Neutron beams

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TU Delft

- why neutrons
- neutron production
  - research reactors
- neutron moderation
- neutron optics

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why neutrons ?

- neutrons have the right wavelengths and energies

  they correspond ideally to the characteristic distances and energies in soft and condensed matter

- neutrons see the nuclei

  they enable isotopic labeling

- neutrons have a magnetic moment

  they give invaluable information on the magnetic properties of condensed matter

- neutrons are a soft probe

  they have no charge and penetrate deep even in heavy metals

- neutrons are rare !!!!!!!

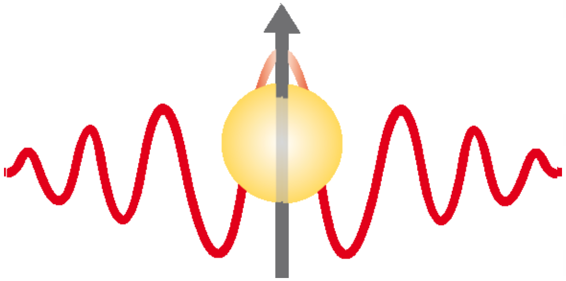
  a most powerful but intensity limited probe

TUDelft

wavelengths and energies ideally suited for structural and dynamical studies of condensed matter

neutron wavelengths ↔ neutron energies

neutron ID card



mass: $1.675\ 10^{-27}$ *kg*

charge: 0

spin : ½

magnetic dipole moment:

$\mu_n = -1.913\mu_N$

wavelengths and energies ideally suited for structural and dynamical studies of condensed matter

neutron wavelengths ⟷ neutron energies

the neutron sources deliver beams with a Maxwell distribution of velocities

$$\varphi(v) \propto v^3 \exp(- \tfrac{1}{2} m v^2 / k_B T)$$

$$E_{av} = \tfrac{1}{2} m v_{av}^2 = 3/2\, k_B T \approx k_B T$$

for a moderator temperature of 300 K

→ mean neutron velocity $\approx 2200 \text{ m s}^{-1}$

De Broglie relation: $\lambda = h/mv$

neutron energy E_n = kinetic energy = $\frac{1}{2} m_n v_n^2$

in "laboratory" units: $E_n = 81.805/\lambda^2$ (E_n in meV, λ in Å)

at λ = 9 Å

1 meV ≡ 0.24 THz ≡ 8 cm^{-1} ≡ 11.6 K

for a moderator temperature of 300 K

mean neutron wavelength ≈ 1.8 Å, mean energy ≈ 26 meV

photons with λ = 1.8 Å have an energy of = 6.9 KeV

$T \sim 8\ 10^5$ K

moderator temperature ↔ wavelength - energy range

„thermal neutrons“

in thermal equilibrium with the temperature of the cooling water around a reactor core (at. 60°C)

$1\ \text{Å} < \lambda < 3\ \text{Å}$

„cold neutrons“

in thermal equilibrium with the temperature of e.g. liquid H_2 („cold source“, ca. 25 K)

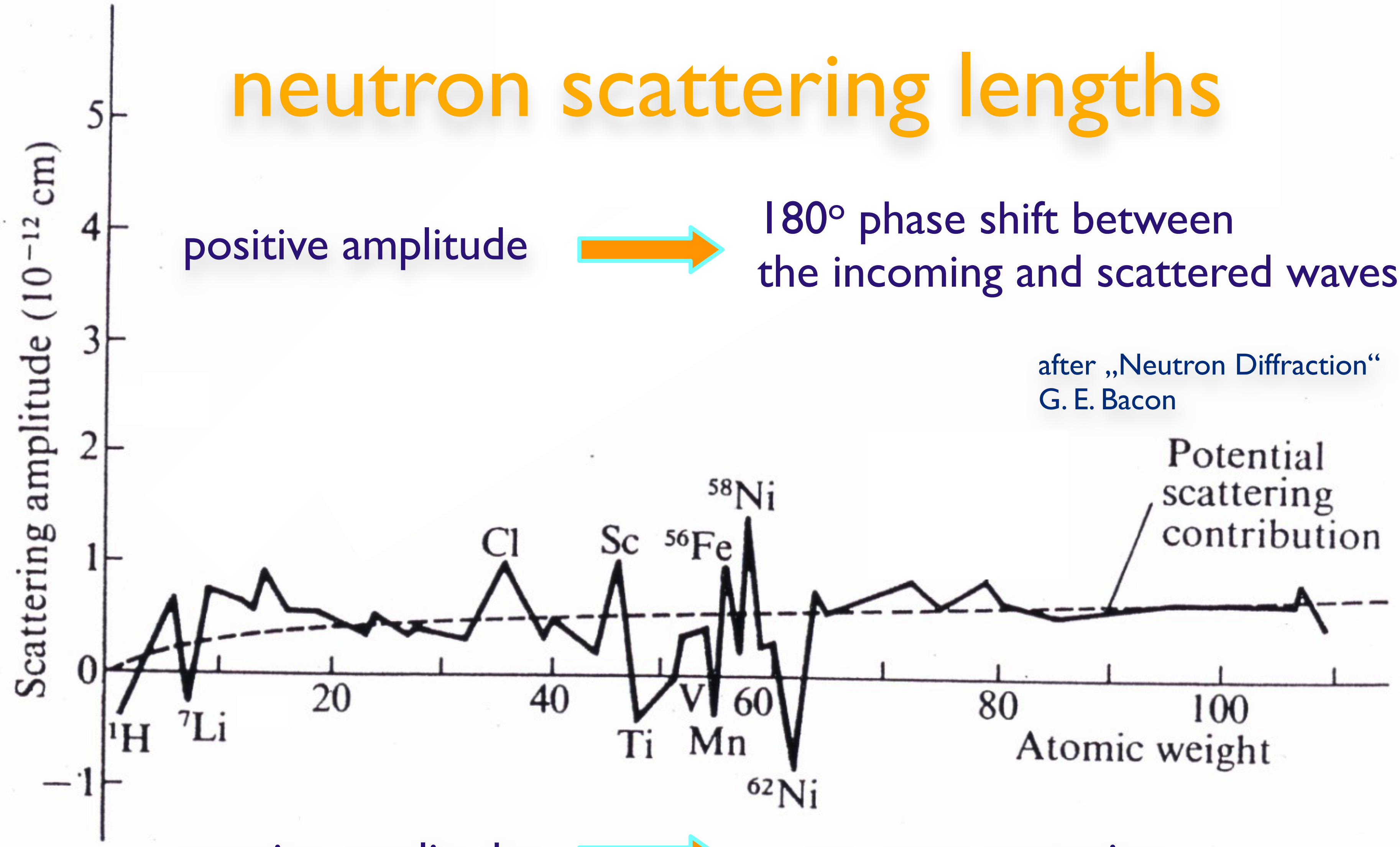
$2.5\ \text{Å} < \lambda < 20\ \text{Å}$

„hot neutrons“

in thermal equilibrium with the temperature of a hot graphite block („hot source“, ca. 2000 K)

$0.4\ \text{Å} < \lambda < 1\ \text{Å}$

neutron scattering lengths

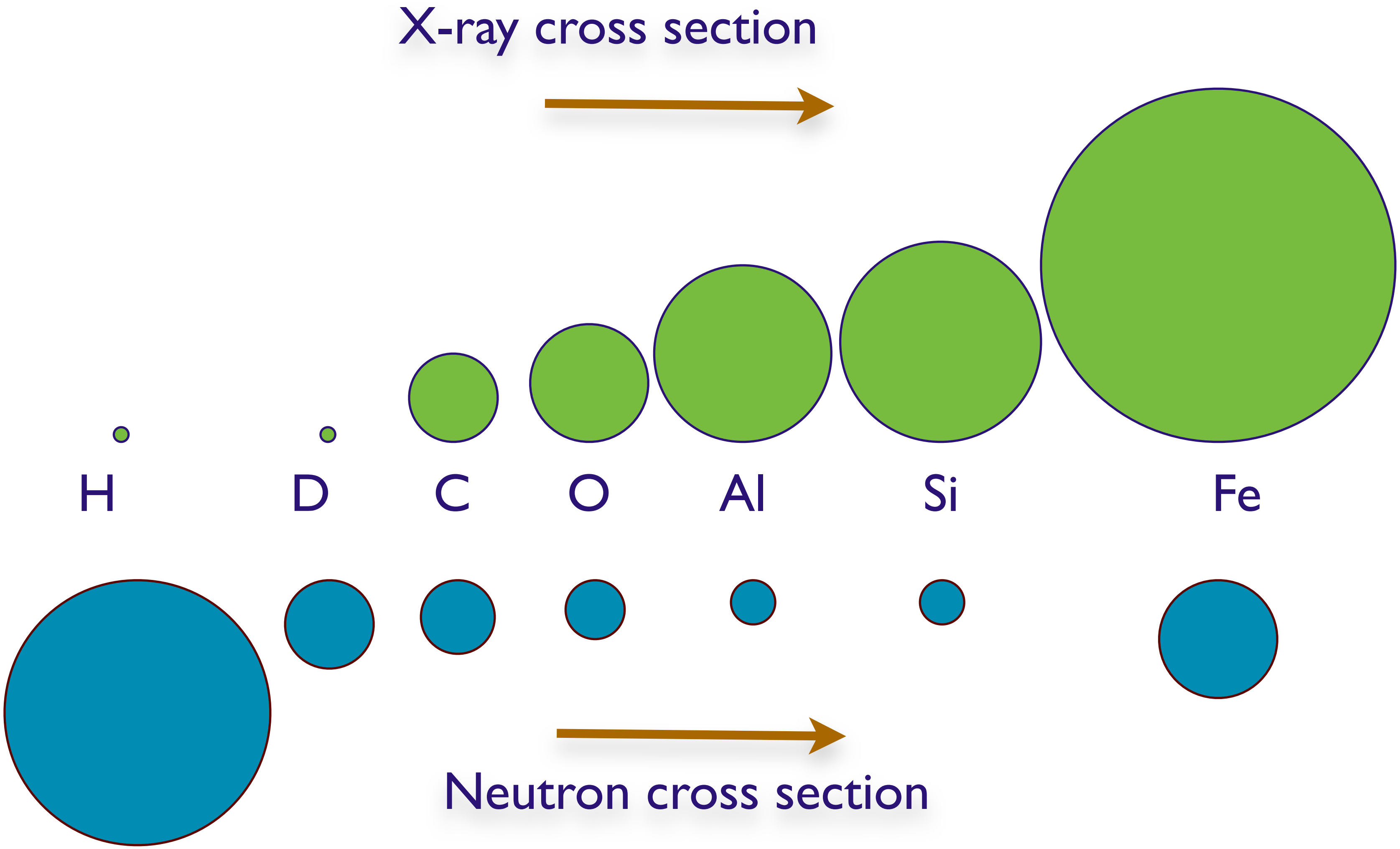


positive amplitude → 180° phase shift between the incoming and scattered waves

after „Neutron Diffraction“
G. E. Bacon

negative amplitudes → resonant scattering

for ^{1}H, ^{7}Li, Ti, V (almost zero), Mn

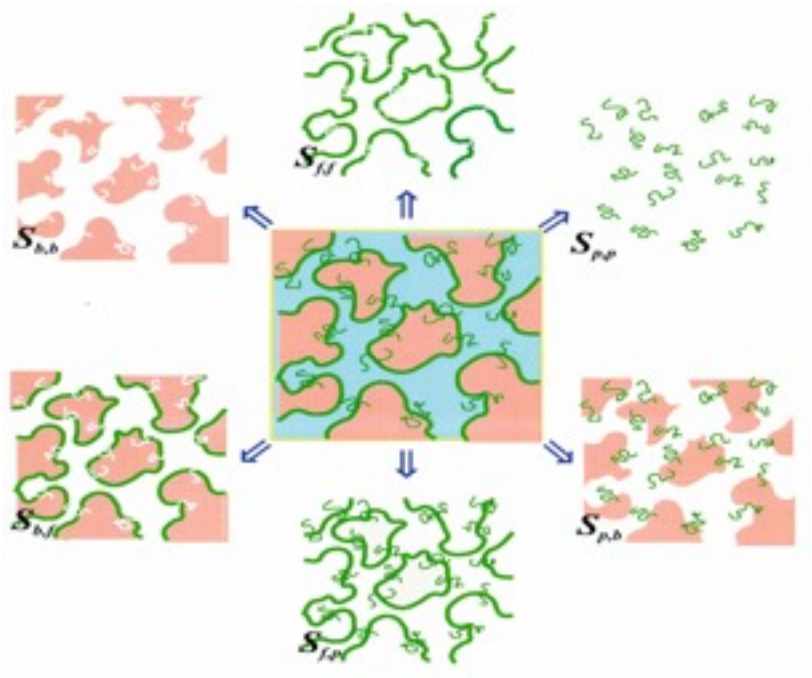

X-ray cross section

Neutron cross section

exemple - hydrogen

big difference in the coherent scattering lengths between H and D

different signs



contrast variation by adequate mixing of H and D

Fully ordered perovskite arrangement

$Ce_3InN_{0.92\pm0.01}$ according to Rietveld refinement,

$Ce_3InN_{0.91\pm0.02}O_{0.05\pm0.01}$ according to elemental analysis

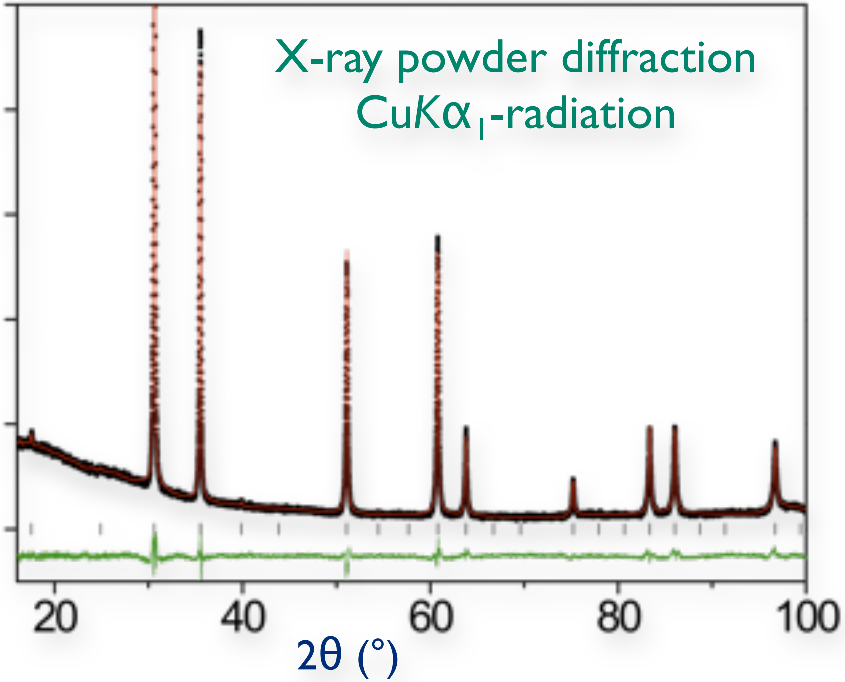
neutrons see the nitrogens!

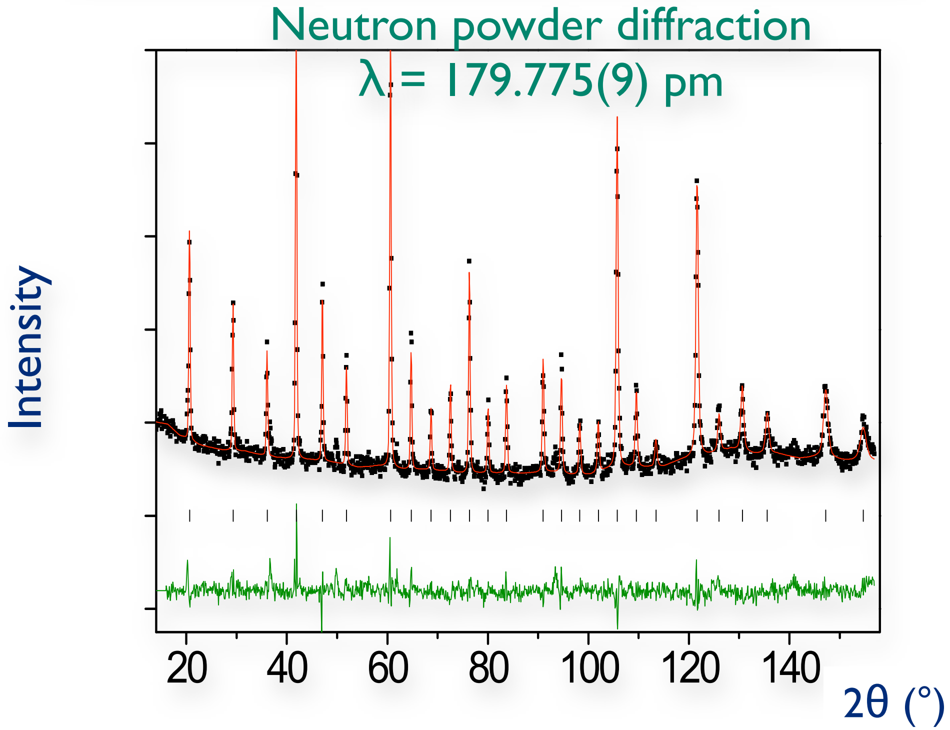
b_{Ce} = 0.48 z=58

b_{In} = 0.41 z=49

b_{N} = 0.94 z=7

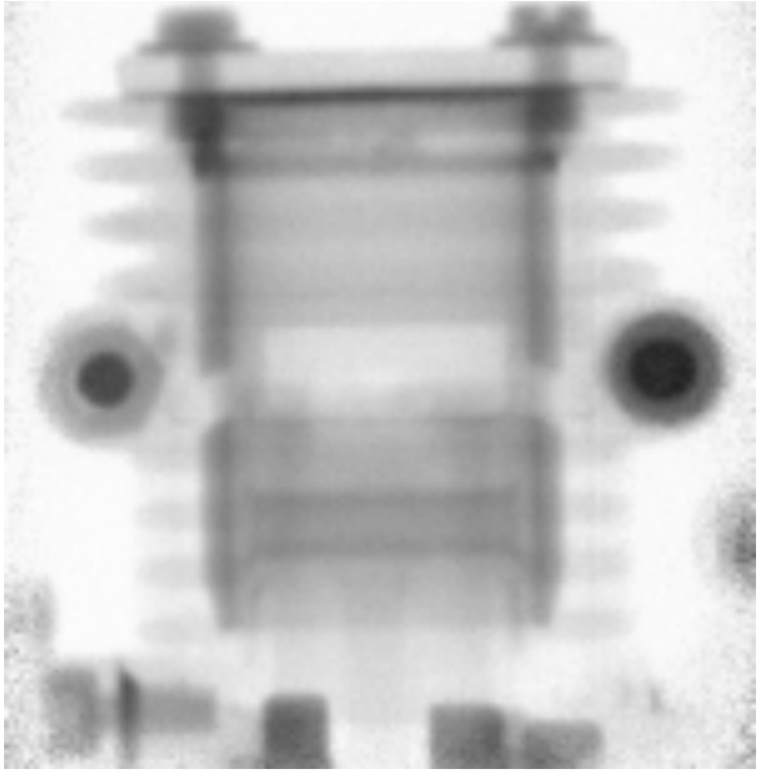
$Pm\bar{3}m$, a = 504.98(2) pm





Martin Kirchner, Walter Schnelle, Frank R. Wagner and Rainer Niewa in Solid State Sciences, 2003

typical penetration depths of thermal neutrons range from mm to cm



bulk properties

imaging of heavy and bulky samples
motors - rotors - batteries

complex sample environments

engine at function (N. Kardjilov et al)

