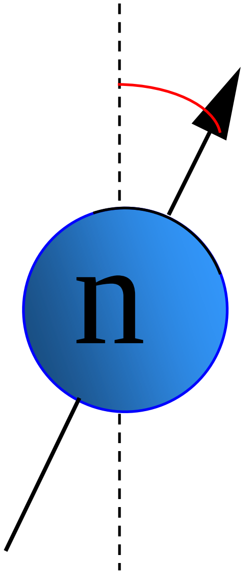
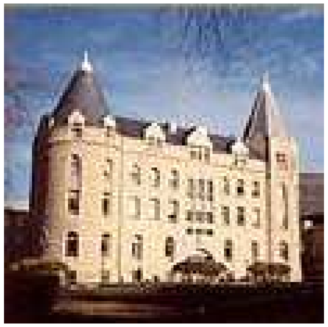


Parity-Violating Neutron Spin Rotation in Liquid-^{4}He

Anna Micherdzinska

THE UNIVERSITY OF
WINNIPEG
1967-2007



INT Seattle, WA, June 8, 2007

Collaboration

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A.M. Micherdzinska[7], H.P. Mumm[8], J.S. Nico[8], A.K. Opper[3], E. Sharapov[9],
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The University of Winnipeg [7]
National Institute of Standards and Technology (NIST) [8]
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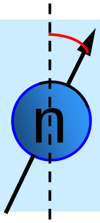
NSF PHY-0100348

Seminar overview

- Motivation
  - Why we study parity violation (**PV)** in neutron spin rotation
  - The theory/model of the weak NN interaction
  - Optical origin of PV spin rotation

- Experiment
  - How will we measure this signal ?
  - Experimental challenges – what backgrounds must be suppressed
  - Design of apparatus
  - Current status

- Summary/Goals

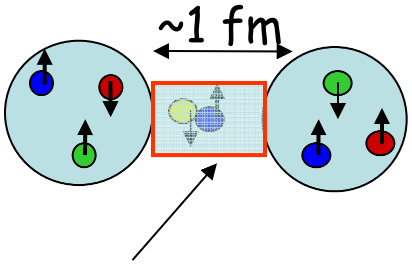


Motivation

- Parity Violation (PV) neutron spin rotation is a probe of the NN weak interaction

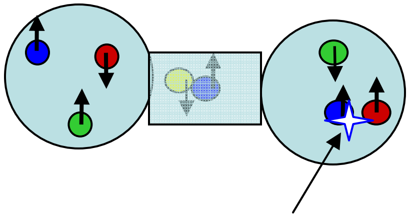
after ~ 50 years of study hadronic weak interaction is not understood
(data + theory is inconsistent)

- Why is it important to understand NN weak interactions ?
  - needed to interpret PV in nuclear and atomic systems
  - sensitive to q-q correlations in nucleon – "inside out probe of QCD"
  - Develop theory of strangeness conserving ($\Delta S=0$) nonleptonic weak interaction



Strong NN force

✧ ~1/100 fm range



Weak NN force

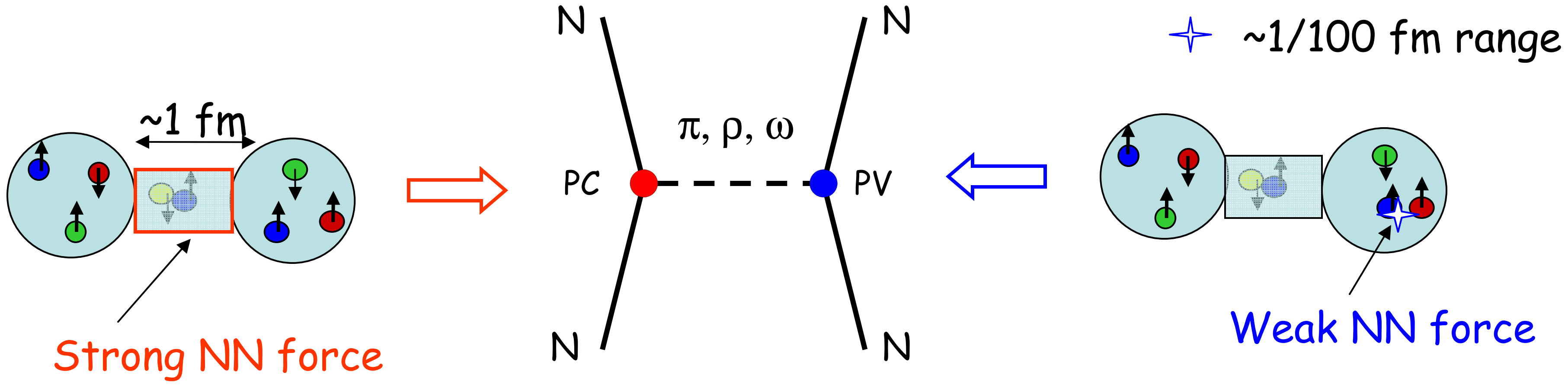
Relative weak/strong amplitudes:
$\sim[e^2/m_W^2]/[g^2/m_\pi^2]\sim10^{-7}$

The NN weak interaction: Theoretical descriptions

1. **DDH** meson exchange model - history, but still used

assumes π, ρ, and ω exchange dominate the low-energy PV NN potential as they do for strong NN

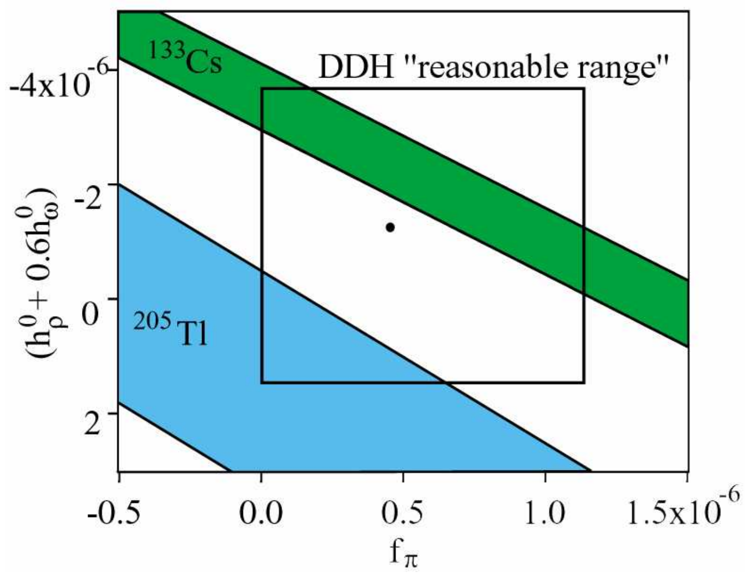
Weak meson exchange coupling constants $f_\pi, h_\rho^0, h_\rho^1, h_\rho^2, h_\rho^{1'}, h_\omega^0, h_\omega^1$

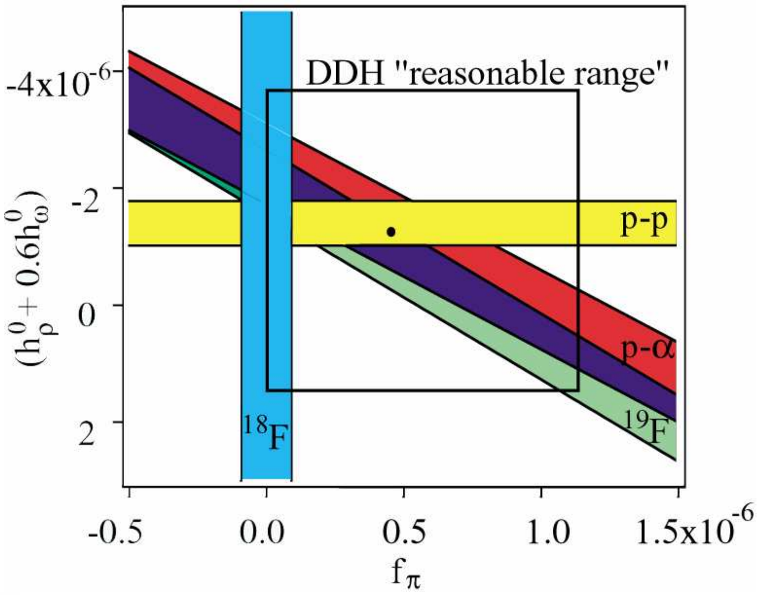


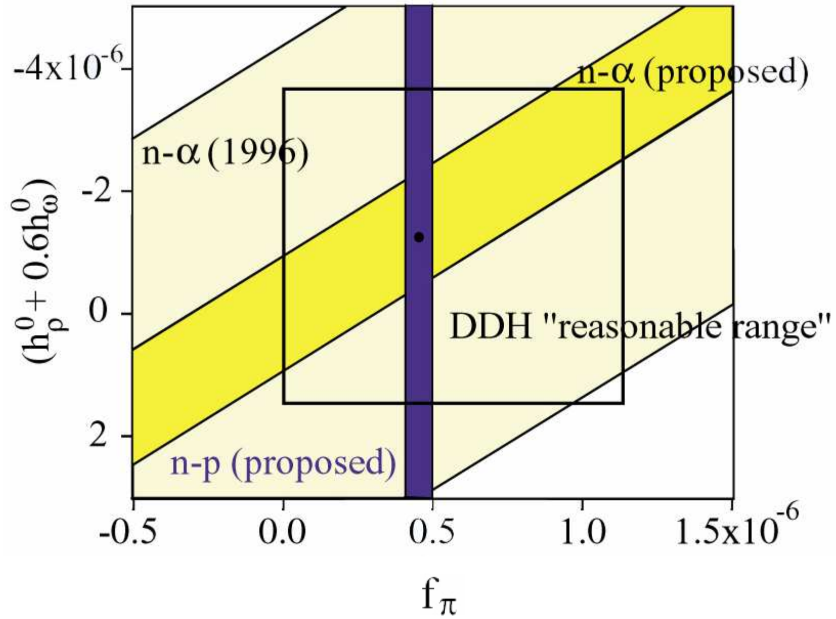
One Meson Exchange model: V^{PV}_{OME}

qq weak processes hidden in the weak NN vertex

Current knowledge about weak NN amplitudes







n-^{4}He orthogonal to ^{133}Cs, p-^{4}He

n-^{4}He spin rotation in terms of weak couplings:
$\phi=10^{-7}$rad/m (Dmitriev)   using DDH "best values"

$\phi=-(0.97f_\pi+0.32h_\rho^0-0.11h_\rho^1+0.22h_\omega^0-0.22h_\omega^1)$ rad/m

n+p->D+γ asymmetry determines f_π
$A_\gamma=-0.11\ f_\pi$ (Desplanques)

plot: $\delta\phi=3\times10^{-7}$ rad/m, $\delta A\gamma=5\times10^{-9}$

NN Weak Meson Couplings

measured

10^{-6}	np A_γ	np ϕ	nD A_γ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	-3.12	0.92	-0.97		-0.34
h_ρ^0		-0.23	-0.50	-0.32	0.08	0.14
h_ρ^1	-0.001		0.10	0.11	0.08	0.05
h_ρ^2		-0.25	0.05		0.03	
h_ω^0		-0.23	-0.16	-0.22	0.07	0.06
h_ω^1	-0.003		-0.002	0.22	0.07	0.06

Column gives relation between PV observable and weak couplings

The NN weak interaction: Theoretical descriptions

V^{PV} was reformulated in the EFT framework

$V^{PV}_{\not\pi}$
good for low energy
(short range interaction)

V^{PV}_{EFT}
(long range interaction due to OPE,
medium range due to TPE)

2. *New “Hybrid” Effective Field Theory description,

*Liu, C.P., Parity Violating Observables of <u>Two-Nucleon Systems</u> in Effective Field Theory,
arXiv: nucl-th/0609078 v1 28 Sep 2006

-wave function from phenomenology
-general operator structure of EFT

In order to completely describe the nuclear PV phenomena at low energy, minimal set of 6 parameters is needed:

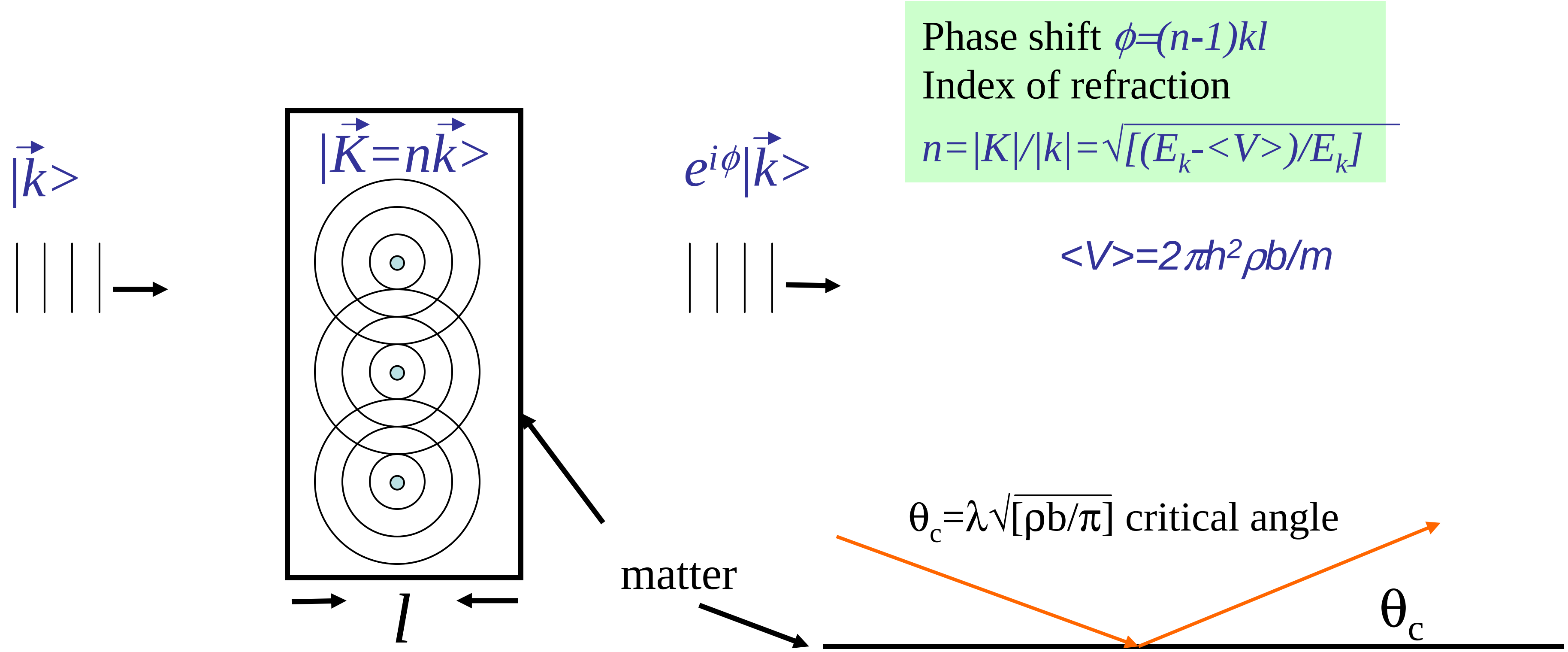
⇒5 low energy constants (Danilov parameters) (related to the S-P scattering amplitudes)

⇒long-range OPE parameter (proportional to the PV π-N coupling constant f_π)

Neutron optics

For neutrons with E<25 meV the λ is on the order of the interatomic spacing in materials ⇨

the wave properties predominate over their particle characteristic ⇨ theory of neutron optics !



