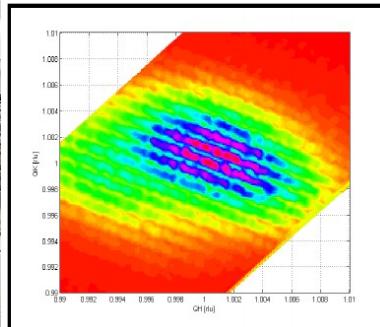
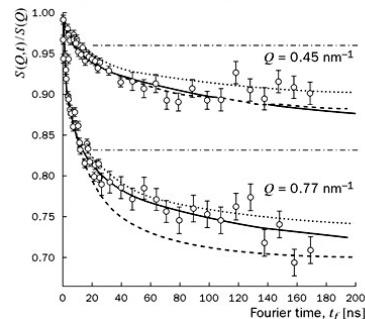


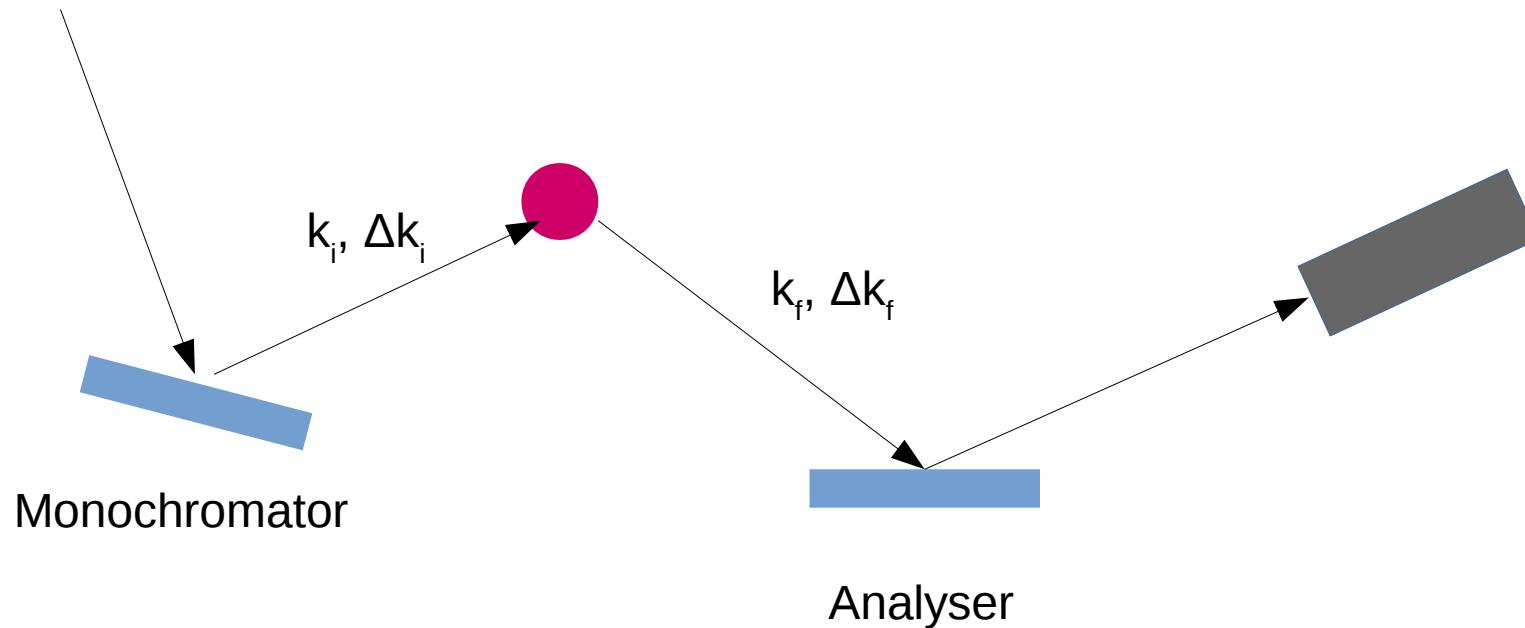
Physics with Neutrons II, SS2016



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!

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

F. Mezei

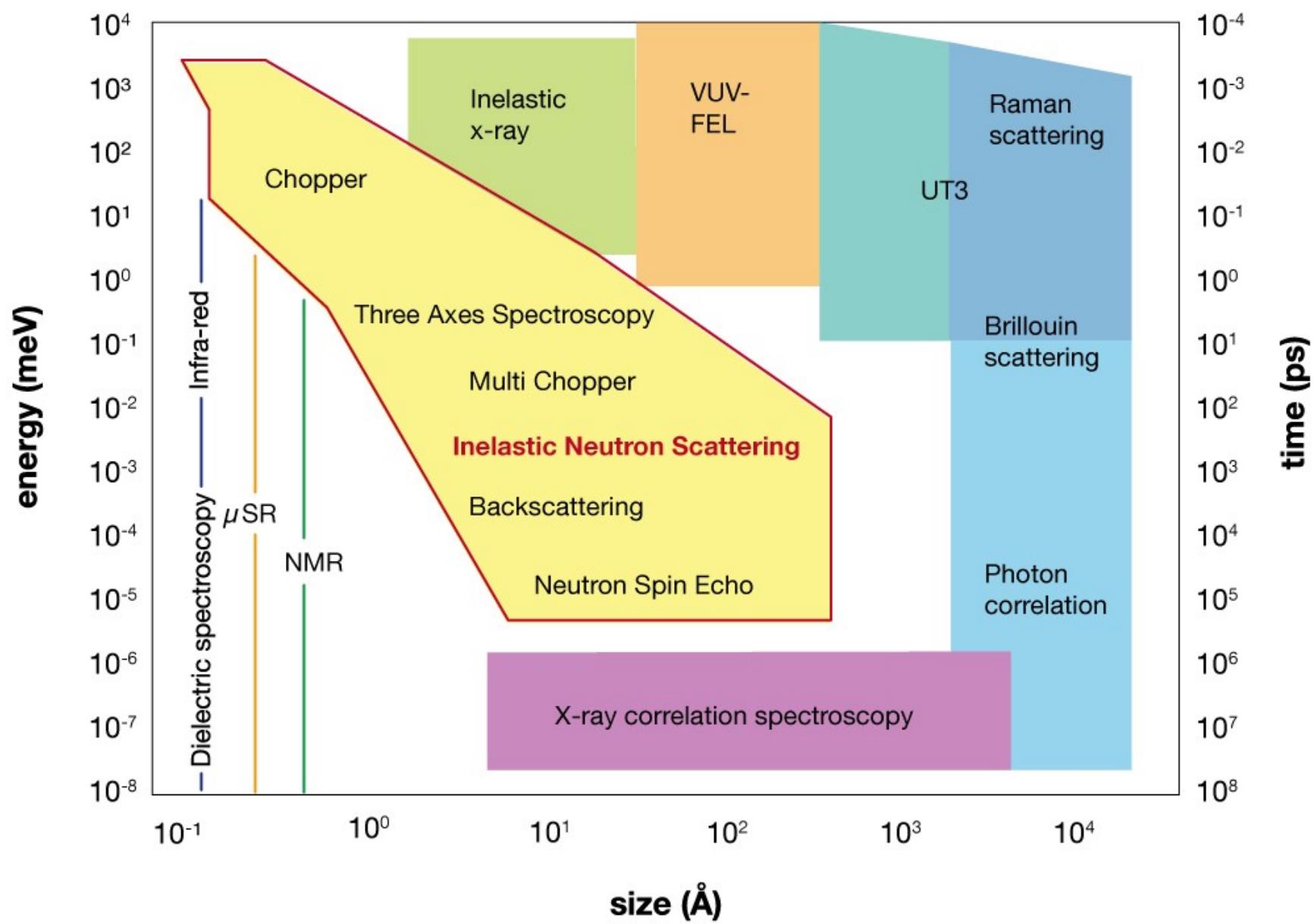
Institut Laue-Langevin, Grenoble, France* and
Central Research Institute for Physics, Budapest, Hungary

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



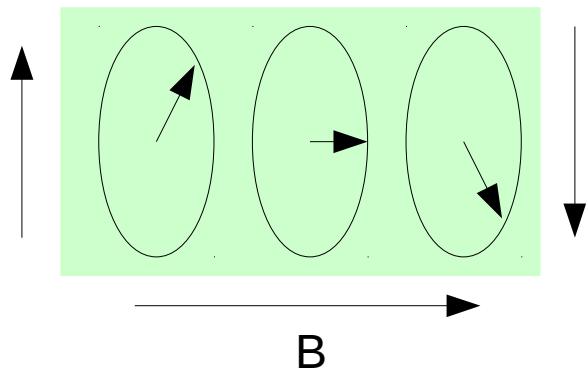
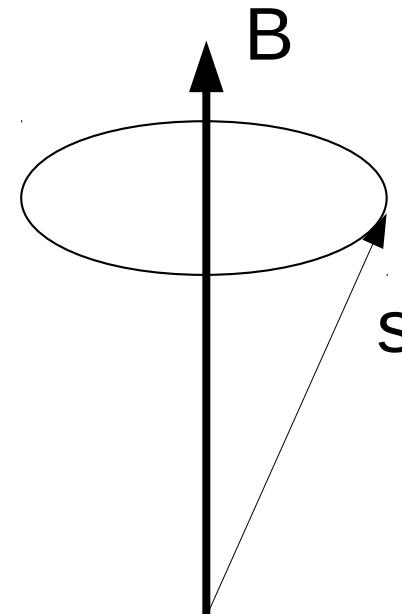
Larmor Precession of a Neutron Spin in magnetic Field

