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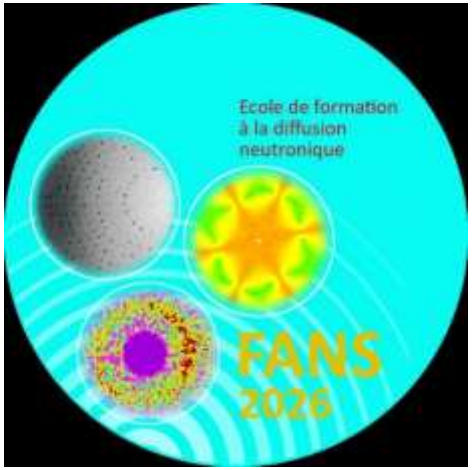
Neutron scattering overview



Neutron scattering length and cross sections

Various instruments

- **Powder, X-crystals**
- **SANS, Triple-axis, …**

Various neutron sources

- **Artificial sources**
- **Neutron generators**

High flux sources

- **Fission/Spallation/Stripping**

Nuclear reactors

Spallation sources

HiCANS

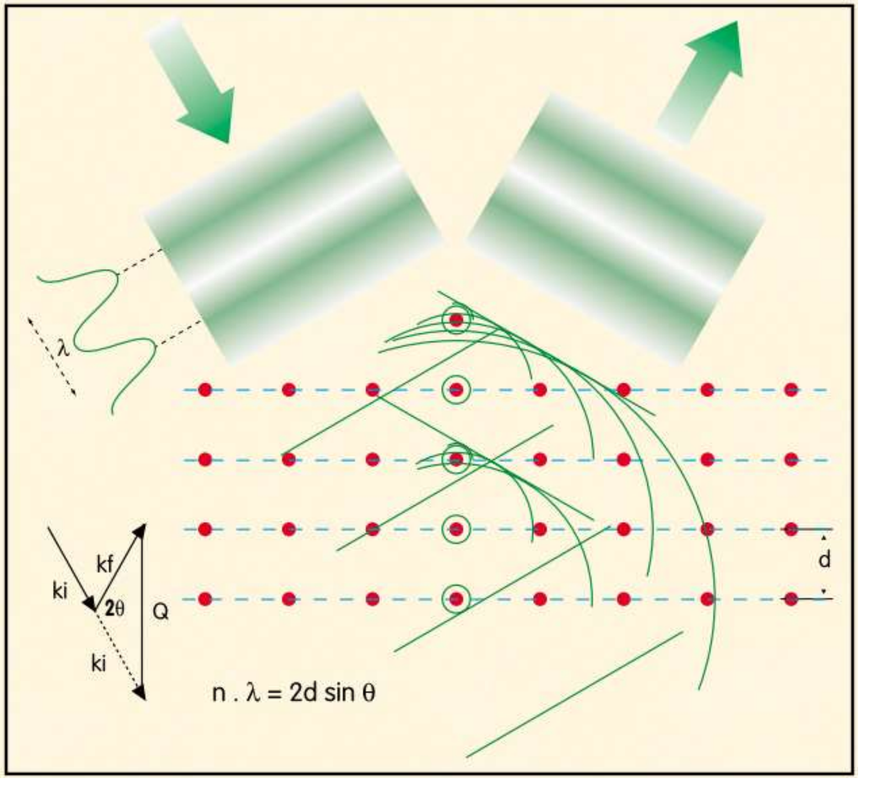
Neutron scattering length and cross sections

Incident plane wave.

Each atom scatters the plane wave and gives secondary waves.

Sum of the waves at the infinity gives the neutron scattering.

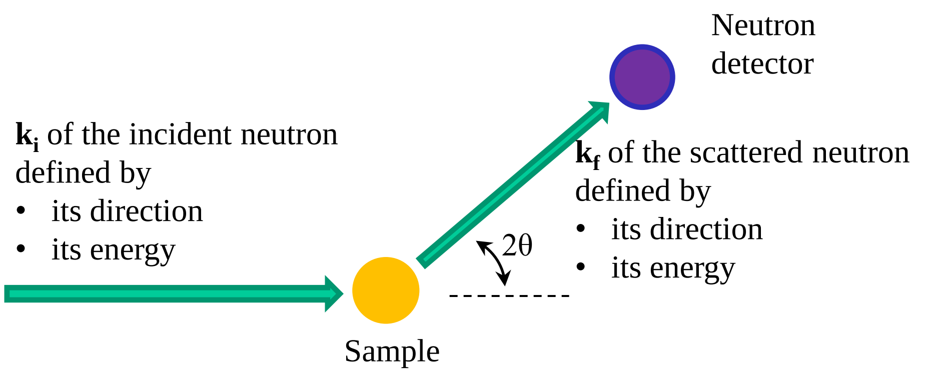
Intensity proportional to the scattering length of the atoms



$$\frac{d^2\sigma}{d\Omega\, d\omega} = \frac{k_f}{k_i}\, b^2\, N\, S(\vec{Q},\omega)$$

Neutron scattering : in practice

$$I = \frac{d^2\sigma}{d\Omega\, d\omega} = \frac{k_f}{k_i}\, b^2\, N\, S(\vec{Q}, \omega)$$



In practice you measure the intensity scattered at **a certain angle** around the sample : I(θ)
The collimation around this angle gives you $d\Omega$

To have $d\omega$ you need to know the **energy or the wavelength** of the incident neutron on your sample and the one of the scattered neutron. 2 different techniques for that :

1 : with monochromators
Scattered the neutron beam on a known crystal like HOPG or Ge or Cu or …
and use the relationship : $n\,\lambda = 2\,d\,\sin(\theta)$
At a certain angle θ, you have a single wavelength λ

2 : with time of flight
use pulsed neutron beams, measure the travel time between 2 known points and use the relationship : $\lambda = t / 253\, L$
with t the time (in µs) spent by the neutron to travel the distance L (in m) and λ the wavelength (in Å).

Neutron scattering length and cross sections

Neutron/matter interaction : Fermi pseudopotential caracterized by a tabulated scattering length b.

$$V(\mathbf{r}) = \frac{2\pi\hbar^2}{m} b\delta(\mathbf{r}),$$

b is complex to take care of the absorption

$$b = b' - ib''.$$

Coherent scattering length : b_c
Incoherent scattering length : b_i (spin interaction)

$$b = b_c + \frac{2b_i}{\sqrt{I(I+1)}} \mathbf{s}\cdot\mathbf{I},$$

2 parts in b' : nuclear (constant in Q), magnetic with a form factor

Cross sections :

$$\sigma_s = 4\pi\langle |b|^2 \rangle,$$

Scattering cross section : sum of coherent and incoherent

$$\sigma_s = \sigma_c + \sigma_i,$$

Coherent and incoherent cross sections

$$\sigma_c = 4\pi|b_c|^2, \sigma_i = 4\pi|b_i|^2,$$

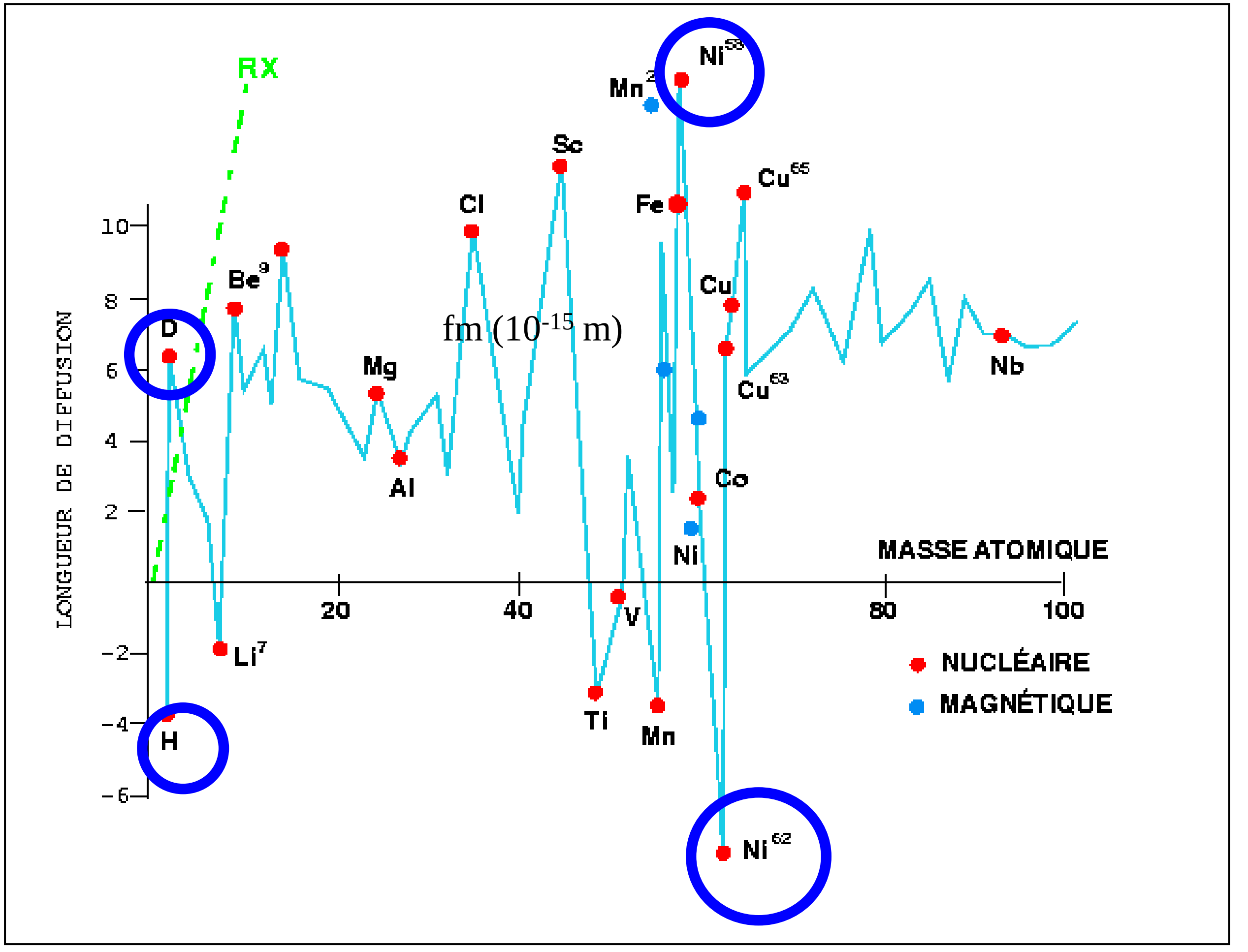
Absorption cross section

$$\sigma_a = \frac{4\pi}{k}\langle b'' \rangle,$$

Neutron scattering length and cross sections

Tables see:
https://ncnr.nist.gov/resources/n-lengths/
https://en.wikipedia.org/wiki/Neutron_scattering_length

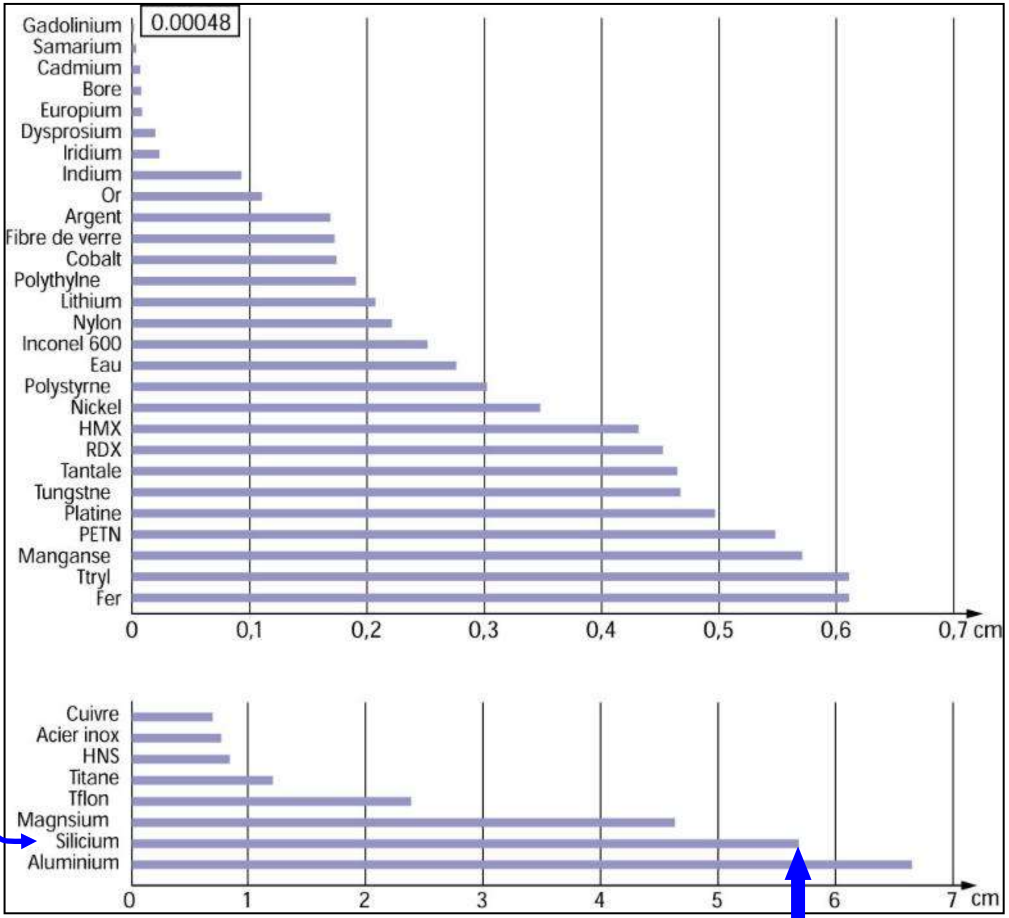
Interaction varies from one isotope to another one



Neutron absorption

Material	σ_s ($10^{-24}cm^2$)	σ_a ($10^{-24}cm^2$)
H	82	0.33
D	7.64	0.0005
O	4.23	0.0002
Si	2.16	.17
Ti	4.35	6.09
Ni	18.5	4.5
H2O	168	0.68
D2O	19.5	0.001
PS-h	700	2.69
PS-d	105	0.03
Gd	180	49700

Absorption cross sections



Penetration length

6

Neutron scattering instruments

Elastic scattering
Structure determination
(where are the atoms ?)

