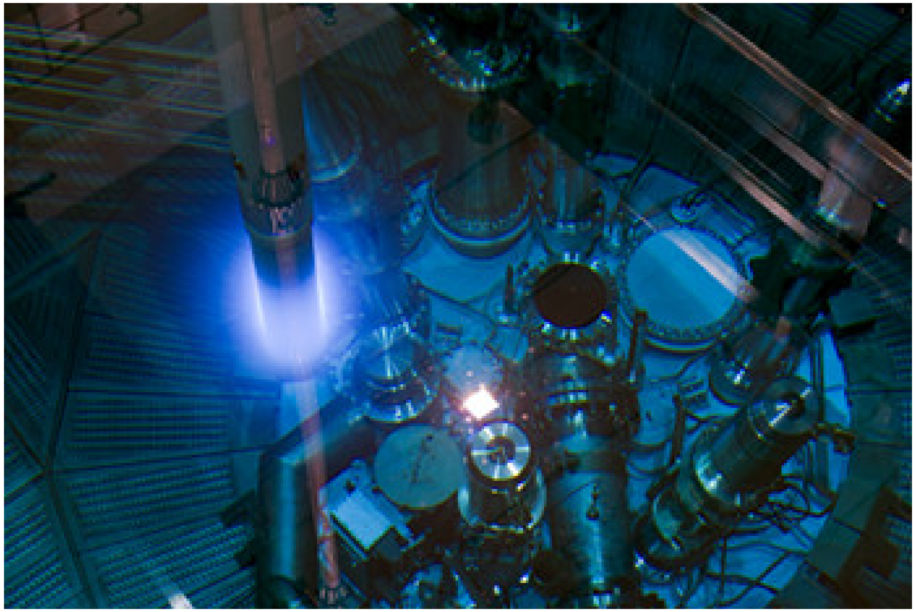
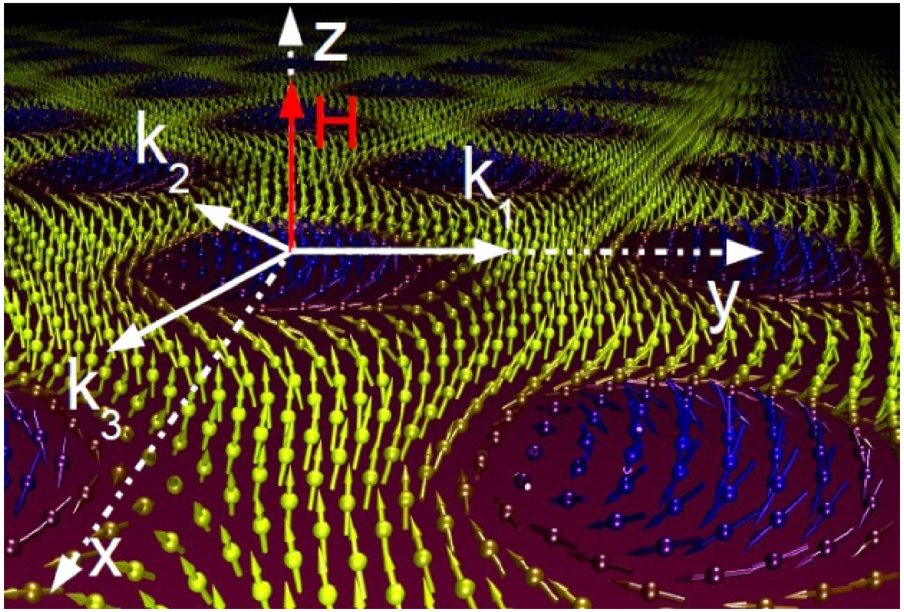
FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

MLZ
Heinz Maier-Leibnitz Zentrum

Physics with Neutrons I, WS 2015/2016

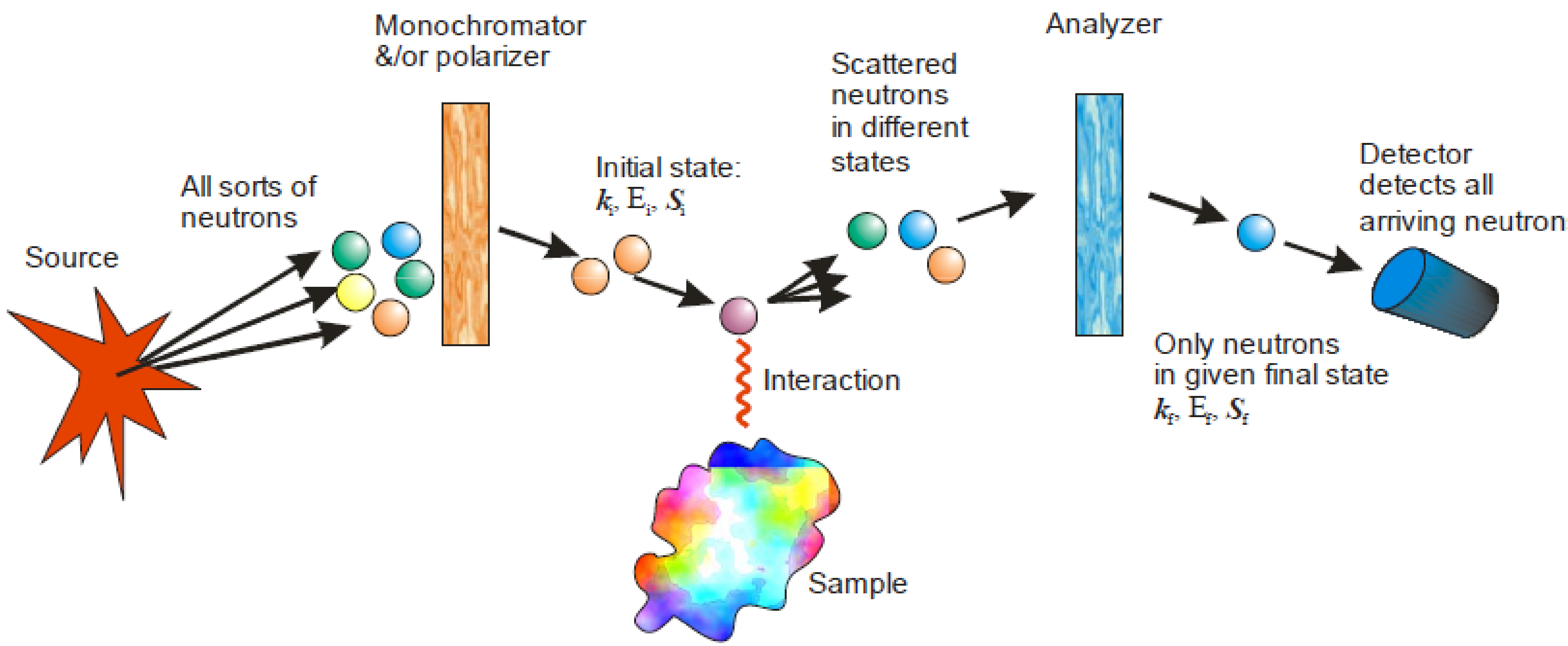




Lecture 2, 26.10.2015

2.1. Essence of a neutron scattering experiment (Reminder)

Fundamental principle of a neutron scattering experiment



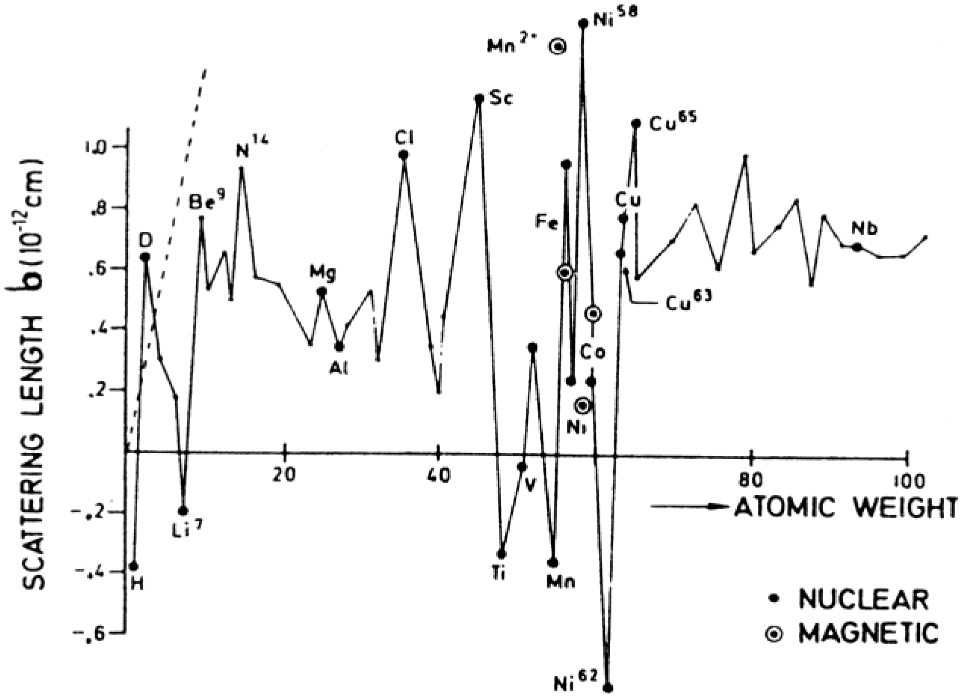
2.2. Basic properties of neutrons – What are the basic properties?

