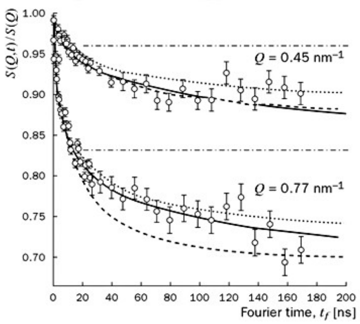
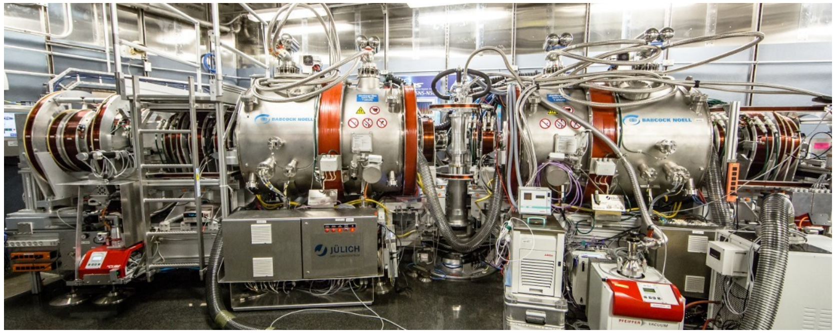
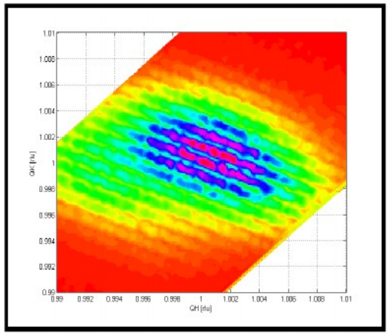
Physics with Neutrons II, SS2016



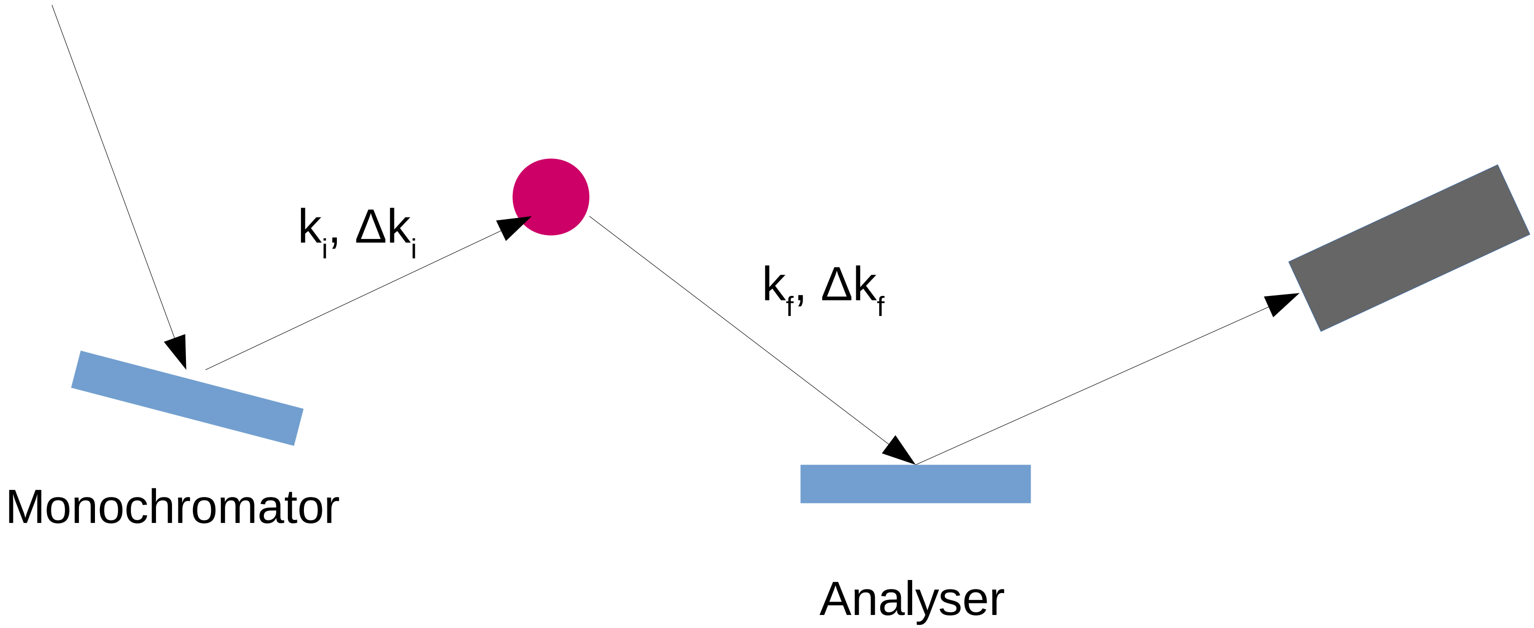




Spin Echo Spectroscopy

Lecture 11, 11.07.2016

Conventional Spectrometer (Triple Axes)



Large structures (polymers, biomolecules, etc.) and phase transitions imply slow dynamics
→ use cold neutrons for low energy transfers, tricks like backscattering geometry

But: resolution of conventional spectrometers are inverse proportional to intensity!
(better monochromator → $\Delta\lambda/\lambda$ smaller → better resolution, but less neutrons)

Goal: decouple resolution from intensity!

Z. Physik 255, 146—160 (1972)

Neutron Spin Echo: A New Concept in Polarized Thermal Neutron Techniques

F. Mezei

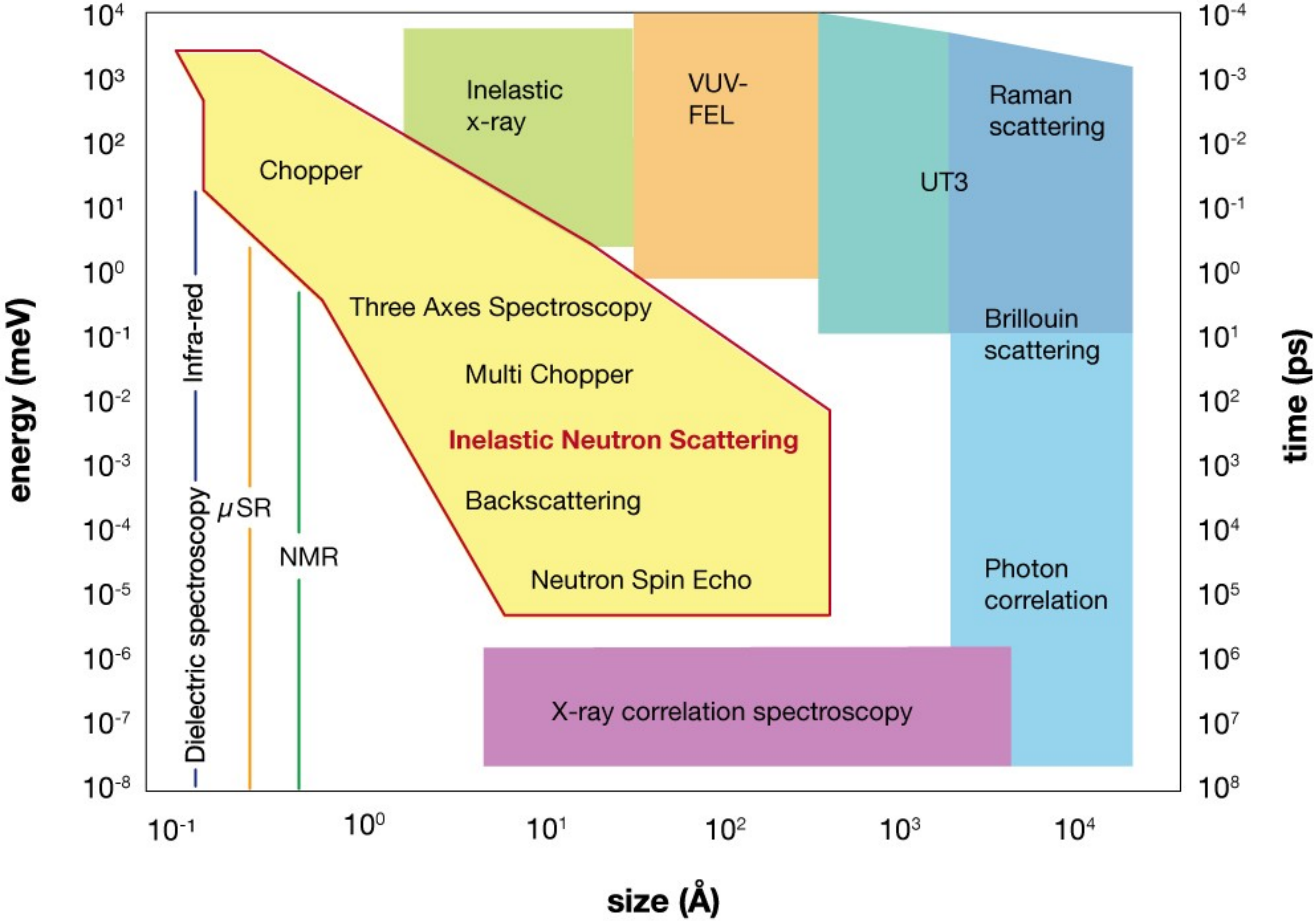
Institut Laue-Langevin, Grenoble, France* and
Central Research Institute for Physics, Budapest, Hungary

Received July 7, 1972

A simple method to change and keep track of neutron beam polarization non-parallel to the magnetic field is described. It makes possible the establishment of a new focusing effect we call neutron spin echo. The technique developed and tested experimentally can be applied in several novel ways, e.g. for neutron spin flipper of superior characteristics, for a very high resolution spectrometer for direct determination of the Fourier transform of the scattering function, for generalised polarization analysis and for the measurement of neutron particle properties with significantly improved precision.

