# Parity-odd Neutron Spin Rotation

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Indiana University
for the NSR collaboration

Physics of Fundamental Symmetries and Interactions
PSI, September 10, 2013

# Why Hadronic Weak Interactions?

We know there is a quark-quark Weak interaction:

$$A_\gamma(^{180}\mathrm{Hf}^* \to \ ^{180}\mathrm{Hf} + \gamma) = -(1.66 \pm 0.18) \times 10^{-2}$$

$$A_h(\vec{n} \ + \ ^{139}\mathrm{La}) = (9.55 \pm 0.35) \times 10^{-2}$$

Enhanced PV signal from compound nuclear resonances

…but we don't fully understand observations because the low-energy (non-perturbative) limit of QCD controls how the HWI manifests itself. Need to study simpler systems:

## Non-leptonic Flavor-changing

meson decays: EFT is effective, but, e.g., ΔI=1/2 rule not fully understood

$$\mathrm{K} \to \pi\pi$$

baryon decays: ΔS=1 hyperon decay properties don't follow from QCD symmetries

Evidence of non-trivial QCD ground state dynamical phenomena?

$$\Lambda \to N\pi$$

## Flavor-conserving NN Interactions

$$\frac{\mathcal{M}_{\mathrm{weak}}}{\mathcal{M}_{\mathrm{strong}}} \sim \frac{e^2/M_{\mathrm{W}}^2}{g^2/M_\pi^2} \sim 10^{-7}$$

Hallmark is use of PV to single out weak part of interaction

- ΔS=0 : is strange quark or light quark dynamics in general responsible for hyperon decay?
- Sensitive to NC effects at low energy, probes the QCD ground state
- NN and few-body systems

# SM Framework for HWI

## Current-current form at low energy ($\Lambda_{QCD} < q < v$)

$$\mathcal{H}_{\mathrm{weak}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} \left( J_\mu^{(\mathrm{C})\dagger} J^{(\mathrm{C})\mu} + \frac{1}{2} J_\mu^{(\mathrm{N})\dagger} J^{(\mathrm{N})\mu} \right) + \mathrm{h.c.}$$

$$J_\mu^{(\mathrm{C})} = \mathcal{U}_{ud} \overline{u} \gamma_\mu (1+\gamma_5) d + \mathcal{U}_{us} \overline{u} \gamma_\mu (1+\gamma_5) s$$

$$J_\mu^{(\mathrm{N})} = \overline{u} \gamma_\mu (1+\gamma_5) u - \overline{d} \gamma_\mu (1+\gamma_5) d - \overline{s} \gamma_\mu (1+\gamma_5) s - 4 \sin^2 \theta_{\mathrm{W}} J_\mu^{\mathrm{em}}$$

$v \sim 246$ GeV

$\Lambda_{\mathrm{HAD}} \sim 1$ GeV

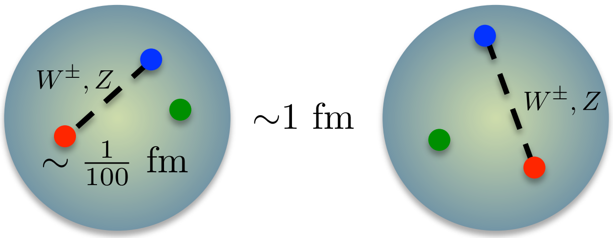
$\Lambda_{\mathrm{QCD}} \sim 200$ MeV

$m_\pi \sim 140$ MeV

$$\Delta I = 2 \longrightarrow J_{I=1}^{(\mathrm{C})} J_{I=1}^{(\mathrm{C})}$$

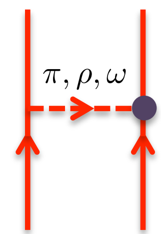
$$\Delta I = 1 \longrightarrow J_{I=1/2}^{(\mathrm{C})} J_{I=1/2}^{(\mathrm{C})} + J_{I=1}^{(\mathrm{N})} J_{I=1}^{(\mathrm{N})}$$

$$\Delta I = 0 \longrightarrow J_{I=0}^{(\mathrm{C})} J_{I=0}^{(\mathrm{C})} + J_{I=0}^{(\mathrm{N})} J_{I=0}^{(\mathrm{N})} + J_{I=1}^{(\mathrm{N})} J_{I=1}^{(\mathrm{N})}$$

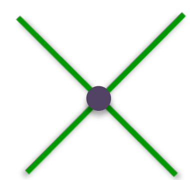



## Calculation of the NN Weak Interaction ($q < \Lambda_{QCD}$)

DDH: Model dependent, seven (non-elementary) meson-nucleon couplings: $h_\pi^1, h_\rho^{0,1,2}, h_\rho^{1'}, h_\omega^{0,1}$

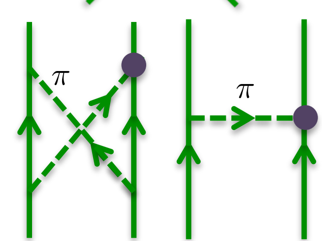



EFT: Model-independent, QCD symmetries built in, perturbative expansion in q/Λ, pionful (q~140MeV) theory has six parameters



$\boxed{\lambda_s^{0,1,2},\ \lambda_t,\ \rho_t,}\ \widetilde{C}_6^\pi \propto h_\pi^1$

$$\boxed{\begin{array}{l} (I=1)^+ \otimes L^+ \otimes (S=0)^- \to {}^1S_0\,, \ldots \\ (I=1)^+ \otimes L^- \otimes (S=1)^+ \to {}^3P_{0,1,2}, \ldots \\ (I=0)^- \otimes L^- \otimes (S=0)^- \to {}^1P_1\,, \ldots \\ (I=0)^- \otimes L^+ \otimes (S=1)^+ \to {}^3S_1\,, \ldots \end{array}}$$



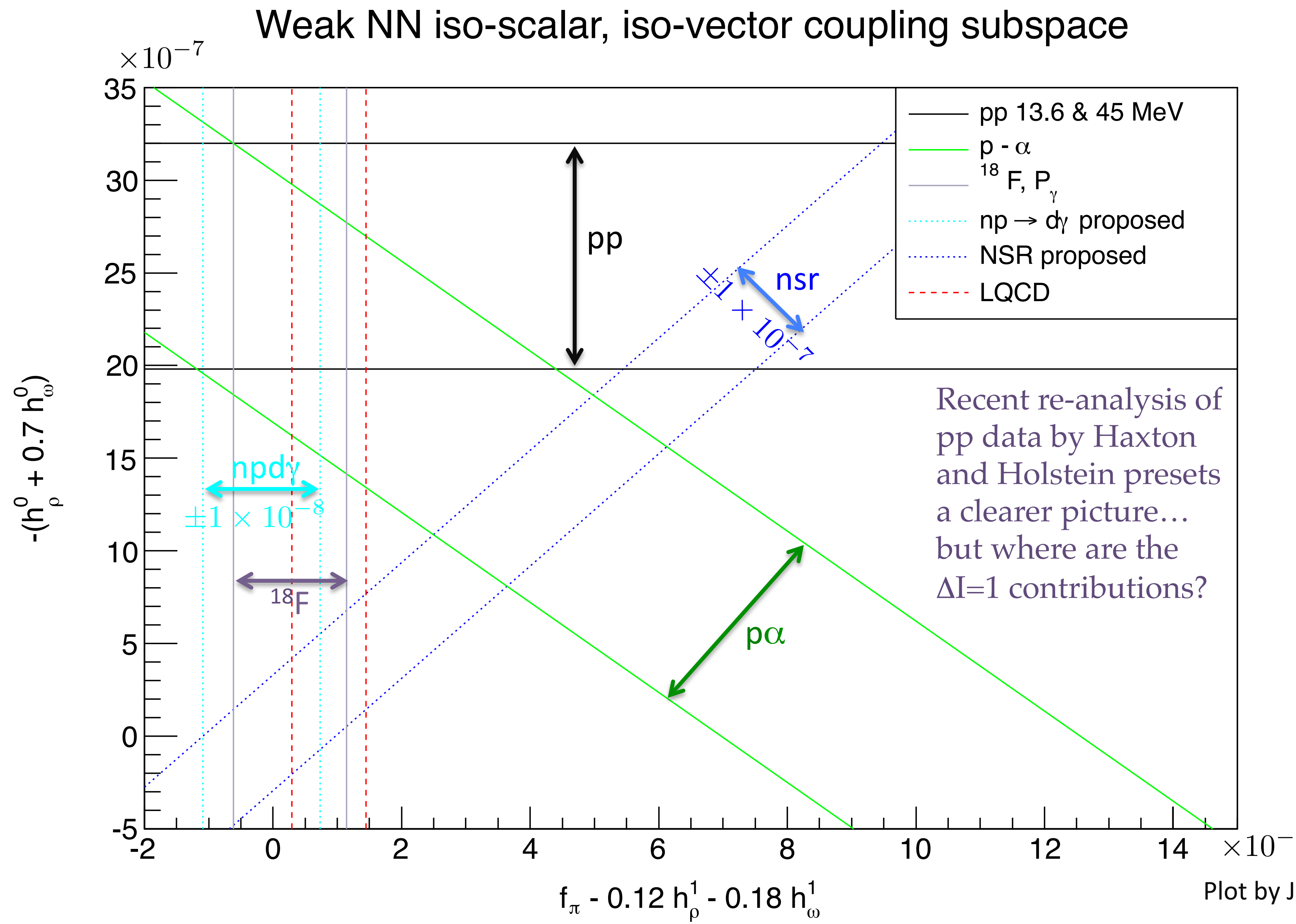

Lattice QCD: Gold standard

# PV Observables in terms of DDH Parameters

| | $h_\pi^1$ | $h_\rho^0$ | $h_\rho^1$ | $h_\rho^2$ | $h_\omega^0$ | $h_\omega^1$ | Status |
|---|---|---|---|---|---|---|---|
| $\phi_{\mathrm{PV}},\ n^4\mathrm{He}$ <br> $\sigma_n \cdot k_n$ | -0.97 | -0.32 | 0.11 | 0 | -0.22 | 0.22 | will run at NIST |
| $A_\gamma,\ npd\gamma$ <br> $\sigma_n \cdot k_\gamma$ | -0.107 | 0 | -0.001 | 0 | 0 | 0.004 | running at SNS |
| $A_p,\ n^3He$ <br> $\sigma_n \cdot k_p$ | -0.189 | -0.036 | 0.019 | -0.001 | -0.033 | 0.041 | proposed at SNS |
| $A_L,\ p\alpha$ <br> $\sigma_p \cdot k_p$ | -0.333 | 0.140 | 0.047 | 0 | 0.059 | 0.059 | 1982-1985 |
| $A_L,\ pp$ <br> $\sigma_p \cdot k_p$ <br> (45 MeV) | 0 | 0.074 | 0.074 | 0.030 | 0.067 | 0.067 | 1991-2003 |
| $P_\gamma,\ ^{18}F$ | 4385 | 0 | 0 | 0 | 0 | 0 | 1978-1987 |

