Neutron Instrumentation

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- What do we measure and need ?
  - Neutron source and guides
  - Measuring techniques
  - Energy selectors and polarisers
  - Sample environments
  - Neutrons detectors
  - Data acquisition system

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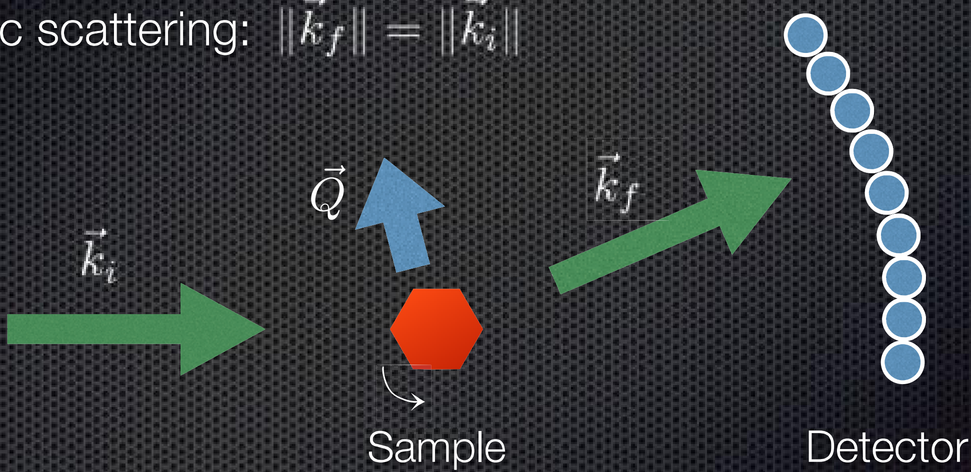
What do we measure ?

- Elastic scattering: $\|\vec{k}_f\| = \|\vec{k}_i\|$



Intensity vs wavevector transfer $\vec{Q} = \vec{k}_f - \vec{k}_i$

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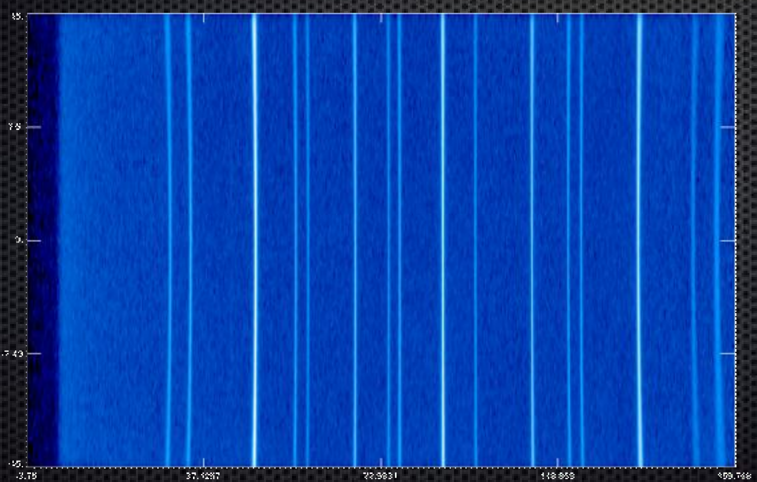
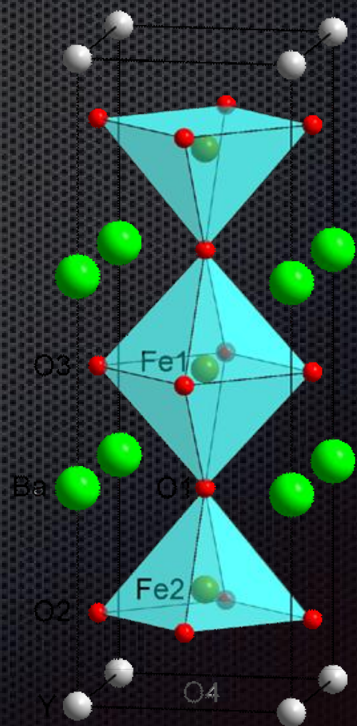
What do we measure ?

- Example: $YBa_2Fe_3O_8$ structure





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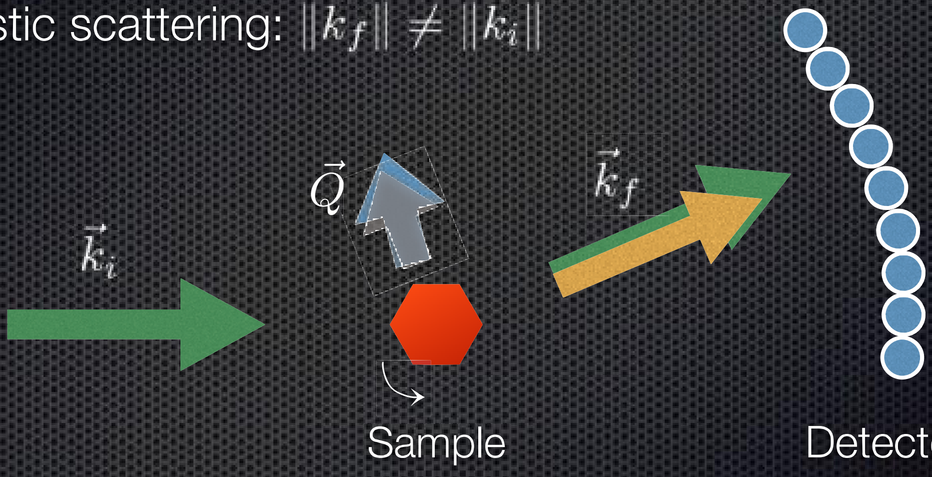
What do we measure ?

- Inelastic scattering: $||\vec{k}_f|| \neq ||\vec{k}_i||$



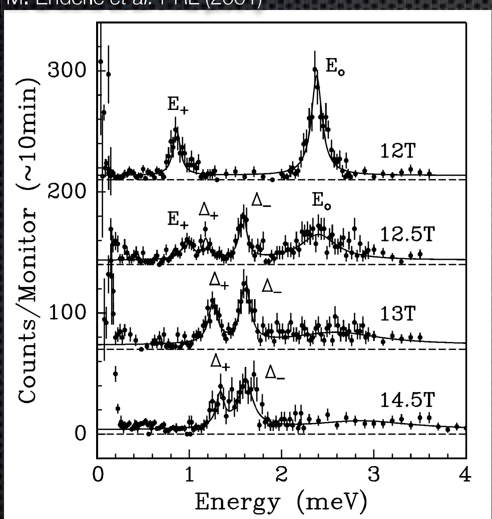
Intensity vs wavevector and energy transfers

$$\vec{Q} = \vec{k}_f - \vec{k}_i, \quad \hbar\omega = E_f - E_i$$

What do we measure ?

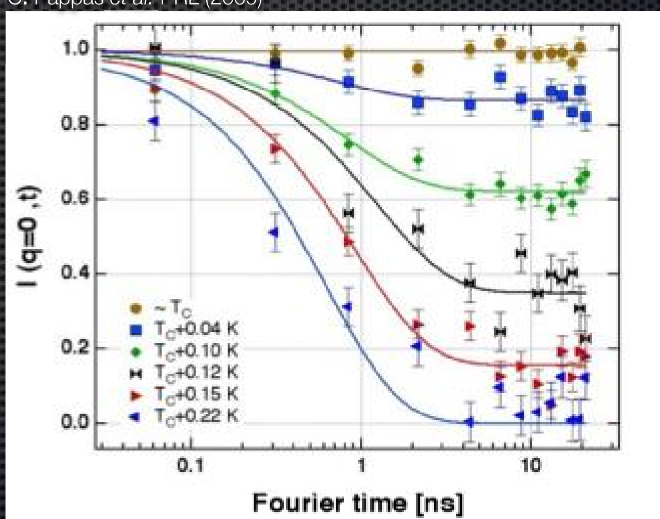
- Examples: correlated motions, relaxation

M. Enderle *et al.* PRL (2001)



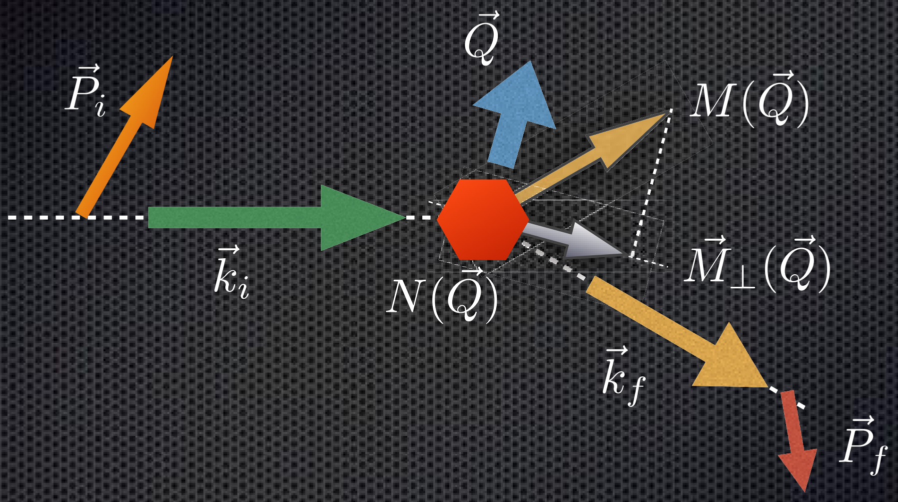
Excitations in $CuGeO_3$

C. Pappas *et al.* PRL (2009)



Skyrmions in MnSi

What do we measure ?



In general, the polarisation of a neutron beam will change both in magnitude and direction upon scattering from a magnetic material.

What do we measure ?

- Polarised neutron scattering (elastic/inelastic):
  - We measure spin-dependent intensities:

$$I_{+,+},\ I_{-,+},\ I_{+,-},\ I_{-,-}$$

  - and components of the scattered polarisation $\vec{P}_f$ for each direction of the incident polarisation $\vec{P}_i$:

$$\mathrm{P}_{i,j} = \frac{P_i\ \mathbb{P}_{i,j}\ + P_j^{\dagger}}{||\vec{P}_f||} \text{ with } (i,j) \in \{x,y,z\}$$

So what do we need ?

- Source of neutrons
- One or two wavelengths
  ↳ Monochromators, choppers, Larmor labelling, etc.
- Incident and scattered neutron directions
  ↳ Collimations, encoded shafts, Tanzboden, slits, etc.
- Incident (and scattered) polarisations
  ↳ Monochromators, supermirrors, spin filters & flippers
- Monitors and detectors

- What do we measure and need ?
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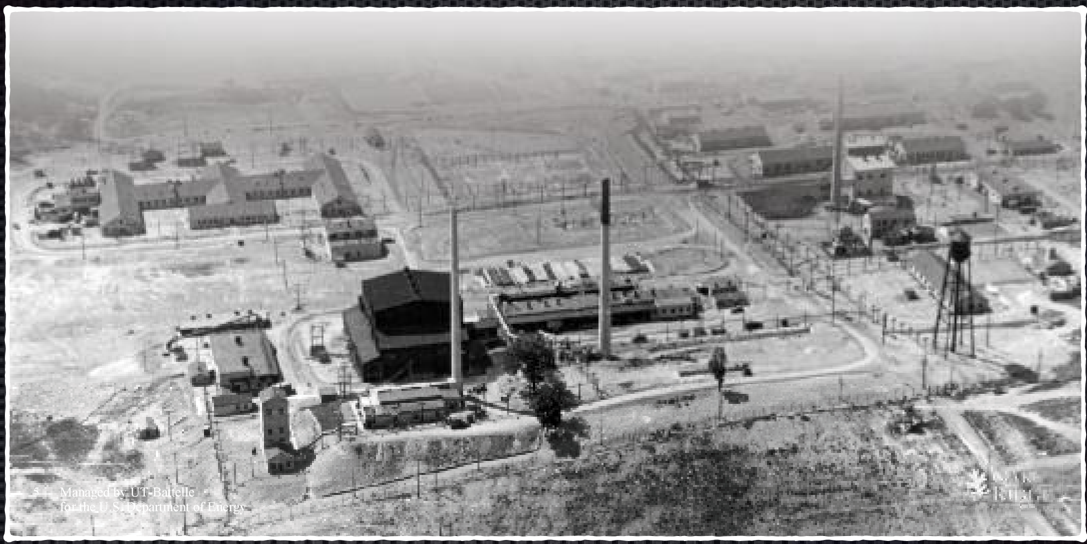
Neutron sources



1943 — Oak Ridge National Lab. (USA)

The Clinton Pile was the world's first continuously operated nuclear rector.