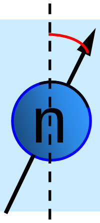
Phase shift $\phi=(n-1)kl$

Index of refraction

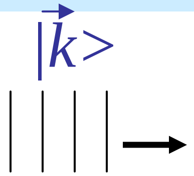
$n=|K|/|k|=\sqrt{[(E_k-\langle V\rangle)/E_k]}$

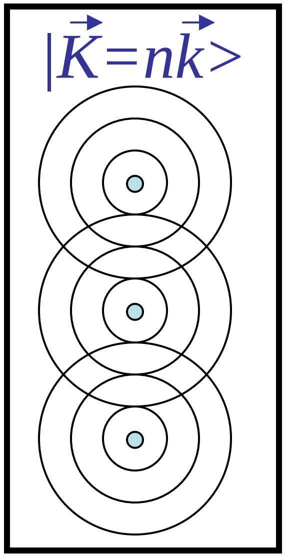
$\langle V\rangle=2\pi\hbar^2\rho b/m$

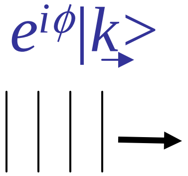
$\theta_c=\lambda\sqrt{[\rho b/\pi]}$ critical angle



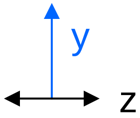
Spin rotation in optics







Incoming neutron with spin along y:



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

PV phase shift is opposite for |+z> and |-z>:

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

The PV rotation of the angle of transverse spin is the accumulated phase difference:

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

Forward scattering amplitude, for low energy neutrons:

$$f(0)=A+\cancel{B(\vec{\sigma}_n\cdot\vec{S}_N)}+C(\vec{\sigma}_n\cdot\vec{k}_n)+\cancel{D(\vec{S}_N\cdot\vec{k}_n)}+\cancel{E(\vec{\sigma}_n\cdot(\vec{k}_n\times\vec{S}_N))}$$

For ^{4}He: $\vec{S}_N = 0$ $\quad f(0) = f_{PC} + f_{PV}(\vec{\sigma}\cdot\vec{k})$

Index of Refraction: $n = 1 + \frac{2\pi\rho}{k^2} f(0)$

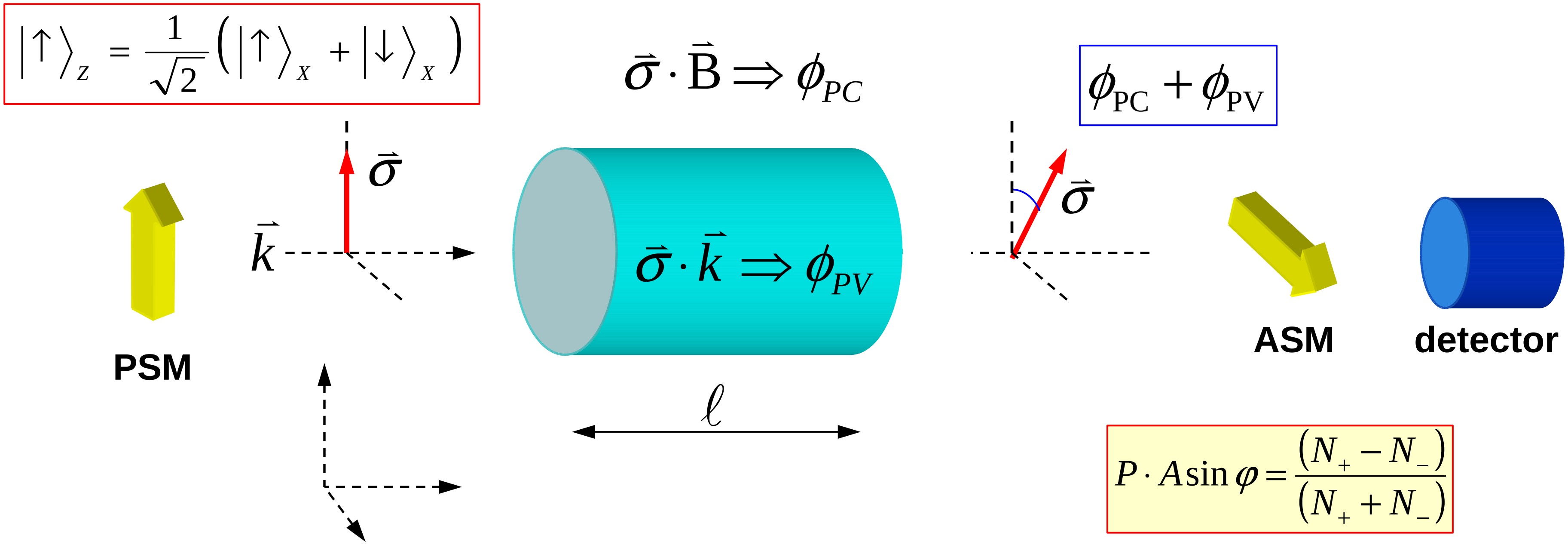
Neutron optical phase shift:

$$\phi = kl\left(1+\frac{2\pi\rho}{k^2}\left(f_{PC} + f_{PV}(\vec{\sigma}\cdot\vec{k})\right)\right)$$

$$\phi_\pm = \phi_{PC} \pm \phi_{PV}$$

$$kl\left(1+\frac{2\pi\rho}{k^2} f_{PC}\right) \qquad 2\pi l\rho f_{PV}$$

Experiment Overview



$$|\uparrow\rangle_z = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_x + |\downarrow\rangle_x\right)$$

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

$$\phi_{PC} + \phi_{PV}$$

$$\vec{\sigma}\cdot\vec{k} \Rightarrow \phi_{PV}$$

$$P \cdot A \sin\varphi = \frac{(N_+ - N_-)}{(N_+ + N_-)}$$

- Opposite-helicity components accumulate different phases from σ · k term in forward scattering amplitude
- PV rotation angle per unit length dϕ/dz related to PV amplitude [ϕ=n·p·l, n-1=2πf/p^2]
- Accumulated phase differences between opposite helicity states cause transversely-polarized neutrons to corkscrew as they propagate through target

PV neutron spin rotation targets: Previous results with slow neutrons

Target	Previous measurement	Reference
^{139}La	-(219 ± 29)x10^{-6} rad/cm	Phys. Rev. C 29, 2389, 1984
Pb (nat.)	(2.24 ± 0.33)x10^{-6} rad/cm	Phys. Lett.119B, 298, 1982
^{117}Sn(7.5% abundance)	-(37 ± 2.5)x10^{-6} rad/cm	Phys. Lett.119B, 298, 1982
^{35}Cl (in CCl$_4$)	PV Gamma asym 2E-5	Many
^{81}Br (in SiBr$_4$ ~50% abundance)	-(131 ± 1.9)x10^{-6} rad/cm (unpublished)	S. Saha Ph.D. thesis 1990 Univ. of Washington

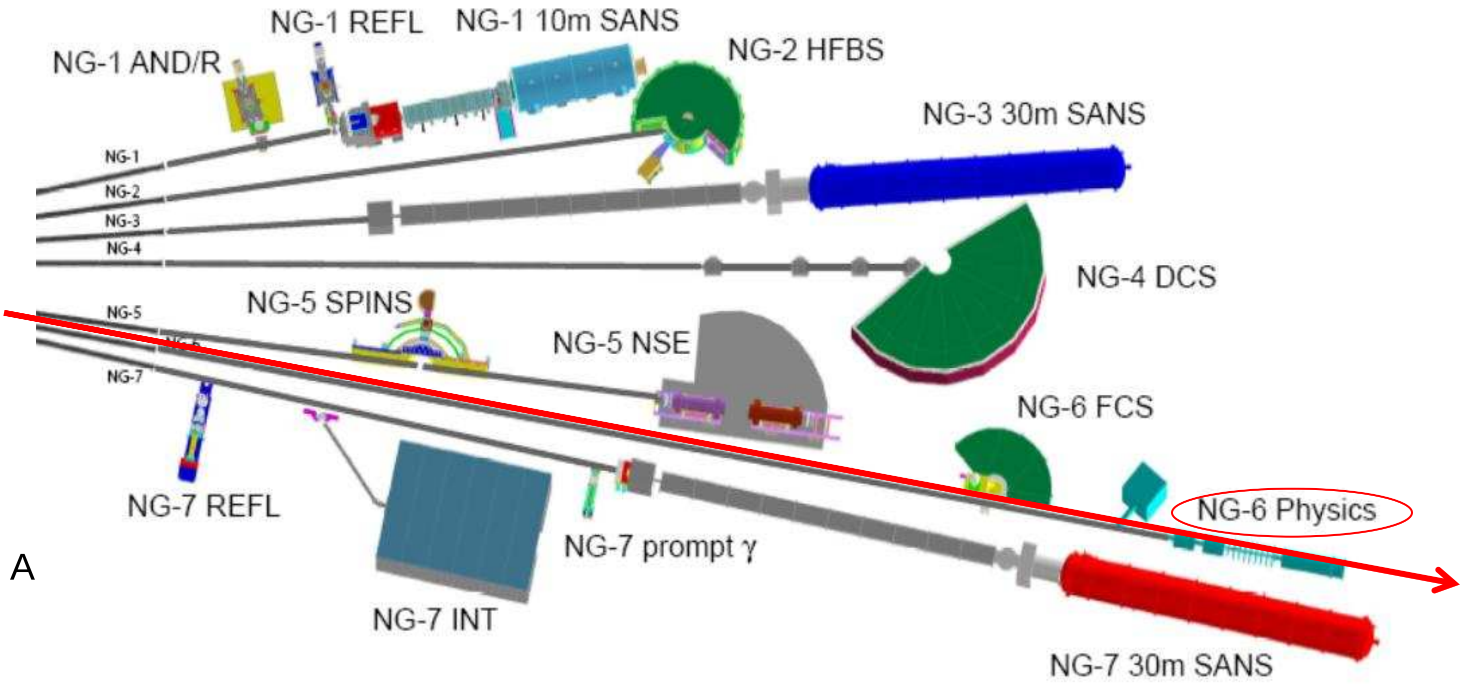
Where will we measure ϕ_{PV} ?
NIST Center for Neutron Research (NCNR)

Eight cold neutron guides, two for fundamental physics (NG-6, NG-7)

Reactor **20 MW**
(fission neutrons)
Moderation
D_2O
Thermal neutrons
Moderation LH

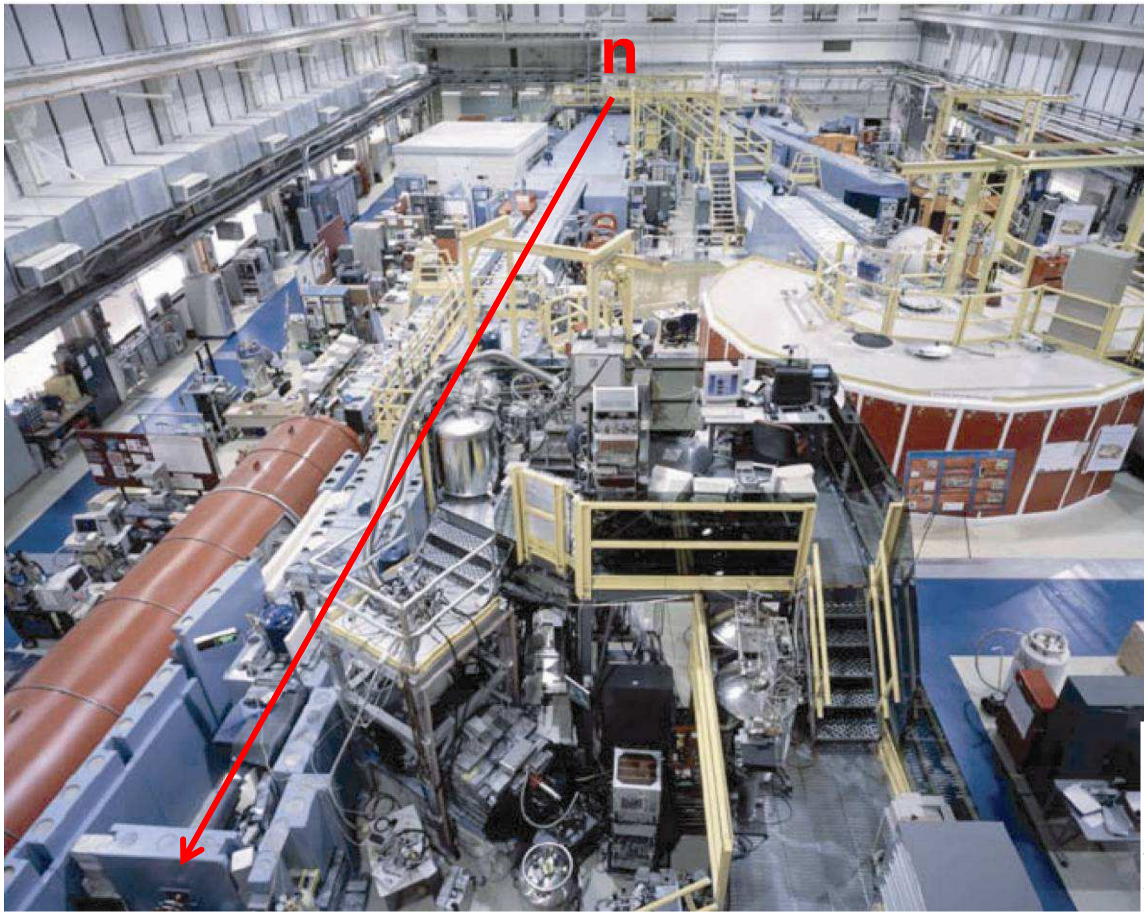
Cold neutrons

E<5 meV; T=20K
wavelength (λ) ~ few A



Cold neutrons are conducted by neutron mirrors (guides) over 80 – 100m with small losses to experimental areas.

Cold Neutron Guide hall at NCNR



^{58}Ni guide θ_c=2.1 mrad/A (21 mrad/nm) good cold neutron guide

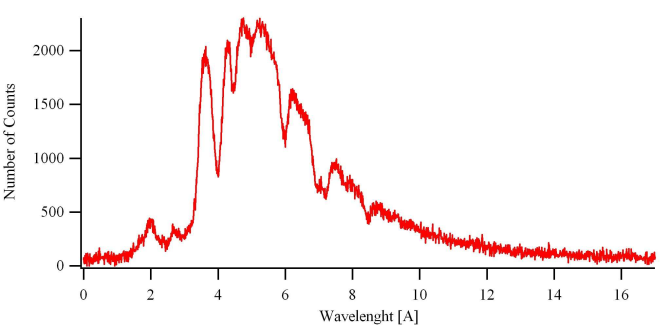
NG-6 Polychromatic beam line

upper half

lower half

2 mono-chromatic beams

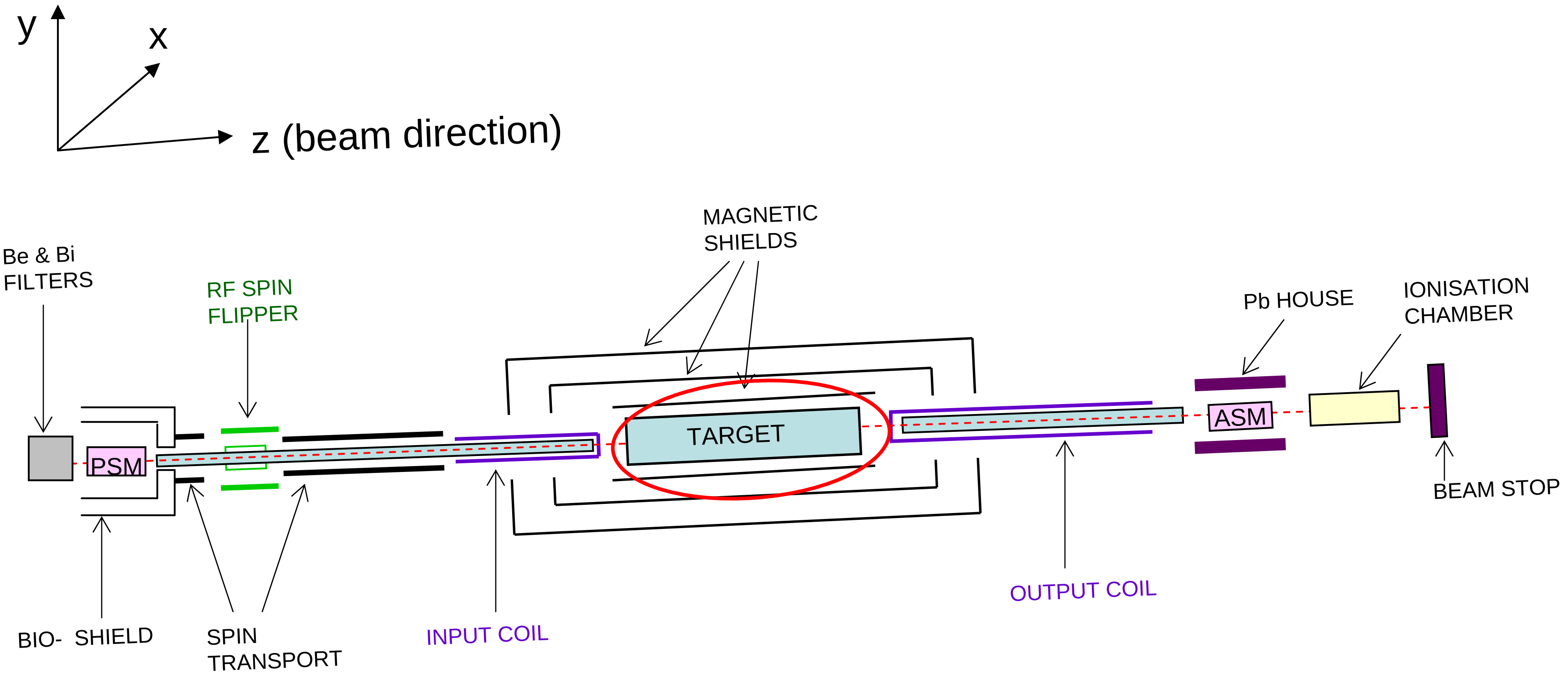
Beam diameter 6cm



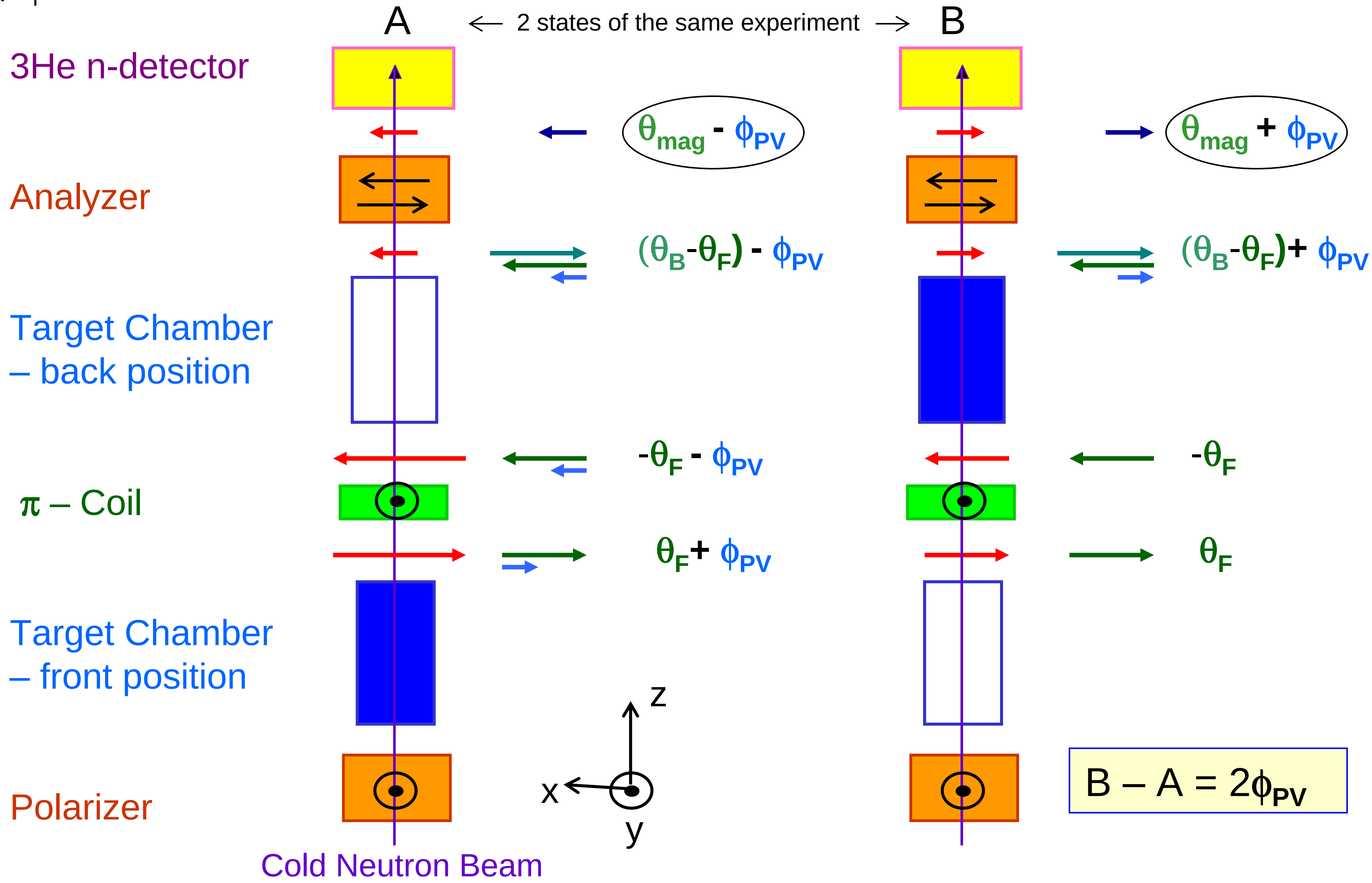
Neutron flux after Be&Bi filters = 1.2 x 10^9 n/cm^2/s

