NEUTRON RESONANCE SPIN ECHO

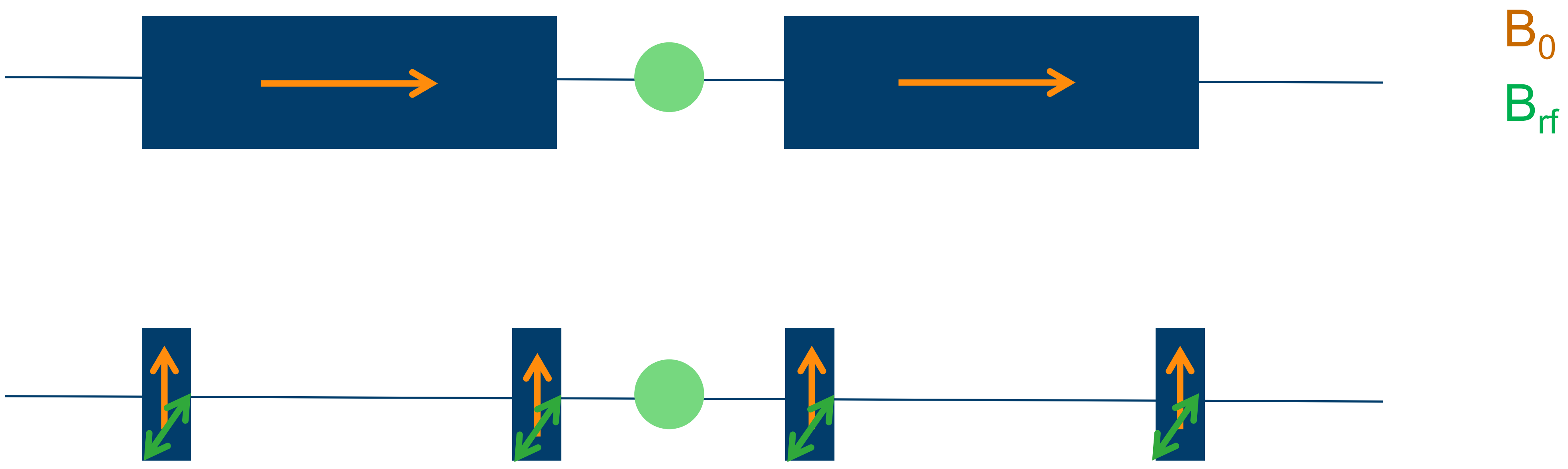
05.07.2025 CHRISTIAN FRANZ

DISCLAIMER

This talk tries to give an overview on the status of NRSE (for QENS) worldwide, however a lot examples come from RESEDA in Munich.

Not everything is my work!

