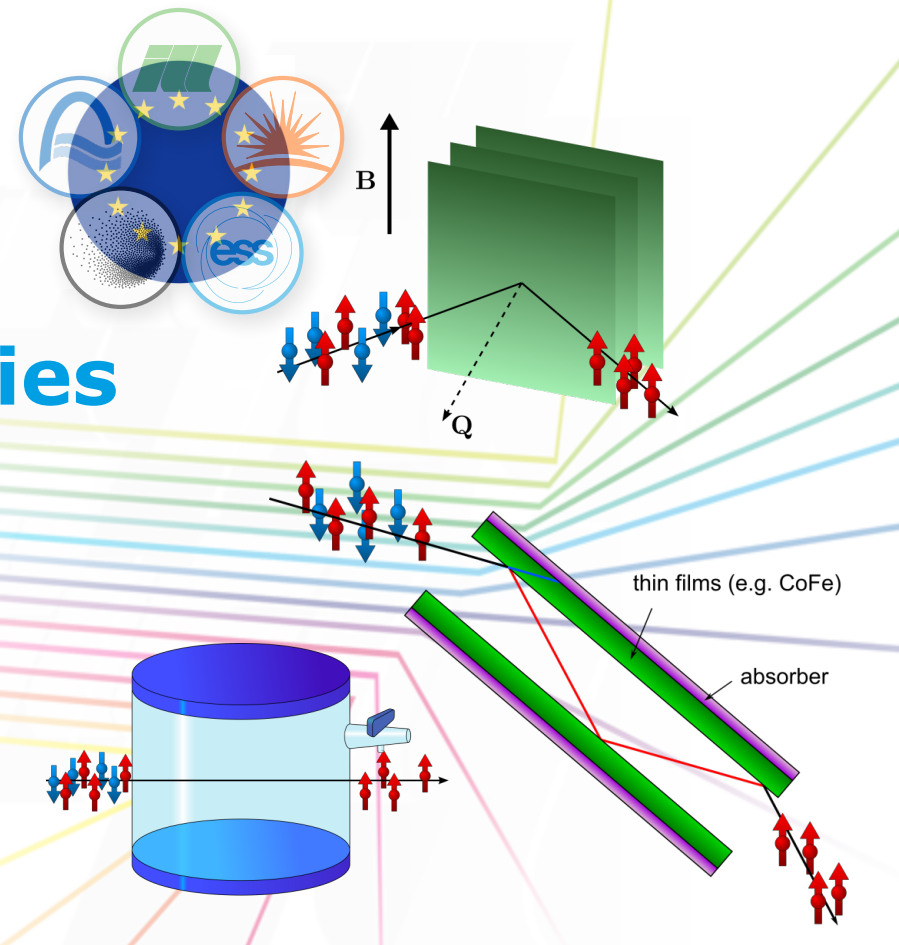


Polarization capabilities

at neutron facilities

in Europe

Navid Qureshi



Outline

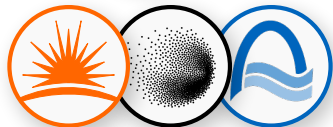
Content of the presentation



History of polarized neutrons *(thanks to E. Lelièvre-Berna)*



Polarized neutrons instruments at the ILL



Polarized neutrons instruments at other European facilities



The future at the ESS



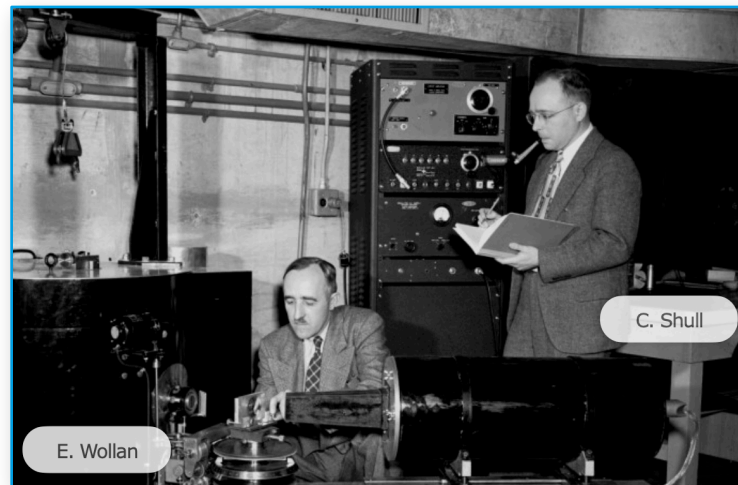
Conclusions



History of polarized neutrons

The pre-ILL period

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- **1963** General theory of neutron polarization analysis by M. Blume and S. Maleev
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$$\frac{1}{2}\mathbf{P}_f \frac{d\sigma}{d\Omega'} = \frac{1}{2}\mathbf{P} \left| \sum_n e^{i\mathbf{K}\cdot\mathbf{n}} |F_N(\mathbf{K})|^2 - \frac{1}{2}\mathbf{P}N \sum_j \left(\frac{1}{3}\langle\{a_j^2\}\rangle - \frac{1}{3}\langle\{a_j\}^2\rangle + \langle\{a_j\}\rangle^2 \right) + \frac{1}{2}\left(\frac{\gamma e^0}{mc^2}\right) \sum_{n_j, n'_j} \exp[i\mathbf{K}\cdot(\mathbf{R}_{n_j} - \mathbf{R}_{n'_j})] \right. \\ \times \left(\langle\{a_j\}\rangle S_{n_j} f_{n_j}(\mathbf{K}) \mathbf{q}_{n_j} + \langle\{a_j\}\rangle S_{n'_j} f_{n'_j}^*(\mathbf{K}) \mathbf{q}_{n'_j} - i\langle\{a_j\}\rangle S_{n_j} f_{n_j}(\mathbf{K}) (\mathbf{P} \times \mathbf{q}_{n_j}) \right. \\ \left. \left. + i\langle\{a_j\}\rangle S_{n'_j} f_{n'_j}^*(\mathbf{K}) (\mathbf{P} \times \mathbf{q}_{n'_j}) \right) + \frac{1}{2}\left(\frac{\gamma e^0}{mc^2}\right)^2 \sum_{n_j, n'_j} \exp[i\mathbf{K}\cdot(\mathbf{R}_{n_j} - \mathbf{R}_{n'_j})] S_{n'_j} S_{n_j} f_{n'_j}^*(\mathbf{K}) f_{n_j}(\mathbf{K}) \right. \\ \left. \times \left(-i(\mathbf{q}_{n'_j} \times \mathbf{q}_{n_j}) + \mathbf{q}_{n'_j} (\mathbf{P} \cdot \mathbf{q}_{n_j}) + (\mathbf{P} \cdot \mathbf{q}_{n'_j}) \mathbf{q}_{n_j} - \mathbf{P} (\mathbf{q}_{n'_j} \cdot \mathbf{q}_{n_j}) \right) \right.$$

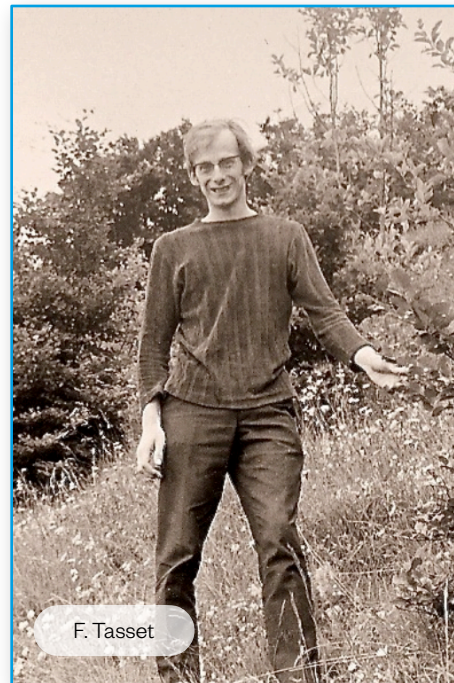
Blume (1963) *Phys. Rev.* **130** 1670



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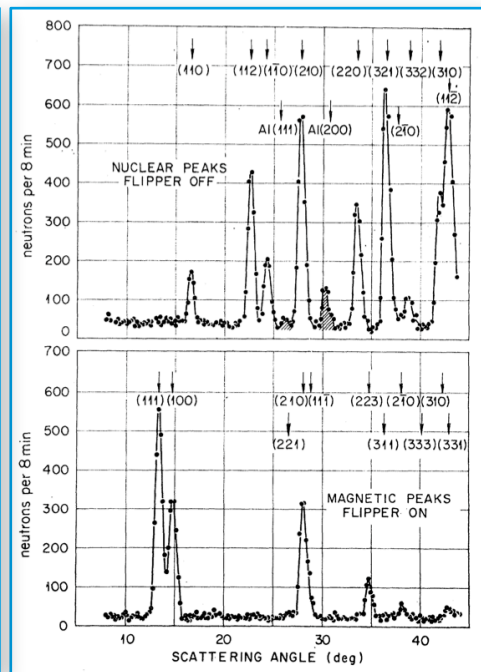
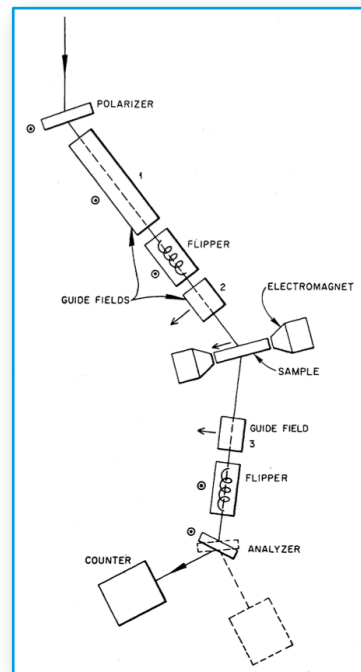