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:

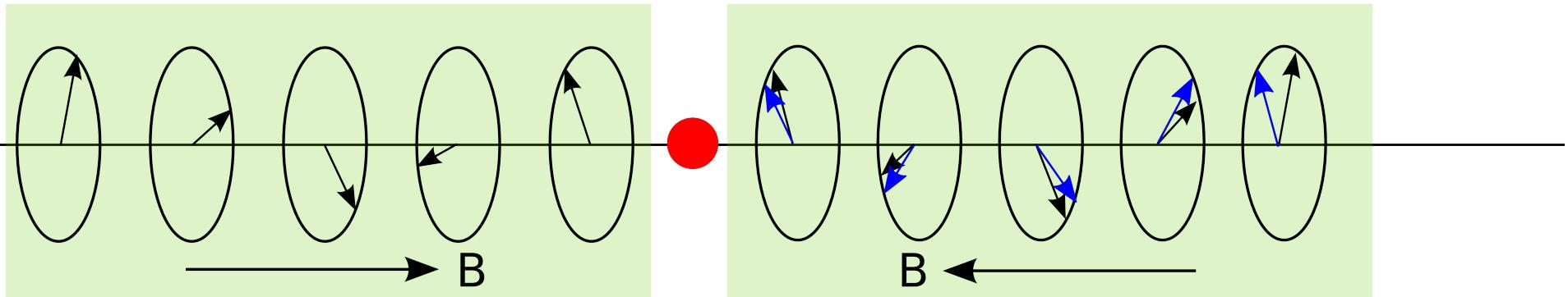
$$\begin{aligned}\gamma &= 2912 * 2\pi \text{Gauss}^{-1} \text{s}^{-1} \\ &= 1.832 \cdot 10^8 \text{T}^{-1} \text{s}^{-1} \\ &= 29.164 \text{MHz T}^{-1}\end{aligned}$$



Application: π or $\pi/2$ 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:

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

$$v_2 = v_1 + \delta v$$

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

Depends only on difference of velocities
Triple axes: k_i and k_f absolutely measured!

Energy transfer in quasielastic scattering:

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

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

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

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

Intermediate scattering function

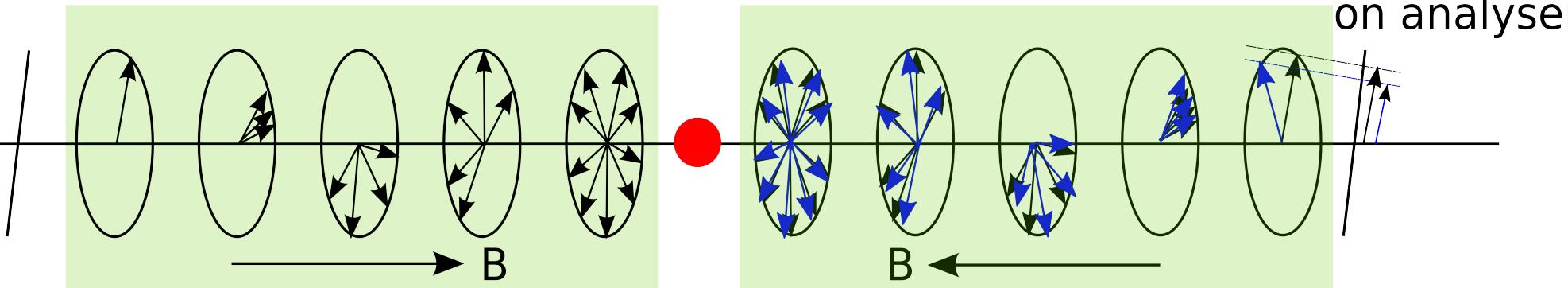
$$P(Q, \tau) = \langle \sigma_x \rangle = \langle \cos \Phi \rangle = \int S(q, \omega) \cos \omega \tau_{NSE} d\omega = I(q, \tau_{NSE})$$

NSE polychromatic

Polariser

Sample

Projection
on analyser



$$v = v(\lambda)$$

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

Energy transfer:

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

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

$$\Phi = \gamma BI \frac{\hbar^2 \omega}{mv^3}$$

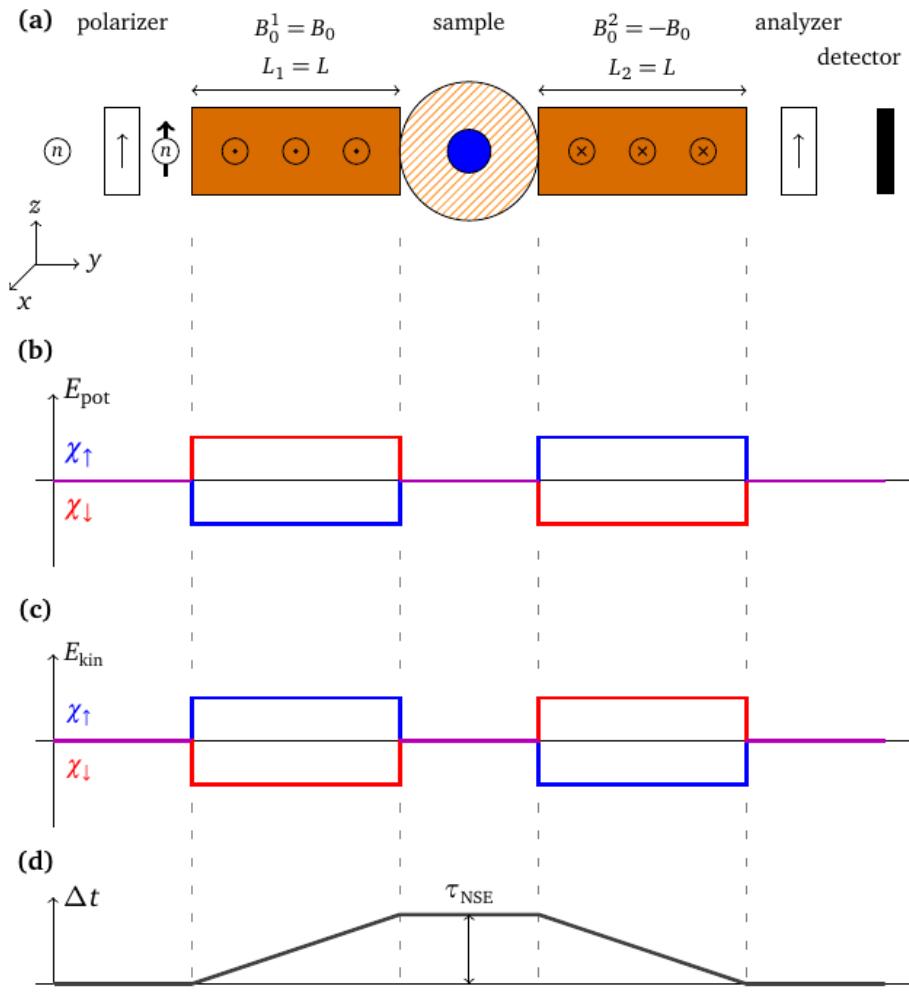
Field Integral J
ideal: $J = B \cdot I$
real: $J = \int B \cdot dI$

