Neutron Instrumentation

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Neutron instrumentation

- What do we measure and need ?
- Neutron guides & shielding
- Measuring techniques
- Sample environments
- Neutrons detectors
- Data acquisition system

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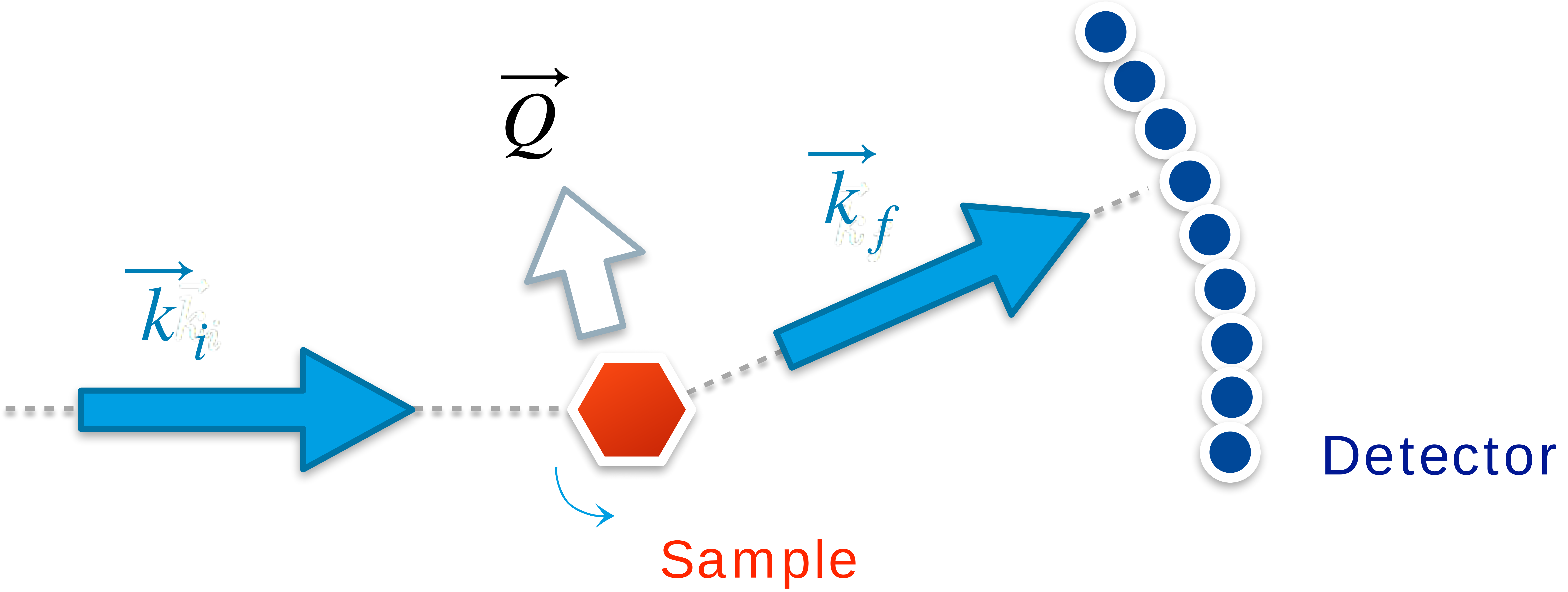
What do we measure ?

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

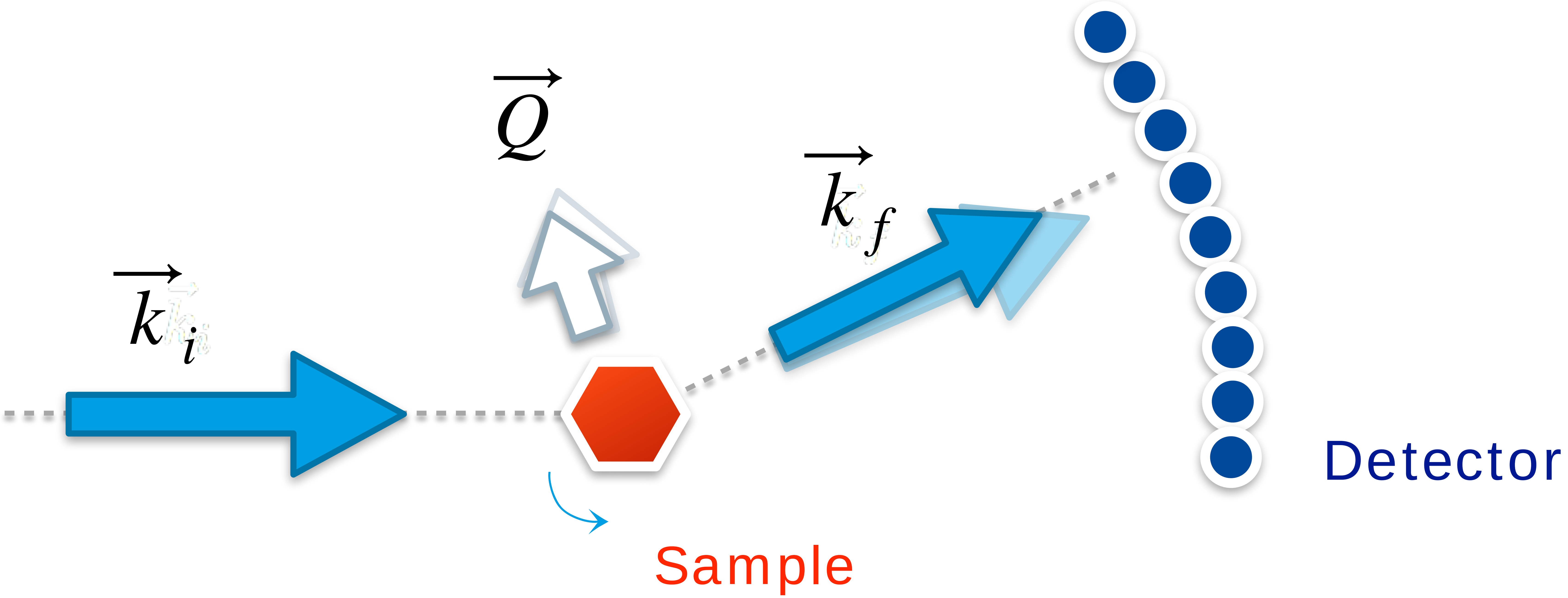


Intensity vs wave-vector transfer

$$\vec{Q} = \vec{k}_f - \vec{k}_i$$

What do we measure ?

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

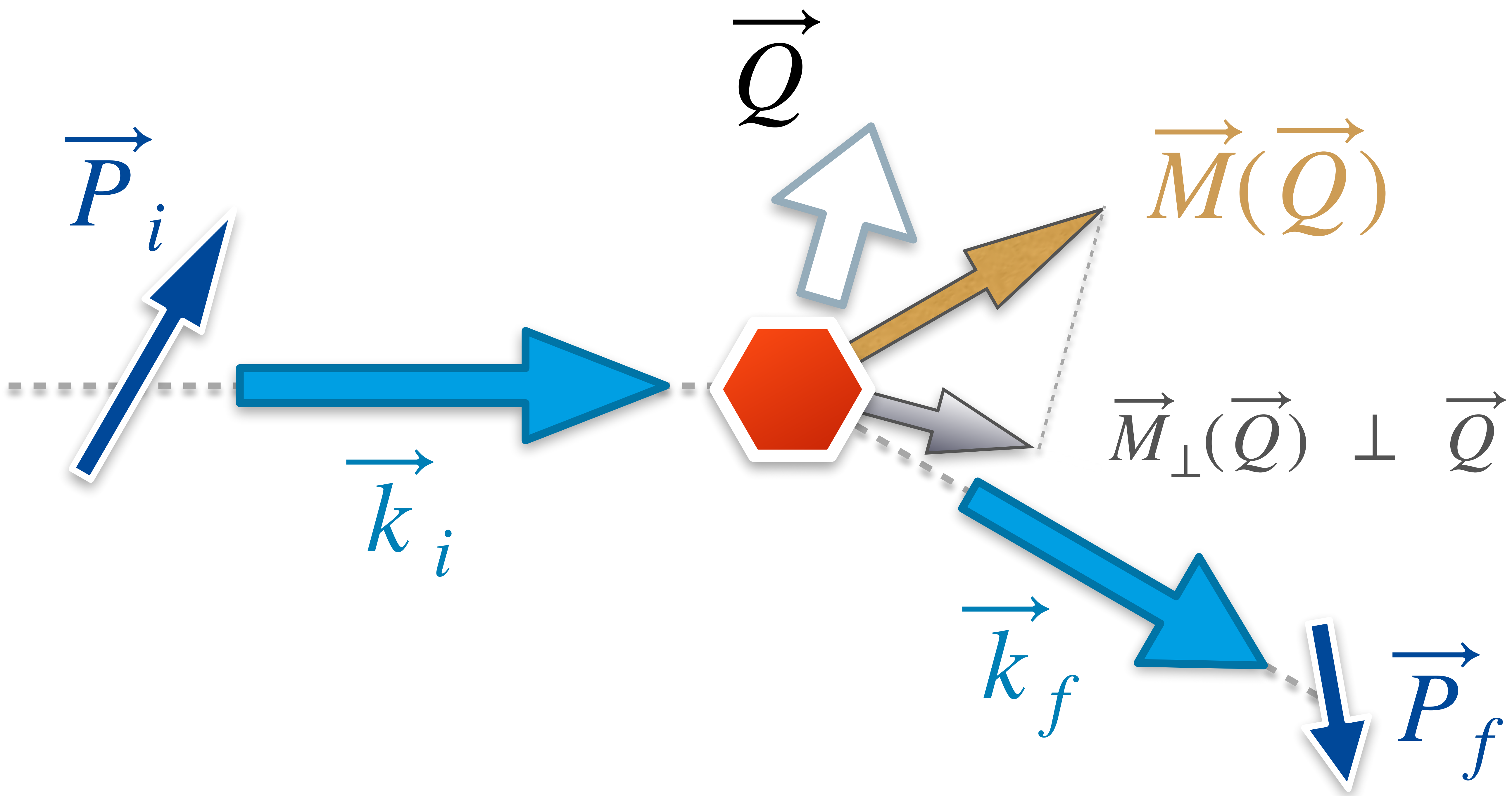


Intensity vs wave-vector & energy transfer

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

What do we measure ?

Polarised neutron scattering



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

- We measure intensities:

$$I\,(\overrightarrow{Q}, \overrightarrow{P}_i, \hbar\omega) \quad \text{where} \quad \overrightarrow{Q} = \overrightarrow{k}_f - \overrightarrow{k}_i,\ \hbar\omega = E_f - E_i$$

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

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

So what do we need ?

- Control the incident (scattered) energies or λ
  - ↳ Monochromators, choppers, analysers, Larmor labelling...
- Control the incident and scattered beam directions
  - ↳ Collimations, encoded shafts, Tanzboden, slits...
- Control the incident (scattered) beam polarisations
  - ↳ Monochromators, analysers, supermirrors, spin filters & flippers...
- Count neutrons with monitors and detectors

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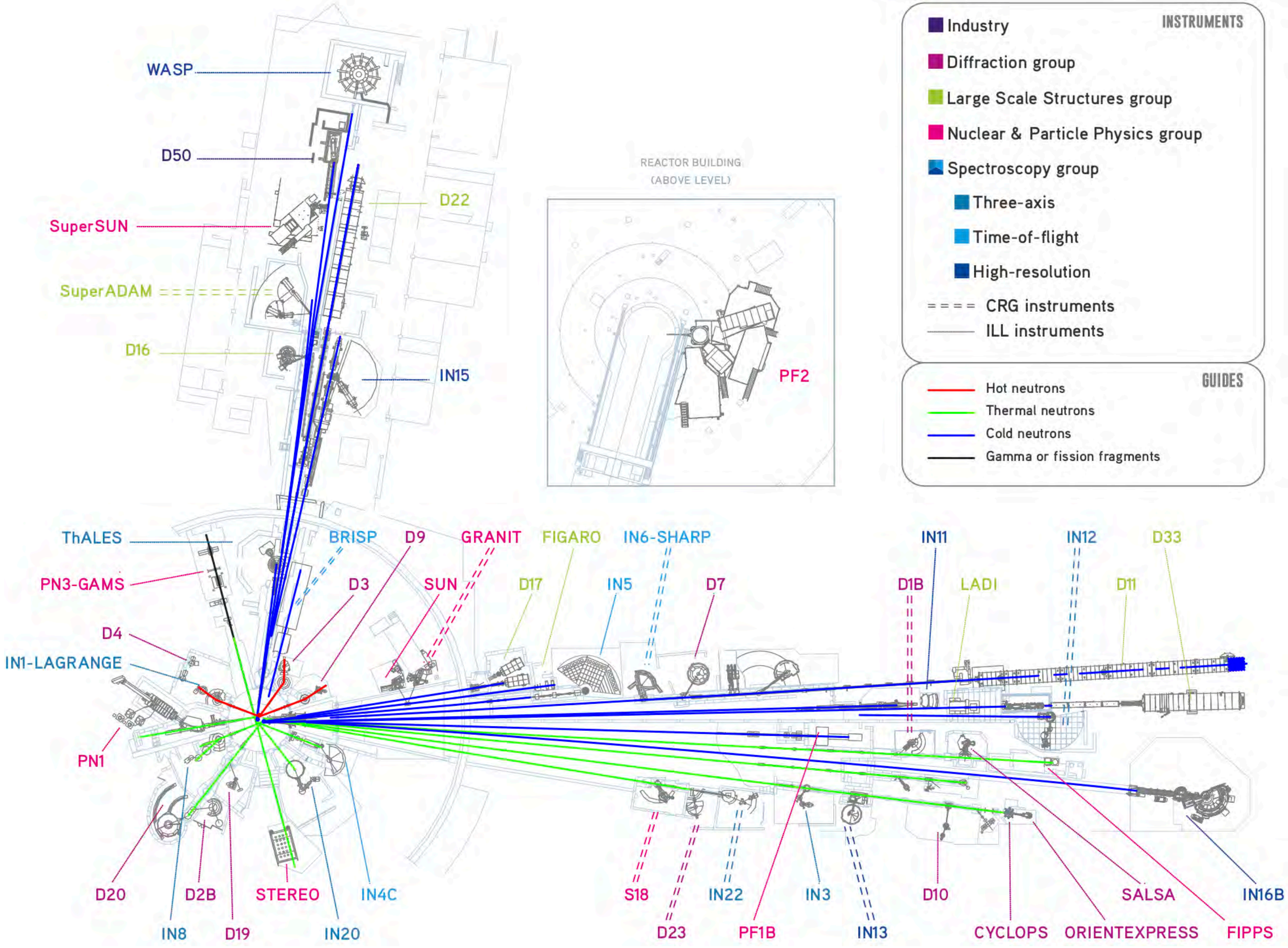
Guides

Constructibility

- A real instrument has to fit in a real space, and it will never be large enough!
- thermal, cold, hot neutrons?
- wide-band, monochromatic?
- divergence, etc.?

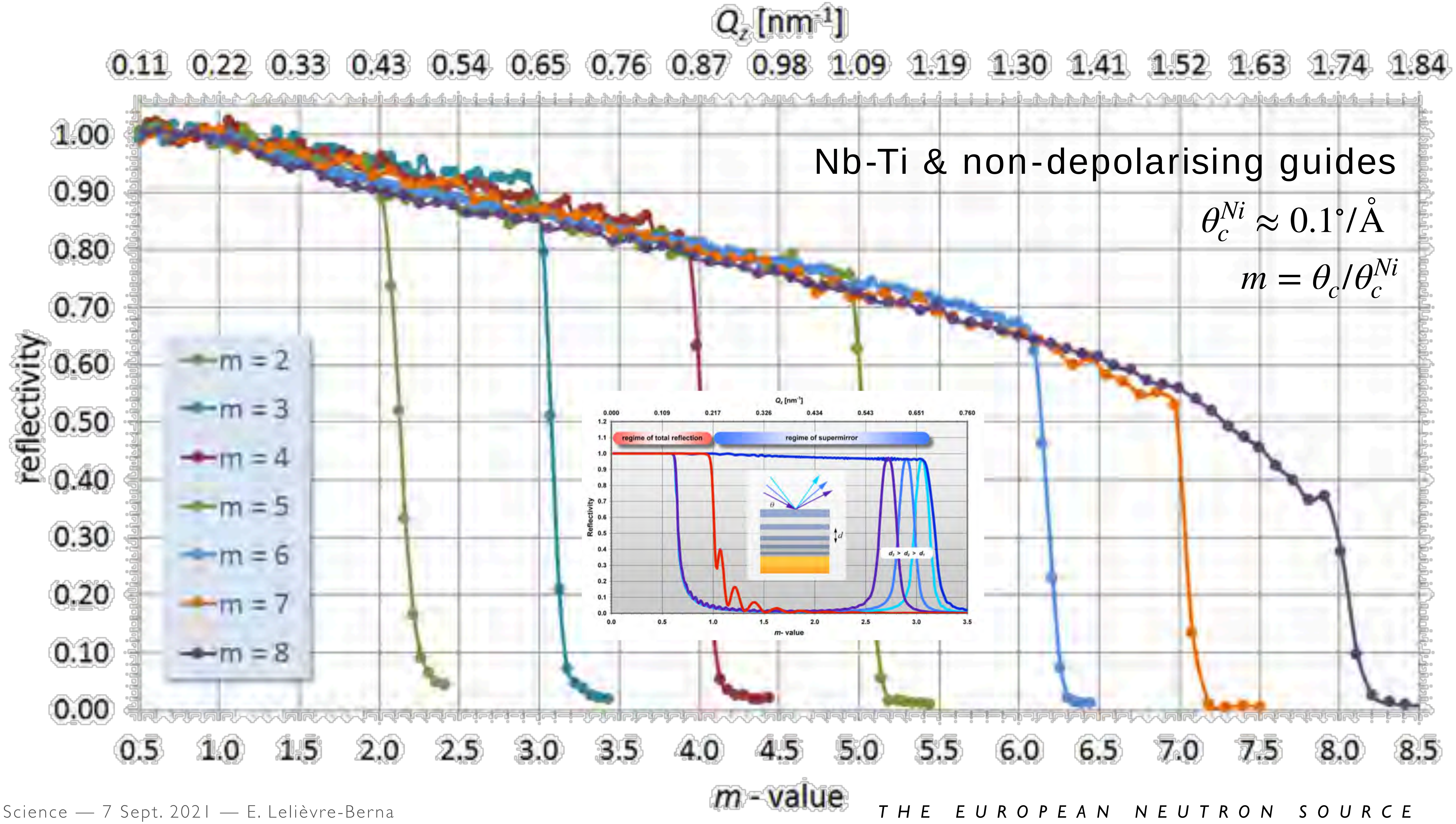


Neutron guides

- A guide is made up of sections joined together
- Glass is cheap and sufficiently thick to hold the vacuum
- Curved guides can eliminate fast neutrons ($R \approx \mathrm{km}$)
- Guides can split, focus, collimate, polarise…