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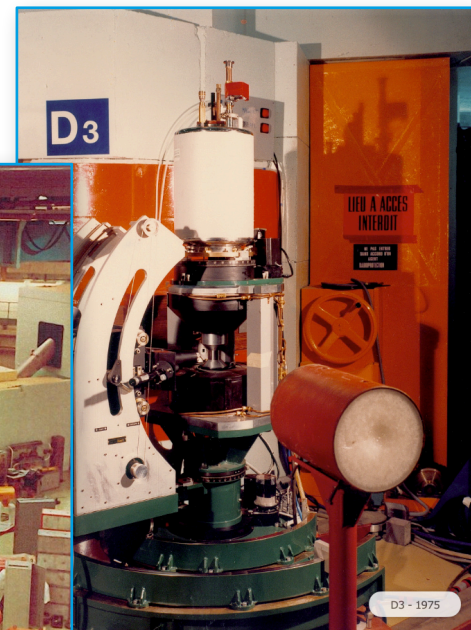
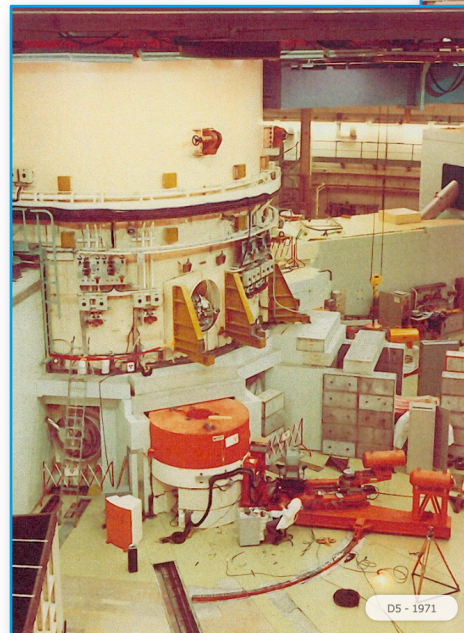
Moon et al. (1969) *Phys. Rev.* **181** 920



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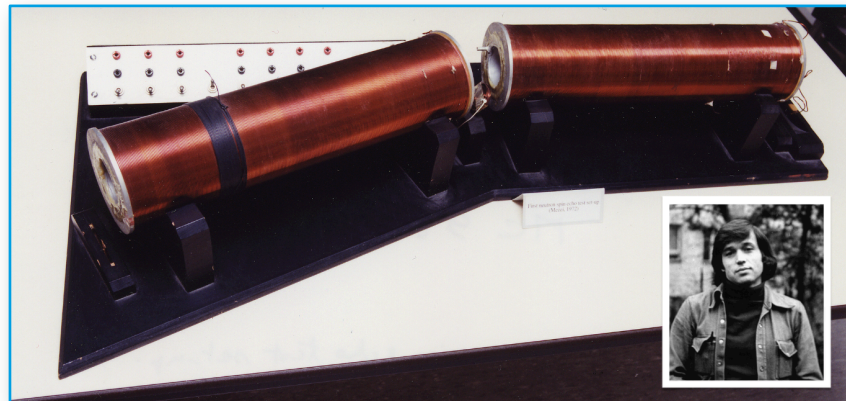




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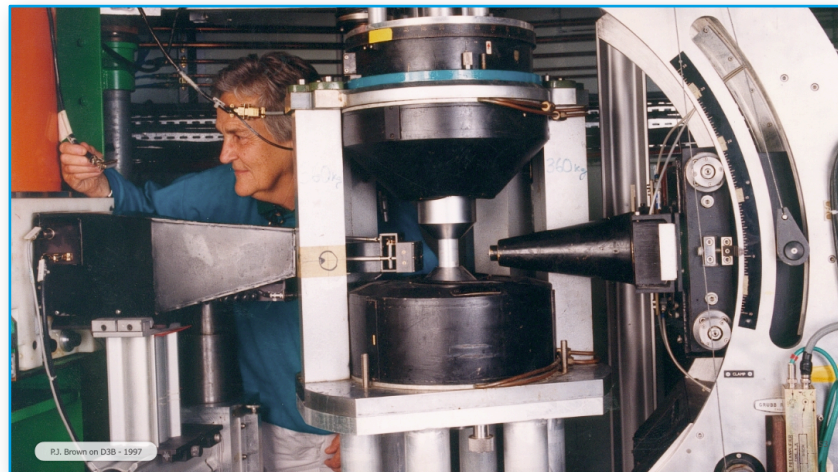




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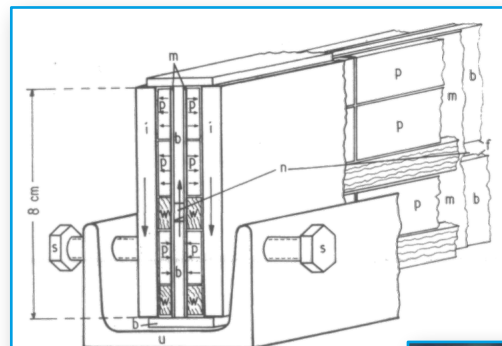
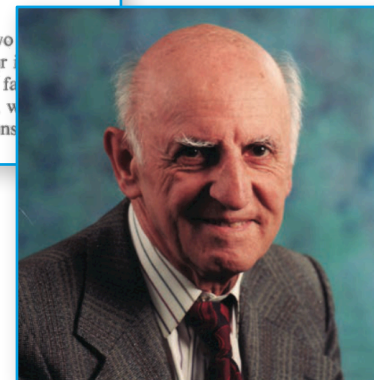


Figure 1 Setup of the neutron guide using two U-profiles. Arrows show the direction of magnetic field or neutron path. p, permanent magnets; b, brass with polished faces; f, mirror sheet; U, U profile; i, iron strip; w, shielding; n, cross section accessible to neutrons for adjustment of curvature





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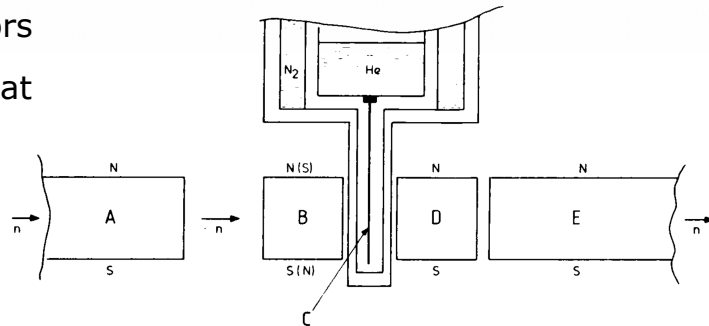


FIG.10. Non-adiabatic spin flipper system that uses an isolating sheet of superconducting niobium [23] (see text).

Forsyth (1979) *At. Energy Rev.* **17** 367



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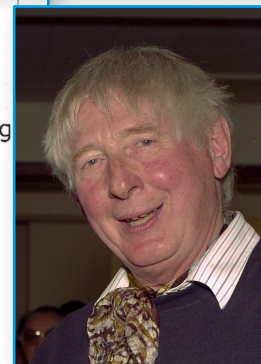
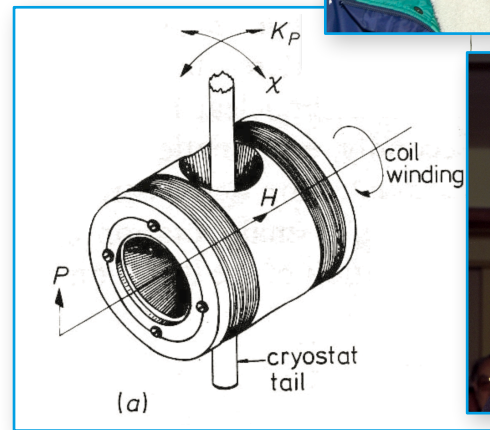




