IX-th school of neutron scattering “Francesco Paolo Ricci”

Application of neutrons to structural determination in soft matter

Neutron production and basic instrument components

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Consiglio Nazionale delle Ricerche

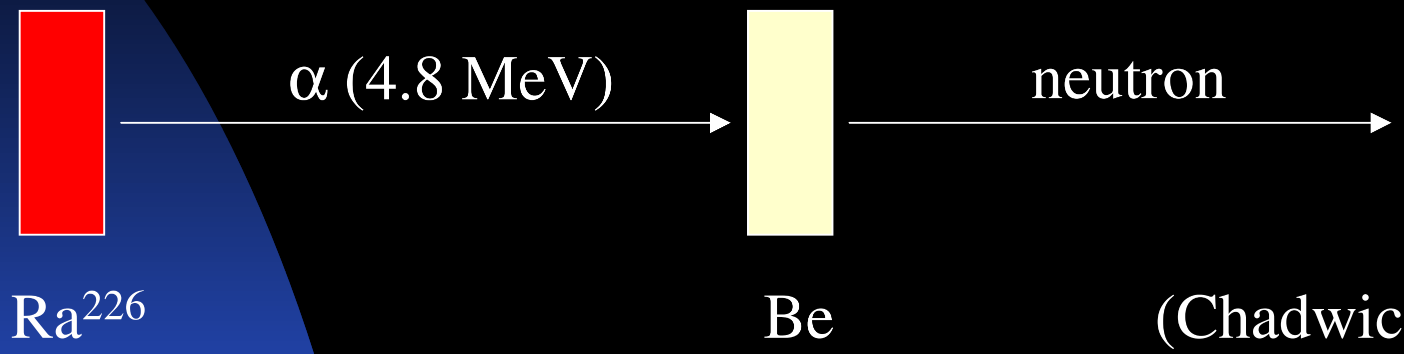
Summary:

- Neutron production
- Modern neutron sources
- Instrument components

Neutron production

- Natural radiative sources
- Fission reactors
- Particle accelerator driven sources

Natural radiative sources
{α, n} reaction

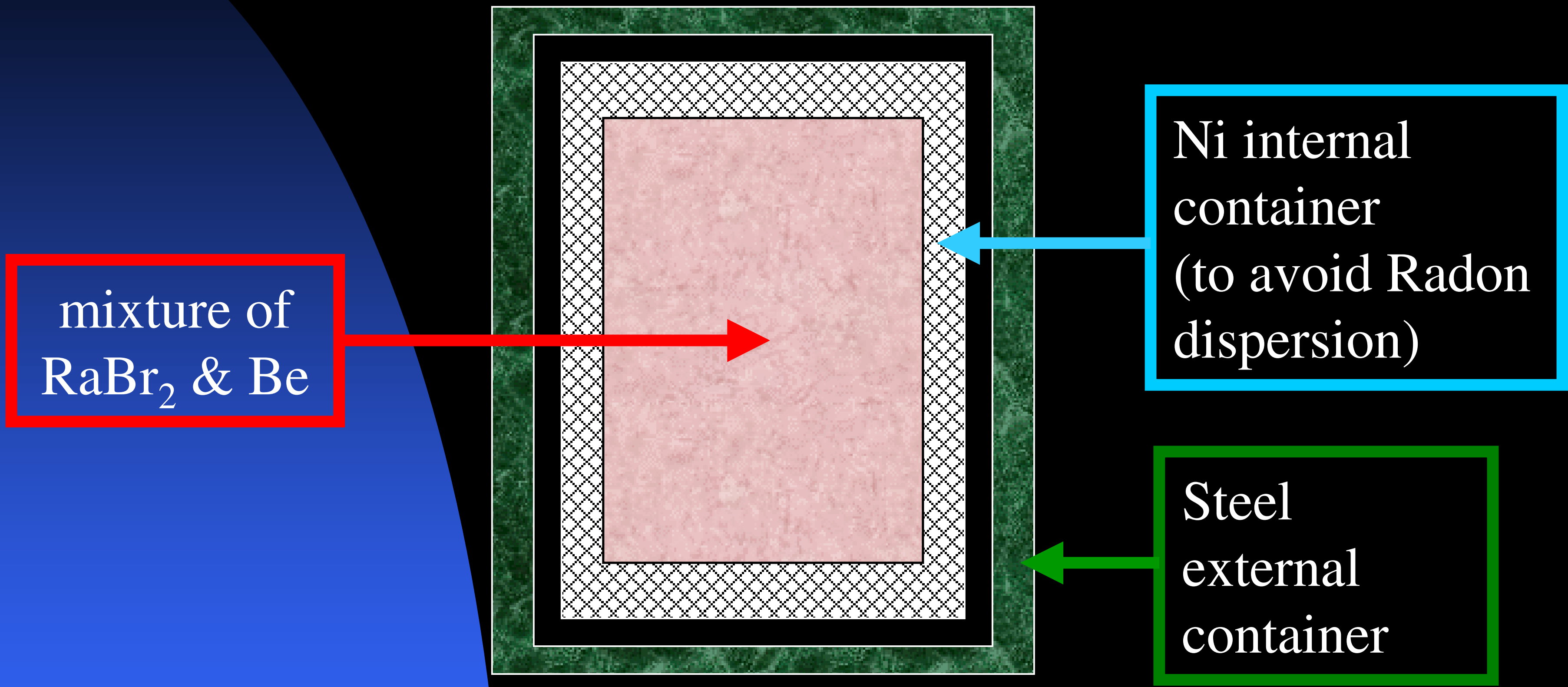


(Chadwick, 1932)

$$^{4}He + {}^{9}Be \rightarrow {}^{12}C + n + 5.7\ \mathrm{Mev}$$

Esothermal Reaction

The Radium-Beryllium source



Typical use: detector tests

Natural radiative sources

{γ, n} reaction

γ (10.8 KeV) → neutron →

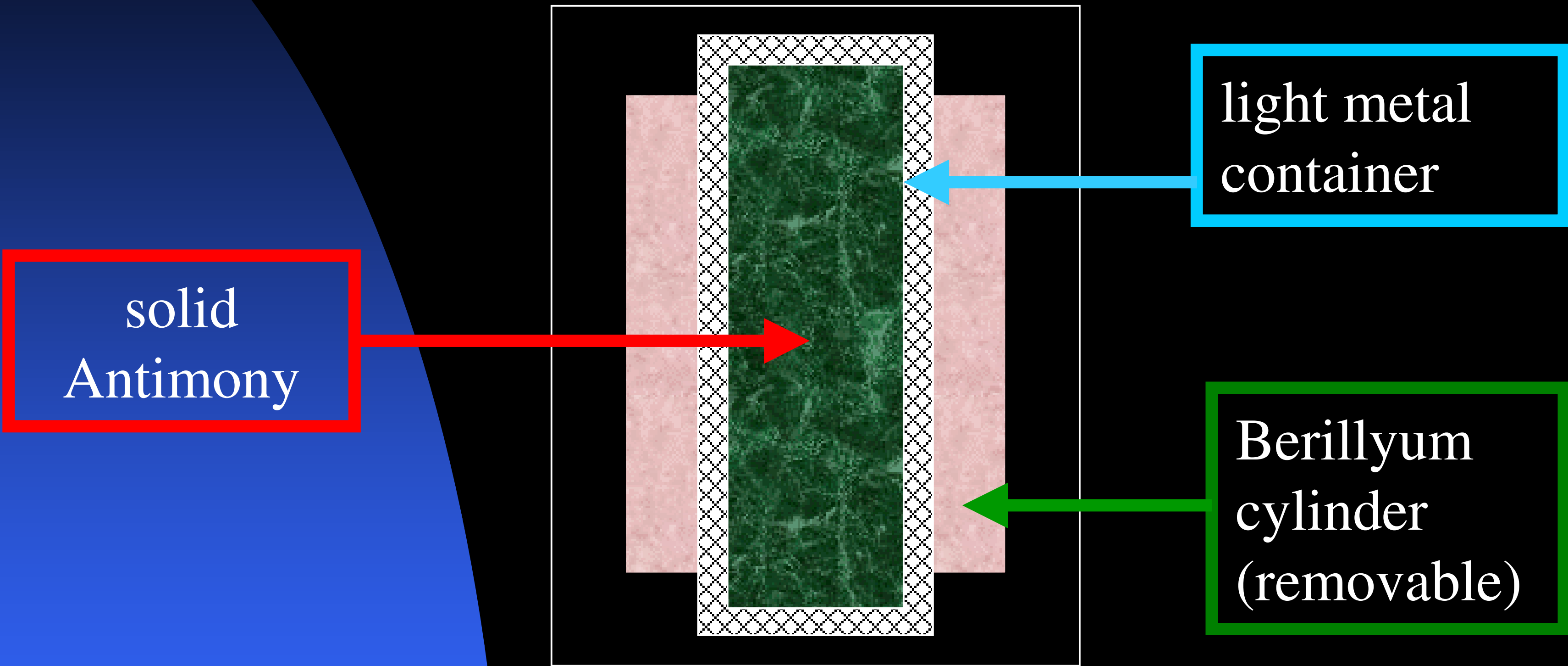
(Antimony) Sb^{124} Be

$$\gamma + {}^{9}Be \rightarrow ({}^{9}Be)^{*} \rightarrow {}^{8}Be + n - 1.66 \text{ Mev}$$

1 weakly bonded neutron

endothermal reaction

The Antimony-Beryllium source



Advantage: it can be turned off!

Modern neutron sources

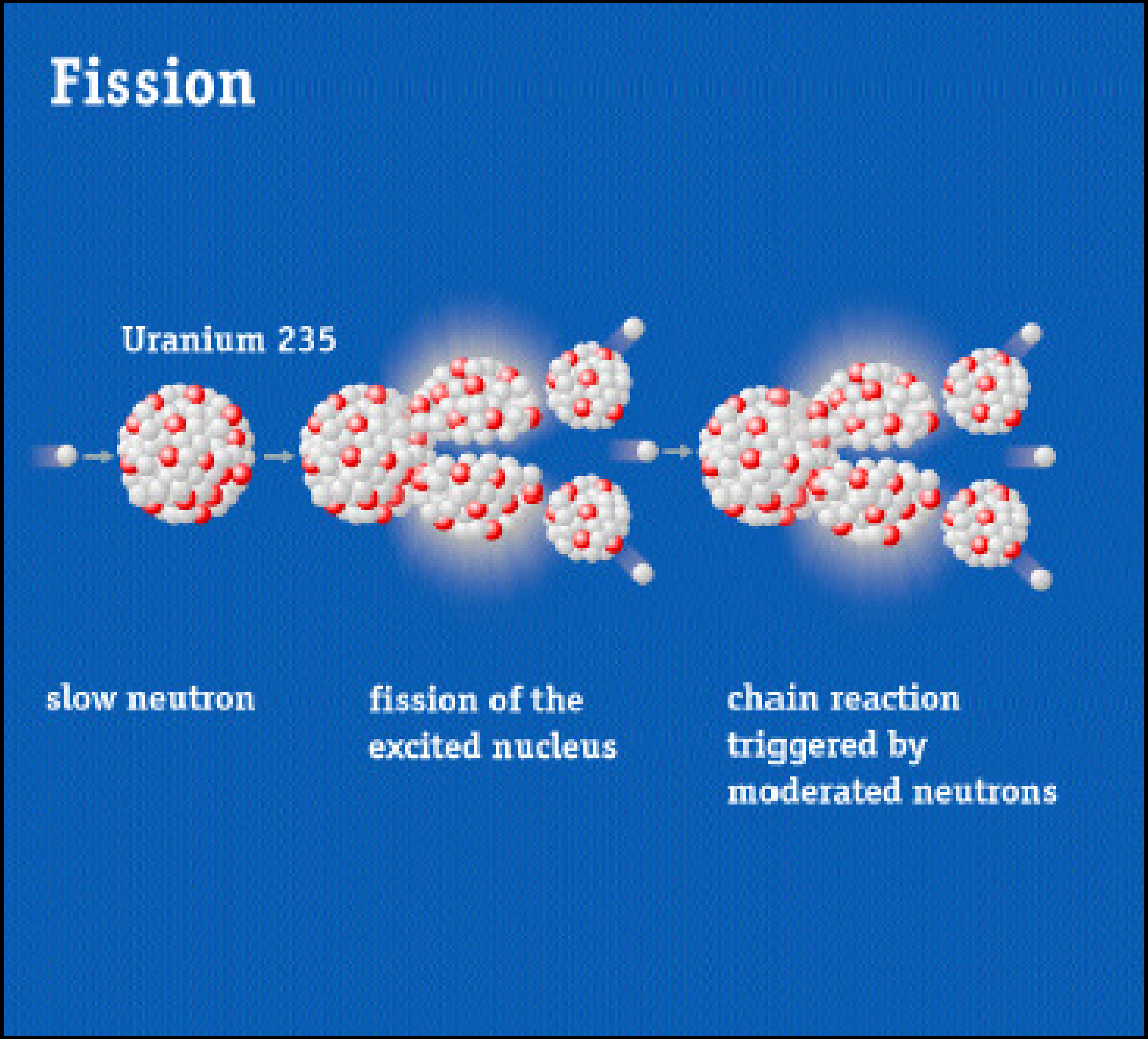
- Nuclear fusion sources
- Fission reactor sources
- Particle accelerator driven sources

Neutron production by fission

- **Bullet:**
  - **slow neutron**
- **Target:**
  - **^{235}U**
- **Nuclear reaction product**
  - **^{236}U (unstable)**

Fission products:

- **2 light nuclei**
- **2-3 fast neutrons**



Example: 20 MW research reactor

$$n + {}^{235}U \rightarrow 2.5\,n + 200\ \text{MeV} + 2\ \text{light nuclides}$$

1 neutron to maintain the reaction ON

0.5 neutron absorbed

1 neutron for utilization

N. of fissions / sec = 20 MW / 200 MeV / fission

= 6.2 x 10^{17} fissions / s

= 6.2 x 10^{17} neutrons / s (for use)