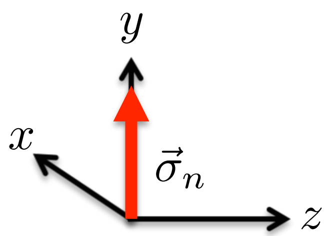
- Recent experiments focus on simple NN and few-nucleon systems
- Many-body systems are also beginning to contribute via measurements of the nuclear anapole moment

# The Current Experimental Landscape, DDH-Style




Plot by J. Fry

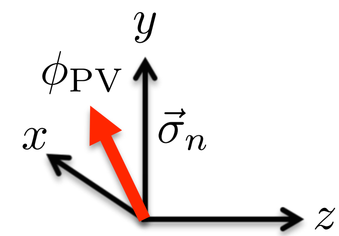
# PV Spin Rotation in $^4$He




4K LHe

$$f(0) = f_{\rm PC} + f_{\rm PV}(\vec{\sigma}_n \cdot \vec{k}_n)$$

$$\langle \vec{S}_{^4\rm He} \rangle = 0$$




$$\psi_n \sim exp\left\{ i \left[ 1 + \frac{2\pi}{k^2} \rho f(0) \right] \vec{k}_0 \cdot \vec{z} \right\}$$

Passage through the $^4$He optical potential results in a helicity-dependent total phase

$$\phi_{\pm} = \underbrace{kz\left(1 + \frac{2\pi\rho}{k^2} f_{\rm PC}\right)}_{\varphi_{\rm PC}} \pm \underbrace{2\pi\rho z f_{\rm PV}}_{\varphi_{\rm PV}}$$

which causes rotation of the neutron polarization

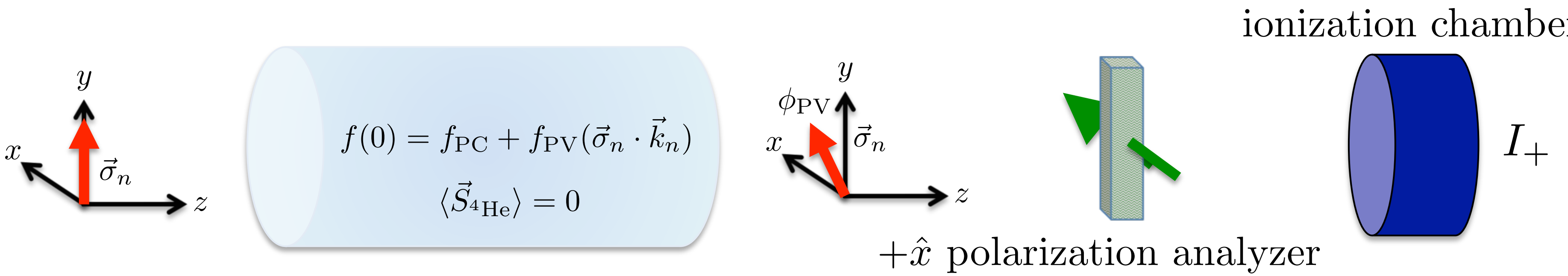
$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\Big[ |+\rangle + |-\rangle \Big] \longrightarrow \frac{1}{\sqrt{2}}\Big[ e^{i(\varphi_{\rm PC}+\varphi_{\rm PV})}\,|+\rangle + e^{i(\varphi_{\rm PC}-\varphi_{\rm PV})}\,|-\rangle \Big]$$

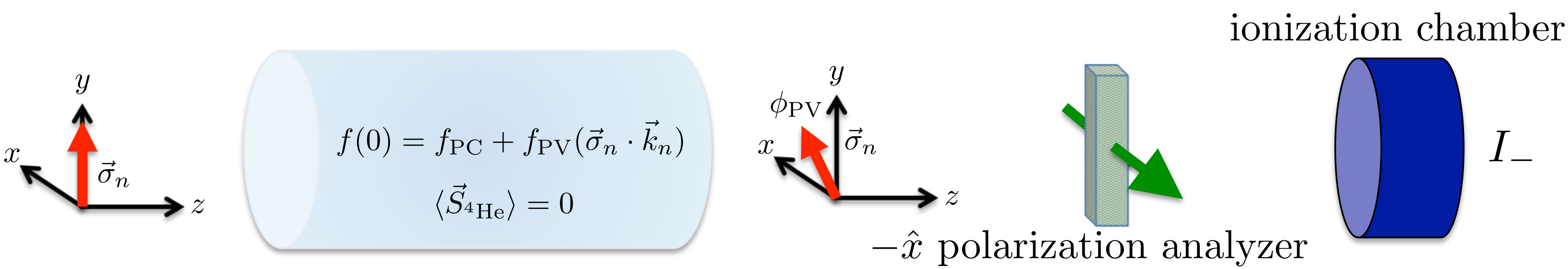
constant in the low-energy limit

$$\boxed{\phi_{\rm PV} = \varphi_+ - \varphi_- = 2\varphi_{\rm PV} = 4\pi\rho z f_{\rm PV}}$$

DDH prediction is [-16,12] x $10^{-7}$ rad/m

# PV Spin Rotation Measurement Technique

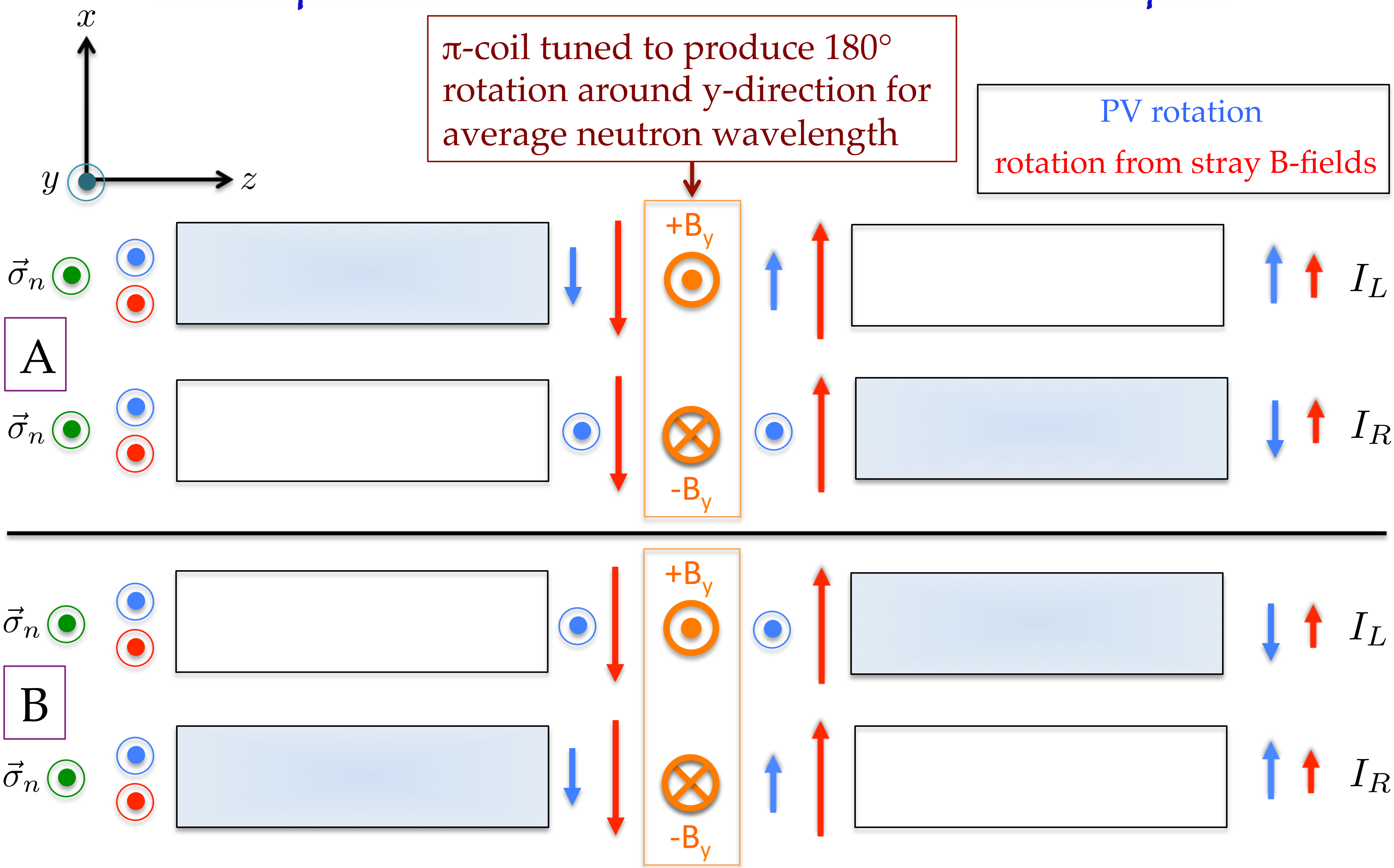



Two measurements produce a spin rotation angle $PA \sin\phi = \dfrac{I_+ - I_-}{I_+ + I_-}$

PV rotation ~$10^{-7}$ rad/m, but earth's field would produce a rotation ~10 rad/m!