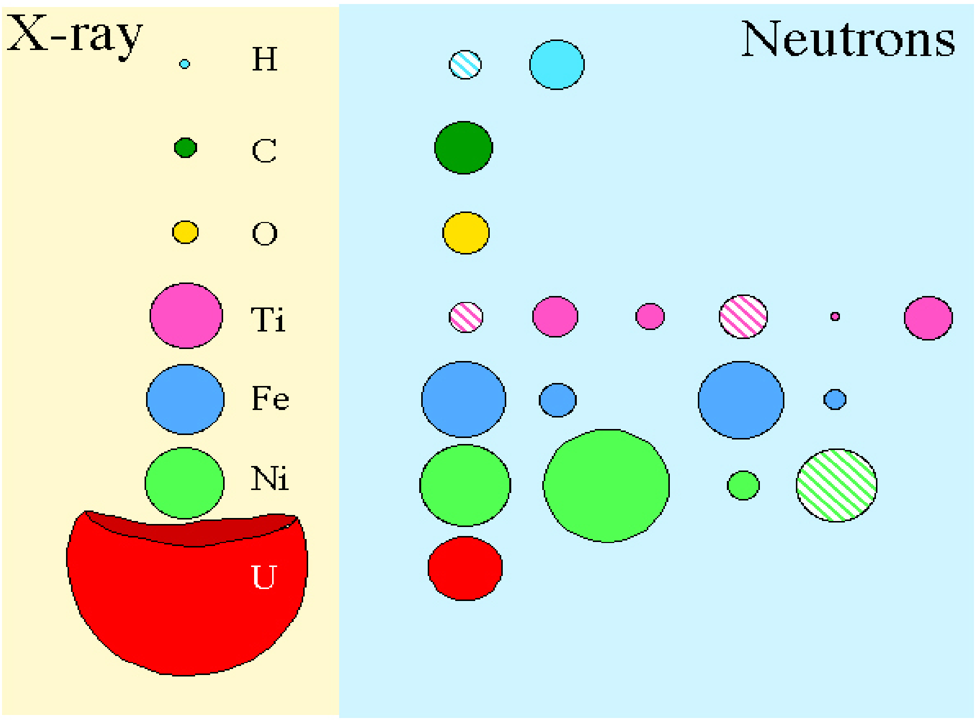
Table 1.2: Properties of the Neutron.

Physical quantity	Quantity	Dimension
Mass	$1.675 \cdot 10^{-27}$	kg
Charge	0	C
Spin	$1/2$	$\hbar$
magn. dipol moment	$\mu_n = -1.913\,\mu_K$	$\mu_K = \frac{e\hbar}{2M_p c}$
nuclear magneton		$1\,\mu_K = 0.505 \cdot 10^{-23}$ erg/G
		$1\,\mu_K = 3.15 \cdot 10^{-14}$ MeV/T
life time (free neutron)	886	s
kinetic energy	$E = \frac{1}{2}mv^2$	meV

2.2. Basic properties of neutrons – Wavelength and interactions

Interaction with matter





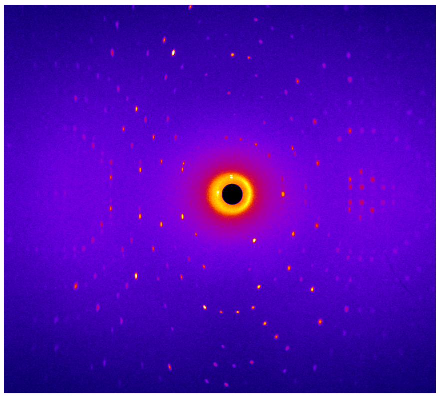
2.2. Basic properties of neutrons – Wavelength and interactions

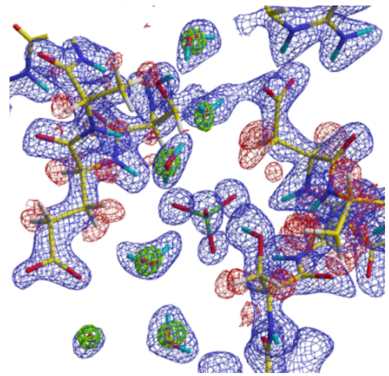
Energy range (eV)	Wavelength (Å)	Classification	Velocity (m/s)	
$0 - 5 \cdot 10^{-3}$	≥ 5	cold	≤ 1000	slow
$5 \cdot 10^{-3} - 10^{-1}$	$1 < \lambda < 5$	thermal	$1000 < v < 4000$	neutrons
$10^{-1} - 1$	$0.3 < \lambda < 1$	epithermal	$4000 < v < 10^4$	
$1 - 10^2$		resonance-		
$10^2 - 10^5$		intermediate		fast
$10^5 - 10^7$	$\lambda < 0.1$	fast	$v > 10^4$	neutrons
$10^7 - 10^{10}$		ultra fast		
$10^{10} - \infty$		relativistic		

Why Neutrons ?!

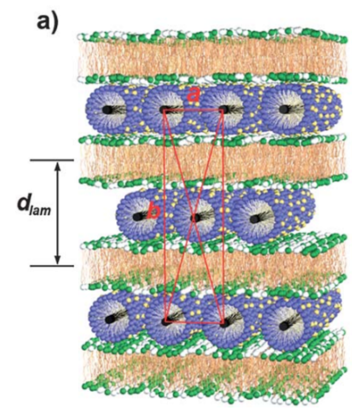
Versatile tool for condensed matter physics

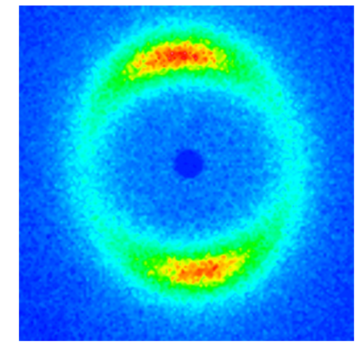
Crystallography





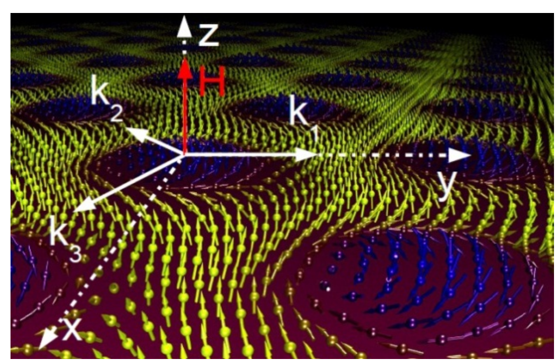
Soft Matter

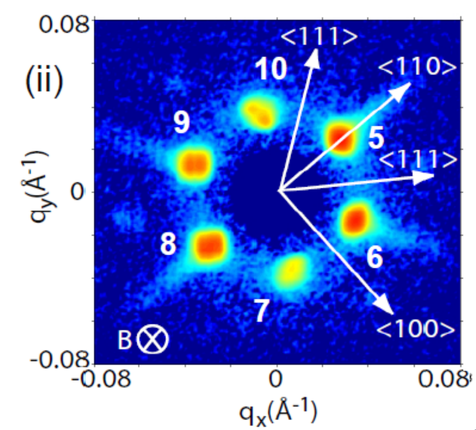




Materials

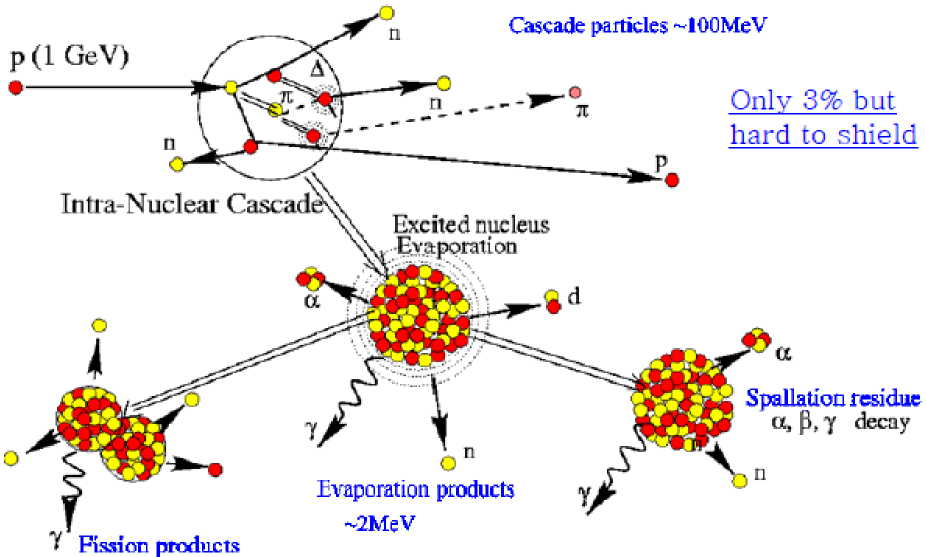
Magnetism & SCES





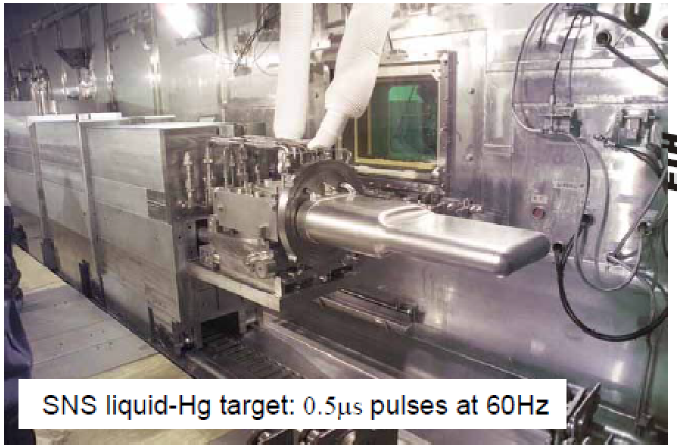
2.3. How are neutrons generated? Spallation and Reactors