- Powder diffraction
- Single crystal diffraction
- SANS
- Reflectivity
- ….

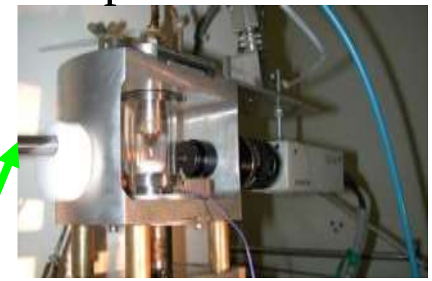
Inelastic scattering
Excitations determination
(how moves atoms ?)

- Triple axis
- Time of flight
- Backscattering
- Spin echo
- ……

<u>Also :</u> neutron radiography, prompt gamma activation, activation analysis, …

Spectrometer control

Sample environment



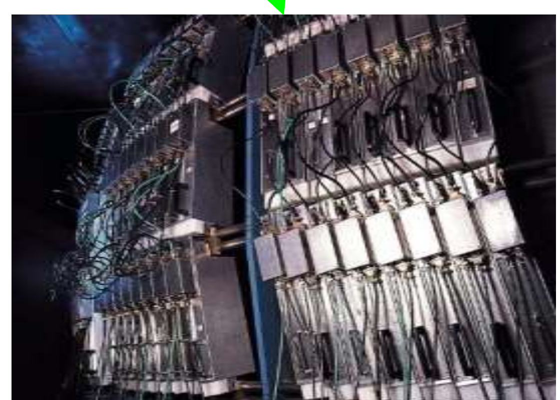
User interface

Electronics

Positioning

Data storage

Immediat processing or afterwards



Detectors

Structure determination by diffraction on powders

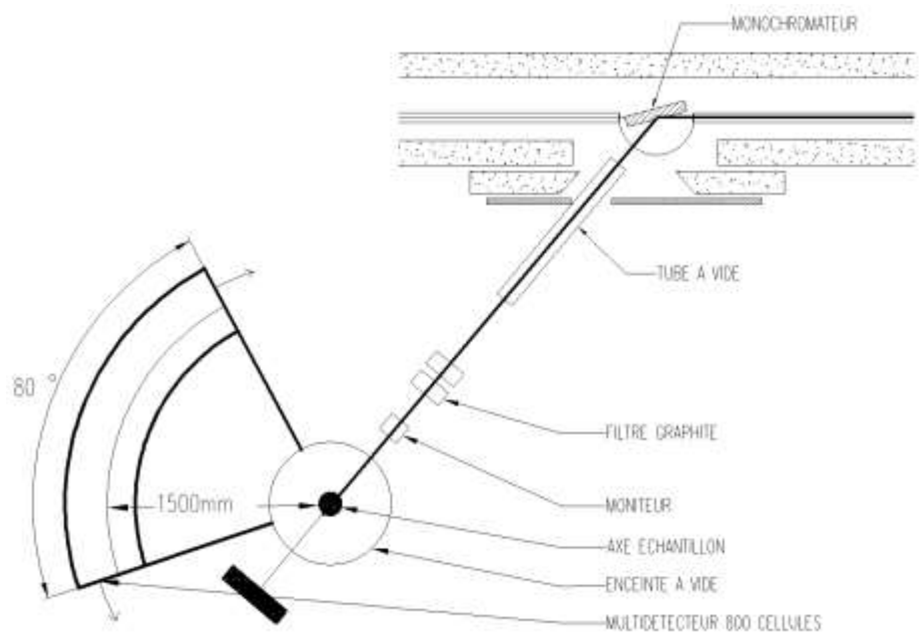
2FDN : D1B

Work horse spectrometer

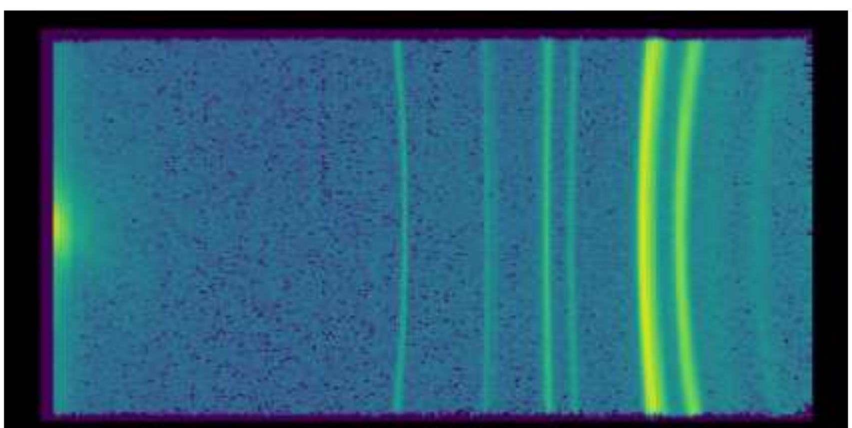
- Measure Debye-Scherrer diffraction cones
- Hot, thermal and cold neutrons
- Vert. focus. Monok at fixed wavelength
- Very large area detectors on pulsed sources (symetric beam)

- **Difficulties** : monochromator and detector
- **Evolutions** : high flux or high res., large detectors

G41 spectrometer at the LLB



Powder measurement at the Sharp multidetector



Structure determination by single crystal diffraction

2FDN : D23

Work horse

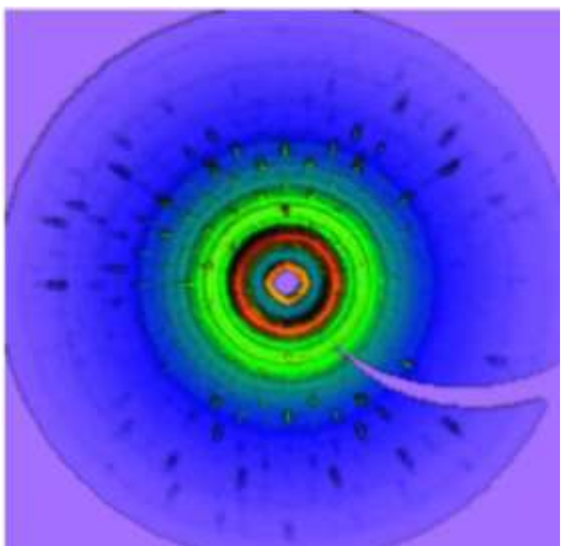
- Measure point diffraction
- Thermal and hot neutrons
- Difficult on pulsed source but …

Evolutions :

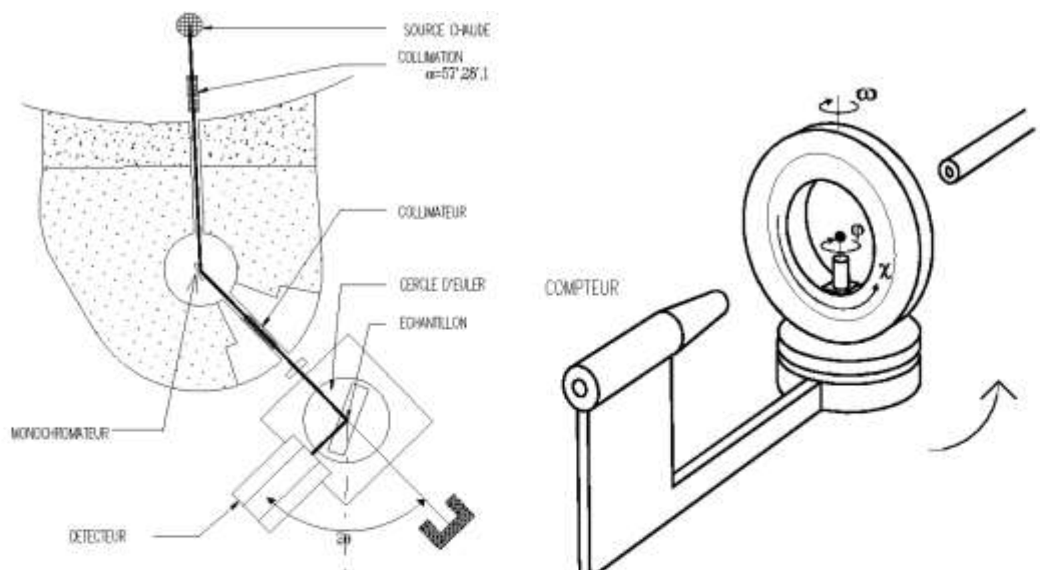
Use of large area detectors with data reconstruction

On pulsed source, same instrument than powder diffractometer

Reciprocal space reconstruction on 5C1-VIP



5C2 spectrometer at the LLB



https://llb.cnrs.fr/wp-content/uploads/2026/06/Menelle-Intro-neutrons-FAN-2026.pdf

Large scale structures (1-100nm) by SANS (Small Angle Neutron scattering)

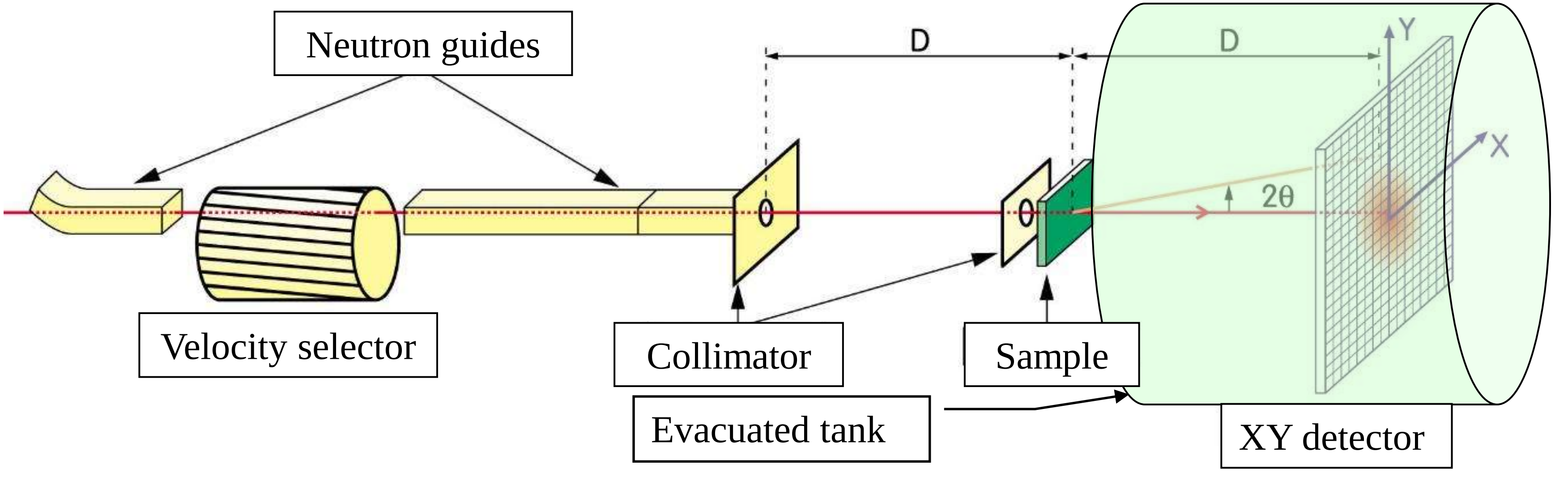
2FDN : SAM at ILL and SANS-LLB at PSI

Work horse

- Cold neutrons
- Easier on continous sources
- Beam : Ø=2cm

Difficulties : background, large area detector, signal change on log scale

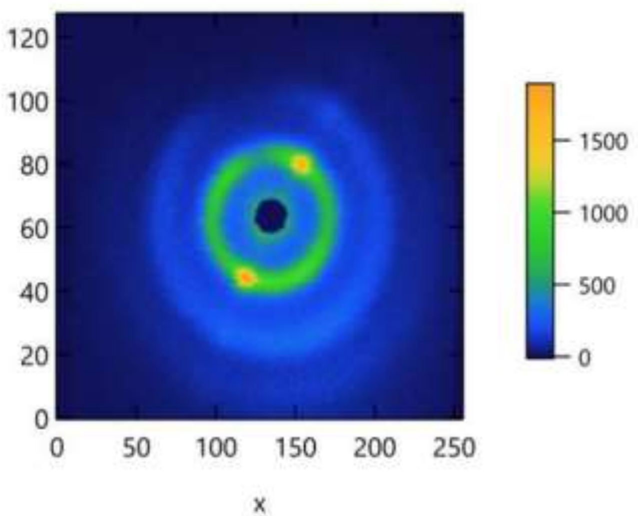
Evolutions : long instruments, focalisation, resolution, Tof



SAM LLB instrument at the ILL

8m/8m red instrument with polarized neutrons. Started 26/03/2024. Mieze and imaging options to be considered.

