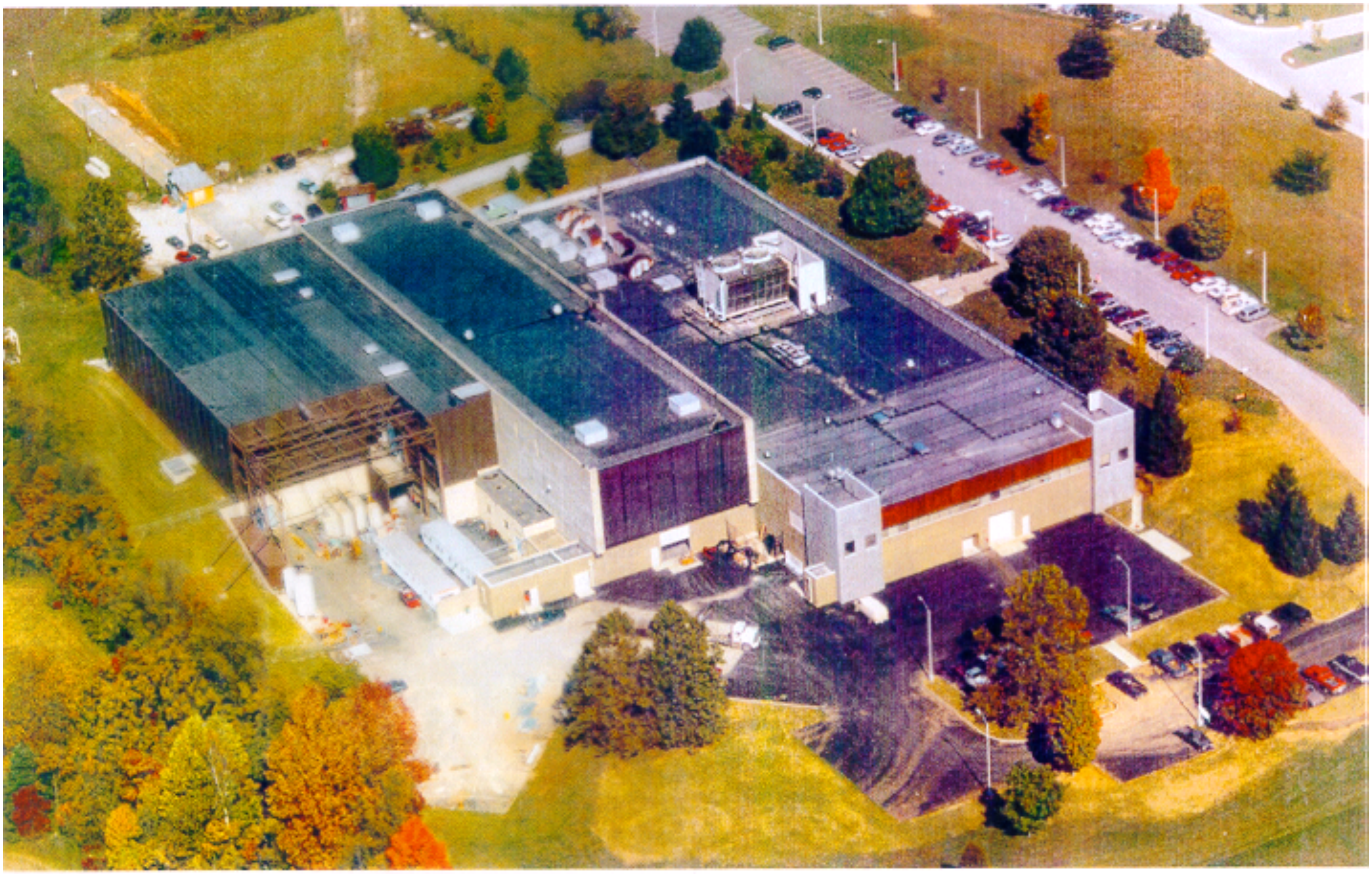
Cold Neutron Moderator Testing at LENS

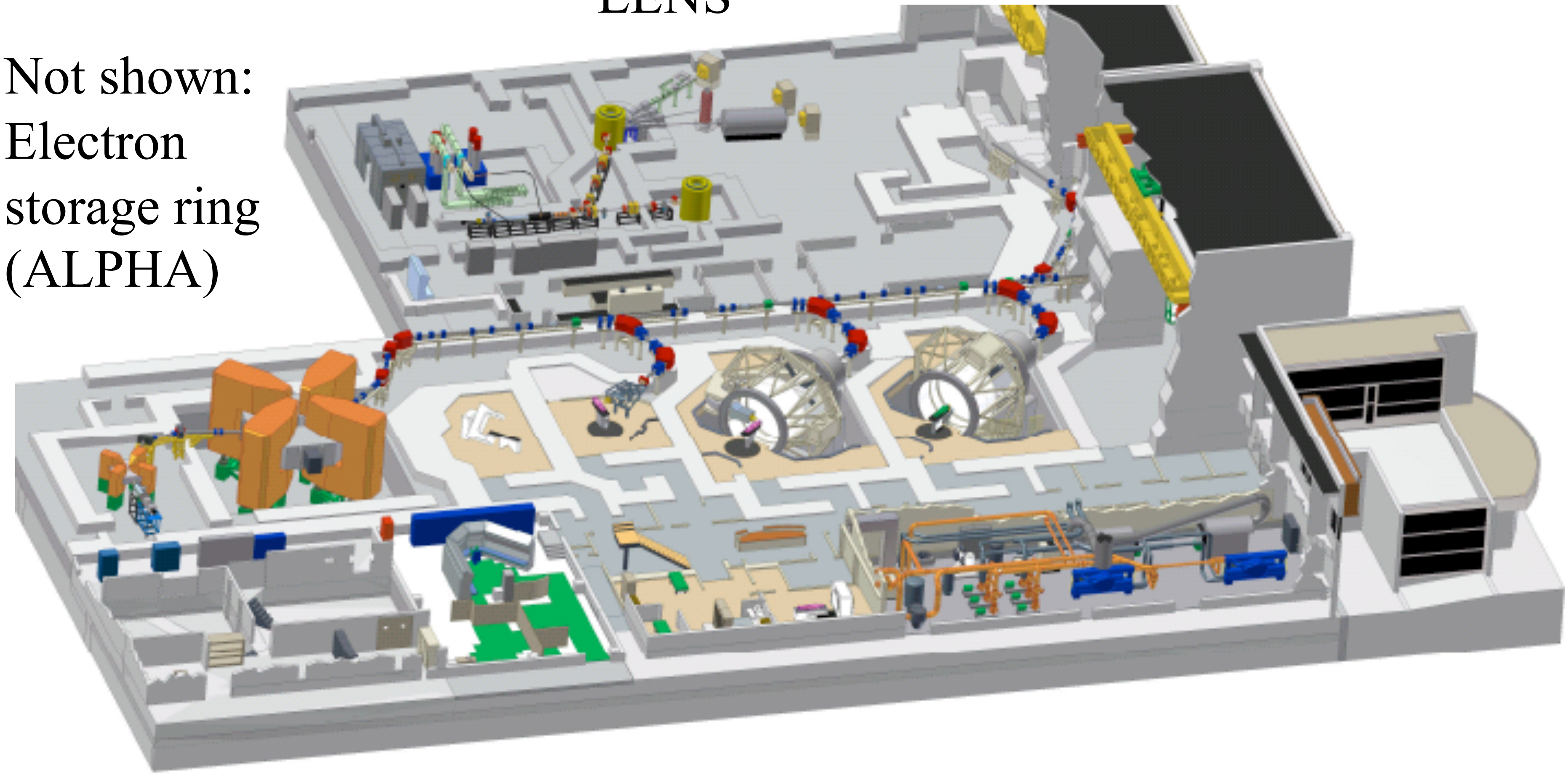
D. V. Baxter, W. M. Snow, C-Y Liu
Indiana University/CEEM

NAVSEA WARFARE CENTERS CRANE
NSF
INDIANA 21st Century Research & Technology Fund

CEEM: Areal View



CEEM: Cutout View/Facilities



LENS

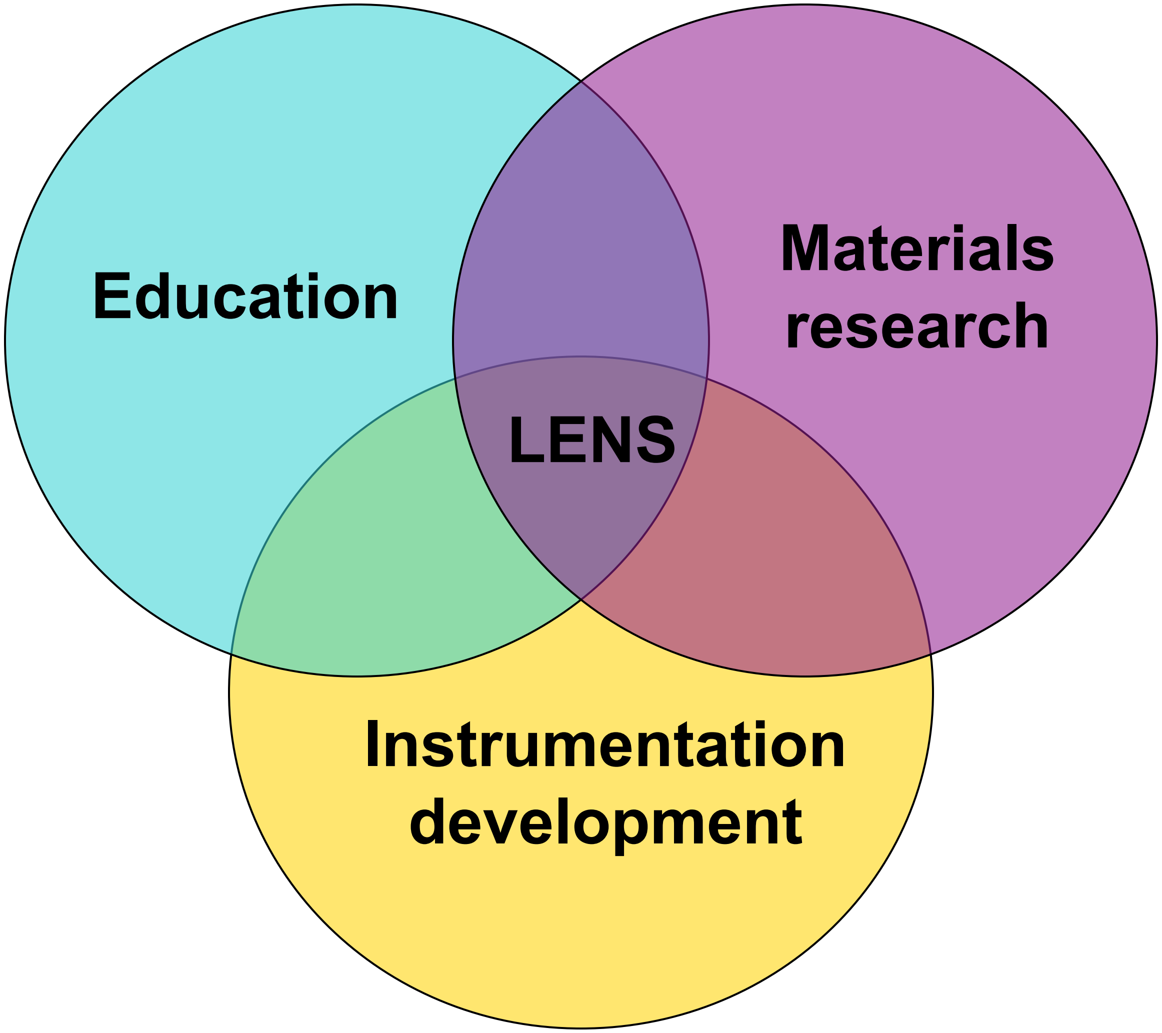
Not shown:
Electron
storage ring
(ALPHA)

Proton Radiation Therapy
(>1000 patients so far)

Low Energy Neutron Source (LENS)

- Based on **proton linac** and low-energy (p,nx) reactions (E_p<13MeV) in Be. 2 target stations:
- **Unmoderated target** for MeV neutron applications in science and engineering (Single Event Effects in electronics, defense, radiography).
- Flexible **target-moderator-reflector** system for moderator development (solid CH_4 at 4K)
- **Variable pulse width** (from <5 μs to more than 1.0 ms).
- In "long-pulse" mode, LENS has time-averaged cold neutron intensity suitable for **neutron scattering** (SANS, neutron spin echo).

LENS Missions (our Venn Diagram)