Spallation source - Pulsed (mostly)



Only 3% but hard to shield

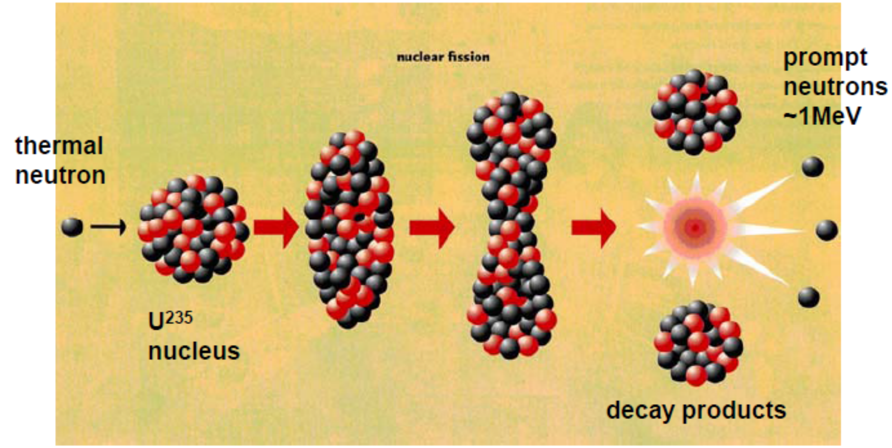
Up to 97%

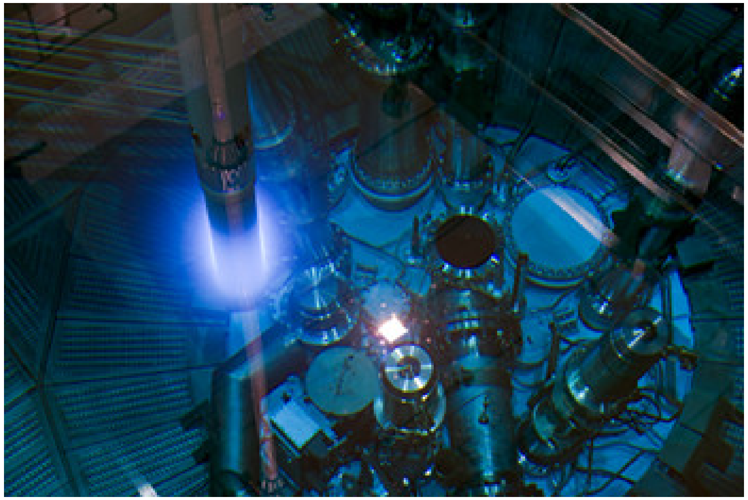


SNS liquid-Hg target: 0.5μs pulses at 60Hz

Reactor source – continuous

Thermal fission of U^{235} ⇨ 2.5 neutrons



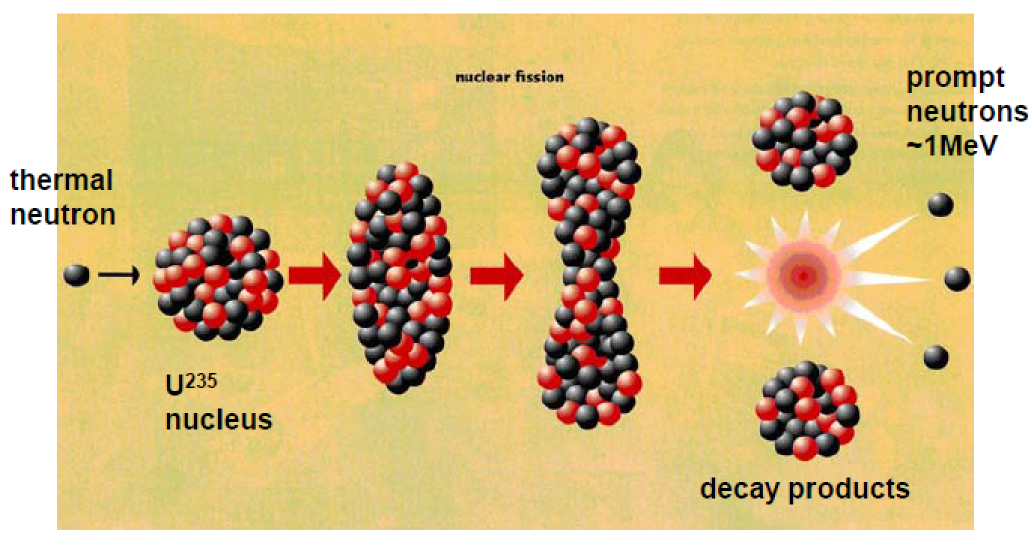


2.3. How are neutrons generated? Thermal fission at reactor sources

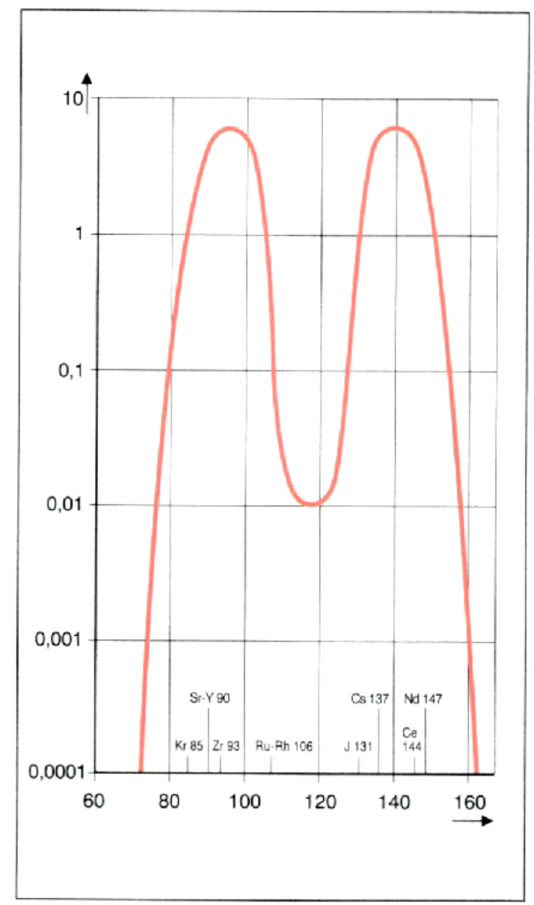
$$U^{235} + n_{th} \to \left(U^{236}\right)^* \xrightarrow{\text{i.e.}} \left(I^{139}\right)^* + \left(Y^{96}\right)^* + n$$

$$\left(I^{139}\right)^* \xrightarrow{2.7s} \left(I^{138}\right)^* + n \xrightarrow{5.9s} \left(Xe^{138}\right)^* + \beta^- \xrightarrow{17m} \left(Cs^{138}\right)^* + \beta^- \xrightarrow{32m} Ba^{138} + \beta^-$$

$$\left(Y^{96}\right)^* \to \left(Y^{95}\right)^* + n \xrightarrow{10.5m} \left(Zr^{95}\right)^* + \beta^- \xrightarrow{63.3d} \left(Nb^{95}\right)^* + \beta^- \xrightarrow{35d} Mo^{95} + \beta^-$$