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

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

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

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

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

Spin Echo Group

P = Ampl / Avg

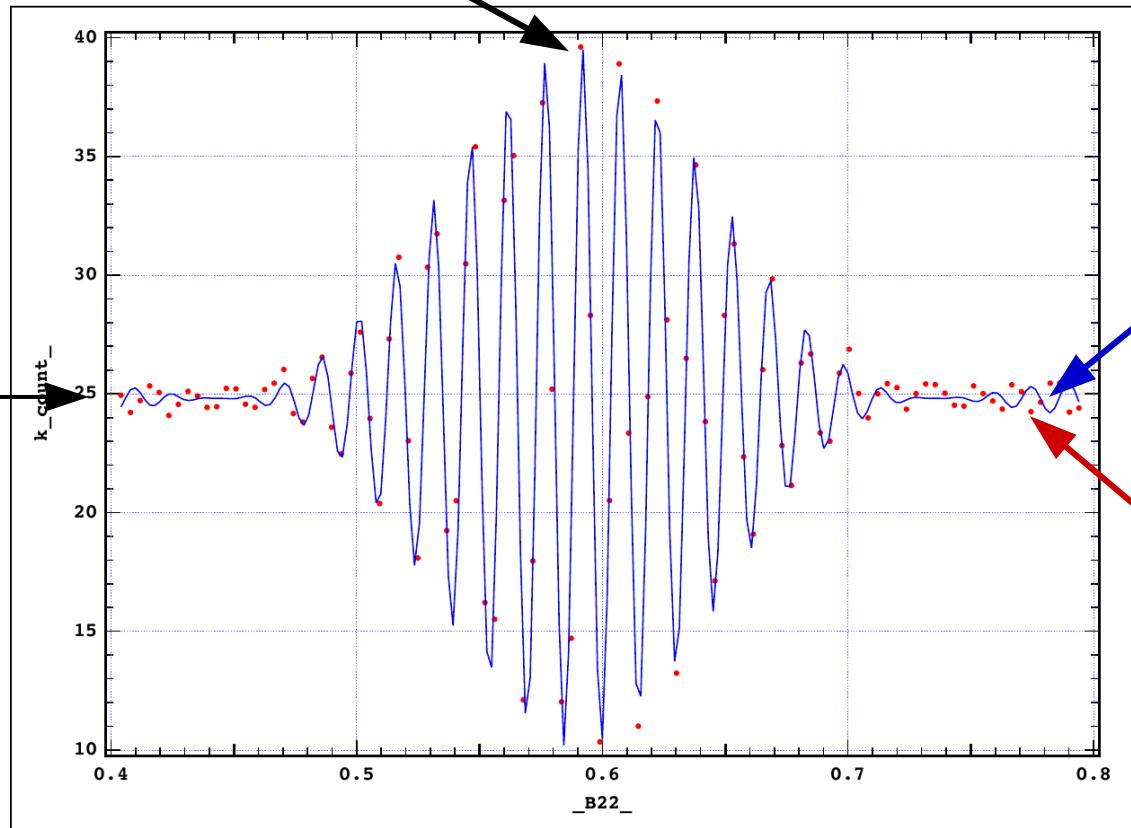
Max Count = Echo Point

Instrument set at
spin echo time τ_1

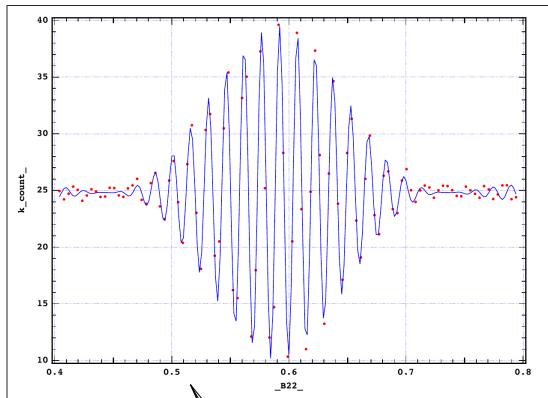
Average Count

Fit to data

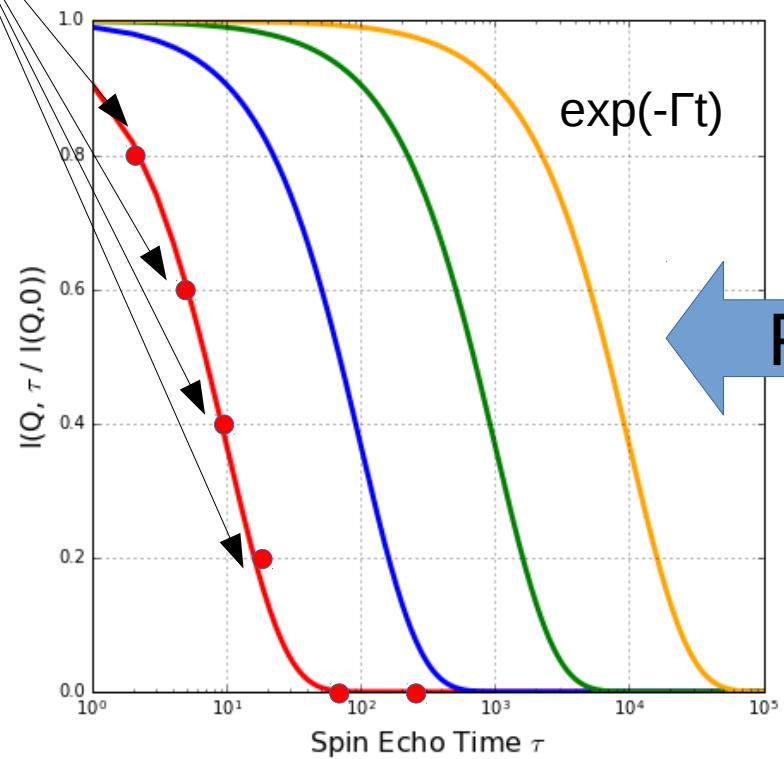
Neutron counts



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

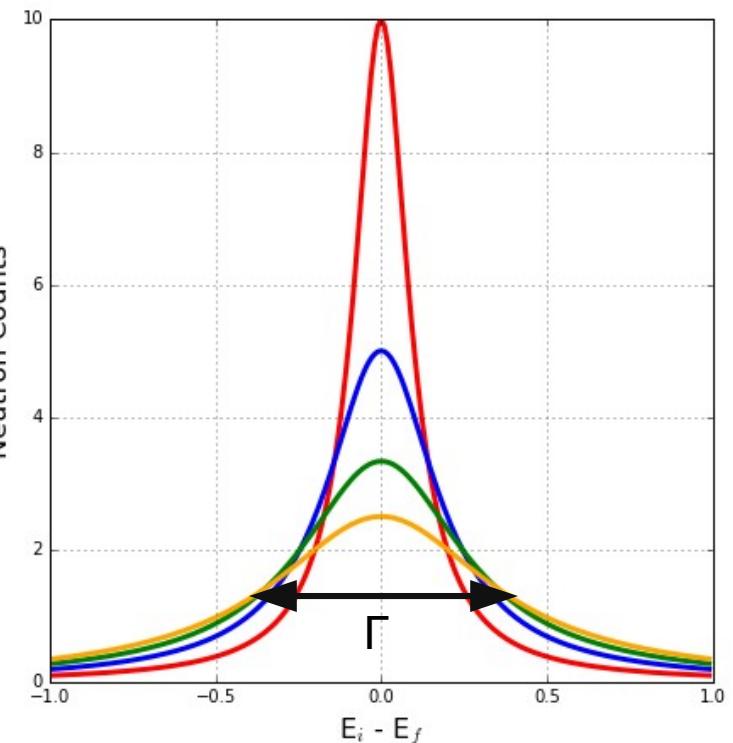


Exponential decay



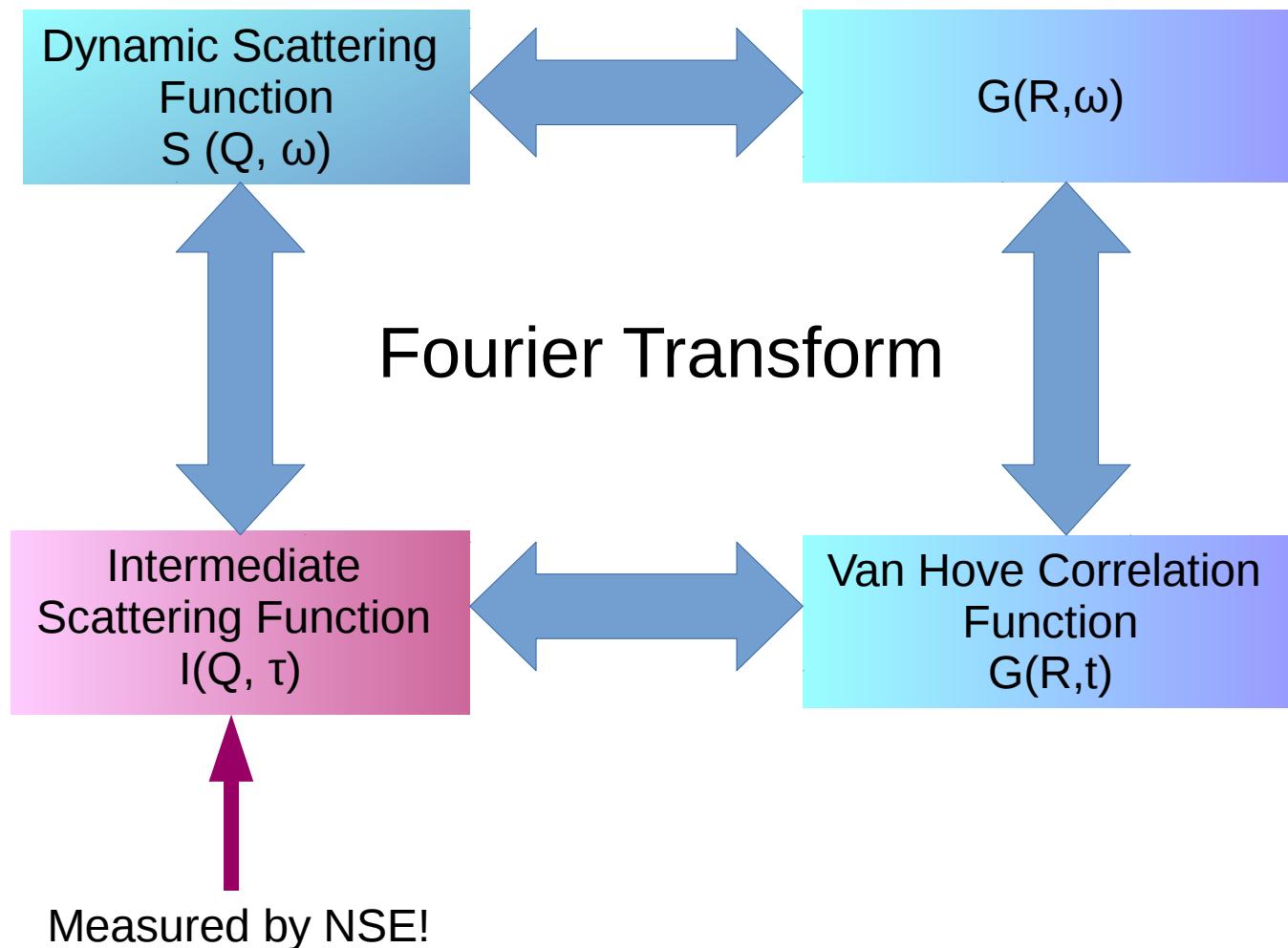
$$P(Q, t) = \frac{\int [\Gamma^2 + \omega^2]^{-1} \cos(\omega t) d\omega}{\int [\Gamma^2 + \omega^2]^{-1} d\omega} = e^{-\Gamma t}$$