I. Introduction

In the traditional technique of polarized thermal neutron beam studies one is concerned only with the component of the beam polarization parallel to the applied magnetic field. The polarizer devices are used to produce a neutron beam polarized parallel to the magnetic field applied


energy (meV)
time (ps)
size (Å)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
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10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^{-1}
10^0
10^1
10^2
10^3
10^4
Chopper
Three Axes Spectroscopy
Multi Chopper
Inelastic Neutron Scattering
Backscattering
Neutron Spin Echo
Inelastic x-ray
VUV-FEL
UT3
Raman scattering
Brillouin scattering
Photon correlation
X-ray correlation spectroscopy
Infra-red
Dielectric spectroscopy
μSR
NMR

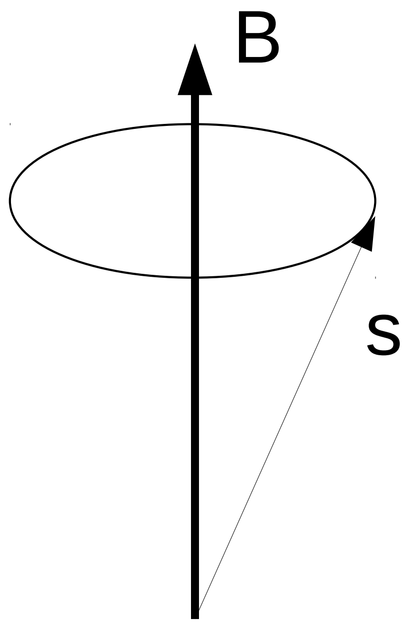
Larmor Precession of a Neutron Spin in magnetic Field

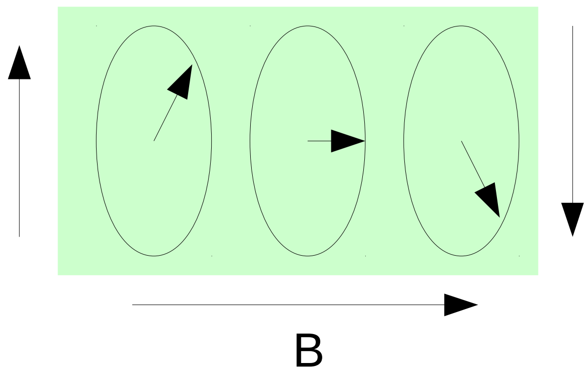
The expectation value of the spin of a spin-1/2 particle in magnetic field is:

$$\frac{d\vec{s}}{dt} = \gamma \vec{s} \times \vec{B} \longrightarrow \boxed{\omega_L = \gamma B}$$

gyromagnetic ratio:

$$\begin{aligned}\gamma &= 2912 * 2\pi \, \text{Gauss}^{-1} s^{-1} \\ &= 1.832 \cdot 10^{8} \, T^{-1} s^{-1} \\ &= 29.164 \, \text{MHz} \, T^{-1}\end{aligned}$$

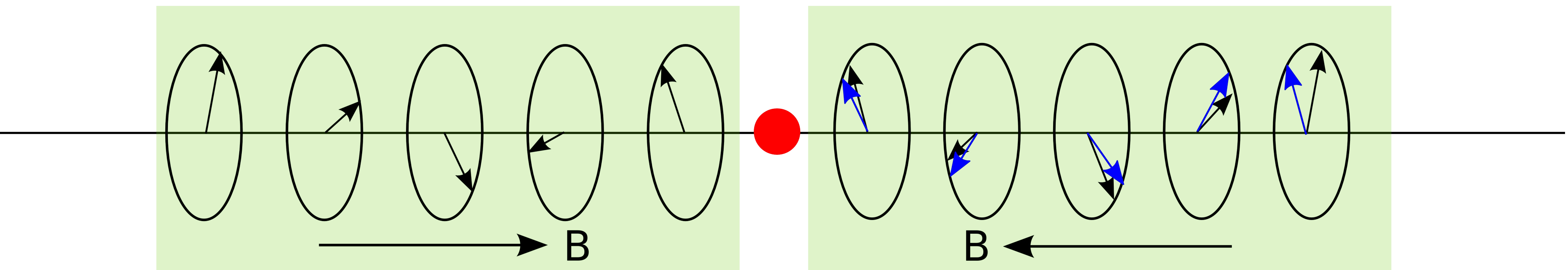




Application: π or π/2 Flipper
(Mezei Flipper)

NSE monochromatic

Sample



Spin Phase accumulated in field:

$$\Phi_1 = \gamma B_0^1 \cdot t_1 = \gamma B_0^1 \frac{L_1}{v_1}$$

$$\Phi_2 = \gamma B_0^2 \cdot t_2 = \gamma B_0^2 \frac{L_2}{v_2}$$

Total spin phase:

$$\Phi = \Phi_1 + \Phi_2 = \gamma \left(\frac{B_0^1 L_1}{v_1} + \frac{B_0^2 L_2}{v_2} \right) = \gamma BL \left(\frac{1}{v_1} - \frac{1}{v_2} \right)$$

$$v_2 = v_1 + \delta v$$

$$\Phi \approx \gamma BL \frac{\delta v}{v_1^2}$$

Depends only on difference of velocities

Triple axes: k_i and k_f absolutely measured!

Energy transfer in quasielastic scattering:

$$\hbar \omega = \frac{m_n}{2} \left((v_1 + \delta v)^2 - v_1^2 \right) \approx m_n v_1 \delta v$$

$$\Phi \approx \gamma BL \frac{\hbar \omega}{m_n v_1^3}$$

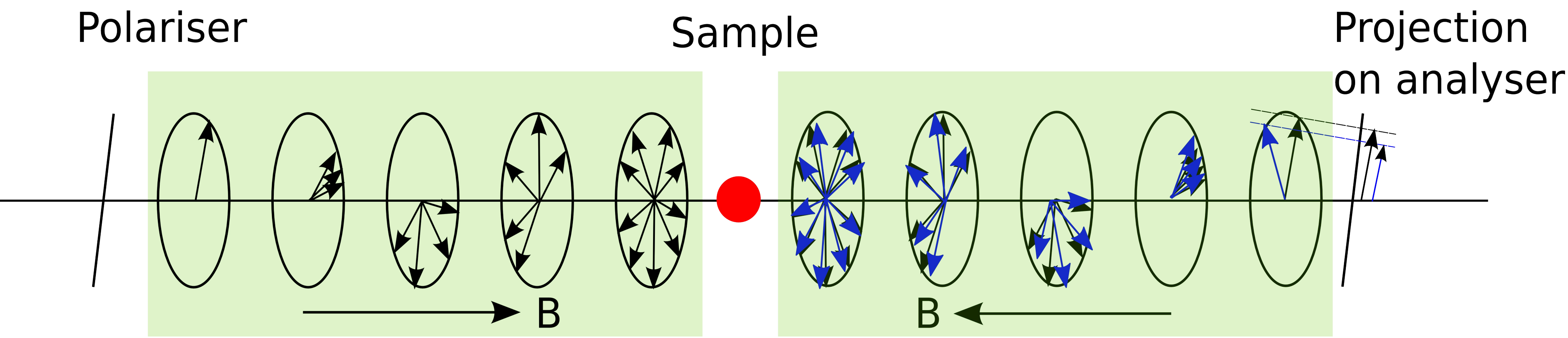
$$\tau_{NSE} = \frac{\gamma \hbar BL}{m_n v_1^3}$$

$$\Phi = \omega \cdot \tau$$

Intermediate scattering function

$$P(Q, \tau) = \langle \sigma_x \rangle = \langle \cos \Phi \rangle = \int S(q, \omega) \cos \omega \tau_{NSE} \, d\omega = I(q, \tau_{NSE})$$

NSE polychromatic



$$v = v(\lambda)$$

$$\Phi = \left\langle \gamma \frac{Bl}{v(\lambda)} - \gamma \frac{Bl}{v(\lambda)+\delta\lambda} \right\rangle \longrightarrow \Phi = \gamma \frac{m}{h} Bl\,\delta\lambda + \underbrace{\gamma \frac{m}{h}(B_0 l - B_1 l)\lambda}_{\to 0 \text{ at spin echo point}}$$

Energy transfer:

$$\hbar\omega = \frac{h^2}{2m}\left[\frac{1}{\lambda^2} - \frac{1}{(\lambda+\delta\lambda)^2}\right] \approx \frac{h^2}{m}\frac{\delta\lambda}{\lambda^3}$$

$$\Phi = \gamma Bl \frac{\hbar^2 \omega}{m v^3}$$

$$\delta\lambda = \frac{\omega}{2\pi h} m \lambda^3$$

Field Integral J

ideal: $J = B \cdot l$

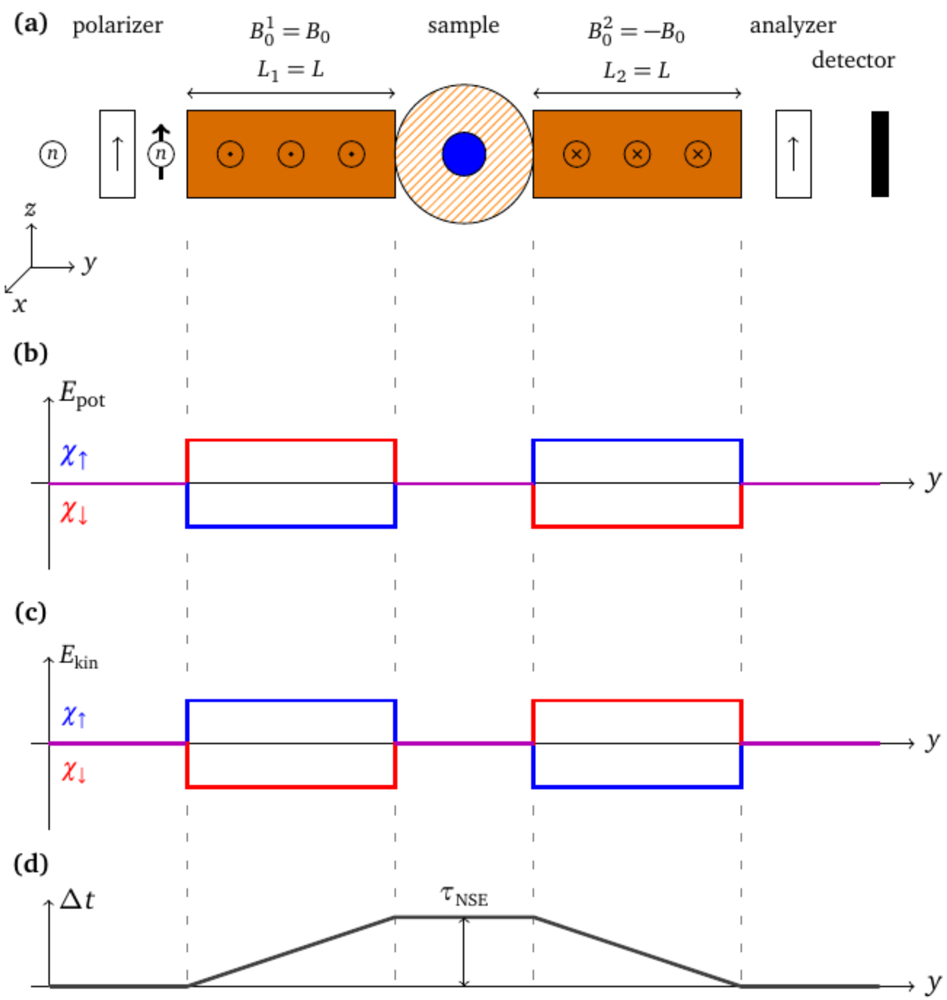
real: $J = \int B \cdot dl$

Wavelength distribution

Intermediate scattering function

$$P(Q,\tau) = \langle \sigma_x \rangle = \langle \cos\Phi \rangle = \int f(\lambda) S(q,\omega) \cos\omega\tau_{NSE}\, d\omega = I(q,\tau_{NSE})$$