Intense team work throughout construction (June '23 → Feb '24)

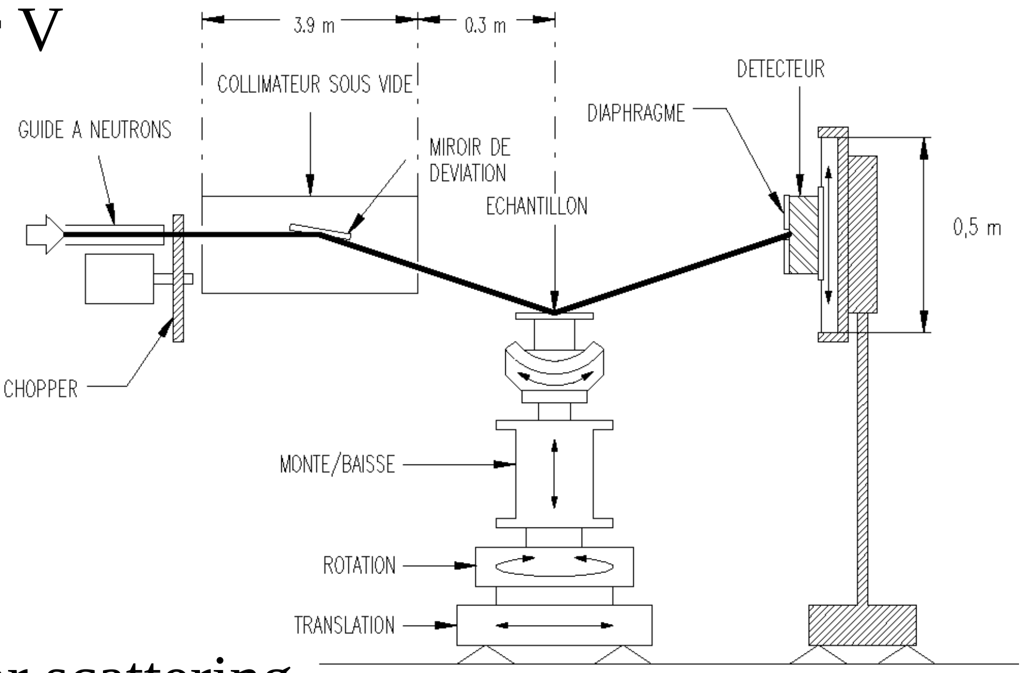


Co nanotubes in Al_2O_3 matrix (*2024/03/22*)
Sample: courstesy G. Chaboussant (LLB)

Studies of surfaces by Reflectivity

Work horse

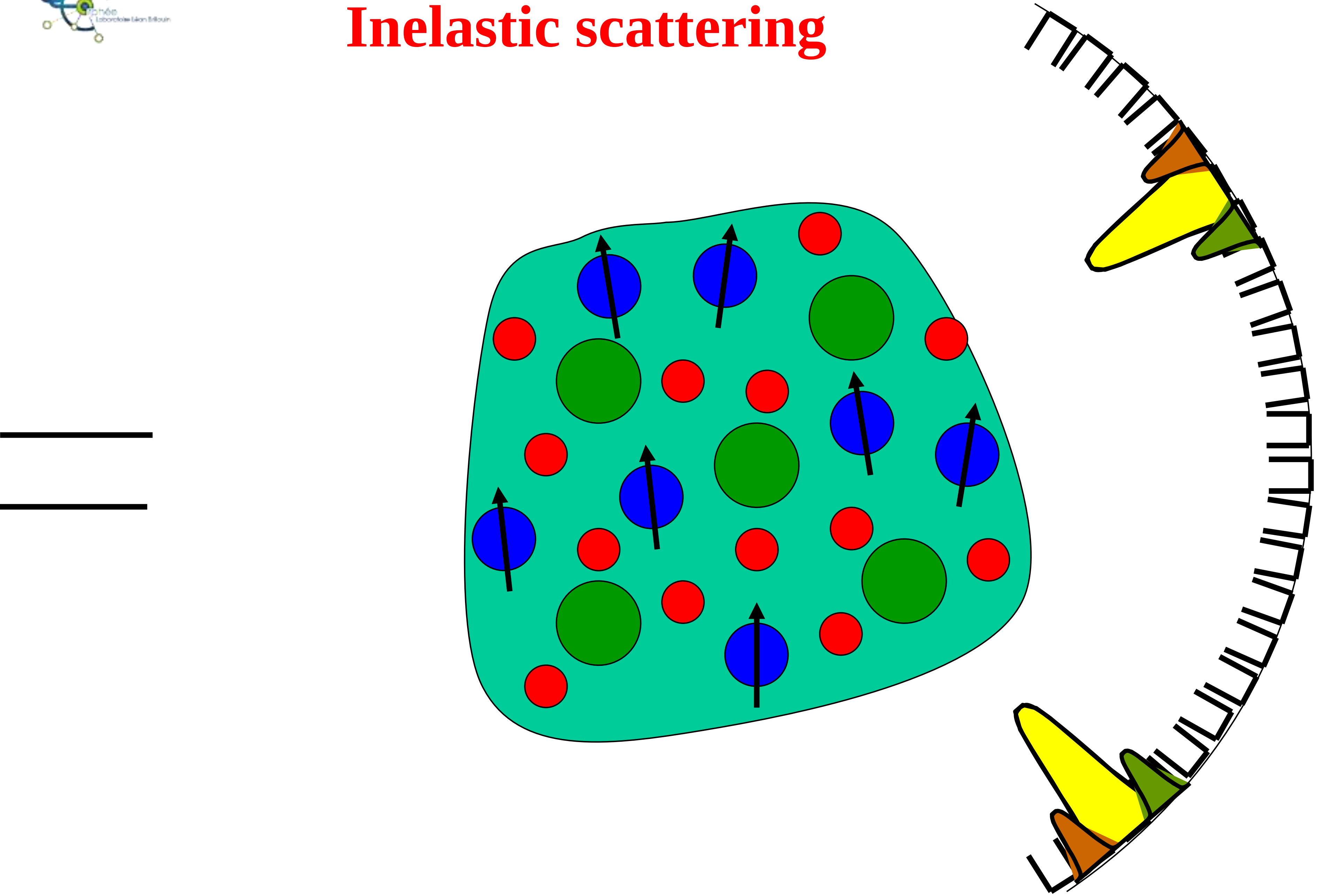
- Adapted to pulsed sources, Tof or fixed λ
- Thin beam : 1mm x 3cm H or V
- Focalisation H or V
- Cold or thermal neutrons



Evolution : measure off-specular scattering

Difficulty : need of a low background

Inelastic scattering



Work horse

- Cold and thermal neutrons
- Focalisation V and H

Triple axis

2FDN : IN12 IN22

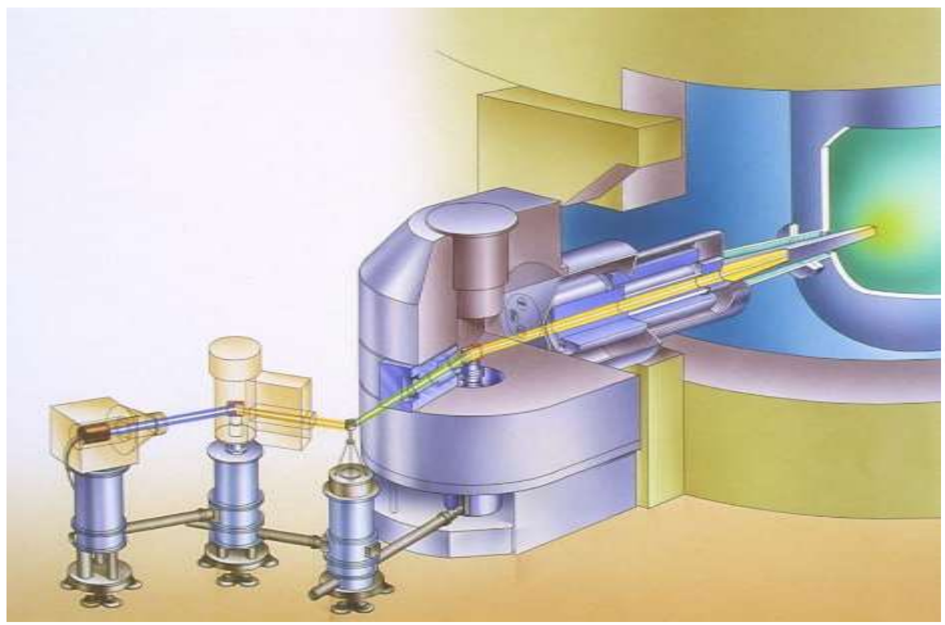
Difficulties :

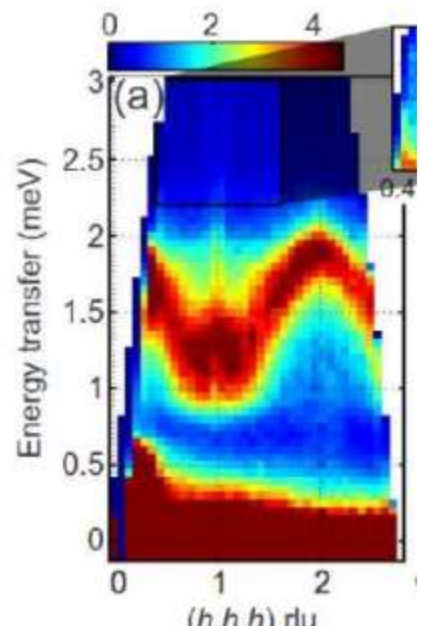
Monochromators, protections

Not efficient on pulsed sources

Evolutions :

Multi analysers for pulsed sources





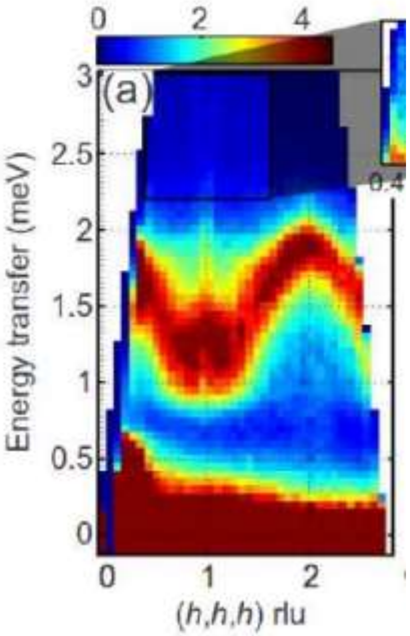
Main interest on continuous sources : use the trajectory you want in S(Q,ω)

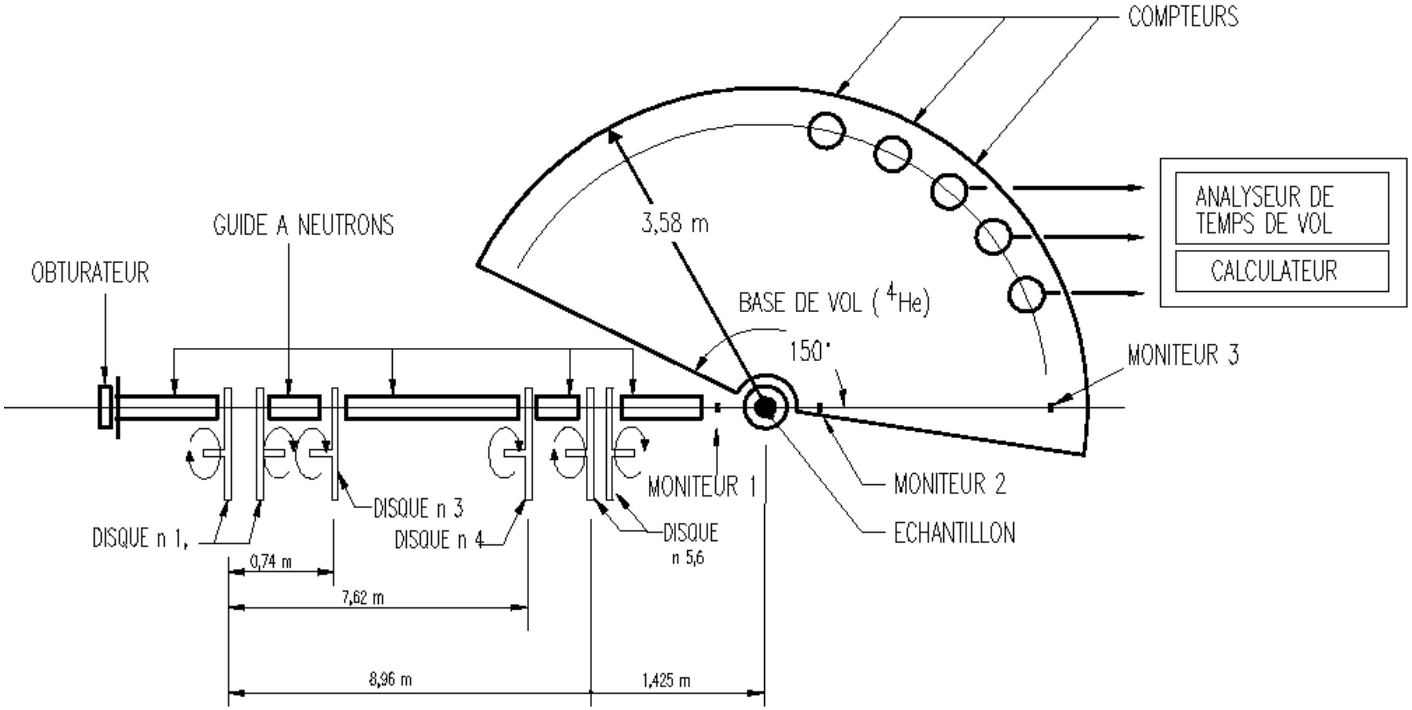
Time of flight spectrometer

2FDN : SHARPER

- Neutrons : thermal or cold
- Adapted to pulsed sources
- H. V. focussing

Evolutions : towards thermal neutrons and polarization





Difficulty : curved routes in reciprocal space S(Q, ω)

Neutron sources in Europe (for neutron scattering)

European sources
- ILL
- ESS

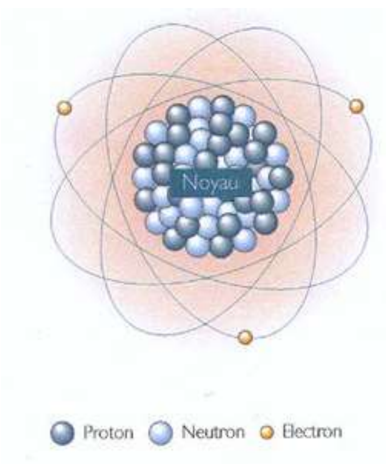
National big sources
- ISIS, UK
- SINQ, Switzerland
- FRM2, Germany
- Dubna, Russia
- PIK, Russia (starting)

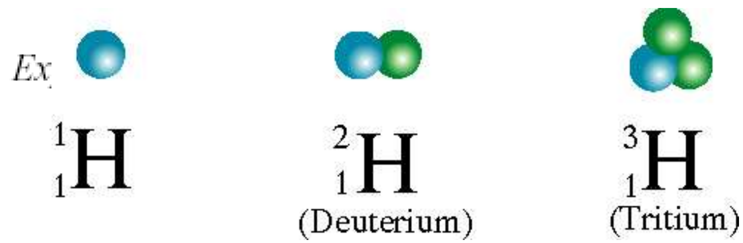
National smaller sources
- NPL, Czech republic
- BNC, Hungary
- Delft, The Netherlands
- Maria, Poland
- WWR-M, Russia