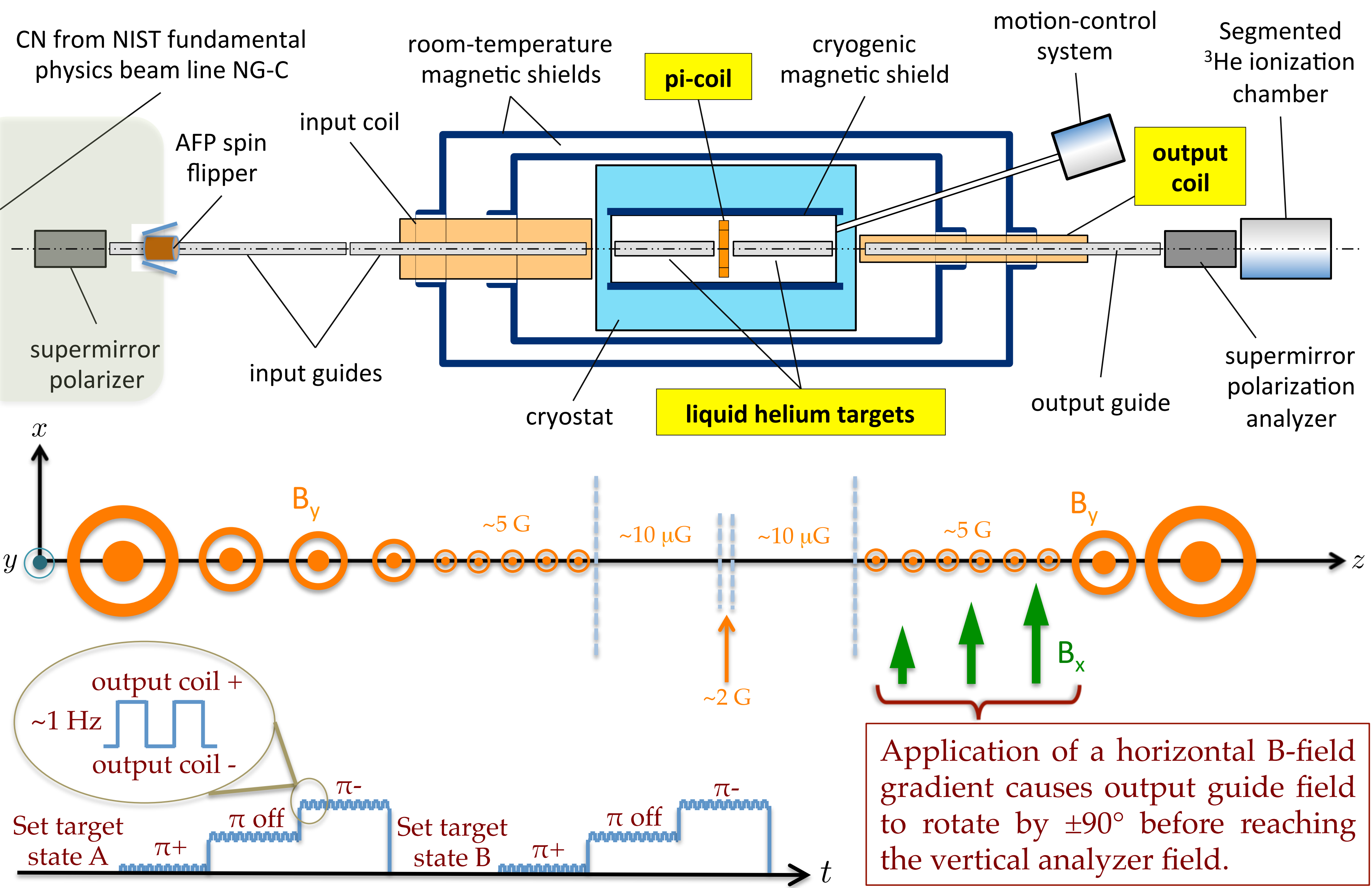
# PV Spin Rotation Measurement Technique




Spin rotation from stray fields as well as left/right field asymmetries cancel

$$\left(\phi_L - \phi_R\right)_A - \left(\phi_L - \phi_R\right)_B = 4\phi_{\mathrm{PV}}$$

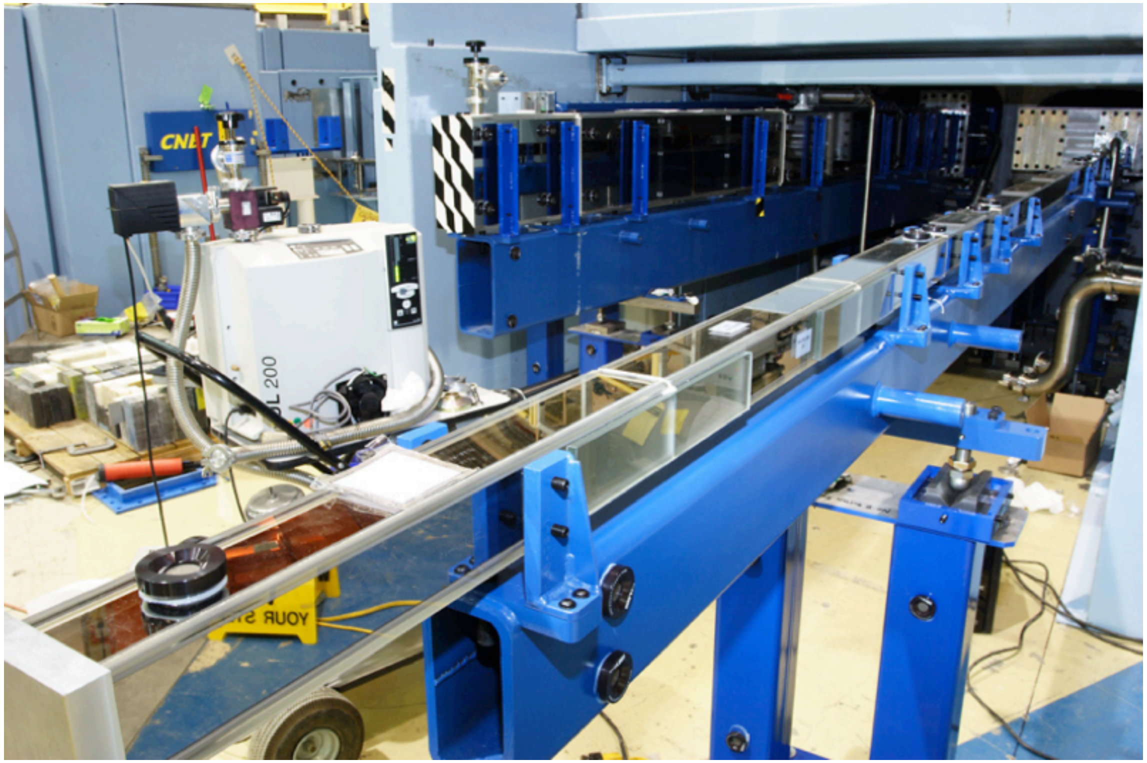
# The Neutron Spin Rotation Experiment

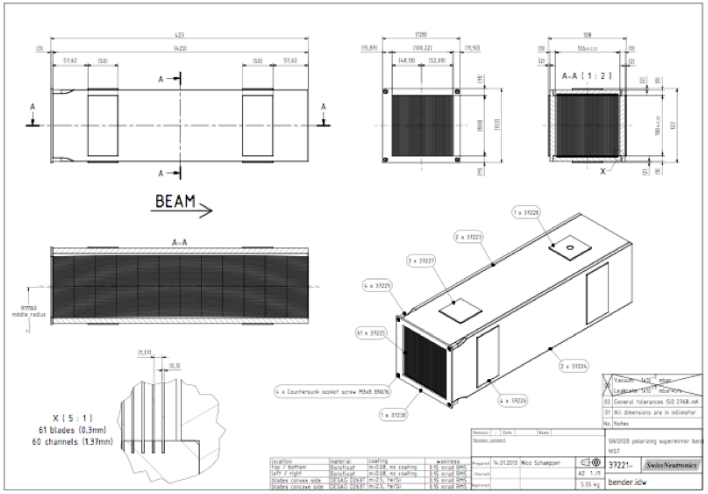


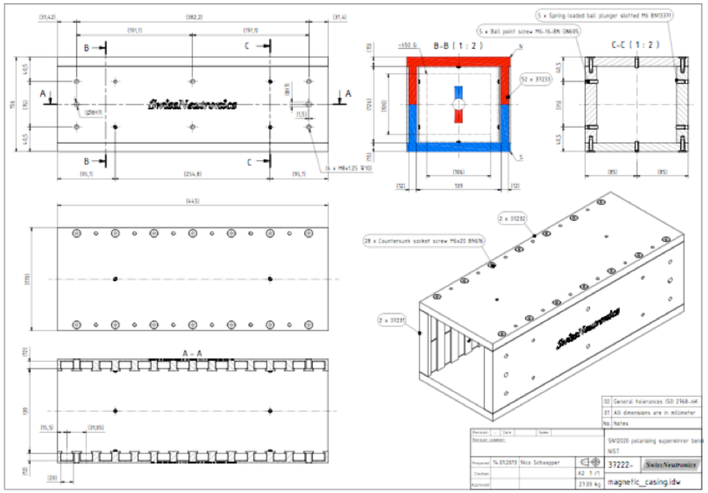

Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

# NSR-III: NIST NG-C Beam Line

- NG-C beam line completed
- NG-C end station ready early 2014
- SM polarizer and analyzer arriving Oct.



