Neutron Sources
&
Neutron Optics

P. Courtois

Service for Neutron Optics
I.L.L.

Neutron Sources & Neutron Optics

- The neutron
- Production of Neutrons
- Neutron Transport – Mirrors & Neutron Guides
- Neutron Optics - Beam Shaping
    - Crystal Monochromators
    - Focusing Devices
    - Filters
    - Polarized Neutrons

NEUTRONS FOR SCIENCE®

The neutron

A particle and a wave...

Particle

- Mass m = 1.675 10^{-27} Kg

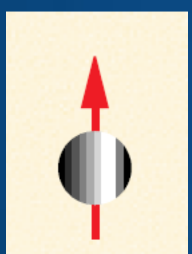
→ Kinetic Energy $E = \frac{1}{2} m v^2 \sim$ meV

- No Charge
- Spin = 1/2
- Magnetic moment $m = -1.913\ \mu_N$
- Beta life time 886 s

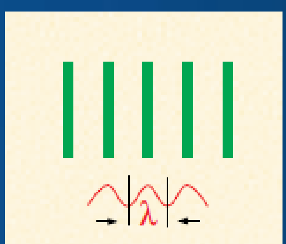
Wave

- Wavelength $\lambda = h/mv \sim$ Å
- Wave vector $k = 2\pi/\lambda$
- Moment $p = \hbar k$
- Energy $E = \hbar^2 k^2/2m$

$$E(\text{meV}) = 81.81 / \lambda^2$$

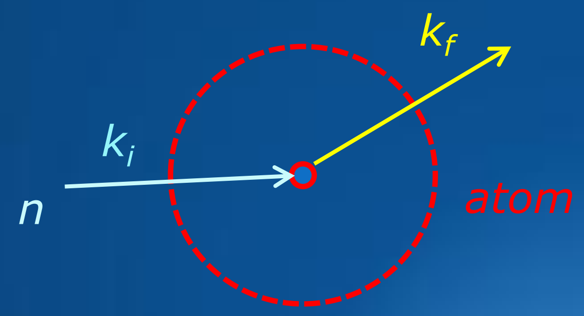


neutrons	E(meV)	λ (Å)
Hot	900-80	0.3 – 1
Thermal	80-5	1 – 4
cold	5-0.03	4 - 50

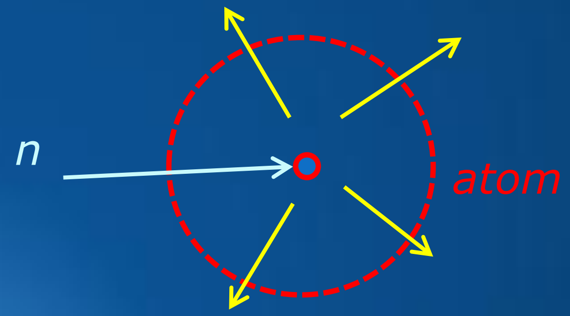


The neutron

- **Interaction with the individual nuclei via short range forces**
  - **Neutron Scattering**
    - Coherent scattering length $\mathbf{b_{coh}}$ (depends on the direction of scattering vector Q = k_i-k_f) → *diffraction, reflection, refraction*
    - Incoherent scattering length $\mathbf{b_{inc}}$ (uniform scattering)



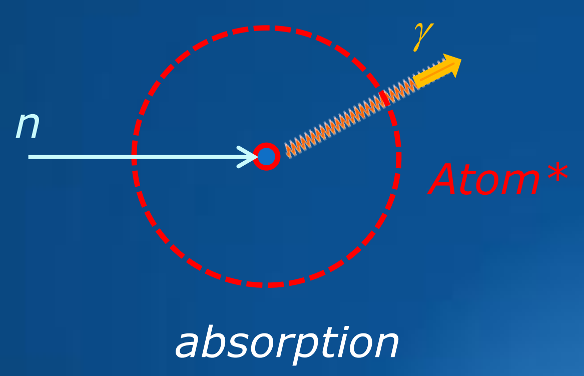
Coherent scattering

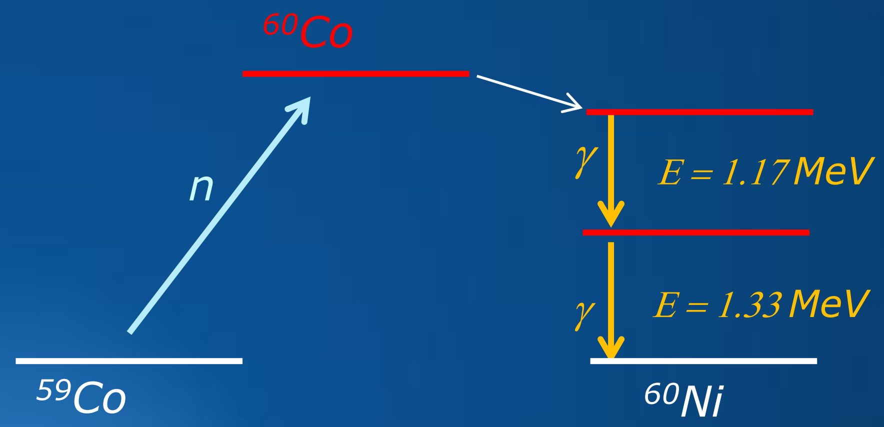


Incoherent scattering

The neutron

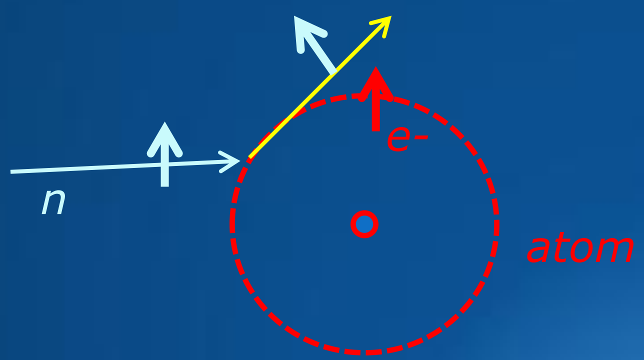
- **Interaction with the individual nuclei via short range forces**
  - **Neutron capture**
    - Absorption cross section : σ_{abs} (~10^{-24} cm^2)
    - Emission of gamma rays (→ radioprotection - shielding)



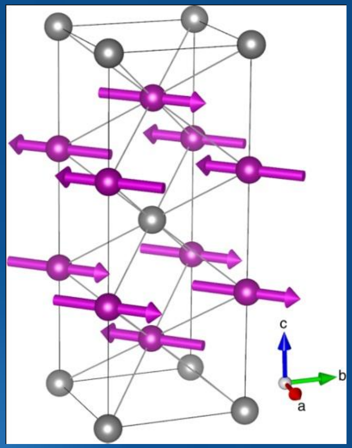


The neutron

- **Interaction with unpaired electrons via a dipole interaction**
  - **Magnetic scattering**
    - Magnetic scattering length $p \approx 0.269\ \mu_{at}\ (10^{-12}\ \text{cm}/\mu_B)$
    - $p \sim b_{coh}$ → *magnetic structures, polarized neutron beams*



Magnetic scattering



Scattering lengths and absorption cross sections of a few elements...

element	b_{coh} (10^{-12}cm)	b_{inc} (10^{-12}cm)	σ_{abs} (10^{-24}cm^2)	
H	-3.74	25.2	0.33	*Background*
D	6.67	4.04	0.0005	*Moderator*
B Gd Cd	-	-	767 48890 2520	*Neutron absorber*
C	6.64	~ 0	0.0035	*Optics*
Ni	10.3	0.64	4.49	
Si	4.14	0.015	0.17	
Cu	7.72	0.20	3.78	

Neutron Sources

Continuous Source
Pulsed Source

Production of Neutrons
fission = continuous source

Fission	***$^{235}U + n$ (meV) → F.P. + 2 or 3n (MeV)***

- *Slow neutrons absorbed by ^{235}U → ~ 2 or 3 fast neutrons per fission*

- *Fast neutrons (~ MeV) are slowed down to meV Energy by collisions in a thermal bath (liquid D_2O) => 1 n sustains the reaction and 1n available*

→ *Production of thermal neutrons* following a Maxwellian distribution at T = 300 K, i.e. $\langle E \rangle = k_b T$ = *25 meV → <v> ~ 2200 m/s*

