Neutron Physics

W. M. Snow
Physics Department
Indiana University
NPSS, Bar Harbor

5 lectures:

1. Physics/Technology of Cold and Ultracold Neutrons
2. Electroweak Standard Model Tests [neutron beta decay]
3. Nuclear physics/QCD [weak interaction between nucleons]
4. Physics Beyond the Standard Model [EDM/T violation]
5. Other interesting stuff that neutrons can do [NNN interaction, searches for extra dimensions,…]

1: Physics/Technology of Cold and Ultracold Neutrons

Neutron sources [reactors/spallation] and neutron moderation

Low energy neutron interactions with matter: neutron optics

Polarized neutrons

"Ultracold" neutrons

Examples

Thanks for slides to: Geoff Greene (Tennessee/ORNL),
K. Bodek (PSI), Chen-Yu Liu (LANL), Jen-chieh Peng (Illinois)

What is “Neutron Physics”?

neutron physics (Fr. physique de neutronique):
a subset of scientific studies begun at the
Institute Laue/Langevin (ILL) in Grenoble, France
which the major users of the facility [condensed matter
physics/chemistry/biology/materials science] found
difficult to classify.

Known to practitioners as **fundamental neutron physics**

Research which uses “low energy” neutrons from nuclear
reactors and accelerator-driven spallation sources to
address questions in nuclear, particle, and astrophysics

“Fundamental” Neutron Physics...

is “Nuclear” physics, but with an “isotope of nothing”

is Particle Physics: but at an energy of 10^{-20} TeV

employs a particle which, according to Big Bang Cosmology, is lucky to be alive

relies on experimental techniques and ideas from atomic and condensed matter physics

is pursued at facilities built mainly for chemistry, materials science, and biology

Neutron Properties

Electric charge: q_n=0, electrically neutral [q_n<10^{-22}e]

Size: r_n~10^{-5}Angstrom=1 Fermi [area~ 10^{-25} cm^2=0.1 "barn"]

Internal Structure: quarks [ddu, m_d~ m_u~few MeV] + gluons

Spin: s_n= 1/2 [Fermi statistics]

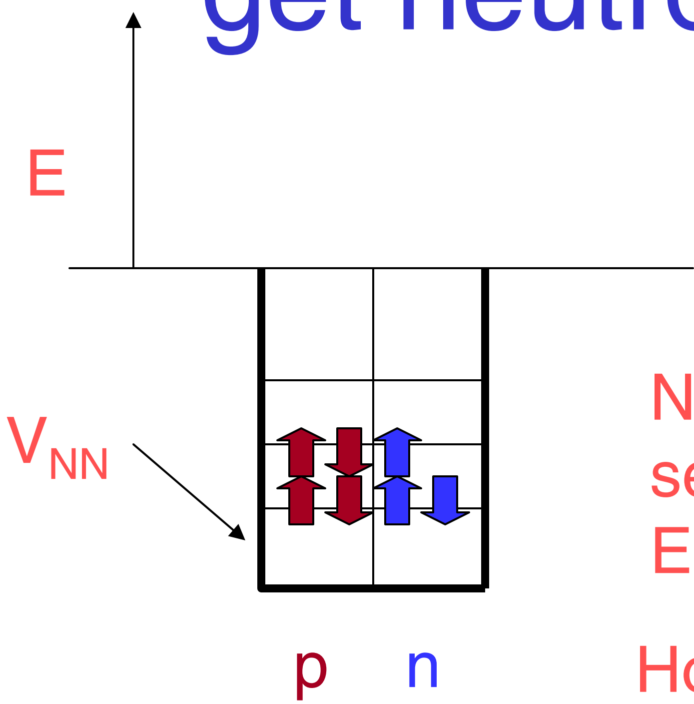
Magnetic Dipole Moment: μ_n/μ_p = -0.68497935(17)

Electric Dipole Moment: zero[d_n < 10^{-26} e-cm]

Mass: m_n=939.566 MeV [m_n> m_p+ m_e, neutrons can decay]

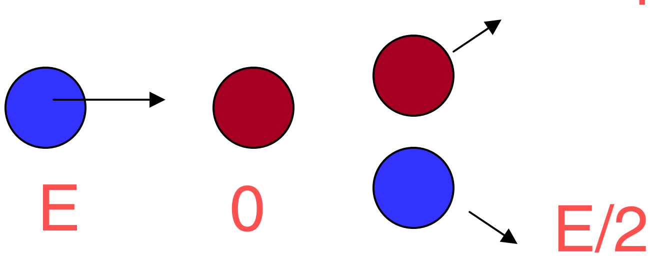
Lifetime: τ_n=885.5 +/- 1.0 seconds

Why is it such hard work to get neutrons to play with?



Neutrons are bound in nuclei, need several MeV for liberation. We want E~kT~25 meV (room temperature)

How to slow down a heavy neutral particle with M_n= M_p ? Lots of collisions…

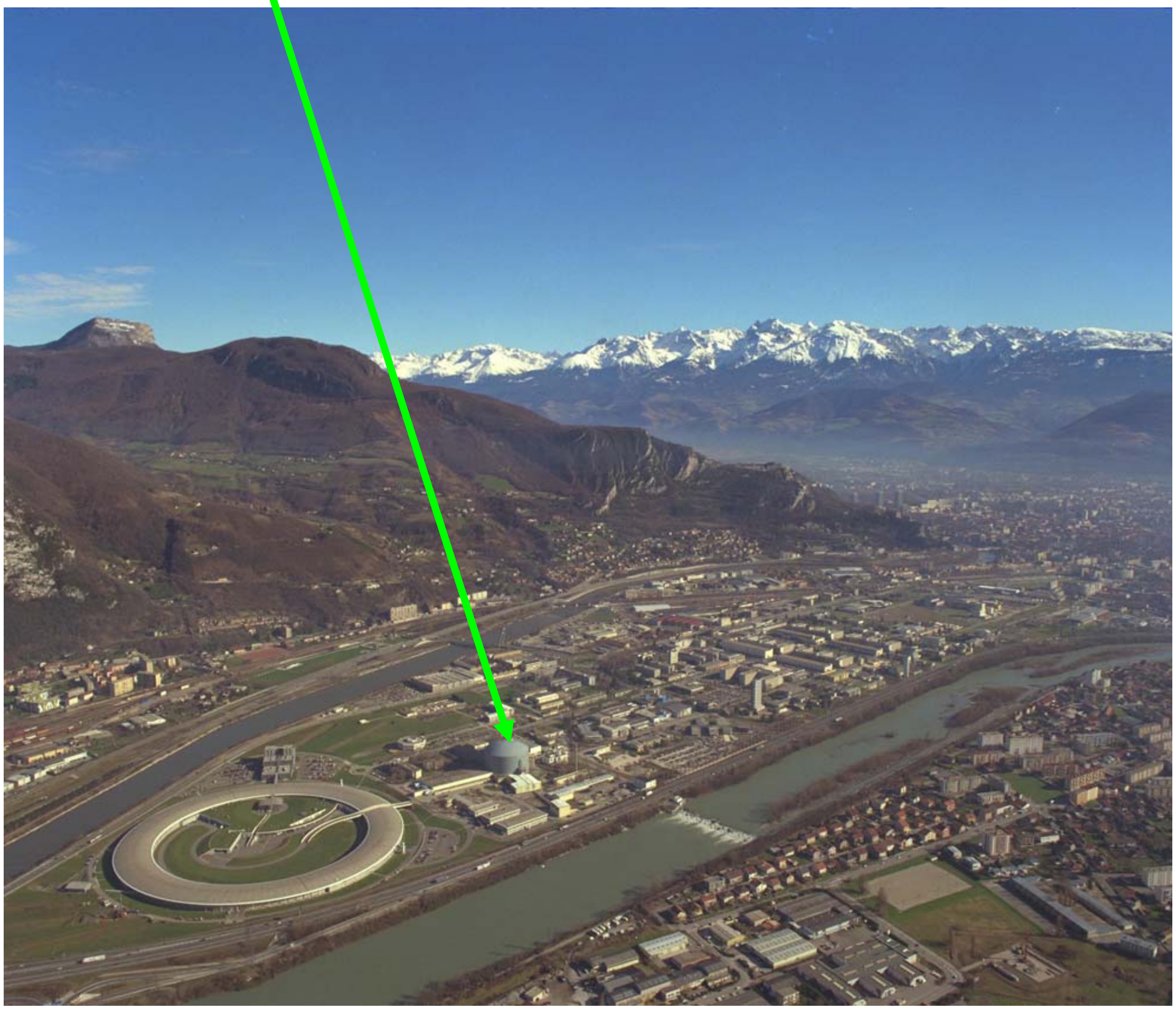


$[1/2]^N$=(1 MeV)/(25 meV) for N collisions

Neutrons are unstable when free->they can't be accumulated easily

ILL, Grenoble

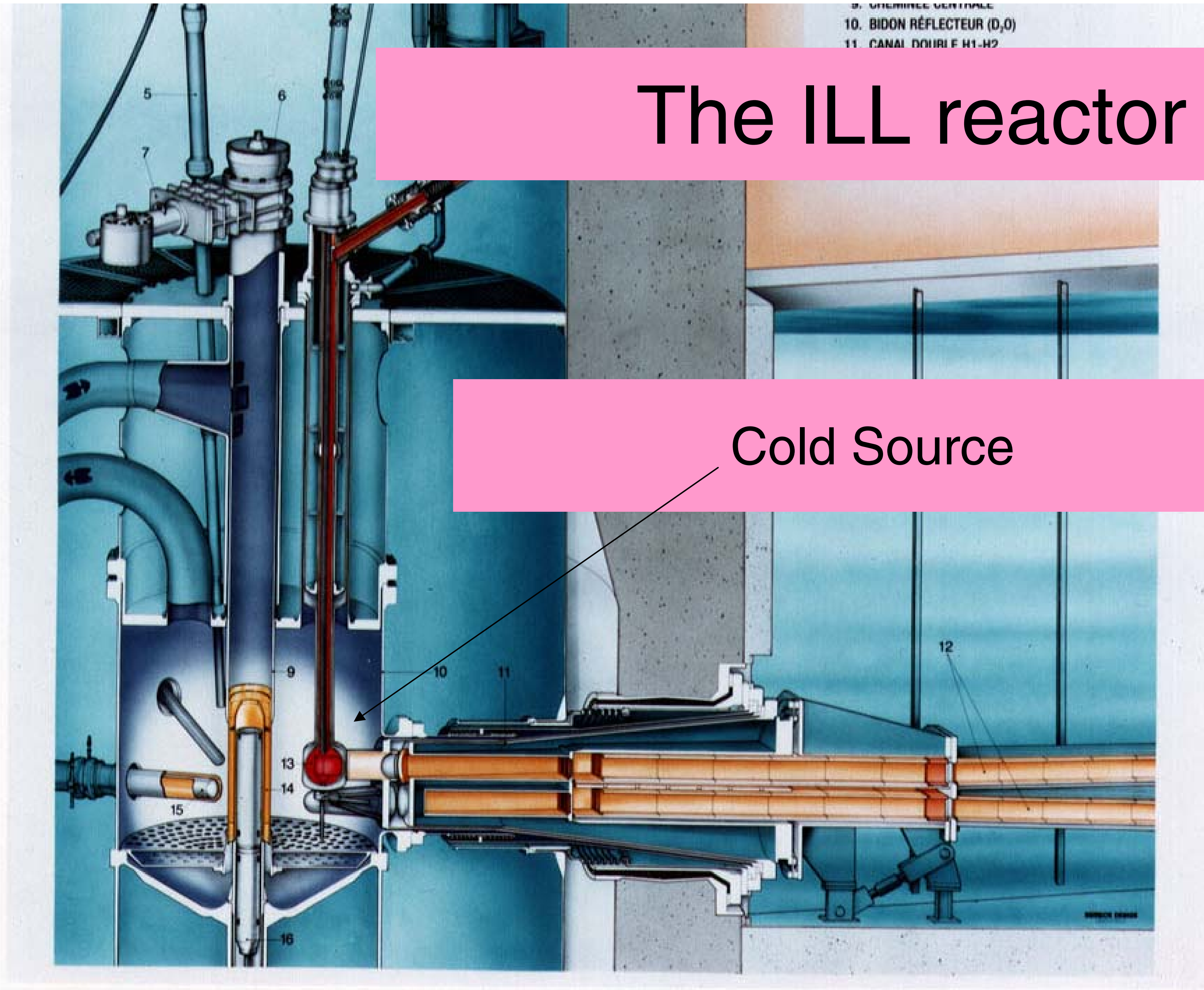
60 MW reactor



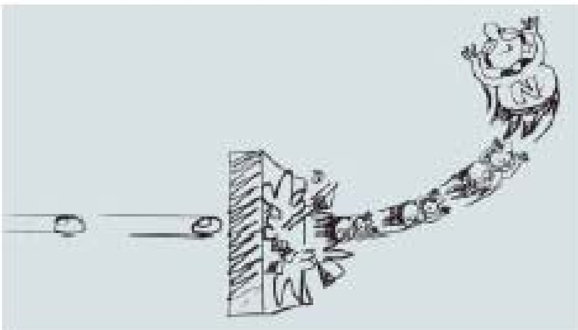
World's most intense source of neutrons for scientific research since 1973

France, UK, Germany founding members

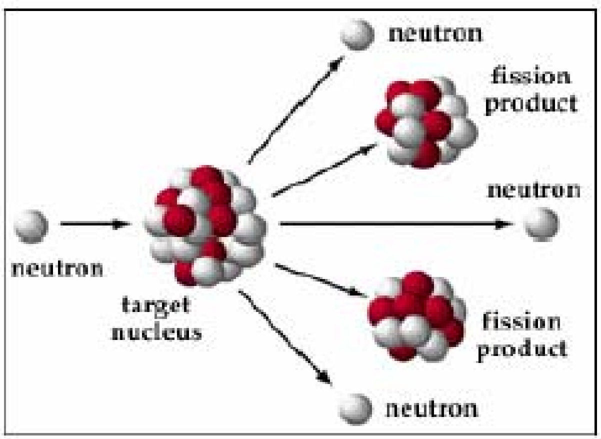
The ILL reactor



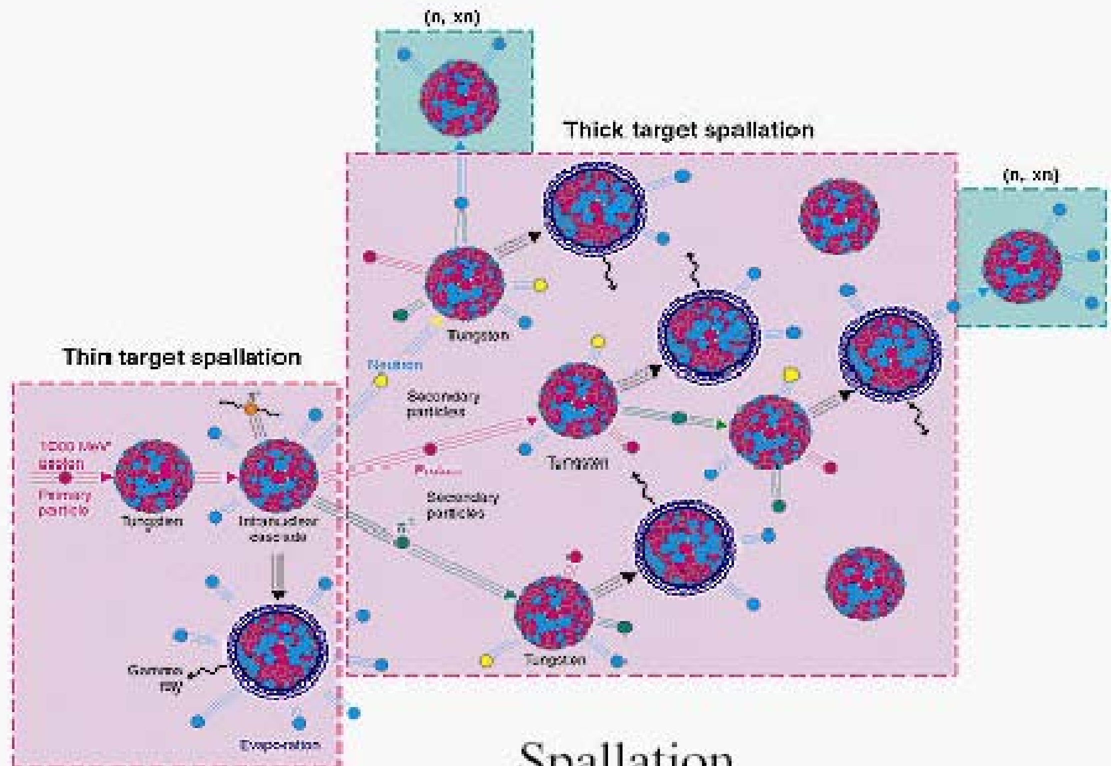
About 1.5 Useful Neutrons Are Produced by Each Fission Event in a Nuclear Reactor Whereas About 25 Neutrons Are Produced by spallation for Each 1-GeV Proton Incident on a Tungsten Target