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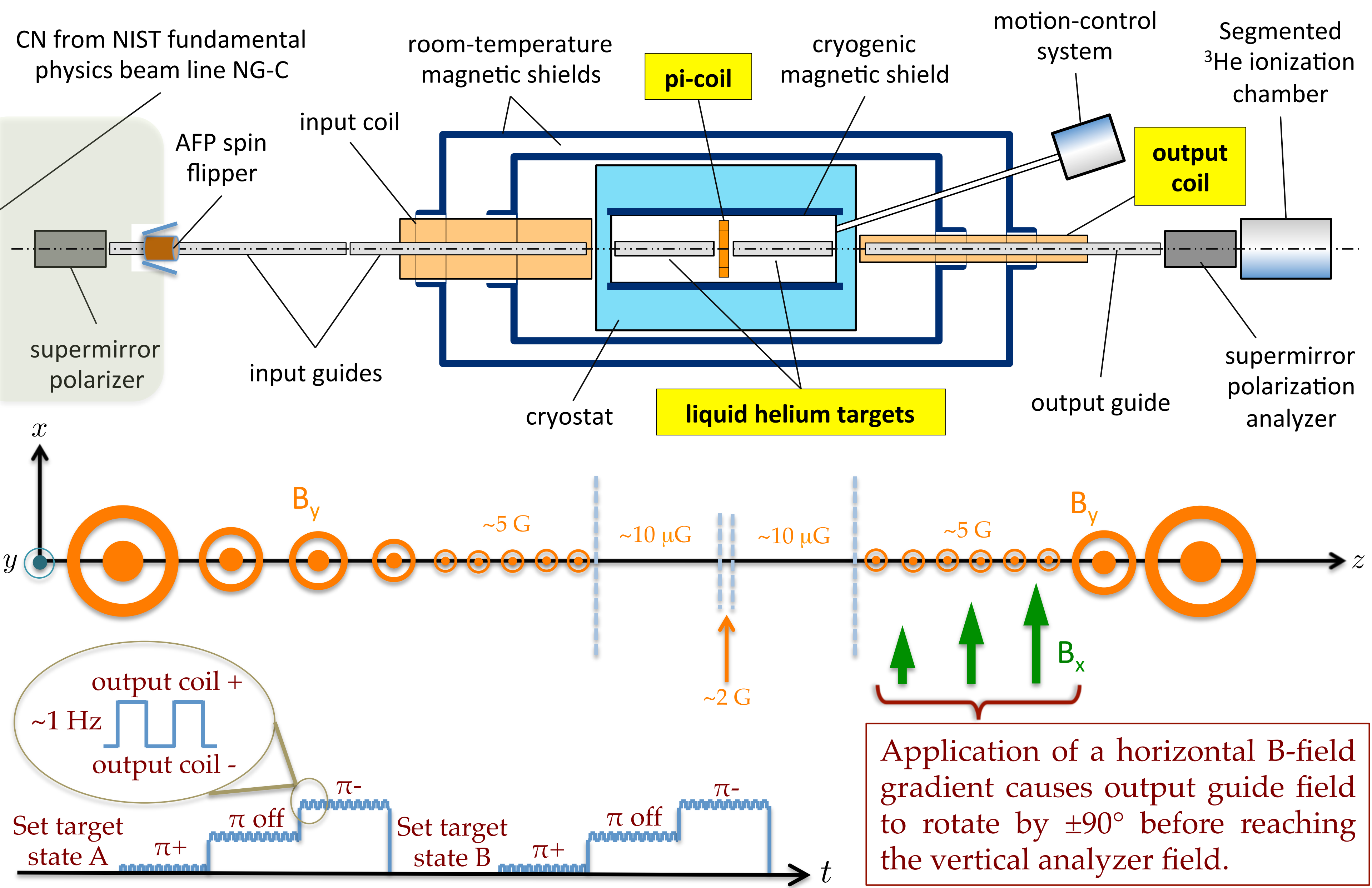
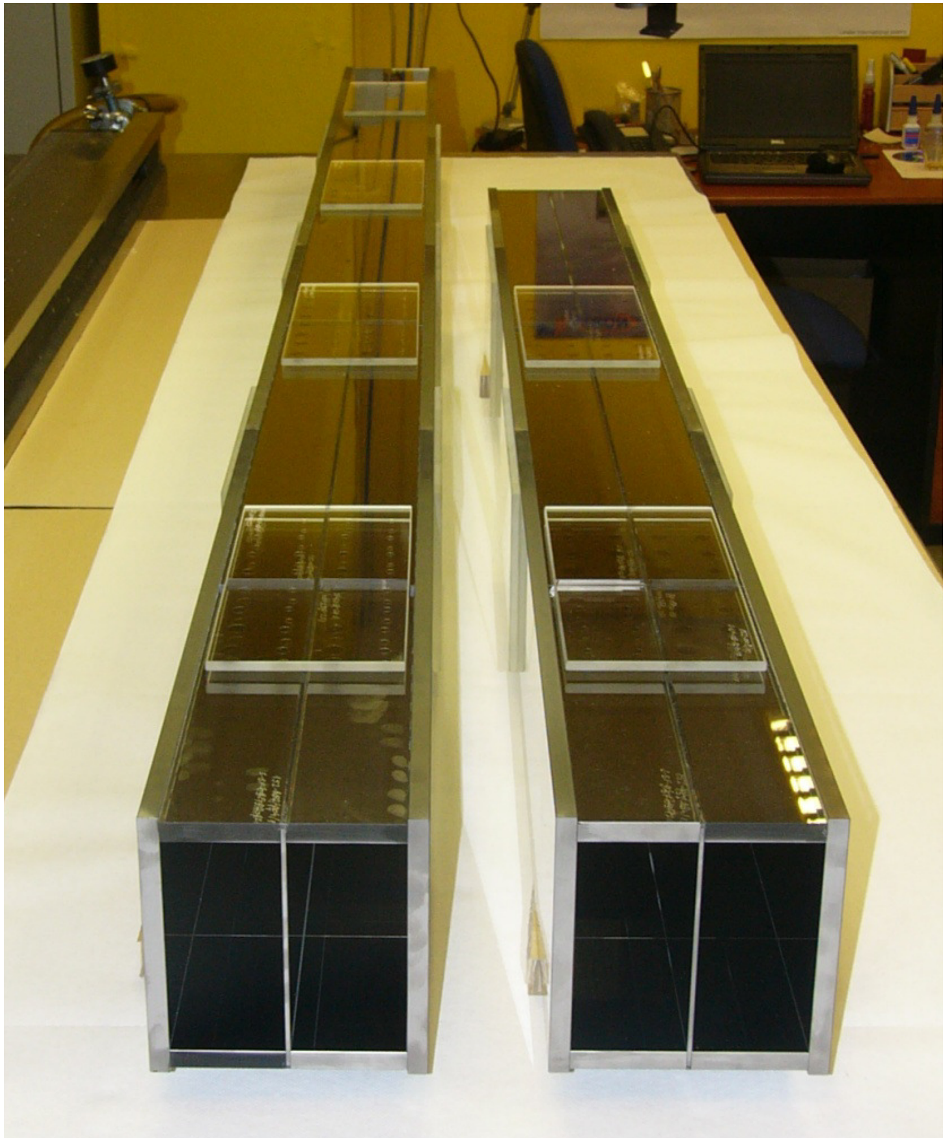



Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

# NSR-III Neutron Guides

- 10cm x 10cm, 1.25 and 2.0 non-magnetic supermirror (NiMo/T) neutron guides
- 1cm thick borofloat glass
- M = 2.0, R > 90%
- depolarization probability per bounce < 1%



