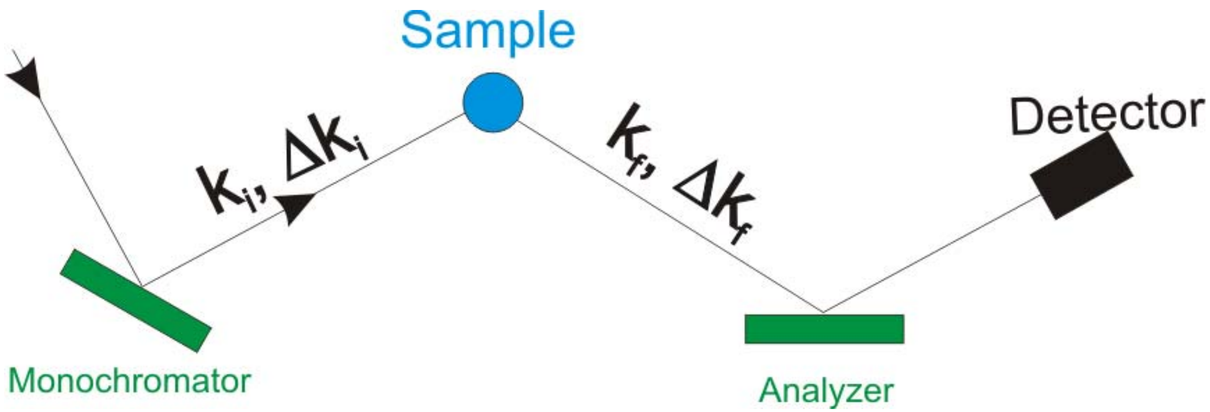
MAX-PLANCK-GESELLSCHAFT

Neutron spin echo

Thomas Keller
Max Planck Institute for Solid State Research

conventional spectrometer (triple axis)



slow dynamics, large molecules : small energies
-> use cold neutrons, backscattering

<u>problem</u>: resolution ~ 1/intensity

solution: neutron spin echo

The Bible

MAX-PLANCK-GESELLSCHAFT

Lecture Notes
in Physics

Edited by J. Ehlers, München, K. Hepp, Zürich
R. Kippenhahn, München, H. A. Weidenmüller, Heidelberg
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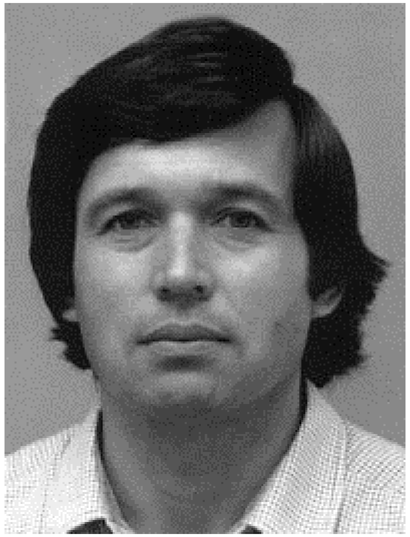
128

Neutron Spin Echo

Proceedings of a
Laue-Langevin Institut Workshop
Grenoble, October 15–16, 1979

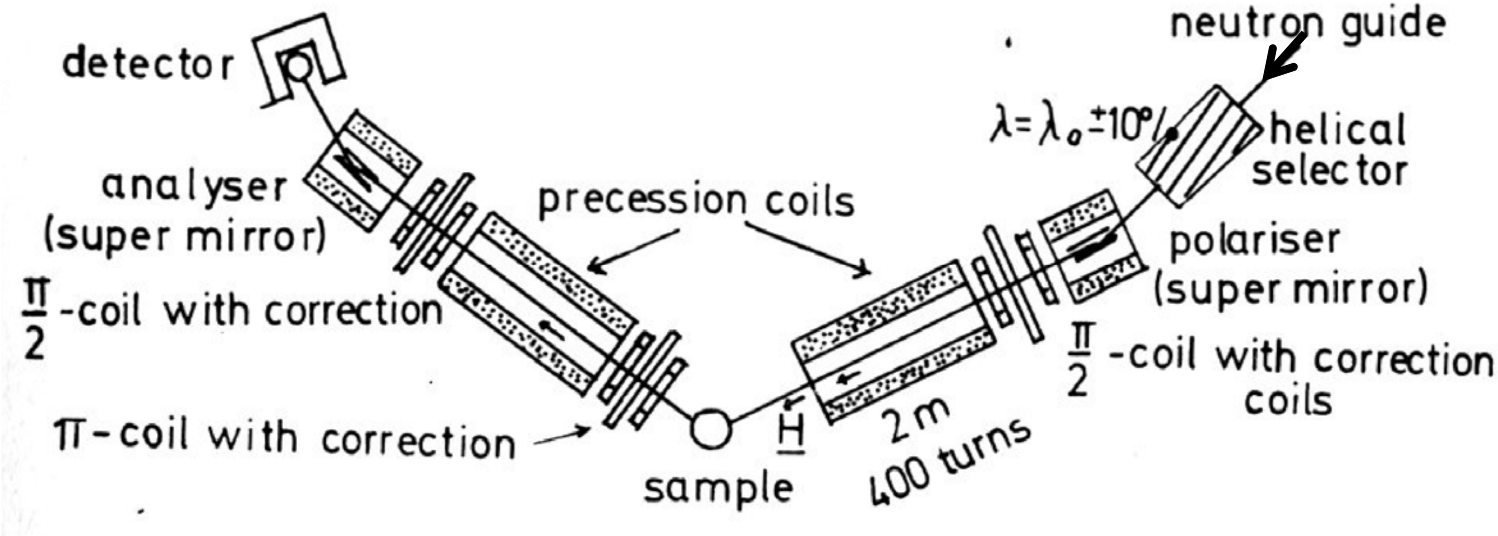
Edited by F. Mezei

Springer-Verlag
Berlin Heidelberg New York 1980



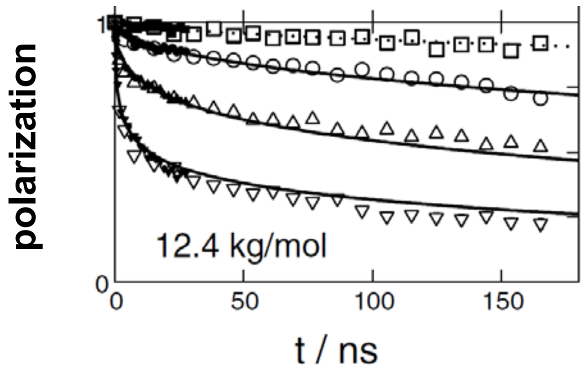
Ferenc Mezei

a spin-echo spectrometer (old IN11)



basic idea: use neutron spin as a internal clock

example



magnetic field ->

de Gennes *reptation*

A. Wischnewski, et al., PRL **88**, 058301 (2002).

outline

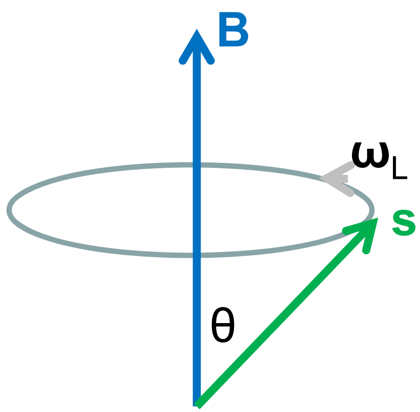
MAX-PLANCK-GESELLSCHAFT

- from Larmor precession to spin-echo

- NSE instruments for quasi elastic scattering

- phonon and magnon lifetimes
  (spin-echo + triple axis)