Consider quasielastic scattering
To be Lorentzian:

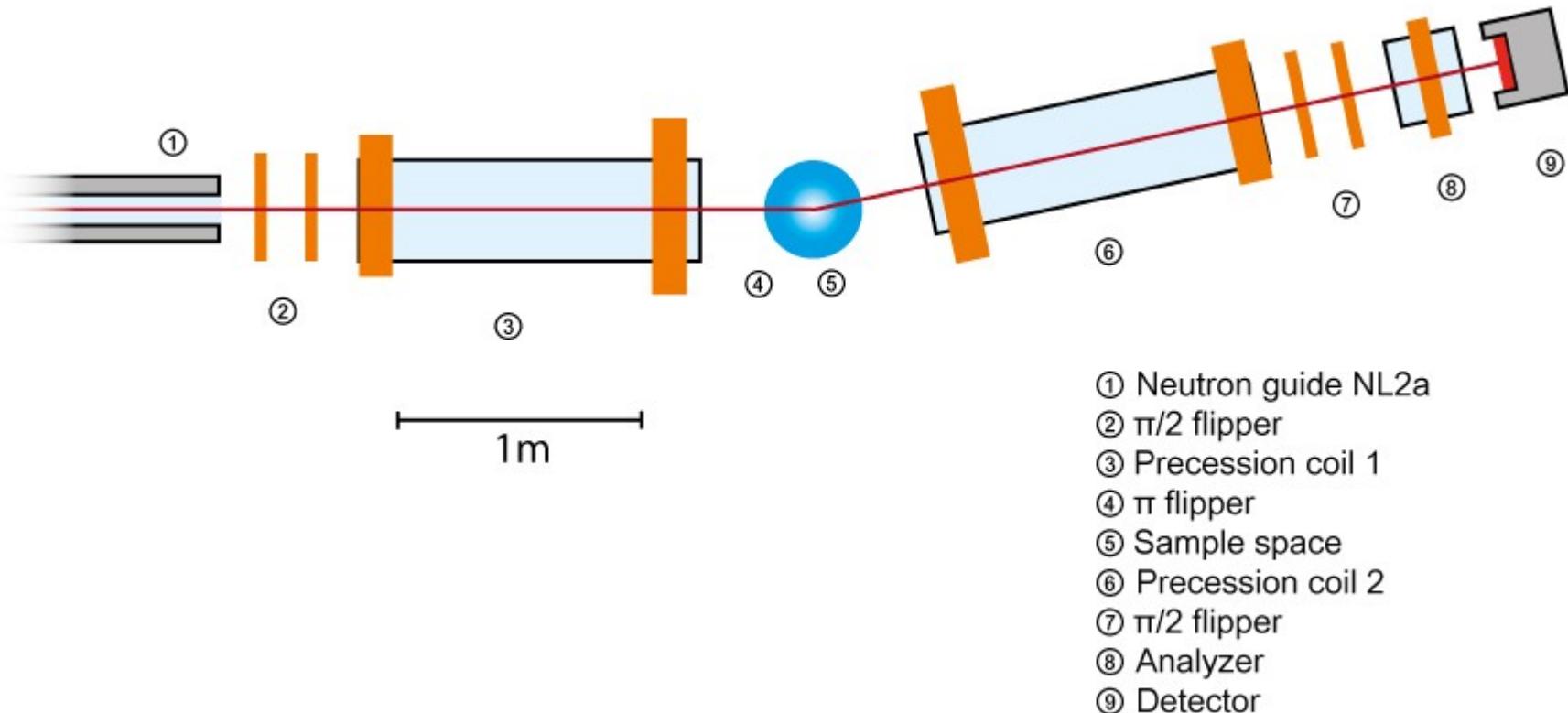


$$S(Q, \omega) \propto \frac{\Gamma}{\Gamma^2 + \omega^2}$$

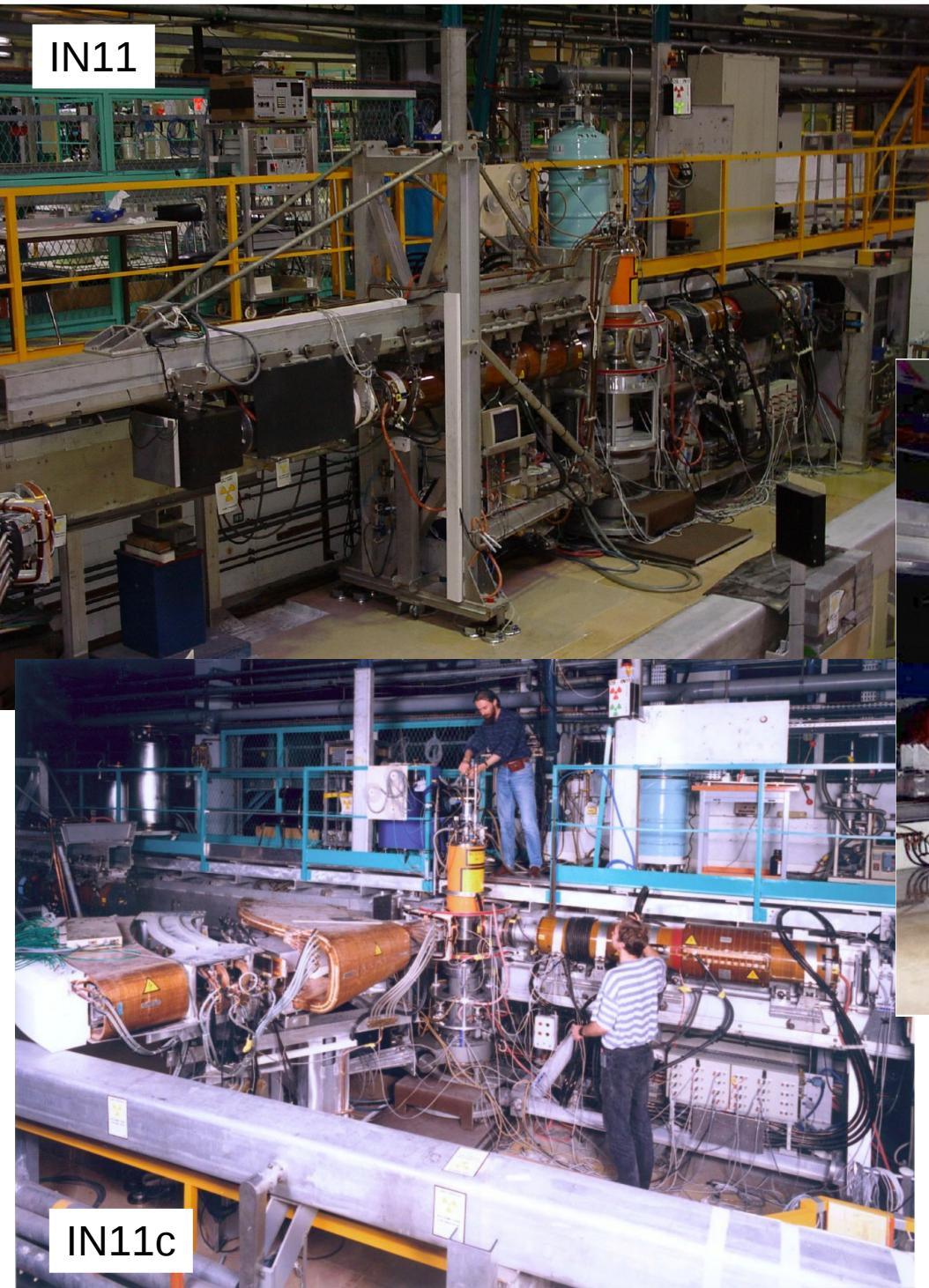
NSE directly measures the intermediate scattering function $I(Q, \tau)$