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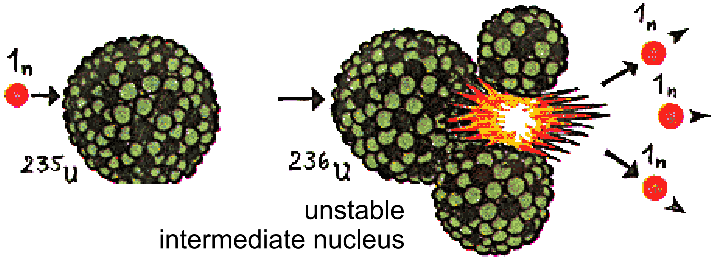
neutron production

fission - reactors

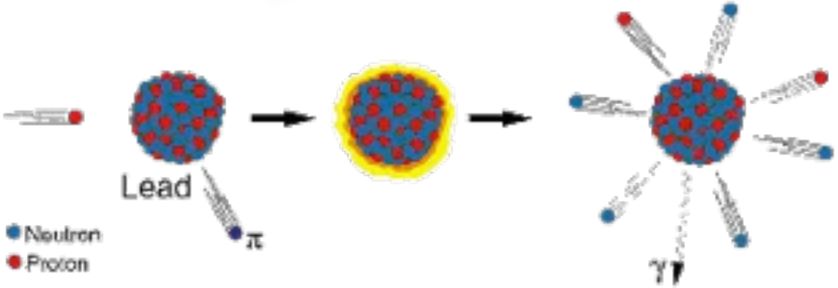


slow neutron capture
of ^{235}U

continuous sources

except Dubna

spallation

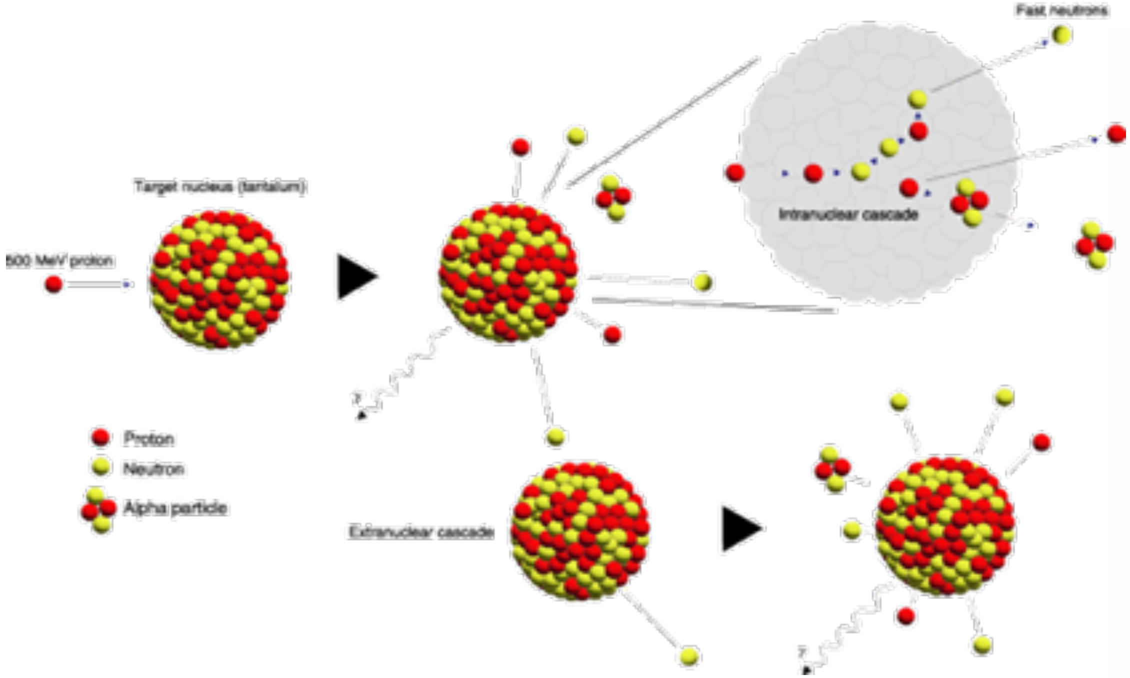


nuclei bombarded with
high energy particles

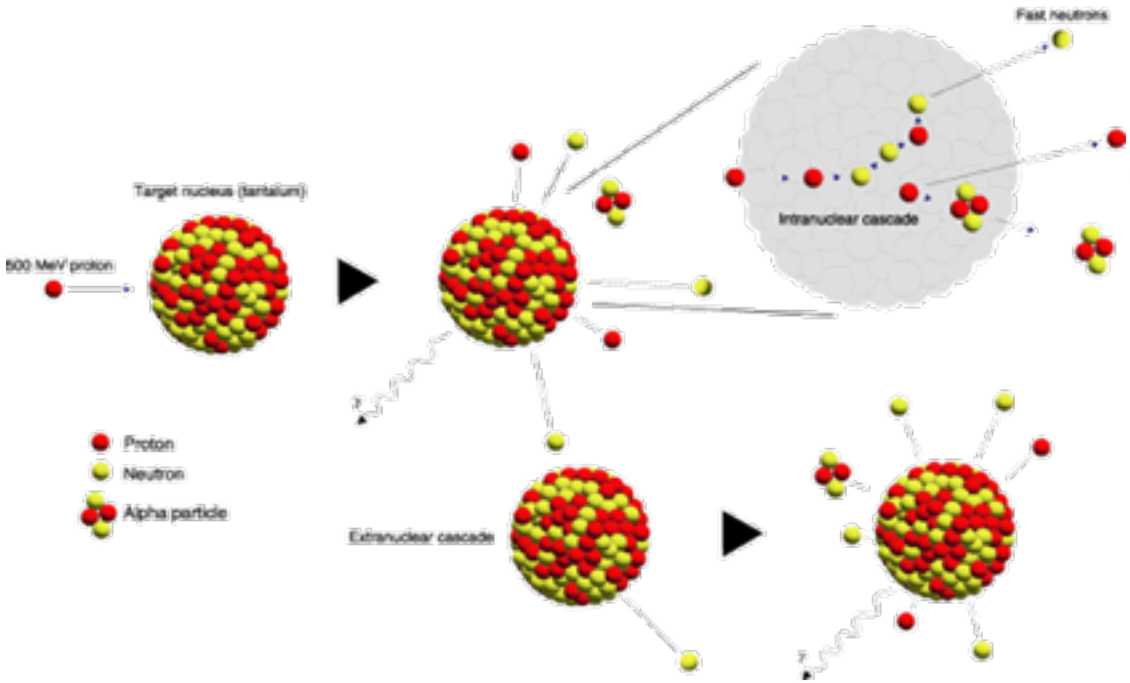
pulsed sources

except PSI

spallation


Target nucleus (tantalum)
500 MeV proton
Fast neutrons
Intranuclear cascade
Proton
Neutron
Alpha particle
Extranuclear cascade

spallation



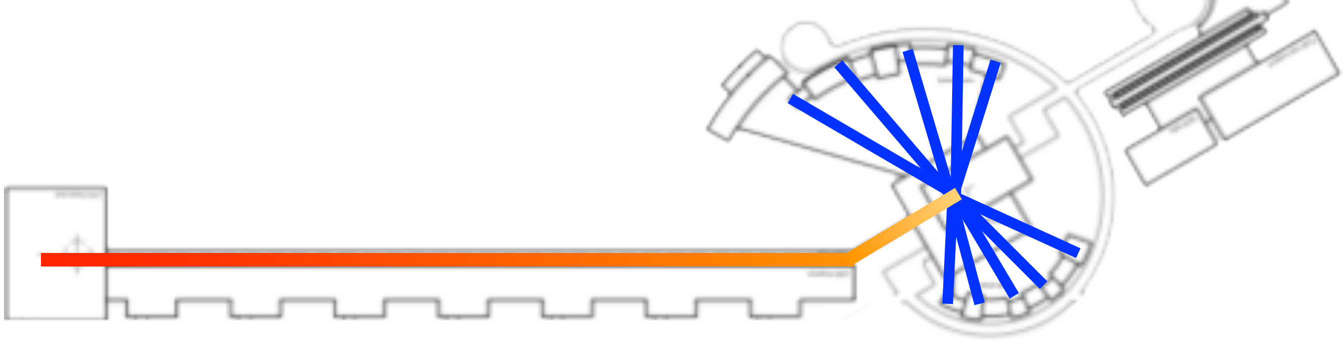
European Spallation Source

1.3 GeV protons

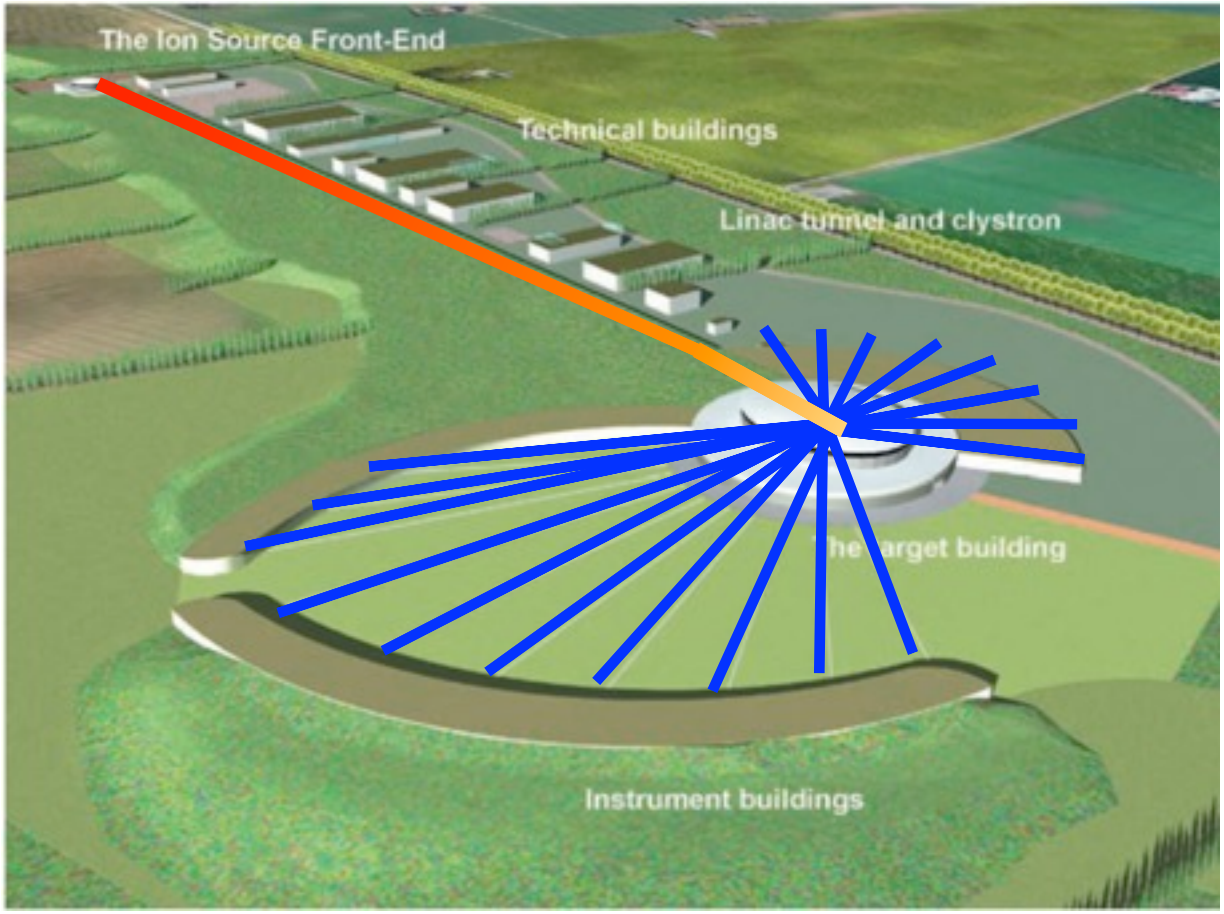
5 MW average beam power

Long Pulse: 16.6 Hz, 2 ms

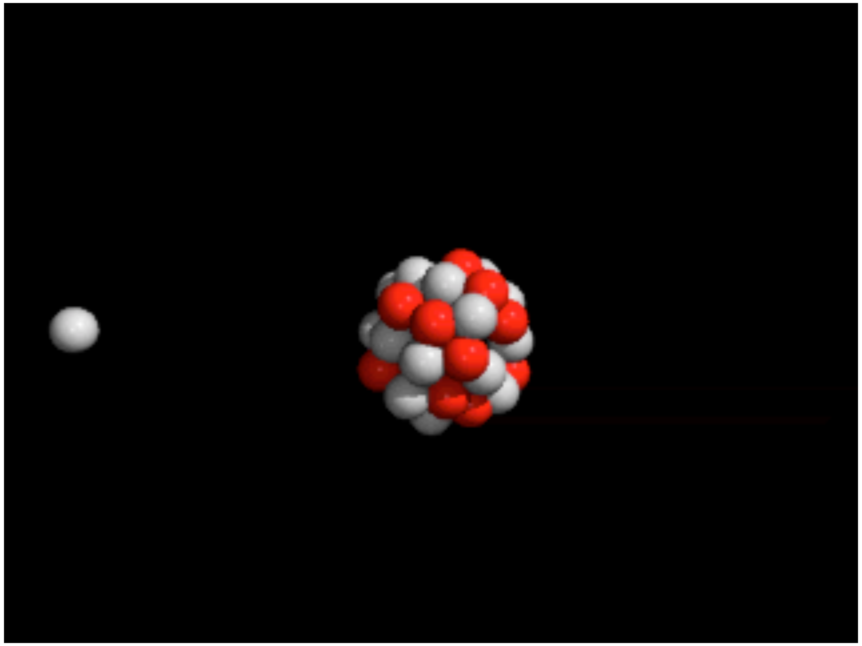
heavy metal target



EUROPEAN
SPALLATION
SOURCE



fission



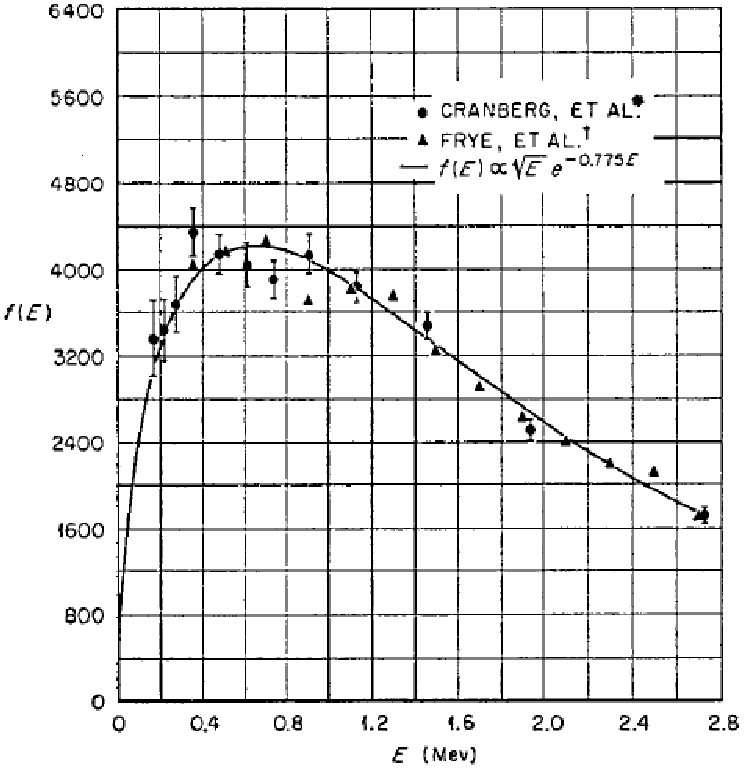
delivers 2-3 neutrons with energies of about

1 MeV

capture of a slow neutron by ^{235}U

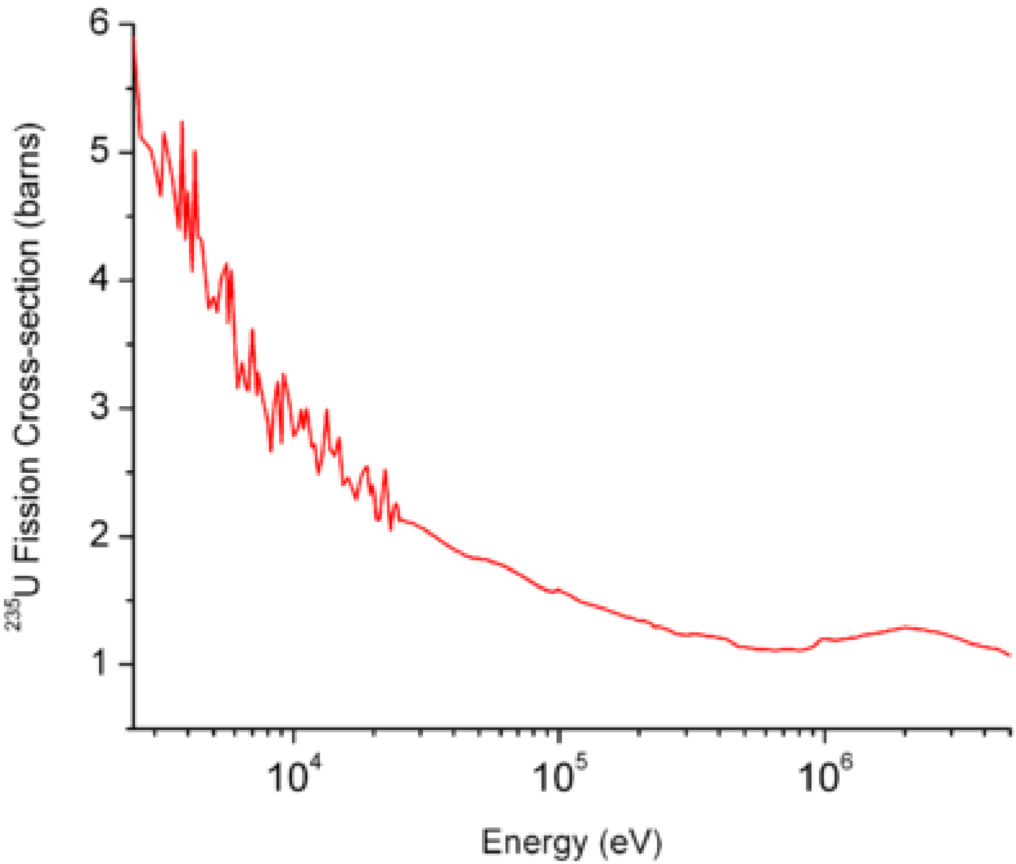
(source: atomicarchive.com)