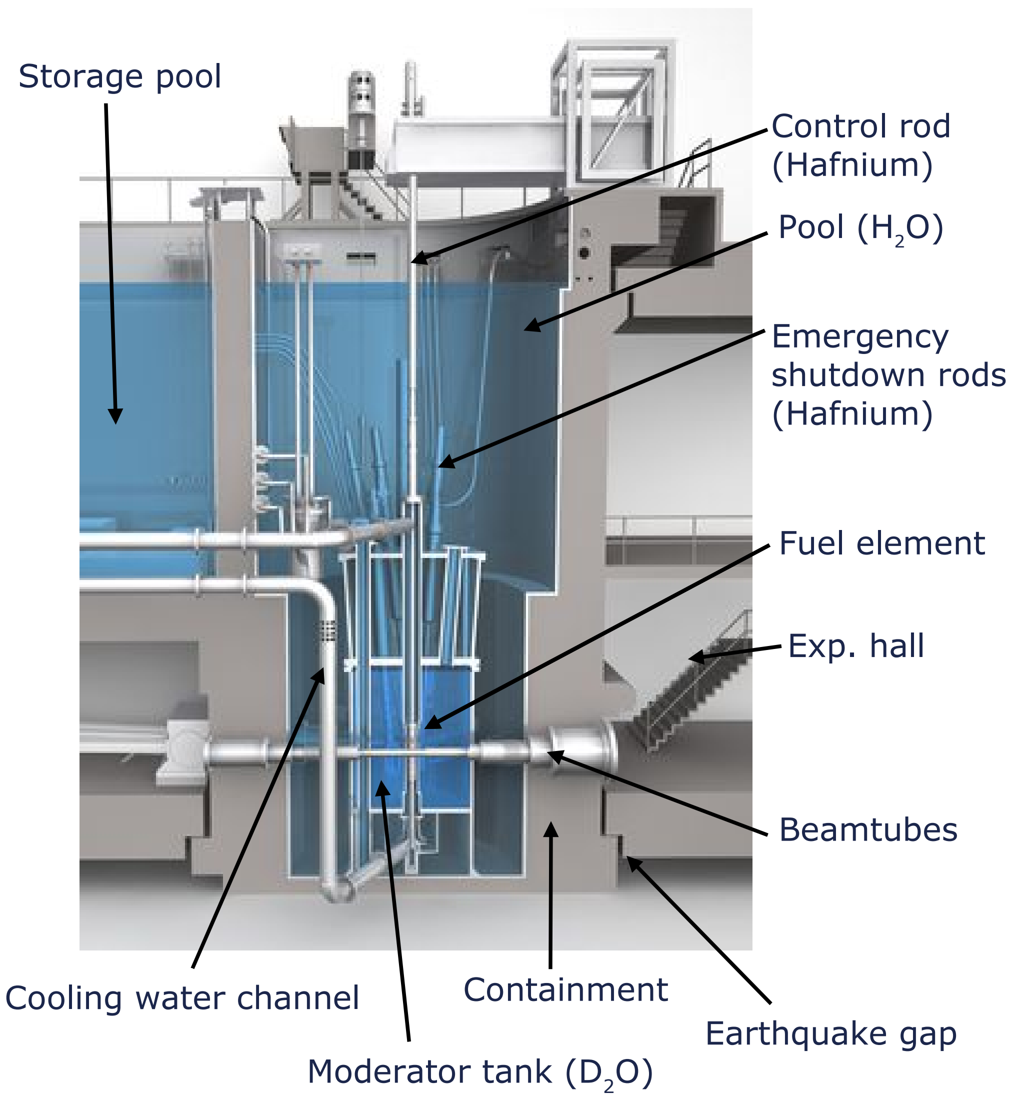


Fission spectrum of ^{235}U

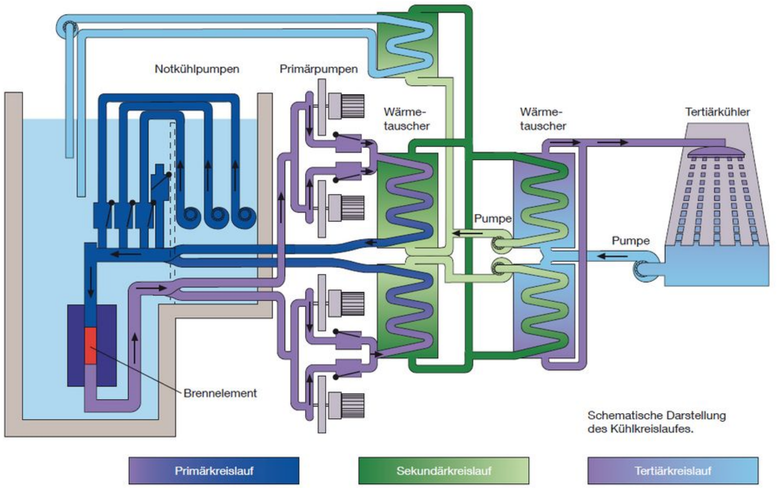


2.3. How are neutrons generated? Example FRM II

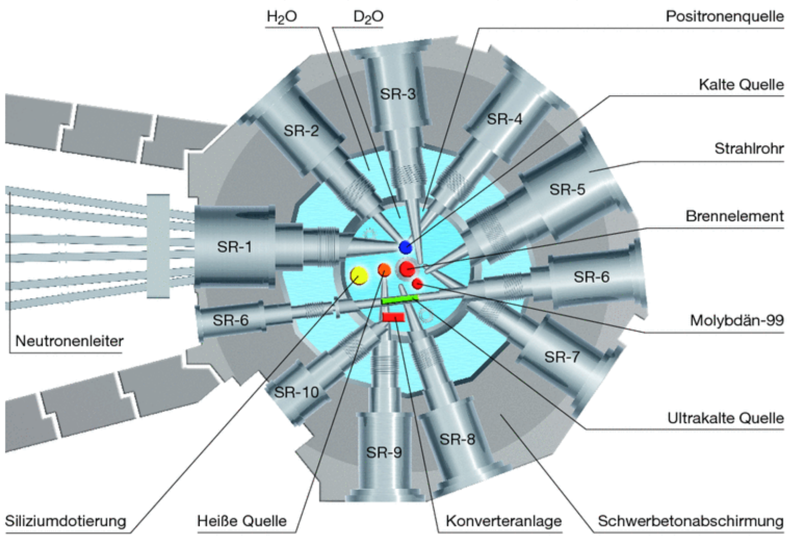
Schematic Principle



Cooling circuit

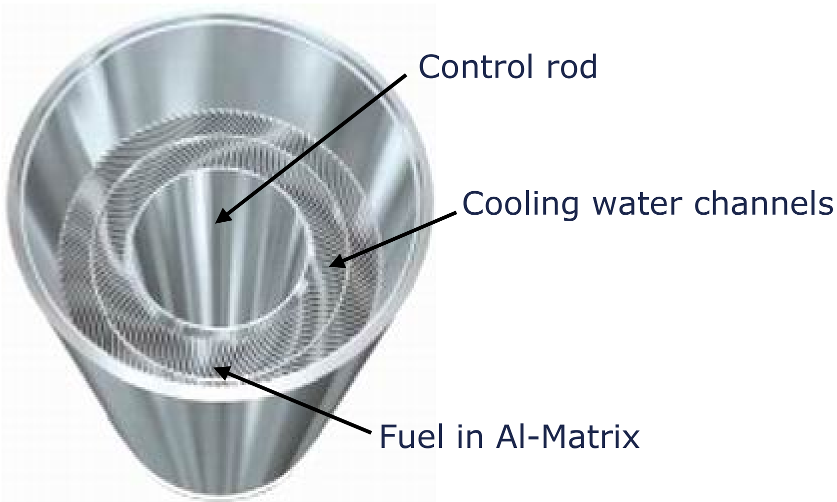


Neutron extraction



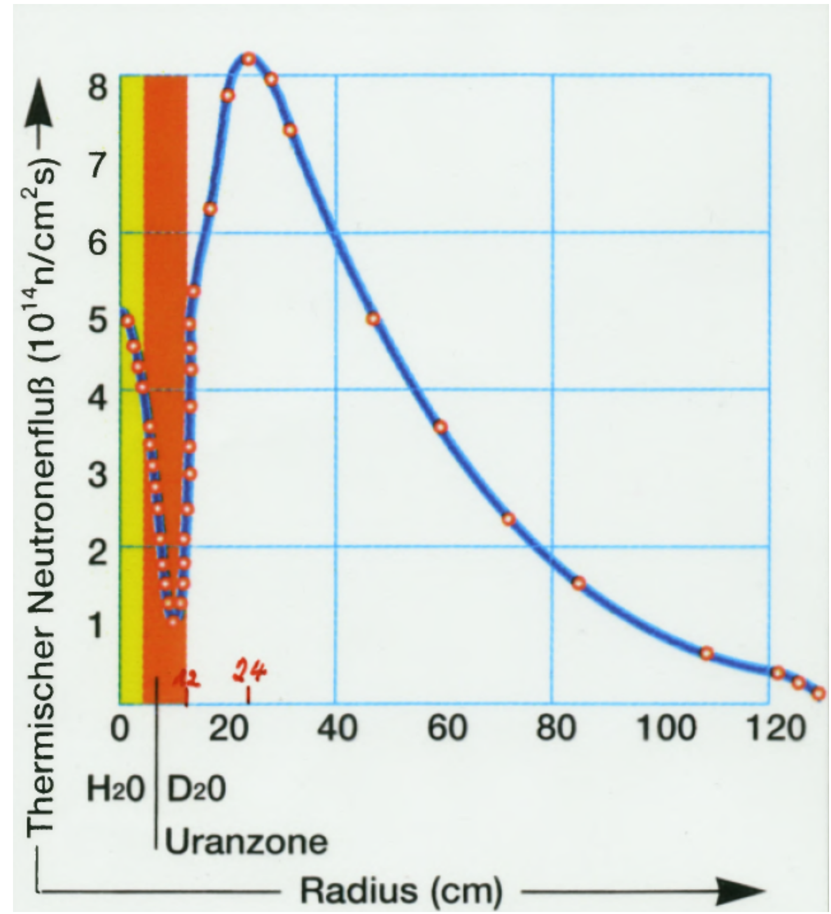
2.3. How are neutrons generated? Example FRM II, some numbers

Fuel element (1.3m length, 0.24m diameter)



- 8.1kg ^{253}U, 92% Enrichment, USi
- 20MW Thermal power
- 60 Days burn-up
- 300kg/s cooling water throughput
- 37°C inlet, 53°C outlet
- Neutron flux $8*10^{14}$n/cm^{2}s

Compact core desing....why?