INT Seattle, WA, June 8, 2007

Neutron spin rotation apparatus



Conceptual target design



A ← 2 states of the same experiment → B

3He n-detector

$\theta_{mag} - \phi_{PV}$

$\theta_{mag} + \phi_{PV}$

Analyzer

$(\theta_B - \theta_F) - \phi_{PV}$

$(\theta_B - \theta_F) + \phi_{PV}$

Target Chamber – back position

$-\theta_F - \phi_{PV}$

$-\theta_F$

π – Coil

$\theta_F + \phi_{PV}$

θ_F

Target Chamber – front position

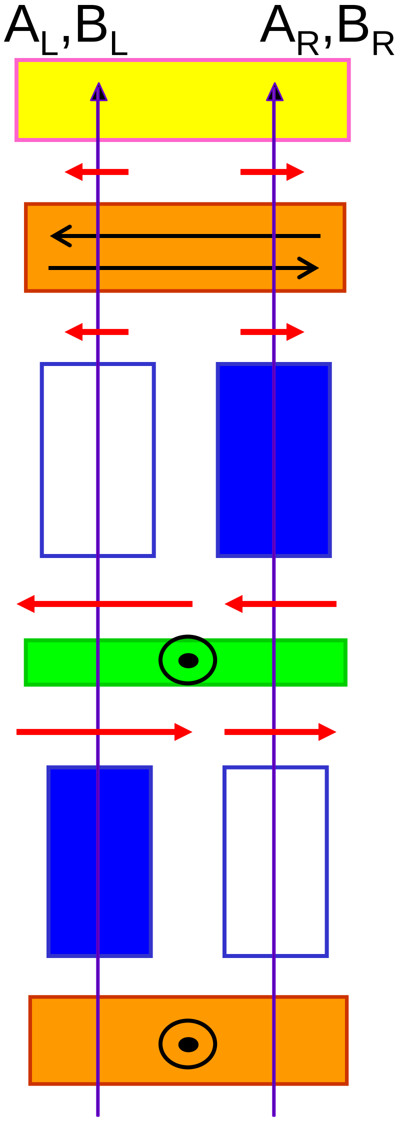
Polarizer

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

Cold Neutron Beam

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

Target design



3He n-detector

Analyzer

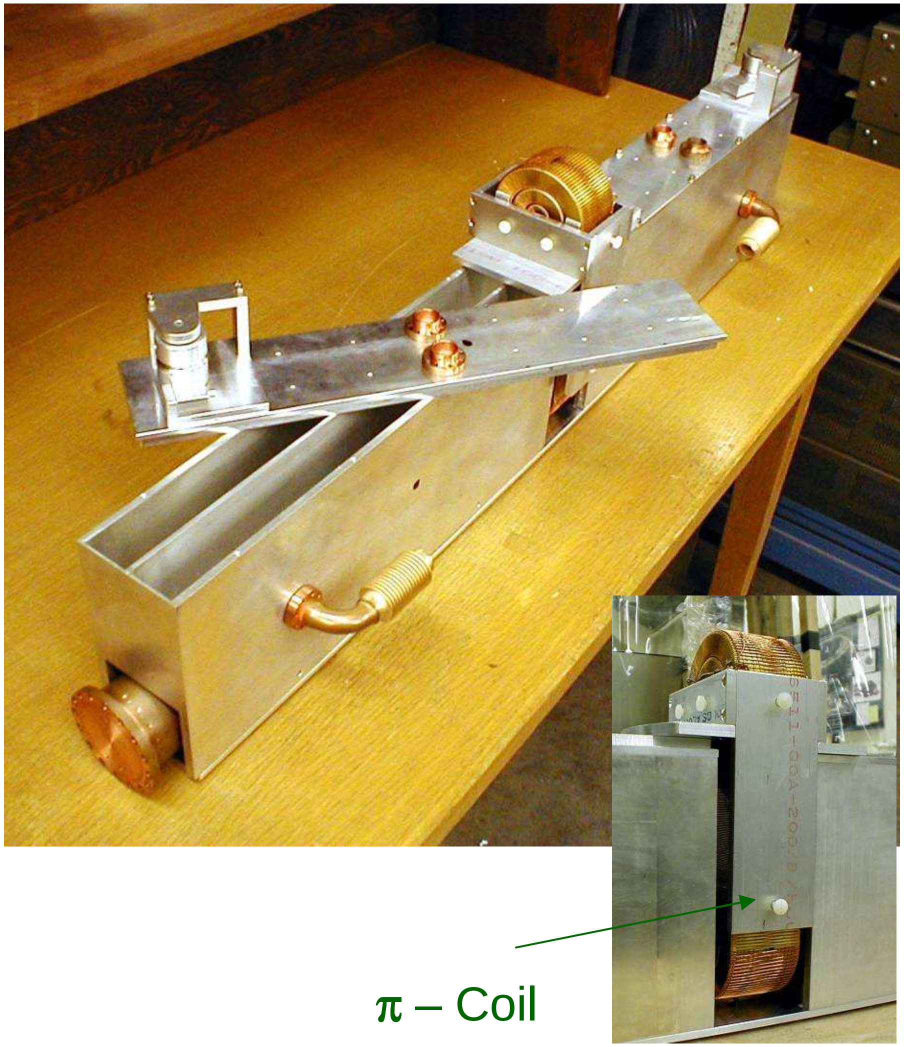
Target Chamber
– back position

π – Coil

Target Chamber
– front position

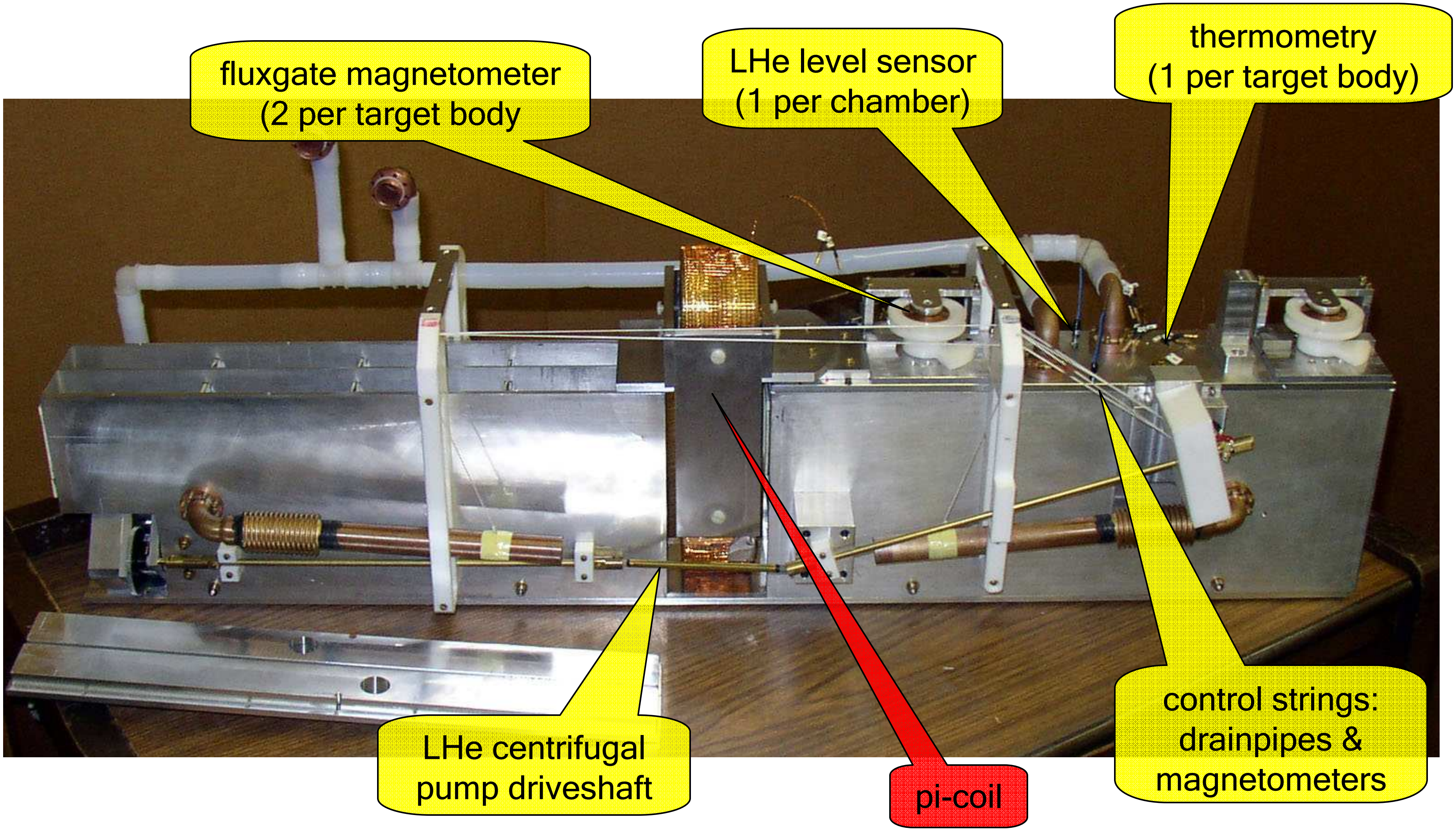
Polarizer

Cold Neutron Beam



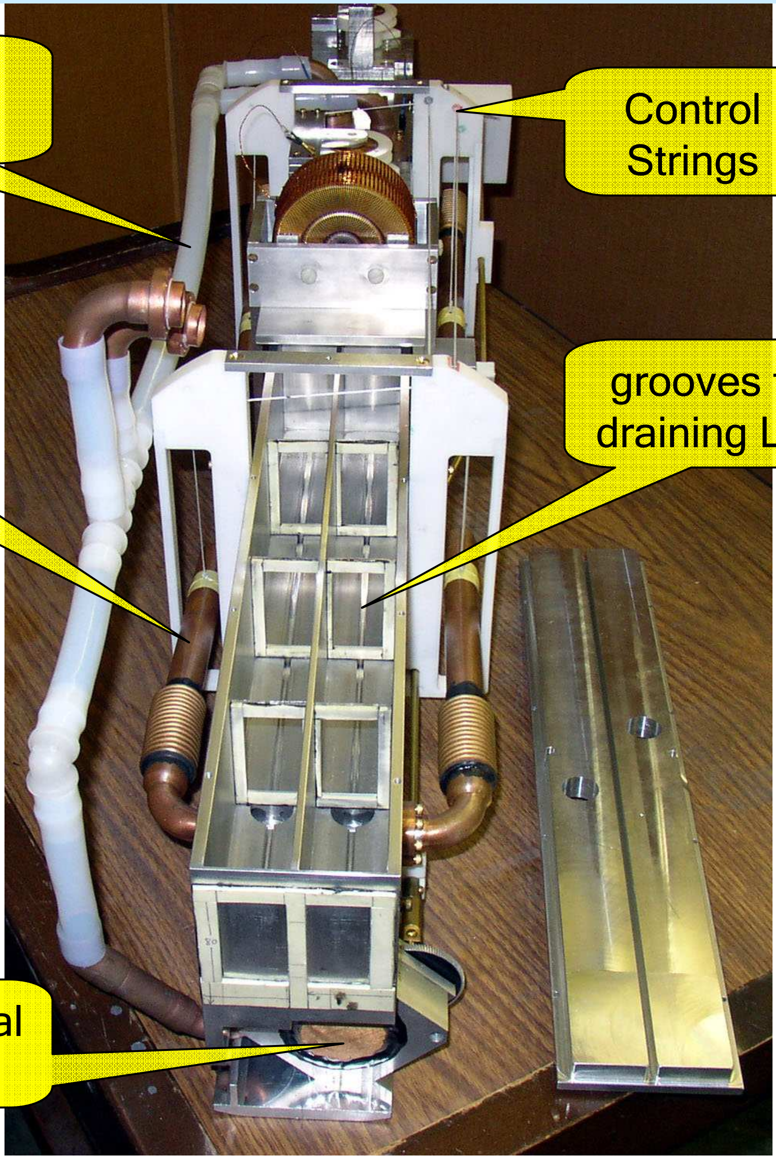
π – Coil

Target Design: Sensors & Motion Control



Target Design: Pump & Drain System

drainpipe ends fitted w/ knife-edge for superfluid-film suppression

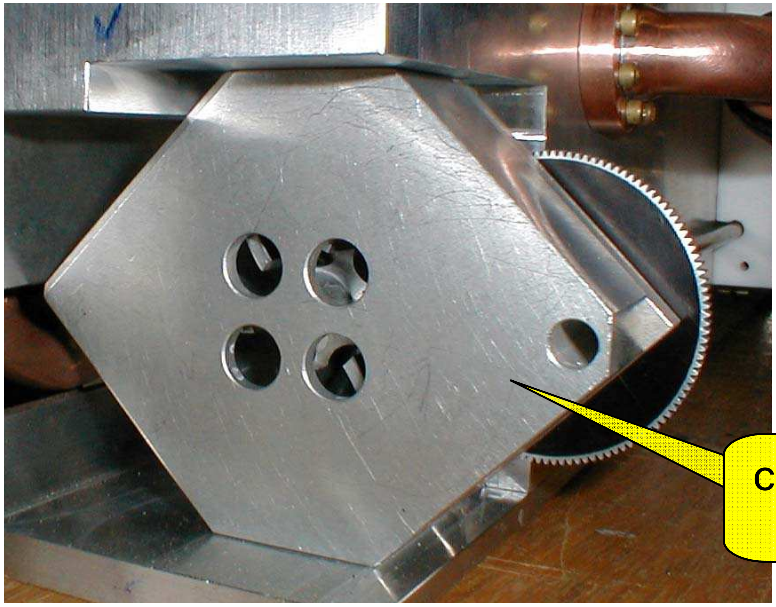


LHe target supply tubing

Control Strings

drainpipes (1 per chamber)