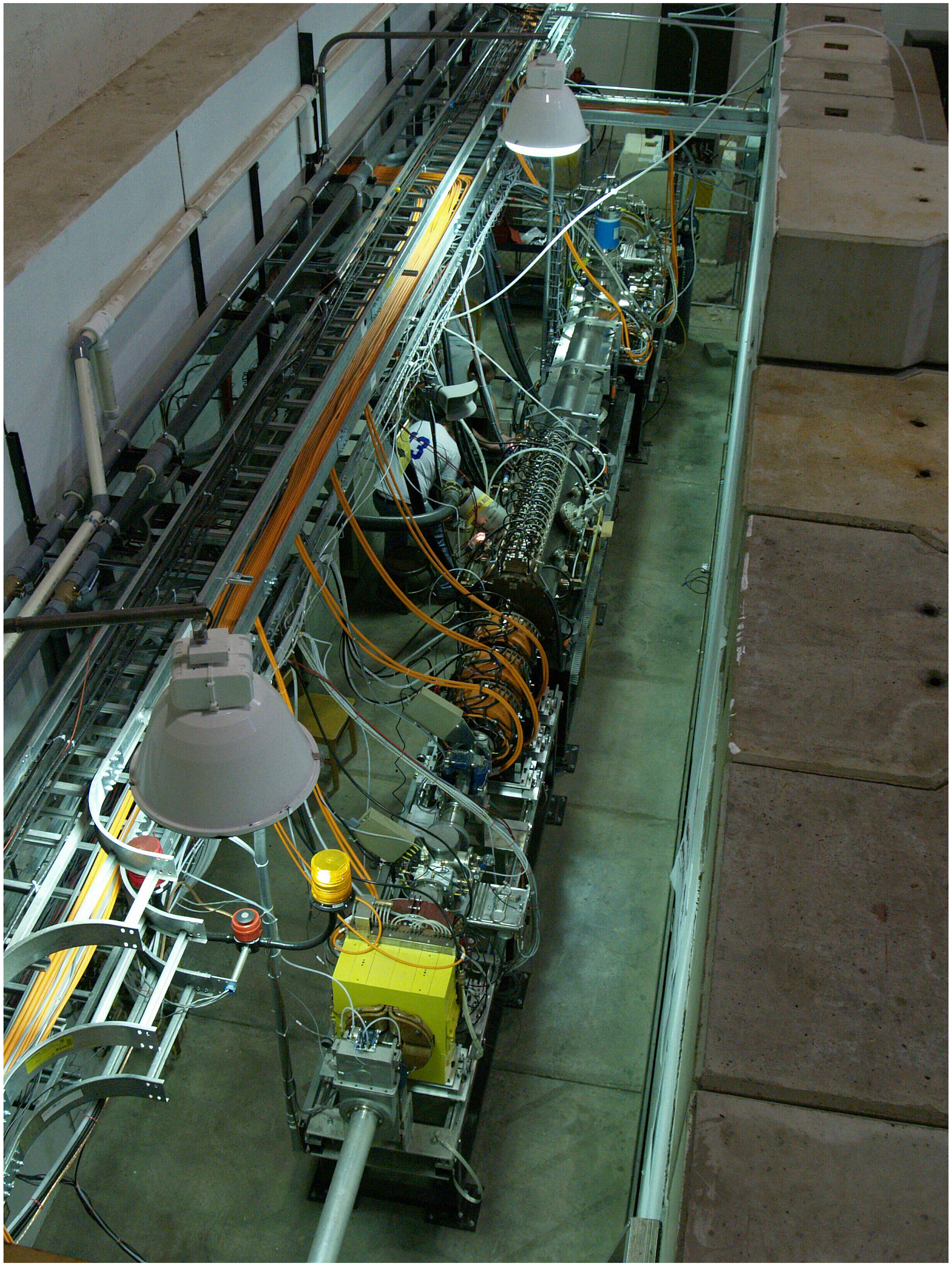
LENS Accelerator

~20 mA peak proton current, Variable frequency/pulse width

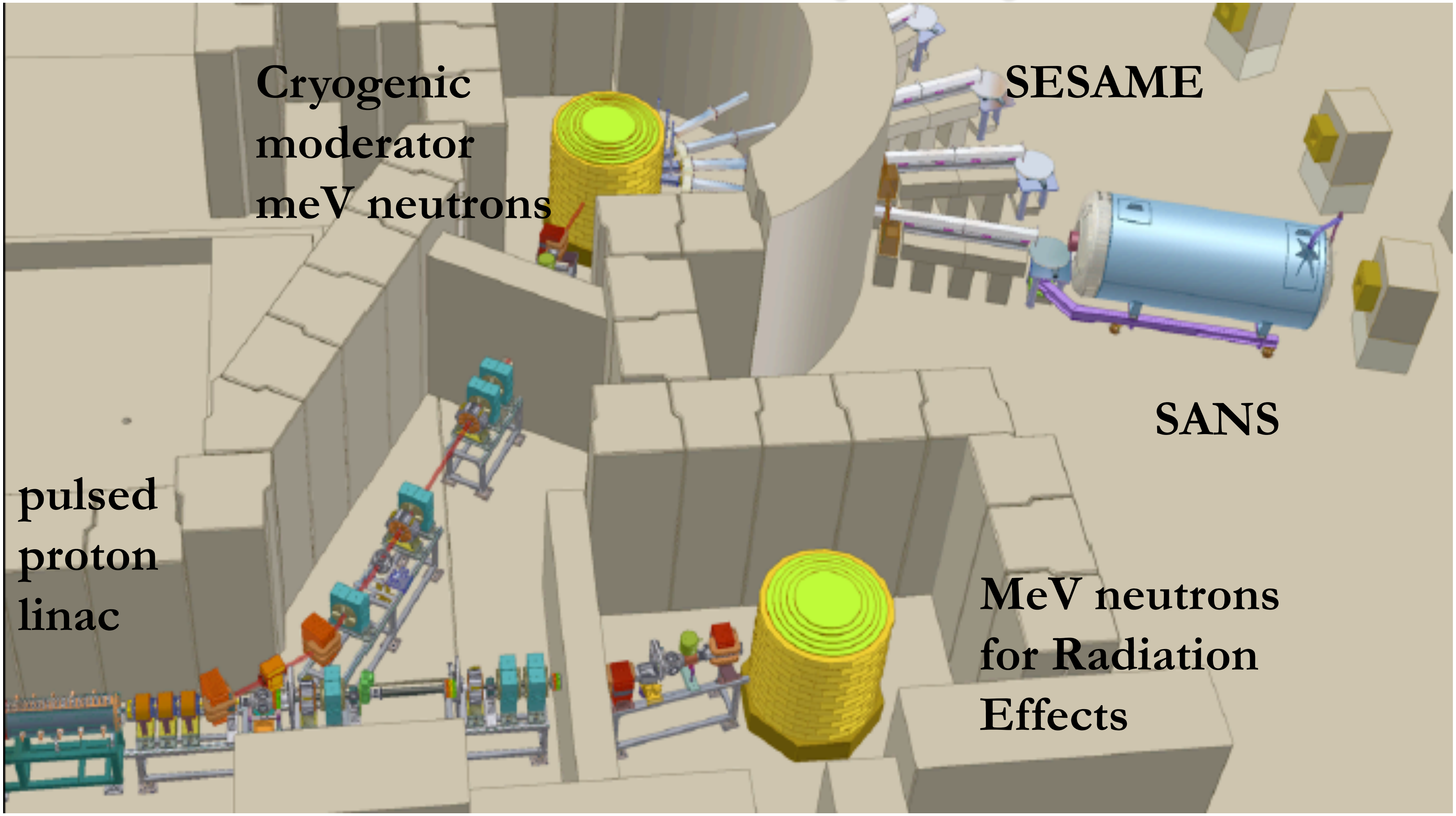
13MeV proton linear accelerator (RFQ/DTLs)

High-power Klystrons in operation

“Neutron physics on a human scale” (F. Mezei)

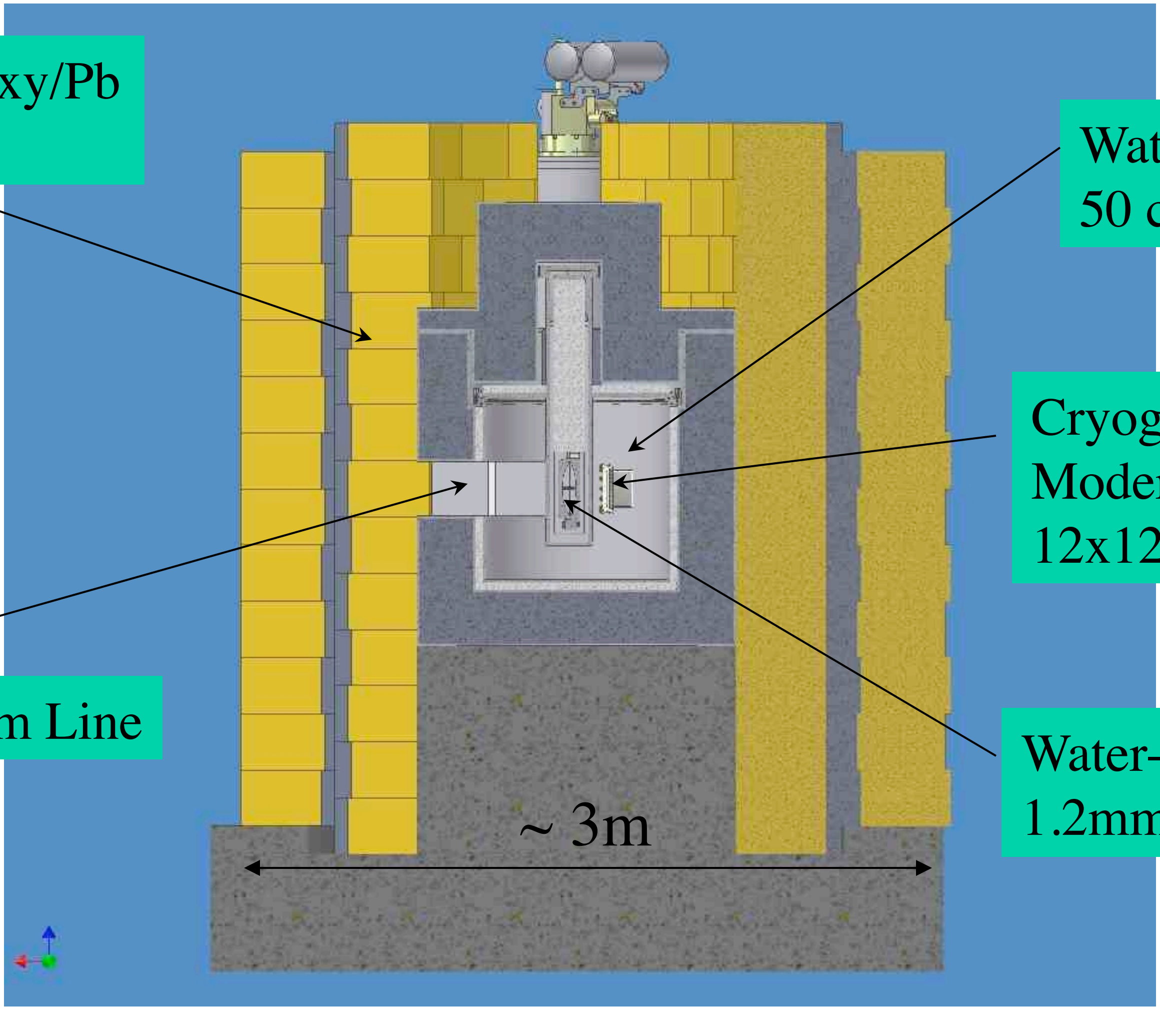


LENS Facility Layout



Designed/built/characterized by graduate students
Local user program in operation

Target Moderator Reflector (TMR)



Borax/PE/Epoxy/Pb complex

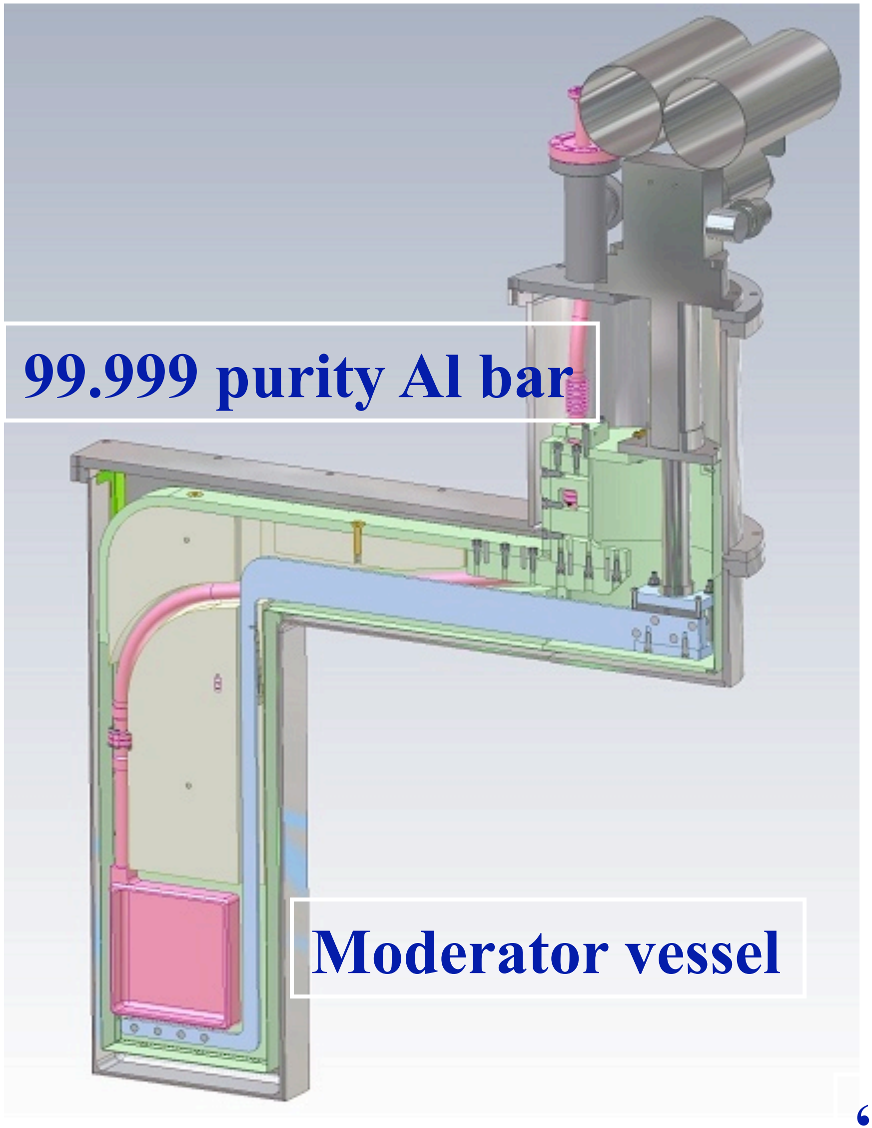
Water Reflector 50 cm dia.