1.5 x 10^{18} neutrons / sec produced in the reactor core

Energy spectrum of a reactor

fission neutrons:
(E > 500 KeV)

$$\Phi(E)dE = \Phi_{fast} \exp\{-E\}\sinh(2E)^{1/2}\, dE$$

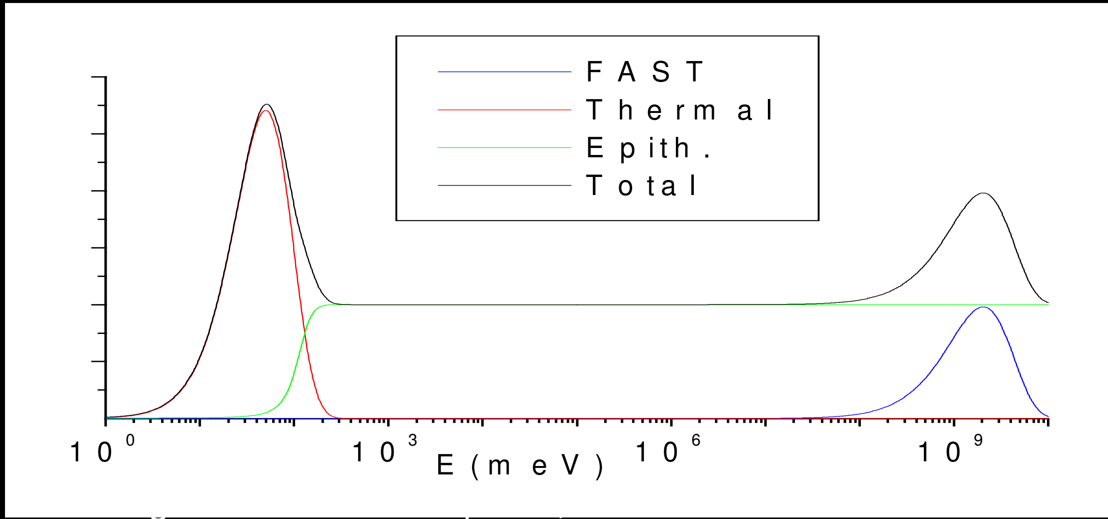
epithermal neutrons:
(200 meV<E<500 KeV)

$$\Phi(E)dE = \Phi_{epith}\, dE/E$$

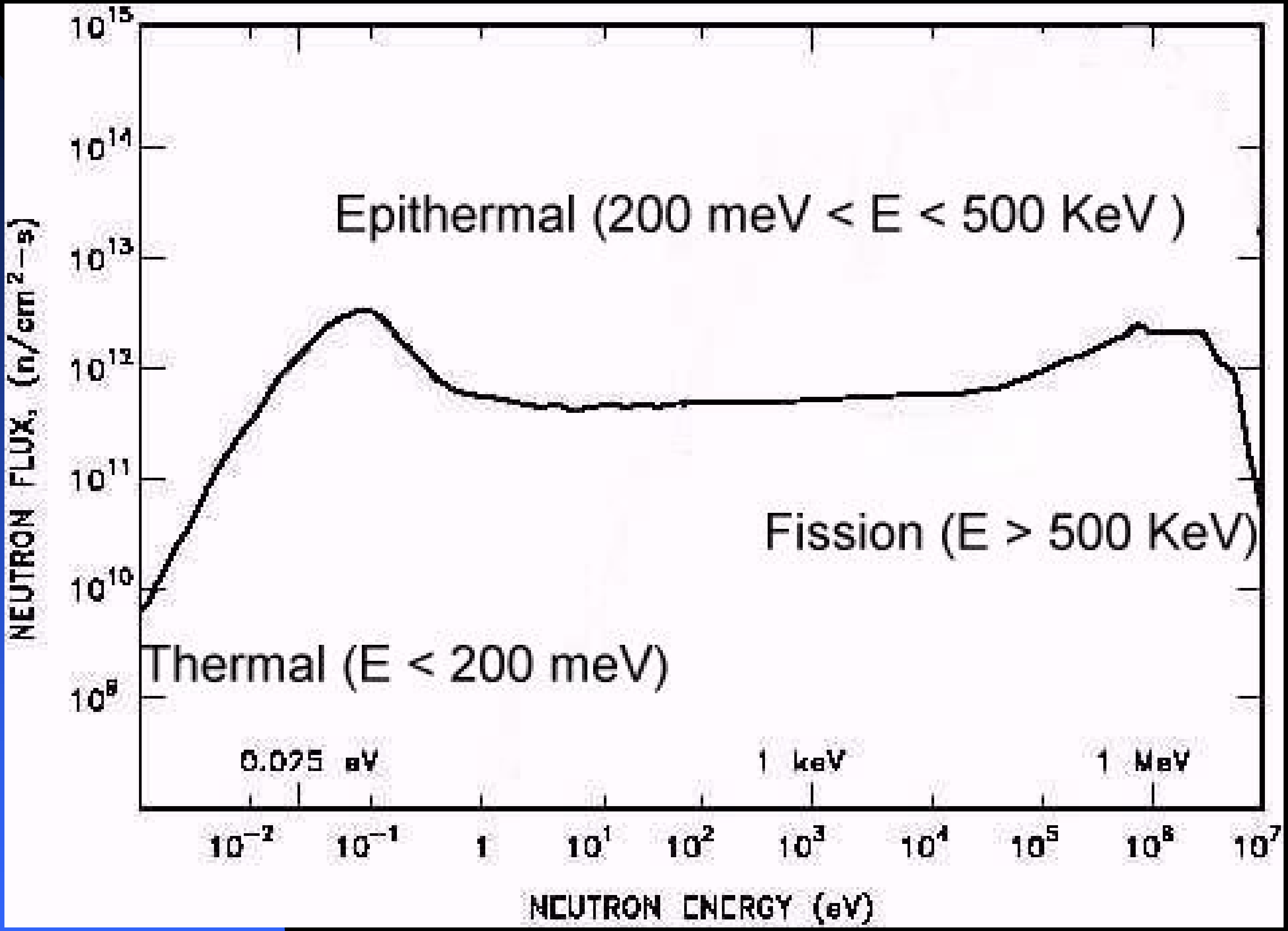
thermal neutrons:
(E < 200 meV)

$$\Phi(E)dE = \Phi_{therm} \frac{E}{k_B T} \exp\left\{-\frac{E}{k_B T}\right\} dE$$

Resulting spectrum:



Reactor spectrum: observed



Example -1: ILL reactor(58 MW)

4.3 x 10^{18} neutrons / s (from fission)

1: safety bar

2: heavy water IN

3: heavy water OUT

4: double neutron guide

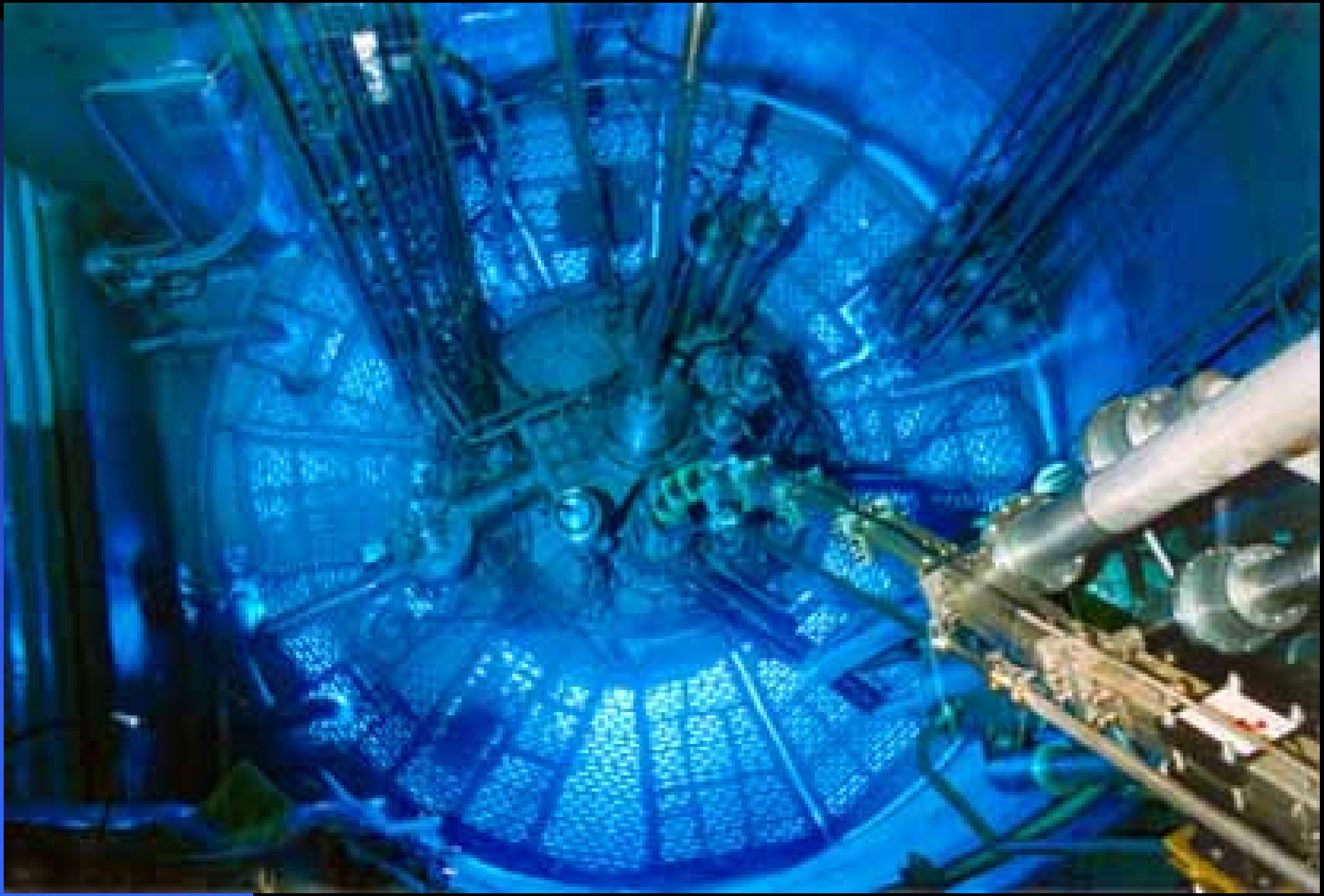
5-7: cold sources

6: reactor core (Uranium 235)

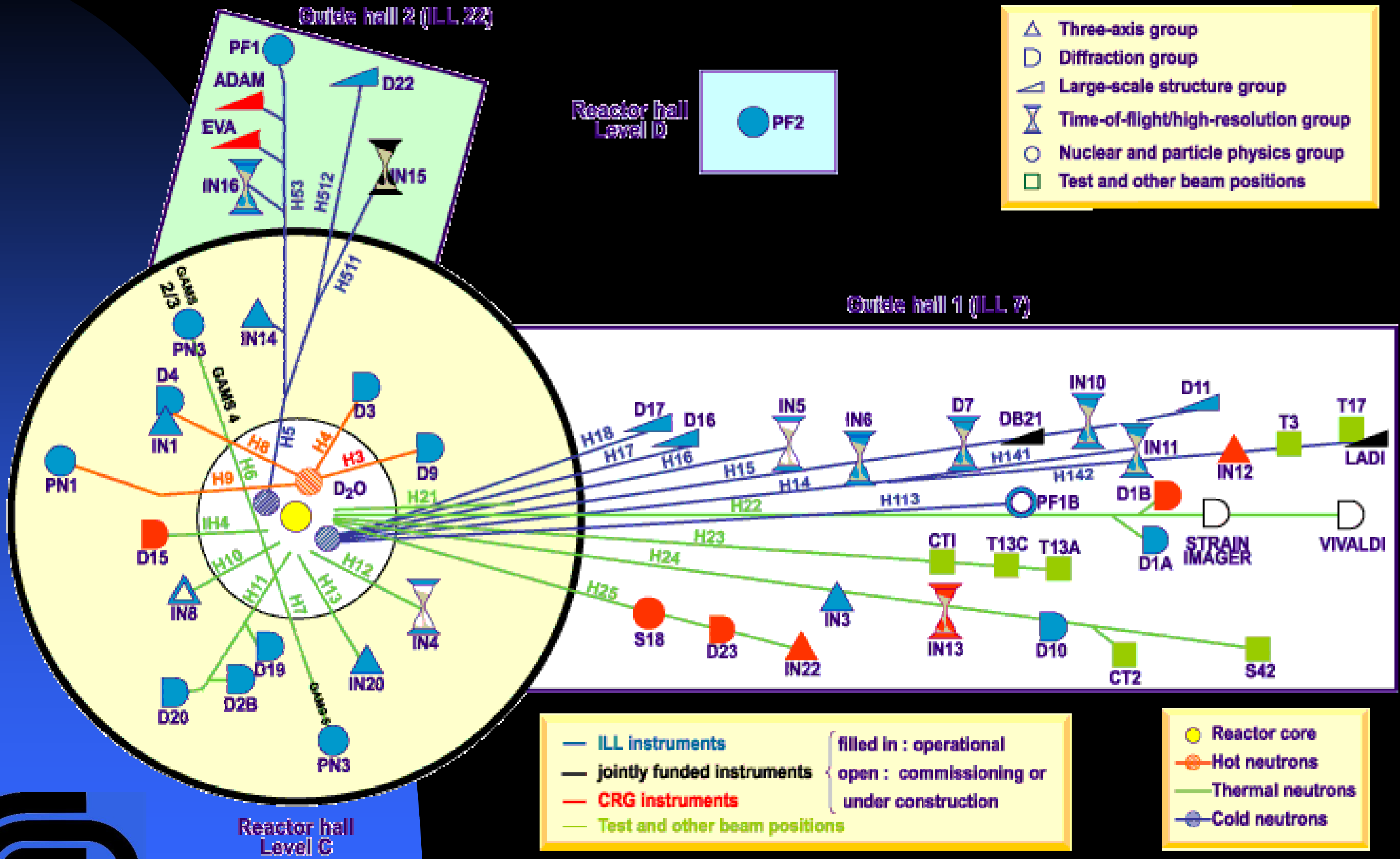
8: control bar (Boron)