Artist's view of spallation



Nuclear Fission

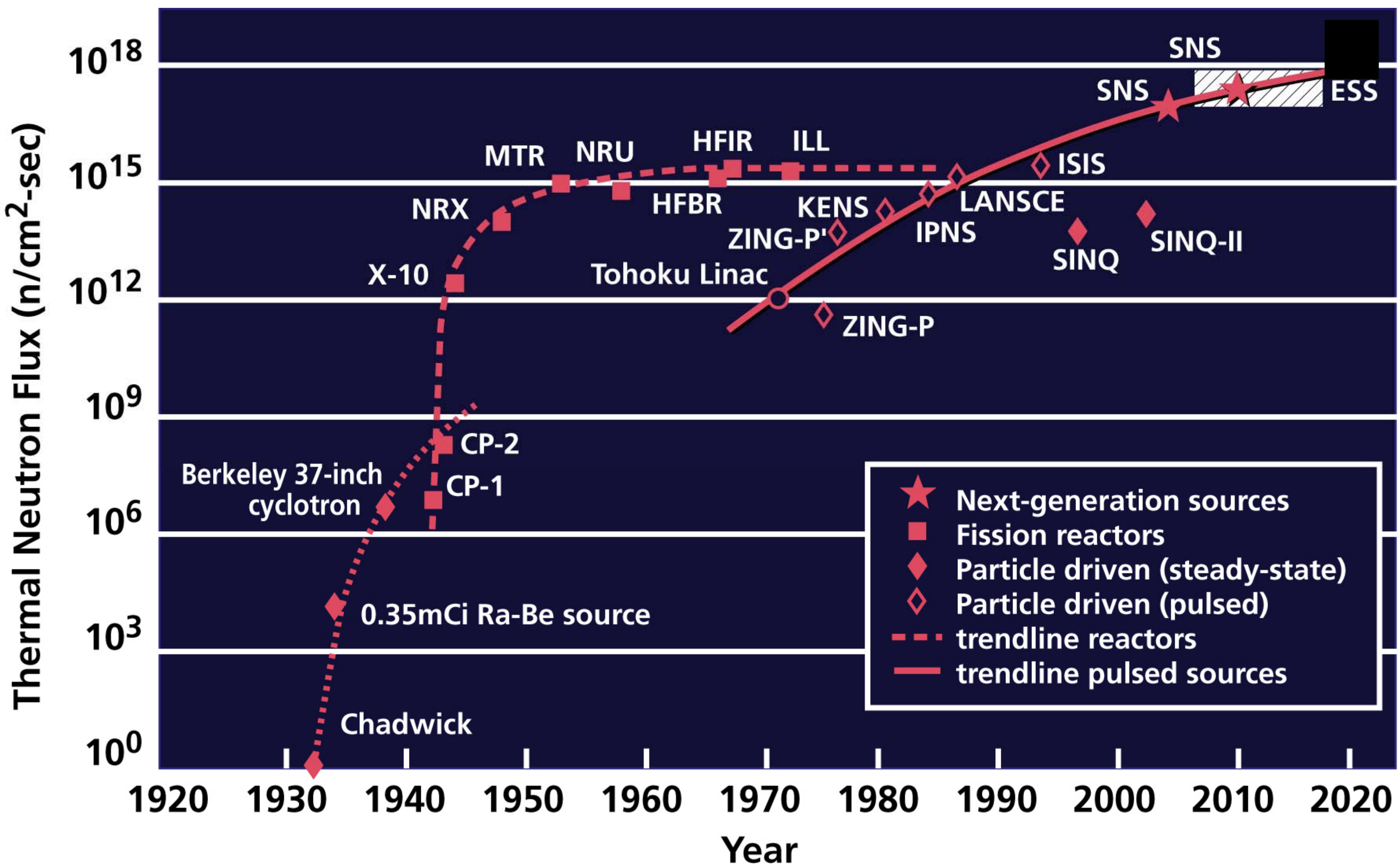


Spallation

From R. Pynn, UCSB

Reactors **are limited by heat removal from the core**

Pulsed sources **have not yet reached that limit**



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

The Spallation Neutron Source

SNS Site Overlay

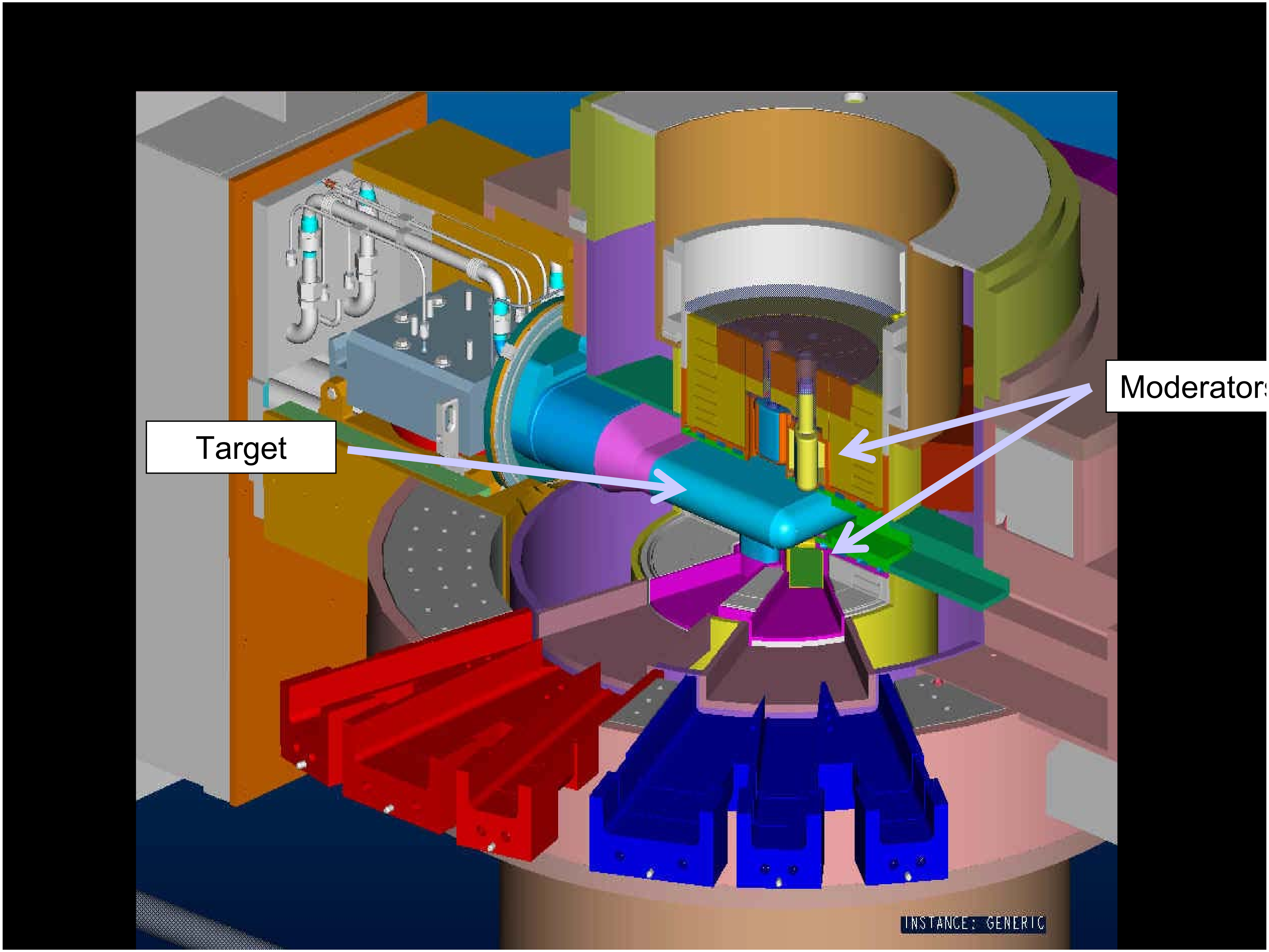
- $1.4B--1GeV protons at 2MW, ready in 2007.
- Short (~1 usec) pulse– mainly for high TOF resolution
- >10 times the power of ISIS

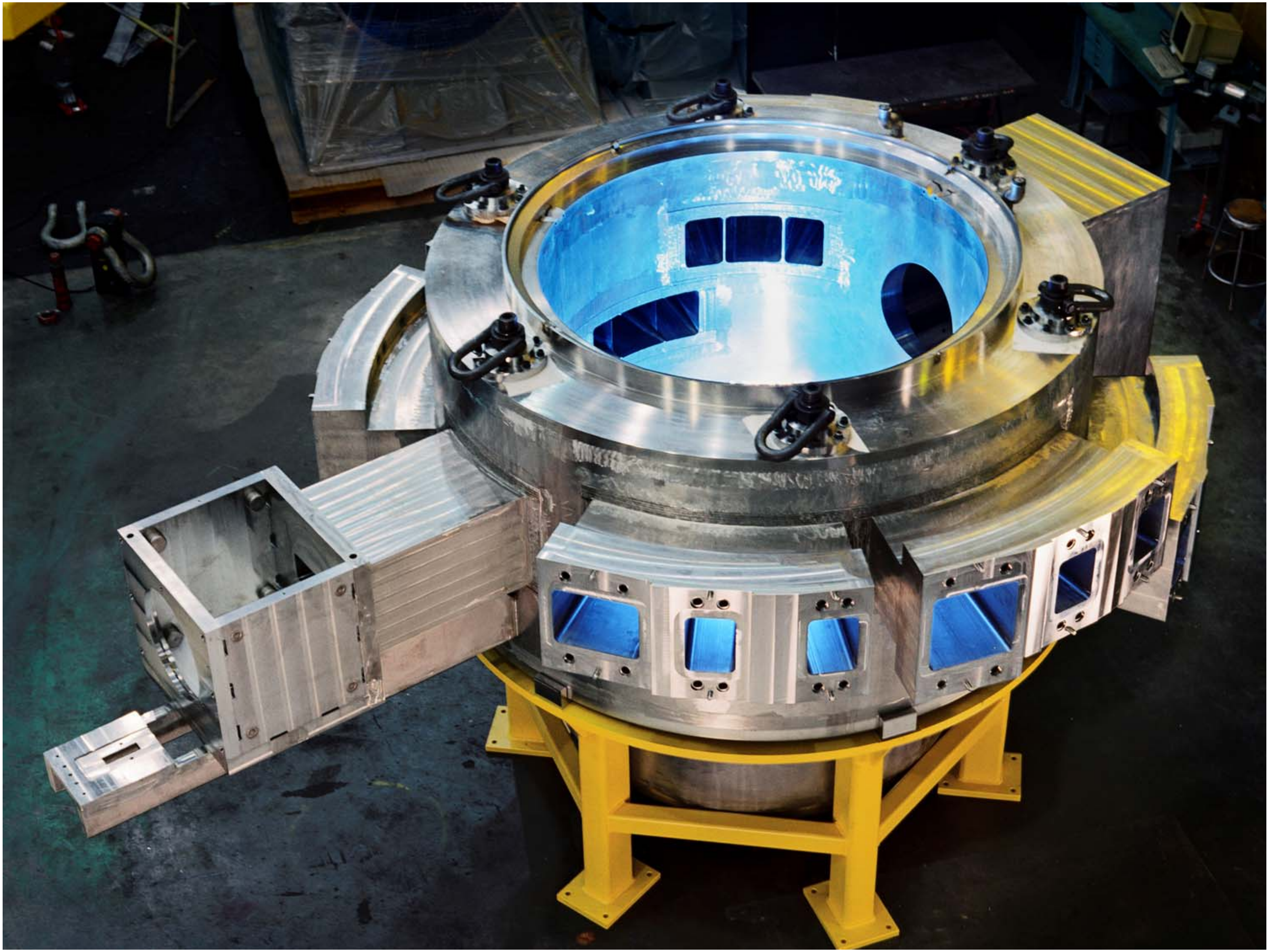
The Spallation Neutron Source

Photo, Oct 2003

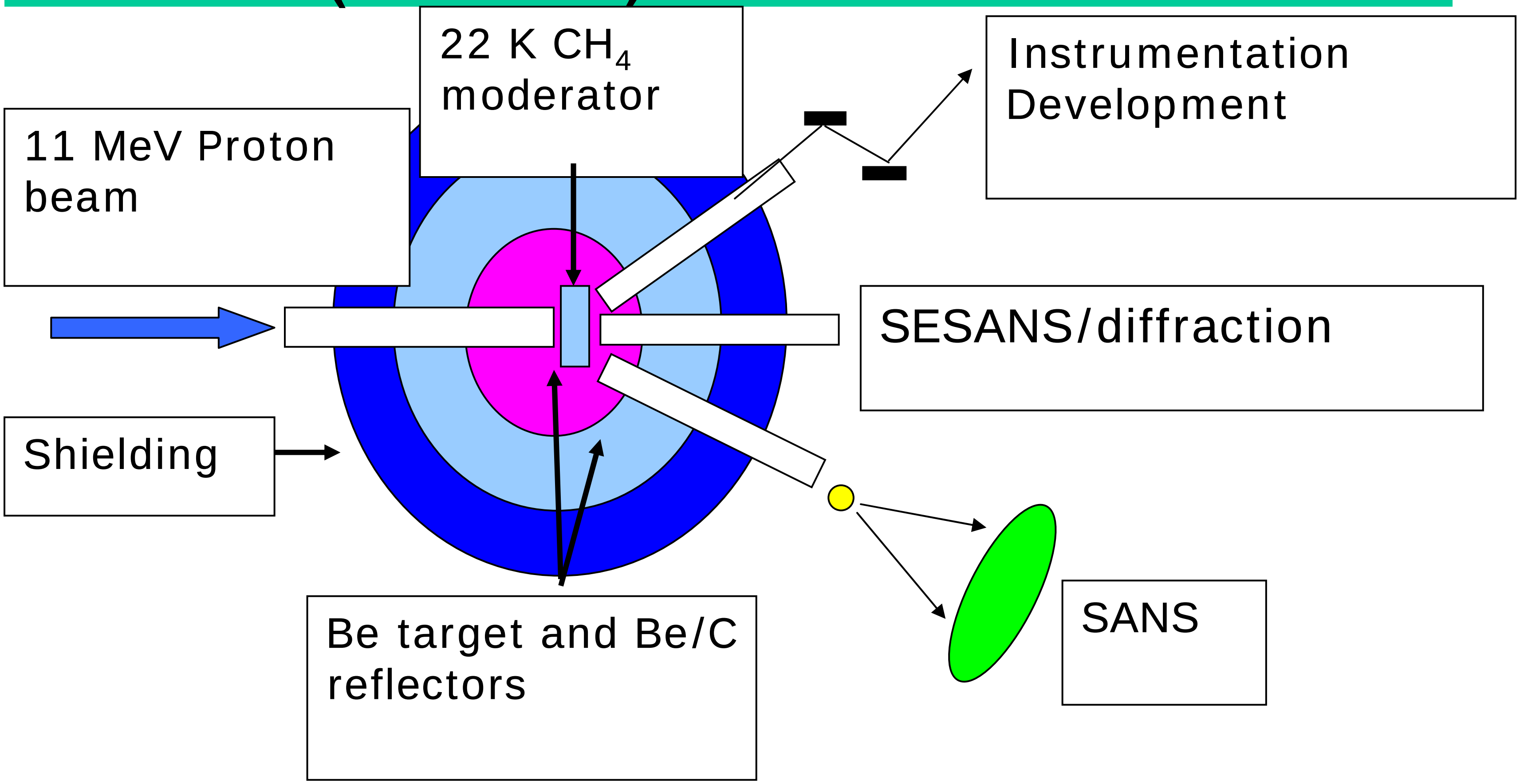
SNS Construction: on schedule for 2007 Operation

photos, April 2003


Target
Moderators
INSTANCE: GENERIC

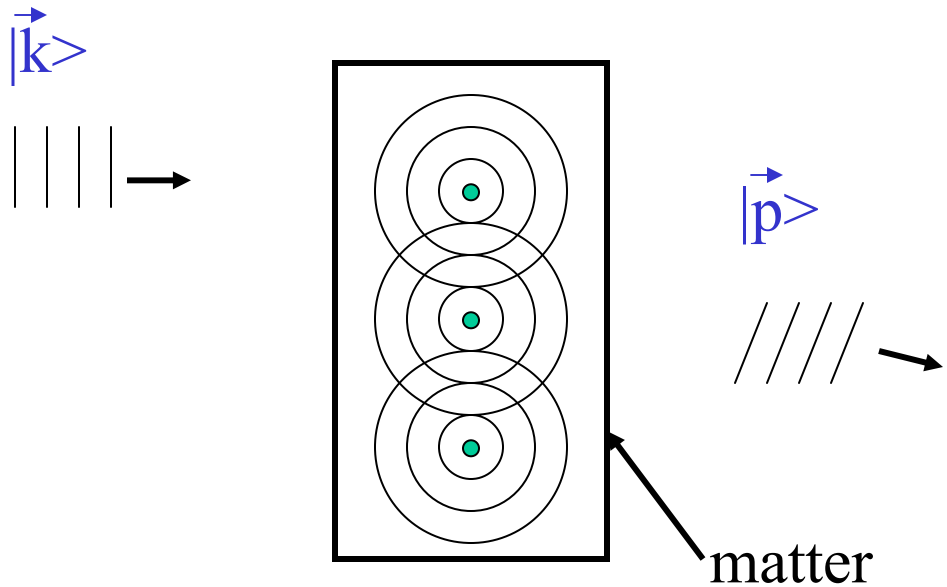


Low Energy Neutron Source (LENS) at Indiana



First university-based pulsed cold neutron source!