- high resolution diffraction (*Larmor diffraction*) spin echo -> Larmor precession



$\omega_L = \gamma B$

γ gyromagnetic ratio = 3kHz/Gauss
θ = const.

spinor: $s = \begin{pmatrix} \cos\frac{\theta}{2} e^{-i\omega t/2} \\ \sin\frac{\theta}{2} e^{i\omega t/2} \end{pmatrix}$

polarization: $P = \langle s \rangle = \begin{pmatrix} \sin\theta\cos\omega t \\ \sin\theta\sin\omega t \\ \cos\theta \end{pmatrix}$

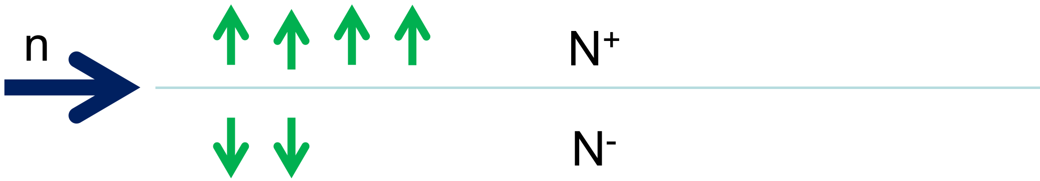
pure QM with plane waves: Golub, Am. J. Phys.

example

earth magnetic field: **0.4G** -> v_L = 1.2kHz
one precession (λ=4Å, v=1000m/s): 0.8m

typ. spin-echo field: **2kG** (0.2T) -> v_L = 6MHz
one precession (λ=4Å, v=1000m/s): 0.17mm

