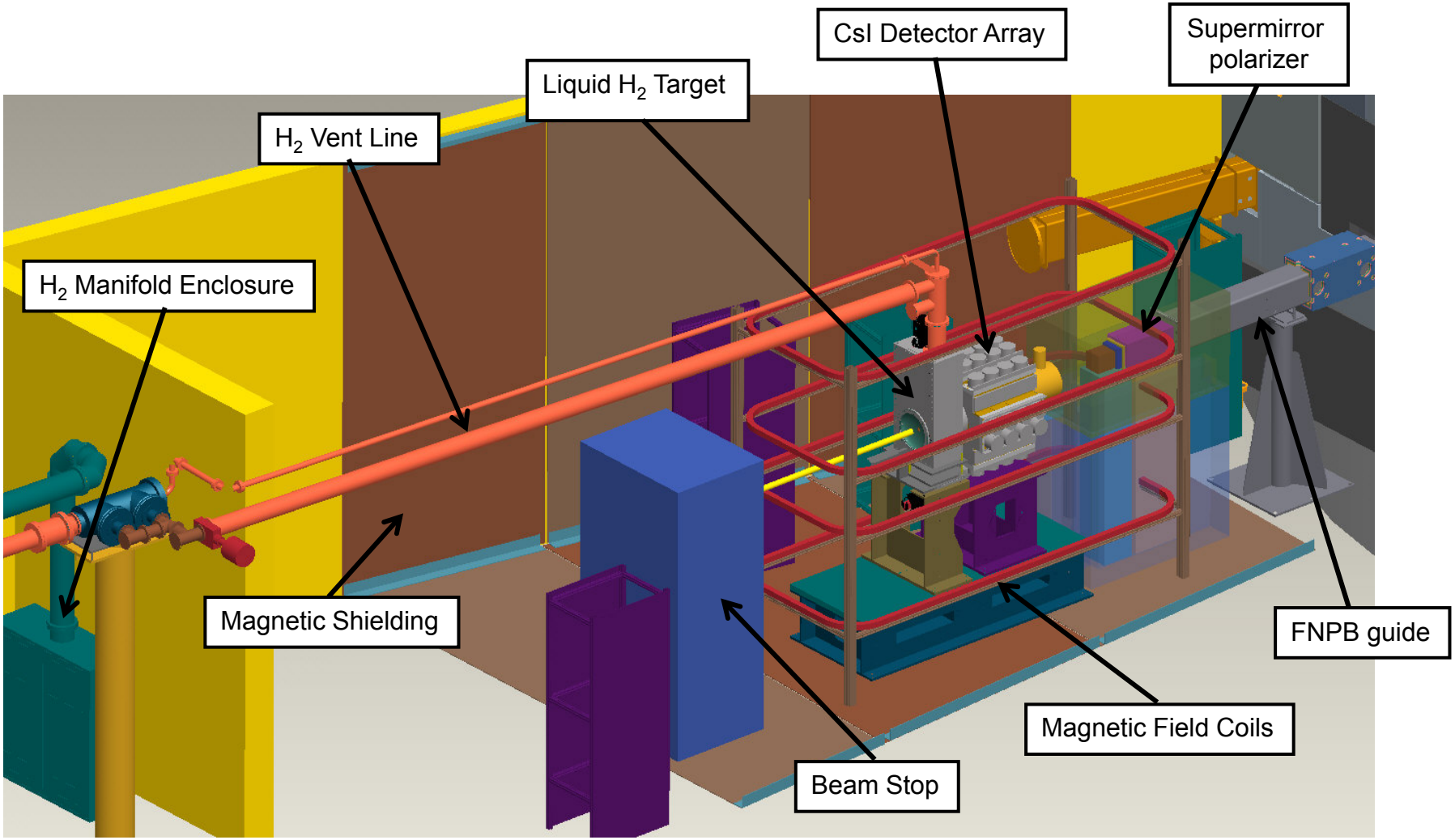
Preliminary results



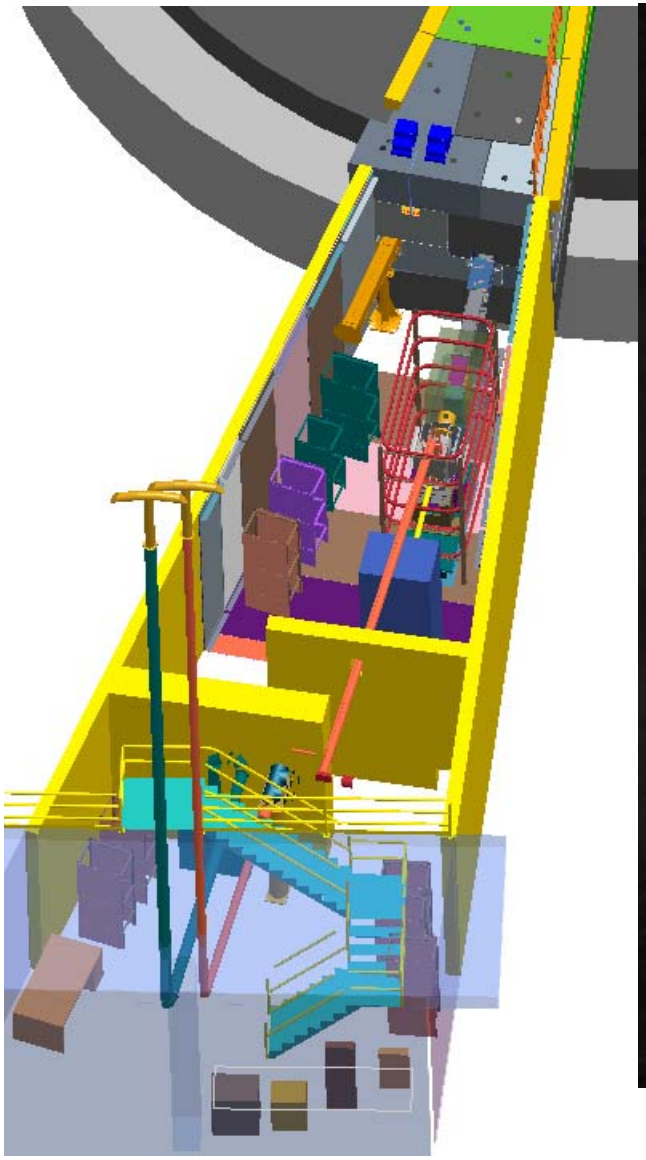
Gain in sensitivity at the SNS

- 12.0 x brighter at the end of the SNS guide
- 4.1 x gain by new SM polarizer
- 6.5 x longer running time
- Higher duty factor at SNS
- projected sensitivity:
  $\delta A = 1 \times 10^{-8}$ in 10^{7}s
- Installation: currently underway
- Commissioning: mid 2009
- Data-taking: early 2010

Experimental setup at the FnPB



NPDGamma cave and shielding



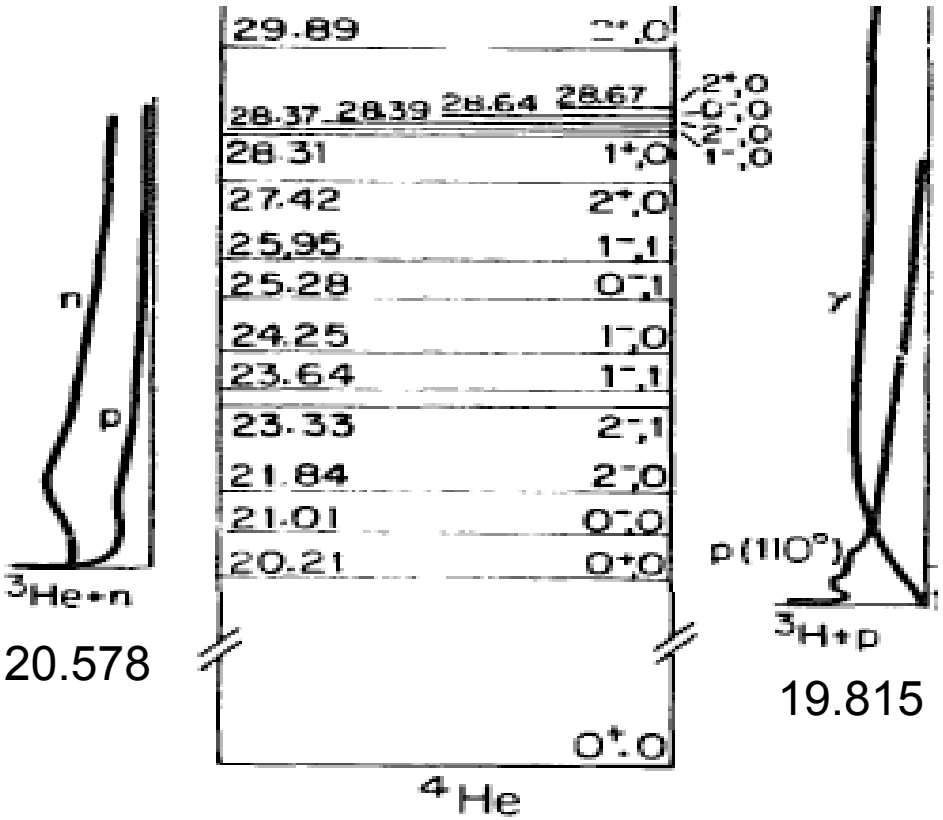
n-^{3}He collaboration

- J.D. Bowman (PI), S.I. Penttilä — Oak Ridge National Laboratory
- M.T. Gericke (PI), S.A. Page, Mark McCrea — University of Manitoba
- C.B. Crawford (PI), Y. Shin, E. Martin — University of Kentucky
- C. Gillis, J. Mei — Indiana University
- J. Martin — University of Winnipeg
- V. Gudkov — University of South Carolina
- M. Viviani — INFN, Sezione di Pisa
- A. Klein, A. Salas-Bacci, A. Hayes, G. Hale — Los Alamos National Lab
- R. Mahurin — University of Tennessee
- P.-N. Seo — Triangle Universities Nuclear Lab
- L. Barron — Universidad Nacional Autónoma de México

n-^{3}He PV Asymmetry

$$\vec{n} + {}^3\mathrm{He} \rightarrow p + t + 764\ \mathrm{keV}$$

S(I): $\frac{1}{2}\left(\frac{1}{2}\right) + \frac{1}{2}\left(\frac{1}{2}\right) \longrightarrow \frac{1}{2}\left(\frac{1}{2}\right) + \frac{1}{2}\left(\frac{1}{2}\right)$