Semi-classical description of NSE



Quantisation direction along x

$$\chi_\downarrow^z = \frac{1}{\sqrt{2}}(\chi_\downarrow^x + \chi_\uparrow^x) = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}^x$$

Potential energy in mag. field

$$E_{pot}^{\uparrow\downarrow} = \pm\mu B$$

$$E_{kin}^{\uparrow\downarrow} = E_{ges} \mp E_{pot}^{\uparrow\downarrow} = E_{ges}\left(1 \mp \frac{E_{pot}^{\uparrow\downarrow}}{E_{ges}}\right)$$

$$t^{\uparrow\downarrow} = \frac{L}{v^{\uparrow\downarrow}} = \frac{L}{v_0} \mp \frac{\hbar\gamma B_z L}{2mv_0^3} = t_0 \mp \frac{\tau_{NSE}}{2}$$

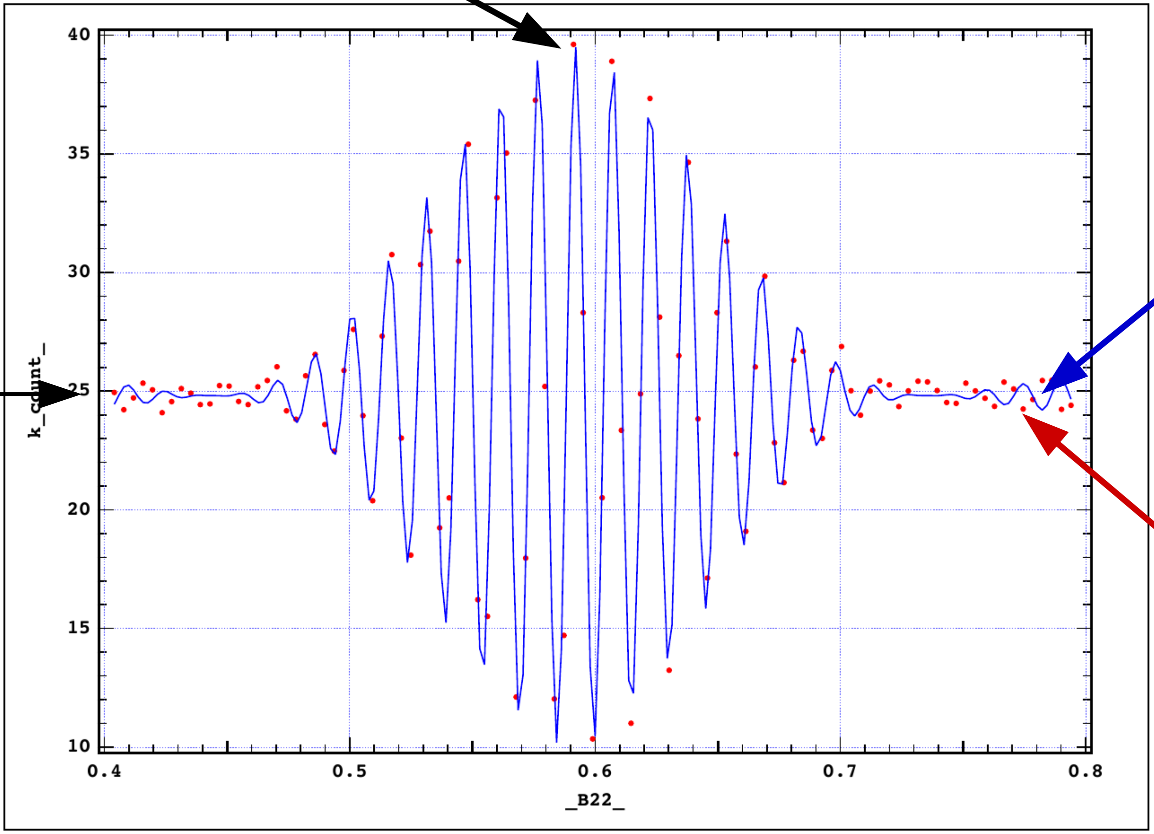
$$t^\uparrow - t^\downarrow = \tau_{NSE}$$

Spin Echo Group

P = Ampl / Avg

Max Count = Echo Point

Instrument set at spin echo time τ_1

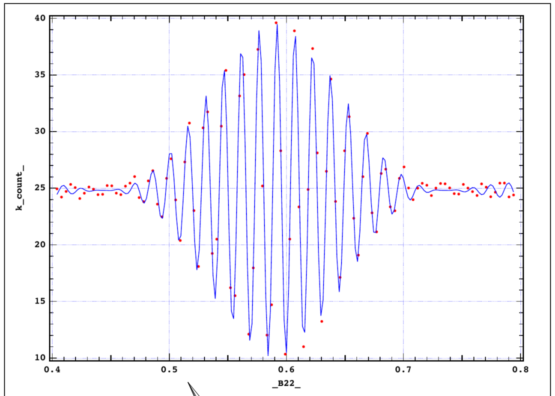


Average Count

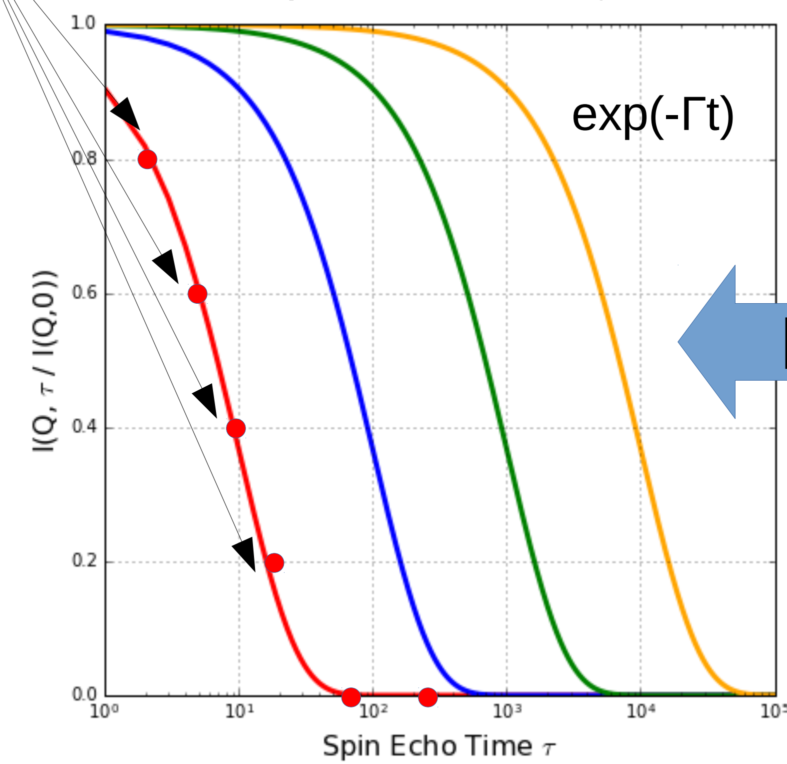
Fit to data

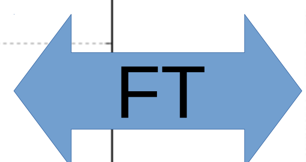
Neutron counts

Envelope: depends on shape of neutron spectrum given by velocity selector f(v)