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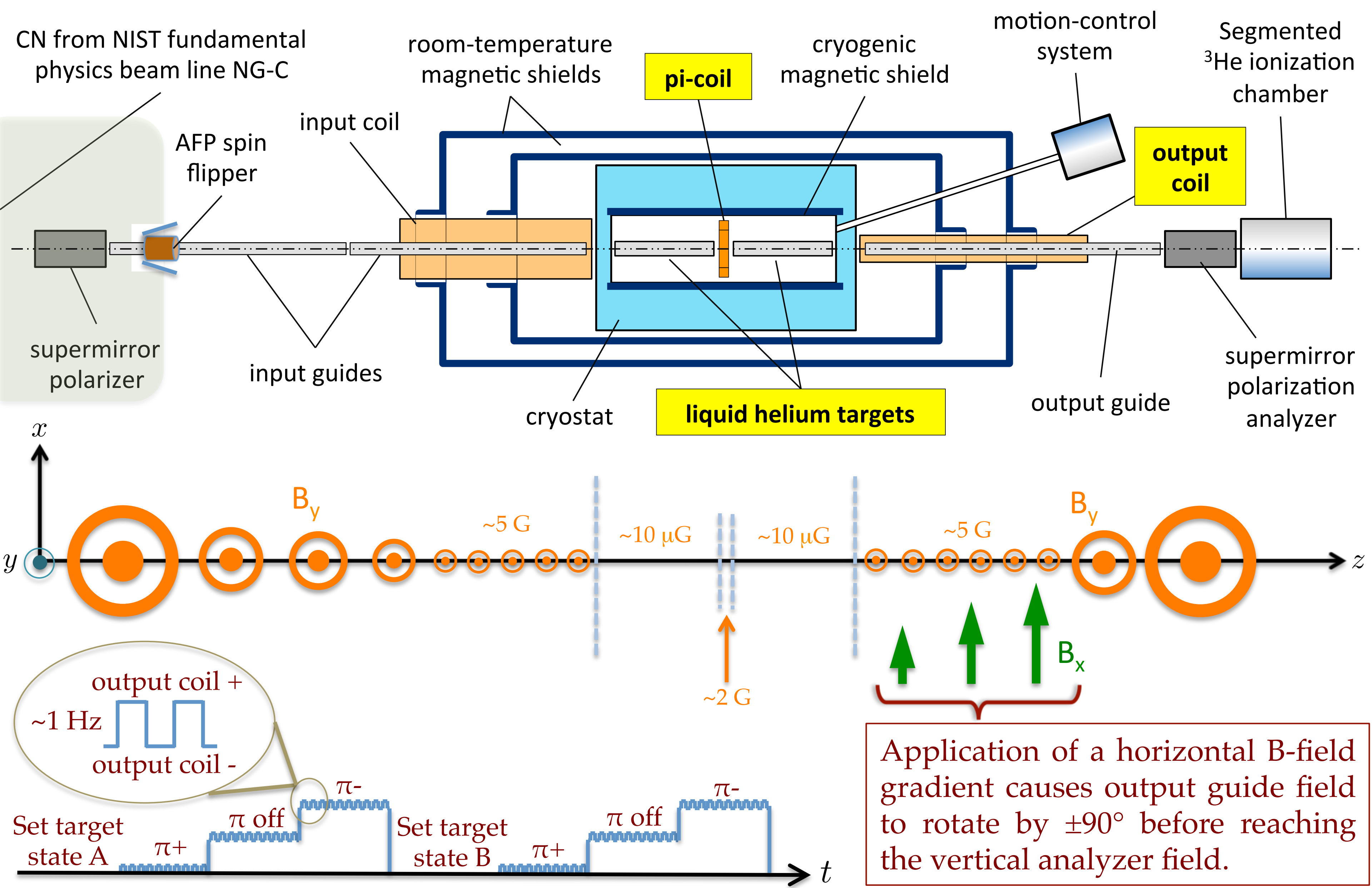
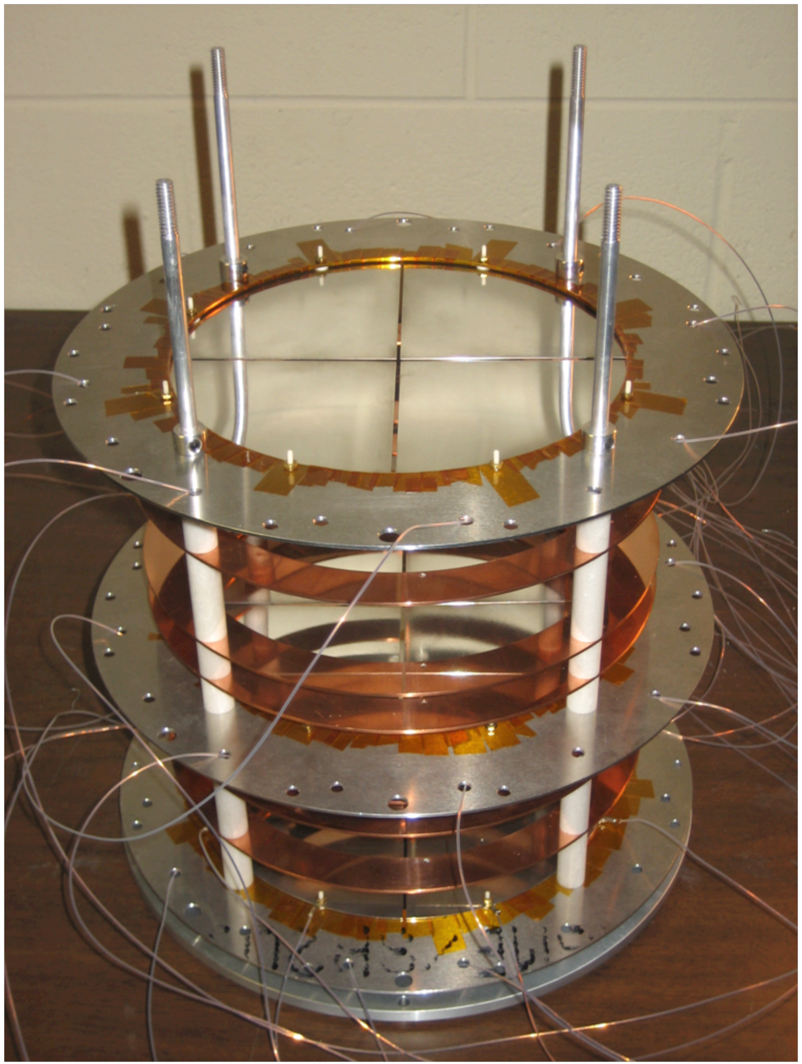



Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

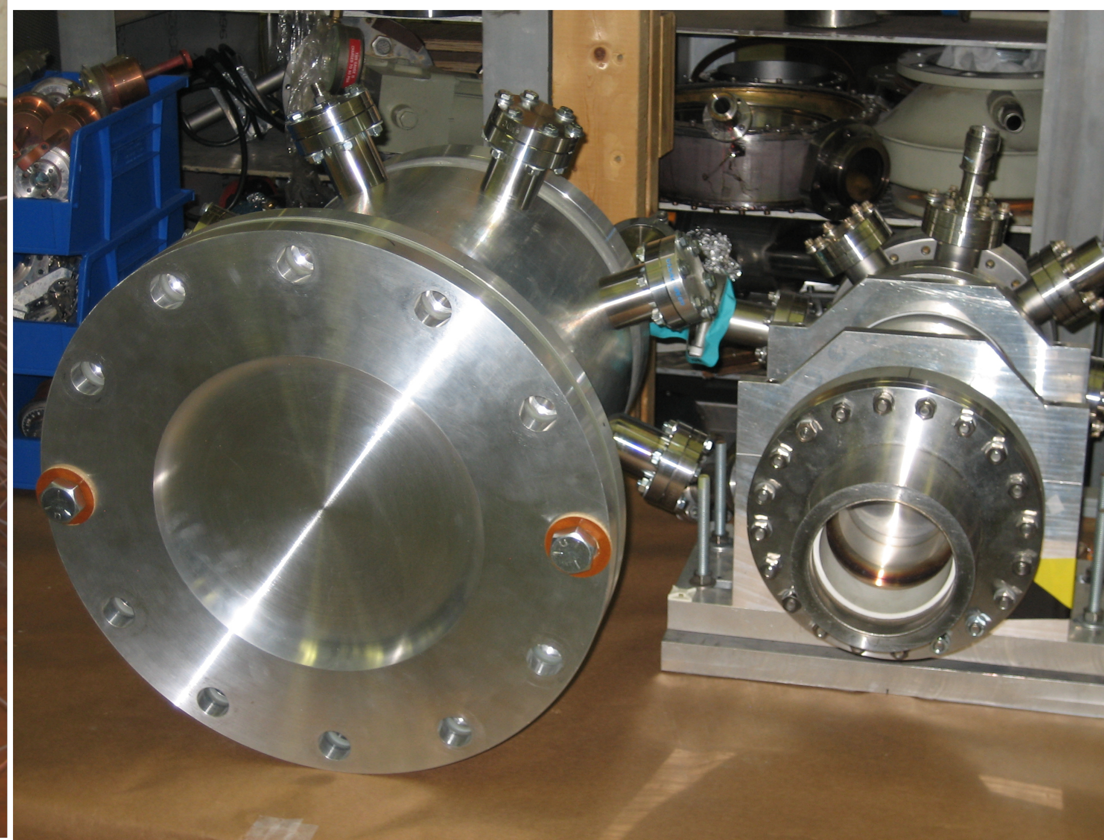
# NSR-III Ionization Chamber

- New ionization chamber constructed and will be tested at Indiana University in October
- Based on the radially and longitudinally segmented detector used for NSR-II