→ *Neutron Flux 10^{14} –10^{15} n/cm^2/s - I.L.L. Flux = 1.5 10^{15} n/cm^2/s*

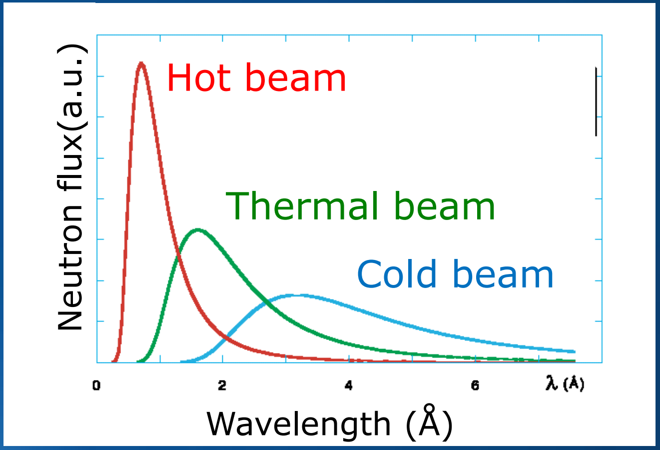
Neutron Sources
Moderators

Neutrons must be moderated to give optimized flux distributions

→ Neutrons follow a Maxwell-Boltzmann distribution with <E> = k_bT

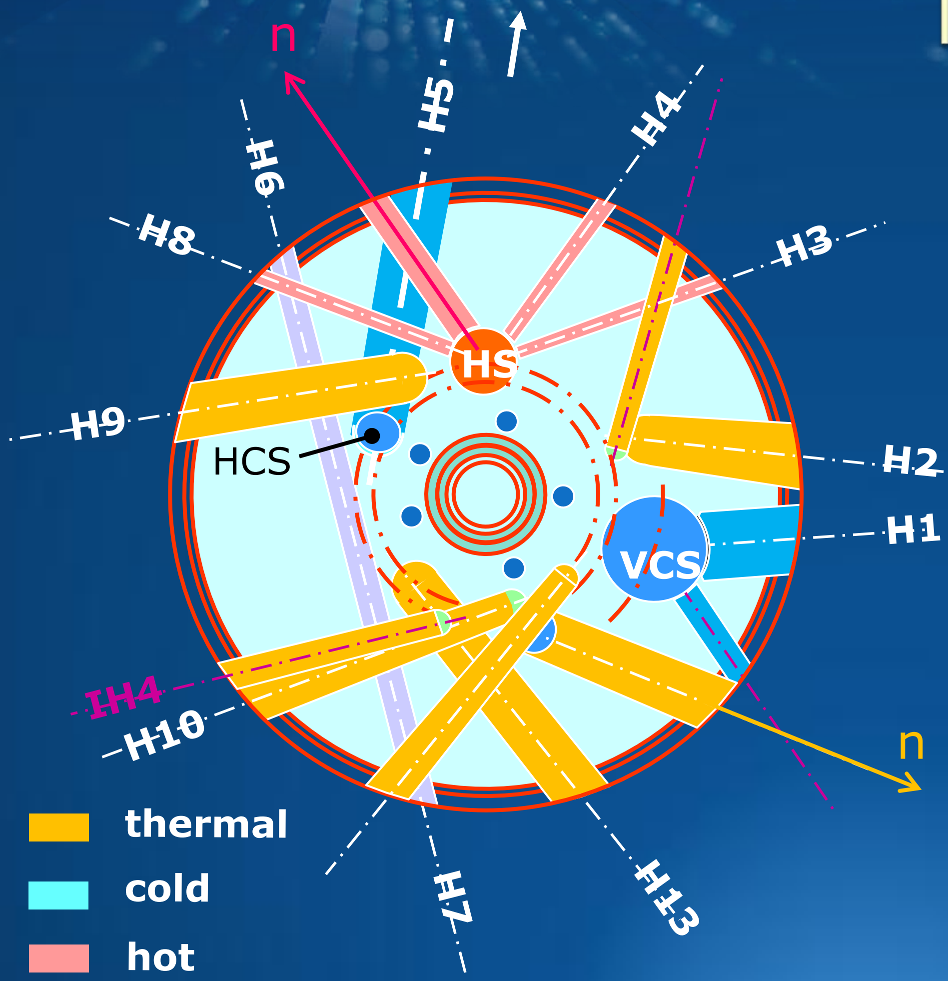
- Cold sources are usually liquid nitrogen at T = 20 K
- Thermal Source is liquid D_2O at room temperature T = 300 K
- Hot source is graphite at T = 2000 K (heated by radiation)

	cold	thermal	Hot
moderator	liquid D_2	D_2O	graphite
moderator temperature	20 K	300K	2000K
neutron wavelength	4 →20 Å	1→ 4Å	0.3 →1Å



Neutron Sources

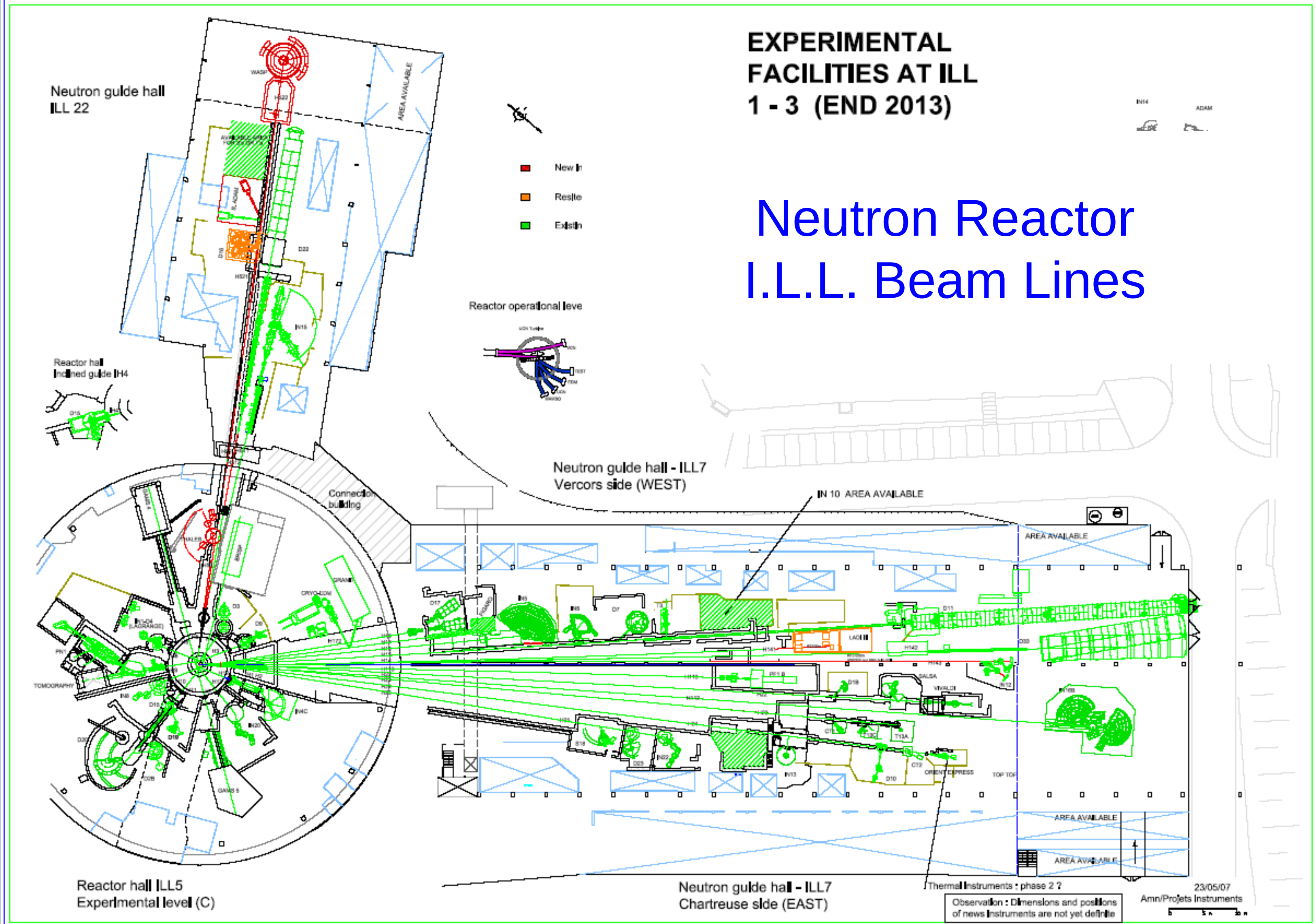
Neutron Extraction



The neutrons stream out of the reactor through a series of tubes which conduct beams of **hot**, **cold** or **thermal** neutrons

New beam tube assembly

Neutron Reactor I.L.L. Beam Lines



Production of Neutrons
spallation = pulsed source

Spallation	***Heavy nucleus + p (GeV) → Fragments + 20 n***	
	W, Pb, U, Hg	*(20 MeV)*

- *Heavy atoms are bombarded with energetic protons (proton beam power ~ 1 MW , proton pulse width ~ 1 μs)*
  → pulses of fast neutrons with E ~ 20 MeV , frequency ~ 50 – 60 Hz

- *Neutrons must be also moderated (liquid H_2O, Liquid H)*

Spallation produces x10 more neutrons than fission

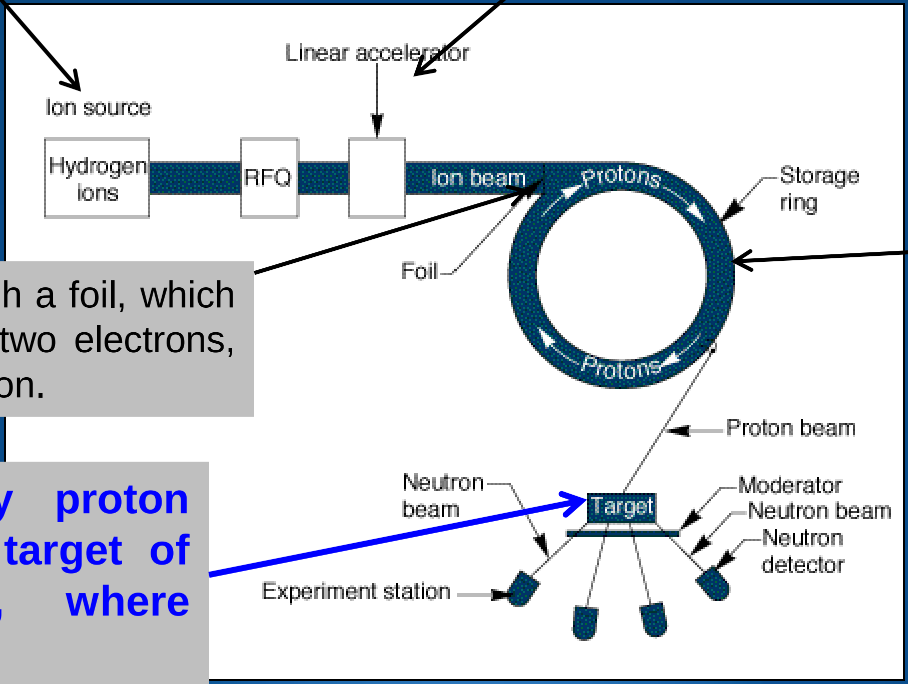
→ High peak Flux ~ 10^{15} –10^{16} n/cm^2/s – pulse width =f(λ)
→ Average peak Flux ~ 10^{14} –10^{15} n/cm^2/s

Production of Neutrons

How a spallation source works ?

Negatively charged hydrogen ions are produced by an ion source.

a linear particle accelerator accelerates H^- to very high energies (GeV)



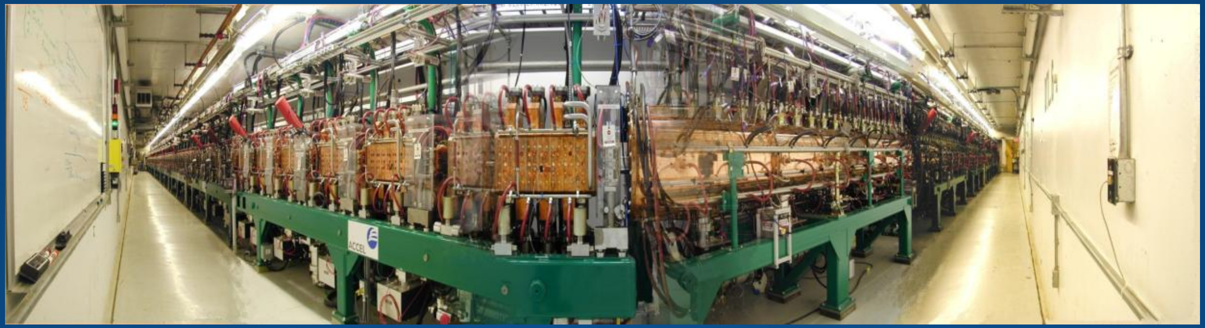
The protons pass into a ring-shaped structure, a proton accumulator ring, where they spin around at very high speeds and accumulate in “bunches.

The ions pass through a foil, which strips off each ion's two electrons, converting it to a proton.