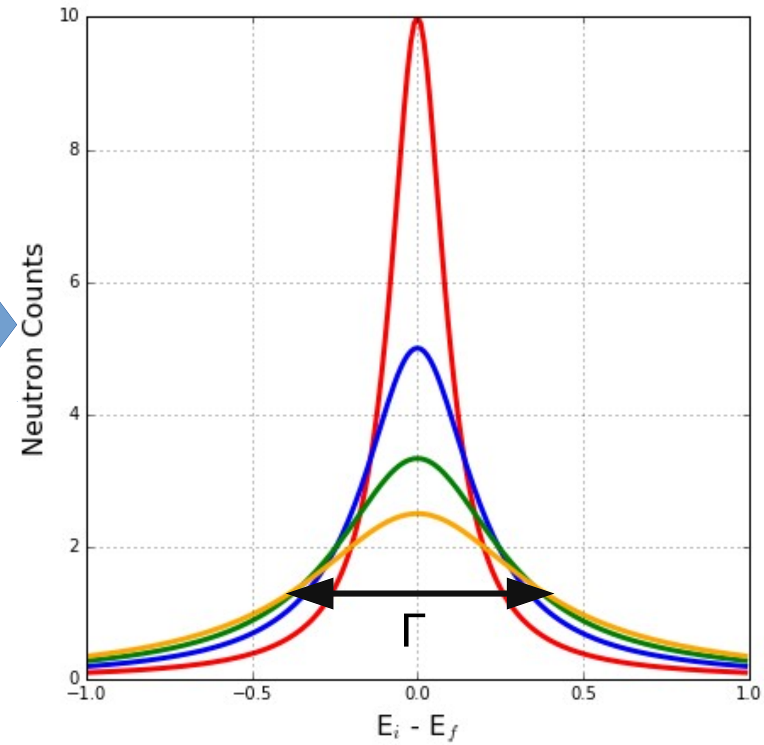


Exponential decay





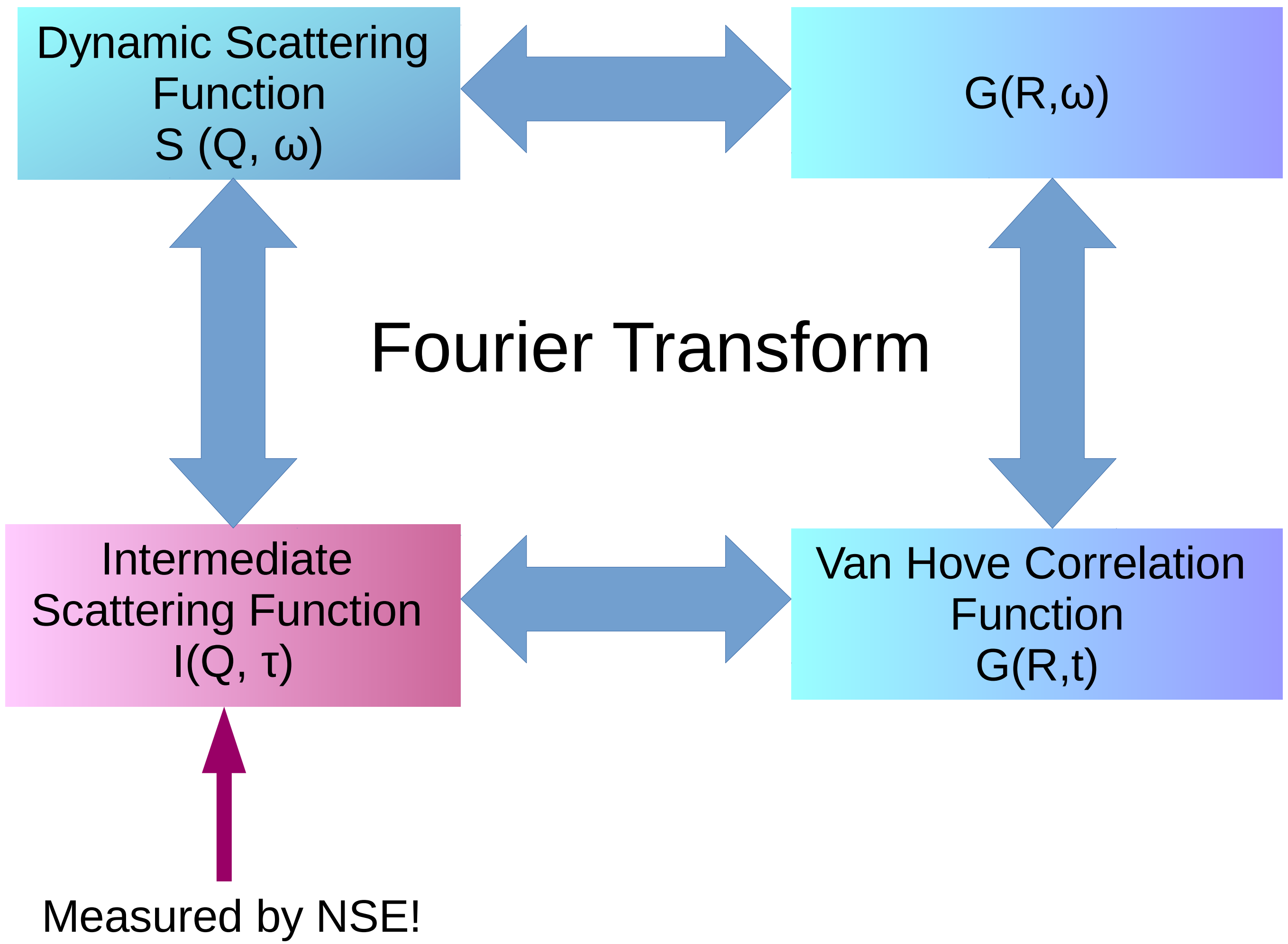
Consider quasielastic scattering
To be **Lorentian**:



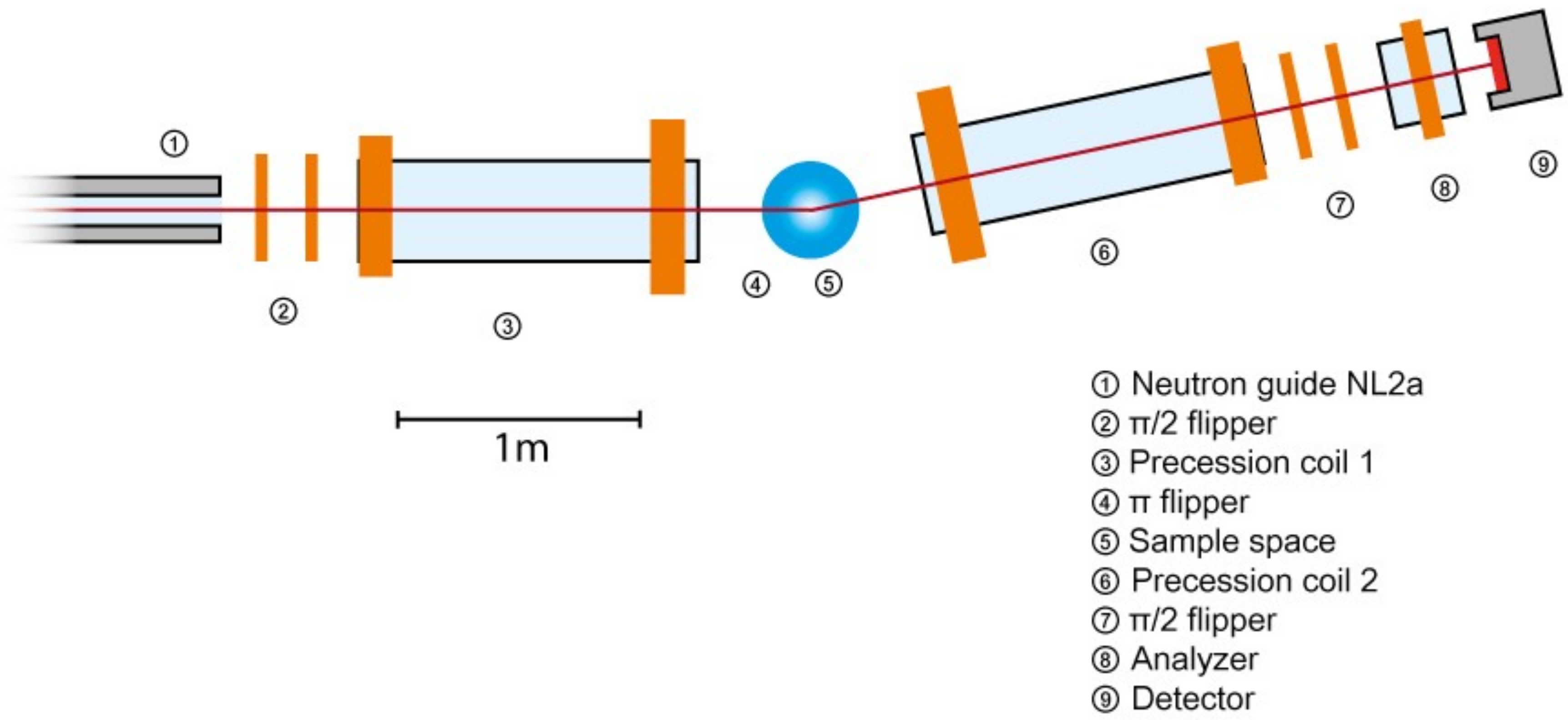
$$P(Q,t)=\frac{\int[\Gamma^2+\omega^2]^{-1}\cos(\omega t)\,d\omega}{\int[\Gamma^2+\omega^2]^{-1}\,d\omega}=e^{-\Gamma\tau}$$

$$S(Q,\omega)\propto\frac{\Gamma}{\Gamma^2+\omega^2}$$

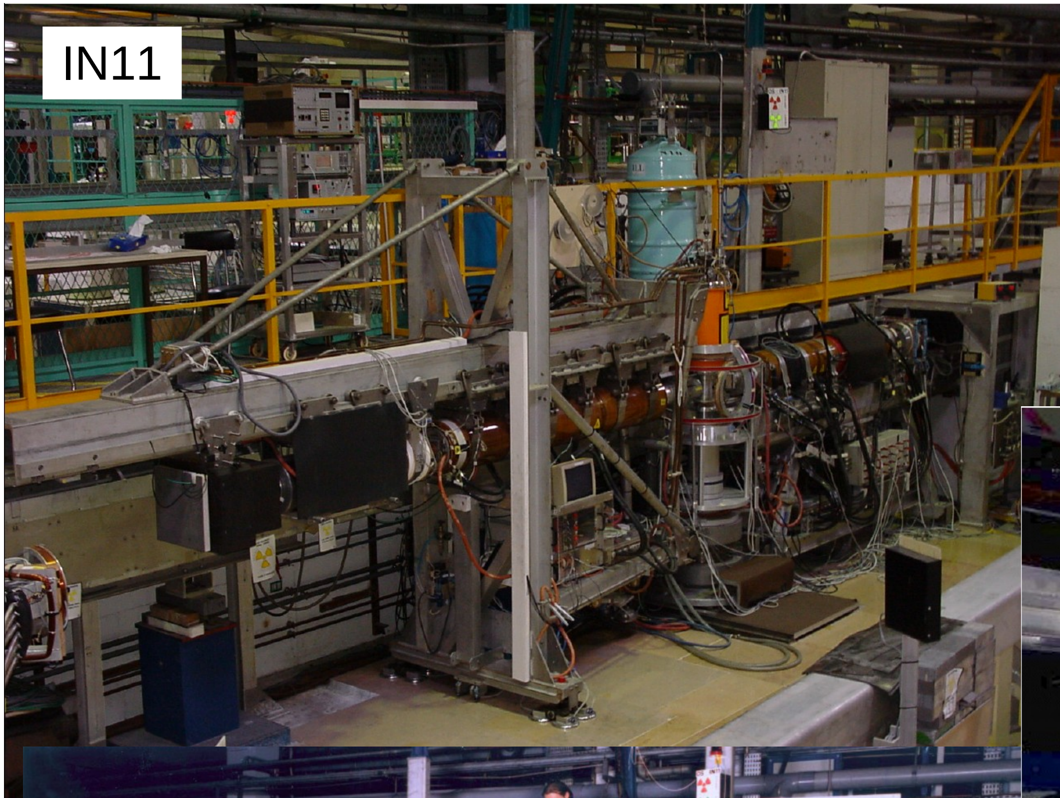
NSE directly measures the intermediate scattering function I(Q,τ)