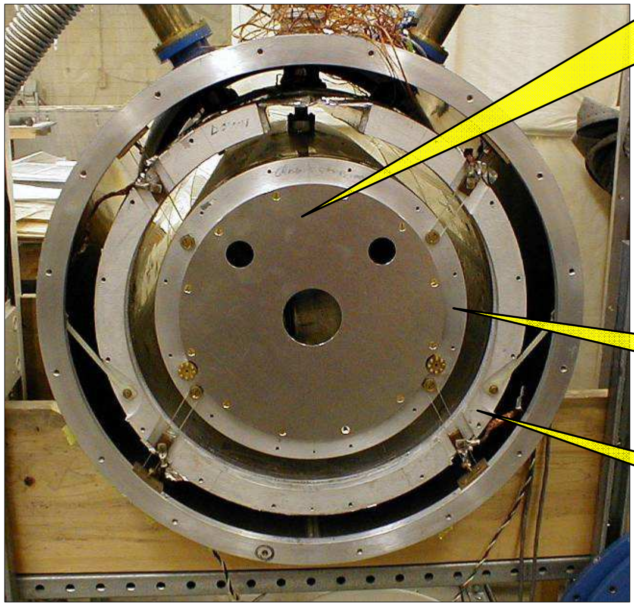
grooves for draining LHe



centrifugal pump

Cryostat

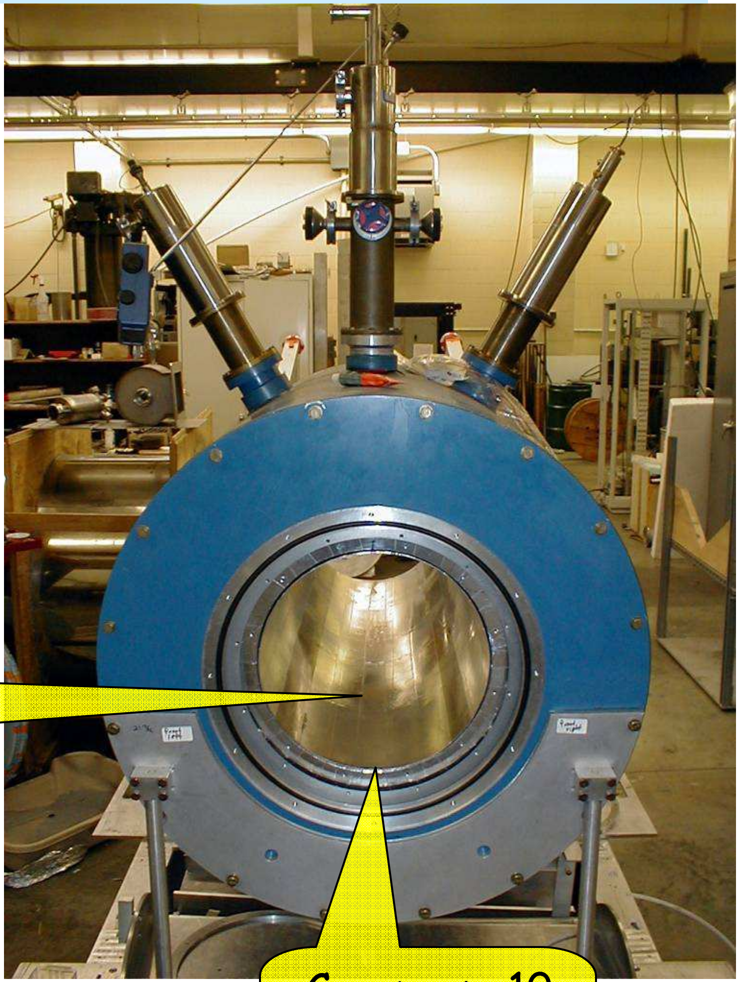
- Oxford horizontal, cold-bore cryostat
  - built from *non-magnetic* materials
  - consists of two coaxial annular vessels housed within a cylindrical main vacuum vessel