Schematic Realisation of an NSE Instrument J-NSE, MLZ



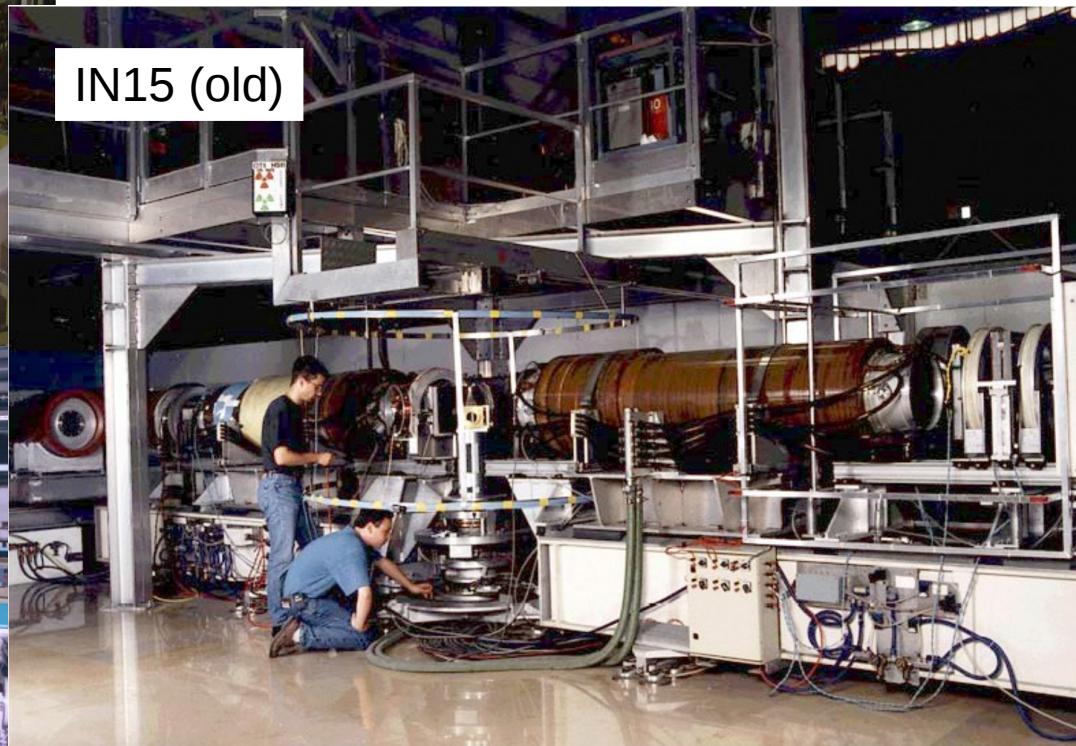
IN11



ILL, Grenoble (France)

IN11 was the first NSE
 $BL = 0.27\text{Tm}$
50ns @ 10Å

IN15 (old)



Old IN15: $BL = 0.27\text{Tm}$
Up to 250ns
New IN15: $BL = 1\text{Tm}$
1 μs @ 18Å

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

Jülich NSE @ SNS Oak Ridge



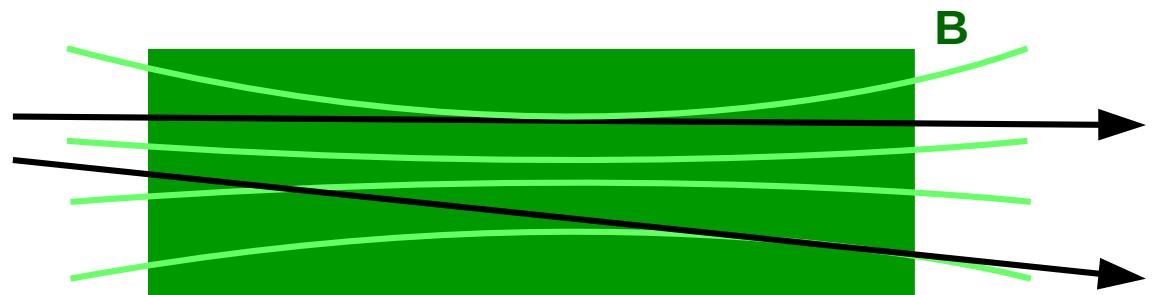
- Similar to J-NSE @ MLZ
- BL = 0.438Tm



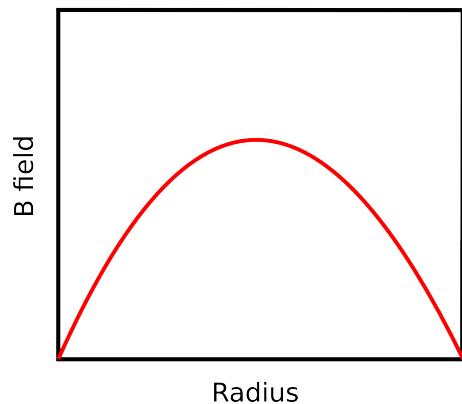
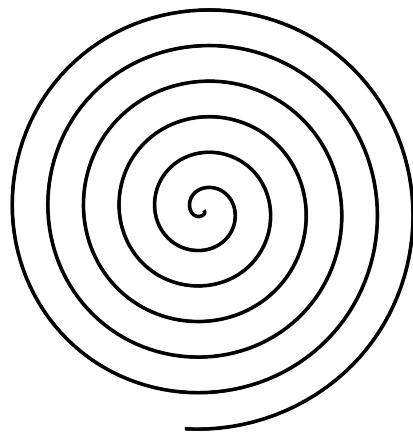
NG5-NSE @ NIST, Gaithersburg

Correcting field imperfections:

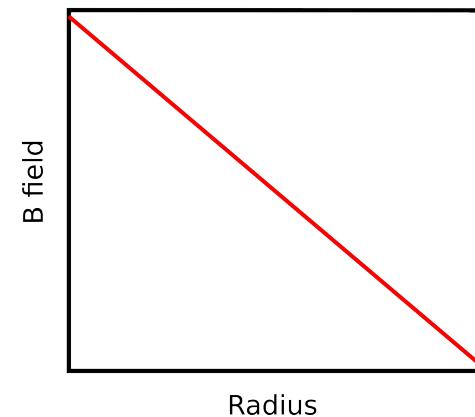
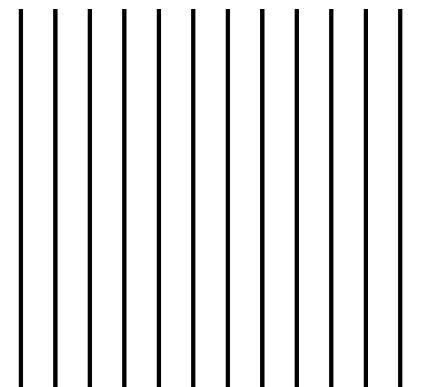
$$\Phi(\lambda) = \gamma \frac{\int \mathbf{B} \cdot d\mathbf{l}}{v}$$



Fresnel coils:

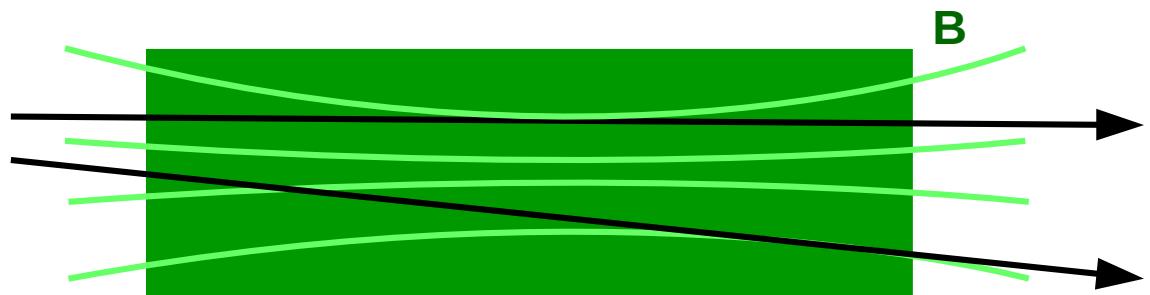


Shifter:

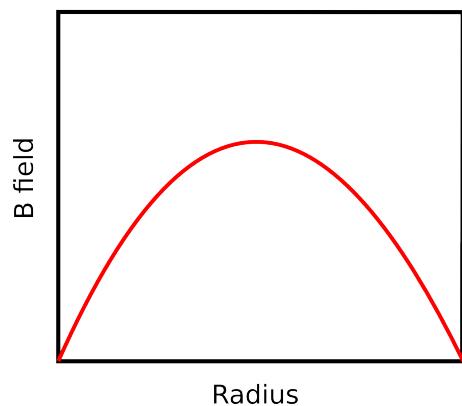
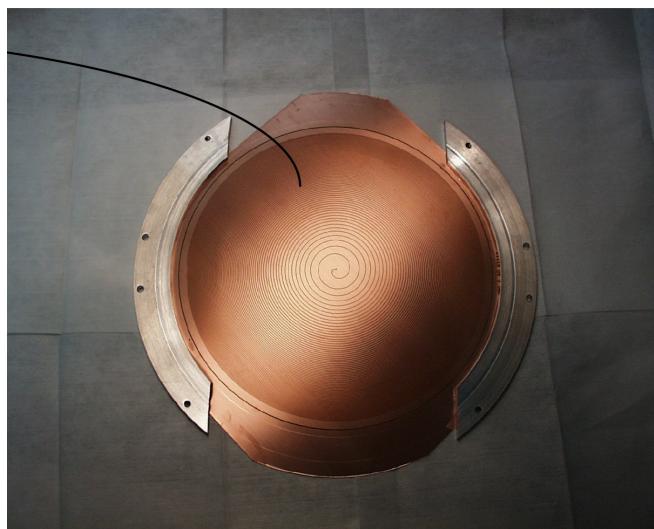


Correcting field imperfections:

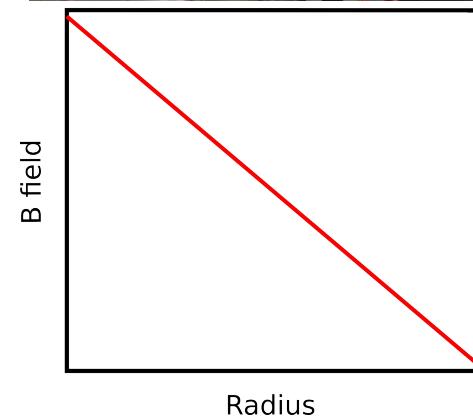
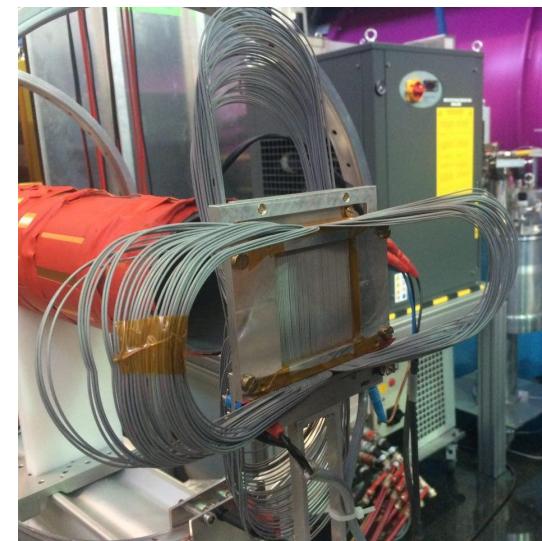
$$\Phi(\lambda) = \gamma \frac{\int \mathbf{B} \cdot d\mathbf{l}}{v}$$



Fresnel coils:



Shifter:

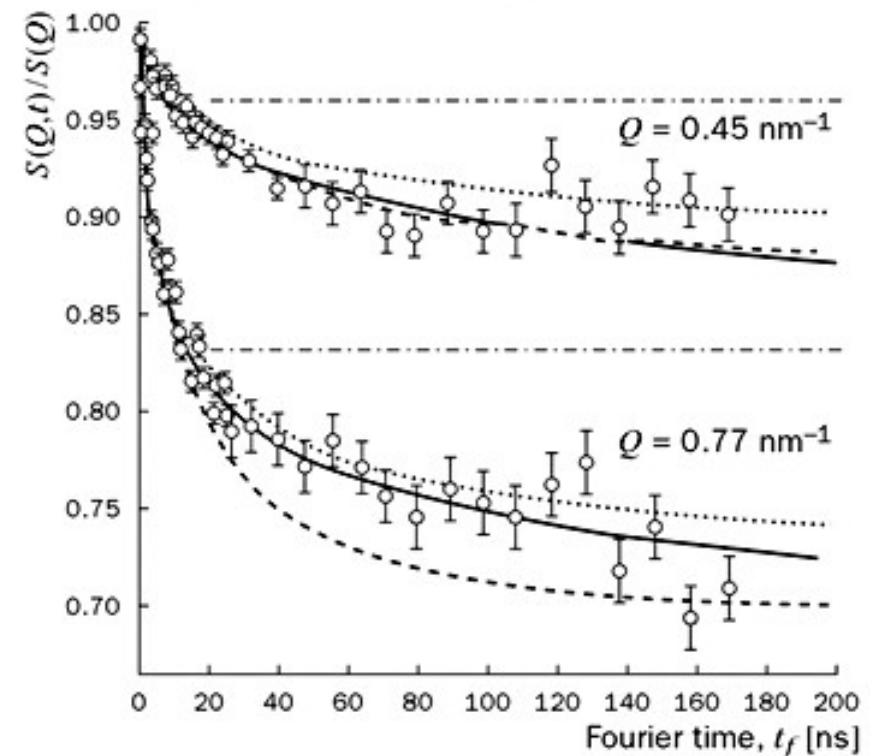
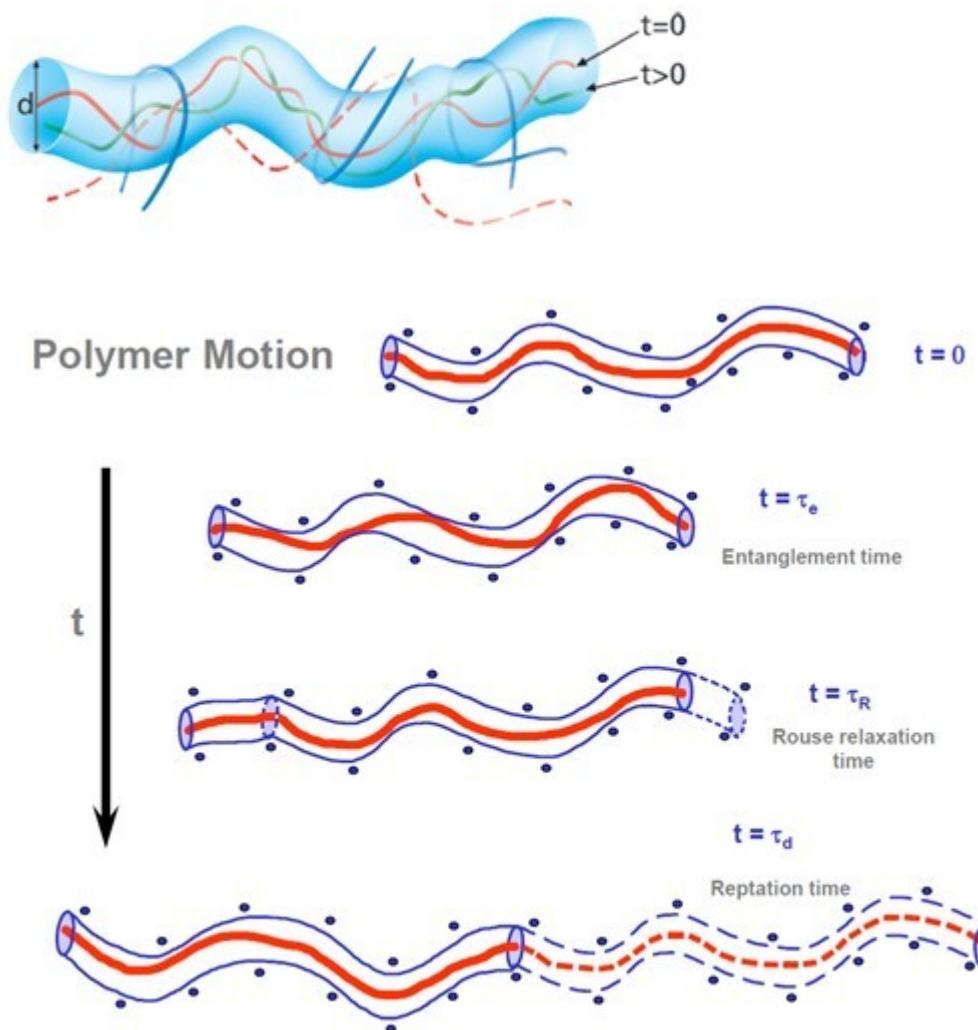