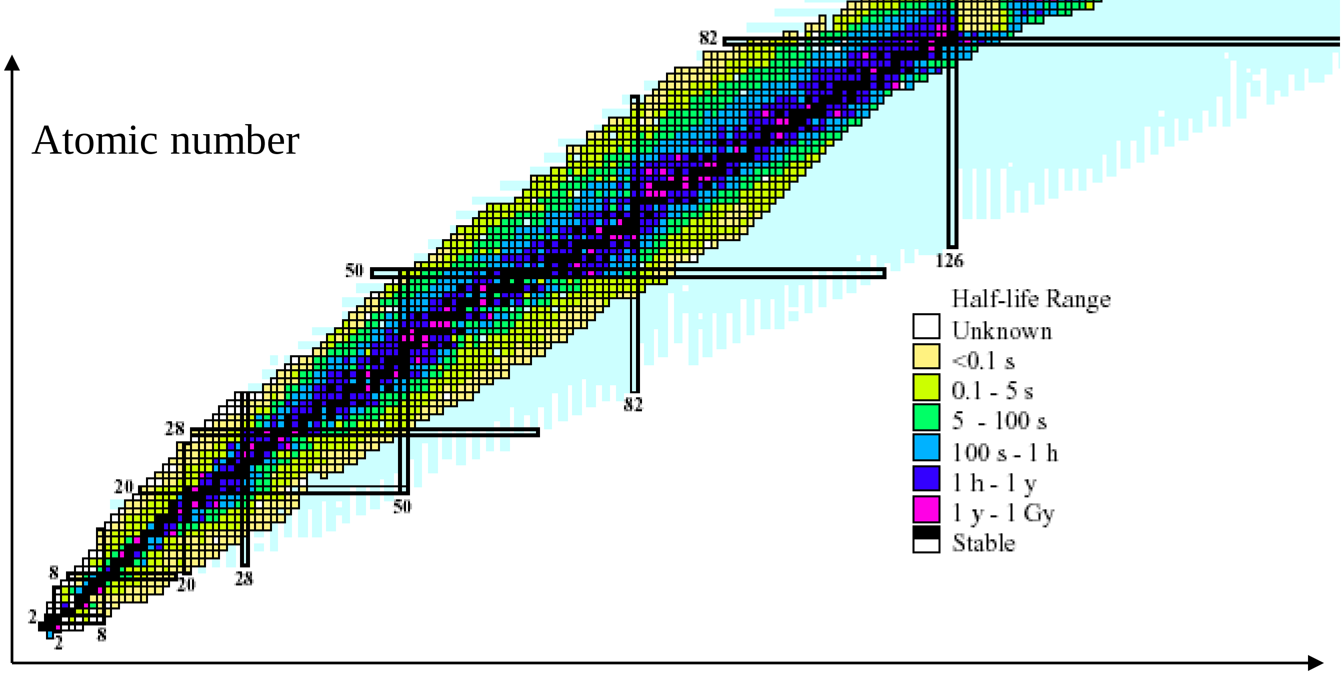
Neutrons in the world :
~4% of the top ranked publications in condensed matter

Where are the neutrons ?

Nucleus : neutrons + protons



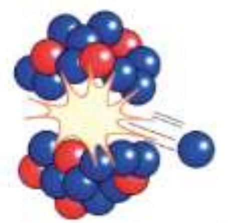




Neutron number

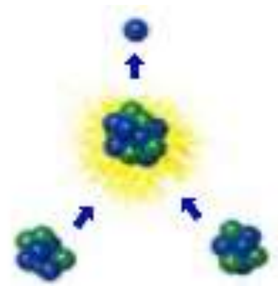
How to obtain a neutron ?

Extract neutron : put a nucleus in an instable state which will loose neutrons while returning to stability

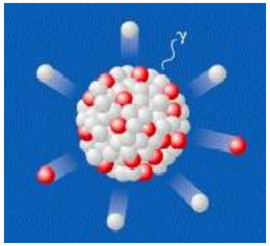


Fission

Fusion



Spallation
Stripping



Very few spontaneous fissions with neutrons emission : Pu, Cm, Cf
Plutonium, Curium, Californium

Obtain neutrons is a **two steps** process

(as well as detect neutrons)

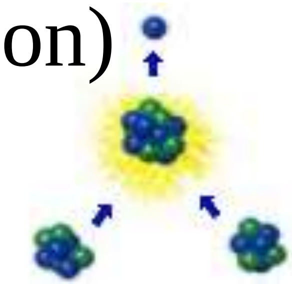
How to excite a nucleus ?

- α radiation (^{4}He)
- γ radiation

Test sources*

10^{6} n/s
15 k€

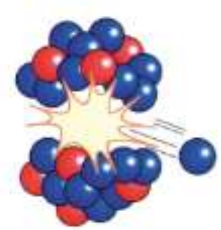
- Deuton (^{2}H) (fusion)



Neutron generators

10^{9} n/s
150 k€

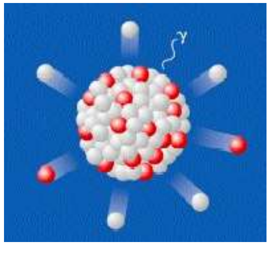
- Neutron (n)



Nuclear reactors

~10^{18} n/s
1 G€

- Proton (p)



Spallation sources
CANS and HiCANS
(Compact Accelerator driven Neutron Sources)

at max 10^{19} n/s
from 10 M€ to 3G€

* : sealed sources for detector calibration
Compact sources with electron bremsstrahlung

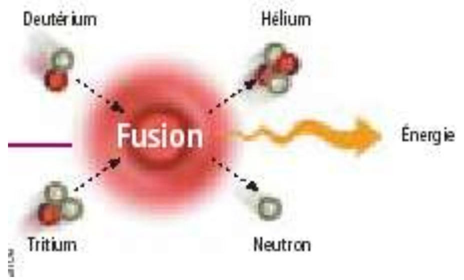
Sodern neutron laptop generator

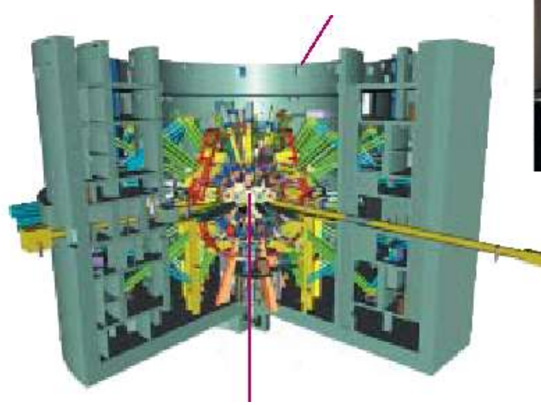
2 10^9 n/s (fast neutrons)
~150 k€

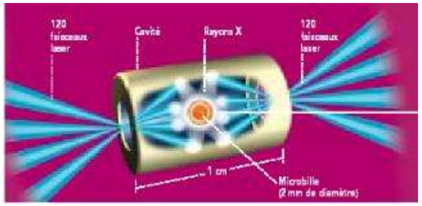
Neutrons with lasers

A. Taylor & al., Science, 315 (2007), pp. 1095
T. Gutberlet & al., Rev. Sci. Instrum. 97, 021501 (2026)

(D,T) fusion reaction





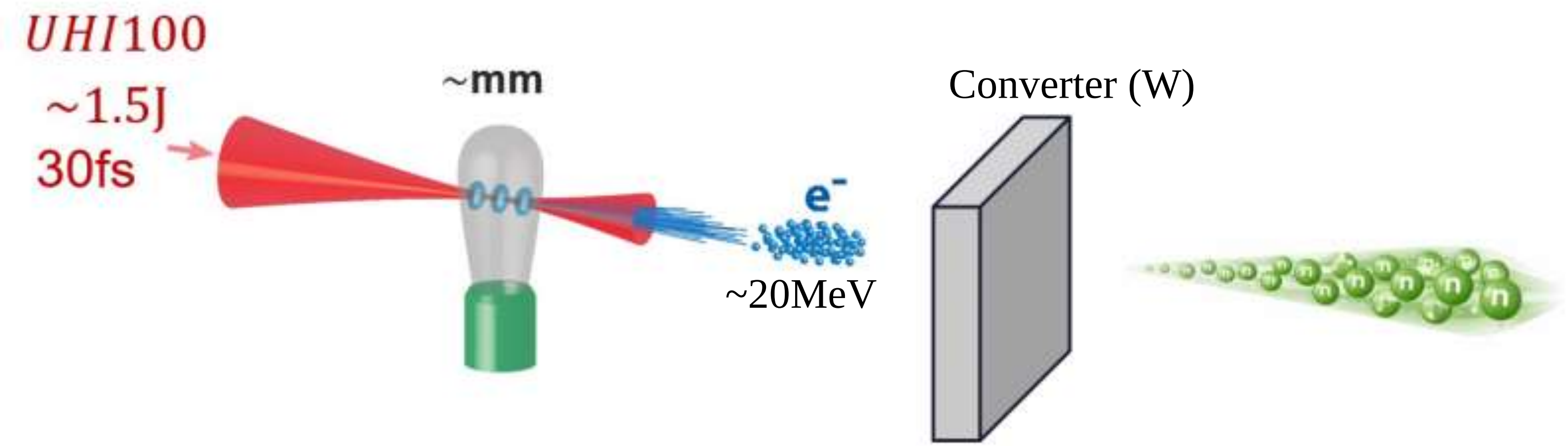


LMJ in Bordeaux

240 laser beams on 1 cm^3 : 1.8 MJ in 10^{-9}s (2 10^{15} W)

Neutrons with lasers

(γ,n) reactions



ALADINS project of LYDIL in Saclay (H. Vincenti)
~10^8n/s demonstrated
~10^{10}n/s expected after optimizations

Use of industrial Ytterbium lasers followed by a time compression stage

Nuclear reactors : fission process

$n^1 + U^{235} \longrightarrow$ 2 fission fragments + $2.5n^1$ + 200 MeV

thermal

- 1 neutron to maintain chain reaction
- 1 neutron escapes & is available for use
- 0.5 neutrons absorbed

1 neutron

2 to 3 neutrons

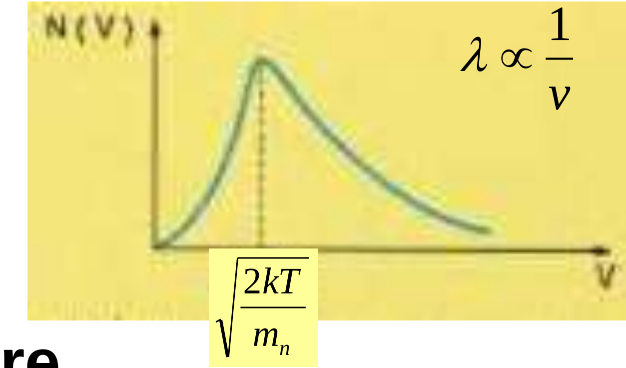
Example: 20 MW Research Reactor

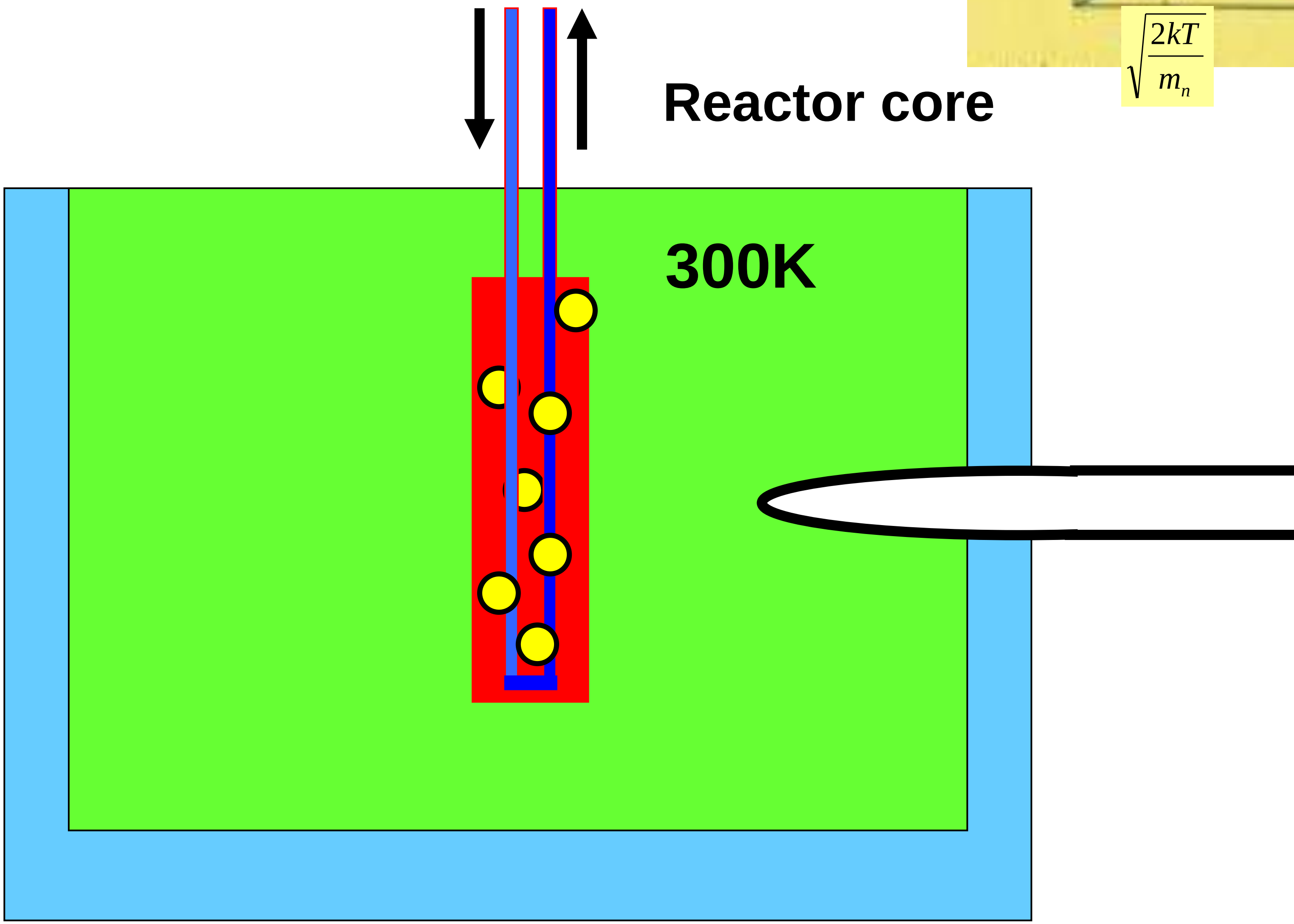
No. of fissions/sec $= \dfrac{20 \times 10^6 \text{ watts}}{200 \text{ MeV/fission}}$ $= 6 \times 10^{17}$ fissions/second