The high-energy proton pulses strike a target of liquid mercury, where spallation occur

Production of Neutrons

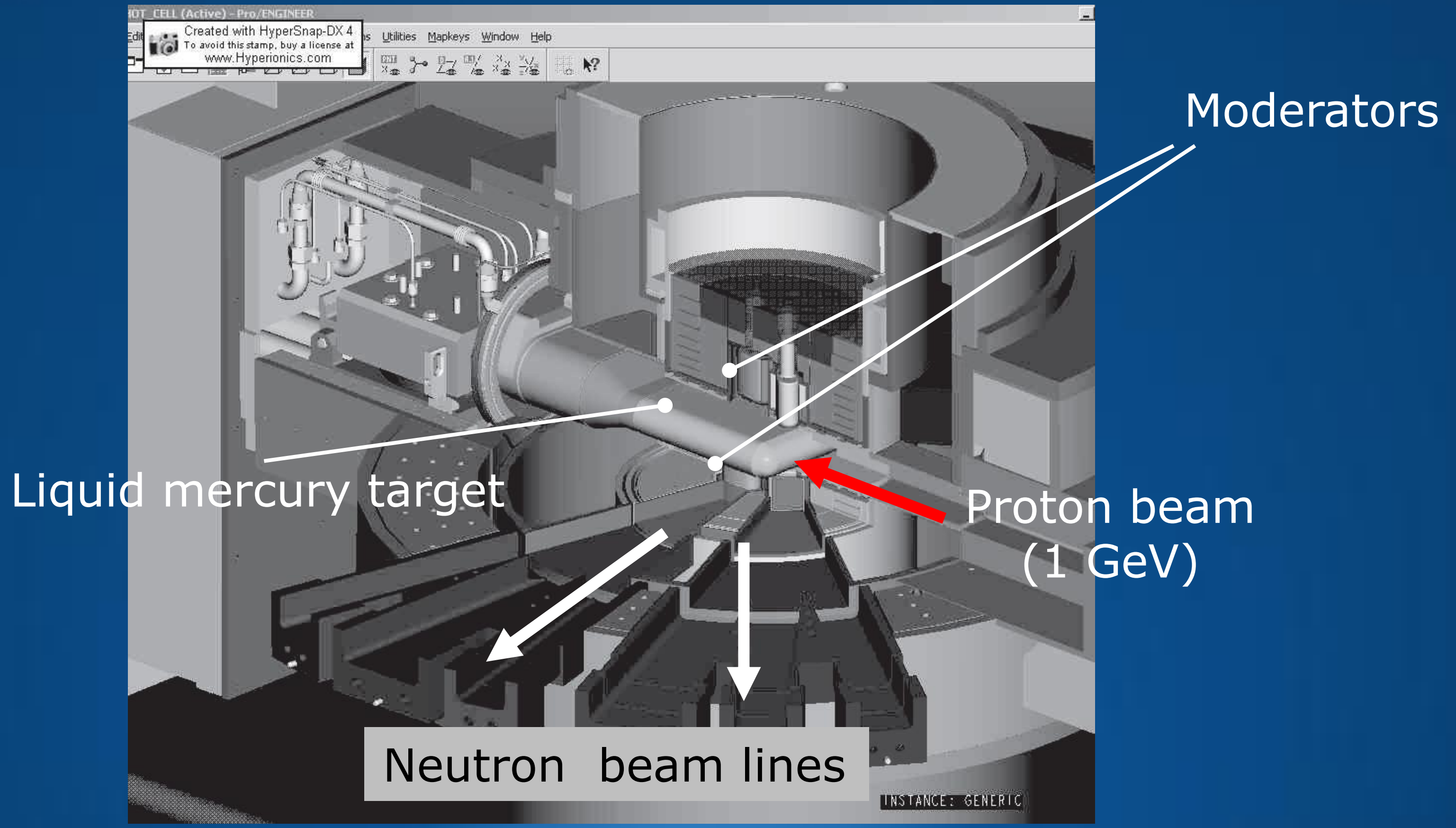
spallation = pulsed source



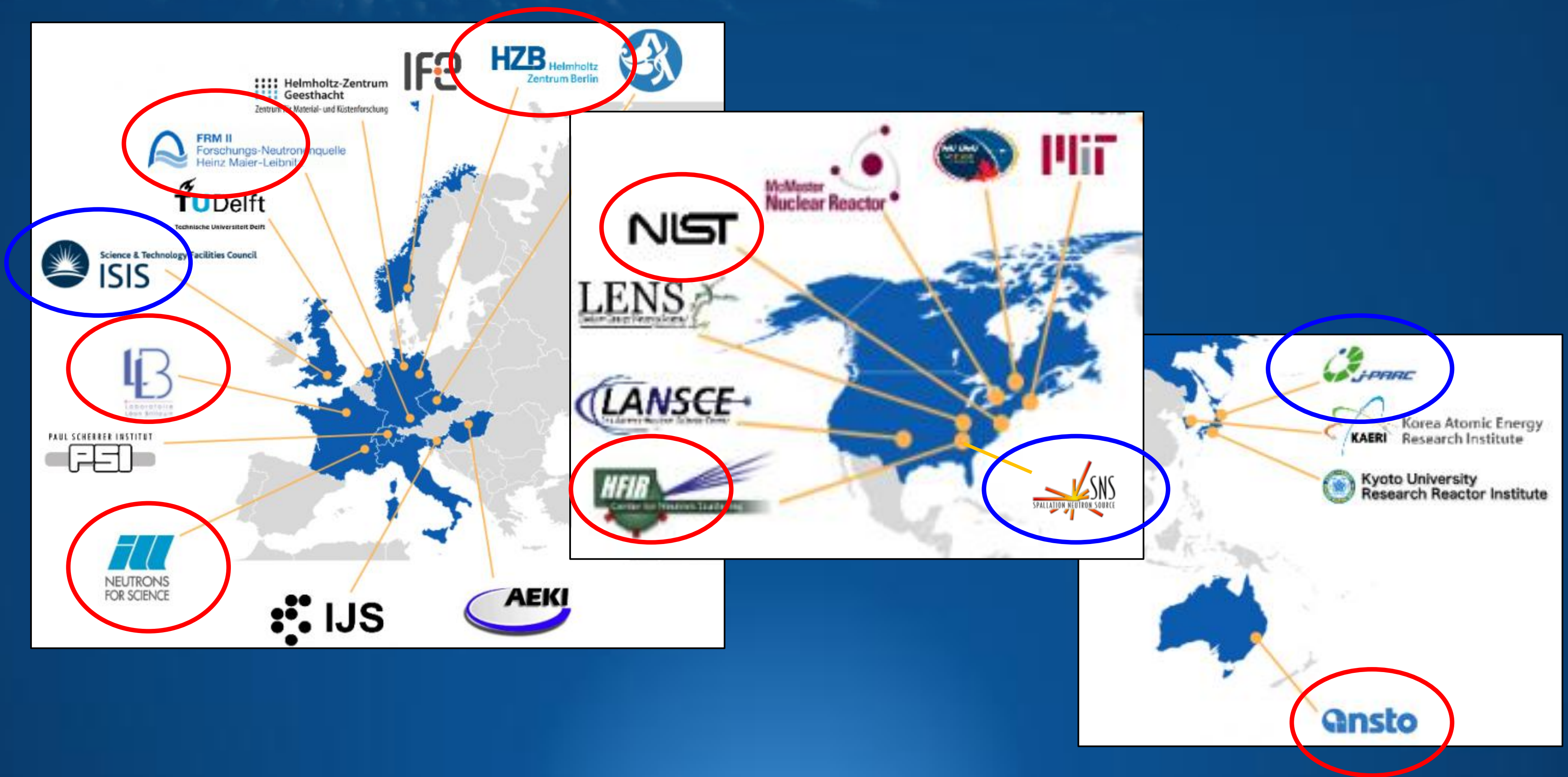
Linear accelerator

High power RF-systems

Neutron Sources
Pulsed Source



Operational Neutron Sources



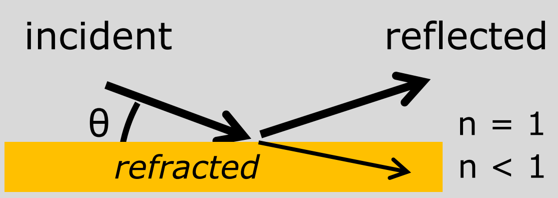
Neutron Transport
From the reactor to the experimental area

Neutron Guides

Neutron transport

Neutron guide

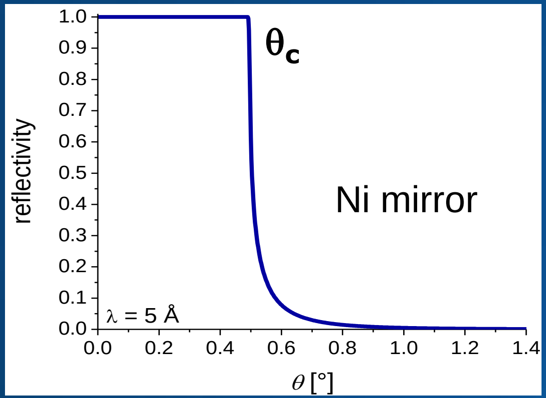
- A neutron guide can transport neutrons over a long distance with “no loss” → reflection from a surface (mirror)



Index of Refraction $n = 1 - \frac{\lambda^2 N b_{coh}}{2\pi}$

Nb_{coh} = Scattering Length Density

N = atoms/cm^3 ; b_{coh} = coherent scattering length



neutron reflection at grazing incidence $\theta \sim 1°$

Total reflection for $\theta < \theta_c$ $\theta_c = \lambda \sqrt{\frac{N b_{coh}}{\pi}}$

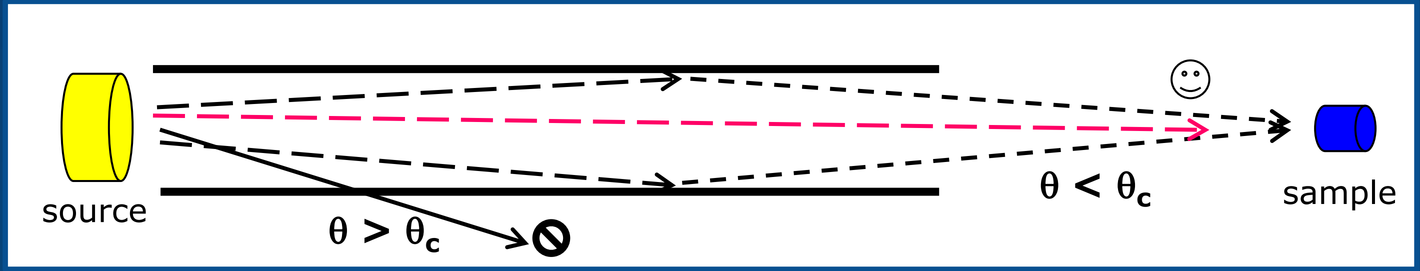
for natural Ni - $\theta_c(°) = 0.1 \times \lambda$ (Å)

e.g. $\theta_c = 1°$ at 10 Å

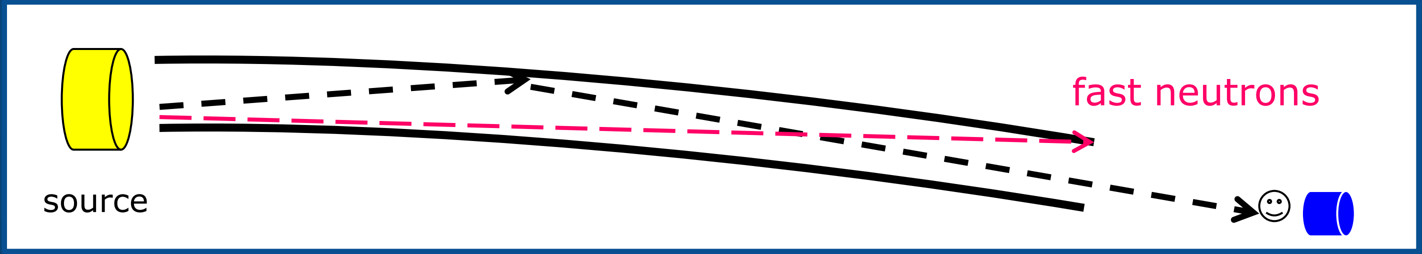
Neutron transport

Neutron guide

- ❑ A neutron guide can increase the neutron flux at sample position (increase of beam divergence)