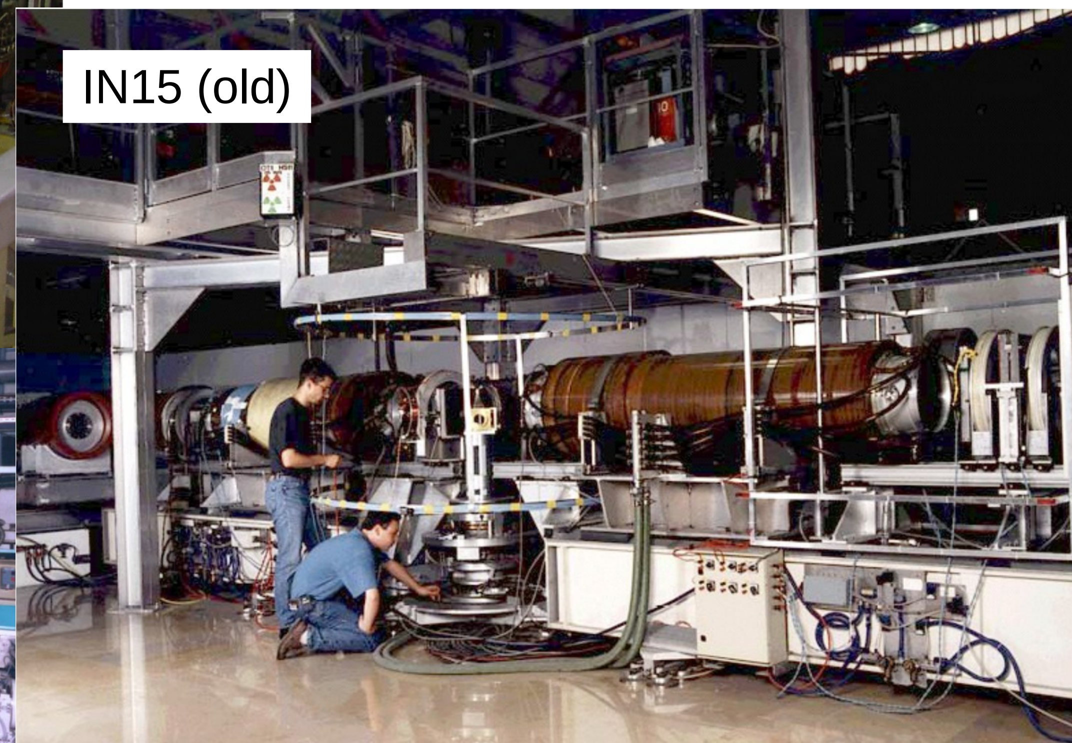
Schematic Realisation of an NSE Instrument
J-NSE, MLZ

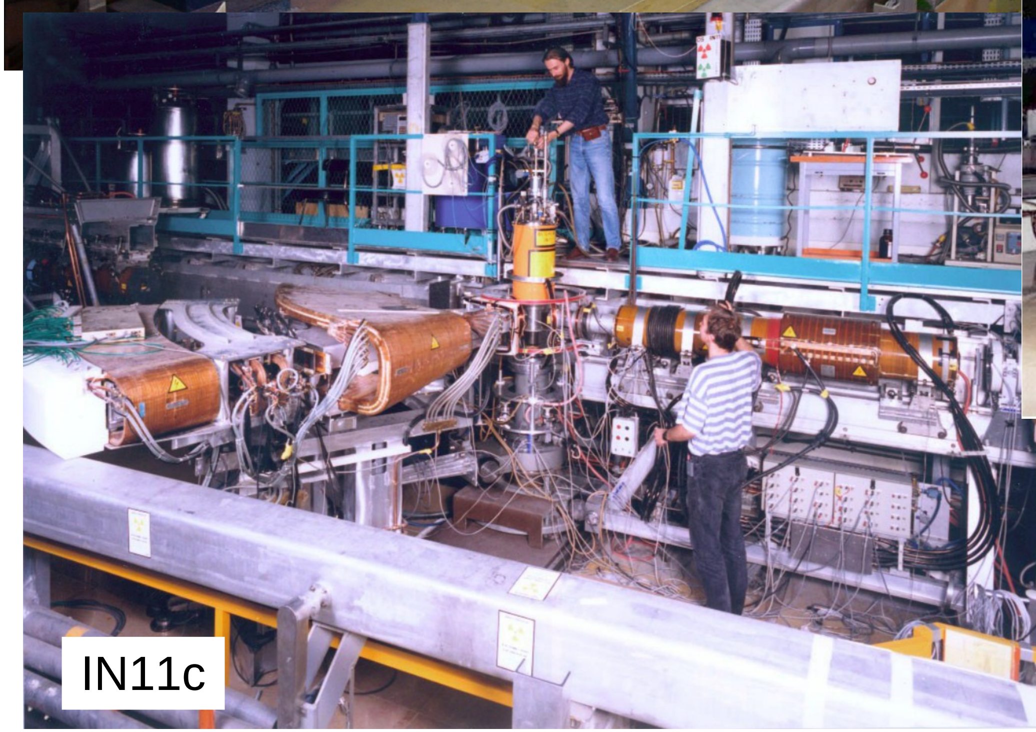


ILL, Grenoble (France)



IN11 was the first NSE
BL = 0.27Tm
50ns @ 10Å





Old IN15: BL = 0.27Tm
Up to 250ns
New IN15: BL = 1Tm
1 µs @ 18Å

Jülich NSE @ SNS Oak Ridge

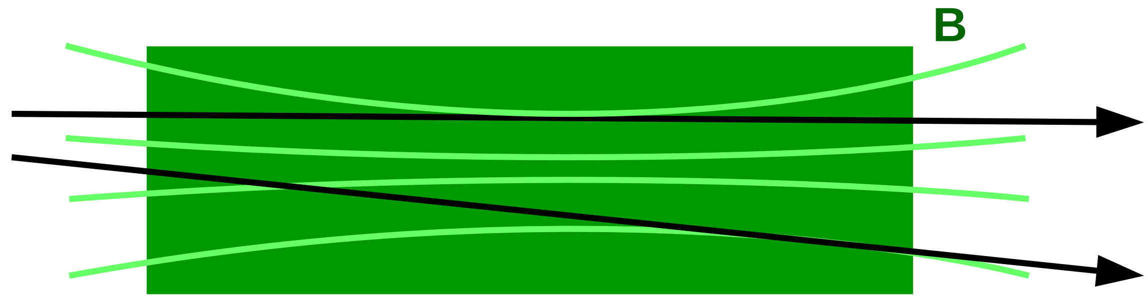
- Superconducting magnets
- BL = 1Tm
- 350ns @ 14Å
- µ-metal chamber

- Similar to J-NSE @ MLZ
- BL = 0.438Tm

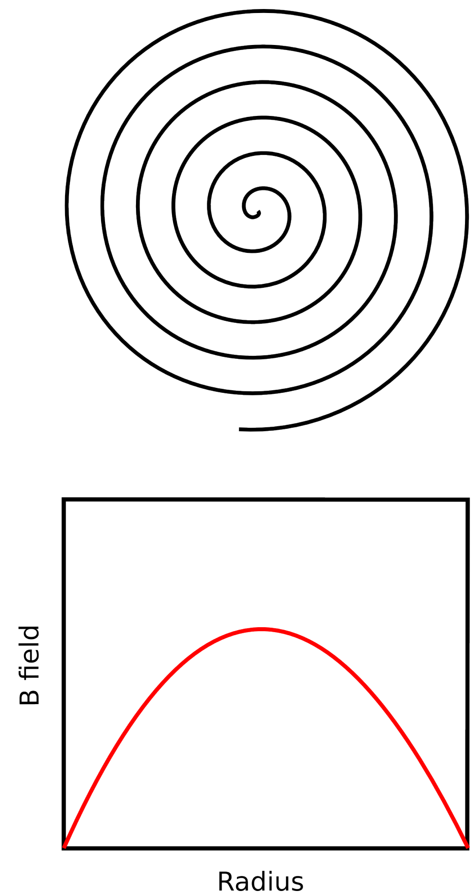
NG5-NSE @ NIST, Gaithersburg

Correcting field imperfections:

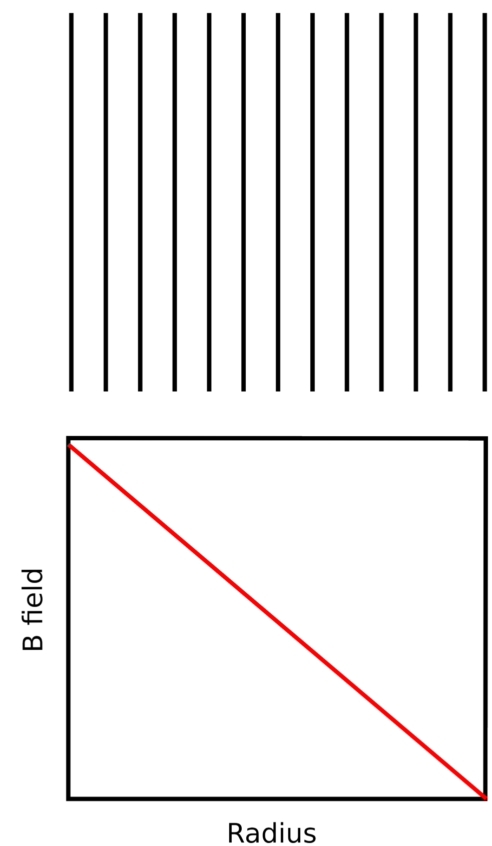
$$\Phi(\lambda) = \gamma \frac{\int \mathbf{B} \cdot \mathbf{dl}}{v}$$



Fresnel coils:

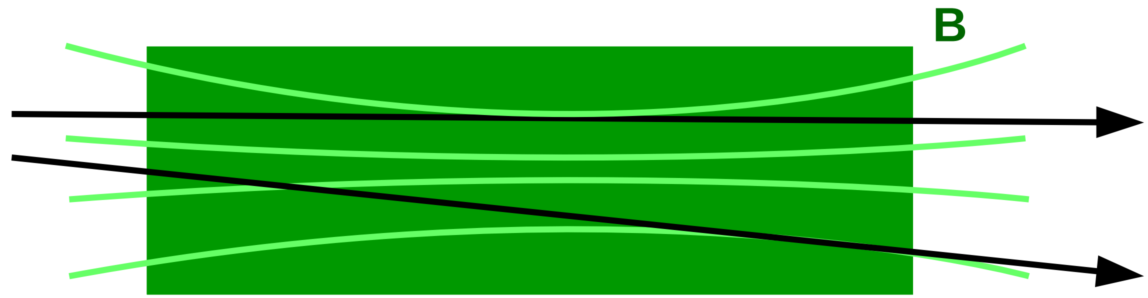


Shifter:

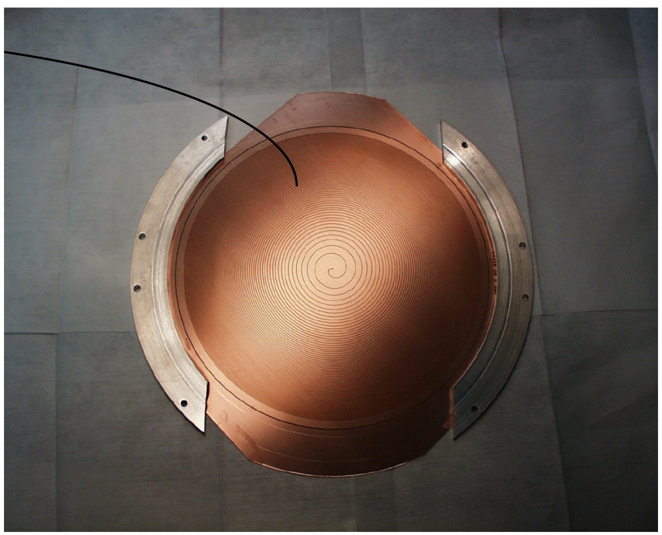


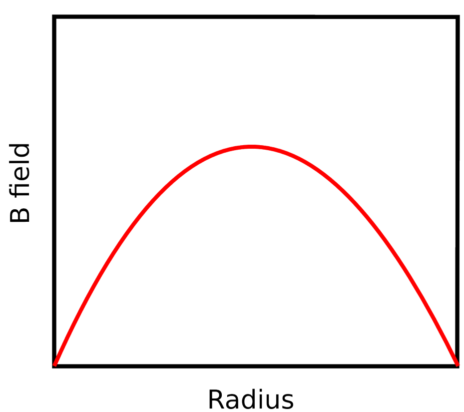
Correcting field imperfections:

$$\Phi(\lambda) = \gamma \frac{\int \mathbf{B} \cdot d\mathbf{l}}{v}$$

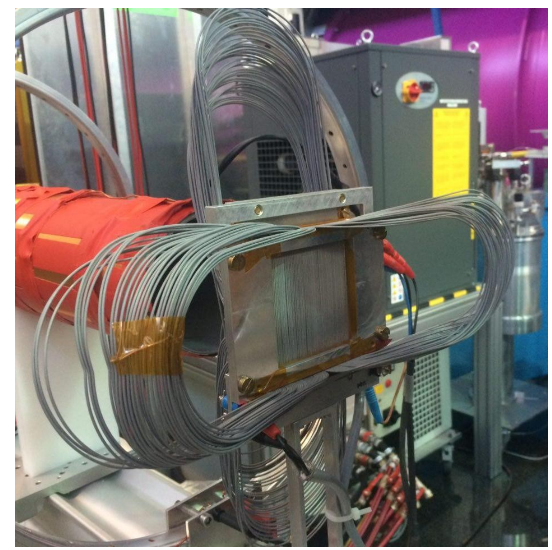


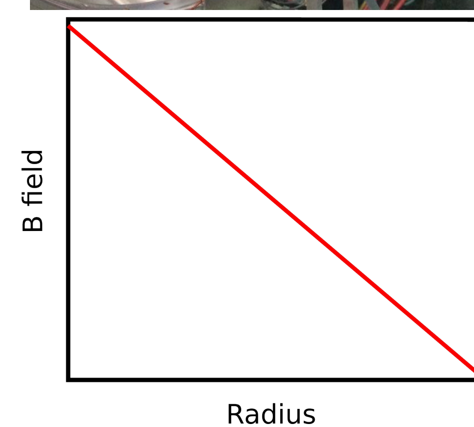
Fresnel coils:





Shifter:





Neutron Spin Echo – Takeaway messages

NSE breaks the relationship between intensity & resolution

- Traditional Instruments – define both incident and scattered wavevectors in order to define E and Q accurately

- Traditional Instruments – use collimators, monochromators, choppers etc to define both k_i and k_f

- NSE – measure the difference between appropriate components of k_i and k_f (original use: measure k_i - k_f i.e. energy change)

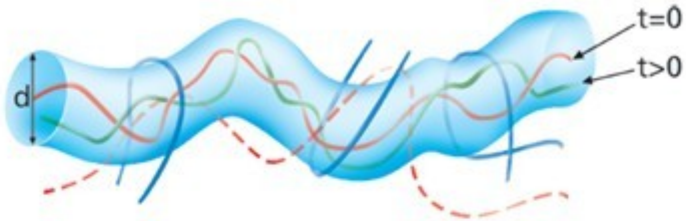
- NSE – use the neutron's spin polarisation to encode the difference betweeen components of k_i and k

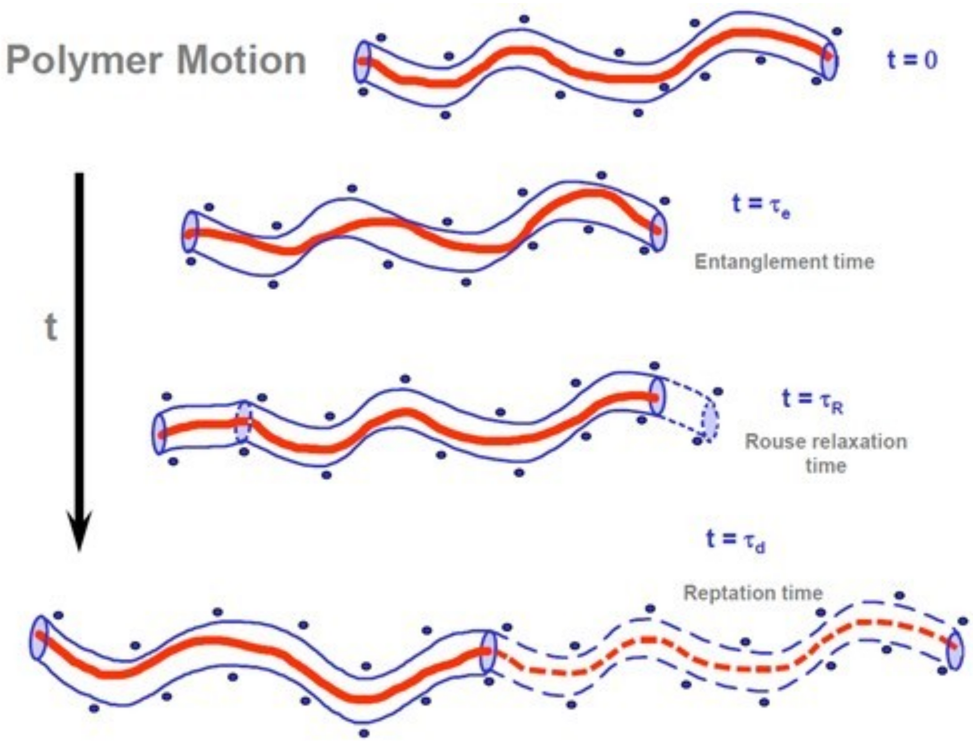
  f

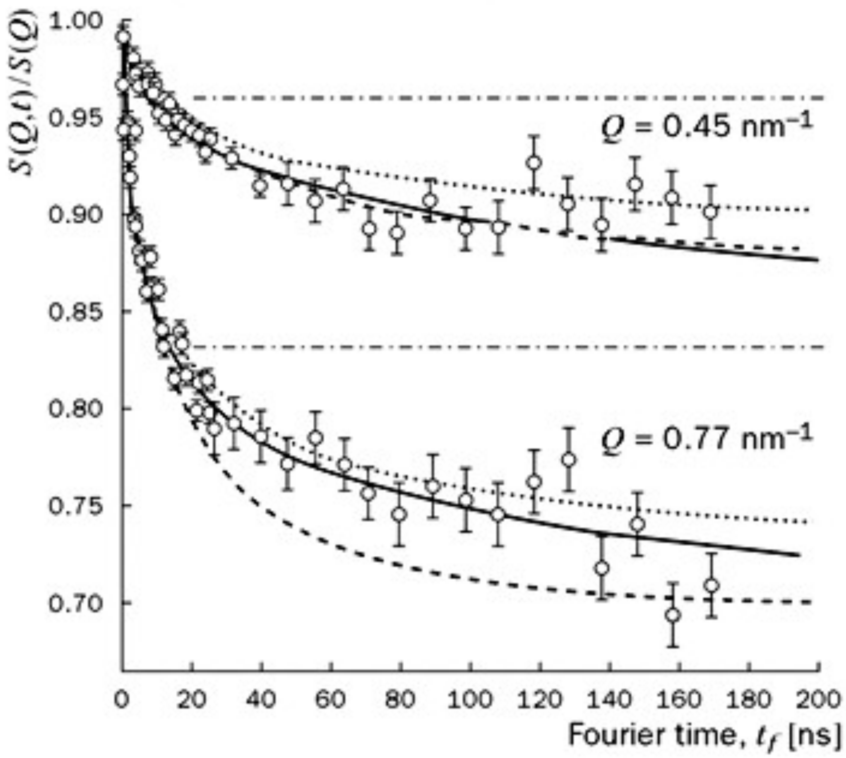
- NSE – can use large beam divergence and /or poor monochromatisation to increase signal intensity, while maintaining very good resolution

Stolen from: Faraone Methods and Applications of SANS, NR and NSE, (2012)