energy distribution of fission neutrons

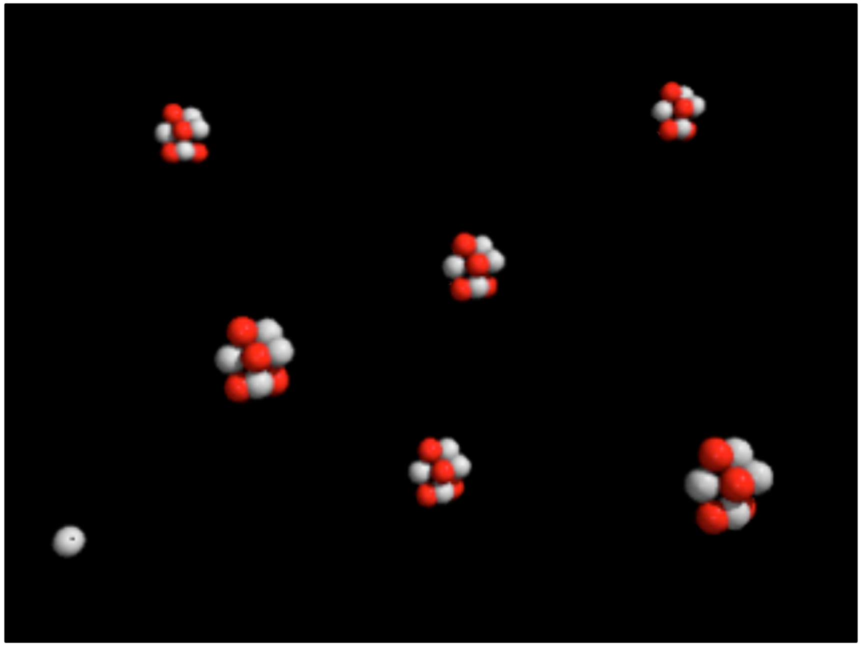


after A. M. Weinberg and E. P. Wigner, The Physical Theory of Neutron Chain Reactors, The University of Chicago Press (1958)

cross section (barns) of ^{235}U as a function of neutron energy



chain reaction



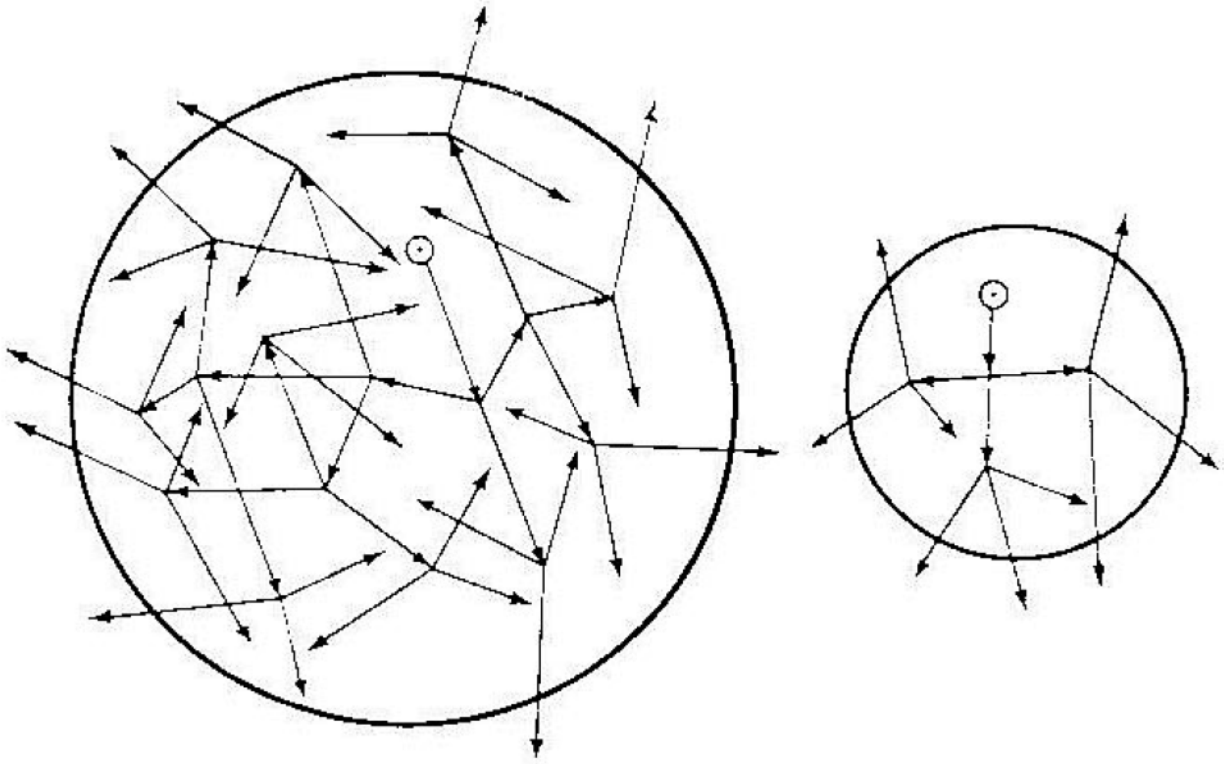
chain reaction

(source: atomicarchive.com)

fission neutrons must be slowed down (moderated) by the surrounding medium (moderator) before they are captured by other ^{235}U leading to a self-sustained "chain reaction"

The quantity of uranium necessary for a chain reaction is known as the critical mass, or the "critical size" of a particular pile.

critical mass



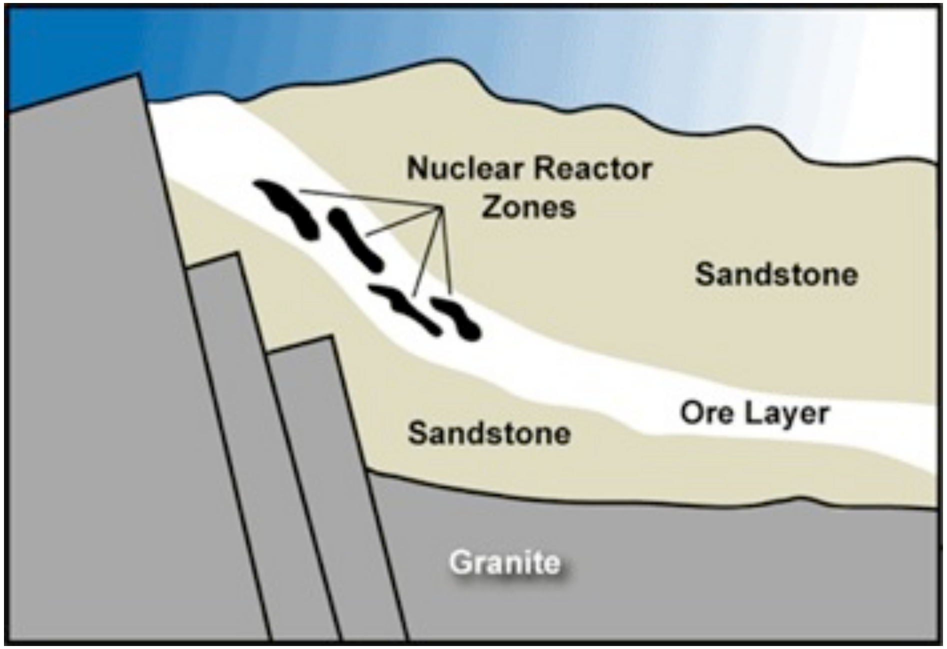
large volume intercepts more neutrons causing fissions, with smaller leakage from the surface, than a smaller volume

the first man made and controlled self sustained chain reaction

Chicago Pile 1 (CP1) diverged on 2.12.1942
part of the Manhattan project (E. Fermi and collaborators)

"If people could see what we're doing with a million-and-a-half of their dollars, they'd think we are crazy. If they knew why we are doing it, they'd know we are."

natural reactors

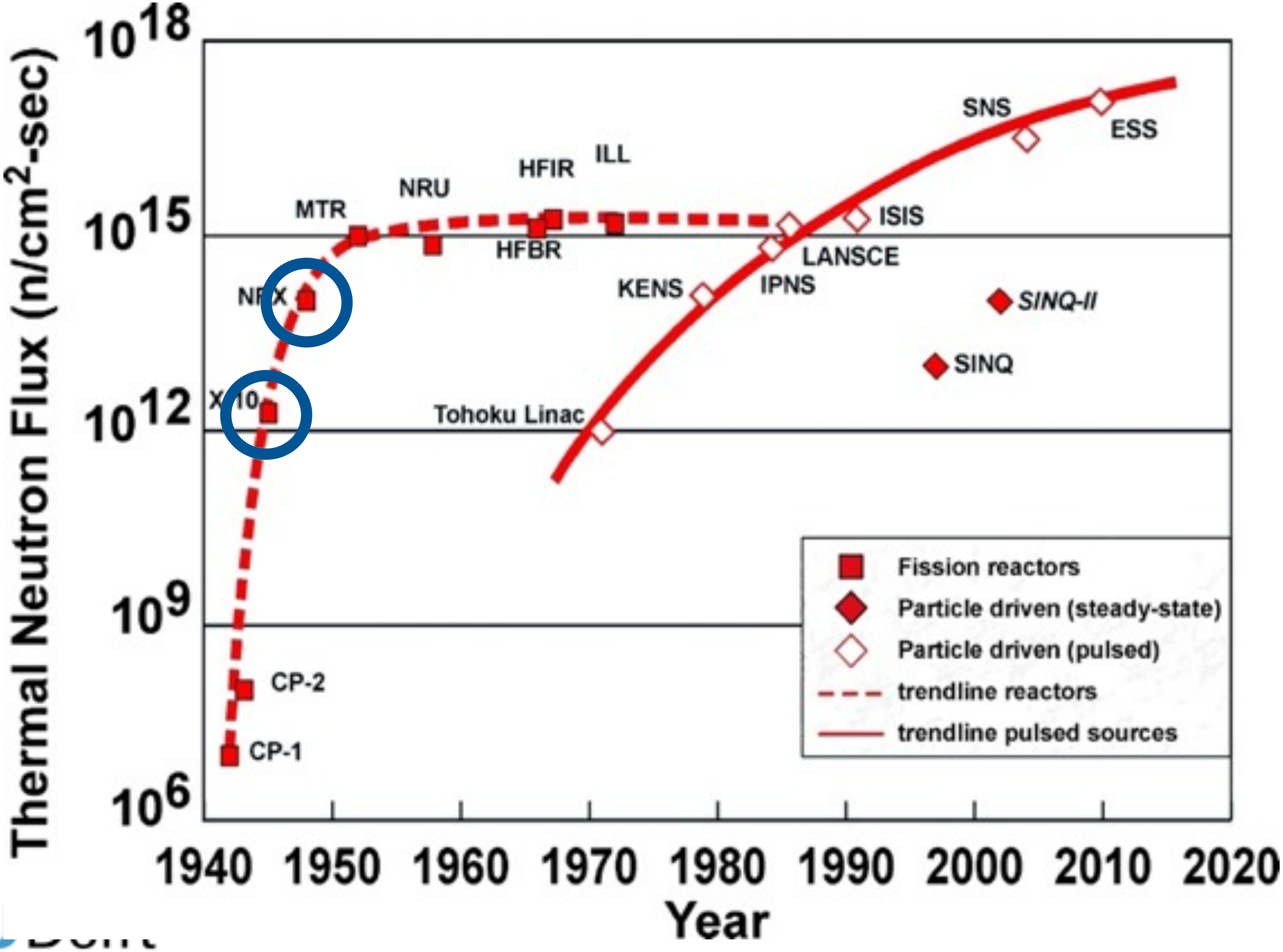


- active 2 billion years ago for 150 million years at a average power of 100 KW
- worked on a 30-minute reaction cycle, accompanied by a 2.5-hour dormant period, or cool-down

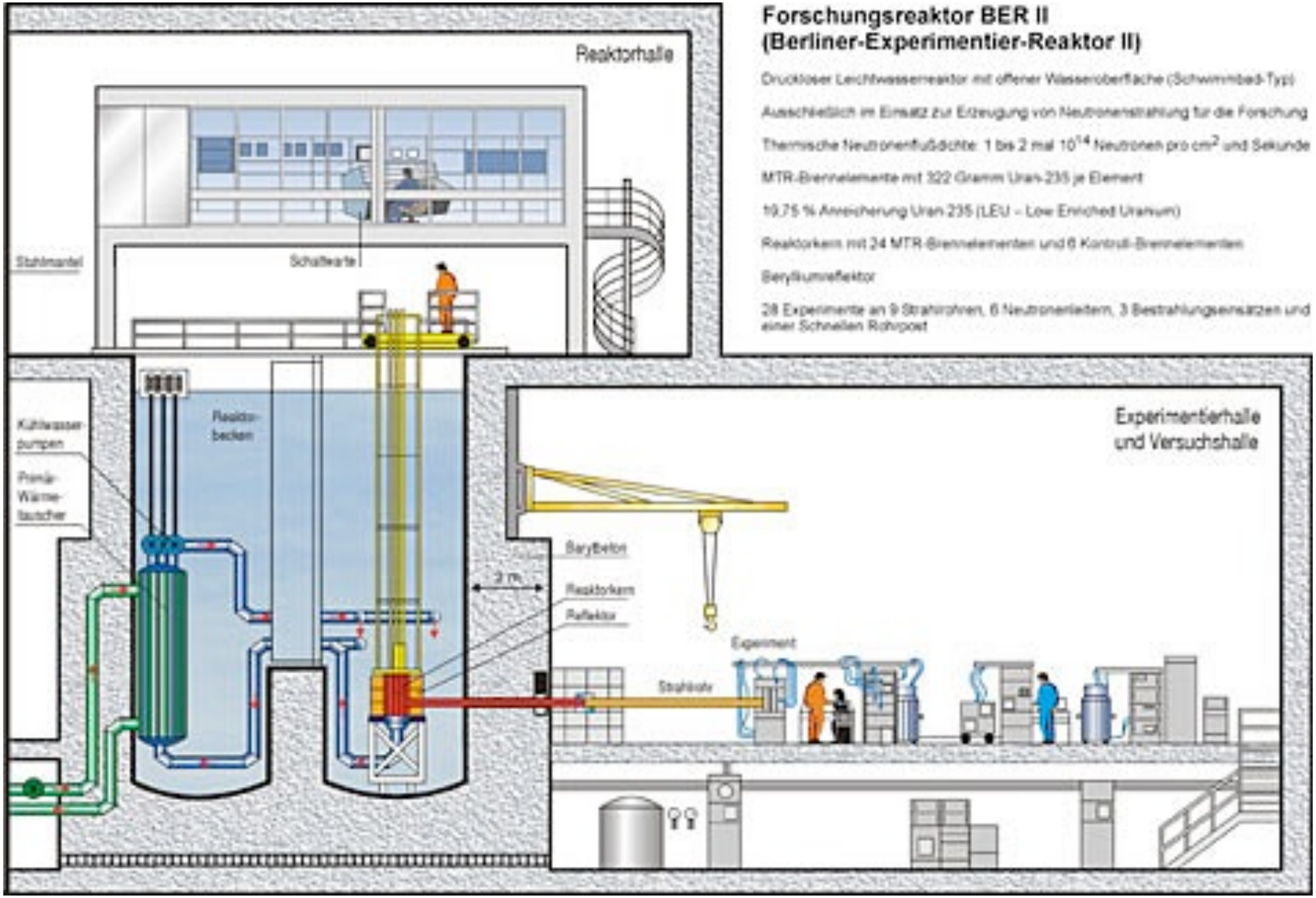
The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.

A. P. Meshik, et al, PRL 2004

evolution of the neutron flux



source: ESS



Forschungsreaktor BER II
(Berliner-Experimentier-Reaktor II)

Druckloser Leichtwasserreaktor mit offener Wasseroberfläche (Schwimmbad-Typ)

Ausschließlich im Einsatz zur Erzeugung von Neutronenstrahlung für die Forschung

Thermische Neutronenflußdichte: 1 bis 2 mal 10^{14} Neutronen pro cm^2 und Sekunde

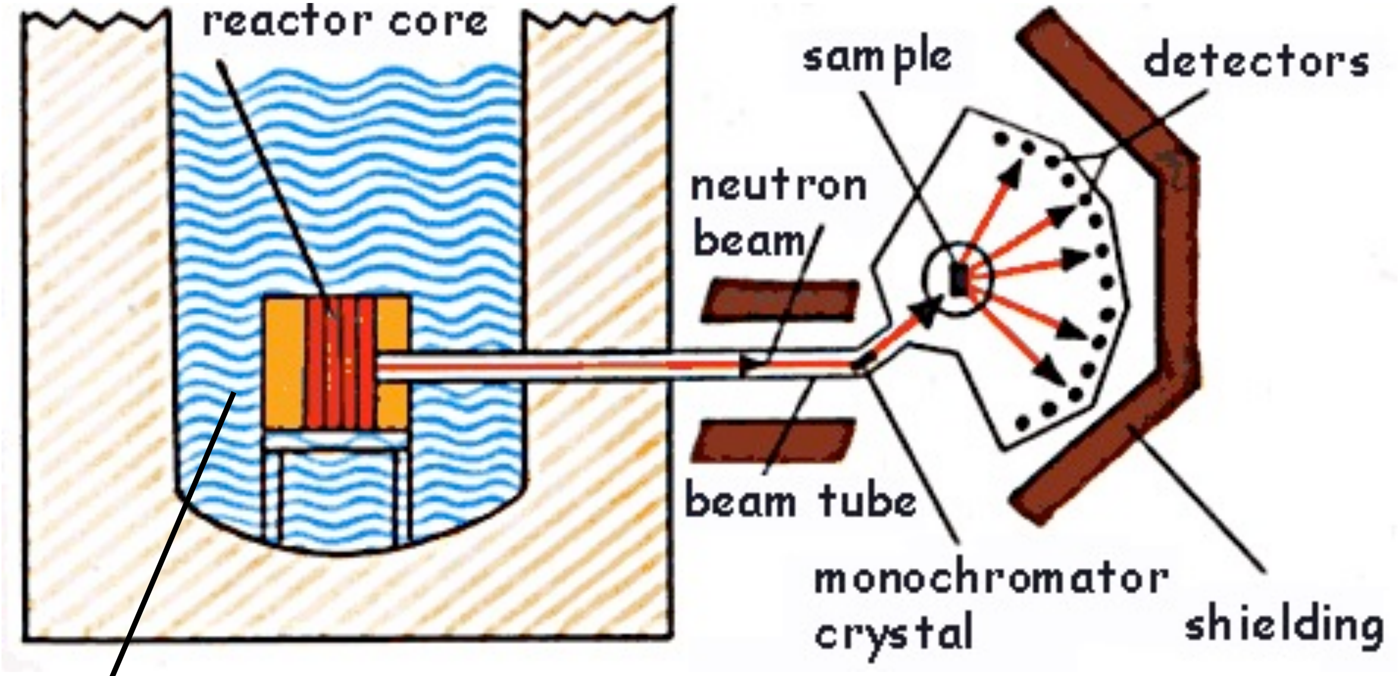
MTR-Brennelemente mit 322 Gramm Uran-235 je Element

19,75 % Anreicherung Uran 235 (LEU – Low Enriched Uranium)