A view of the reactor pool

Blue light: Cerenkov radiation



ILL: instruments map

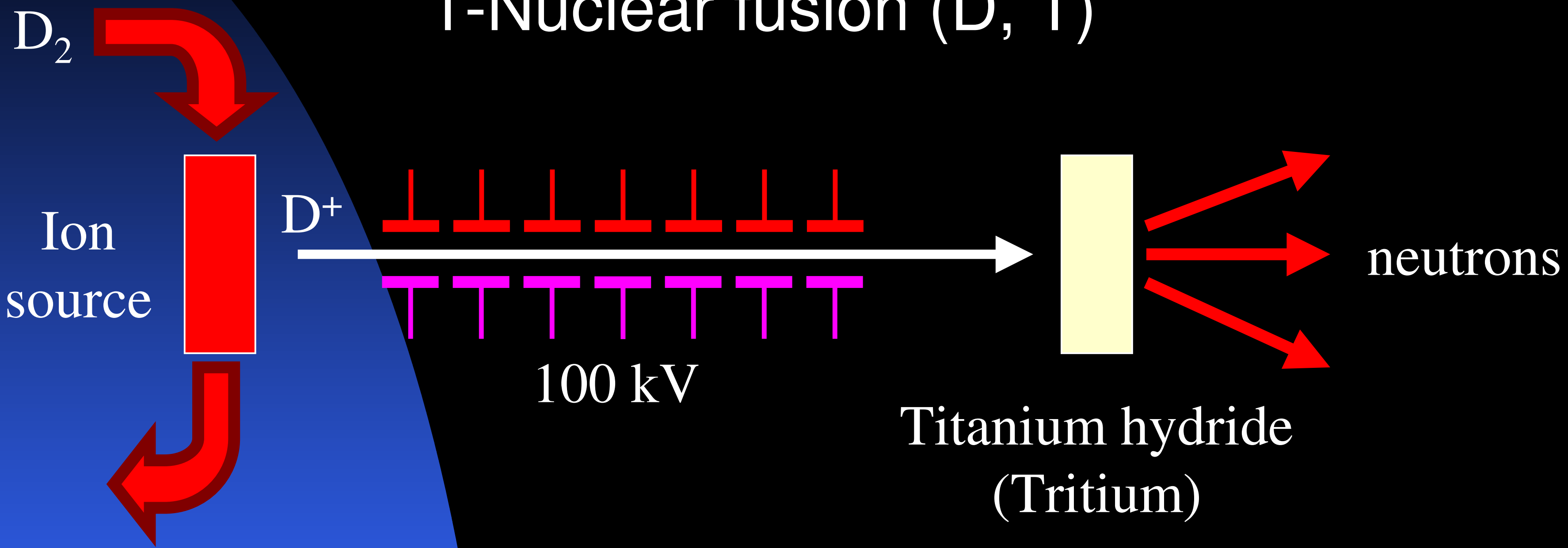


Example -2: FRM II reactor (20 MW)

1.5 10^{18} neutrons / s (from fission)

Particle accelerator driven sources (1)

1-Nuclear fusion (D, T)



$$^{2}H + ^{3}H \rightarrow ^{4}He + n + 17.6 \text{ Mev}$$

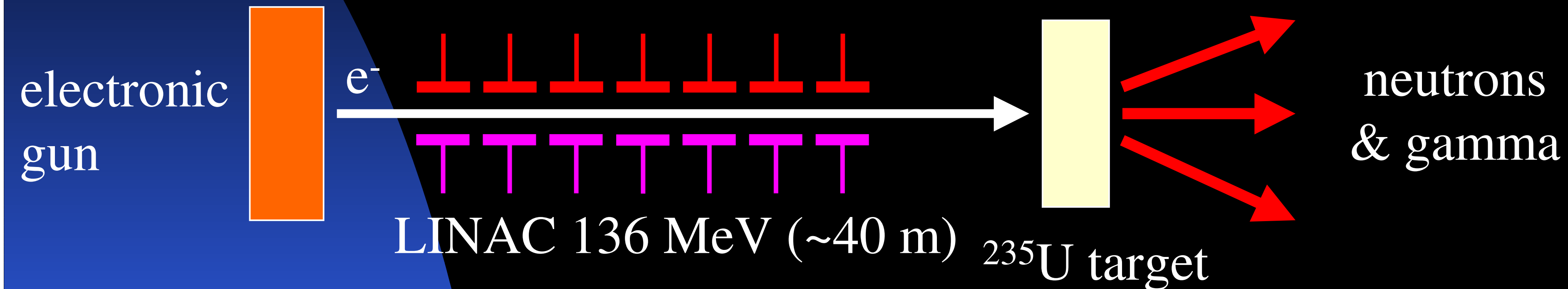
Flux: ~10^{11} neutrons / sec

Portable neutron source

- Source dimensions:
  - diameter: 35 - 130 mm
  - length: 450 - 1000 mm
- neutron output: 10^8 - 10^{10} n/s
- pulse width: 1 - 100 ms
- pulse frequency: 1 - 100 Hz
- life time: 100 - 500 hours

Particle-accelerators driven sources (2)

2-Bremsstrahlung from electron-beam (LISONE@Frascati)



$$e^{-} \rightarrow \gamma_{bremsstrahlung} \rightarrow (\gamma, n) \rightarrow (\gamma, fission)$$

Advantages:

- Full control on frequency & pulse width

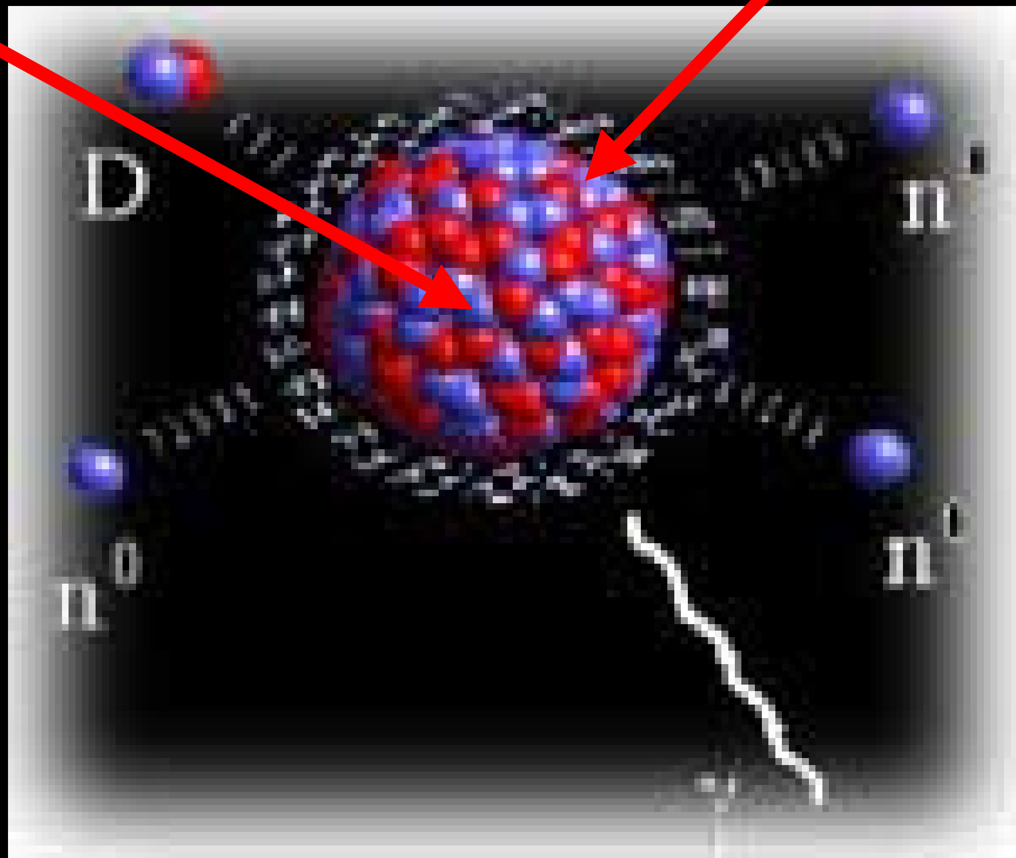
Disadvantages:

- High γ-ray background

Spallation neutron sources
(to spall = to splinter, break away)

High energy protons

Target: Tungsten

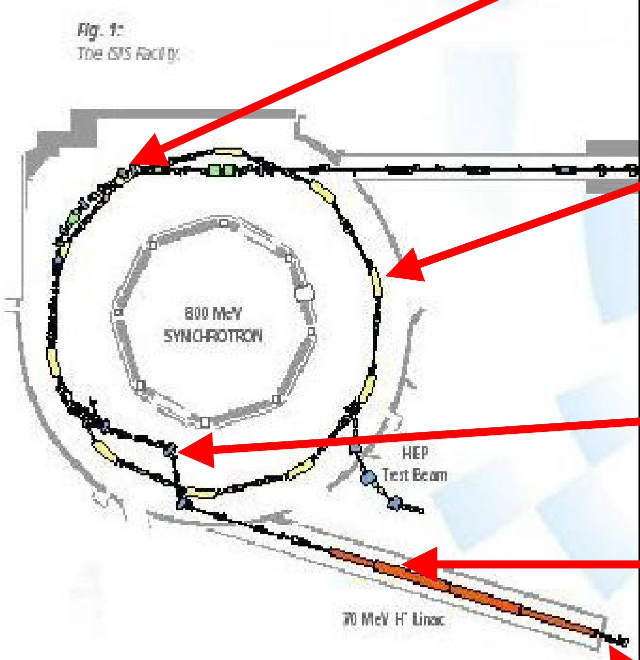


- Highly excited nuclear state
- Relaxation:
  - Radiative decay
  - Evaporation of light nuclides
- 15-30 neutrons / event

Proton accelerator sources

- Linear accelerators (LAMPF, Los Alamos)
  - **High current**
  - **High duty-cycle (high frequency / long pulses)**
- Cyclotron (TRIUMF, Canada; SINQ, Swisse)
  - **continuous operation**
- Synchrotron (ISIS, UK; IPNS & SNS, USA; KENS, Japan)
  - **Low Current**
  - **Relatively short pulse**
  - **Modest duty-cycle (Typical frequency ~50 Hz)**

Example: ISIS pulsed neutron source
(1: accelerator)



Extraction & stripping H^+

Synchrotron

accumulation

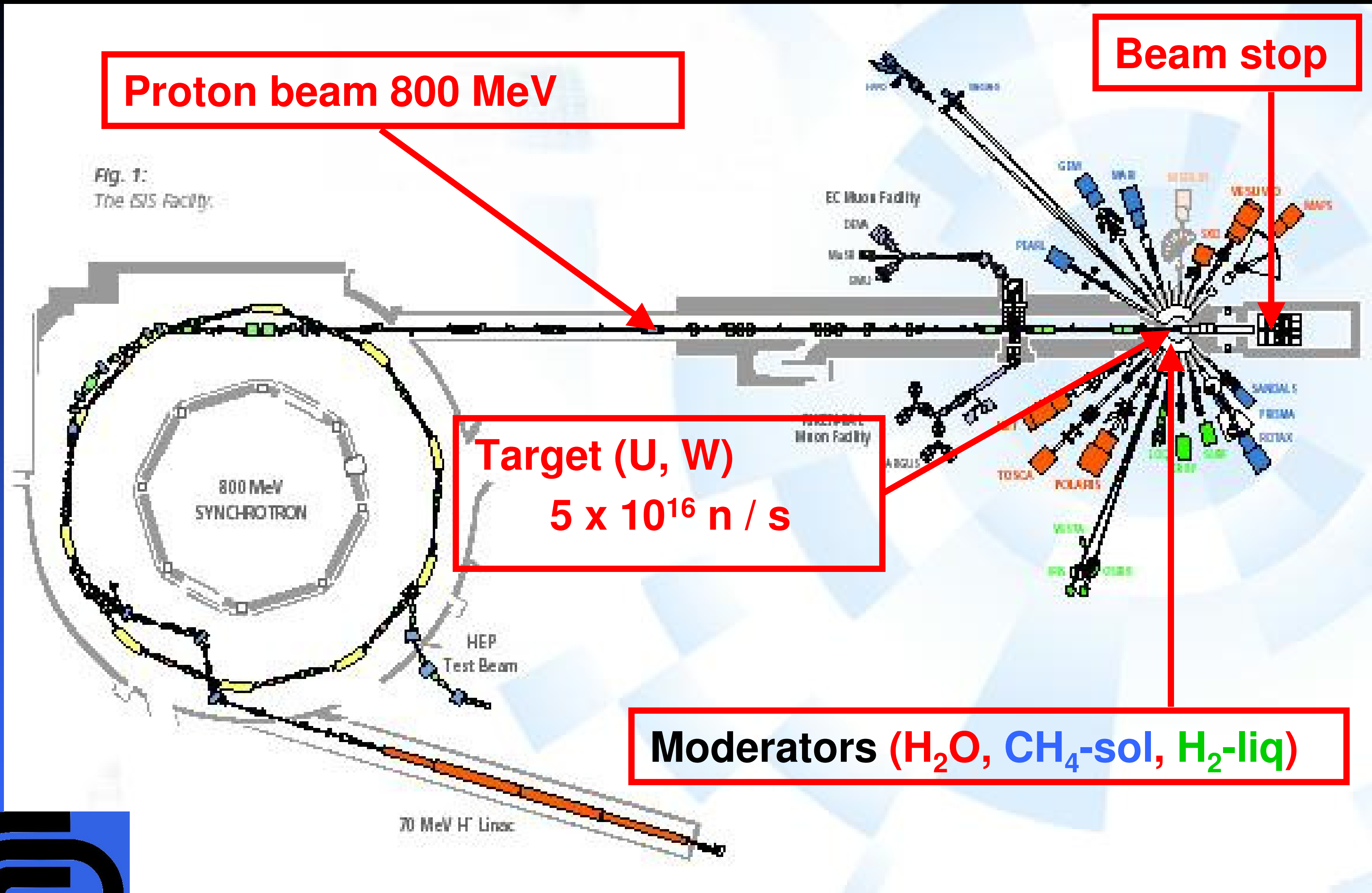
acceleration (800 MeV)