Neutron Spin Echo – Takeaway messages

NSE breaks the relationship between intensity & resolution

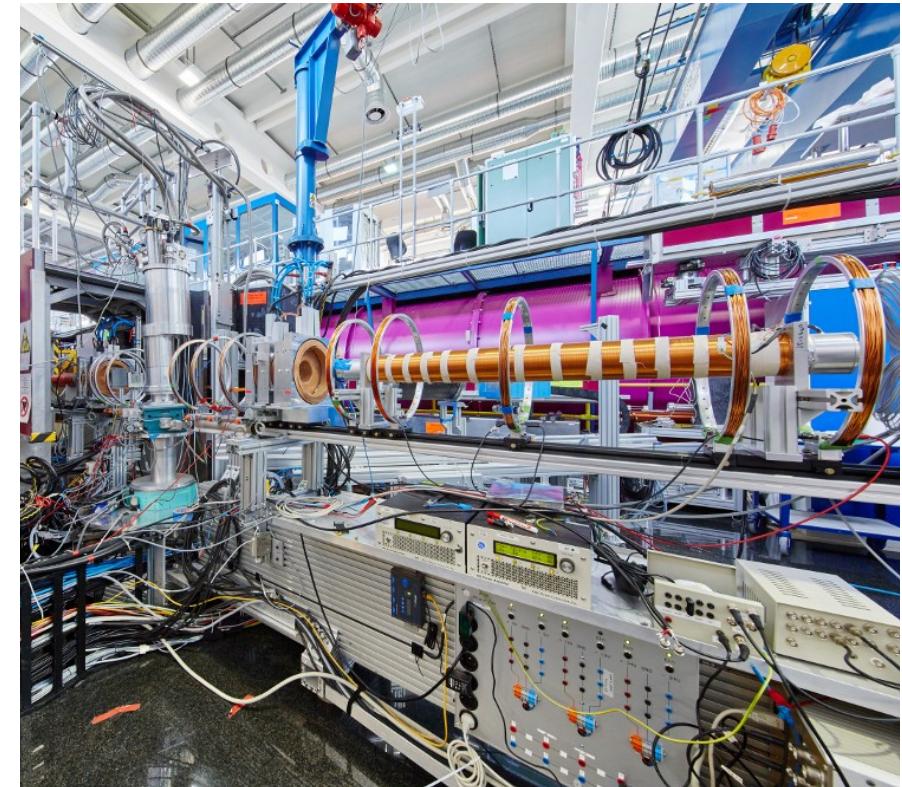
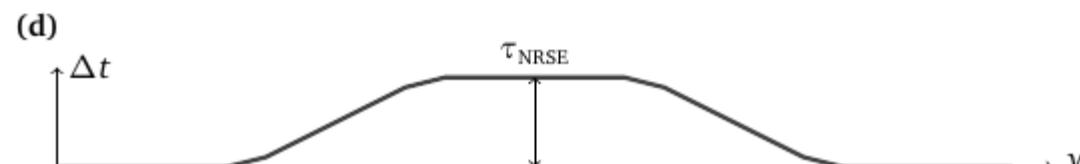
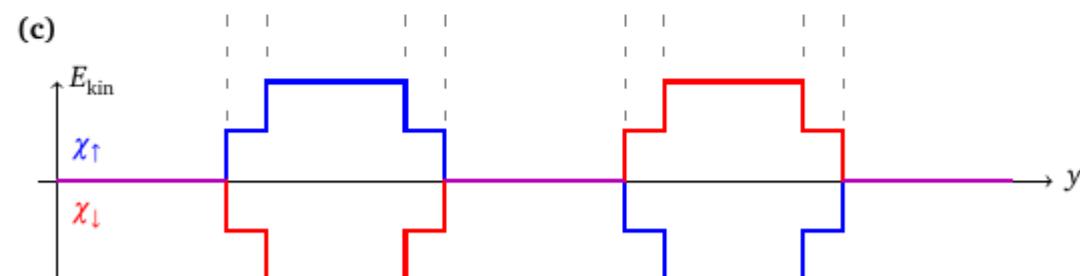
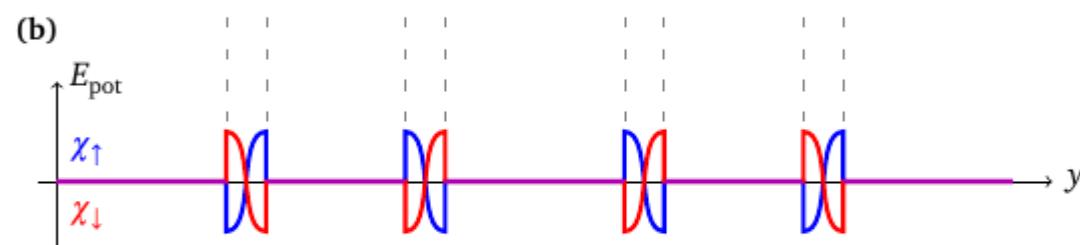
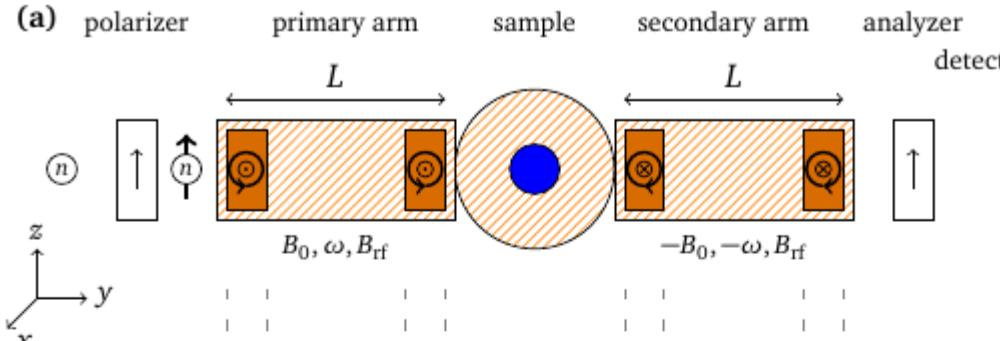
- **Traditional Instruments** – define both incident and scattered wavevectors in order to define E and Q accurately
- **Traditional Instruments** – use collimators, monochromators, choppers etc to define both k_i and k_f
- **NSE** – measure the difference between appropriate components of k_i and k_f (original use: measure $k_i - k_f$ i.e. energy change)
- **NSE** – use the neutron's spin polarisation to encode the difference between components of k_i and k
- **NSE**^f – can use large beam divergence and /or poor monochromatisation to increase signal intensity, while maintaining very good resolution

Example: de Gennes reptation in polymers



Only few % protonated chains in a deuterated matrix

(Longitudinal) Neutron Resonant Spin Echo

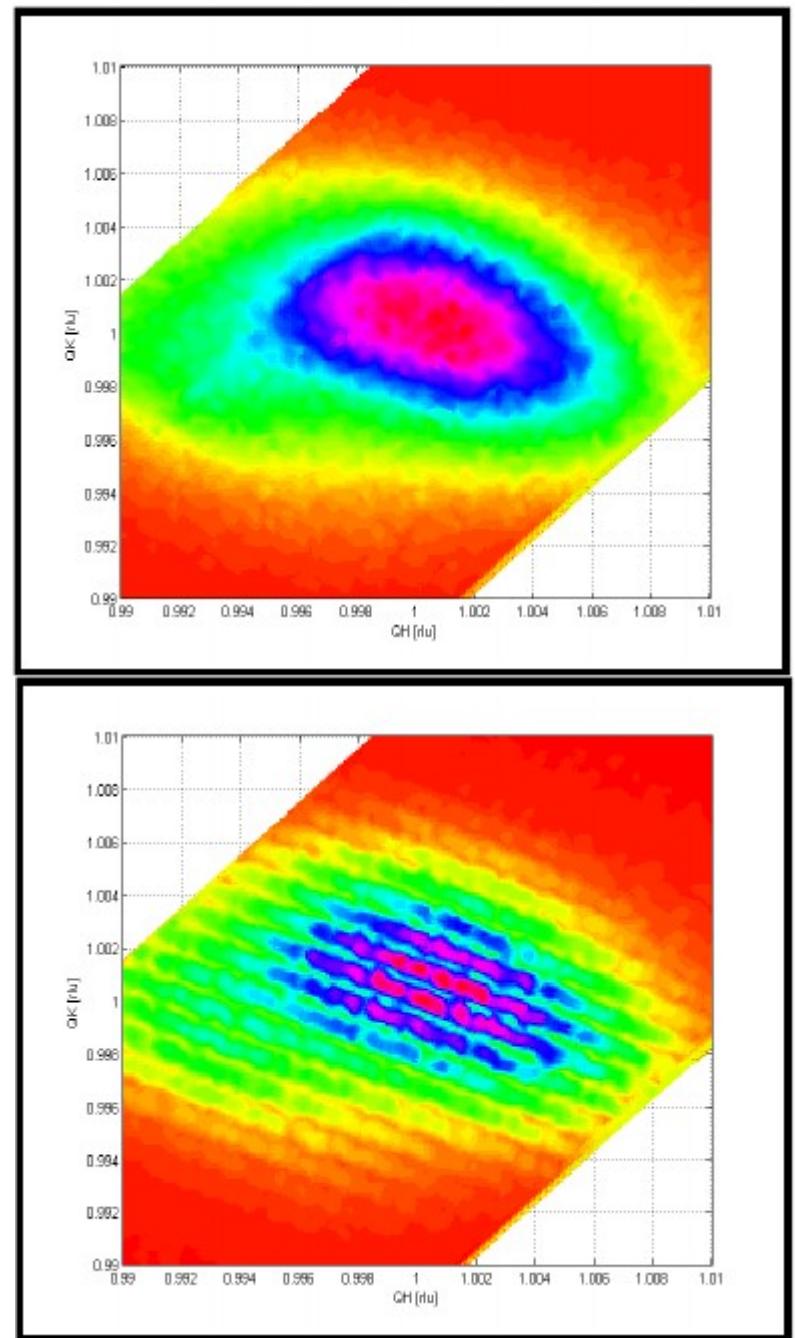
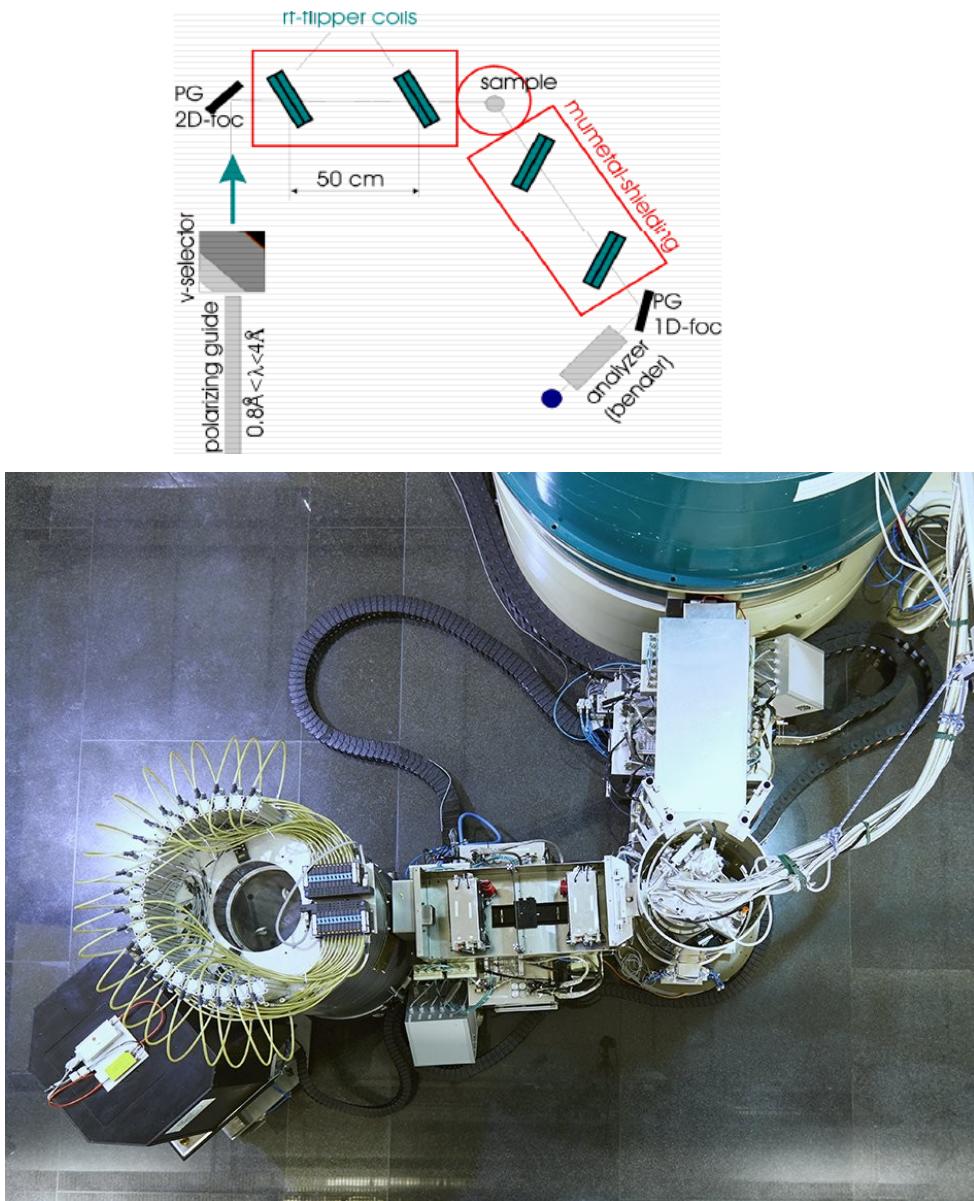