Neutron-Matter Interaction



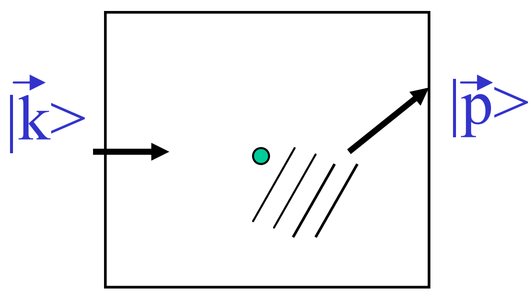
Thermal neutrons: $\lambda \sim 2A$
$R_{nuc} \sim 10^{-5}$ A
kR>>1->elastic scattering
f_{scatt}=b= s-wave scattering length
b can be positive or negative

Inelastic scattering: $|\vec{k}| \neq |\vec{p}|$, energy transferred to localized excitations in matter (phonons, magnons,…)

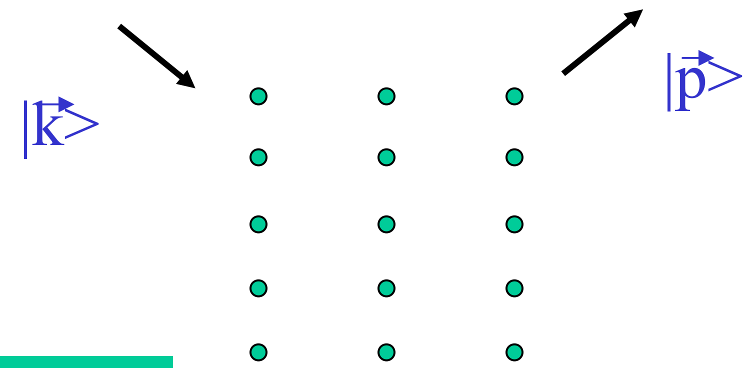
Elastic scattering: $|k| = |p|$, energy transferred to object as a whole->quantum mechanical state of matter unchanged…

Neutrons in Condensed Matter

for a “thermal” neutron ($E_K=mv^2/2=3/2\ k_BT$, T=300K-> E_K=25 meV)
the de Broglie wavelength of the neutron is $\lambda \approx 2$ Angstroms



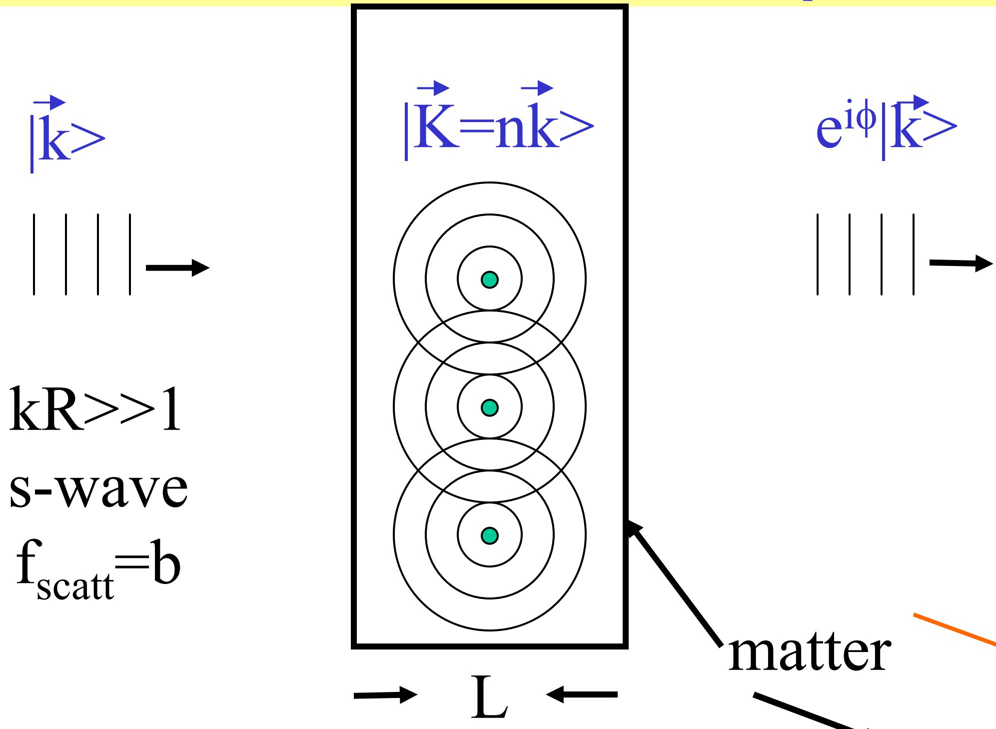
phonon



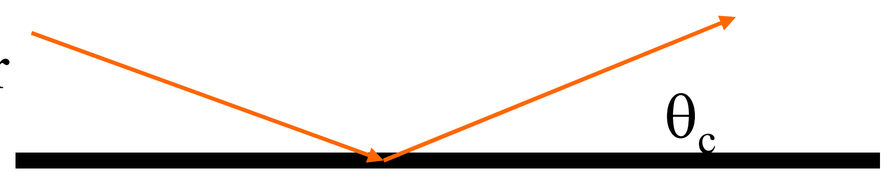
diffraction

Thermal neutrons have the right energies and momenta to match excitations (phonons, spin waves, molecular rotations…) and static structures (crystals, molecular shapes,…) in condensed media

Neutron Optical Potential



Phase shift $\phi=(n-1)kL$
Index of refraction
$n=|K|/|k|=\sqrt{[(E_k-\langle V\rangle)/E_k]}$



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

$\langle V_{strong}\rangle=2\pi h^2\rho b_s/m$, ~+/- 100 neV
$\langle V_{mag}\rangle=\mu B$, ~+/- 60 neV/Tesla
$\langle V_{grav}\rangle=mgz$~100 neV/m
$\langle V_{weak}\rangle=[2\pi h^2\rho b_w/m]\vec{s}\cdot\vec{k}/|k|\sim10^{-7}\langle V_{strong}\rangle$

For $E_k-\langle V\rangle$ negative,
neutron reflects
from the optical potential

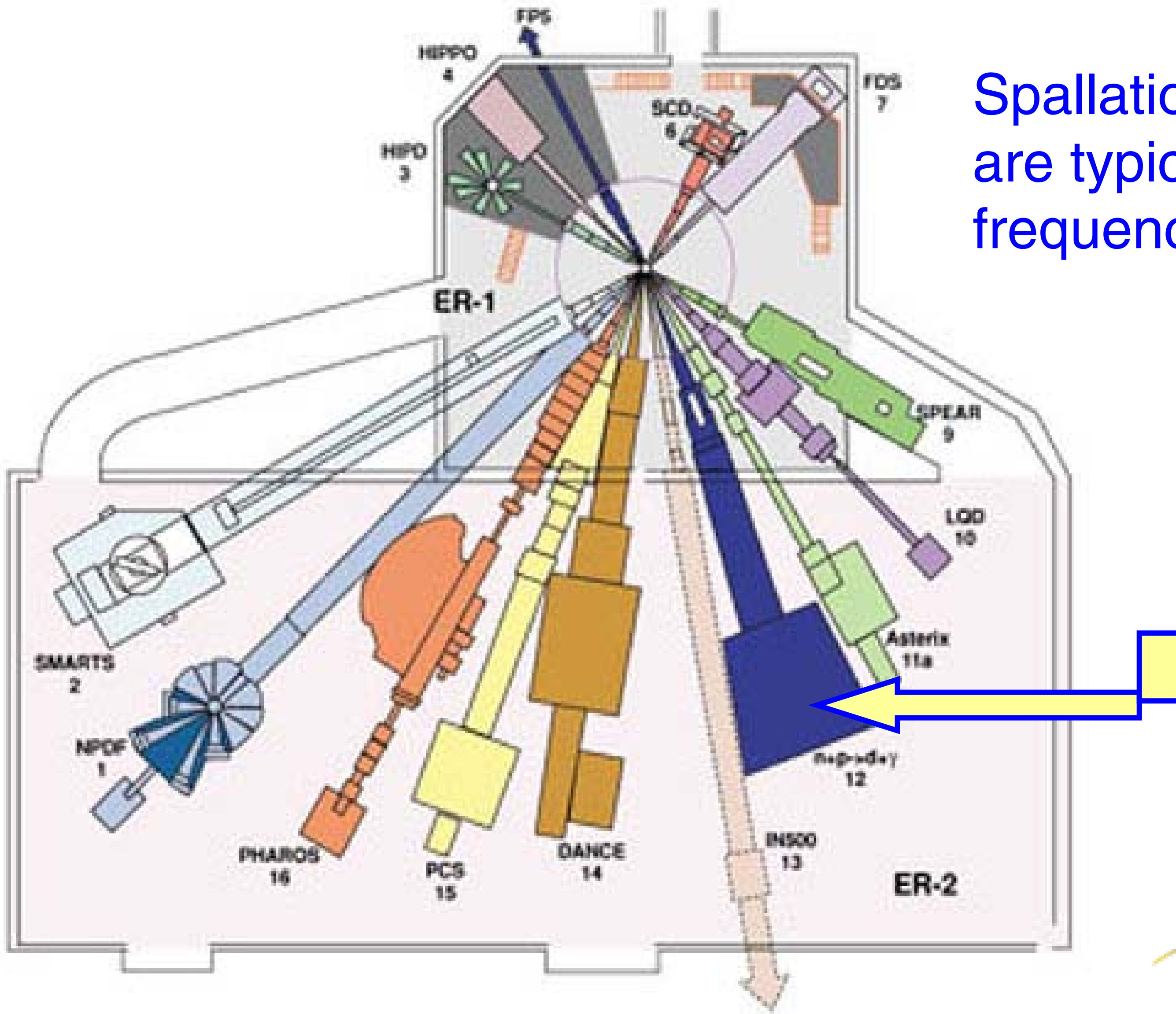
NIST Cold Neutron Guide Hall

Reactor makes neutrons, cooled to ~20K by liquid hydrogen

←

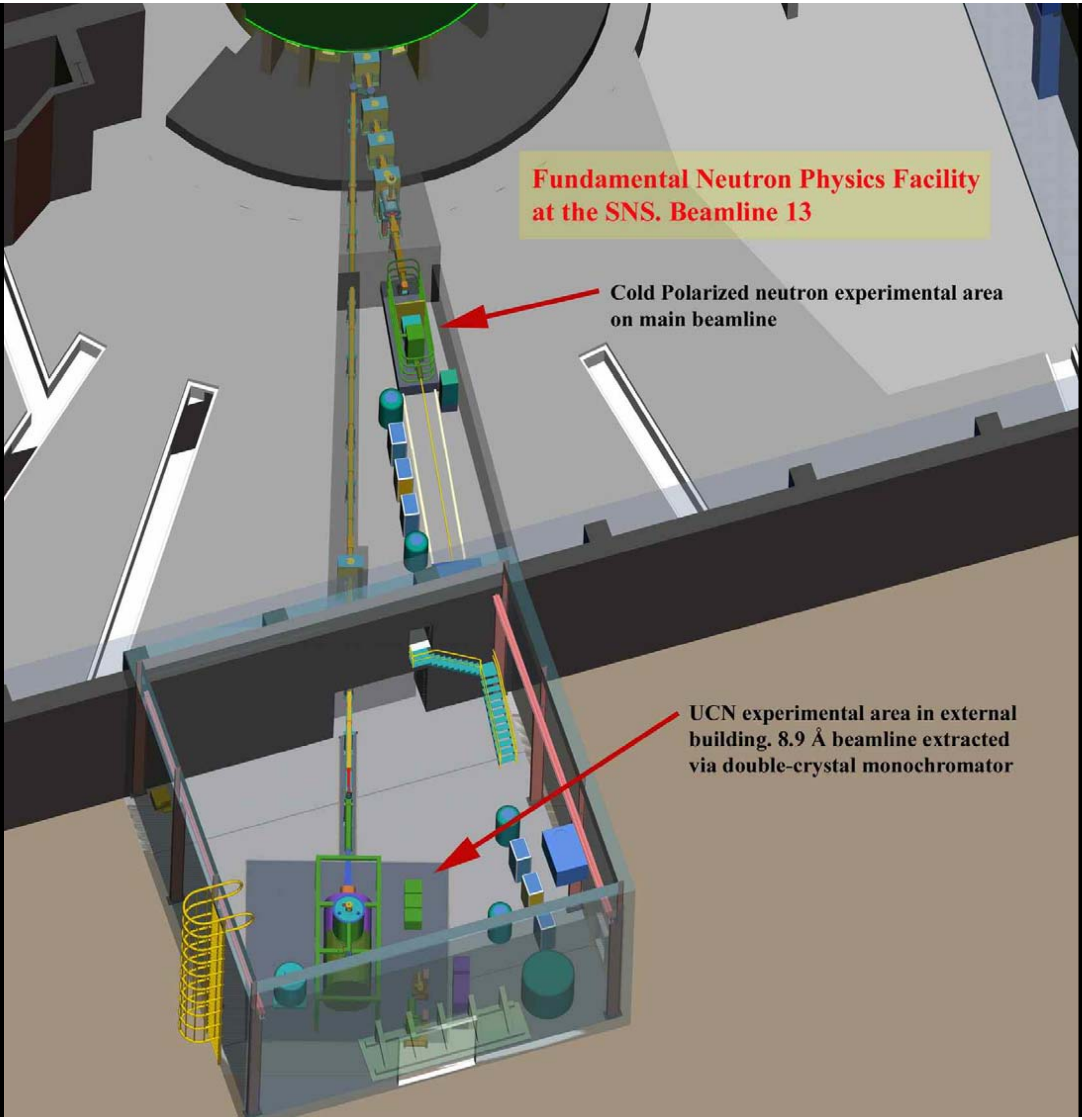
Neutron mirrors (“guides”) conduct the neutrons ~100 meters with small losses.

LANSCE Guide Hall



Spallation neutron sources are typically pulsed at frequencies of 10-60 Hz

Los Alamos NATIONAL LABORATORY


Fundamental Neutron Physics Facility
at the SNS. Beamline 13
Cold Polarized neutron experimental area
on main beamline
UCN experimental area in external
building. 8.9 Å beamline extracted
via double-crystal monochromator

Comparison of Source Brightness

Source Brightness[x10^{10}(n/cm^2/s/sr/Å)]

	time-averaged	**peak**
LANSCE **@80kW**	2.5	~1250
SNS **@1.4MW**	~70	~12000
NIST **@20MW**	~150	~150
ILL **@57MW**	~450	~450
HFIR **@80MW**	~450	~450

From G. Greene, UT/ORNL

Cold Neutron Beams@ SNS

Capture Flux:

The estimated density of neutrons in an SNS cold beam will be: $\rho \approx 10^4 n \cdot cm^{-3}$

Absolute Flux

The estimated flux of neutrons in an SNS cold beam will be: $d^2 / dAdt \approx 10^9 n \cdot cm^{-2} \cdot s^{-1}$

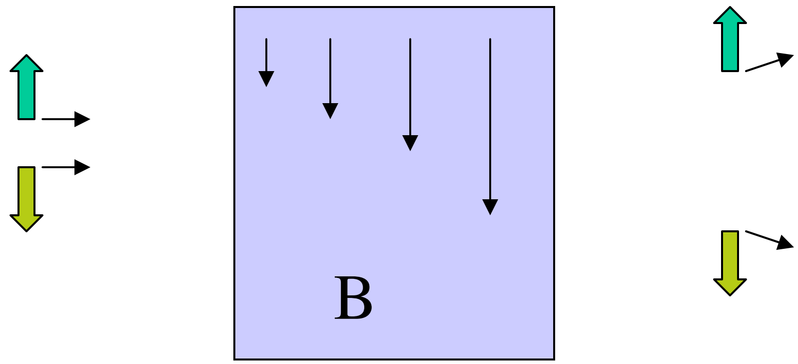
Fluence

The estimated fluence of neutrons in an SNS cold beam will be: $d^2 / dt \approx 10^{11} n \cdot s^{-1}$

How to Polarize Neutrons?

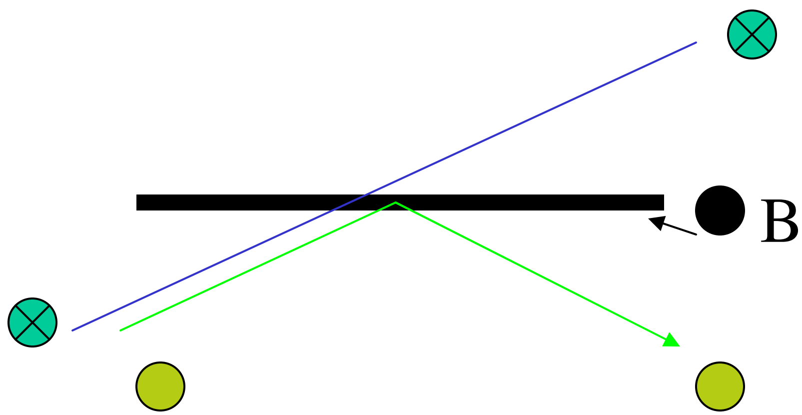
Force of nature	Does it depend on neutron spin?	How big is it?
Gravity	Yes if the other object has spin	Very, very small
Weak interaction (causes beta decay)	Yes, even if the other object has no spin	Only very small (=measurable)
Electromagnetism	Yes, due to magnetic moment in B	$\mu \bullet B$~300neV/T
Strong interaction	Yes	~100neV(varies with nucleus)

What methods have been used?