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Neutron sources

2013 — Oak Ridge National Lab. (USA)

1.4 MW Spallation Neutron Source

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Neutron sources

2023 — European Spallation Source (Sweden)

5 MW long pulse source — 1.8 Billion €

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5 MW long pulse source — 1.8 Billion €

Neutron sources

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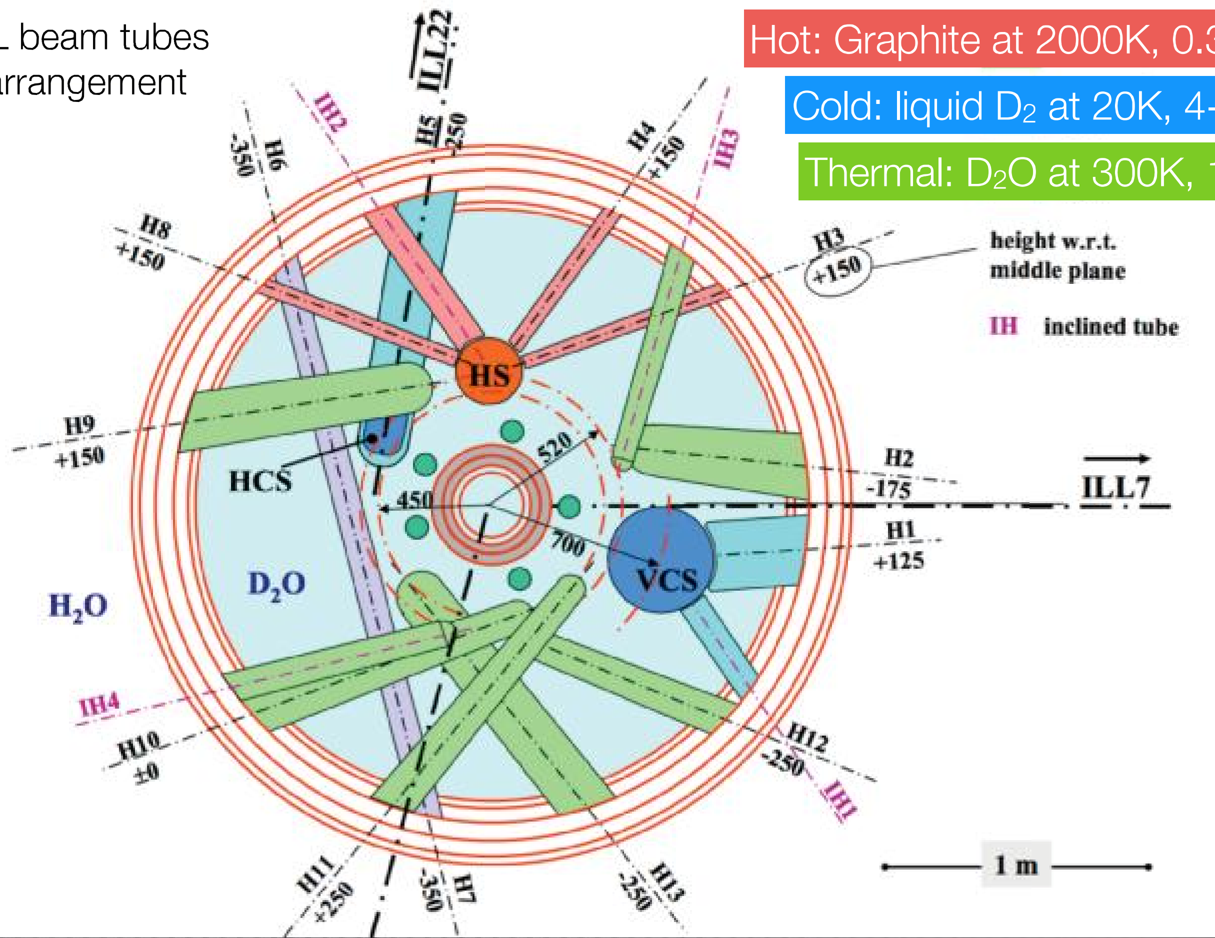
ILL beam tubes arrangement

Hot: Graphite at 2000K, 0.3-1Å

Cold: liquid D_2 at 20K, 4-20Å

Thermal: D_2O at 300K, 1-4Å



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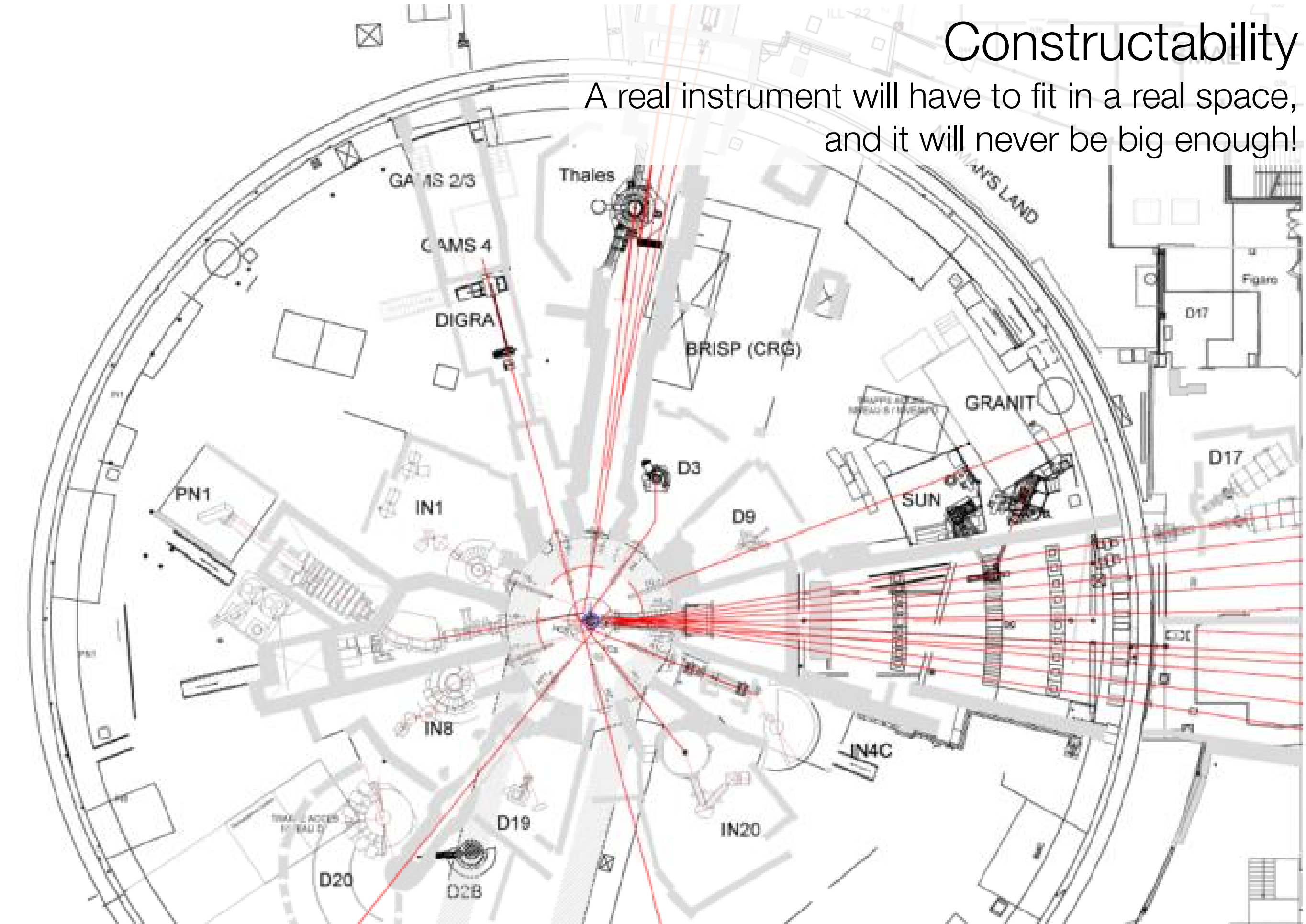
Constructability

A real instrument will have to fit in a real space, and it will never be big enough!



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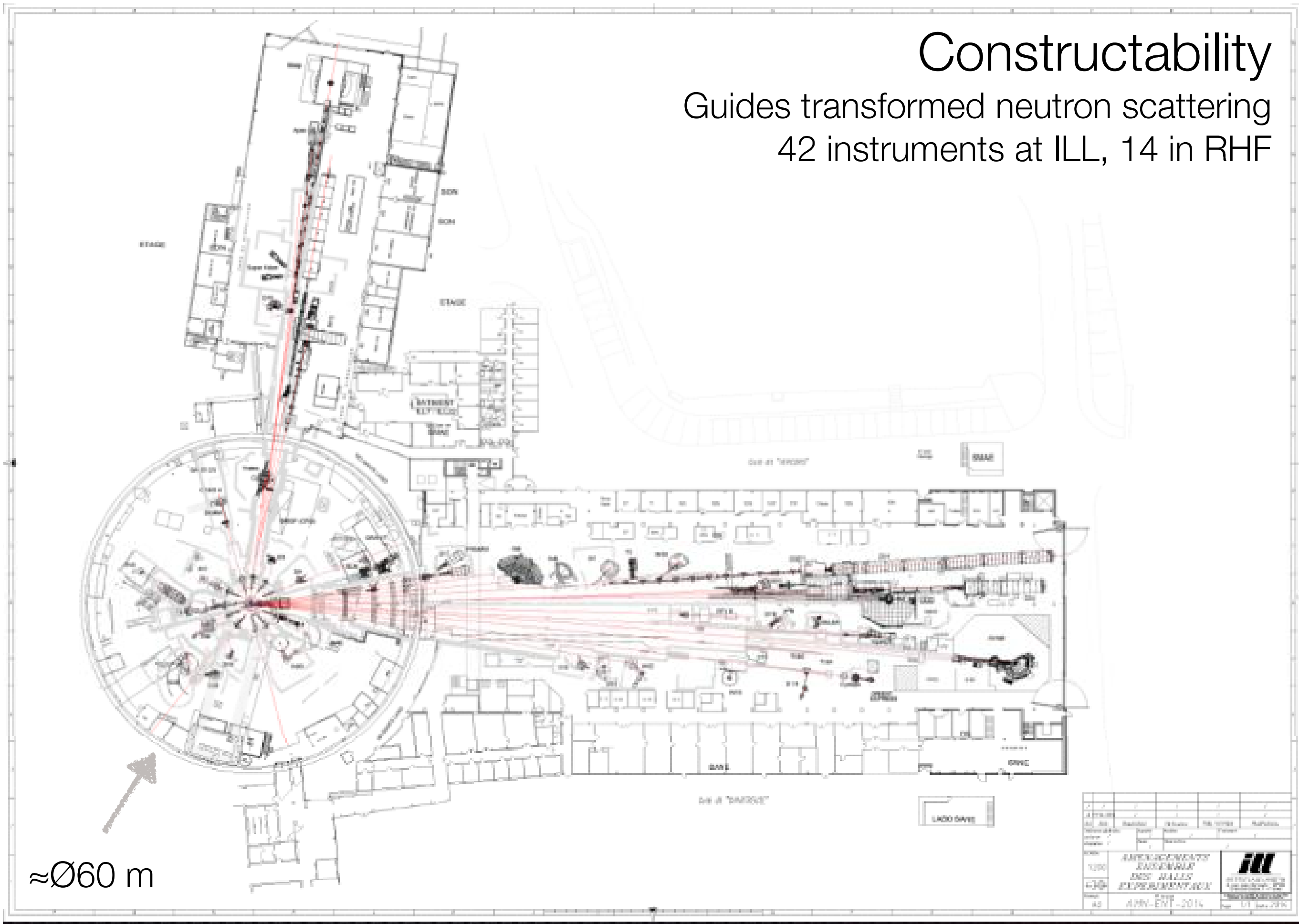
Constructability