Cryogenic (Methane) Moderator (4K) 12x12x1 cm3

Neutron Beam Line

Water-cooled Be Target 1.2mm thick

Target/Moderator Test Assembly

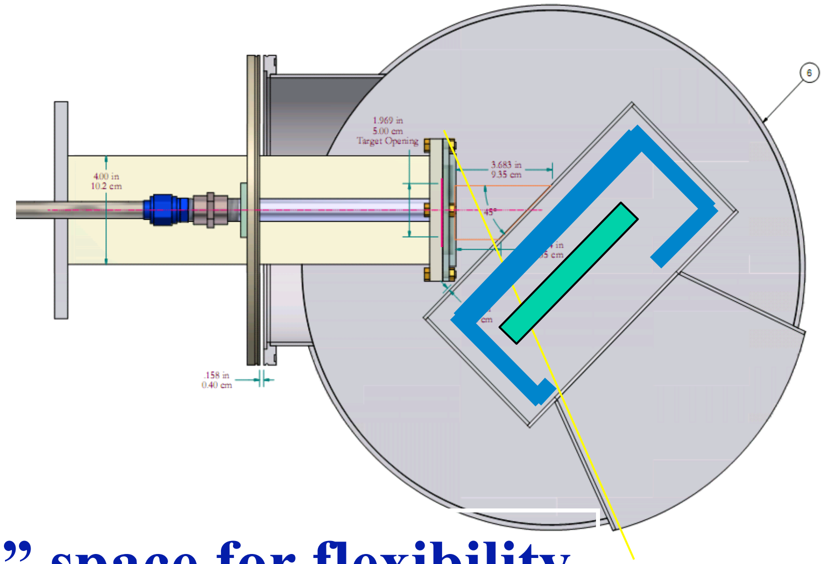


PT-410 pulse tube cryorefrigerator

99.999 purity Al bar

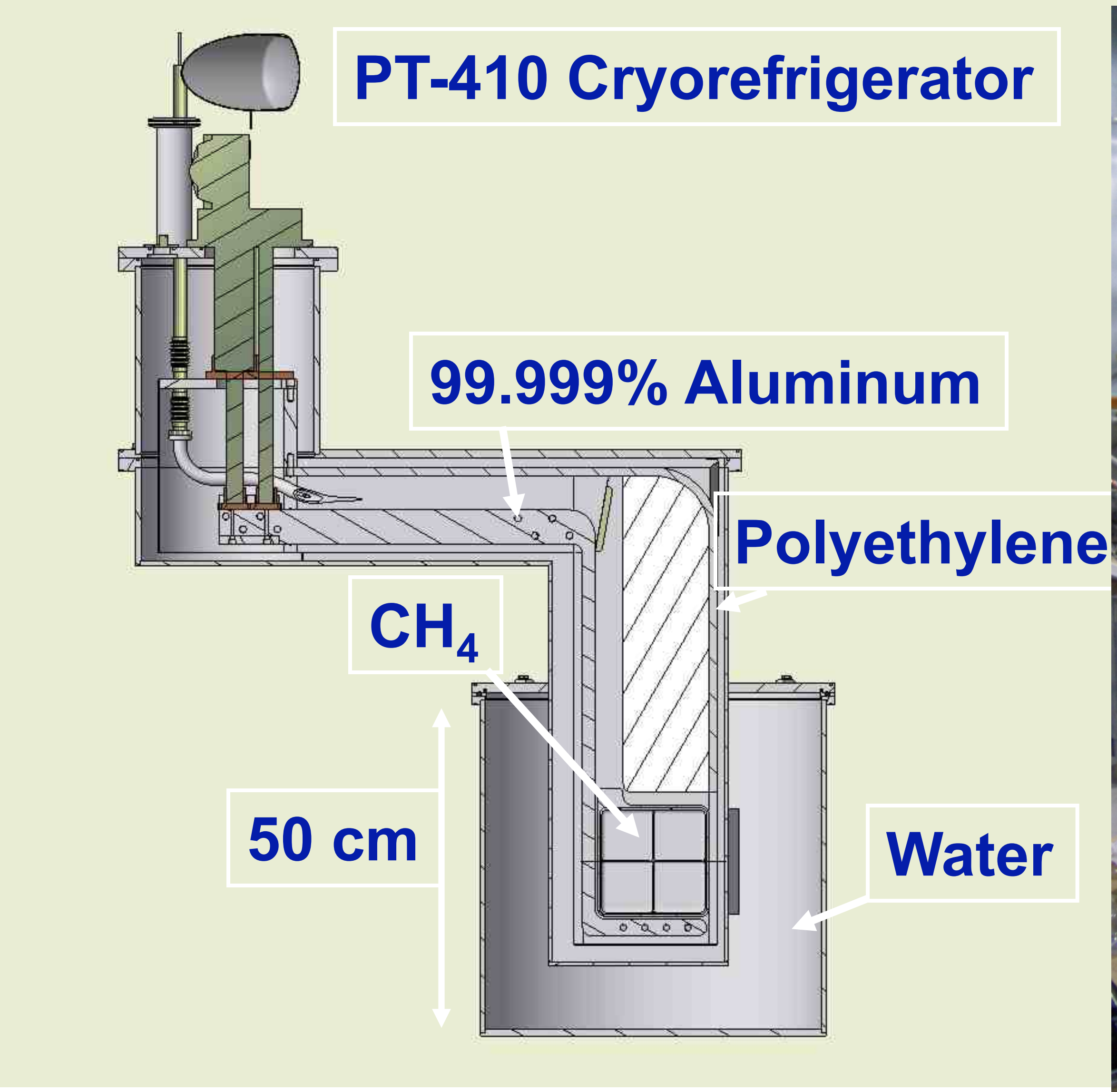
Moderator vessel

Top view of target/moderator



“extra” space for flexibility

4K LENS Cold Neutron Moderator



PT-410 Cryorefrigerator

99.999% Aluminum

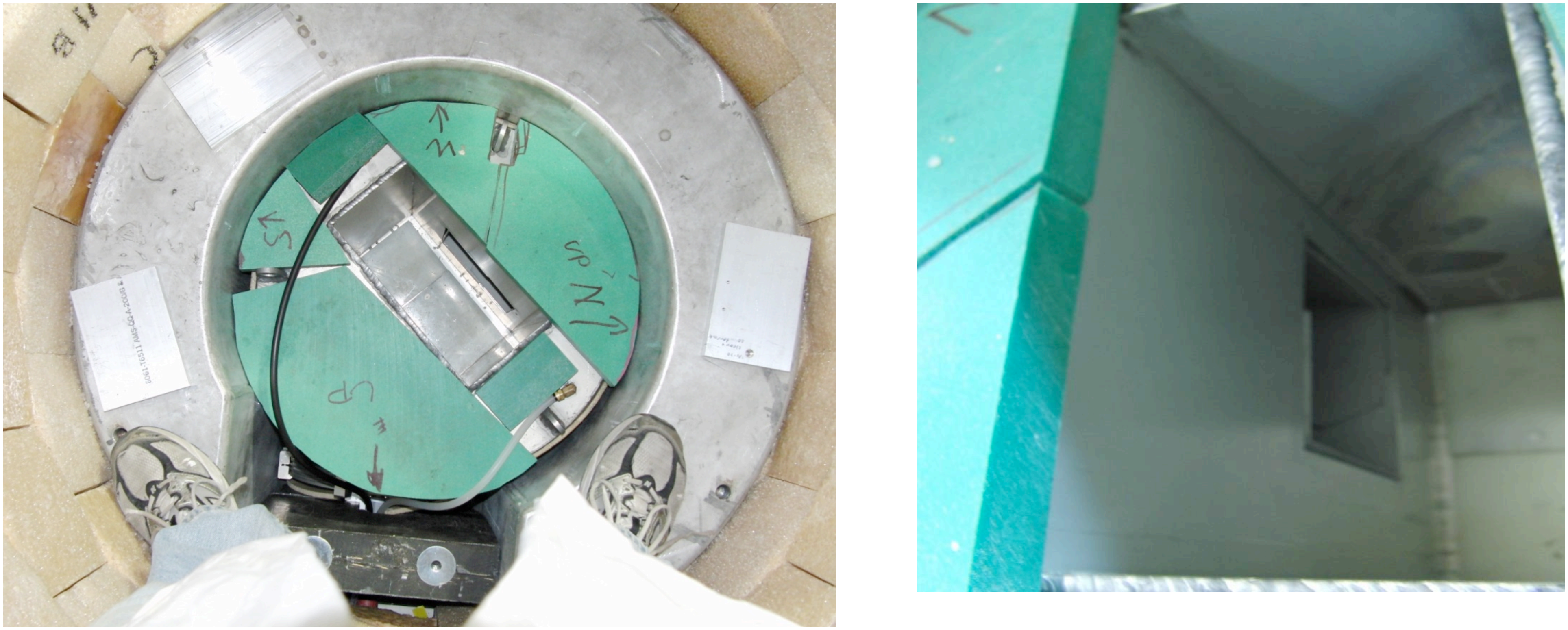
Polyethylene

CH_4

50 cm

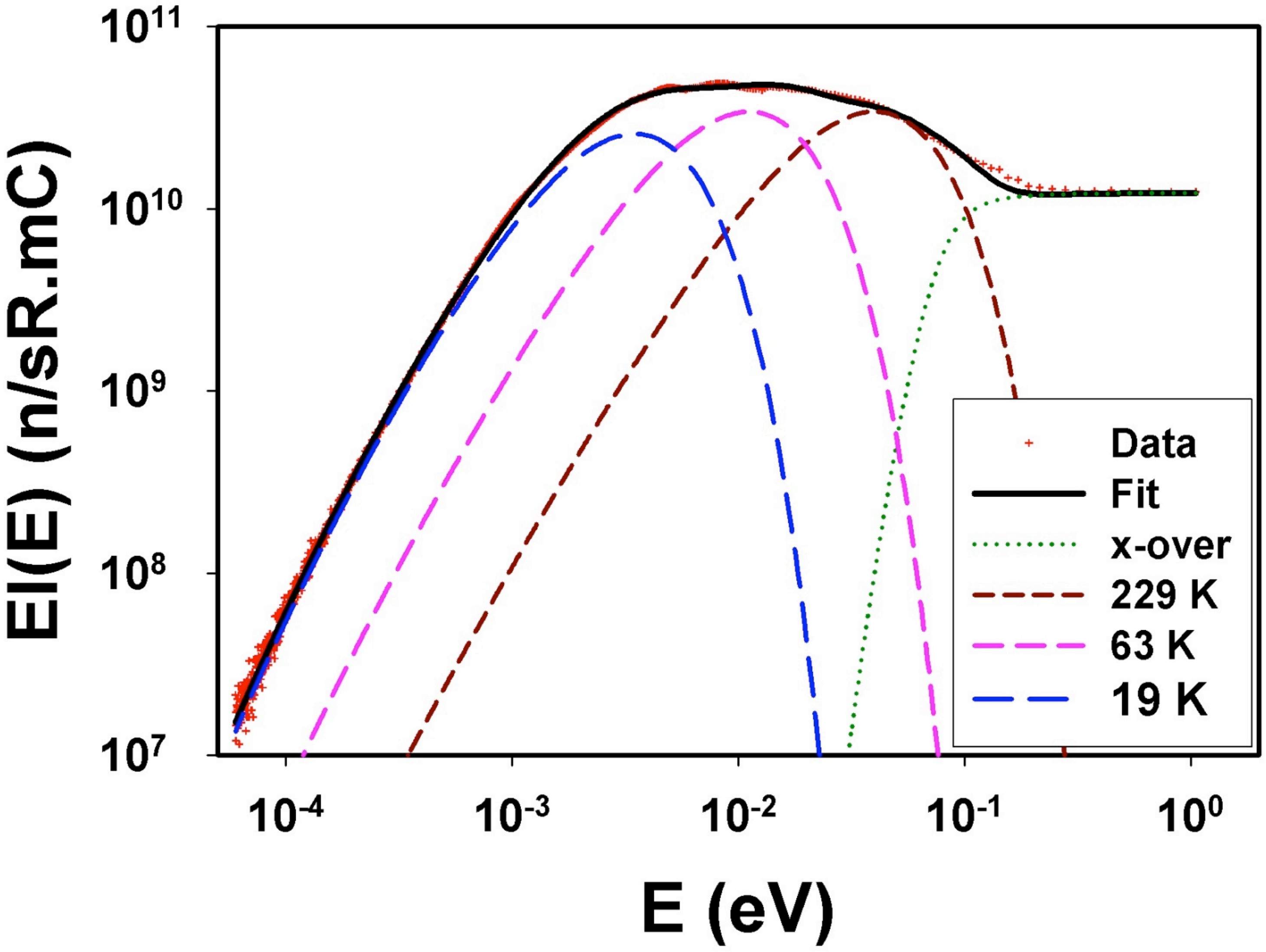
Water

Research on Prototype Moderators

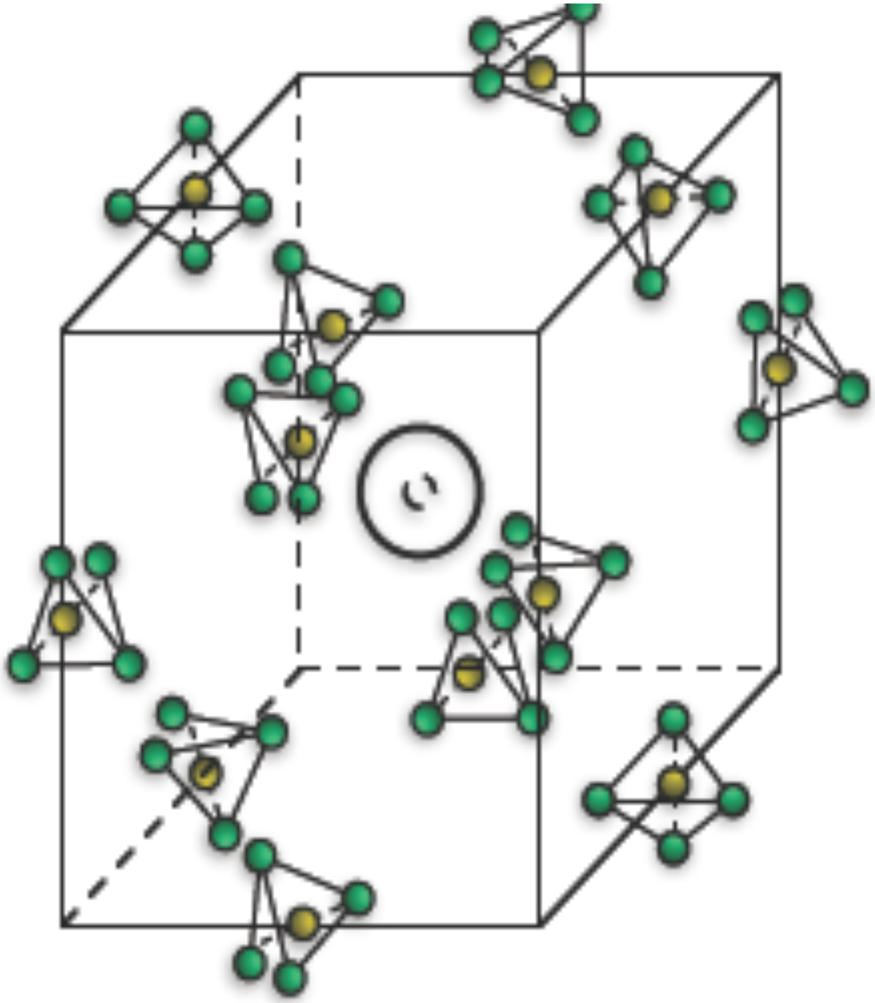


View of the reflector (inside a lead cask to shield gammas) and the cavity available for test moderators. The proton beam enters from bottom of left-hand image.

Fit to the Spectrum 13 MeV, CH4, 6K



Phase II Structure of Solid Methane



CH4 is the brightest-known cold neutron moderator (not useable at high power sources due to rad damage)

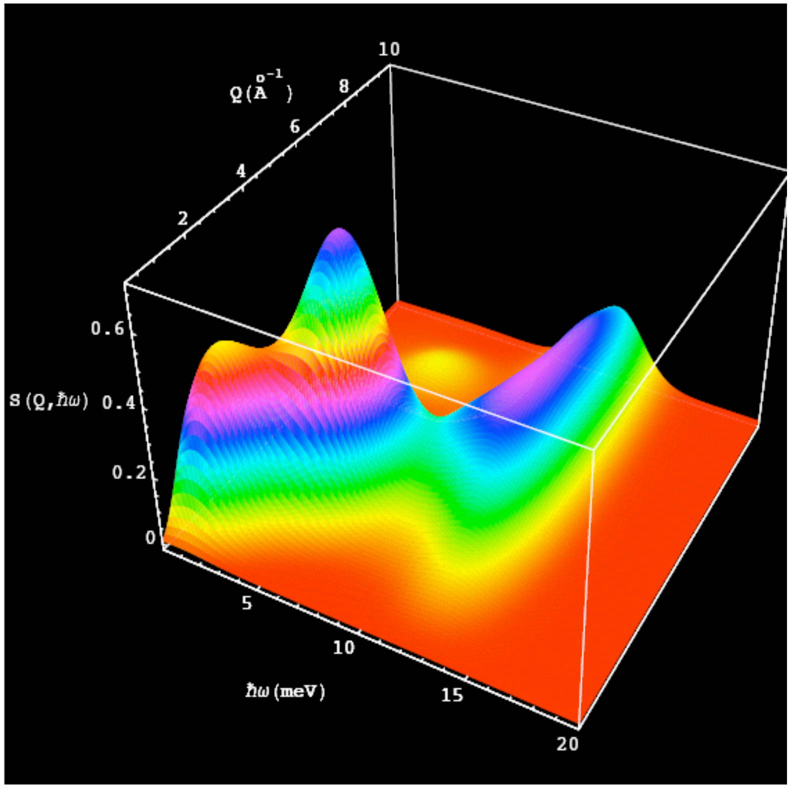
Below 20 K

¼ of the CH4 are free rotors
¾ are hindered rotors

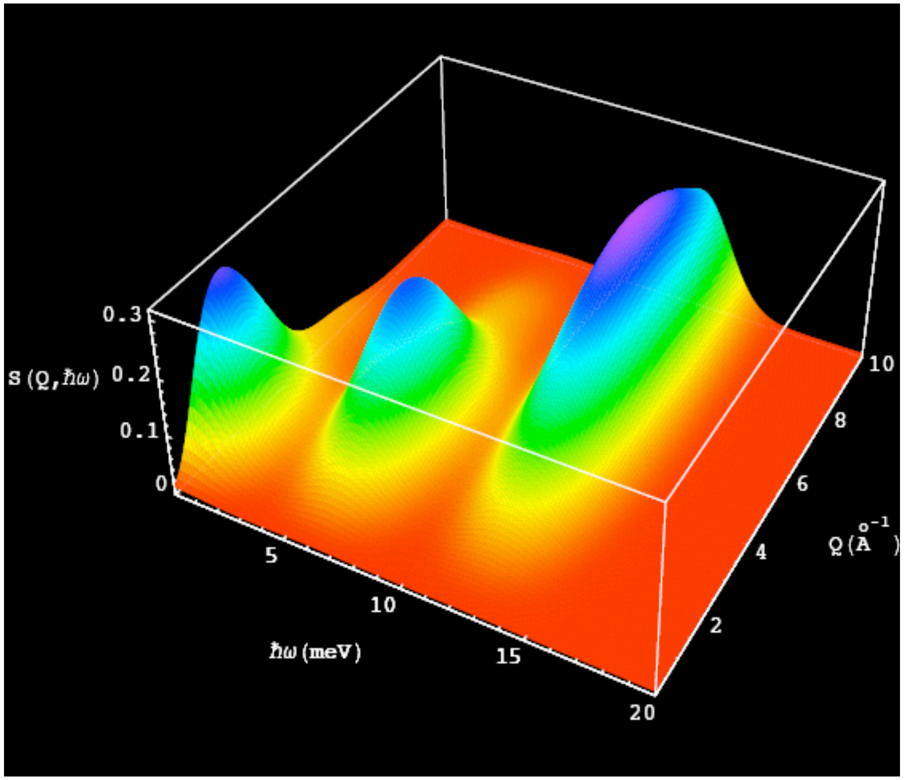
Above 20K

All sites are free rotors

S(q,omega) in CH4
Phase I and II (Y. Shin)