4K thermal shield

LHe volume: 30L

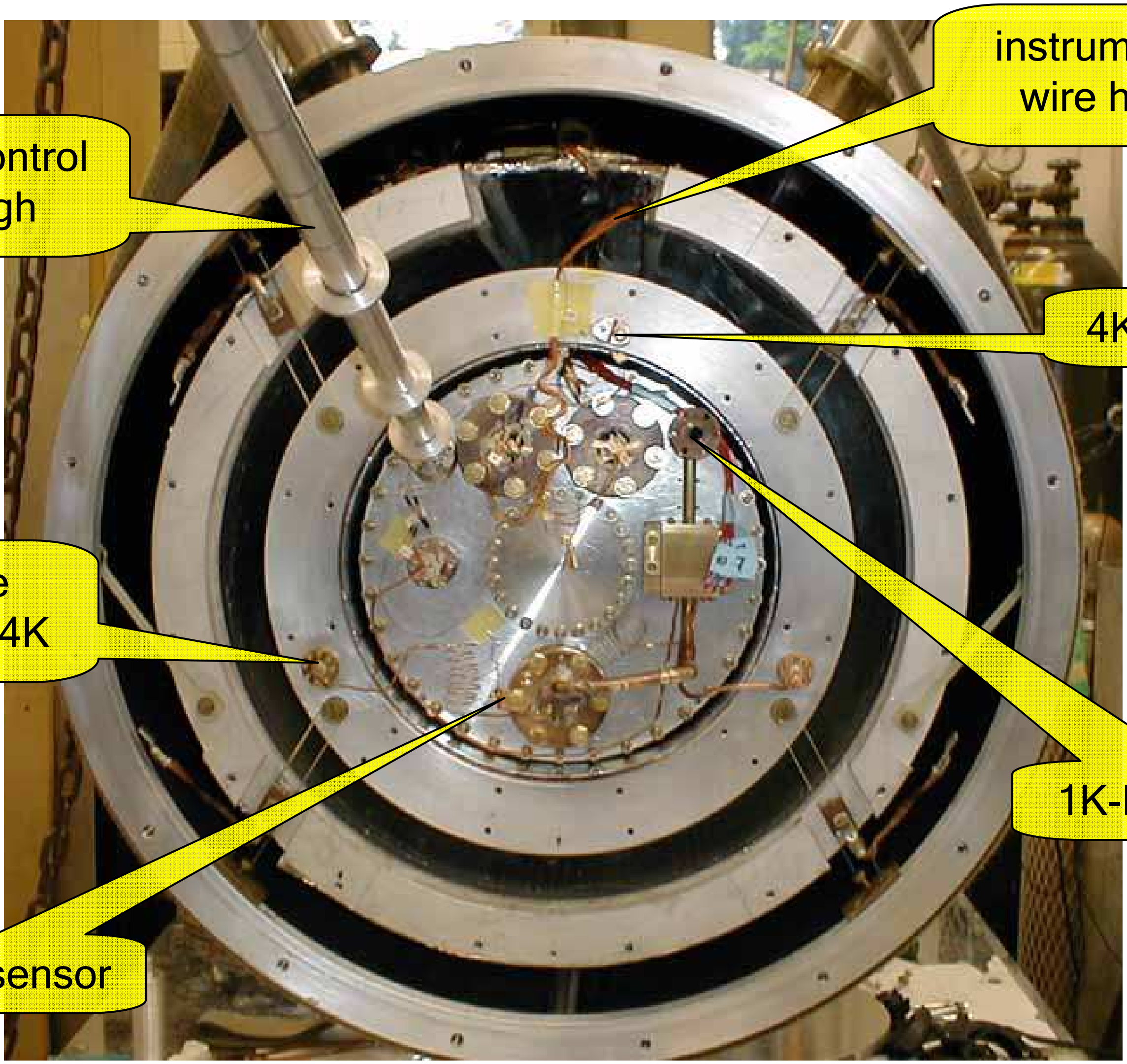
LN2 volume: 50L



cold bore:
30.5 cm dia
100 cm long

Cryoperm 10 cylinder lines coldbore

Insert & Feedthroughs - Assembly



instrumentation wire harness

2K motion control feedthrough

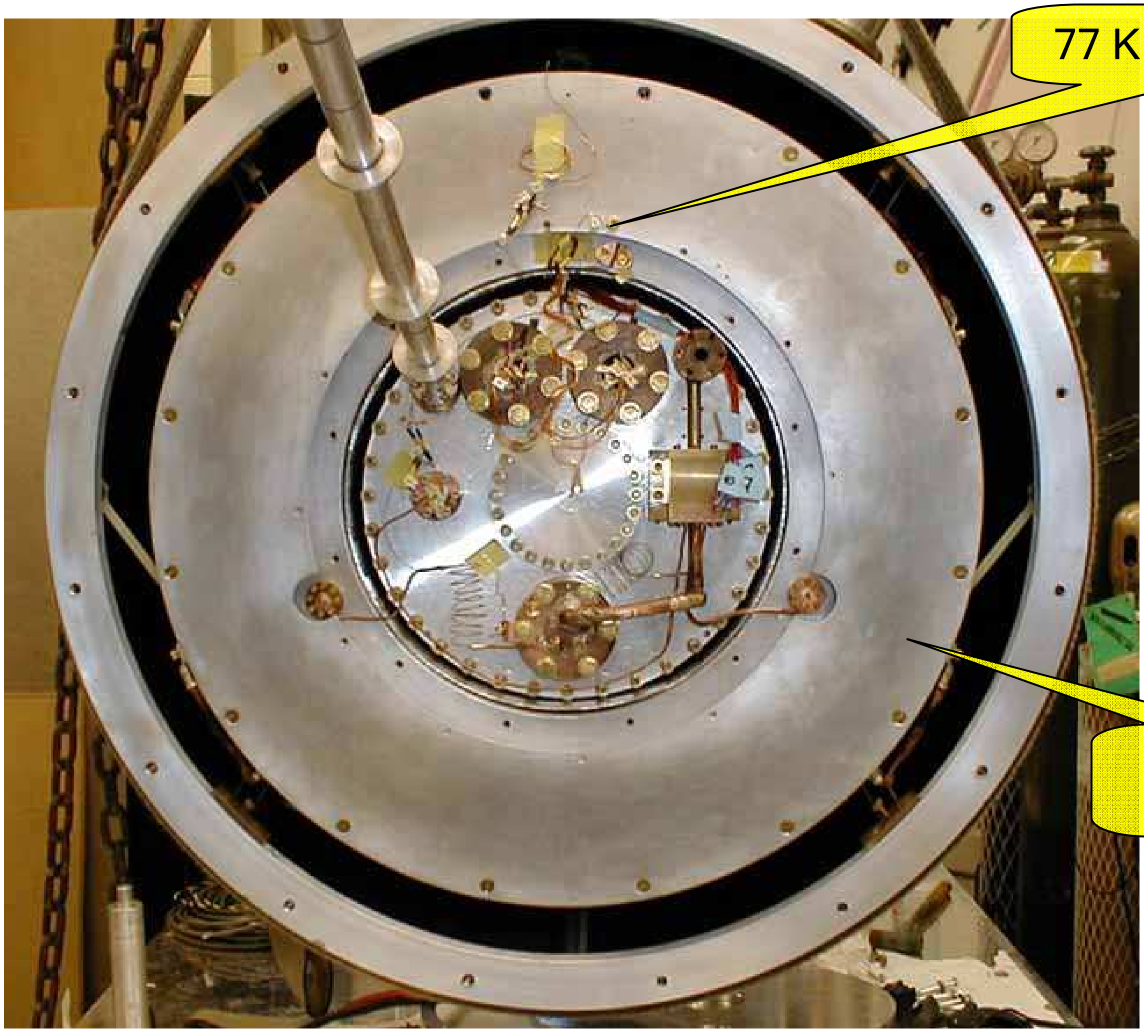
4K temp sensor

capillary line connection to 4K

1K-Pot pump line

2K temp sensor

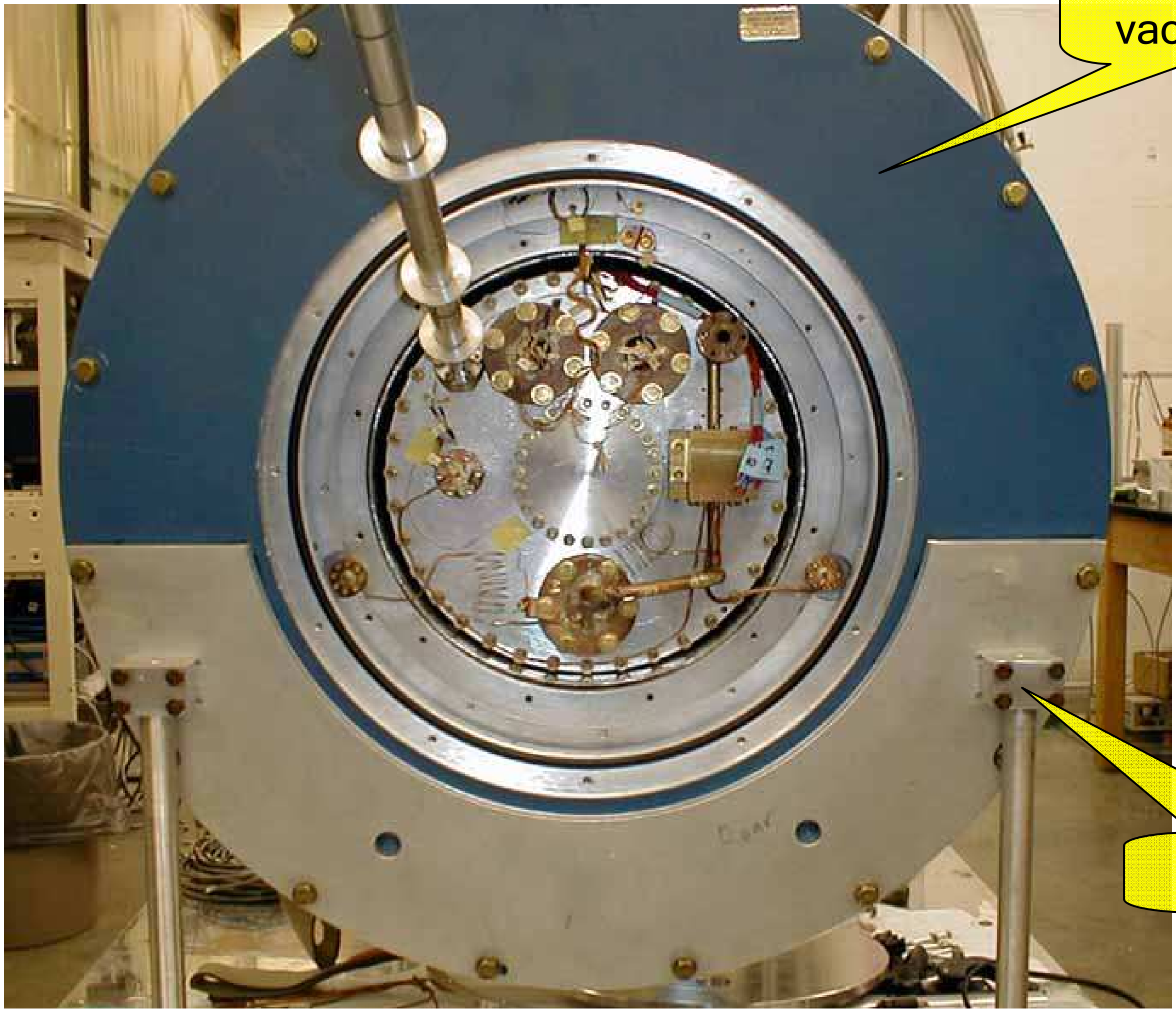
Insert & Feedthroughs - Assembly



77 K temp sensor

77K thermal shield

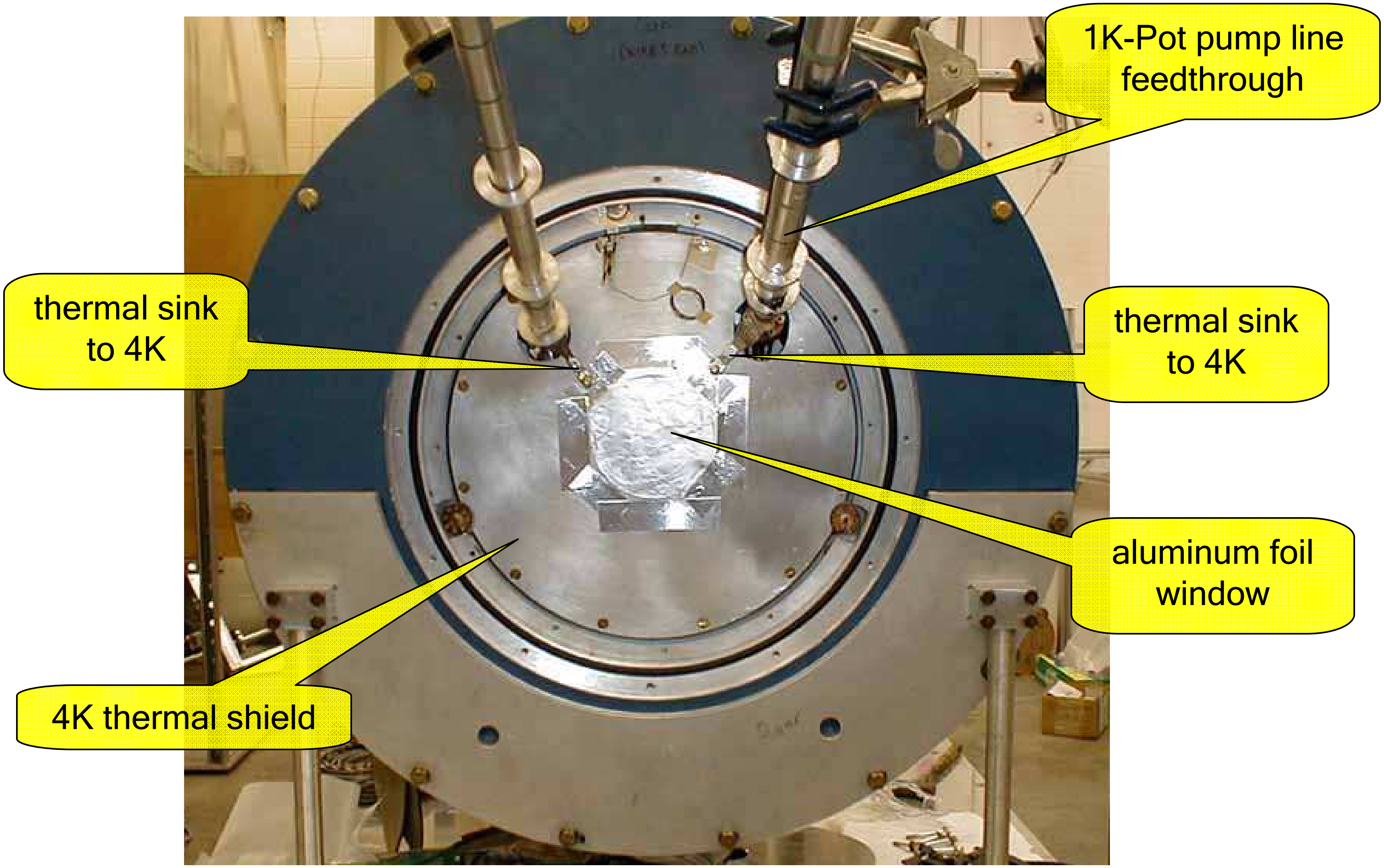
Insert & Feedthroughs - Assembly



300K main vac flange

Cryostat support

Insert & Feedthroughs - Assembly



1K-Pot pump line feedthrough

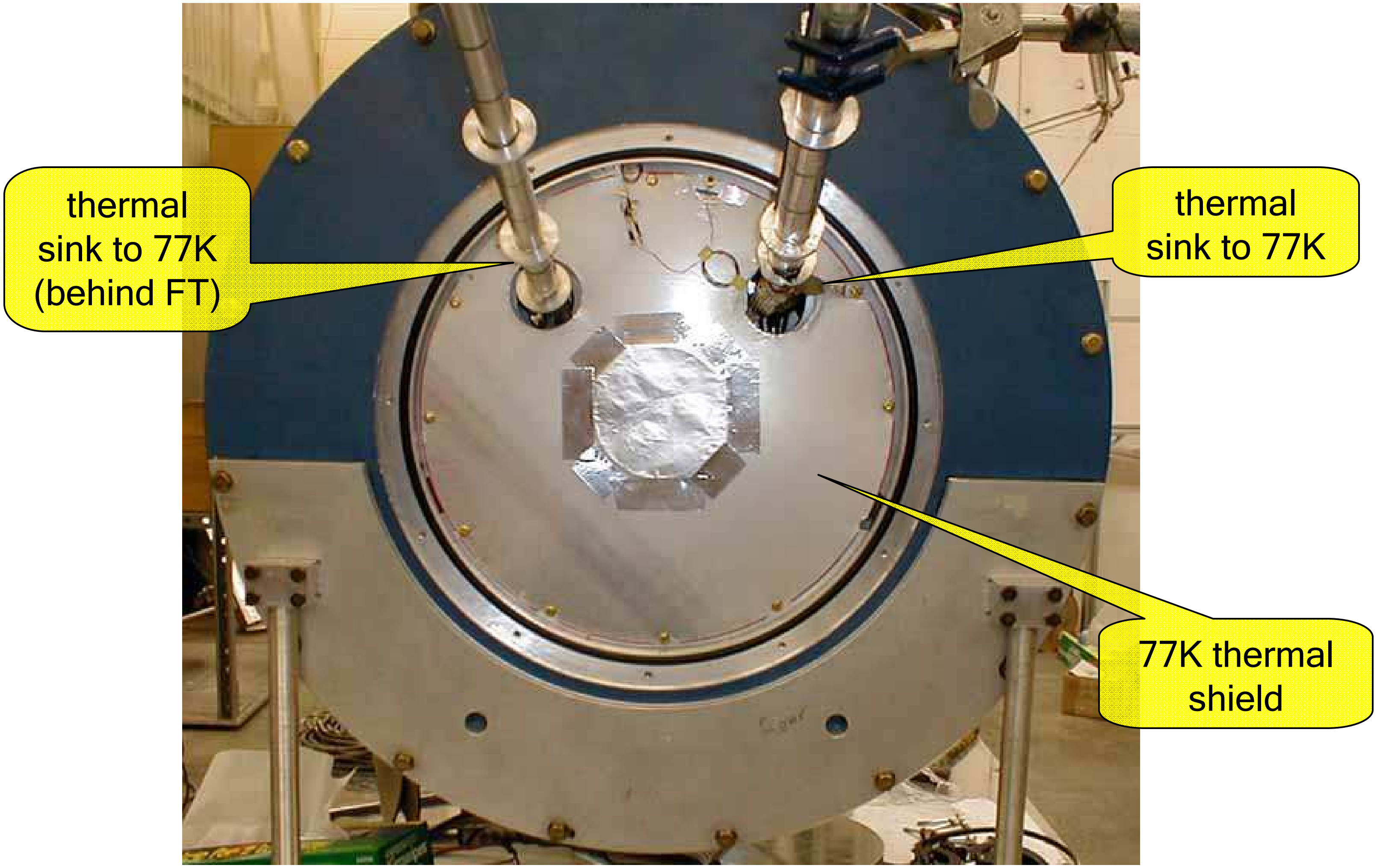
thermal sink to 4K

thermal sink to 4K

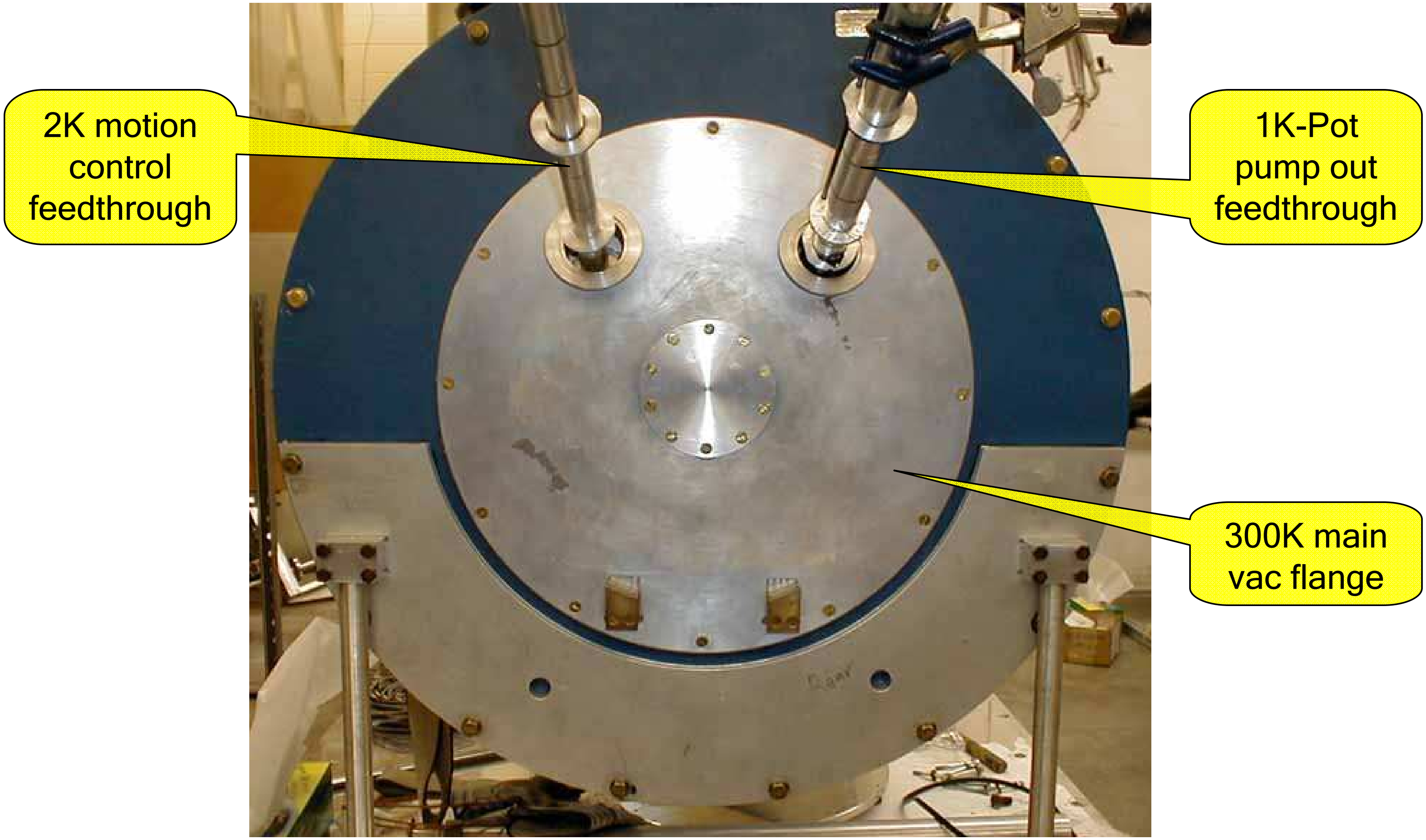
aluminum foil window

4K thermal shield

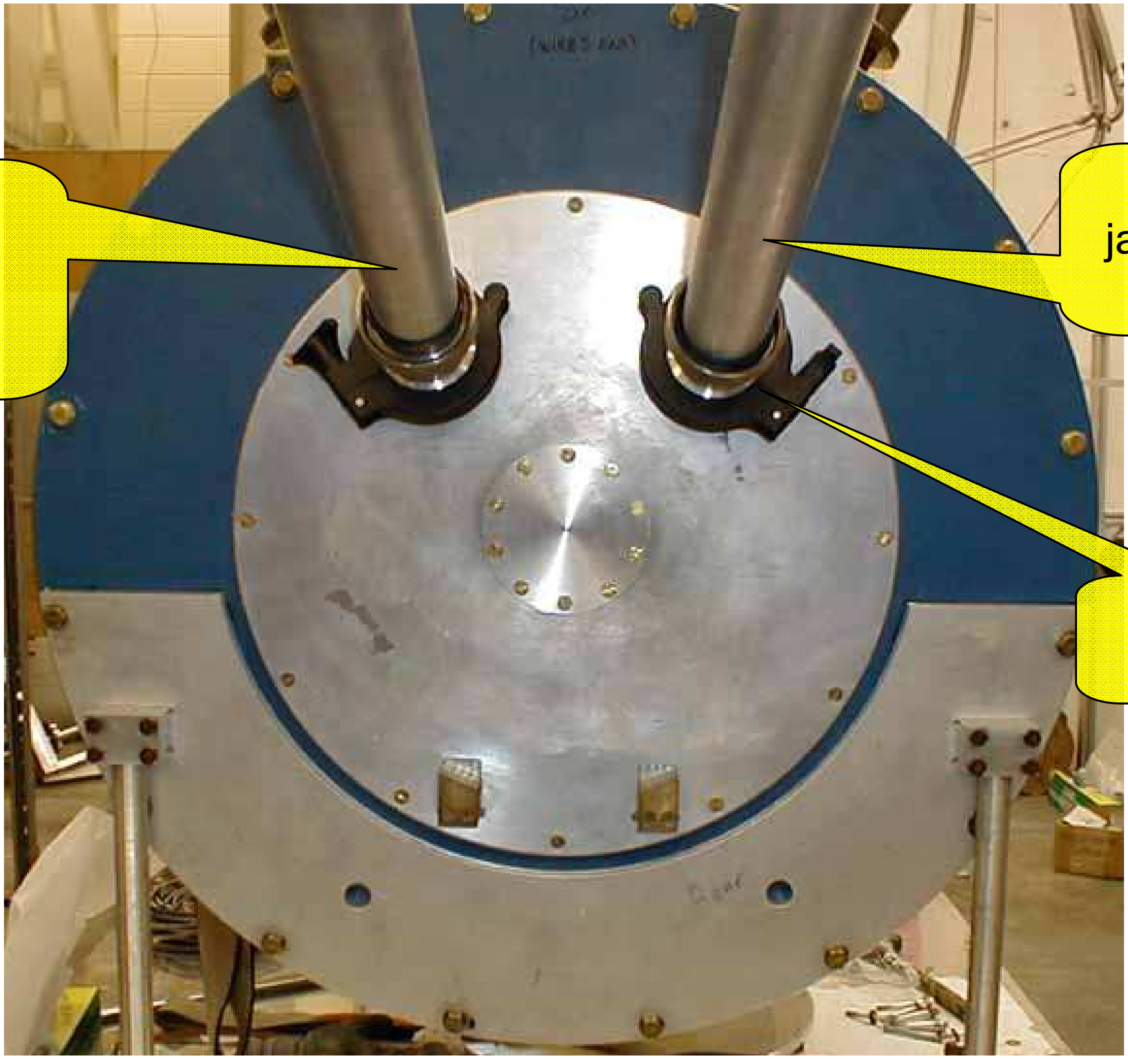
Insert & Feedthroughs - Assembly



Insert & Feedthroughs - Assembly



Insert & Feedthroughs - Assembly



300K vacuum jacket for 2K motion control feedthrough

2K MCB:
strings and
driveshaft

300K vacuum jacket for 1K-pot pump line

4K MCB:
1K-pot pump line &
trim coil access

ISO-KF flanges

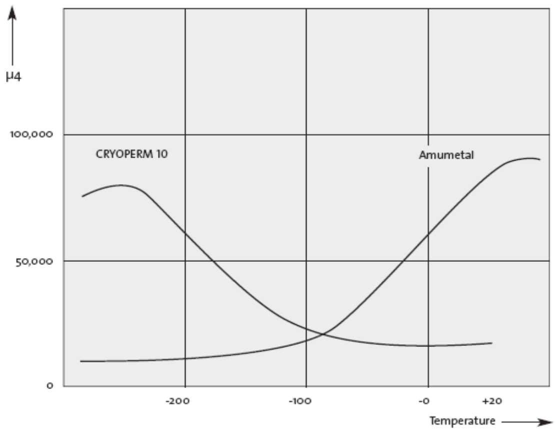
Magnetic shielding

Magnetic field is responsible for almost all of systematic effects !

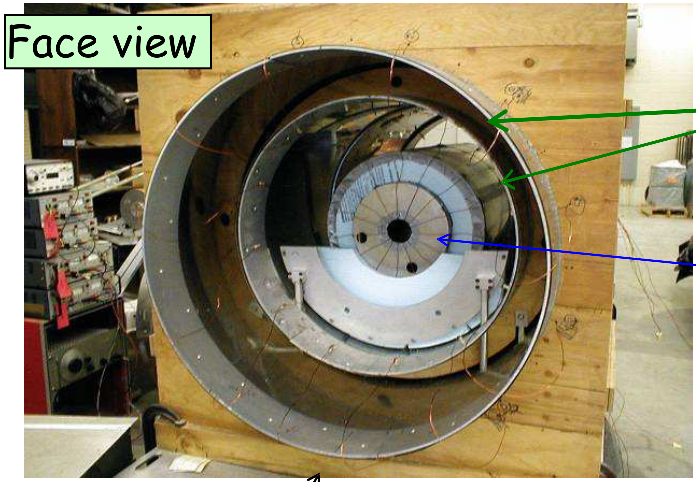
(1μT cause rotation of 5A neutrons ~ 2 mrad/m)

Goal: to reach as low as possible and constant longitudinal B field in the target region (B < 50nT)

Surrounding target region with ferromagnetic shields will cause the magnetic flux to concentrate in the shielding material



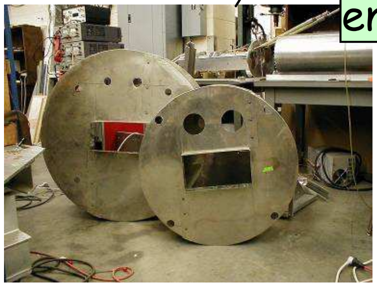
Face view



2 outer
CO-NETIC AA shield

1 inner
CRYOPERM-10 shield

endcaps

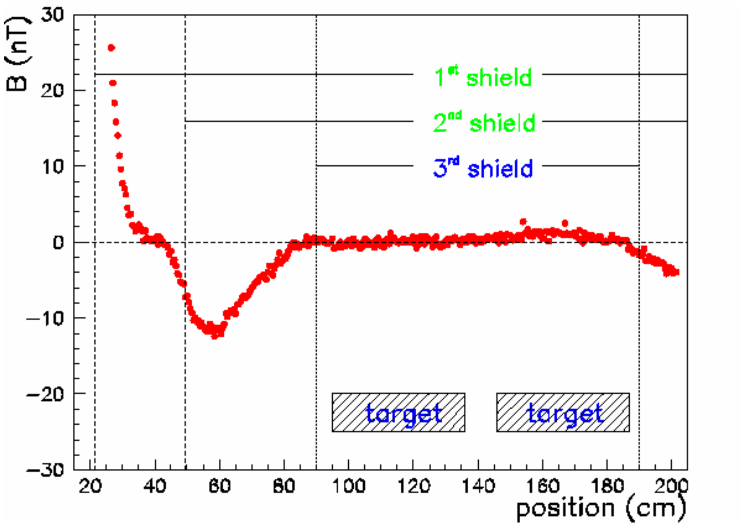


are
mounted on
both sides

Side view

Suppressing the magnetic field

⇒Magnetic shields



Using our mu-metal shield we can suppress longitudinal B field by ~10^6

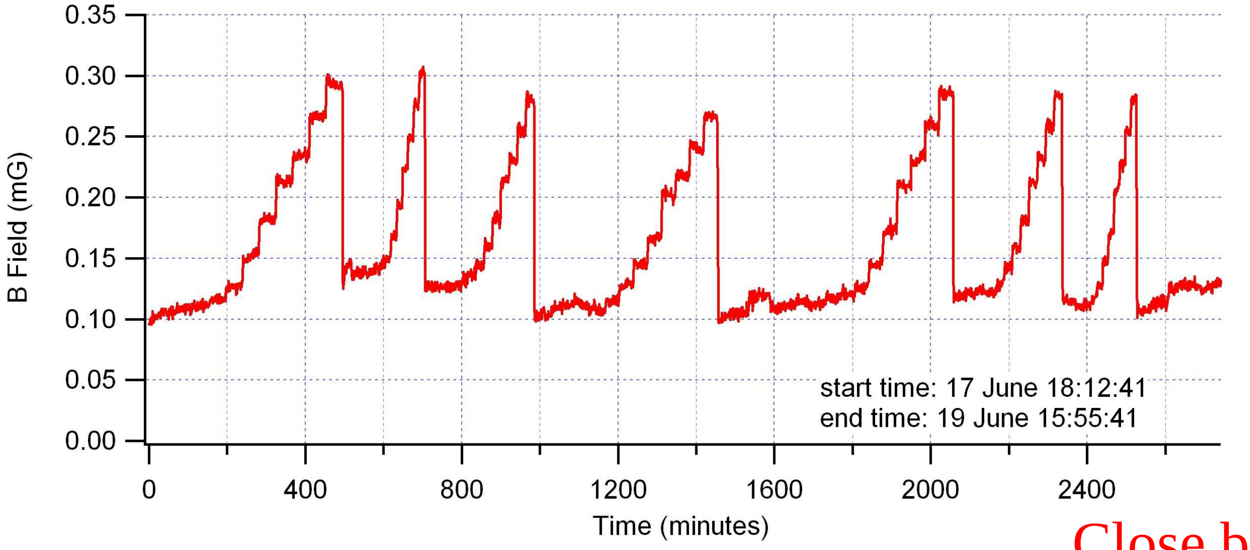
To monitor longitudinal B files 4 fluxgate magnetometers are mounted on the target lid.