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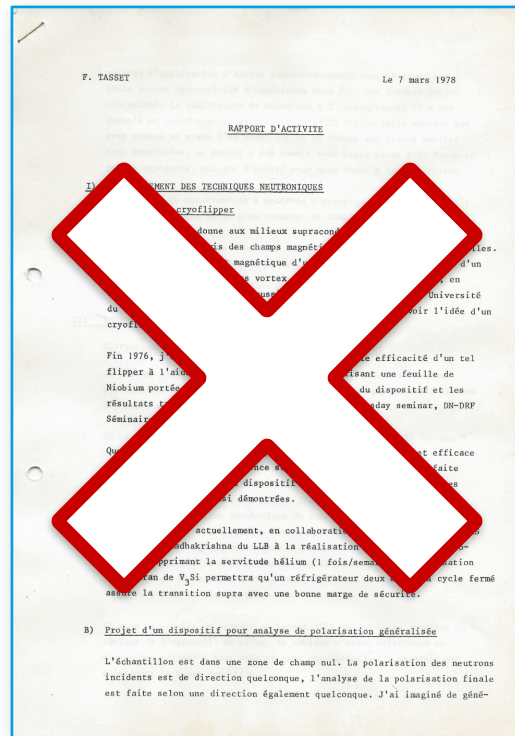




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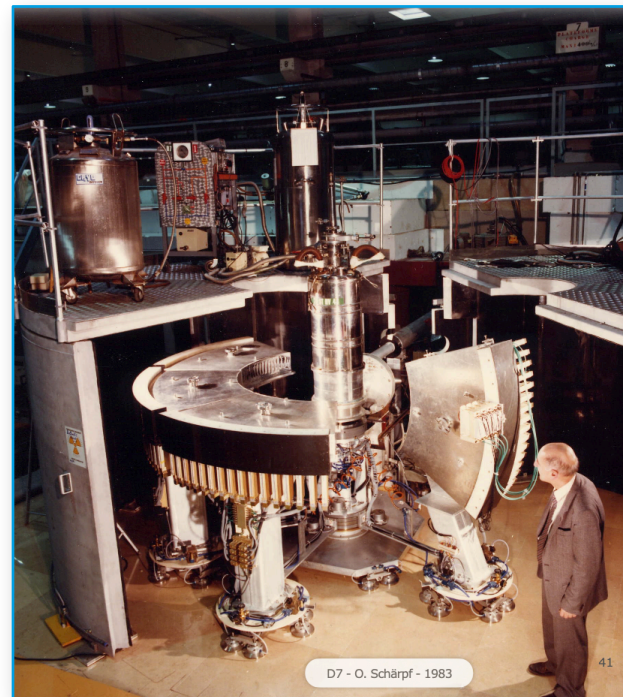




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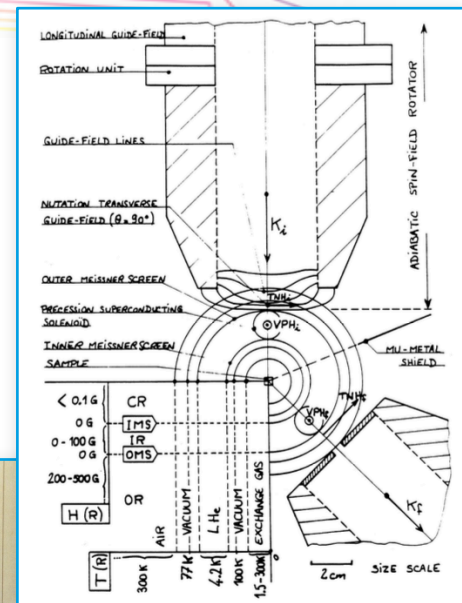




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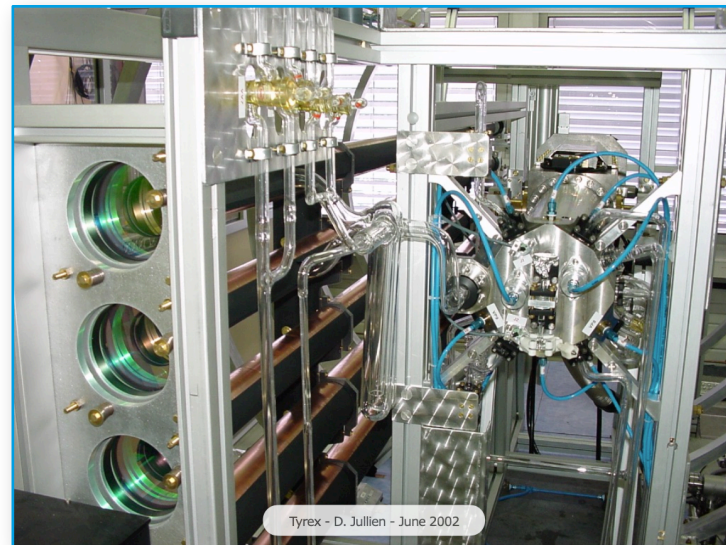
S. Pujol checking the alignment of the precession coils



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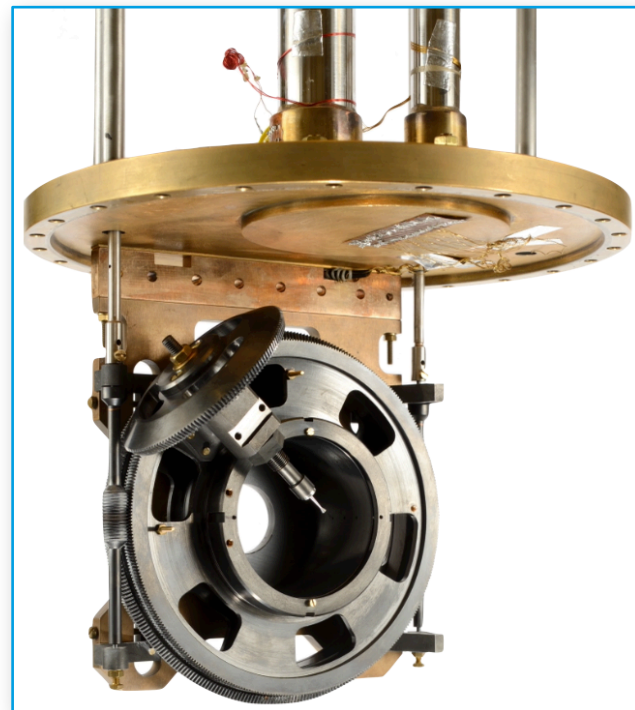




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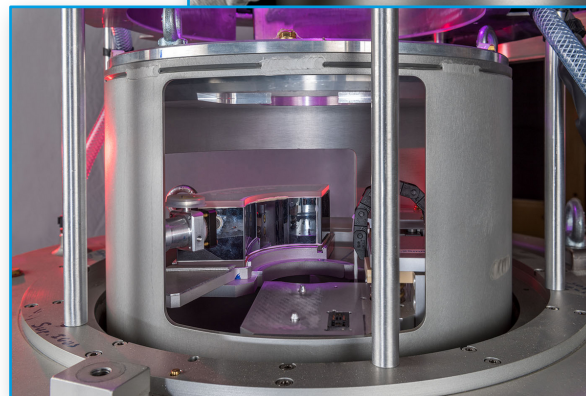




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Polarized neutrons at the ILL

Institut Laue-Langevin (Grenoble, France)



Diffraction

- **D3** - Spin-polarized hot neutron diffractometer
- **D007** - Diffuse scattering diffractometer

Spectroscopy

- **ThALES** - Cold triple-axis spectrometer
- **IN12** - Cold triple-axis spectrometer
- **IN20** - Thermal triple-axis spectrometer
- **IN22** - Thermal triple-axis spectrometer
- **WASP** - Neutron Spin Echo spectrometer
- **IN15** - Neutron Spin Echo spectrometer

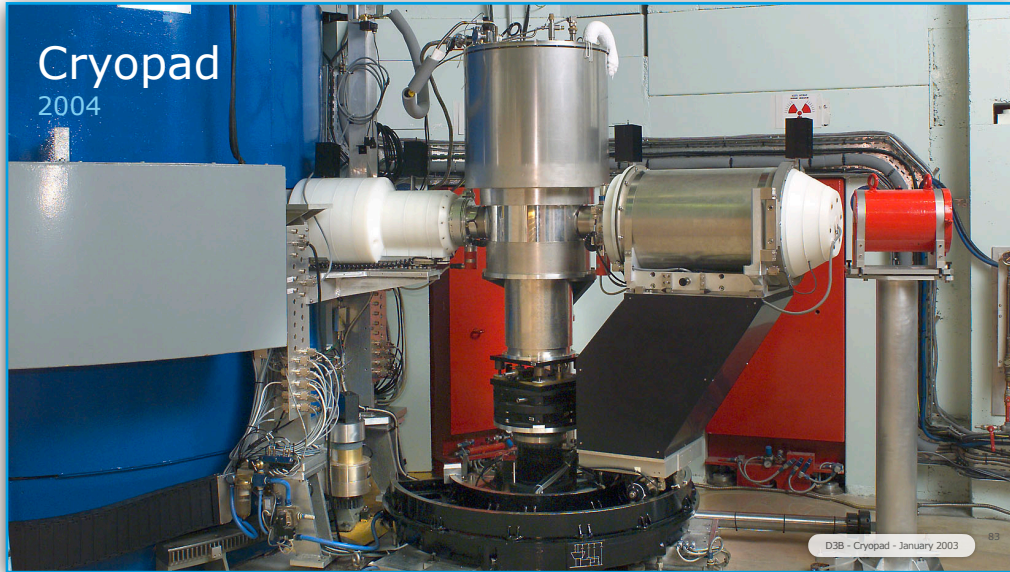
Large-scale structures

- **D22** - Large dynamic range SANS diffractometer
- **D33** - Massive dynamic q-range SANS diffractometer
- **SAM** - compact high-brilliance SANS diffractometer
- **SuperADAM** - reflectometer
- **D17** - Reflectometer with horizontal scattering geometry
- **NEXT** - polarized neutron imaging
- **MoTo** - Monochromatic tomography