Example: de Gennes reptation in polymers



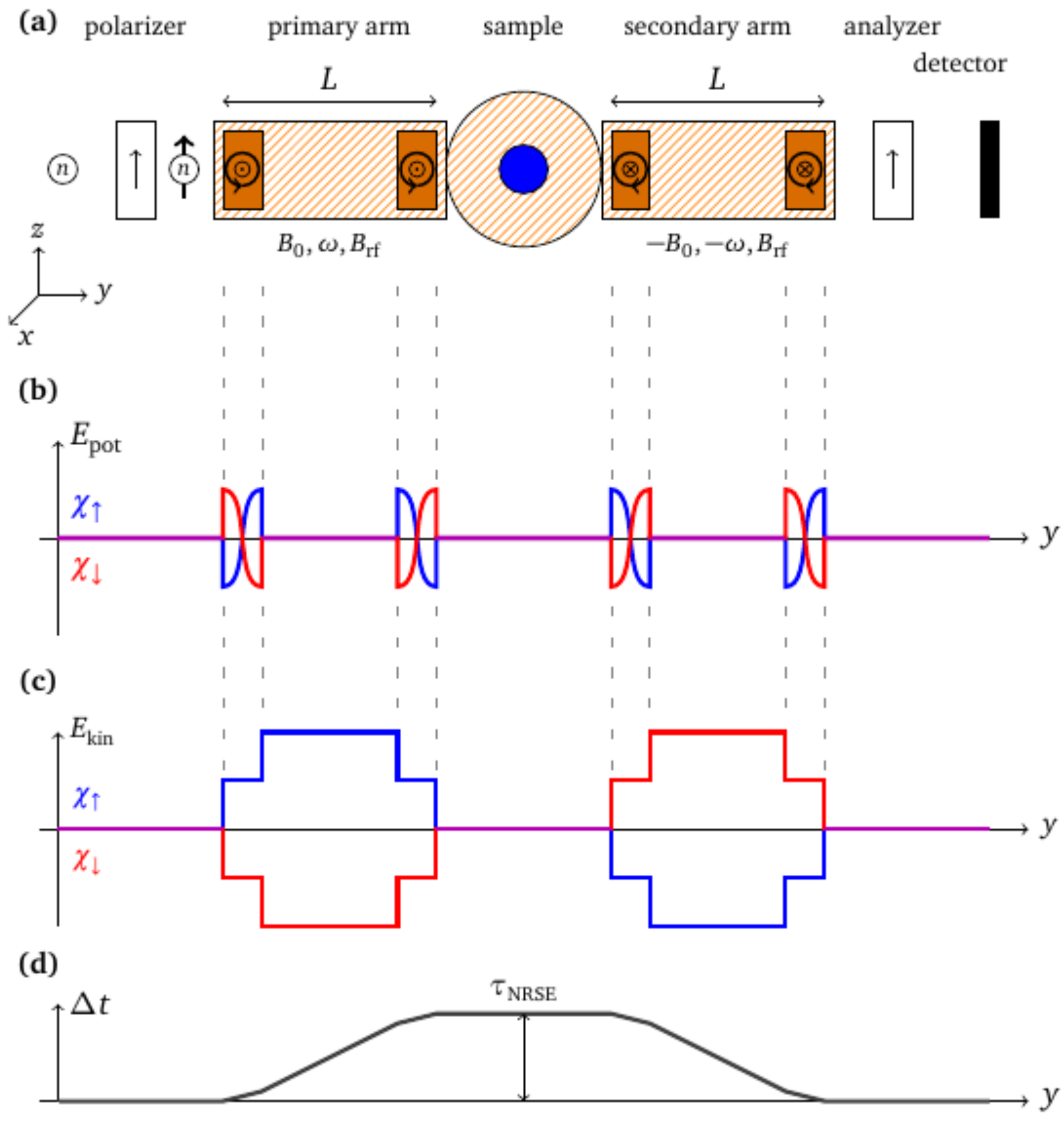


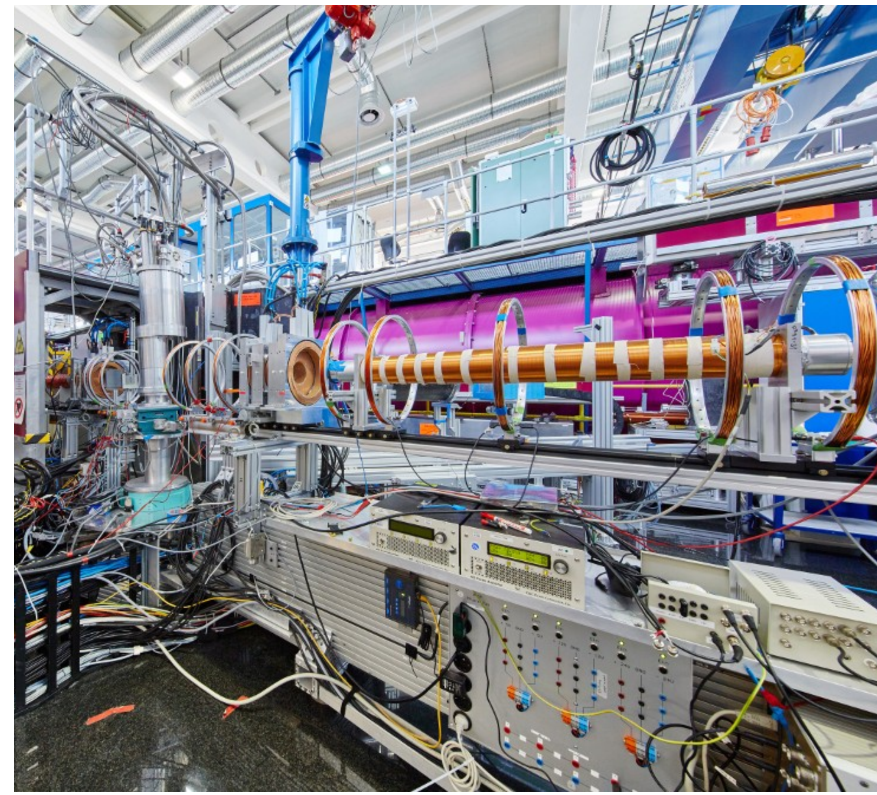


Only few % protonated chains in a deuterated matrix

A. Radulescu, JCNS, (2014)

(Longitudinal) Neutron Resonant Spin Echo

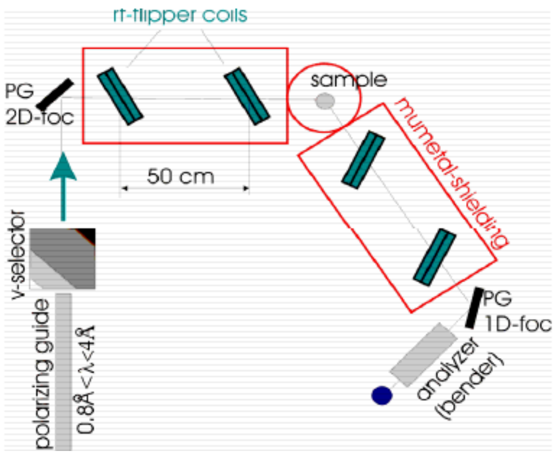


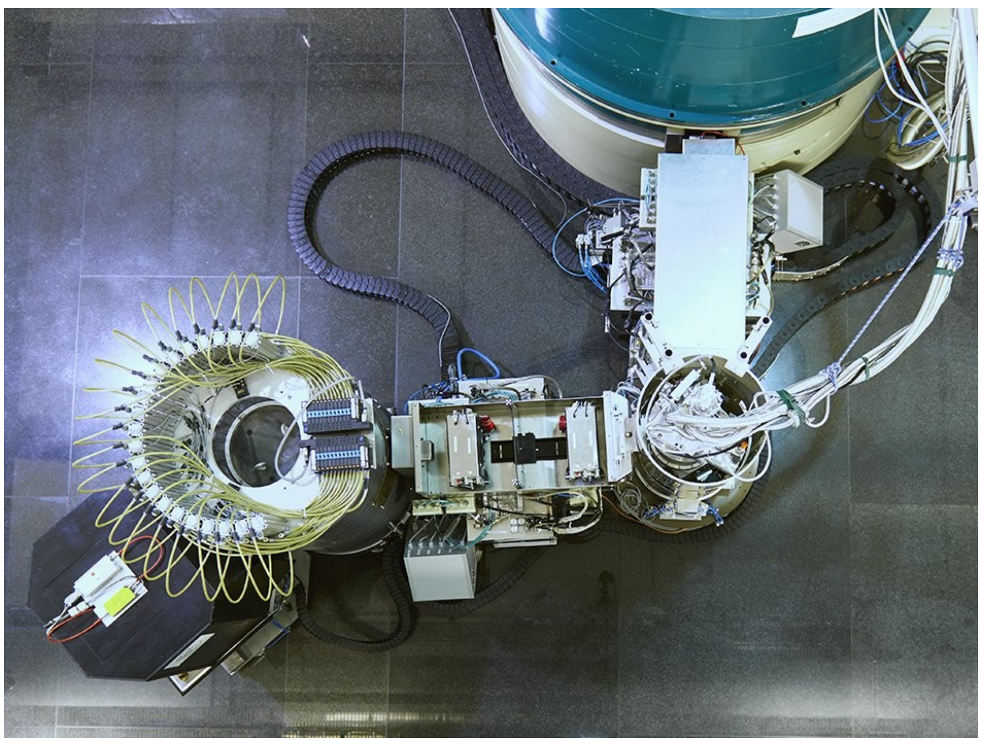


$$\tau_{NRSE} = \frac{2\hbar\gamma B_0 L}{mv^3} = \frac{2\hbar\omega L}{mv^3} = 2\tau_{NSE}$$

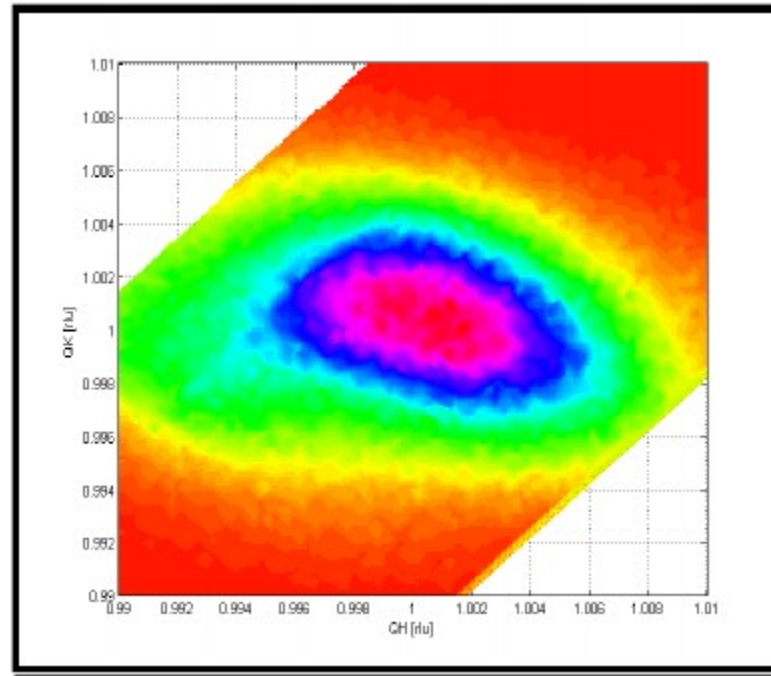
NRSE: Goulob, Gähler
LNRSE: Häußer, Schmidt