Tilley, Weller, Hale, Nucl. Phys. A541, 1 (1992)

PV observables:

$\sigma_n \cdot k_n$ ~ k_n very small for low-energy neutrons

$\sigma_n \cdot k_p$, $\sigma_n \cdot k_t$ - essentially the same asym.
- must discriminate between back-to-back proton-triton

- 4He $J^\pi = 0^+$ resonance
  $${}^1S_0(I=0) \leftrightarrow {}^3P_0(I=0)$$
- sensitive to EFT coupling $\lambda_s^{I=0}$ or DDH couplings $h_\rho^0,\ h_\omega^0$
- ~10% ΔI=1 contribution (Gerry Hale, qualitative)
- A ~ 3×10^{-7} (M. Viviani, PISA)

Extraction of DDH couplings

	np A_γ	nD A_γ	n^{3}He A_p	np ϕ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	0.92	-0.18	-3.12	-0.97		-0.34
h_ρ^0		-0.50	-0.14	-0. 23	-0.32	0.08	0.14
h_ρ^1	-0.001	0.10	0.027		0.11	0.08	0.05
h_ρ^2		0.05	0.0012	-0.25		0.03	
h_ω^0		-0.16	-0.13	-0. 23	-0.22	0.07	0.06
h_ω^1	-0.003	-0.002	0.05		0.22	0.07	0.06

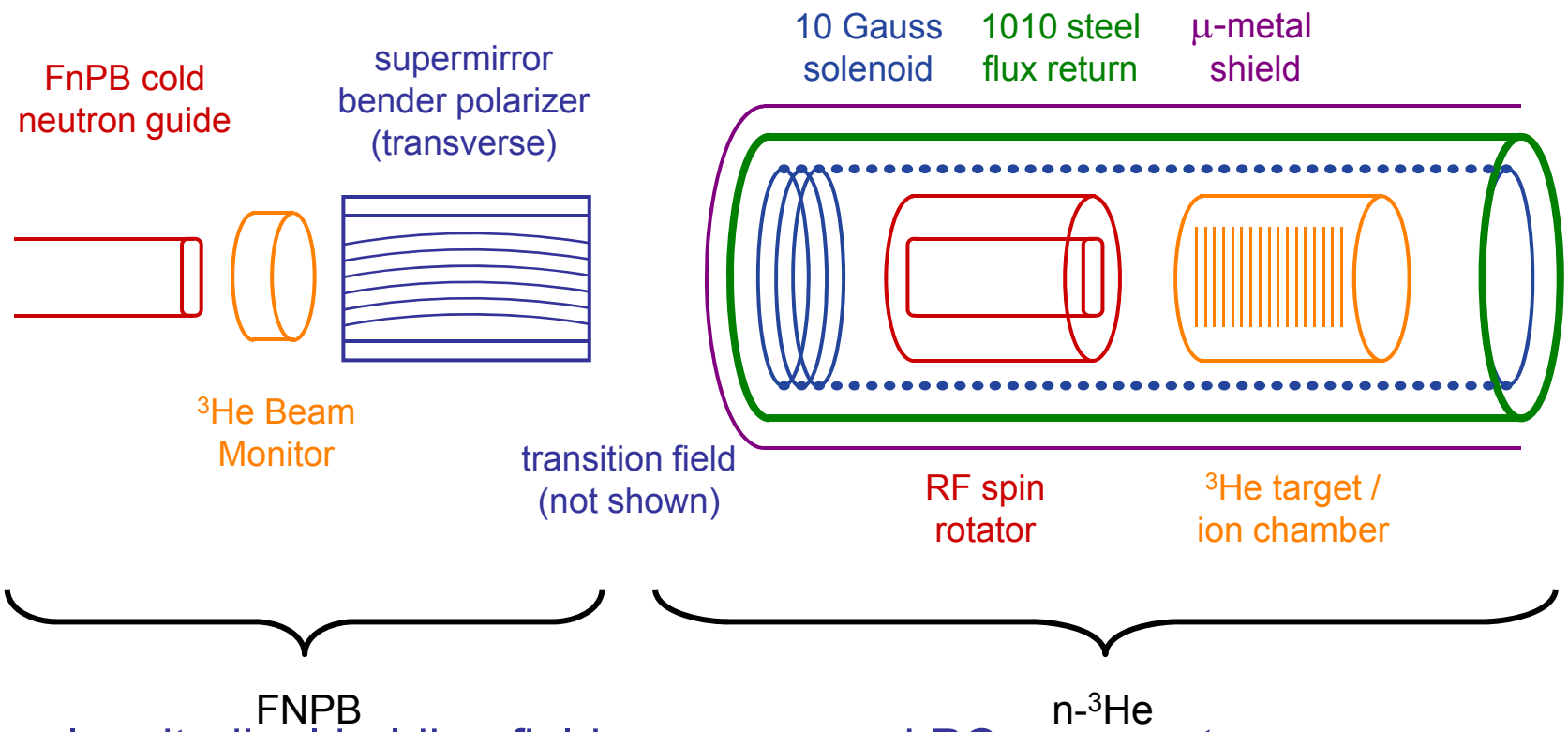
n-^{3}He:

M. Viviani

(PISA)

f_π	h_ρ^0	h_ρ^2	h_ω^0	
4.6	-11.4	-9.5	-1.9	DDH Best Value
0.0–11.4	-30.8–11.4	-11.–7.6	-10.3–5.7	DDH Reasonable Range
8.1%	15.8%	77.2%	36.4%	present / DDH Range (%)
5.8	14.0	64.7	36.4	present + npdγ
3.3	13.8	30.6	35.0	present + n^{3}He
3.1	13.4	30.3	34.0	present + npdγ + n^{3}He
8.2	24.6	132.6	36.4	present few body + npdγ
6.7	14.9	33.0	35.8	present few body + npdγ + n^{3}He

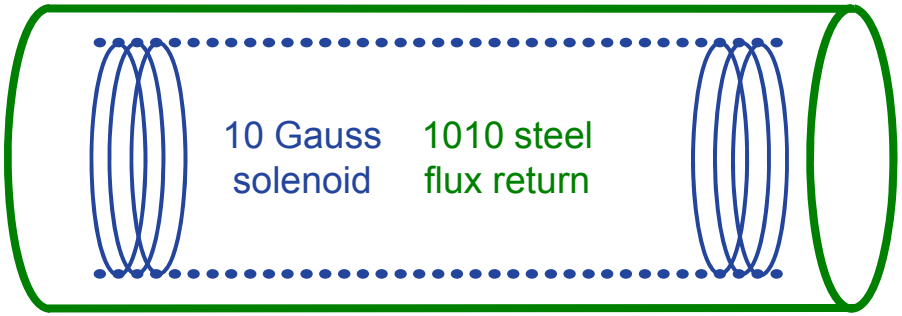
Experimental setup



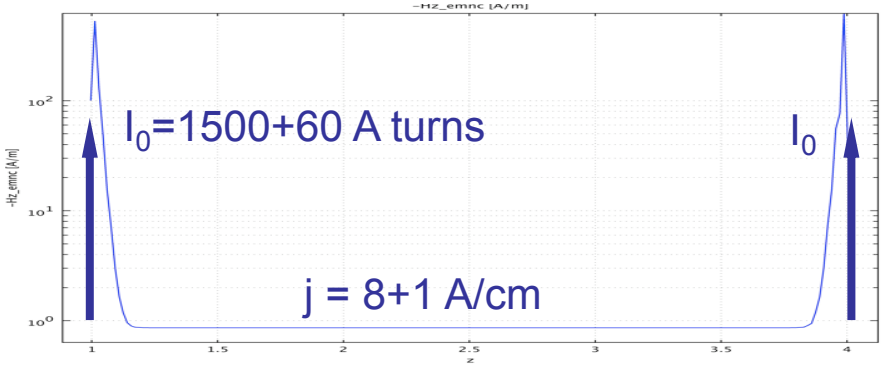
- longitudinal holding field – suppressed PC asymmetry
- RF spin flipper – negligible spin-dependent neutron velocity
- ^{3}He ion chamber – both target and detector

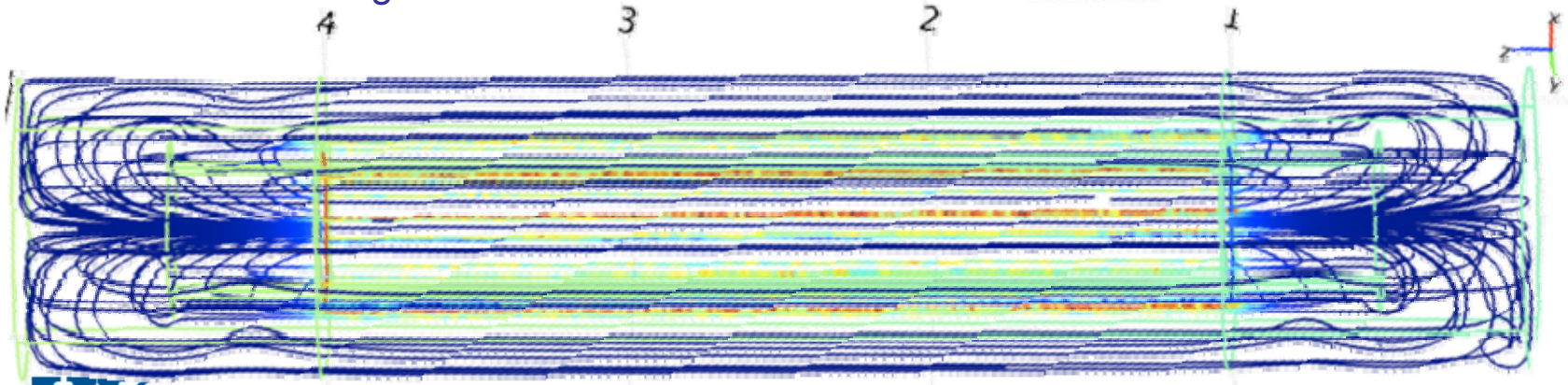
Solenoid holding field

- uniformity requirements
  - $\delta B \sim 0.3$ G $\mu ¢ \delta B/2E_n = 10^{-10} < \delta A_z$
  - $\theta_z \sim 0.1^{\pm}$ + alignment of wires
- preliminary design
  - solenoid with compensation coils at end for uniformity
  - μ-metal shield for residual earth's field
  - 1010 steel flux return to prevent saturation of μ-metal
- design parameters
  - 3 m length x 50 cm diameter
  - B =10 G for spin flipper
  - j = 9 A/cm winding density
  - I_0 = 1560 A (or end-cap windings)
- simulation using COMSOL



3 m £ 50 cm diam. 4 m £ 55 cm diam.