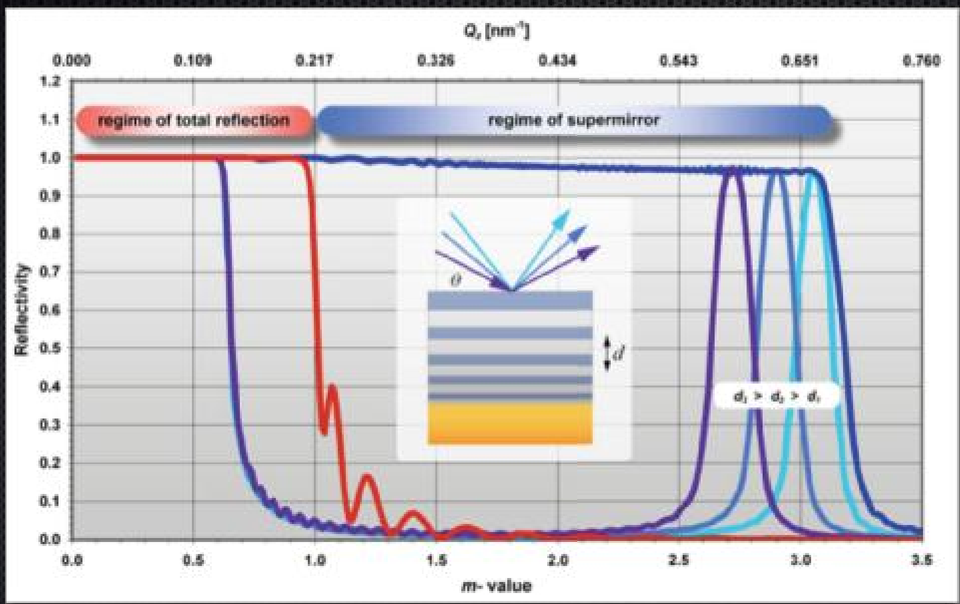
Guides transformed neutron scattering
42 instruments at ILL, 14 in RHF



Supermirror neutron guides

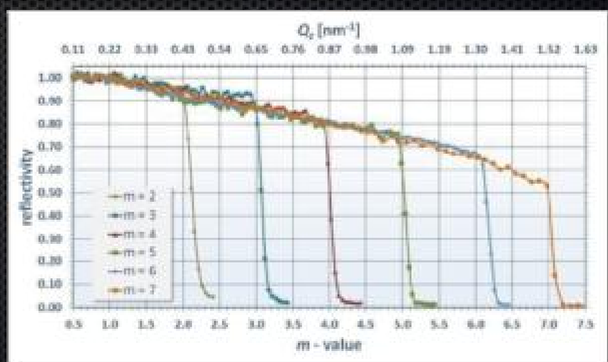
- A guide is made up of sections joined together
- Glass is sufficiently thick to hold the vacuum
- Curved guides can eliminate fast neutrons
- Guides can focus, collimate, polarise…

Supermirror neutron guides



$$m = \theta_c/\theta_c^{Ni}, \quad \theta_c^{Ni} \approx 0.1°/\text{Å}$$

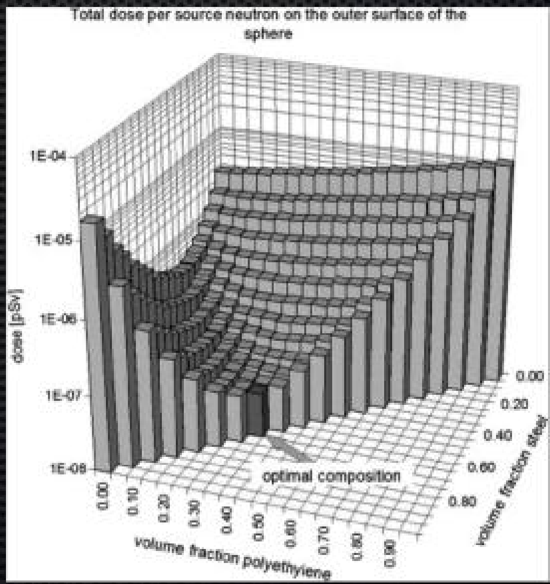
H5 installation in 2014 at ILL



Swiss Neutronics

Shield against fast neutrons, thermal neutrons, gammas

- Hydrogeneous: concrete, wax, polyethylene
- Lead, Iron (steel)
- Boron, ^{6}Li, Cd, Gd/GdO
- We always need better shielding…



Calzada *et al.* NIMA 651 (2011) 77

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Introduction

In 1944, Ernest O. Wollan and Lyle B. Borst performed pioneering neutron diffraction experiments with a modified X-ray diffractometer.

Introduction

Ernest O. Wollan & Clifford G. Shull taking data on a double-crystal neutron spectrometer at the ORNL X-10 graphite reactor in 1949.

Measuring techniques

- Neutronography
- Diffraction (elastic scattering)
  - Powder diffraction: low and high resolutions
  - Single crystal diffraction: normal-beam, 4-circle, Laue
  - Small angle scattering
  - Reflectometry (horizontal, vertical)

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Measuring techniques

- Spectroscopy (inelastic scattering):
  - Three-axis: hot, thermal and cold energies (≈ meV)
  - Time-of-flight (≈0.1 meV)
  - Backscattering (≈ µeV)
  - Spin-echo: std/para/ferro, etc. (≈0.2 neV to 200 µeV)
- Nuclear & particle physics instruments

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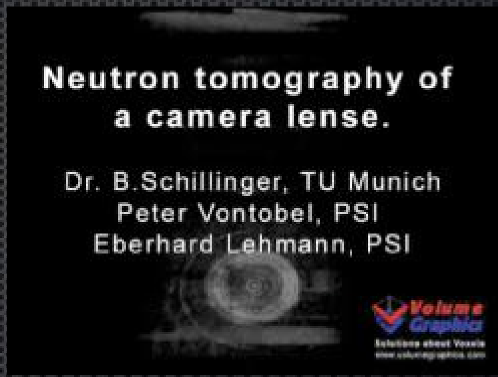
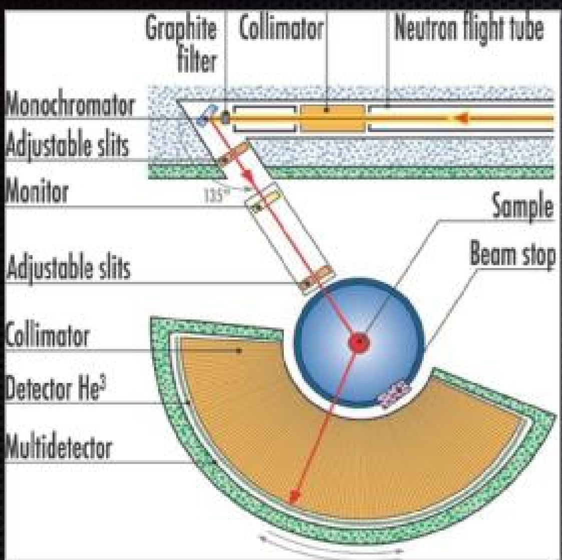
Measuring techniques