Information will be use to further decrease B field by using trim coils wound on the target canister (feed back system).

But 2nT (fluxgate sensitivity) in the target region still not good enough (causes rotation 100 times bigger than ϕ_{pv})

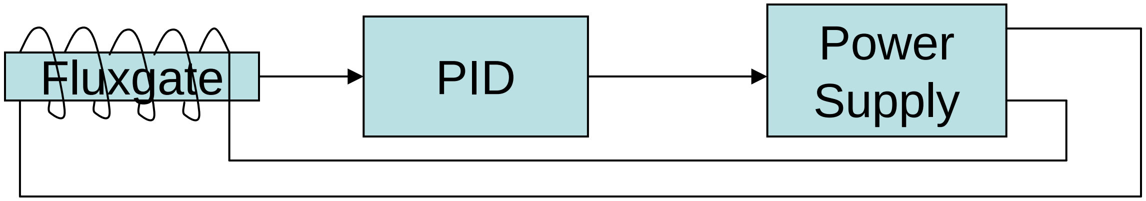
⇒Target design – to extract tiny PV signal from much bigger due to magnetic field

“Nice” surprise at NIST



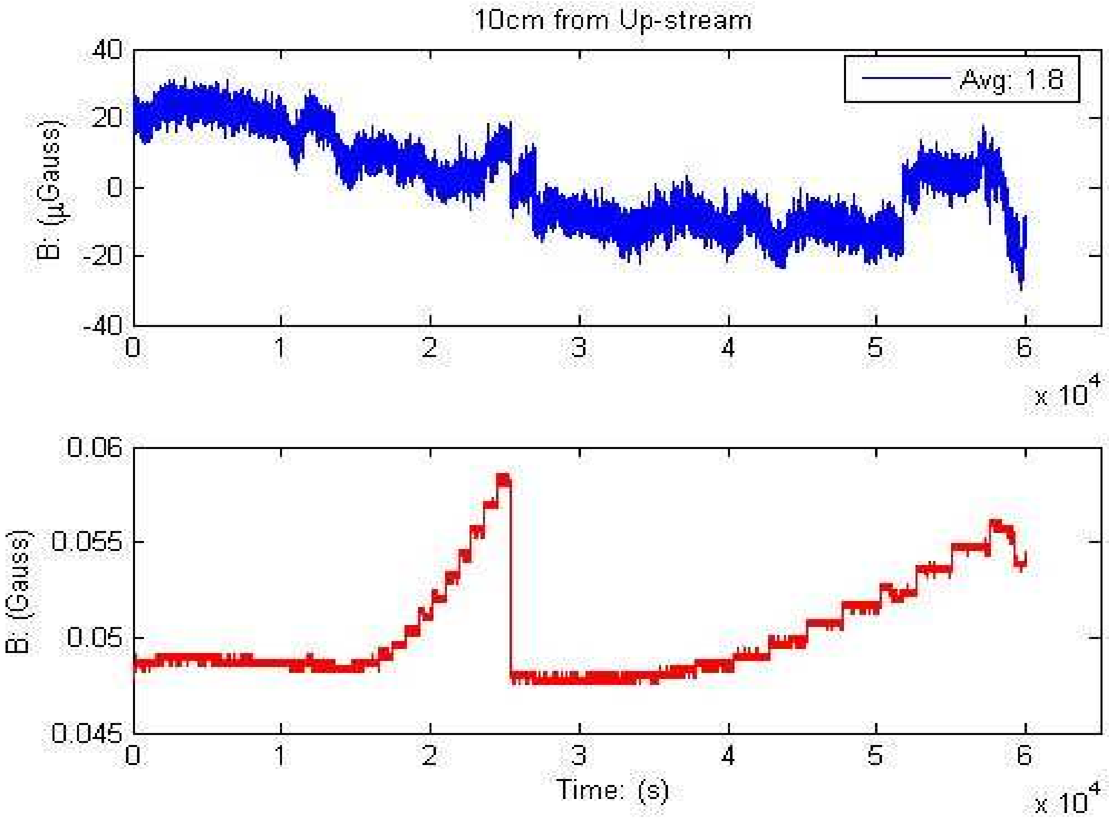
Close by magnet !

Problem was Fixed by monitoring magnetic file by fluxgate (on outer layer of magnetic shields) connected to PID controller and coil surrounding magnetic shields



“Nice” surprise at NIST

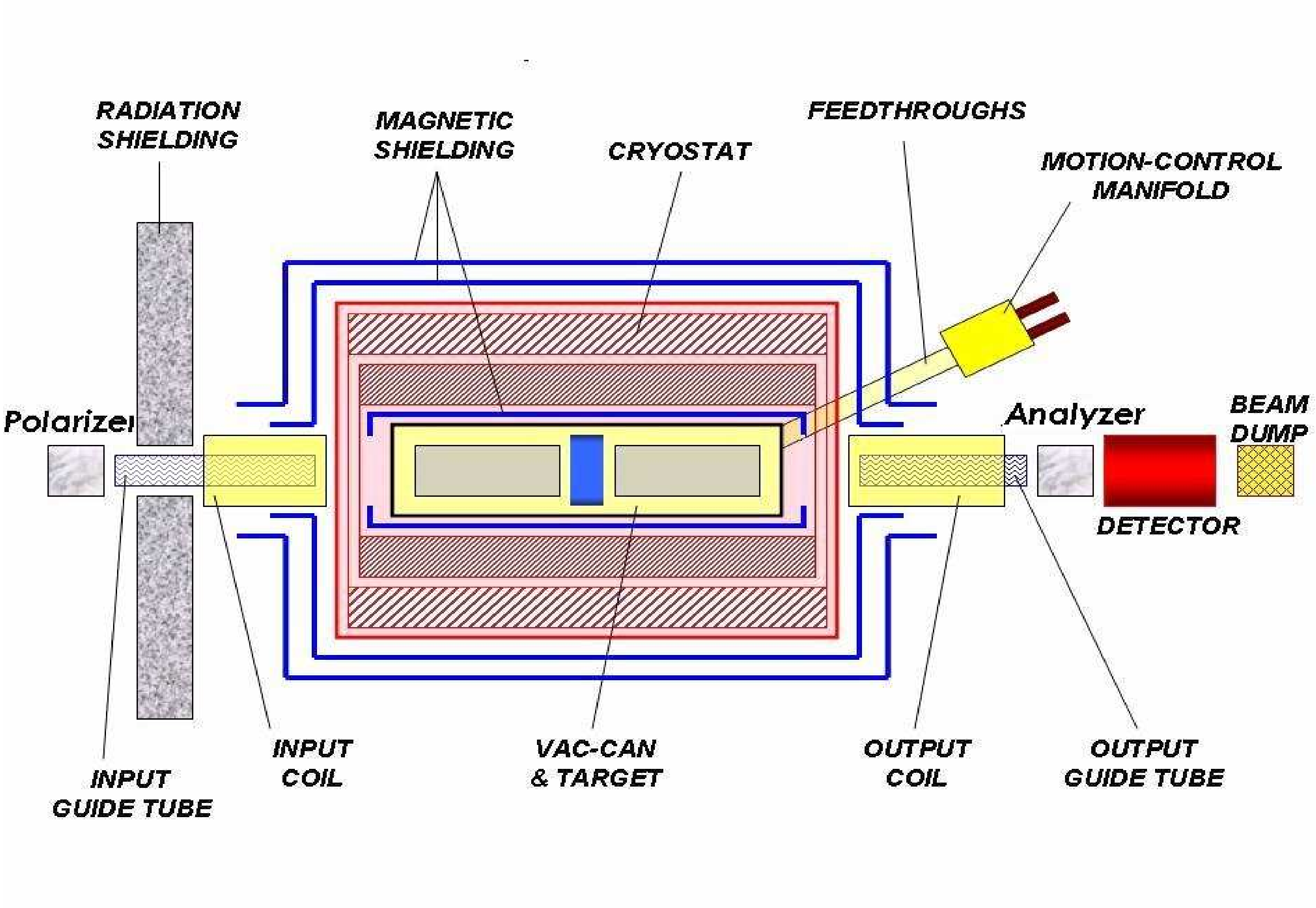
By using PID we could suppress magnetic flux by a factor of ~1000



Flux measured inside of 2 magnetic shields

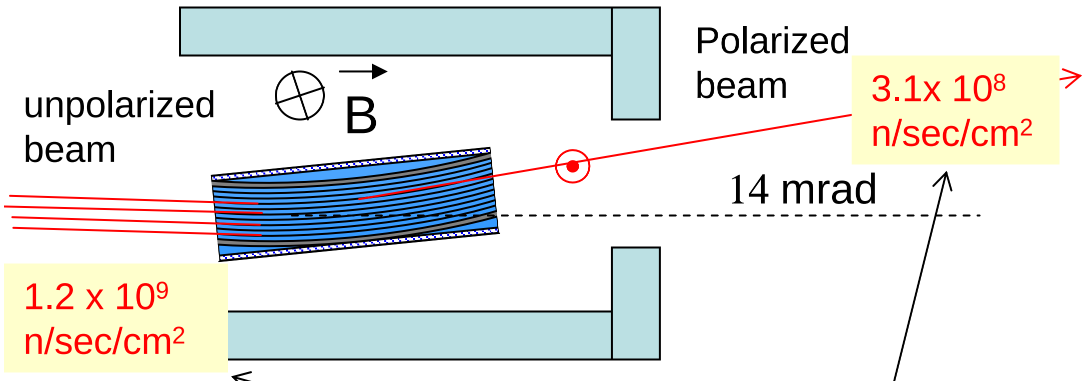
Flux measured outside of 2 magnetic shields

Cross section of Spin Rotation Apparatus

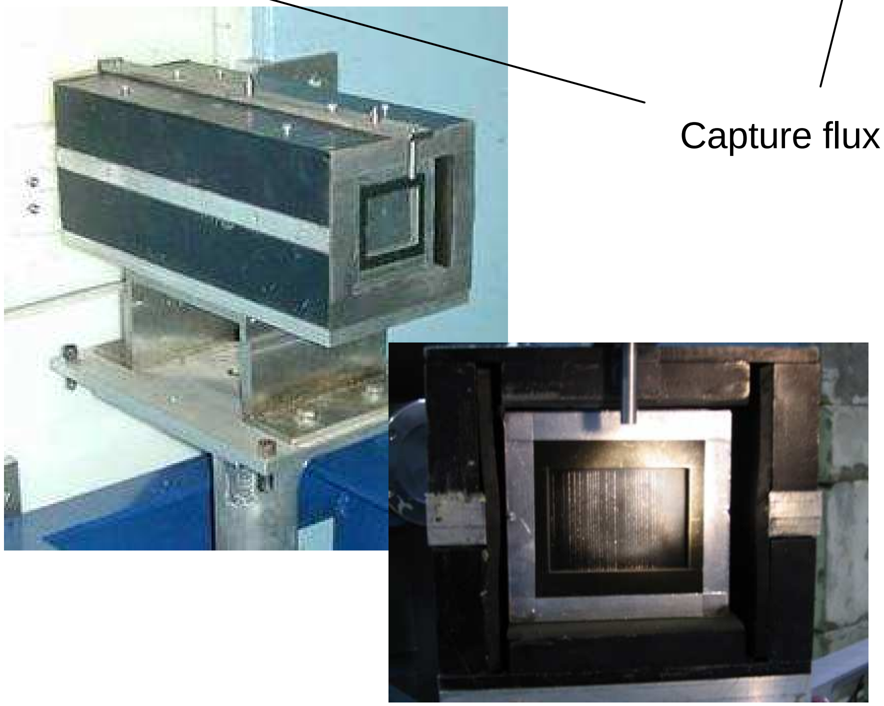


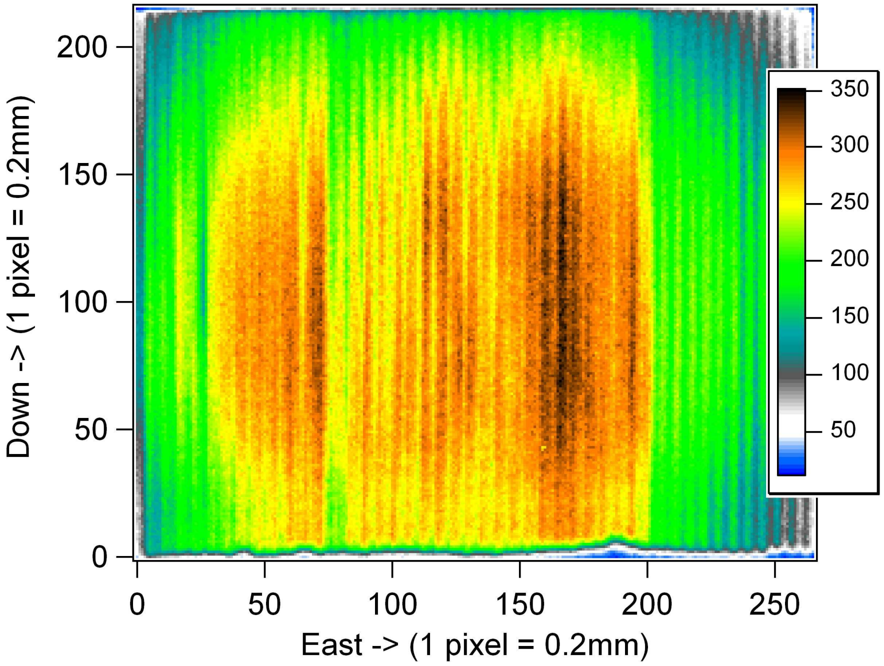
Polarizing Super Mirror

- spin-dependent scattering from magnetized mirrors
- Alternating layers of magnetic surface (cobalt) and absorptive layer (titanium and gadolinium); 1mm separation; Placed in 300 G permanent box.
- Typical polarization: 98%; transmission: 25%



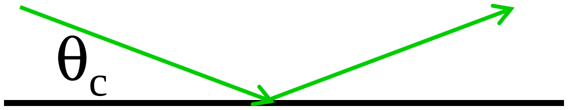
Capture flux



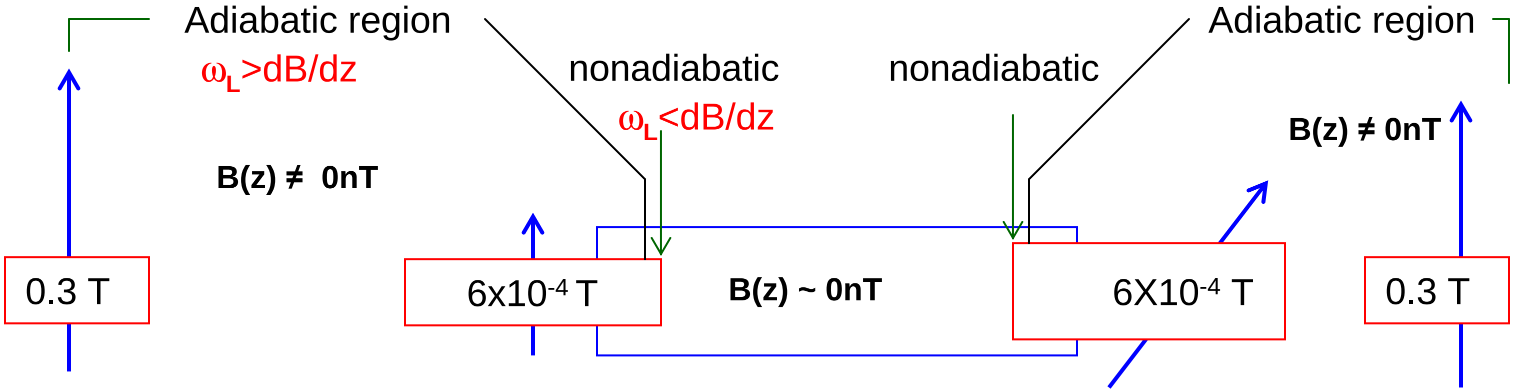


How we transport polarized neutrons – input guide & spin transport

To transport neutrons – we are using float glass guide (θ_c=12mrad/nm)



To maintain neutron polarization ⇨ B filed pointed in the direction of neutron polarization is needed (spin transport)



Adiabatic region

ω_L>dB/dz

nonadiabatic

ω_L<dB/dz

nonadiabatic

Adiabatic region

B(z) ≠ 0nT

B(z) ≠ 0nT

B(z) ~ 0nT

0.3 T

$6x10^{-4}$ T

$6X10^{-4}$ T

0.3 T

SMP

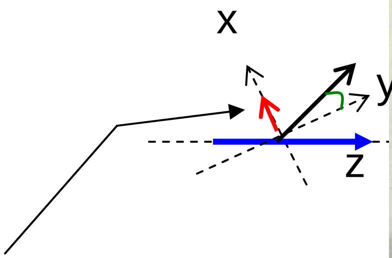
Input guide & Input coil

output guide & output coil

ASM

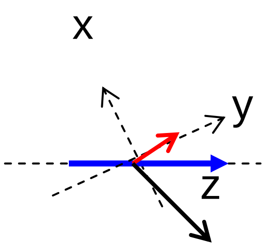
How we transport polarized neutrons – output coil