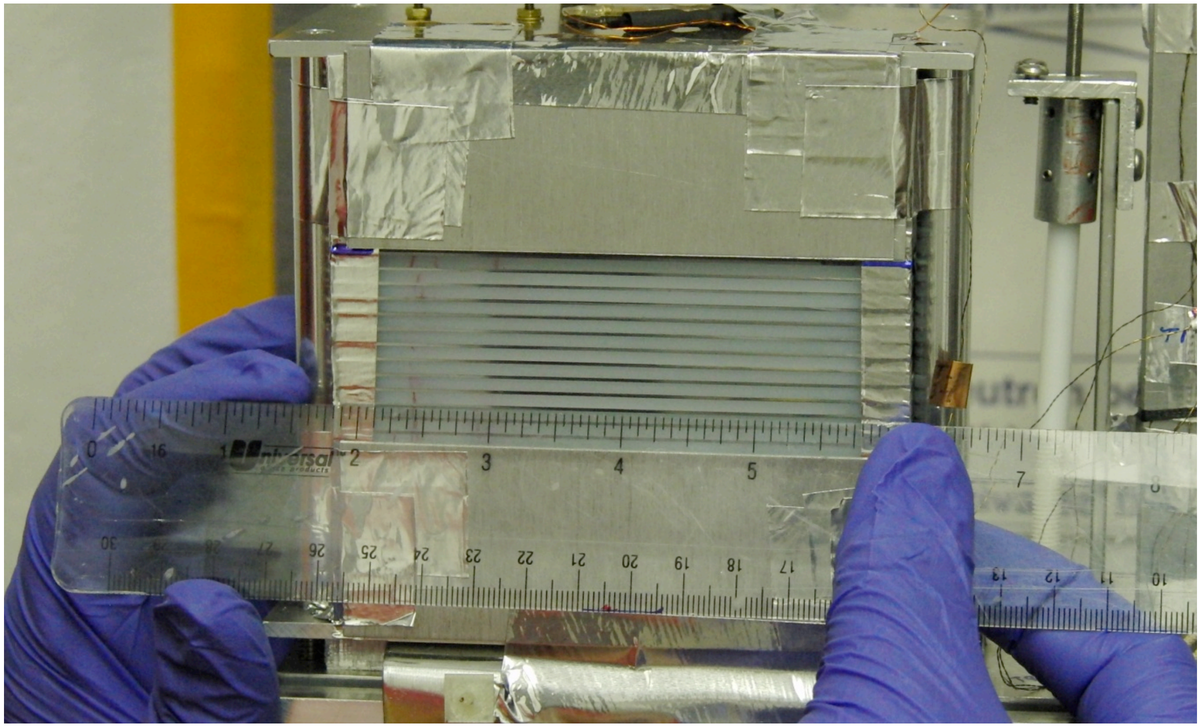


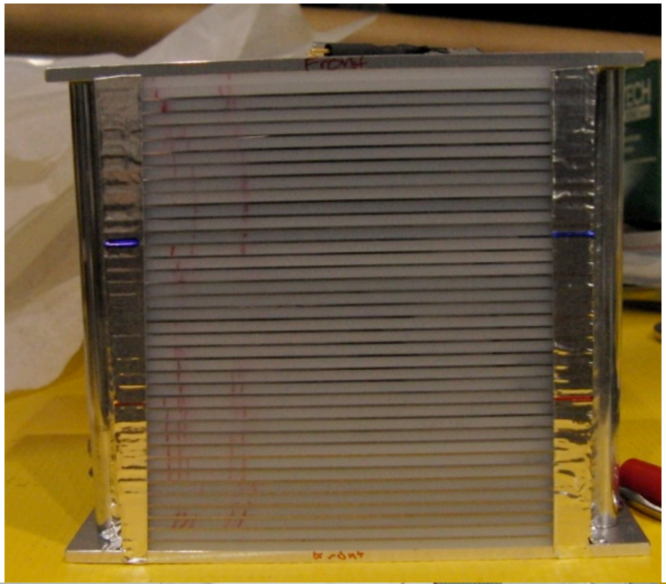
Phase II

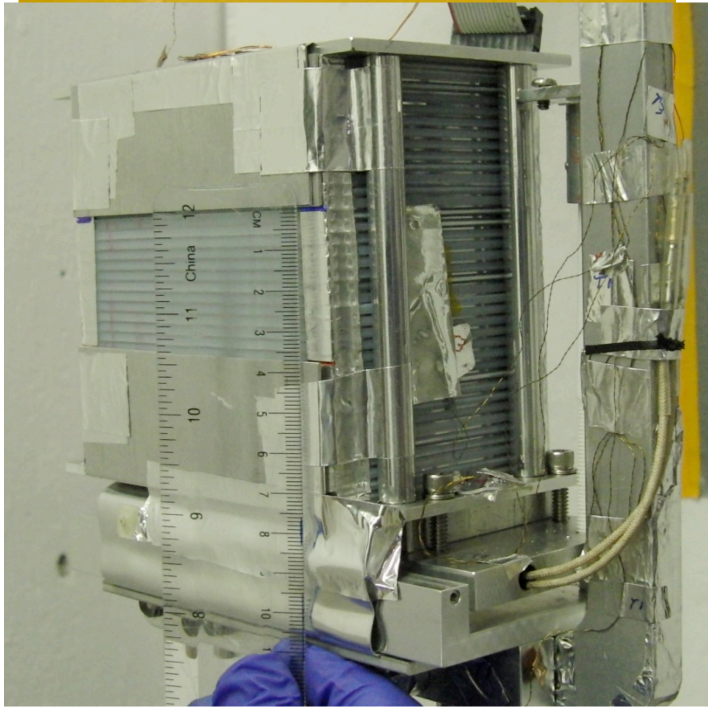


Phase I

PE/Si vaned moderator test

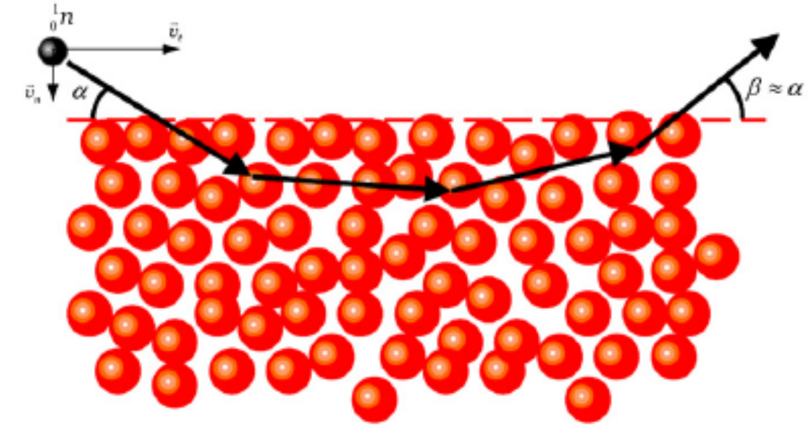


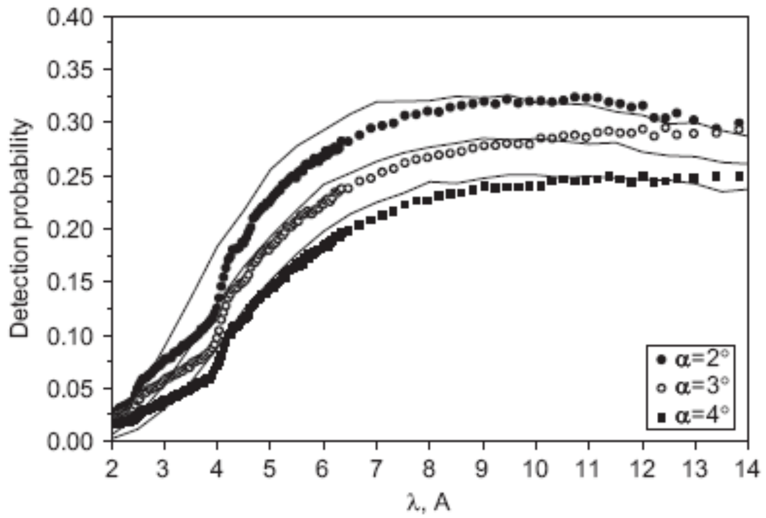


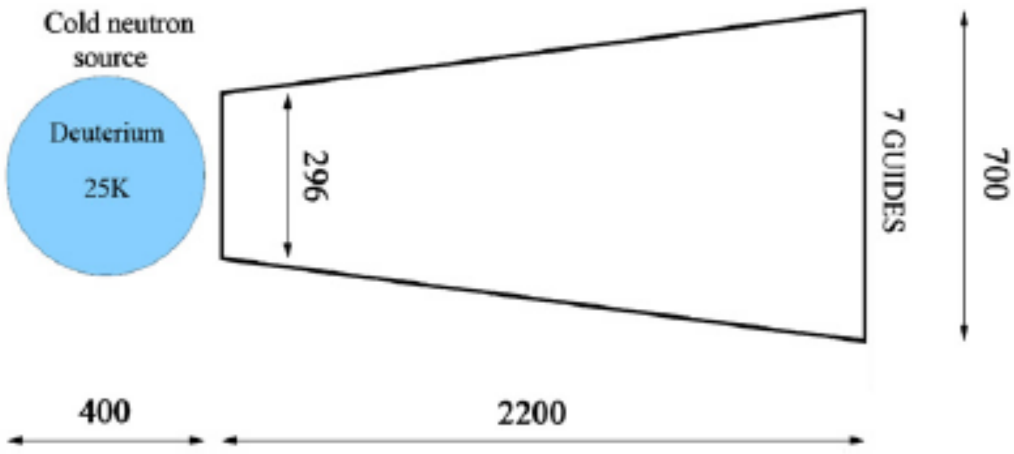


Test idea (supported by MCNP) of improved extraction of cold neutrons from deep within the moderator volume (Baxter et al, Physics Procedia [Elsevir, 2012])

Diamond nanoparticles as reflector?







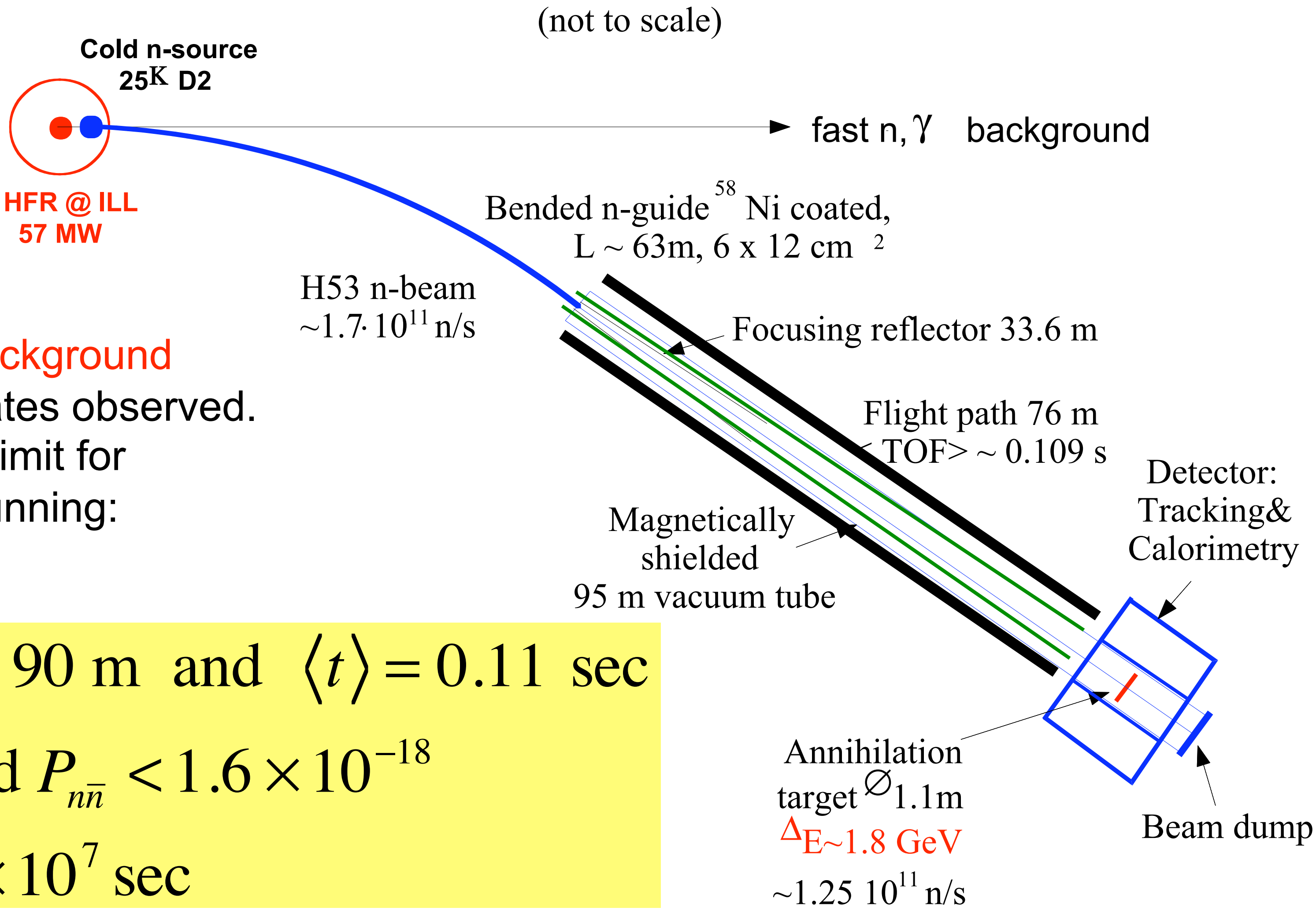
R Cubitt et al. NIMA 622, 182-85 (2010)

Can high-albedo materials such as diamond nanoparticles be used as radiation-hard reflectors near the moderator to improve cold/VCN brightness?

Magnetic Shielding for nnbar

W. M. Snow
Indiana University/CEEM

N-Nbar search at ILL (Heidelberg-ILL-Padova-Pavia)



(not to scale)

Cold n-source
25^{K} D2

HFR @ ILL
57 MW

fast n, γ background

Bended n-guide ^{58}Ni coated,
L ~ 63m, 6 x 12 cm ^{2}

H53 n-beam
$\sim 1.7 \cdot 10^{11}$ n/s

Focusing reflector 33.6 m

Flight path 76 m
TOF> ~ 0.109 s

Detector:
Tracking&
Calorimetry

Magnetically
shielded
95 m vacuum tube

Annihilation
target $\varnothing$1.1m
ΔE~1.8 GeV

$\sim 1.25\ 10^{11}$ n/s

Beam dump

No GeV background

No candidates observed.
Measured limit for
a year of running:

$$\text{with L} \sim 90\text{ m and } \langle t \rangle = 0.11\text{ sec}$$

$$\text{measured } P_{n\bar{n}} < 1.6 \times 10^{-18}$$

$$\tau > 8.6 \times 10^{7}\text{ sec}$$

Baldo-Ceolin M. et al., Z. Phys. C63,409 (1994).

Quasifree Condition: B Shielding

$\mu B t << \hbar$ ILL achieved |B|<10 nT over 1m diameter, 80 m beam,one layer 1mm shield in SS vacuum tank, 1% reduction in oscillation efficiency (Bitter et al, NIM A309, 521 (1991). For new experiment need |B|<~1 nT