- ❑ Curved guides are used in preference to avoid direct line of sight and then fast neutrons are not transmitted (small critical angle)

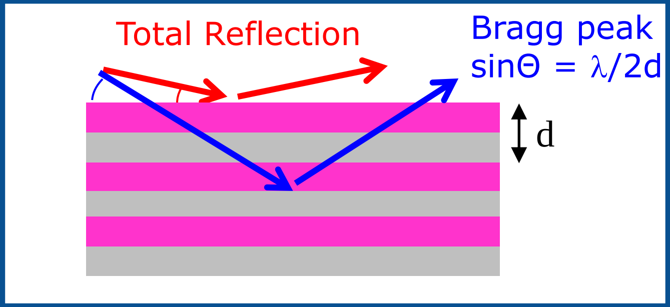


Multilayers

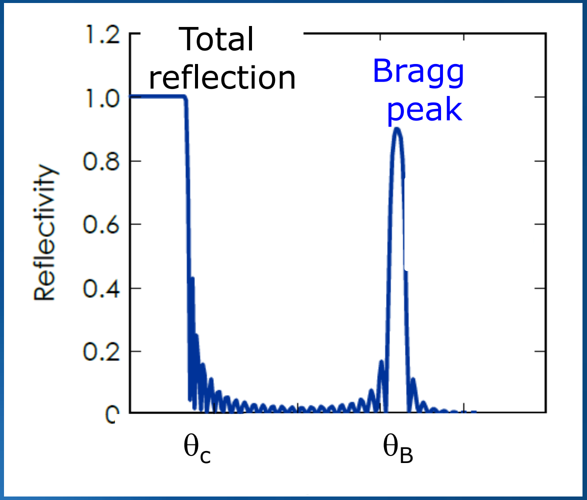
Reflection from a periodic multilayer

Total reflection for $\theta < \theta_c$ + additional Bragg peak at $\theta_B = \lambda/2d\sin\theta$

Neutron Reflectivity $$R = \frac{4N^2 d^4 (N_1 b_1 - N_2 b_2)^2}{\pi^2 n^4}$$ N : number of bi-layers



(e.g. : d ~ 100 Å – λ= 5Å
→ diffraction peak at $\theta \approx 1.4°$)



$$m = \frac{\theta_c^{sm}}{\theta_c^{Ni}}$$

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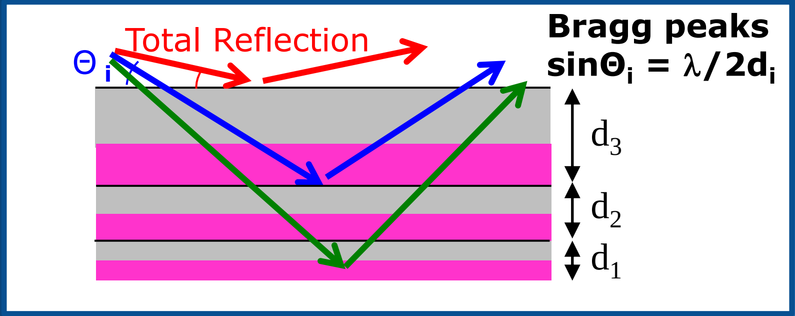
Neutron Super-Mirrors

Reflection from a super-mirror,
a sequence of bi-layers of variable thicknesses d

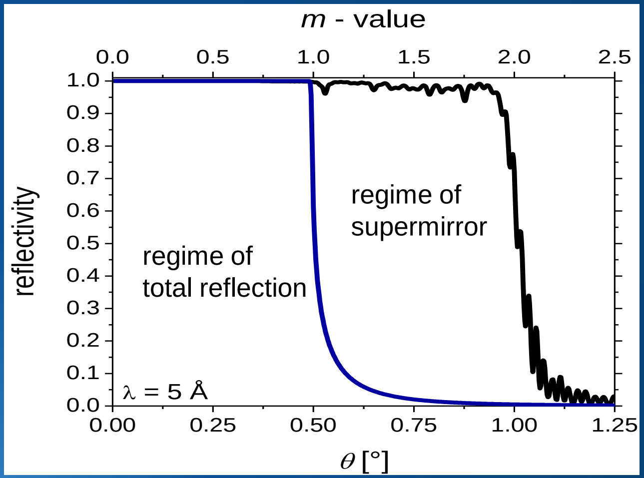
Total reflection for $\theta < \theta_c$ + additional Bragg peaks

→ significant increase in critical angle ($\theta_c = \lambda / 2d_{min}$)

$$\theta_c^{SM} = m\theta_c^{Ni} \longrightarrow Gain = \left(\frac{\theta_c^{sm}}{\theta_c^{Ni}}\right)^2 \propto m^2$$



e.g. : d =100 Å – λ= 5Å → diffraction peak at θ ≈ 1.4 °
d =50Å – λ= 5Å → diffraction peak at θ ≈ 2.8 °

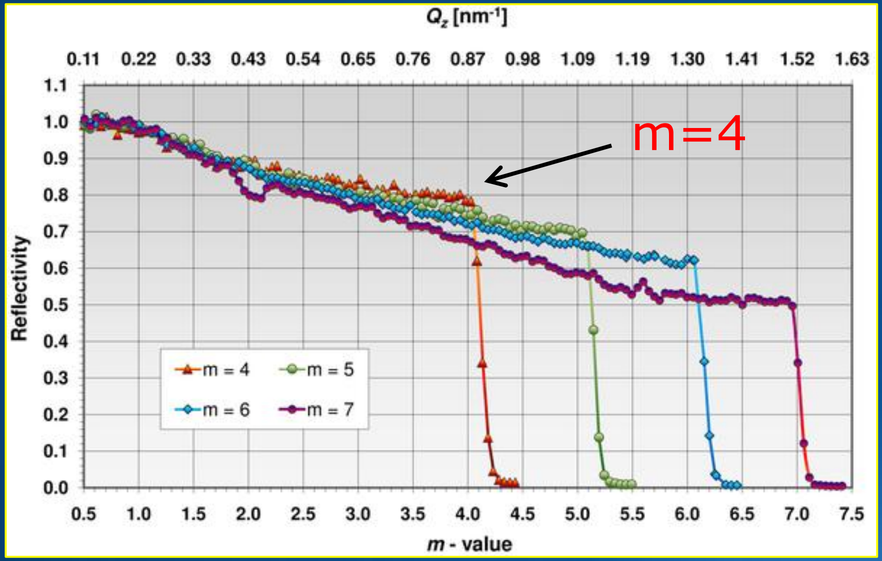


Ni/Ti super-mirrors

Neutron Reflectivity R ∝ $(N_1b_1-N_2b_2)^2$

Ni *Nb= 9.40 (10^{-6}Å^{-2})*
Ti *Nb= -1.95 (10^{-6}Å^{-2})*

High contrast → high reflectivity !



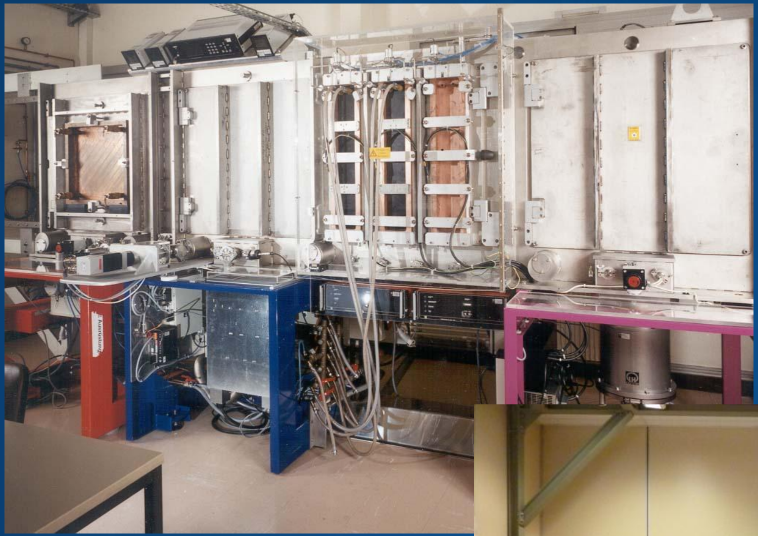
Reflectivity profiles of Ni/Ti super-mirrors for 4 ≤m ≤ 7
(sources : www.swissneutronics.ch)

High performances !!

- R > 80% for m=4 Ni/Ti
- Gain factor / Ni guide = 16
- but transmission T ∝ R^n !!

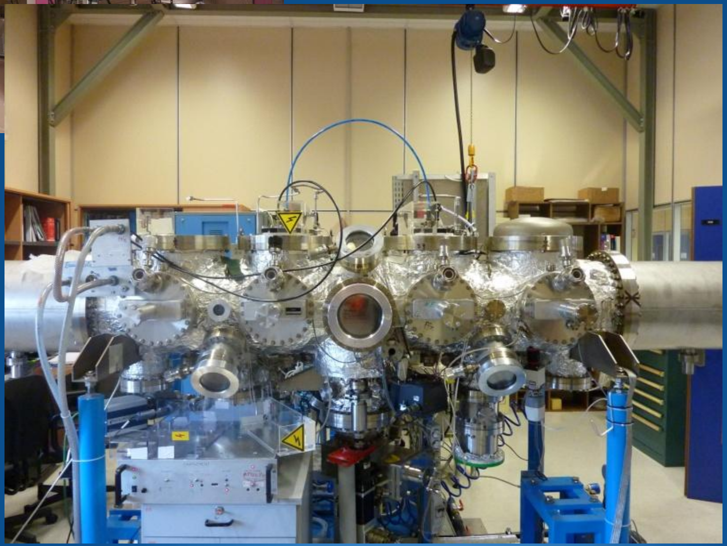
eg : for a 100 m long guide , at least ten reflections → T<10% ...