2.3. How are neutrons generated? Other concepts

„Pulsed bomb" concept, IBR-2 reactor, Dubna, Russia

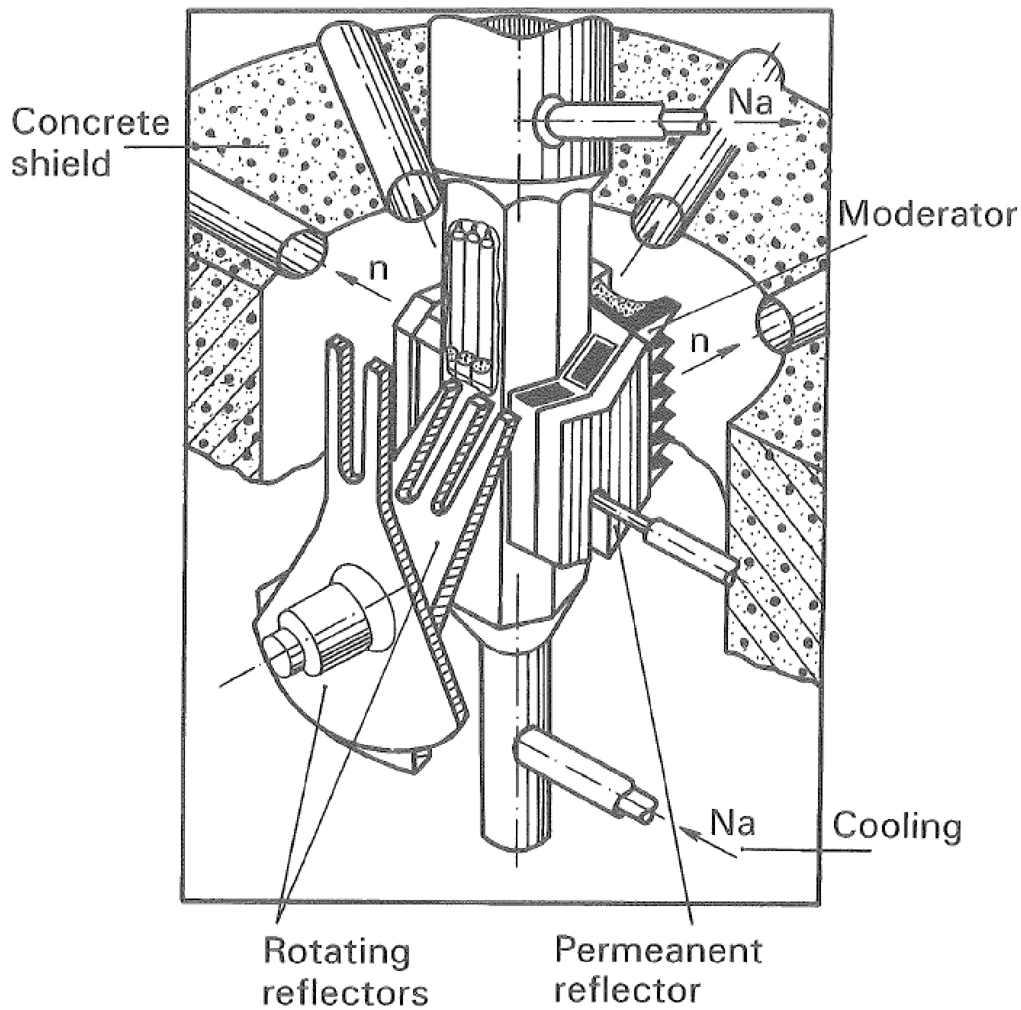
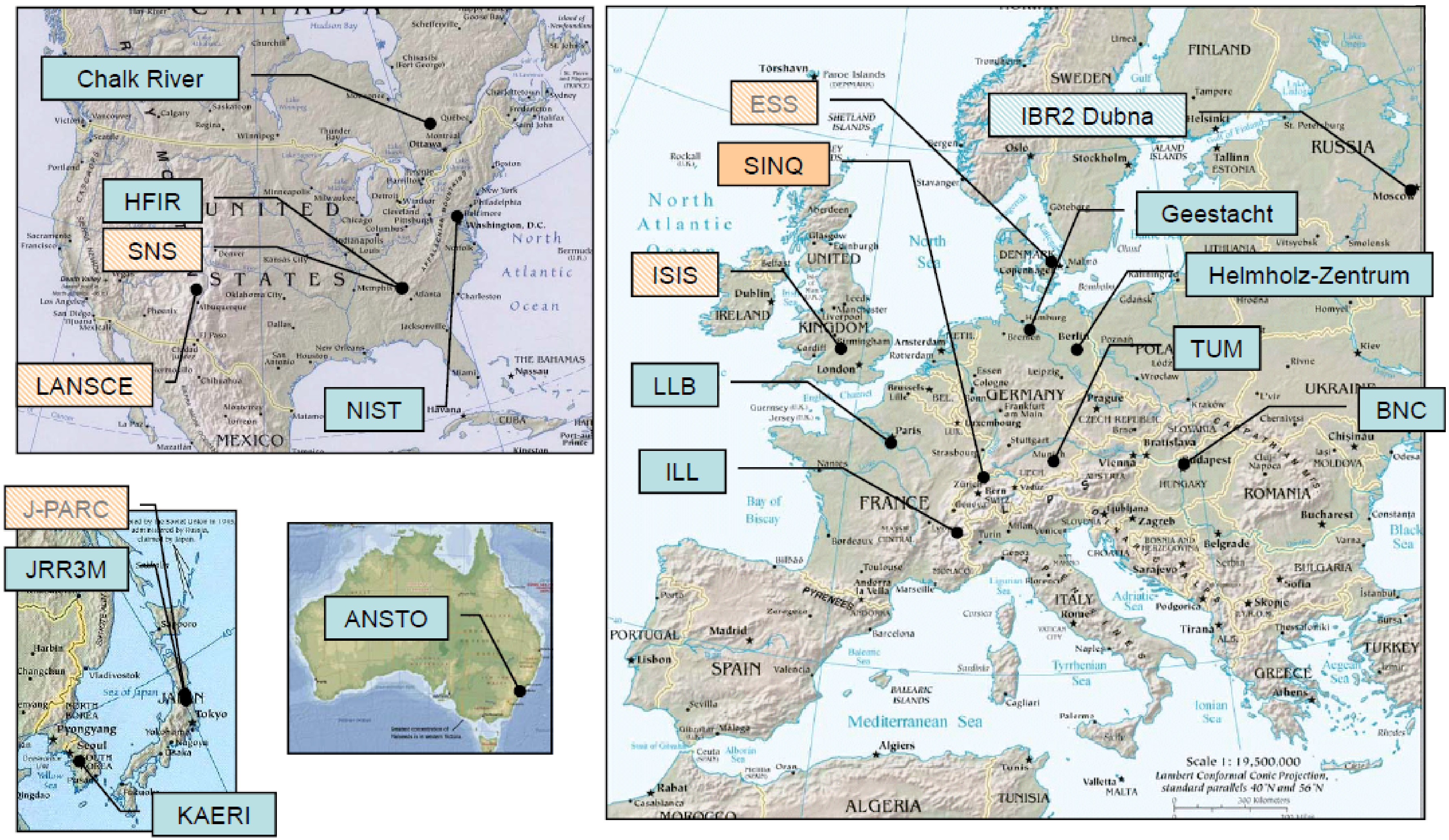


Fig. 1.15. The scheme of the IBR-2 reactor with rotating reflectors.