REPLACING NSE COILS BY NRSE FLIPPERS

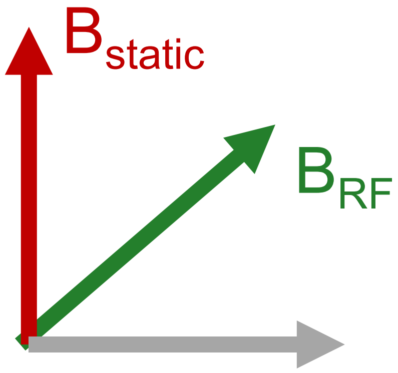


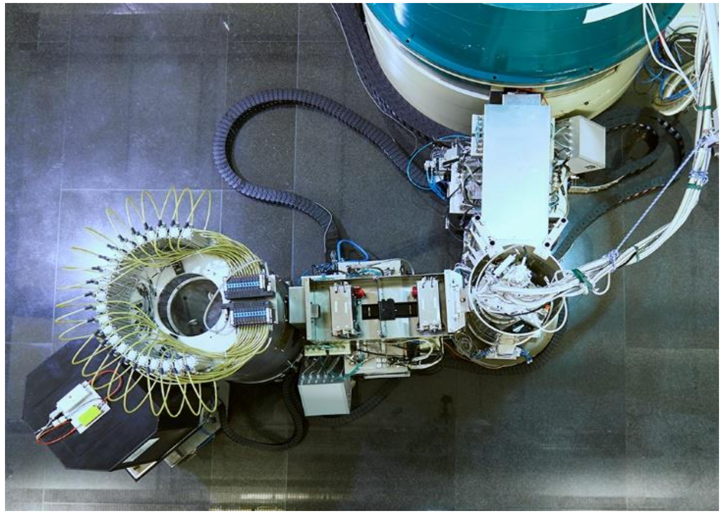
$$\varphi = 2B_0\gamma t - \varphi_0$$

Goulub, Gähler

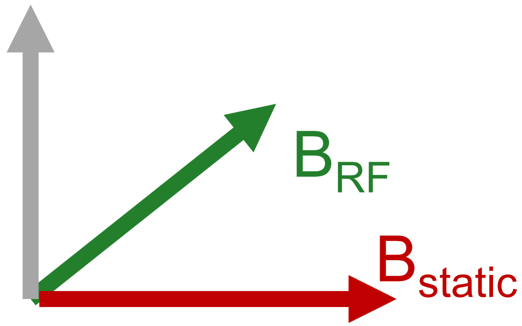
NEUTRON RESONANCE SPIN ECHO GEOMETRY

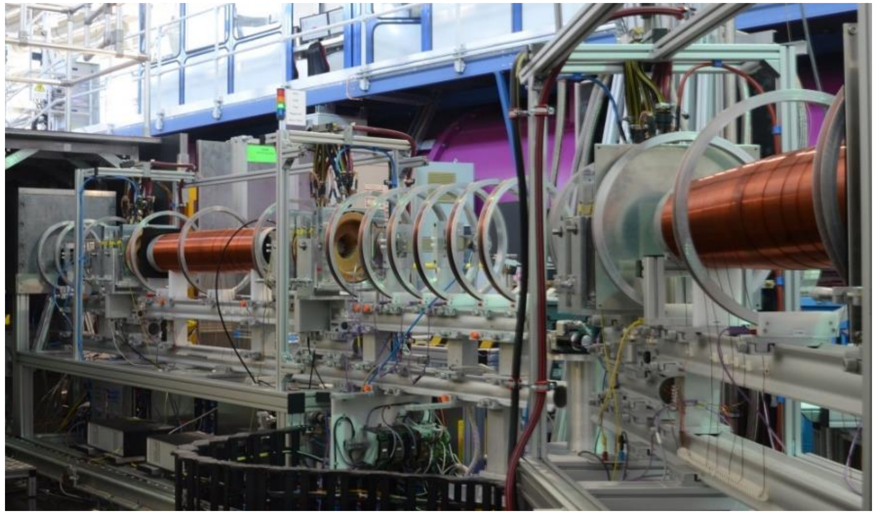
„Classic“ transverse NRSE



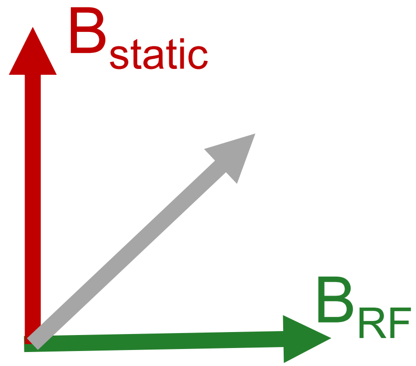


longitudinal NRSE



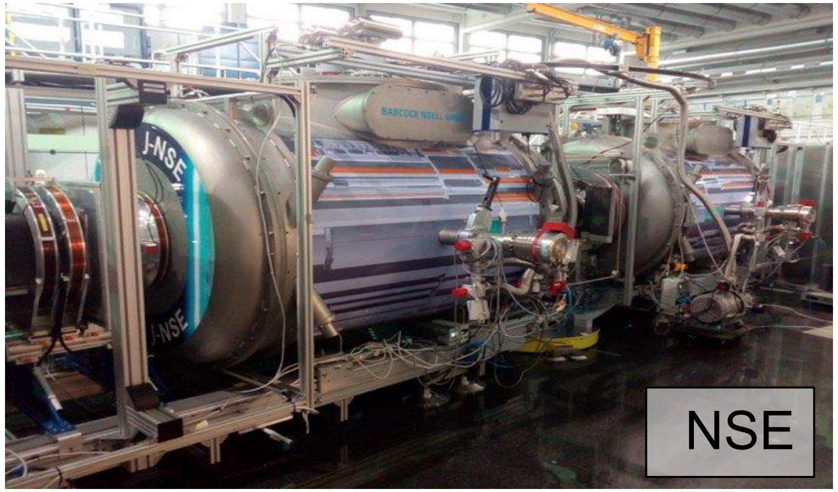


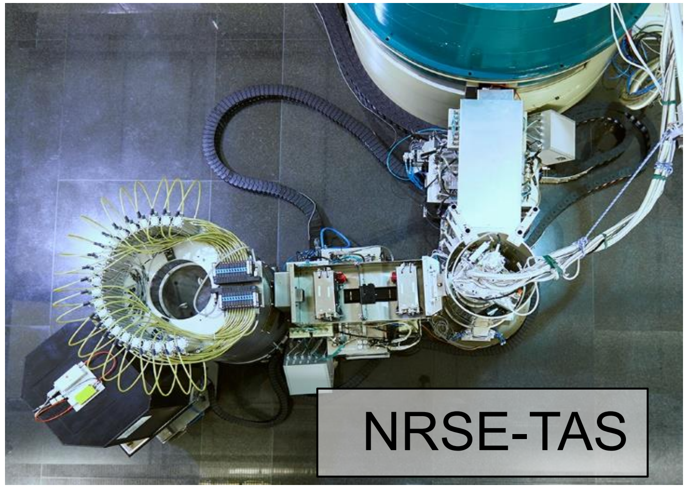
New transverse NRSE

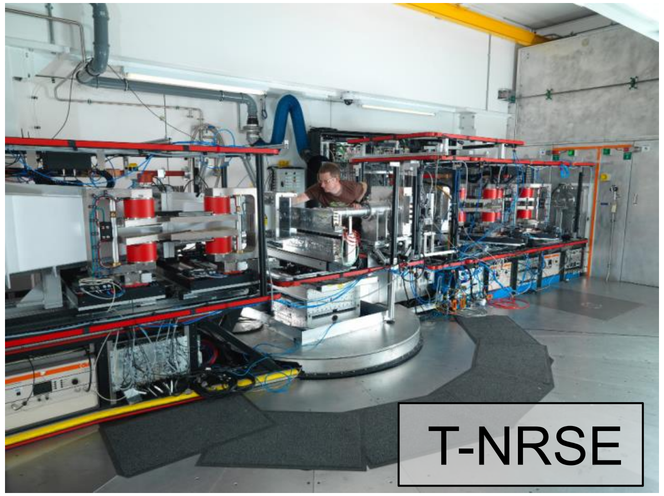


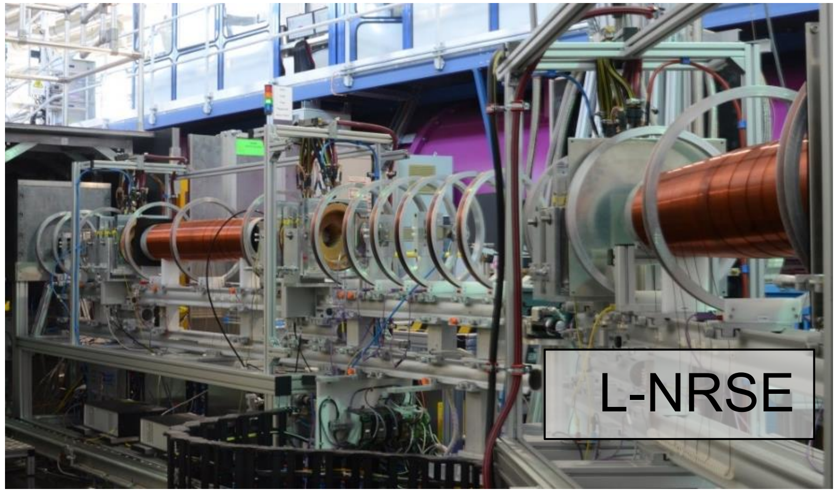
NEUTRON SPIN ECHO TECHNIQUES WORLDWIDE

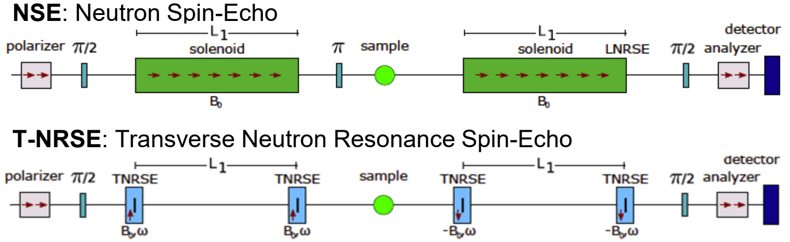
Normal and superconducting versions!

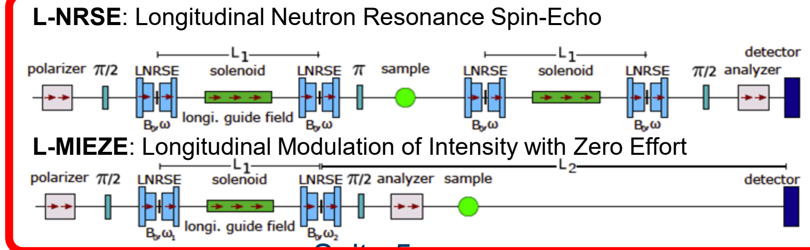


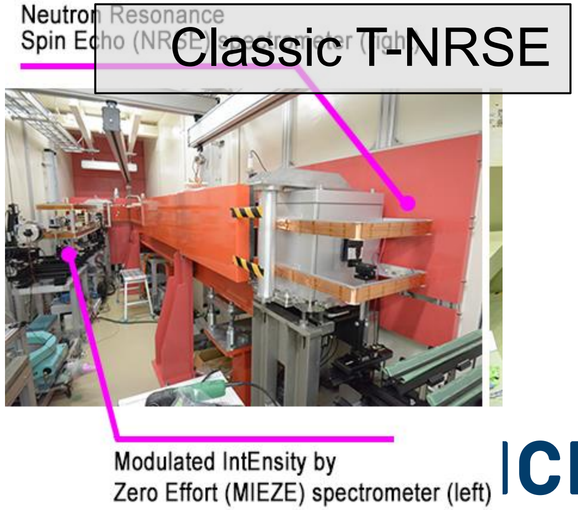












LONGITUDINAL VS. TRANSVERSAL

Transverse field geometry

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- Larmor diffraction (LaDiff)
- Phonon focussing (TRISP)

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- Field inhomogenities
- Beam divergence
- limited to few ns

Longitudinal field geometry

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- Self-correction for non-divergent beams
- Fresnel, Pythagoras coils
- Large dynamic range

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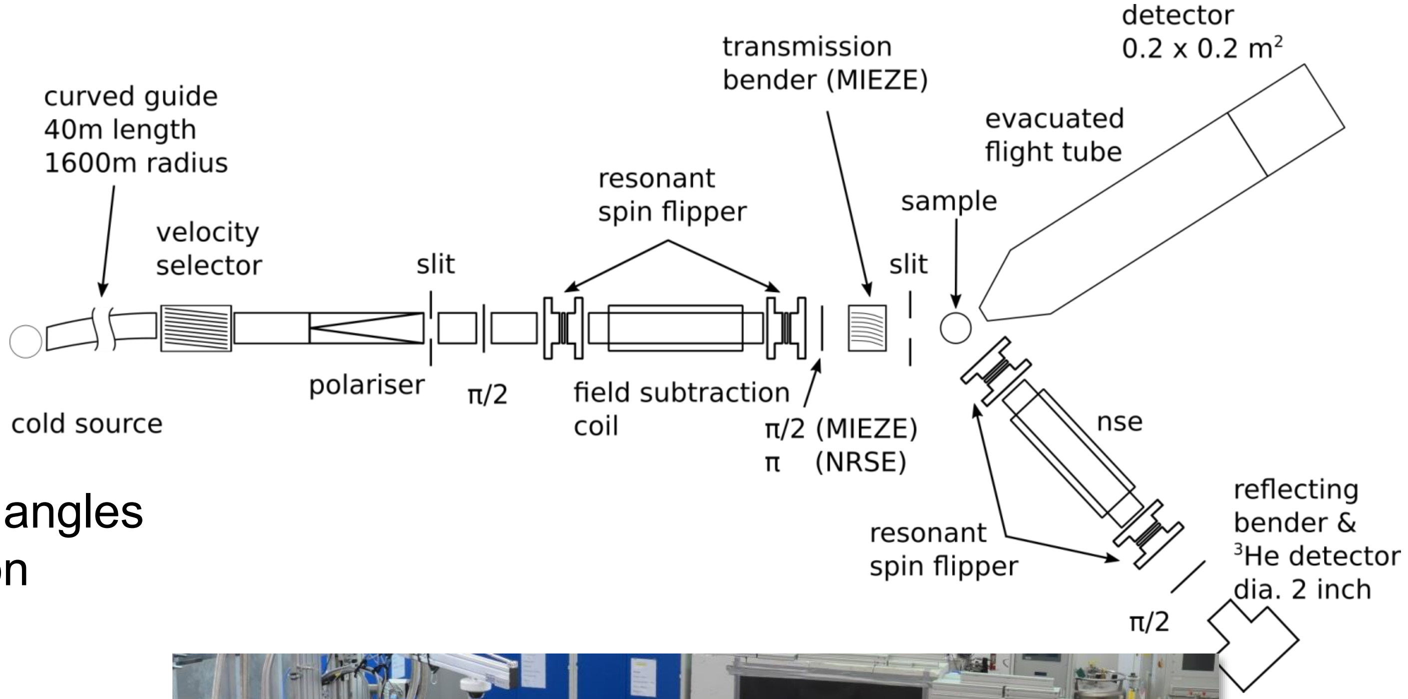
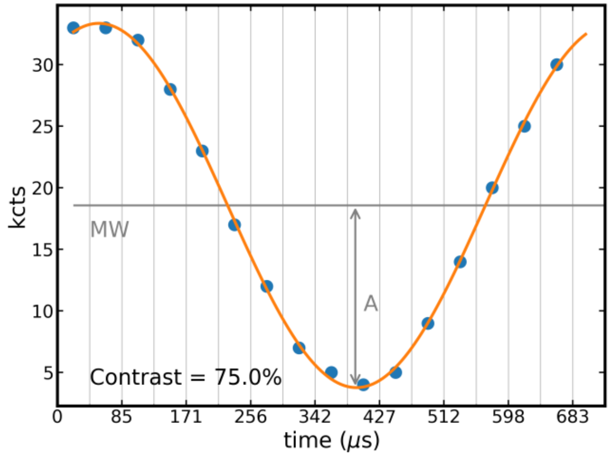
- no Larmor diffraction
- no inelastic focussing