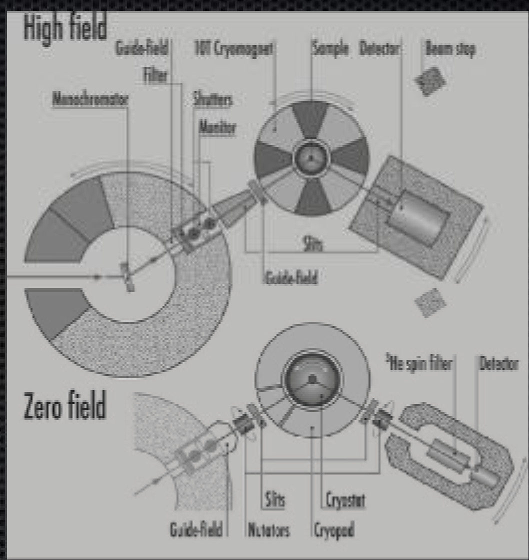


5 µm resolution available — complementary to x-rays

Powder diffraction

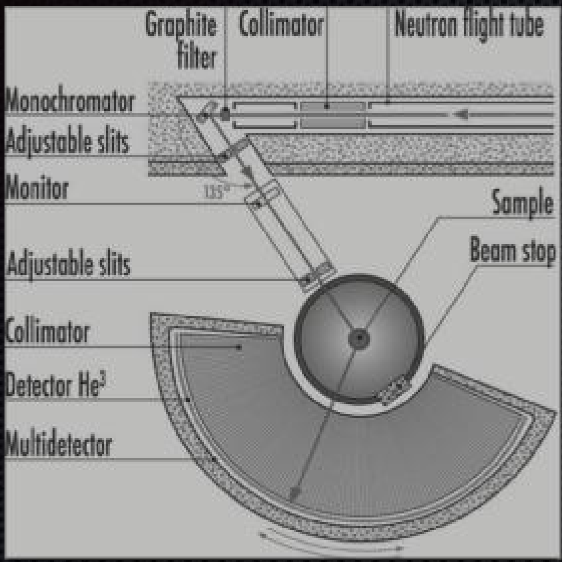
Crystal diffraction

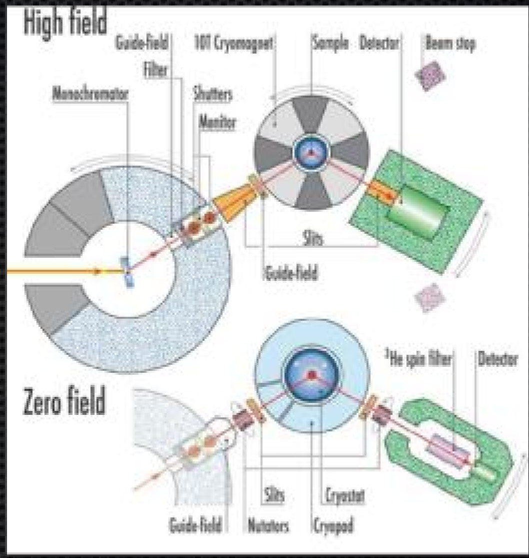




Powder diffraction

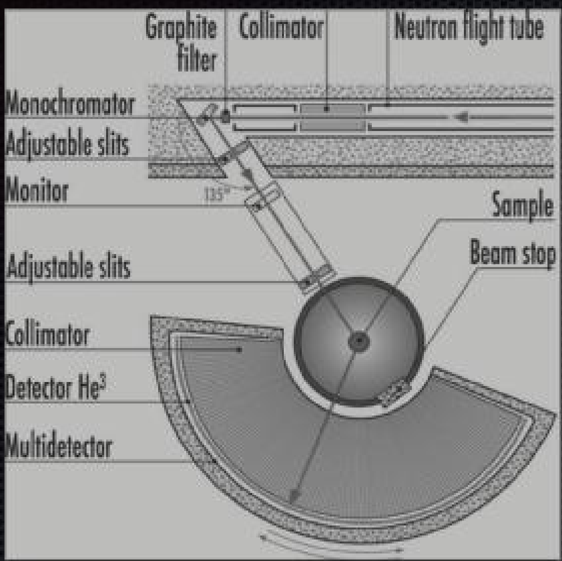
Crystal diffraction

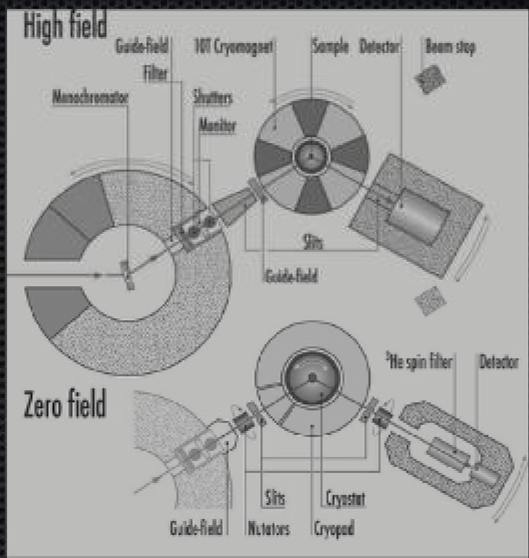




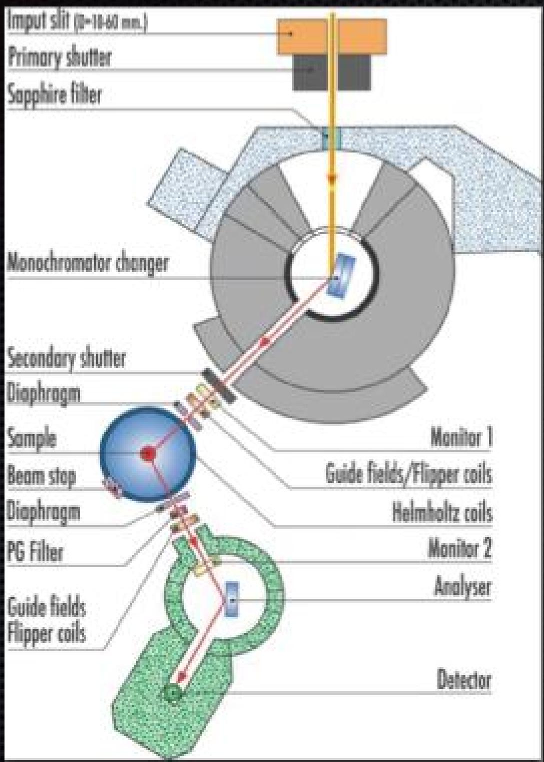
Powder diffraction

Crystal diffraction

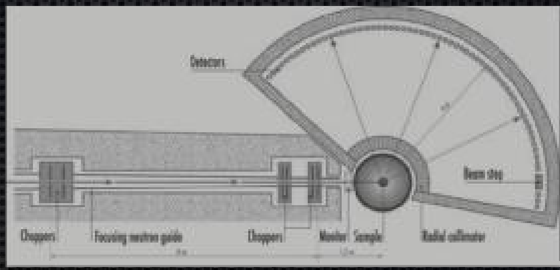




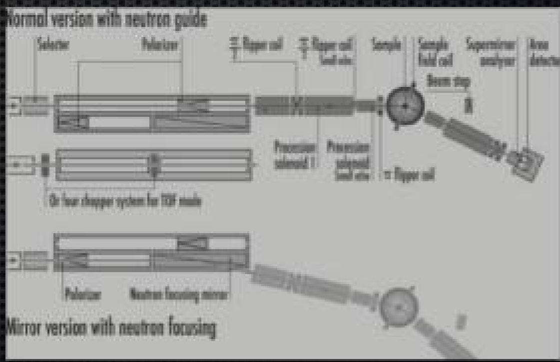
Three-axis



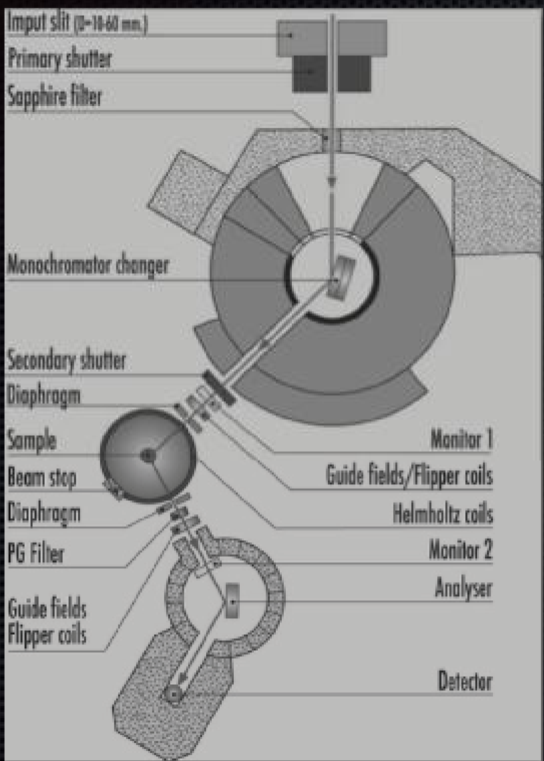
Time of flight



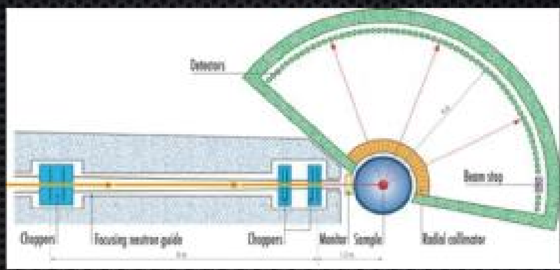
Spin-echo



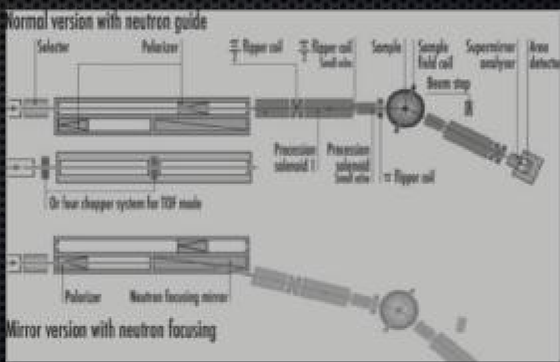
Three-axis



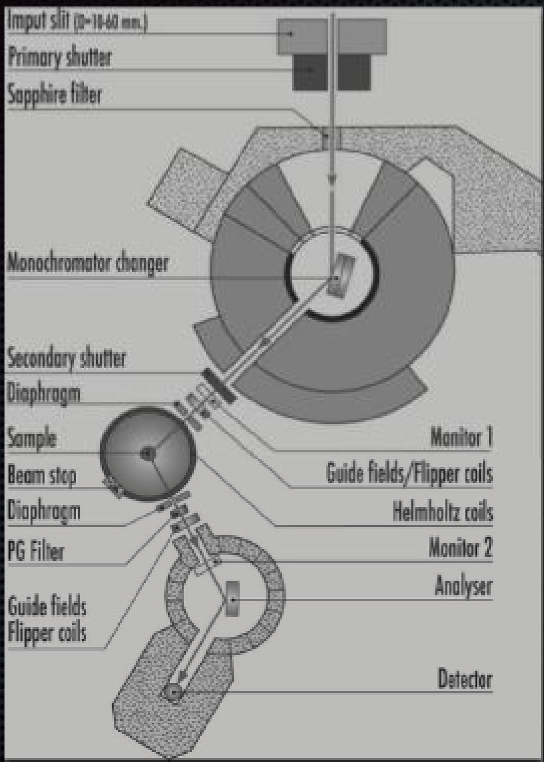
Time of flight



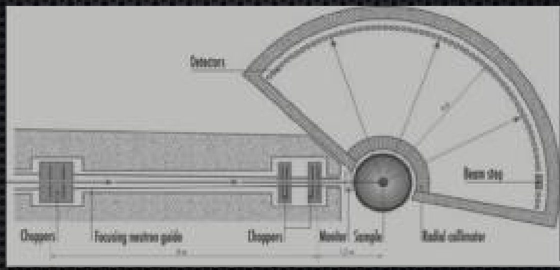
Spin-echo



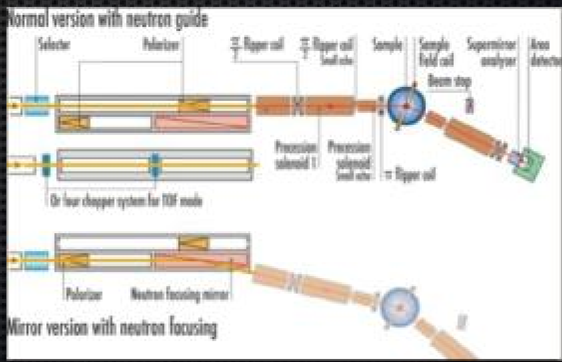
Three-axis



Time of flight



Spin-echo



- What do we measure and need ?
  - Neutron source and guides
  - Measuring techniques
  - Energy selectors and polarisers
  - Sample environments
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Energy selectors & polarisers

- Energy selection
  - Monochromators
  - Time-of-flight selection devices
- Spin selection, manipulation
  - Polarising crystals, supermirrors, ^{3}He spin filters, etc.
- Removal of unwanted energies and neutrons
  - Filters (e.g. Be, MgO), (oscillating) collimators, slits, etc.

Monochromators

- Array of single crystals
  - To select energy (and polarisation)
  - Cu, Si, HOPG, Heusler, Diamond…
  - Flat or focusing vertically (and horizontally)
  - Optimised mosaic

Bridgman furnace at ILL

Monochromators

Heusler (Cu_2MnAl) polarising crystal (ILL)

Ø80x300 mm^3 Cu crystal (ILL)

Monochromators

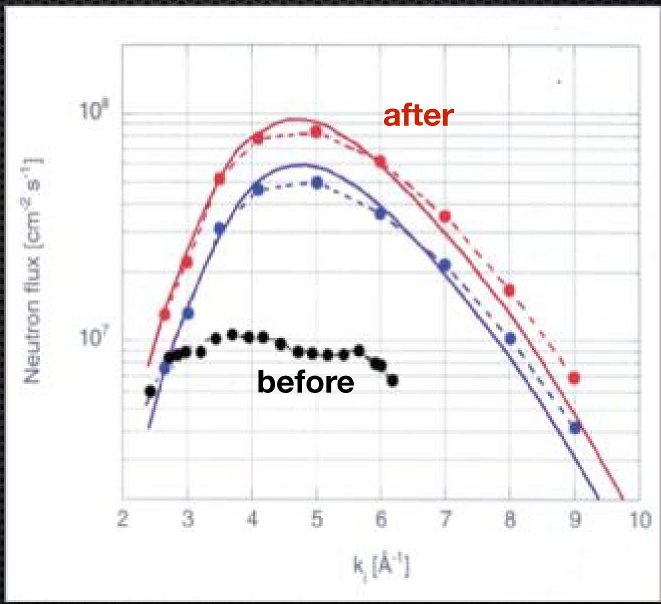
IN8 doubly-focusing monochromator

D20 Cu monochromator

Monochromators

IN20 Monochromator

75 Heusler crystals

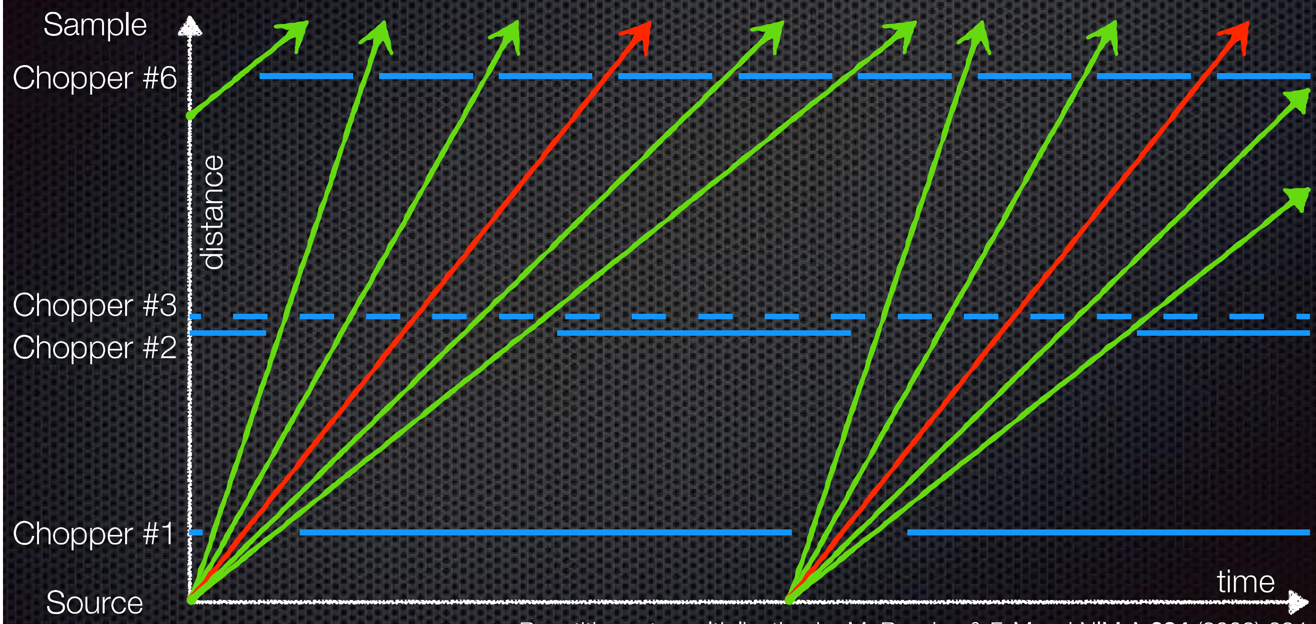


92% polarisation, x10 flux (from Kulda *et al.*)

Time of Flight devices

- Disk choppers
  - T_0 choppers to stop fast neutrons (pulsed sources)
  - Bandwidth-limiting choppers (prevent frame overlap)
  - E_0 or Fermi choppers to transmit a very narrow bandwidth of neutrons (e.g. to define E_i)
- Velocity selectors