Neutron guides

E.g. supermirrors from Swiss Neutronics



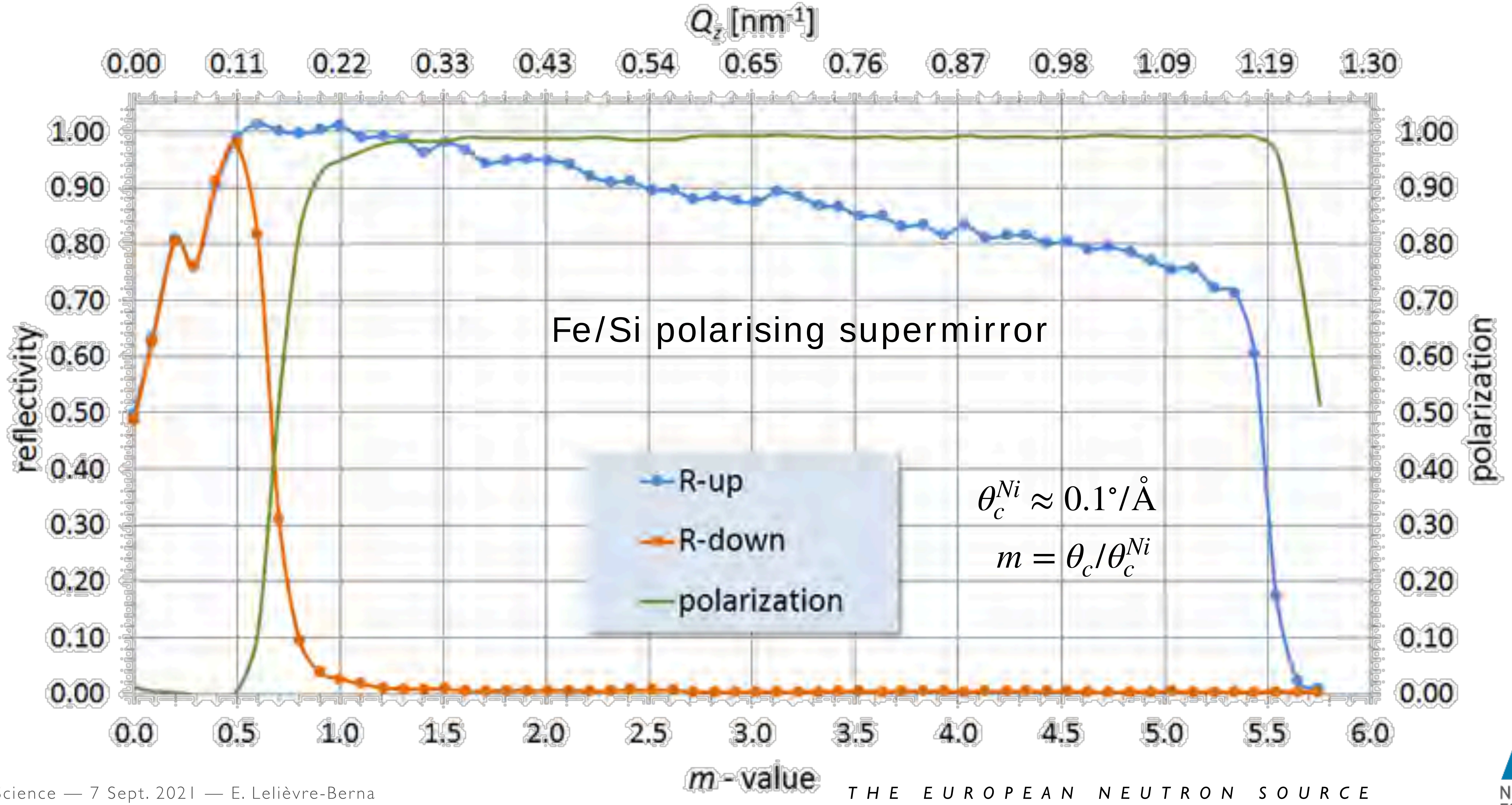
Nb-Ti & non-depolarising guides

$$\theta_c^{Ni} \approx 0.1°/\text{Å}$$

$$m = \theta_c / \theta_c^{Ni}$$

Neutron guides

E.g. supermirrors from Swiss Neutronics



Neutron guides

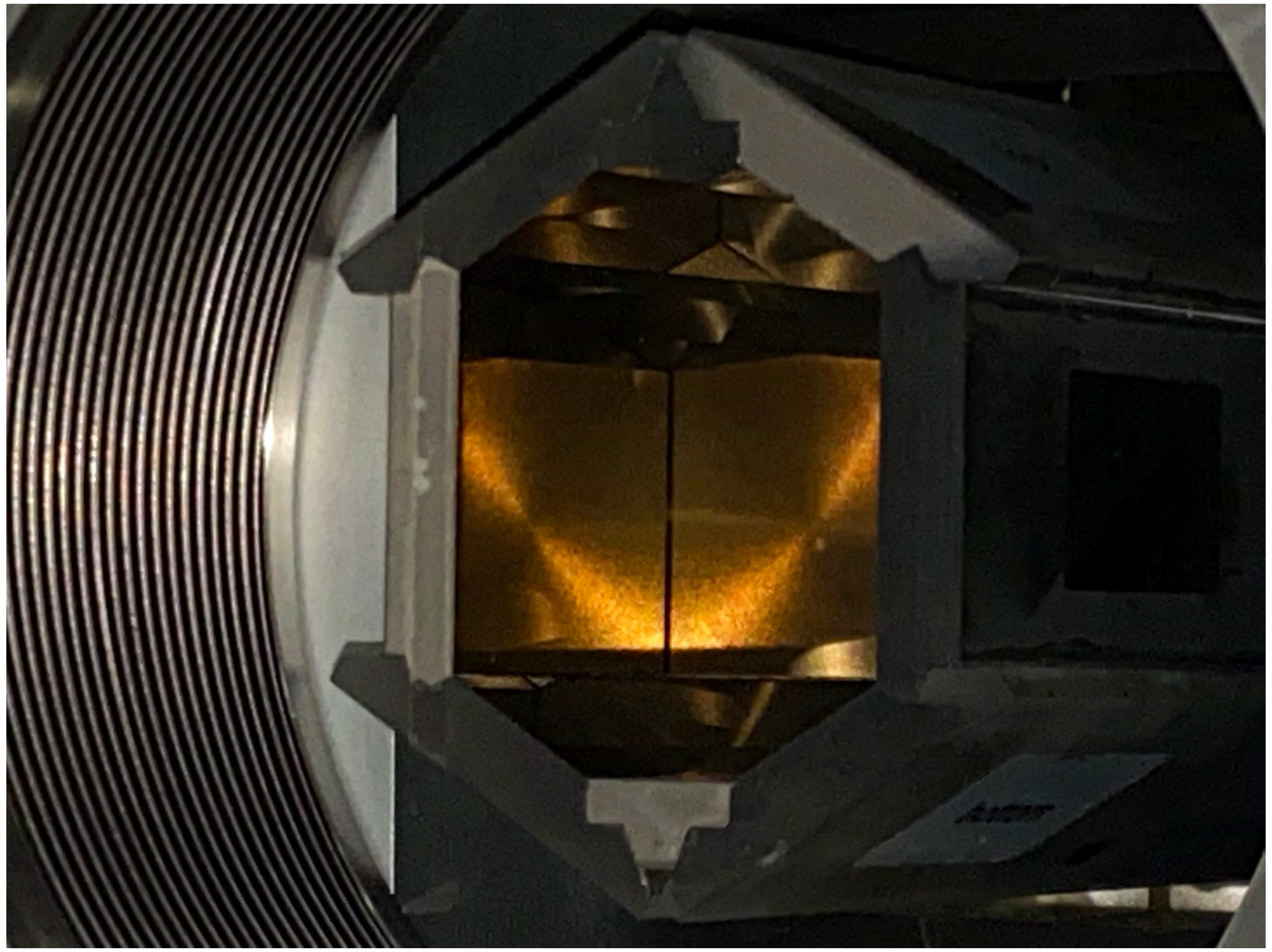
H5 installation in 2014 at ILL

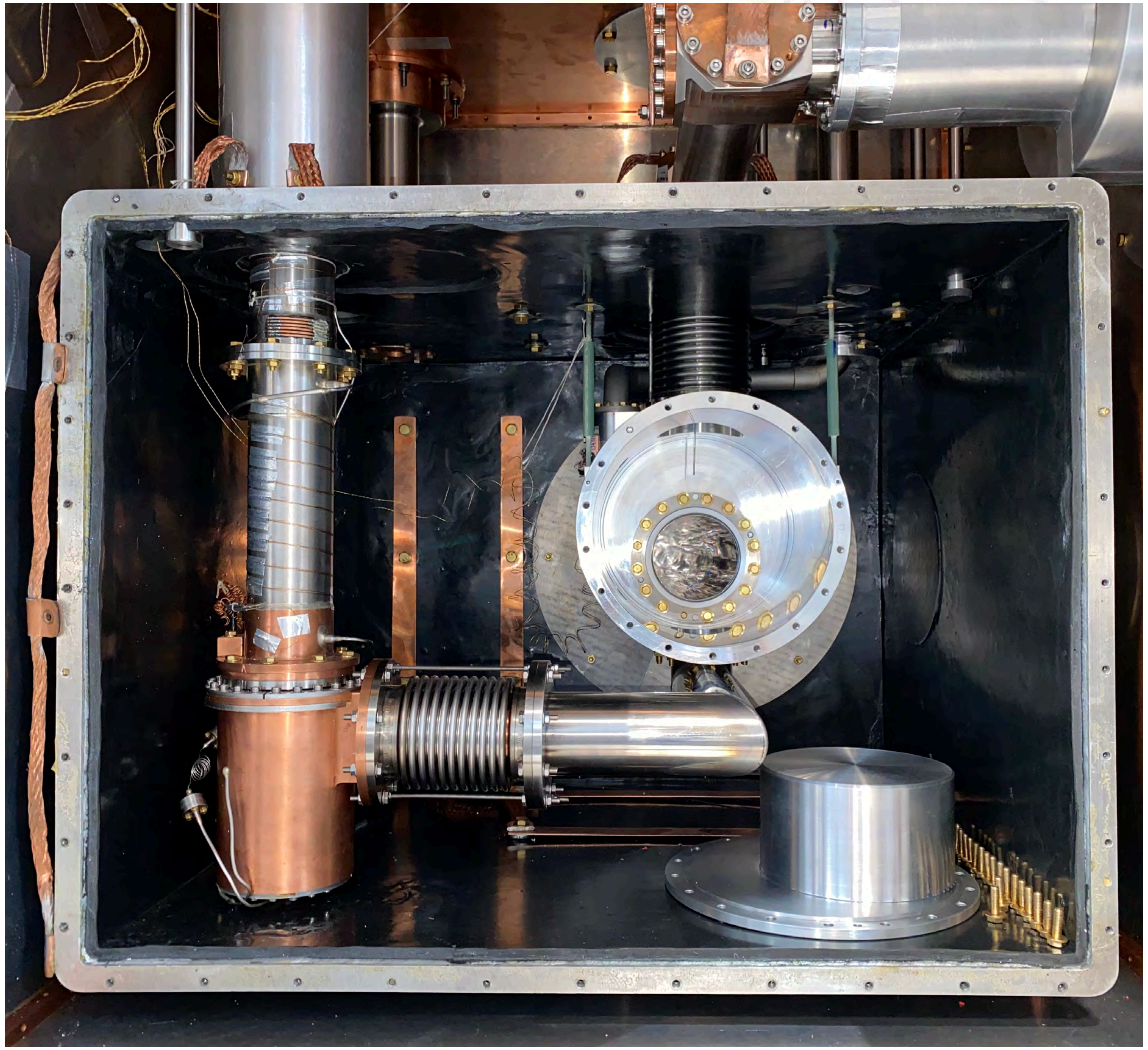
S-DH GmbH

Neutron guides

of the UCN source in 2021 at ILL

S-DH GmbH

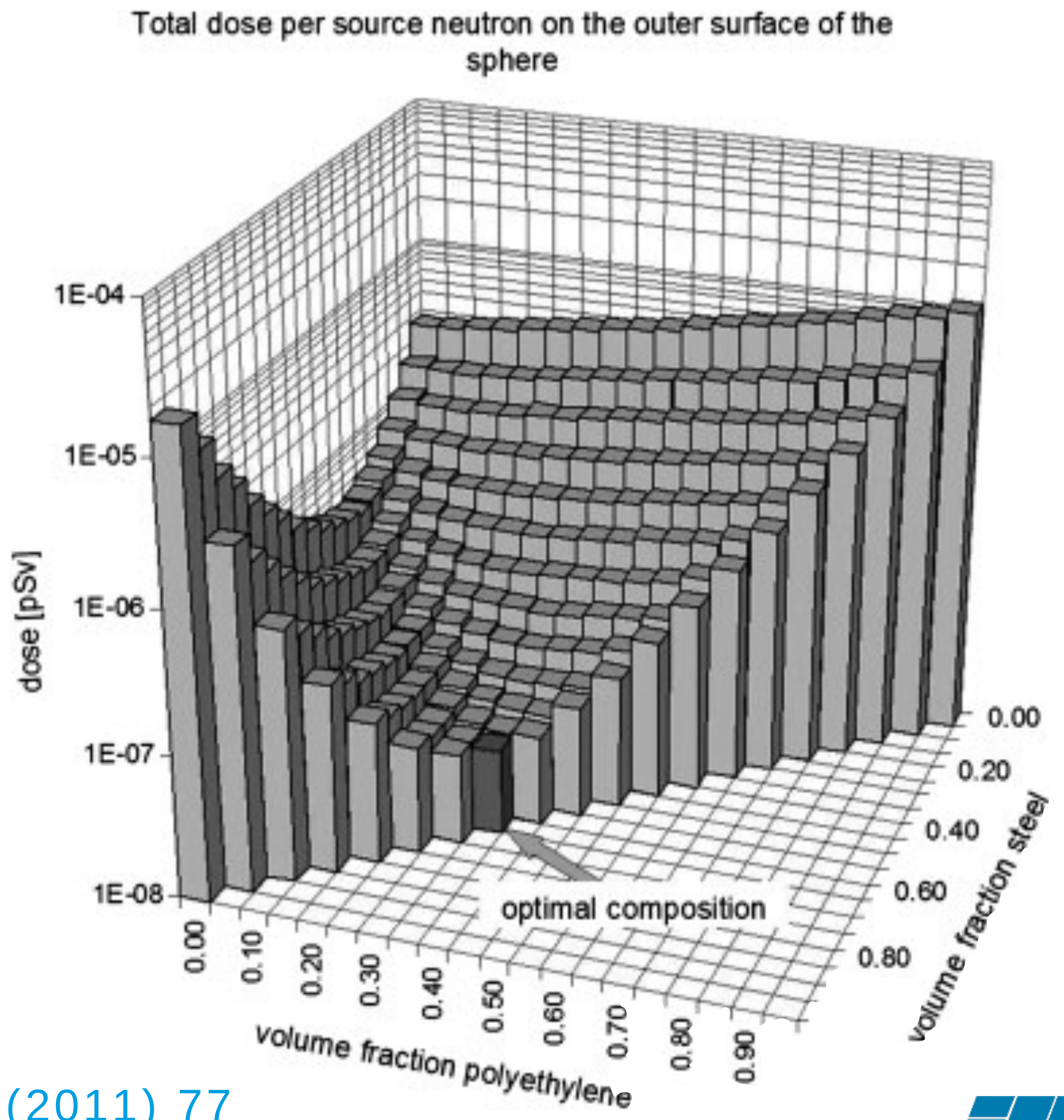




Shield against neutrons & gammas

- Hydrogeneous
  - concrete, wax, polyethylene
- Boron, ^{6}Li, Cd, Gd/GdO
- Lead, Iron (soft steel)

- Number of collected neutrons x25 since 2000 at ILL. The shielding efficiency must continuously be improved to save space!



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

Neutron guides & shielding

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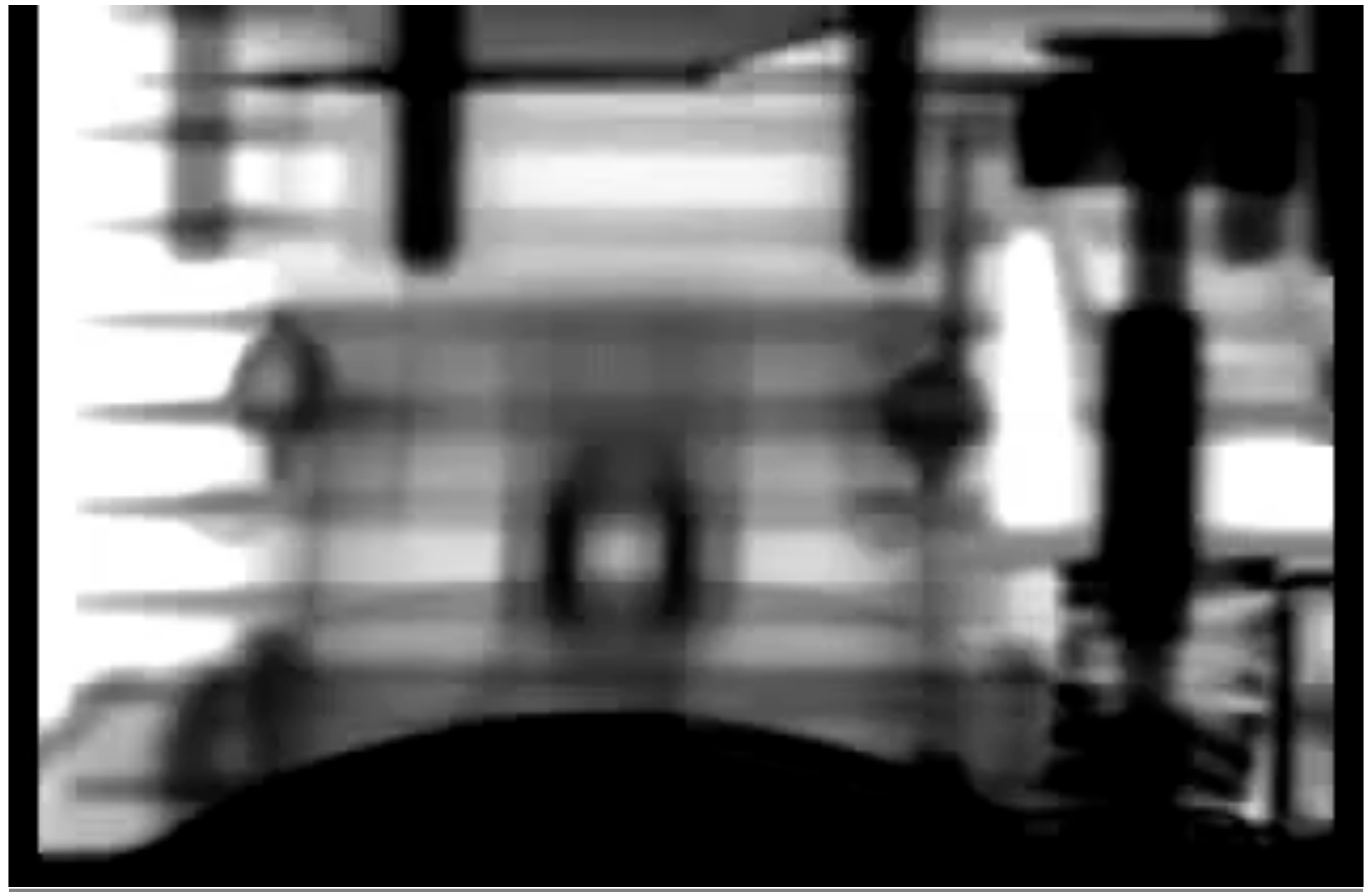
Measuring techniques

Neutronography

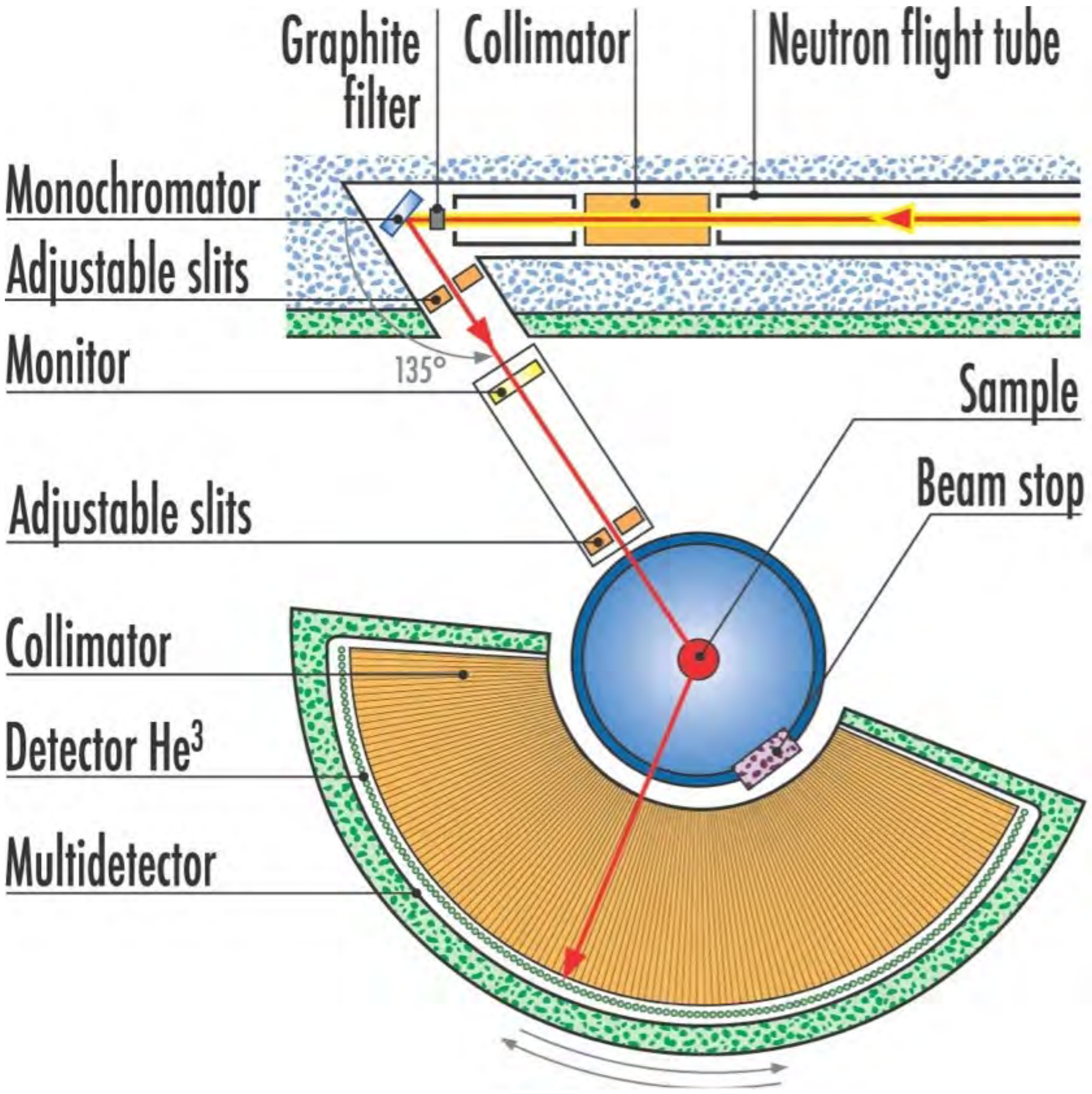


5 µm resolution — complementary to x-rays

Measuring techniques

Elastic scattering

- Powder diffraction
  - collimator, filter
  - focusing monochromator
  - (spin polariser)
  - slits, monitor
  - collimators
  - detectors



Measuring techniques

Monochromators

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

Ø80x300 mm³ Cu crystal

Bridgman furnace

Heusler (Cu_2MnAl) polarising crystal

Measuring techniques

Monochromators

- Array of single crystals
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  - Cu, Si, HOPG, Heusler, Diamond…
  - Flat, focusing vertically and/or horizontally
  - Optimised mosaic

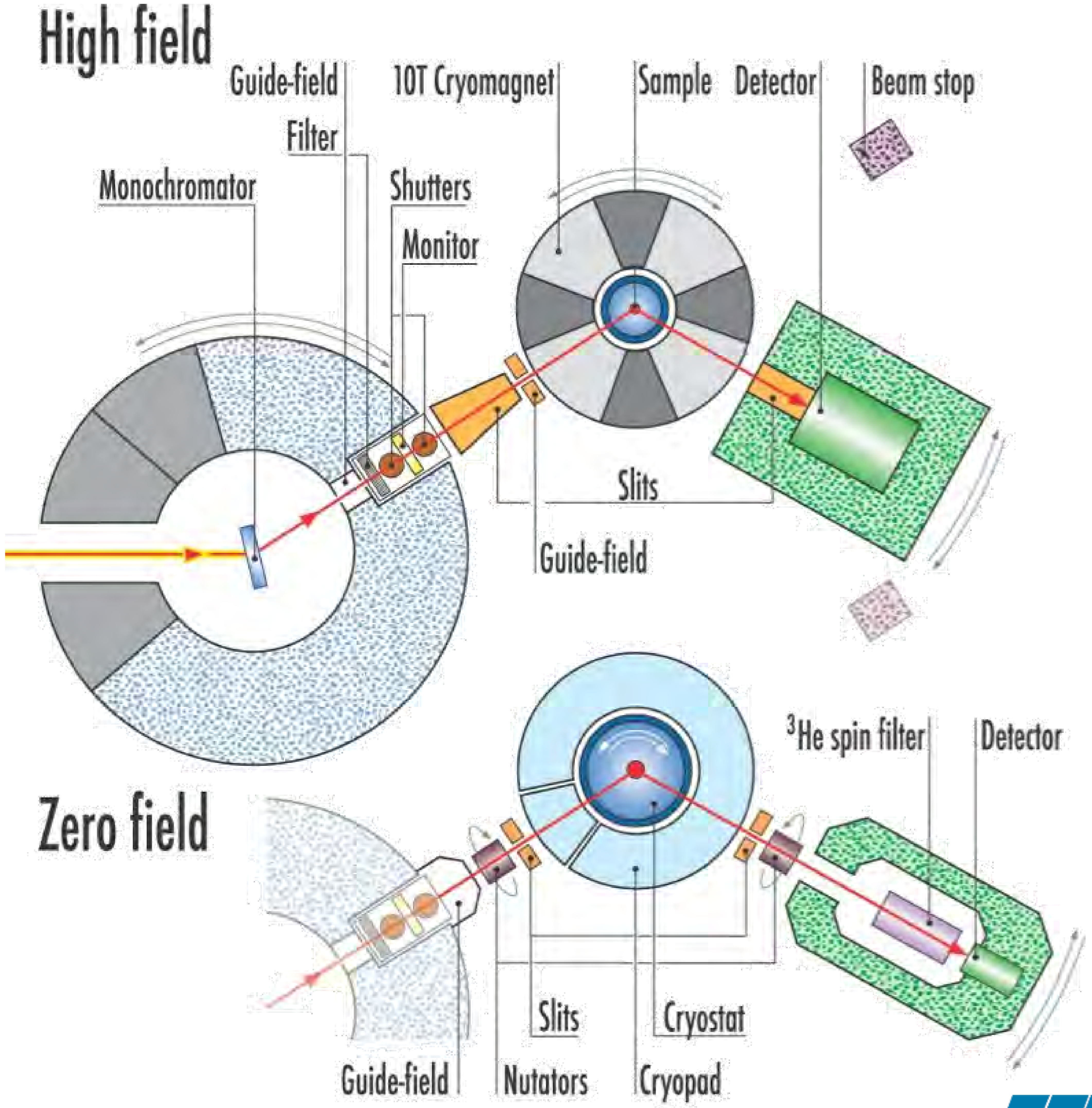
IN8 doubly-focusing monochromator

D20 vertically focusing Cu monochromator

Measuring techniques

Elastic scattering

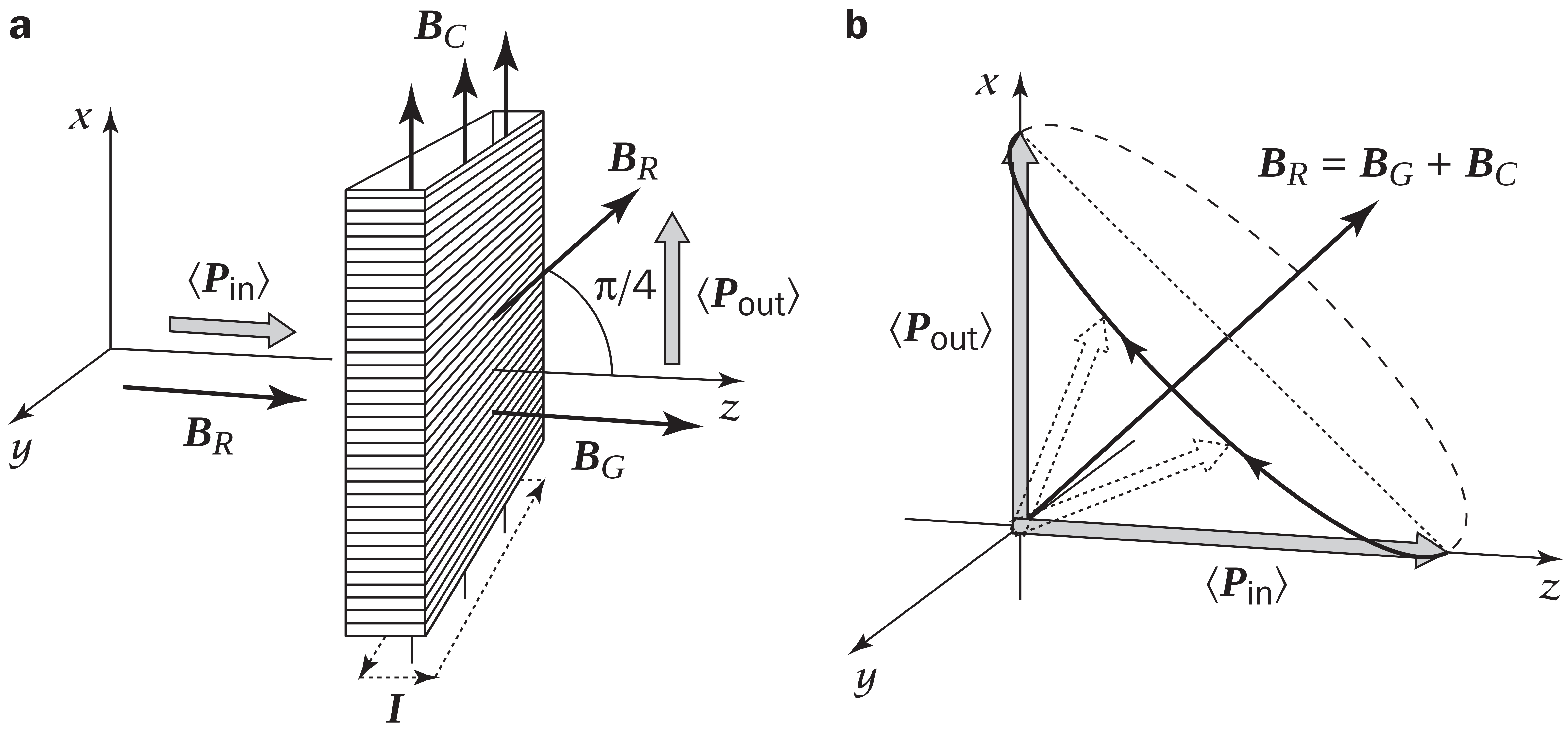
- Crystal diffraction
  - (polarising) monochromator
  - harmonic filters
  - monitor, (spin flipper)
  - collimation, slits, (cradle)
  - (polarimeter & spin analyser)
  - single or PSD detector



Measuring techniques

Spin flippers

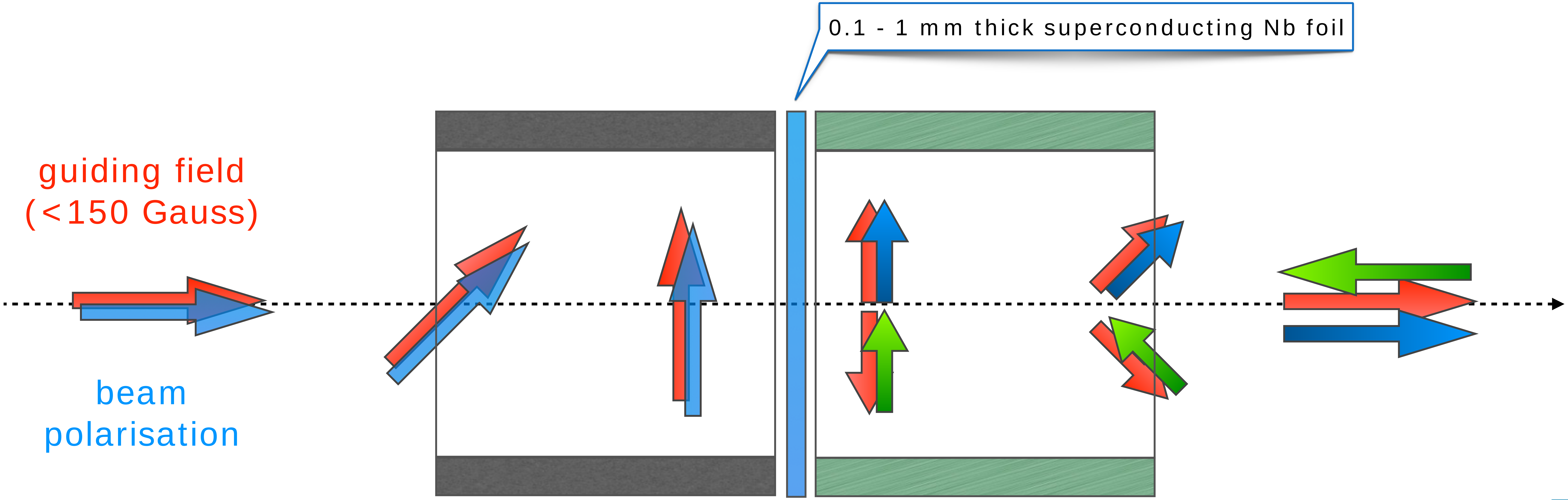
- Mezei’s flipper: sensitive to environmental magnetic fields, neutron wavelength dependent, for cold and thermal neutrons only



Measuring techniques

Spin flippers

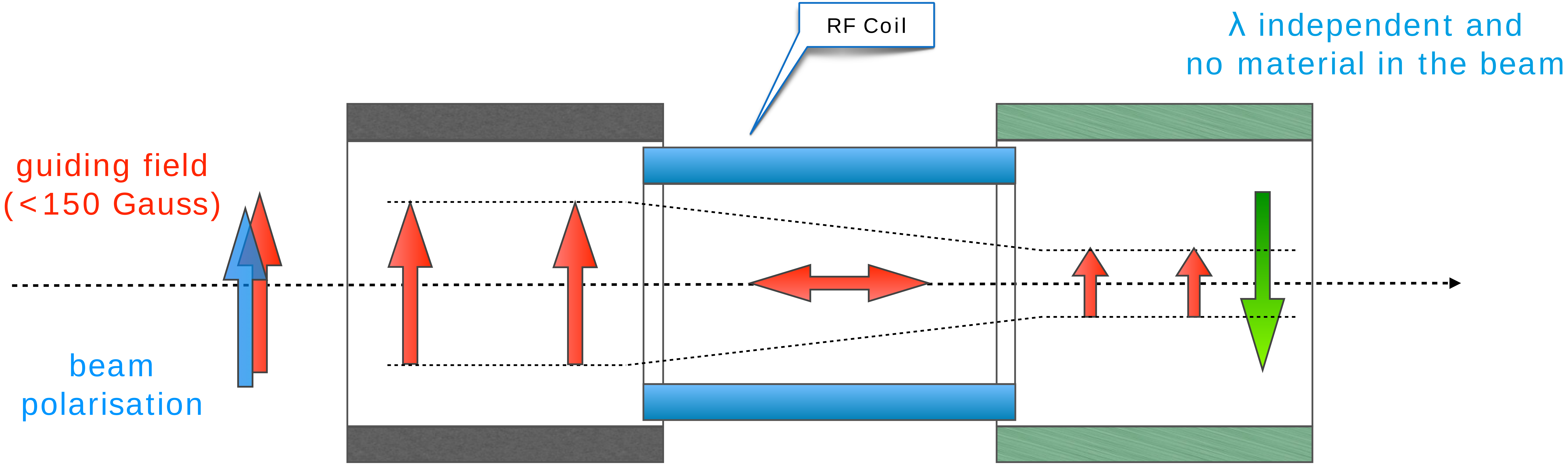
- Cryoflipper (Tasset's flipper): neutron wavelength independent, 99.9% efficiency down to 0.3 Å, operates in up to 400 G stray fields



Measuring techniques

Spin flippers

- RF flipper: in the rotating frame of the neutron, the polarisation follows the effective field and rotates adiabatically.