Häußler, Schmidt, Chem. Phys., 2005, 7, 1245-1249

DIVERSE APPLICATIONS: NRSE AND MIEZE

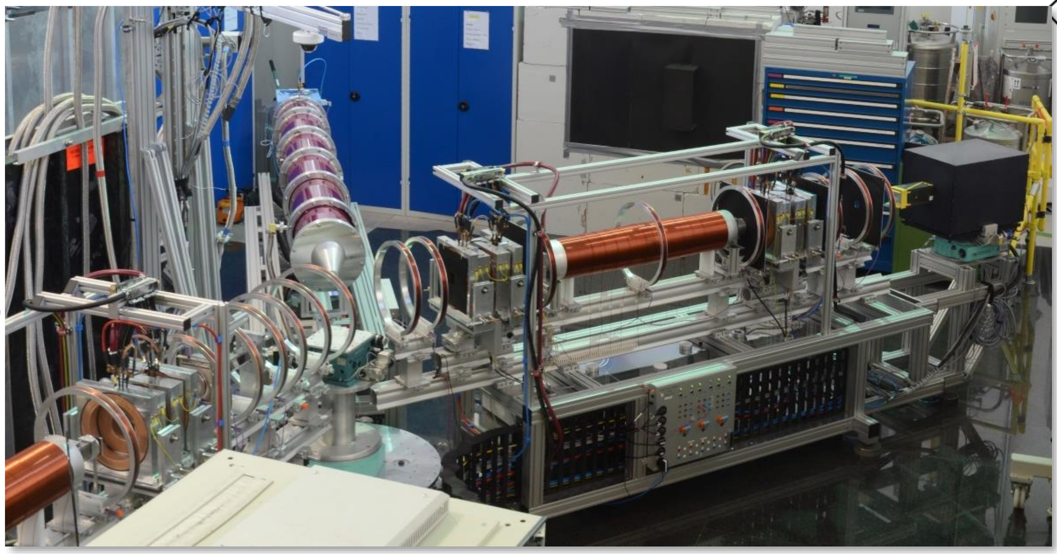
reseda

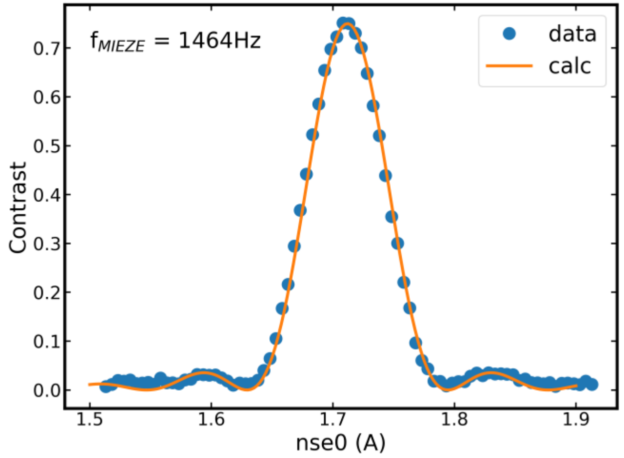




NRSE:
- Large scattering angles
- Highest resolution

MIEZE:
- Depolarising conditions
- Ferromagnets
- Magn. Fields
- Strong incoherent samples (e.g. hydrogen)

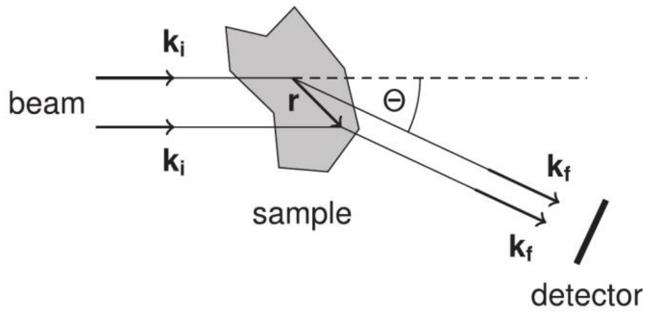


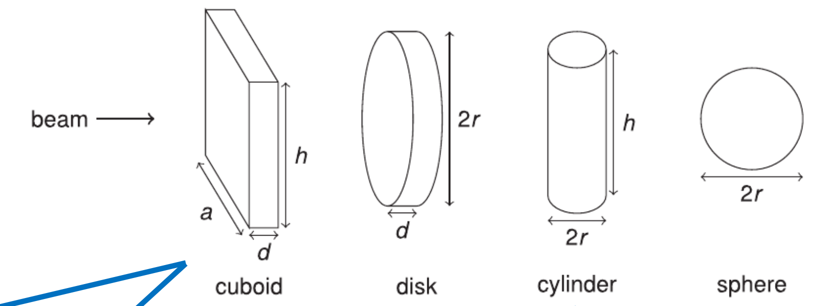


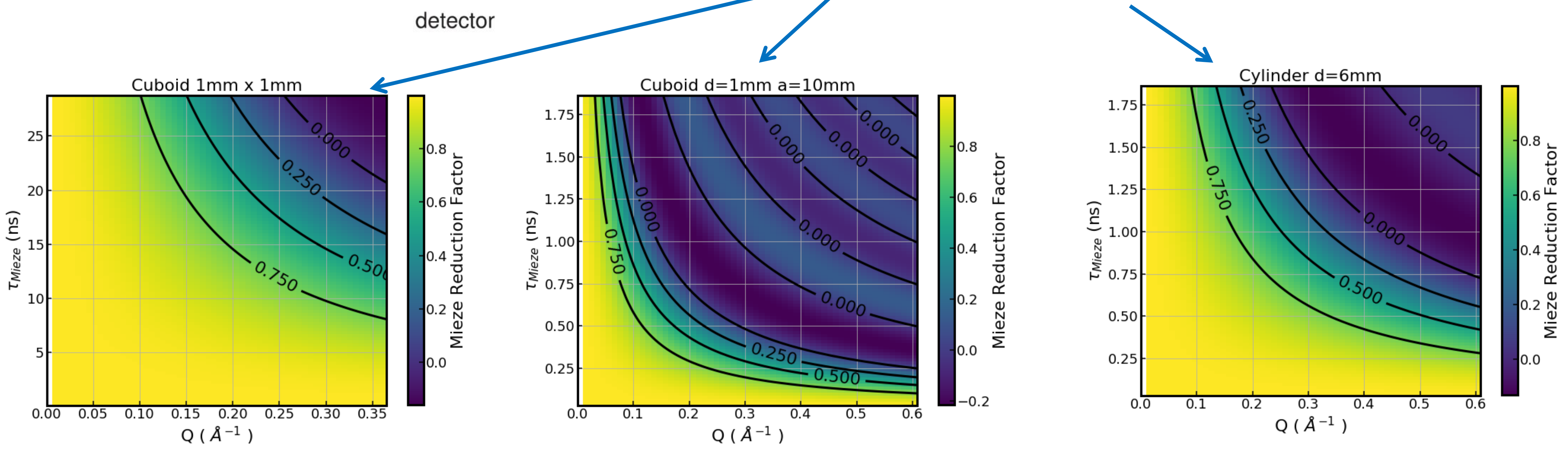
CF et al. NIM-A, **939**, 22 (2019)
CF et al. JPSJ, **88**, 081002 (2019)

MIEZE GEOMETRY REDUCTION FACTOR

Small sample favorable for high resolution







Brandl *et al.* NIMA **654** 394 (2011)
Martin *et al.* NIMA **882** 11 (2018)