generates 1.5×10^{18} neutrons/sec in the whole reactor volume

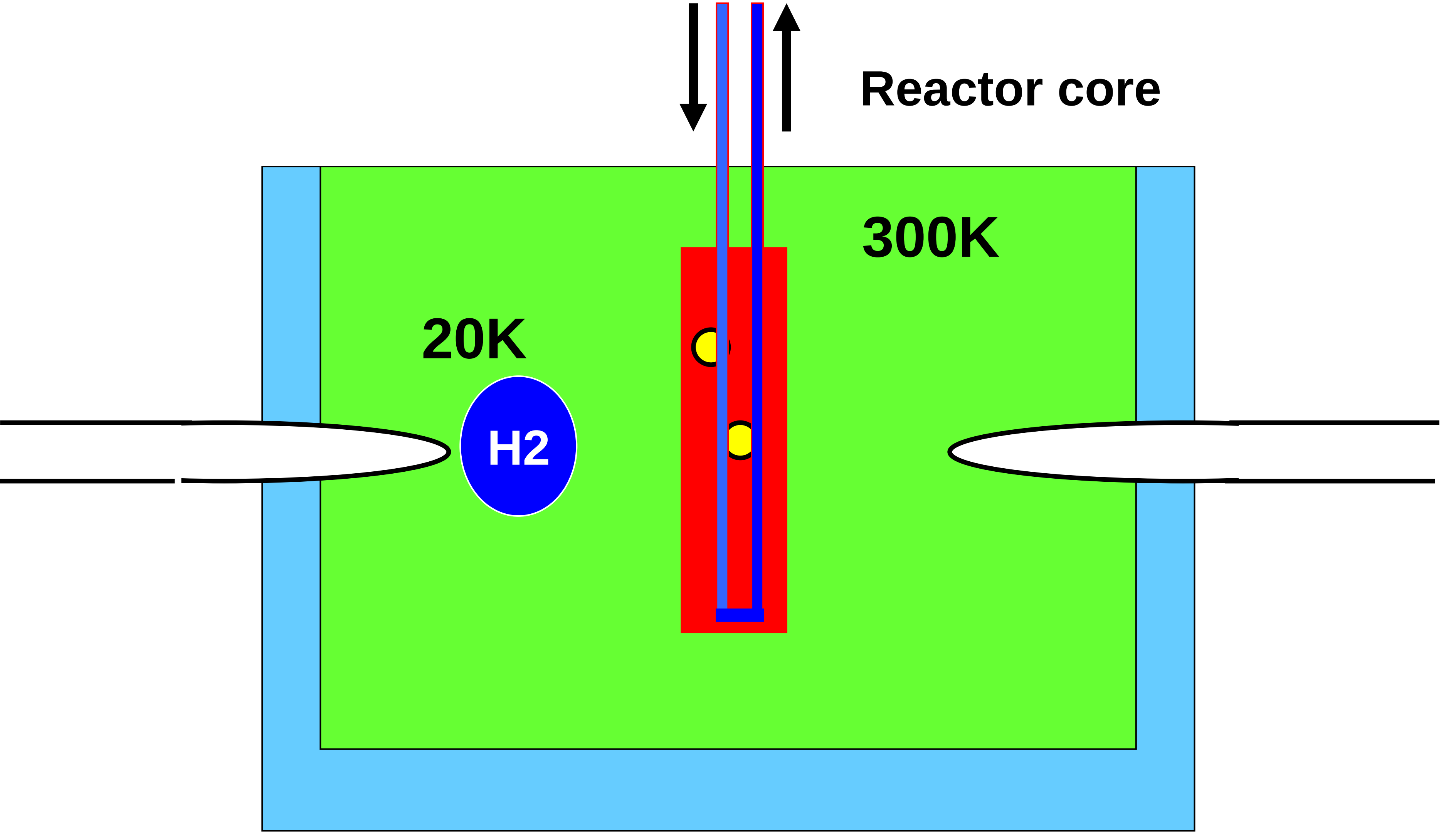
small core volume required for high brilliance (<0.1m^3)

Thermalisation





Thermalisation



Energy Temperature Wavelength

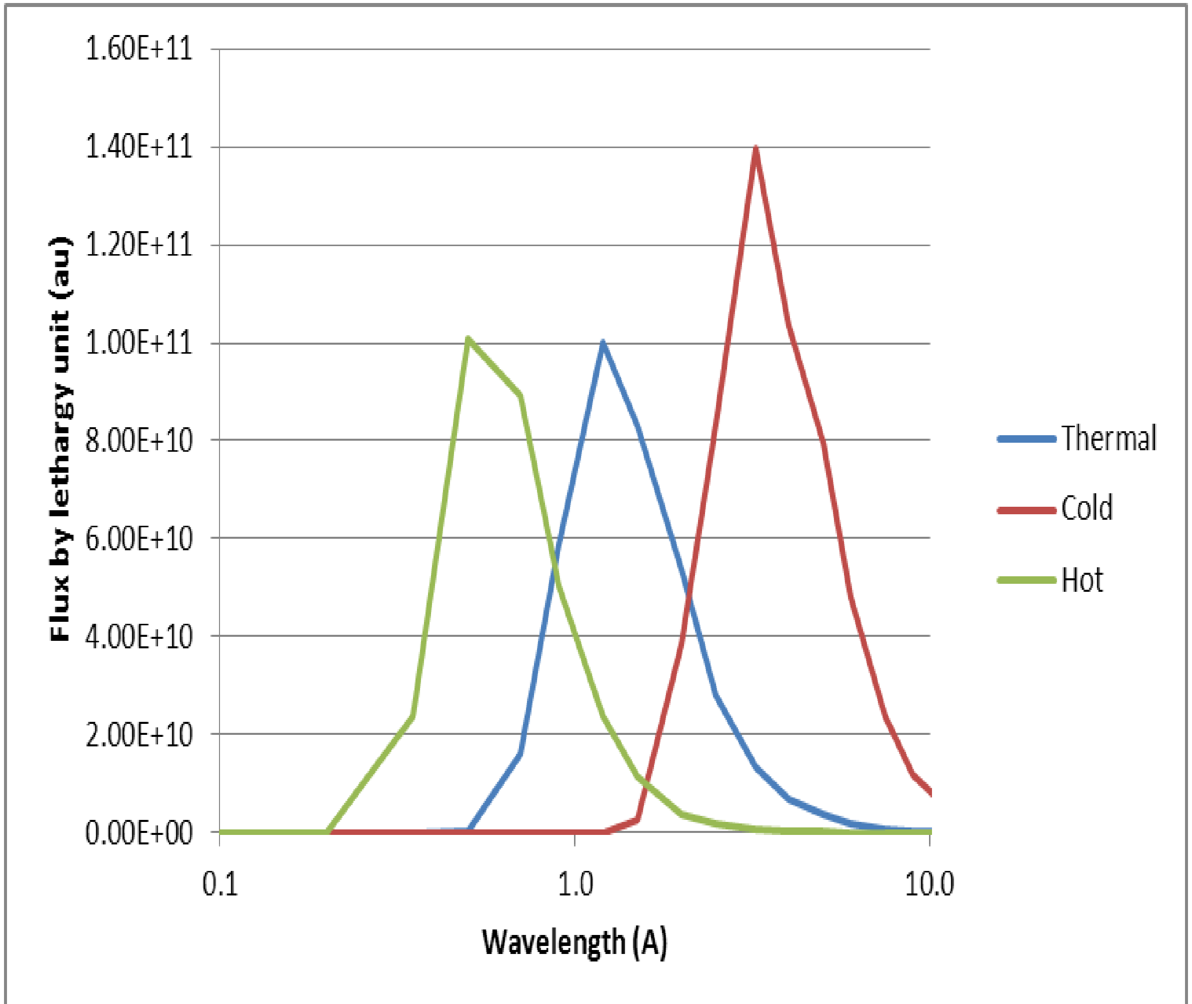
- Kinetic energy (E), Velocity (v), Wavelength (λ), Wavevector (k)

  $E = m_n v^2/2 = k_B T = (hk/2\pi)^2/2\ m_n;\ k = 2\pi/\lambda = m_n v/\ (h/2\pi)$

	Energy (meV)	Temperature(k)	Wavelength (nm)
Cold	0.1 – 10	1 – 120	0.4 – 3
Thermal	5 – 100	60 – 1000	0.1 – 0.4
Hot	100 - 500	1000 - 6000	0.04 – 0.1

Room temperature ~ 25 meV ~ 0.18 nm ~ 2200 m/s

Hot Thermal Cold



<u>Hot neutrons</u>
Structures of liquids and single crystals

<u>Thermal neutrons</u>
Powder, single crystals and triple axis

<u>Cold neutrons</u>
Powder, triple axis, quasi-elastic, SANS, neutron radiography