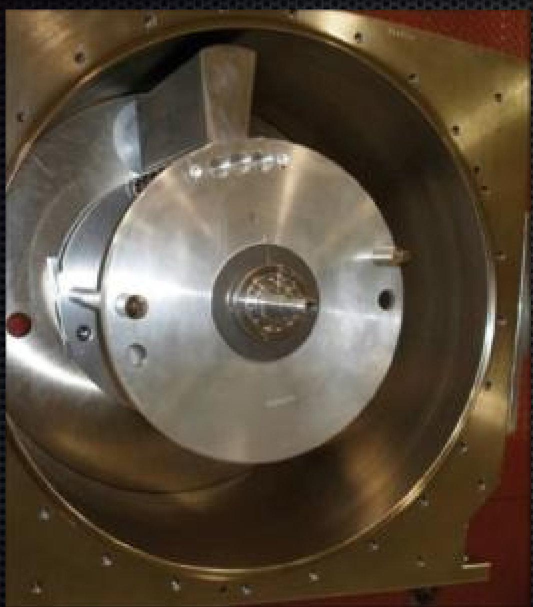
Time of Flight technique



Repetition rate multiplication by M. Russina & F. Mezei NIM A **604** (2009) 624

T_0 choppers

Courtesy to I. Anderson



Single-blade rotor

Assembled chopper unit

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Bandwidth-limiting choppers

Courtesy to I. Anderson

60 Hz chopper disk (TOPAZ, SNS)

Installed on beam line

Bandwidth-limiting choppers

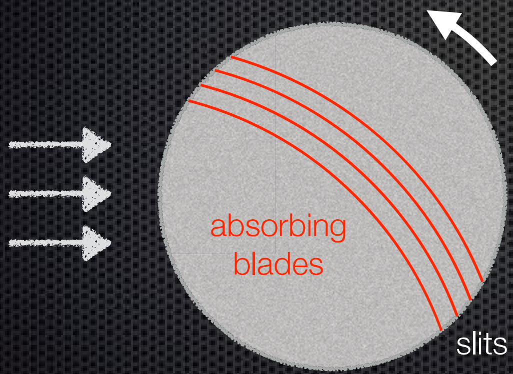
Courtesy to I. Anderson

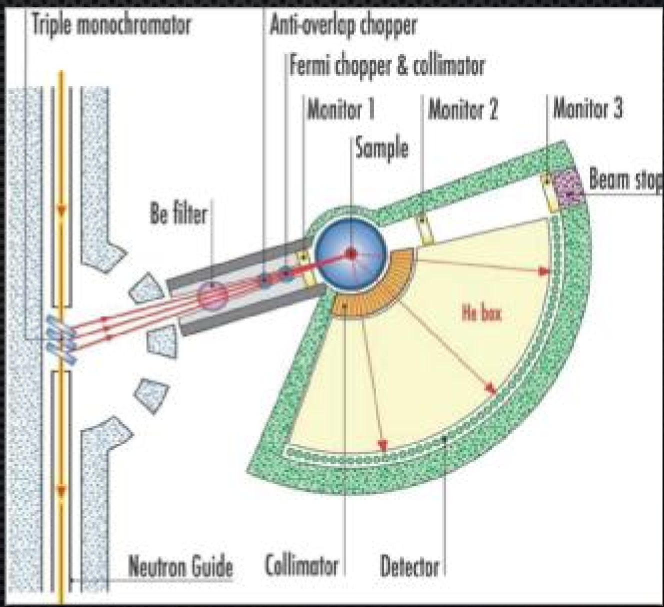
300 Hz dual counter-rotating disks

Installed on beam line

Fermi choppers

- ToF focusing
- Monochromator





IN6 layout

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Velocity selectors

- Large Δλ/λ, typically 10% resolution
- High transmission, between 5 and 30%
- Typically 1.000 rpm
- Multi-disc or multi-blade

Astrium GmbH

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Spin selection, manipulation

- The polarisation can be seen as a vector in space
- Polarisers & spin analysers:
  - Heusler crystals, supermirrors, ^{3}He spin filters
- Spin flippers: Mezei, Tasset, RF adiabatic, etc.
- Zero-field polarimeters: Cryopad, MuPad

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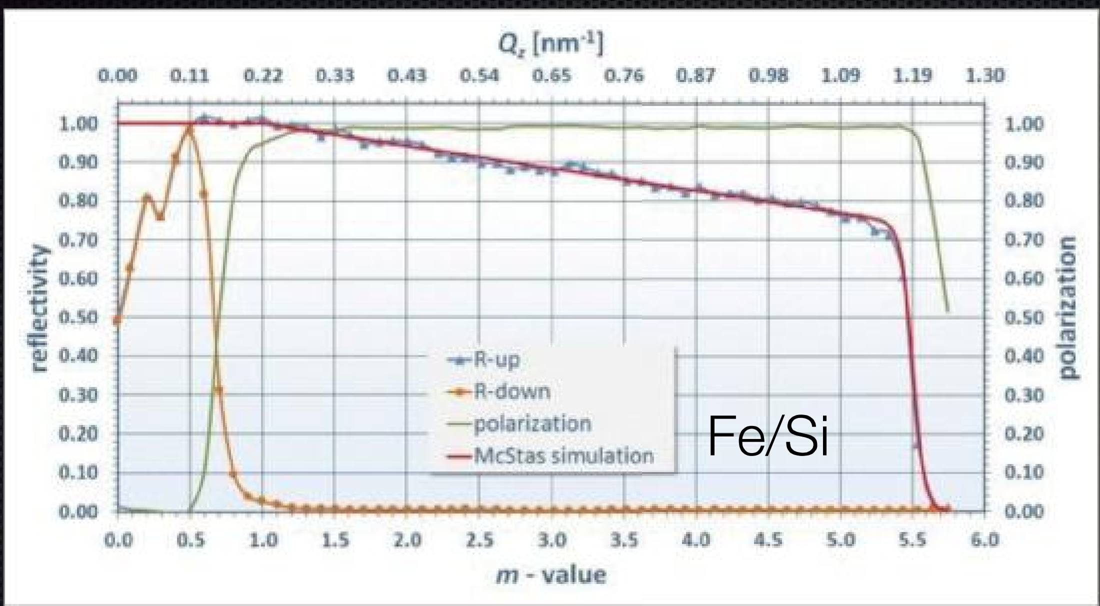
Polarising supermirrors



Swiss Neutronics

$$m = \theta_c/\theta_c^{Ni}, \quad \theta_c^{Ni} \approx 0.1°/\text{Å}$$

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Polarising supermirrors

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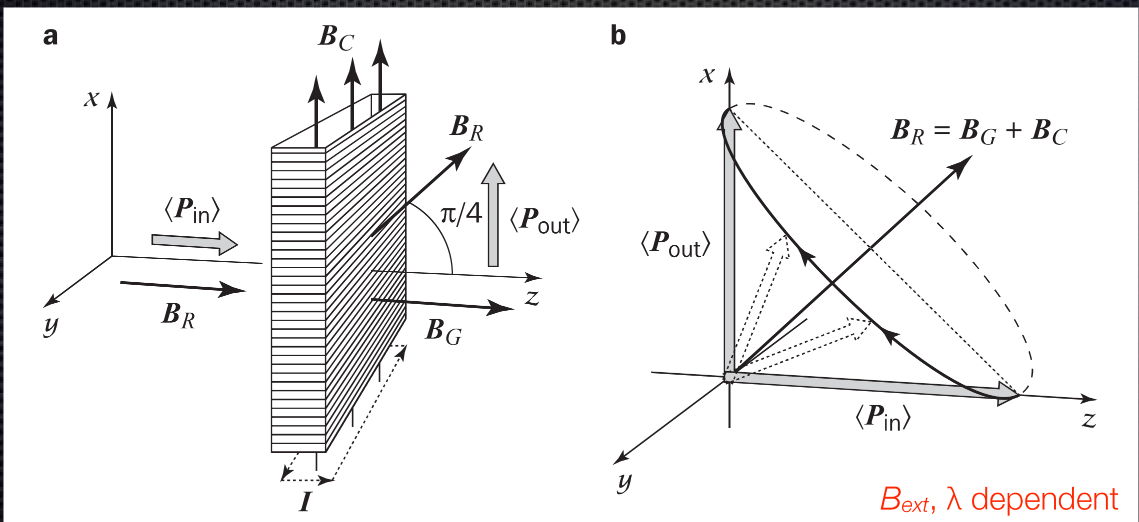
Spin flippers (Mezei)

- Example of a π/2 flipper: the neutrons enter and exit the coil non-adiabatically.



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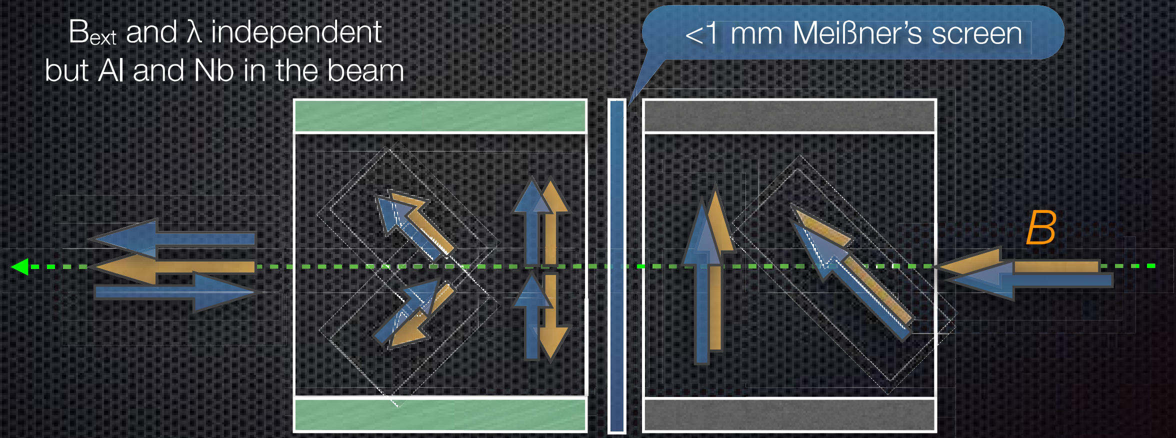
Spin flippers (Tasset)

- The neutrons enter the second coil non-adiabatically. Perfect flipper even in 400 Gauss stray field.

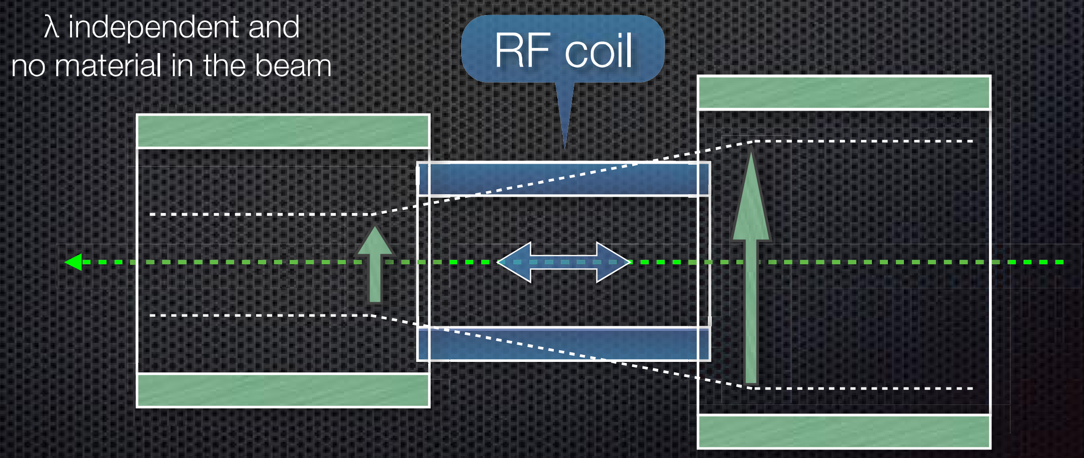


Spin flippers (Tasset)

- 99.9% efficient
- λ > 0.4 Å
- 10L liquid He
- 3 weeks He autonomy
- Al & Nb in beam
- To be cooled down in zero field !

Spin flippers (RF adiabatic)

- In the rotating frame of the neutron, the polarisation follows the effective field and rotates adiabatically.