Online Calculator (FRMII WebApps:)
https://webapps.frm2.tum.de/reseda_redfac/

NRSE VS. MIEZE

Neutron Resonance Spin Echo

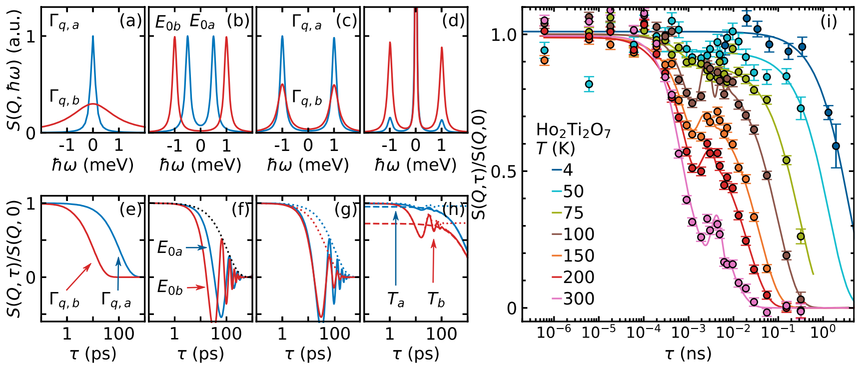
- ✓ Similar to conventional NSE (smaller detector area)
- ✓ Very high resolution possible
- ✓ High momentum transfers possible
- ✗ No external magnetic field
- ✗ Magnetic samples difficult
- ✗ Strong incoherent scatterer reduce polarisation (deuteration)

Modulation of Intensity with zero effort

- ✓ Similar to **high-resolution TOF** (or SANS with energy resolution)
- ✓ **Magnetic field** possible (17T unshielded proven)
- ✓ **Ferromagnetic samples** possible (see data on UGe_2)
- ✓ Ideal for **incoherent scattering** (see data on pure water!)
- ✗ Reduced resolution (depends on detector position)
- ✗ Momentum transfer limited by sample geometry (and size)

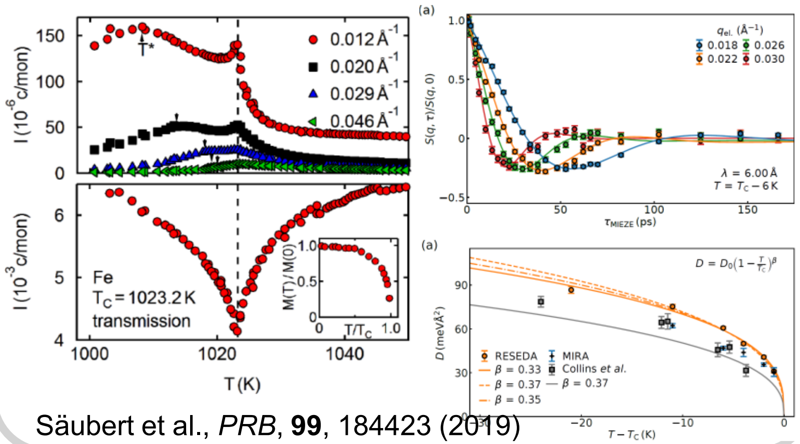
MIEZE SCIENTIFIC EXAMPLES

Spin Excitations in $Ho_2Ti_2O_7$



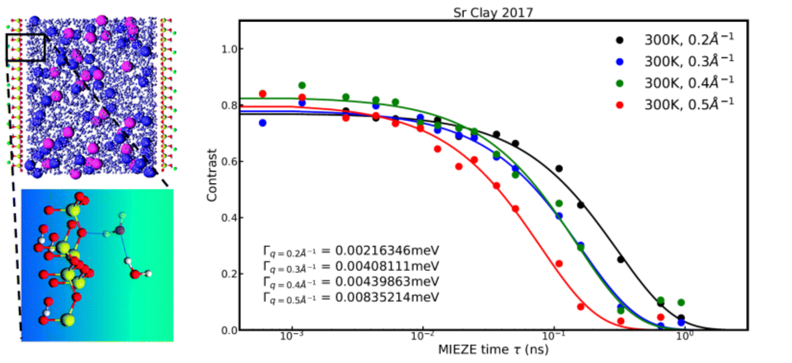
A. Wendl et al., in preparation

Spin Waves in Fe



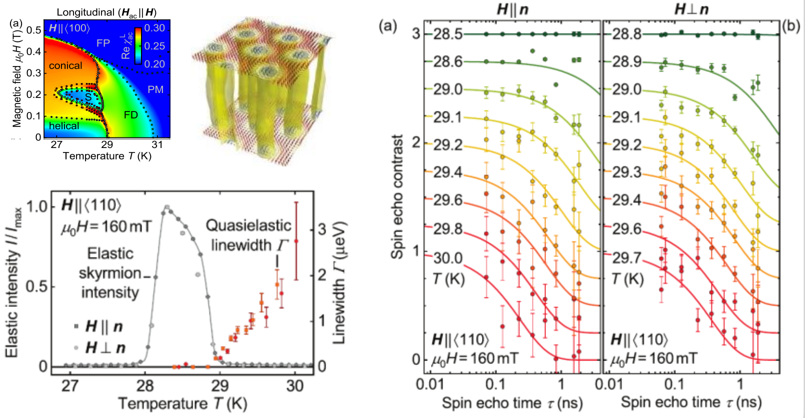
Säubert et al., *PRB*, **99**, 184423 (2019)

Water in confinement



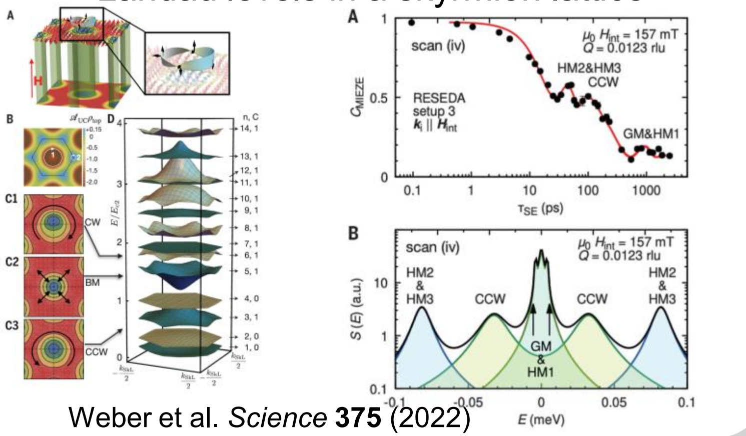
V. Marry & E. Dubois

Weak crystallization of fluctuating skyrmion textures in MnSi



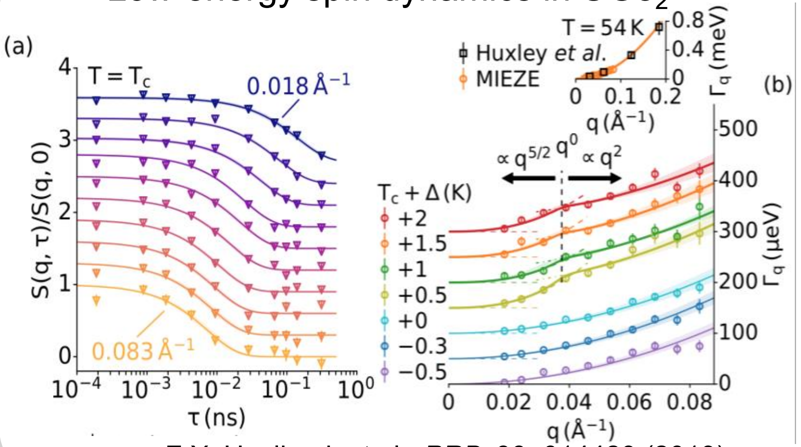
J. Kindervater et al. *PRX*, **9**, 041059 (2019)

Topological magnon band structure of emergent Landau levels in a skyrmion lattice



Weber et al. *Science* **375** (2022)

Low-energy spin dynamics in UGe_2



F.X. Haslbeck et al., *PRB*, **99**, 014429 (2019)

COMPARE MIEZE WITH TOF

Using H_2O

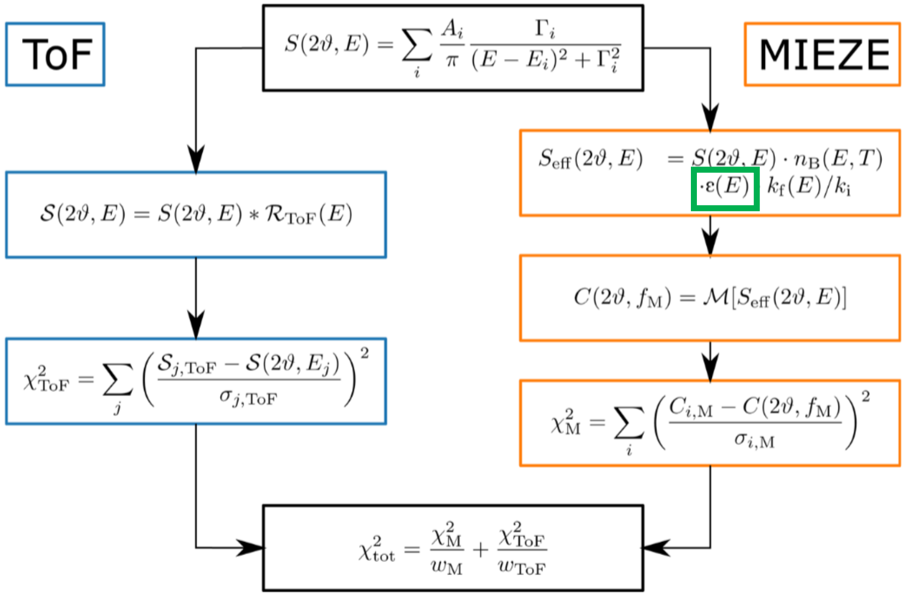
- Heuristic model for H_2O
- ToF: TOFTOF (MLZ)
  FOCUS (PSI)
- MIEZE: RESEDA (MLZ)
- For ToF: Convolution with instrument resolution
- For MIEZE: Bose-factor, detector efficiency, k_f/k_i, go beyond spin-echo approximation
- Sample geometry plays an important role