Production of super-mirrors
Magnetron sputtering

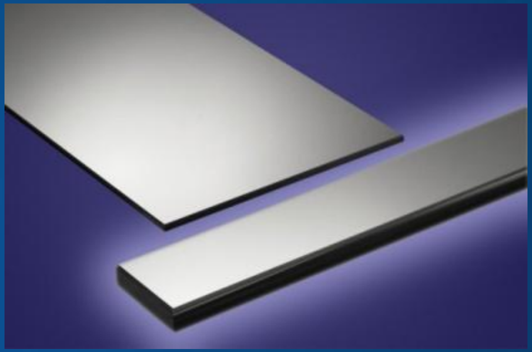


Sputtering machine (ILL)
Production 0.8 m^2 / day

Suppliers
- SwissNeutronics (Switzerland)
- S-DH (Germany)
- Mirrotron (Hungary)
- but also ILL, HZB....



Sputtering machine (ILL)
0.2 m^2 / day



Neutron transport

From the reactor to the experimental area...

Neutron Guide

m=2 Ni/Ti supermirrors

Length > 50 m

Section ~ 20 x 10 cm^2

4 reflective internal surfaces

Curvature R ~ 1-10 km

Beam Shaping

Monochromatization
Focusing
Polarization...

Liouville's Theorem

- The Phase space density is constant.

➢ For neutron beams: the number of neutrons per unit of time, energy, solid angle and area is constant.

➢ Simply stated: it costs flux to increase resolution and it costs resolution to increase flux.

The optimization of instrument performance is always a compromise between flux and resolution

Crystal Monochromator

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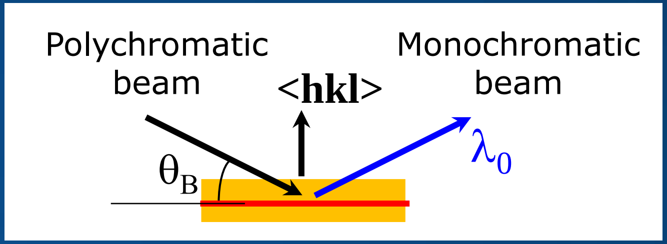
Use of mosaic crystals to select a given wavelength band according to the Bragg's Law

$$2\, d_{hkl}\ \sin\theta_B = n\lambda$$

d= distance of the lattice planes (hkl)

θ_B = Bragg angle



➢The relative bandwidth $\Delta\lambda/\lambda$ is given for Gaussian distributions by $\Delta\lambda/\lambda = (\alpha^2 + \beta^2)^{1/2}\cot\theta_B$

α the divergence of the primary beam

β the full width at half maximum of the neutron "rocking curve" or *neutron mosaic spread*

- ❑ The divergence α of the primary beam is typically 0.2°–1°

  If $\alpha \sim \beta$, the resolution and intensity are said to be optimised

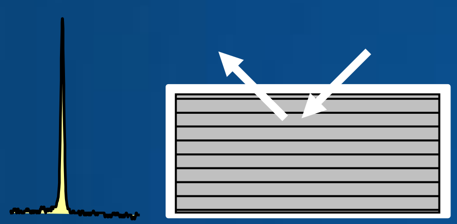
- ➢ **Needs of crystals with a mosaic spread β typically in the range *0.2°- 0.8°***

Crystal Monochromator

The mosaic crystal

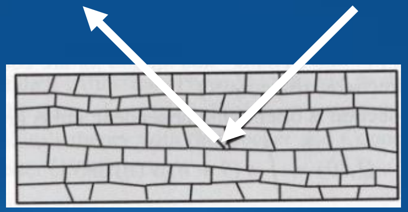
- Defect free crystal = perfect crystal
- Crystal with defects such as dislocations = mosaic crystal

A mosaic crystal consists of a distribution *W(θ) of small crystallites (perfect crystals) making small angles relative to the nominal plane. W(θ) is usually taken to be a Gaussian distribution.*

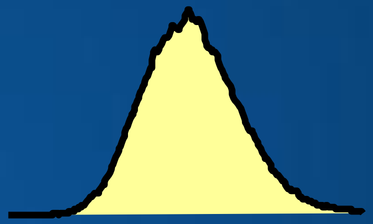


width < 0.001°

Perfect crystal



Mosaic crystal

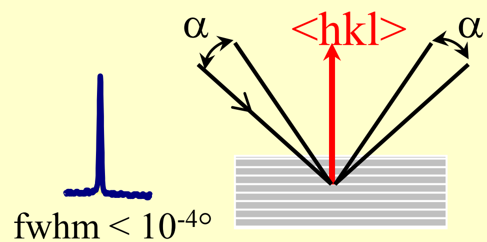


width > 0.05 °

$$w(\theta) = \frac{1}{\sqrt{2\pi\eta}} \exp(-\Delta^2 / 2\eta^2)$$

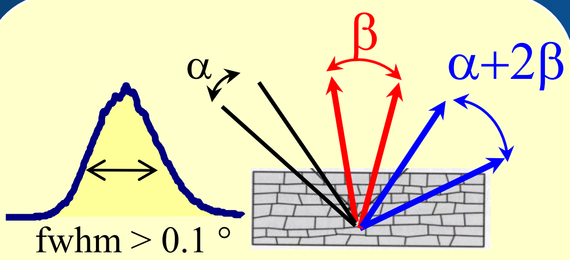
Crystal Monochromator

Perfect crystal vs mosaic crystal



$\Delta\lambda/\lambda = \alpha \cot\theta_B$; flux → 0 !

Perfect crystal



$\Delta\lambda/\lambda = (\alpha^2 + \beta^2)^{1/2} \cot\theta_B$

Mosaic crystal

Perfect crystal

- ❑ The reflection range of perfect crystals is of the order of 0.001°.
- ❑ Perfect crystals do not reflect efficiently neutrons from the source of divergence α.
- ➢ Very high resolution but no intensity

Not suitable for neutron beams !

Mosaic Crystal

- ❑ The reflection range of mosaic crystals is of the order of 0.3 °, even more....
- ❑ Mosaic crystals can reflect efficiently neutrons from the source of divergence α, if β ~ α.
- ➢ High intensity and reasonable resolution

Suitable for neutron beams !

Crystal Monochromator

What kind of crystals are suitable ?

- *High neutron reflectivity $\propto$ scattering power Q* $Q = (F_{hkl} e^{-W}/V)^2 \lambda^3 / \sin 2\theta_B$
  - Large structure factor F_{hkl}
  - High coherent scattering length b_{coh} ($F_{hkl} \propto b_{coh}$)
  - Small unit cell Volume & compact structures = Cubic, Diamond
  - d-spacing optimized for a given wavelength ($d \sim \lambda$)

- *Low background* → low incoherent scattering length
- *Small attenuation* → low absorption cross sections

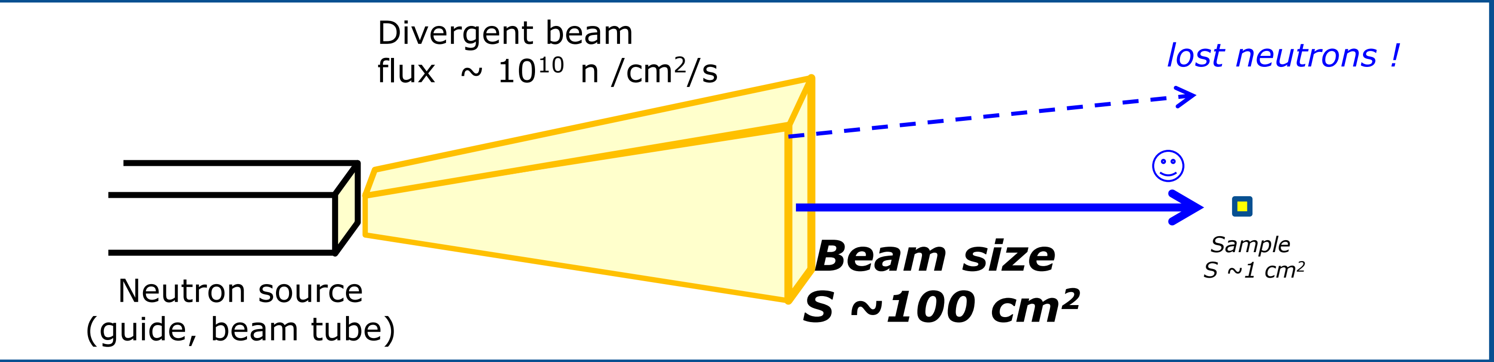
> *Availability of large single crystals with suitable width and uniform mosaic block distribution :* ***Copper, Germanium, Silicium, Graphite***

Common materials used as crystal monochromators

Crystal	orientation	Crystal Mosaic	Neutron Energy	Application
Cu *d_{111}= 2.08 Å*	(111) (220) (200) (113)	0.01° – 3°	Hot Thermal	*High resolution or high flux*
C (graphite) *d_{002}= 3.35 Å*	HOPG(002)	0.5°- 3°	Cold Thermal	*High flux*
Si *d_{111}= 3.13 Å*	(111) (113)	Perfect bent	Cold Thermal	*High resolution*
Ge *d_{111}= 3.26 Å*	(111) (113) (115)	< 0.25°	Cold Thermal	*High resolution*
KC_8 *d_{002}= 5.3 Å*	(002)	2°- 5°	Cold	*High flux*

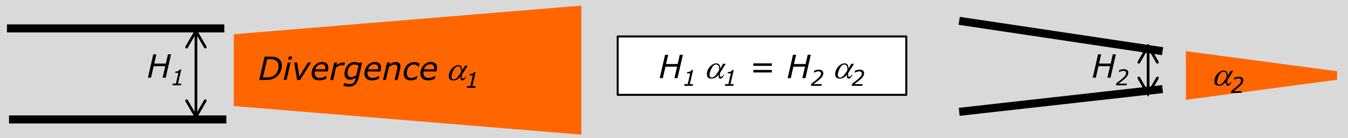
Hot neutrons λ ~0.3-1 Å ; thermal λ ~1- 4 Å; cold λ~ 4-20 Å

Neutron Optics
Focusing Devices



Beam Size >> Sample size

➢ Focusing devices are used to increase the neutron flux at the sample position. However, the increase of neutron flux implies a degradation of the angular resolution. (Liouville's theorem !)