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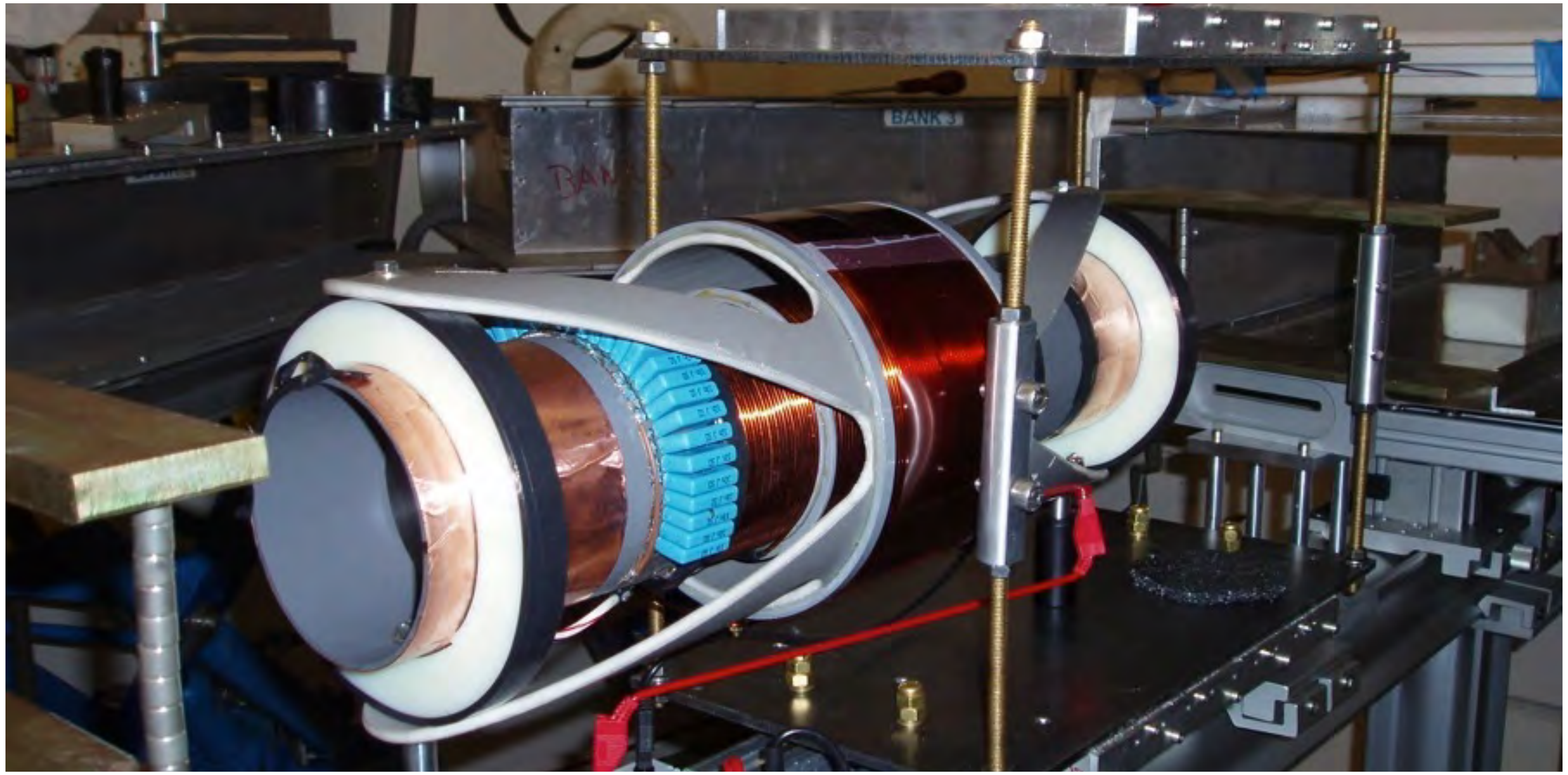

λ independent and
no material in the beam

Measuring techniques

Spin polariser & flipper

- ^{3}He spin filters are characterised by their opacity:

$$\mathcal{O} = N \ell \, \sigma_{\nparallel}$$
$$\simeq 0.0732 \; p[\text{bar}] \; \ell[\text{cm}] \; \lambda[\text{Å}]$$

- The total transmission and polarising efficiency are:

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

$$P_\epsilon = \tanh(\mathcal{O} P_{^3\text{He}})$$

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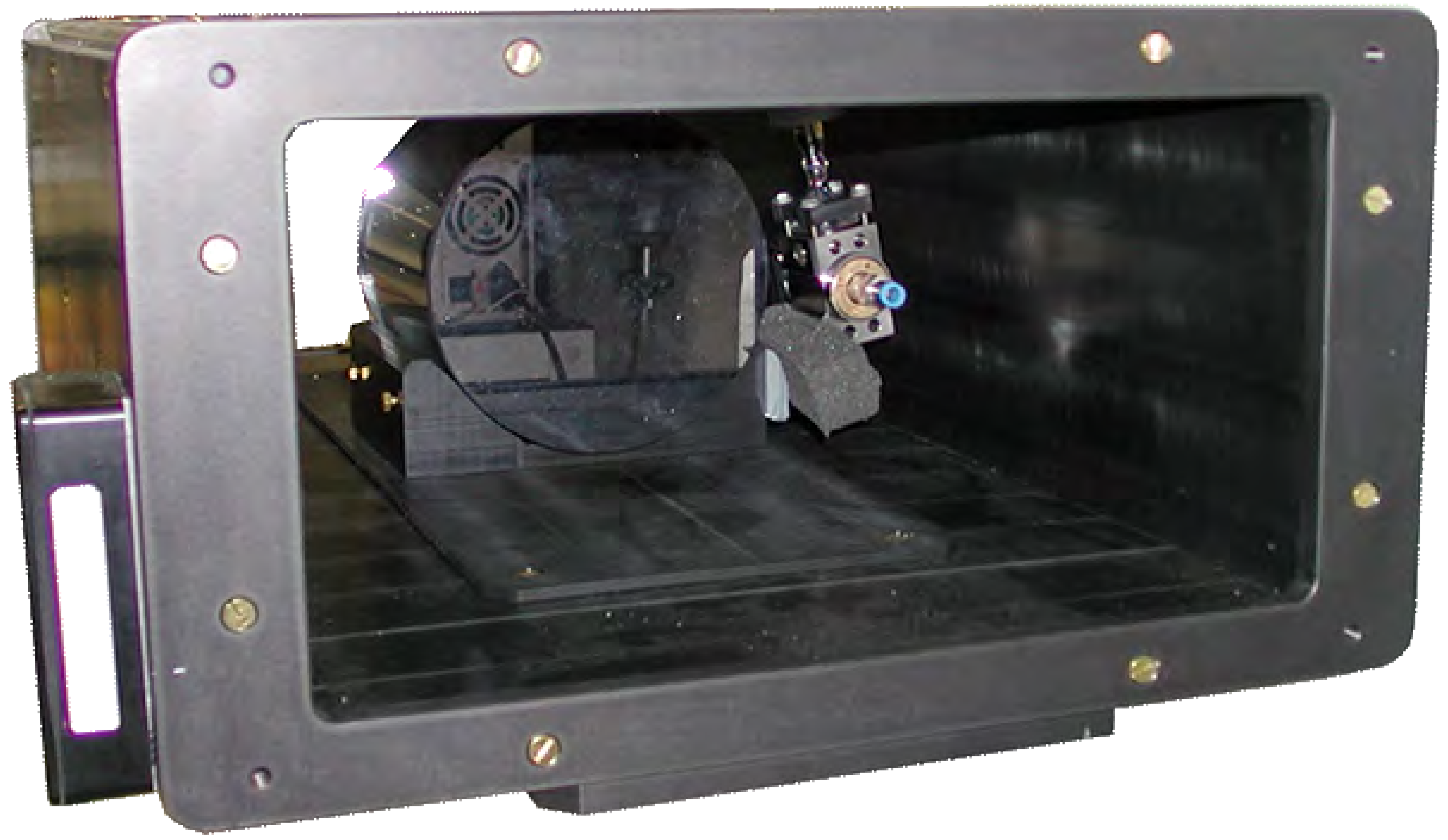
Banna-shaped Quartz cell

Quartz cell

Si-windowed cell



magneto static cavity

Measuring techniques

Manipulation of the beam polarisation (polarimeter)

- Cryopad:

  Cryogenic

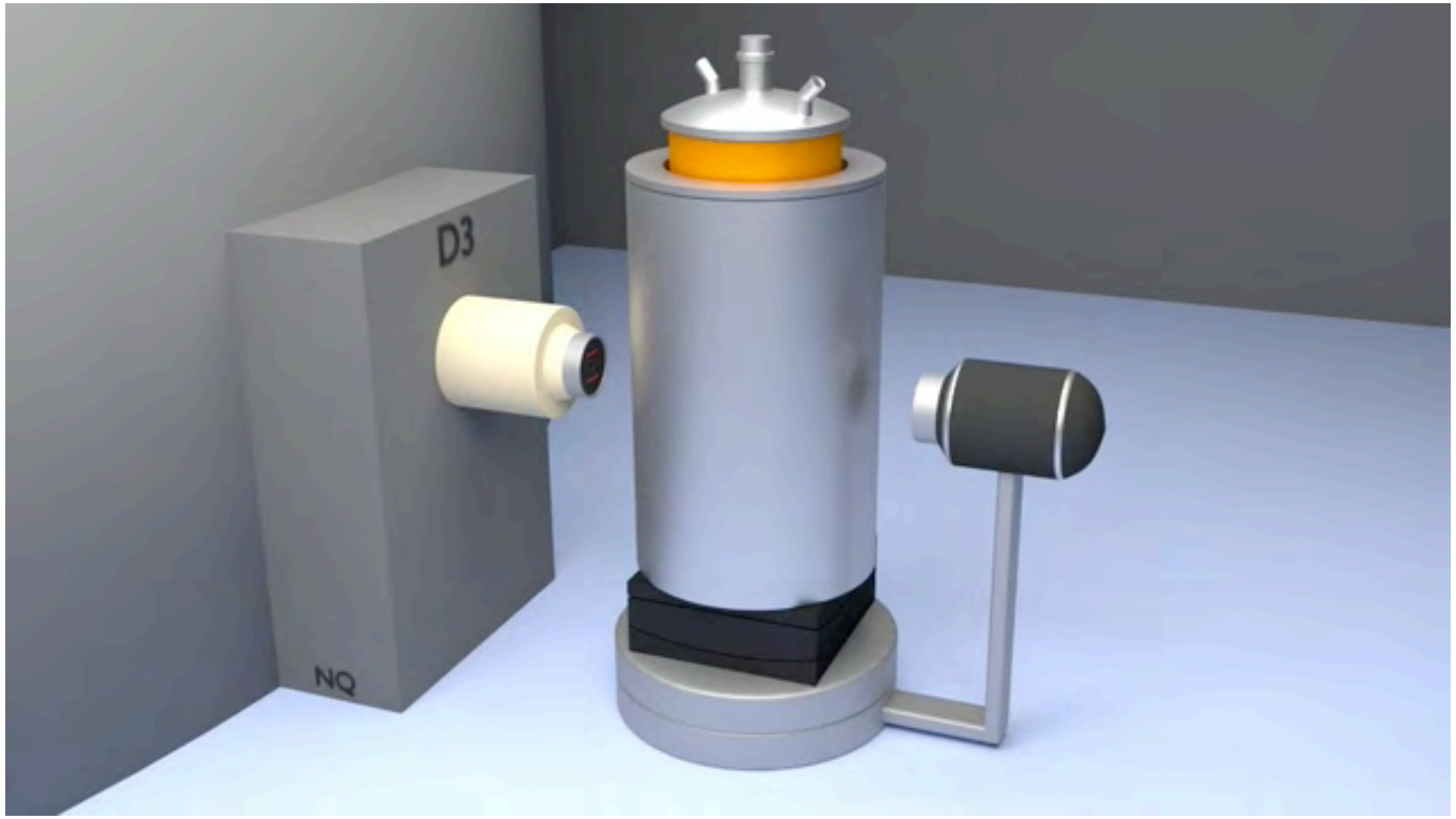
  Polarisation

  Analysis

  Device

- sample in zero field

- manipulates the beam polarisation vector before and after the sample



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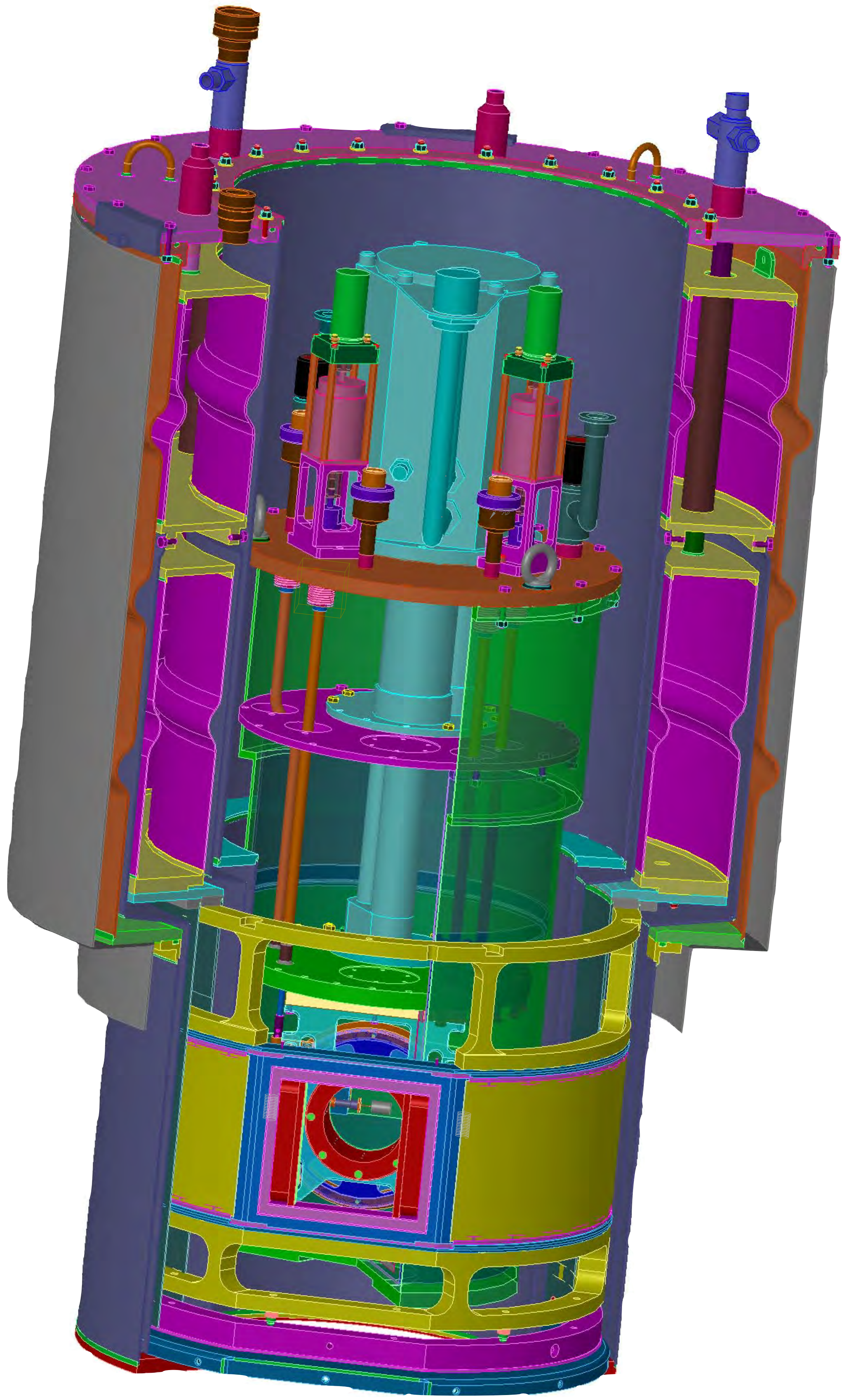


Measuring techniques

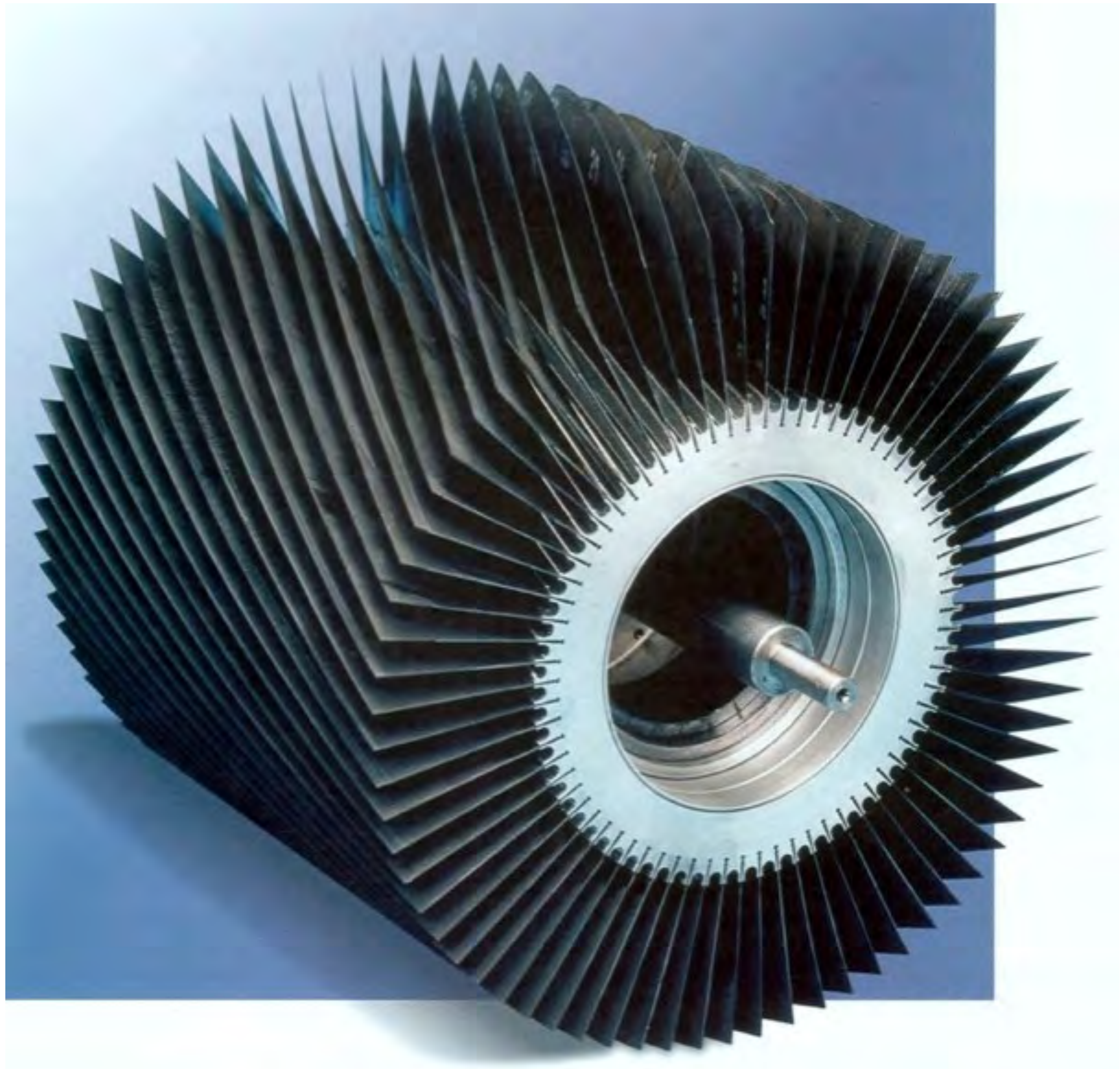
Elastic scattering

- Small angle neutron scattering (SANS)
  - velocity selector, (polariser + flipper), filter, (choppers in TOF mode), collimators, slits, detector(s) in evacuated chamber

Measuring techniques

Velocity selectors

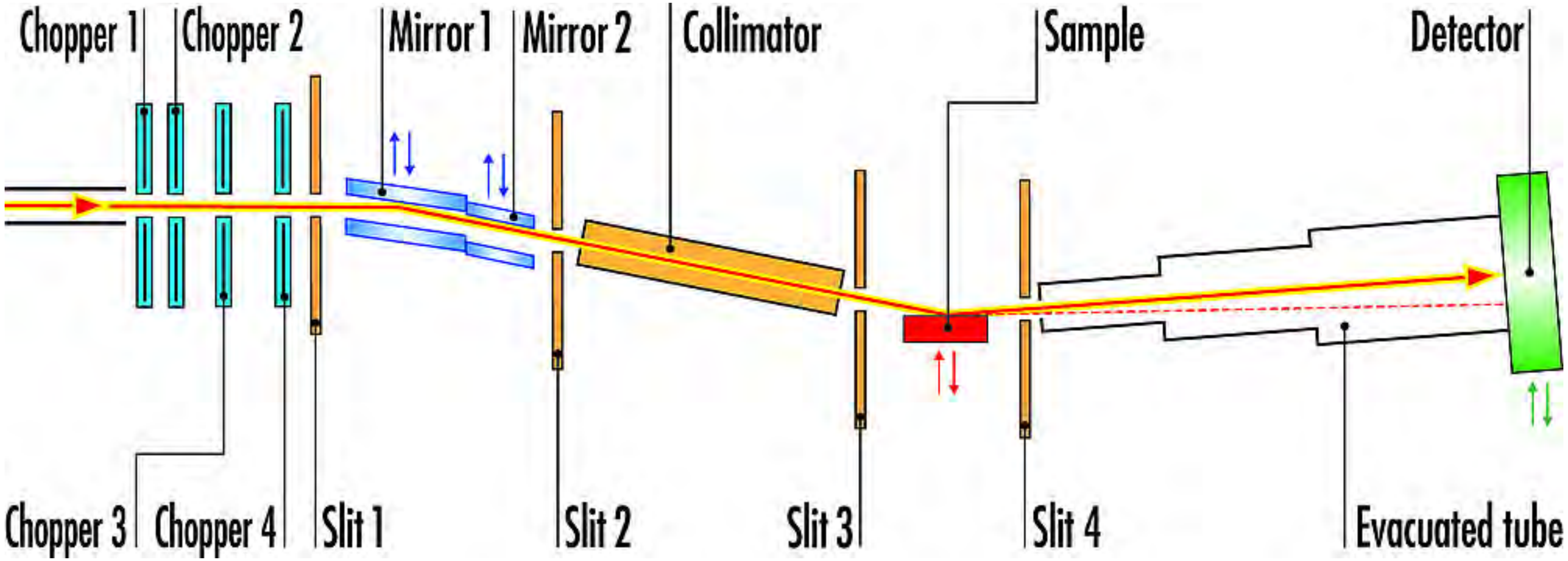
- Large Δλ/λ: typically 10 to 12% fwhm resolution
- High transmission: from 75 to 95%
- Rotation frequency: from 1.000 to +5.000 Hz
- Multi-disc or multi-blade



Measuring techniques

Specular & off-specular scattering

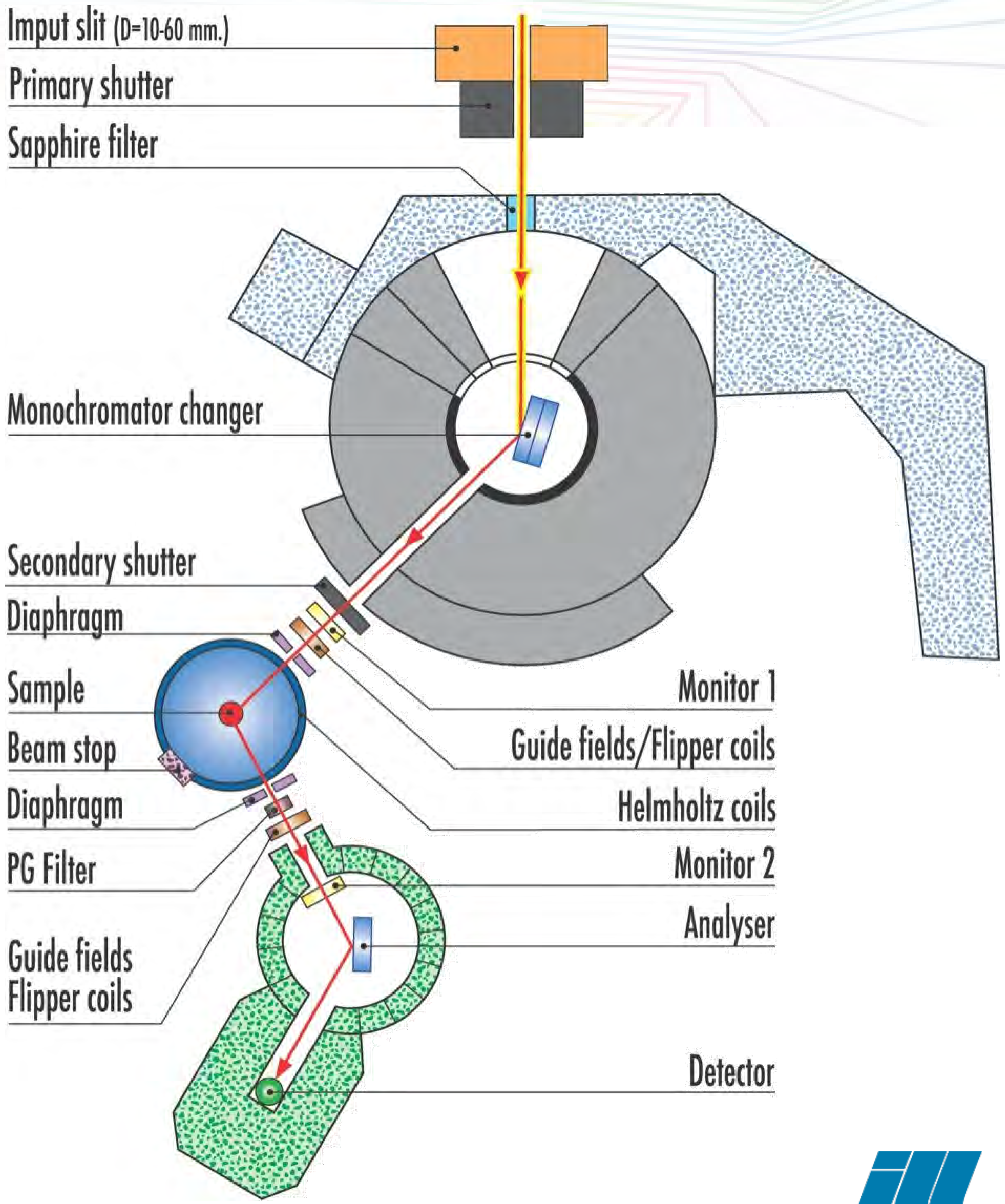
- Horizontal or vertical reflectometry
  - monochromator or choppers (TOF mode), (polariser + flipper), monitor, collimator, slits, detector in evacuated chamber



Measuring techniques

Inelastic scattering

- Three-axis spectroscopy
  - collimator, (filter, velocity selector)
  - (polarising) monochromator
  - slits before (and after) sample
  - (spin) analyser
  - single or PSD detector
  - very low neutron background



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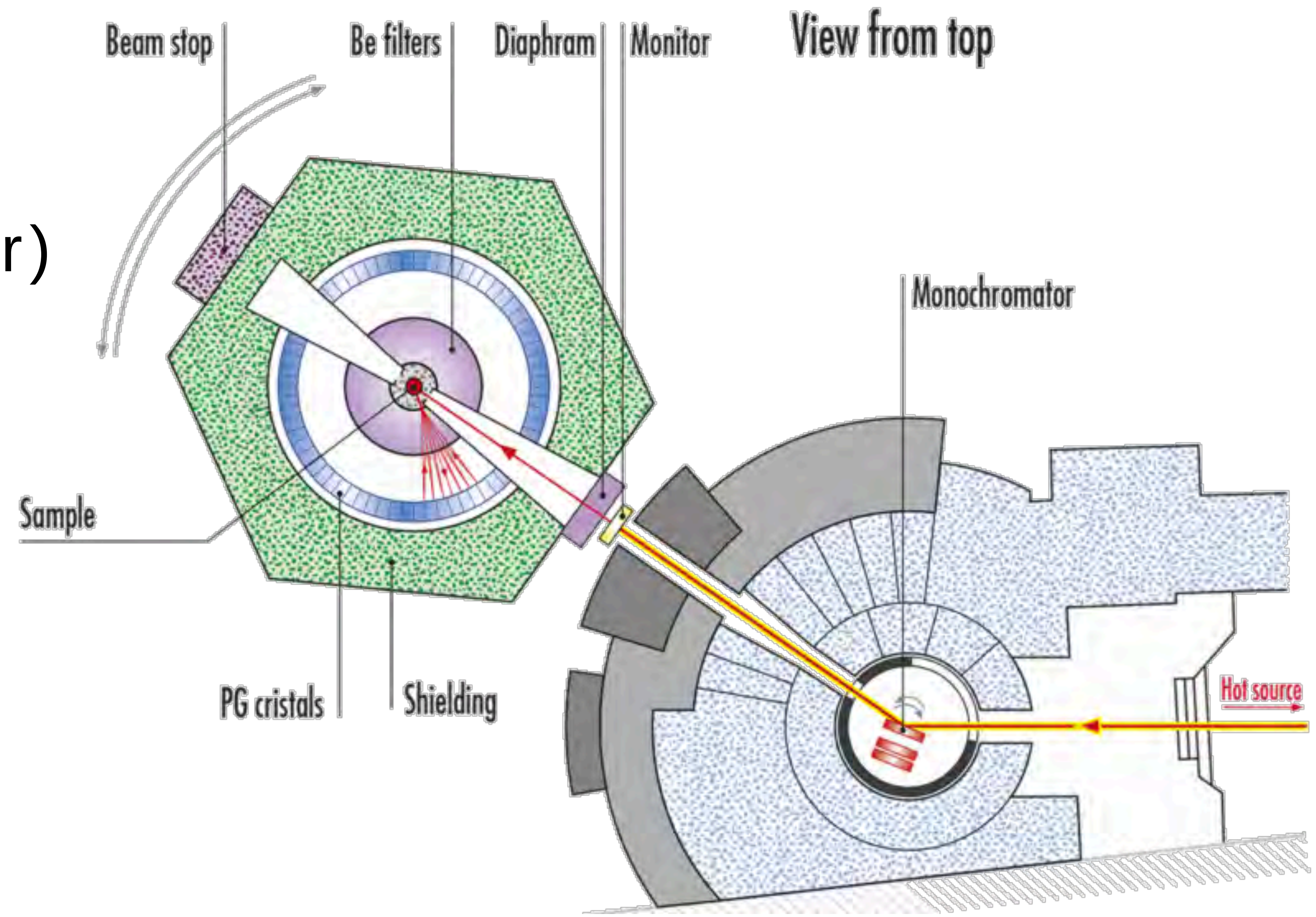