Polarized neutrons at the ILL

D3 - Spin-polarized hot neutrons diffractometer



- Incident wavelength $0.42 < \lambda < 0.84 \text{ \AA}$
- Zero-field, high-field and liquids options
- Polarizing monochromator with optional ^3He polarization analysis

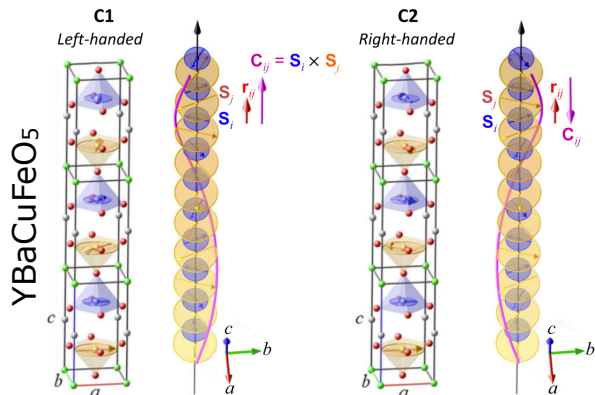




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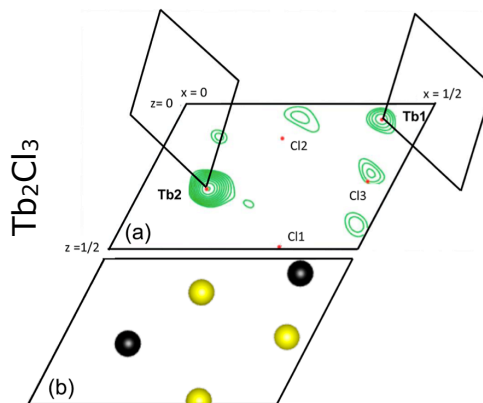
SNP (~60%)



Romaguera et al., (2024) *Commun. Mater.* **5** 273

complex magnetic structures
and magnetic domains

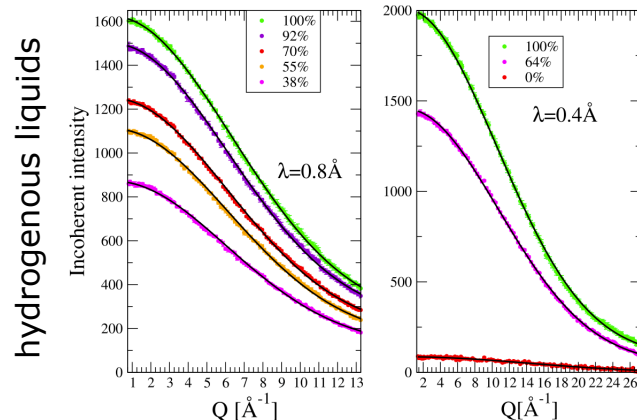
Spin densities (~40%)



Kremer et al. (2024) *Chem. Mater.* **36** 7036

small moments, absorbing samples
recent revival: altermagnets

Liquids (occasional)



Temleitner et al. (2022) *J. Mol. Liq.* **350** 118535

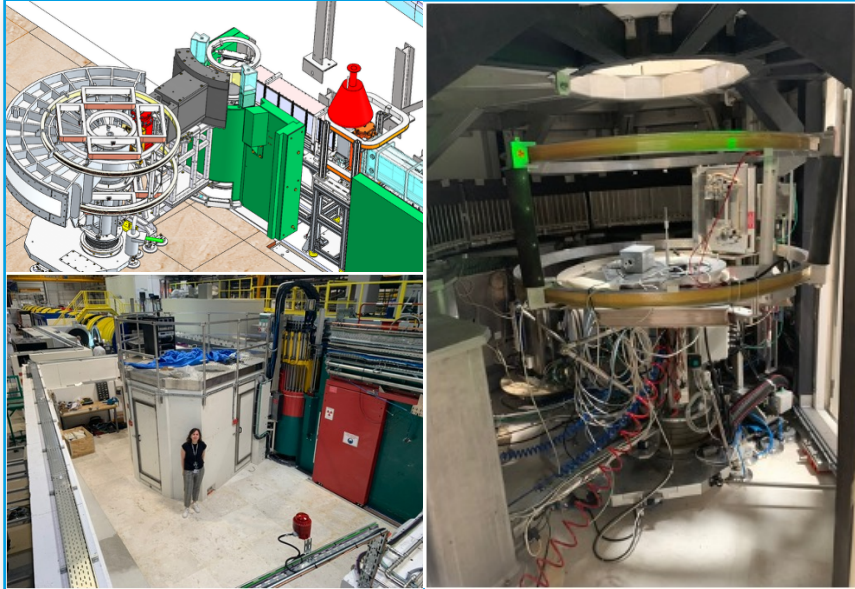
$$I_{\text{coh}}(Q) = I^{\text{NSF}}(Q) - \frac{1}{2}I^{\text{SF}}(Q) \quad I_{\text{incoh}}(Q) = \frac{3}{2}I^{\text{SF}}(Q)$$



Polarized neutrons at the ILL

D007 - Diffuse scattering diffractometer

Nilsen et al. (2020) *NIMA* **951** 162990



- Incident wavelength $3 < \lambda < 6 \text{ \AA}$
- Q-range: $0.1 < Q < 4 \text{ \AA}^{-1}$
- Supermirror bender polarizers and analyzers for permanent polarization analysis
- Time-of-flight option

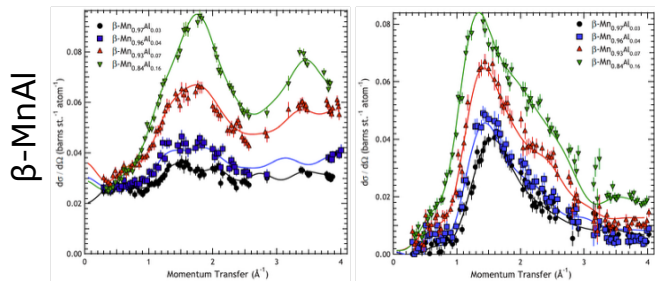


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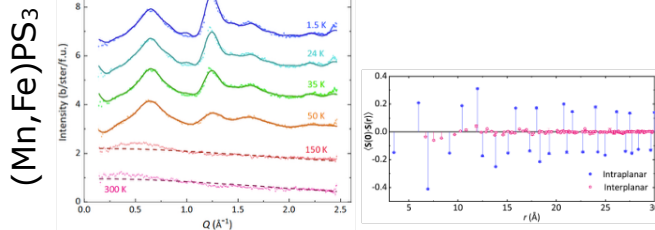
D007 - Diffuse scattering diffractometer

Nilsen et al. (2020) *NIMA* **951** 162990

Powder-like samples (~70%)

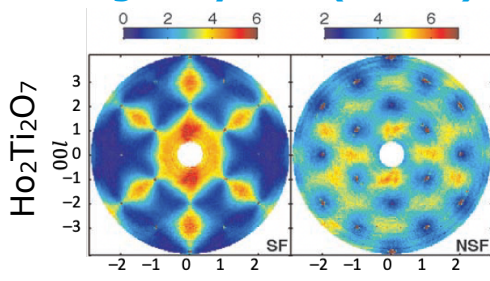


Stewart et al. (2008) *Phys. Rev. B* **78** 014428

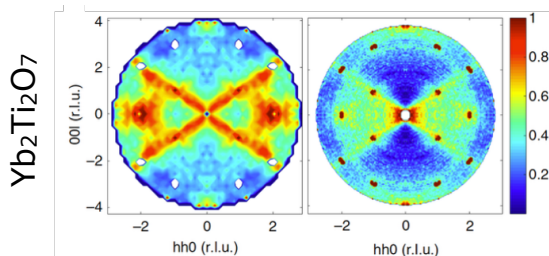


Graham et al. (2020) *Phys. Rev. Mater* **4** 084401

Single crystals (~30%)

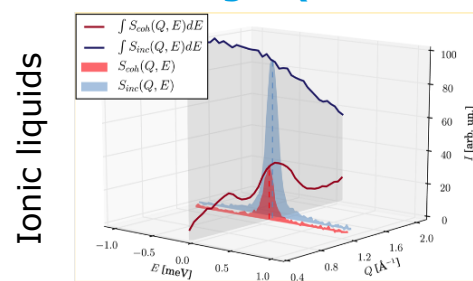


Fennell et al. (2009) *Science* **326** 1177582

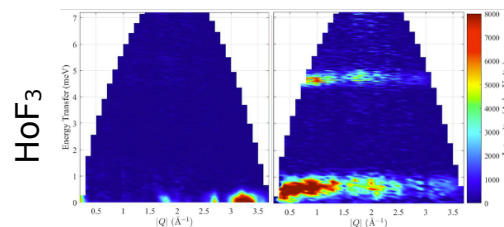


Bowman et al. (2019) *Nat. Commun.* **10** 637

Time-of-flight (occasional)