polarization I

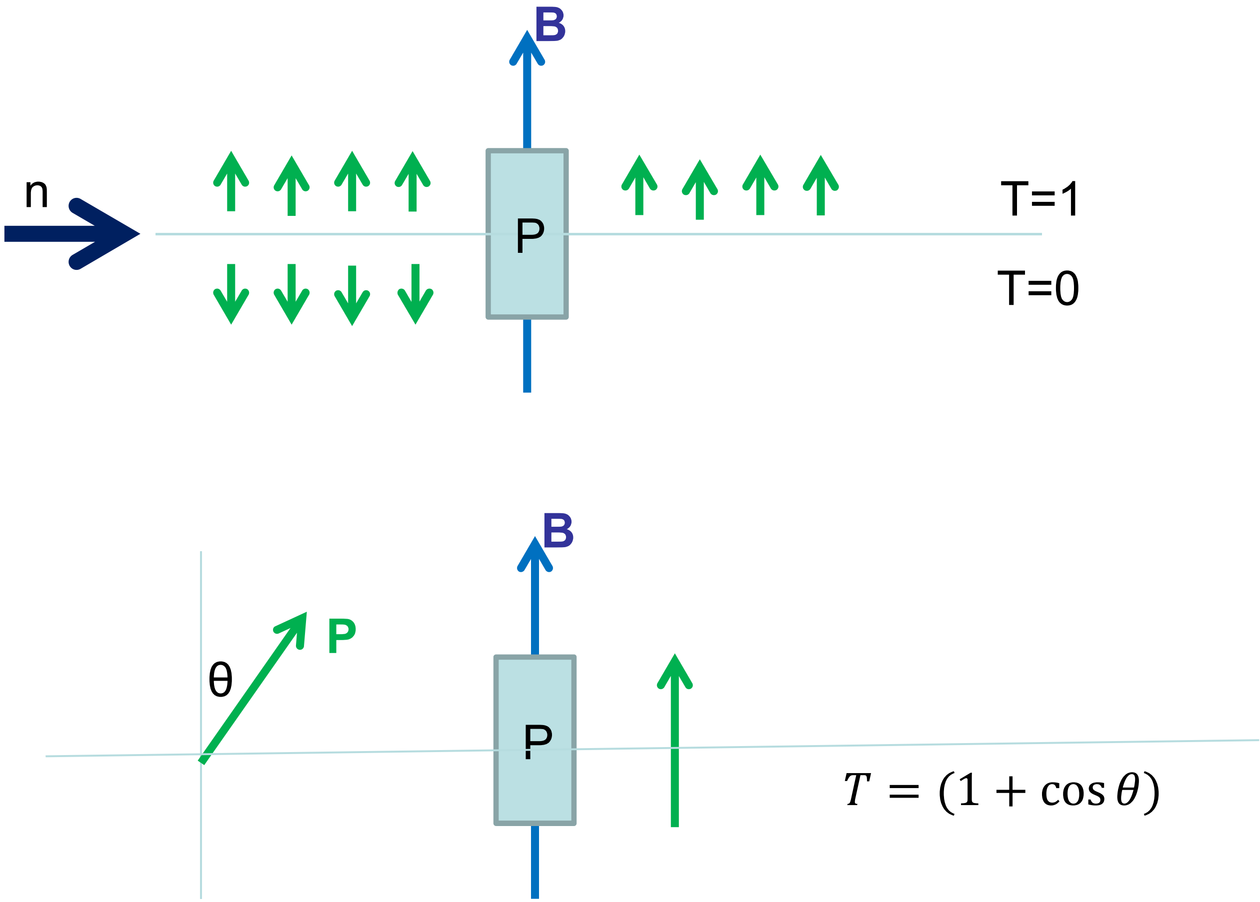


$$P = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

$$P = \cos\theta$$

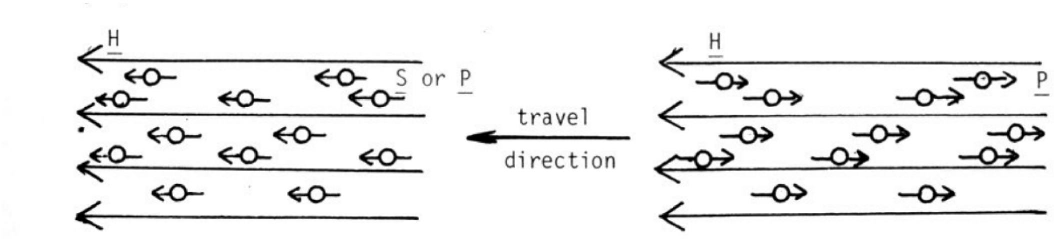
$$P = < \cos\theta >$$

polarization II



guide fields

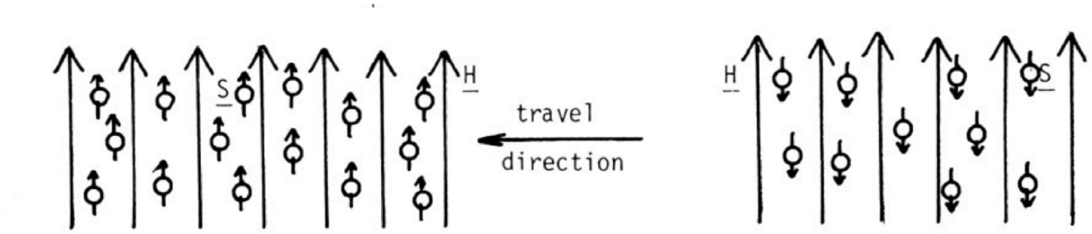
retain the direction of ***s*** (or ***P***)



longitudinal (coils)

parallel

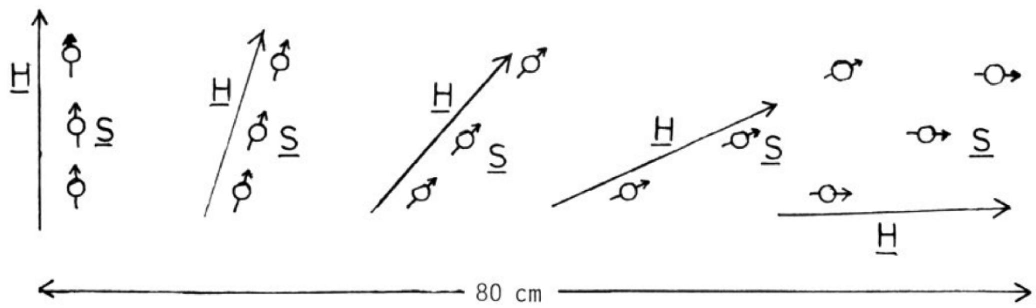
anti-parallel



transverse (permanent)

slow (adiabatic) change of guide field

what means 'slow'?



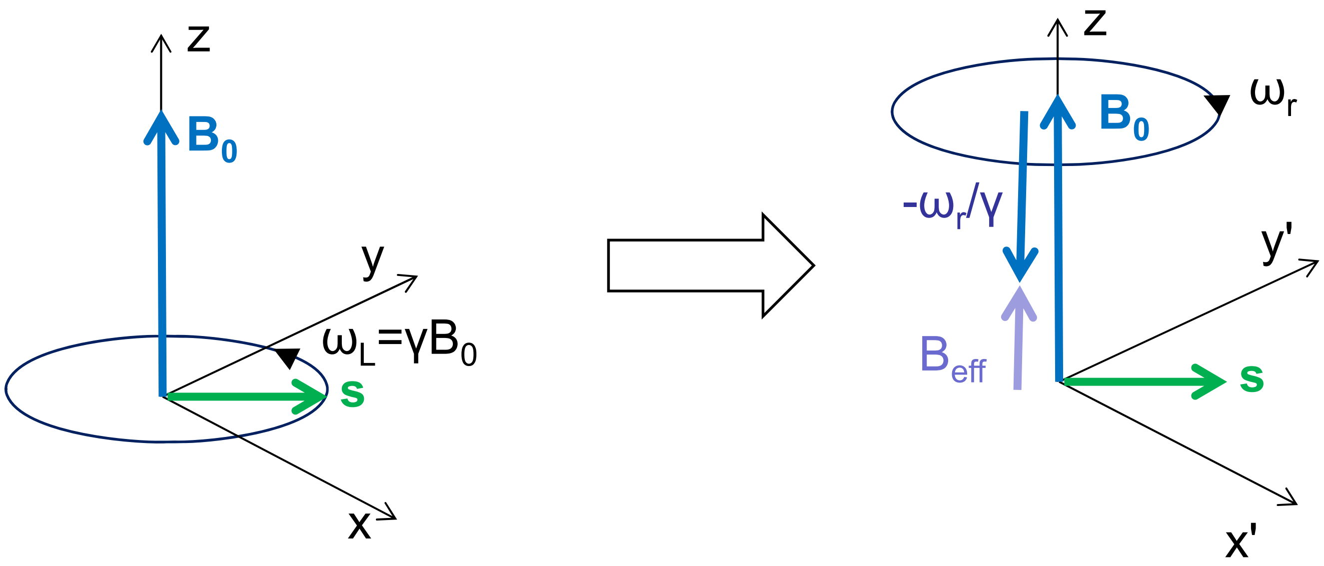
$v[m/s] = 3956/\lambda[Å]$

rotation frequency: $\omega = \frac{\pi}{2}\frac{v}{\Delta L} = \frac{\pi}{2}\frac{3956}{\Delta L[\mathrm{m}]\,\lambda[Å]}$

-> powerful concept: rotating coordinates

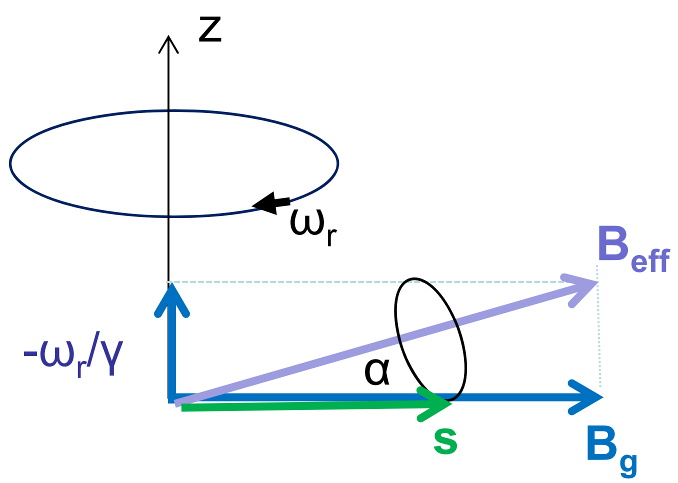
transformation to a rotating system

MAX-PLANCK-GESELLSCHAFT



Rabi, Ramsey, Schwinger, Rev. Mod. Phys. 26, 167 (1954).