B gradients (Stern-Gerlach, sextupole magnets) electromagnetic

$F=(\mu\bullet\nabla)B$

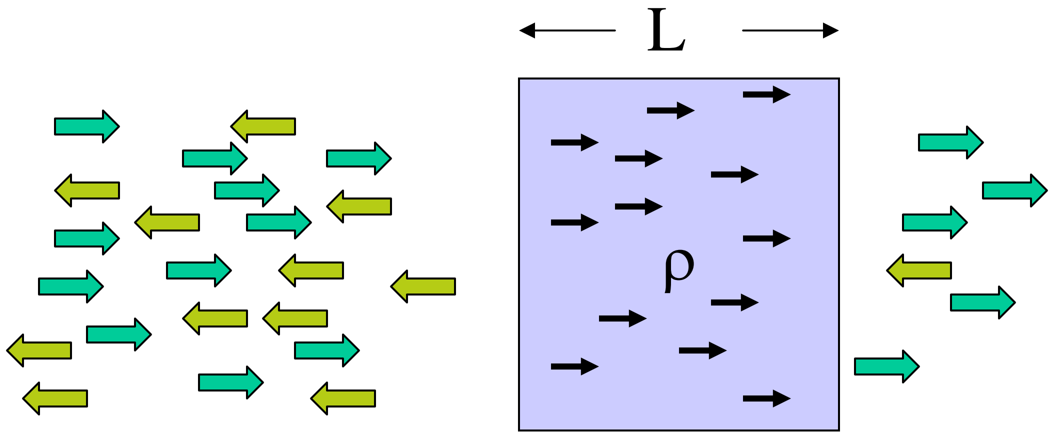


Reflection from magnetic mirror: electromagnetic+ strong

$f\pm=a(\text{strong}) \;\; +/- \;\; a(\text{EM})$

with $|a(\text{strong})|=|a(\text{EM})|$

$\Rightarrow f+=2a,\ f-=0$

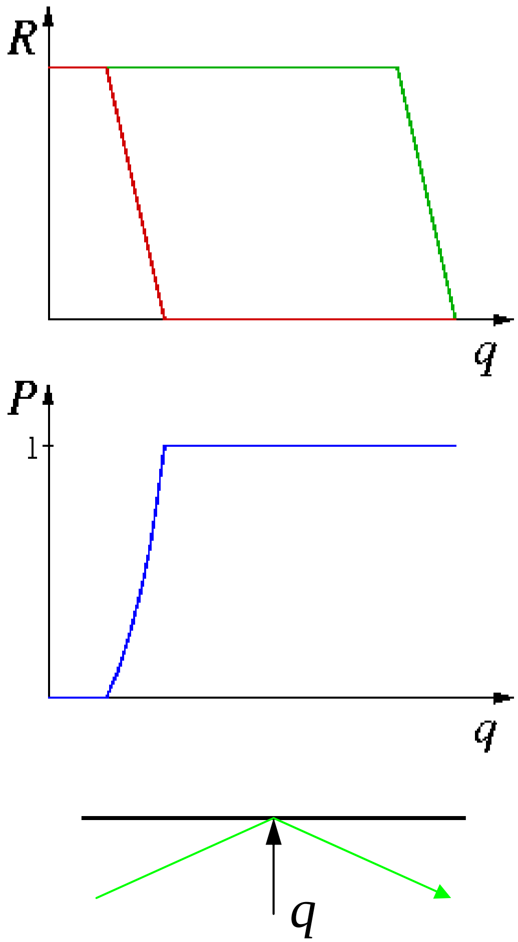


Transmission through polarized nuclei: strong

$\sigma+\neq\sigma- \Rightarrow T+ \neq T-$

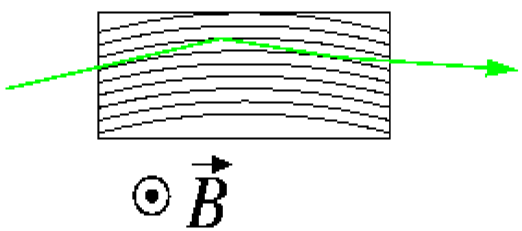
Spin Filter: $T_{\pm}=\exp[-\rho\sigma_{\pm}L]$

Polarisers for Neutrons: Super Mirrors



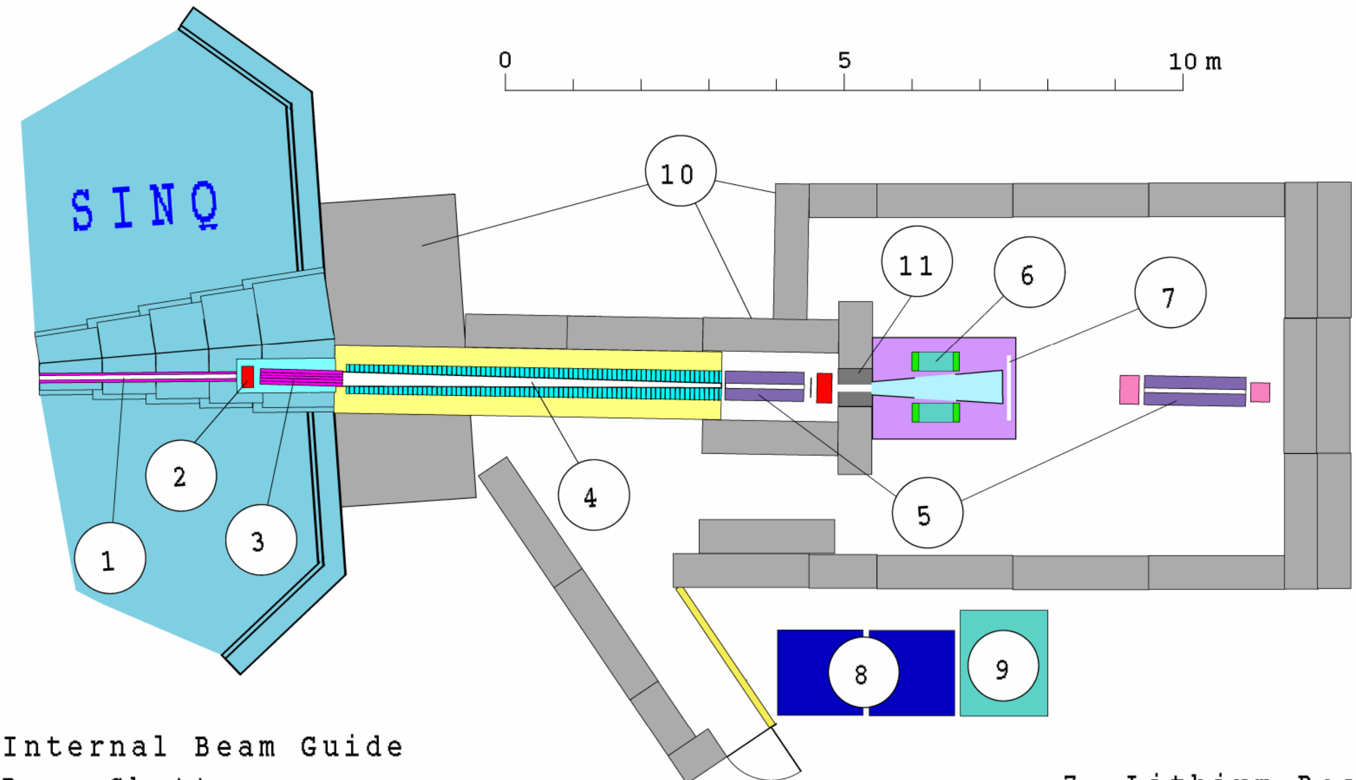
Magnetized mirror has large optical potential for one spin state**,** small for other spin state
-> spin states possess different critical angles for total reflection

To cover the whole beam the mirrors are stacked so that every neutron in the beam reflects once



Schärpf, *Physica B* **156/157** (1989) 639

FUNSPIN – Polarized Cold Neutron Facility at PSI



1. Internal Beam Guide
2. Beam Shutter
3. Polarizer
4. Focusing Guide
5. Spin Flippers
6. Neutron Decay Detection System
7. Lithium Beam Dump
8. Electronics
9. Gas System
10. Radiation Shields
11. Boron/Lithium Collimator

Figure 4: Layout of the Polarized Cold Neutron Facility at PSI.

FUNSPIN Polarized Cold Neutron Facility at PSI

Large momentum acceptance neutron beam guide

Super-mirrors:	450 Ni/Ti layers, $m \approx 3$
Flux density (unpolarized):	$\approx 10^9\,\mathrm{cm^{-2}s^{-1}mA^{-1}}$
Termal equivalent:	$\approx 3 \times 10^9\,\mathrm{cm^{-2}s^{-1}mA^{-1}}$
Total unpolarized:	$\approx 10^{11}\,\mathrm{s^{-1}mA^{-1}}$
Polarizer:	multi-slit, magn. super-mirrors
Focusing section:	$8 \times 15\,\mathrm{cm^2} \rightarrow 4 \times 15\,\mathrm{cm^2}$
Flux density (polarized):	$\approx 2 \times 10^8\,\mathrm{cm^{-2}s^{-1}mA^{-1}}$
Total polarized:	$\approx 1.2 \times 10^{10}\,\mathrm{s^{-1}mA^{-1}}$
Average polarization:	$> 97\%$
Spin guiding field:	permanent magnets
Equipment:	RF-spin flippers, beam chopper

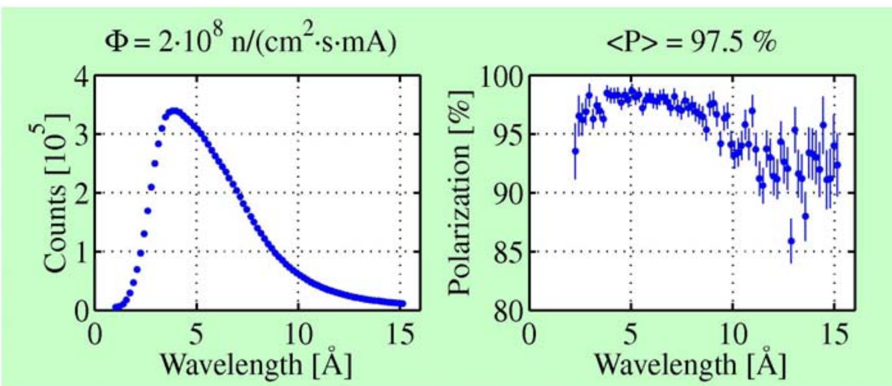


Figure 5: (a) Neutron wavelength spectrum measured using the TOF technique and a thin ^{3}He transmission detector. (b) Wavelength dependence of the beam polarization.

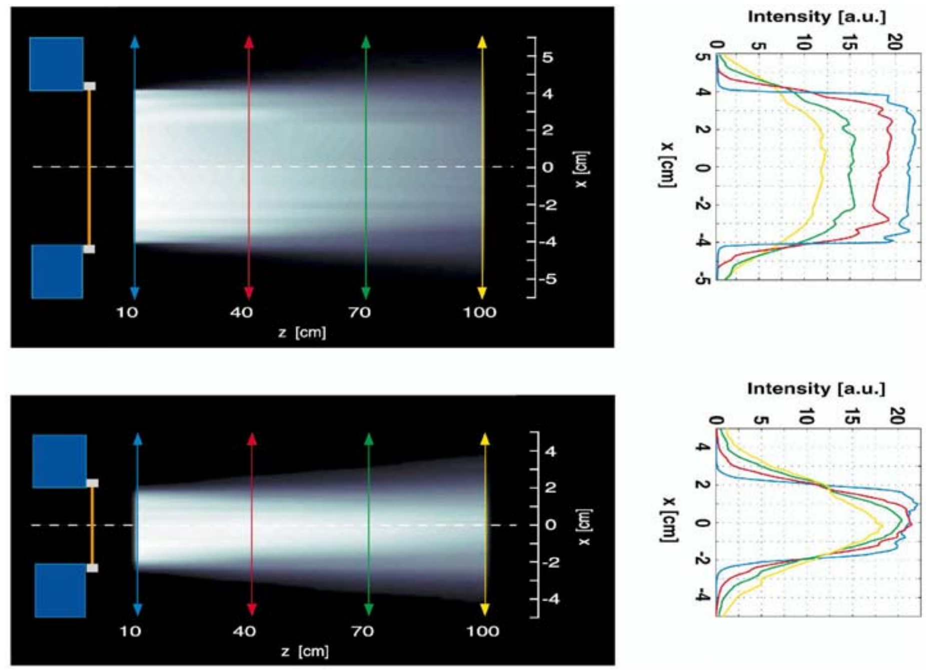
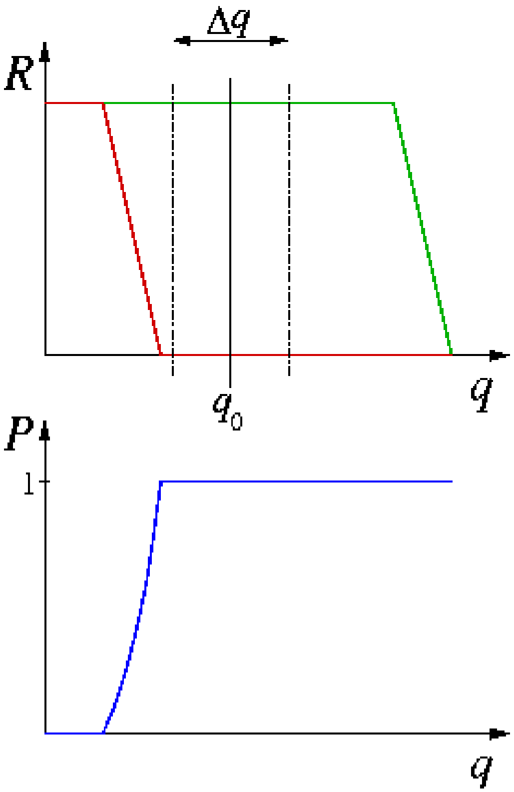


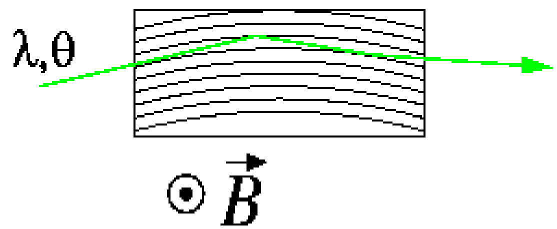
Figure 6: Beam profiles (right) and a representation of the beam intensity obtained by interpolation (left). Upper panel: unpolarized beam (SINQ insert). Lower panel: polarized beam (experimental position).

$P_{av} = (89.9 \pm 0.8)\ \%$

(over fiducial volume of the beam)

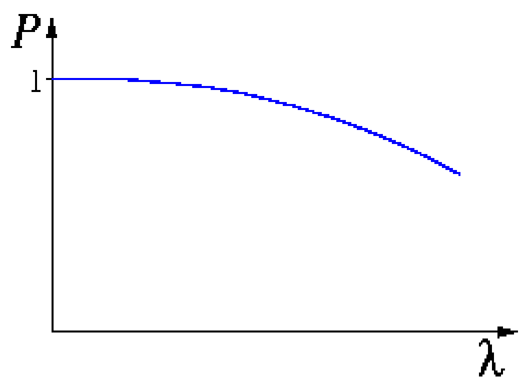
Problems with Supermirror Polarizers

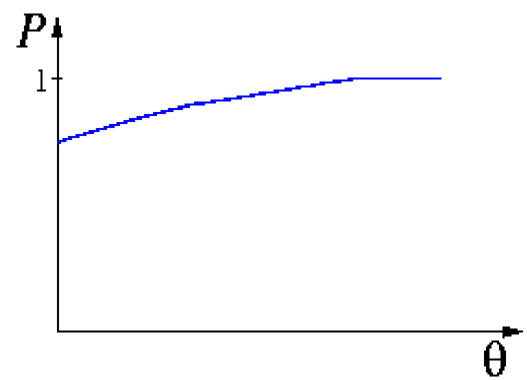




$$\Delta q = \Delta q(\lambda, \theta)$$

$$q_0 = q_0(\lambda, \theta)$$



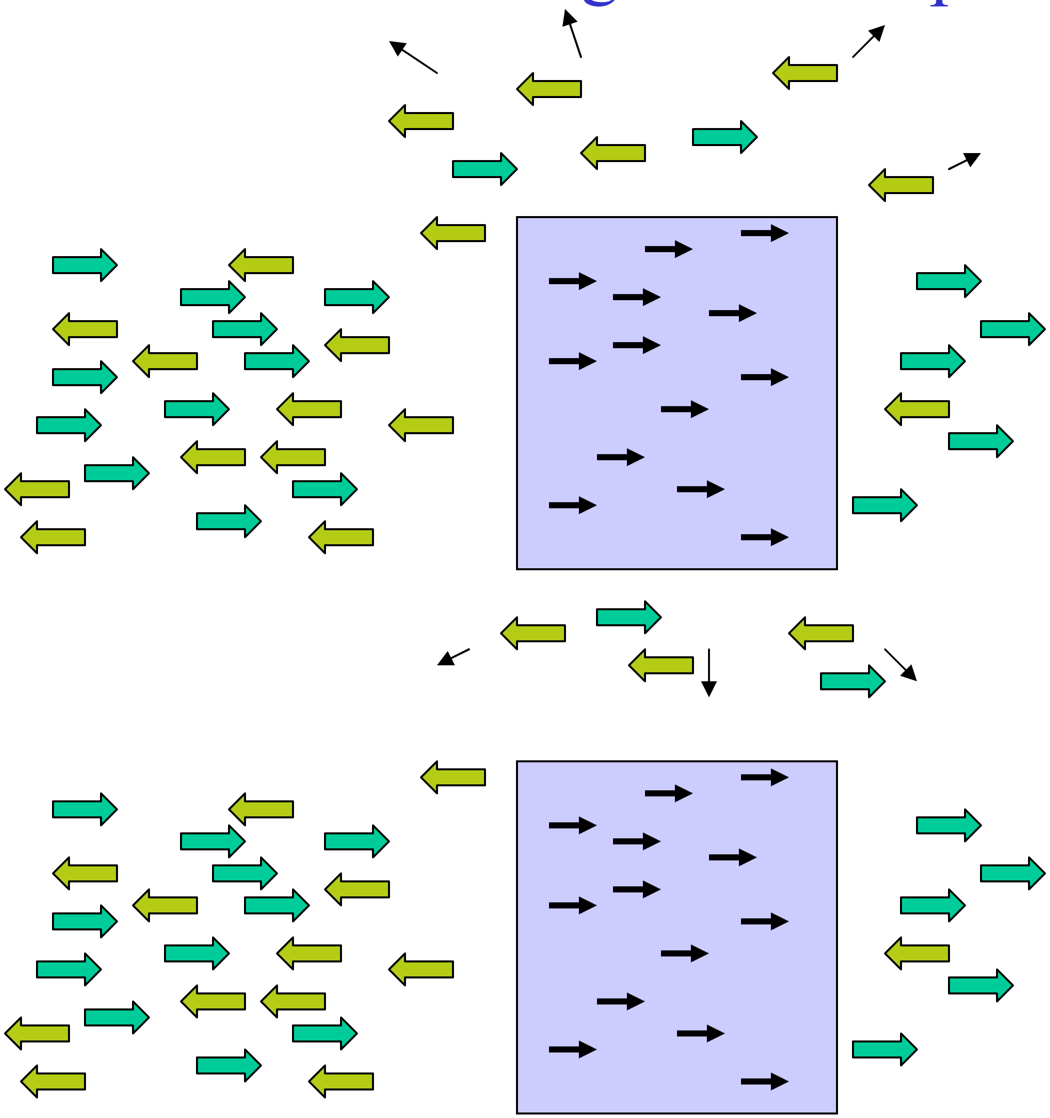


⇒Wavelength dependence

⇒Angular dependence

What Can Cause $\sigma_+ \neq \sigma_-$?