Burankova et al. (2014) *J. Phys. Chem. B* **118** 14452



Dixey et al. (2023) *APL Mater.* **11** 041126



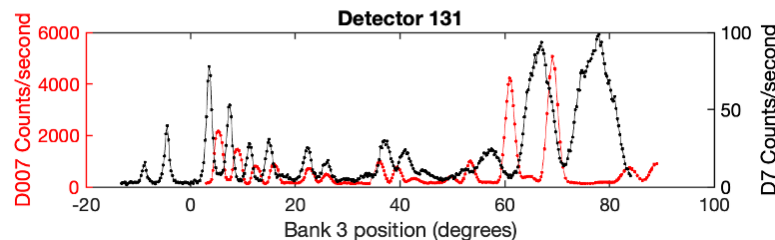
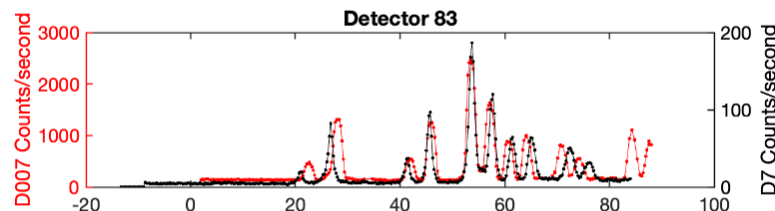
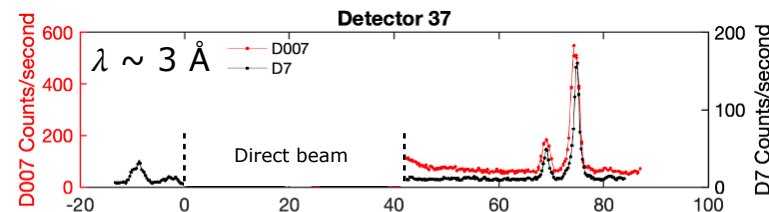
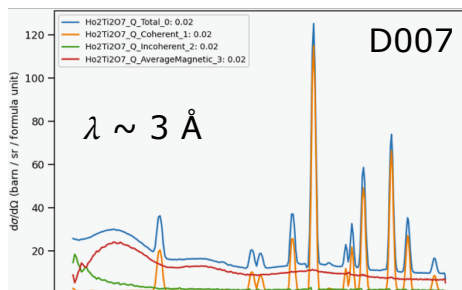
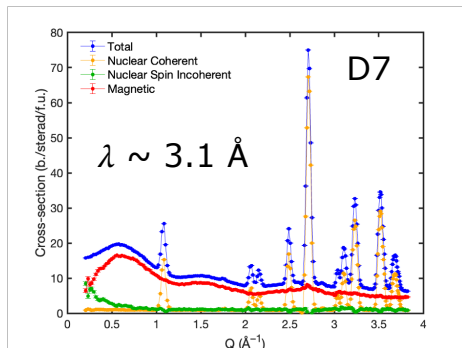
Polarized neutrons at the ILL

D007 - Diffuse scattering diffractometer

Nilsen et al. (2020) *NIMA* **951** 162990

D7 → D007 upgrade

- Signal-to-noise roughly the same
- Rough estimate for flux gains ~ 15
- Comparable resolution

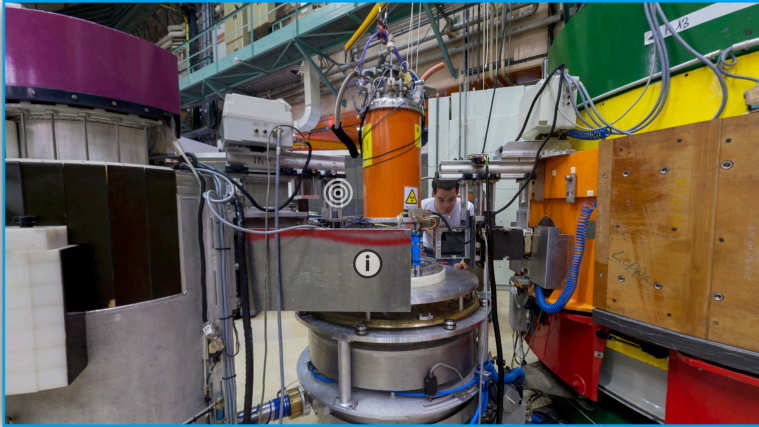




Polarized neutrons at the ILL

IN20 - thermal triple-axis spectrometer

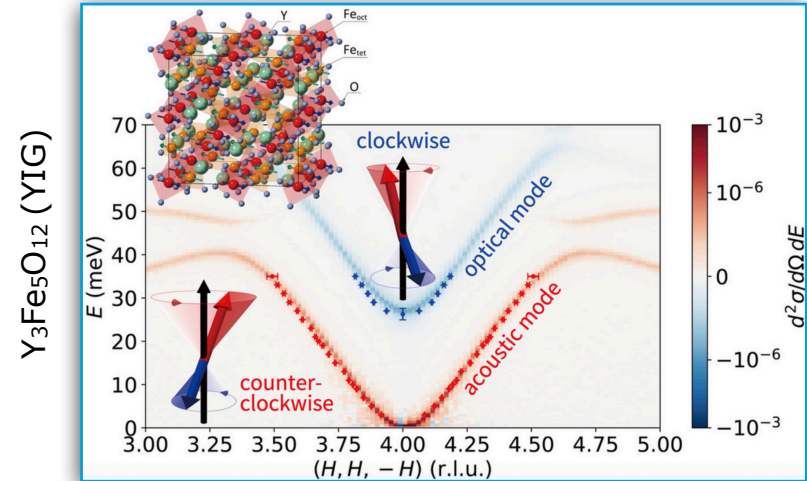
Kulda et al. (2002) *Appl. Phys. A* **74** s246



- Energy transfer up to 100 meV (0.8 - 3 meV resolution)
- Polarizing and analyzing Heusler crystals
- Compatible with Cryopad and Flatcone
- TASSE (μeV resolution)

Polarization capabilities in Europe | Navid Qureshi

Magnon polarization



Nambu et al. (2020) *Phys. Rev. Lett.* **125** 027201

Magnonics, spin-caloritronics



Polarized neutrons at the MLZ

Maier-Leibnitz Zentrum / FRM-II (Garching, Germany)



Diffraction

- **POLI** - Spin-polarized hot neutron diffractometer
- **DNS** - Diffuse scattering diffractometer

Spectroscopy

- **KOMPASS** - Cold triple-axis spectrometer
- **PANDA** - Cold triple-axis spectrometer
- **RESEDA** - Resonance spin-echo spectrometer
- **TOPAS*** - Thermal TOF spectrometer
- **LaDiff*** - Cold triple-axis spectrometer with Larmor diffraction

Large-scale structures

- **SANS-1** - SANS diffractometer
- **KWS-1** - SANS diffractometer
- **MARIA** - reflectometer
- **NREX** - reflectometer with X-ray option

**No operation since 2020,
restart hopefully end of 2026**



Polarized neutrons at ISIS

ISIS Neutron and Muon Source (Didcot, UK)



Spectroscopy

- **PLET** - Cold TOF spectrometer
- **SHERPA*** - QENS spectrometer

Diffraction

- **WISH*** - cold-neutron diffractometer

Large-scale structures

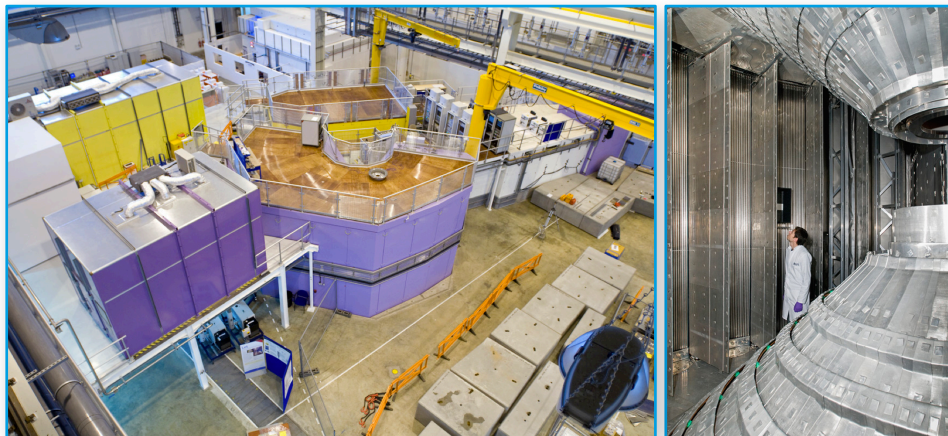
- **Larmor** - High-throughput (SE)SANS diffractometer
- **Zoom** - SANS diffractometer
- **PolRef** - reflectometer
- **OffSpec** - TOF reflectometer with spin-echo option
- **IMAT** - imaging