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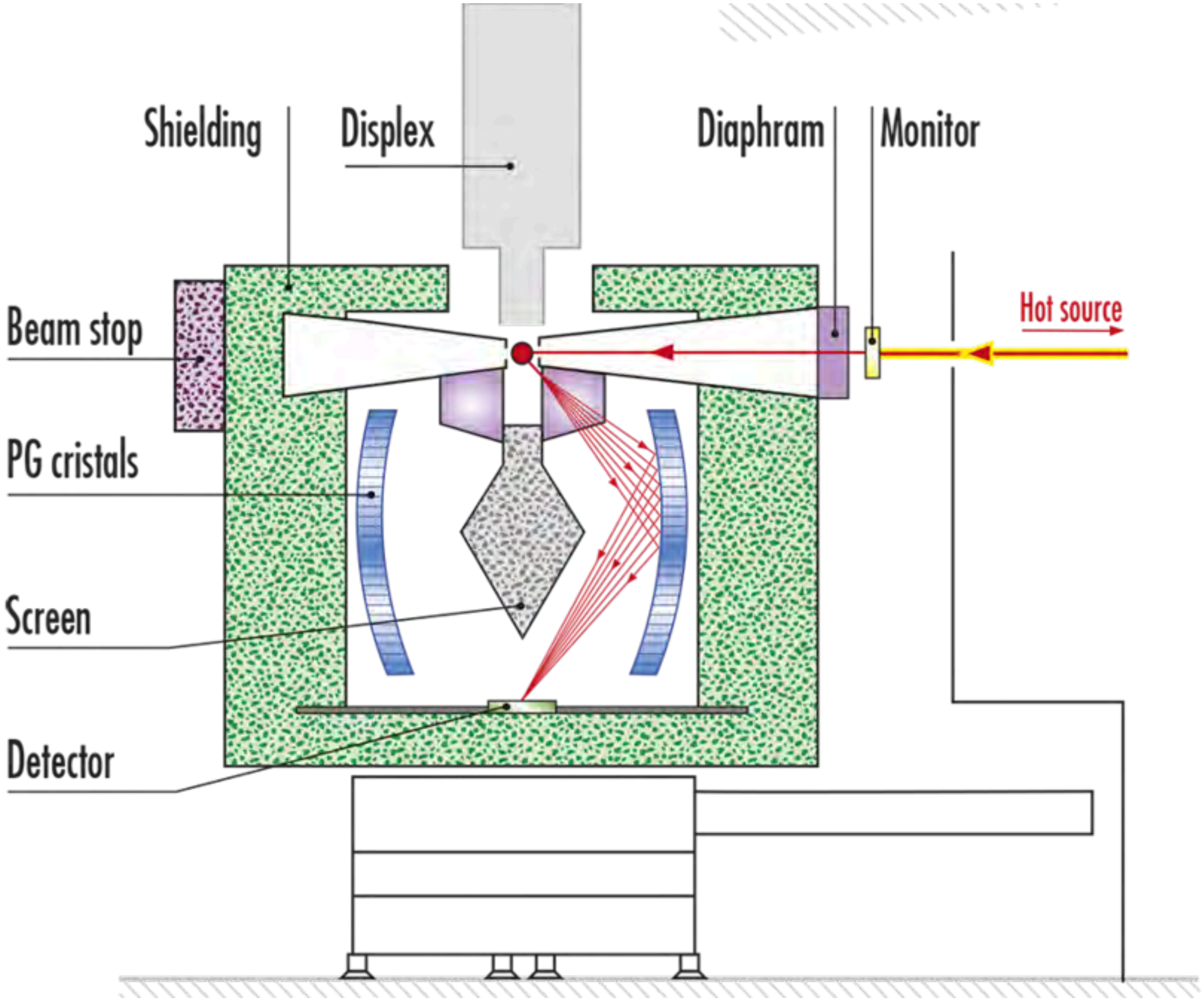
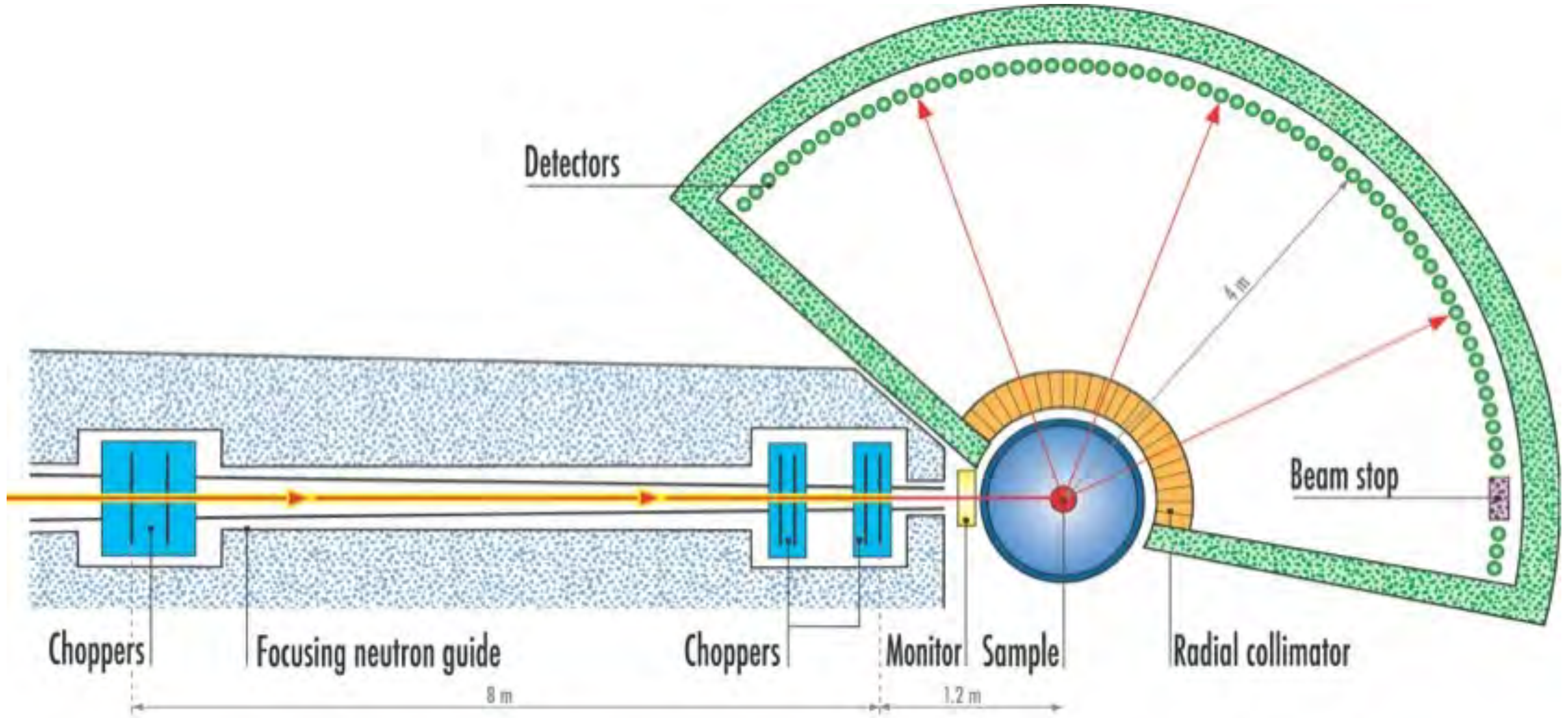
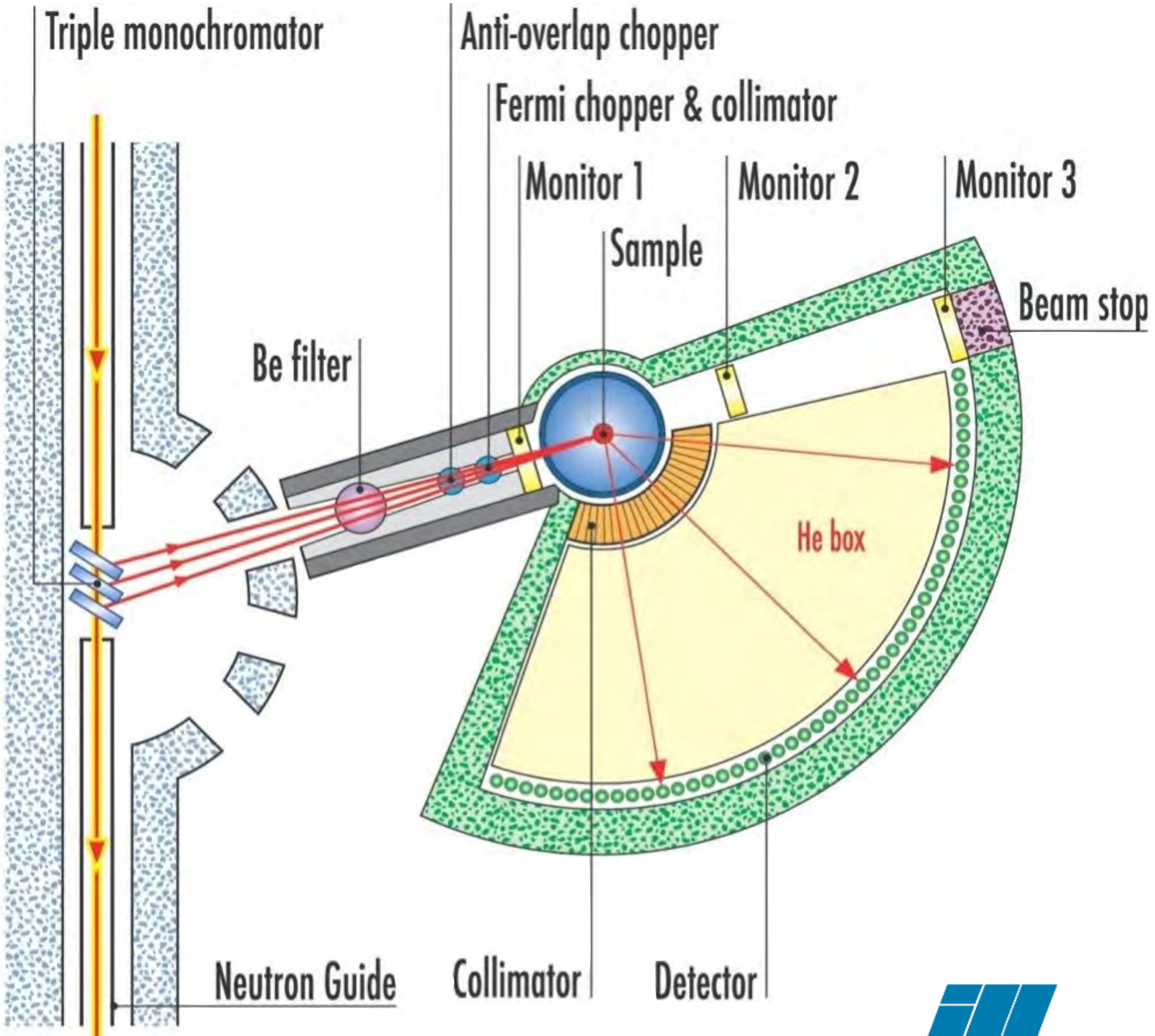


Measuring techniques

Inelastic scattering

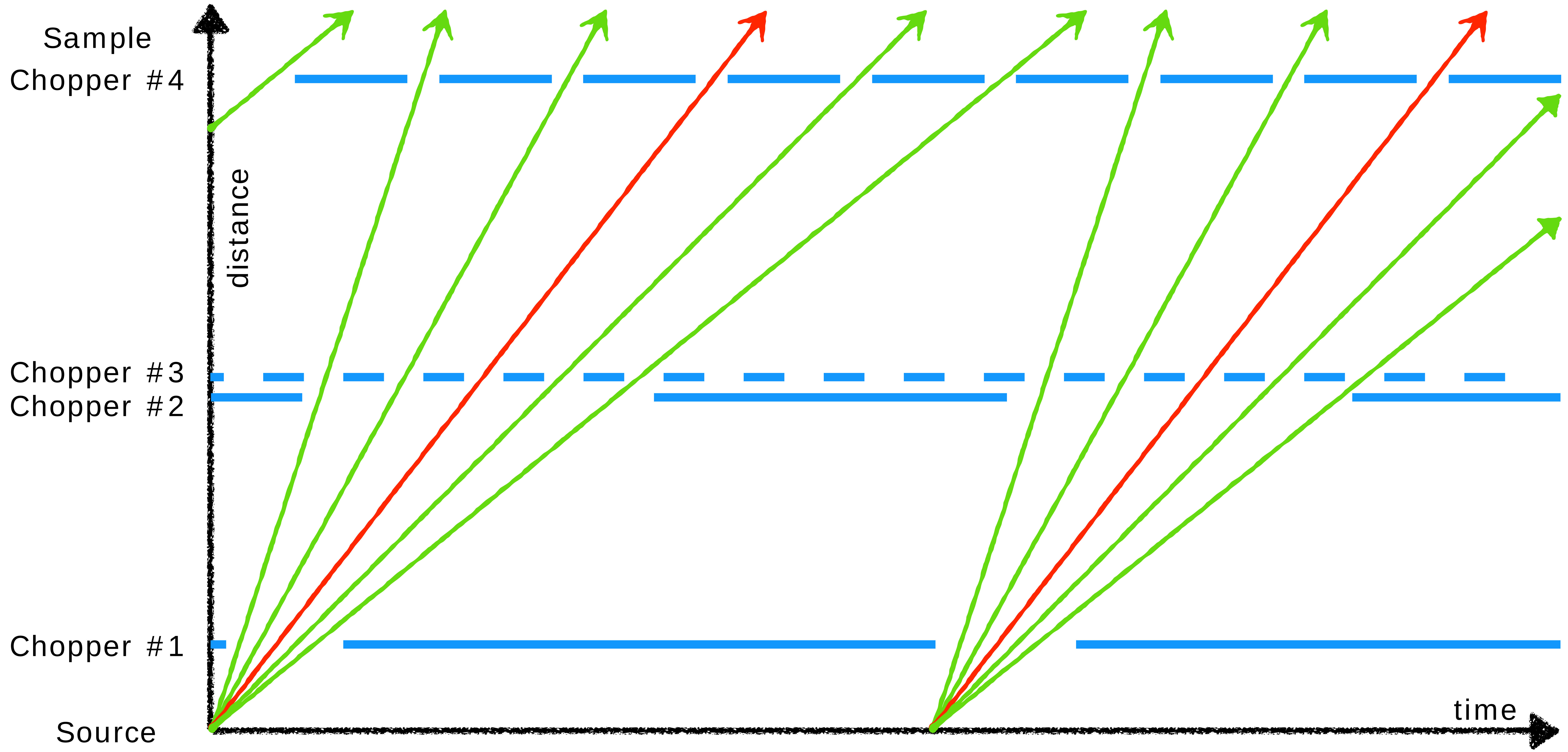
- Time of flight spectroscopy
  - choppers, monitor, collimator
  - (monochromator, filter, choppers)





Measuring techniques

Choppers - Time of flight technique



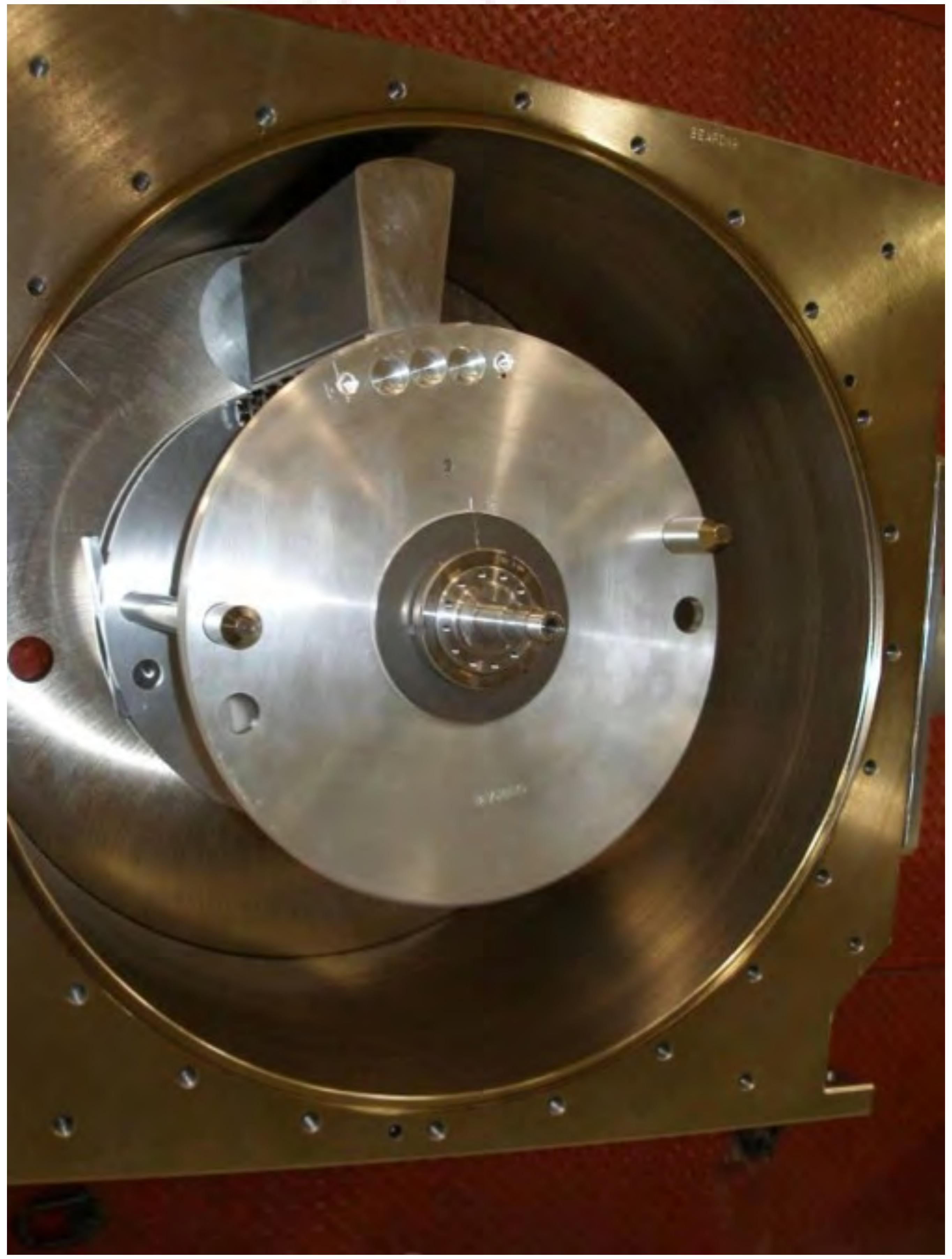
Repetition rate multiplication by M. Russina & F. Mezei NIM A 604 (2009) 624

Measuring techniques

Choppers - Time of flight technique

- T0 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)

assembled T_0 chopper unit



T_0 single-blade rotor

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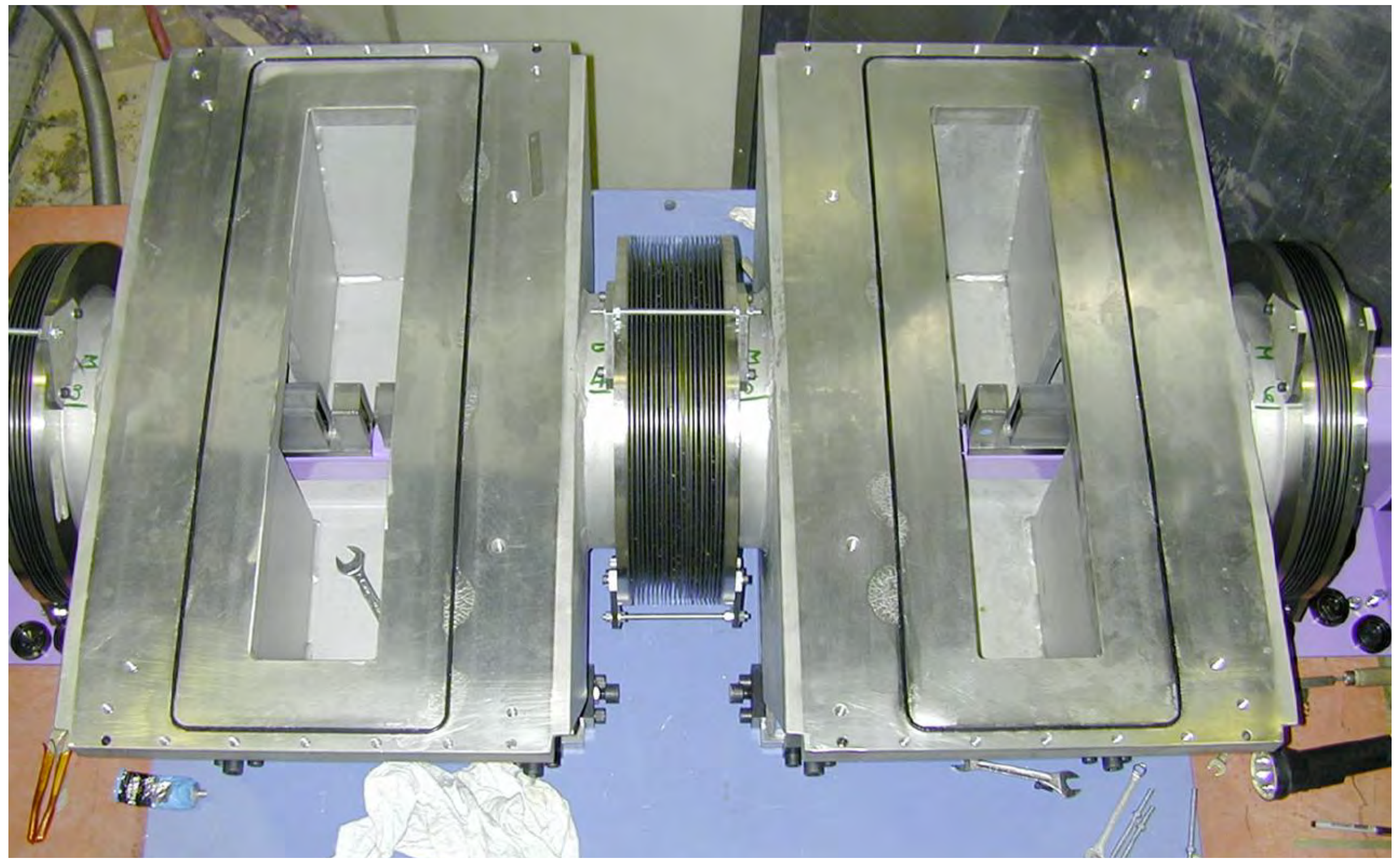
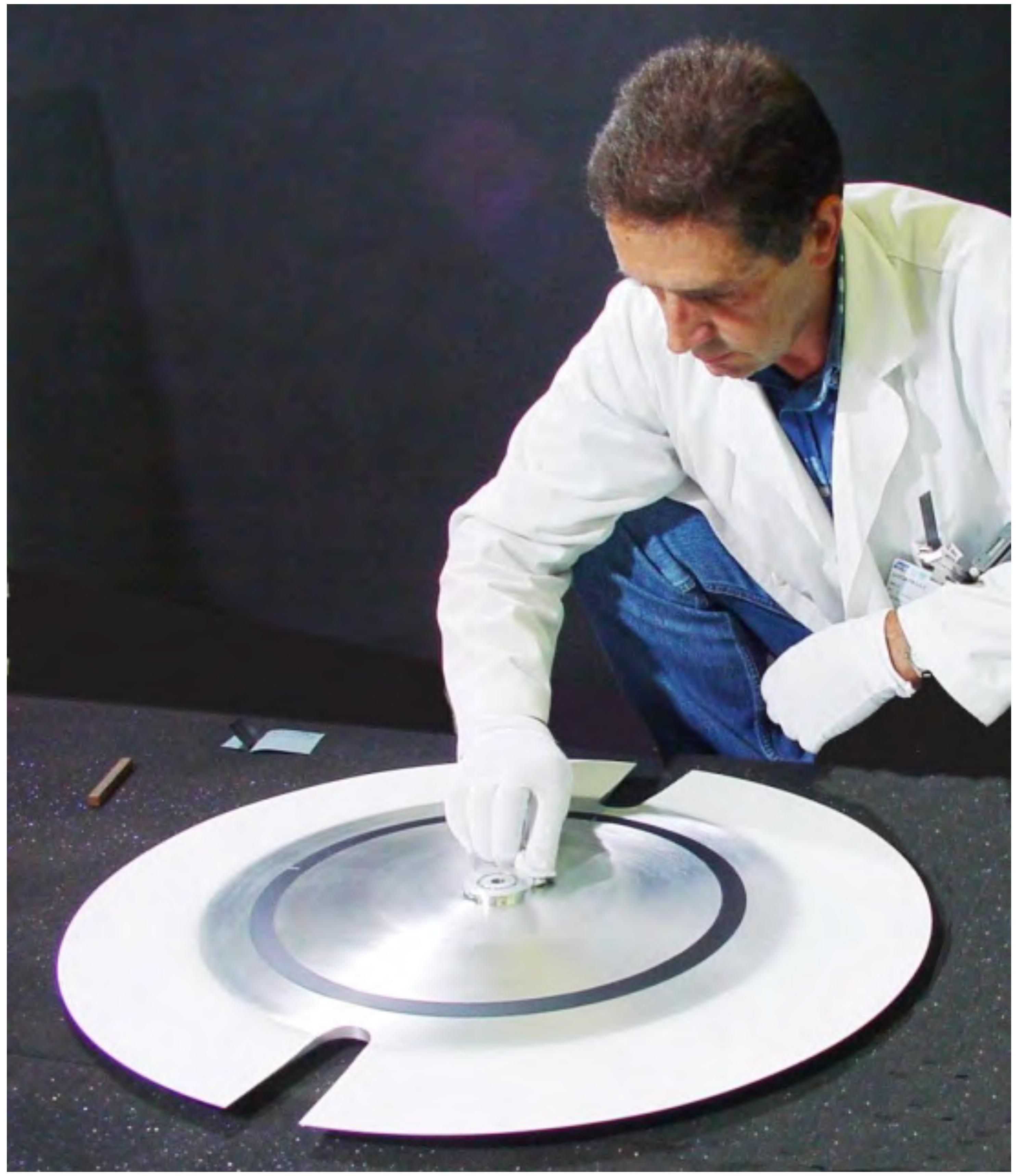