Reaktorkern mit 24 MTR-Brennelementen und 6 Kontroll-Brennelementen

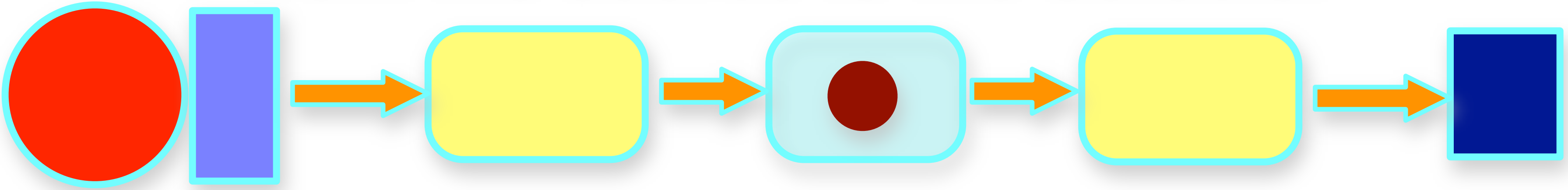
Berylliumreflektor

28 Experimente an 9 Strahlrohren, 6 Neutronenleitern, 3 Bestrahlungseinsätzen und einer Schnellen Rohrpost



moderator - reflector

from the source to the detector



source

moderator

PSE IN

sample and
sample environment

PSE OUT

detector

Neutron flux

$$\varphi = \Phi\ \eta\ \boxed{dE\ d\Omega} / 4\pi$$

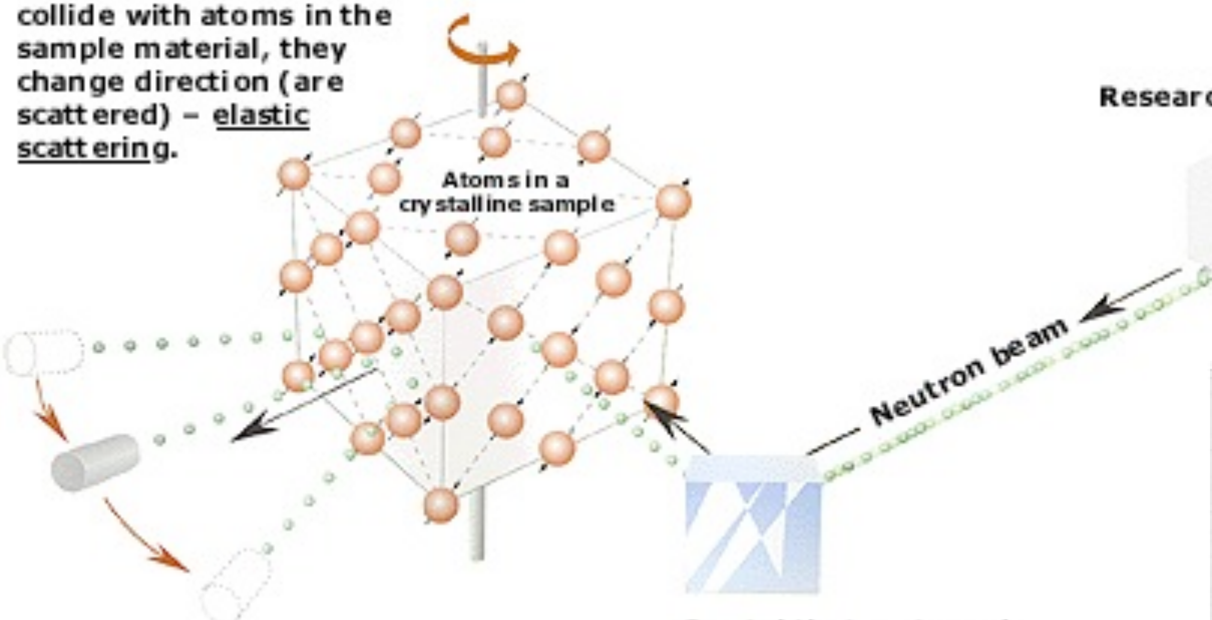
source flux distribution

intensity losses

field of neutron instrumentation

definition of the beam : Q, E and polarisation

Neutrons show where atoms are



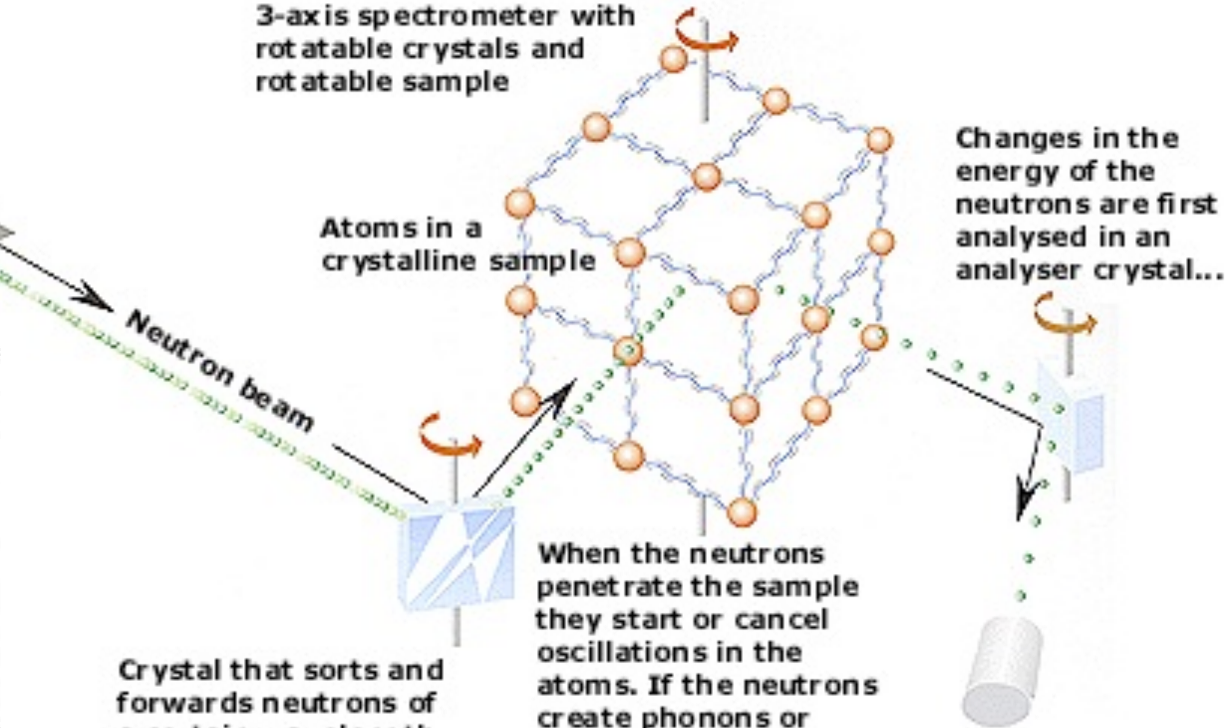
When the neutrons collide with atoms in the sample material, they change direction (are scattered) – elastic scattering.

Detectors record the directions of the neutrons and a diffraction pattern is obtained.
The pattern shows the positions of the atoms relative to one another.

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

Clifford G. Shull

Neutrons show what atoms do



3-axis spectrometer with rotatable crystals and rotatable sample

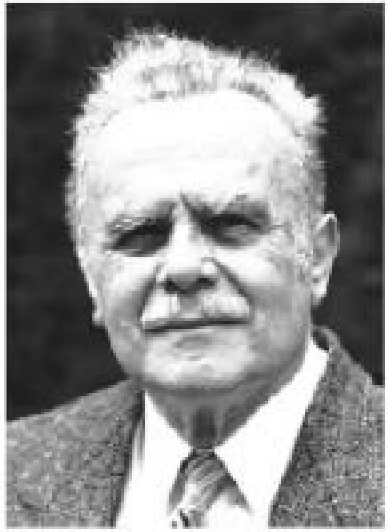
Atoms in a crystalline sample

Changes in the energy of the neutrons are first analysed in an analyser crystal...

Crystal that sorts and forwards neutrons of a certain wavelength (energy) – monochromatized neutrons

When the neutrons penetrate the sample they start or cancel oscillations in the atoms. If the neutrons create phonons or magnons they themselves lose the energy these absorb – <u>inelastic scattering</u>

...and the neutrons then counted in a detector.

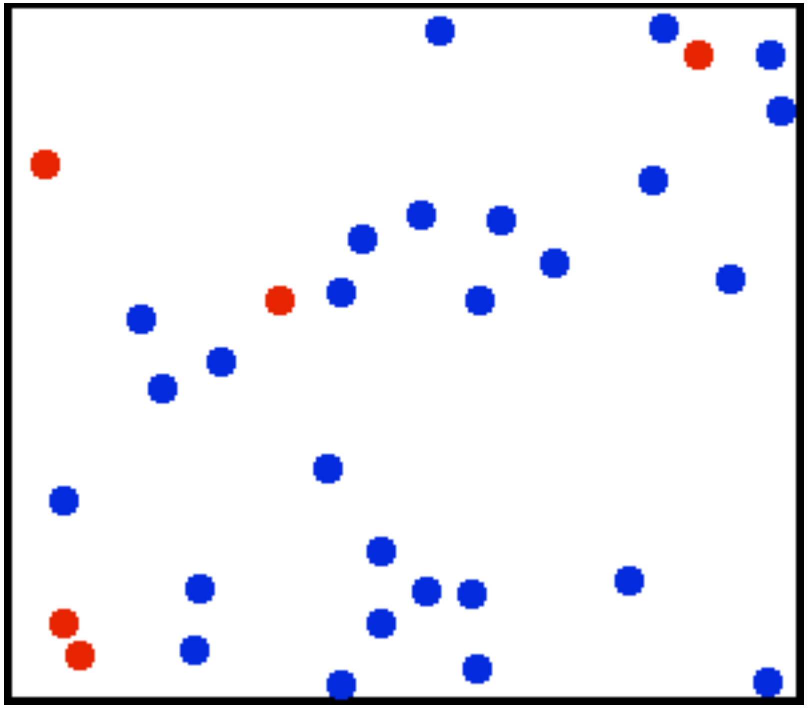


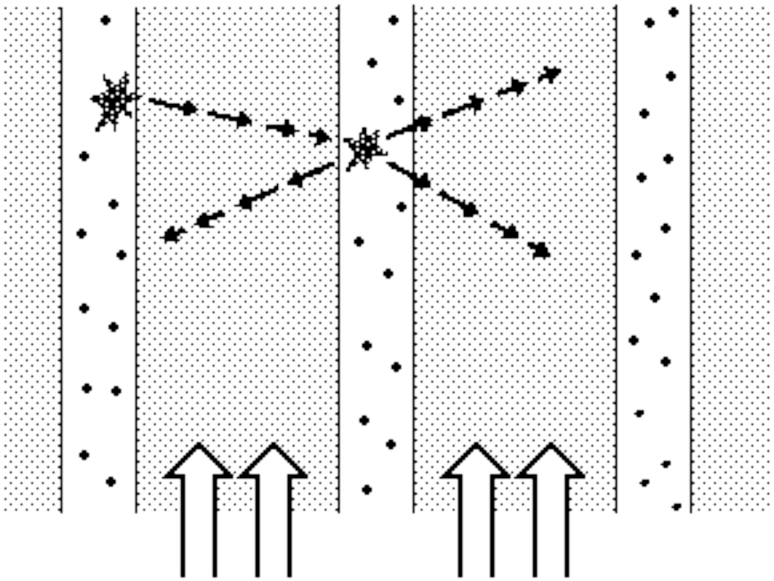
Bertram N. Brockhouse

- why neutrons
- neutron production
  - research reactors
- **neutron moderation**
- neutron optics

TU Delft

elastic collision of equal masses





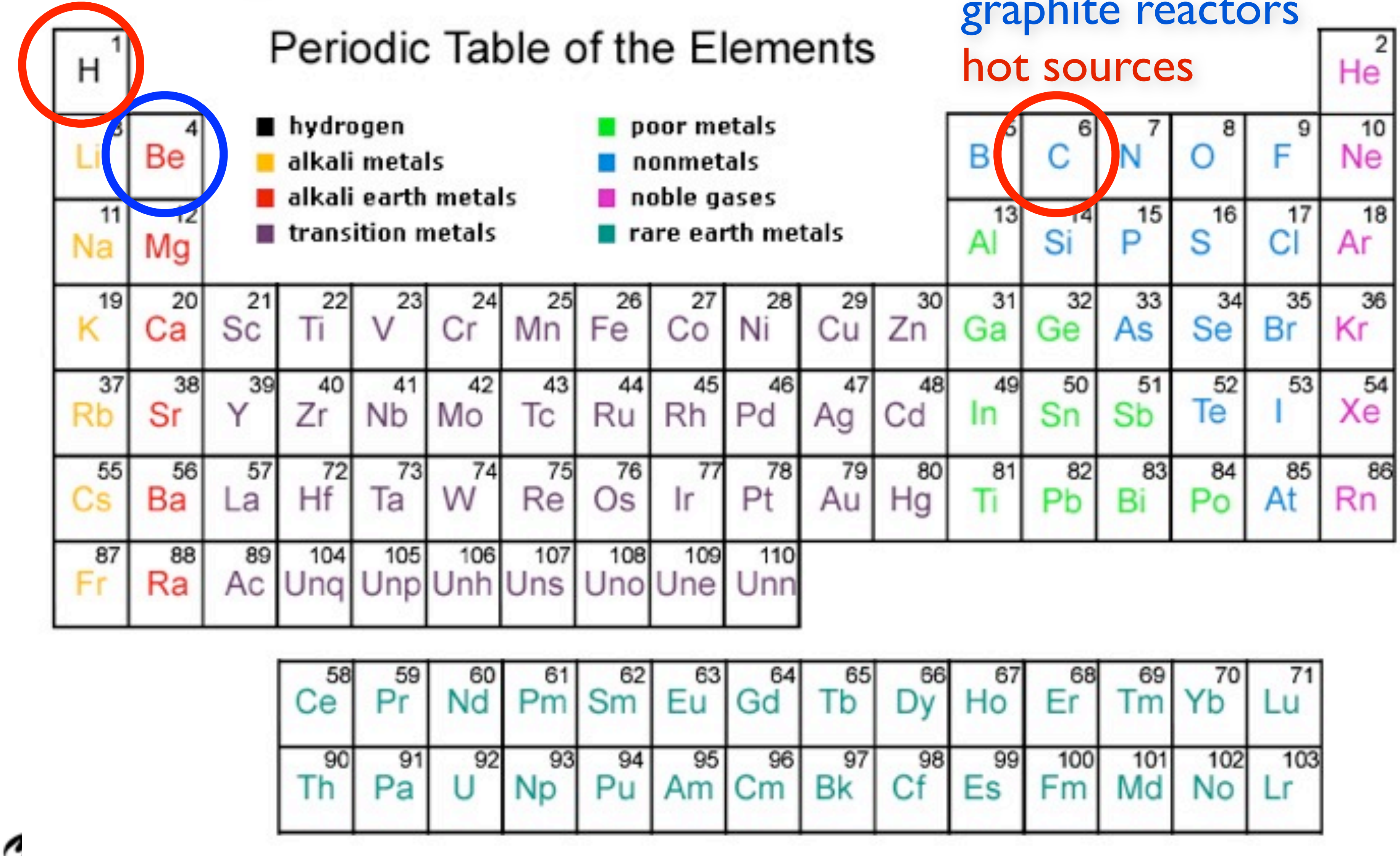
water as coolant and moderator flows between fuel rods.

H_2O L H_2

D_2O L D_2

graphite reactors

hot sources



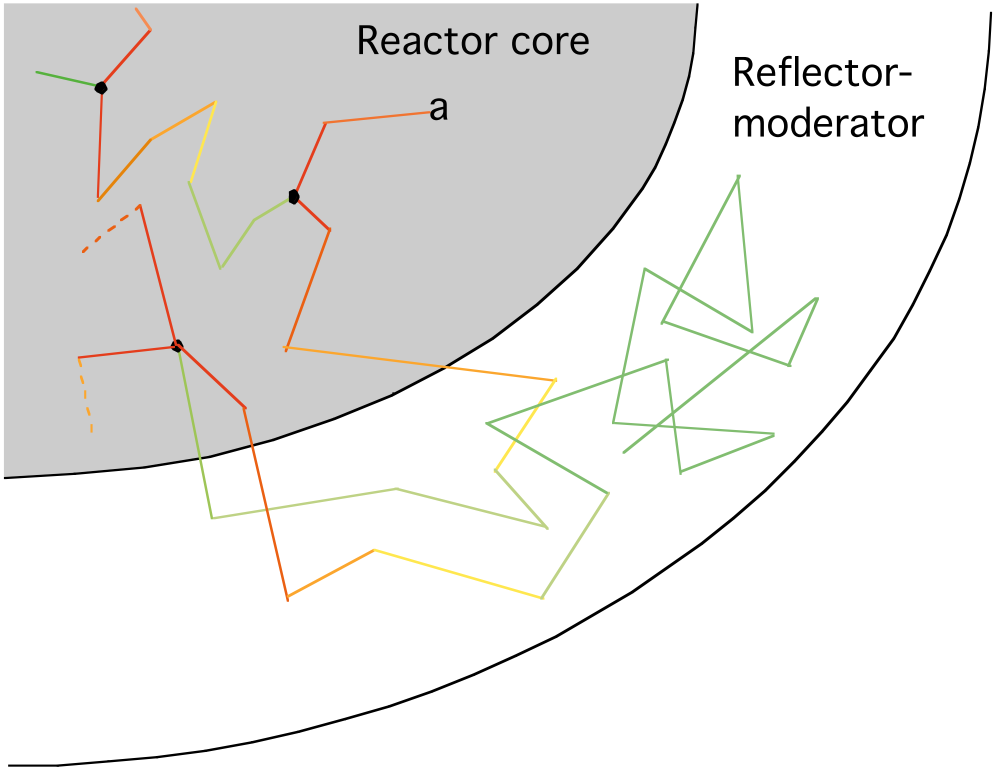
Periodic Table of the Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- ■ hydrogen
- ■ alkali metals
- ■ alkali earth metals
- ■ transition metals
- ■ poor metals
- ■ nonmetals
- ■ noble gases
- ■ rare earth metals

moderation process

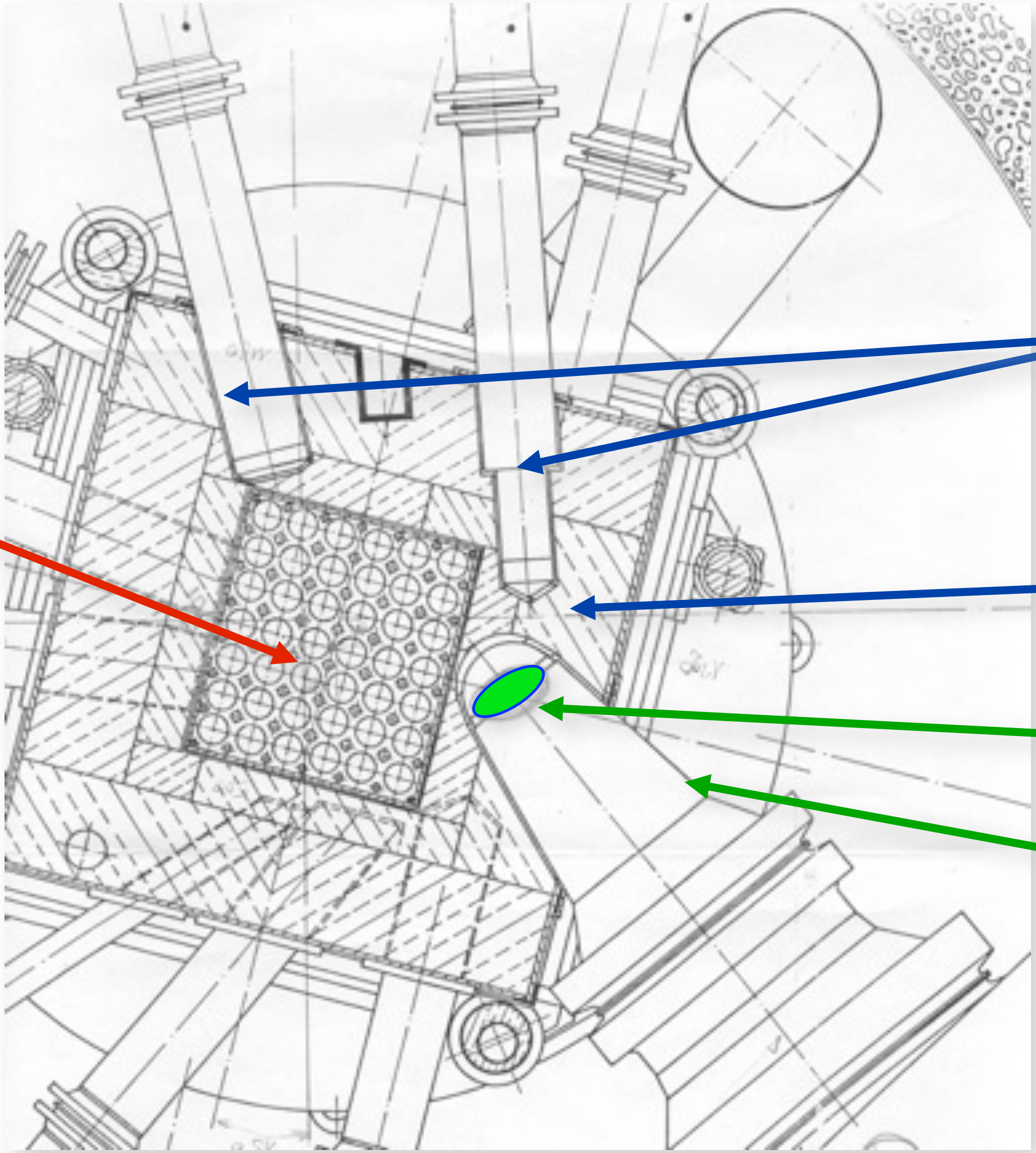


The fast neutrons produced by fission (heavy dots) lose energy by random collisions with the nuclei of the moderator and reflector.