Polarized neutrons at ISIS

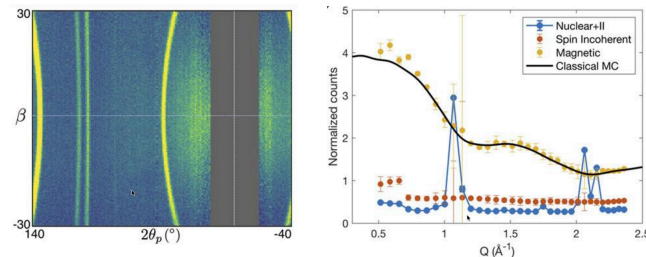
PLET - Cold TOF spectrometer

Nilsen et al. (2017) *J. Phys.: Conf. Ser.* **862** 012019 Bewley et al. (2011) *NIMA* **637** 128



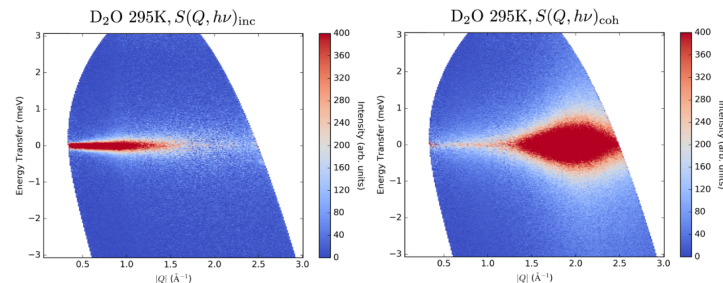
- quasi-elastic and inelastic measurements
- dynamic range: 0.5 - 30 meV
- optional large solid angle ^3He polarization analysis
- unique high energy resolution (18 μeV)

Magnetism ($\sim 70\%$)

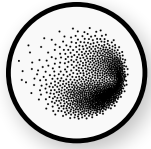


Nilsen et al. (2022) *Rev. Sci. Instrum.* **93** 063902

QENS ($\sim 30\%$)



Arbe et al. (2020) *Phys. Rev. Research* **2** 022015(R)



Polarized neutrons at the PSI

Paul Scherrer Institute (Villigen, Switzerland)



Spectroscopy

- **TASP** - Cold triple-axis spectrometer (option: MuPAD)

Large-scale structures

- **SANS-I** - SANS diffractometer
- **AMOR** - vertical TOF reflectometer
- **NARZISS** - reflectometer (test instrument)



The future at the ESS

The polarized neutrons instrument suite

11 of the 15 ESS instruments under construction aim to offer polarized neutrons

Diffraction

- **DREAM** - diffractometer (focus on colder neutrons)
- **HEIMDAL** - diffractometer (focus on thermal neutrons)
- **MAGiC** - diffractometer (cold and thermal neutrons)

Spectroscopy

- **BIFROST** - spectrometer
- **CSPEC** - spectrometer
- **MIRACLES** - spectrometer
- **T-REX** - spectrometer

Large-scale structures

- **ODIN** - imaging instrument
- **SKADI** - SANS diffractometer
- **ESTIA** - reflectometer
- **FREIA** - reflectometer

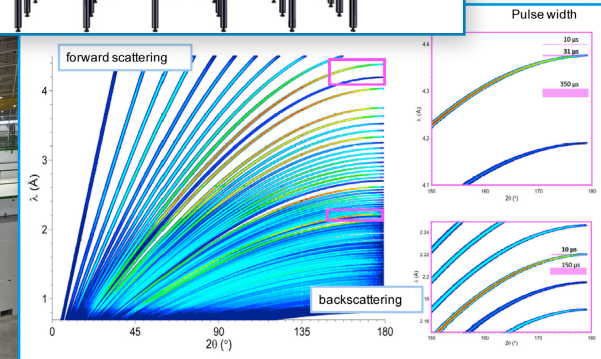
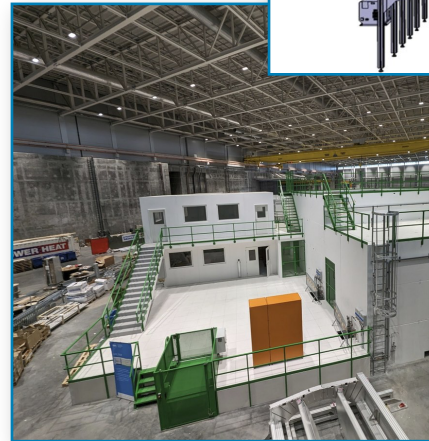
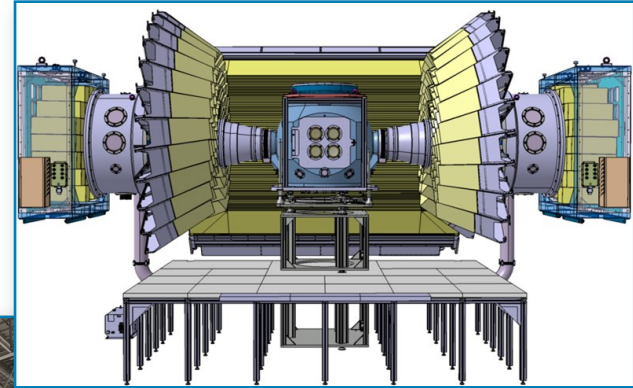


The future at the ESS

DREAM (Diffraction Resolved by Energy and Angle Measurements)



- Horizontal cylindrical geometry
- 0.5 - 4 Å
- Simultaneously views both cold and thermal moderators
- Unprecedented peak brightness with flexible resolution
- ^3He polarizer and analyzer
- XYZ method
- PDF, (magnetic) crystallography, 2D Rietveld analysis, large unit cells, in-situ studies of batteries, access to limited SANS region





The future at the ESS

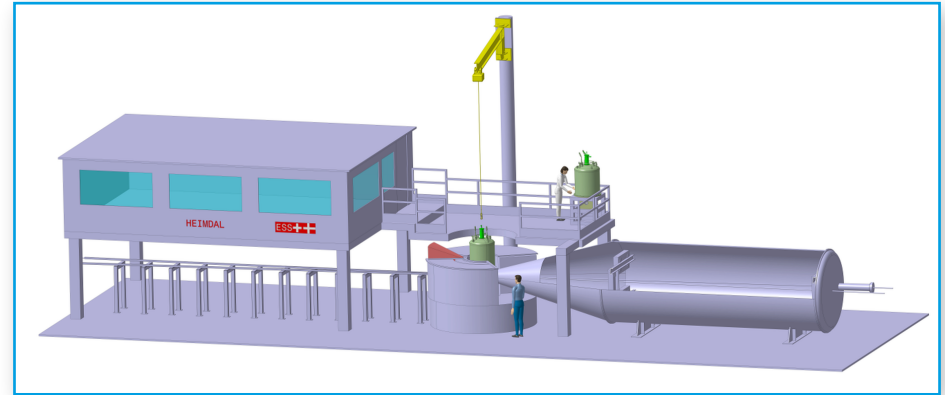
HEIMDAL (Norse Mythology: a god with most keen senses)



Institute for Energy Technology



- Vertical cylindrical geometry
- Multi-length scale neutron scattering covering almost nine orders of magnitude from 0.01 nm to 50 mm
- Thermal powder diffractometer (later combined with SANS and imaging using cold guide)
- ^3He polarizer and analyzer
- XYZ method
- PDF, (magnetic) crystallography and later: SANS, imaging to study functional materials over broad length scales



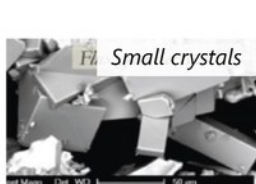
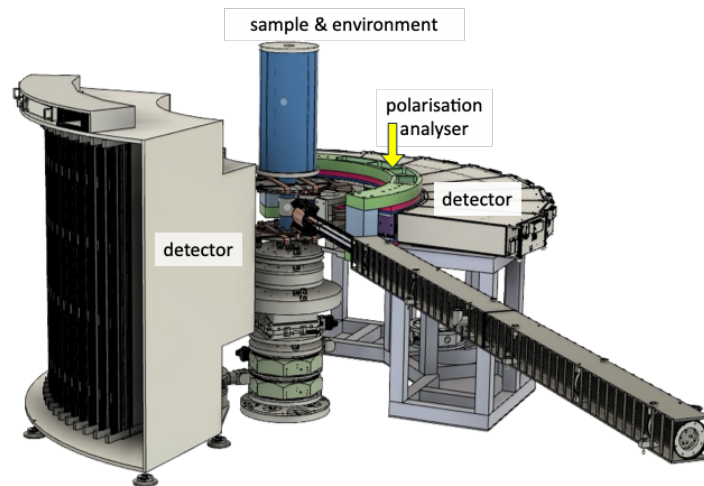