Injector

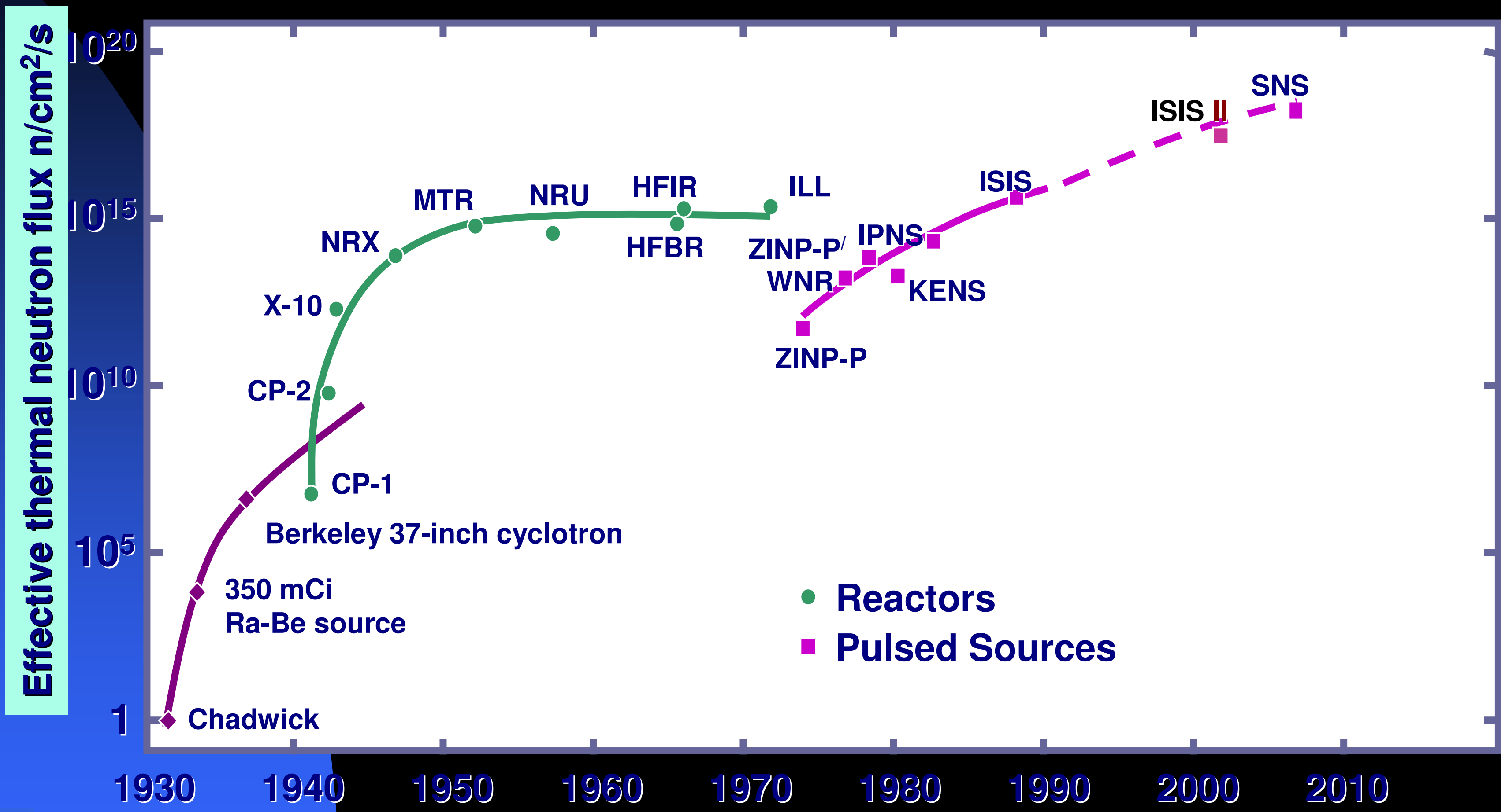
Linear accelerator (80 -100 MeV)

H^- Ion source

The (old) pulsed neutron source ISIS



Neutron source intensity:
historical data



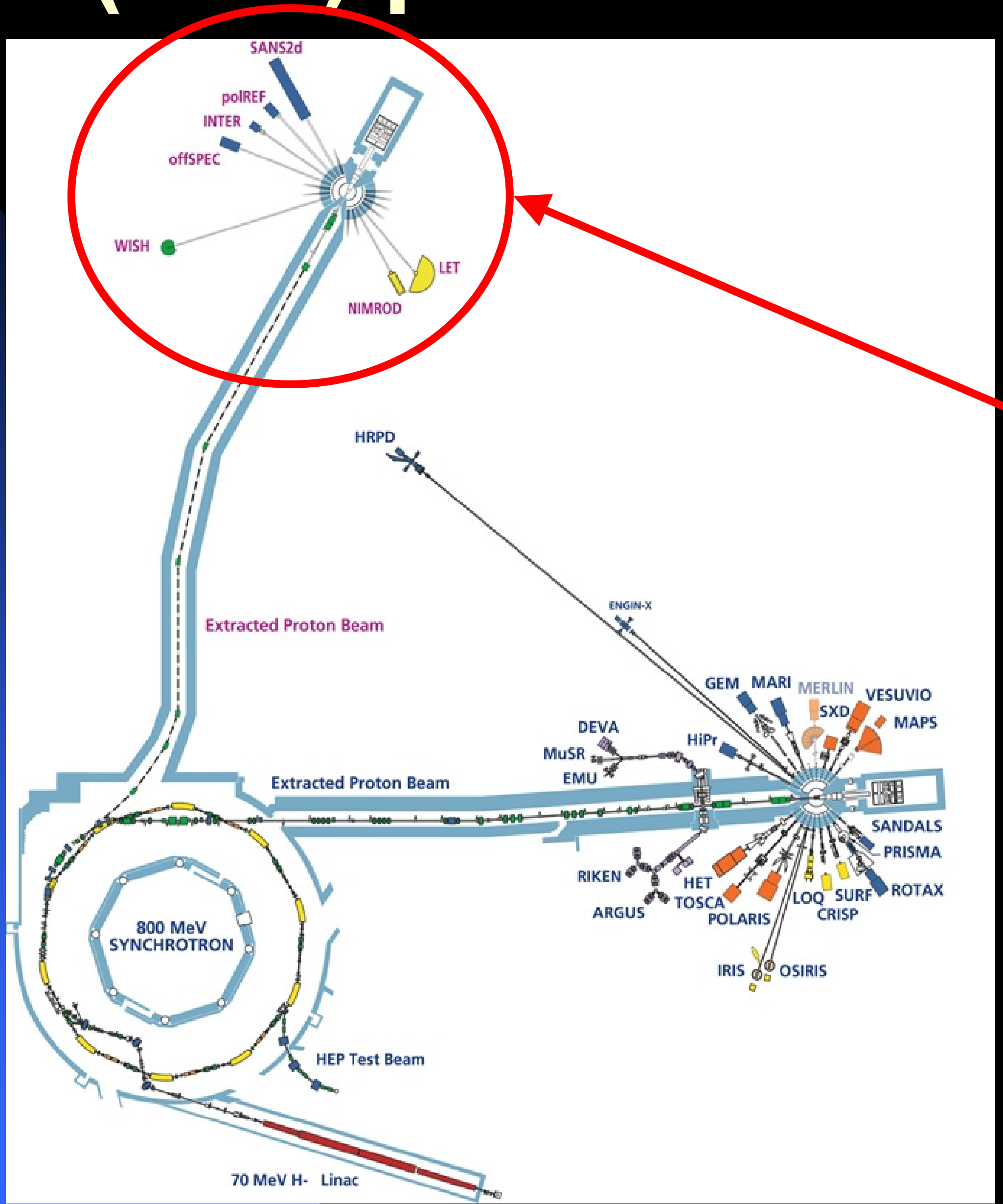
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Reactors – pulsed sources
a comparison

Reactors	Pulsed sources
More thermal neutrons	More epythermal neutrons
fission neutrons: easily shielded	fast neutrons: time selection
Metods of analysis: flexible	Method of analysis: time of flight
Natural operation: “continuous”	Natural operation: “pulsed”
Average flux increase: difficult	Peak flux increase: possible
Resolving power: problem tunable	Shorter pulse ⇒ higher resolution
Resolution function: Gaussian	Resolution function: asymmetrical
Mature and optimized techniques	New techniques: development possible

The (new) pulsed neutron source

ISIS-TS2



2nd Target Station
Presently,
under development
1st neutrons on
August 2008 !!!

ISIS-2: the new neutron source

ISIS-2: the new neutron source

The SNS pulsed neutron source
(Oak Ridge, USA)

The J-park spallation neutron source (Japan)

The European Spallation Source (ESS)

- Feasibility study (1994-2004)
- Two consortia now active:
  - Sweden-Denmark Consortium (Lund)
  - Spain-Hungary Consortium (Bilbao)

Instrument Components

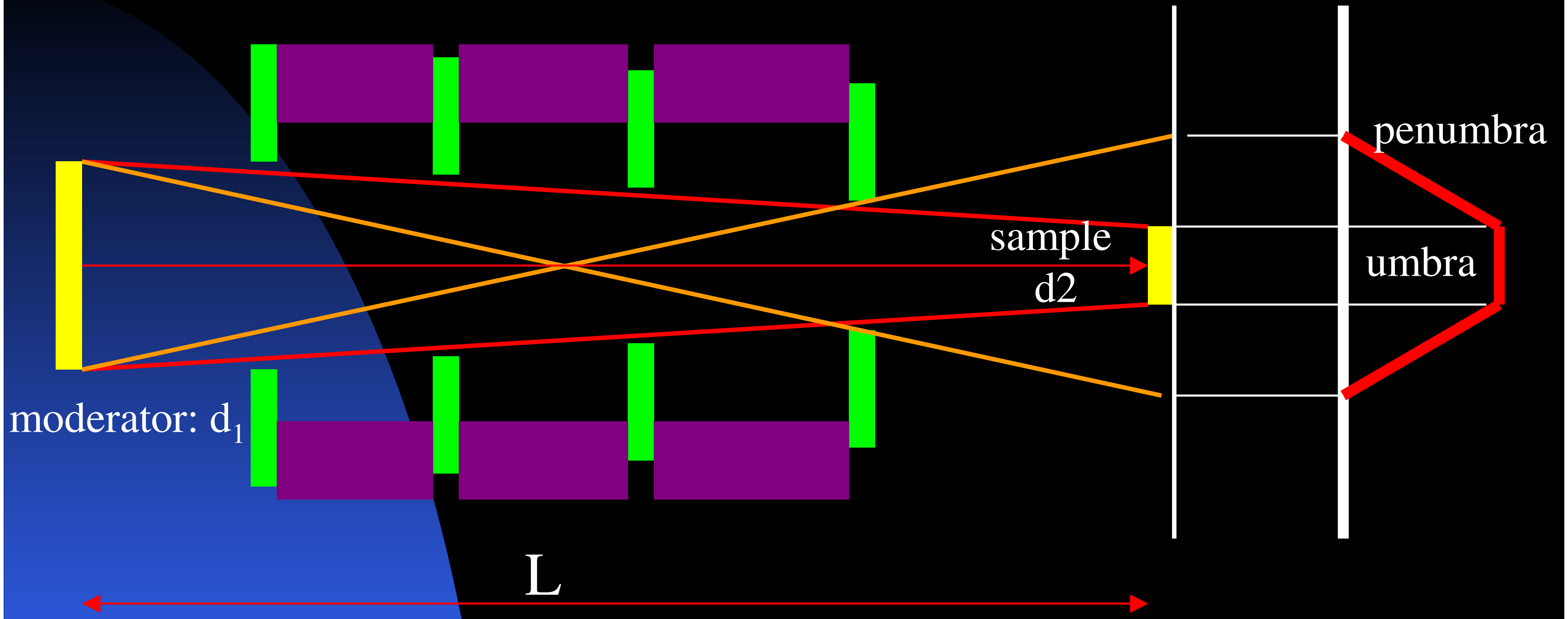
- Neutron guides and collimators
- Mechanical velocity-selectors
- Crystal monochromators
- Passive filters
- Detectors

Neutron collimators and guides

- Pipe collimator
- Soller collimator
- Complex collimator

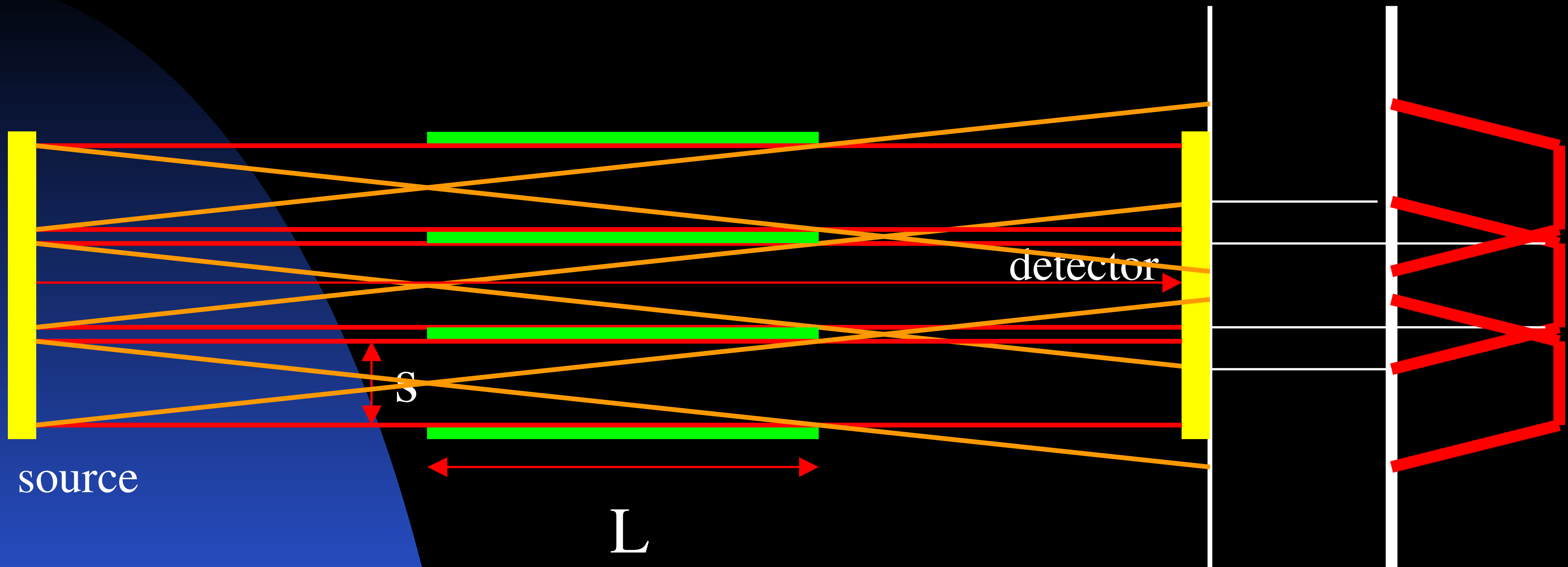
- Reflection e refraction
- Neutron guides
- Curved guides

Pipe collimator



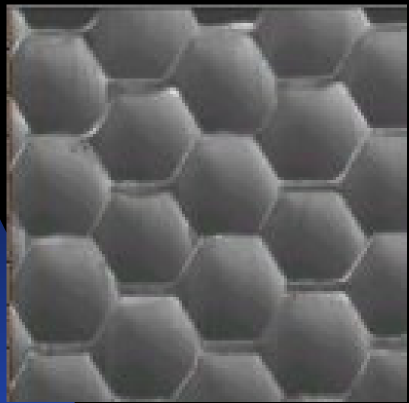
$$\alpha = \frac{d_1 + d_2}{L}$$ = beam divergence