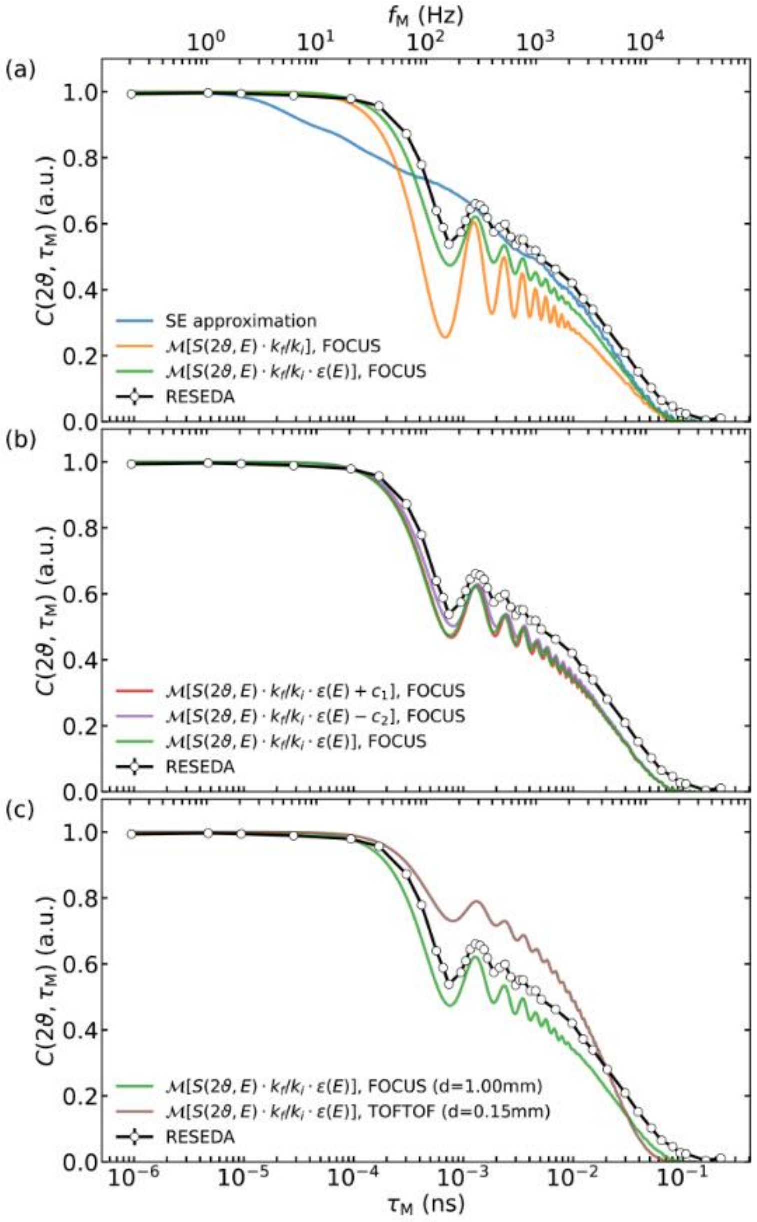
- **Large dynamic range possible!**

$$C = \langle \cos \Phi_{\mathrm{D}} \rangle_E = \langle \cos(2\pi f_{\mathrm{M}} \Delta t_{\mathrm{D}}) \rangle_E \qquad (21)$$

$$= \frac{\int_{-\infty}^{\infty} \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}E} \cos(2\pi f_{\mathrm{M}} \Delta t_{\mathrm{D}})\,\mathrm{d}E}{\int_{-\infty}^{\infty} \frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}E}\,\mathrm{d}E} \qquad (22)$$

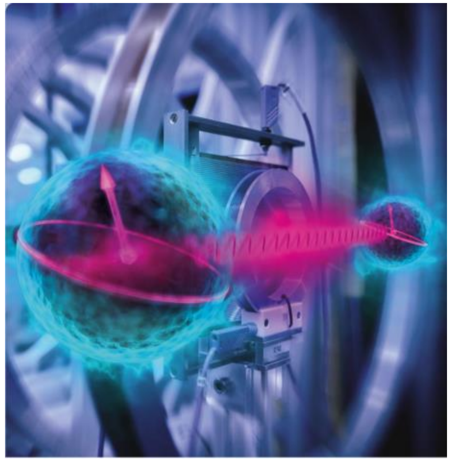
$$= \frac{\int_{-\infty}^{\infty} \frac{k_{\mathrm{f}}}{k_{\mathrm{i}}} S(2\vartheta, E) \cos\left[2\pi f_{\mathrm{M}} L_{\mathrm{SD}} \left(\frac{1}{v_1} - \frac{1}{\sqrt{v_1^2 + 2E/m}}\right)\right] \mathrm{d}E}{\int_{-\infty}^{\infty} \frac{k_{\mathrm{f}}}{k_{\mathrm{i}}} S(2\vartheta, E)\,\mathrm{d}E}. \qquad (23)$$

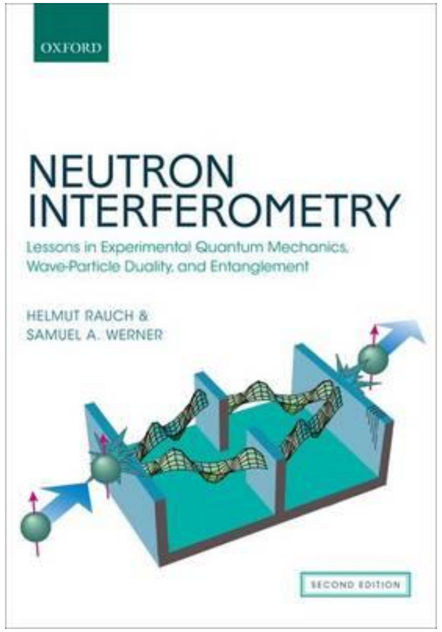




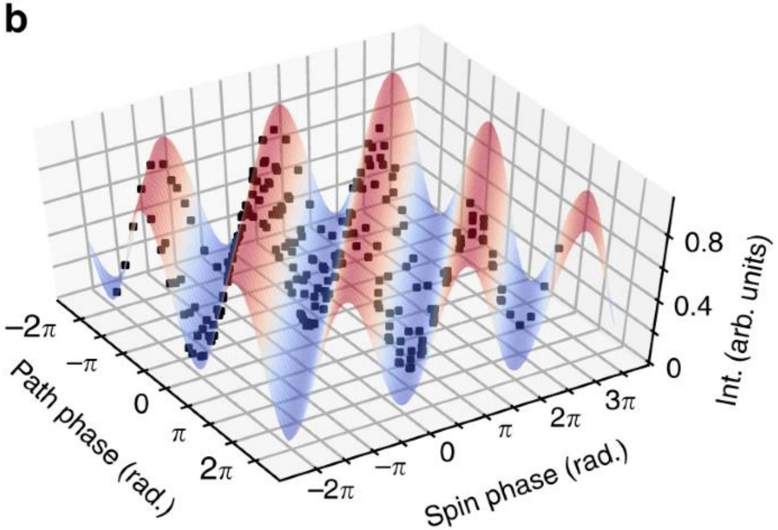
Beddrich *et al.* J. Appl. Cryst. **58** (2025)

ENTANGLEMENT IN QUANTUM SYSTEMS

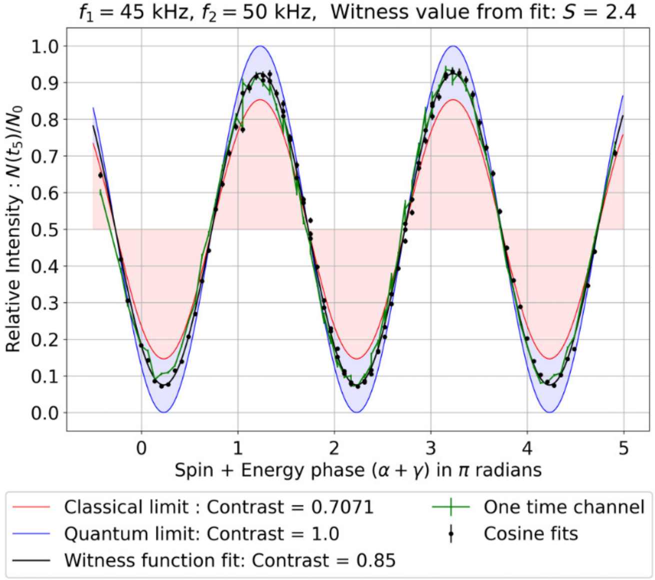




Larmor :