NG-C Ion Chamber

NG-6 Ion Chamber



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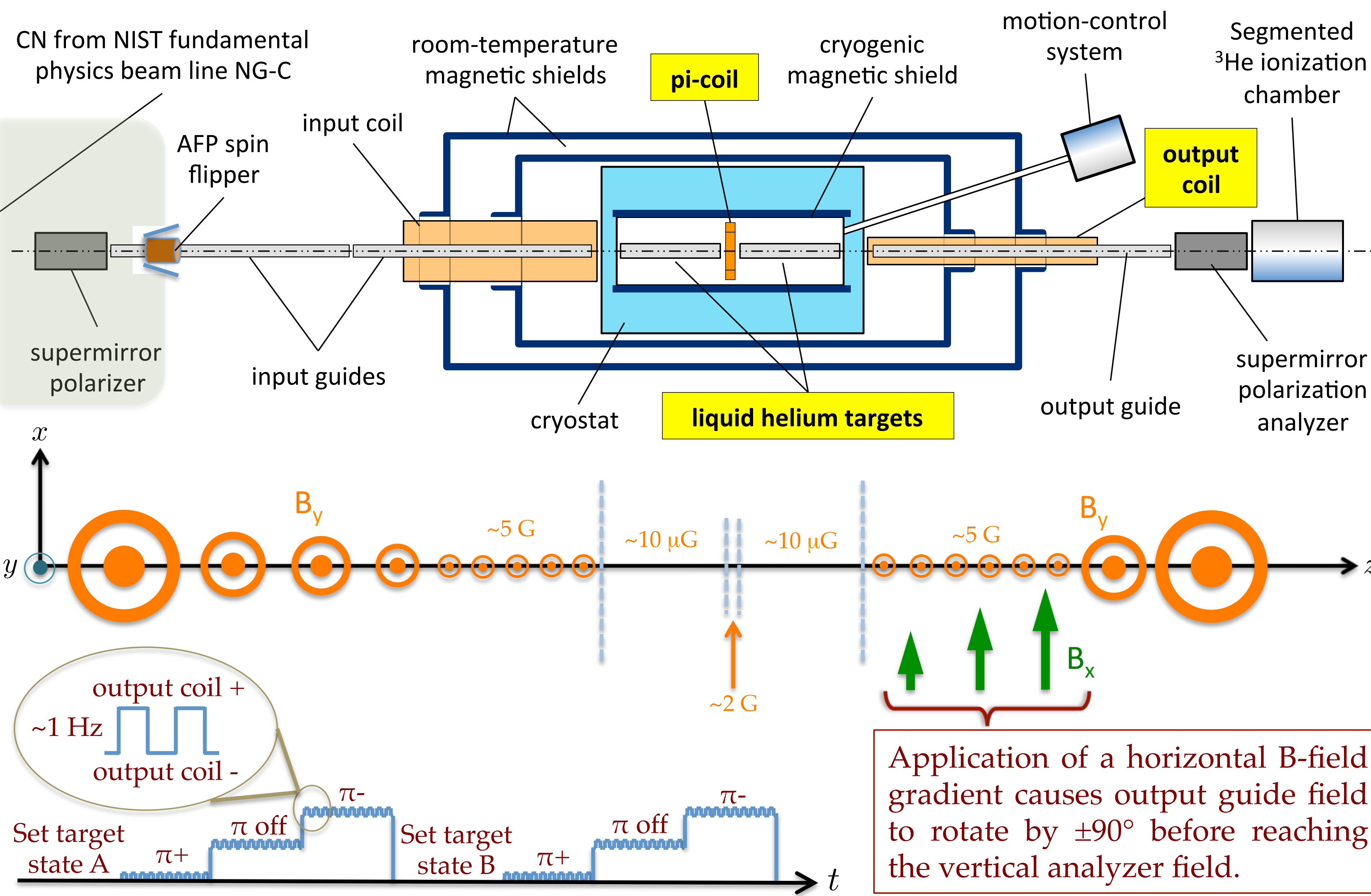
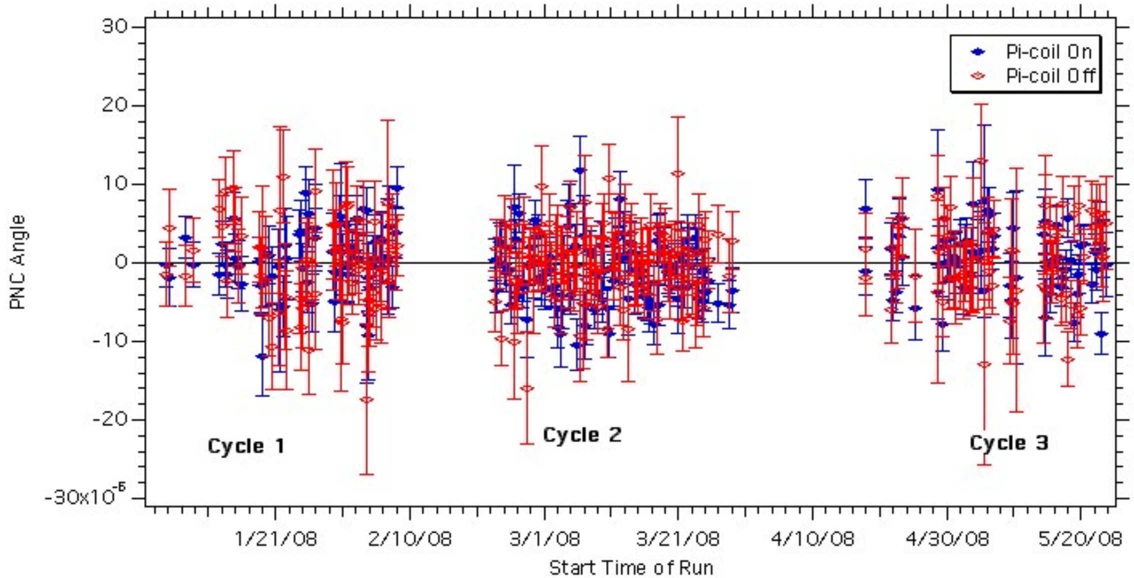


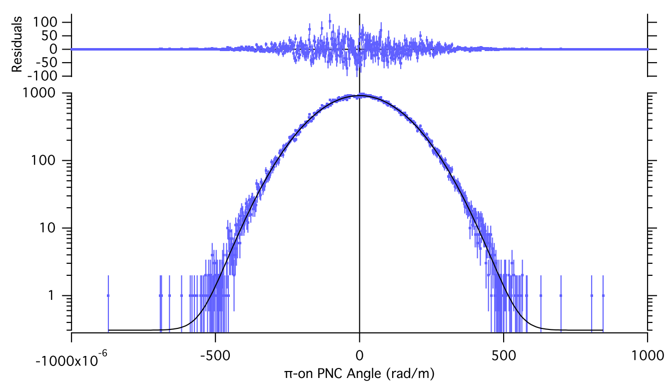

Application of a horizontal B-field gradient causes output guide field to rotate by ±90° before reaching the vertical analyzer field.

# NSR-II

$$\frac{d\phi_{PV}}{dz} = [1.7 \pm 9.1\ (stat) \pm 1.4\ (sys)] \times 10^{-7}\ \mathrm{rad/m}$$

2008 NIST Fundamental Physics Beam Line NG-6




C. D. Bass et al., Nucl. Instrum. Meth. A612, 69-82 (2009).
A. M. Micherdzinska et al., Nucl. Instrum. Meth. A631, 80 (2011).
W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

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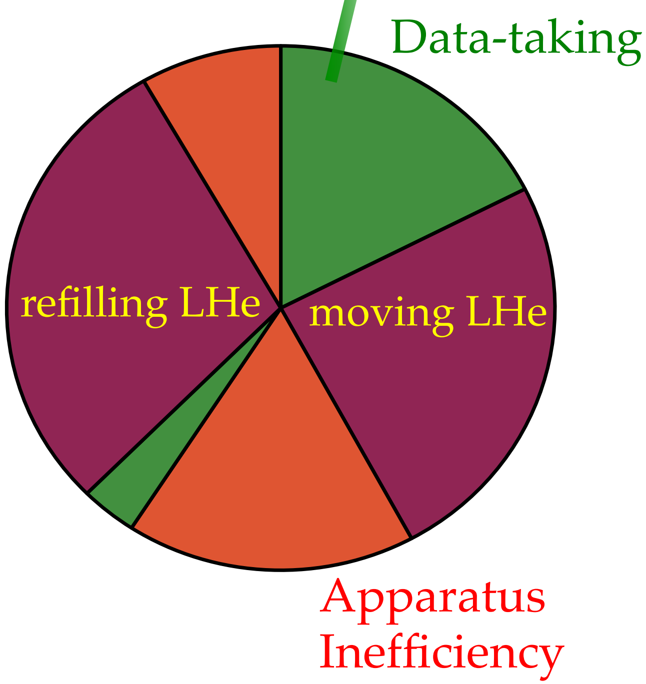



| Source | NSR-II Uncertainty (rad/m) | NSR-II Method | NSR-III Uncertainty (rad/m) |
|---|---|---|---|
| L 4He diamagnetism | $2 \times 10^{-9}$ | calc | $2 \times 10^{-10}$ |
| L 4He optical potential | $3 \times 10^{-9}$ | calc | $3 \times 10^{-10}$ |
| Neutron E spectrum shift | $8 \times 10^{-9}$ | calc | $8 \times 10^{-10}$ |
| Refraction/reflection | $3 \times 10^{-10}$ | calc | $3 \times 10^{-11}$ |
| Non-forward scattering | $2 \times 10^{-8}$ | calc | $2 \times 10^{-9}$ |
| Polarimeter non-uniformity | $1 \times 10^{-8}$ | meas | $<1 \times 10^{-8}$ |
| | | | |
| B amplification | $<4 \times 10^{-8}$ | meas | $<4 \times 10^{-9}$ |
| B gradient amplification | $<3 \times 10^{-8}$ | meas | $<3 \times 10^{-9}$ |
| PA/target nonuniformity | $<6 \times 10^{-8}$ | meas | $<6 \times 10^{-8}$ |
| Total | $1.4 \times 10^{-7}$ | | $\leq 1 \times 10^{-7}$ |