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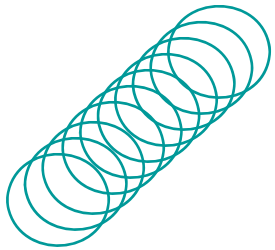
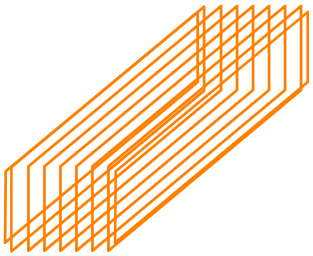
Radio frequency spin rotator

- extension of design for NPDGamma
  - P-N Seo *et al*., Phys. Rev. ST Accel. Beam, vol 11, 084701 (2008)
- new resonator for n-3He experiment
  - transverse horizontal RF B-field
  - longitudinal / transverse flipping
  - no fringe field - 100% efficiency
  - compact geometry - efficient
    - small diameter solenoid
  - matched to driver electronics for NPDGamma spin flipper
- prototype design
  - parasitic with similar design for nEDM guide field near cryostat
  - fabrication and testing at UKy – 2009



NPDGamma windings

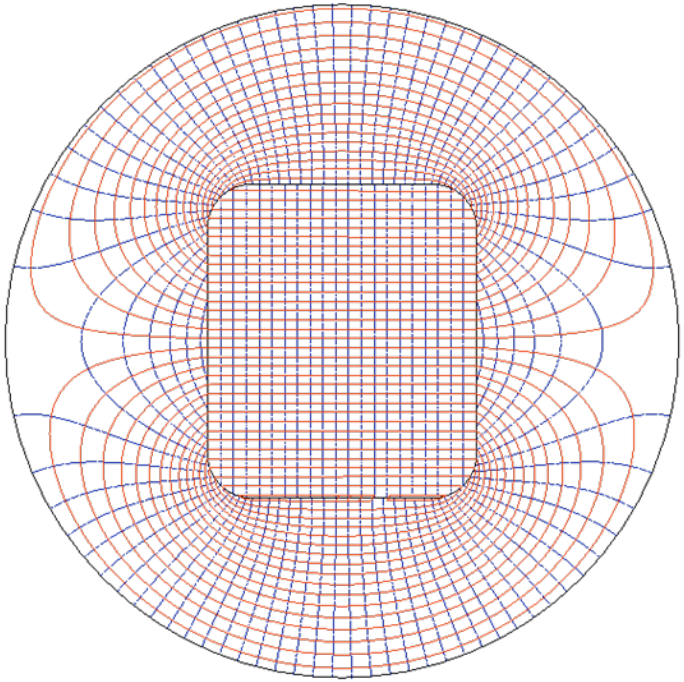


n-^{3}He windings

Magnetostatic calculation with COMSOL

red - transverse field lines

blue - end-cap windings



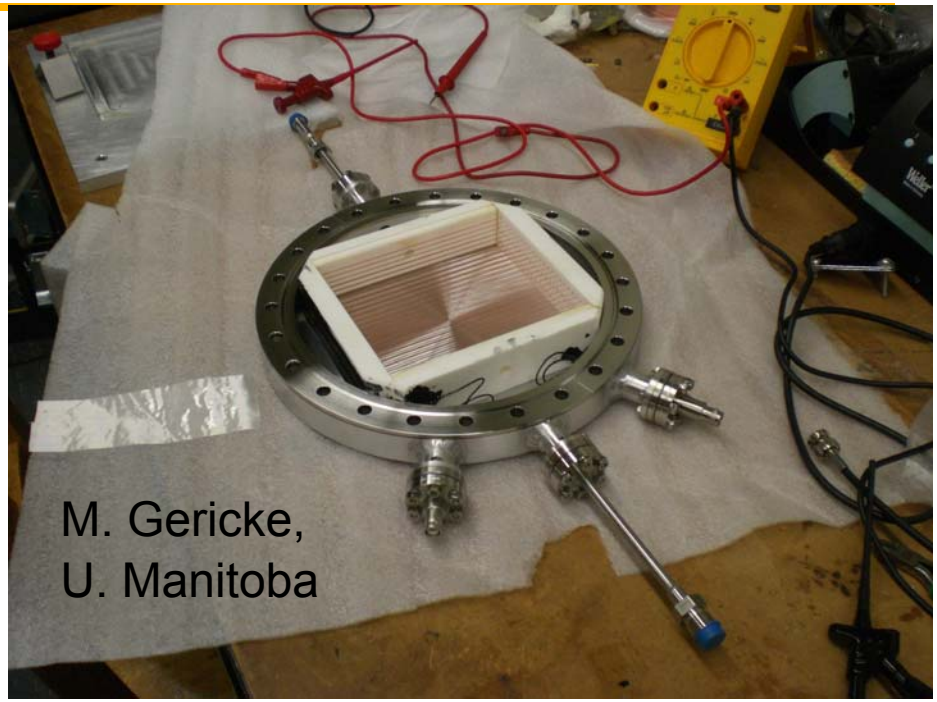
$$\nabla^2 \Phi_M = 0 \qquad \frac{\partial \Phi_M}{\partial n} = H_n$$