rotating guide field



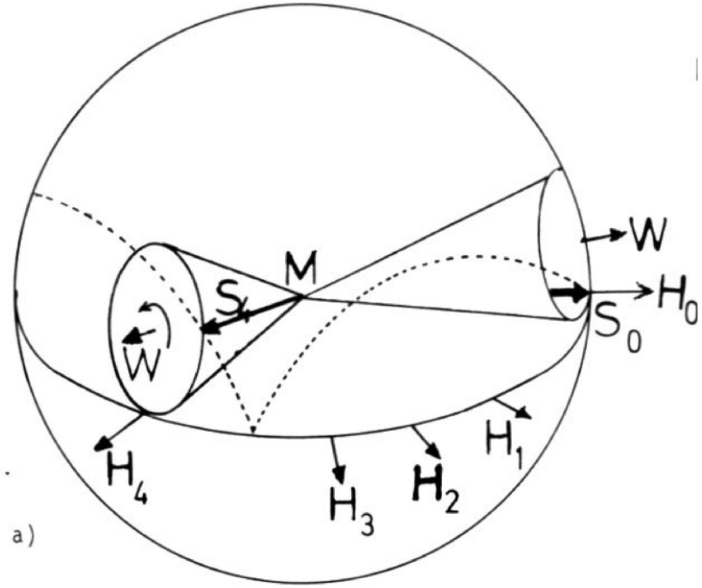
$$\tan\alpha = -\frac{\omega_r}{\gamma B_g}$$

$$P = \cos\alpha$$

α should be small -> $\omega_r \ll \gamma B_g$

rotation freq. << Larmor freq.

Schärpf picture



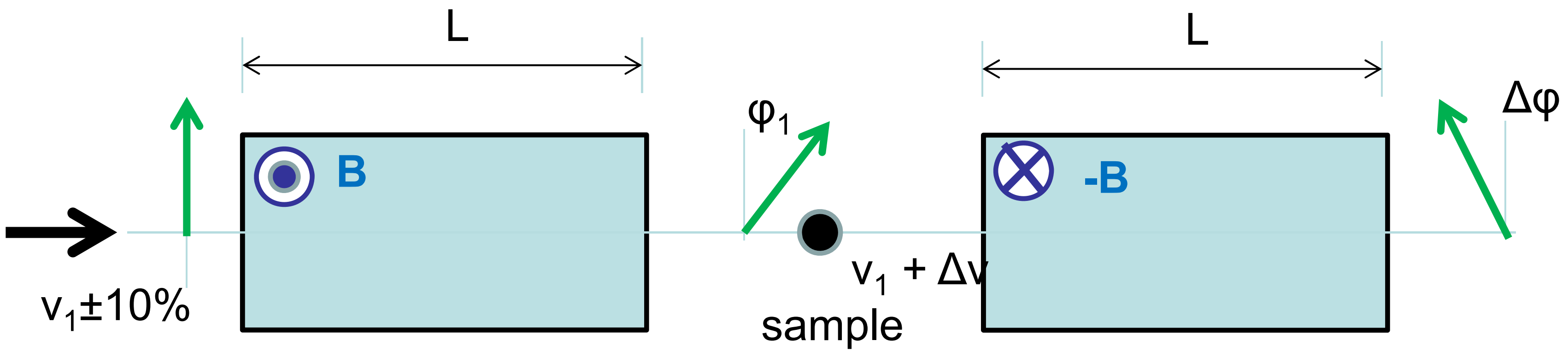
guide field: example

rotate $\mathbf{B}_g$ by 90° on 10cm, (v=1000m/s):
v_{rot} = 2.5kHz, B_{rot} = 0.8G

P=0.90 -> B_g = 1.6G (α=25°)
P=0.99 -> B_g = 5.6G (α=8°)

usual rule: B_g / B_{rot} = 10 -> P=0.995 (α=5°)

a simple spin-echo instrument



$$\phi = \gamma B t$$
$$= \gamma B L / v_1$$

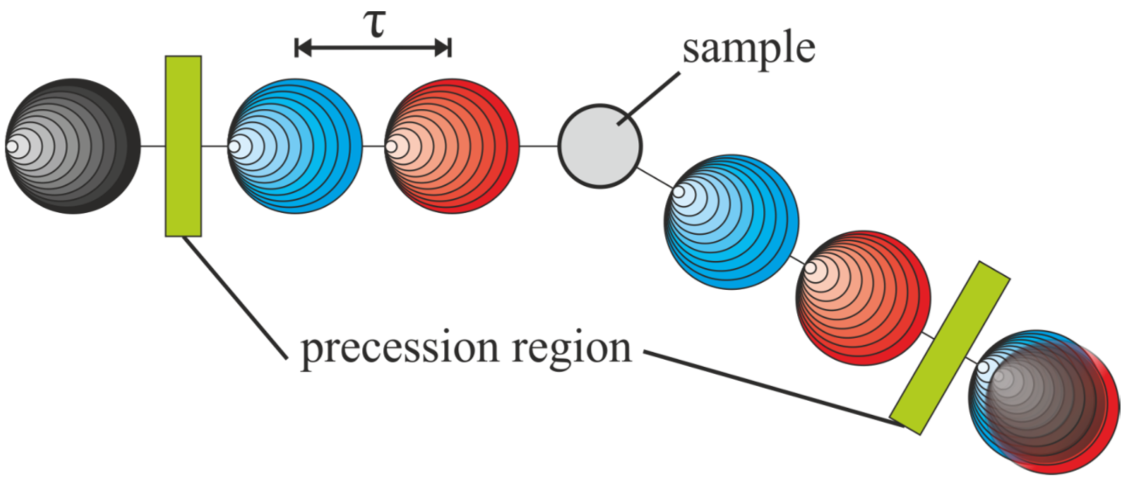
$$\Delta\phi = 2\pi\gamma B L \left(\frac{1}{v_1} - \frac{1}{v_1 + \Delta v} \right)$$

$$\Delta\phi = 2\pi \frac{\gamma B L}{v^2} \Delta v$$

$$\Delta E = \hbar \cdot \omega$$

$$\Delta\phi = \tau_{\mathrm{NSE}} \cdot \omega \quad \text{with} \quad \tau_{\mathrm{NSE}} = \frac{2\pi\gamma B L}{m v^3}$$

semi-classical picture

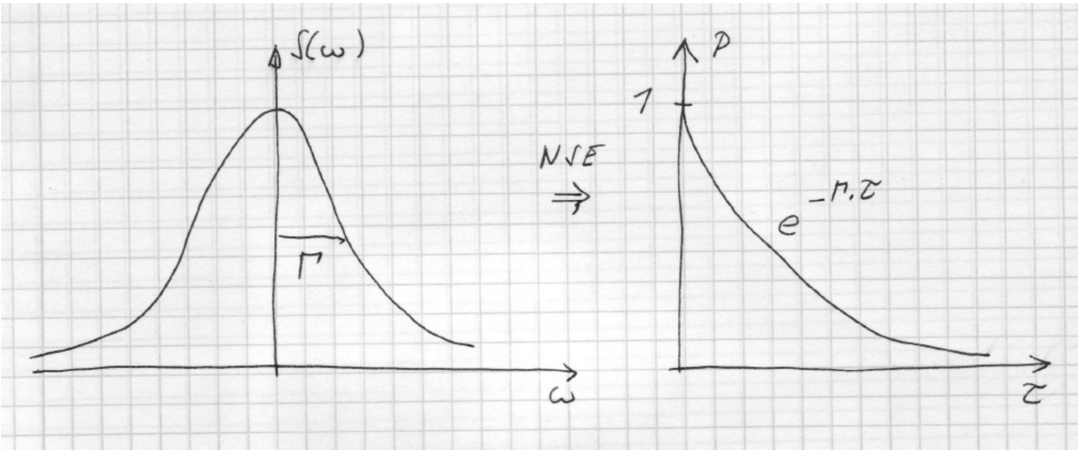


Gähler, Golub, Mezei, Felber PRA 58, 280 (1998)