The future at the ESS

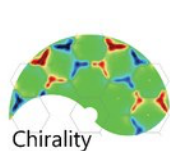
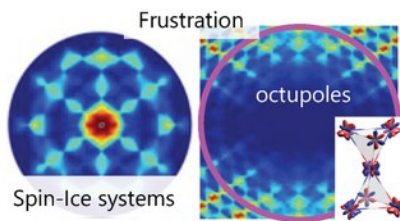
MAGiC (MAGnetIC single-crystal diffractometer)



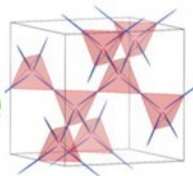
- 0.6 - 6 Å
- Can switch between cold and thermal moderators
- Polarizing guide (thermal) or bender (cold)
- Polarization >98% for $\lambda < 2$ Å (thermal), >96% (cold)
- Optional XYZ setup with solid-state analyzer (cold)
- Magnetic structures, magnetic diffuse scattering
- Sub-mm samples and thin films



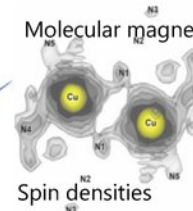
New magnetic phases



Chirality

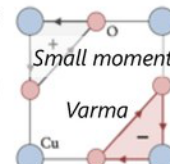


Spin anisotropies



Molecular magnets

Spin densities



Small moments

Varma

Superconductivity

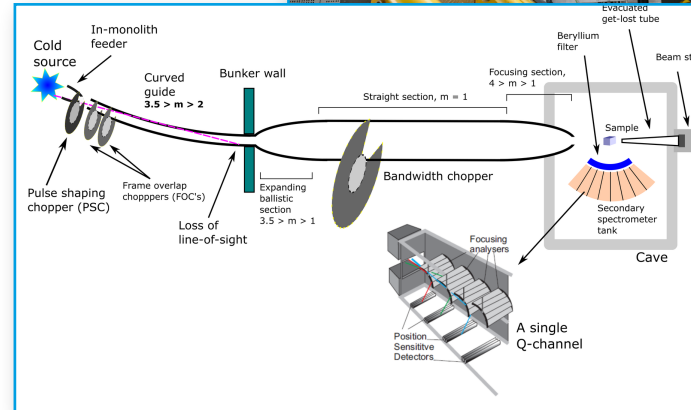
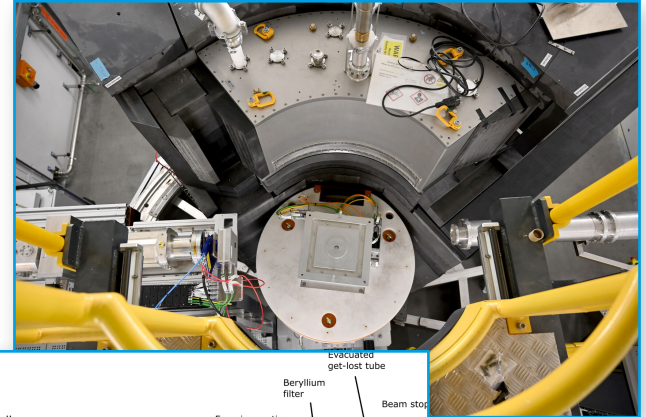


The future at the ESS

BIFROST (rainbow bridge in Norse mythology)



- Cold neutron spectroscopy: 0 - 40 meV range
- Supermirrors for polarizing (>95%) and analyzing
- Pulse-adapted + multiplexing = orders of magnitude in efficiency gain
- Optimal flux (2.3 - 4 Å): 10^{10} n/s/cm²
- Best resolution ($\Delta E = 0 - 6$ meV): 20 μ eV
- Intricate physics in magnetism, superconductivity, energy/functional materials
- High pressure quantum magnetism



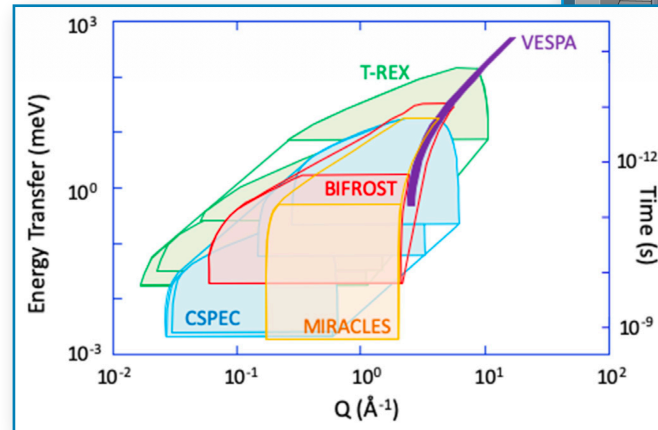
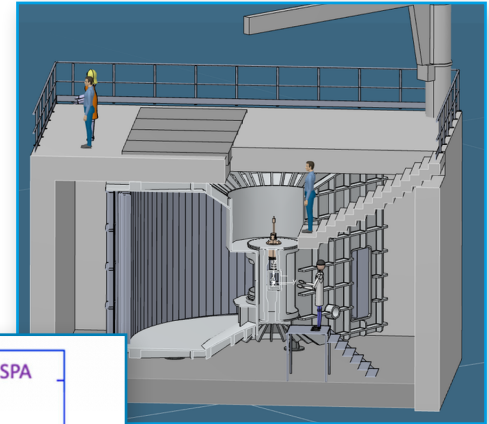


The future at the ESS

CSPEC (Cold Chopper Spectrometer)



- Designed for 3 - 10 Å neutrons
- Polarizing supermirror with ³He wide-angle analyzer
- Picosecond dynamic behavior in life science, energy/functional materials and magnetism
- Follow kinetic events in-situ or in-operando



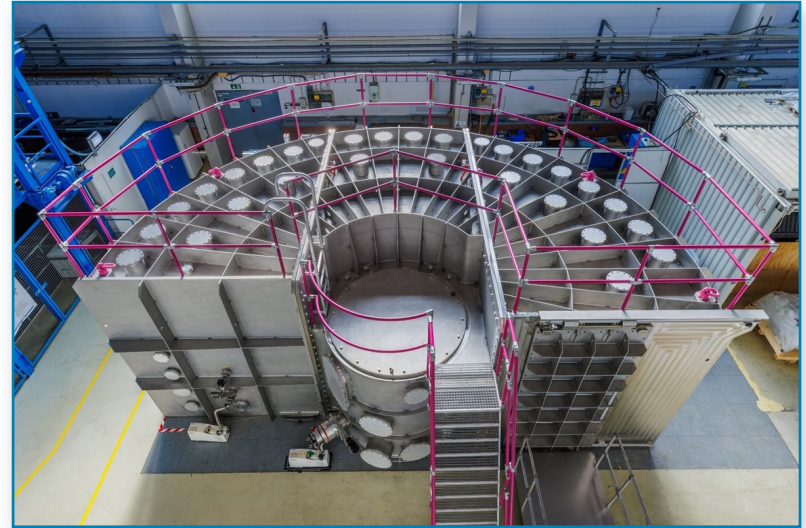


The future at the ESS

T-REX (Time-of-flight Reciprocal space Explorer)



- Designed for energy transfers between 20 μeV and 140 meV
- Flexibility between Q-resolution and flux
- V-cavity polarizer (cold) and ^3He cell (thermal)
- Polarization analysis with wide-angle ^3He
- Separation of magnetic spectra from nuclear scattering, eigenvectors of magnetic excitations, separation of coherent and nuclear spin-incoherent scattering
- H-containing samples, quantum magnets, etc.





The future at the ESS

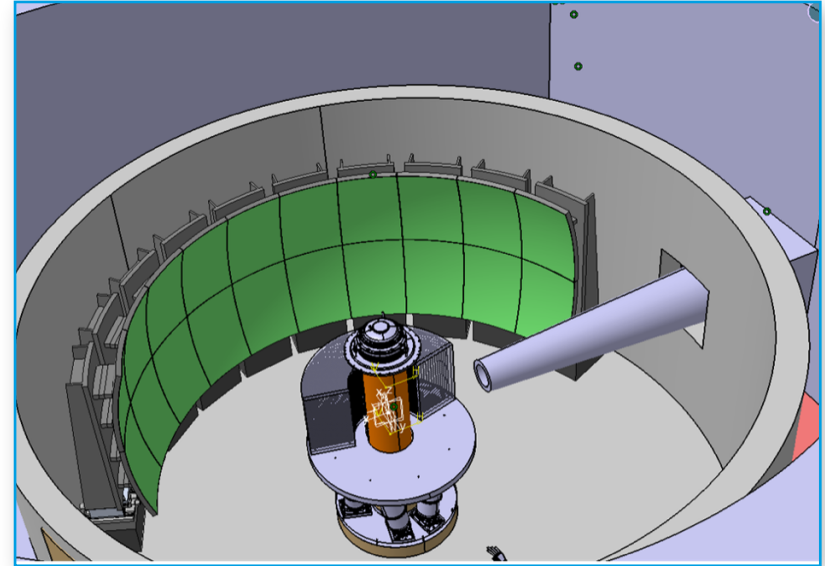
MIRACLES



ESS
bilbao



- Time-of-flight backscattering instrument
- 2 - 20 Å neutrons
- 4×10^7 n/s/cm² in high-resolution mode ($\Delta E = 2 \mu\text{eV}$)
- V-cavity polarizer for >95% at $\lambda > 5 \text{ \AA}$
- ³He wide-angle analyzer
- Dynamic processes over a wide energy range
- QENS and low-energy inelastic excitations