Neutron Focusing Devices

Theory vs reality

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Theory

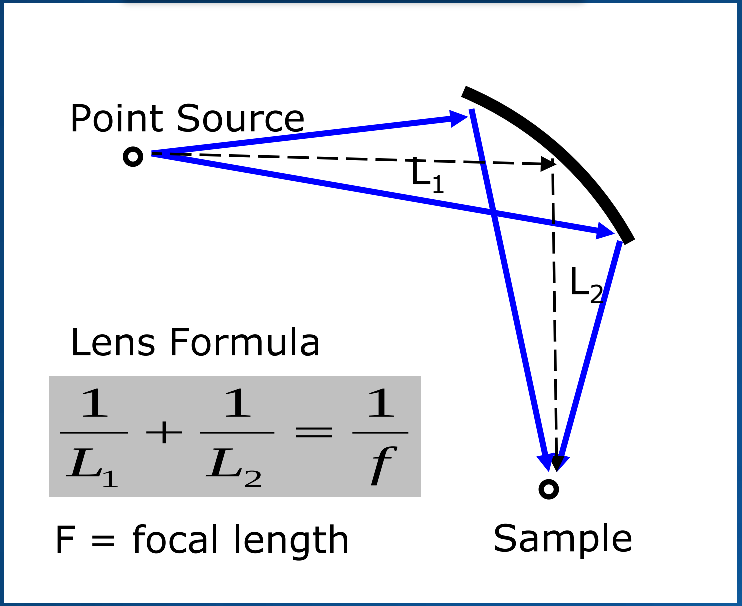
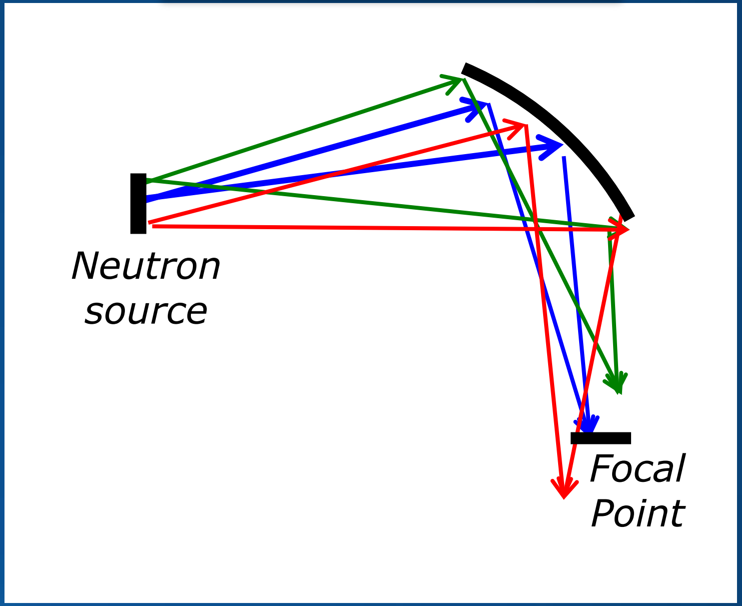


Image Size = Source size

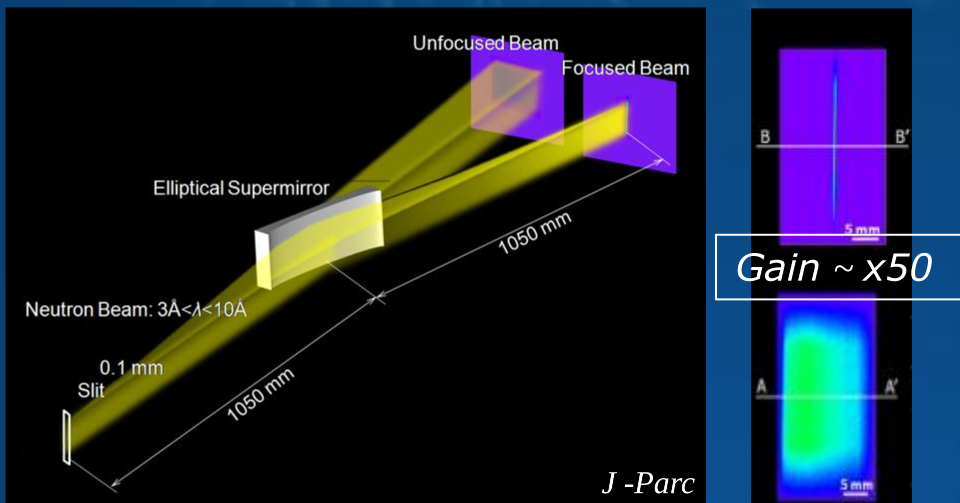
Reality



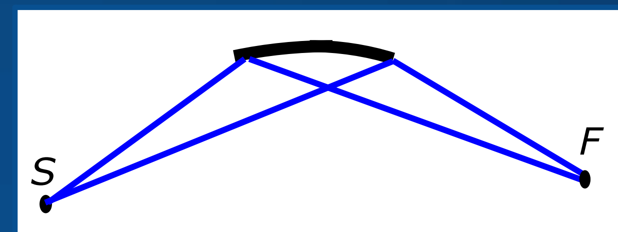
Optical « aberrations » due to the large size of the source

Neutron Focusing Devices

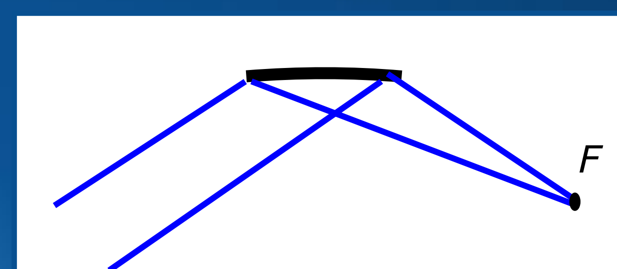
Elliptic or parabolic mirrors



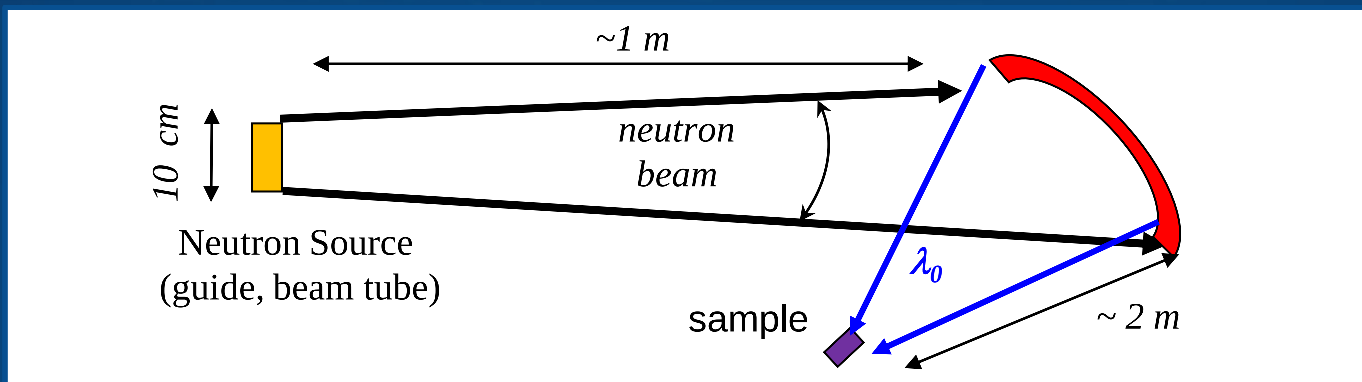
Elliptic mirrors



Parabolic mirrors



Focusing Monochromators



- Monochromators must have a large active area to cover the full tranverse dimensions of the incoming neutron beam

- A typical monochromator consists of an array of single crystal pieces having dimensions comparable to the sample size

Neutron Focusing Devices

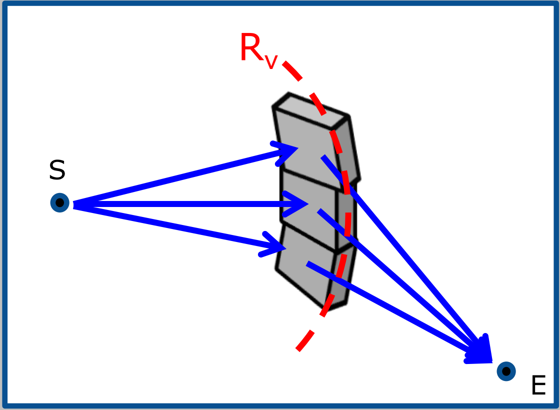
Focusing Monochromators

NEUTRONS FOR SCIENCE®

Vertical Focusing

$$\frac{1}{R_v} = \frac{1}{2sin\theta}\left(\frac{1}{L_{ME}} + \frac{1}{L_{MS}}\right)$$

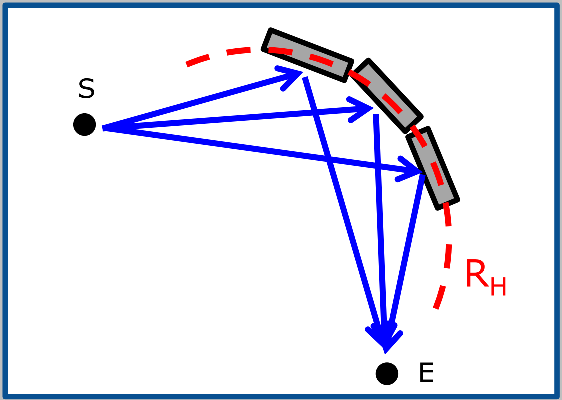
- Image size ~ crystal size (height)
- Gain in flux ∝ compression factor
- **Increase of vertical divergence**



Horizontal Focusing

$$\frac{1}{R_h} = \frac{sin\theta}{2}\left(\frac{1}{L_{ME}} + \frac{1}{L_{MS}}\right)$$

- Gain in flux
- **Horizontal focusing affects δλ/λ and Q resolution**



Neutron Focusing Devices

Fixed focusing Monochromators

- **Fixed vertical Curvature**
- Production of a fixed neutron wavelength at a given take-off angle
- No horizontal focusing to keep high Q resolution