NSR-II : 5cm x 5cm

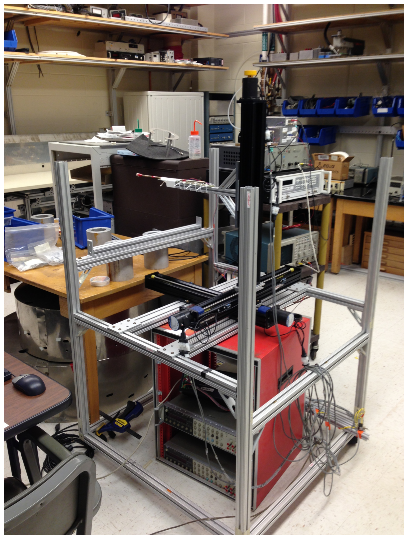
NSR-III : 10cm x 10cm

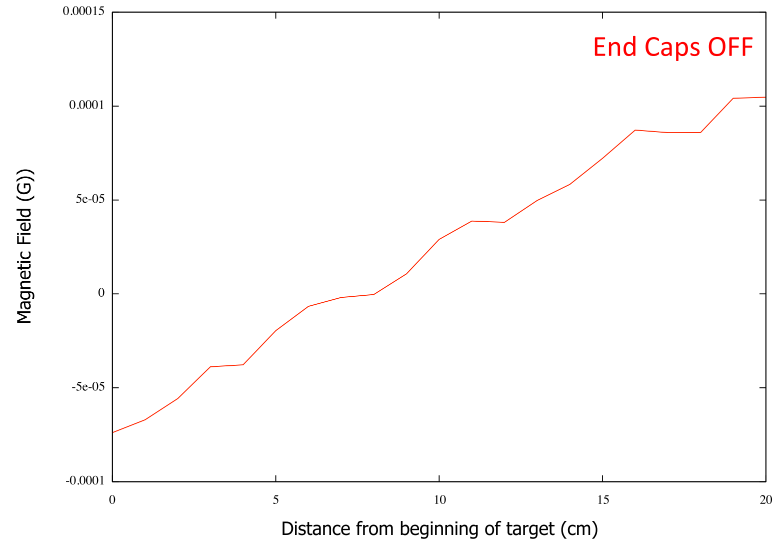
x 10 in neutron flux

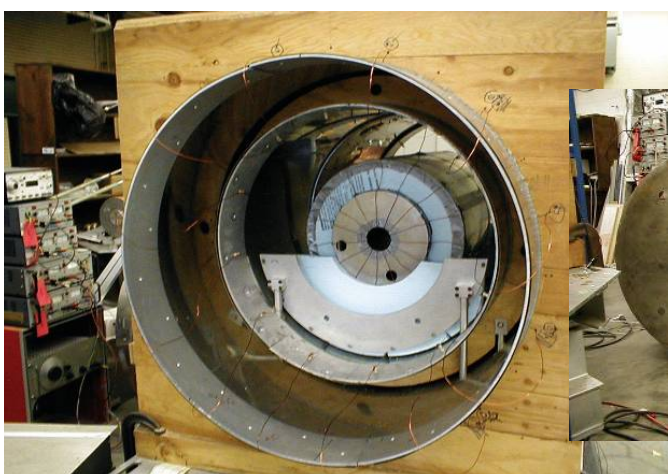
x 40 effective increase in polarized cold neutron flux from enhanced neutron transport

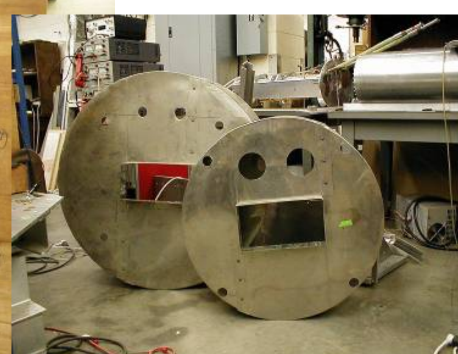
# NSR-III Magnetic Shielding

- Three nested layers of μ metal shielding (two external and one internal); demonstrated to reduce B-field in target region to <10μG, a factor of ten improvement from NSR-II.
- In-situ de-gaussing, internal fluxgate magnetometers, trim coils, and active field cancelation supplement the passive shields.







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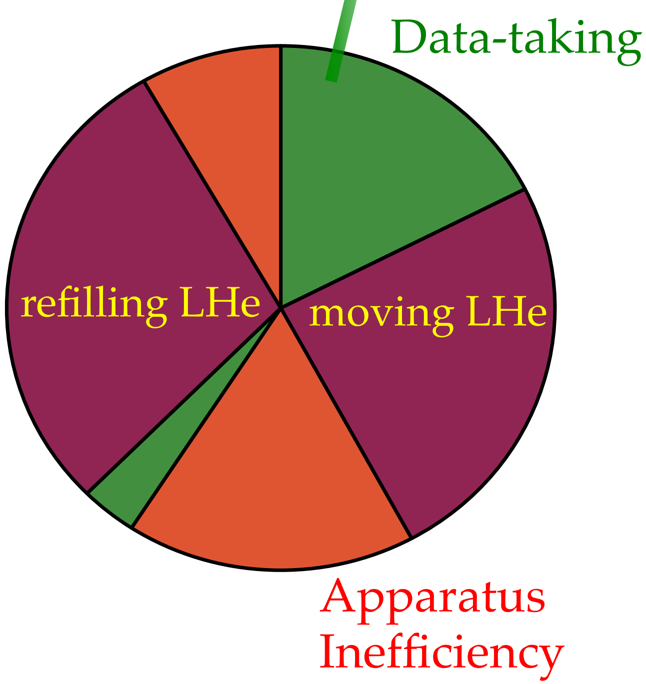


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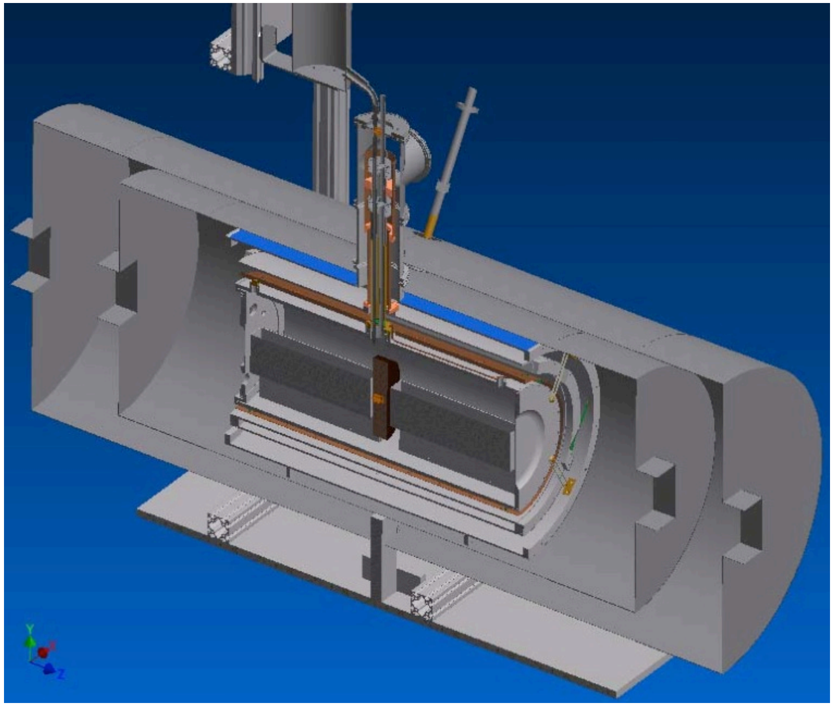
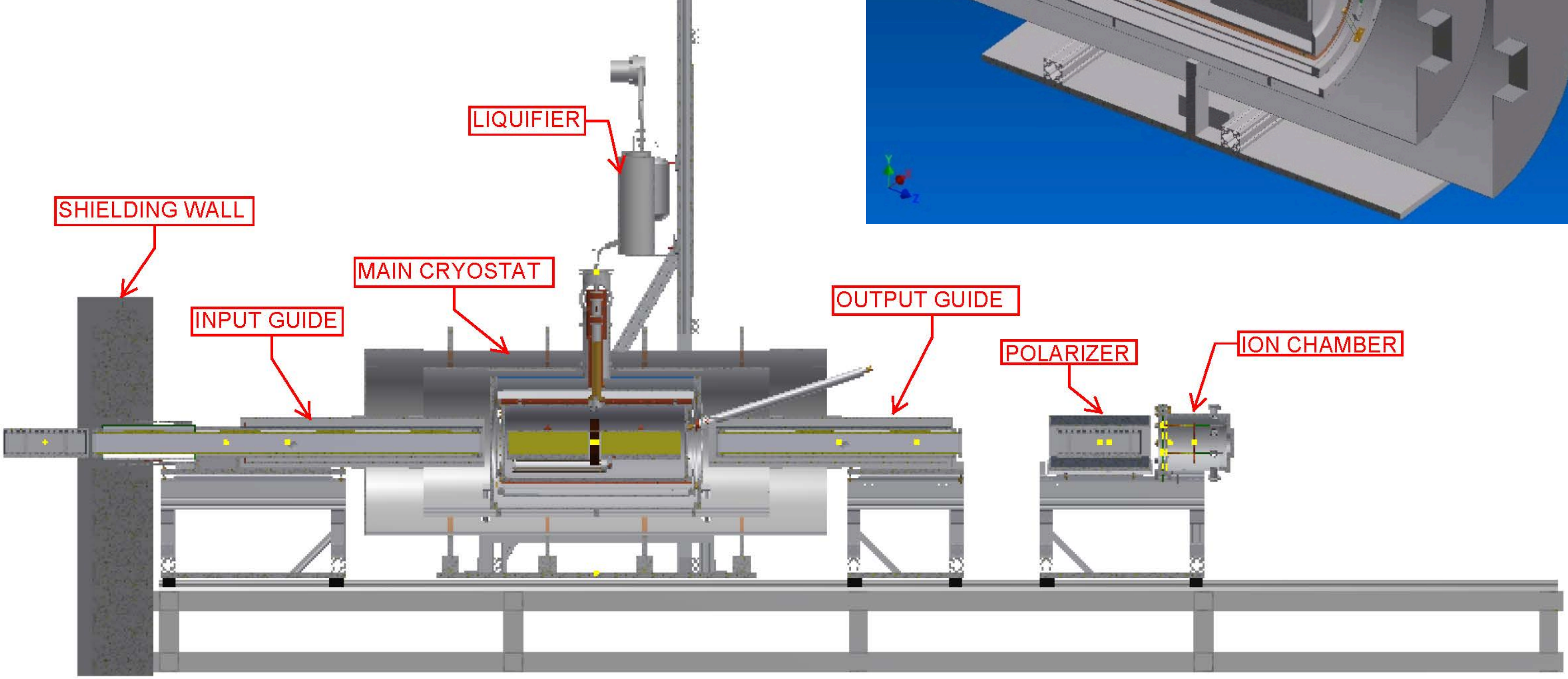
x 10 in neutron flux
x 40 effective increase in polarized cold neutron flux from enhanced neutron transport