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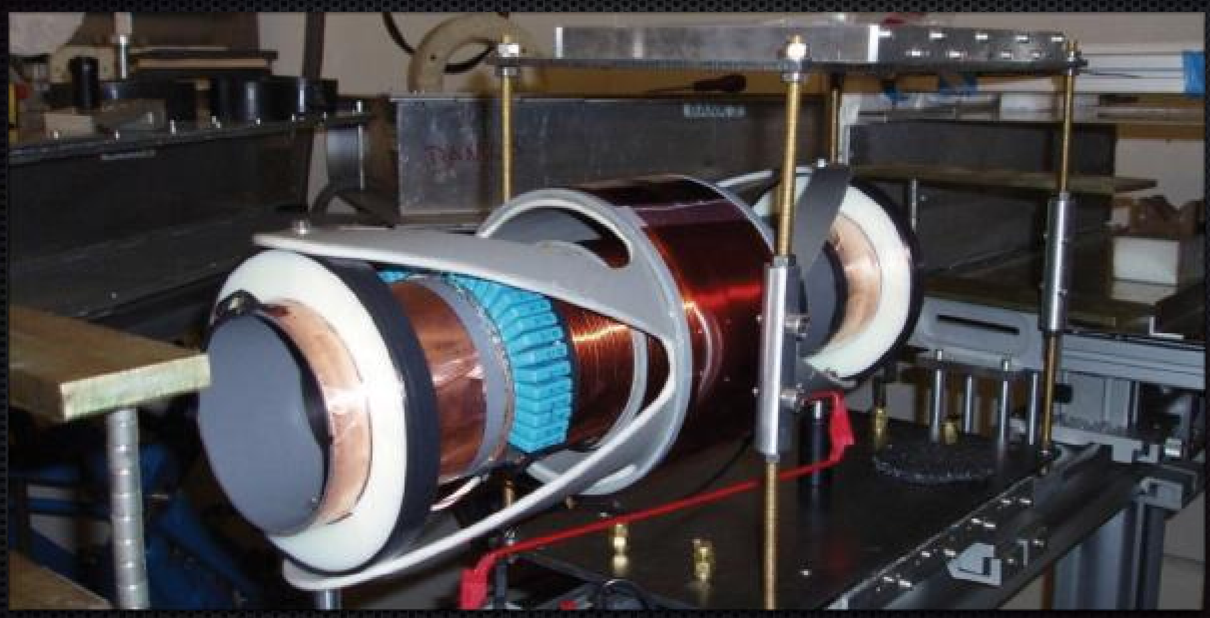
Spin flippers (RF adiabatic)



153 kHz/10 A adiabatic flipper for λ>0.4Å

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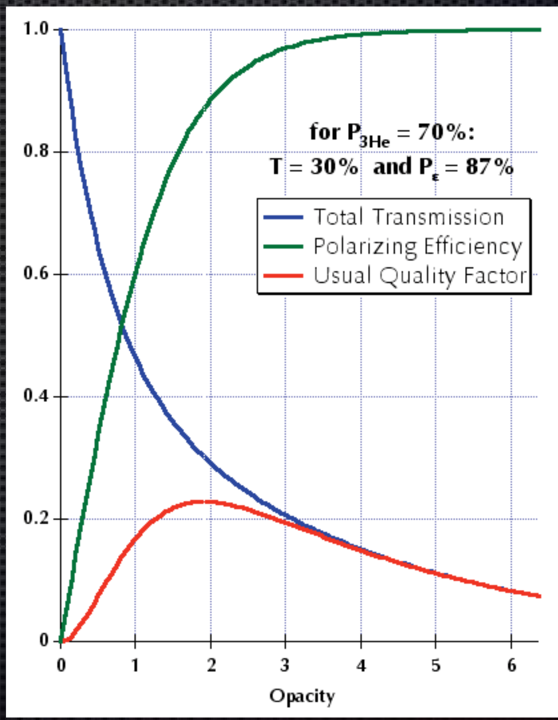
^{3}He spin filters

- Spin filters are characterised by their opacity:

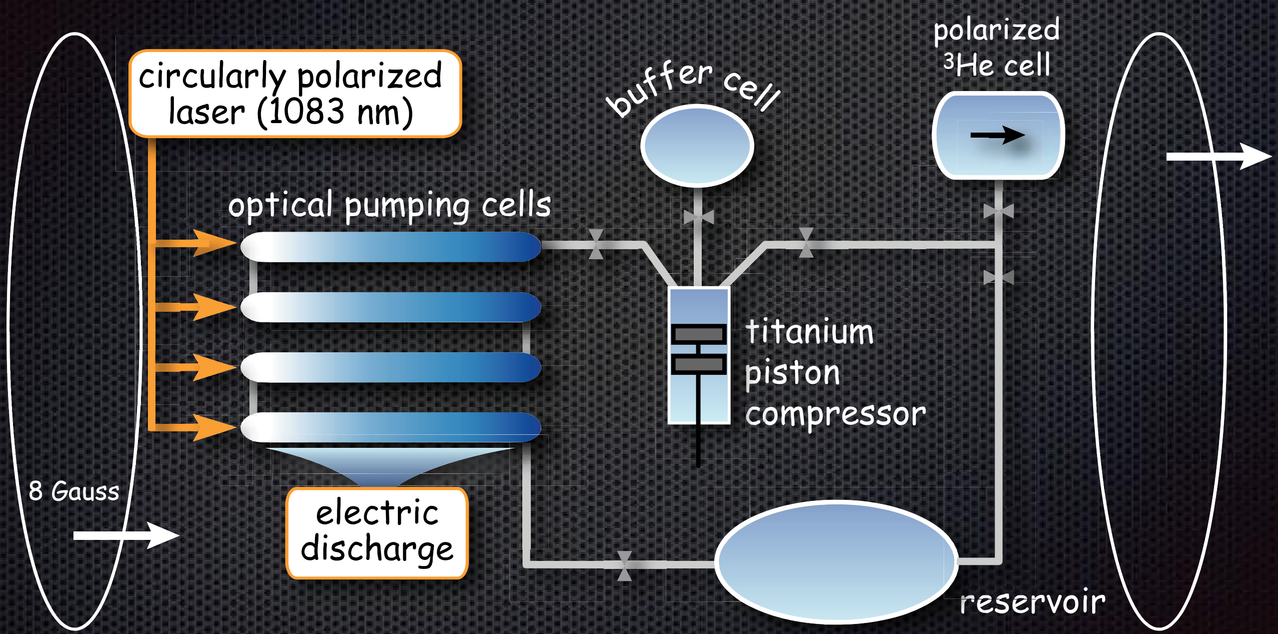
$$\mathcal{O} = N\,\ell\,\sigma_{\not\uparrow\!\uparrow}$$
$$\simeq 0.0797\; p[\text{bar}]\; \ell[\text{cm}]\; \lambda[\text{Å}]$$

- The total transmission and polarising efficiency are:

$$T_n \propto \cosh\left(\mathcal{O}P_{^3He}\right)$$
$$P_\epsilon = \tanh\left(\mathcal{O}P_{^3He}\right)$$



^{3}He spin filters



One way to polarise ^{3}He nuclei: metastable exchange optical pumping

^{3}He spin filters

MEOP station developed at ILL

^{3}He spin filters

- The main difficulty resides in the ability to build good cells and preserve the ^{3}He polarisation on the instrument:



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^{3}He spin filters

- The main difficulty resides in the ability to build good cells and preserve the ^{3}He polarisation on the instrument:

$$\frac{1}{T_1} = \frac{1}{T_{wall}} + \frac{1}{T_{field}} + \frac{1}{T_{dipolar}}$$

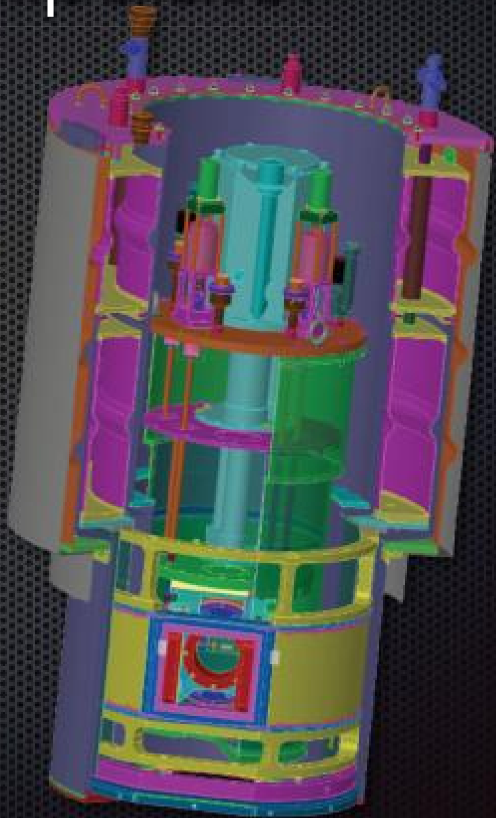
$$= \gamma \frac{S}{V} + \frac{14\,400}{p\,[\text{bar}]} \left(\frac{1}{B_0} \frac{\partial B_\perp}{\partial r_\perp\,[\text{cm}]} \right)^2 + \frac{p\,[\text{bar}]}{830}$$

$$\text{i.e. essentially } \frac{1}{B_0} \frac{\partial B_\perp}{\partial r_\perp} \ll 5 \cdot 10^{-4} \text{cm}^{-1}$$

^{3}He spin filters

Ø140 Si-windowed cell, pneumatic valve, permanent static field, flipper included.

Polarisation manipulator



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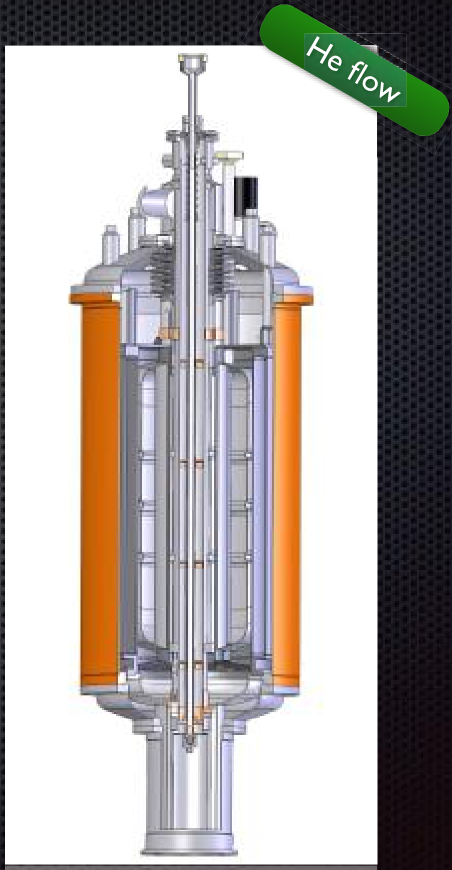
Cryogenics

- **Cryostats**

  1.5 / 2.8 to 320 K

- **Cryofurnaces**

  1.5 to 550 / 650 K



Cryogenics

- **Cryostats**

  1.5 / 2.8 to 320 K

- **Cryofurnaces**

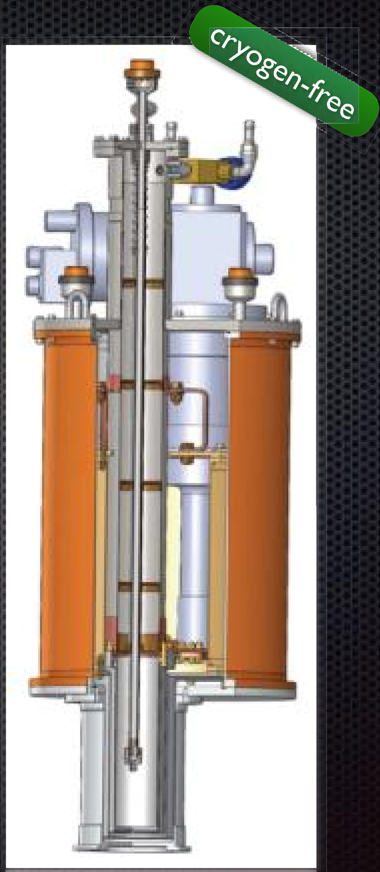
  1.5 to 550 / 650 K

- **Dry cryostats**

  1.8 to 320 K

Cryogenics

- **Cryostats**
  1.5 / 2.8 to 320 K
- **Cryofurnaces**
  1.5 to 550 / 650 K
- **Dry cryostats**
  1.8 to 320 K with JT
  2.7 to 620 K without JT
- **Goniometers, de-twining**