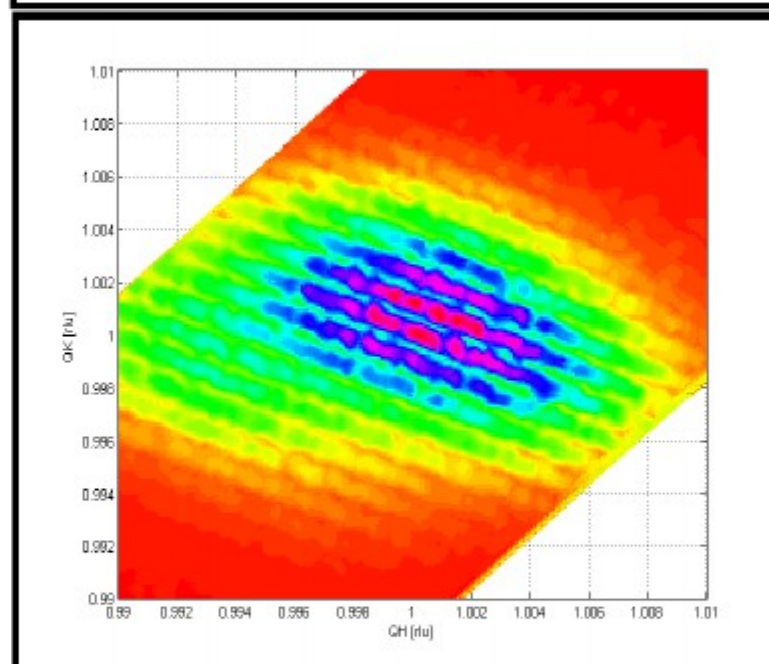
NRSE and triple axes spectroscopy



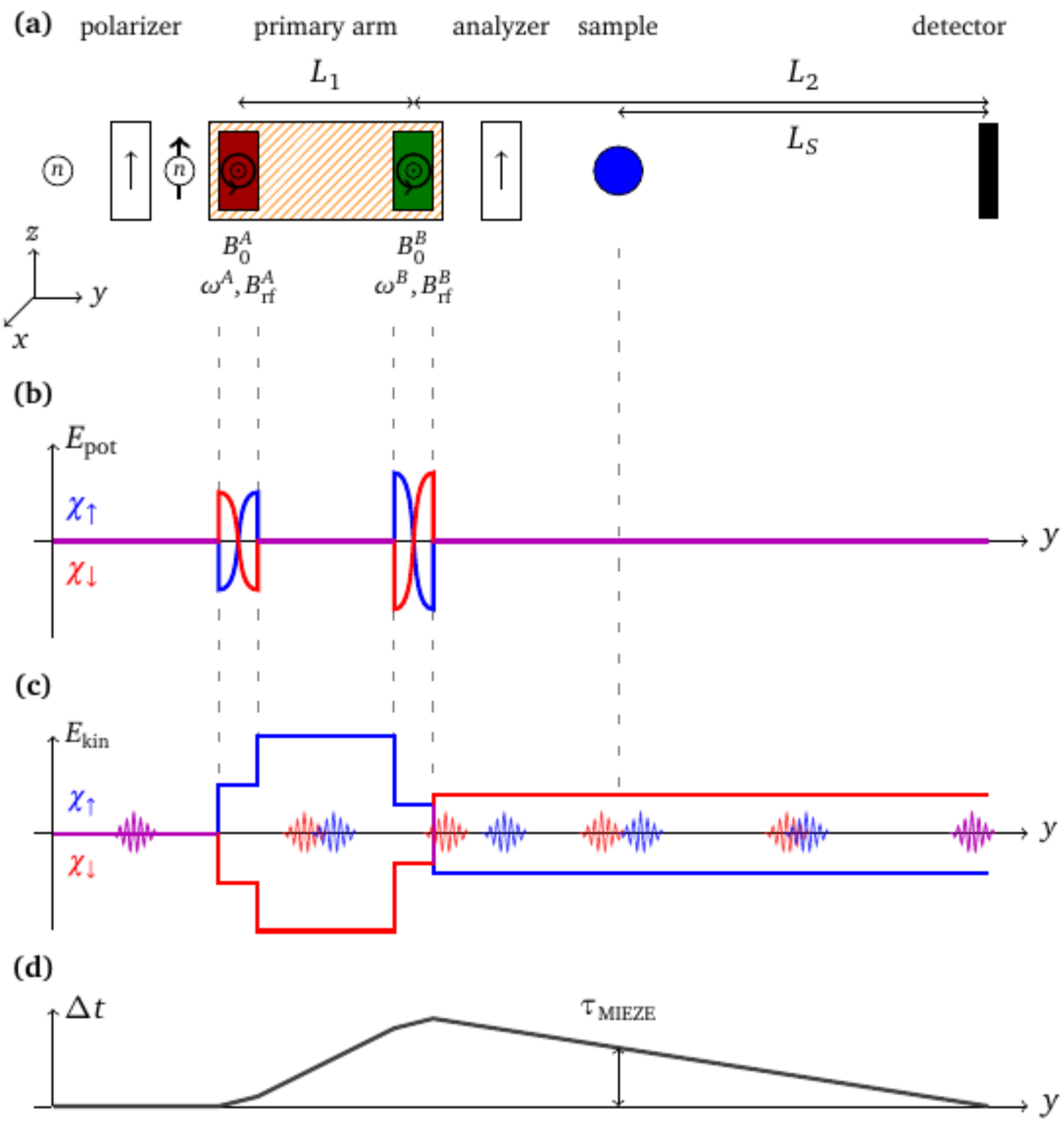


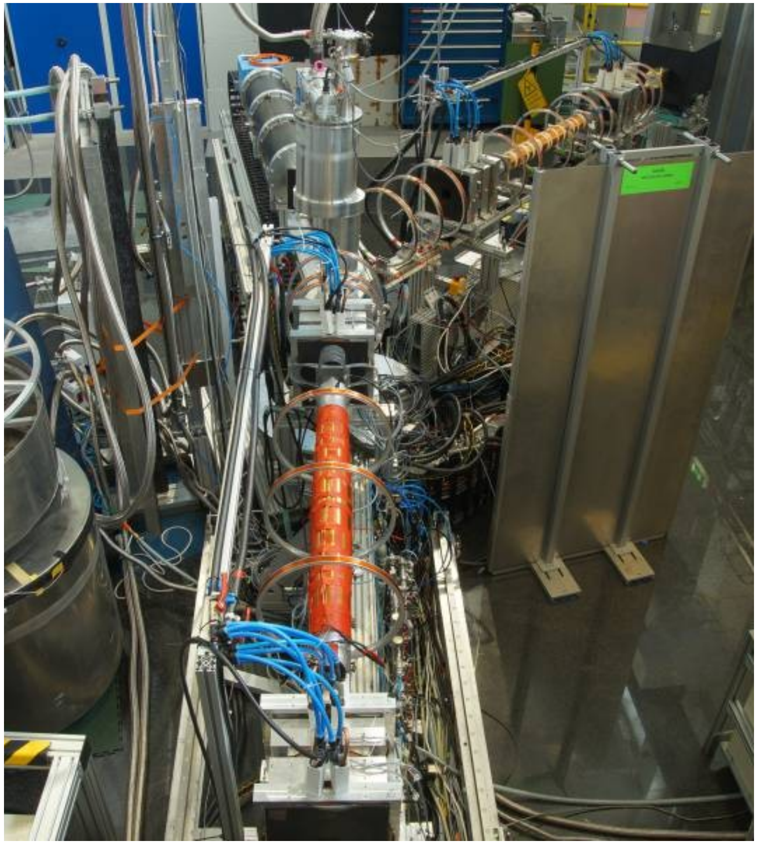
TRISP @ FRMII





Modulation of Intensity by Zero Effort (MIEZE)

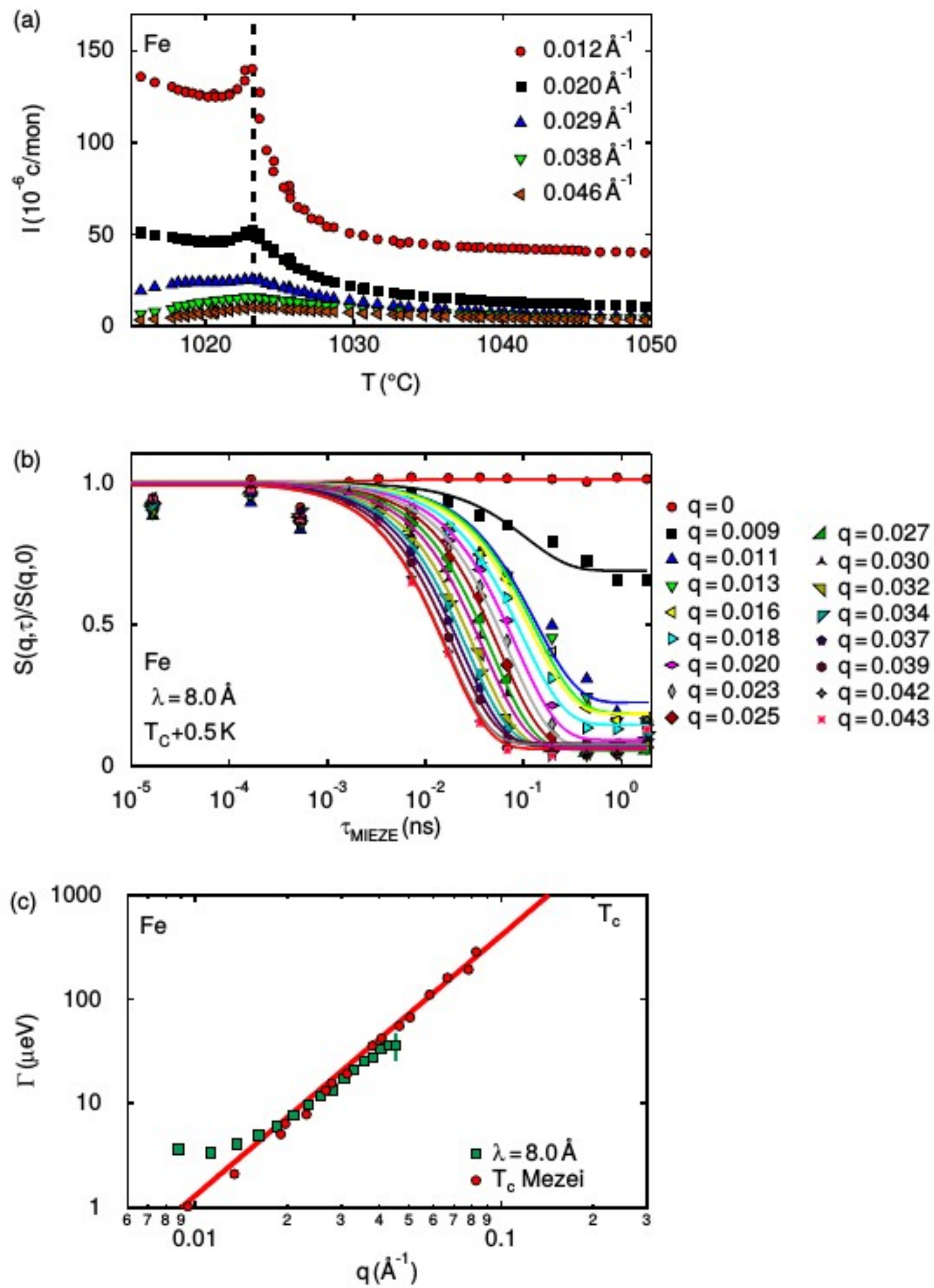




$$\tau_{MIEZE} = \frac{h}{m} \cdot \frac{L_S(\omega_B - \omega_A)}{v^3}$$

$$= \frac{m^2}{\pi h^2} \cdot L_S(\omega_B - \omega_A)\lambda^3$$

Ferromagnetic Fluctuations in Fe near T_c



J. Kindervater, PhD thesis, 2015