2.3. How are neutrons generated? Overview over active sources

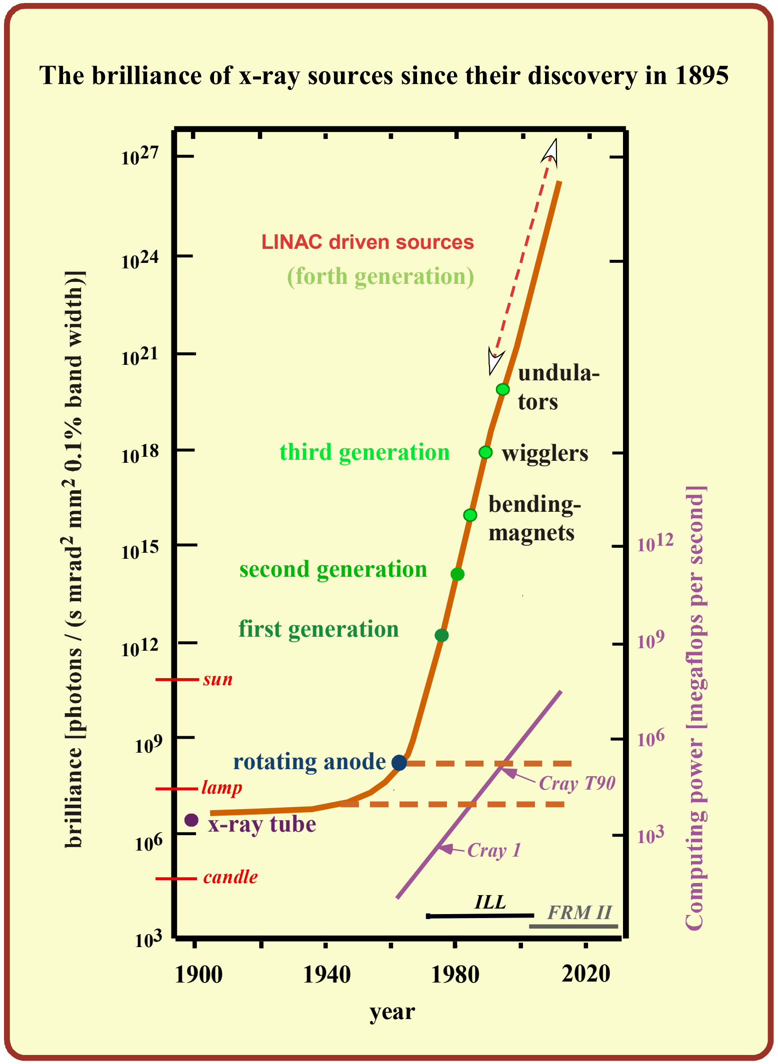


2.3. How are neutrons generated? Overview over active sources

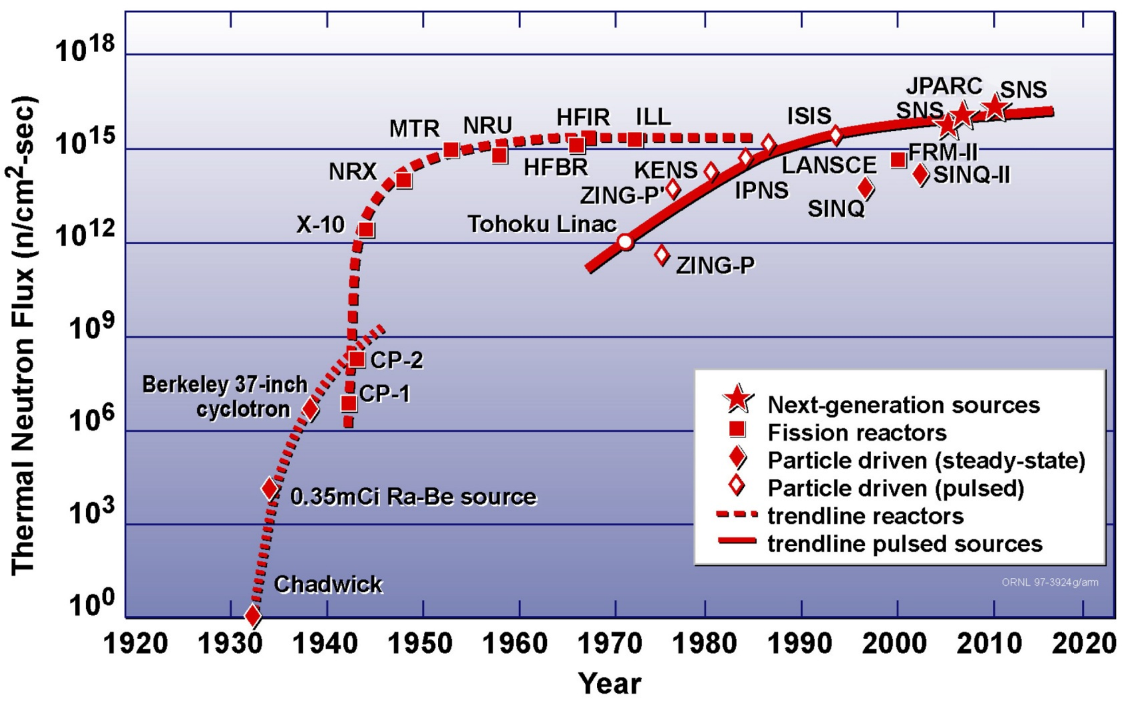
	High flux reactor (HFR) Grenoble (Fr)	Pulsed reactor IBR-2 Dubna (Ru)	Spallation source ISIS Chilton (UK)	European spallation source ESS (project) Hg-Target H2O moderator	FRM II TU-Munich Garching
Peak flux ($cm^{-2}s^{-1}$)	$1.2 \cdot 10^{15}$	$2 \cdot 10^{16}$	$4.5 \cdot 10^{15}$	$\cong 3.6 \cdot 10^{16}$	$6.4 \cdot 10^{14}$
Aver. flux ($cm^{-2}s^{-1}$)	$1.2 \cdot 10^{15}$	$2 \cdot 10^{13}$	$7 \cdot 10^{12}$	$\cong 1.2 \cdot 10^{15}$	$6.4 \cdot 10^{14}$
Pulse repet. rate (s^{-1})	NA	5	50	14	NA
Pulse duration (μ s)	NA	250	30	2860	NA
Power (MW)	57	2	0.2	5	20

2.3. How are neutrons generated? Comparison to X-Ray sources

Photons



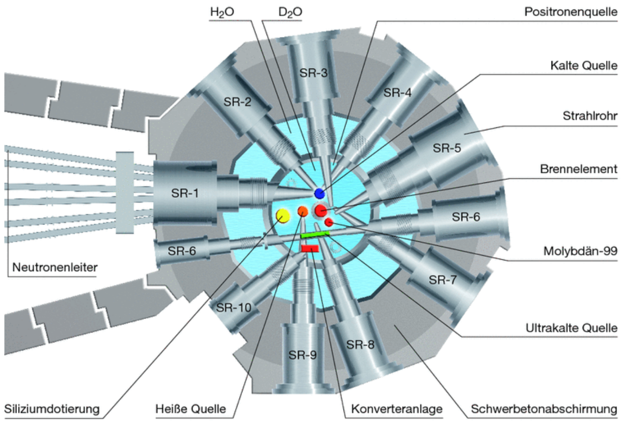
Neutrons



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

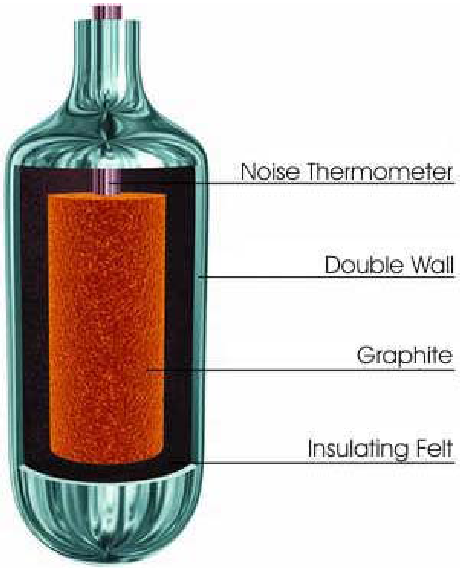
2.4. Neutron (Re-)Moderation: Secondary sources

Energy range (eV)	Wavelength (Å)	Classification	Velocity (m/s)	
$0 - 5 \cdot 10^{-3}$	≥ 5	cold	≤ 1000	slow
$5 \cdot 10^{-3} - 10^{-1}$	$1 < \lambda < 5$	thermal	$1000 < v < 4000$	neutrons
$10^{-1} - 1$	$0.3 < \lambda < 1$	epithermal	$4000 < v < 10^4$	
$1 - 10^2$		resonance-		
$10^2 - 10^5$		intermediate		fast
$10^5 - 10^7$	$\lambda < 0.1$	fast	$v > 10^4$	neutrons
$10^7 - 10^{10}$		ultra fast		
$10^{10} - \infty$		relativistic		



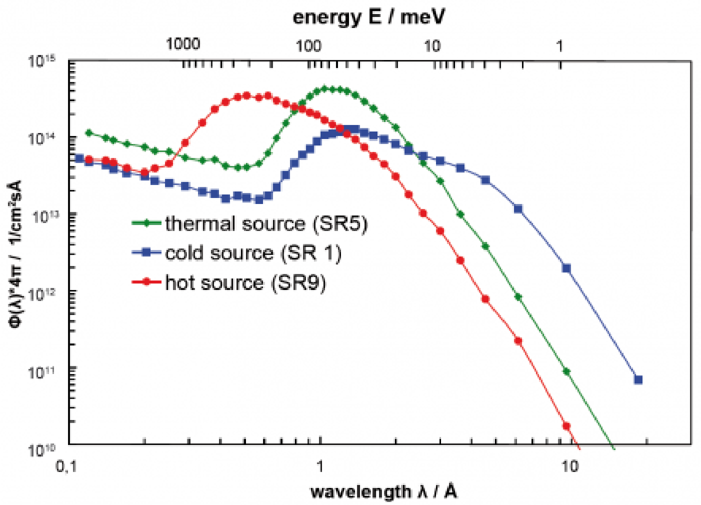
Cold source (liquid D2, 22K)

Hot source (graphite, 2000K)



2.4. Neutron (Re-)Moderation: Secondary sources

Typical spectra (@ FRM II)



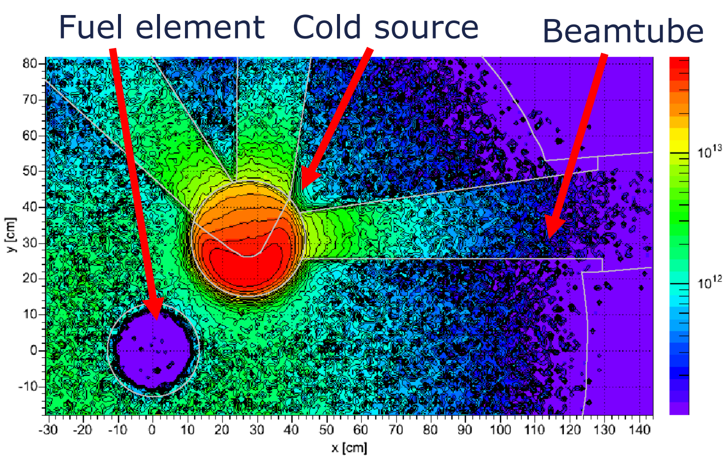
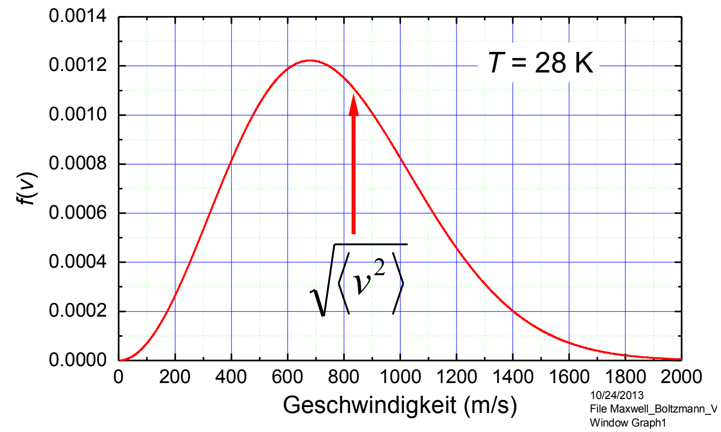


Fig. 2.12: Neutron flux [cm^{-2} sec^{-1}] around the reactor core and the cold source in the 'cold' energy range below 2.5 meV. All values below 10^{11} cm^{-2} sec^{-1} are displayed in violet.