Soller collimator



$$\alpha = \frac{s}{L} = \text{beam divergence}$$

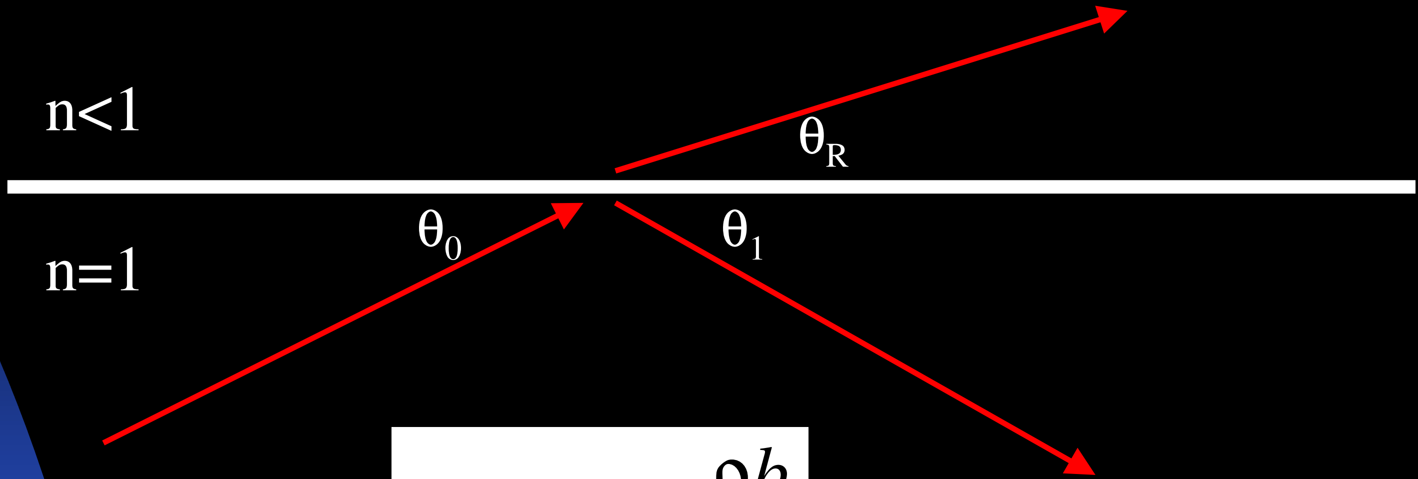
Complex collimators



- Honeycomb collimator

- Cylindrical collimator

Reflection & refraction

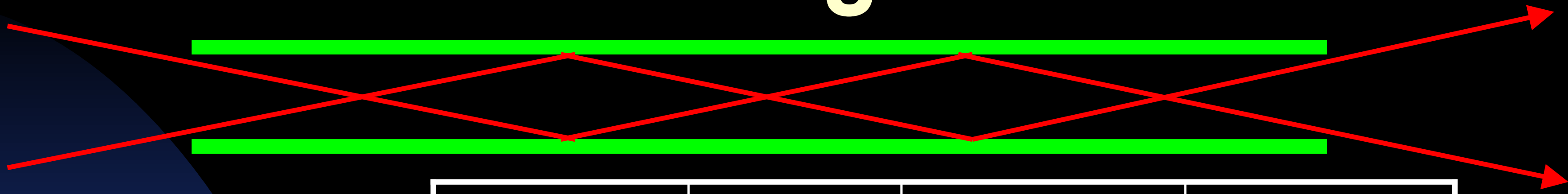


neutron refractive index: $n^2 = 1 - \lambda^2 \frac{\rho b}{\pi}$

$\cos(\theta_0) = n\cos(\theta_R)$ refraction law $n < 1 \Rightarrow \theta_0 > \theta_R$

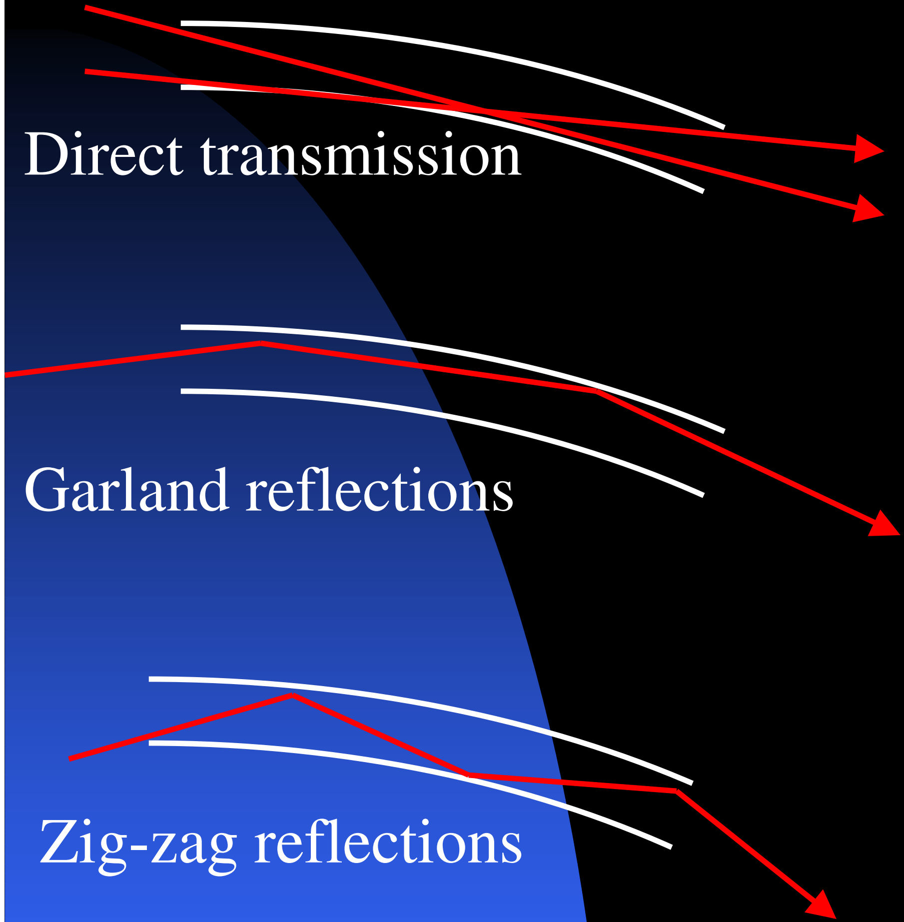
Limit angle (total reflection): $\cos(\theta_0) = n$

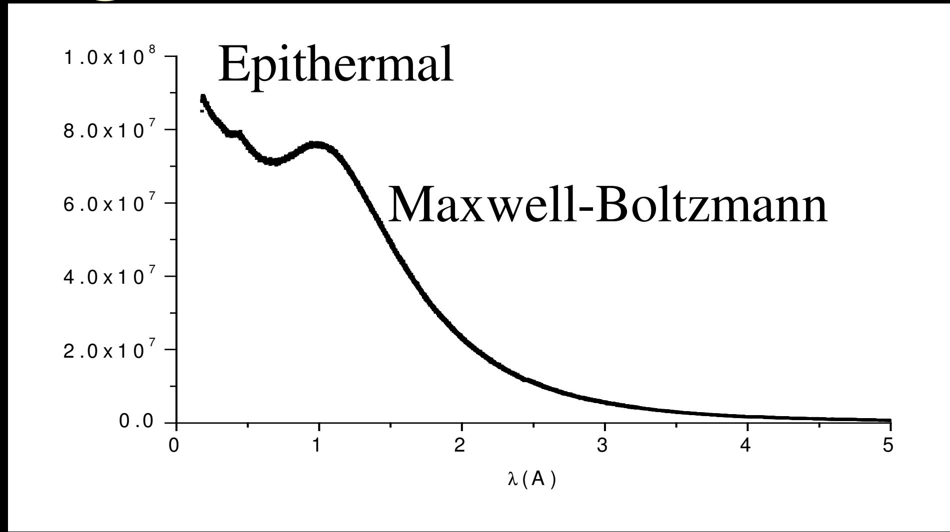
Neutron guides

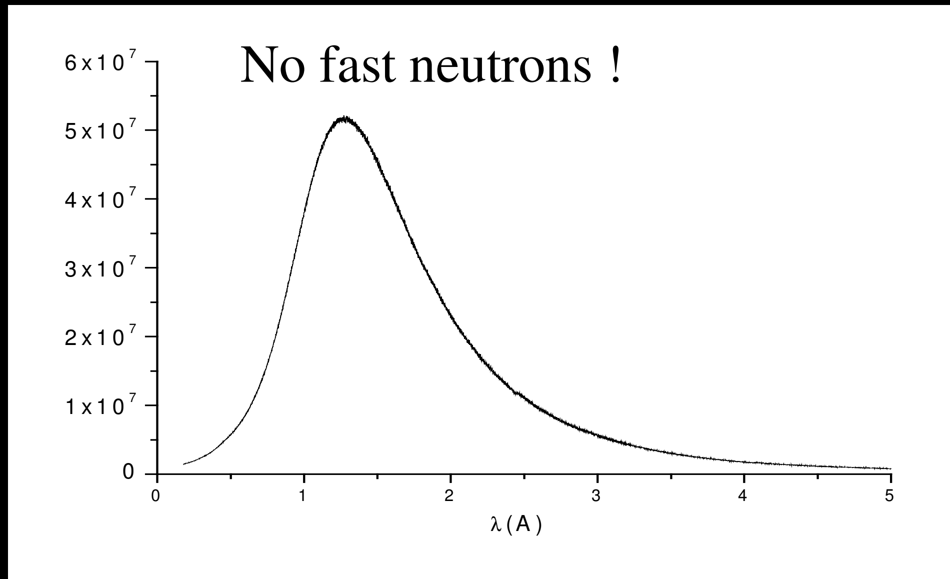


Element	ρ (nm^{-3})	b (10^{-12} cm)	θ_c / deg (@ 10A)
Ni^{58}	91.29	1.44	1.17
C (diam.)	176.19	.665	1.11
Be	123.62	.779	1.00
Ni	91.29	1.03	0.99
Fe	84.76	.954	0.92
C (graf.)	113.31	.665	0.89
Cu	84.92	.772	0.83
Al	60.26	.345	0.46

Curved guides



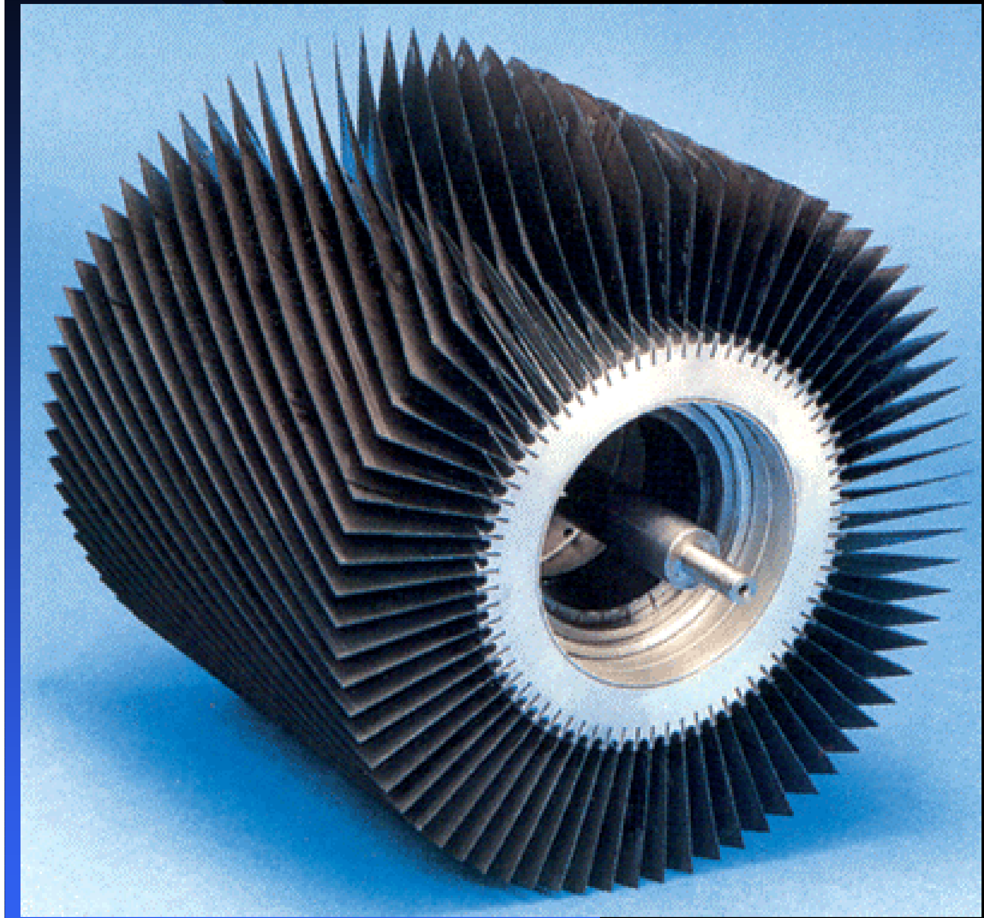




Mechanical velocity selectors

- Helical gap selector
- Fermi chopper
  - straight channel
  - curved channel
- disk chopper

Helical gap velocity selector



ω = angular velocity

φ = dephasing angle

s = channel dimension

R= radial dimension

L = length

v = neutron velocity

$$v = \frac{\omega L}{\varphi}$$

transit condition

Resolution: $$\frac{\Delta v}{v} = \frac{2s}{R\varphi}$$

Fermi Chopper

PHYSICAL REVIEW VOLUME 72, NUMBER 3 AUGUST 1, 1947

A Thermal Neutron Velocity Selector and Its Application to the Measurement of the Cross Section of Boron

E. FERMI, J. MARSHALL, AND L. MARSHALL
Argonne National Laboratory, University of Chicago, Chicago,** Illinois*

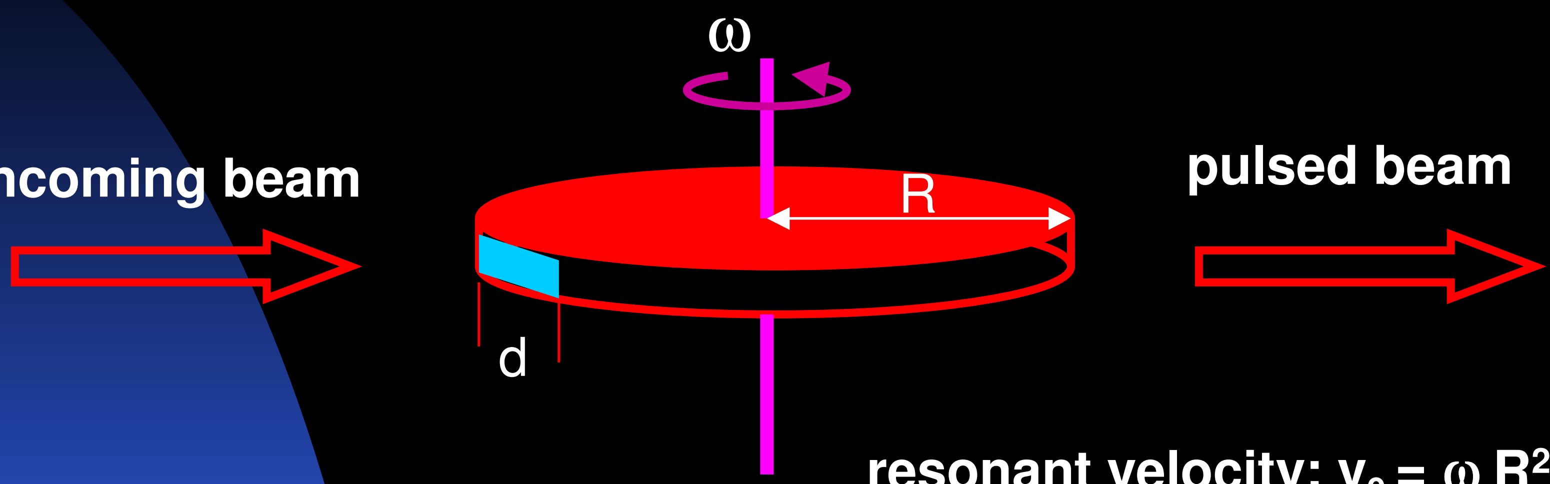
(Received April 25, 1947)

A mechanical velocity selector for the study of monochromatic neutrons in the range of energies below 0.3 ev is described.