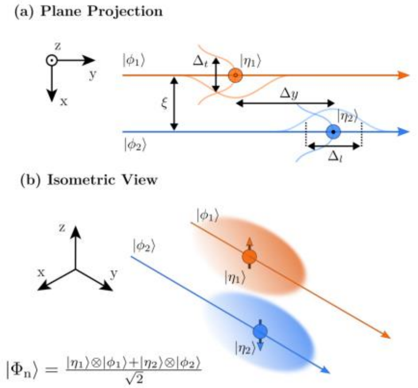


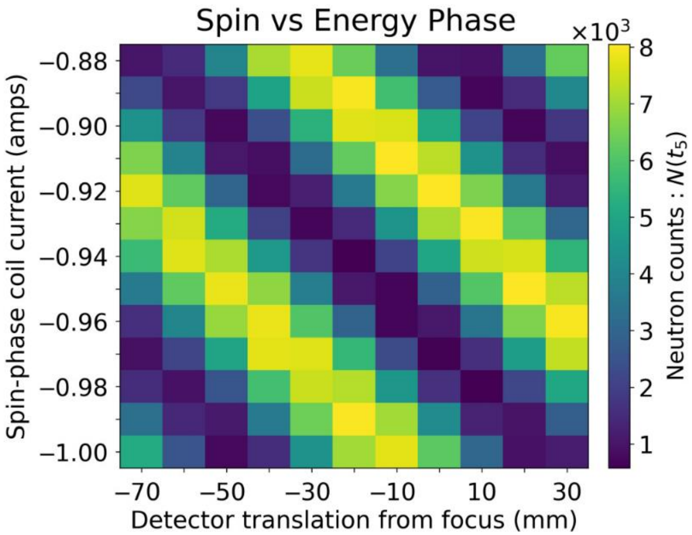
Reseda :



CHSH inequality
:

$$|S| \leqslant 2 \qquad \text{(classical statistics)},$$
$$|S| \leqslant 2\sqrt{2} \qquad \text{(quantum statistics)}.$$





Shen et al. *Nature Comm.* **11** (2020)
Kuhn et al. *Phys. Rev. Res.* **3** (2021)
Leiner *et al.*, Phys. Rev. Applied **22**, (2024)

PULSED SOURCE & LOW DIMENSION MODERATOR

General considerations

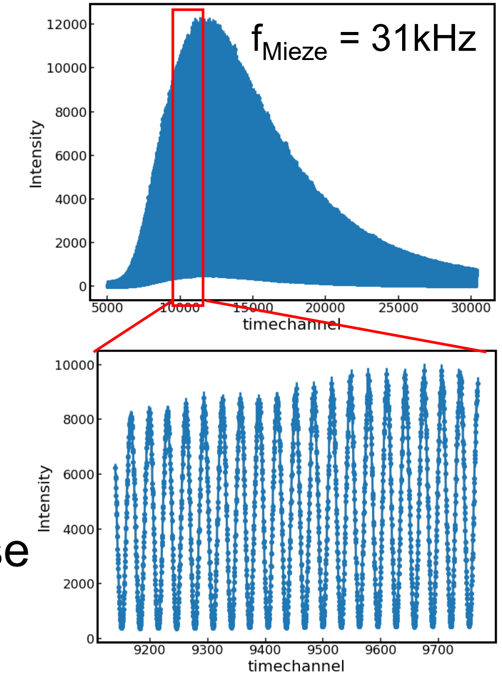
continous source vs. pulsed source

- measure at constant field integral, but get a range of spin-echo times
- most efficient for flat neutron spectrum

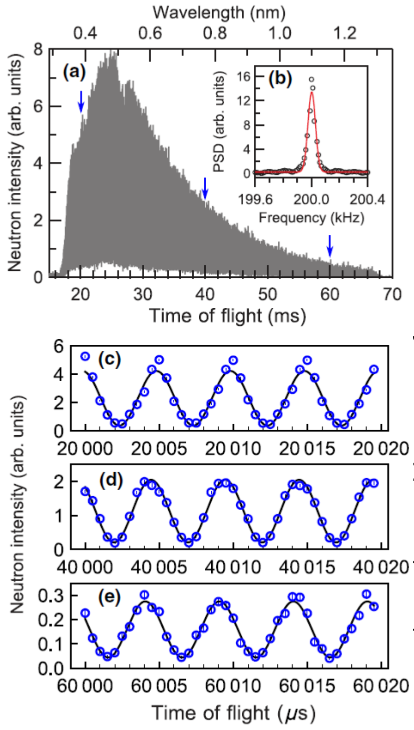
requirements

- polarise large wavelength band
- B_0 fields stay constant during pulse
- RF field amplitude has to change
- π/2 flipper current has to change
- Fast detector with event mode data

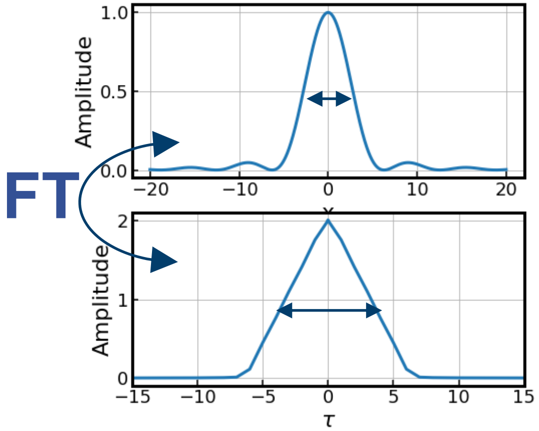
McStas MIEZE at HBS Source

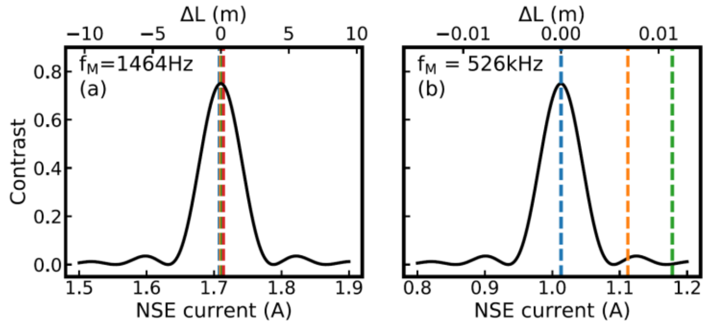


1) Moderator-detector distance: 10m
2) with a wavelength frame of 3-10 Å
3) Δλ/λ of 11% @ 3 Å, Δλ/λ of 3.3% @ 10 Å



T. Oda et al. *Phys. Rev. Appl.* **14** (2020)





several meter

only mm!

Brandl et al. *Nucl.Instrum.Meth.A*, ***667*** *(2012)*
Georgii et al. *Nucl.Instrum.Meth.A* **837** (2016)
Geerits et al. Rev. Sci. Instr., **90** (2019)
Kuhn et al. *Journ. Appl. Cryst.* **54** (2021)
Funama et al. *JPS Conf. Proc.* **33** (2021)

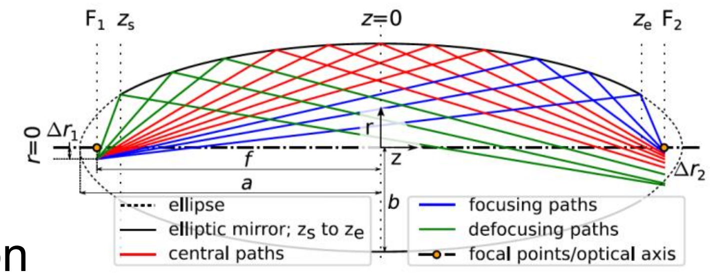
PULSED SOURCE & LOW DIMENSION MODERATOR

NEUTRON TRANSPORT AND PRIMARY SPECTROMETER

Neutron transport

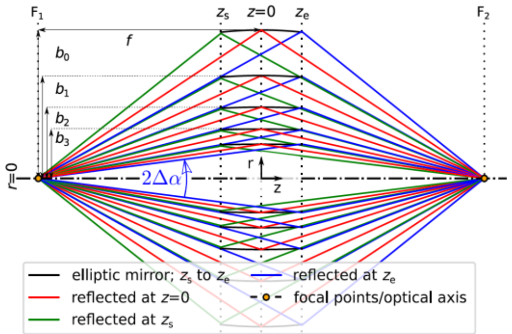
- maximise flux at sample position
- optimise for small samples
- small flippers allow higher resolution
- slit system for SANS appications