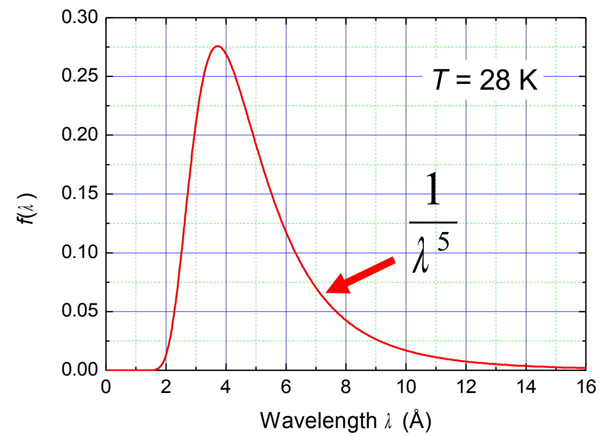
Cold wavelength/velocity spectrum



$$f(v) = \frac{4v^2}{\sqrt{\pi}}\left(\frac{m_n}{2k_BT}\right)^{3/2} e^{-\frac{1}{2}\frac{m_n v^2}{k_BT}}$$

$$\langle v^2 \rangle = \int_0^\infty dv\, f(v) v^2 = \frac{3kT}{m}$$

$$\sqrt{\langle v^2 \rangle} = 832\,\frac{\mathrm{m}}{\mathrm{s}}$$



$$f(\lambda) = \frac{2\lambda_T^4}{\lambda^5} e^{-\frac{1}{2}\frac{1}{k_BT}\frac{h^2}{m_n\lambda^2}}$$

$$\lambda_T = \frac{h}{\sqrt{2m_nk_BT}}$$

$$\lambda_{max} = \frac{h}{\sqrt{5m_nk_BT}} = 3.68\ \text{Å}$$

2.5. Detecting Neutrons – disadvantage of being neutral

Gaseous counters (^3He)

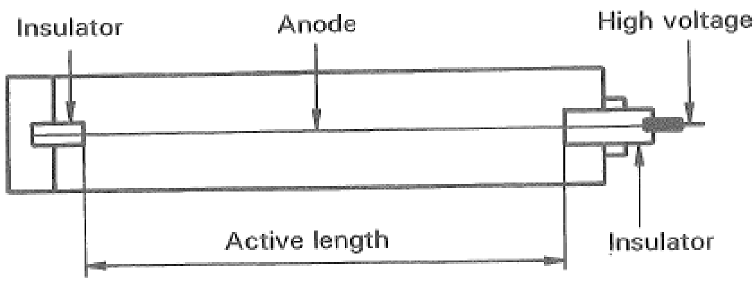


Fig. 1.1. Schematic drawing of a gaseous proportional detector.

$^3He + n \longrightarrow T + p + 0.765 MeV$

Fission chamber (^{235}U)

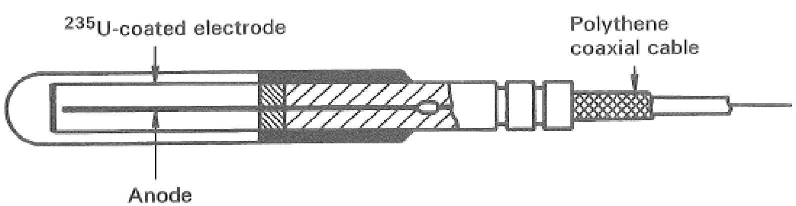
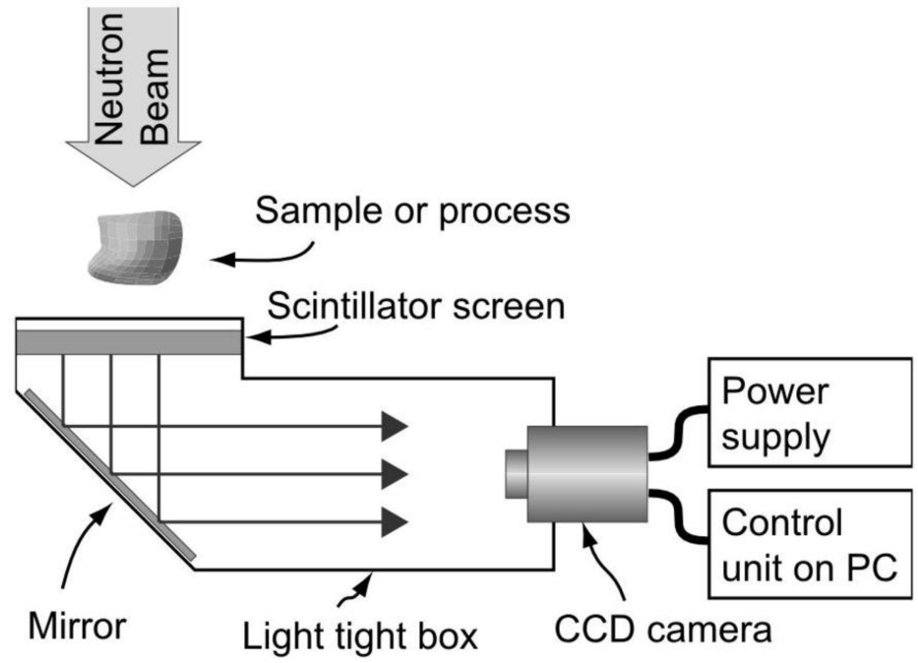


Fig. 1.2. Layout of the fission chamber.

Used as beam monitor

Scintillation detectors (Gd, ^6Li, ^{10}B)

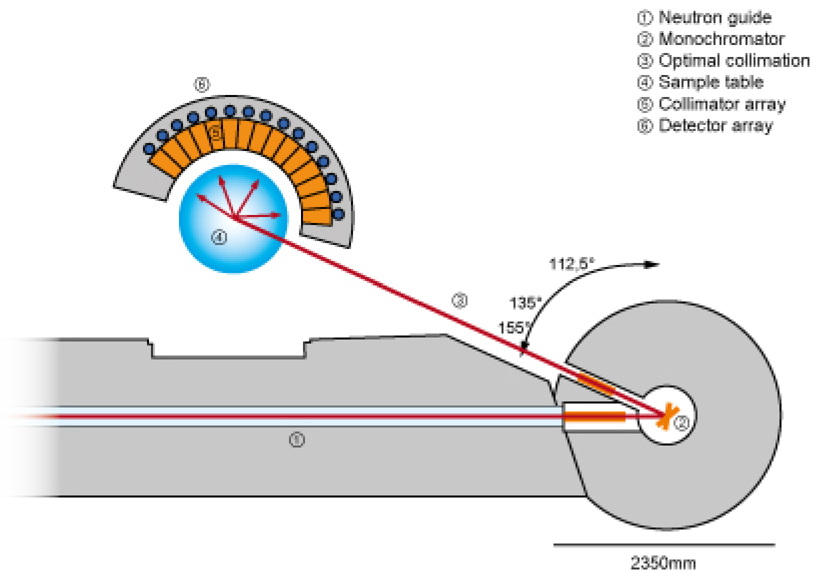
$^6Li + n \longrightarrow T + {}^4He + 4.78 MeV$

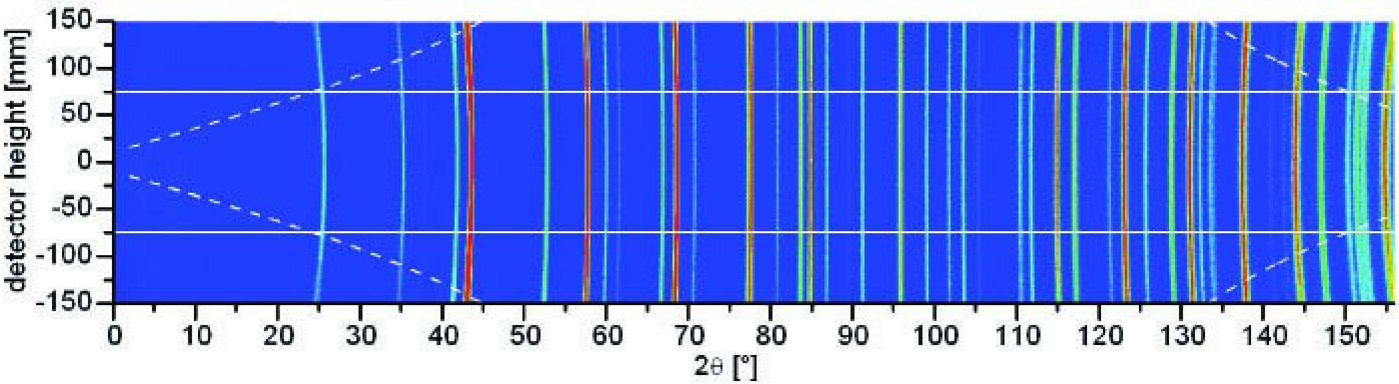


Used with CCD or photomulitplier

2.6. Overview on neutron instrumentation (part I)

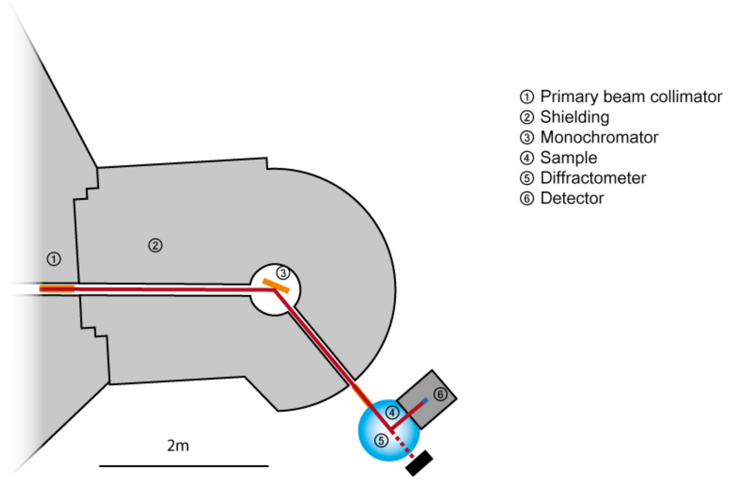
Powder diffraction (SPODI @ MLZ)