Water provides easy maintenance and radiation protection

Orphée reactor

14 MW

3*3 core, central Be reflector

6kg HEU, 25*25*90cm^3 core

Plate type fuel

Cycles of 100 days

2m heavy water reflector

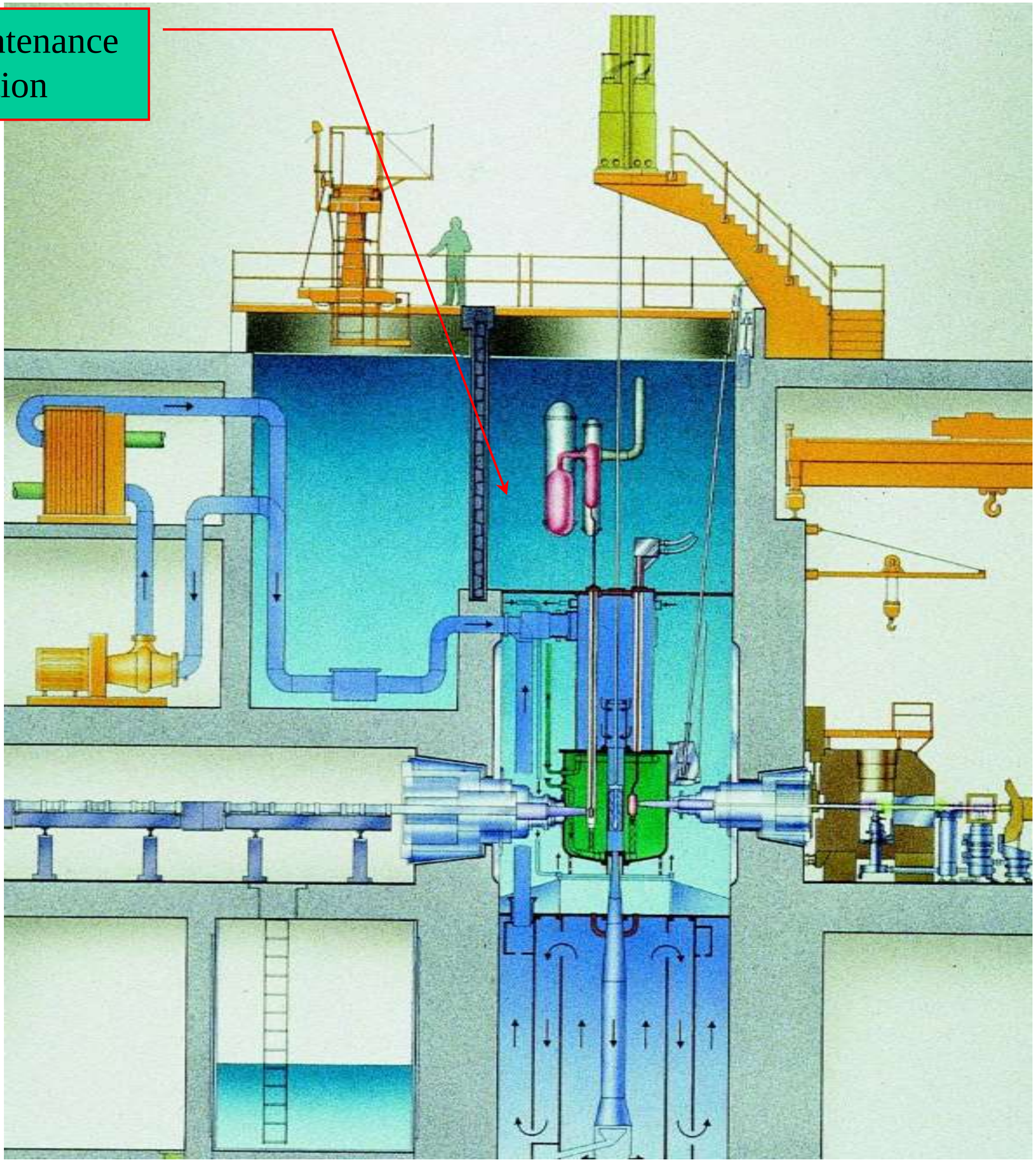
2 liquid H_2 cold sources

1 hot source

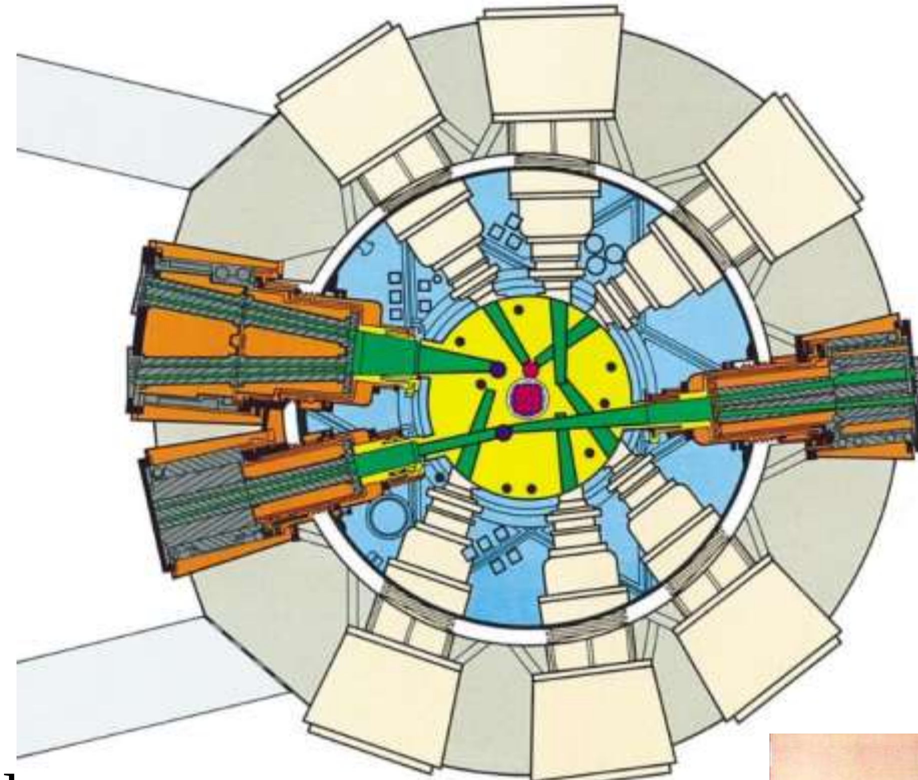
Light water primary cooling

Secondary cooling

Containment



Tangential beam tubes



<u>9 beam plugs</u>

- 5 thermal
- 1 hot
- 3 cold

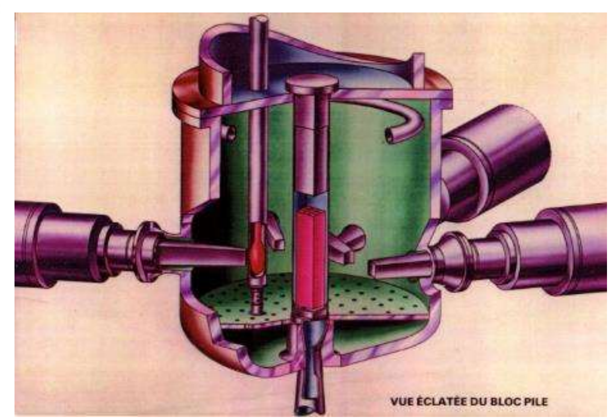
8 with 2 channels

1 with 4 channels

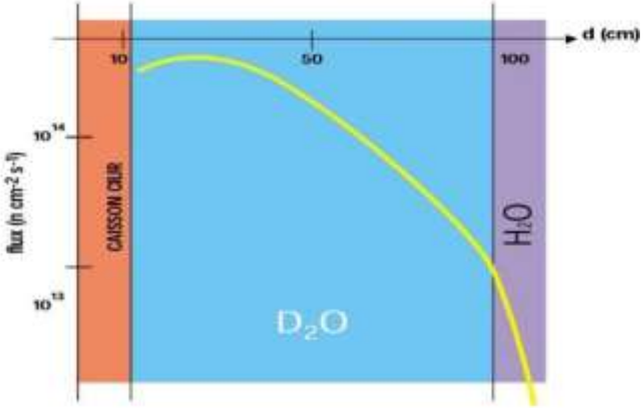
Feeds 9 cold neutron guides

No direct view of the core from the exit of the beam tubes :

less fast neutrons
gamma rays
and
other particles

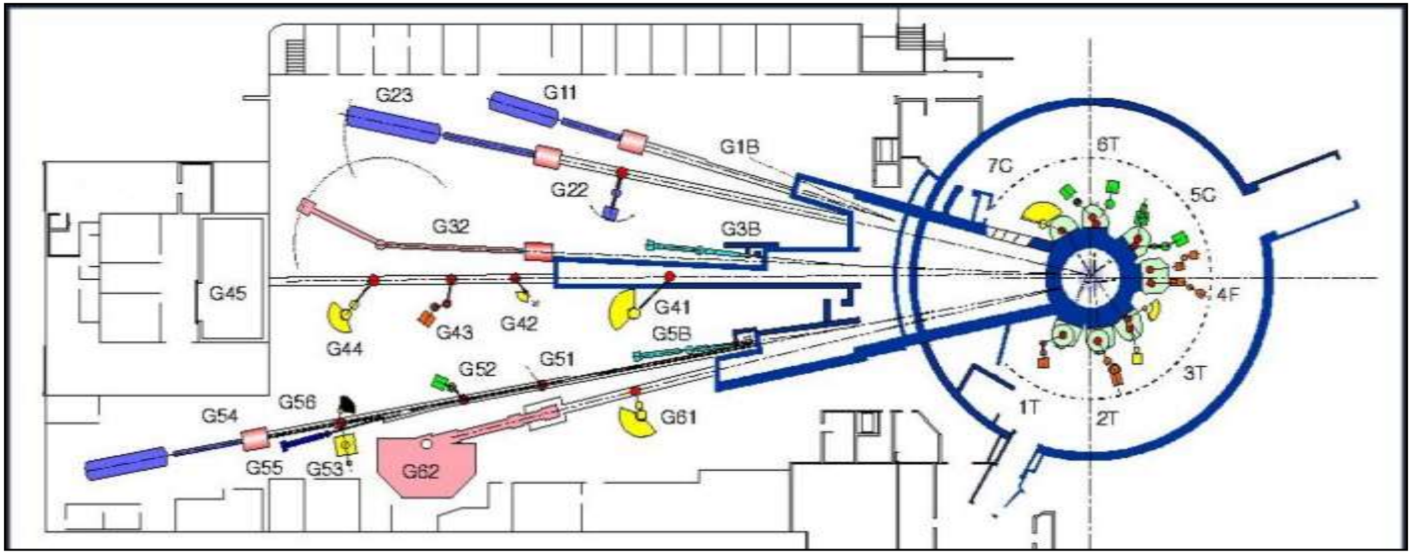


Thermal neutron flux



In D2O vessel : 3 10^{14} n $cm^{-2}s^{-1}$

(at 360mm from core center)



Guides :

Reactor face : 9 10^9 n $cm^{-2}s^{-1}$

Containment exit : 1.9 10^9 n $cm^{-2}s^{-1}$

End of guide : 1.3 10^9 n $cm^{-2}s^{-1}$

In pile beams :

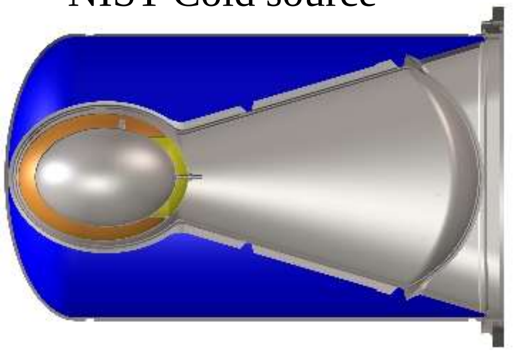
Thermal : 11 10^9 n $cm^{-2}s^{-1}$

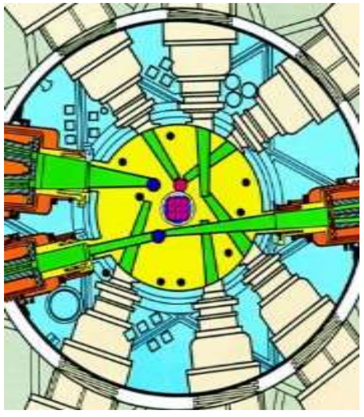
Hot : 7 10^9 n $cm^{-2}s^{-1}$

Cold : 17 10^9 n $cm^{-2}s^{-1}$

Liquid H_2 or D_2 Cold Sources

NIST Cold source





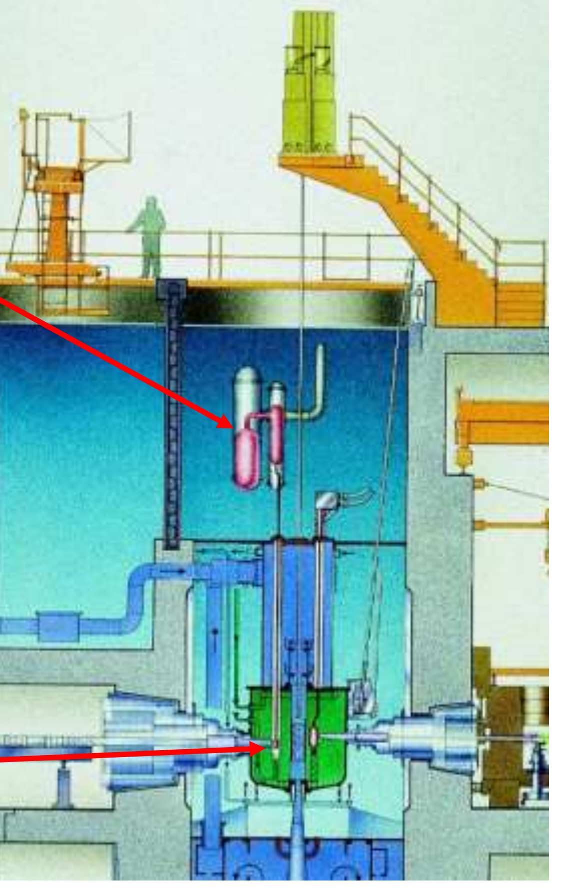
Feeds

2 in pile beams

9 guides

7meV

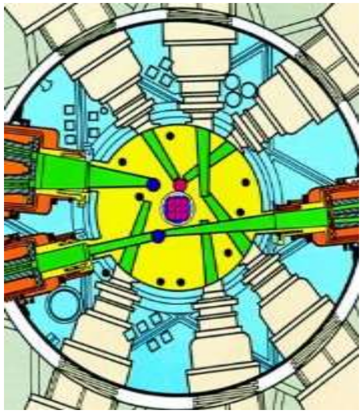
He/H_2 heat exchanger,
H_2 tank under water



Lenticular to annular in 1995
Øext=130mm Øint=110mm
h=300mm T=20K
400mm from core

Cold source socket

Graphite Hot Source



Feeds

2 in pile beams

400meV

Hot source setting

at 270mm from core center

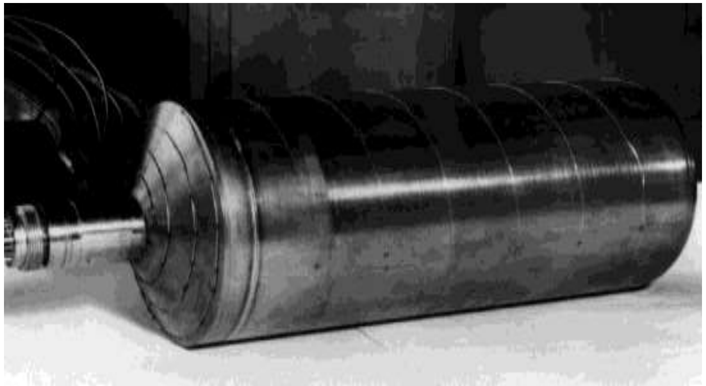
Ø=120mm

h=200mm

Graphite at 1300°C

Under vacuum

Heated by the core radiations



Beam tubes and shutters

Empty tubes

Al or Zr windows

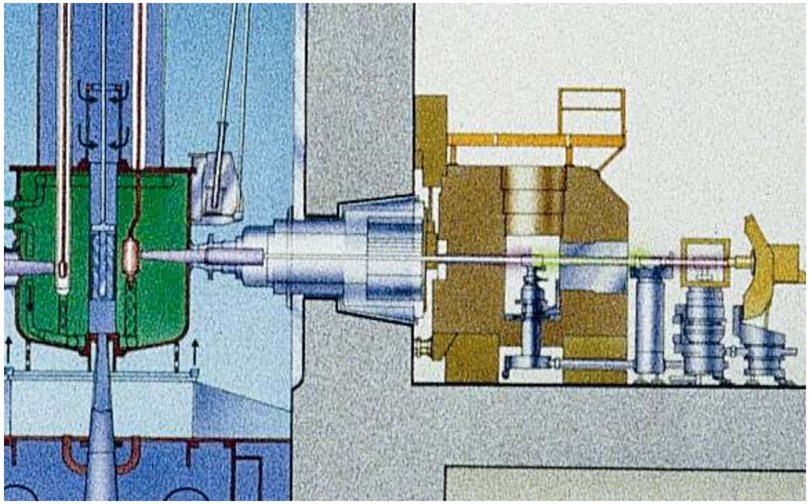
Collimators

Evacuated or He gas

Size optimized (shielding ←→ flux)