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Cryogenics

De-twinning crystals remotely inside cryostats

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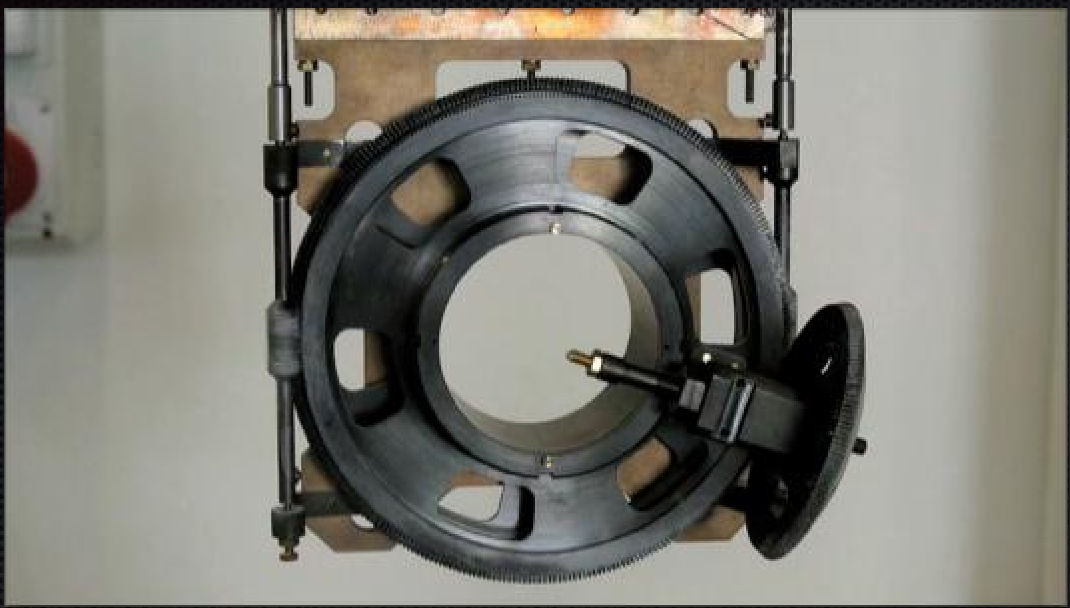
Goniostick

To orient samples in cryostats and cryomagnets



Cryocradle

To orient samples in polarimeters down to 3 K

Cryogenics

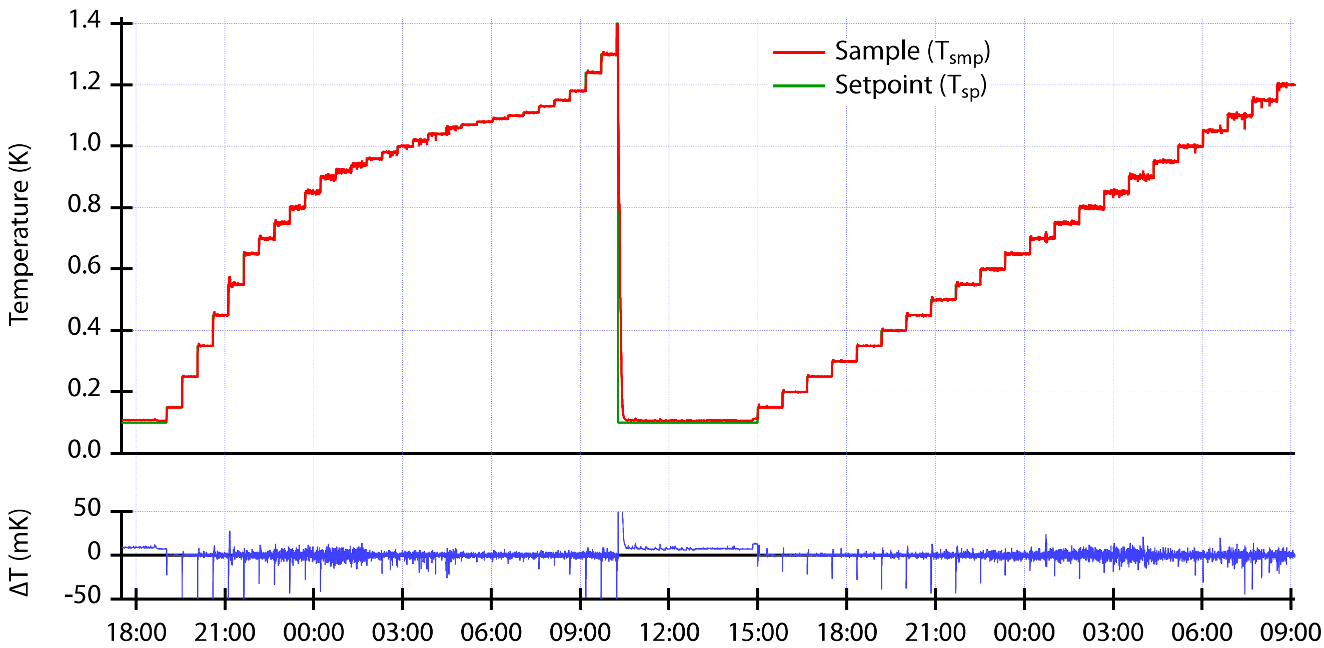
- **Dilution fridges**

  15 / 35 mK to 320 K

- **^{3}He fridges**

  350 mK to 320 K

Cryogenics



Cryogenics

- **Dilution fridges**

  15 / 35 mK to 320 K

- **^{3}He fridges**

  350 mK to 320 K

- **4-circle dilution fridge**

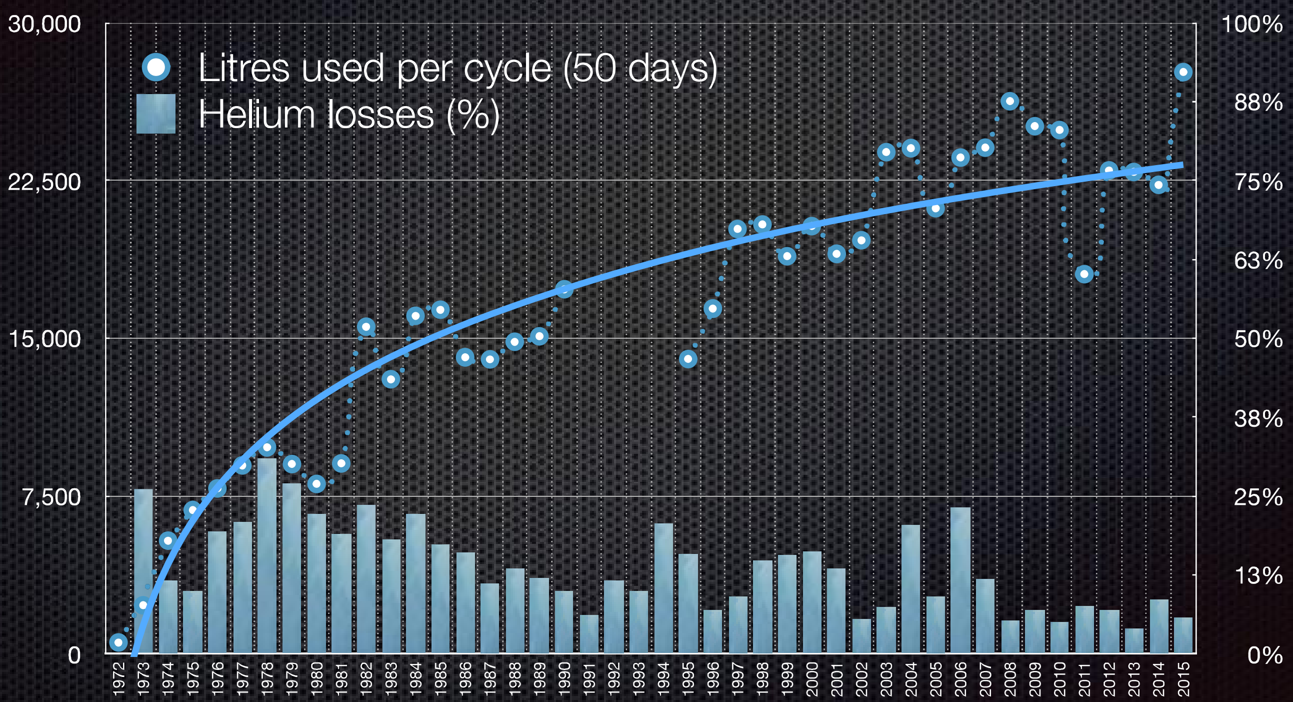
  100 mK closed-cycle

- **For large samples/pressure cells**

  Closed-cycle dilution cryostat

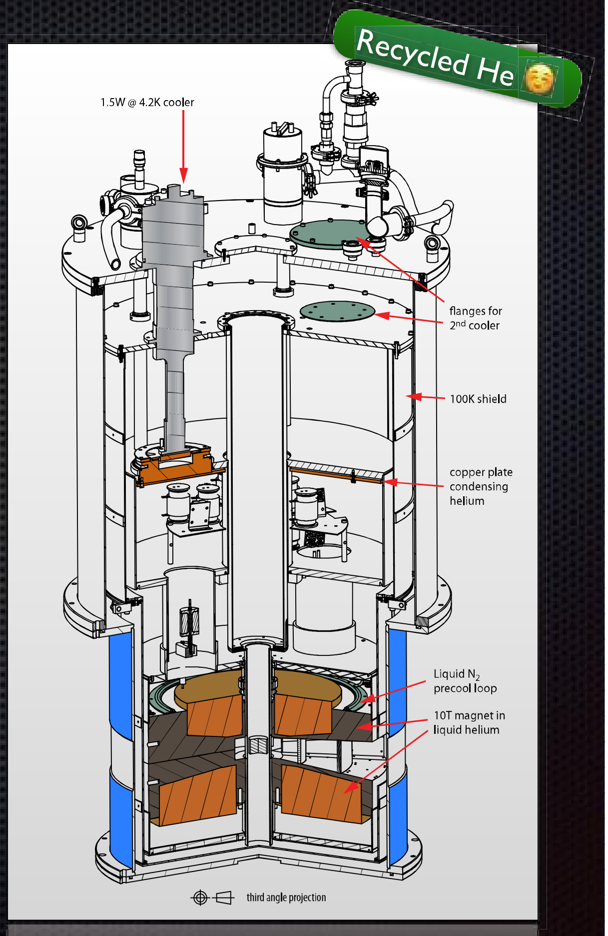
Cryogenics

It is worth recovering helium: ≈14 M€ saved since 1972



High B fields

- **Hor. field cryomagnets**
  - 17 T static — T > 100 mK
  - 40 T pulsed — T > 2 K
- **Vert. field cryomagnets**
  - 7 T with sapphire windows
  - 11 T with large openings
  - 15 T / 30 mK — 300 K
  - Zero-boil-off option



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High temperature

- **Standard furnaces**
  - 320 to 1900K
  - V, Nb resistors
  - Sapphire windows
  - mirror furnace
- **Automatic power racks**
- **Furnace for cradles**
- **Laser heating, levitation**

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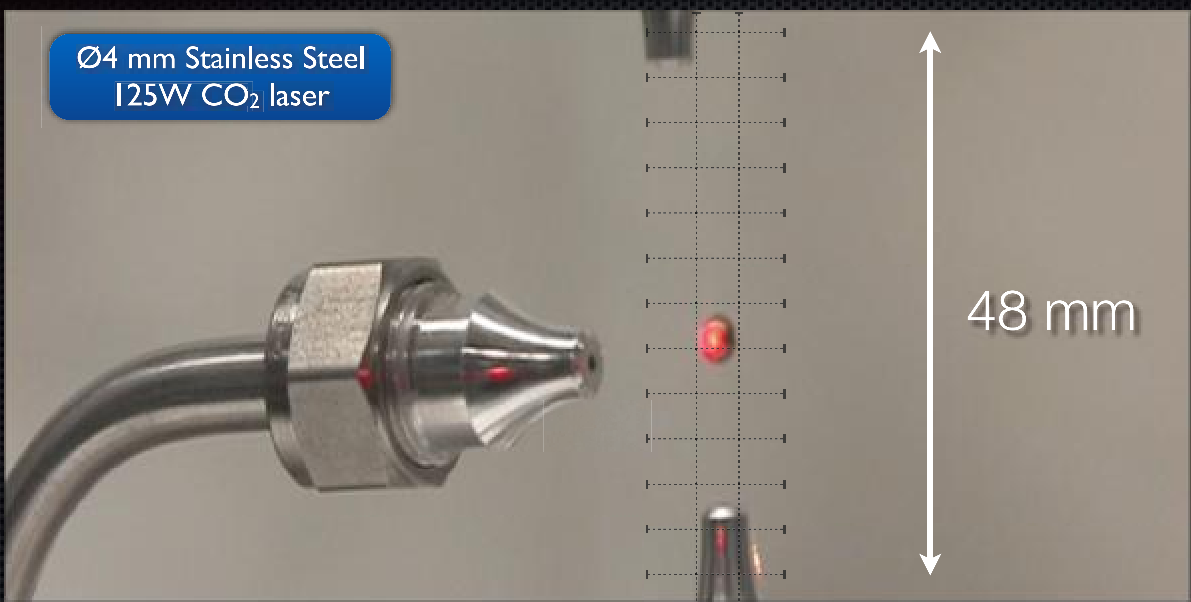
High temperature

- Standard furnaces
- Automatic power racks
- Furnace for cradles
  - 300 to 1100 K in 1h30
  - 30' to cool down to 650 K
  - 30' to replace the heater
- Laser heating, levitation