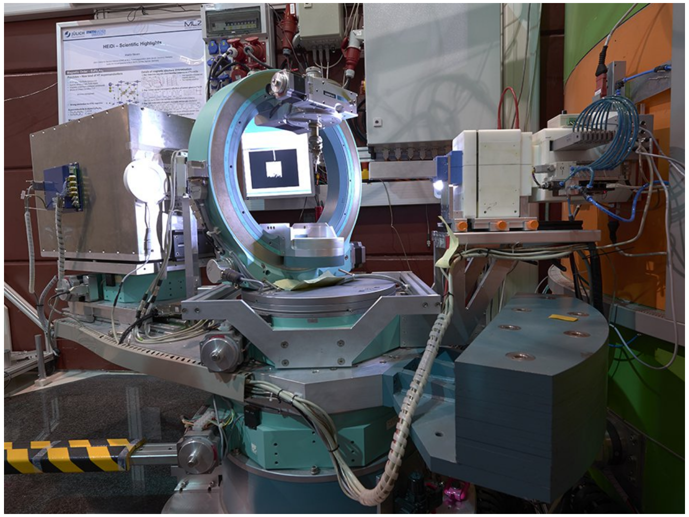




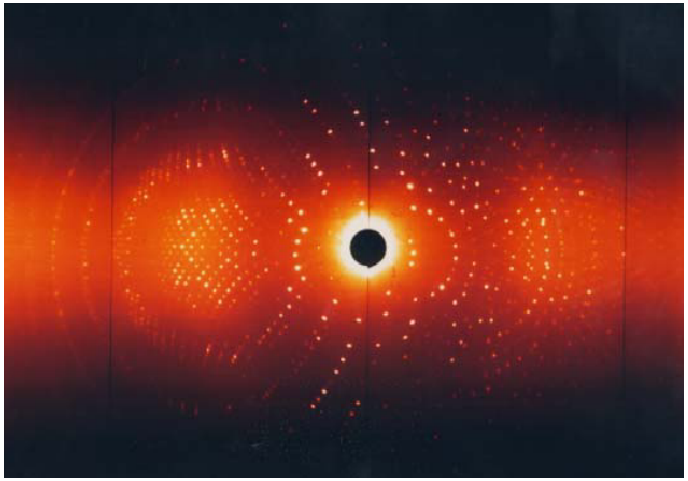
2.6. Overview on neutron instrumentation (part I)

Single X-tal diffraction (HEIDI @ MLZ)

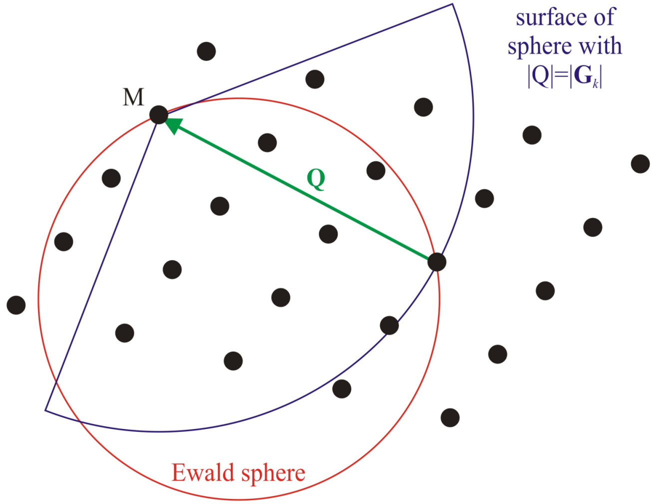




Laue method:

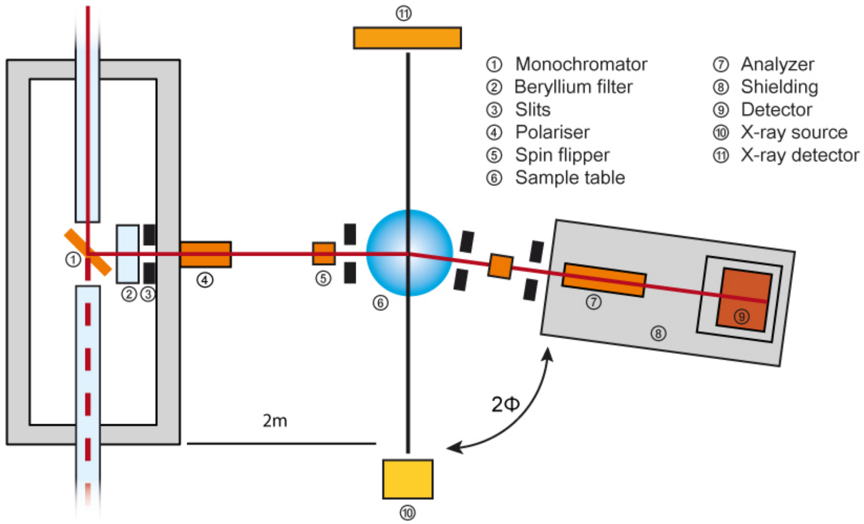


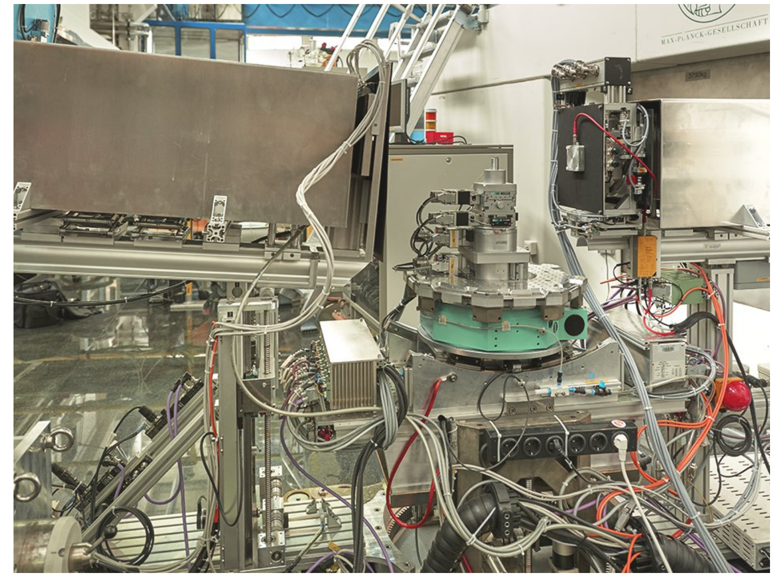
Bragg Brentano method:

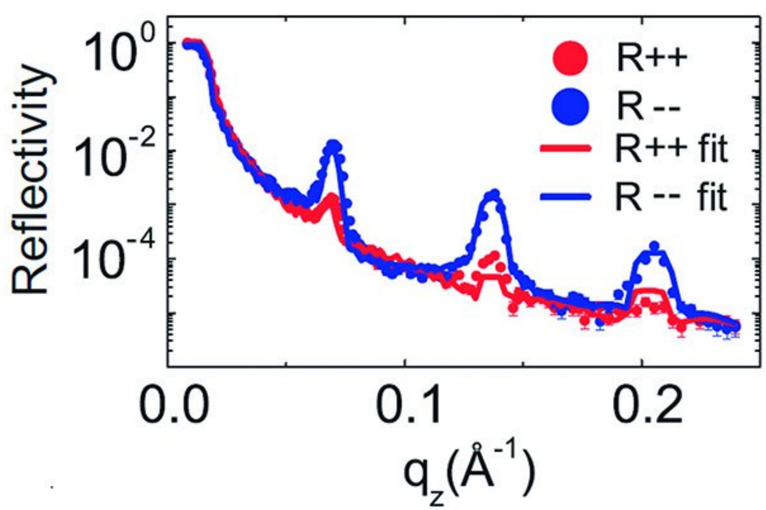


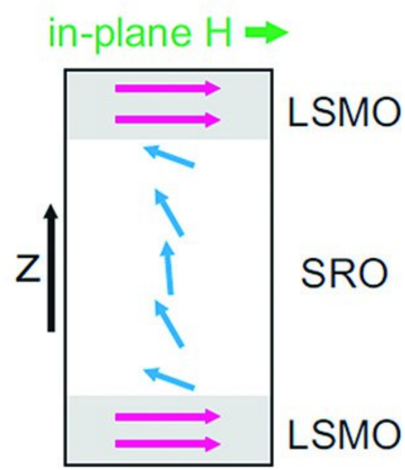
2.6. Overview on neutron instrumentation (part I)

Reflectometry (NREX @ MLZ)









2.6. Overview on neutron instrumentation (part I)

Small angle neutron scattering (SANS-1@ MLZ)