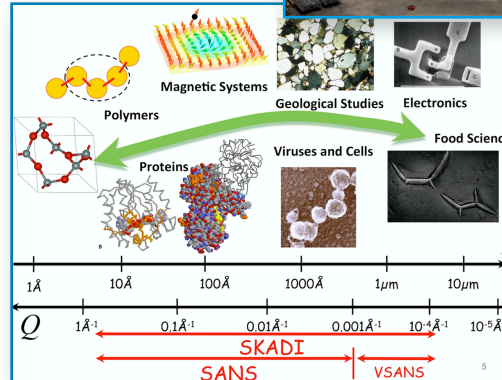


The future at the ESS

SKADI (Small-K Advanced Diffractometer)



- Wavelength range: typical 3 - 8 Å (up to 21 Å)
- Supermirror polarizer with ³He analyzer
- High Q-resolution combined with access to very low Q will support studies of skyrmions and vortex lattices in superconductors



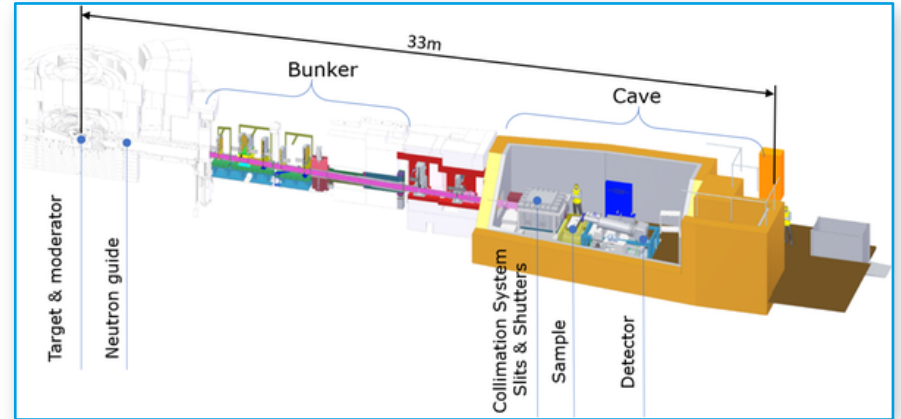


The future at the ESS

FREIA (Fast Reflectometer for Extended Interfacial Analysis)



- Wavelength range: 2 - 10 Å
- Liquids reflectometer
- ^3He polarizer and analyzer
- Polarized neutrons for magnetic reference layer technique (as a foreseen upgrade)
- Self-assembly of surfactants, polymers and proteins at interfaces; rearrangement processes, inter-diffusion, surface reactions etc.



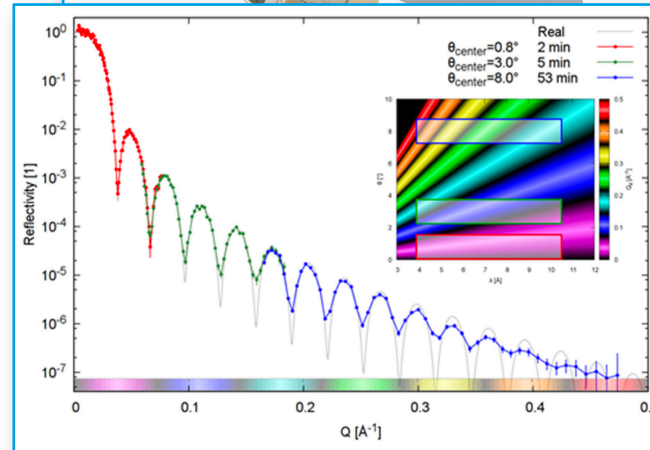
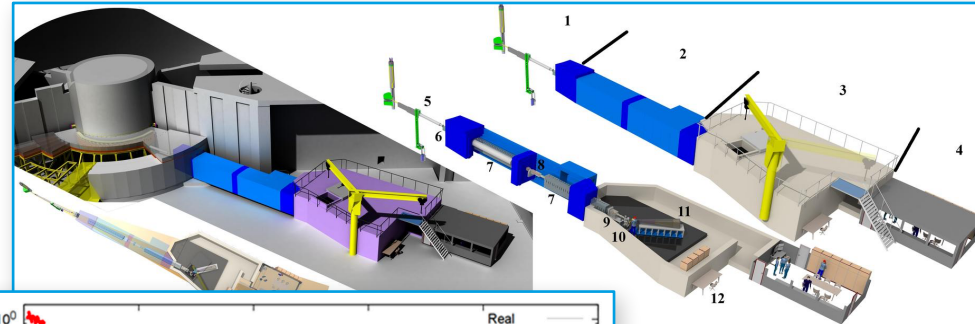


The future at the ESS

ESTIA (Greek goddess of the hearth)



- Focusing reflectometer for small samples
- Focus of 0.1 mm x 1 mm with 10^9 n/s/cm²
- Optional polarization and analysis using transmission mirrors
- Unprecedented count rate with 0.5 mm resolution
- Surfaces, thin films and magnetic phenomena





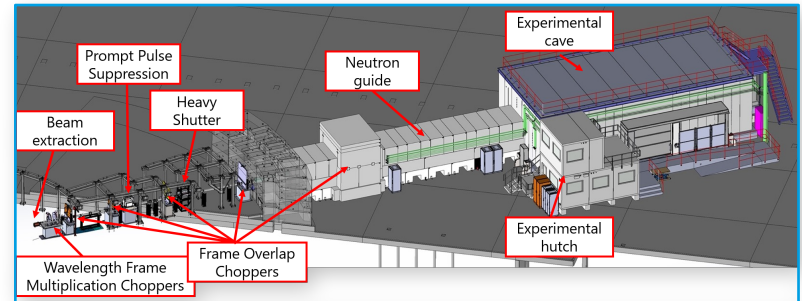
The future at the ESS

ODIN (Optical and Diffraction Imaging with Neutrons) TUM

Technische Universität München



- Wavelength band: 2.5 - 11 Å
- From purely attenuation-based to polarization-dependent imaging (as upgrade)
- Polarizing v-cavity for >95% polarization with compact super mirror analyzer (sample is placed as close as possible to the detector)
- ^3He analyzers are studied for more wavelength flexibility
- 5 - 50 μm resolution
- Visualize inhomogeneities in magnetic fields and structures, magnetic phase transitions, individual magnetic domains, spatially resolved SANS in engineering materials



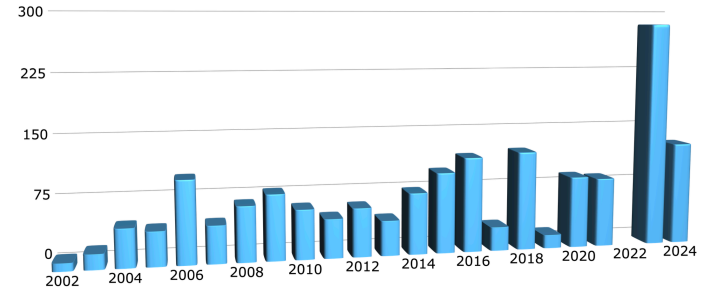


Conclusions

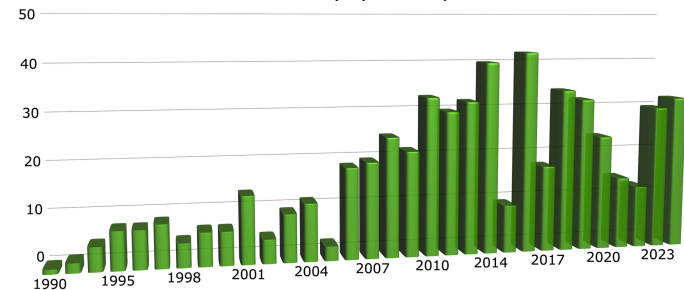
Polarized neutrons in the world

- Polarized neutrons are used extensively (magnetism, separation of coherent from spin-incoherent scattering, dynamical processes with high-resolution NSE)
- ILL: 40% of the 40+ instruments offer a polarized neutron option, 25% of the total beam time exploits polarization
- Doubling of polarized neutrons capacity in the past two decades
- Trend continues: 25 new and 13 existing unpolarized instruments plan to include polarized neutrons
- More than 70 polarized neutrons experiment in the world in the next 10-15 years Lee et al. (2023) EPJ Web of Conf. **286** 03004

number of ^3He cells delivered at ILL



number of ILL Cryopad experiments





NEUTRONS
FOR SOCIETY

INSTITUT LAUE LANGEVIN

THE EUROPEAN NEUTRON SOURCE



NEUTRONS
FOR SOCIETY