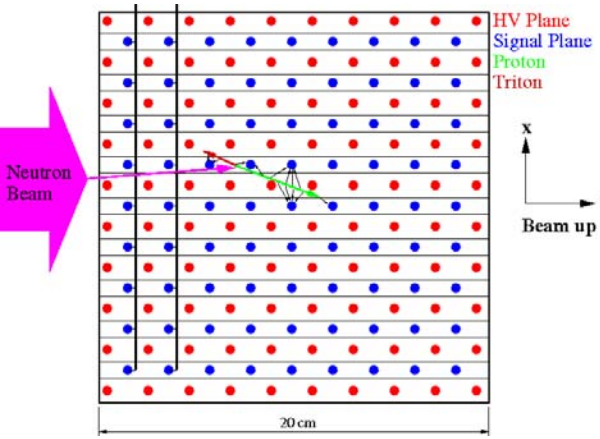
$$\hat{\boldsymbol{n}} \times \boldsymbol{H} = \boldsymbol{j} \qquad -\boldsymbol{\nabla} \Phi_M = \boldsymbol{H}$$

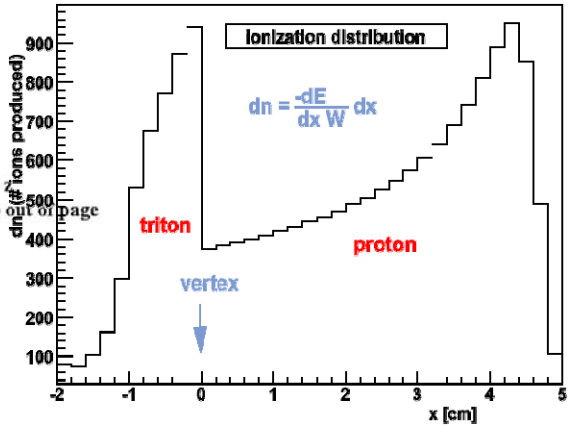
$$\boldsymbol{\nabla} \Phi_M \cdot \boldsymbol{j} = 0 \qquad \Delta \Phi_M = \int \boldsymbol{j} \cdot \boldsymbol{dl}$$

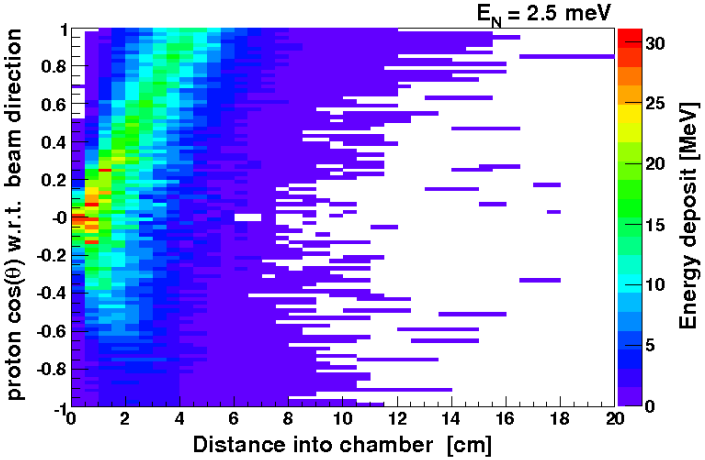
^{3}He target / ion chamber

- MC simulations of sensitivity to proton asymmetry
  - including wire correlations
  - δ A ~ 6 /pN
- tests at LANSCE FP12
  - fission chamber flux calibration
  - prototype drift chamber R&D
  - new beam monitors for SNS
- design of new ion chamber for NPDGamma, test at LANL