$\sigma_{total} = \sigma_{scattering} + \sigma_{absorption}$



Scattering: hard to get
$\sigma_{+scatter} >> \sigma_{-scatter}$
(Hydrogen is good)

Absorption: can be very large at resonance for one spin state
$\sigma_{+absorb} >> \sigma_{-absorb}$ easier

Reaction products:
(1) Gammas (almost all)
(2) Charged particles (^3He, ^6Li,…)

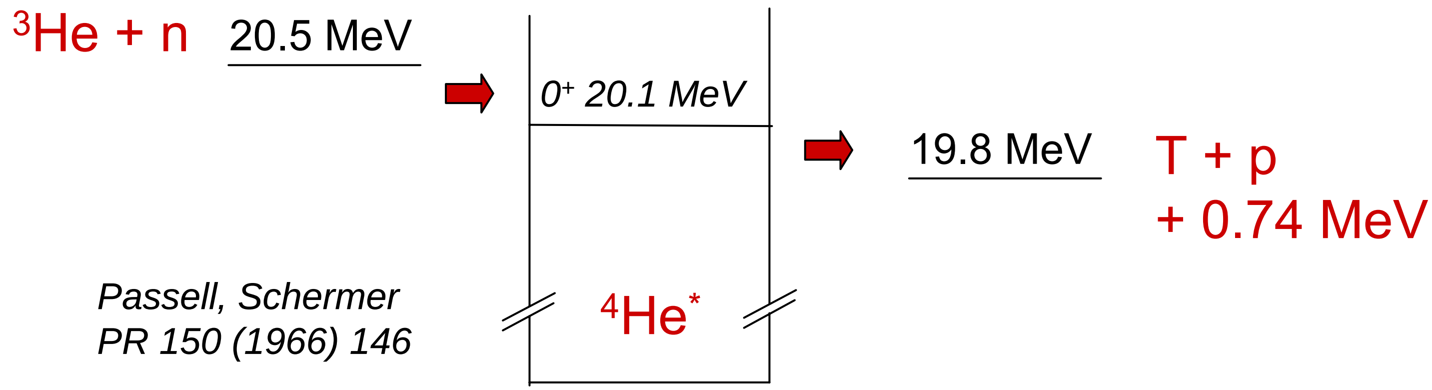
Properties of a perfect polarizer

Formula for $\sigma\pm$ for neutron(spin=1/2) + nucleus (spin=I, P_N):
$\sigma\pm=\sigma_0(1\pm\rho\ P_N)$, $\rho=\{-1$ for J=I-1/2…,I/(I+1) for J-I+1/2$\}$
$\Rightarrow$we want a J= I-1/2 resonance so that $\sigma_-=2\ \sigma_0$ and $\sigma_+=0$

Once we polarize the nucleus, we want it to stay polarized!
An object with I=1/2 cannot have a quadrupole moment (quantum mechanics)-> it does not feel tensor fields (electric field gradients,…). Closed electron shells are also good to isolate nucleus from the external world
$\Rightarrow$we want I=1/2, noble gas element

Final wish list: we want a noble gas element with an I=1/2 nucleus with large absorption resonance in J=0 channel and charged particles, not gammas, for reaction products

3He is Almost Perfect!



Noble gas

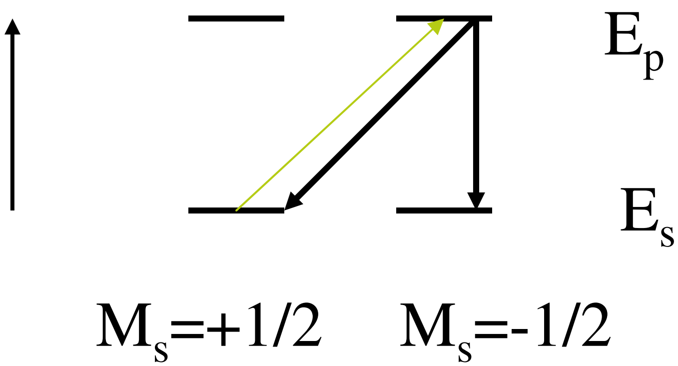
I=1/2

n+3He->4He*(J=0 resonance!)

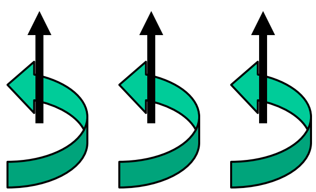
$\sigma_-=2\ \sigma_0=\sim$10,000 barns at 25 meV
$\sigma_{+,absorb}=\sim 0$
$\sigma_{+,scatter}$=few barns
σ_γ= few microbarns

Polarize by “Optical Pumping”

Atomic electron energy levels



Circularly polarized photons, S=1, on atomic resonance E_p- E_s



Finally: hyperfine interaction between electron and nucleus polarizes nucleus

One photon is absorbed

Only ΔM=±1 allowed

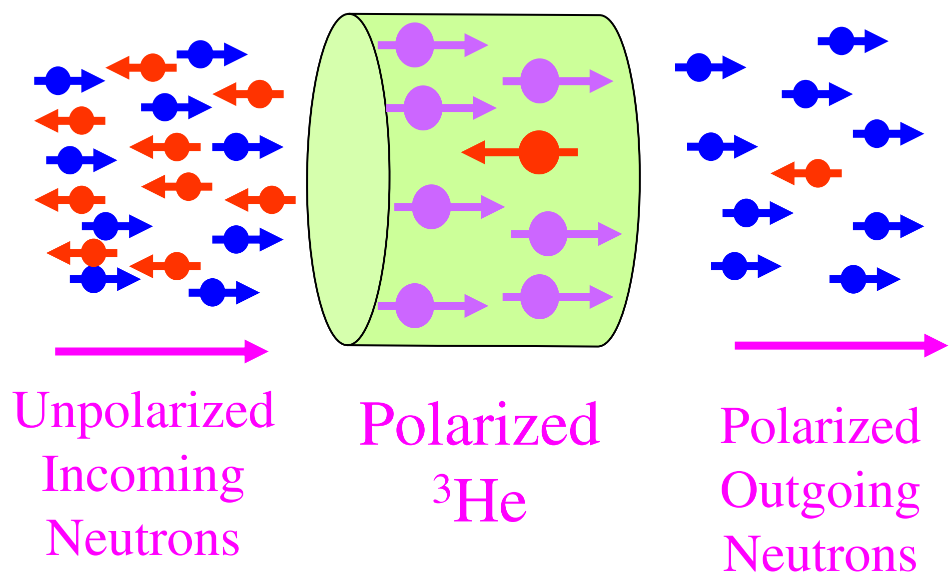
Atom in excited state can decay back to either ground state

Keep absorbing photon again and again, eventually all ground state atoms in M_s=-1/2 substate

-> electron is polarized!

Polarized ^{3}He as Neutron Spin Filter

- strongly spin-dependent neutron absorption cross section.

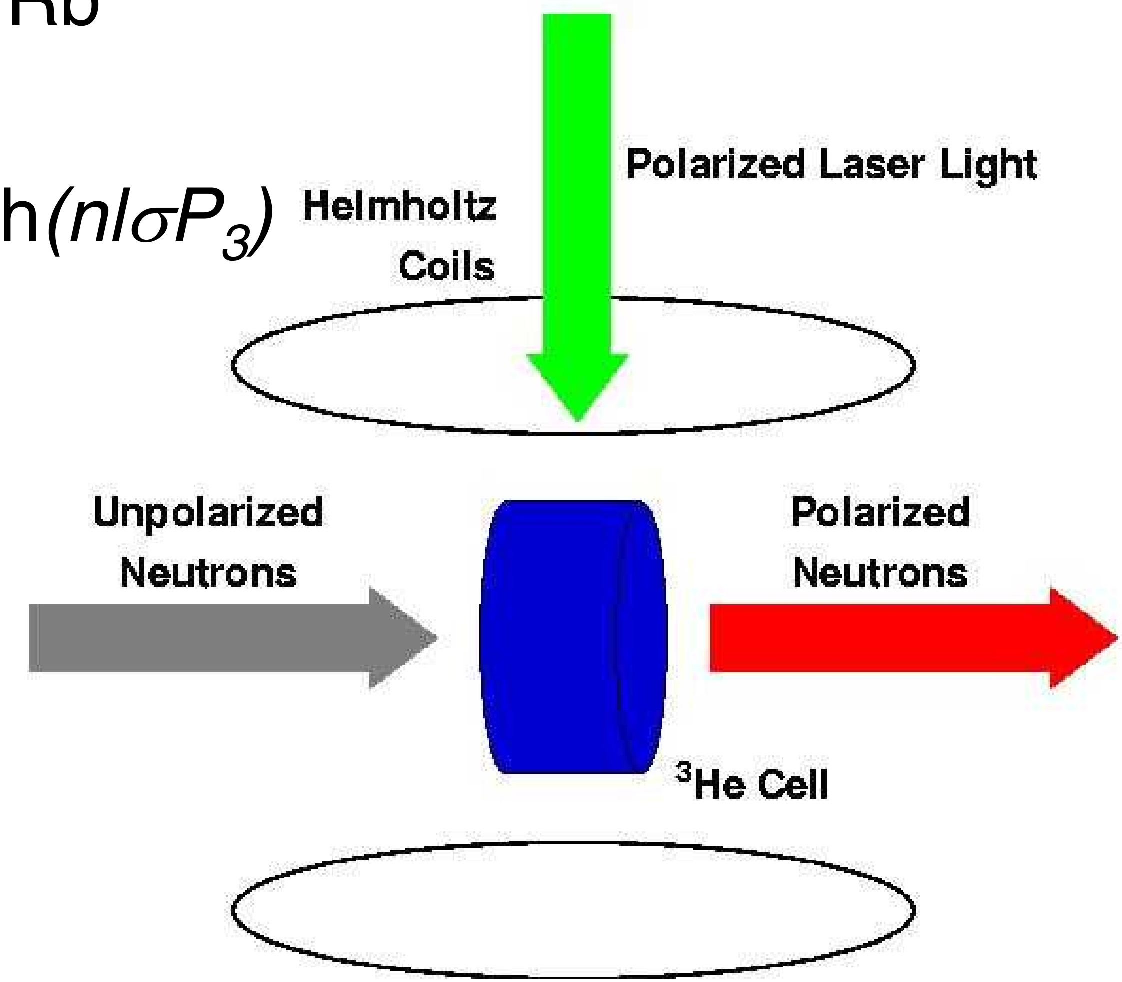


$$P_n = \frac{T^+ - T^-}{T^+ + T^-} = \tanh\left[\sigma(\lambda) N_{He} L P_{He}\right] = \sqrt{1 - \left(\frac{T_0}{T_n}\right)^2}$$

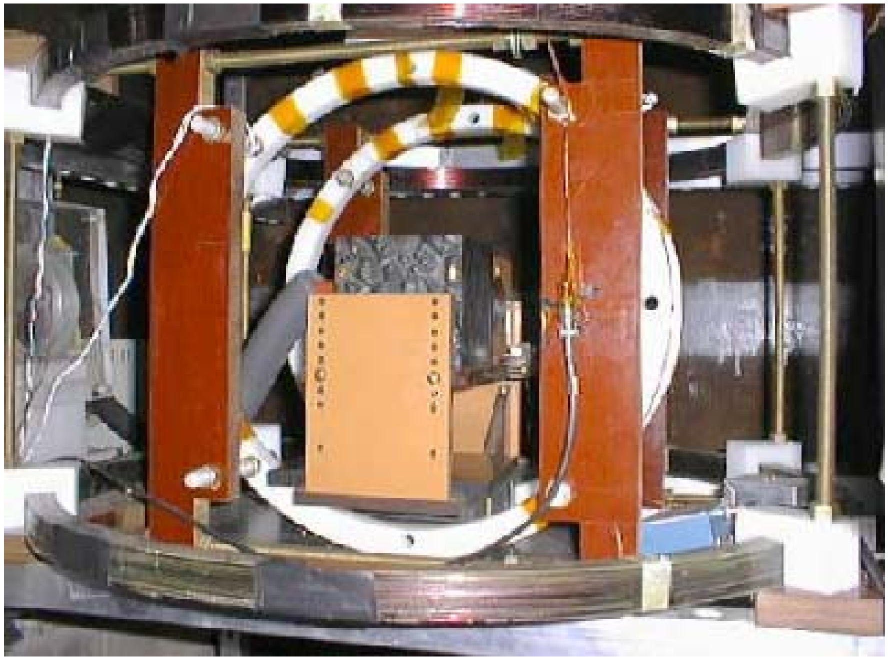
$$T_n = T_E \exp\left(-\sigma N_{He} L\right) \cosh\left(\sigma N_{He} L P_{He}\right)$$

Neutron Polarizer: Atomic Physics

- Polarized ^{3}He Neutron Spin Filter
  - Single cell Optical Pumping
    Spin Exchange w/ Rb
  - $P_n = \tanh(nl\sigma P_3)$
  - $t_n = t_0 \exp(-nl\sigma)\cosh(nl\sigma P_3)$



^{3}He Spin-Filter Setup

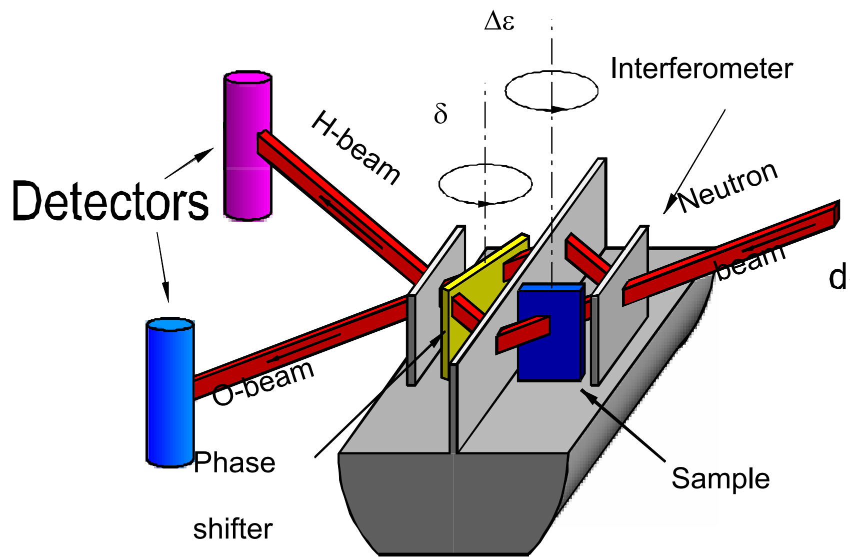


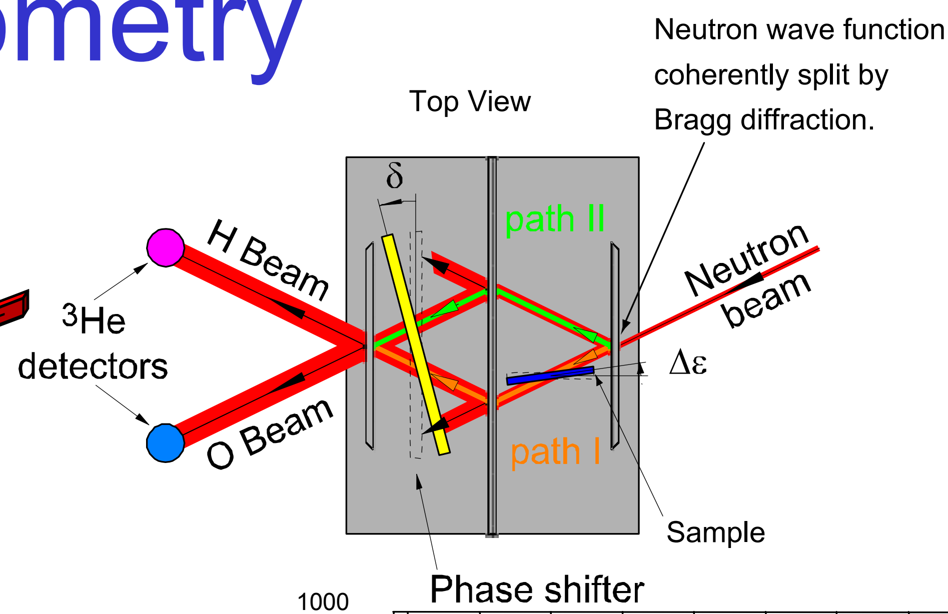
A 11-cm in diameter cell has T_1> 500 hr. ^{3}He polarization 65% has been measured.