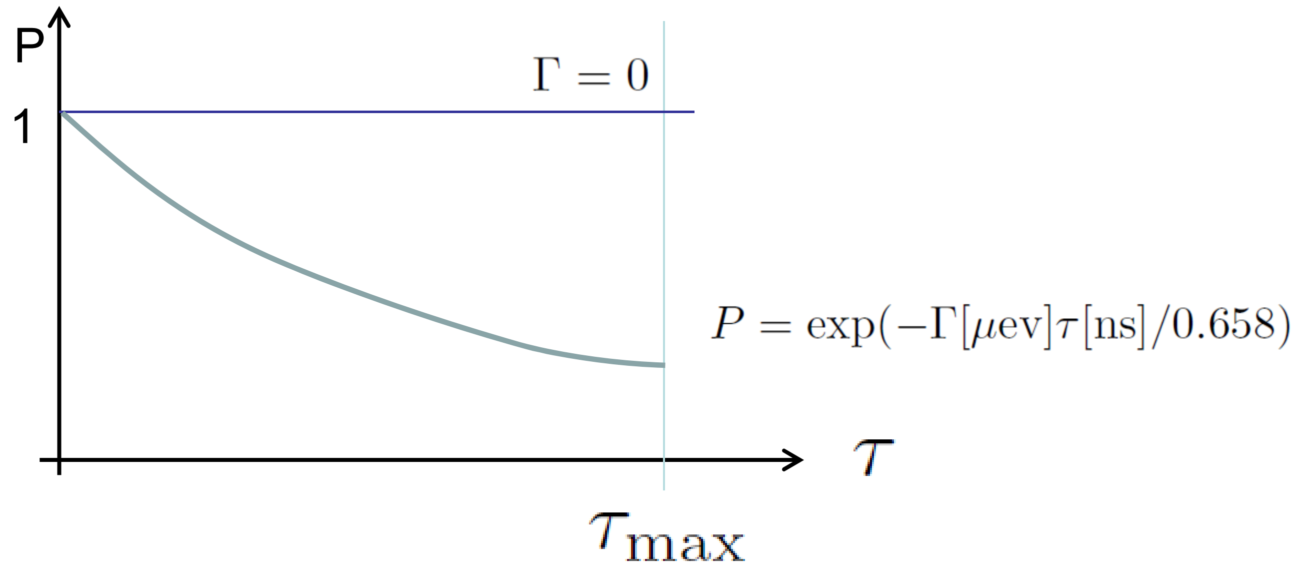
spin echo polarization

$$P(\tau_{\text{NSE}}) = \int S(\omega) \cos(\omega \cdot \tau_{\text{NSE}}) d\omega$$

Lorentzian: $S(\omega) = \frac{1}{\pi} \cdot \frac{\Gamma}{\Gamma^2 + \omega^2}$ $\qquad$ $P(\tau_{\text{NSE}}) = \exp(-\Gamma \cdot \tau_{\text{NSE}})$