IN5 chopper housings

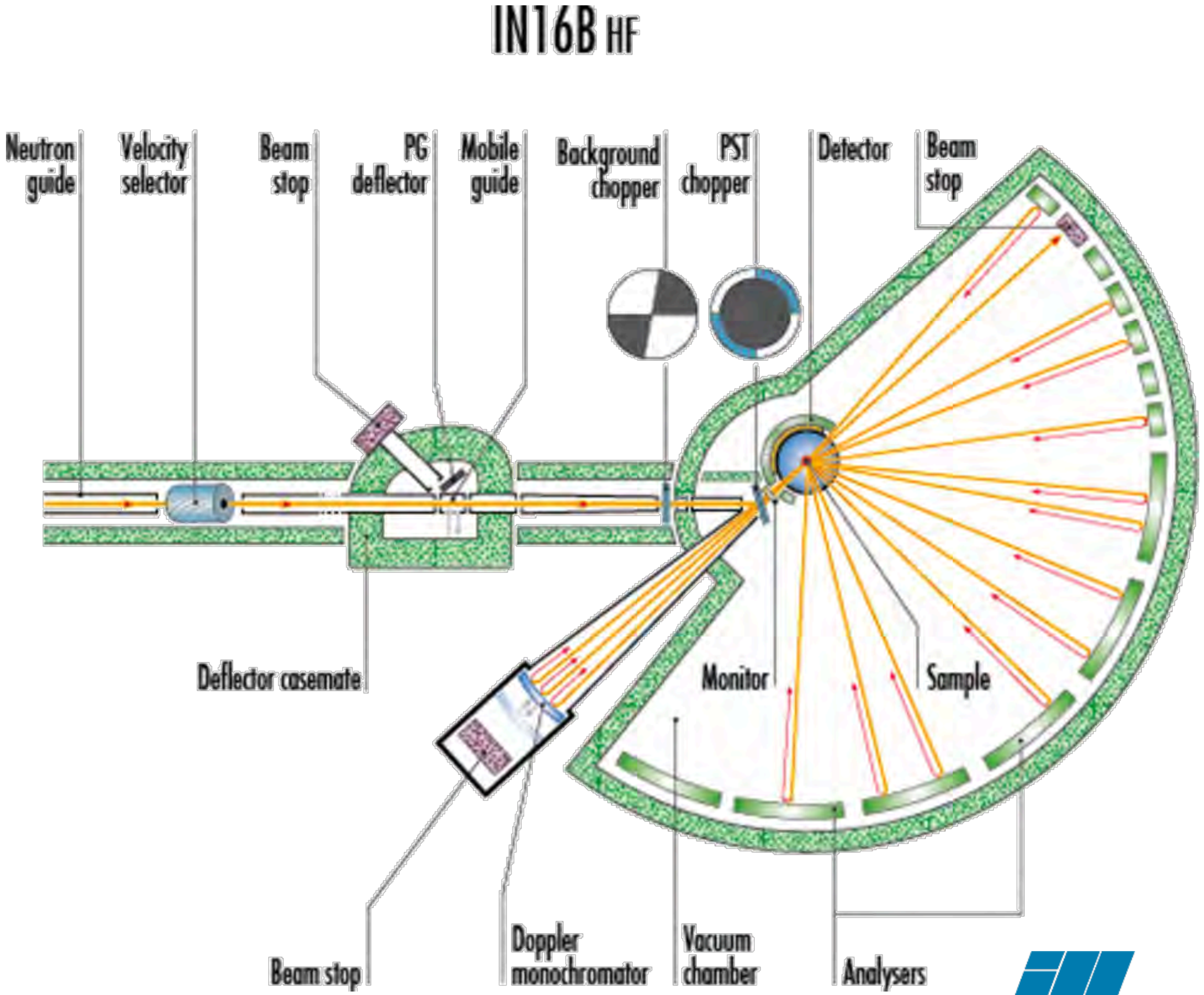


IN5 chopper disc

Measuring techniques

Quasi-elastic scattering

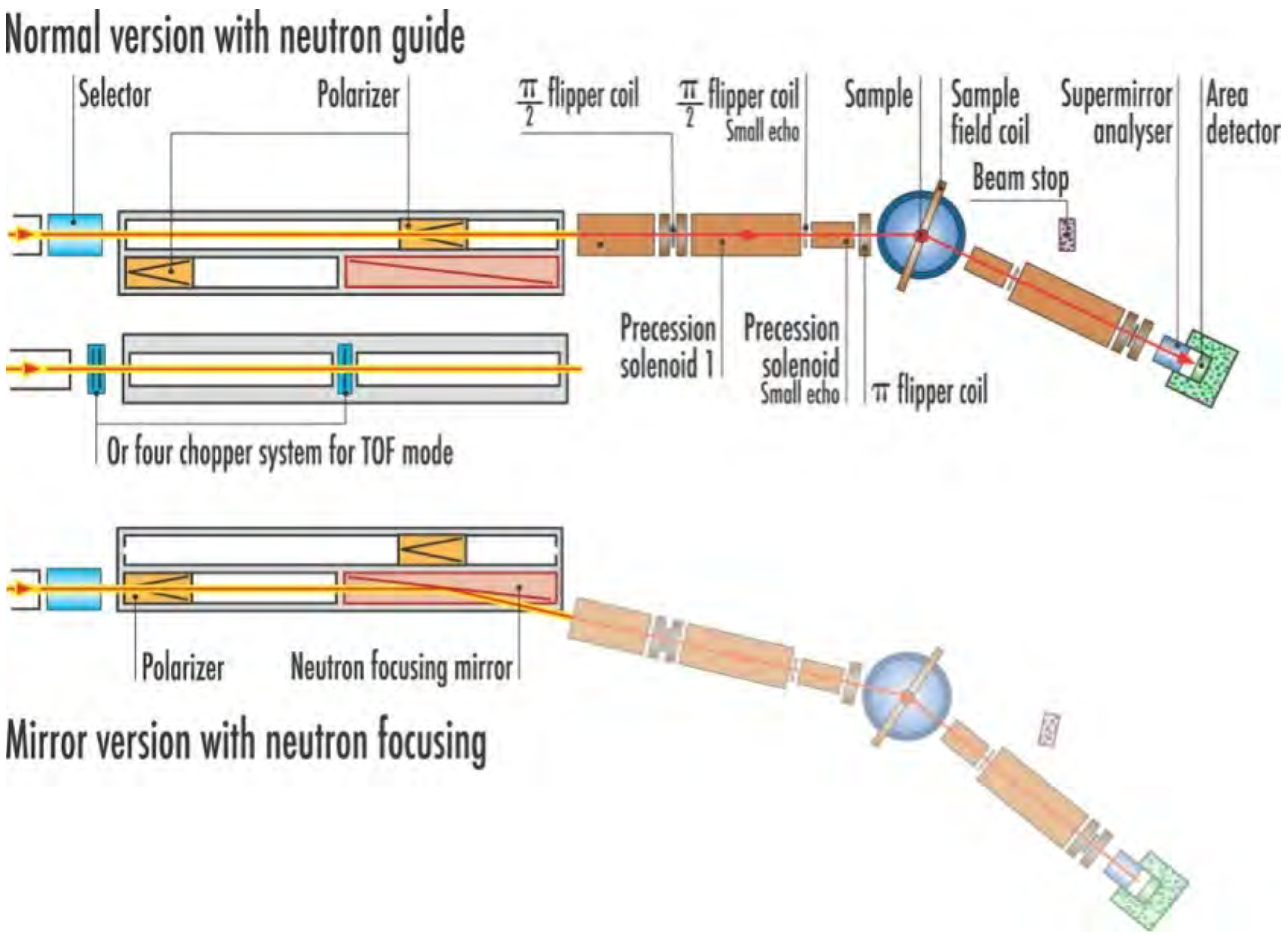
- Backscattering
  - velocity selector
  - background and phase space transformation choppers
  - Doppler monochromator
  - analysers
  - position sensitive detector (PSD)



Measuring techniques

Quasi-elastic scattering

- Neutron spin echo
  - velocity selector
  - polarising supermirrors
  - precession solenoids
  - π and π/2 flippers
  - spin analyser, PSD detector
  - choppers for TOF mode



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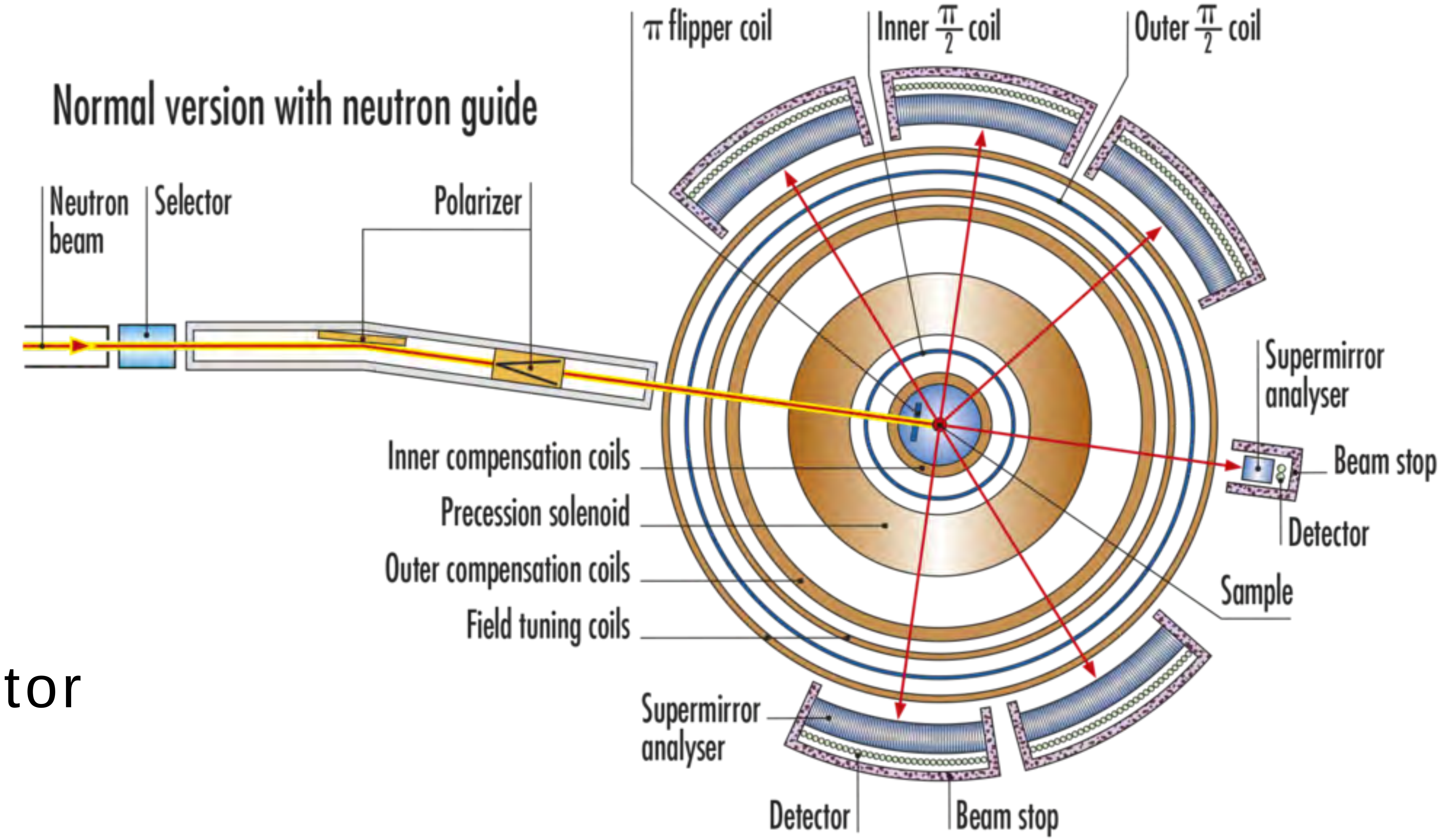
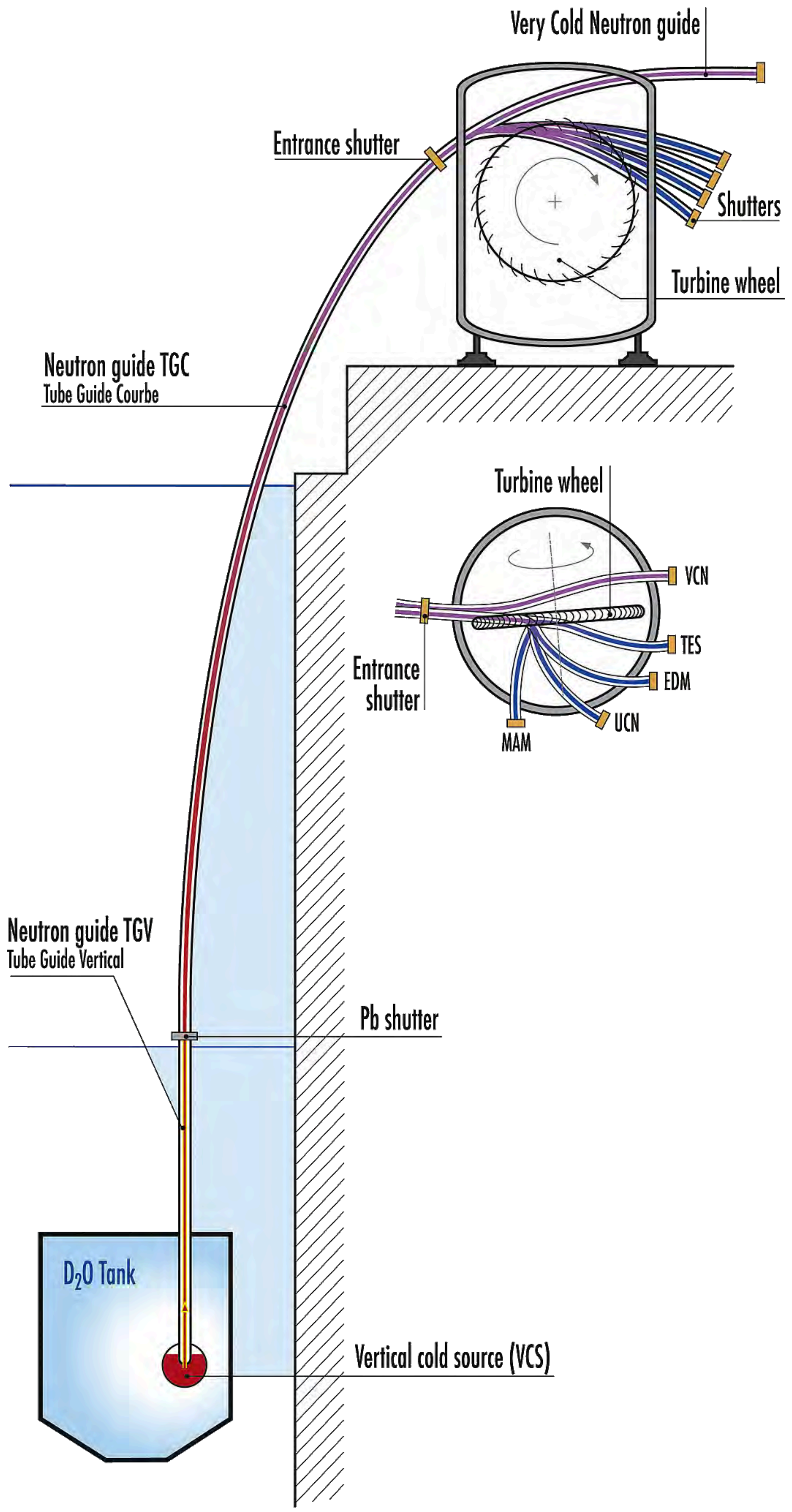
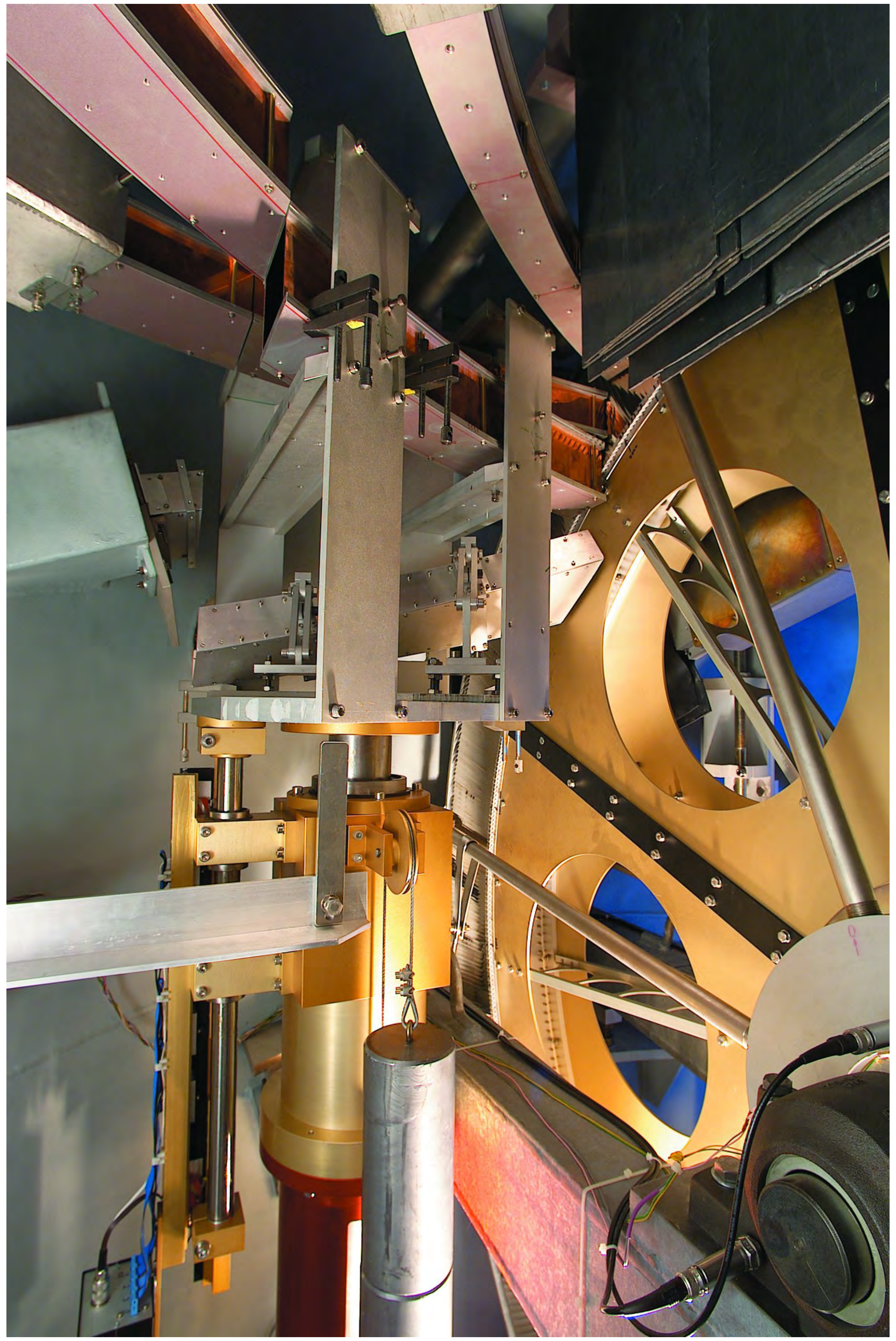


Measuring techniques

Nuclear & particle physics

- dedicated instruments or beam facilities shared by a community
- MeV, cold (meV) and ultra-cold (neV) neutron sources
- often long experiments for testing fundamentals models or measuring constants
- experiments studying nuclei





turbine wheel

Measuring techniques

Nuclear & particle physics

- Ultra-cold neutron source under construction

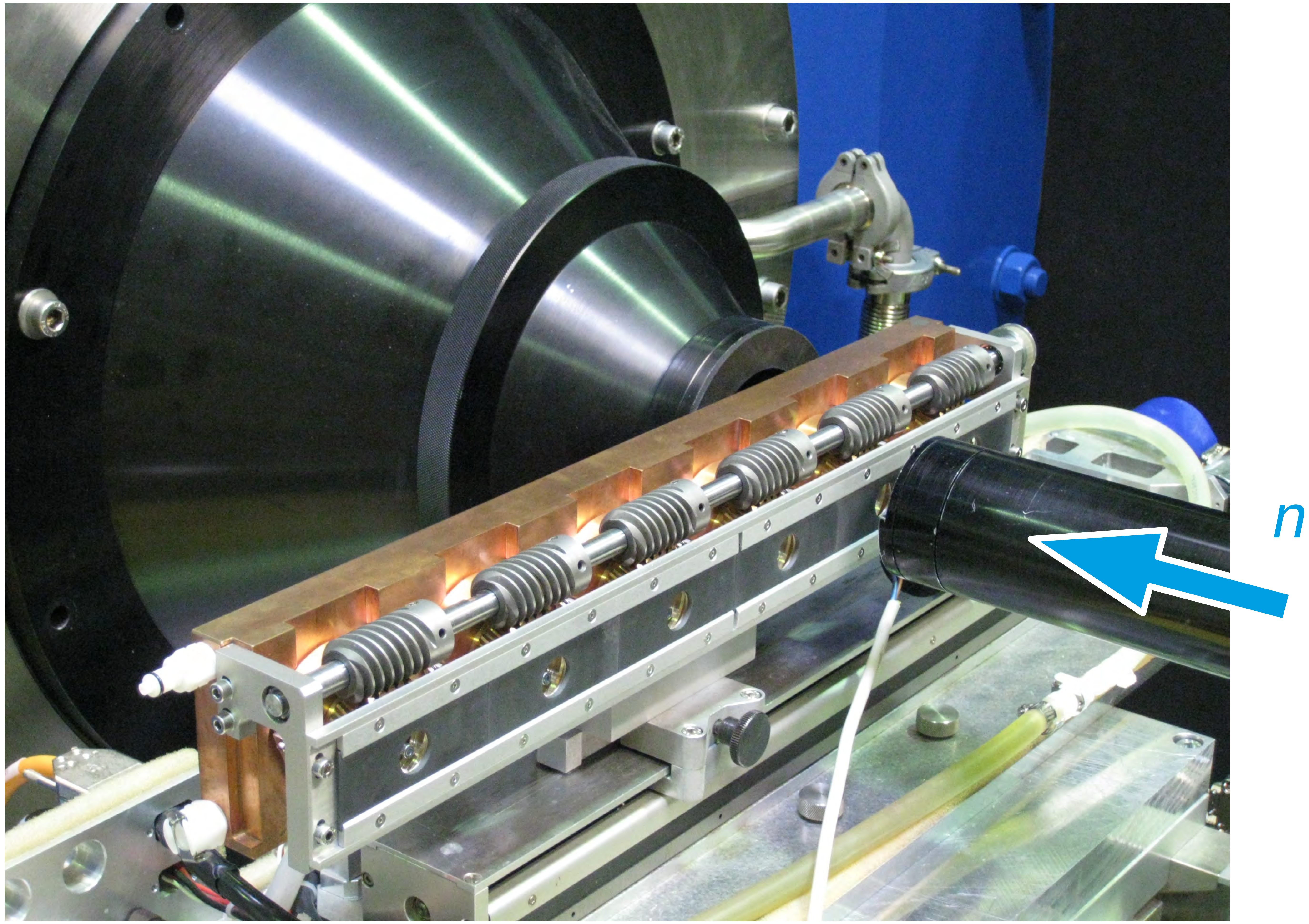
Neutron instrumentation

- What do we measure and need ?
- Neutron guides & shielding
- Measuring techniques
- Sample environments
- Neutrons detectors
- Data acquisition system

Sample environments

Ambient environments

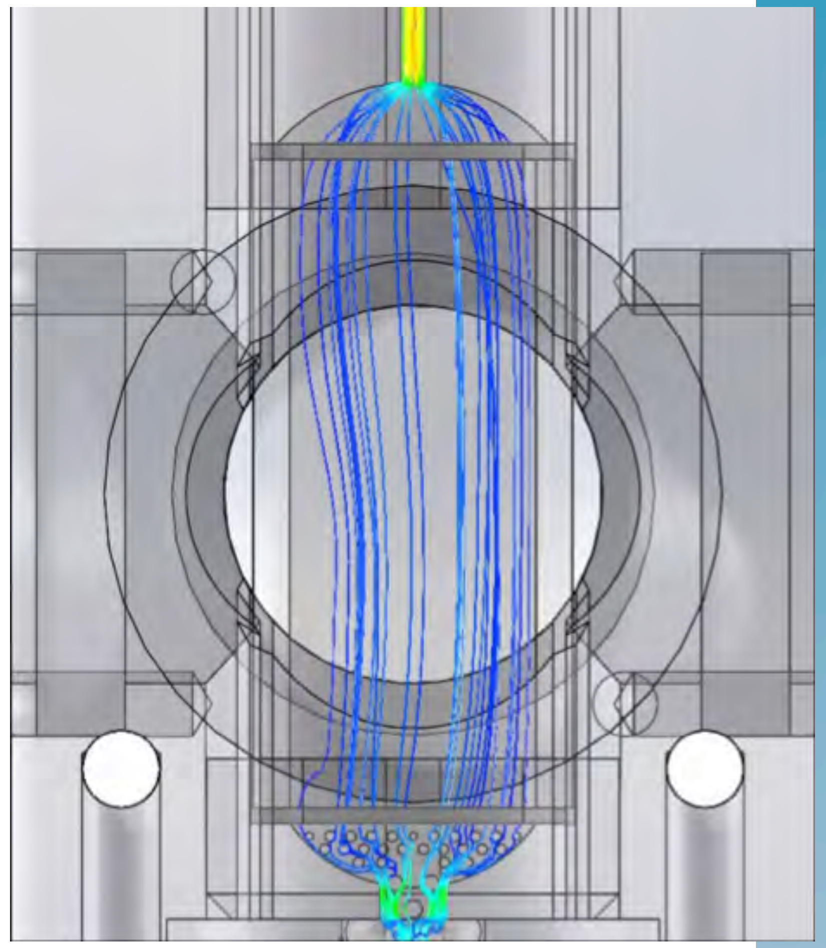
- SANS sample changers
  - up to 3x8 samples
  - -20 to +150°C
  - independently settable temperature or not
  - compatible with in-situ dynamic light scattering
  - low-background design
  - sample mixing option

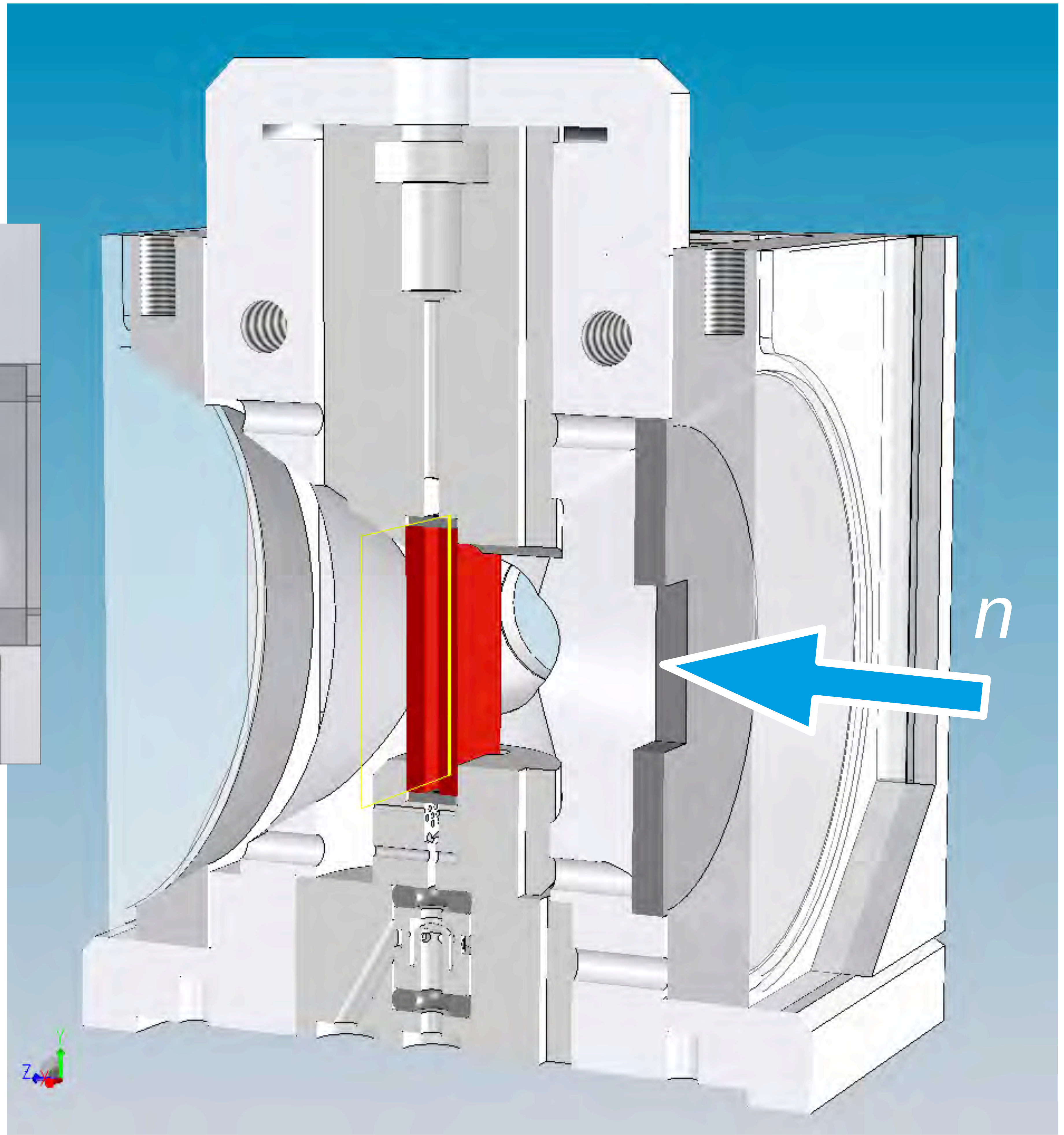


Sample environments

Ambient environments

- Stopped-flow observation heads for SANS
  - reduced sample volume
  - controlled temperature
  - B_4C neutron slits
  - reversible with SF system
  - compatible with two types of Hellma cells (1, 2 mm neutron path)
  - side windows provided for in-situ dynamic light scattering

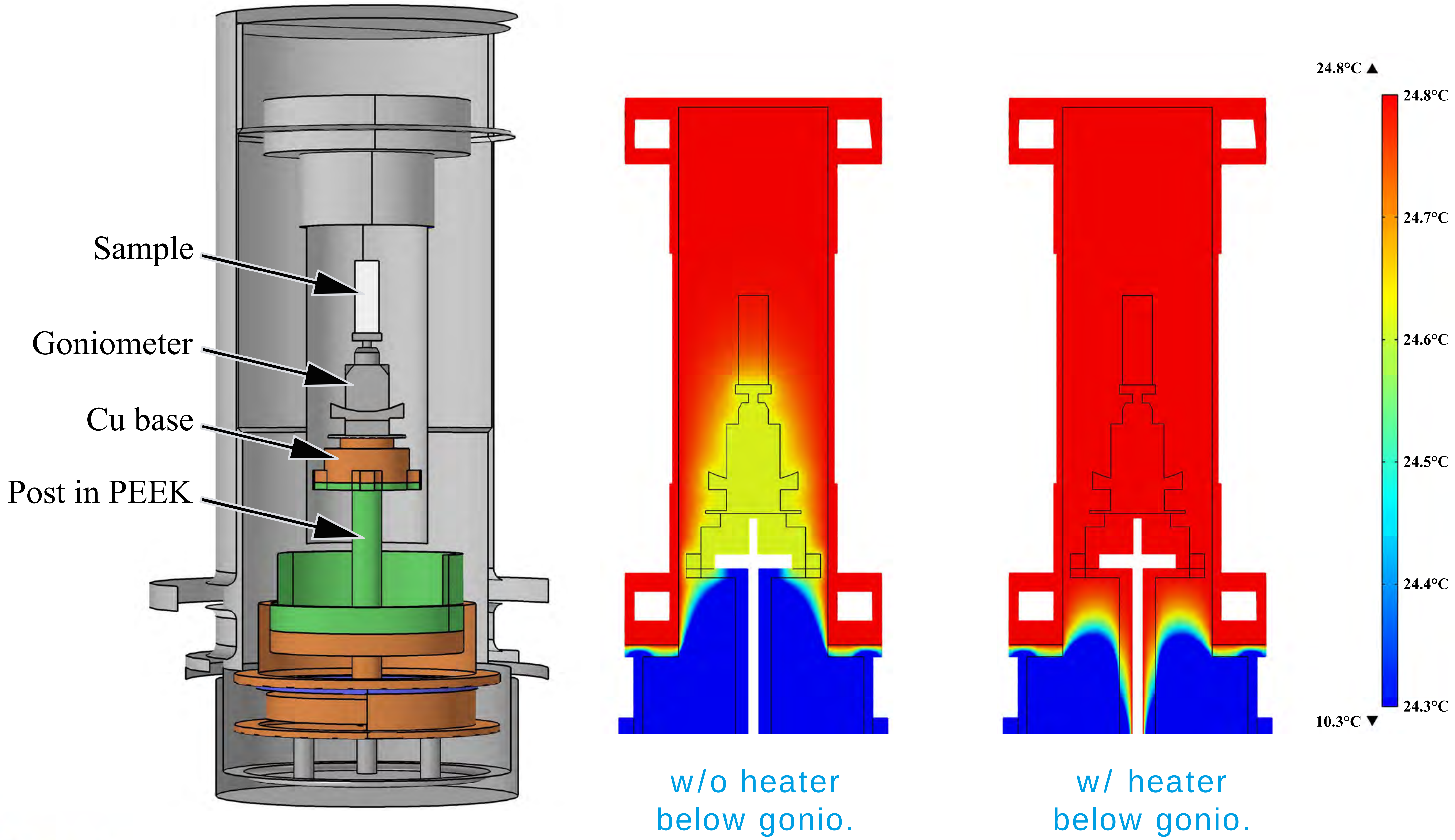




Sample environments

Ambient environments

- Humidity chambers
  - up to 100%RH
  - 10%RH steps in 10-25’
  - 0.1%RH stability
  - sample mounted, aligned and stabilised off-line
  - electronics providing T and %RH direct control
  - H_2O or D_2O.