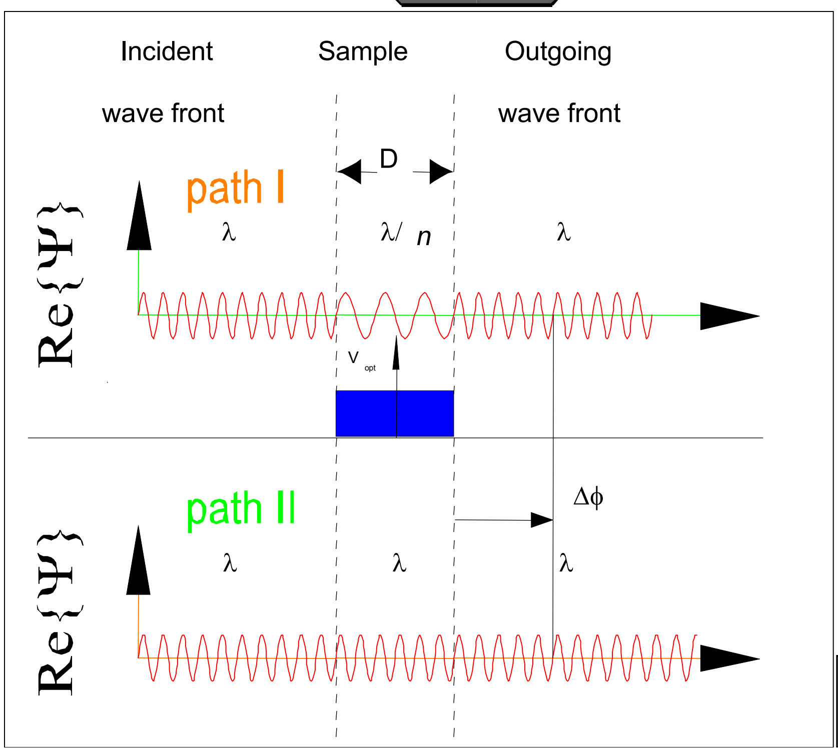
100 W light at 795 nm

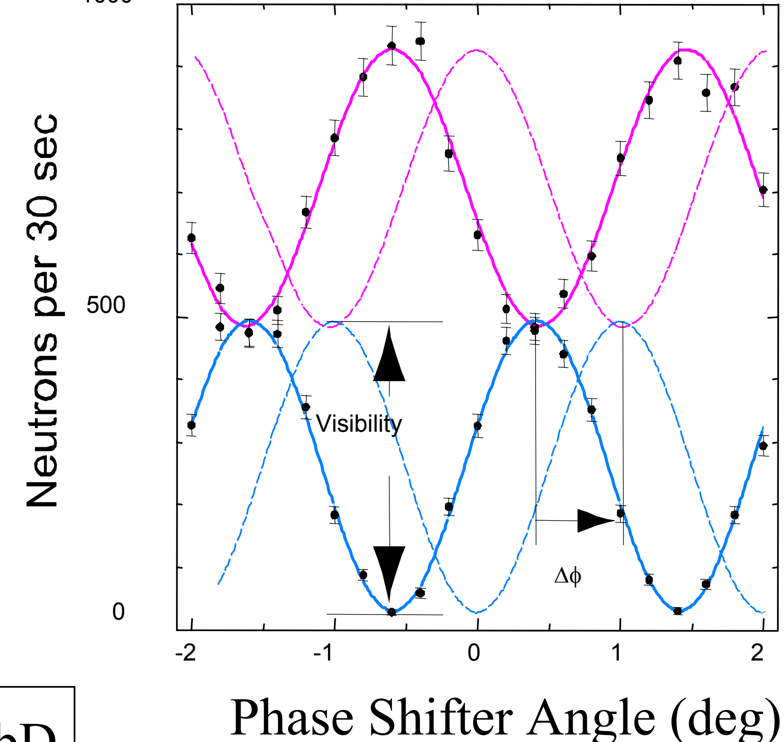
- Large area, 11 cm in dia, ^{3}He cells are required to cover the beam.
- ^{3}He spin filter allows a compact experimental setup.
- ^{3}He spin filter offers an extra spin flip without a change of the *B* field.

Neutron Interferometry





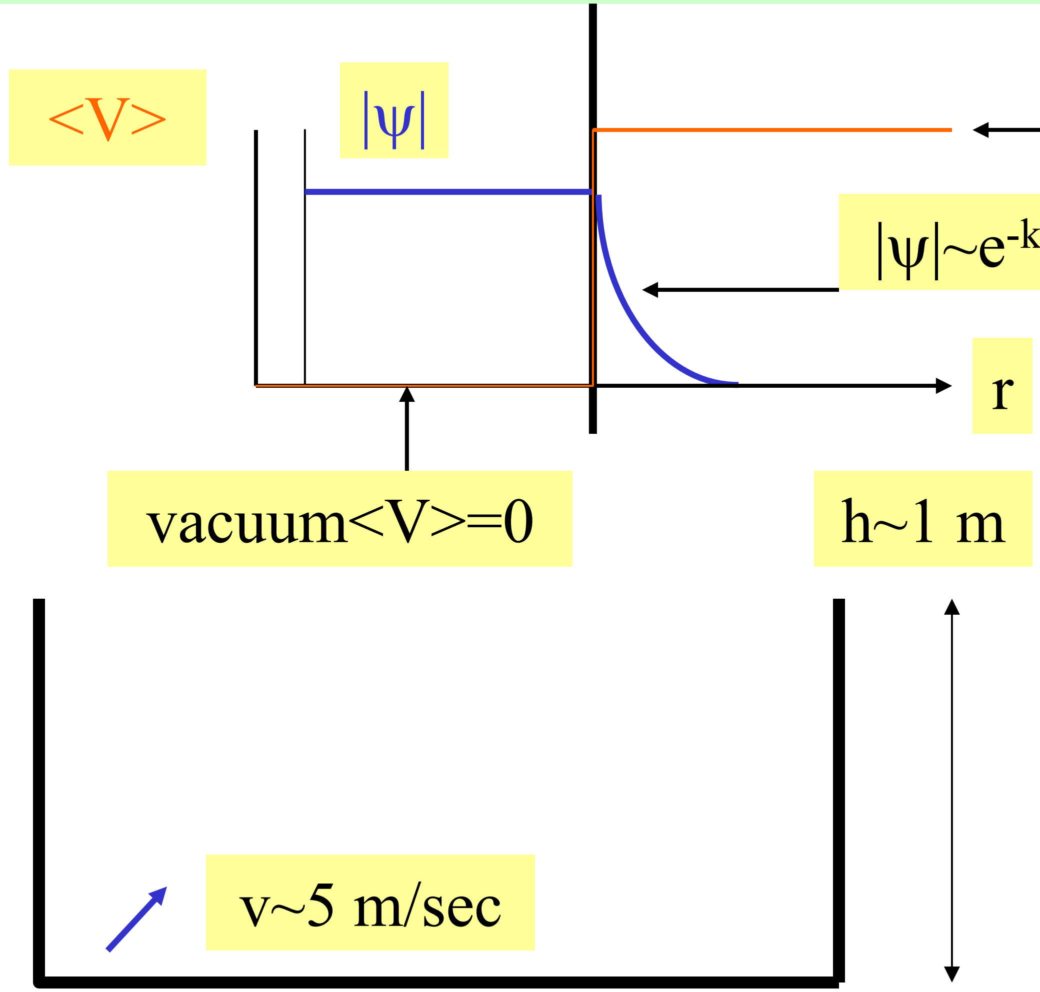




$$\Delta\phi = -\lambda NbD$$

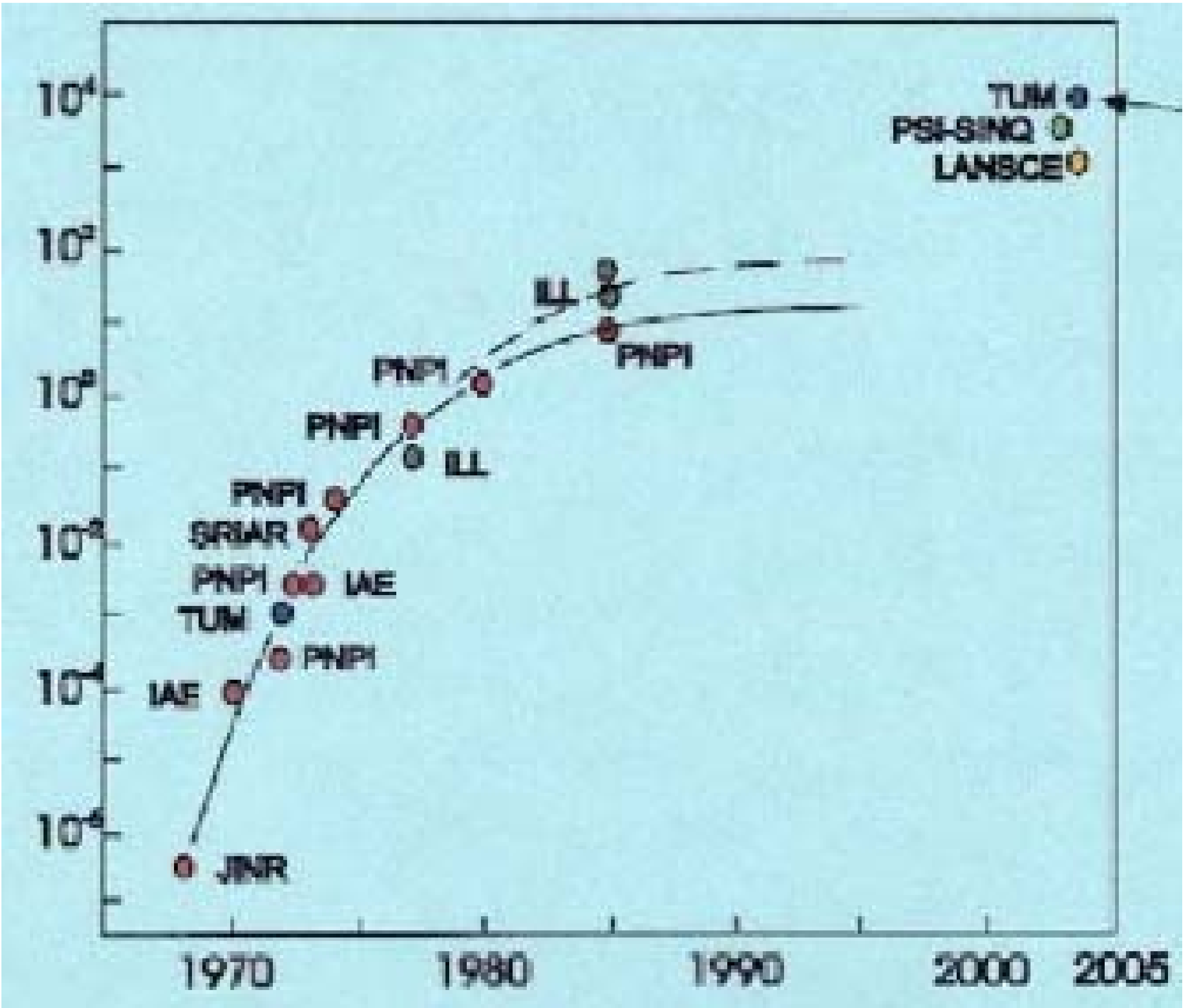
"Ultracold" Neutrons (UCN)

For very low energies (E_k-<V> negative, <V>~300 neV), matter forms a potential barrier for neutrons.



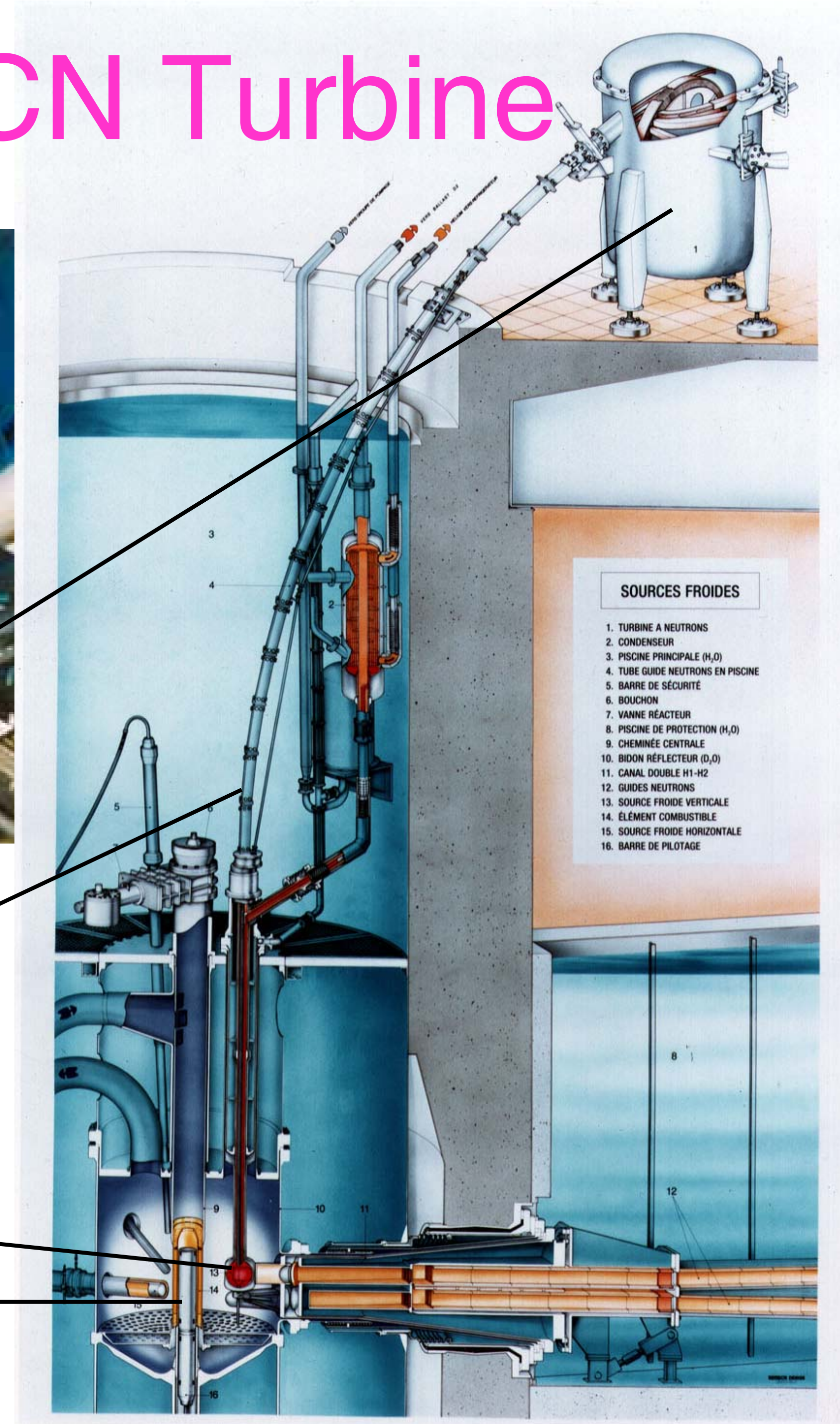
A neutron gas can be bottled (ρ~100/cc) using total external reflection. Due to gravity the bottle does not need a lid on top. Also B gradients can be used.

Overview of existing UCN Sources



- Neutron moderation
  - Tail of Maxwell-Boltzman distribution
  - Nucn = $10^{-13}\ \Phi_0$
- Conservative force
  - Gravity deceleration
  - Turbine deceleration
  - could not increase the phase space density.
- Superthermal source.