Random walk-like trajectories outside the core are due to a series of collisions, which bring the neutrons in thermodynamic equilibrium with the reflector-moderator.

Some neutrons may return to the core and cause another fission. Others find their way into the neutron beams.
after J. M. Carpenter, Argonne National Laboratory

BER II core and cold source



reactor core

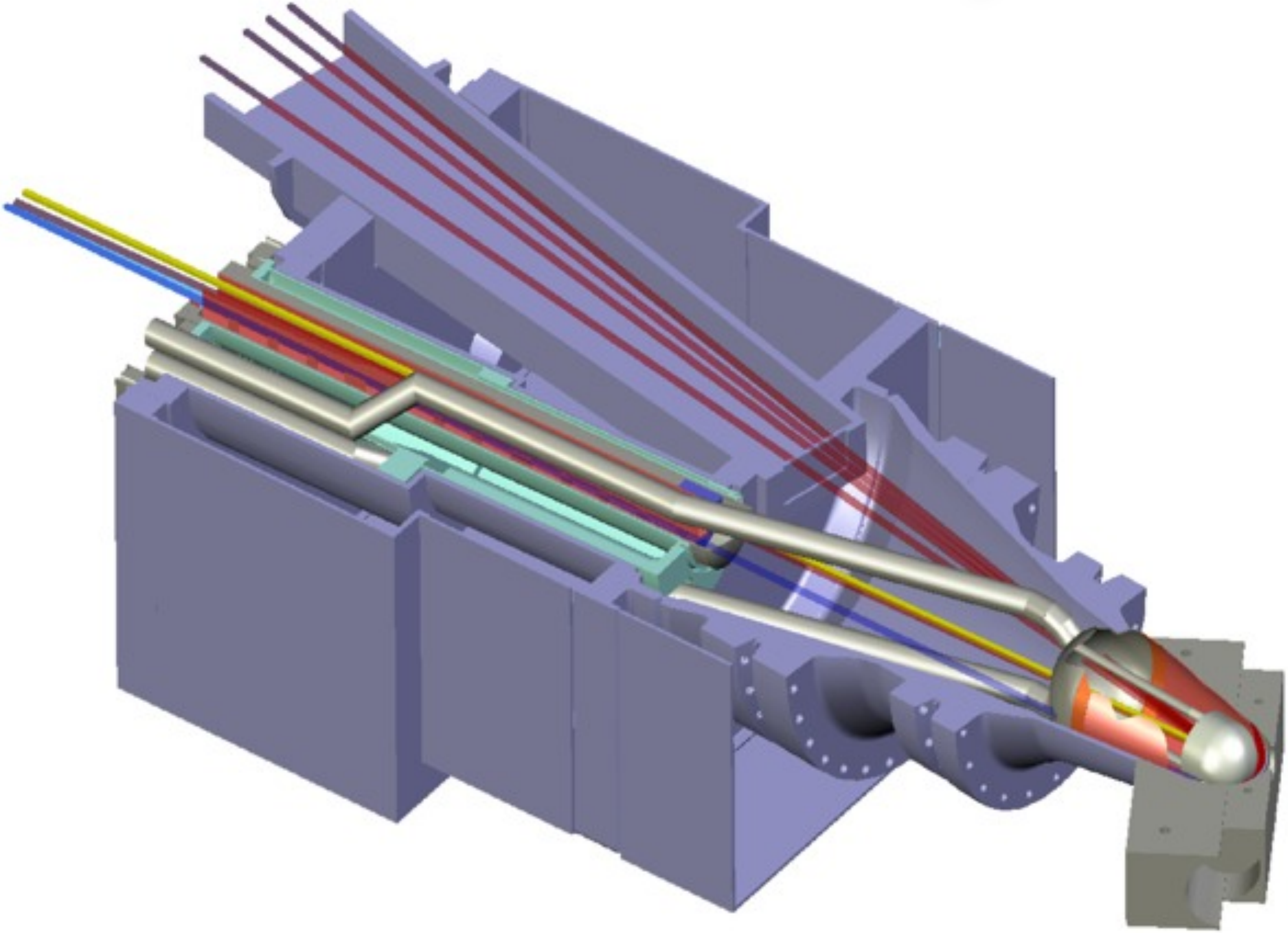
Thermal beam tubes

Thermal source (Be reflector)

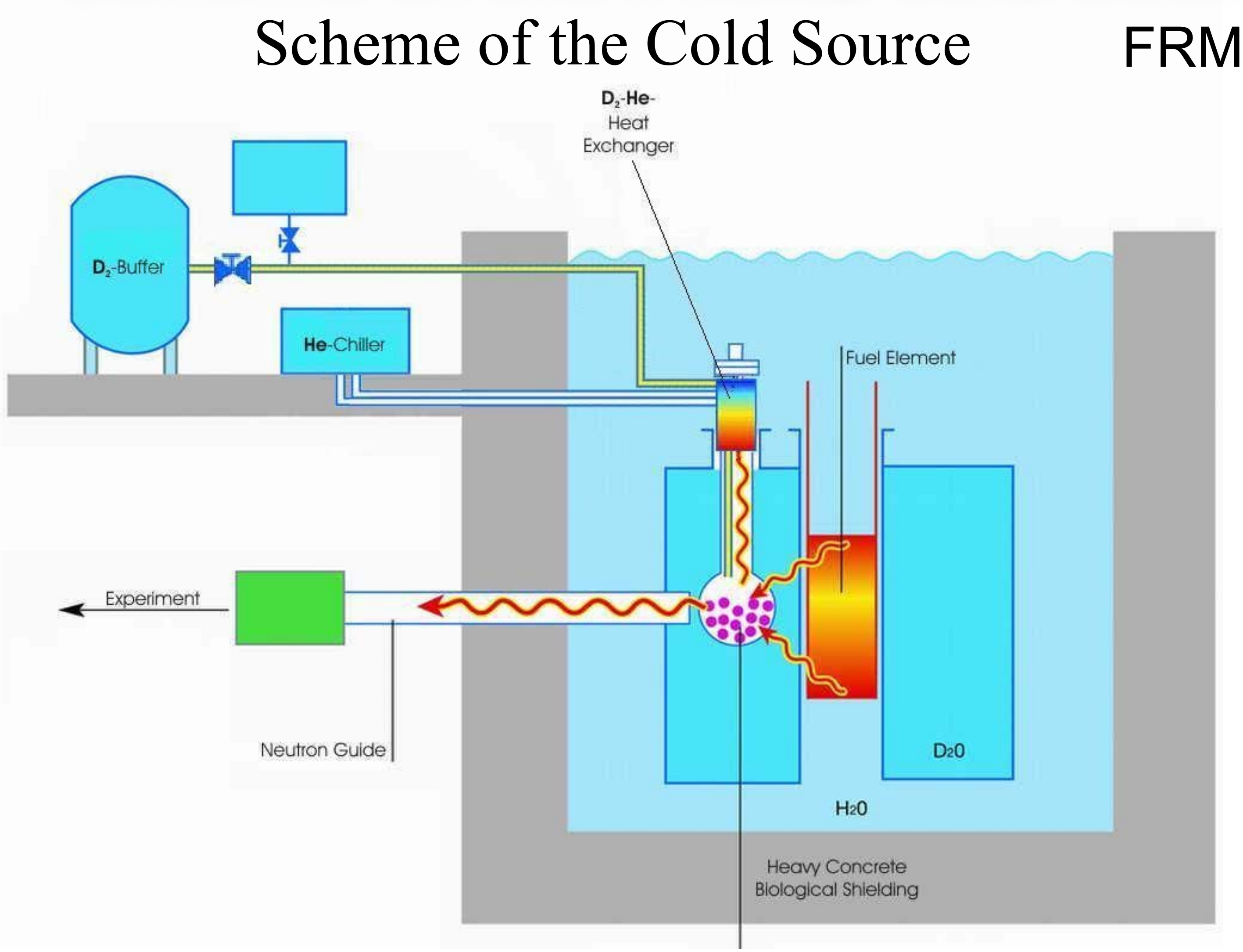
Cold source

Conical tube

cold neutron extraction system



scheme of the FRM2 cold source



FRM2 cold source

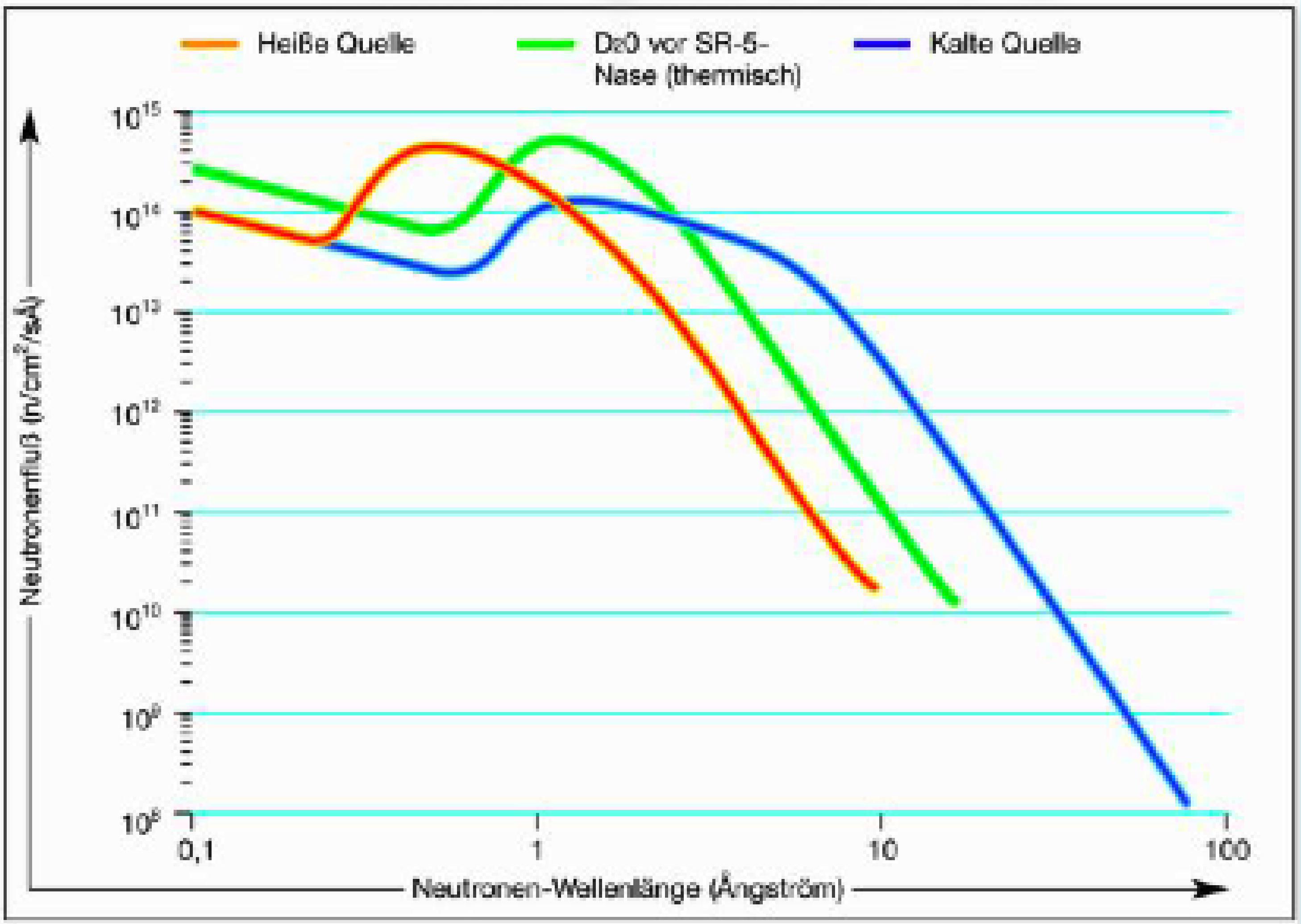
Liquid Deuterium Moderator

volume moderator vessel	25 liters
volume of liquid D_2	~ 13 liters
temperature	25 K

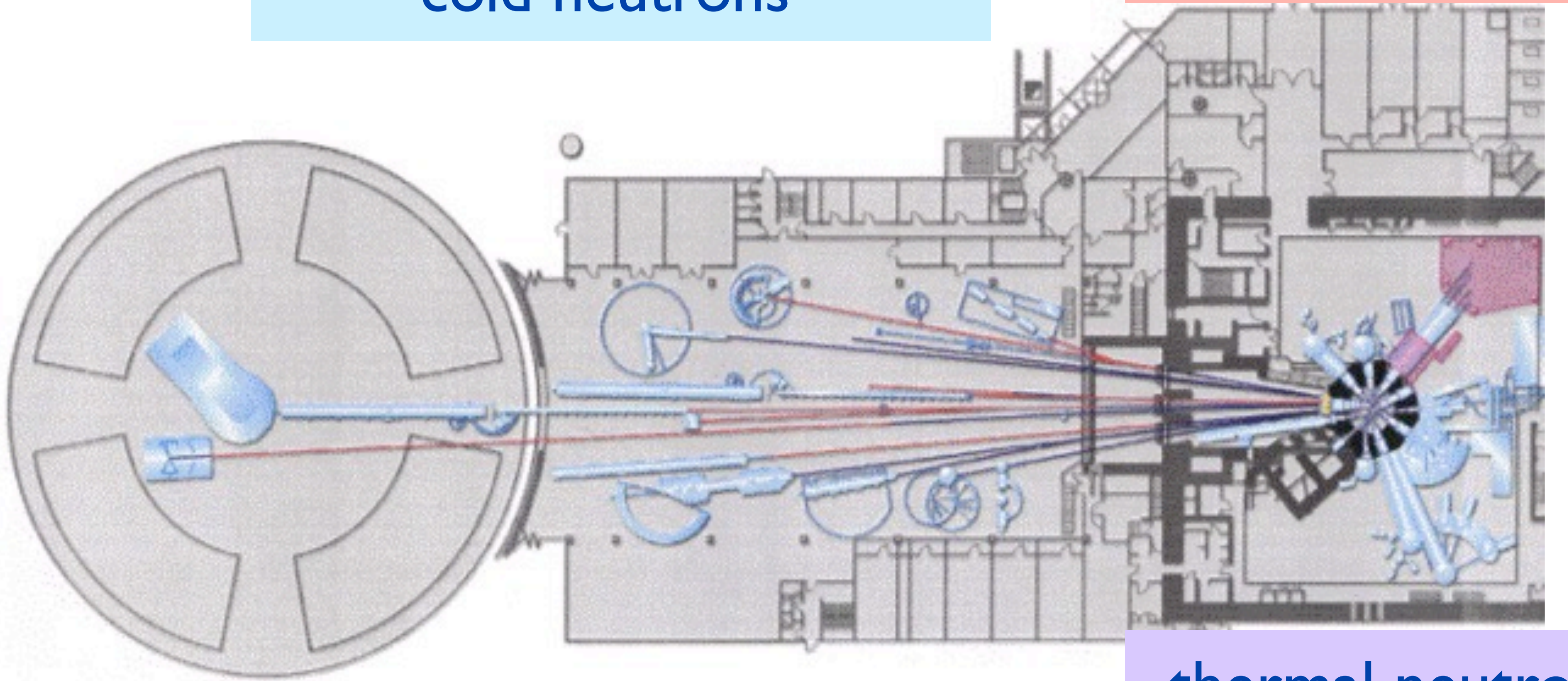
3 Beam Tubes
for cold neutron experiments