If nnbar candidate signal seen, easy to “turn it off” by increasing B

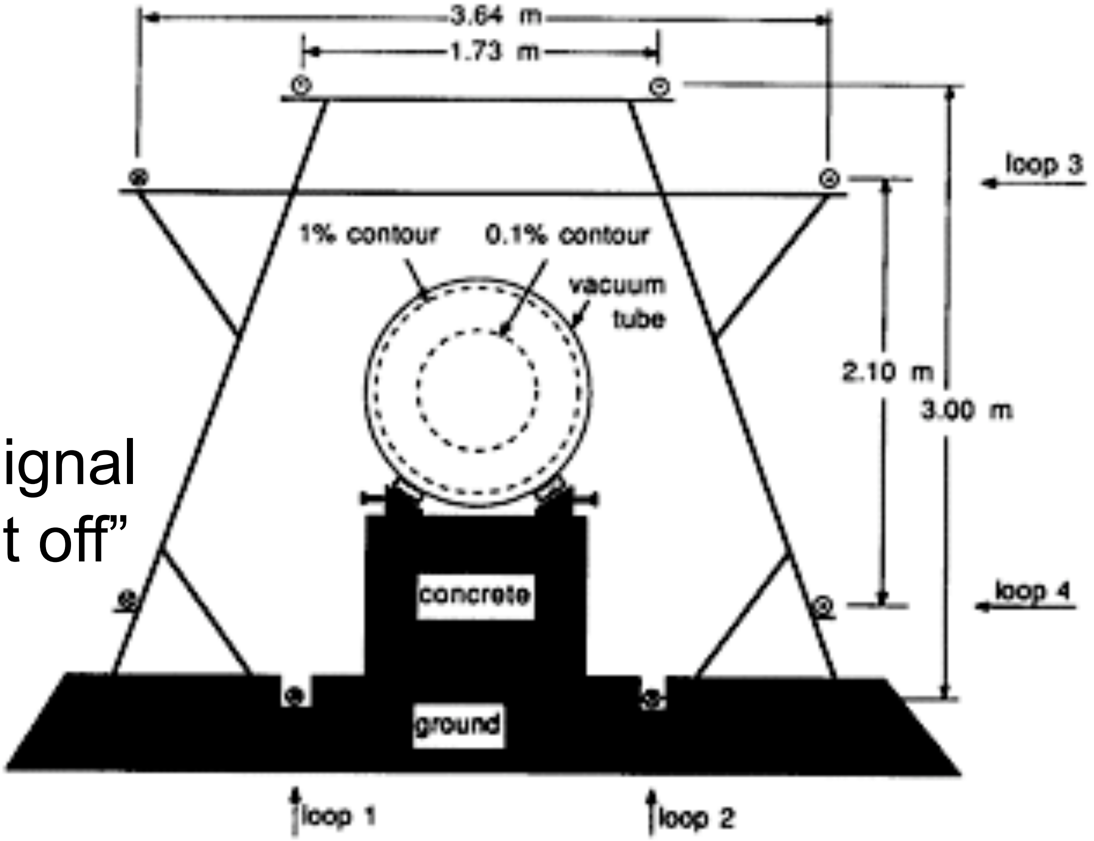
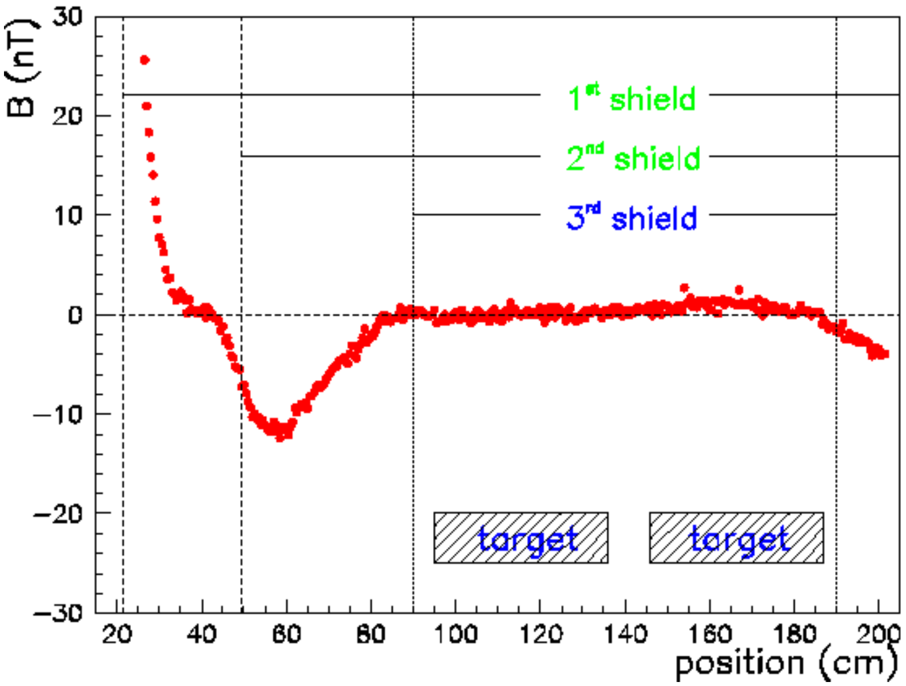
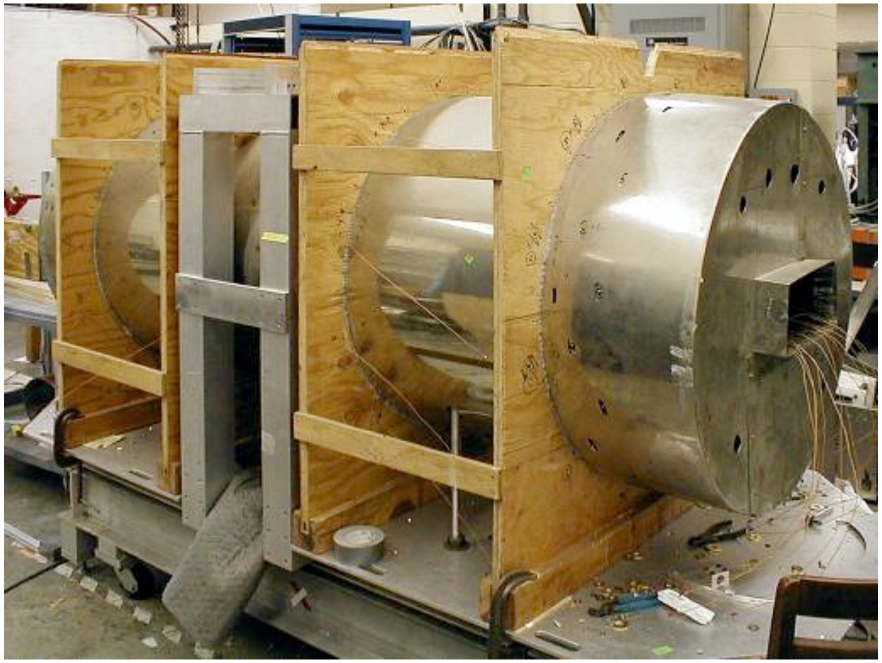


Fig. 10. The transverse field compensation system. Loops 1 and 2 are under 49 A current and compensate the horizontal field component; loops 3 and 4 are under 120 A current and compensate the vertical field component.

Magnetic Shielding Measurements
for neutron spin rotation measurements at NIST





B~1 nT are routinely obtained in relatively small (few m^3) volumes with multiple shields

Large size of any n-nbar apparatus poses a challenge.

Magnetic Shielding for NEDM Experiment At Petersburg Nuclear Physics Institute

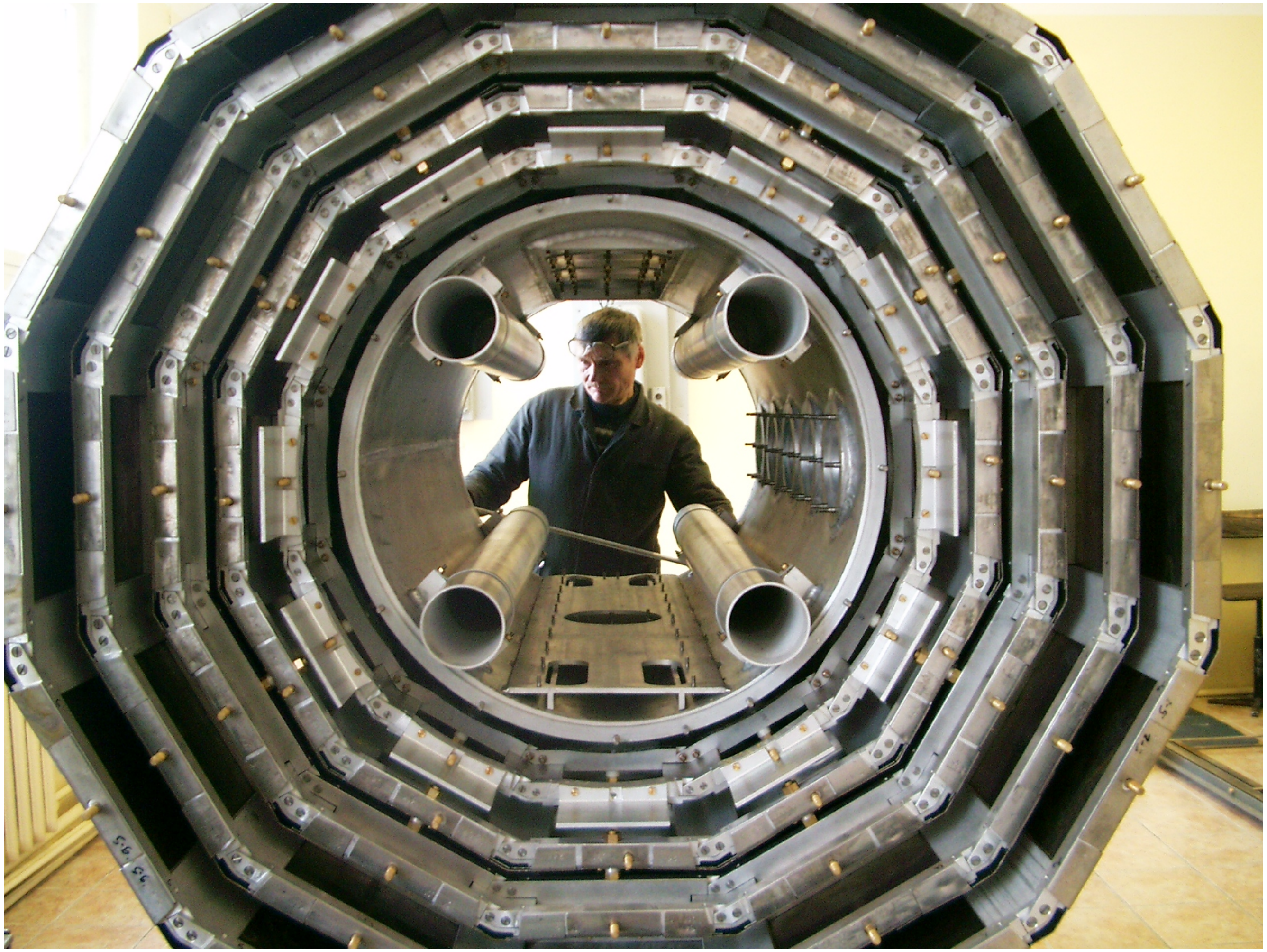


Photo courtesy A. Serebrov

Quasifree Condition: Neutrons as the magnetometer

Performed by polarized neutrons and use of neutron spin echo spectroscopy (U. Schmidt et al, NIM A320, 569 (1992).

May need polarizers and analyzers
with larger phase space acceptance to polarize and analyze beam

U. Schmidt et al. / Propagation of a neutron beam 571

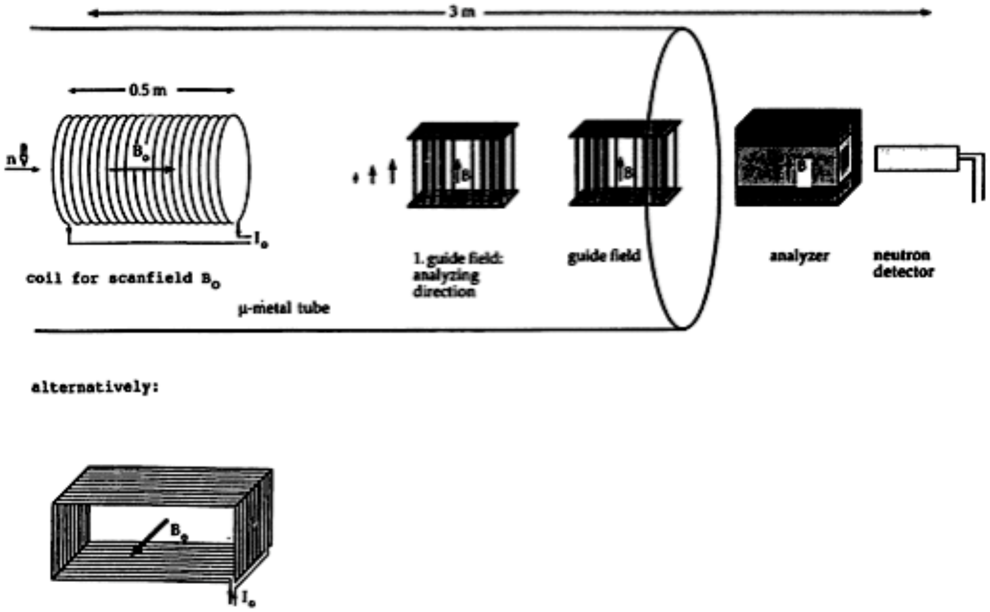


Fig. 3. Polarized neutron analyser equipment at the exit of the zero-field region, at 70 m distance to the polarizers of fig. 2.

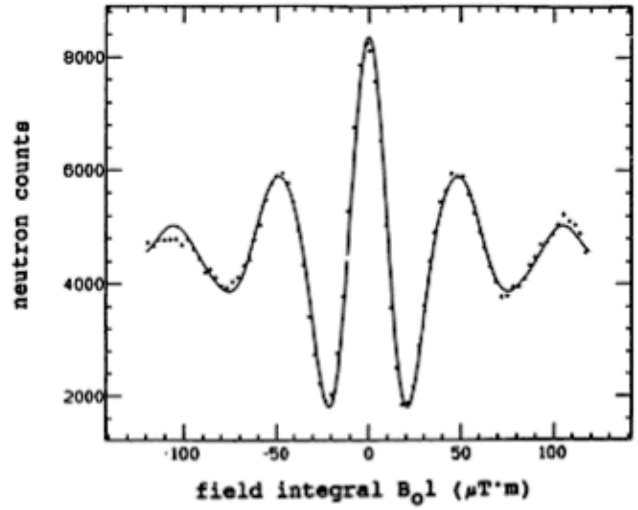
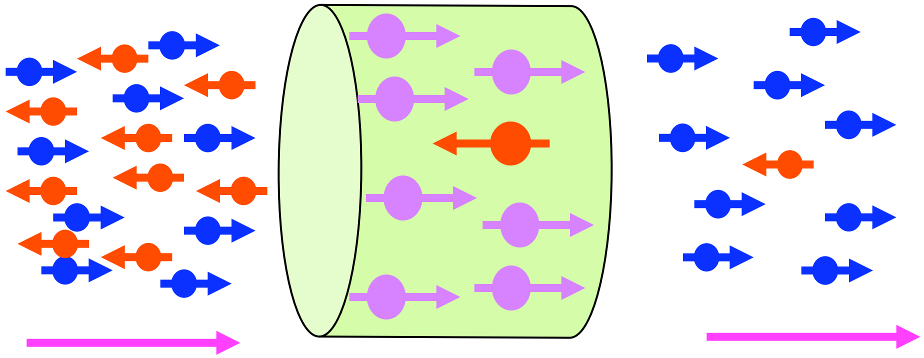


Fig. 4. Neutron-spin echo curve produced with the apparatus of figs. 2 and 3. The zero-offset of this curve measures the residual magnetic field along the magnetically shielded 70 m long neutron beam line to $\langle B_z \rangle = 4$ nT, via a neutron spin precession angle of $\phi = 2°$. The solid line is a fit to the theoretical lineshape.

POLARIZED ^{3}He for Neutron Polarimetry

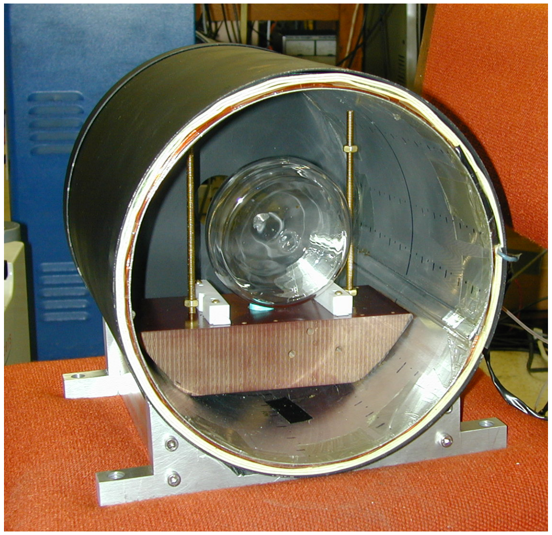
Use neutrons as magnetometers. Polarize/analyze neutron beam using 3He



unpolarized incoming neutrons

polarized ^{3}He

polarized outgoing neutrons



Polarized ^{3}He cell (11 cm diameter)

Large neutron phase space acceptance

Polarizer/analyzer pair can measure B using neutron spin rotation

NIST, Indiana, Hamilton, Wisconsin

DOE DEFG0203ER46093

Required R&D

- Identification of scheme for suppression of external magnetic fields/field gradients in the presence of the μ-metal;

- Identification of an assembly, annealing, and demagnetization strategy;

- Measurement of the ambient magnetic field at the proposed location;

- Preliminary mechanical design of the shield;

- Analysis of the loss of sensitivity of the oscillation measurement to residual magnetic fields;

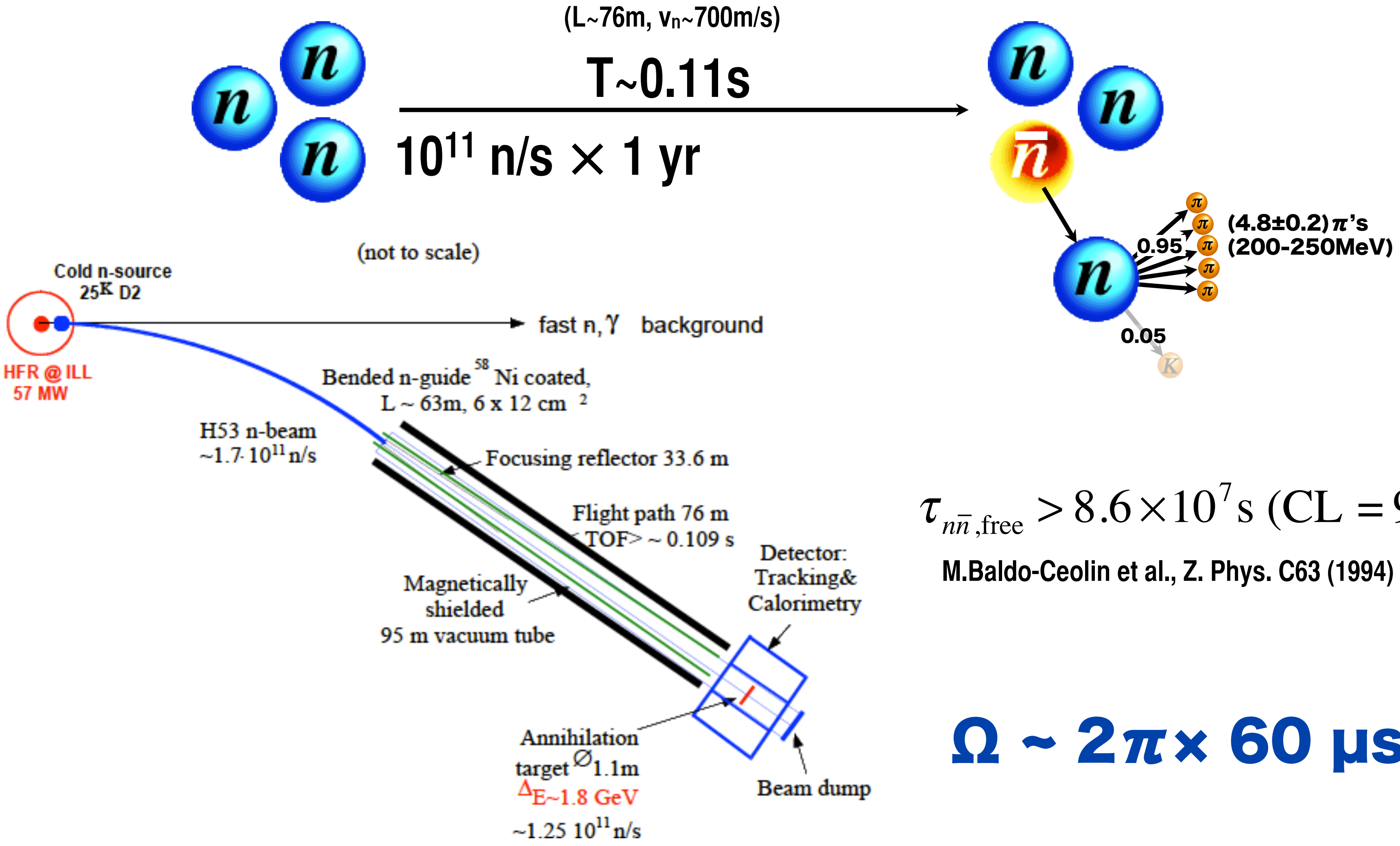
- Investigation of materials compatibility for the vacuum chamber.