Simulation with MCNP

H15 guide change at the ILL

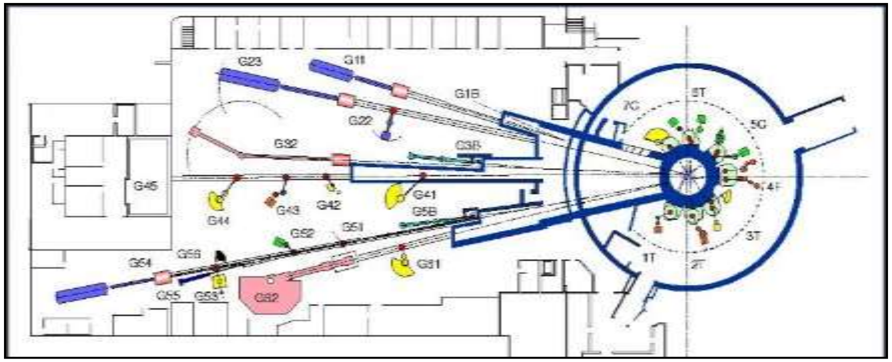


Beam plug installation

Shutter installation

Monochromator protection

Guide system



Neutron guides : glass tubes coated with Ni

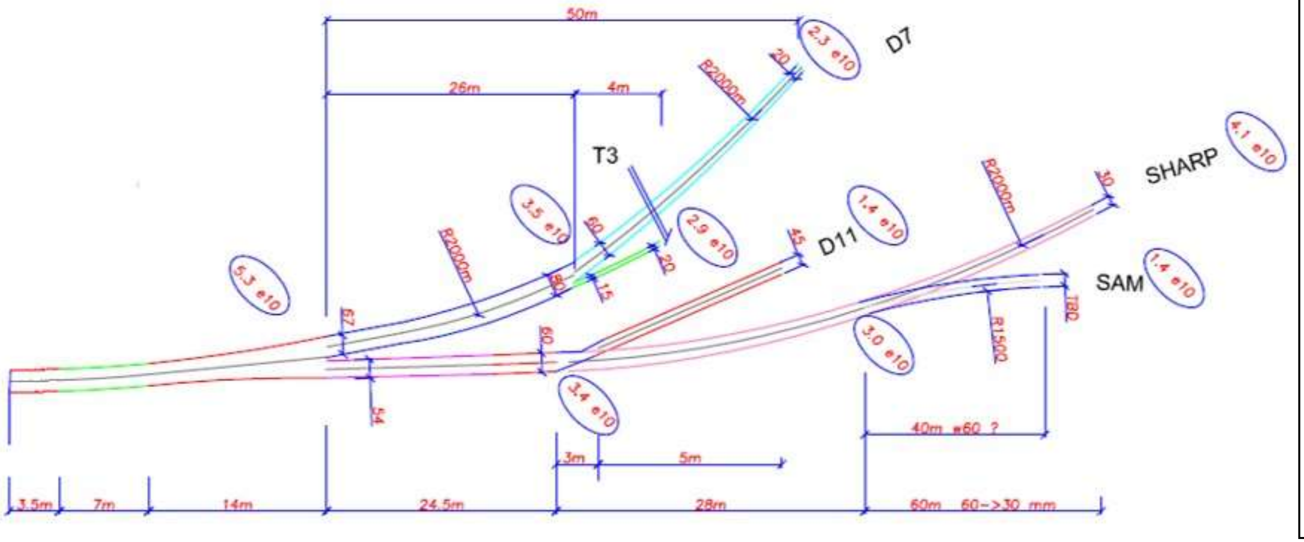
Total reflection on Ni : 0.1°/Å

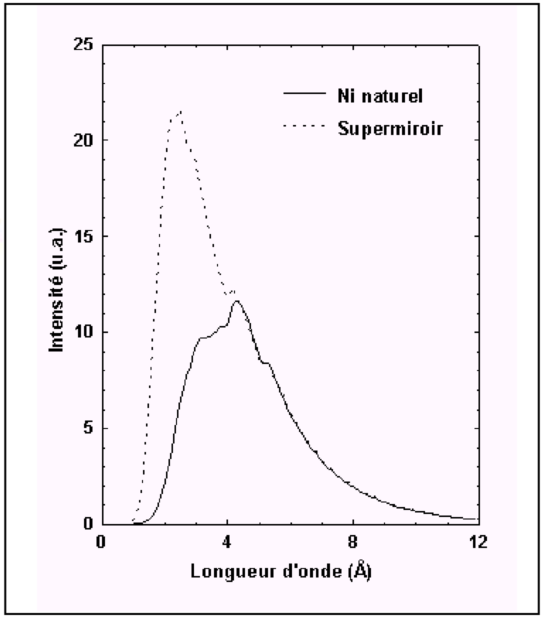
Curved to avoid direct sight view

Large distance to source :

- Low background
- Larger space
- More instruments

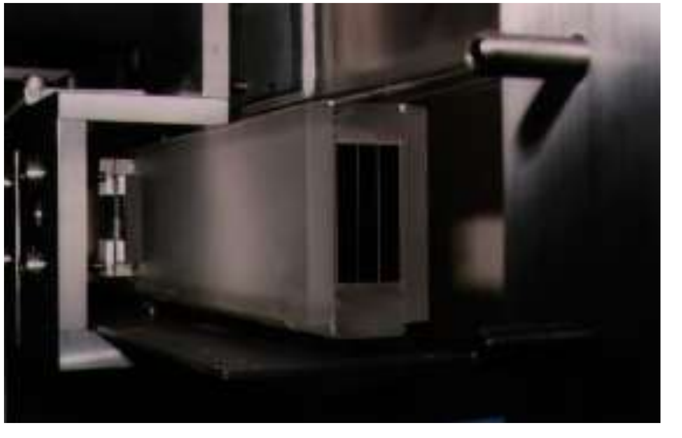
Guides : Supermirror, multichannel parabolic, balistic, elliptic, …





<u>Constant guides evolution using multilayers :</u>

- Provide more flux on instrument (x 5)
- Provide shorter λ on instrument $\lambda^* = \frac{1}{\alpha}\sqrt{\frac{2W}{R}}$
- Provide more end guide positions
- **Check for ageing !**
- Many geometries possible; flexibility : H15



Limitations of reactors

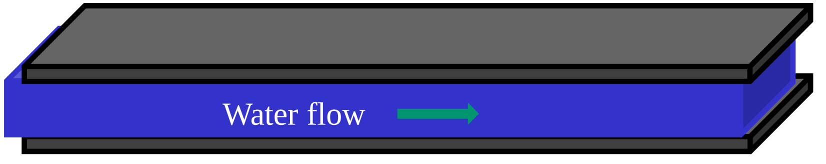
Chain reaction ➔ Safety

Ageing of materials ➔ Safety

Heat extraction ➔ Limit in reactions density

Orphée cooling : 300 l/s at 25°C

Balance between :



- U density
- Size of water tubes for high speed flow

Limits of thermo hydraulic; bubbles are forbidden

Heat released per neutron produced

PROCESS	*EXAMPLE*	*NEUTRON YIELD*	*ENERGY (HEAT) RELEASED MeV/Neutron*
(α,n) reaction	*Radium beryllium lab source*	8 x 10^{-5}/alpha	6600,000
(D,T) fusion	*400 keV deuterons on tritium loaded target*	4 x 10^{-5} /deuteron	10,000
Photofission	*100 MeV electrons on uranium*	5 x 10^{-2} /electron	2,000
Fission	*U^{235} (n,fission) in reactor*	0.5/fission	180
Spallation Stripping	*800 MeV protons on tantalum* *15 MeV protons on Be*	40/proton 0.01/proton	30 1500
(D,T) fusion	*Laser fusion (Megajoule)*	1/fusion	18

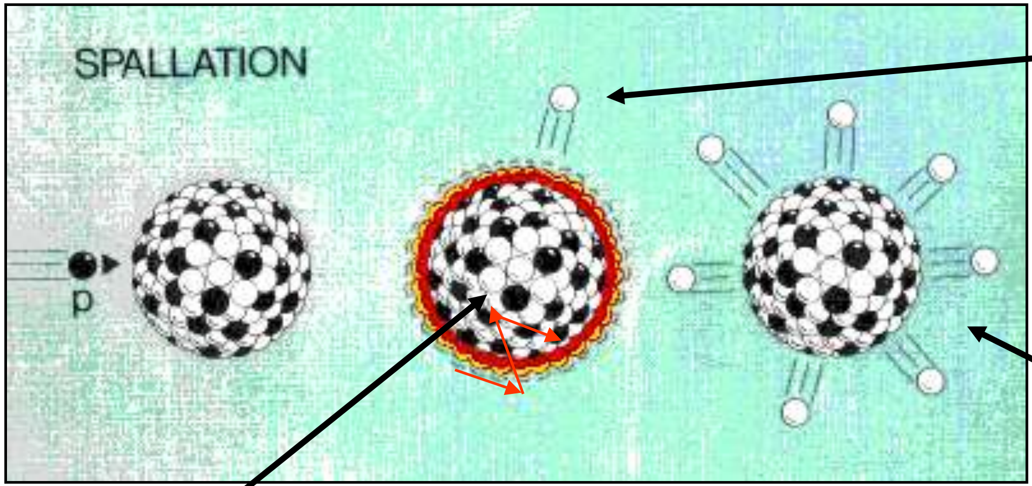
Stripping : a low efficiency process, but create neutrons in a small volume

15 MeV protons stopped in less than 5 mm

800 MeV protons stopped in more than 100 mm

Brilliance of a similar order of magnitude

Spallation : 1 - less heat



2. Inter Nuclear Cascade

Up to 40 neutrons per incident proton

3. Evaporation

1. Internal Cascade
(highly excited state)

Drawbacks

- Production of high energy neutrons
- High gamma background
- Need heavy protections

Advantages

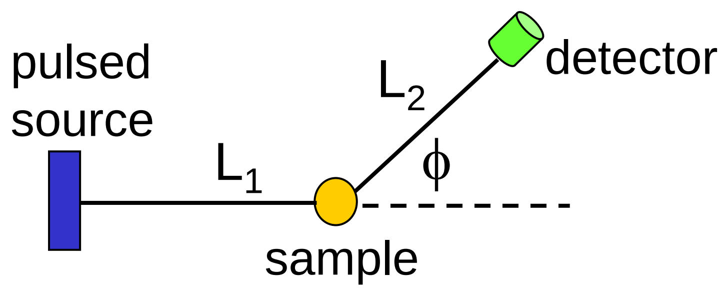
- no chain reaction
- pulsed operation (usually)
- 40 neutrons/proton

Use of low energy protons (3-25 Mev on Be), cheaper but less neutrons :

- Less gammas
- Less fast neutrons
- Less activation (in target and accelerator)
- Less neutrons

Spallation : 2 - better use of neutrons produced

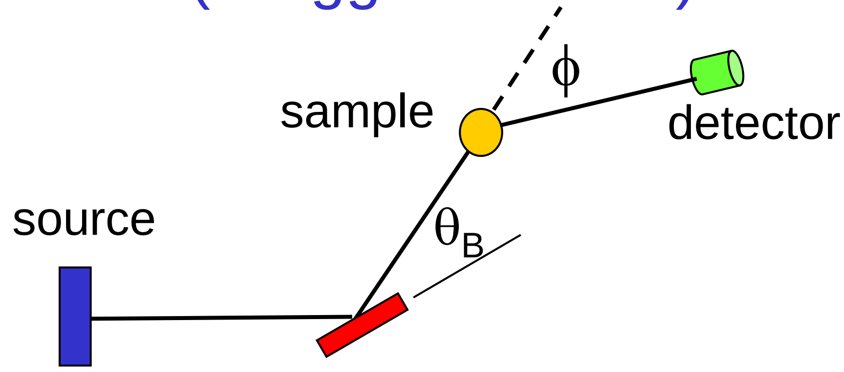
time-of-flight (TOF-Choppers)



$$\lambda = \frac{4000}{v} = \frac{4000\,(t-t_0)}{L}$$

$$\delta\lambda \sim \delta t_0, \delta t, \delta L$$

crystal monochromator (Bragg diffraction)



$$\lambda = \frac{2d_c \sin(\theta_B)}{n}$$

$$\delta\lambda \sim \delta d_c, \delta\theta_B$$

Proton accelerators

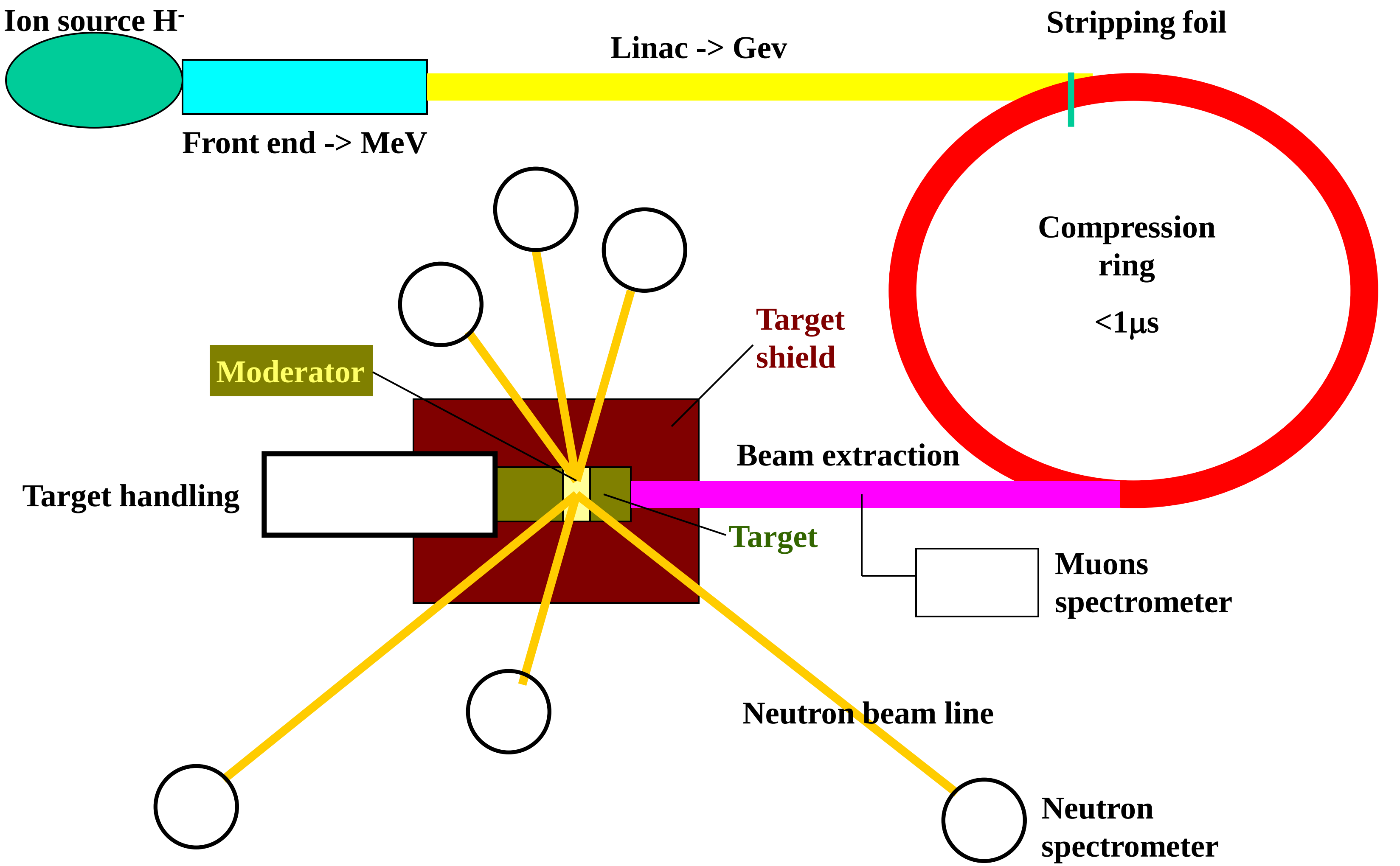
- Linear Accelerators ESS, SNS, J-Parc
  - high current (up to 100 mA)
  - high duty cycle; long pulses
  - need storage ring or compression ring for short pulses
- Cyclotrons SINQ
  - continuous beam (MHz range)
  - Low current (max 2 mA)
- Synchrotrons ISIS
  - modest current (rapid cycling)
  - narrow pulse (single turn extraction)
  - modest duty cycle