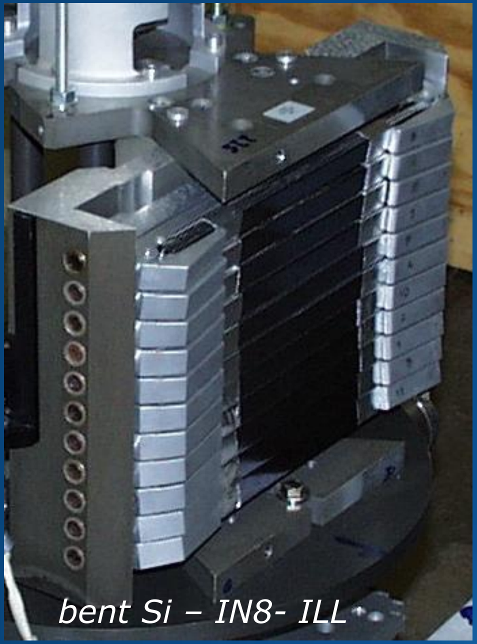
Neutron diffractometers

Neutron Focusing Devices
Double focusing Monochromators

Double variable focusing Monochromator

- Optimization of instrument performances for a wide energy range

Tree axis spectrometers



bent Si – IN8- ILL

Cu - IN8 – ILL

Neutron Filters

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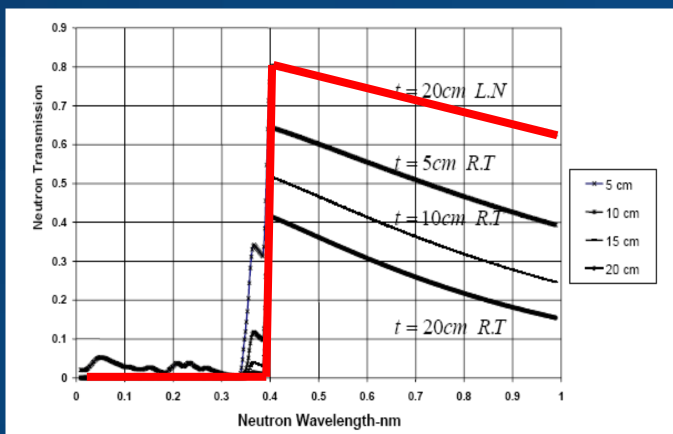
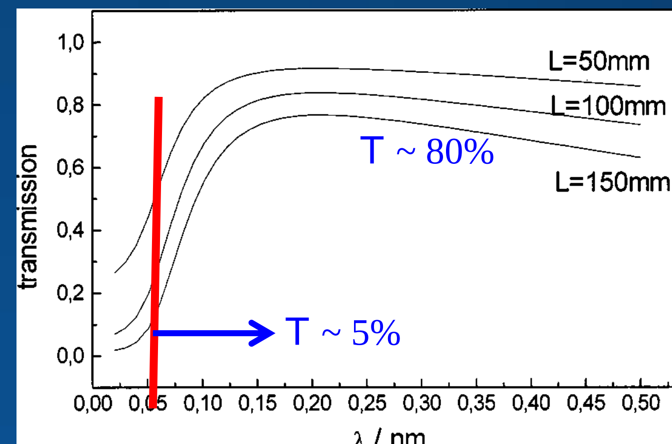
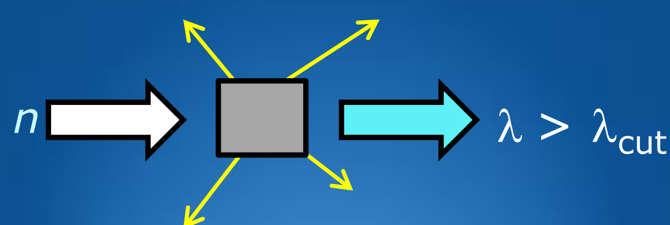
Filters are used to select out unwanted neutrons



Polycristalline Beryllium at 77K
Cut-off at $\lambda < \lambda_{max} = 2d_{Be\ max} = 4$ Å
➢ **cold neutron beams !**

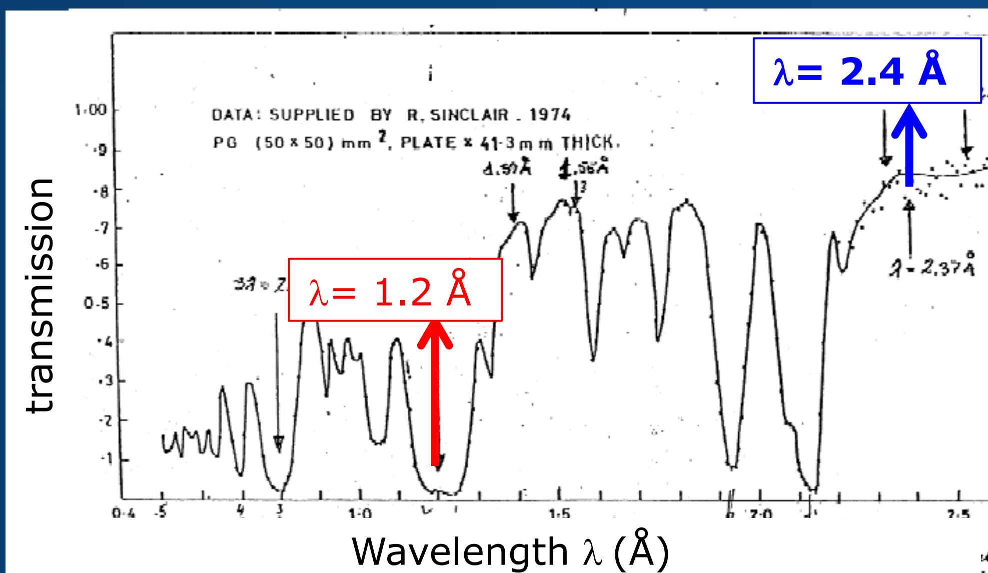


Perfect Saphir crystal is used to select out **fast neutrons of $\lambda < 0.5$ Å**
➢ **Reduction of background**



Neutron Filters

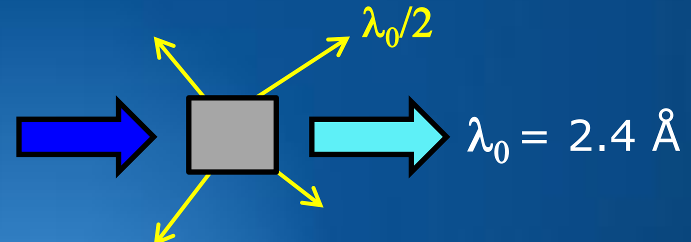
Filters are used to select out unwanted neutrons



Pyrolitic Graphite is commonly used for eliminating **higher-order contamination** of a monochromated neutron beam.

PG filter has strong attenuation at 1.2 Å but passes 2.4 Å

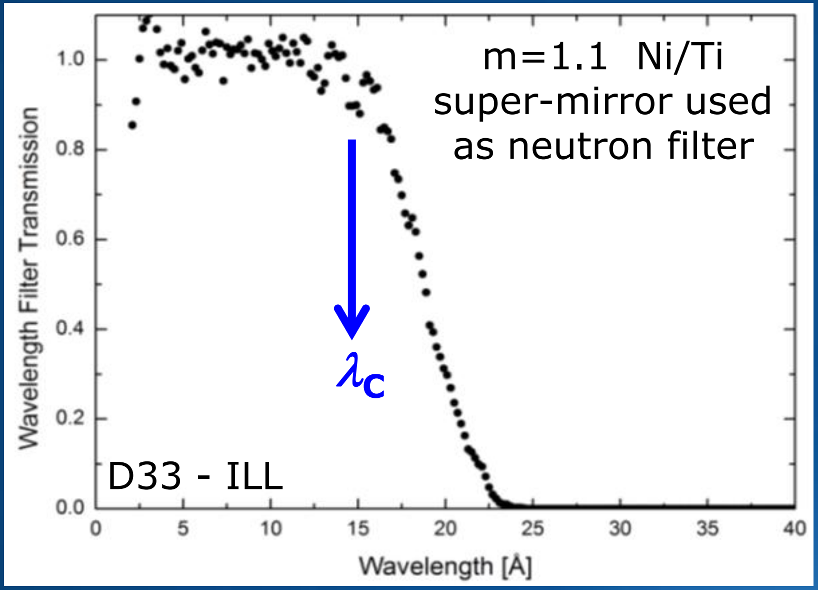
monochromatic beam $\lambda = 2.4$ Å
\+ second order contamination $\lambda/2$

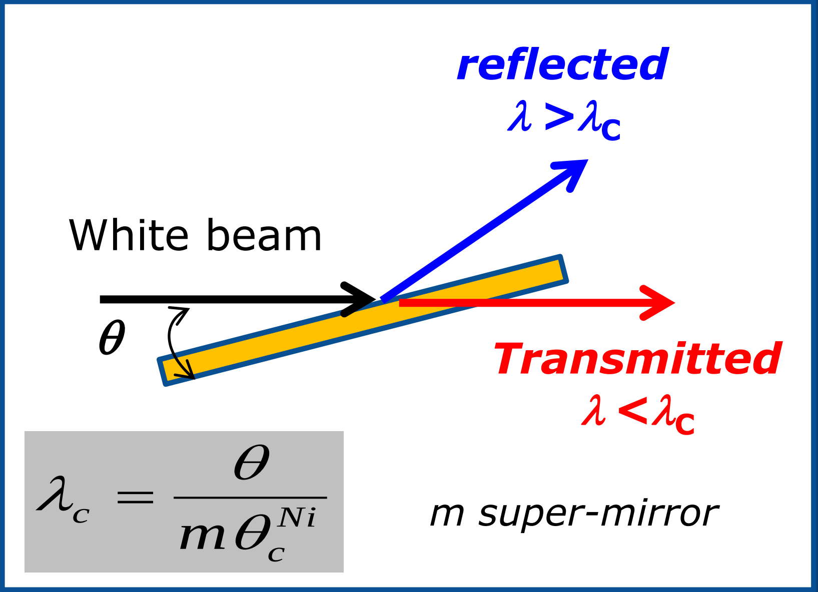


Neutron Filters

Filters are used to select out unwanted neutrons

Neutron long wavelength cut-off filter





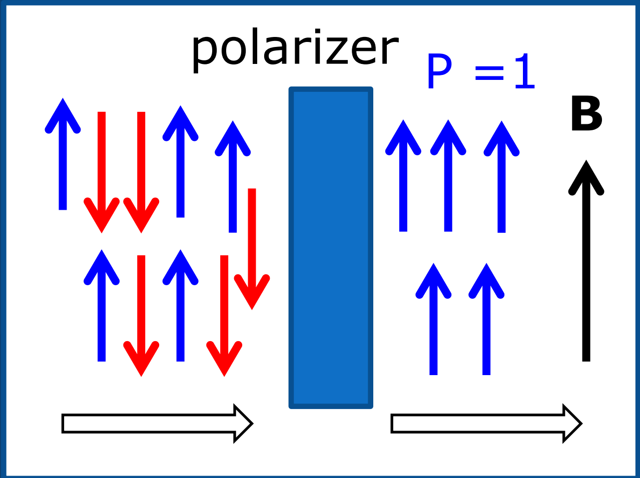
$$\lambda_c = \frac{\theta}{m\theta_c^{Ni}}$$

Polarized neutron beams

The polarizing efficiency of a polarizer is defined as :

$$P = \frac{N_+ - N_-}{N_+ + N_-}$$

N+/- number of neutrons with spin parallel (+), or antiparallel (-), to the guide field in the outgoing beam