- Verify maintenance of the field condition

Supermirrors (multilayer mirrors)

H. Shimizu

Experimental Setup of ILL $n\bar{n}$ Experiment

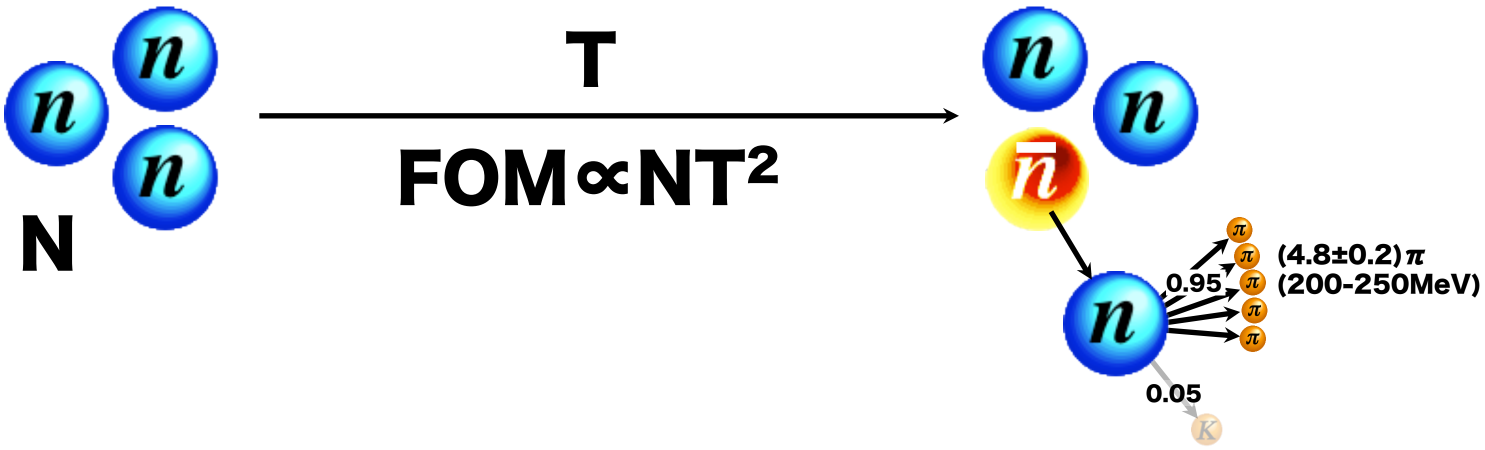


$$\tau_{n\bar{n},\mathrm{free}} > 8.6 \times 10^{7}\,\mathrm{s}\ (\mathrm{CL} = 90\%)$$

M.Baldo-Ceolin et al., Z. Phys. C63 (1994) 409.

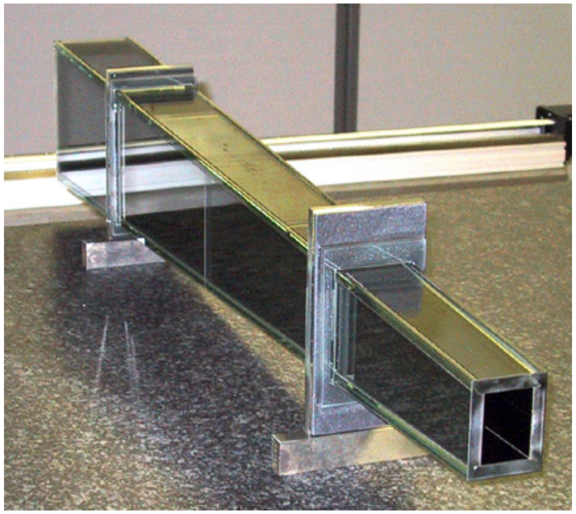
Ω ~ $2\pi \times 60$ μsr

Neutron Optics for $n\bar{n}$ Oscillation

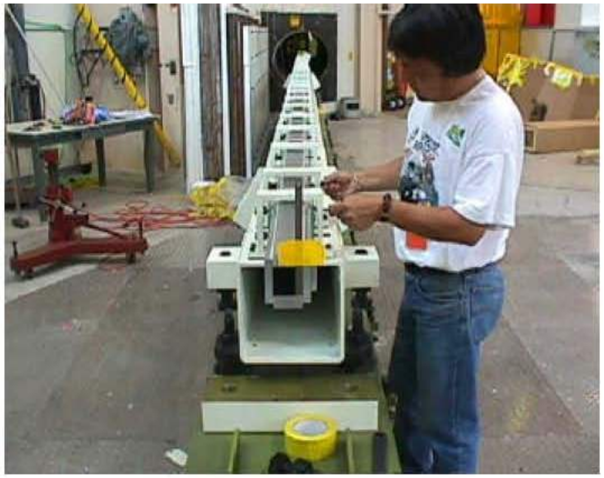


$$\propto \underbrace{\int \Phi\,[\mathrm{n\ cm^{-3}(m/s)^{-3}}]}_{\text{phase space density}} \times \boxed{\underbrace{A[\mathrm{cm^2}]\,A_v[\mathrm{(m/s)^2}]\,\Omega\,[\mathrm{sr}]}_{\text{acceptance}}} \times \underbrace{T^2\,[\mathrm{s^2}]\,dv_n}_{\text{free-flight time}}$$

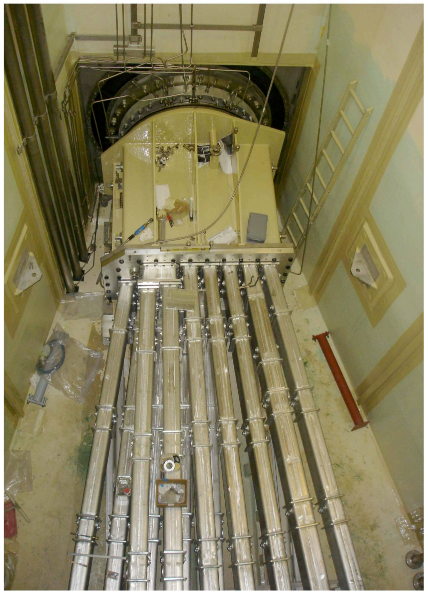
Neutron Supermirrors with m=3.5 are "Items of Commerce"