1 vertical Beam Tube
is not in use

neutron spectra at FRM2



FRM2 layout



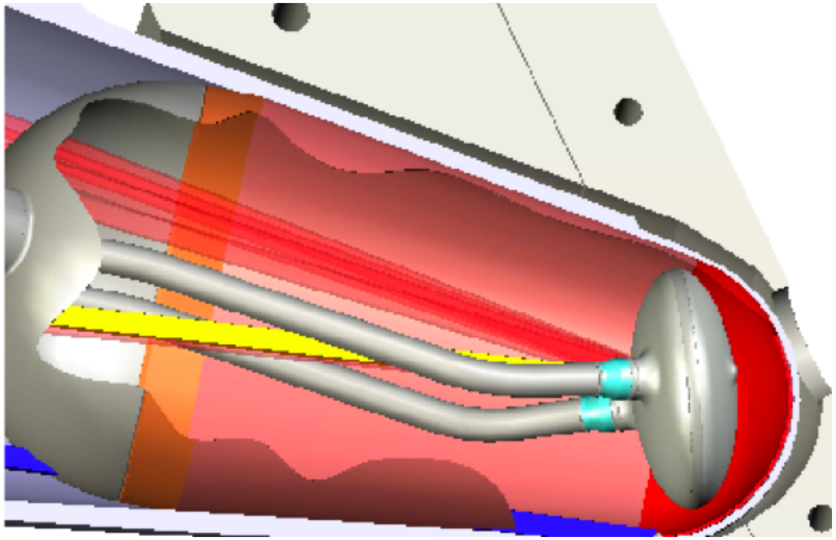
cold neutrons

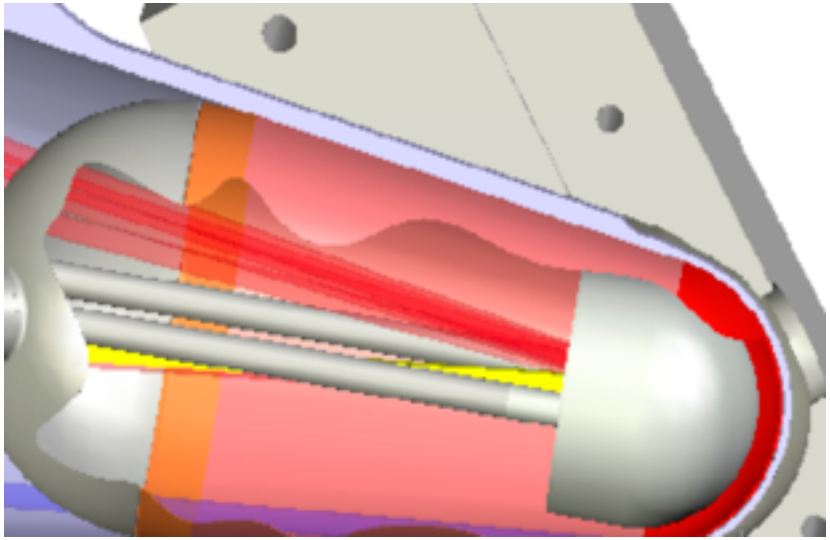
hot neutrons

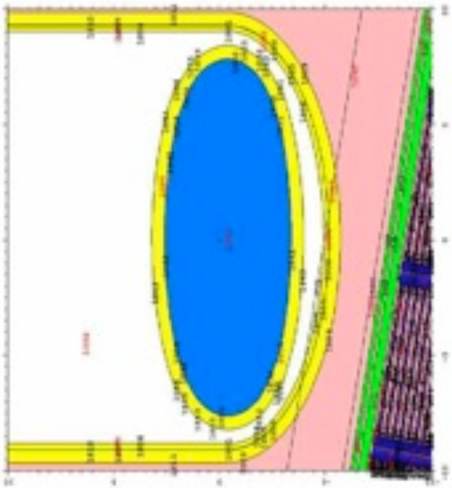
thermal neutrons

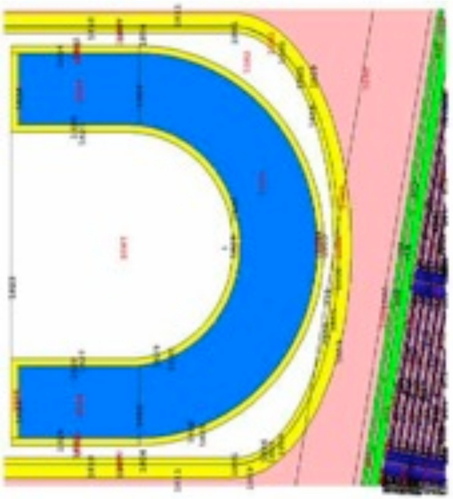
FRM2 layout

old and new designs for cold sources

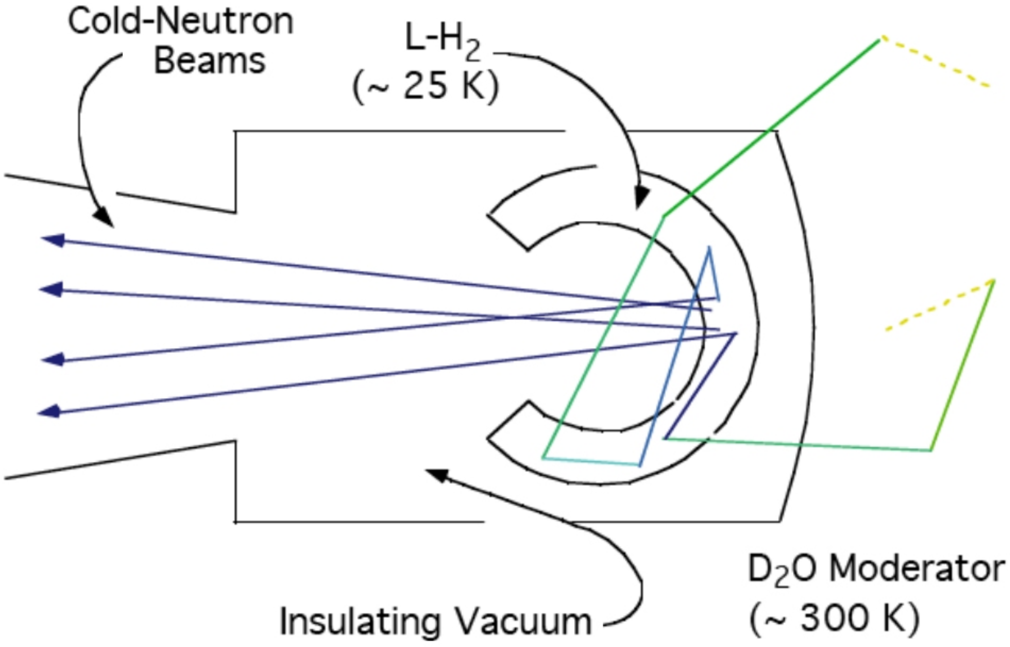


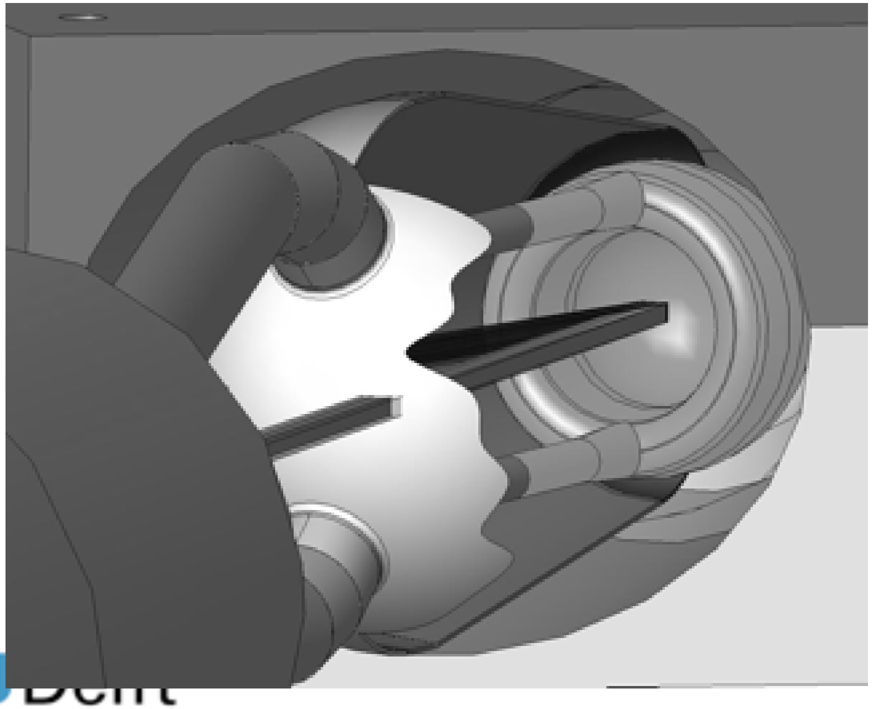




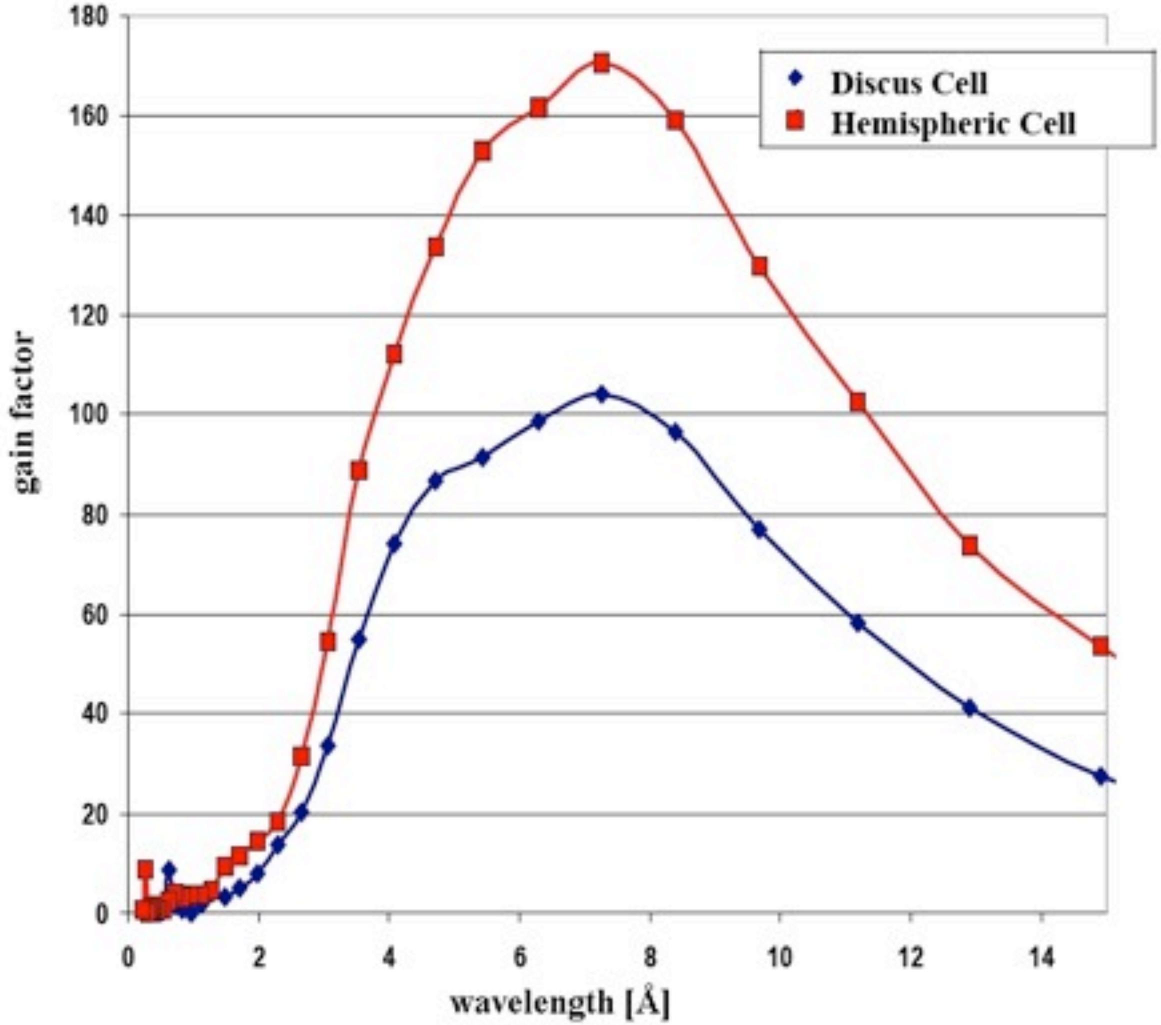


schematic representation of the moderation process

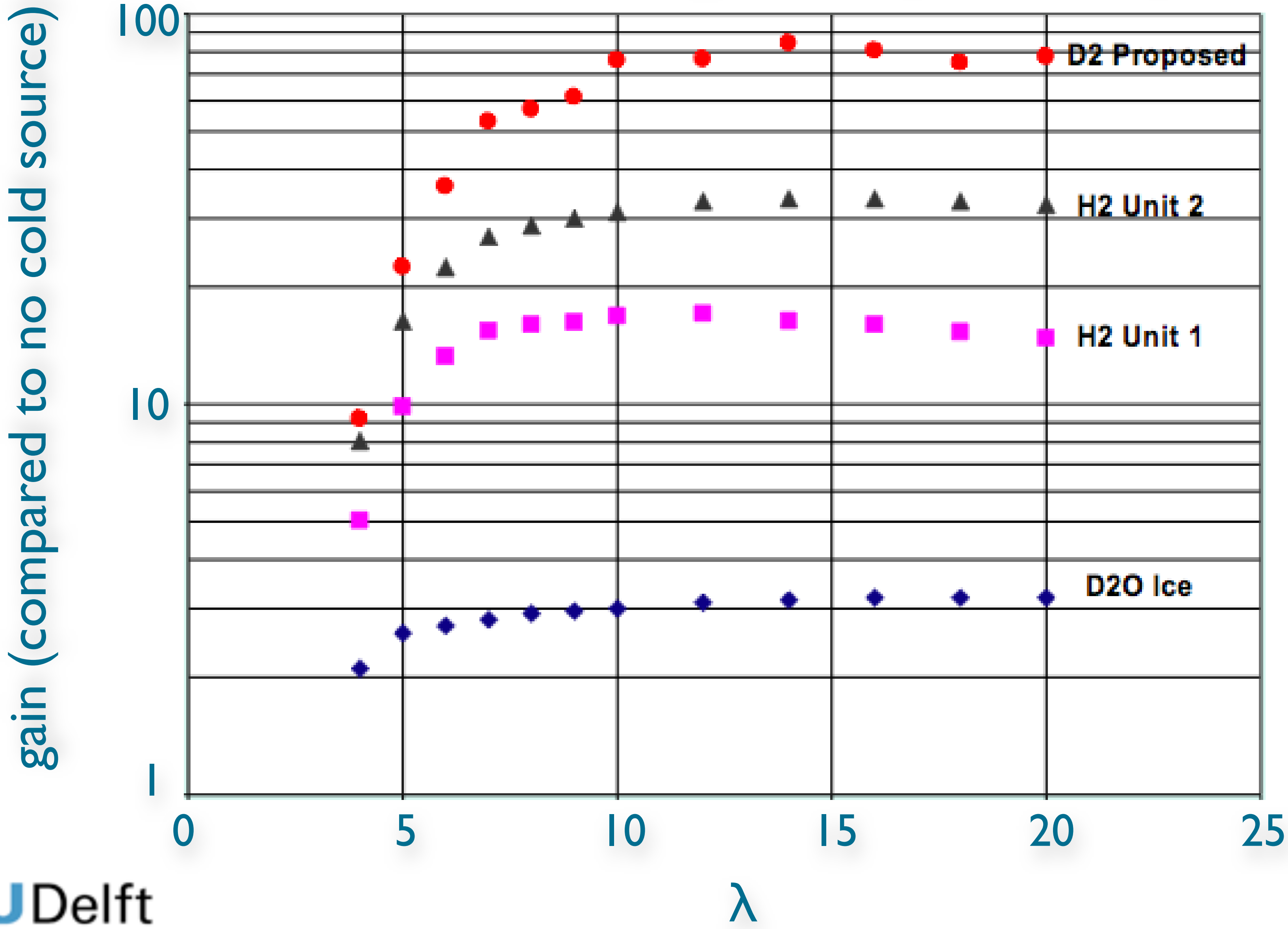




view of cold source

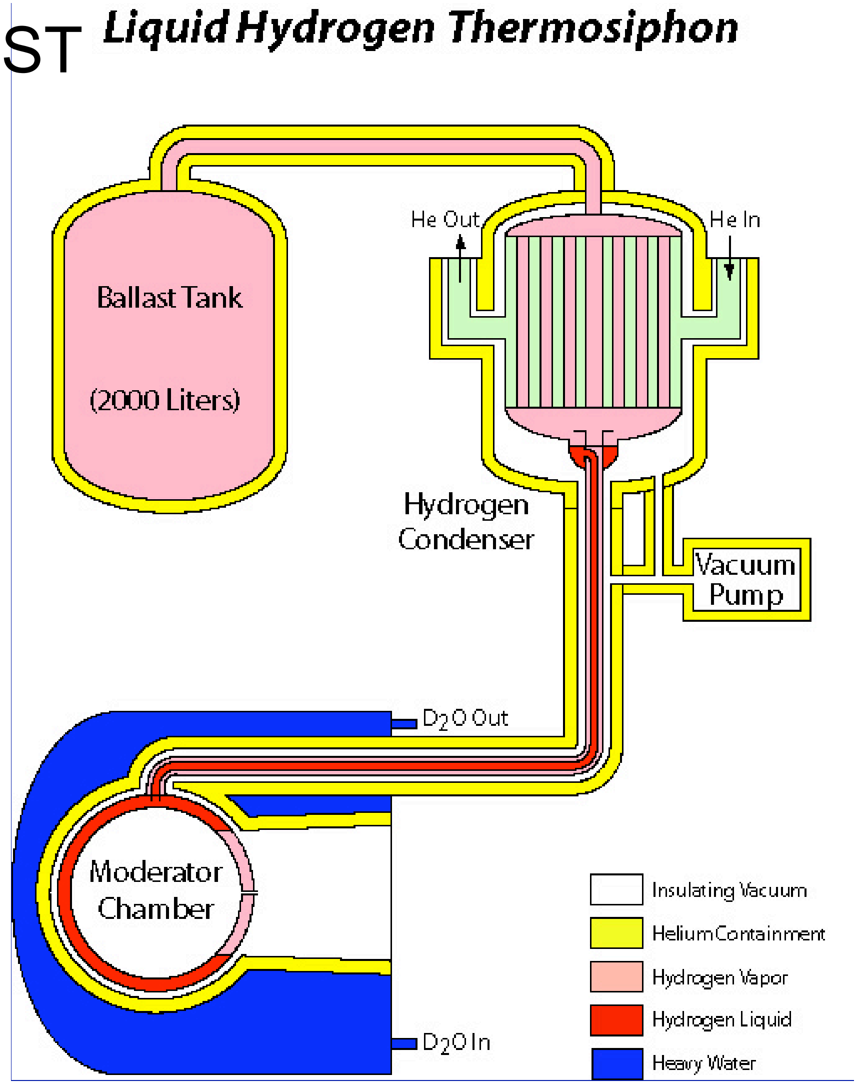

180
160
140
120
100
80
60
40
20
0
gain factor
0
2
4
6
8
10
12
14
wavelength [Å]
◆ Discus Cell
■ Hemispheric Cell

Neutron flux gains (@NIST)



The LD_2 source must also be passively safe, simple and reliable

NIST



Liquid Hydrogen Thermosiphon

- A thermosiphon is the simplest way to supply the source with LD_2.
  - Cold helium gas cools the condenser below 20 K.
  - Deuterium liquefies and flows by gravity to the moderator chamber.
  - Vapor rises to the condenser and a naturally circulating system is established.
- The system is closed to minimize gas handling (No vents or pressure relief).
- Low pressures: 3 bar warm, 1 bar operating
- All system components are surrounded by He containments.
- Rigorous quality assurance.