B ~free region;
weak interaction: ϕ_{PV}

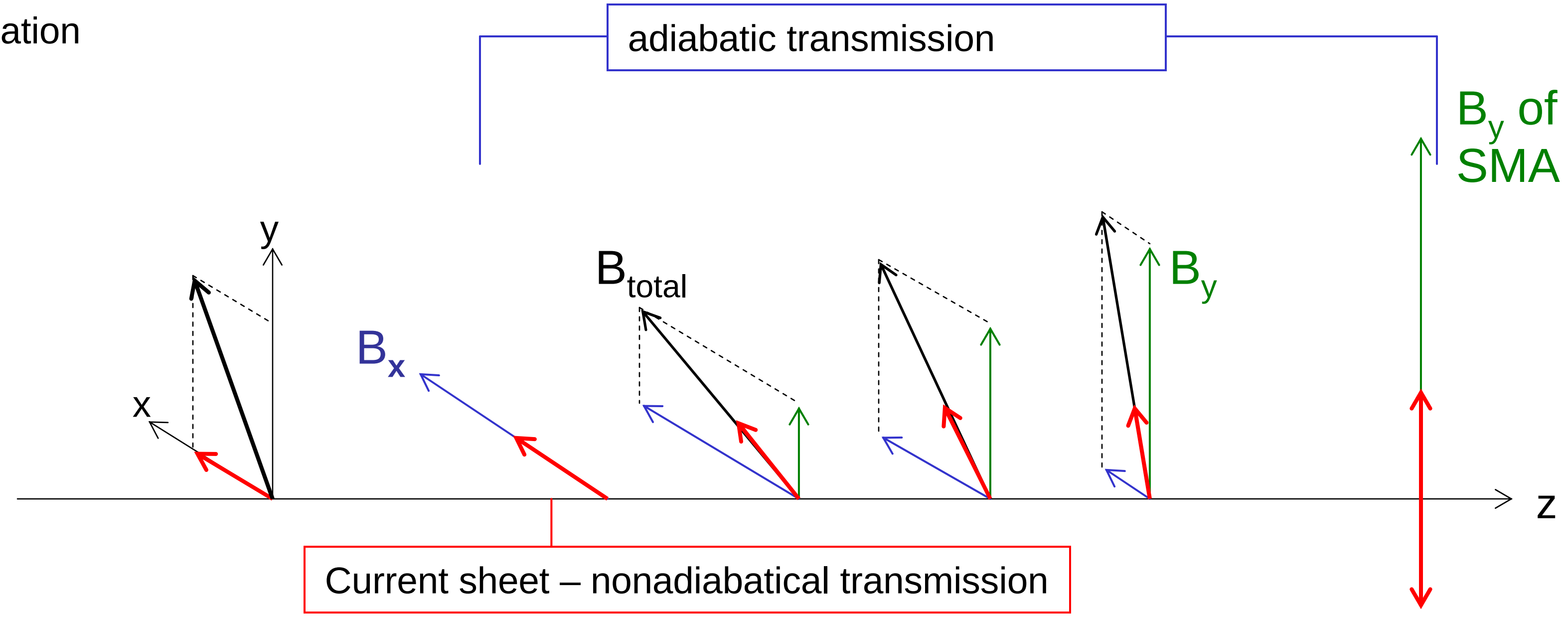


This component shows size of rotation

output coil



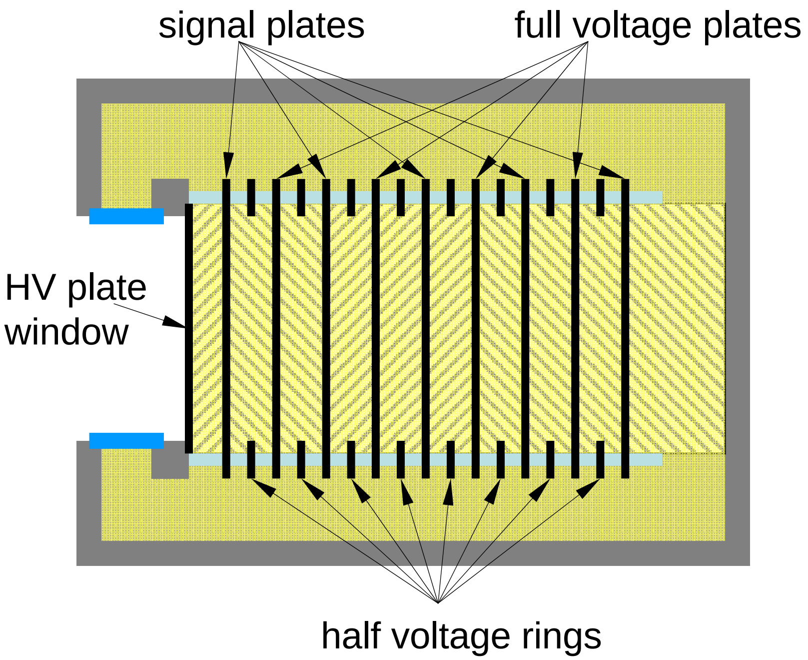
Output Coil – nonadiabatic spin flipper and 90° adiabatic spin rotator.

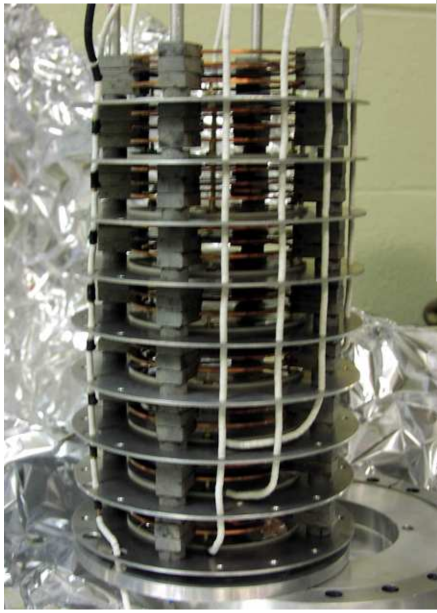


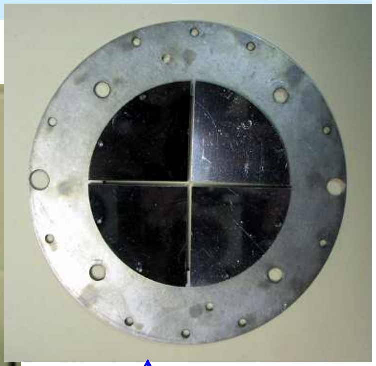
adiabatic transmission

Current sheet – nonadiabatical transmission

Segmented ^{3}He ionization chamber







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

- ^{3}He and Ar gas mixture
- Neutrons detected through $n+{}^3He \rightarrow {}^3H+{}^1H$
- 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)]

Systematic Effects in PV Spin Rotation

Associated with residual longitudinal B **(**B< 10 nT **)**

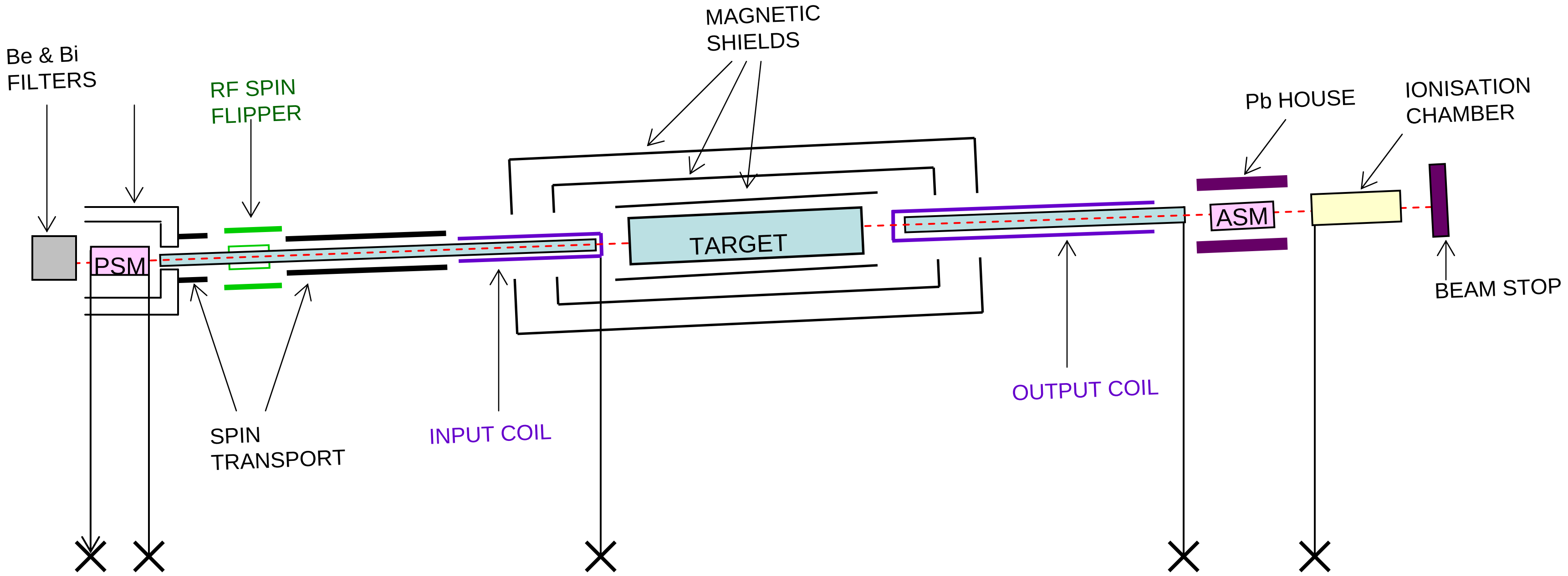
effect		estimate of size
– **He diamagnetism** **(size of diamagnetism in 4He ~ 10^{-6})**	**($B_{He} \neq B_{vac}$)**	**~10^{-8} rad/m**
– **He optical potential** **(^{4}He slows down the neutron – neutron velocity change 10^{-6})**	**($V_{He} \neq V_{vac}$)**	**~10^{-8} rad/m**
– **small angle scattering in He** **(different solid angle of 2 targets)**	$\int \frac{\vec{B}_1 \cdot d\vec{\ell}_1}{v_1} \neq \int \frac{\vec{B}_2 \cdot d\vec{\ell}_2}{v_2}$	**~10^{-8} rad/m**

LHe $\Longleftrightarrow$ superfluid LHe: decrease small angle scattering by ~(×5)

PV spin rotation independent of neutron energy, B rotation depends on neutron energy. At NIST we will amplify effects by increasing B in separate measurements. However, no time-of-flight… (future SNS !)

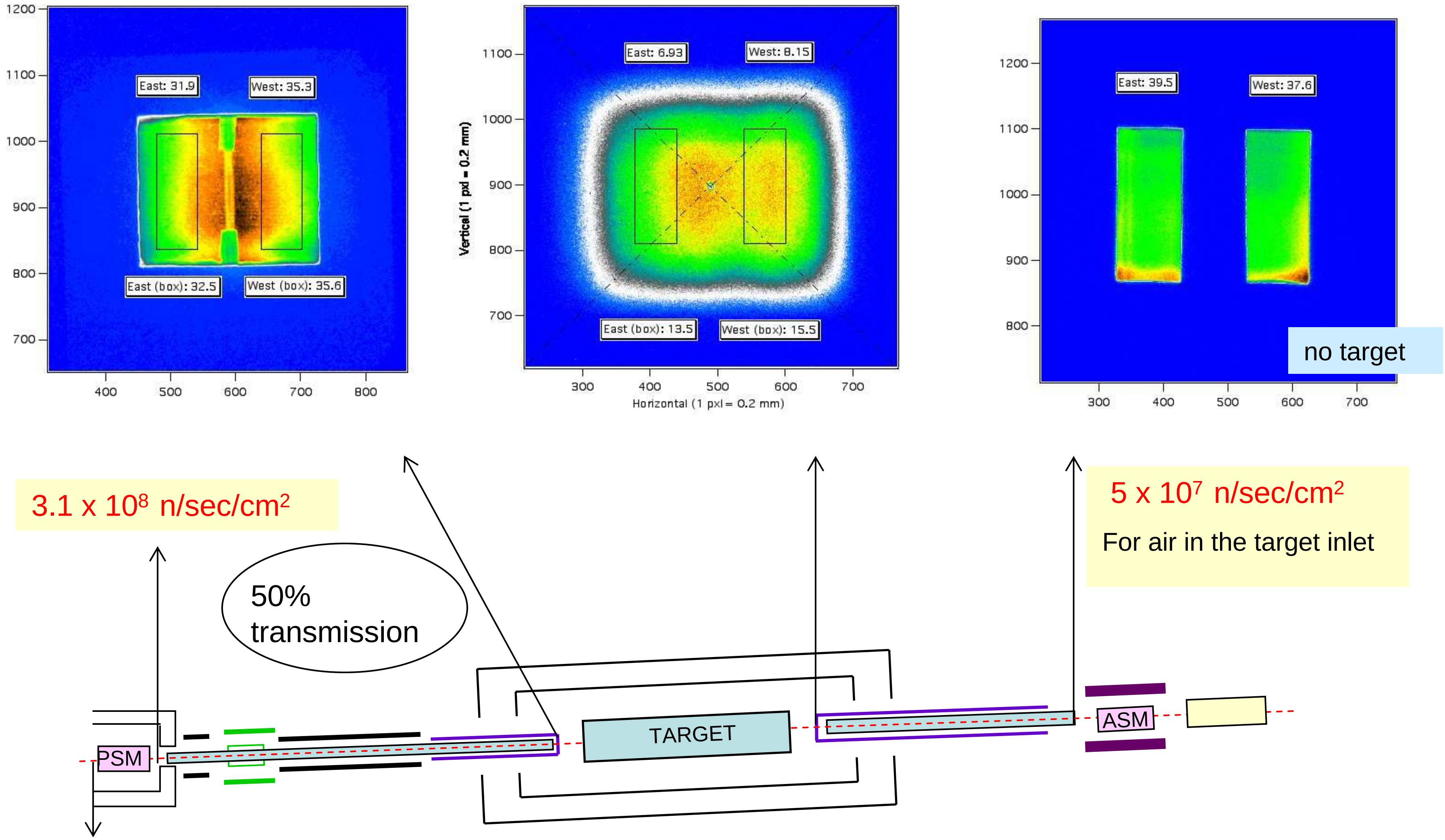
previous version (1996): upper bound on systematic effects < 2×10^{-7} rad/m
our goal: systematic effects < 1×10^{-7}rad/m

Before real measurement we need to understand beam and apparatus behavior – systematic check of beam and apparatus behavior



- Beam intensity distribution as I(λ) / chopper – TOF, ionisation chamber
- Beam intensity distribution as I(x,y) / image plate
- Polarization product (PA) as a f(λ) /PSM, ASM, chopper – TOF
- Neutron capture flux (fluence rate) /calibrated fission chamber

Beam spatial distribution



no target

3.1 x 10^8 n/sec/cm^2

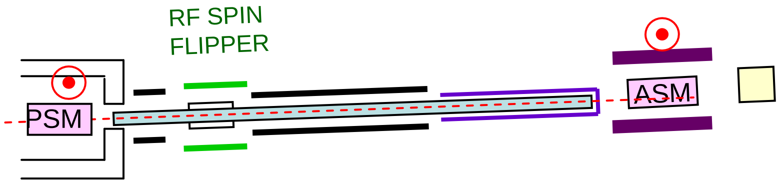
50% transmission

5 x 10^7 n/sec/cm^2

For air in the target inlet

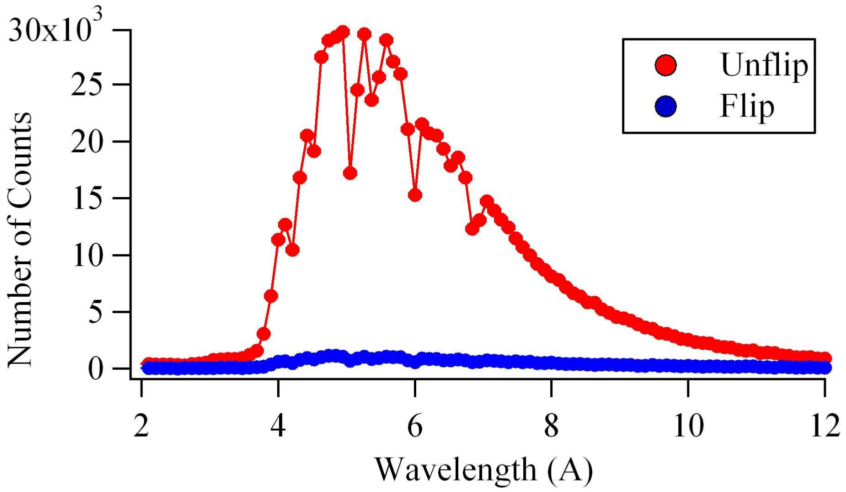
1.2 x 10^9 n/sec/cm^2

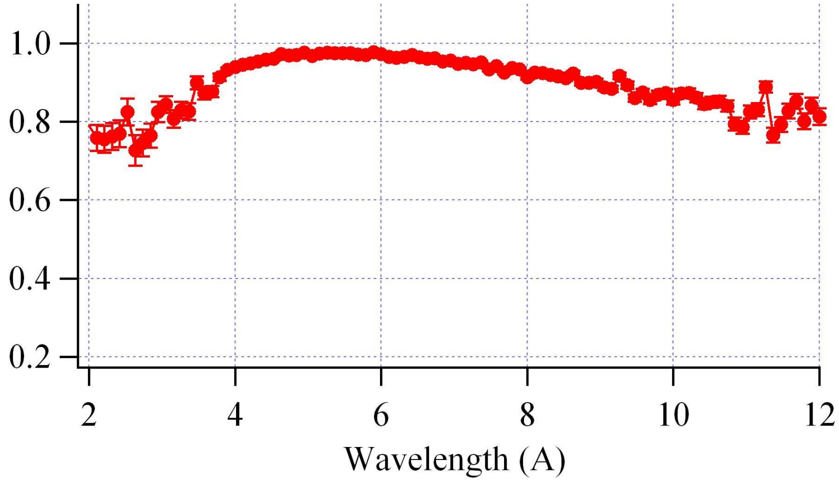
Polarization Product PA



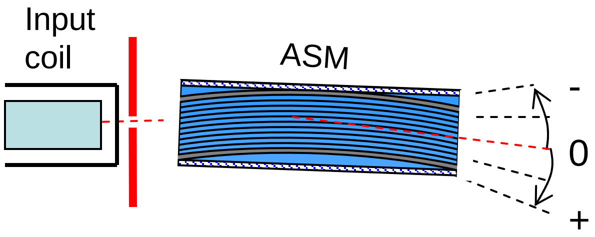
PA=(U-F)/(sU+F)