HZB Helmholtz Zentrum Berlin

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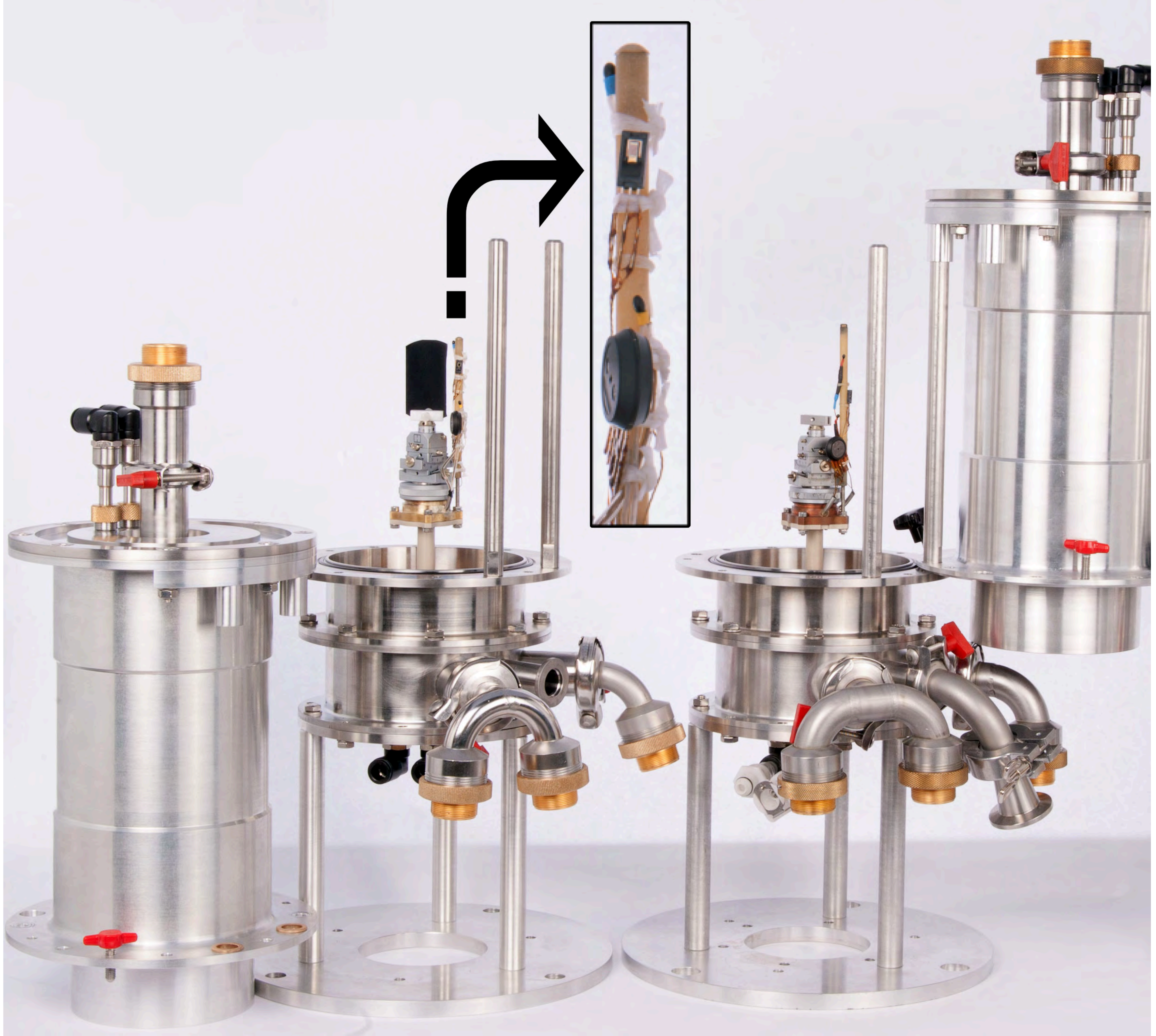

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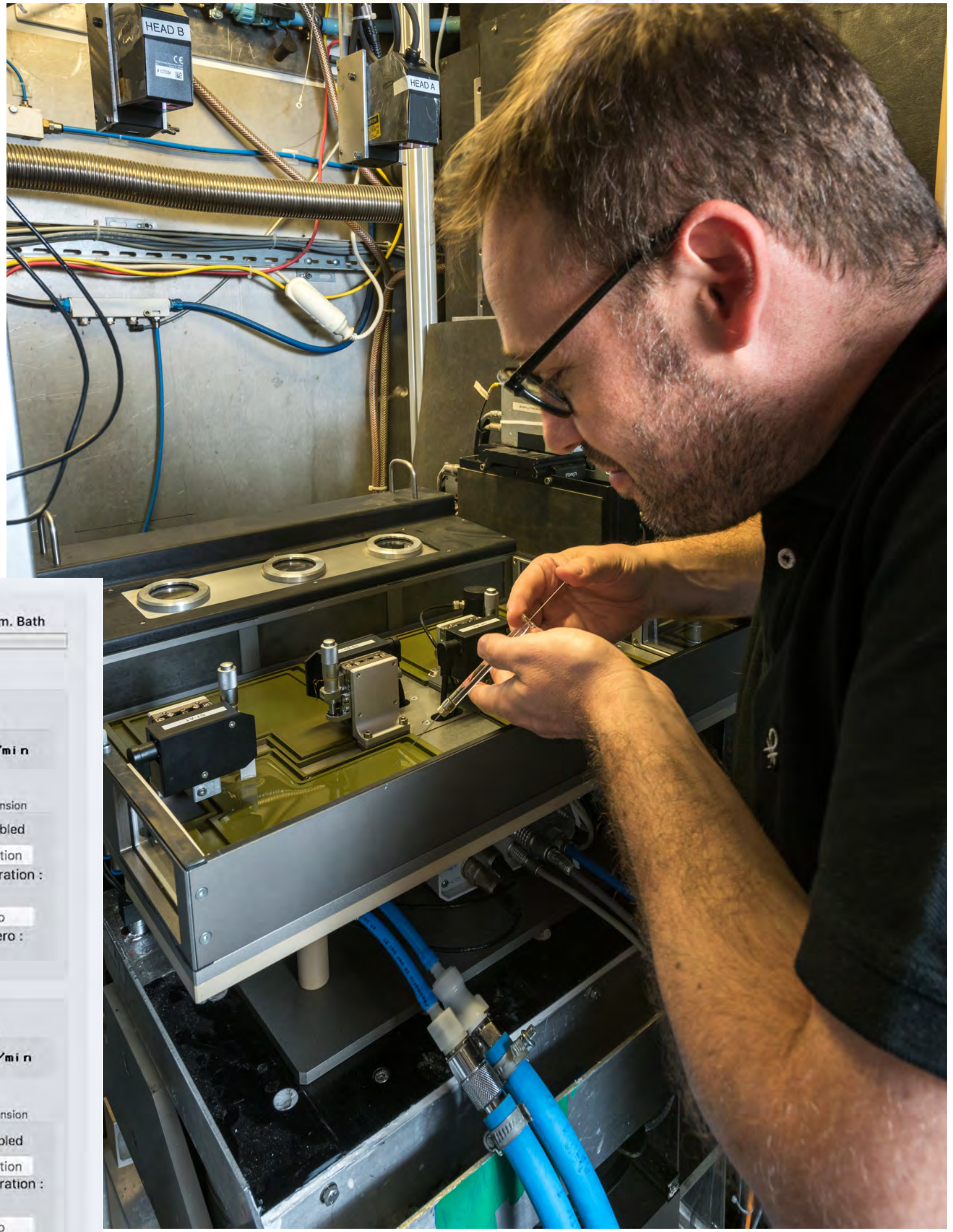
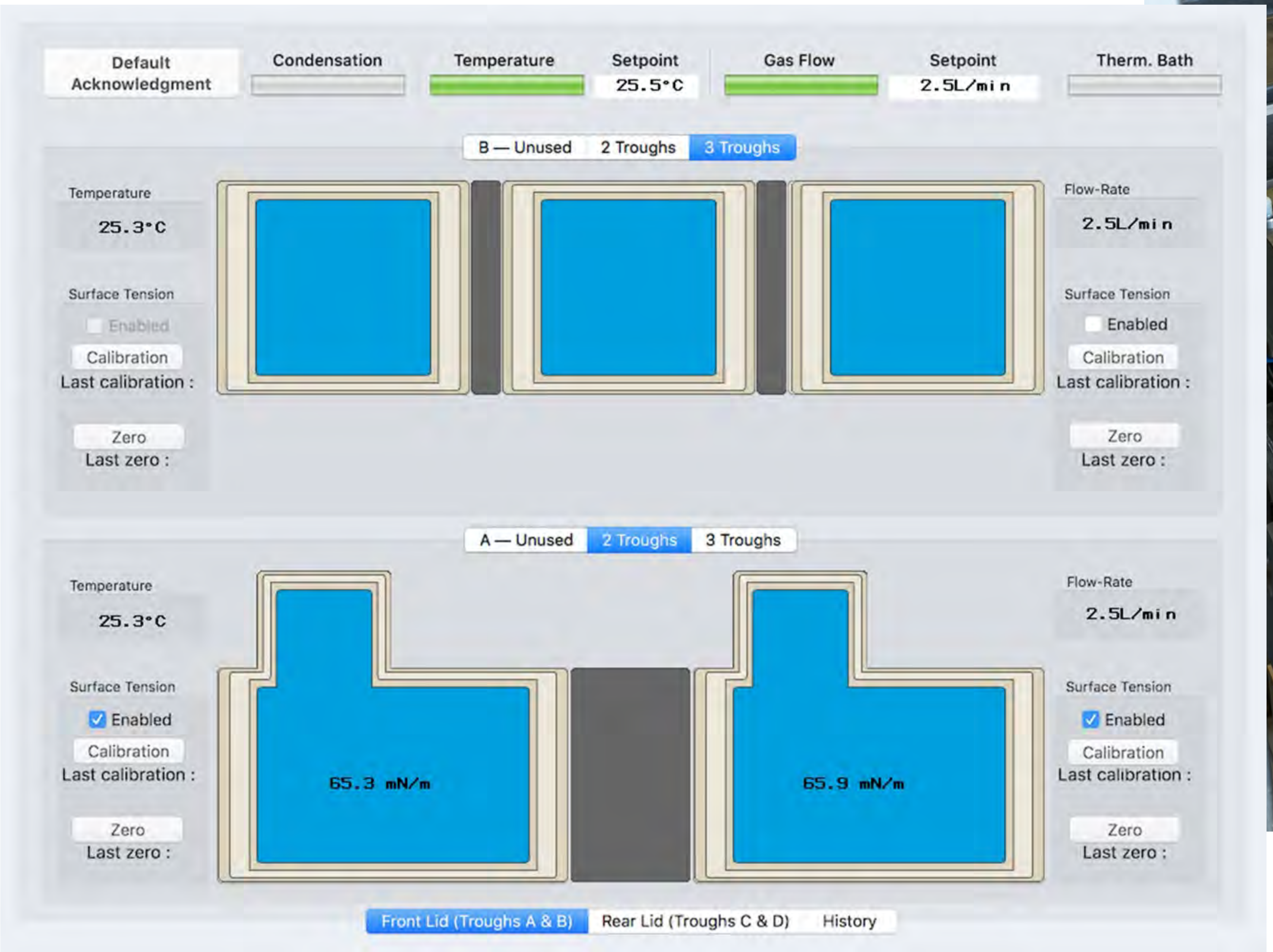
Sample environments

Ambient environments

- Adsorption troughs for reflectometry
  - up to 12 troughs
  - 2 different volumes
  - in-situ surface tension monitoring
  - temperature ctrl
  - gas sorption ctrl
  - no condensation
  - B_4C absorbers

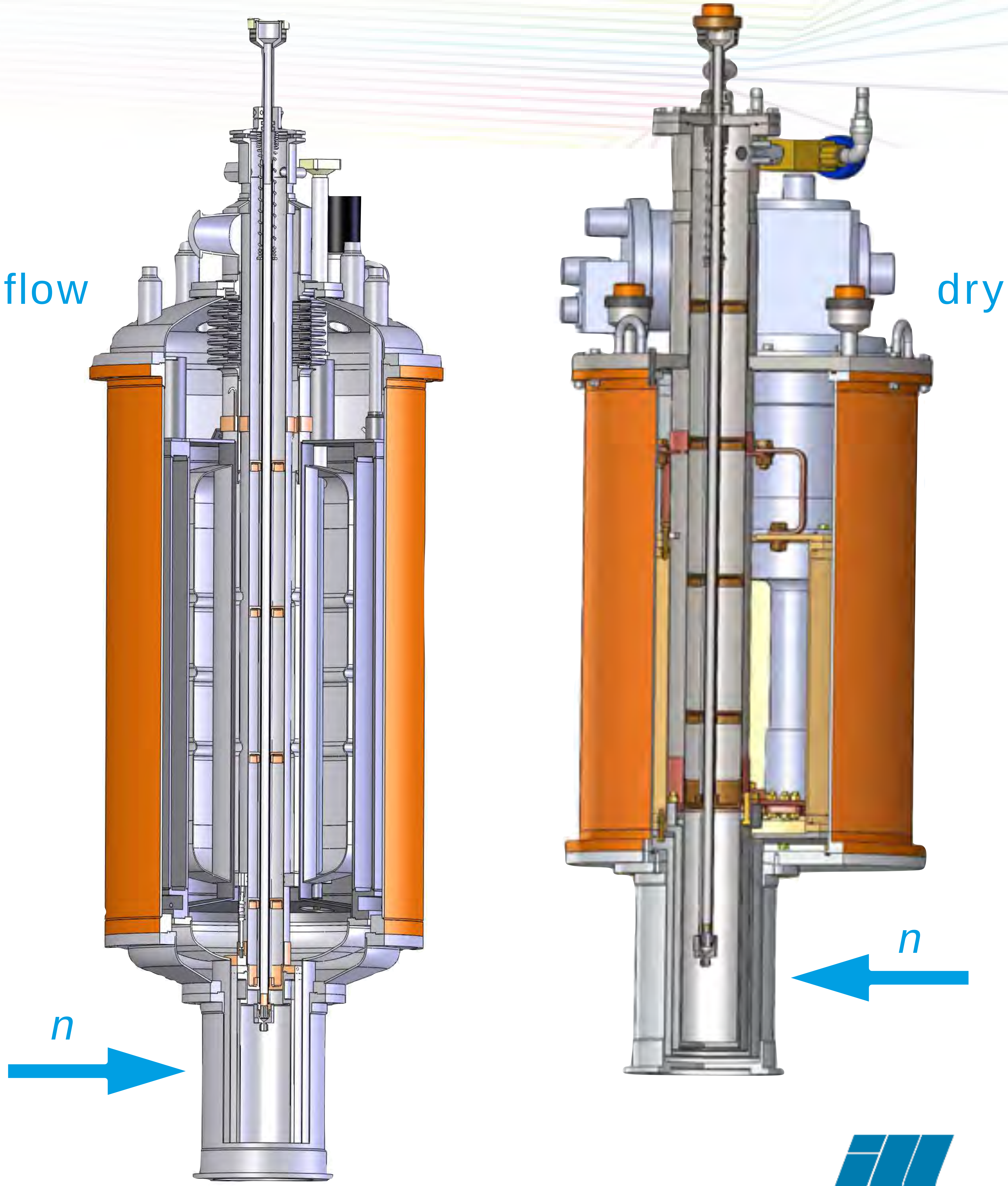




Sample environments

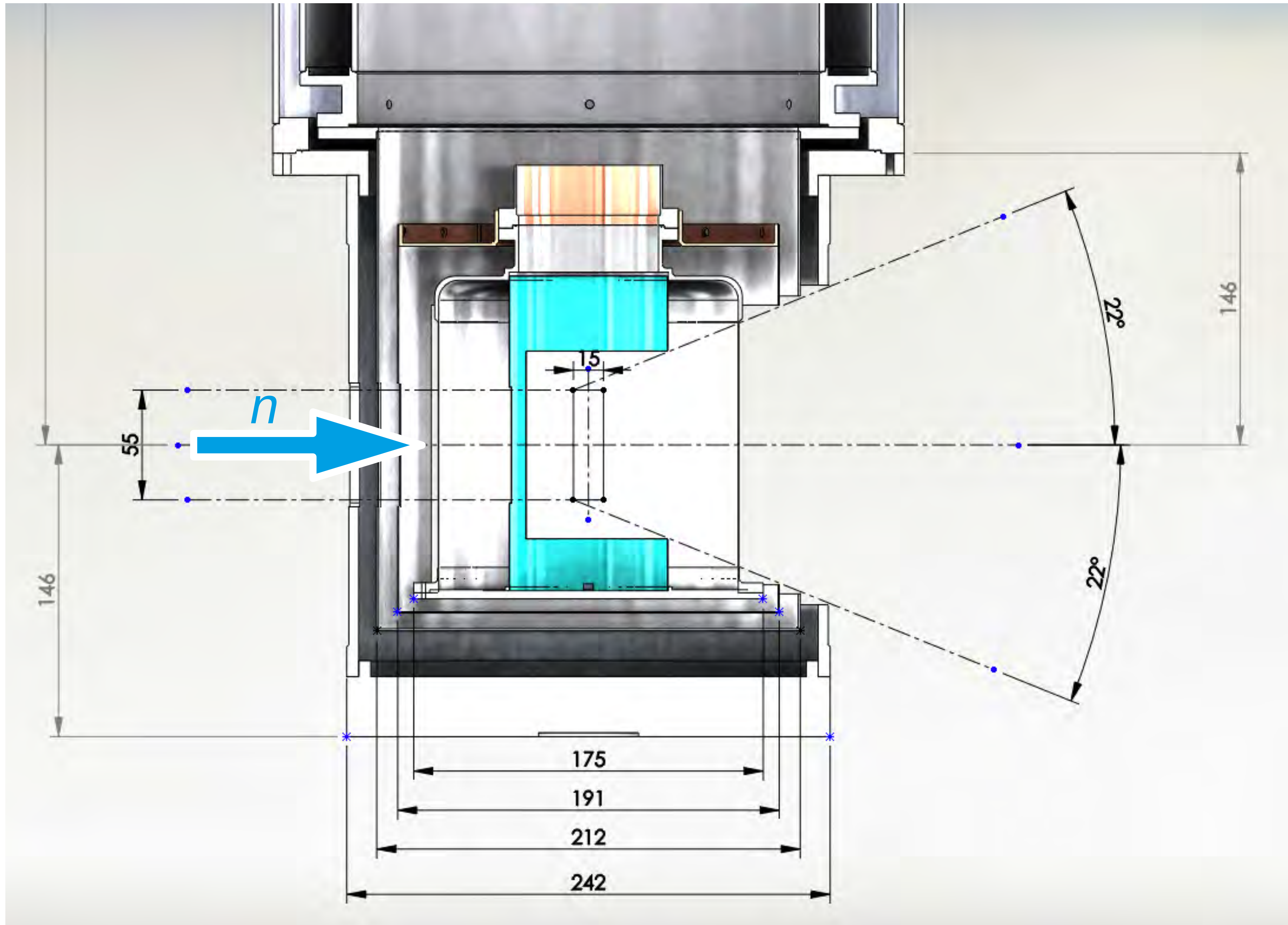
Low temperatures

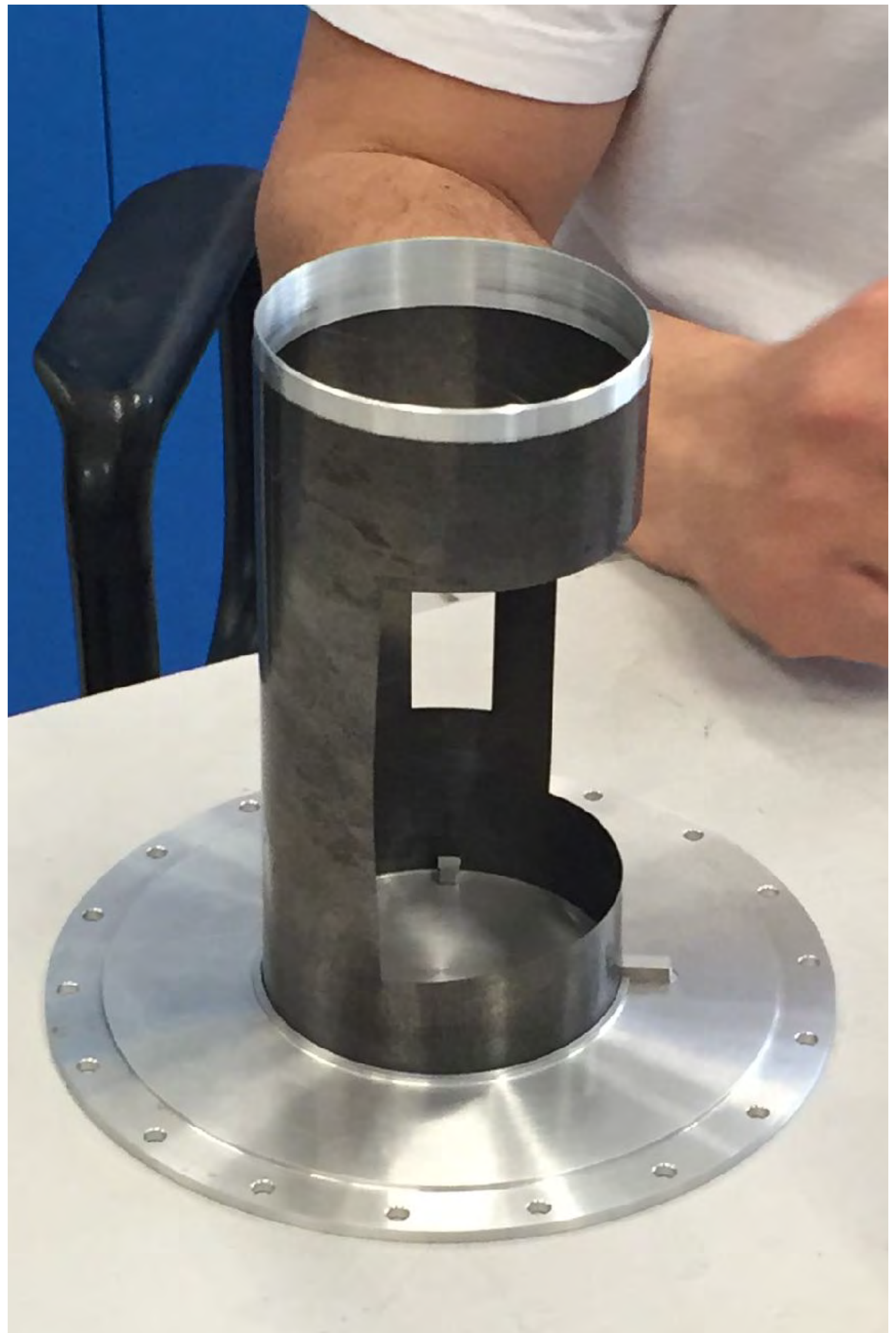
- He-flow cryostats
  - 1.5 / 2.8 to 320 K
  - Ø330-450 mm
- He-flow cryofurnaces
  - 1.5 to 550 / 650 K
  - Ø330-450 mm
- Dry cryostats (cryogen-free)
  - 1.8 to 320 K with JT
  - 2.7 to 620 K without JT