# NSR-III Cryogenics

- Improved cryogenic design for reduced heat load, simpler assembly/disassembly, and more robust operation
- He re-liquefier removes necessity of LHe fills
- R&D on new LHe pump to reduce target change time





# NSR-III Cryogenics

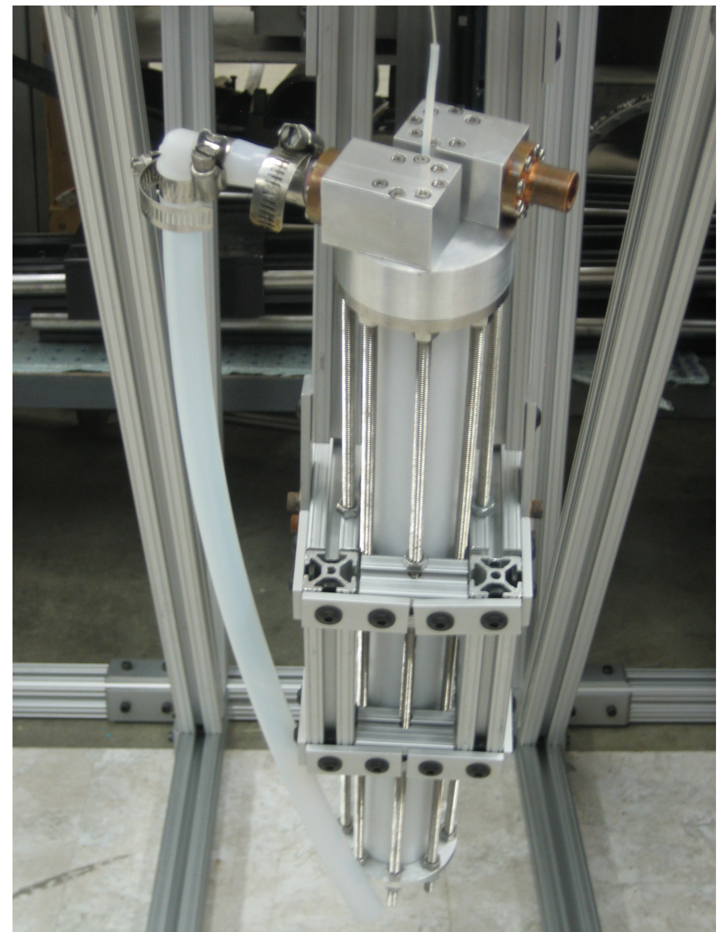
## Re-Liquefier

- Cryomech pulse tube re-liquefier tested for three months of continuous operation
- Observed a liquefaction rate from warm gas of 12L/day
- Demonstrated ability to continuously maintain LHe volume comparable to spin rotation cryostat with little intervention under a heat load of ~600mW

cold head motor
pulse tube cold head
He re-liquefier
LHe into cryostat
He gas return
test cryostat
heater control
LHe level monitor
pressure monitor

## R&D on New LHe Pump

- Bellows pump demonstrated equivalent of 100 days of data-taking in water
- Pumping rate in water is ten times larger than previous centrifugal pump
- Cryogenics tests are underway



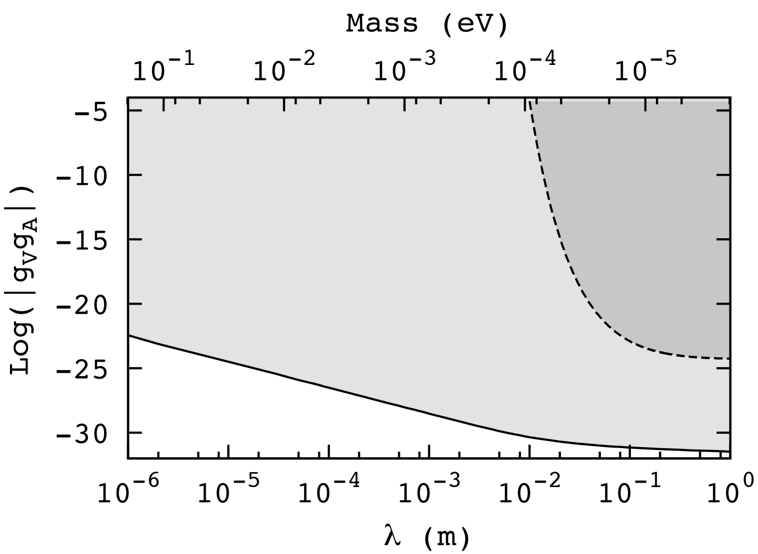
# Additional Physics with our Apparatus

There is vigorous interest in placing constraints on spin- and momentum- dependent mesoscopic exotic forces:

**A New Limit on Possible Long-Range Parity-odd Interactions of the Neutron from Neutron Spin Rotation in Liquid $^4He$**

H.Yan and W. M. Snow*
*Indiana University, Bloomington, Indiana 47408, USA and*
*Center for Exploration of Energy and Matter, Indiana University, Bloomington, IN 47408*
(Dated: November 23, 2012)

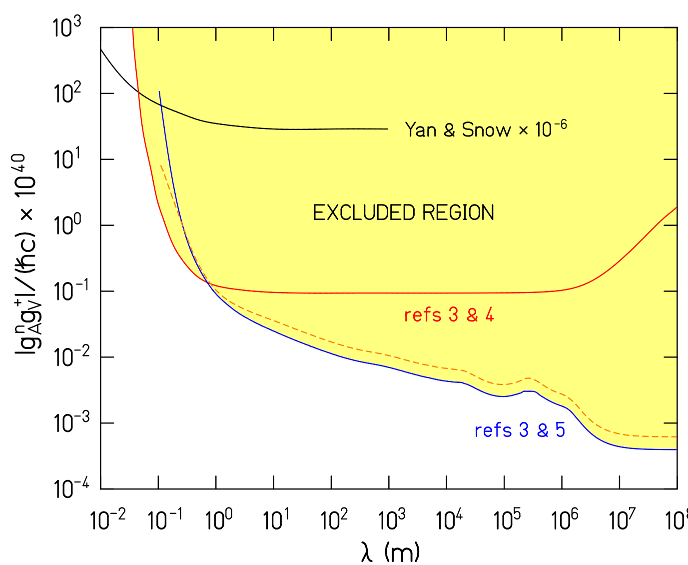
Phys. Rev. Lett. **110**, 082003 (2013)




**Improved Limits on Long-Range Parity-Odd Interactions of the Neutron**

E. G. Adelberger and T. A. Wagner
*Center for Experimental Nuclear Physics and Astrophysics,*
*Box 354290, University of Washington, Seattle, WA 98195-4290*
(Dated: July 26, 2013)

arXiv:1307.6602 [hep-ex]




Such interactions can be generated by a new light vector boson $X_\mu$ coupling to a fermion

$$\mathcal{L} = \overline{\psi}(g_V \gamma^\mu + g_A \gamma^\mu \gamma_5)\psi X_\mu$$

Examples of the interaction potentials generated by such a coupling include

$$V \sim g_V g_A \vec{\sigma} \cdot \vec{v} \qquad V \sim g_A^2 \vec{\sigma} \cdot (\vec{v} \times \hat{r})$$

# NSR Collaboration

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C. D. Bass

*Gettysburg College*

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*Bhabha Atomic Research Centre*

Prakash Chandra Rout, S. Santra

*Georgia State University*

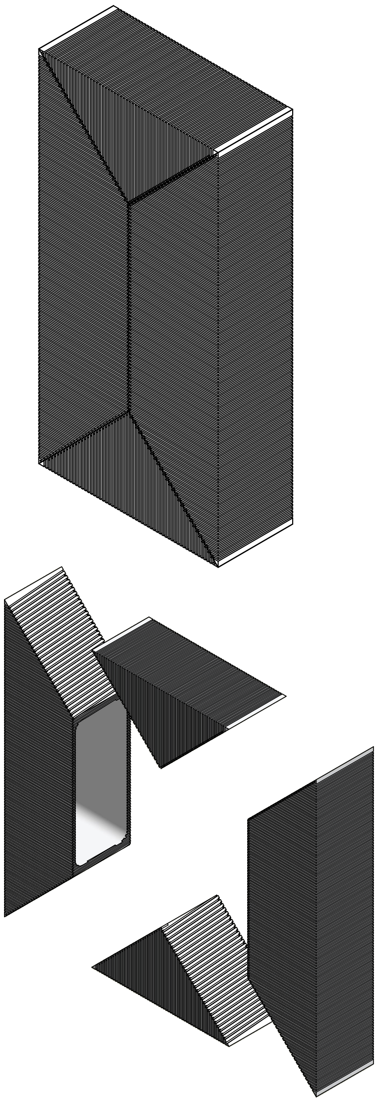
Churamani Paudel, M. G. Sarsour

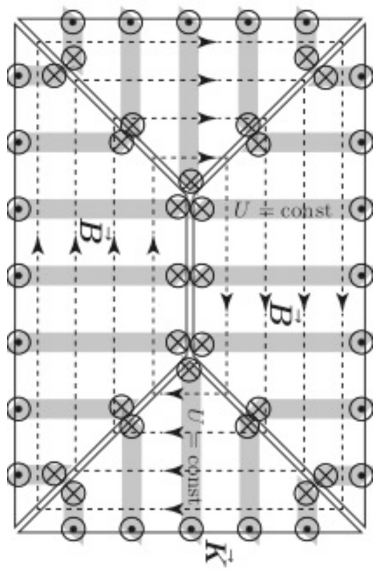
*Florida State University*

S. van Sciver

# NSR-III Input, Output, and Pi Coils

Pi-Coil design by Chris Crawford (University of Kentucky)






Input and output by Libertad Barrón Palos (Universidad Nacional Autónoma de México Instituto de Física)