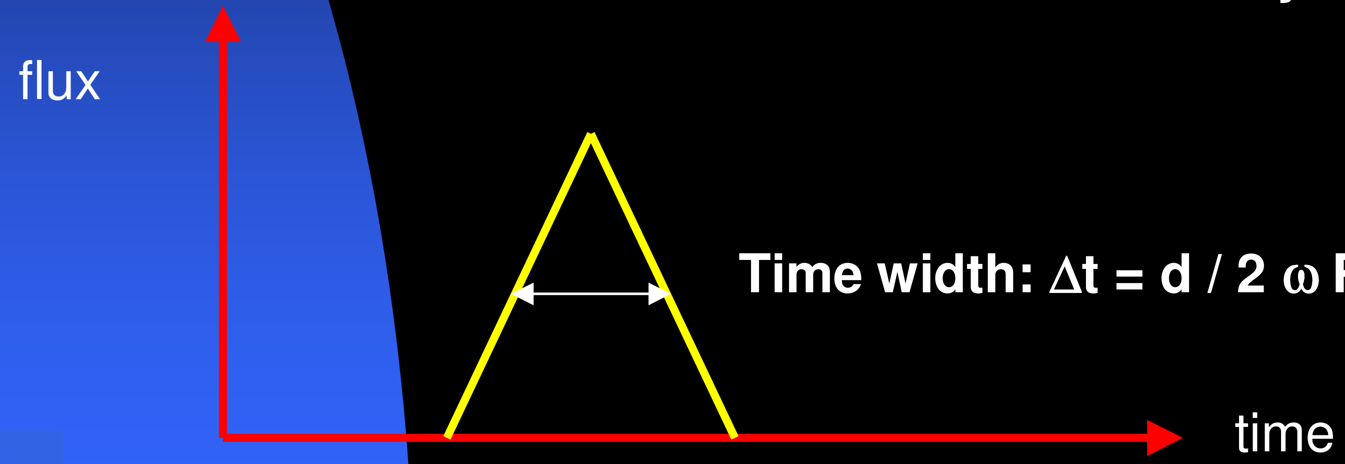
The instrument has been applied to the measurement of the cross section of boron, which is found to be 703×10^{-24} cm^2 for neutrons of 2200 meters per second velocity.

- US patent N. 2524379
- Date: March 10, 1950

Fermi chopper : straight slit

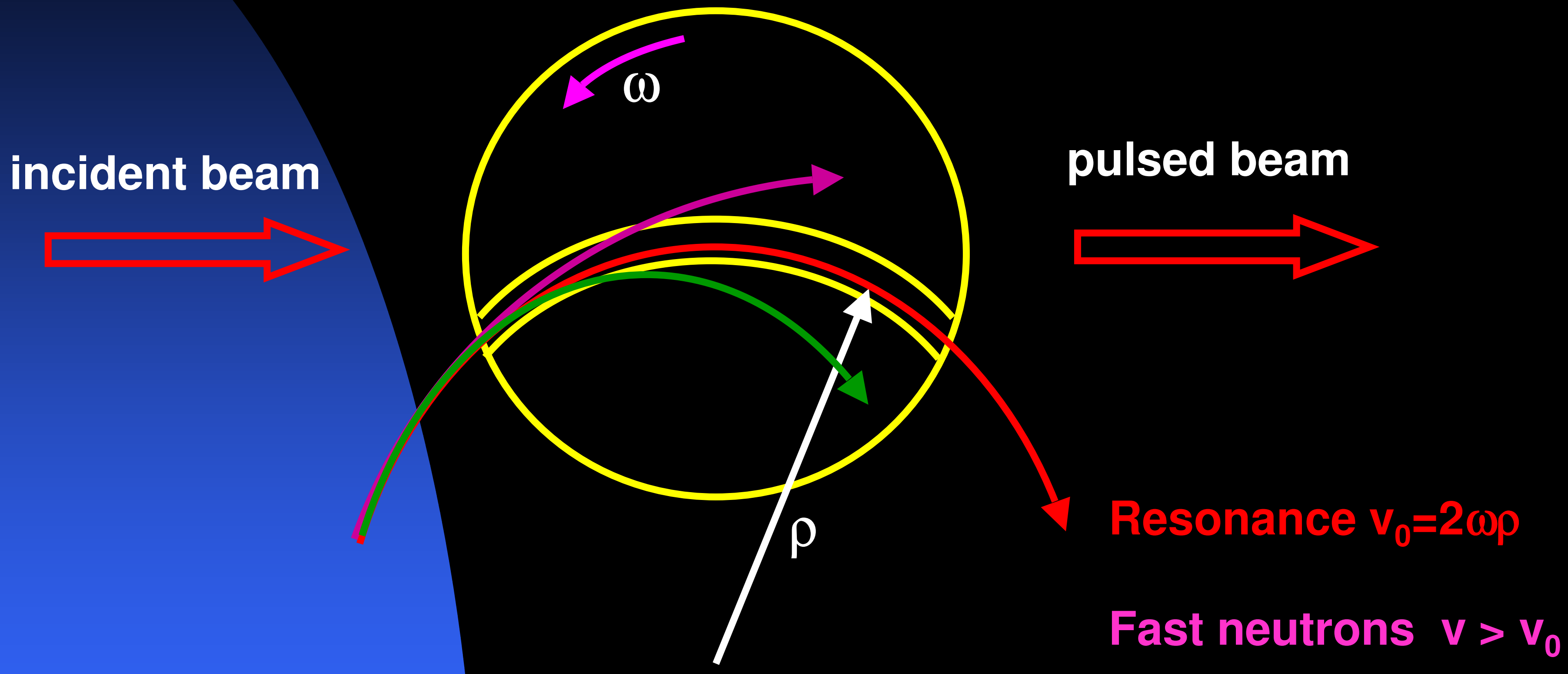


resonant velocity: $v_0 = \omega R^2 / d$

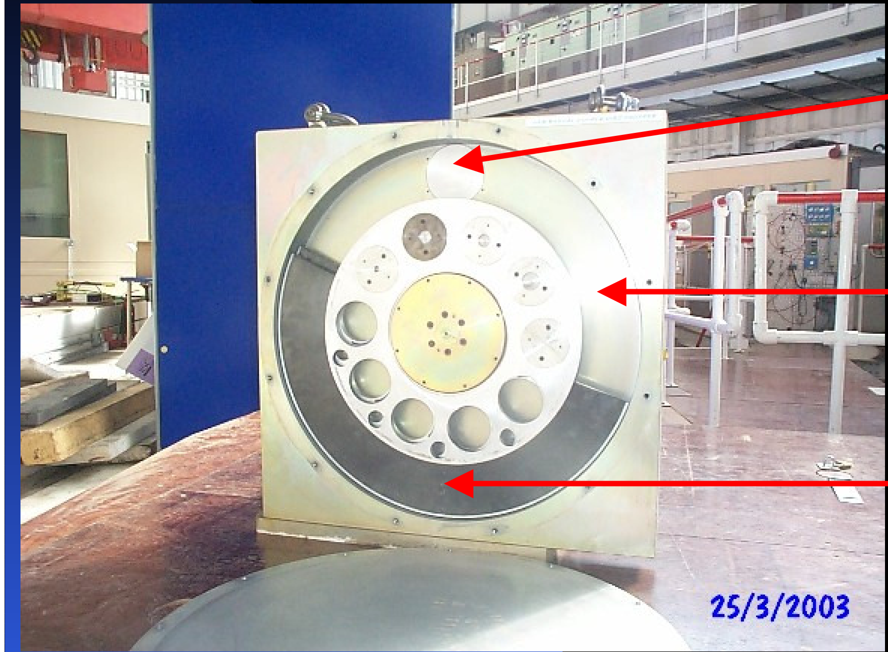


Time width: $\Delta t = d / 2 \omega R$

Fermi chopper (curved slit)