Sample environments

Low-background cryostat tail

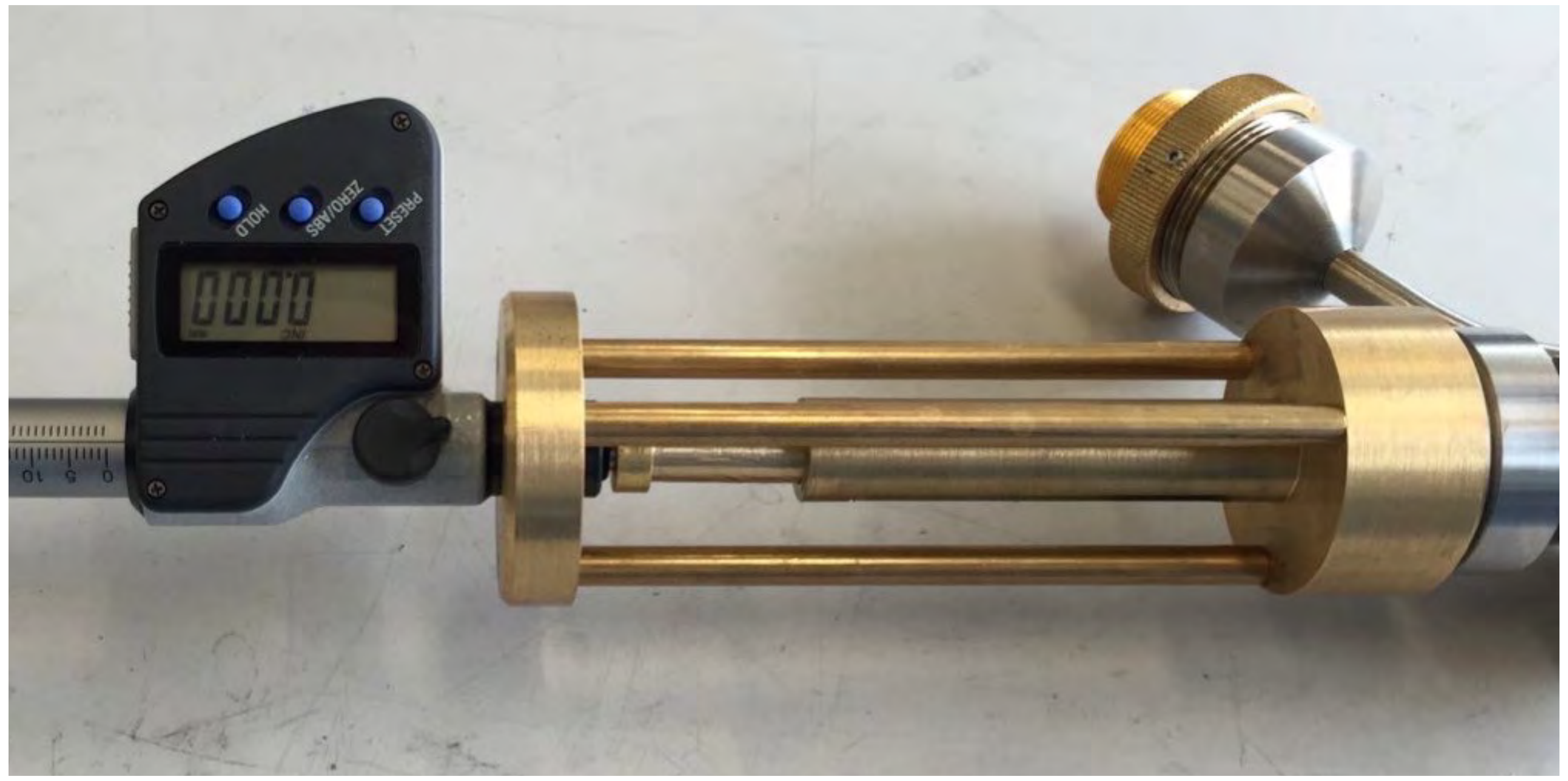


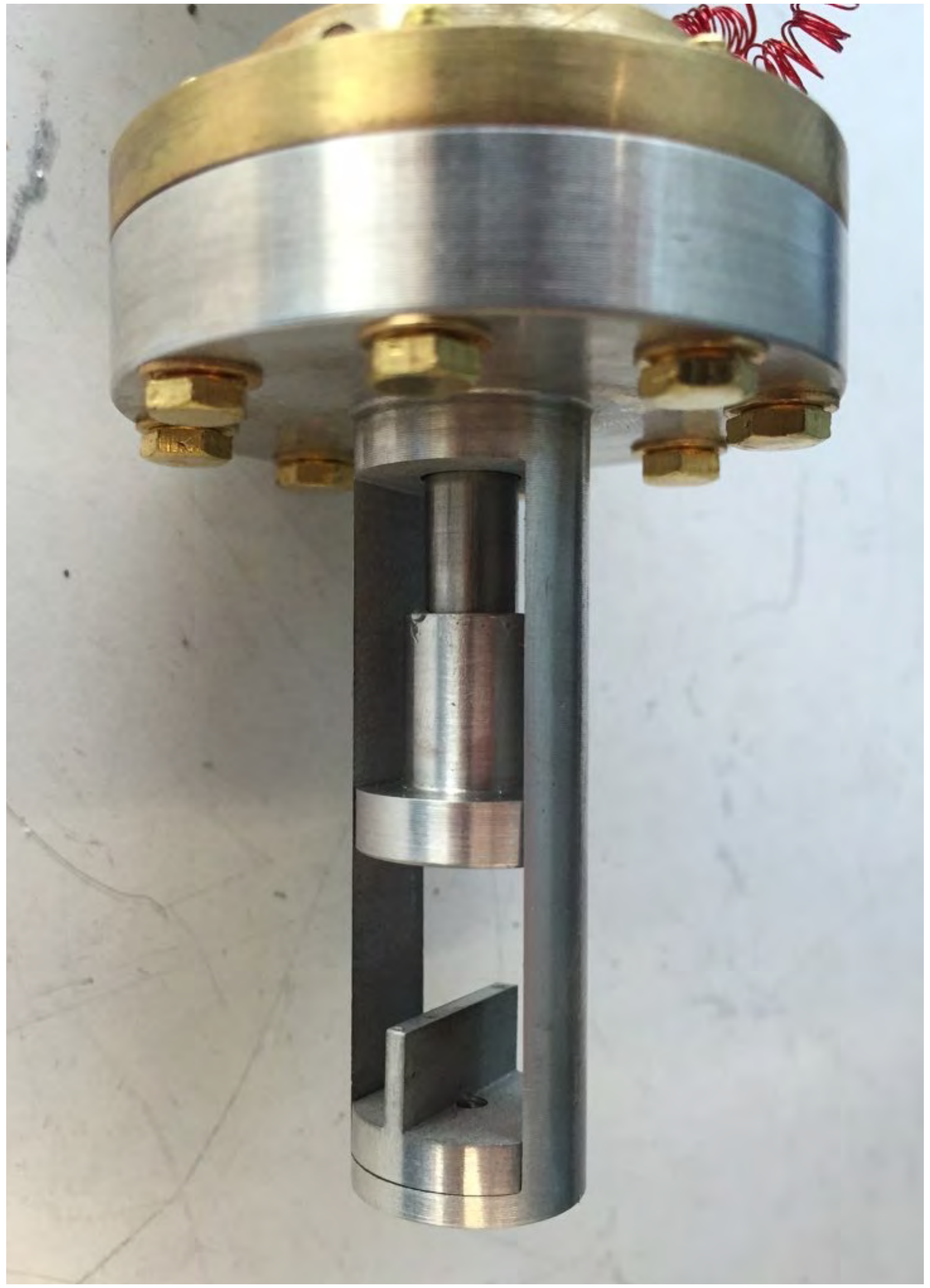


Sample environments

De-twin crystals remotely at low-T

- T-independent uniaxial pressure applied remotely
- 1.5 K base temperature
- 120 N max. force





Sample environments

Align crystals remotely at low-T

- Goniostick (licensed to IRELEC)
  - non-magnetic
  - ±7° sample tilting
  - ±0.02° reproducibility
  - ±10 mm vertical tuning
  - ±180° vertical rotation
  - fits inside >Ø36 mm bore cryostats/magnets
  - available inside cryostats and magnets

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Sample environments

Align crystals remotely at low-T

- Cryocradle
  - non-magnetic, fits inside zero-field polarimeter Cryopad
  - flexible arms to cancel backlash and manage thermal expansion

$$3 < T < 300\text{K}$$

$$-30 < \chi < +210°$$

$$-180 < \varphi < +180°$$

$$-40 < 2\theta < +120°$$

Sample environments

Ultra-low temperature systems

- ^{3}He fridges/inserts
  - down to 350 mK
- Dilution fridges/inserts
  - down to 15 or 40 mK
- Compact dilution fridge
  - down to 100 mK
- Large dilution cryostats
  - for high-pressure cells, complex environments

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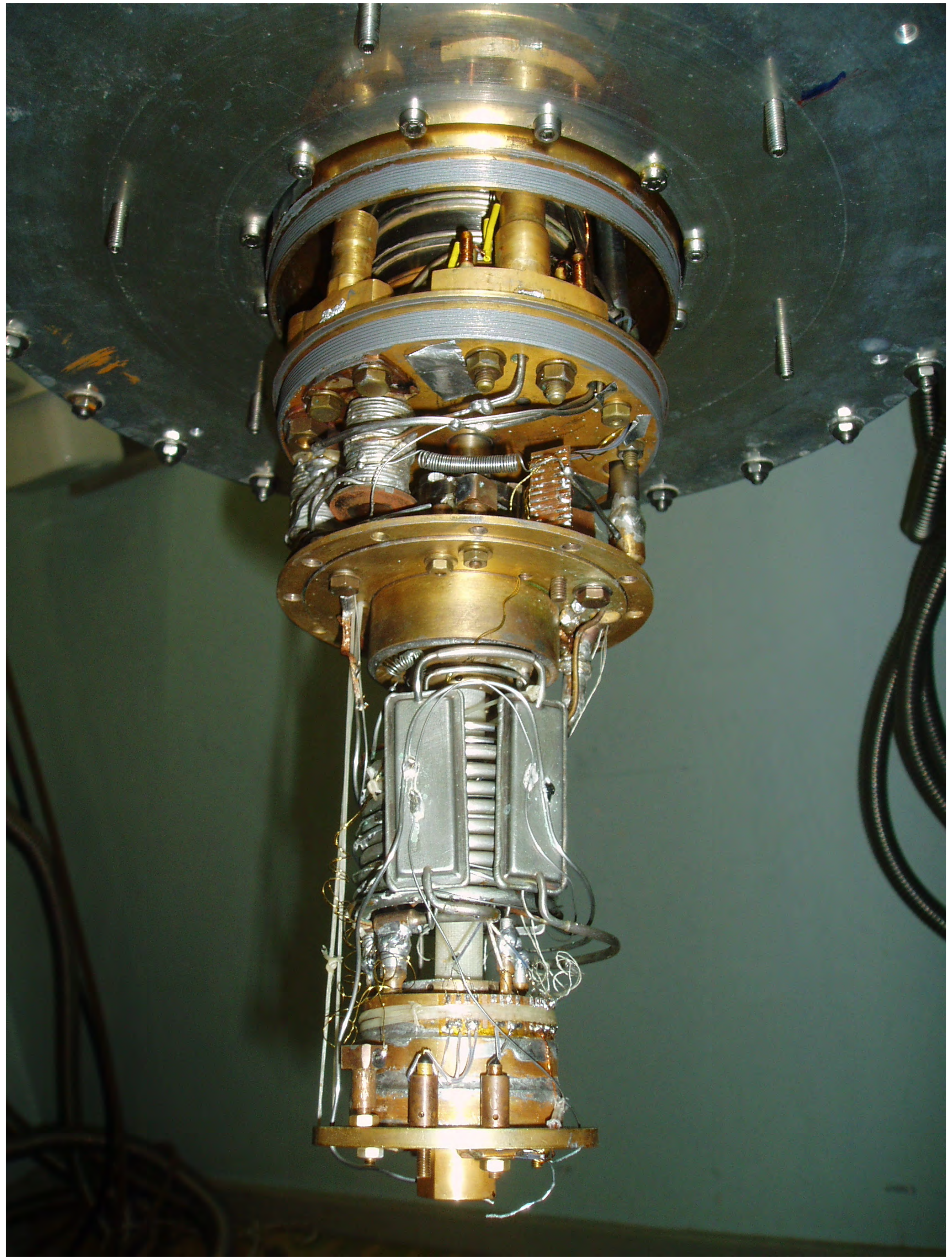

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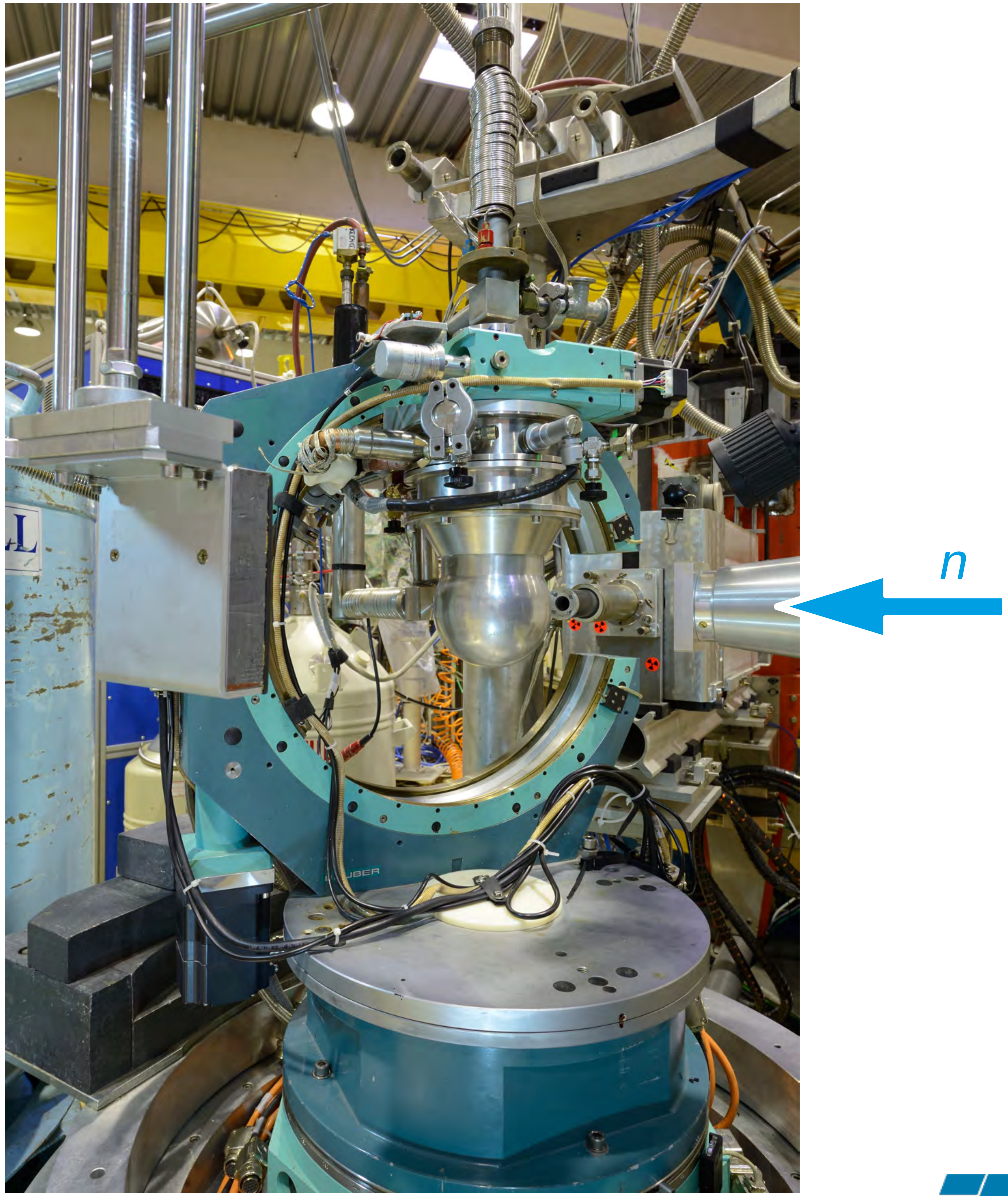
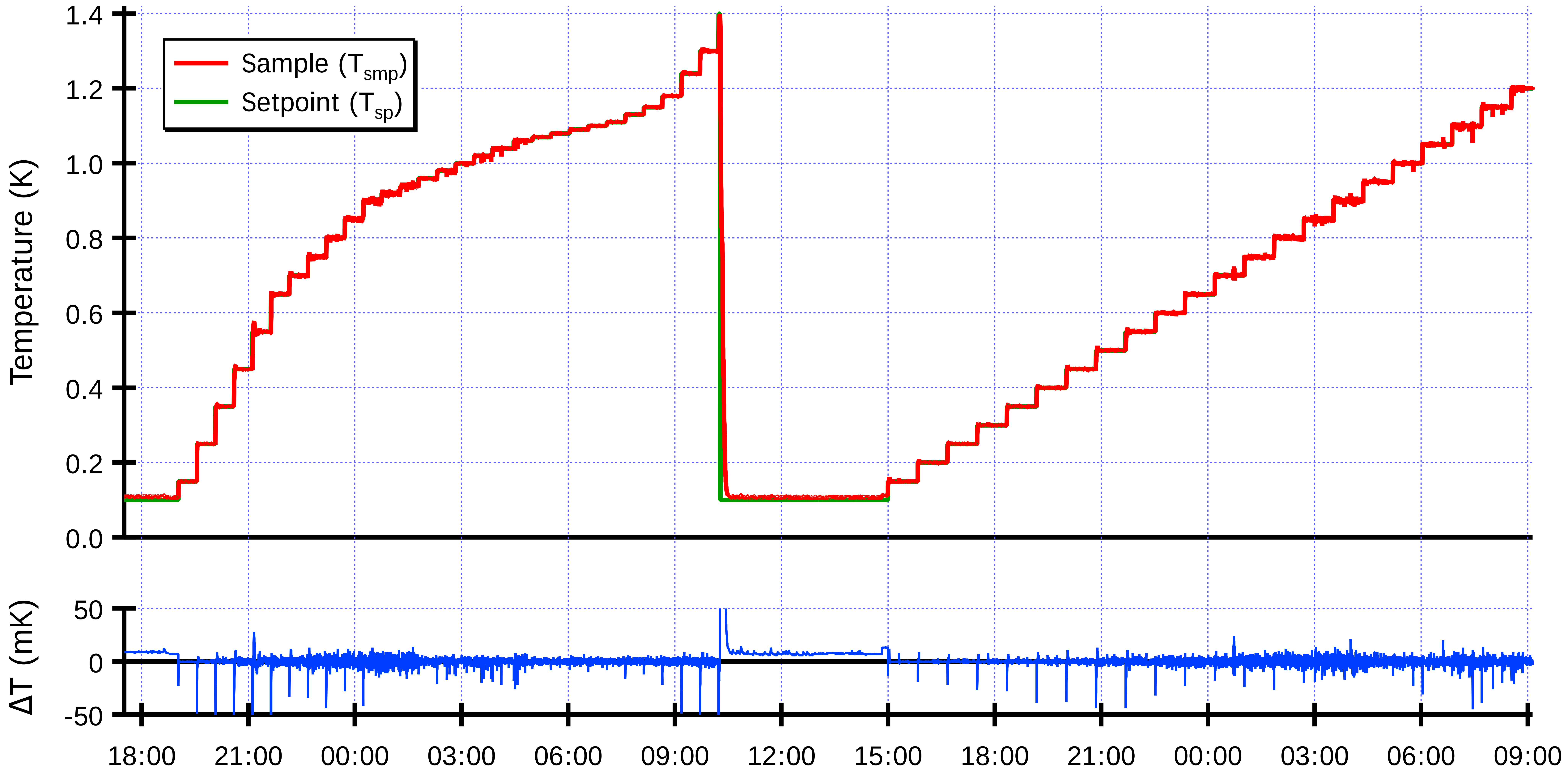


Sample environments

Gravity insensitive dilution refrigerator on D10 (ILL)



Sample environments

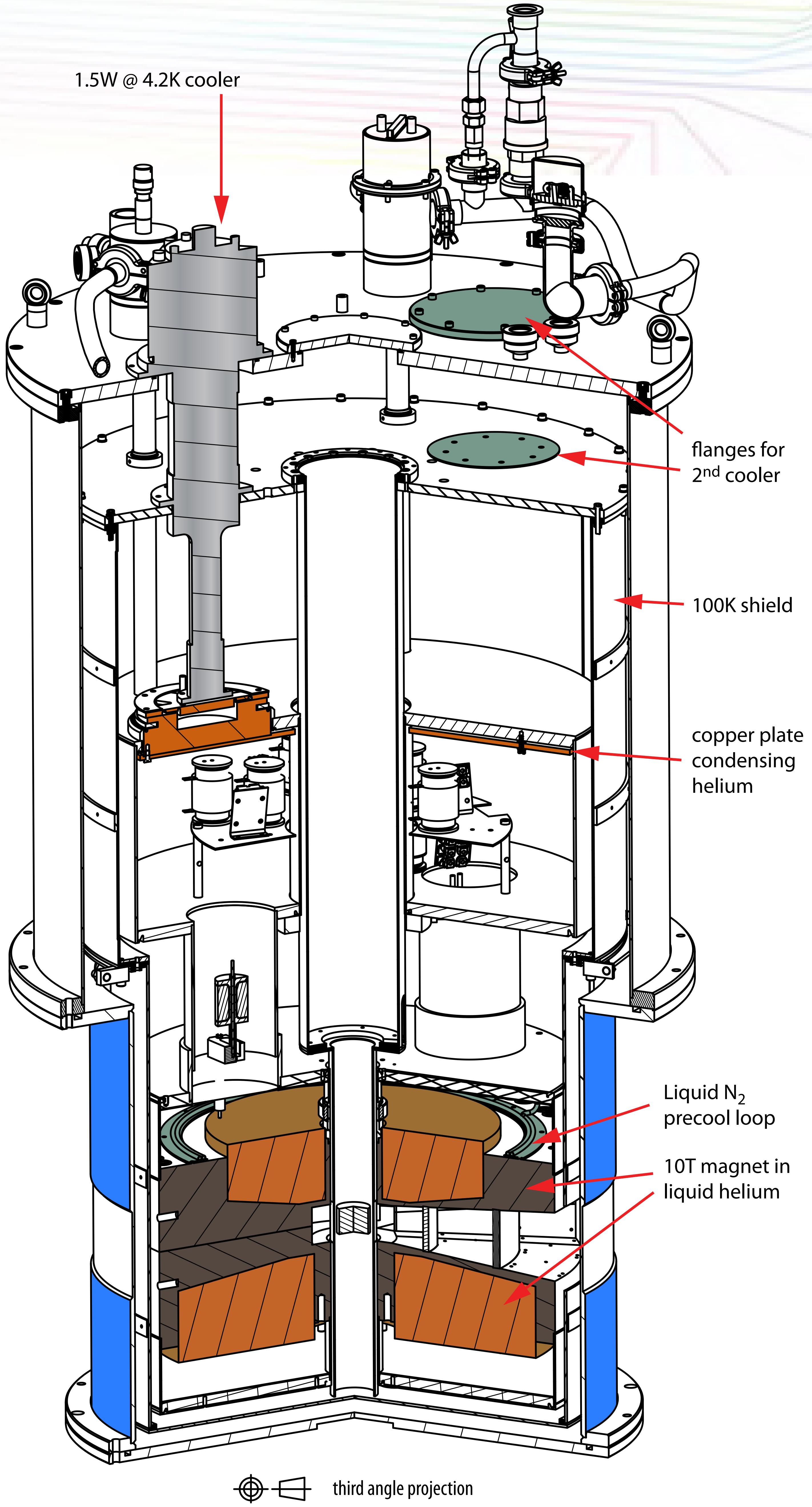
Standard resistive furnaces

- 320 to 2000 K
- V or Nb in beams
- automated control
- 2 and 3.5 kVA
- Ethernet
- 3 versions:
  - standard
  - cradle (single crystal diffraction)
  - sapphire windows (SANS)

Sample environments

Static high-field cryomagnets

- Vertical field (Ø800 mm)
  - up to 15T, top-loading
  - 40 mK dilution insert,
  - symmetric or asymmetric
  - self-shielded or not
  - 2T Dy booster + focusing
- Horizontal field (≈400 mm)
  - up to 17T, bottom-loading



Sample environments

40T pulsed-field cryomagnet

- Available at ILL through collaboration with CNRS/LNCMI Toulouse

  Ø8 mm sample

  2K base temperature

  ±15° incident horizontal access

  ±30° outgoing horizontal access

  ±7° outgoing vertical access

  … and 1.000L liquid N_2 / day at 40T

Sample environments

40T pulsed-field cryomagnet

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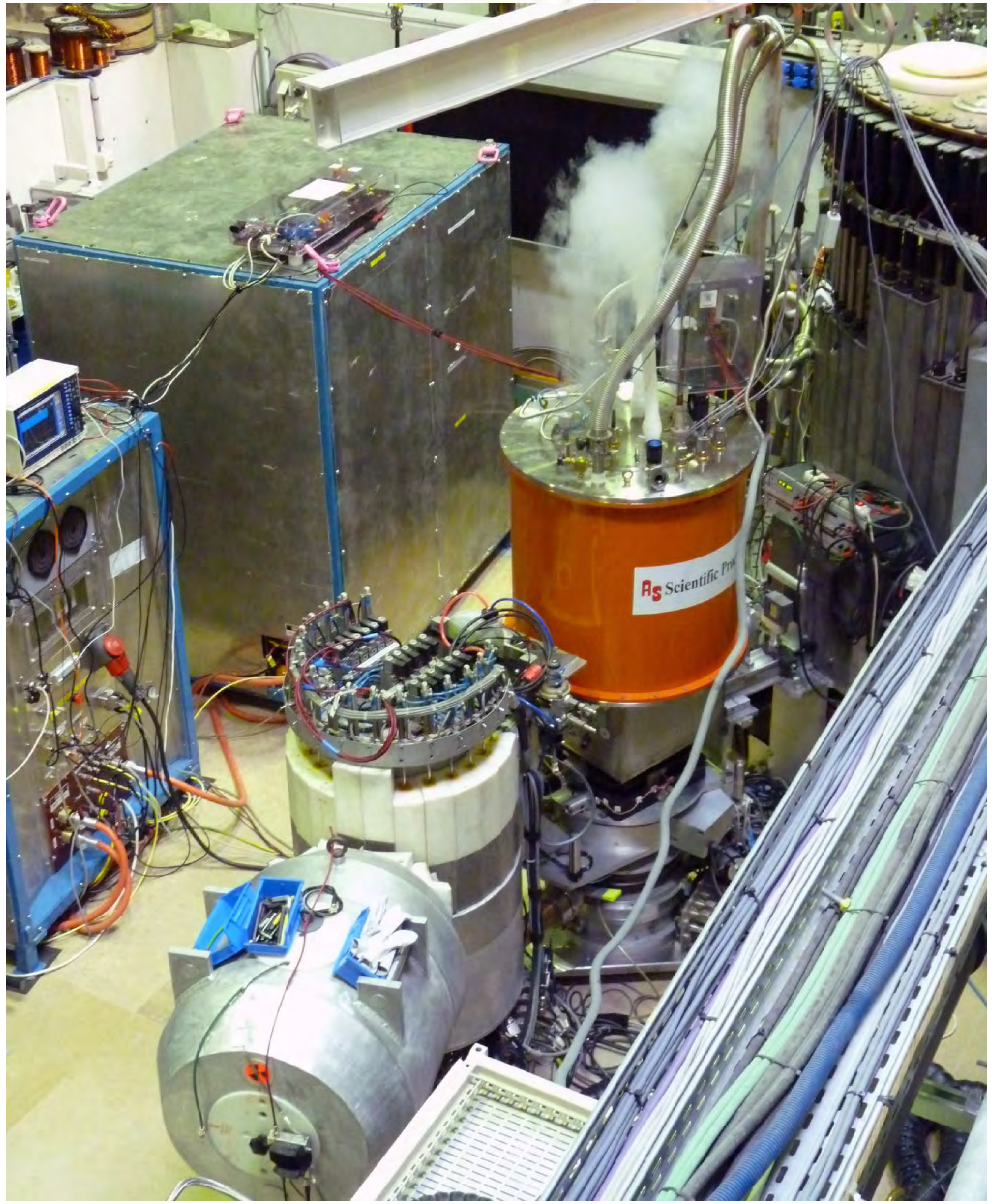
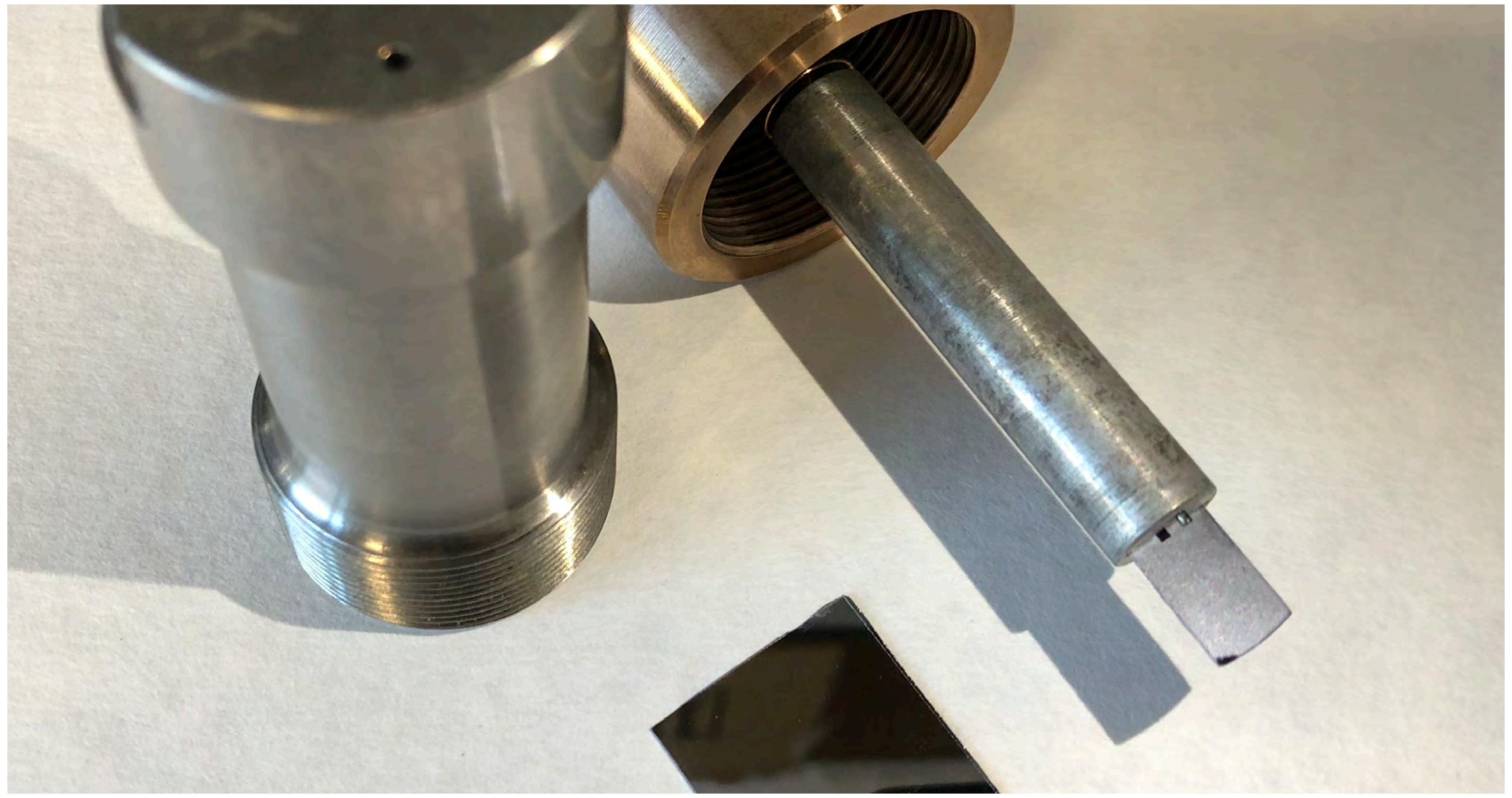