- why neutrons
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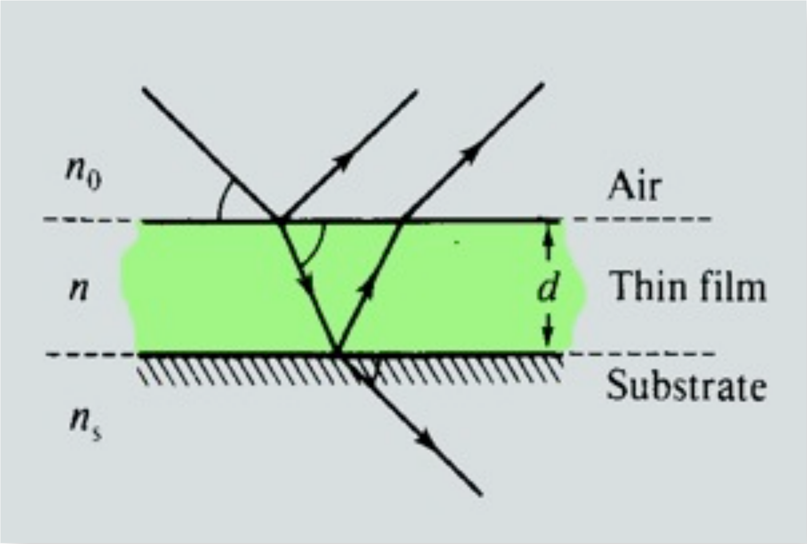
  - research reactors
- neutron moderation
- **neutron optics**

beam extraction and delivery

neutron guides or how to maximize $d\Omega$

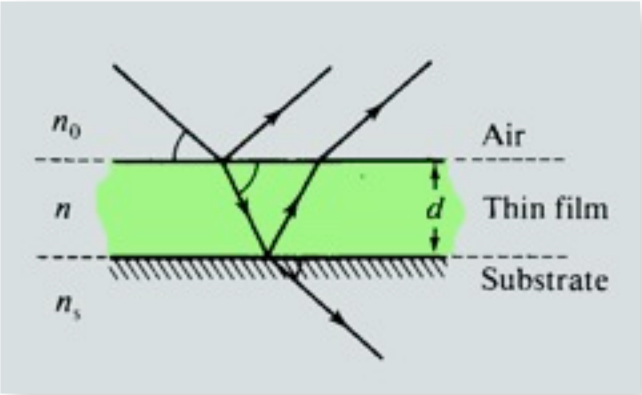


total reflection angle of neutrons

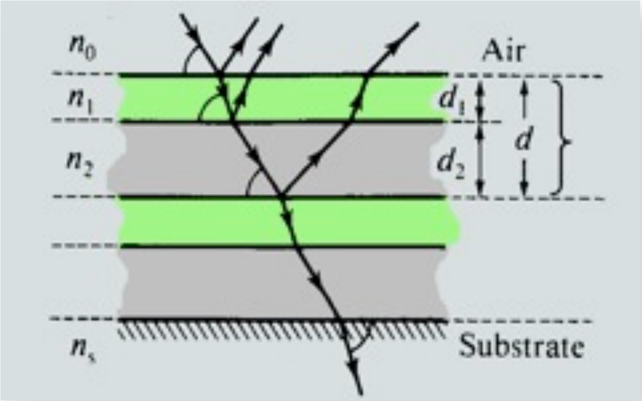
$$\theta_c \propto \lambda$$

for Ni $\theta_c \approx 0.1° \lambda$

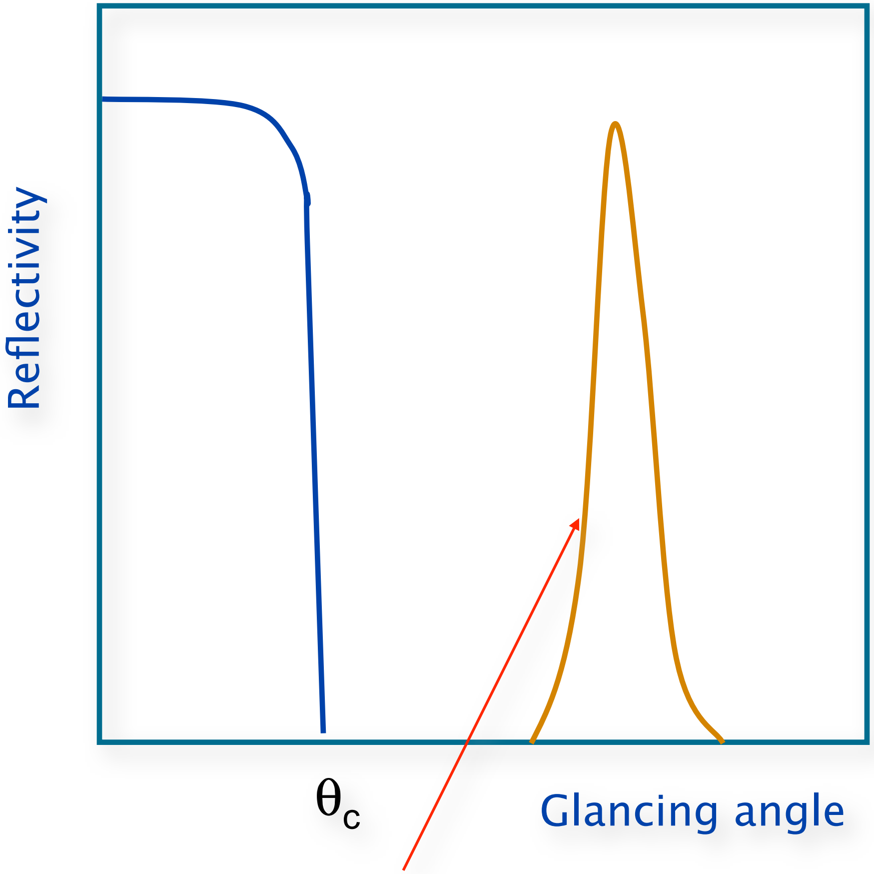
$m = 1$



Thin film (eg Ni^{58})

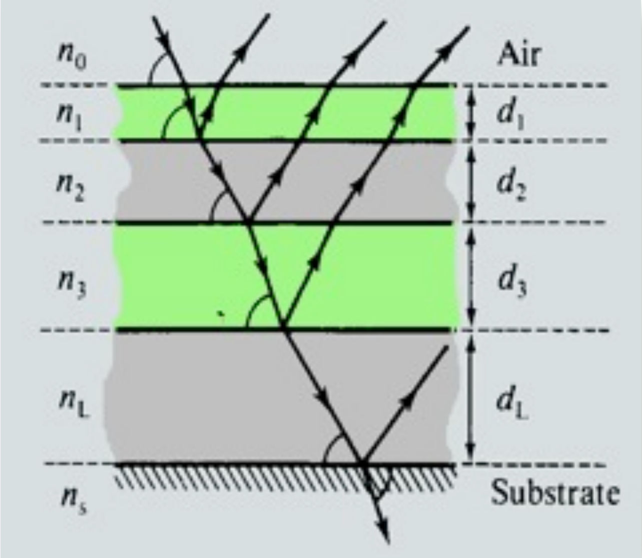


Bi-layers (eg Ni/Ti)

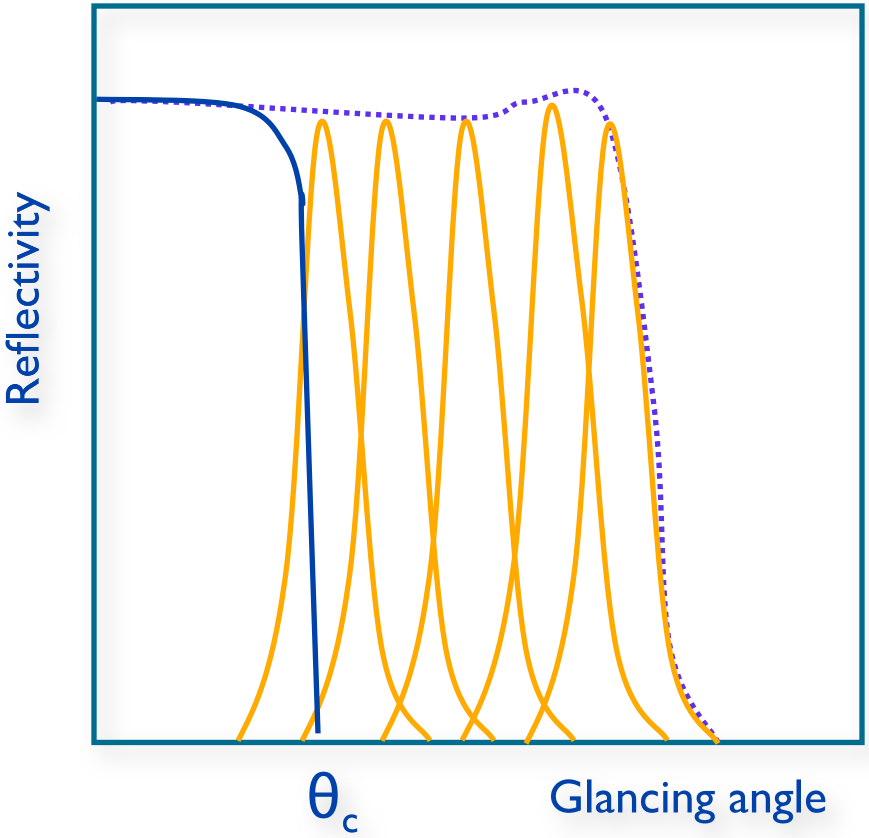


The multi-bilayer system introduces an additional Bragg peak at $\theta = \lambda/2d$

after Bob Cywinski



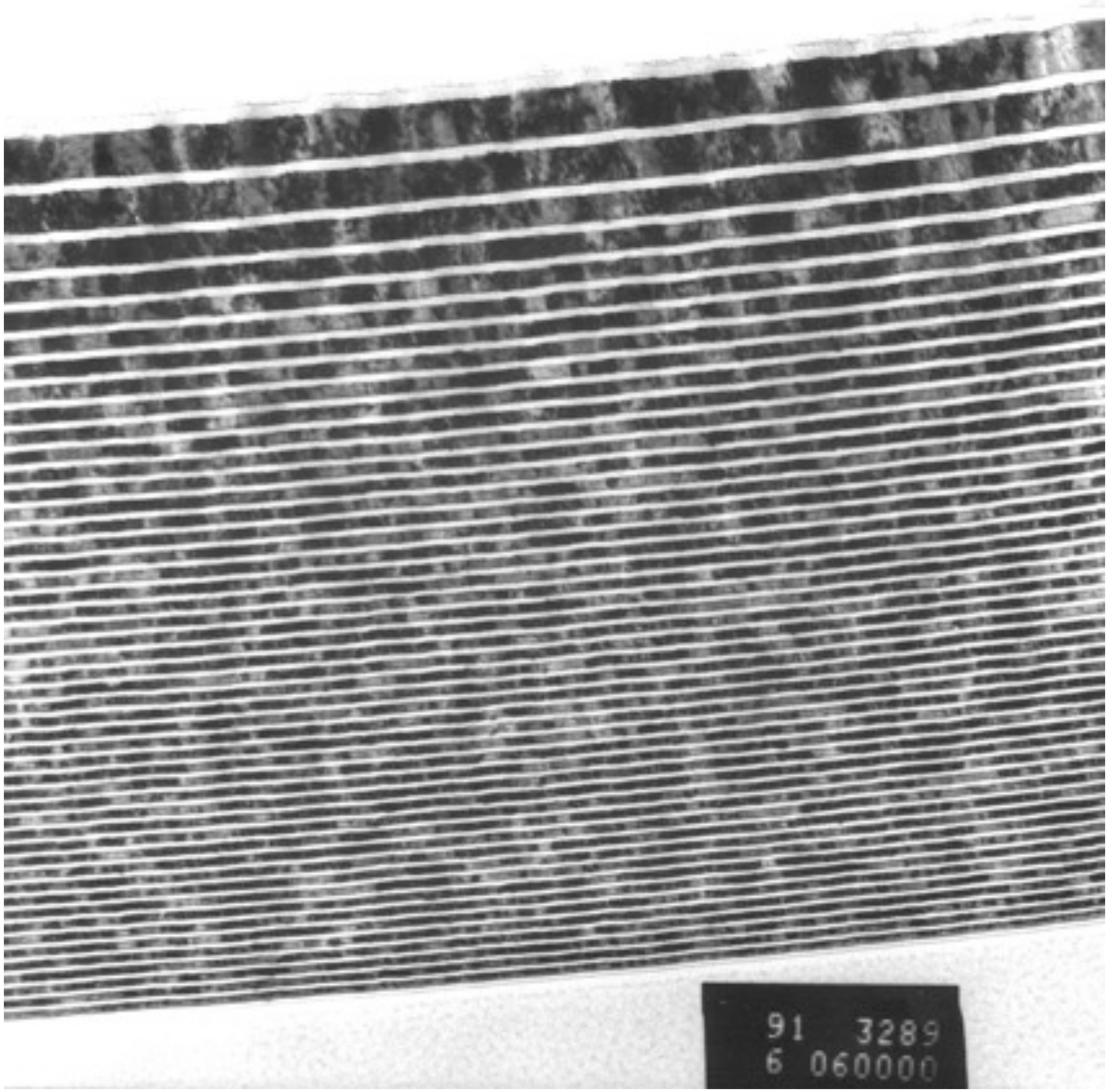
Supermirror systems
(eg Ni/Ti, Fe/Si etc)



A gradient in the lattice spacing of the bilayers results in a range of effective Bragg angles, and therefore a reflectivity which extends from m=3 to m=4 times the θ/λ values expected for normal mirror reflections