U- Unflip
F- flip
s – spin-flip efficiency
(s=0.95 ± 0.05)



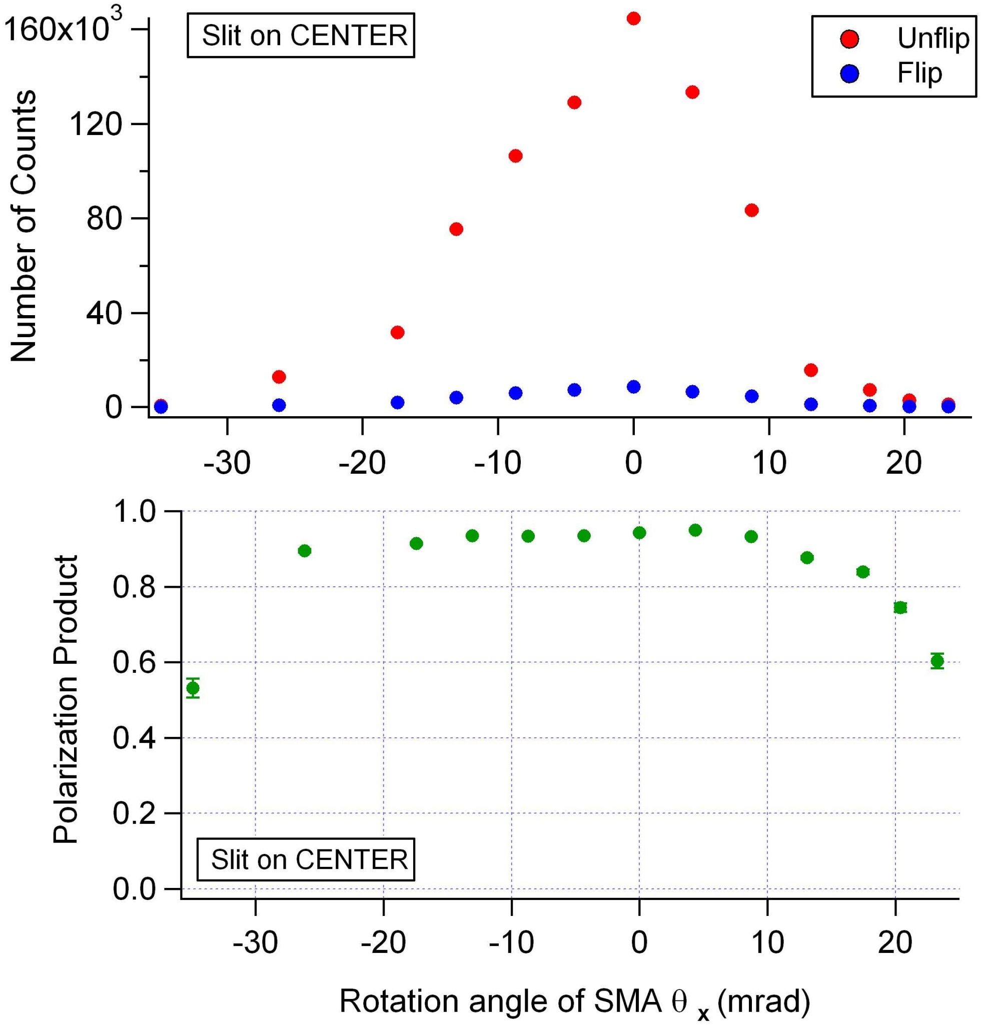


PA as a function of angle



For 5mm slit in the
CENTRAL position

PA does not change with angle



What we learned from beam characteristic measurements

1. Polarization product

- Does not change with angle - no problem with divergent neutrons.

2. Fluence rate:

This is sufficient to reach sensitivity goal 3×10^{-7} rad/m

3. Noise:

a) Electronic noise < Signal/50

b) In individual half on neutron beam is consistent with past beam intensity noise measurement at NG-6

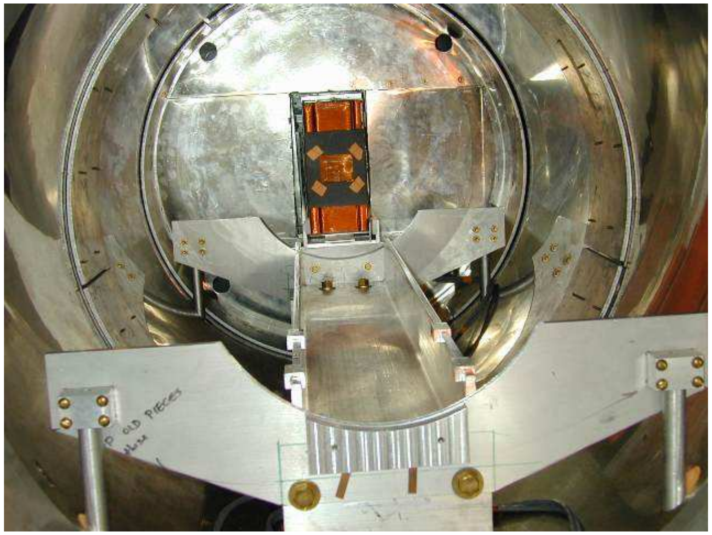
c) Removing common-mode intensity noise by taking L/R ratio in rates reduce noise in angle/asymmetry by about factor of 5

No extra noise above that from neutron beam:

NIST beam intensity noise is $\sim 1.3^{-3}$/sqrt(Hz)

From our analysis, noise is $\sim 1.2^{-3}$/sqrt(Hz)

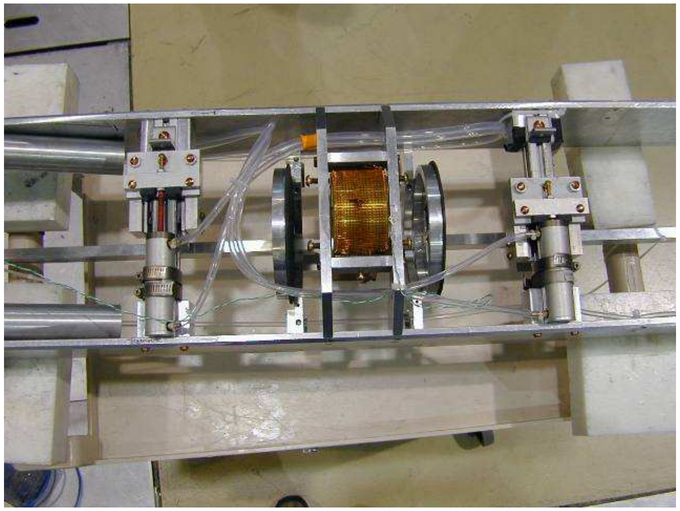
Room Temperature Target

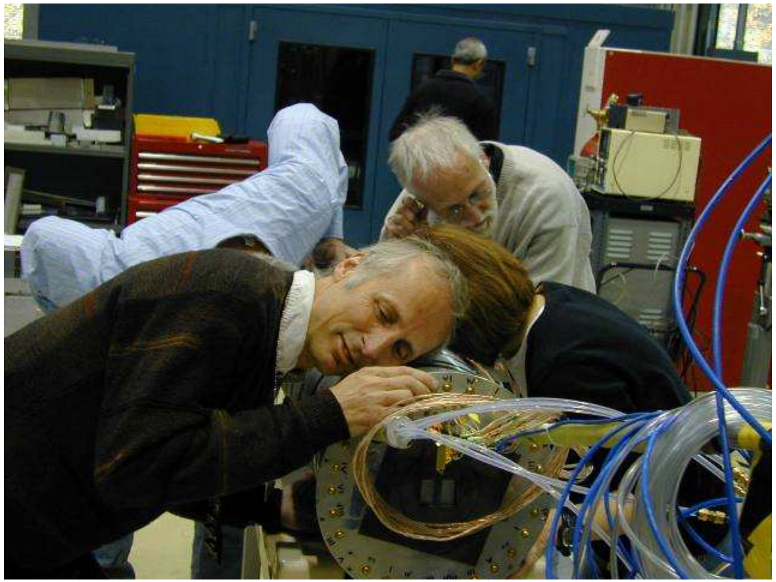


Looking inside the magnetic
shields – towards the input coil,

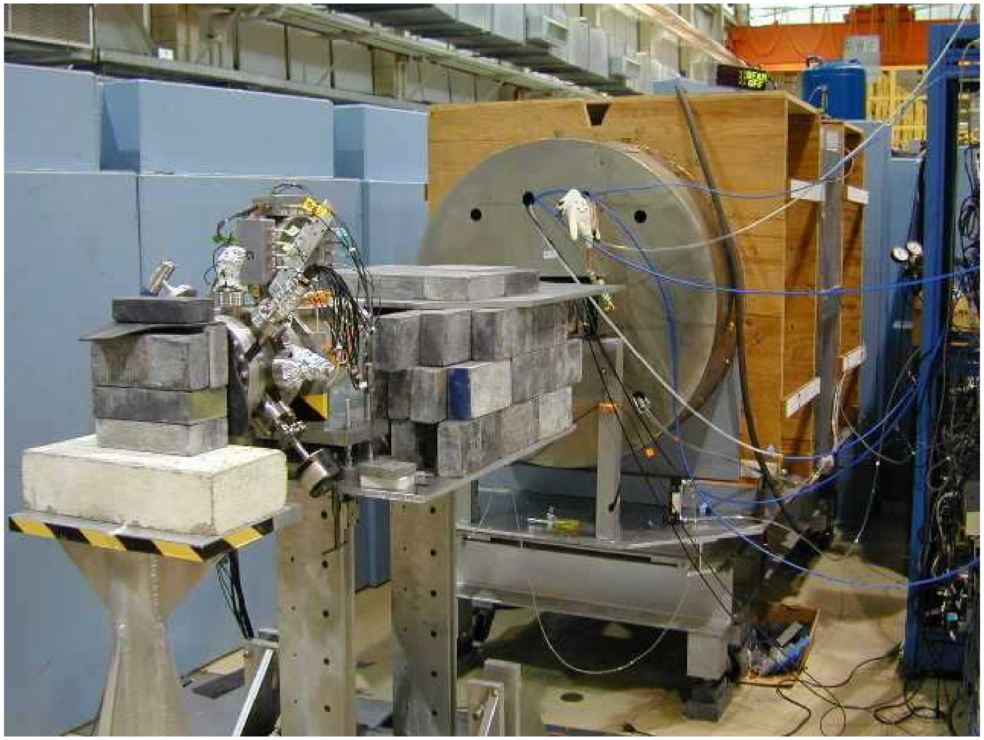
What is the sound of just one piston clacking?

Moving targets, Pi coil, Collimators

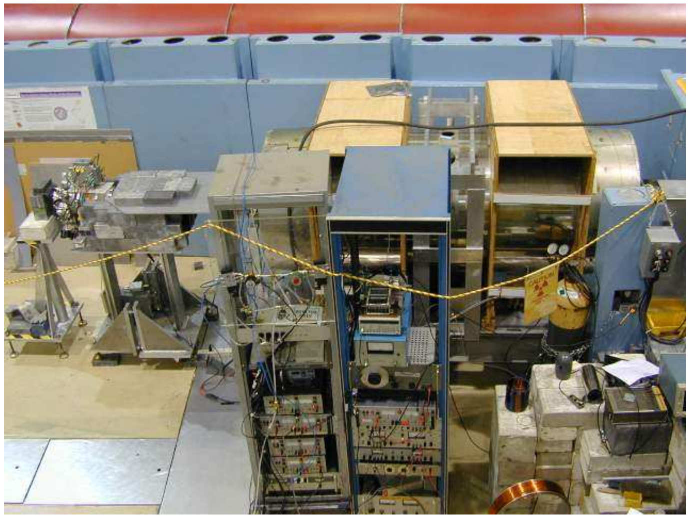




The Setup

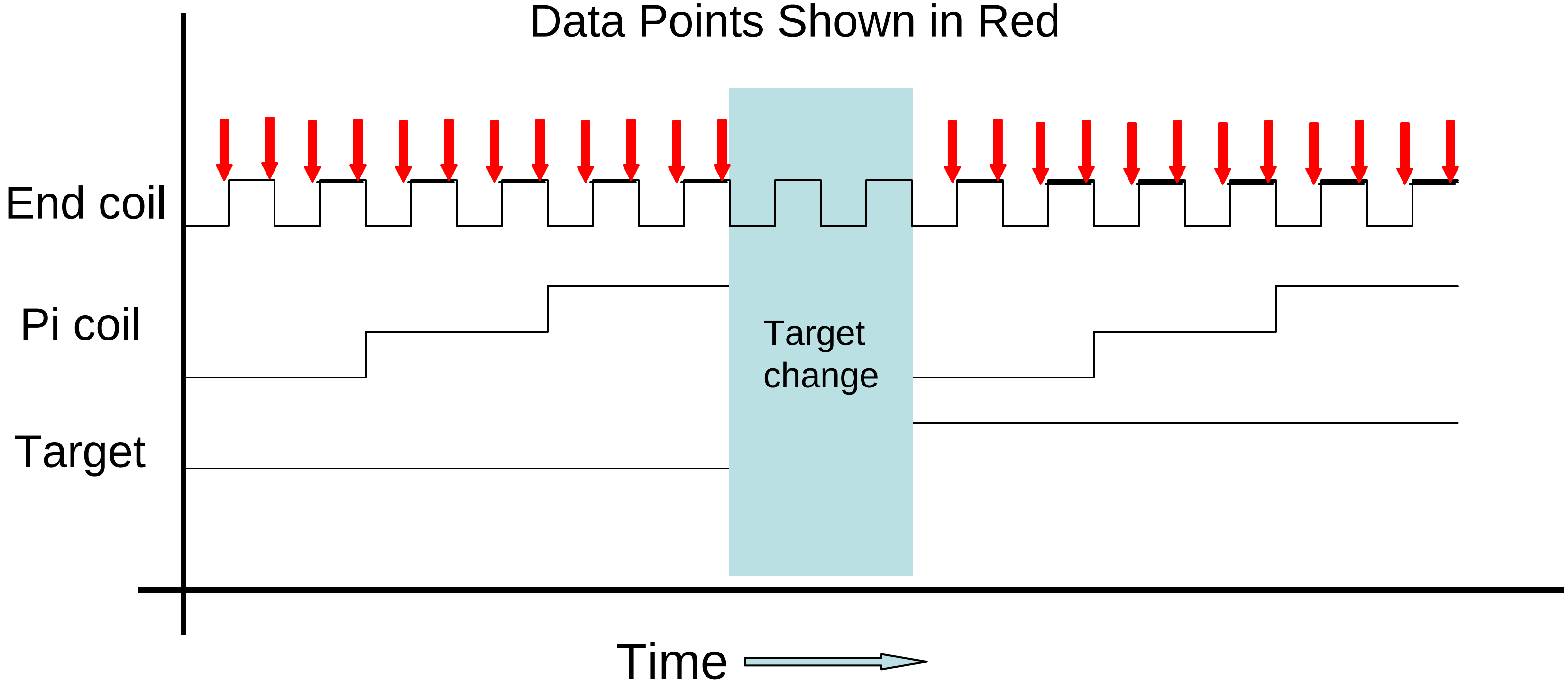


The whole system on the beam !



Measurement Time Line

Data Points Shown in Red



End coil

Pi coil

Target

Target change

Time

Summary

1. We will perform challenging search for neutron spin rotation in LHe at NIST this year
2. Experimental apparatus was updated since 1996 measurement

   $(\phi_{PV}(n,\alpha) = \ (8.0 \pm 14 \text{ (stat)} \pm 2.2 \text{ (syst)})\times 10^{-7}$ rad/m)

   - New target, additional CRYOPERM magnetic shield, monitoring magnetic field outside and in the target region, active trim coils, all nonmagnetic materials, use of superfluid LHe.
   - NIST: increase the detected beam flux by a factor of 1.5, monitoring magnetic field outside of our apparatus.

- Beam characteristic measurements completed at NG-6 NCNR

4. Successful measurement (sensitivity goal $\phi_{PV}=3\times10^{-7}$ rad/m of data taking) will broaden our knowledge about NN weak interaction
5. Letter of intent approved to perform PV neutron spin rotation in LHe at SNS (sensitivity goal $\phi_{PV}=1\times10^{-7}$ rad/m)