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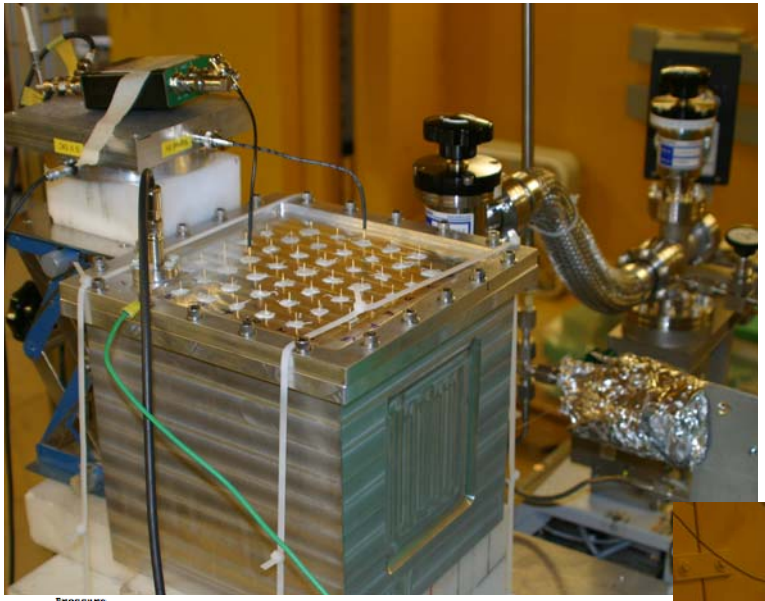
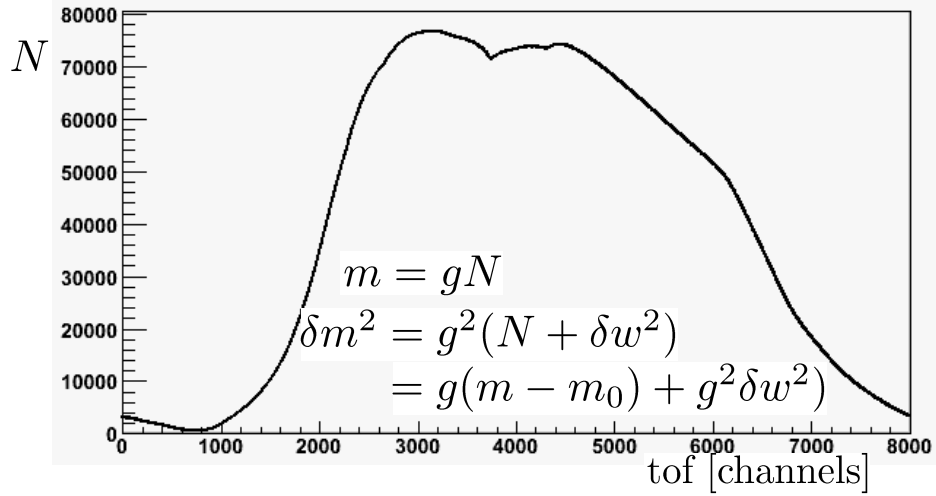
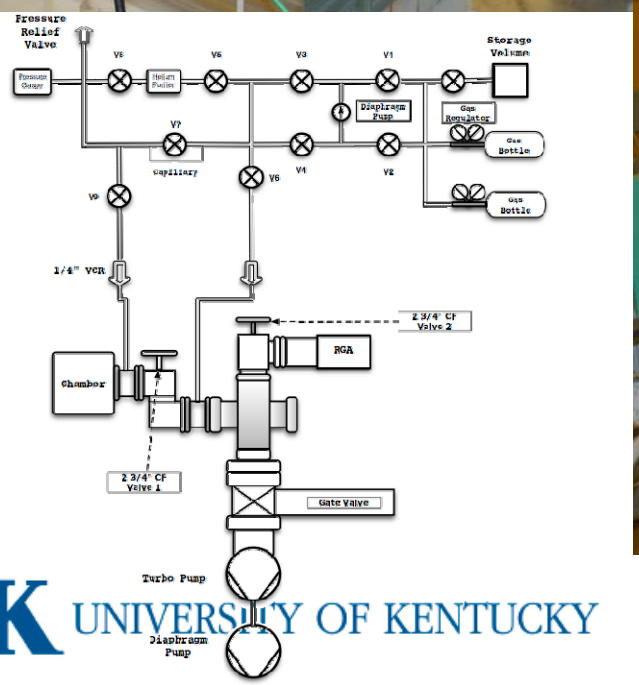
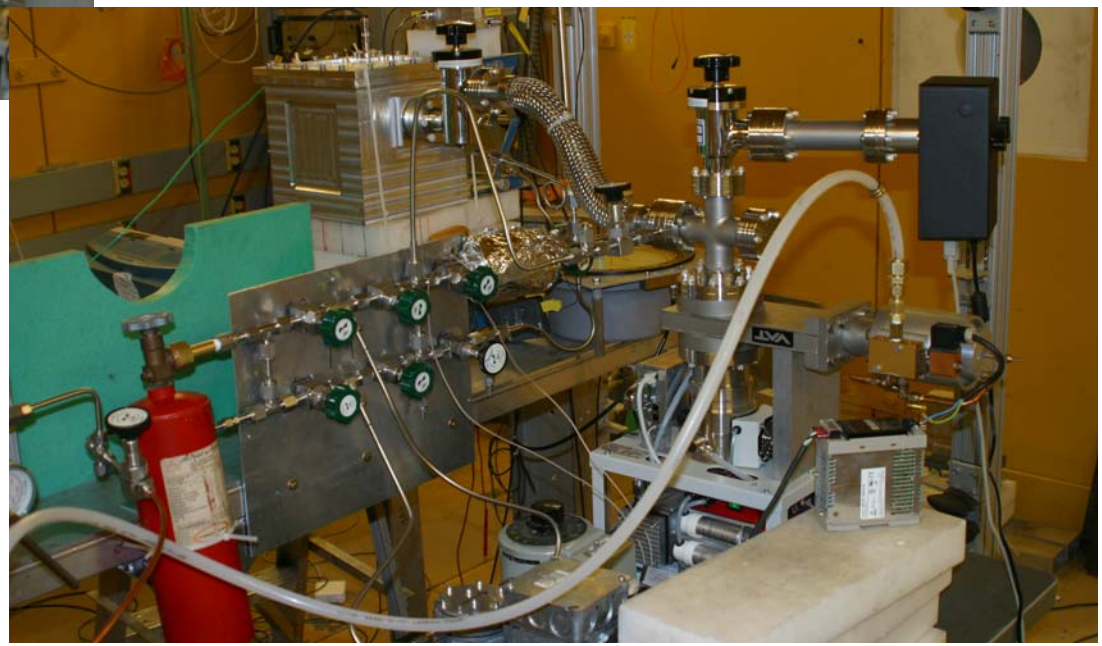
LANSCE FP12 ^{3}He chamber R&D









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NDPGamma vs. NDTGamma

- capture cross section
  - 1000x smaller in D_2O
  - σ_H = .3326 b, σ_D = .000519 b
- neutron polarization
  - para-hydrogen: no depolarization
  - D_2O: spin-flip scattering
- expected asymmetry
  - 20 times larger than NPDGamma

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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TIFF (Uncompressed) decompressor
are needed to see this picture.