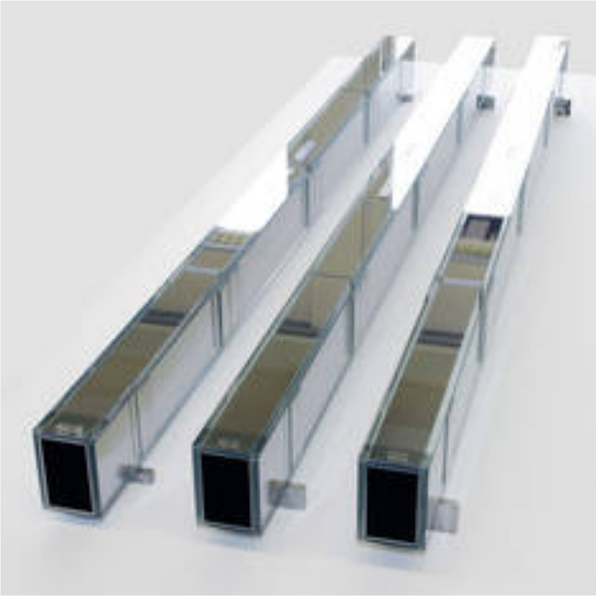
Focusing Guide



Guide Installation



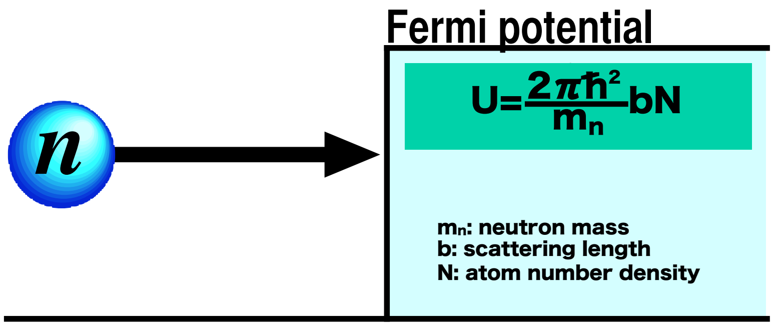
Guide Array in Reactor



Guide Manufacturers Catalog

Photos
Swiss Neutronics,
LANL,
ILL

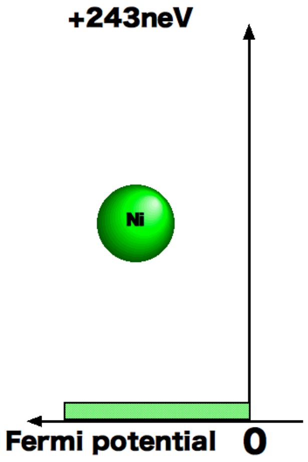
Neutron Reflection



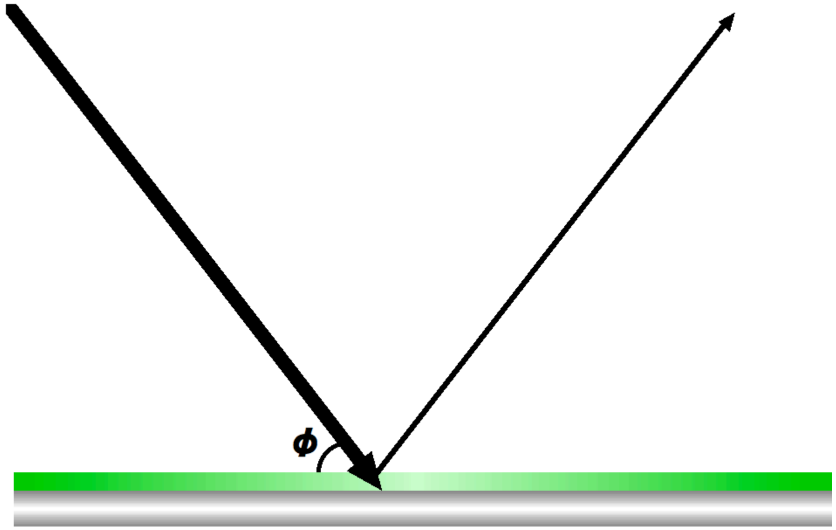
Fermi potential

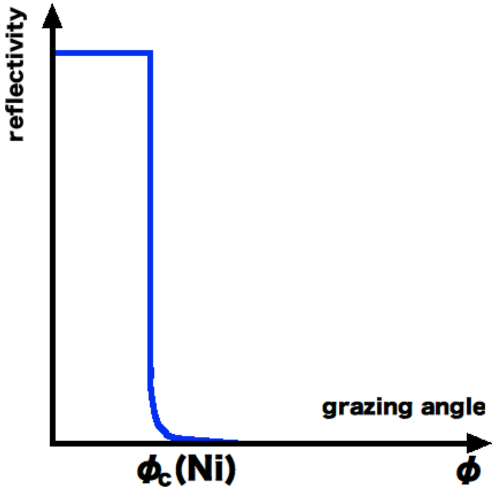
$$U=\frac{2\pi\hbar^2}{m_n}bN$$

m_n: neutron mass
b: scattering length
N: atom number density



neutron wavelength : λ

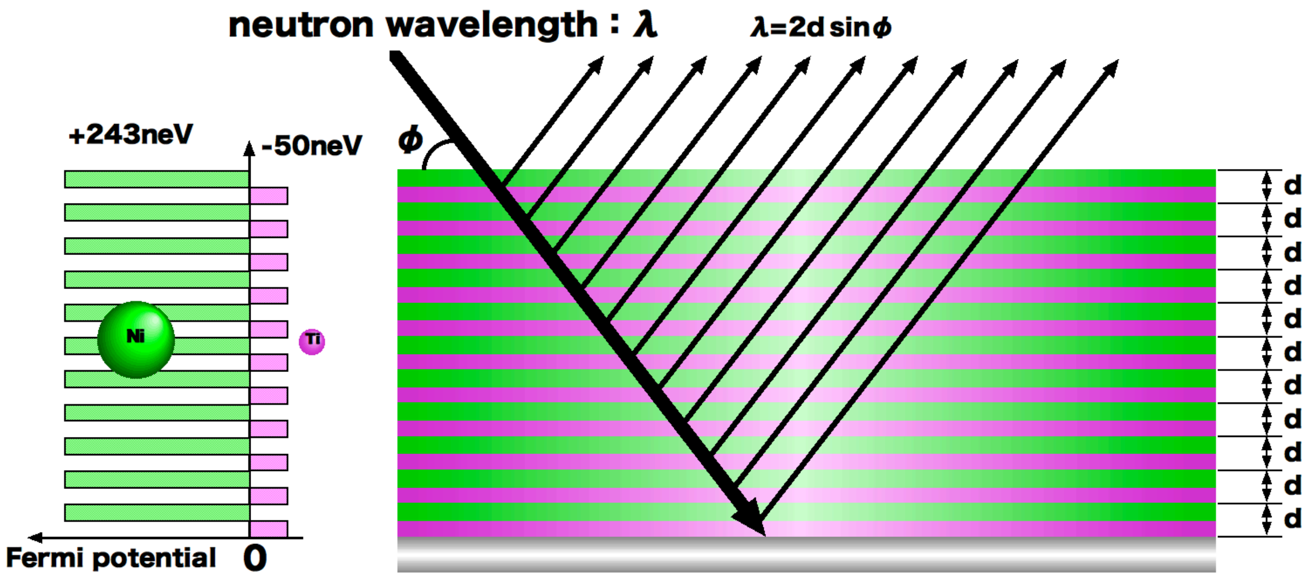


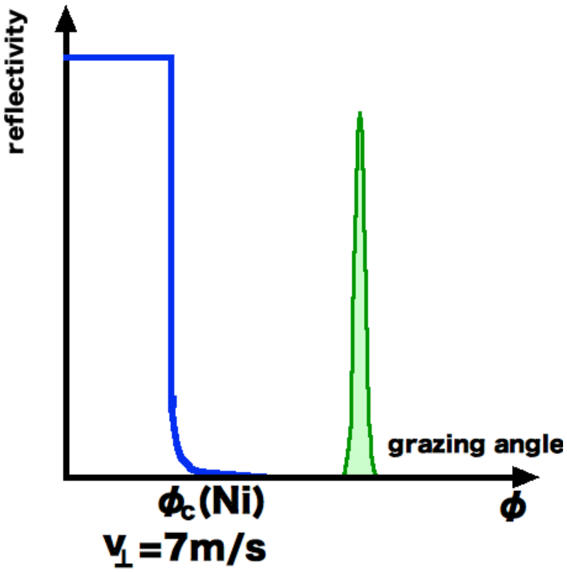


ϕ_c(Ni)
$v_\perp$=7m/s
critical angle of total reflection

ϕ_c(Ni)/λ=1.7 mrad/Å
$v_\perp$(Ni)=7 m/s

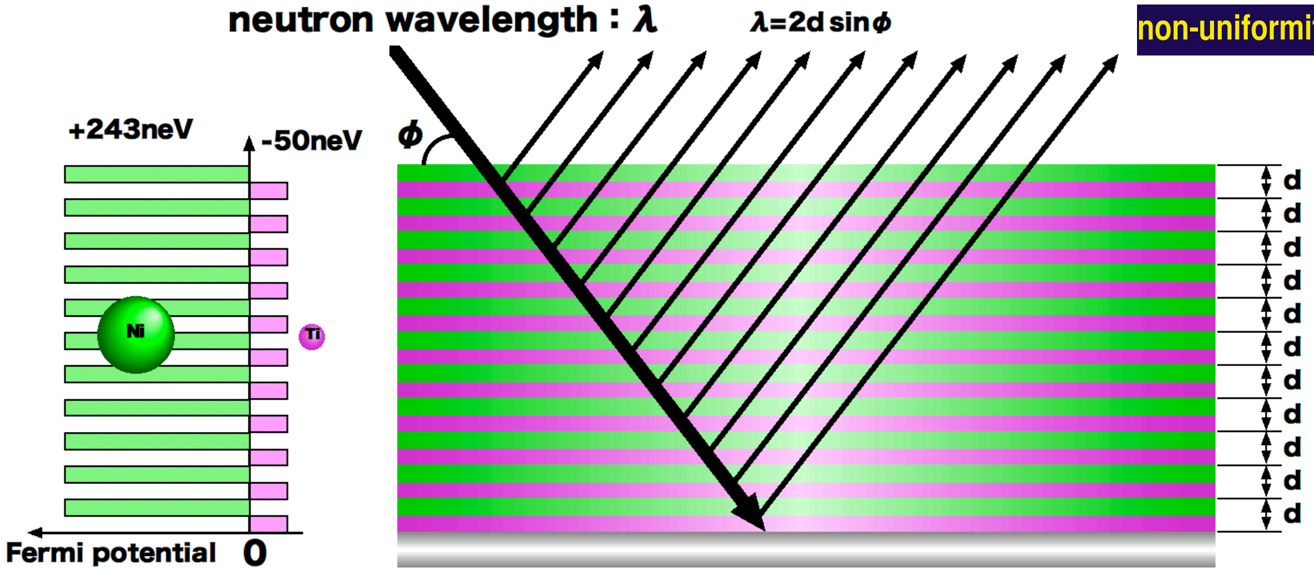
Multilayer Mirror (Monochromator)



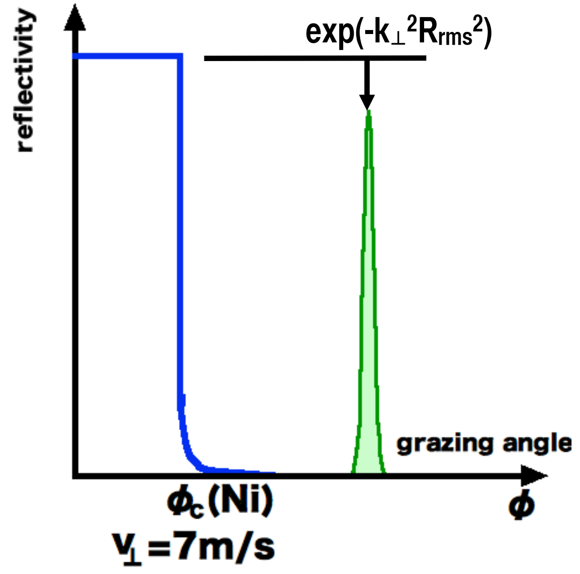


ϕ_c(Ni)/λ=1.7 mrad/Å
$v_\perp$(Ni)=7 m/s

Multilayer Mirror (Monochromator)

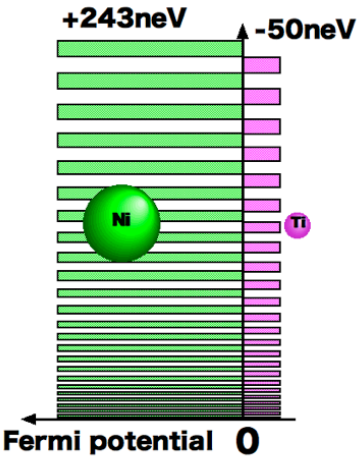


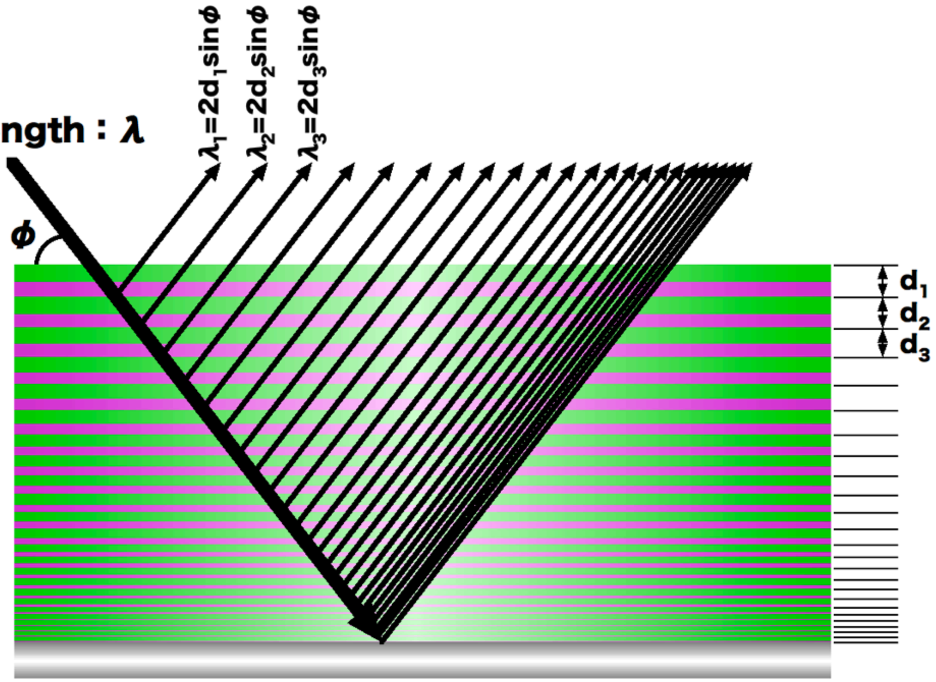
non-uniformity and roughness decreases the reflectivity

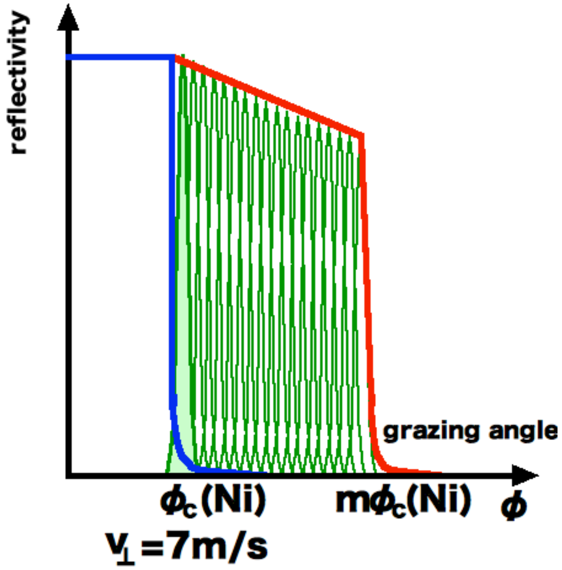


ϕ_c(Ni)/λ=1.7 mrad/Å
$v_{\perp}$(Ni)=7 m/s

Supermirror



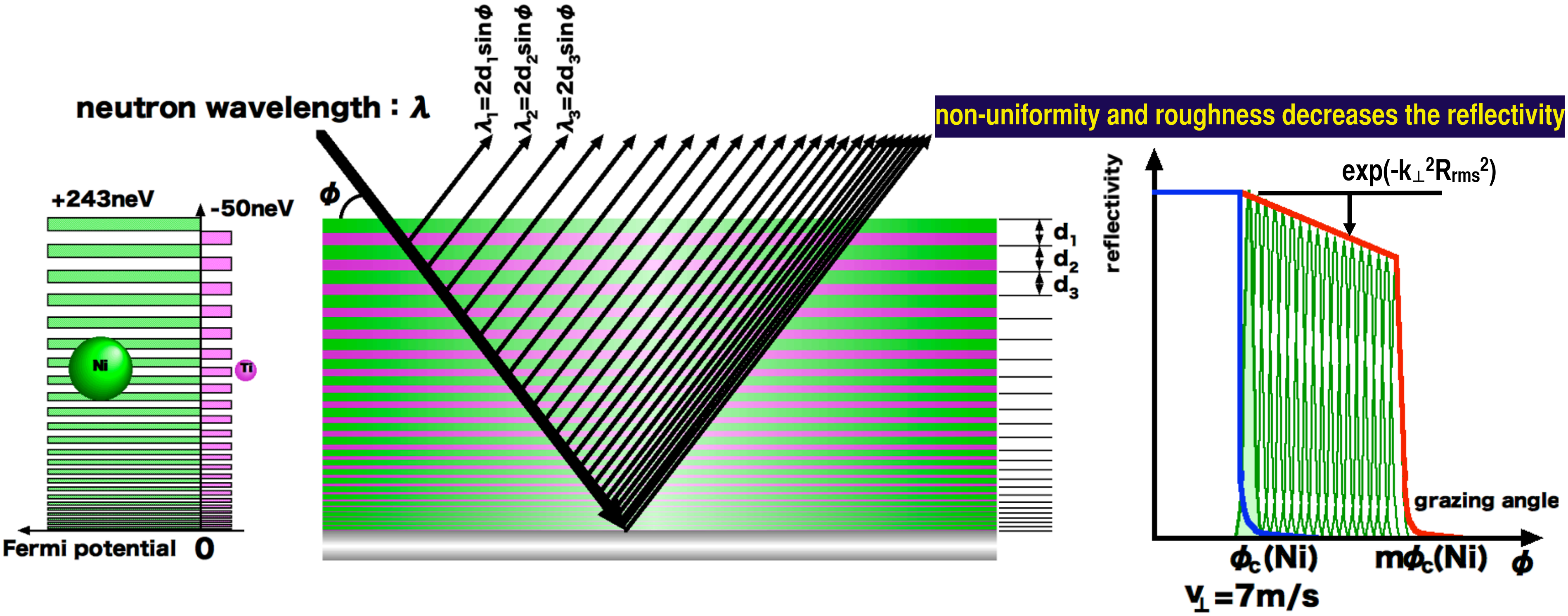




$m = \phi_c / \phi_c(\mathrm{Ni}) = v_c(\mathrm{Ni}) / v_c$

$\phi_c(\mathrm{Ni}) / \lambda = 1.7\ \mathrm{mrad/Å}$
$v_\perp(\mathrm{Ni}) = 7\ \mathrm{m/s}$

Supermirror



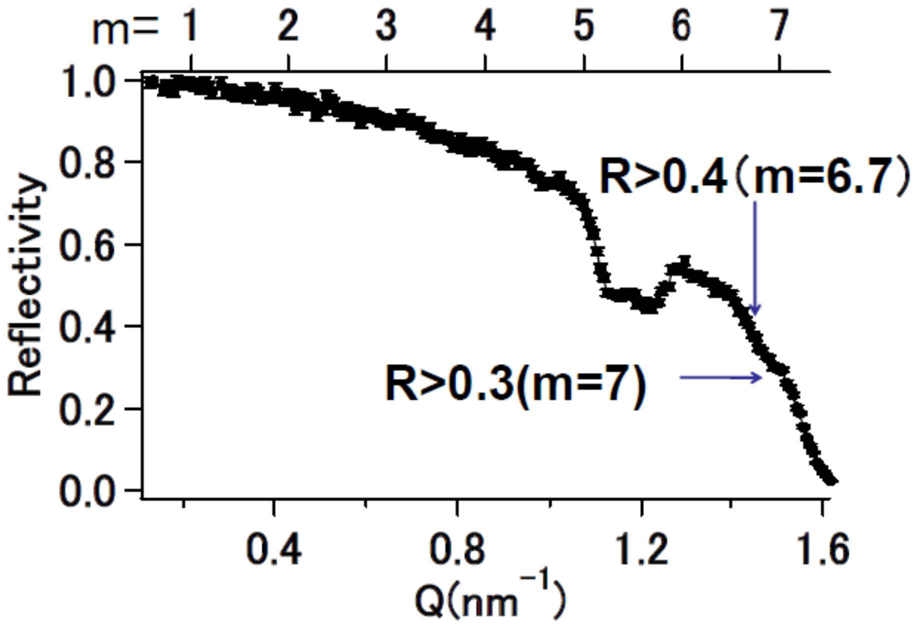
non-uniformity and roughness decreases the reflectivity

$m = \phi_c/\phi_c(\mathrm{Ni}) = v_c(\mathrm{Ni})/v_c$

$\phi_c(\mathrm{Ni})/\lambda = 1.7$ mrad/Å
$v_\perp(\mathrm{Ni}) = 7$ m/s

First m=7 Supermirror

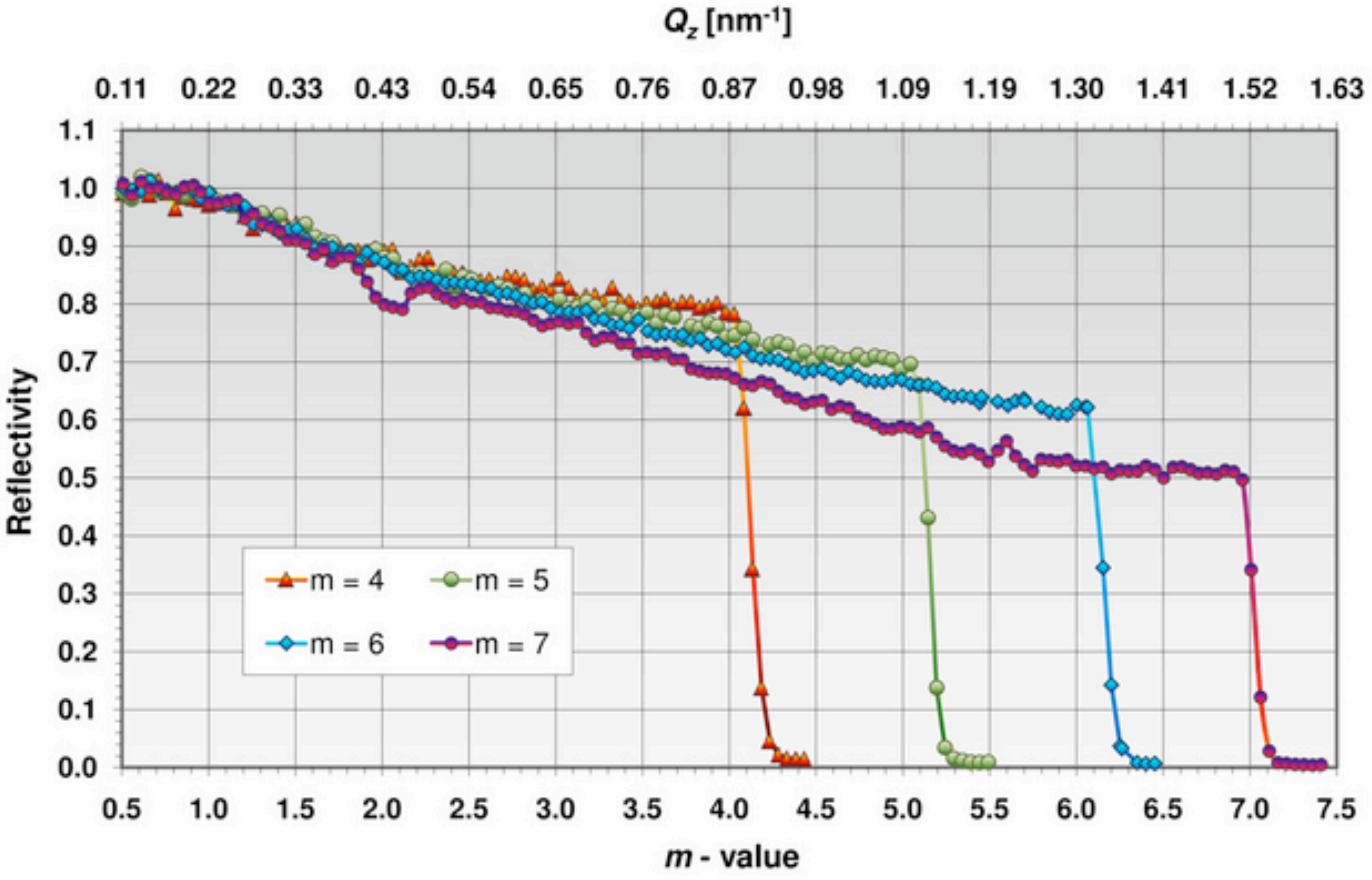
m=5 (4766 bilayers)
+ m=7 (7131 bilayers)