after Bob Cywinski

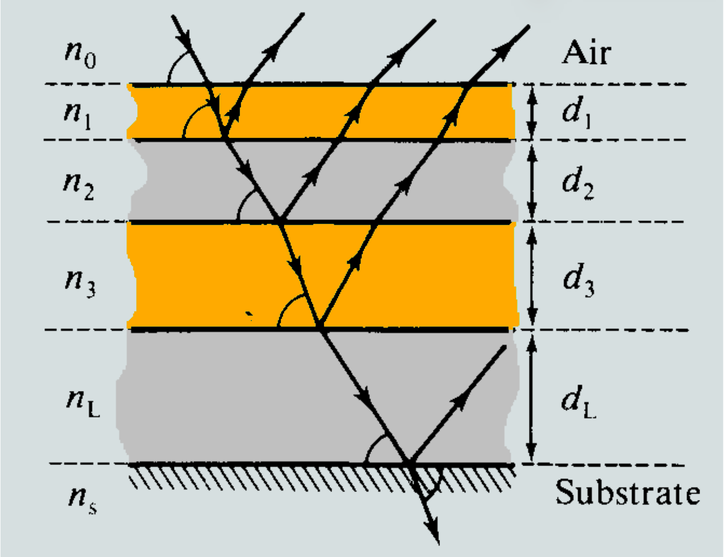
See Mezei, Commun Phys 1 81 1976



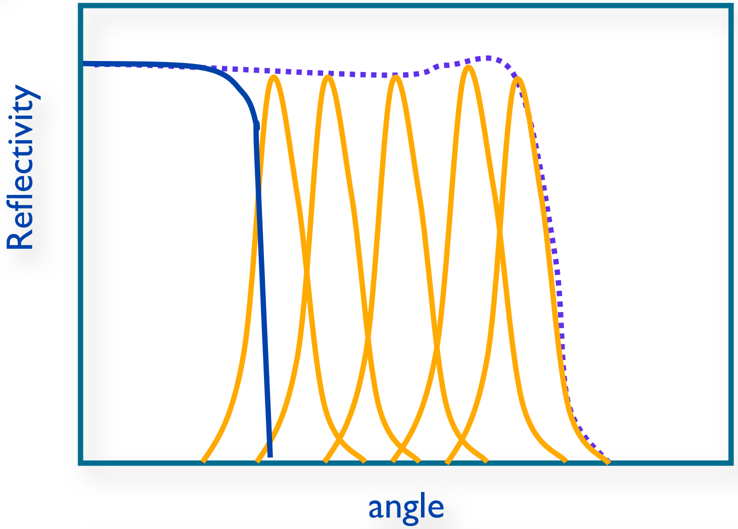
NiTi supermirror m=2

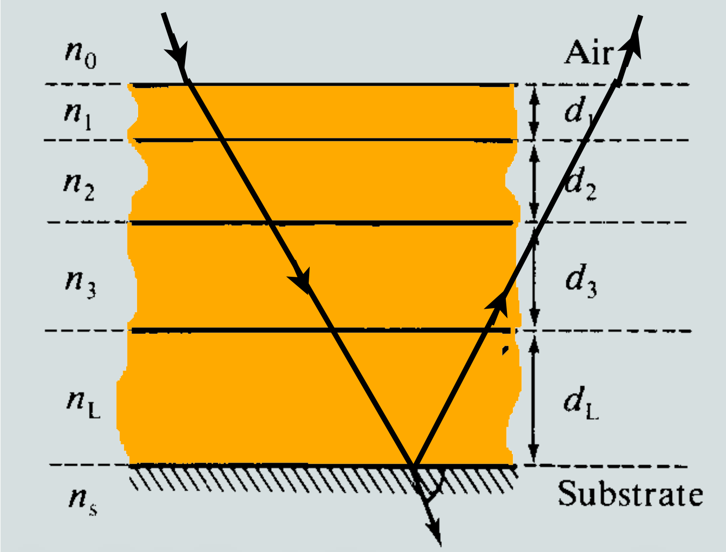
TEM picture
P. Schubert-Bischof
BENSC

polarizing supermirrors

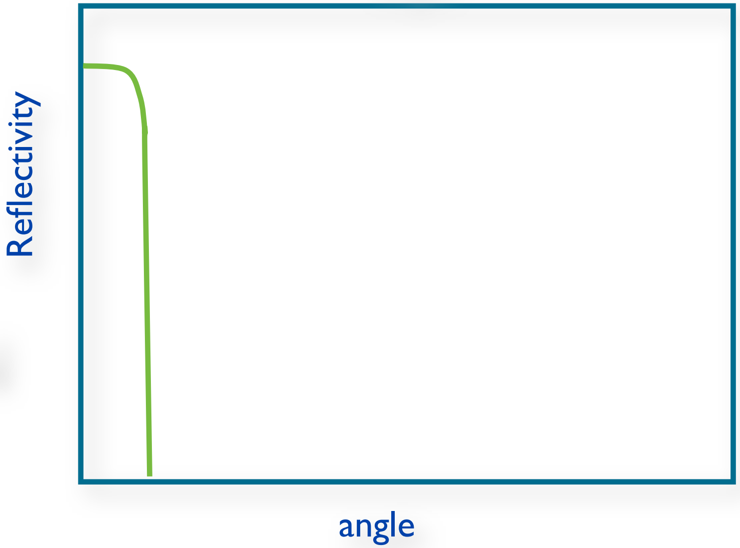


spin
UP





spin
DOWN



after Bob Cywinski

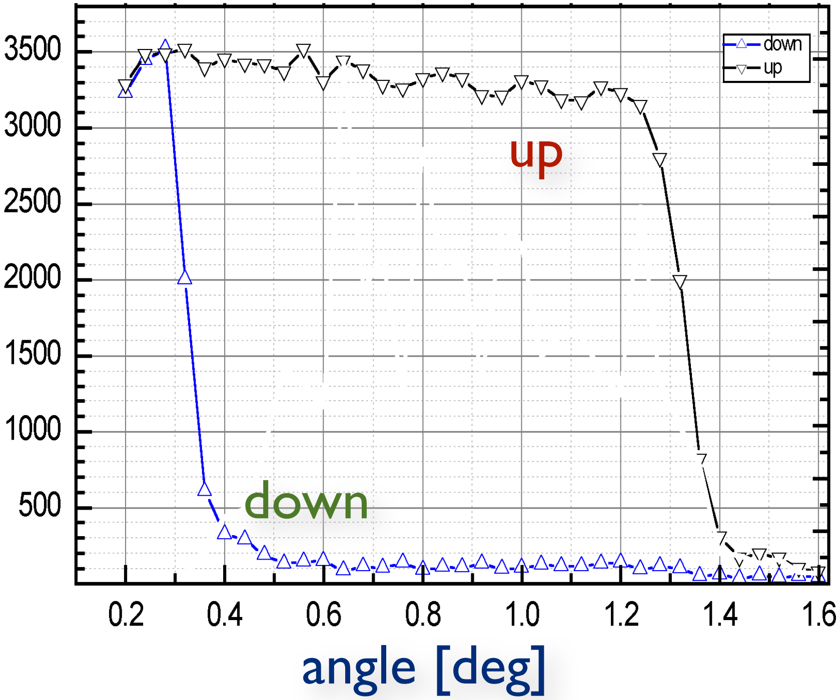
supermirrors like eg Fe/Si

See Mezei, Commun Phys 1 81 1976

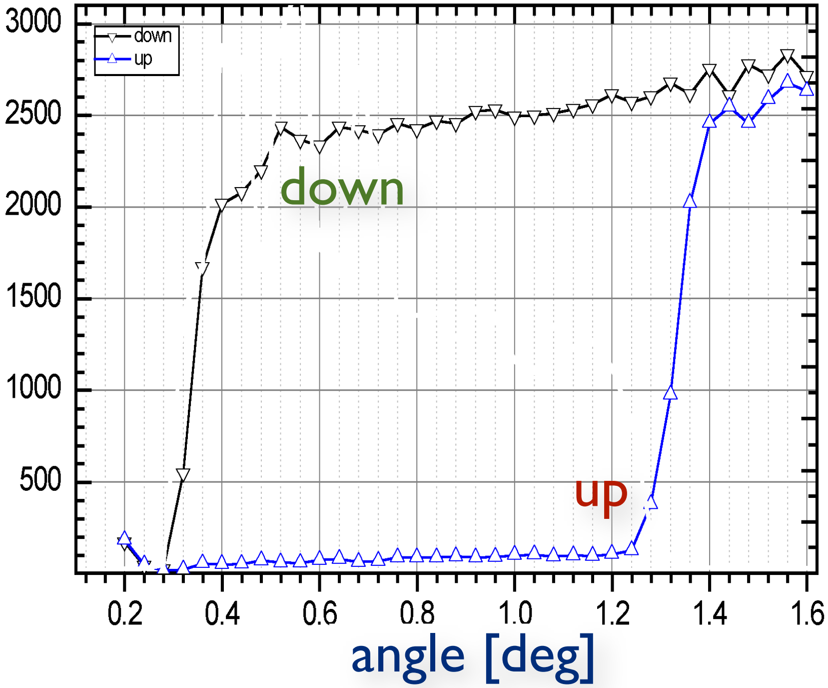
polarizing supermirrors

Fe-Si SM for m=2.6 on a Si wafer

reflection



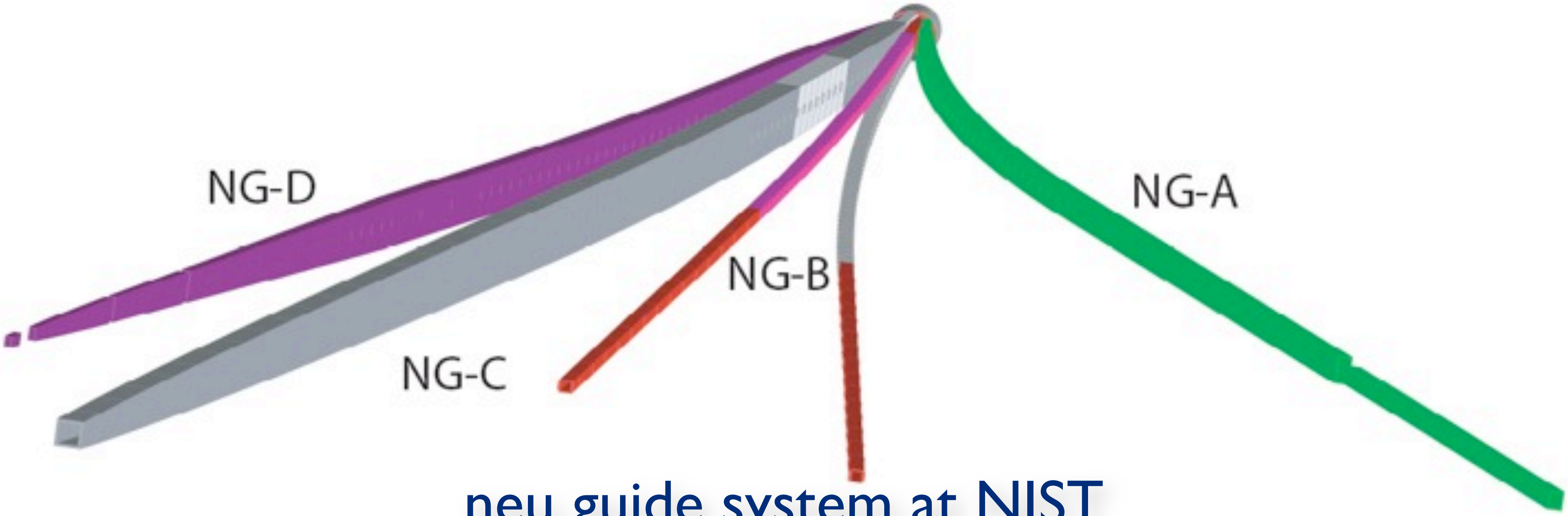
transmission



Th. Krist

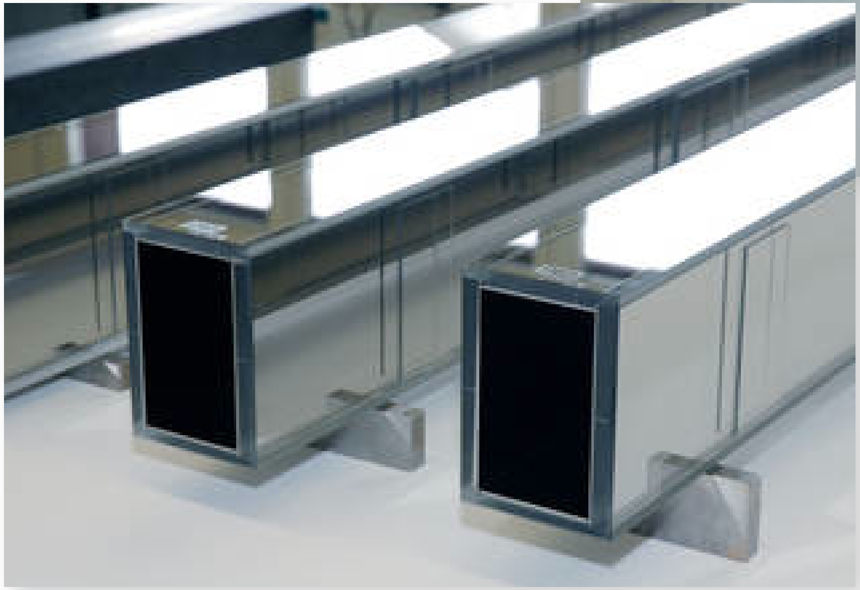
neutron guides :

- ballistic
- elliptical
- beam splitters
- polarising guides



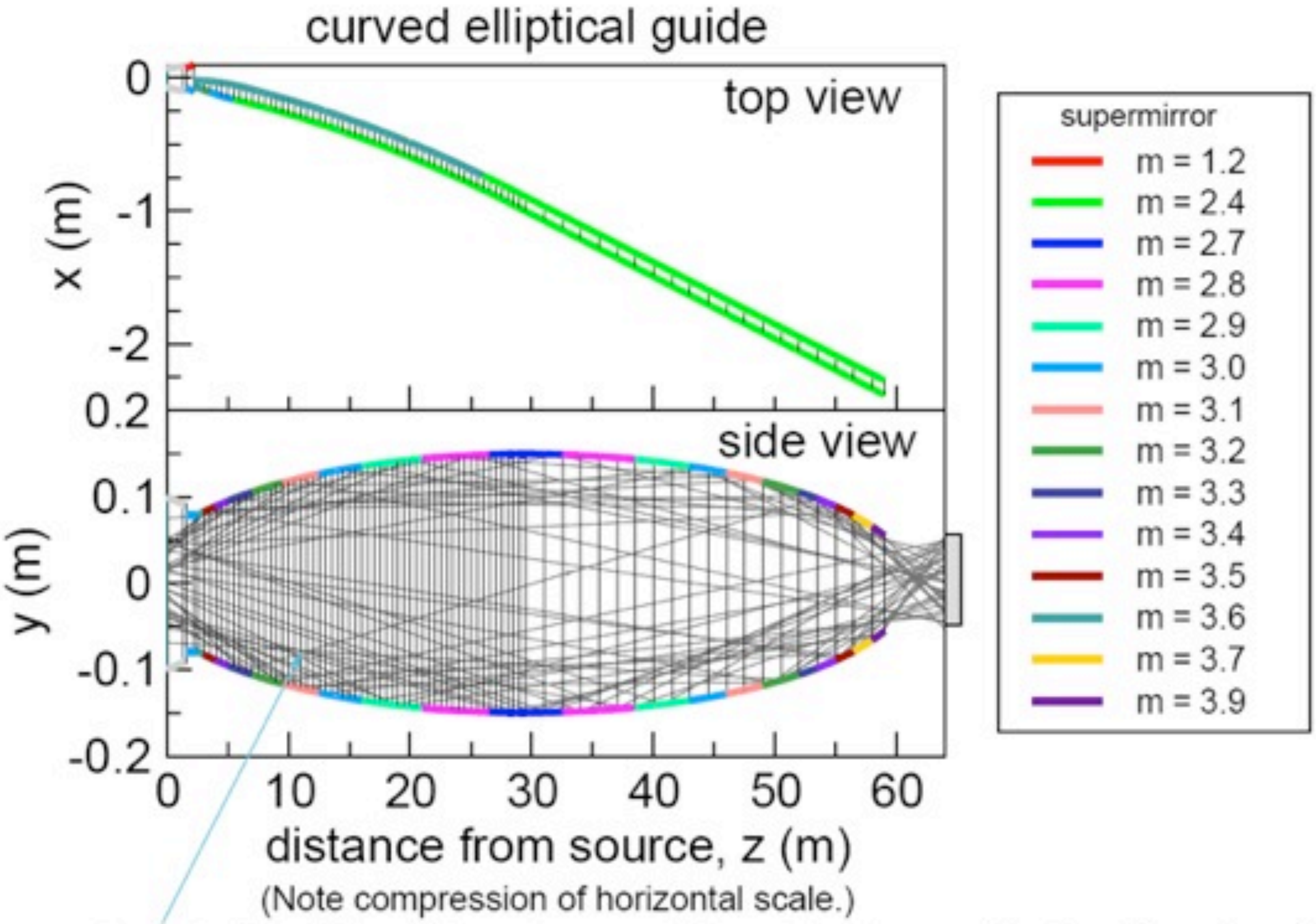
neu guide system at NIST

guides at ANSTO



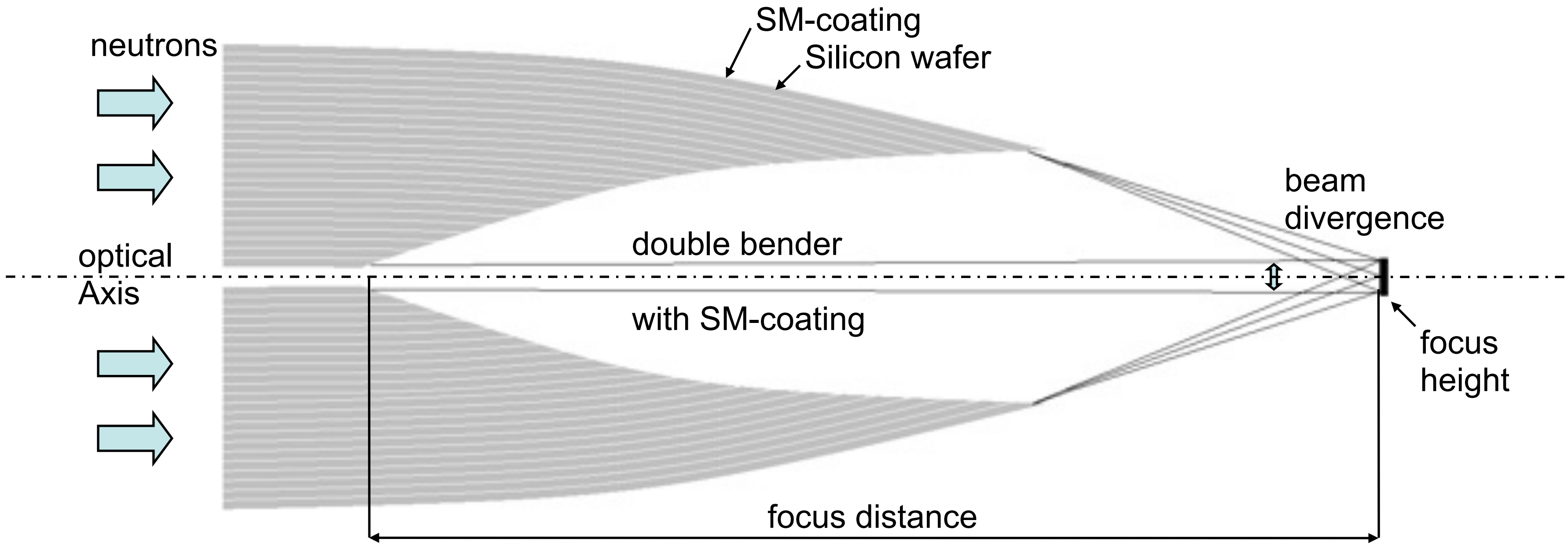
Elliptic guides of the High Resolution Powder Diffractometer at ISIS.

guide installation
at the SNS



some trajectories of $\lambda = 4$ Å neutrons making at least one reflection from the elliptical surface and reaching the 11 cm x 11 cm sample (gray rectangle) 5 m from exit

new focussing elements

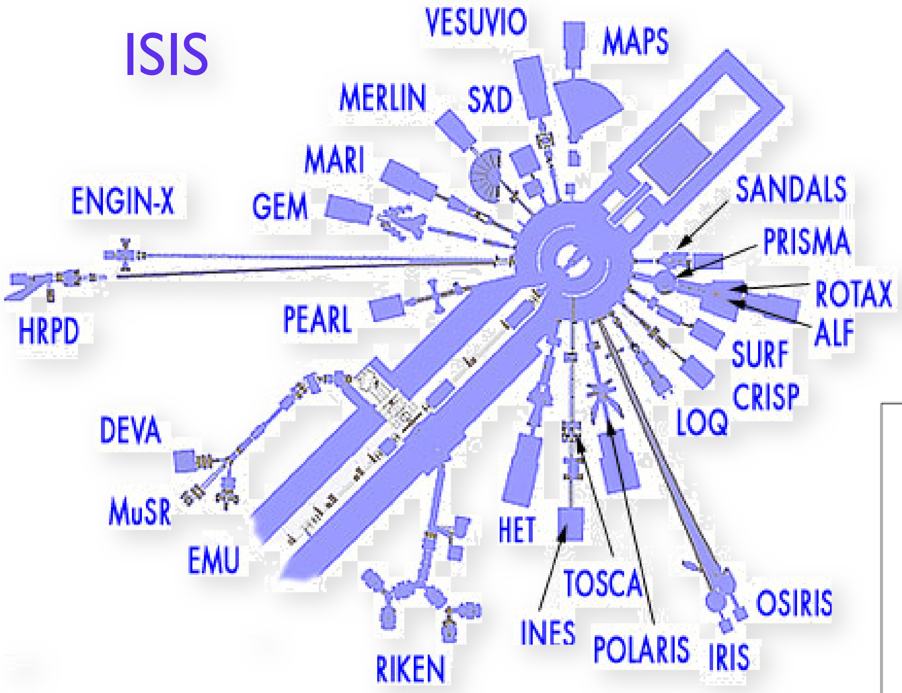


- 2x95x150µm bended Silicon Wafer
- m=2 supermirror coating
- exp. focus distance: 171mm

Th. Krist

TU Delft

ISIS

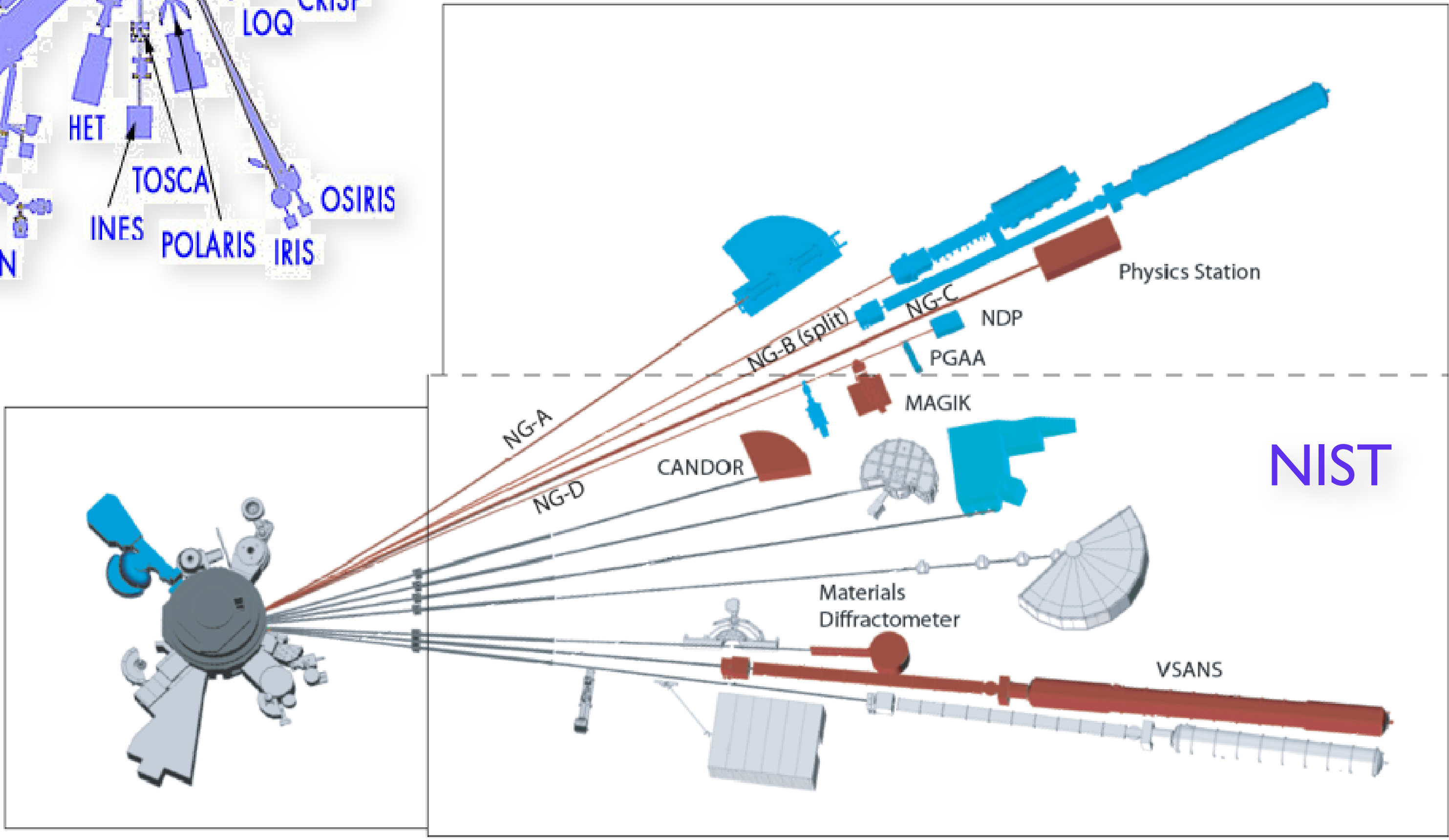


spallation sources:

the time structure of the source defines the position of instruments

reactors

no limits to the distance from the source



NIST