Disk chopper



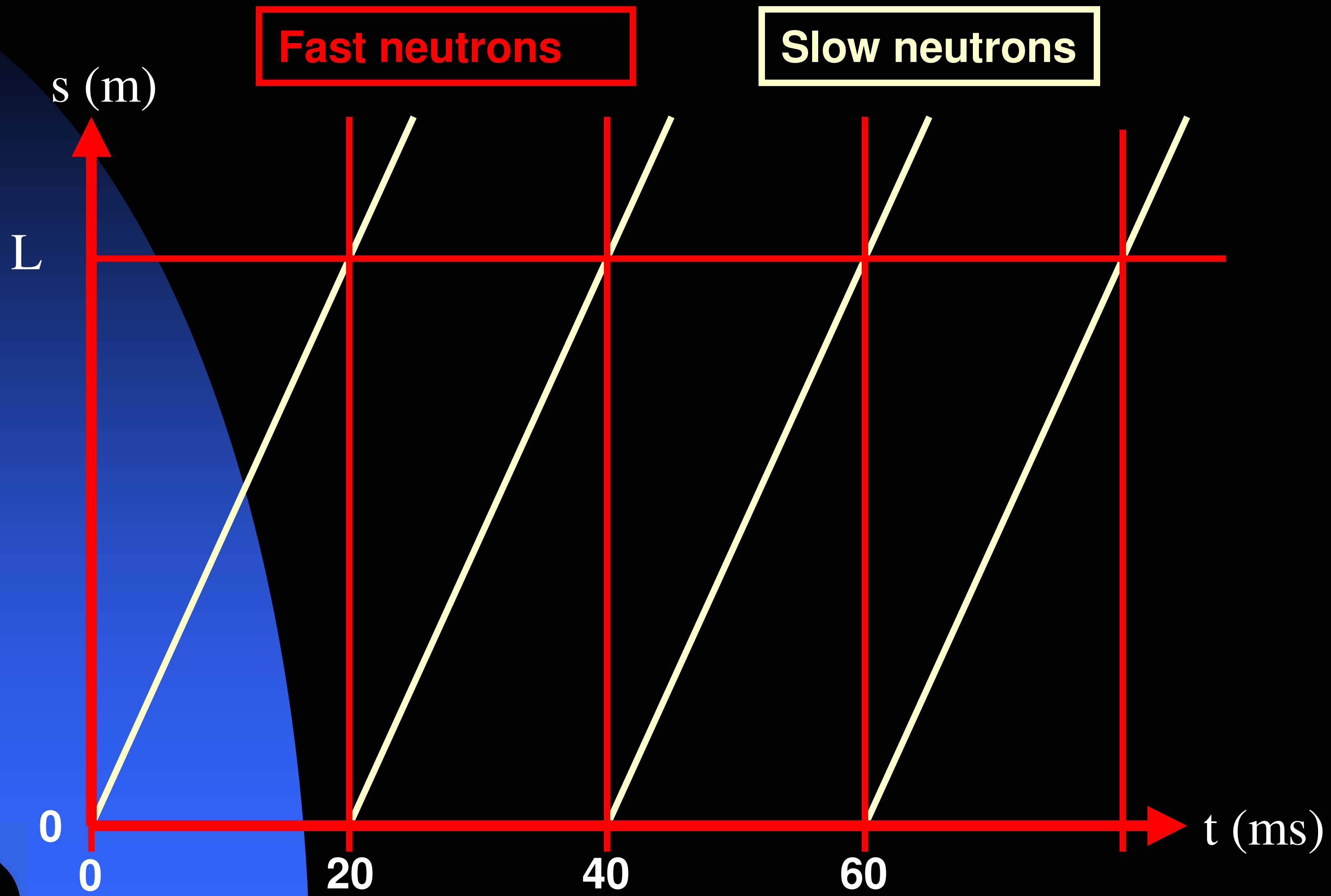
neutron beam

transparent material

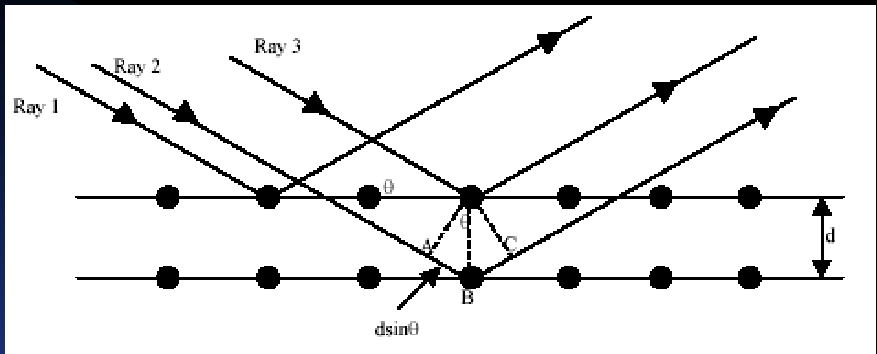
absorbing material

typical use: soppression of "frame-overlap" effect on pulsed neutron sources

“Frame-overlap” problem

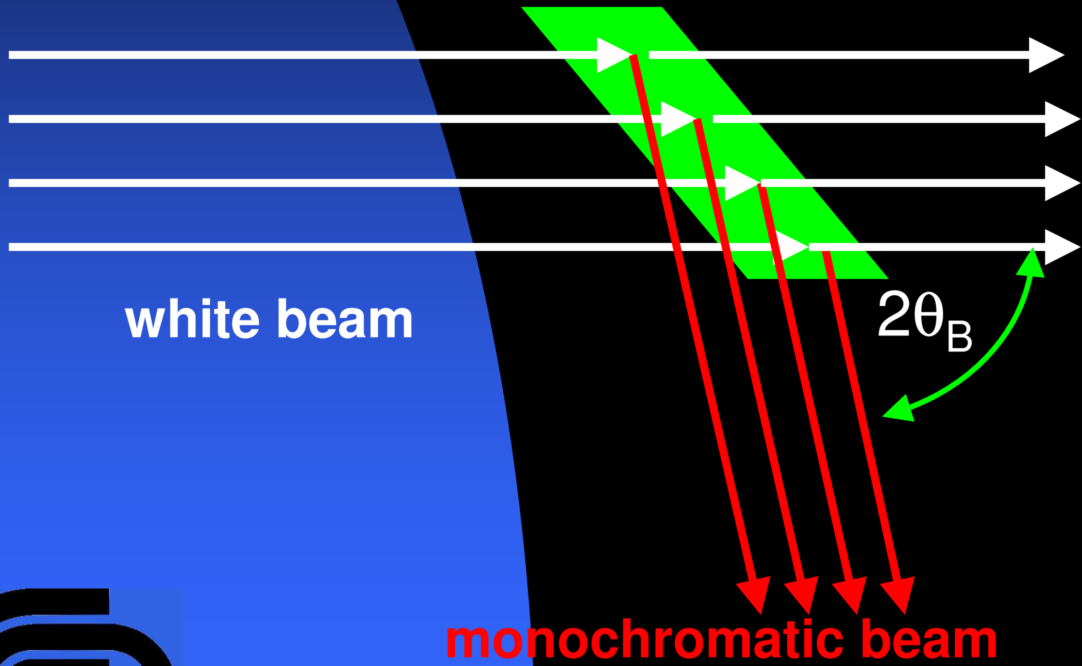


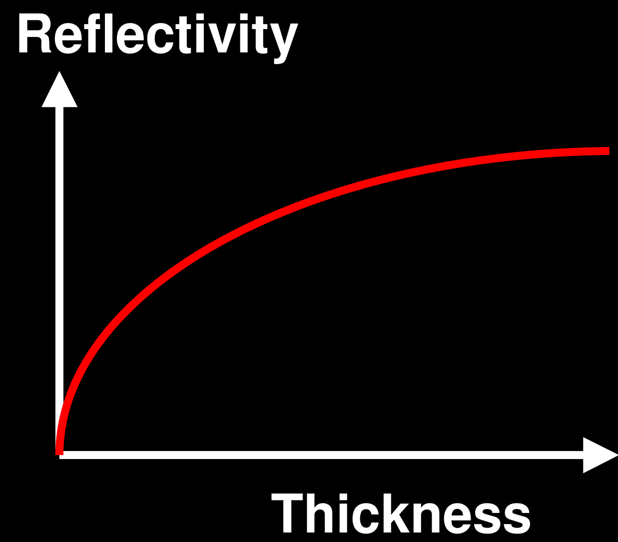
Crystal monochromators



Bragg law:

$$2d\sin\theta = n\lambda$$



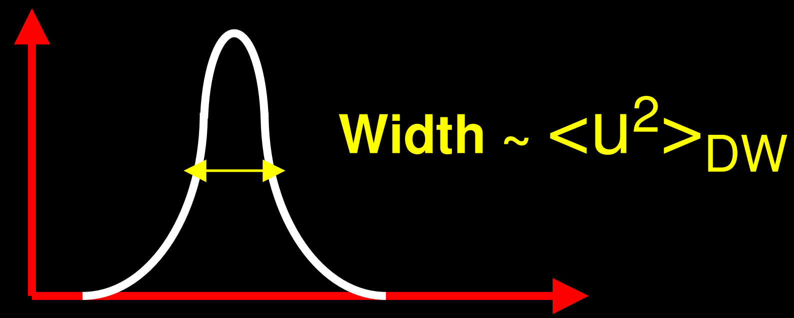


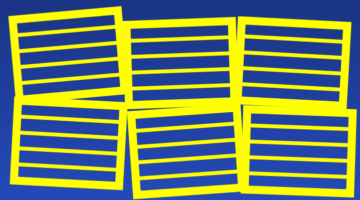
Ideal crystal chacteristics

- Large σ_{coh}
- Small σ_{abs}
- Suitable interplane distance (d)
- Easy to grow
- Small mean square displ. $\langle u^2 \rangle_{DW}$
- Suitable mosaic

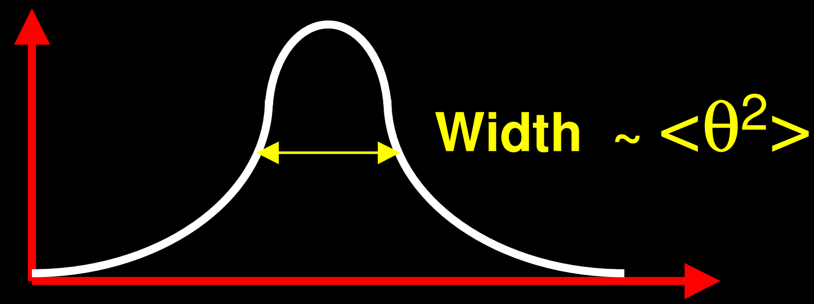
mosaic in a crystal

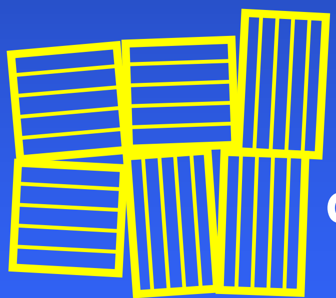
perfect crystal



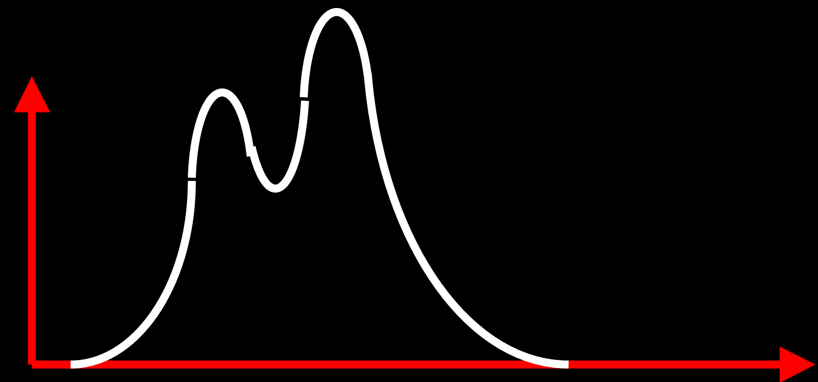


mosaic in a crystal





disordered crystal

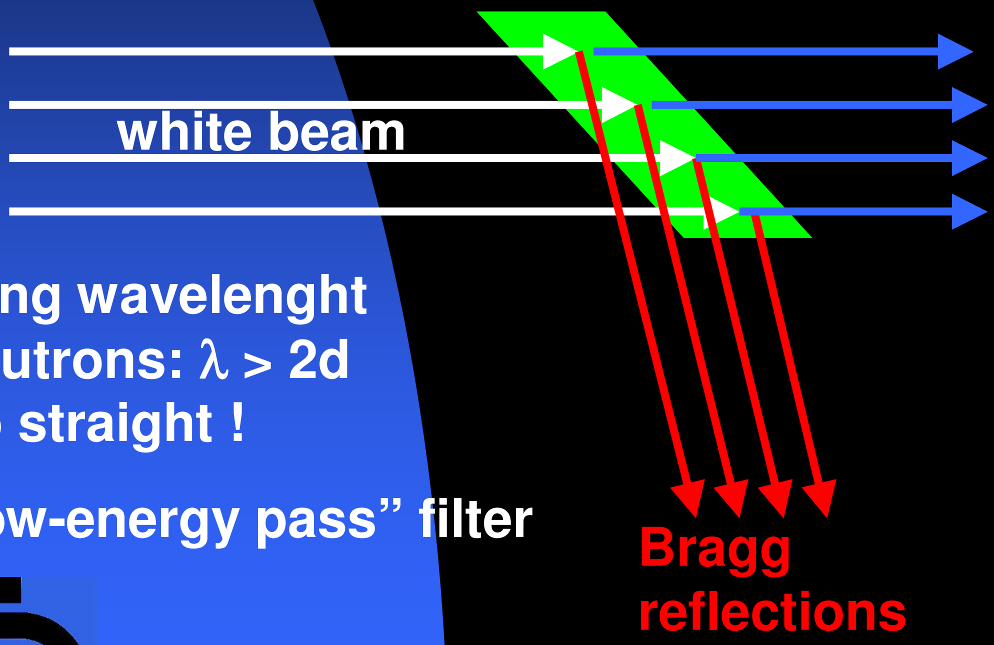


passive filters (Bragg threshold)

Bragg condition:

$$\lambda_{Bragg} = \frac{2d\,\sin\theta}{n} \leq 2d\,\sin\theta \leq 2d$$

If $\lambda \geq 2d$ **no Bragg reflection possible!!!**



- **Long wavelenght neutrons: λ > 2d go straight !**
- **“low-energy pass” filter**

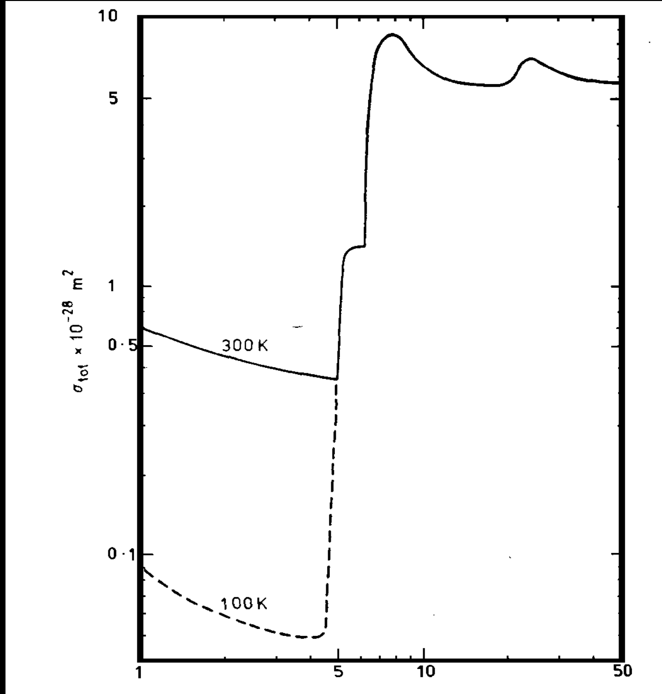
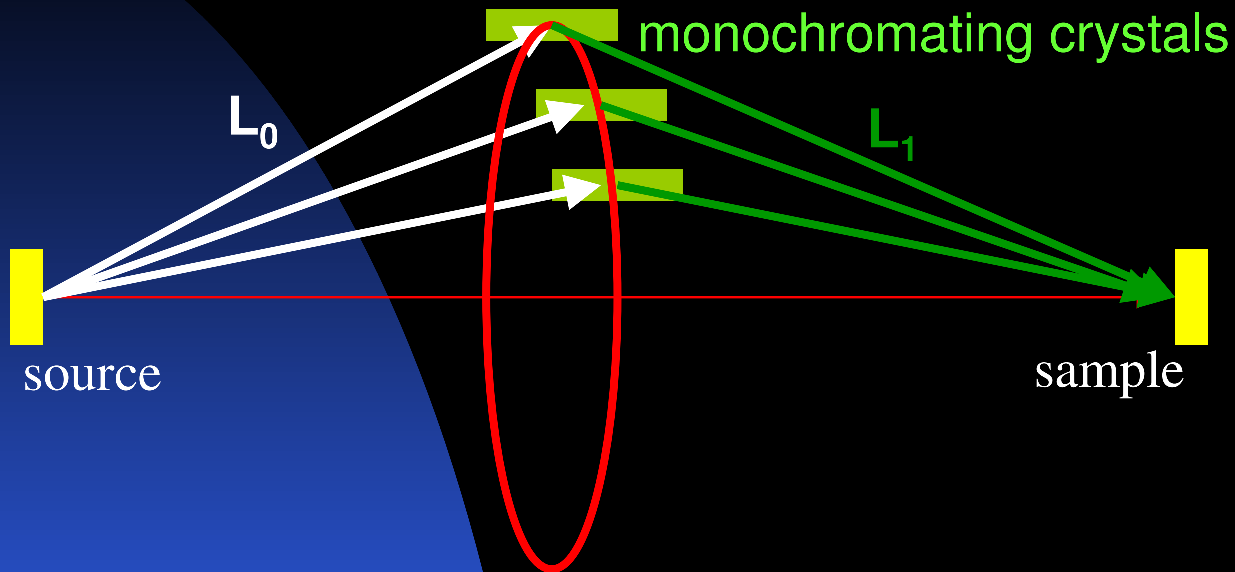


Figure 9.26. The total cross-section of beryllium at 100 and 300 K[162].