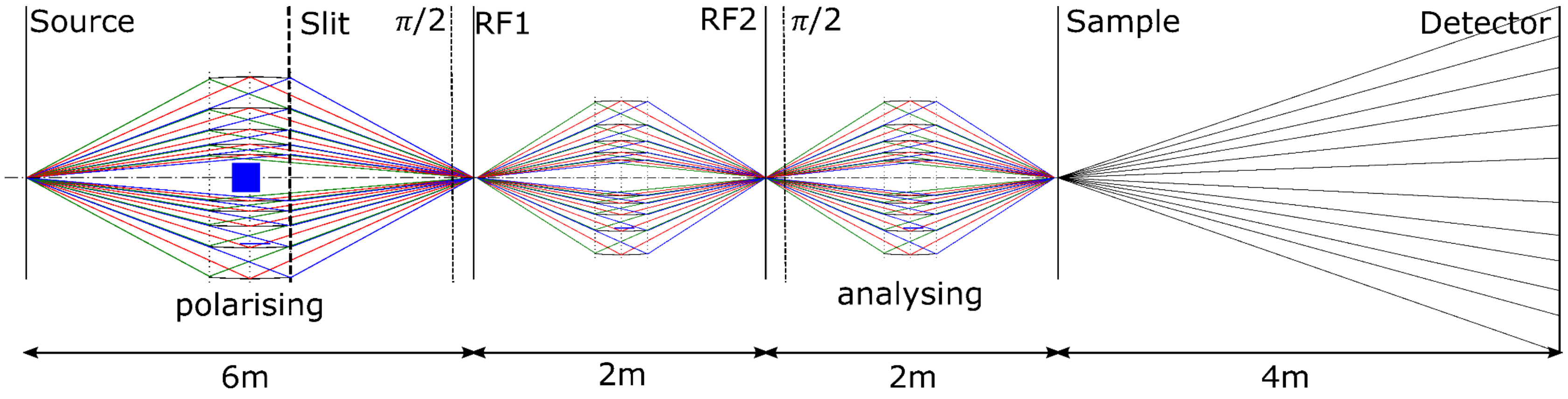
Elliptic guide

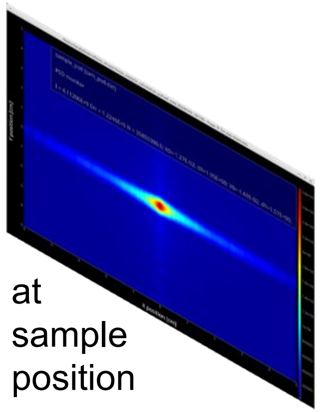


C. Herb, arXiv:2202.07899v1 (2022)

Nested mirror optics (NMO)





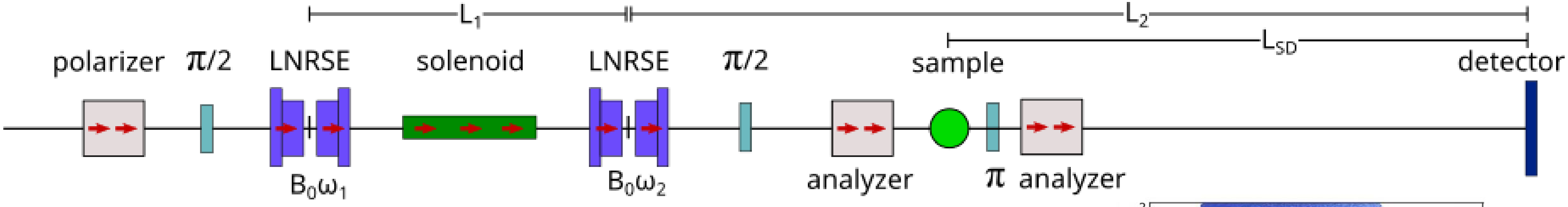


at sample position

HBS Technical Design Report (2024)

POLARISATION ANALYSIS FOR MIEZE

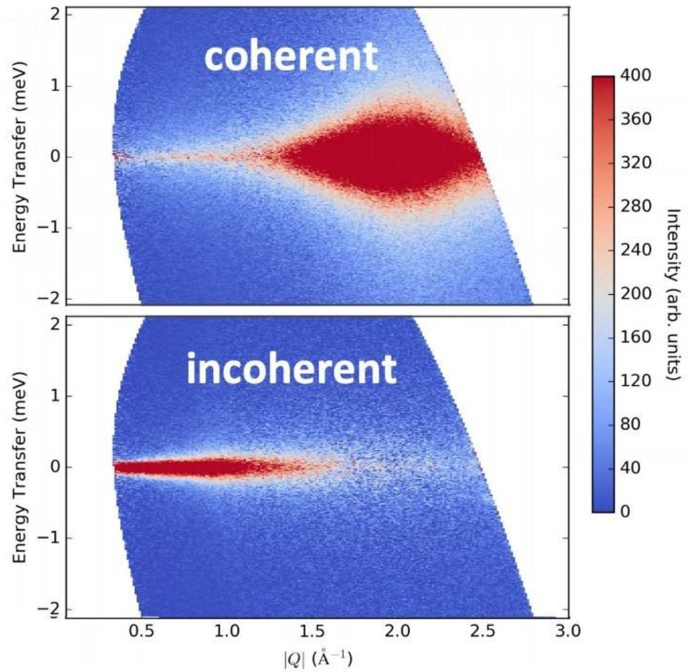
In z-direction



- Beam is still polarised at the sample position!

- Second analyser after the sample with π-flipper
- Magnetic field from analyser enough to preserve polarisation

- Separate coherent/incoherent
- Separate nuclear/magnetic
- XYZ or SNP possible, but needs space around sample

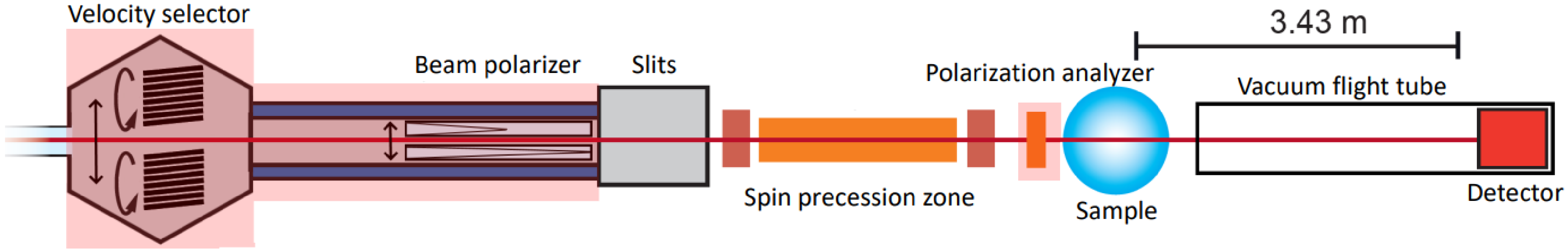


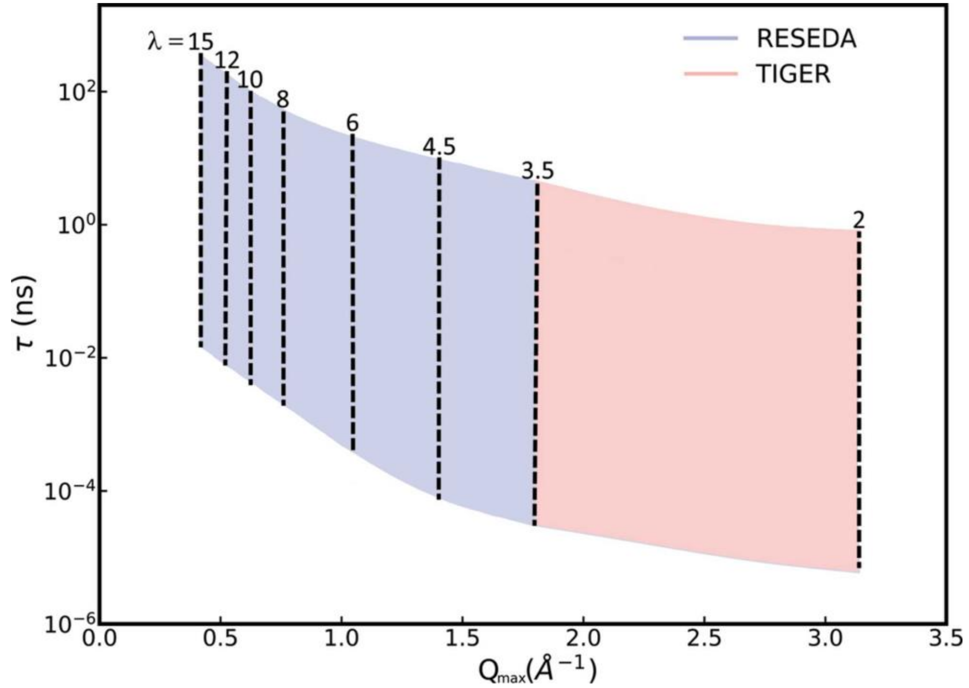
Arbe et. al., Phys. Rev. Research 2, (2020)

THERMAL NRSE & MIEZE

TIGER @ RESEDA

J. K. Jochum





Extending the measurement capabilities of RESEDA towards thermal wavelengths

→ Larger momentum transfer Q

→ Larger energy transfer (smaller τ)