Aerodynamic levitation

Collaboration with CEMHTI, SIMAP and Soleil

High pressure

- Which materials can we use in the beam ?
  - Aluminium 7049A-T6: transparent but strong signal into detector above ΔE ≈ 5 meV
  - Hardened CuBe alloy: less signal above ΔE ≈ 5 meV but activates quickly in high flux beams
  - TiZr alloy: no Bragg peak but incoherent scattering
  - Sapphire: transparent but fragile
- Pressure transmitter: He, Fluorinert FC-770…

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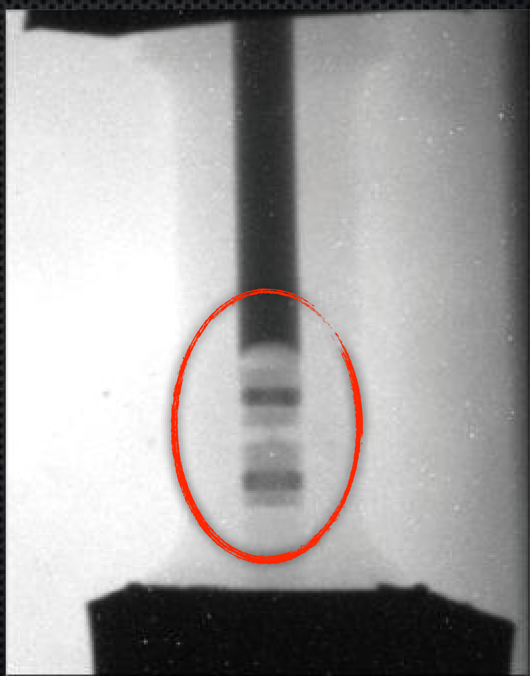
High pressure

- **Clamps (fluorinert)**
  1 to 3 GPa
- **Cells (liq. or gas)**
  0.5 to 25 GPa
  at 3 K in 7 hours
  Automatic control
- **Gas loading capability**



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High pressure

Collaboration with S. Klotz (IMPMC)

- **Clamps (fluorinert)**
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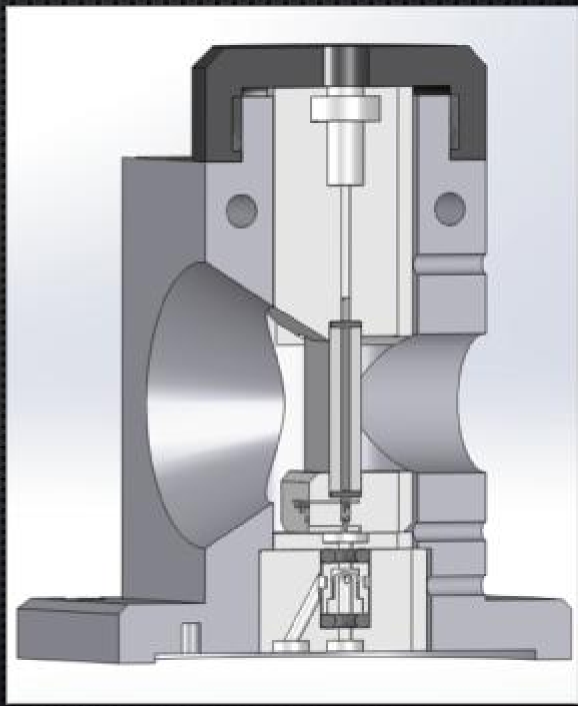
  Automatic control
- **Gas loading capability**

What else?

- Stopped-flow heads
- Liquid-liquid interface cells
- Humidity chambers
- High-pressure cells for bio
- Rheometers, E-field cells
- Adsorption troughs, etc.



Sample Environment…

- Stopped-flow heads
- Liquid-liquid interface cells
- Humidity chambers
- High-pressure cells for bio
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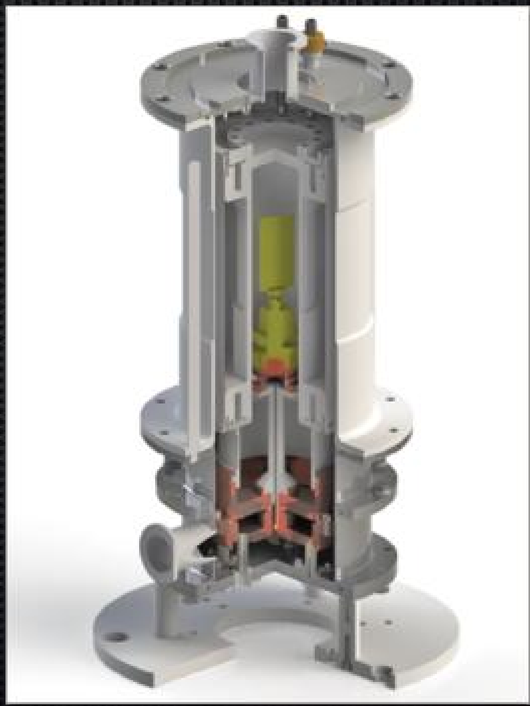

- What do we measure and need ?
  - Neutron source and guides
  - Measuring techniques
  - Energy selectors and polarisers
  - Sample environments
  - Neutrons detectors
  - Data acquisition system

Neutron Detectors

- We cannot directly detect slow neutrons: they carry too little energy and have no charge.
- We need to use nuclear reactions to convert neutrons into energetic charged particles.
- Then, we can use some of the many types of charged particle detectors

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Neutron Detectors

- Ionisation mode: Electrons drift to anode, producing a charge pulse with no gas multiplication. Typically employed in low-efficiency beam-monitor detectors.
- Proportional Mode: If voltage is high enough, electron collisions ionise gas atoms producing even more electrons. Gas amplification increases the collected charge proportional to the initial charge produced.
- Other techniques: CCD cameras, image plates (Laue), scintillation detectors (n + ^{6}Li → ^{4}He + ^{3}H + 4.79 MeV).

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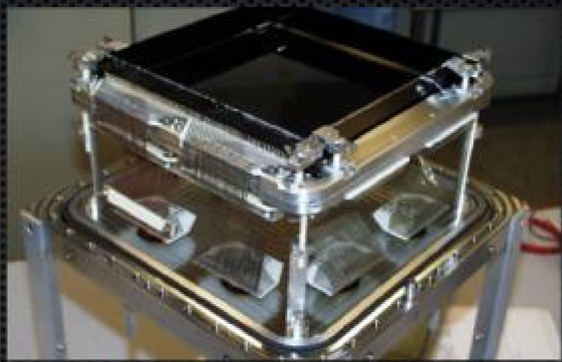
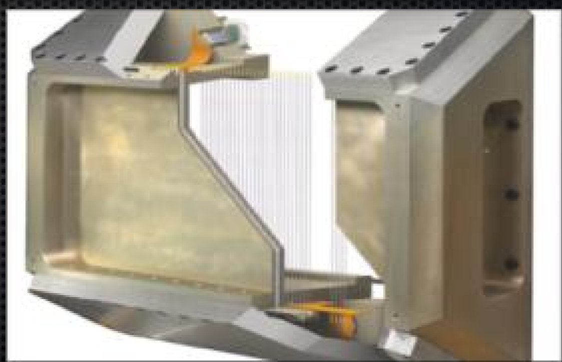
Neutron Detectors

- Spatial resolution is “generally” not an issue, in the range of 1 mm to 1 cm i.e. roughly the sample size
- Fast neutrons, electronics and gammas lead to background noise. Counting mode is more appropriate than integrating mode.
- High detection efficiency required for scattered neutrons, but low efficiency is enough for incident beam.

19x19 cm^2 high res, high count rate



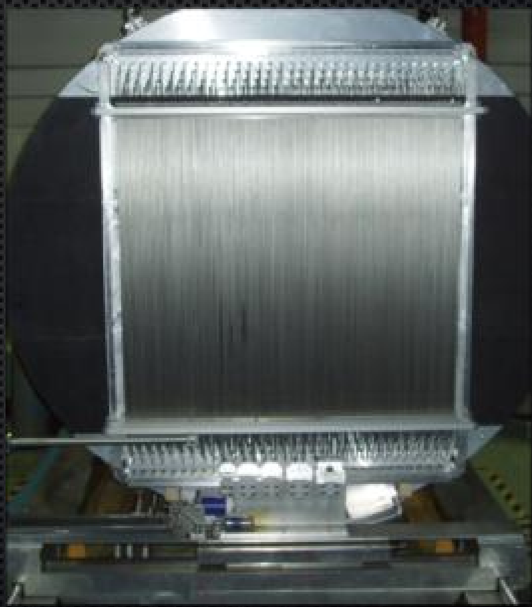


ToF: 30 m^2 low-res, low count rate

Reflect., SANS: Monobloc multitube

Neutron Detectors

Old XY counter — 200 kHz max.



New 128 PSD counter — x50 better

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  - Neutron source and guides
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  - Sample environments
  - Neutrons detectors
  - Data acquisition system

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Data acquisition system

- Speaks in physical units, ranges with physical entities
- Acts as a super-calculator for the local contact to access complex instrument's configurations
- Provides performance optimiser for fine adjustments or advanced regulations
- Checks jobs, estimates run-time, execute jobs safely
- Also provides command-line tools, remote access, etc.

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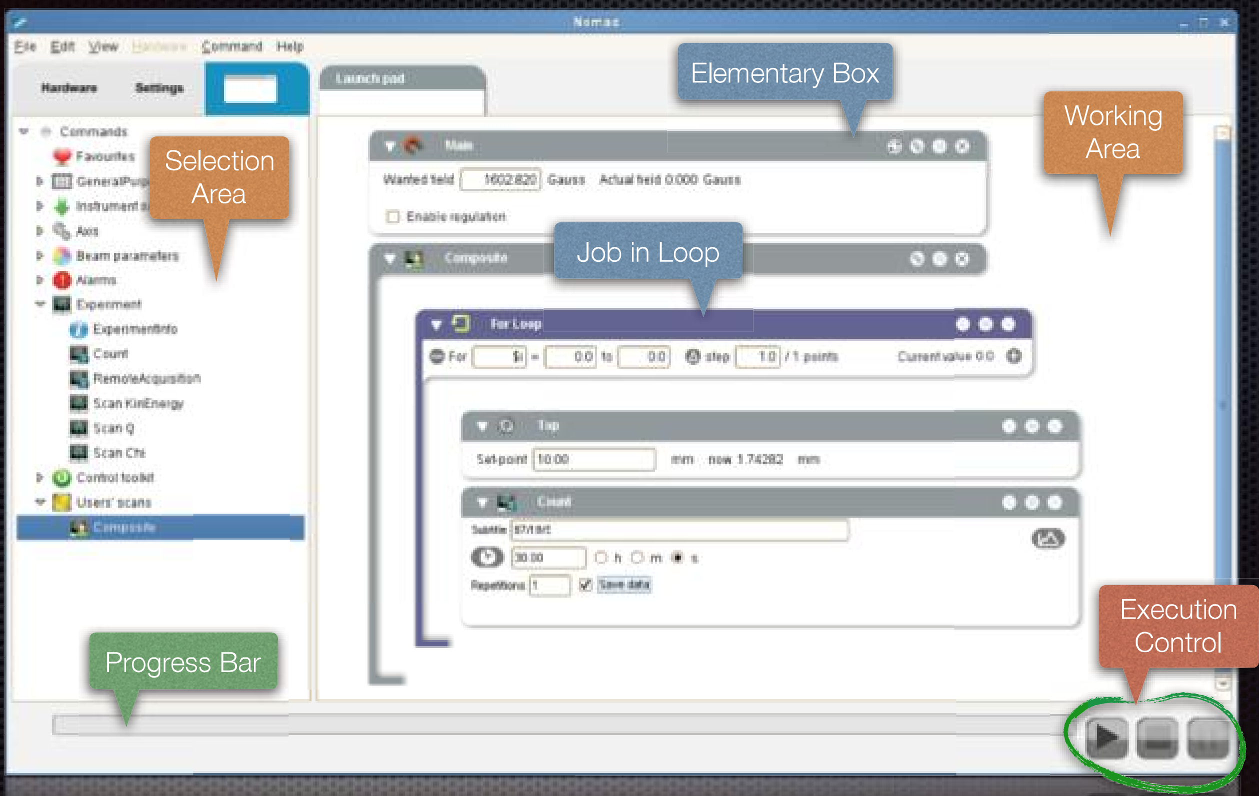
Data acquisition hardware

- VME crates (low power)
- NIM crates (high power)
- Power supplies for DC and stepper motors, flippers, guiding fields, etc.
- Sample env. controllers



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M. Kreuz — Neutron Guides, ILL
P. Mutti — Instrument control, ILL

european photon & neutron science campus

NEUTRONS FOR SCIENCE

Thank you for your attention