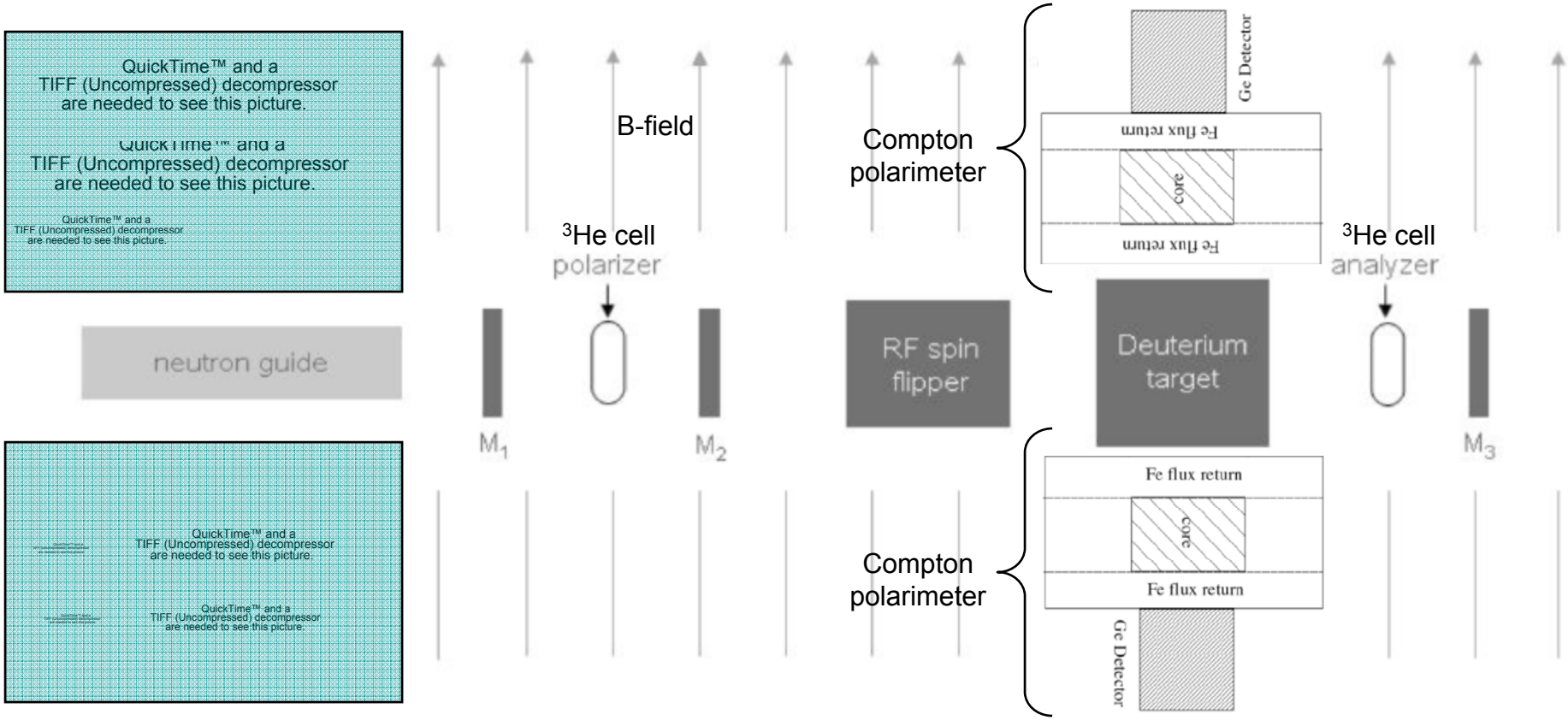
  - previous measurement (ILL)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

  - goal: measure δA_γ = 4£10^{-7} at the SNS

Neutron Depolarization in D_2O

- Compton Polarimetry test run at LANSCE: 2008, 2009
- DePauw U., Indiana U., U. Kentucky, U.N.A. Mexico, Michigan U., Hamilton C., NIST, ORNL, LANL



NDTγ Target Design

- need extremely low background
- conflict with D_2 safety requirement of thick vacuum chamber
- must shield gammas from all windows
- D_2O ice needs cooled from outside shielding
- target thickness optimization: 13 cm

Indiana Univ.

Conclusion

- there is a viable program to measure the HWI with PV reactions in few-body systems
- p-p, p-α elastic scattering complete
- n-α spin rotation has taken data
- $n + p \rightarrow d + \gamma$ will run at the SNS in 2010
- $n + {}^3He \rightarrow t + p$ will run at the SNS in 2011
- $n + p \rightarrow d + \gamma$ and others are in planning stage
- we will soon have significant tests of EFT in the $\Delta S = 0$ sector using few-body reactions only