The ILL reactor UCN Turbine



UCN Neutron turbine
A. Steyerl (TUM - 1986)

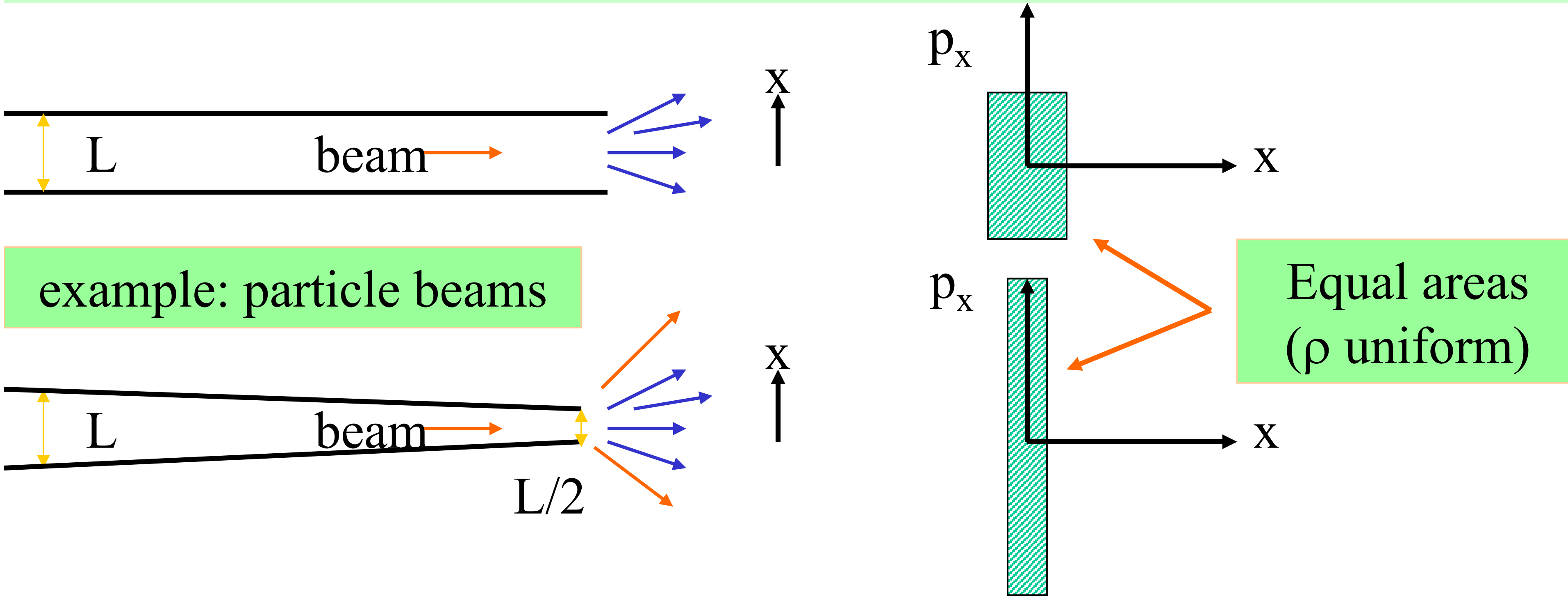
Vertical guide tube

Cold source

Reactor core

Making More UCN: Liouville's Theorem

Describe an ensemble of neutrons by a density in phase space: $\rho(r,p)d^3r d^3p$. L's theorem: phase space volume occupied by particles is constant if only "conservative" forces [=derivable from a potential] act



UCN gas in a bottle with d^3p filled $[0,p_{max}]$: $N(r)d^3r$ constant.
Need dissipative (non-conservative) interaction to increase $N(r)$

“Superthermal” UCN Sources

- **superfluid 4He:** highest densities, fed by 1 meV monochromatic neutrons using phonon cooling, need to extract UCN from 4He at <0.5K

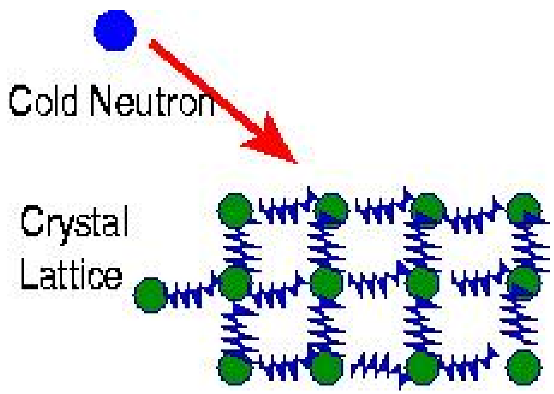
- **solid D2:** high currents, fed by ~4 meV neutron spectrum using phonon cooling, needs to be maintained in ortho state at ~5K

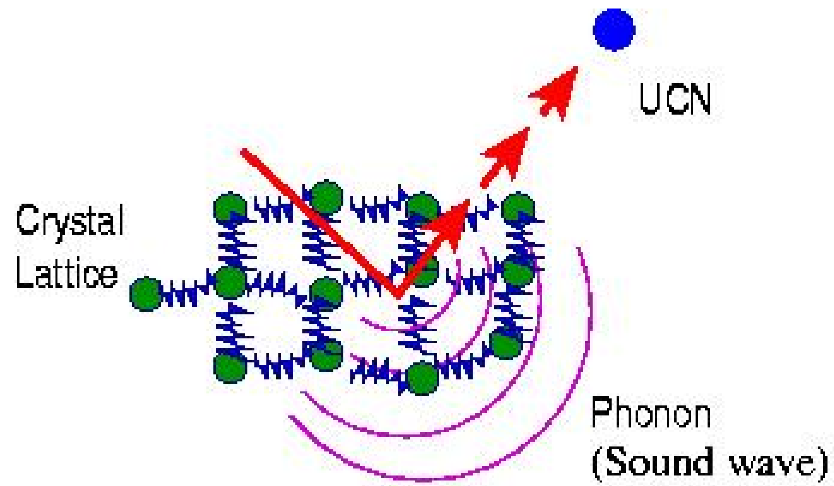
- **solid O2:** highest potential currents, fed by ~1 meV neutron spectrum by magnon cooling, needs to operate ~2K

Superthermal Process: Beats Liouville a Dissipative Process

R. Golub and J. M. Pendlebury, Phys. Lett, A**53**, 133 (1975)

- Cold neutrons downscatter in the solid, giving up almost all their energy, becoming UCN.

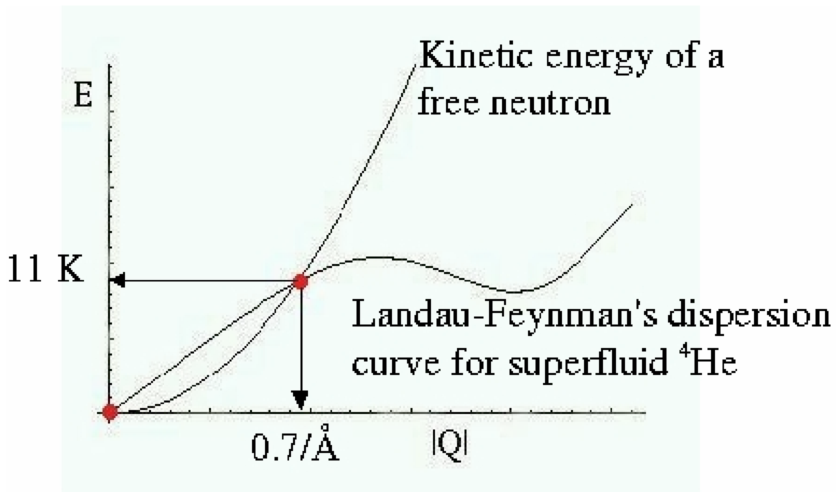




- UCN upscattering (the reverse process) is suppressed by controlling the moderator at low temperatures.

Liquid ^{4}HeII as a UCN Source

- Isotropic liquid ⇒ Single degenerate dispersion curve for HeII.



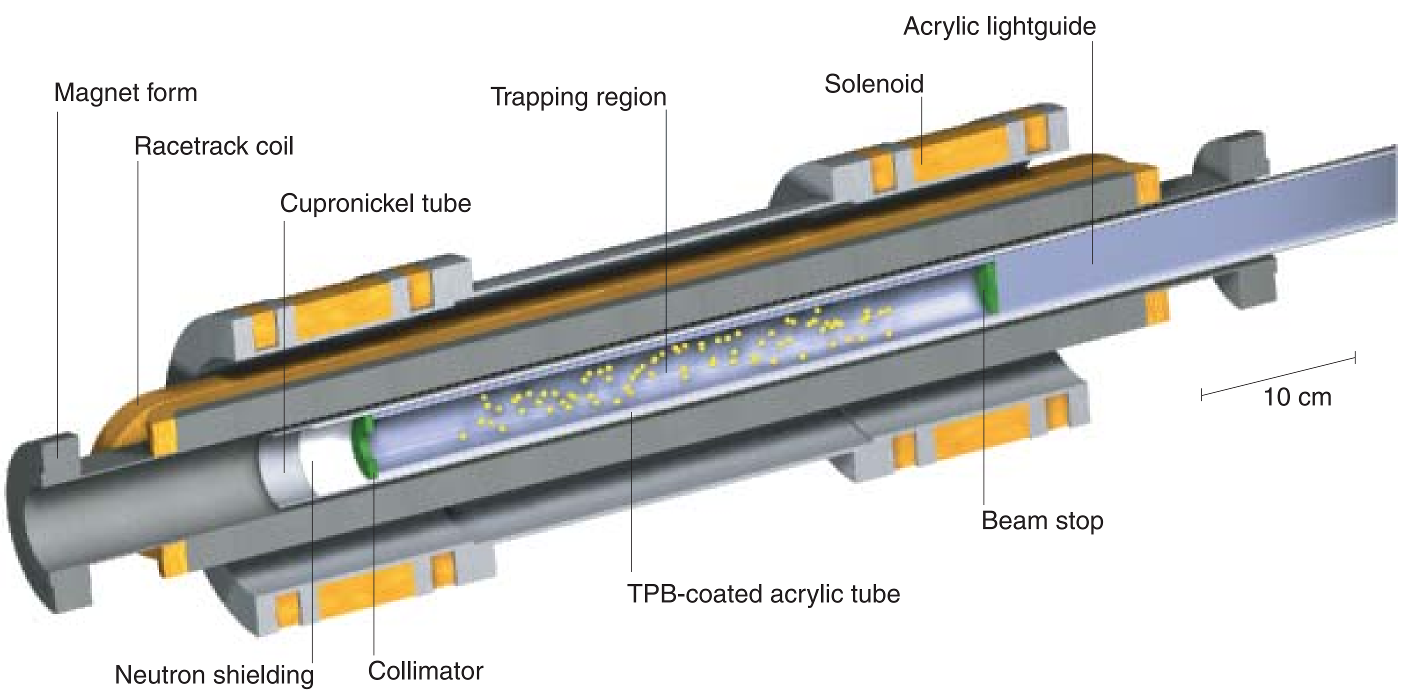
σ_{coh}= 1.34 barn
σ_{inc}= 0 barn

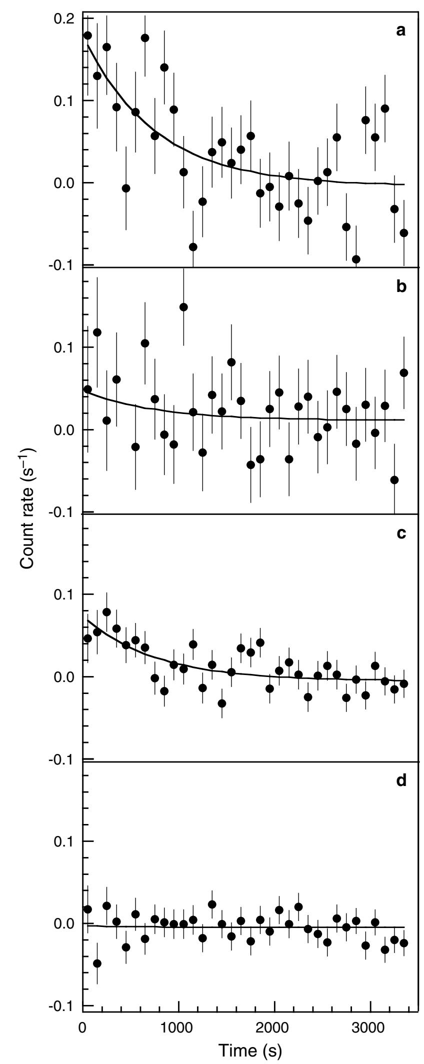
- Incident cold neutron with momentum of 0.7 A^{-1} (1 mev) can excite a phonon in ^{4}He and become an UCN
- No nuclear absorption loss for neutrons (σ_{abs} = 0).
- UCN can accumulate up to the β-decay time.
  – Produce a large steady-state density.

UCN Production in Superfluid ^{4}He

Magnetic Trapping of UCN

(Nature 403 (2000) 62)



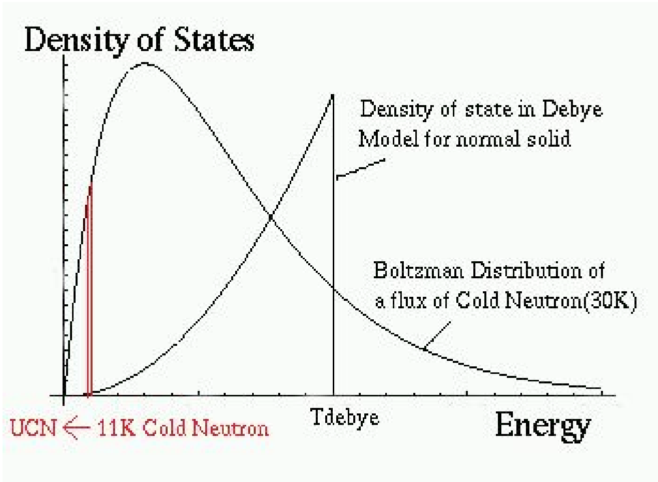


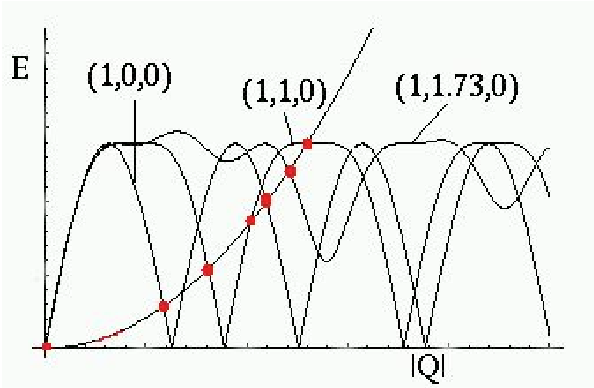
560 ± 160 UCNs trapped per cycle (observed)

480 ± 100 UCNs trapped per cycle (predicted)

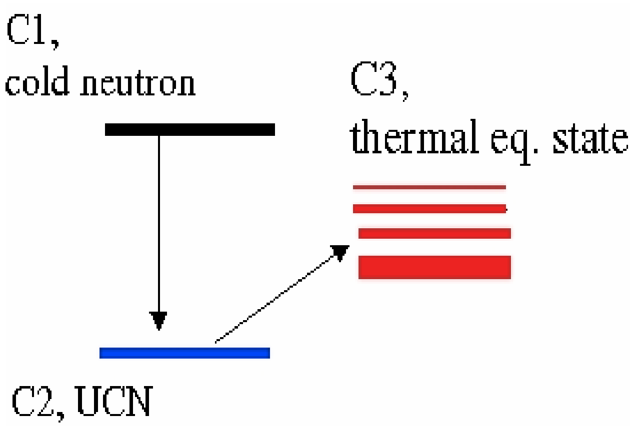
Solid Deuterium as a UCN Source

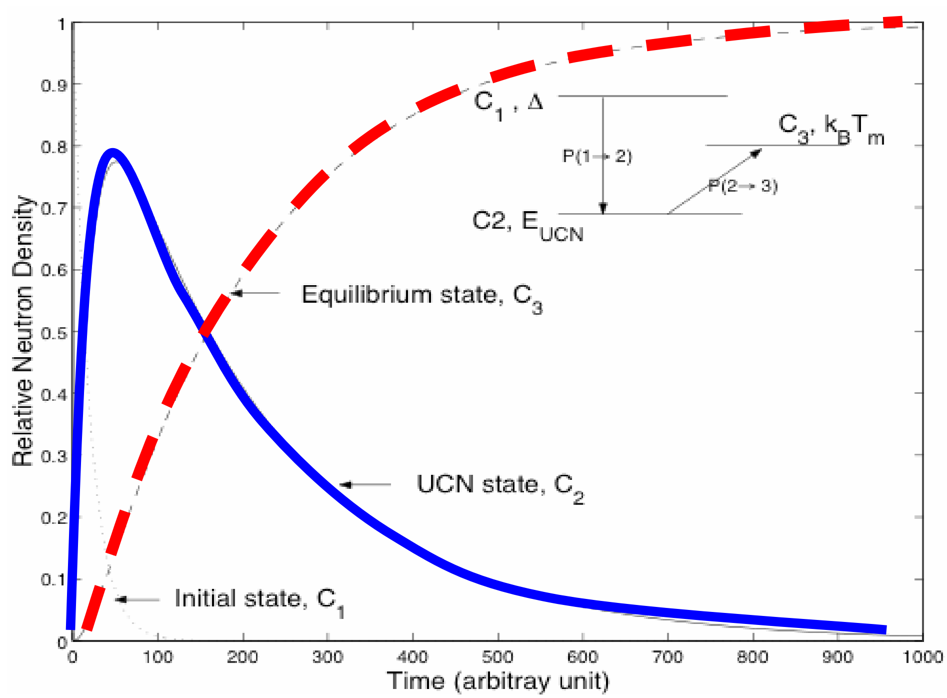
- σ_{inc} = 2.04 barn
  - Momentum is not conserved.
  - CN with energy smaller than the T_{debye} participate in the UCN production.
- σ_{coh} = 5.59 barn
  - The anisotropic dispersion curves broaden the inelastic scattering criteria for UCN production.
- More efficient use of cold neutrons.
  - Produce a large current(flux) of UCN.
- However, large UCN loss due to the nuclear absorption.