Cyclotrons

Size :
from a room to a whole building (PSI).
Radiation protection needed

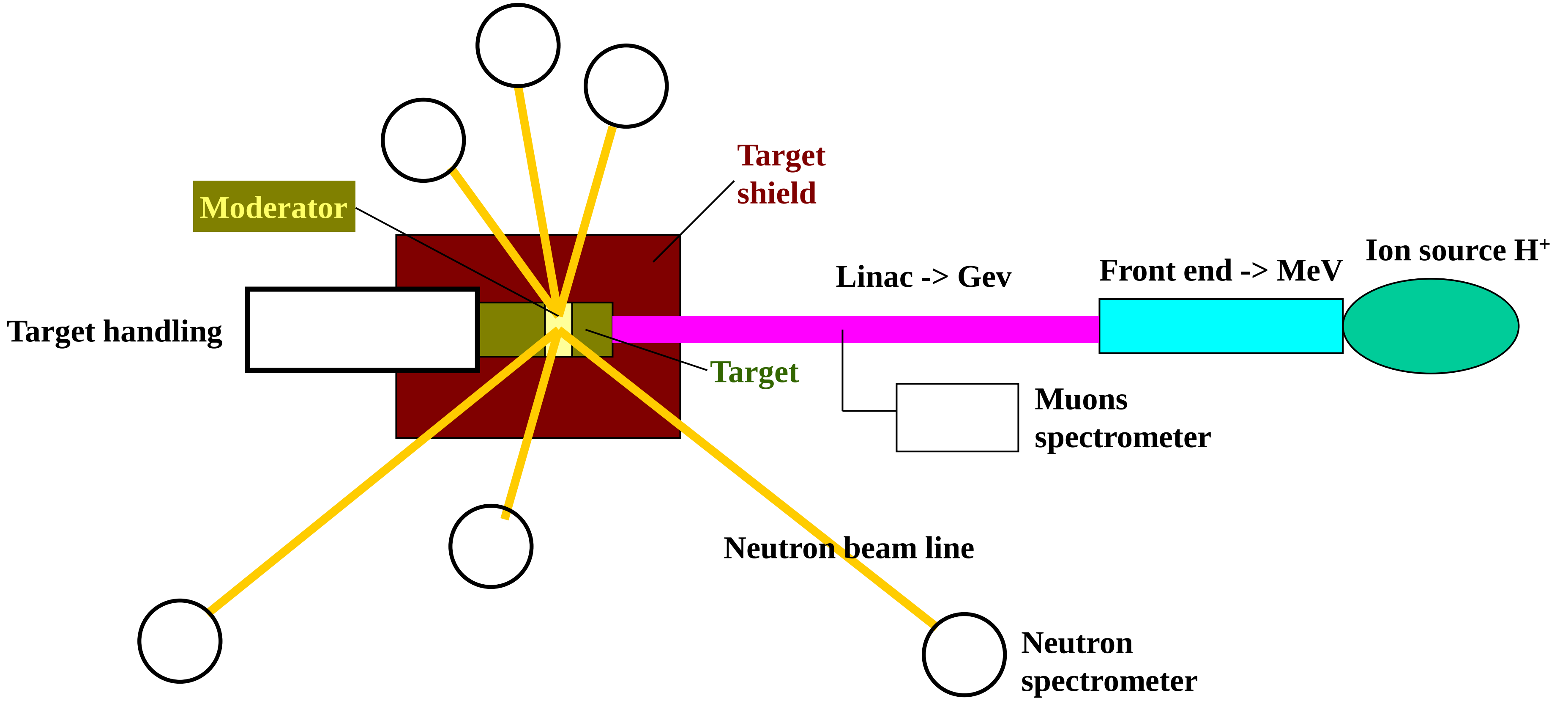
Industrial cyclotrons (IBA) can be used for neutron radiography, real time neutron activation analysis or delayed neutron activation analysis, **radioisotope production**

Layout of a short pulse spallation source with accelerator



Long pulse spallation source

No compression ring (>100µs)



ESS

In construction near Lund

First stone in october 2014

1 target

5 MW (2 x SNS = 4 x JSNS = 30 x ISIS)

2.5 GeV

50 mA

Superconducting linac

- **LP : 14 Hz, 2860μs pulses (high flux)**

44 instruments

15 in a first stage at 2 MW

User operation start end 2027

France : 8% of construction cost

Current sources and projects

Around 50 research reactors in the world and 8 spallation sources

Main reactors in Europe :

ILL – Grenoble (till 2033)
FRM-II – Münich (2004 restart 2027?)
BNC – Budapest (till 2030)
IRI – Delft – The Netherlands
Gatchina - Russia
NPL – Prague - Czech Republic

Reactors outside Europe

OPAL – Australia (2006)
Hanaro – Korea (1995, restart 2022)
CARR – China (2011)
PIK – Russia (2025 ?)
RA-10 – Argentina (2027 ?)
HFIR, NIST, Murr – USA
Dhruva India
JRR3M – Japan (1990, restart 2022)
RMB – Brésil (2030 ?)
JRTR – Jordan (2020)
Egypt, Marocco, Indonesia …

Spallation sources (world) :

SNS – Oak-ridge – USA (2006)
J-Park – Japan (2008)
C-SNS – China (2019)
ISIS – Oxford – UK
SINQ - PSI – Switzerland

ESS – 2027 ?
Lund Sweden

Special reactors :

IBR2 Dubna

Compact sources : a solution for future local needs ?

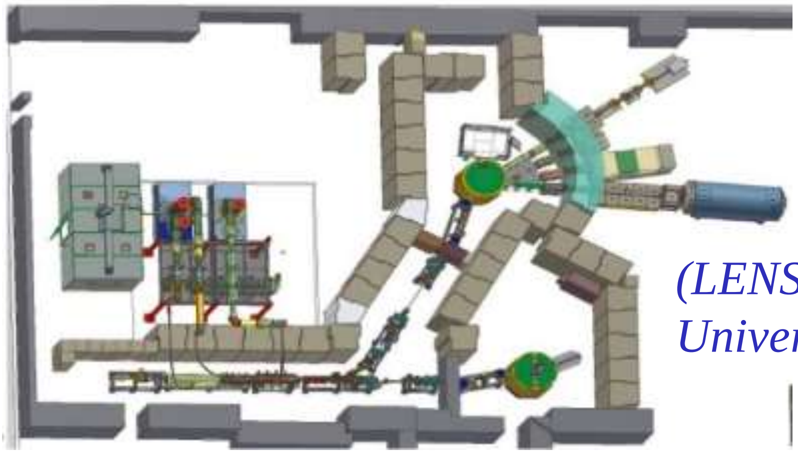
Concept :

Produce less neutrons but increase brilliance with compact target/moderator

Provide at max 10^8 n/cm^2/s thermal neutrons at beam port.

Typical specifications :

- Proton accelerator (10-100 MeV, 100mA)
- 1 to 3 targets (Be, Ta, Li, Ga, …); different rep. rates and pulse width
- 1 or 2 optimized moderator par target
- 2 to 5 instruments per target
- Optimized beam transport (high m guides)
- Large area detectors with high efficiency



(LENS) at Indiana University

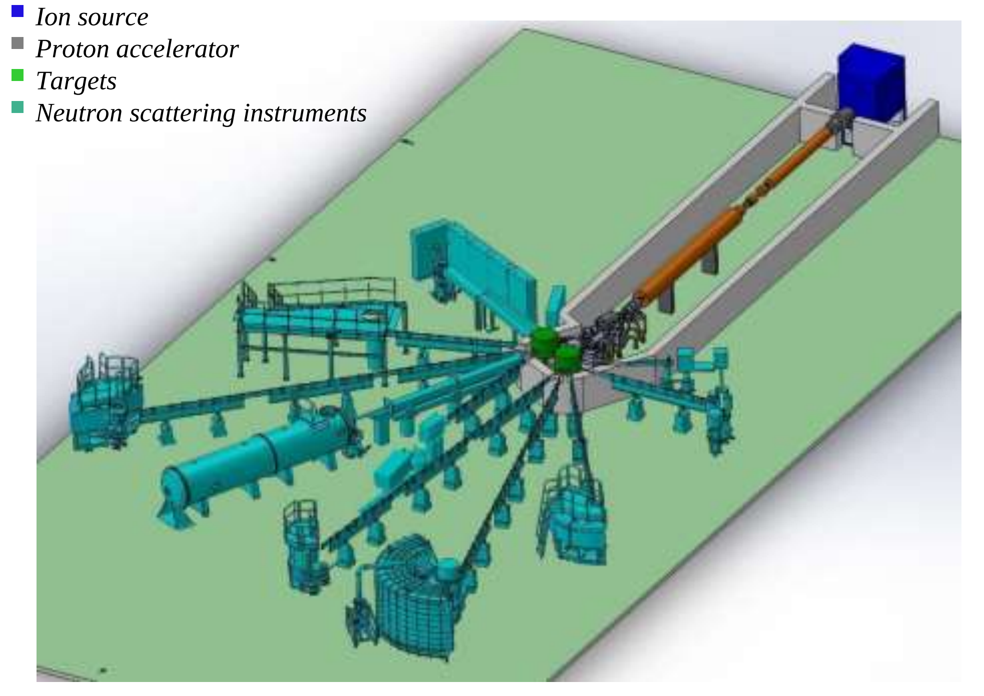
Easely scalable between 3MeV to 100MeV and 1mA to 100mA, or 10M€ to 300M€

Main Pb : Target ageing

ICONE the French compact source project

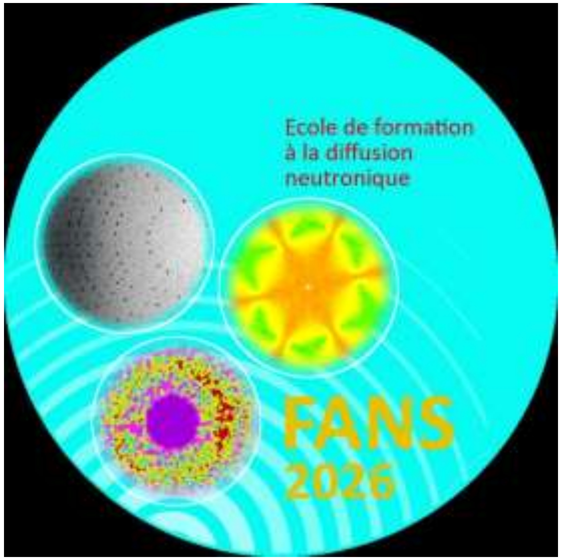
ICONE :

(Innovative COmpact NEutron facility)

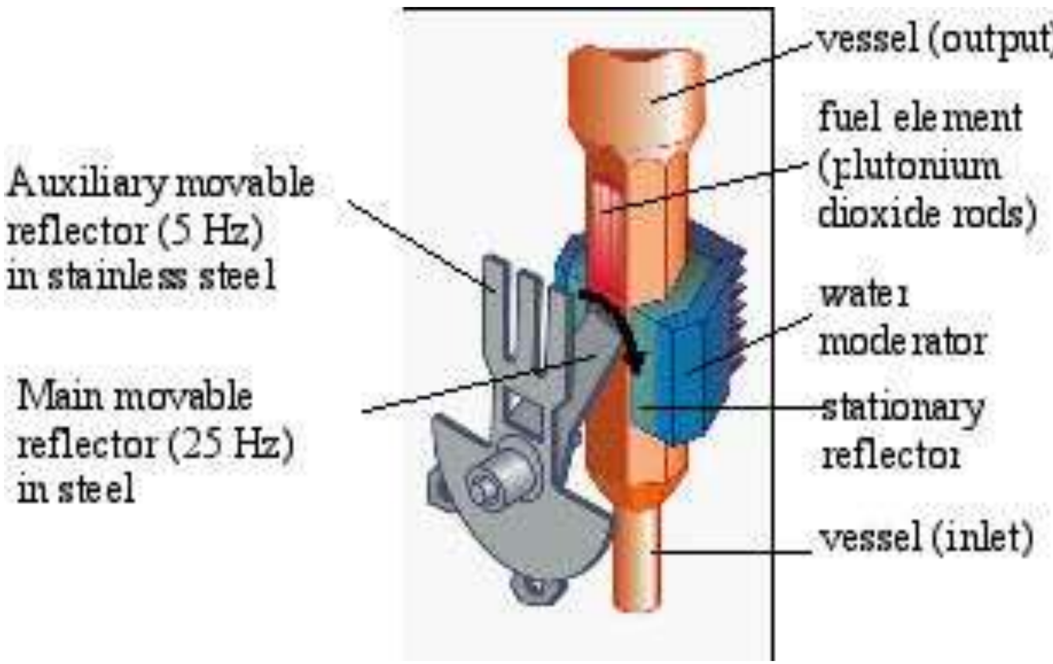


- Proton beam
- 100 mA peak current
- 25 MeV
- Be target
- 2 targets
  - Long pulses, 4% duty cycle, 2 msec – 20 Hz, 80 kW, 5 10^8 $n_{th}/cm^2/s$ at target wall
  - Short pulses, 2% duty cycle, 200 µsec – 100 Hz, 40 kW, 2.5 10^8 $n_{th}/cm^2/s$ at target wall
- 6 instruments per target

Thank you



Dubna : a pulsed reactor



2 MW

Pulse width : 320 µs