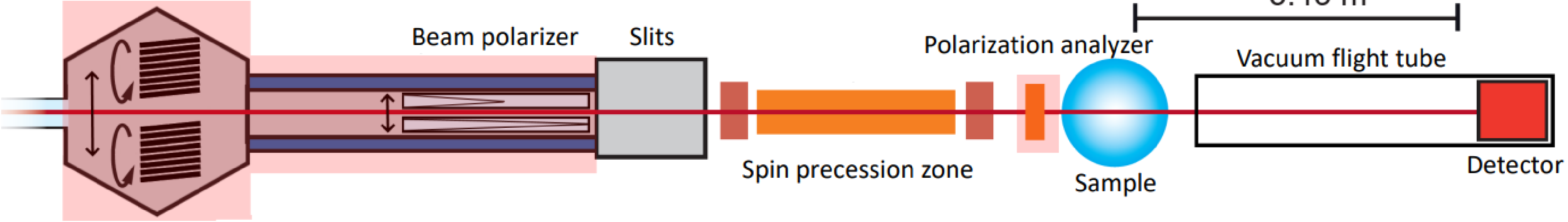
e.g.: 2Å → ΔEmax = 2.05meV

Q_{max} = 3.14Å^{-1}

$τ_{max}$ = 0.85 ns (QE: 7.23μeV)

THERMAL NRSE & MIEZE

TIGER @ RESEDA



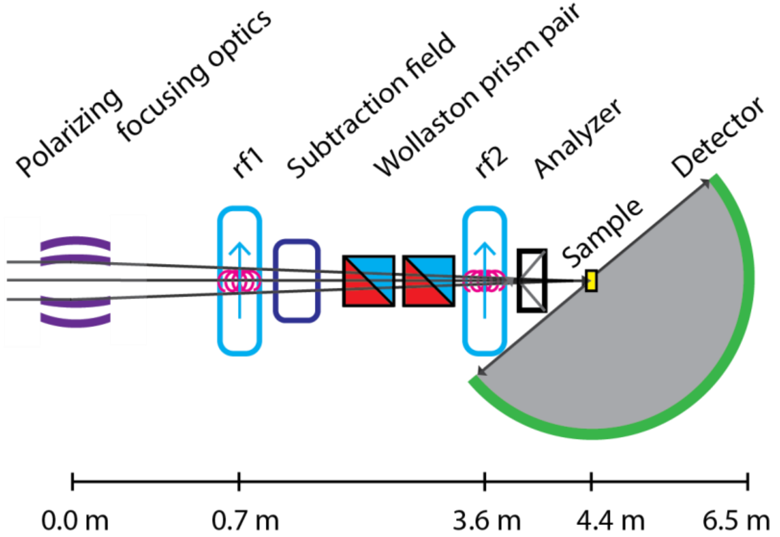
J. K. Jochum

New Science Cases:

- Investigation of Quantum Spin Liquid Candidates
- Accurate determination of low-lying Crystal Electric Fields
- Measuring Spectra/Decay of AF Magnons
- Hidden processes in disordered hard matter systems
- As thermal neutrons have a lower absorption coefficient → Lithium and Hydrogen Dynamics
- Q-independent processes on timescales down to femto seconds
- Diffusion in ionic liquids and solvent based electrolytes

WIDE ANGLE MIEZE (WAMI)

offers high intensity probe of diffusion and relaxation



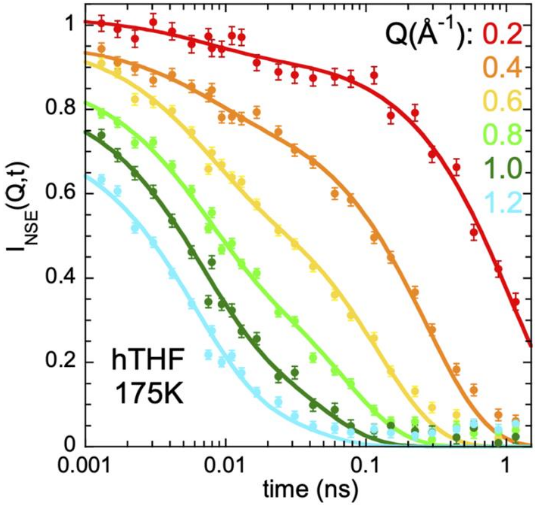
Kuhn, S, in preparation

Large spherical detector + large bandwidth = high intensity

Preserves key MIEZE advantages of:
- Wide neutron bandwidth
- Large dynamic range (similar Fourier times as WASP)
- Nothing between sample and detector
- Depolarizing samples do not change signal
  - Hydrogenous, magnetic, sample environment ok

Requires beam focusing to 1 mm and thin, large detector

Science case:
Complex/confined liquids



Steve Kuhn

Tertahydrofuran on WASP

Arbe, A., Nilsen G, et al. *J. Chem. Phys.* 158, 184502 (2023)

Detailed pLET and WASP study determined coherent and incoherent scattering functions of van der Waals liquid

Incoherent hydrogen scattering does not reduce MIEZE resolution

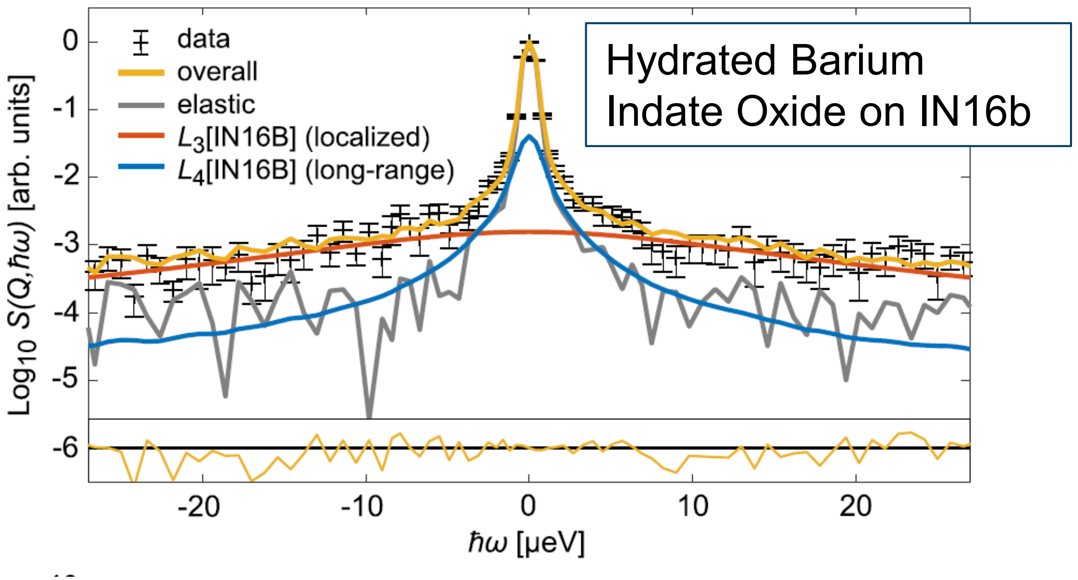
WAMI would offer measurement in time domain and simultaneous measurement of many *Q*
- Option to add He-3 analyzer after sample to differentiate coherent and incoherent scattering

Confined liquids also large field suitable for WAMI
High pressure cells compatible with beam focusing

WIDE ANGLE MIEZE (WAMI)

offers high intensity probe of diffusion and relaxation

Science case: Batteries



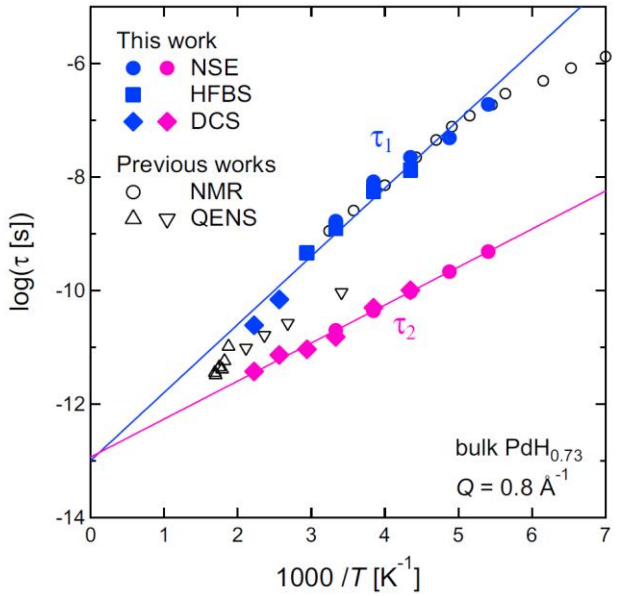
Perrichon, A. et al Chem. Mater. 35 6713 (2023)

QENS finds a novel method for higher proton conductivity in batteries by measuring multiple residence times

Small samples encouraged for WAMI - useful for novel materials that are hard to synthesize

Glass relaxation times also well-suited for WAMI

Science case: Hydrogen Storage



Palladium hydride shown to have two relaxation states by QENS

WAMI offers wide dynamic range to cover most of tau range with one instrument – similar energy range as WASP and IN16b

Kofu, M. et al. *Phys. Rev. B* 94, 064303 (2016)

Science case: iron oxide nanoparticles – see next 2 speakers

Option to add He-3 analyzer after sample to differentiate spin flip and non spin flip scattering

INSTEAD OF A SUMMERY…

Thanks for a very refreshing conference!

Do you see your science case represented here?

Let us know!

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