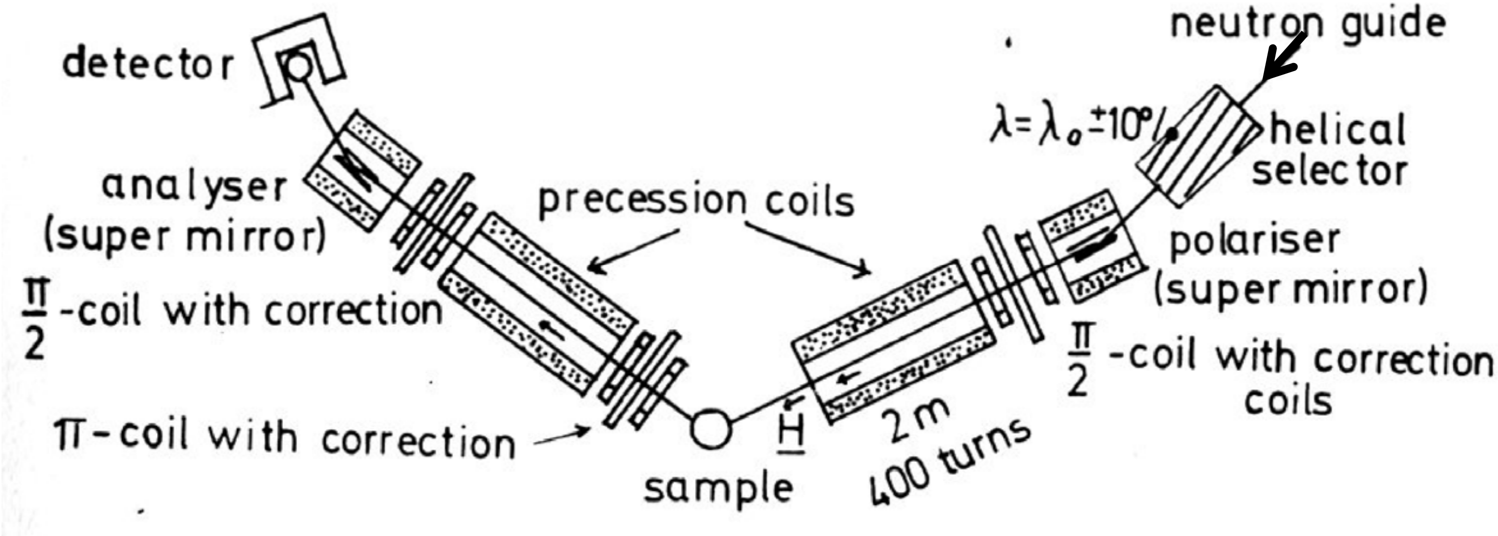


resolution



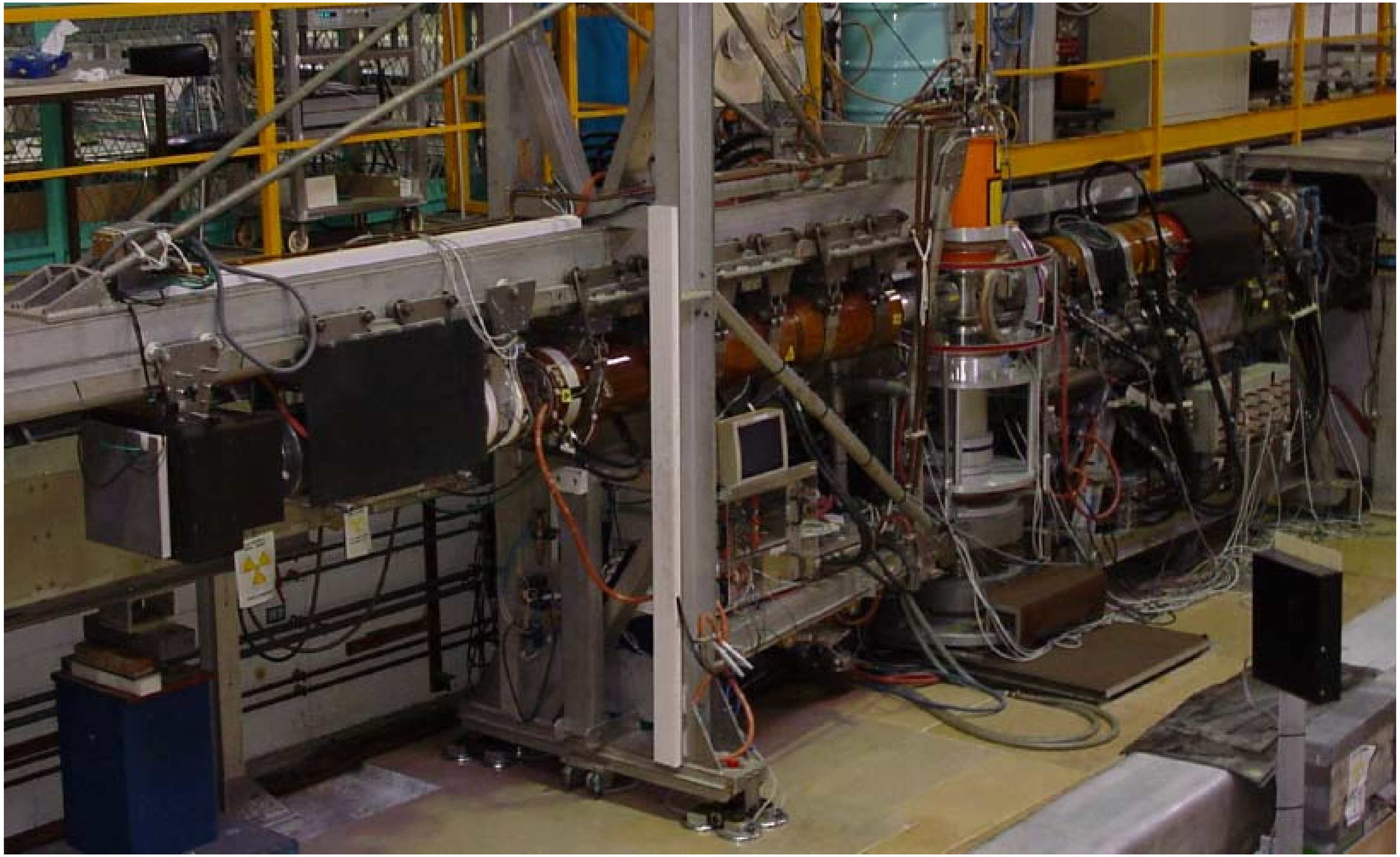
IN15: τ_{max} = 500ns -> Γ = 0.001μeV

a more realistic spin-echo (old IN11)

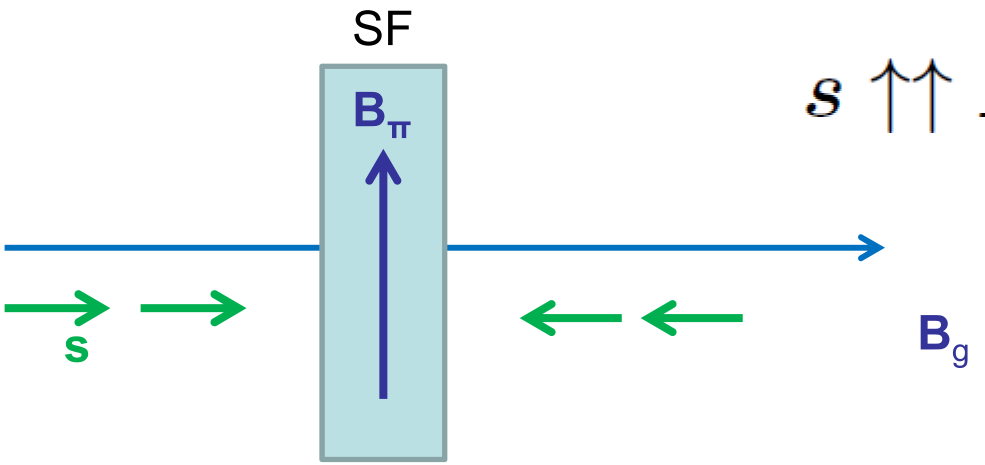


IN11

MAX-PLANCK-GESELLSCHAFT



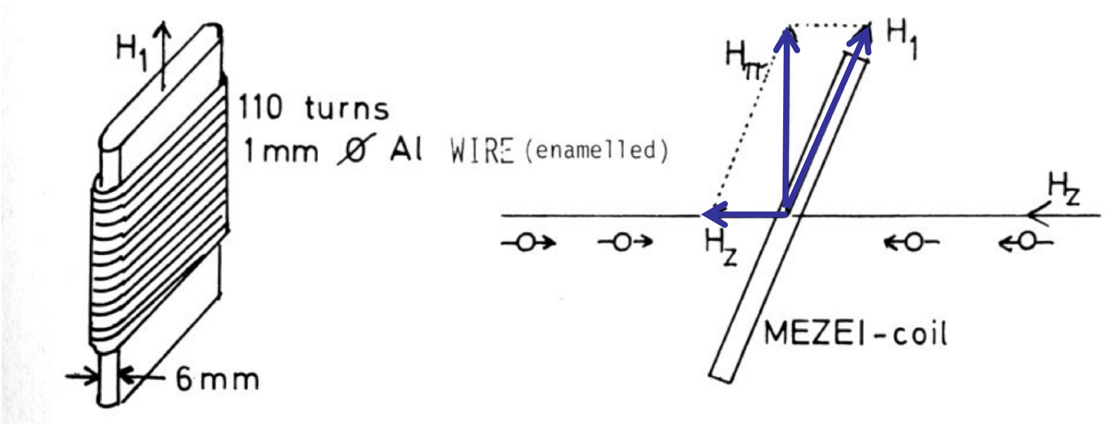
spin flipper – Mezei π-flipper I



$$\boldsymbol{s} \uparrow\uparrow \boldsymbol{B_g} \rightarrow \boldsymbol{s} \uparrow\downarrow \boldsymbol{B_g}$$