Principal methods

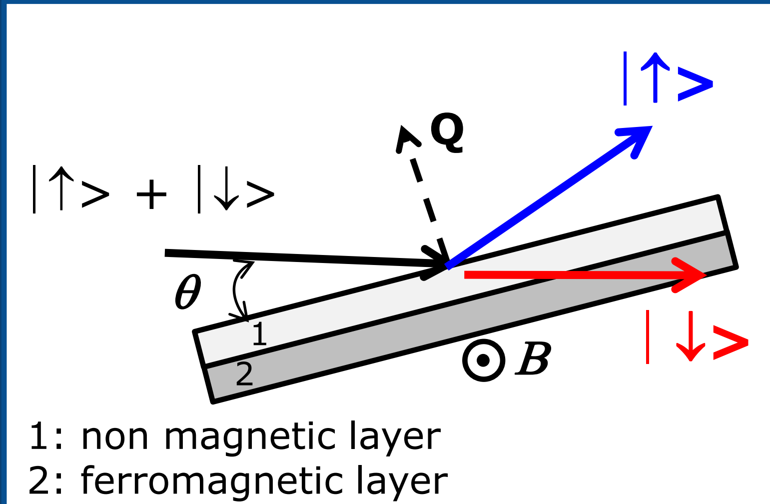
- Polarizing super-mirrors (reflection, transmission)
- Heusler Cu_2MnAl crystal
- He^3 spin filters

Polarizing super-mirrors

Refraction index of
a ferromagnetic layer

$$n = 1 - \frac{\lambda^2 N (b \pm p)}{2\pi}$$

→ Magnetic contribution



Reflectivity R of a bilayer system

$|\uparrow\rangle$: $R+ \propto [N_1 b_1 - N_2(b_2 + p_2)]^2$

$|\downarrow\rangle$: $R- \propto [N_1 b_1 - N_2(b_2 - p_2)]^2$

Polarization

$\mathbf{N_1 b_1 = N_2(b_2 \pm p_2)}$

→ Reflection / Transmission
of one spin state

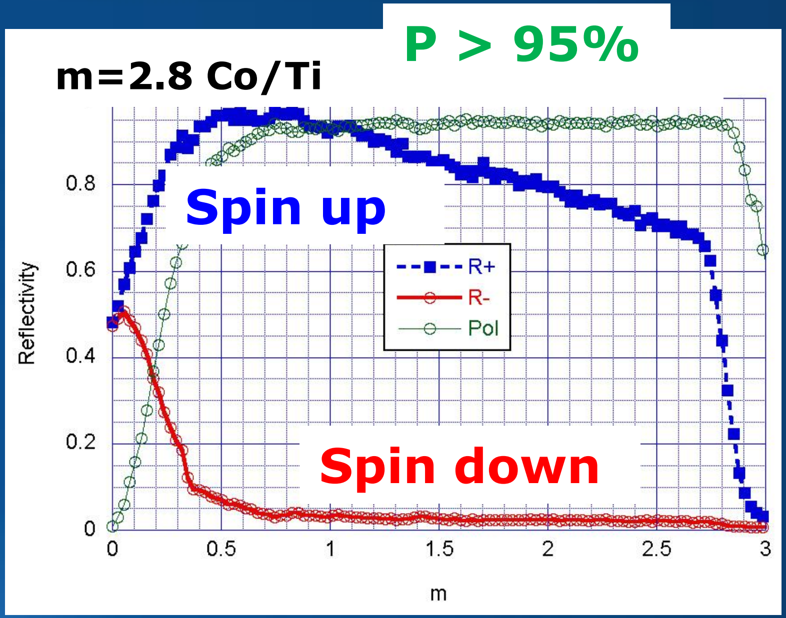
Polarizing Super-mirrors
Co/Ti and Fe/Si

❑ Co/Ti super-mirrors

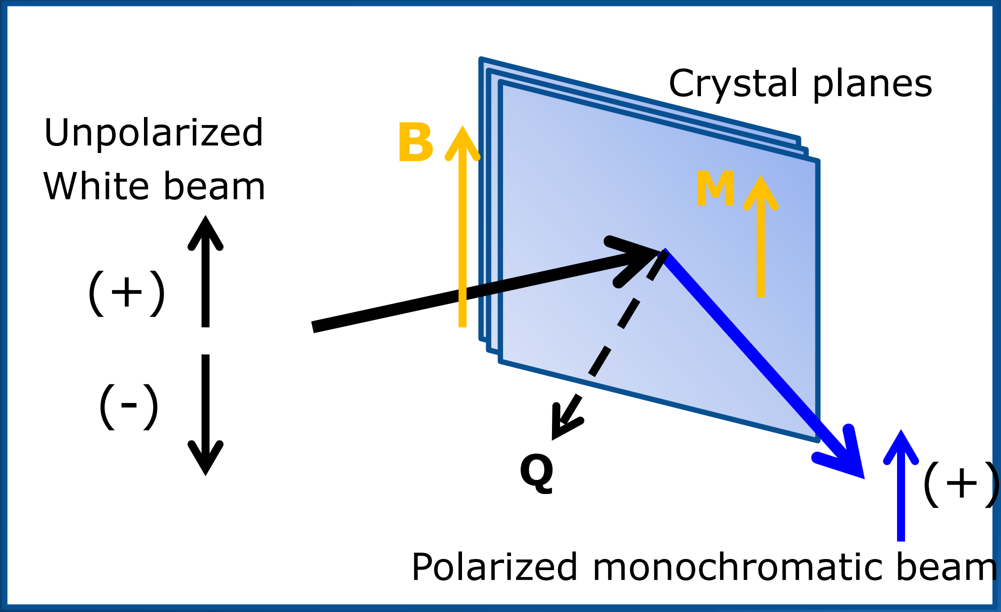
- $N(b+p)_{Co} = 6.55$ *(10^{-6}Å^{-2})* ;
- $N(b-p)_{Co} = -2.00 \approx Nb_{Ti} = -1.95$ *(10^{-6}Å^{-2})*
- *P > 95%*
- *m = 3* → polarization analysis

❑ Fe/Si super-mirrors

- $N(b+p)_{Fe} = 13.04$ *(10^{-6}Å^{-2})* ;
- $N(b-p)_{Fe} = 3.08 \approx Nb_{Si} = 2.08$ *(10^{-6}Å^{-2})*
- *P > 95%*
- Polarizer in reflection / Transmission geometry



Polarizing crystal monochromators



Bragg reflection from a ferromagnetic crystal

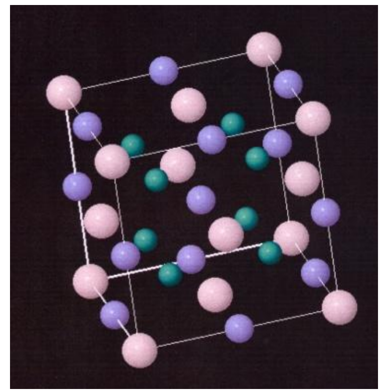
- $I^+ \propto [F_N(Q) + F_M(Q)]^2$
- $I^- \propto [F_N(Q) - F_M(Q)]^2$

$F_N(Q)$ nuclear structure factor
$F_N(Q)$ magnetic structure factor

Polarization
$\mathbf{F_N(Q) = \pm F_M(Q)}$

Polarizing crystal
Heusler alloy Cu_2MnAl

- Mn
- Cu
- Al



Cubic structure L_{21}

Structures Factors

Nuclear
$F_{111N} = 4\ (f_{Mn} - f_{Al})$

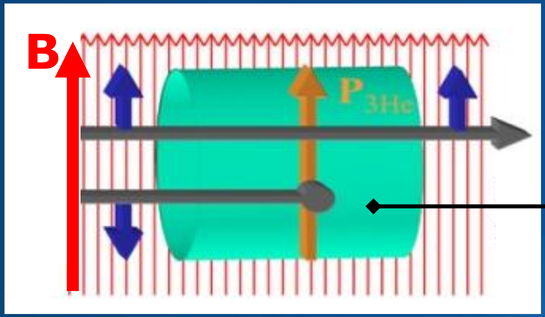
Magnetic
$F_{111M} = 4\ p_{Mn}$

• (111) reflection	$F_{111N} = -F_{111M}$
• Mosaic	$0.2° < \text{fwhm} < 0.6°$
• Reflectivity	$R_{experimental} \approx R_{theoretical}$
• Polarization	$P > 92\ \%$

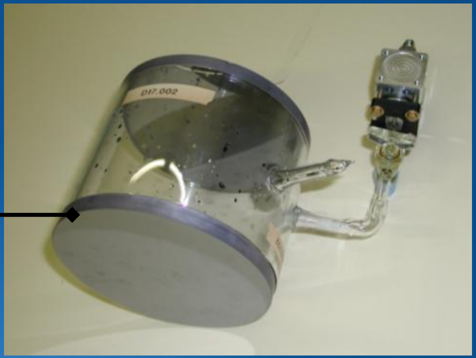
Polarized ^{3}Helium spin filters

- **Absorption cross section of ^{3}Helium nuclei**
  - If the nuclear spin of He and the neutron spin are parallel, $\sigma_{a\uparrow\uparrow}$ **≈ 0**
  - If the nuclear spin of He and the neutron spin are anti-parallel, $\sigma_{a\,\uparrow\downarrow} \approx 6000$ barns

For fully polarized ^{3}He (P_{He} = *1), one spin state goes through the filter with zero* absorption. The other spin state is almost fully absorbed since σ_a = *6000 barns → polarized neutron beam*



Transmission of one spin state



3He spin filter cell

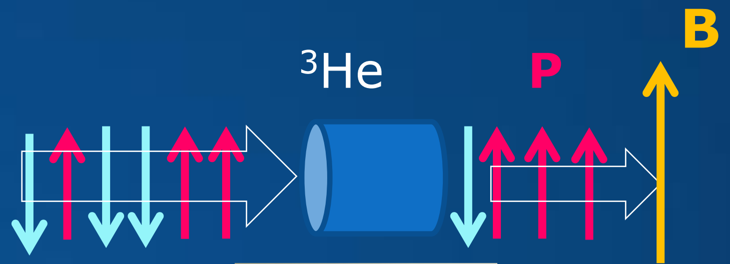
Polarized ^{3}Helium spin filters

Performances

- Polarization of ^{3}He nuclei $P_{3He} \sim 75 - 80\%$
→ **Neutron Polarization $P_{neutrons} > 95\%$**

- Transmission T ≈ 30%

- Applications for hot, thermal or cold neutrons



- Polarized neutron beams
- Polarization analysis

Summary

Neutron Sources

- Production of Neutrons : Reactor and Spallation
- Continuous sources & pulsed sources
- Neutron moderation – Maxwell distribution
- Cold, Thermal and hot neutron beams
- 10 facilities world-wide

Summary

Neutron Optics

- **Neutron transport :** Neutron Guides – Super-mirrors & Critical angle
- **Monochromatization** by crystal diffraction: Cu, Ge, Si, HOPG and i-HOPG mosaic crystals
- **Filters**: Be, Saphir or HOPG...
- **Focusing Devices:** Vertical and Horizontal focusing
- **Production of polarized neutron beams**: Heusler crystals, Co/Ti and Fe/Si super-mirrors , He3 spin filters

Neutron Optics obeys to Liouville's theorem !
it costs flux to increase resolution
and it costs resolution to increase flux.

NEUTRONS FOR SCIENCE ®

Thank you for your attention