$$\tau_{\text{NRSE}} = \frac{2\hbar\gamma B_0 L}{mv^3} = \frac{2\hbar\omega L}{mv^3} = 2\tau_{\text{NSE}}$$

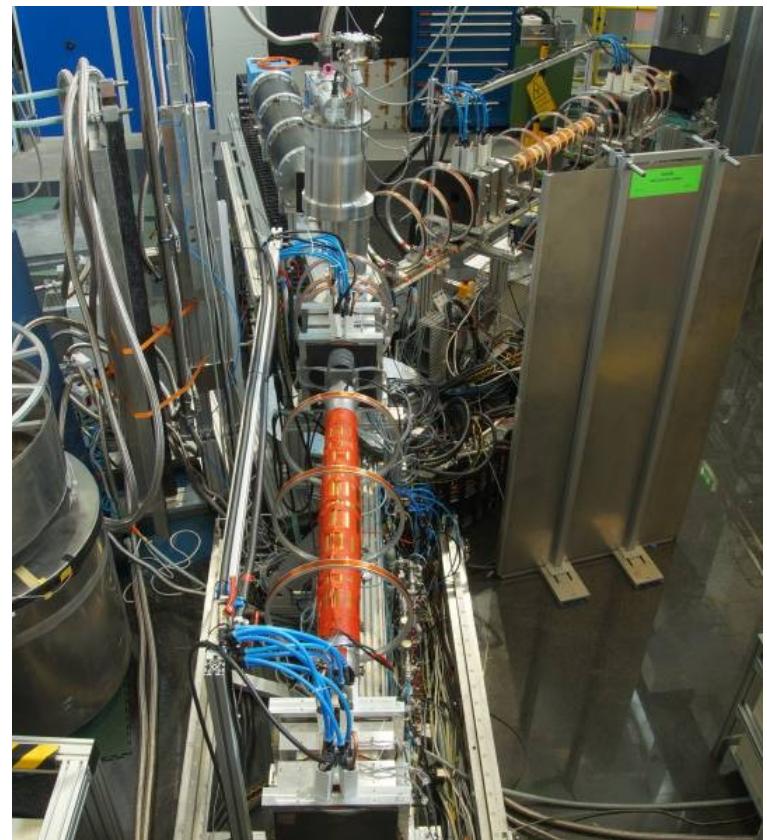
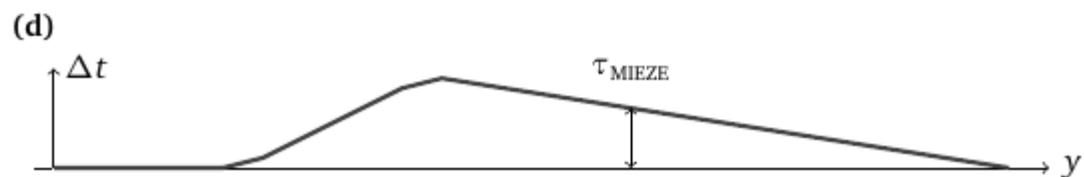
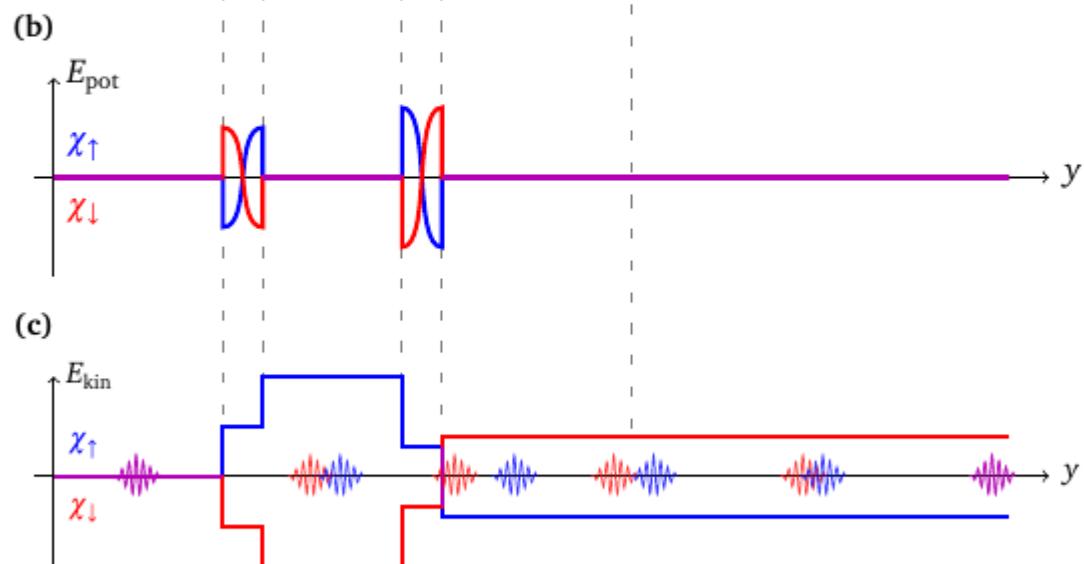
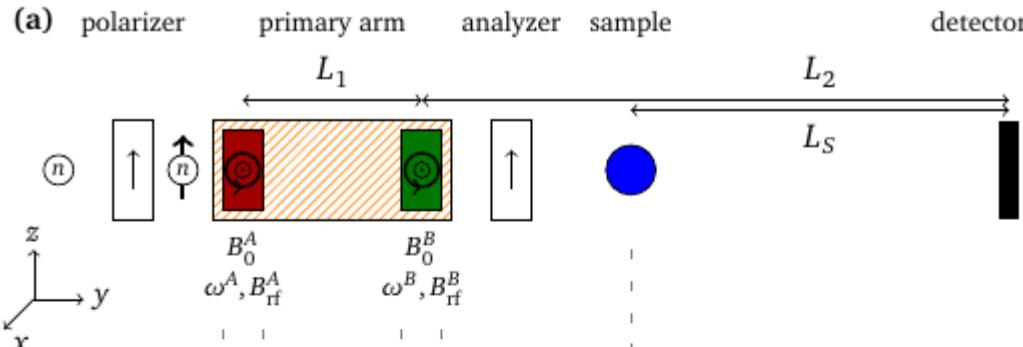
NRSE: Goulob, Gähler

LNRSE: Häußer, Schmidt

NRSE and triple axes spectroscopy



Modulation of Intensity by Zero Effort (MIEZE)



$$\begin{aligned}\tau_{\text{MIEZE}} &= \frac{\hbar}{m} \cdot \frac{L_s(\omega_B - \omega_A)}{v^3} \\ &= \frac{m^2}{\pi \hbar^2} \cdot L_s (\omega_B - \omega_A) \lambda^3\end{aligned}$$

Ferromagnetic Fluctuations in Fe near T_c