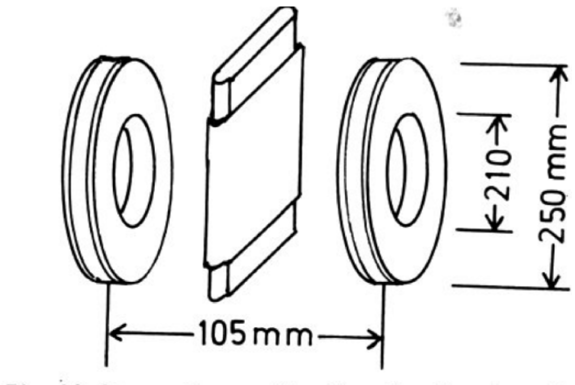
$$\boldsymbol{B_\pi} = \frac{67.8\mathrm{G}}{\lambda[\text{Å}]d[\mathrm{cm}]}$$

Mezei π-flipper II

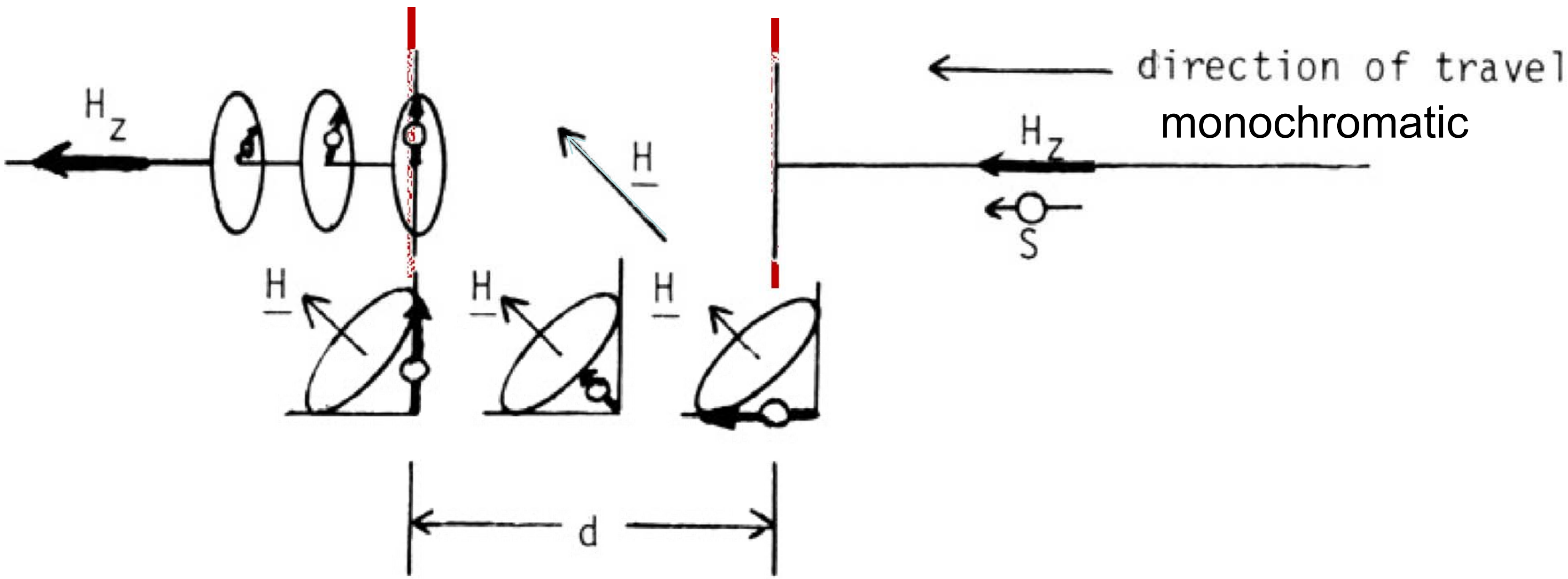


$$B_{\text{long coil}}[\mathrm{G}] = 1.26 \times n[\mathrm{cm}^{-1}] \times I[A]$$