Vertical focussing



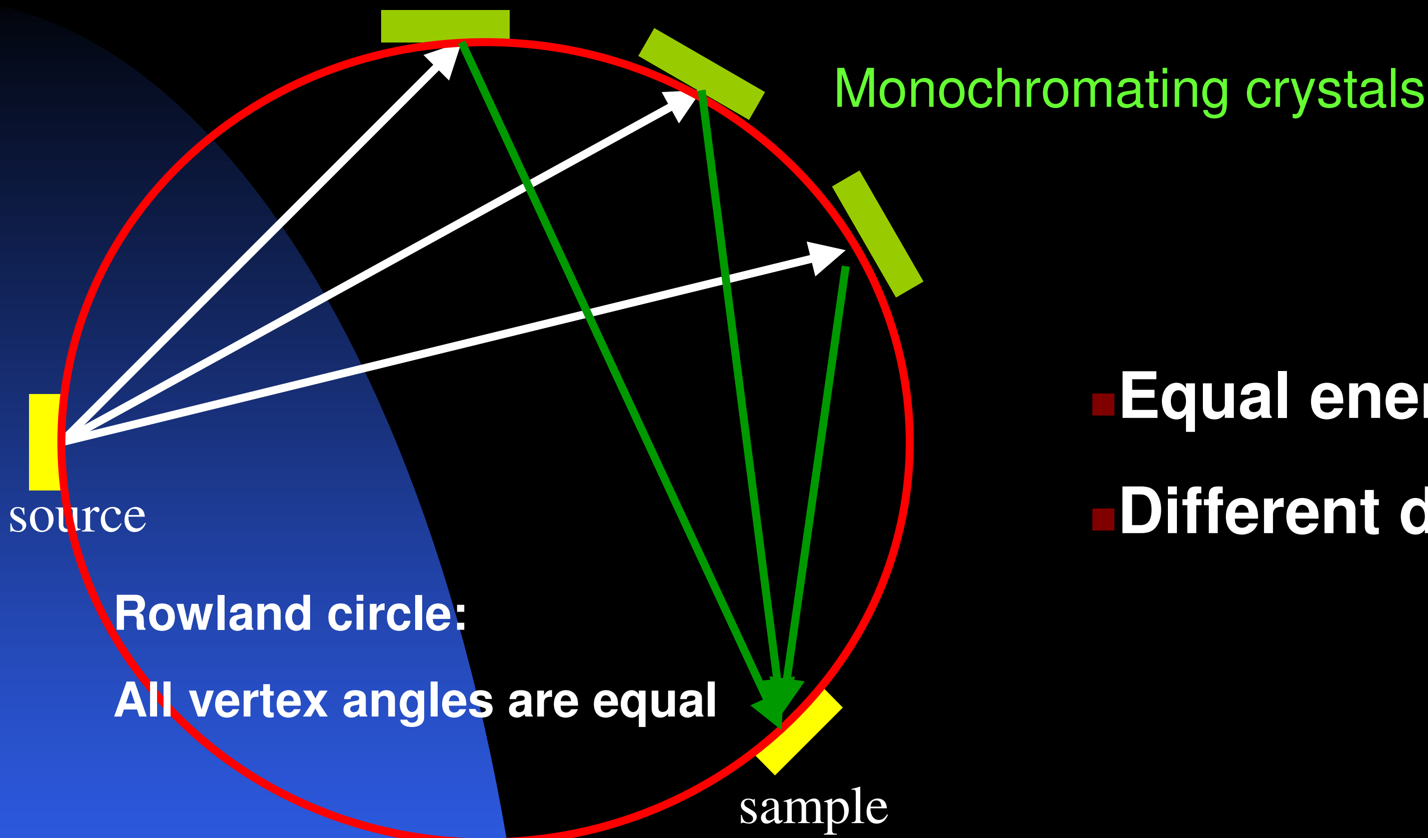
- Equal energies
- Equal distances
- Equal time

Suitable to increase the flux on the sample

on continuous & pulsed neutron sources

N B) this increases the spread in $\vec{k}_0$

Horizontal focussing



Rowland circle:

All vertex angles are equal

- **Equal energies**
- **Different distances**

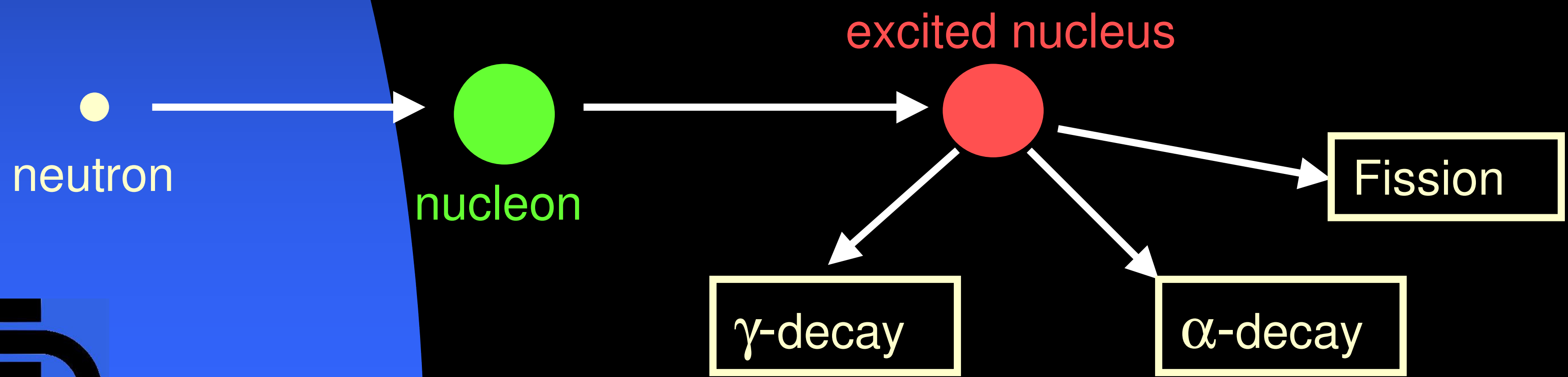
Does NOT work on pulsed neutron sources

N.B.) increases spread in $\vec{k}_0$

neutron detectors

- Neutrons:
  - weak interaction with matter
    $\Rightarrow$ linear response theory

  However …
  - Detection is difficult
    - primary ionization: negligible
    - secondary ionization: from nuclear reactions



nuclear reactions suitable for neutron detection

$$n + {}^{3}He \rightarrow {}^{3}H + p + 770\ \text{keV}$$

^{3}He gas detectors

$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + \alpha + 2.3\ MeV$$

BF_3 gas detectors

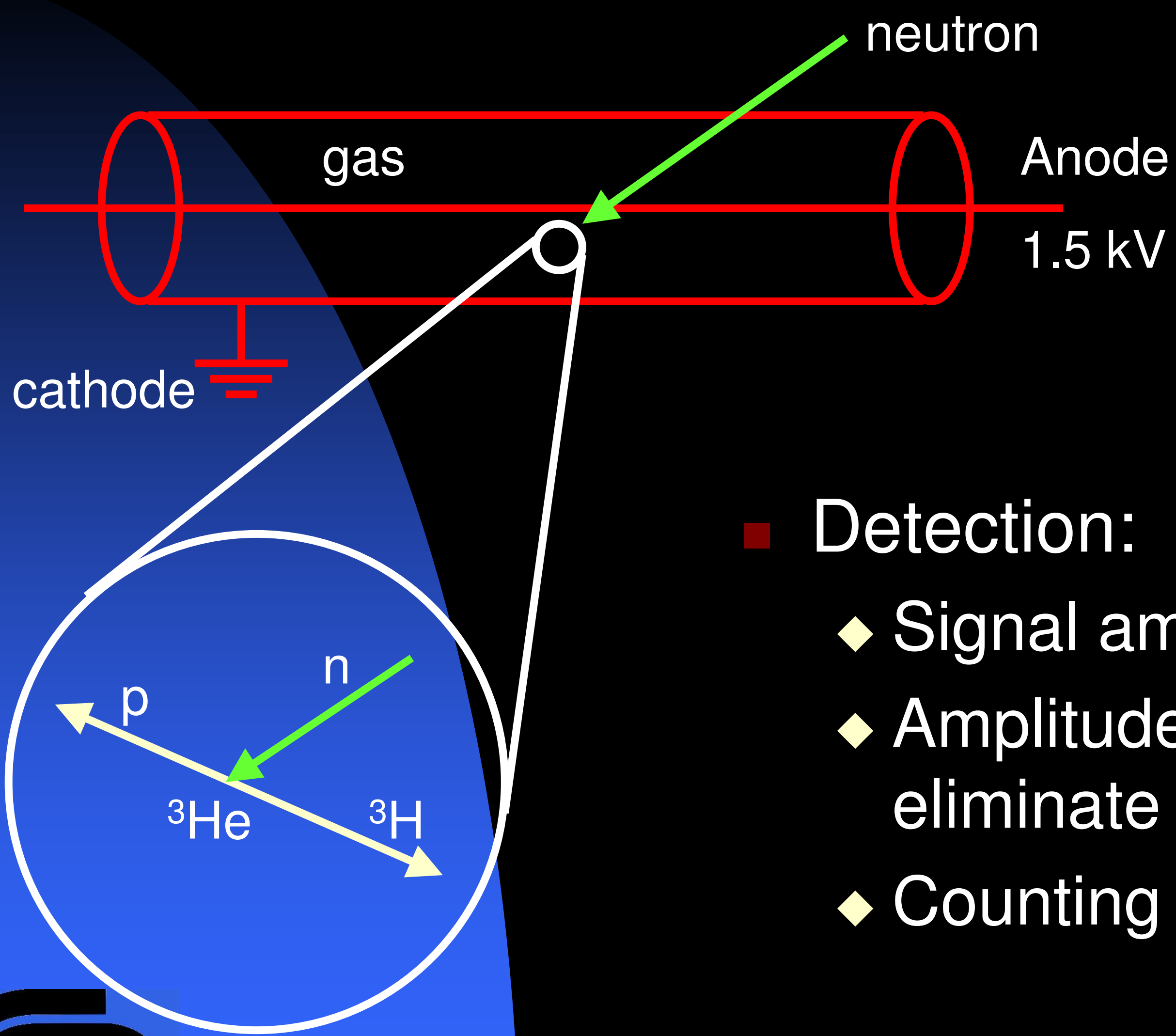
$$n + {}^{6}Li \rightarrow {}^{3}H + \alpha + 4.79\ MeV$$

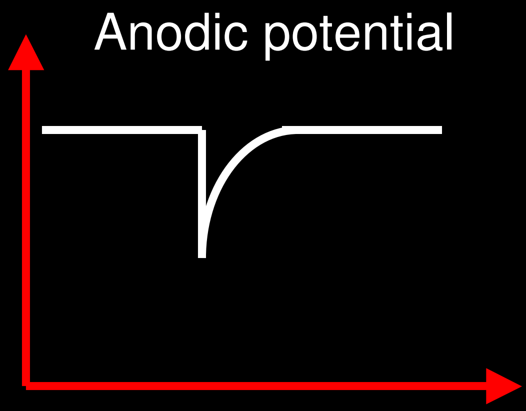
Scintillation detectors

$$n + {}^{235}U \rightarrow fission + 195\ MeV$$

Fissione detectors

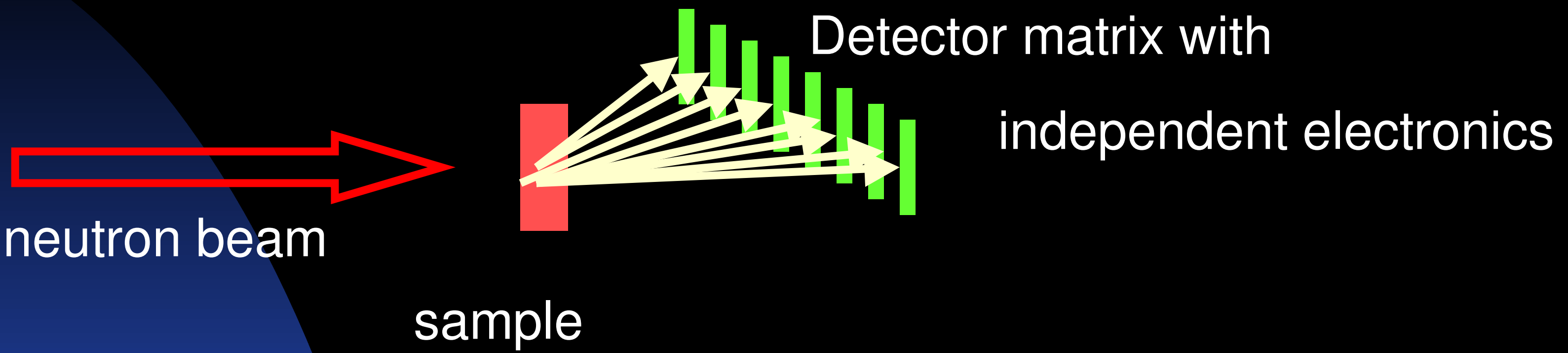
proportional gas detectors

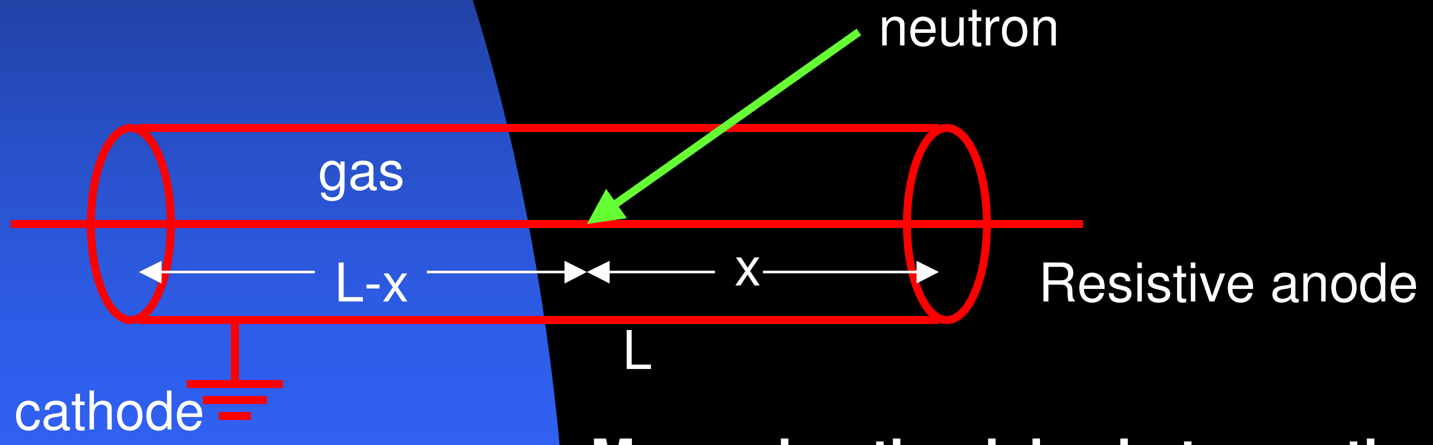




- Detection:
  - Signal amplification
  - Amplitude discrimination (to eliminate spurious counts)
  - Counting

Position-sensitive detectors





Measuring the delay between the 2 signals is possible to obtain x