m=4-7 Supermirrors

http://www.swissneutronics.ch/

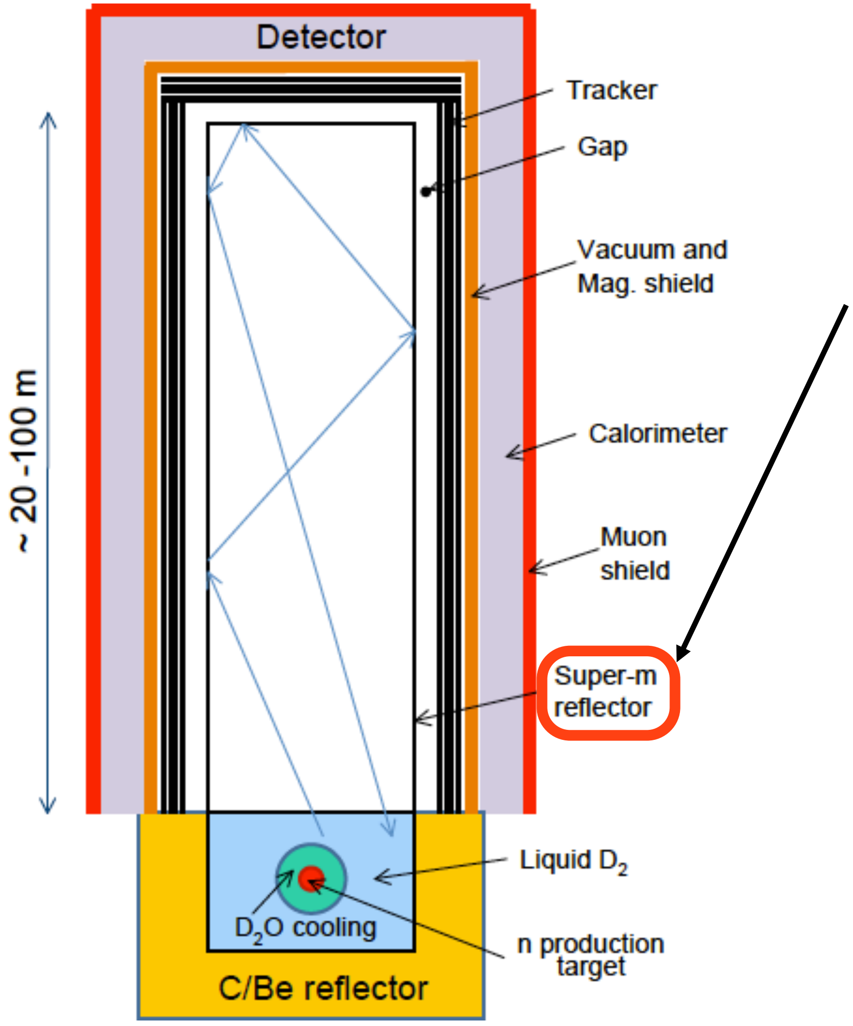
Supermirror: commercially available up to m=7 ($v_\perp$=50m/s)



Option B

10-100m Vertical Flight Path

n-nbar experiment using very cold neutrons



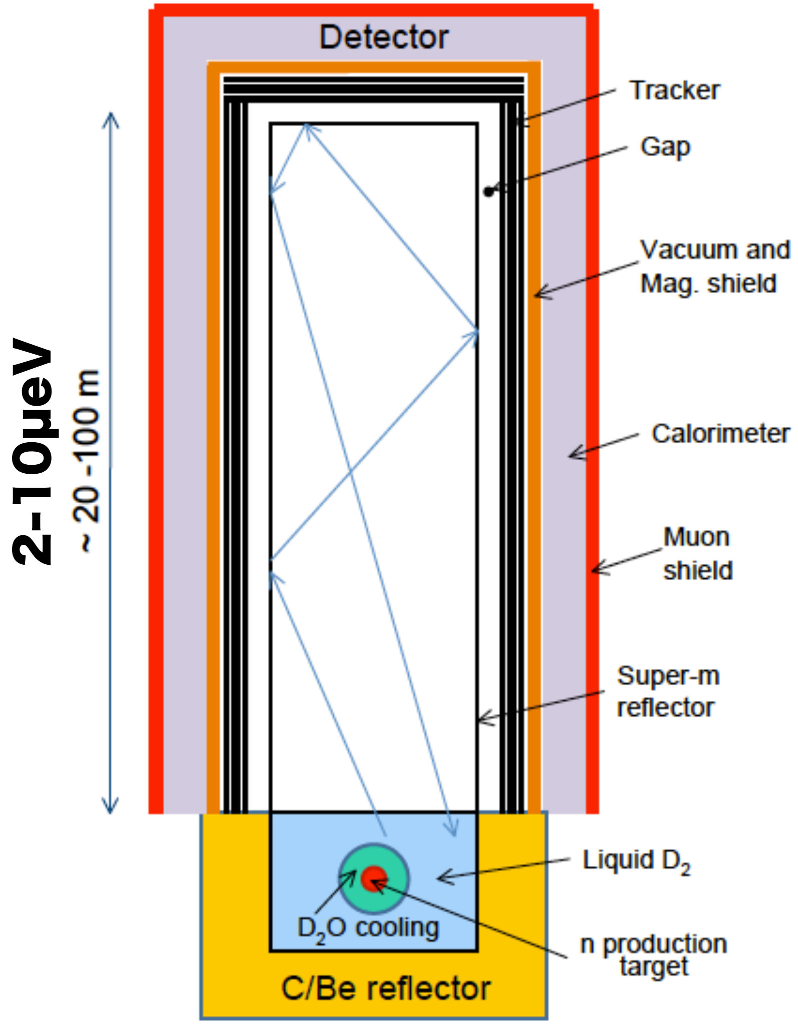
super-m reflector

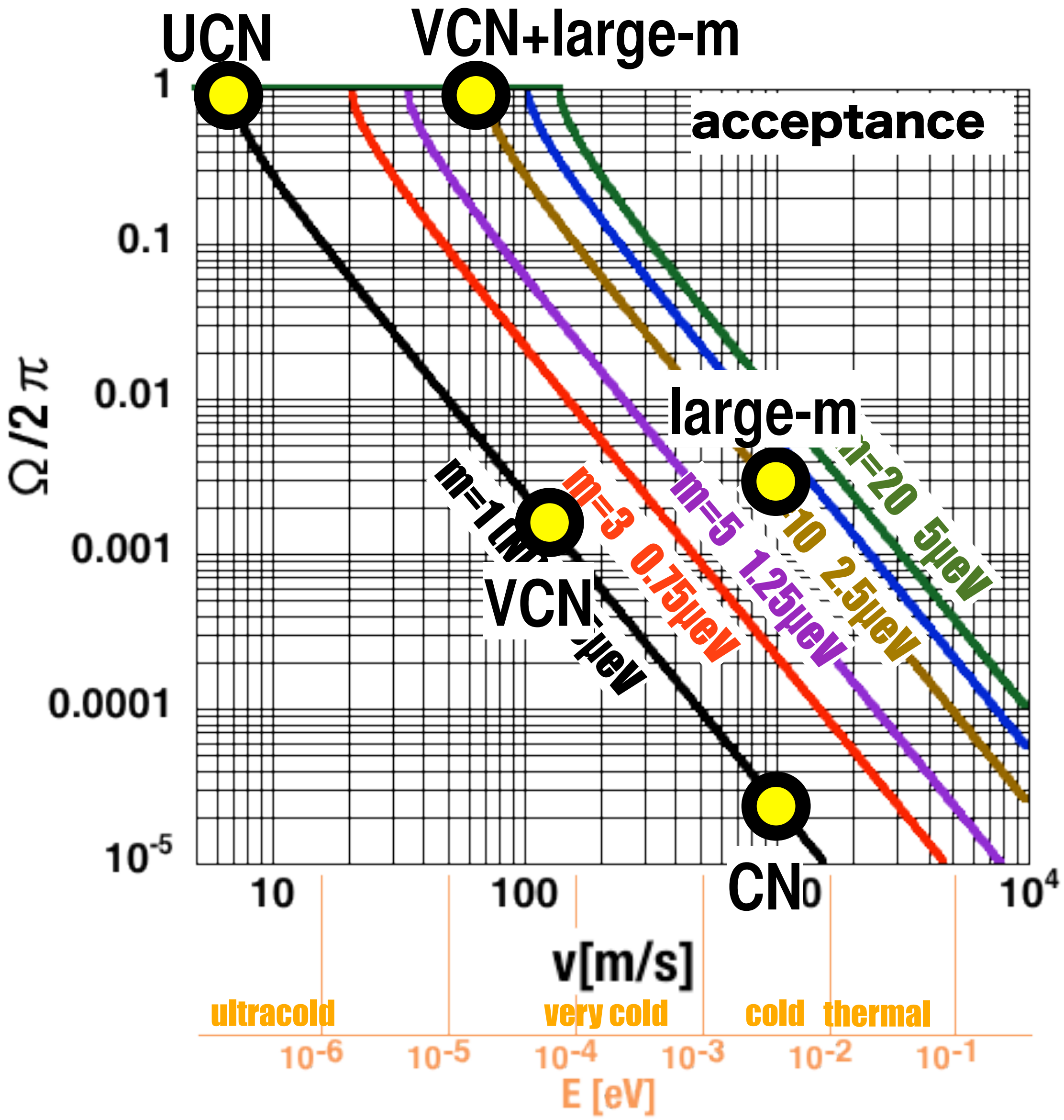
‖ for enlarging acceptance

multilayer neutron mirror

(Super-m)

n-nbar experiment using very cold neutrons

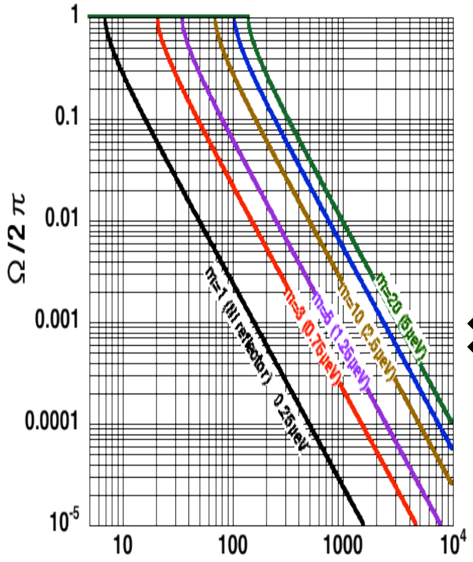




Folding acceptance and spectrum: illustration

acceptance

spectrum



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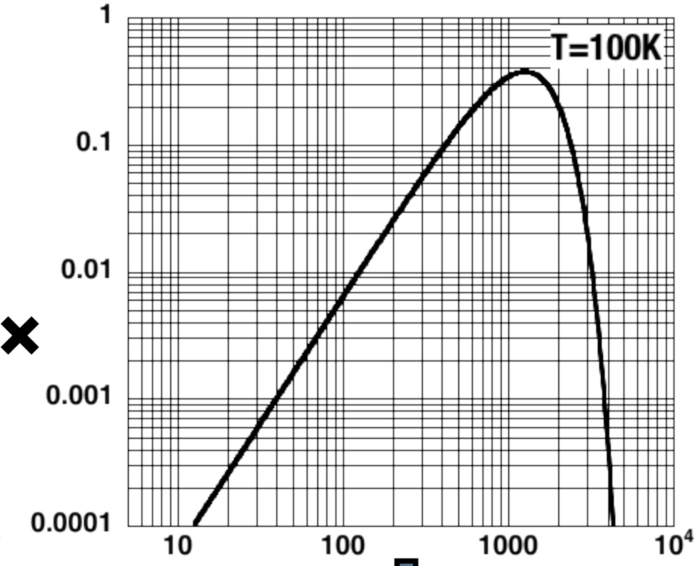

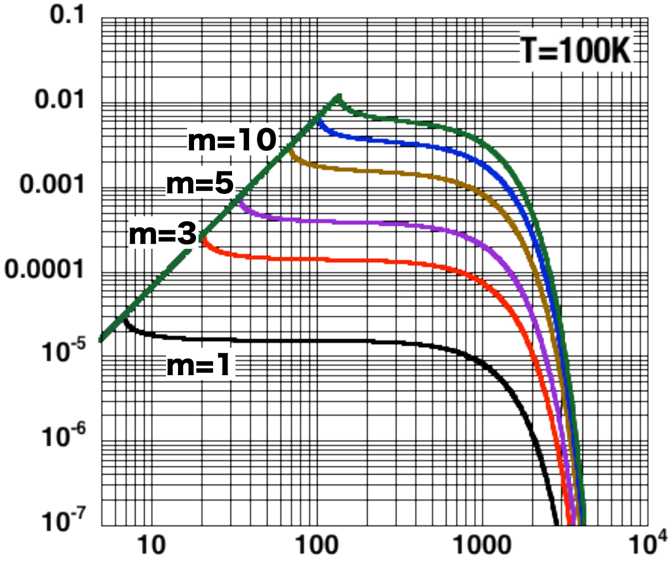

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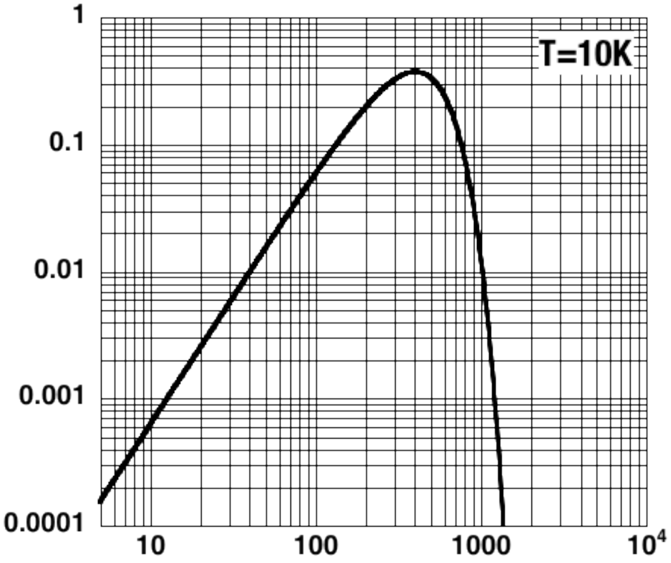

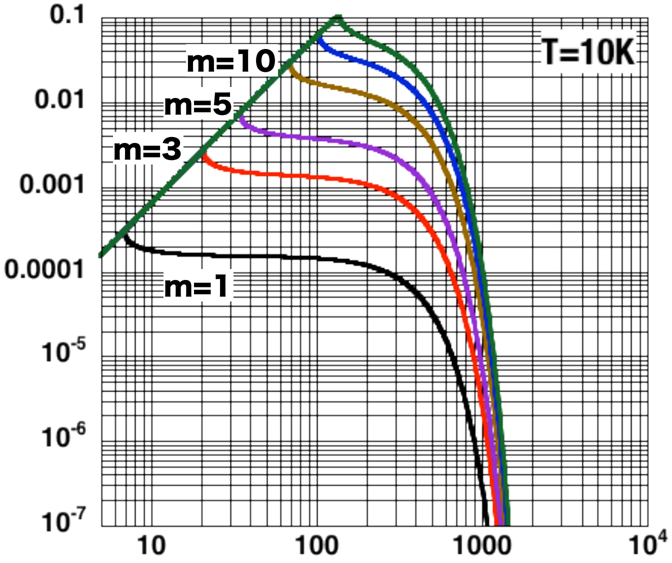

(Some) Issues

- Current neutron guide coatings are optimized for many reflections:
  High reflectivity more important than high critical angle.
- Current guide construction methods are not easily “scalable”
- Current world wide capacity is ~1000 m^2/year
- No commercial source in the US.
- …

Summary

Multilayer mirrors can enhance the figure-of-merit for n-nbar experiments.

Multilayer fabrication technology was remarkably improved in the past decade.

supermirrors m≤7 exist

Other (coupled) issues:

Focusing geometry (~elliptical)
Spectrum