Sample environments

High-pressure cells for membrane layers and systems in solutions

- Al, TiZr and CuBe versions
- 250, 600 and 700 MPa cells
- compatible with "non-freezing" stick
- hosts samples on substrates



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Sample environments

300 and 500 MPa cells for SANS: 84% transmission at 6 Å

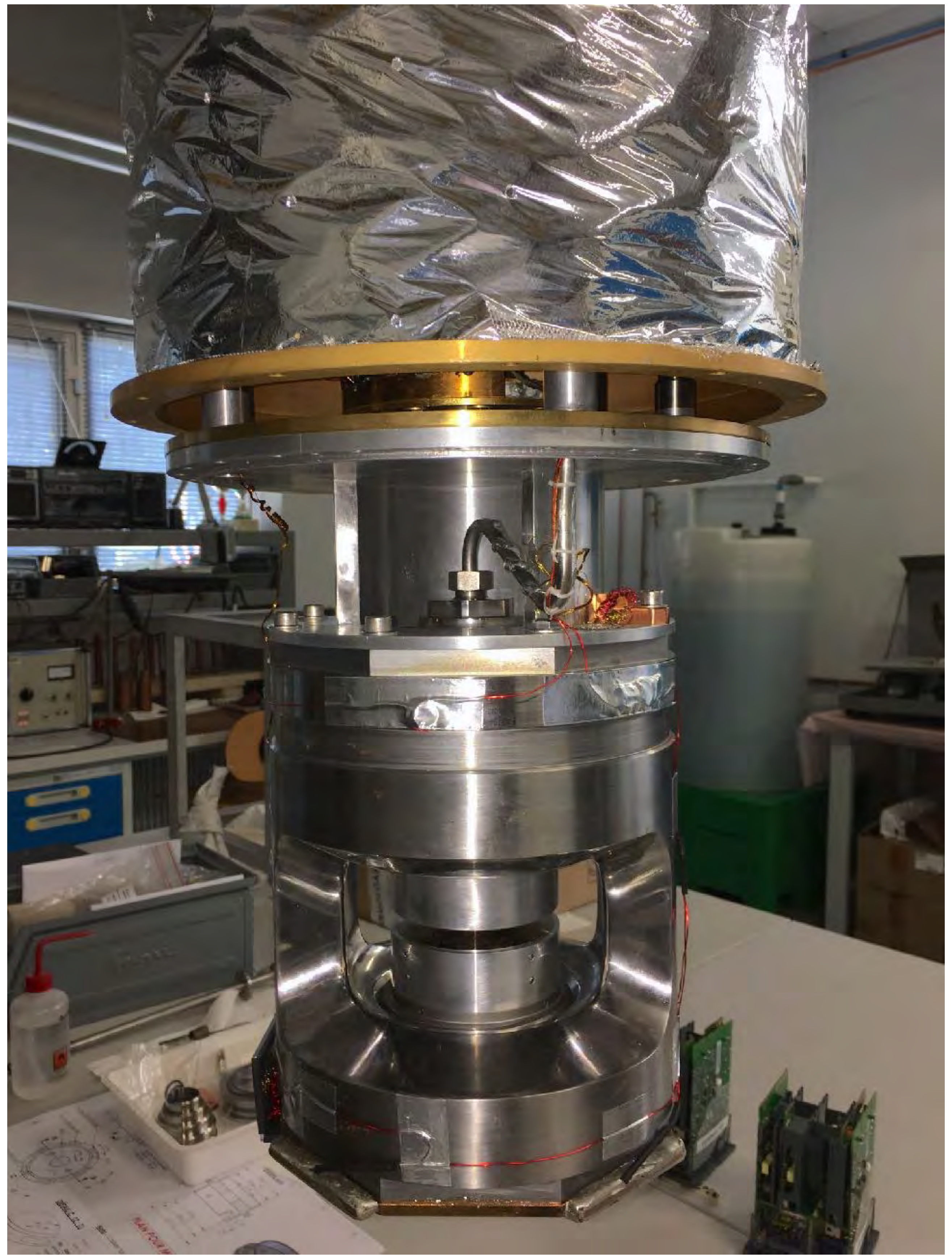
Project funded by the European Union (GA n°283883)

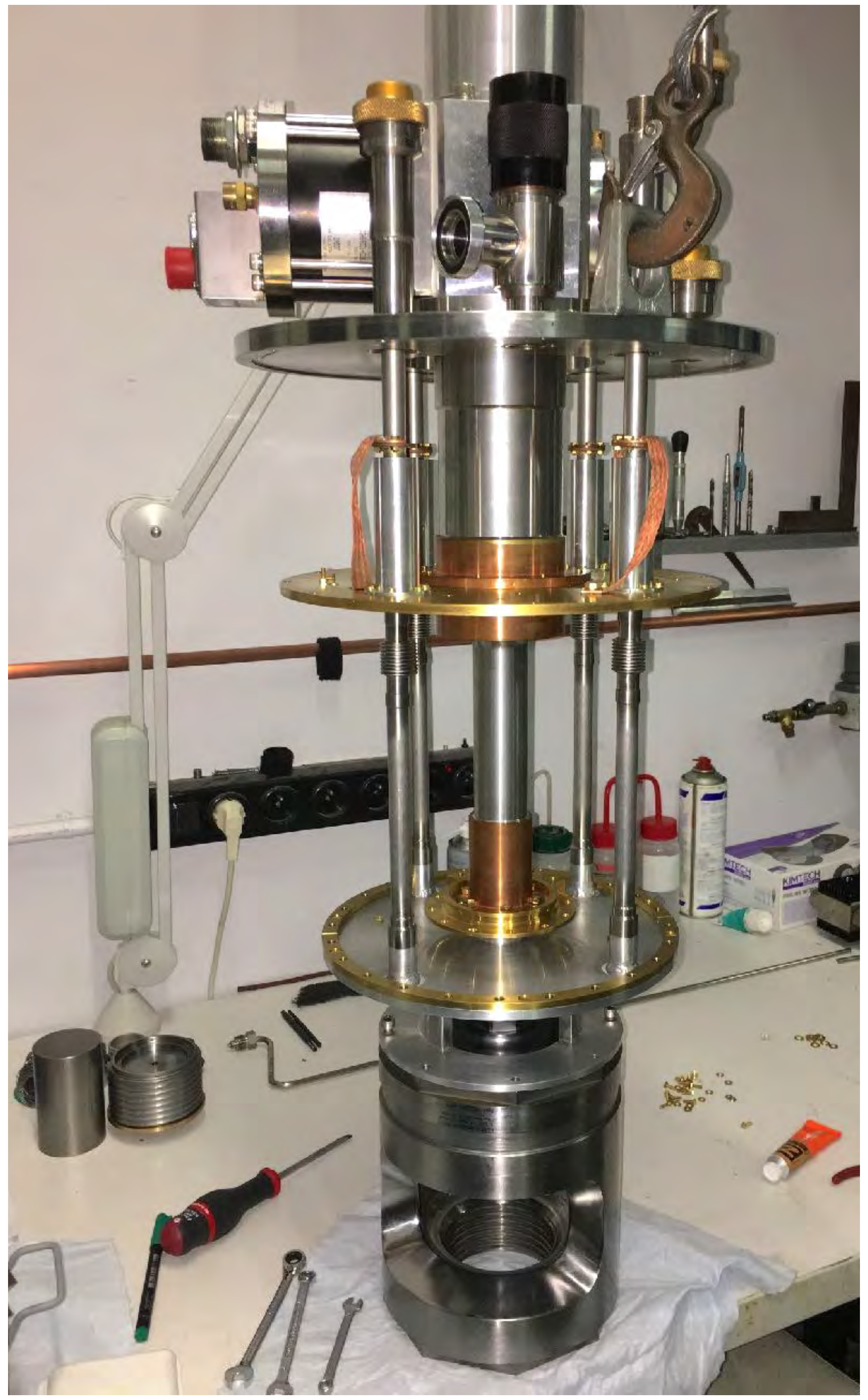
Sample environments

High-pressure at low-T for diffraction

- 23 GPa max
- Automated pressure & temperature control

300K → (2 hours) → 80K → (3 hours) → 4K → (30 min) → 1.8K for 7h





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Neutron instrumentation

- What do we measure and need ?
- Neutron guides & shielding
- Measuring techniques
- Sample environments
- Neutrons detectors
- Data acquisition system

Neutron detectors

Remarks…

- 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

Neutron detectors

Common charged particle detector types

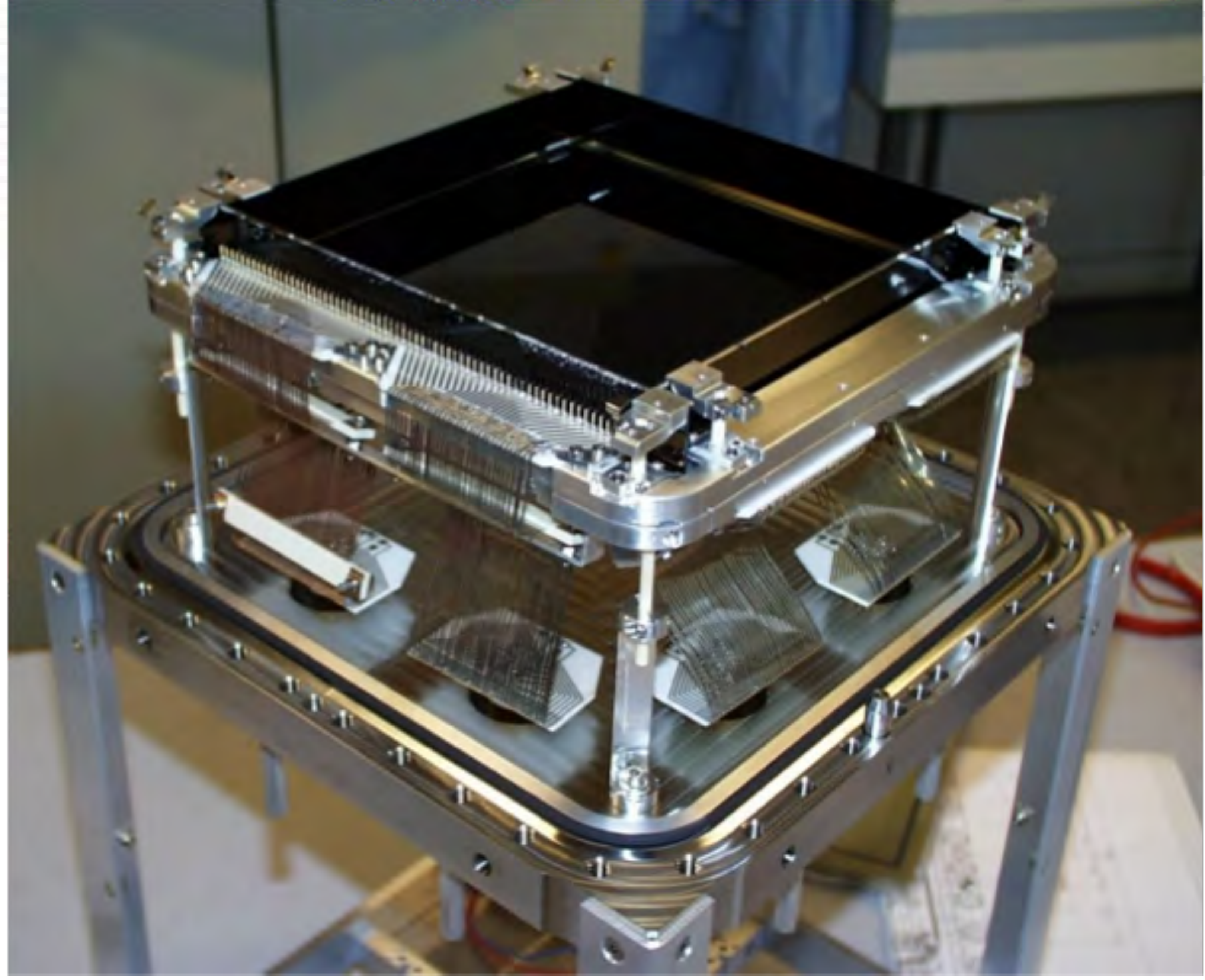
- Ionisation mode: Electrons drift to anode, producing a charge pulse with no gas multiplication. Typically employed in low-efficiency beam-monitor detectors.
- Proportional mode: If voltage high enough, electron collisions ionise gas atoms producing even more electrons. Gas amplification increases the collected charge.
- Other techniques: CCD cameras, image plates (Laue), scintillation detectors, boron detectors.

Neutron detectors

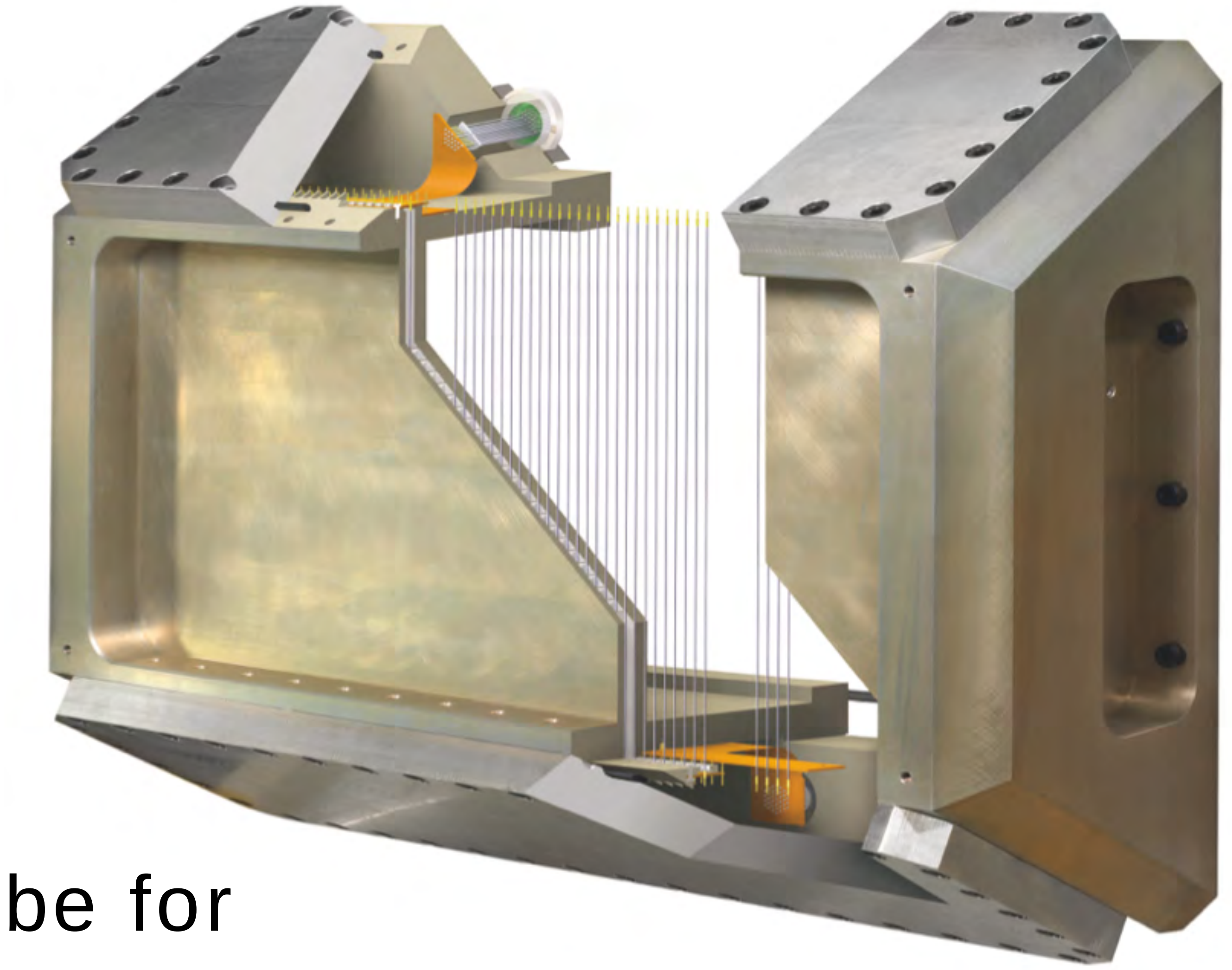
- Spatial resolution is “generally” not an issue, in the range of 1-10 mm i.e. ≈ sample size
- Fast neutrons, electronics and gammas lead to background noise. Counting mode is more appropriate than integrating mode.
- High detection efficiency required for scattered neutrons, low efficiency enough for incident beam.

Neutron detectors

19x19 cm² high res, high count rate for diffraction

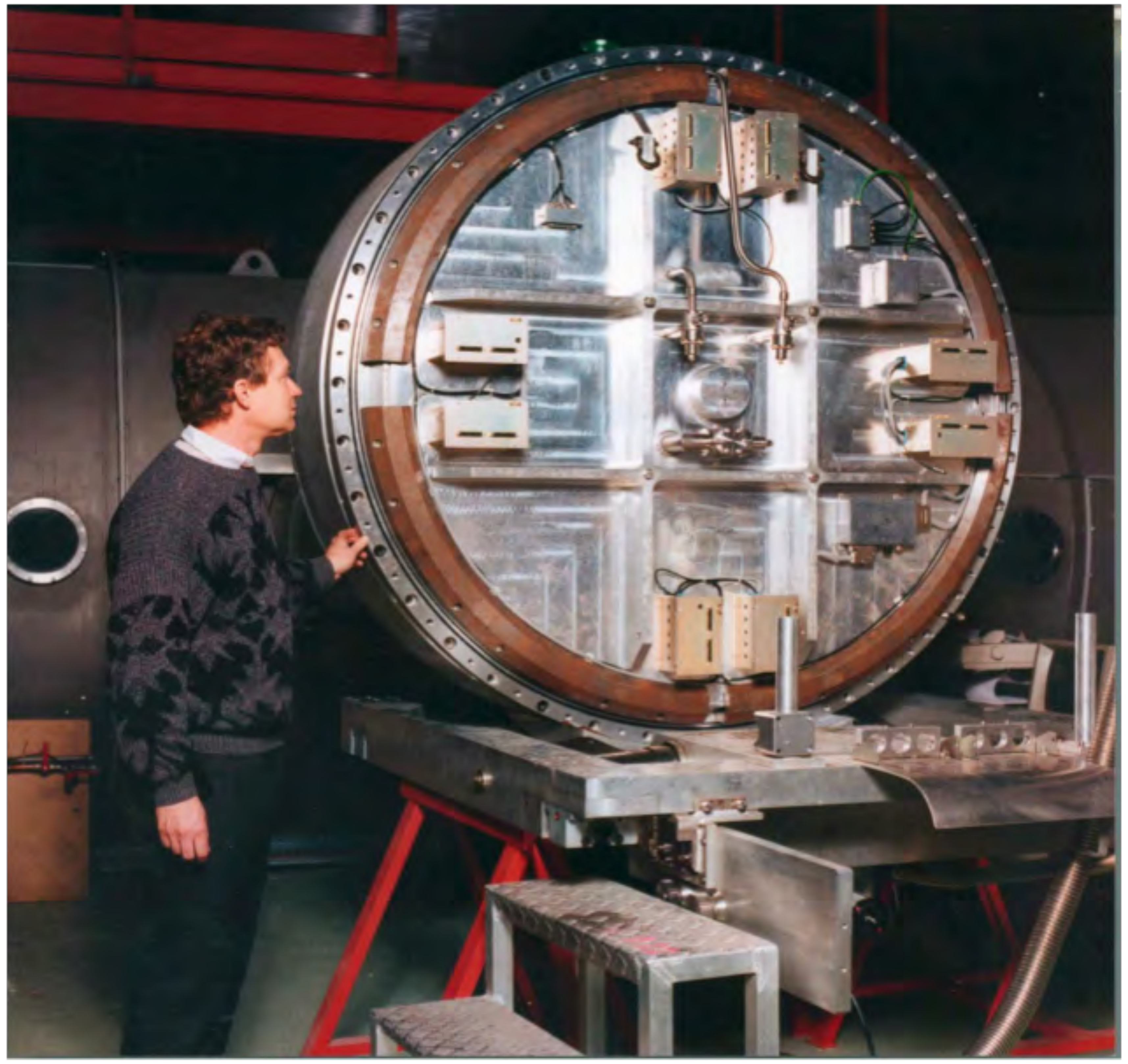


30 m² low-res, low count rate for time of flight

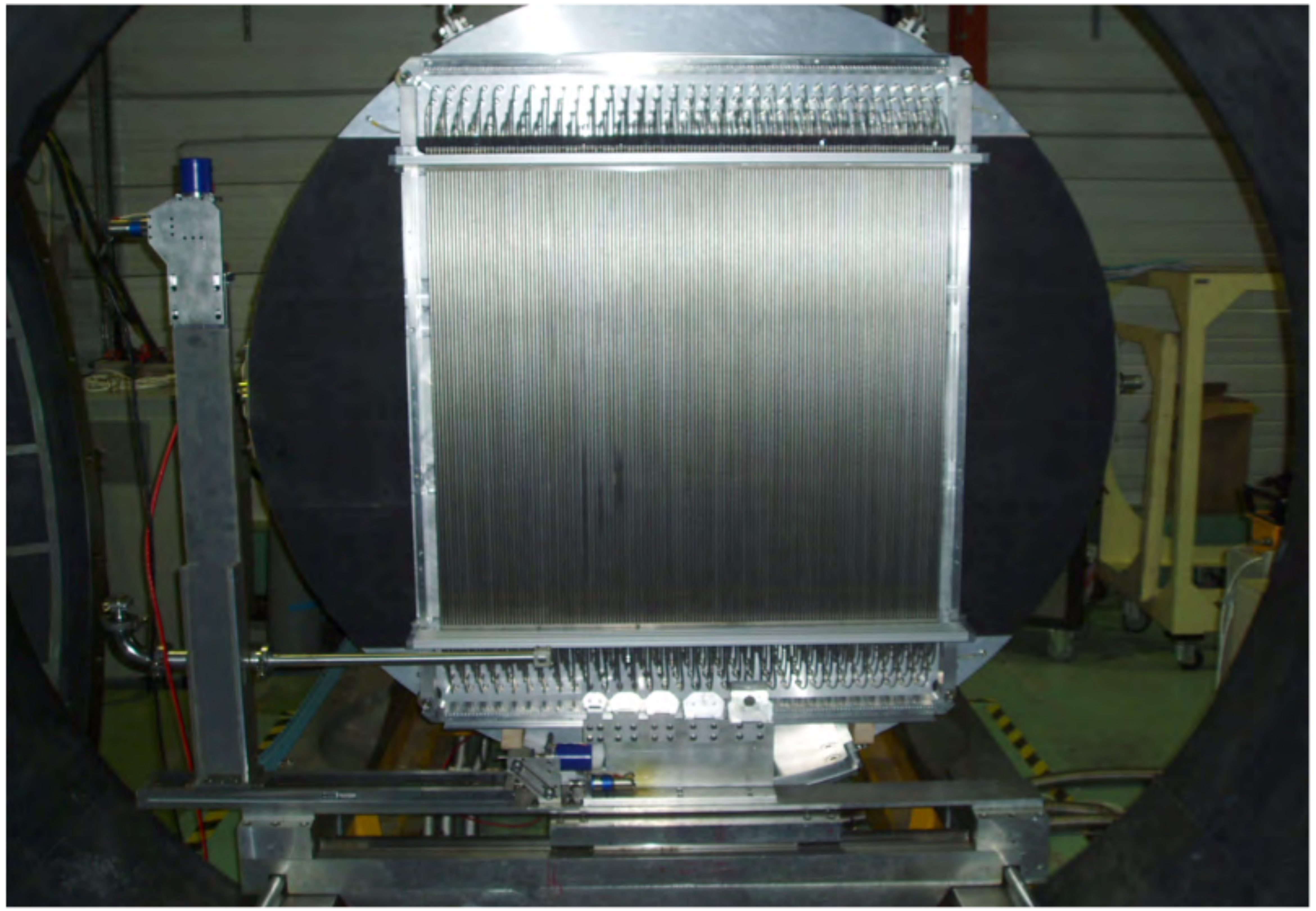


Monobloc multitube for Reflectometry, SANS

Neutron detectors



Old XY counter — 200 kHz max



New 128 PSD counter — 10 MHz max


160° @ 0.1° resolution

Neutron instrumentation

- What do we measure and need ?
- Neutron guides & shielding
- Measuring techniques
- Sample environments
- Neutrons detectors
- Data acquisition system

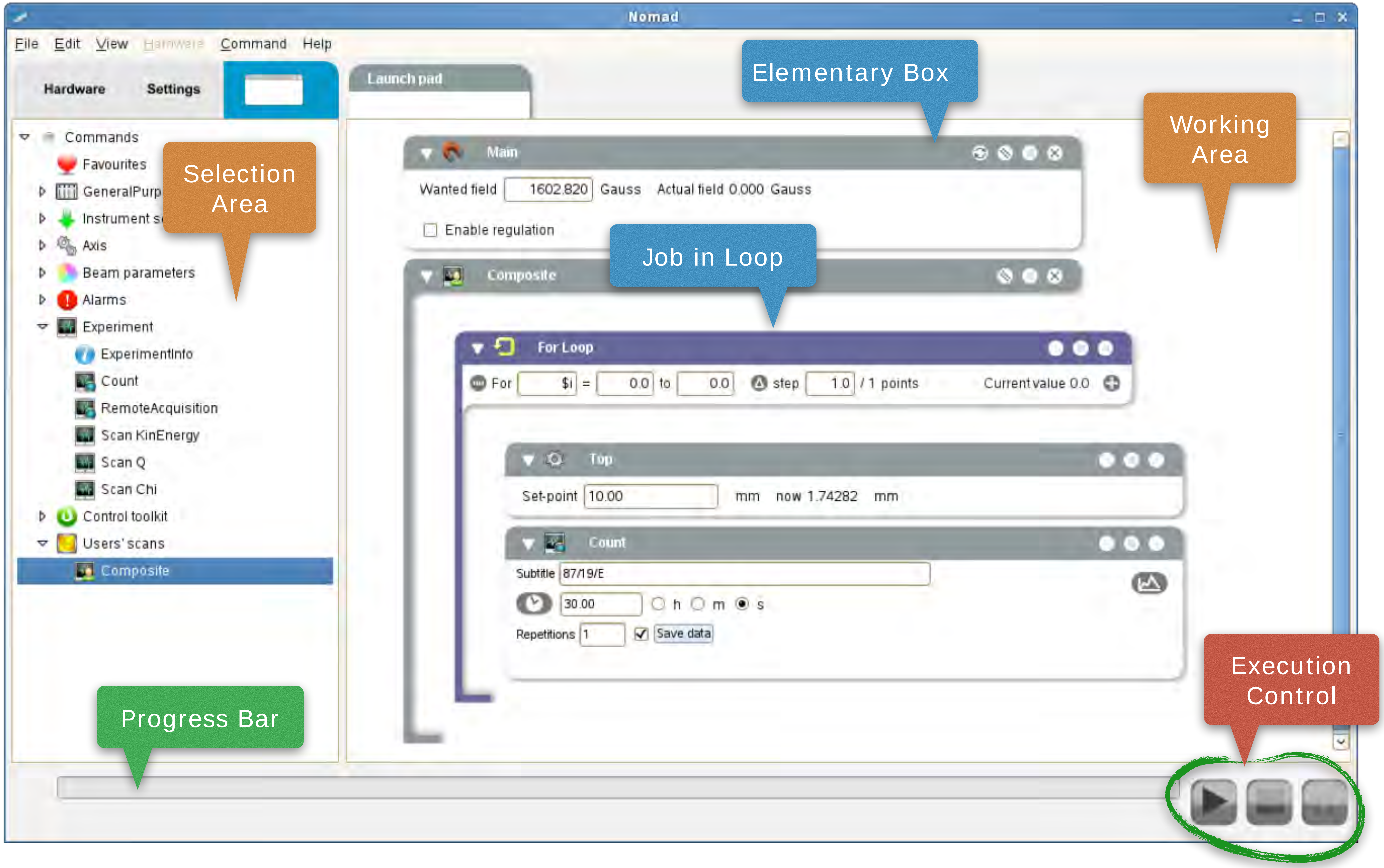
Data acquisition hardware

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

Data acquisition software

- Speaks in physical units
- 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, executes jobs safely
- Provides command-line tools, remote access, etc.

Data acquisition software



Special thanks to...

I. Anderson — ORNL (USA)

P. Courtois — Neutron Optics, ILL

B. Guérard — Neutron Detectors, ILL

M. Kreuz — Neutron Guides, ILL

P. Mutti — Instrument control, ILL

... and you!