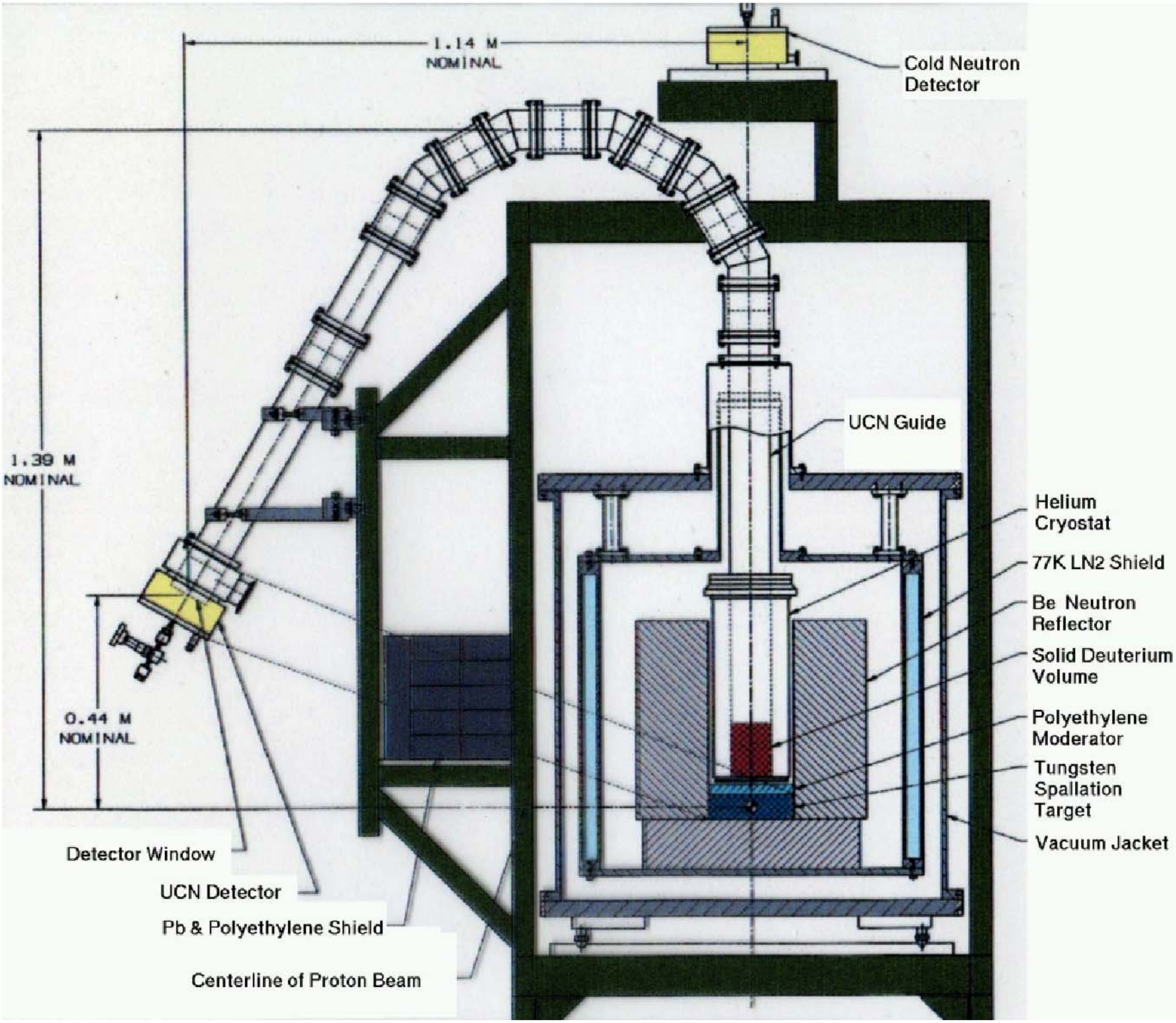
Dynamics of UCN Production





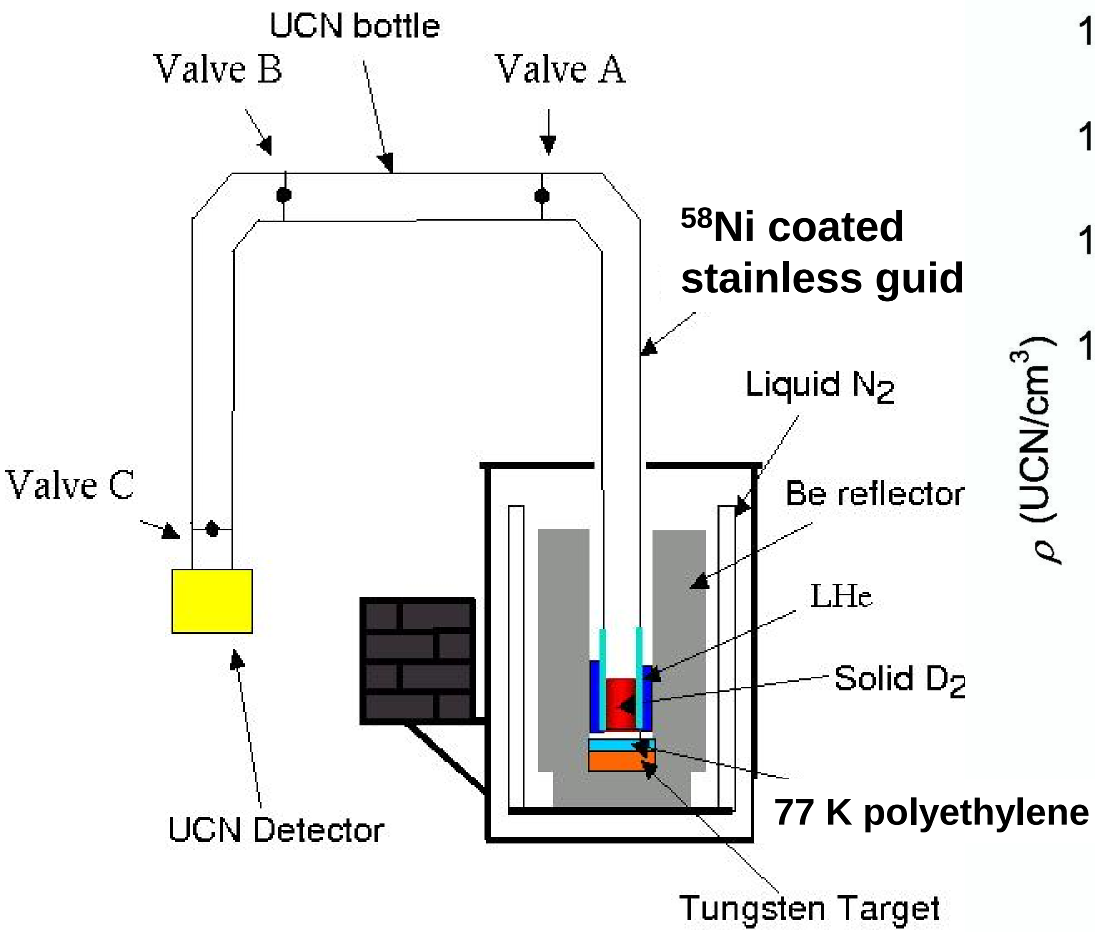
- Lifetime of UCN in the source material is a critical parameter in the establishment of large UCN densities.
- Extract UCN out of the source before it is thermalized ⇒ Spallation N source + Separation of the source and the storage + a UCN Valve

Solid Deuterium Source at LANL

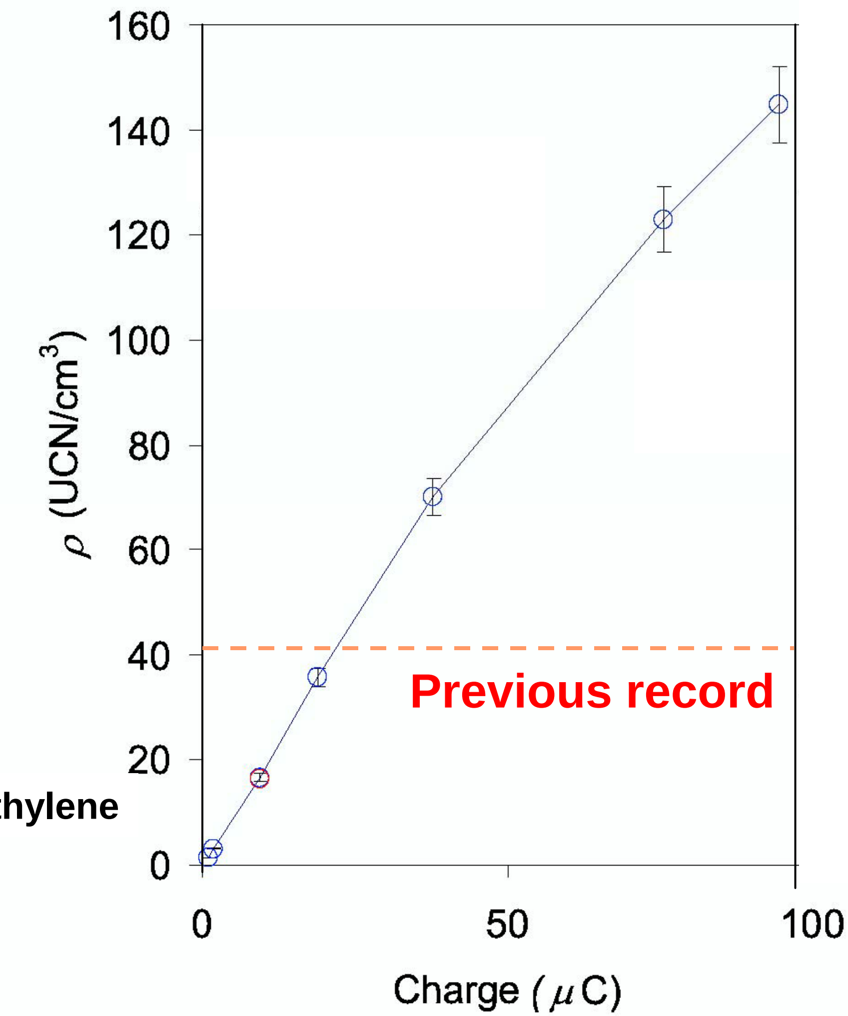


SD_2 UCN Source

Based on R.Golub and K.Böning Z.Phys.B51,95,(83)



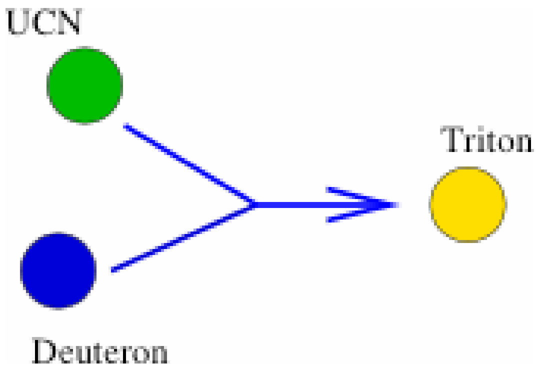
World record UCN density



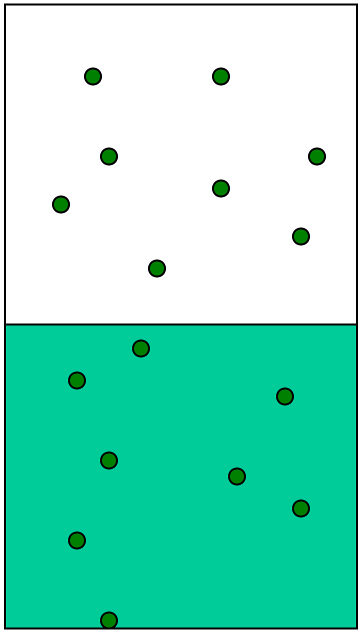
C.L.Morris *et al.* PRL **89**, 272501 (2002)

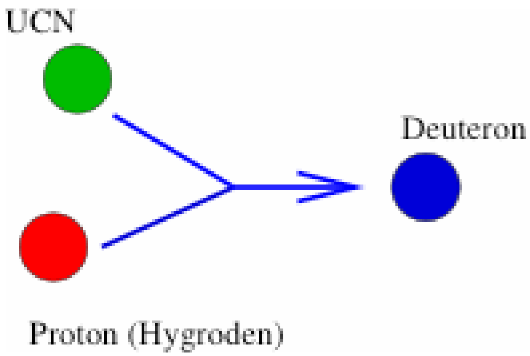
A. Saunders *et al.* nucl-ex/0312021

UCN Loss in Solid Deuterium

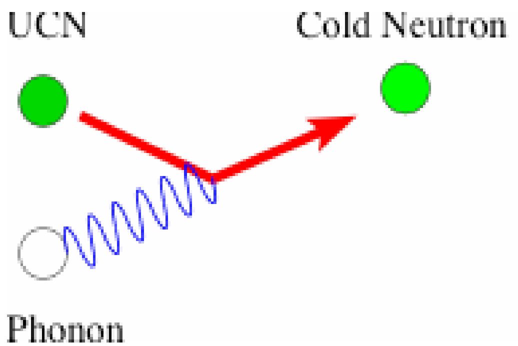


Nuclear absorption by S-D_2
τ ~ 150 msec

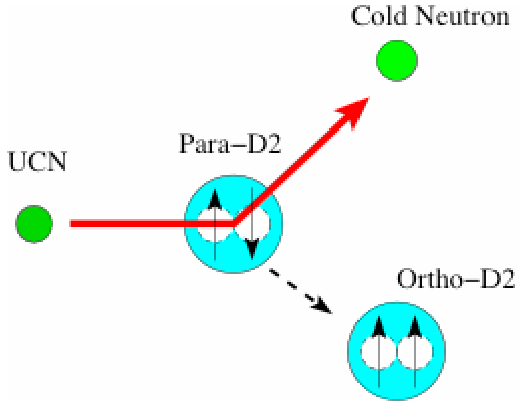




Nuclear absorption by Hydrogen Impurities, **τ ~ 150 msec/0.2% of H**

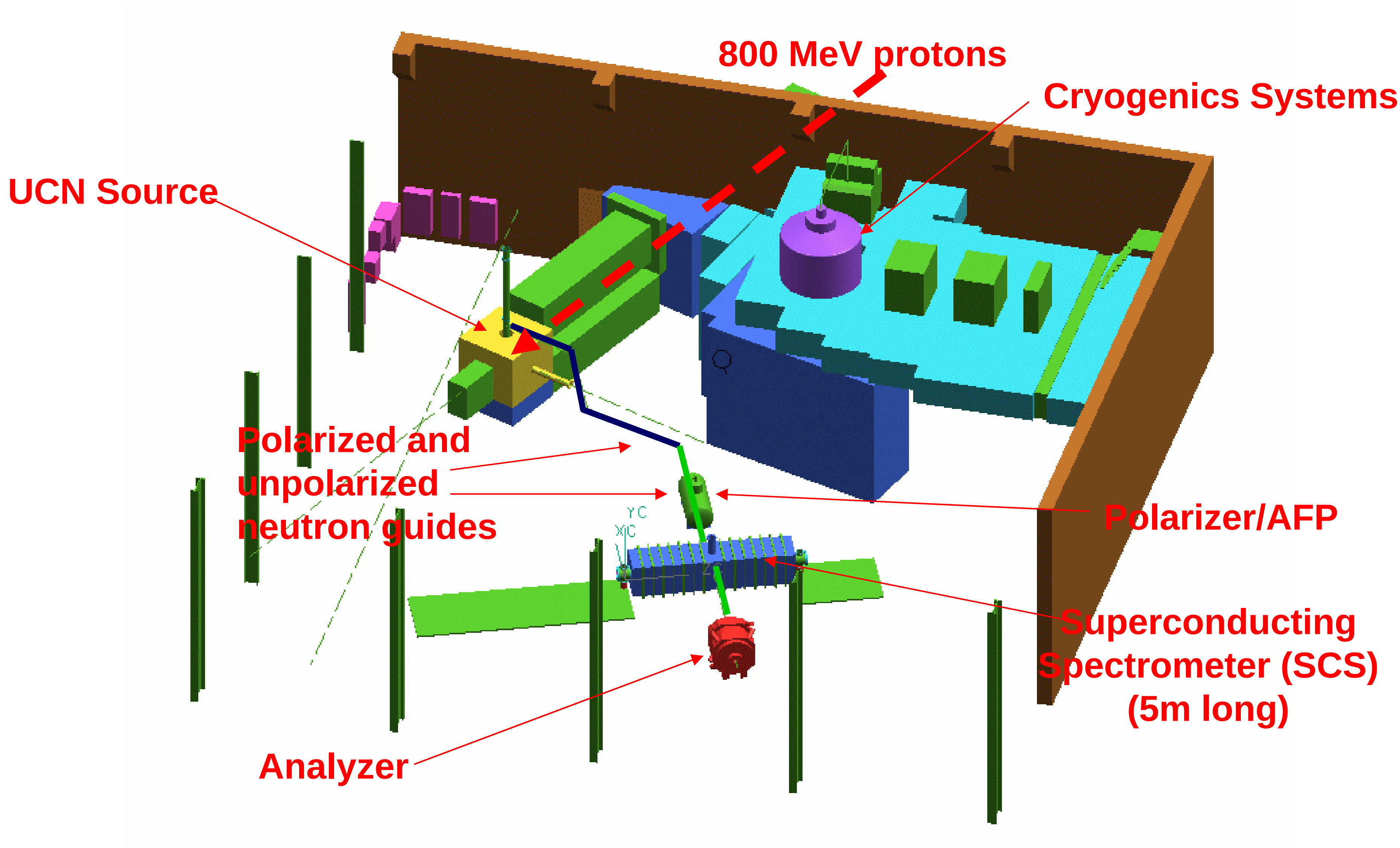


UCN upscattering by phonons
τ ~ 150 msec at T = 5K



UCN upscattering by para-D_2
τ ~ 150 msec/1% of para-D_2

Experiment Layout at LANSCE



Physics/Technology of Cold and Ultracold Neutrons

Uses techniques and concepts from atomic physics, condensed matter physics,low temperature physics, optics

Neutrons can be highly polarized, guided, and trapped

Energy range: ~100 neV to ~25 meV

CW and pulsed sources available