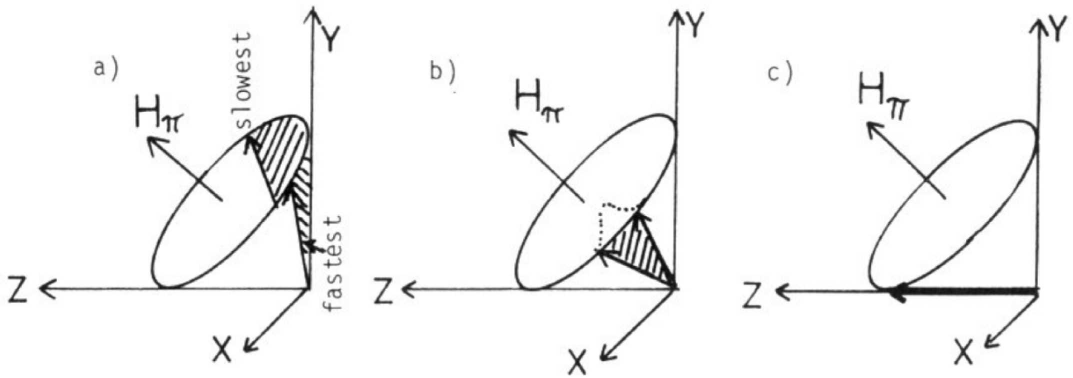
4Å, d=6mm, 10 turns/cm -> B=28G, I=2.2A



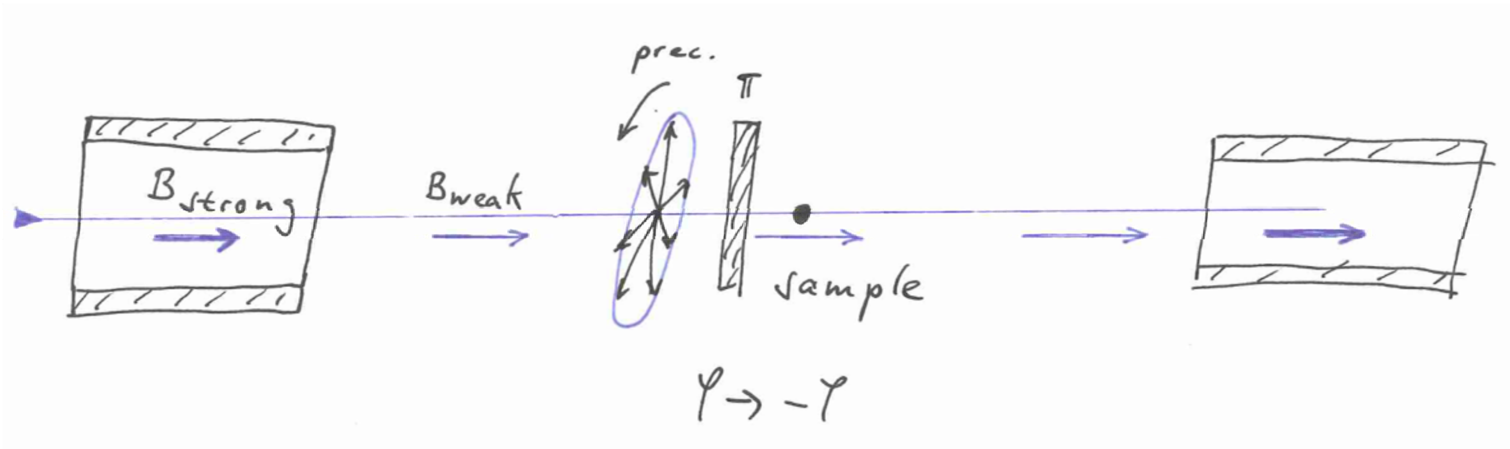
start / stop precession: π/2 - flipper



π/2 – flipper polychromatic

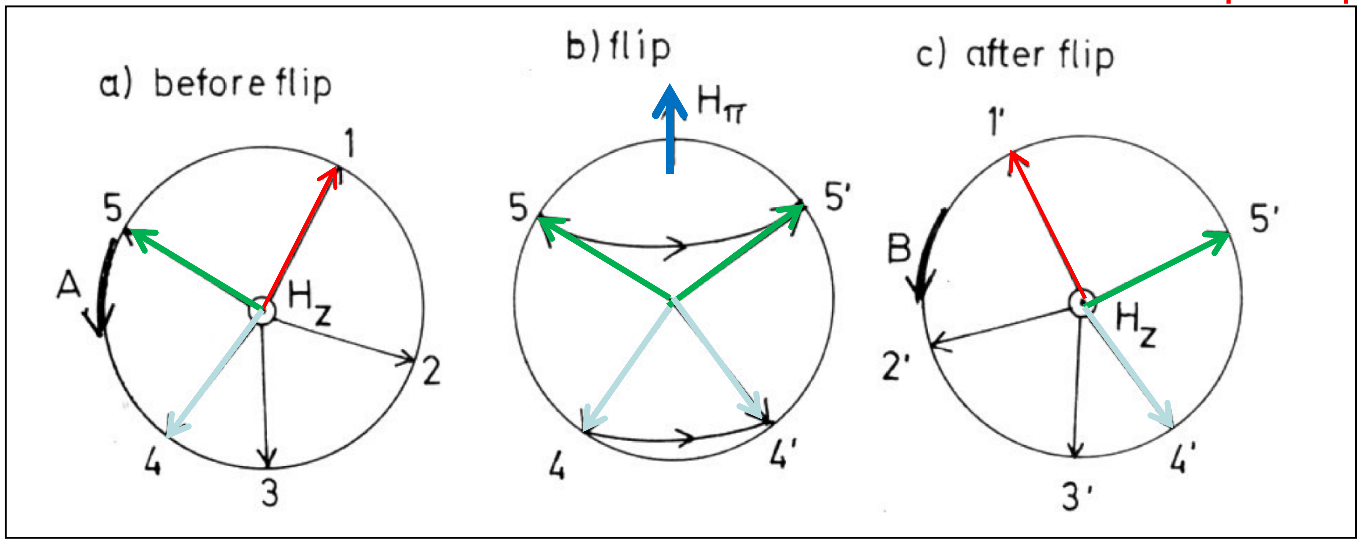


inversion of precession: π - flipper



view in beam direction

φ -> -φ



field homogeneity, precession coils

old IN11: tau=50ns @ 10Å (4MHz)
->10^4 precessions

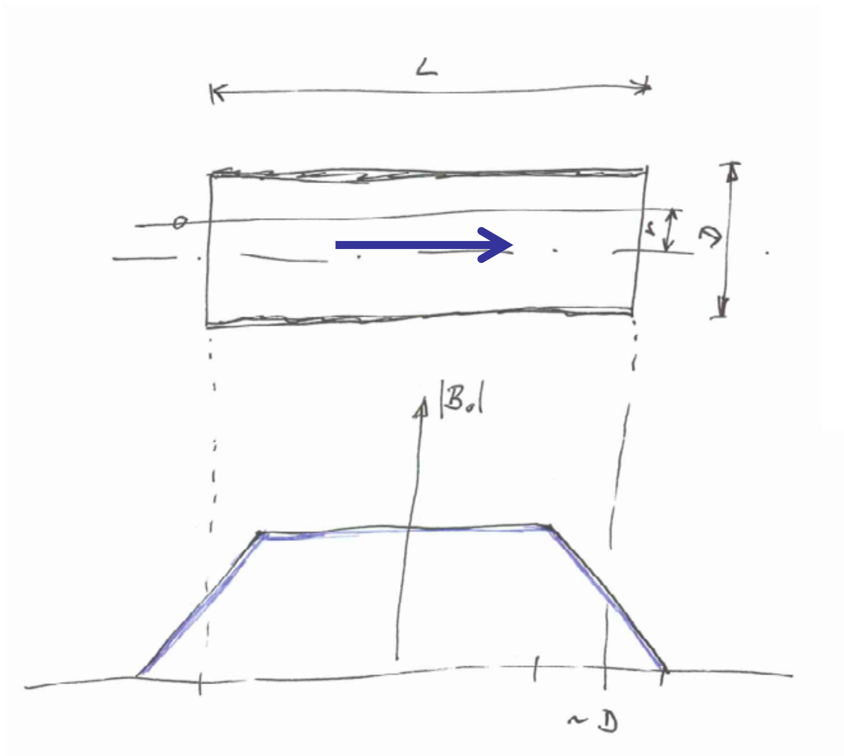
-> field integral J = B x L:

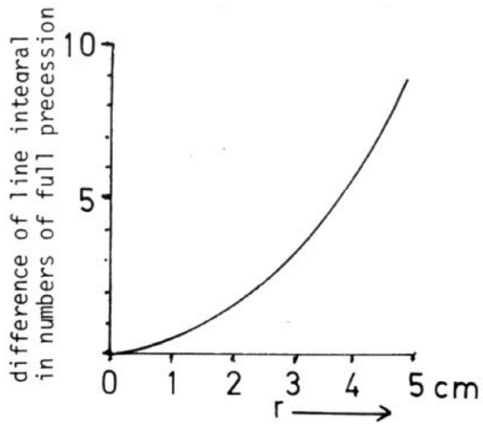
$\Delta J/J \ll 10^{-4}$ -> 10^{-6}

2 problems:
- J in solenoid is not uniform $J \sim r^2$
- beam divergent (typ.1°)

solenoid

B changes in one direction -> inhomogeneity perpendicular





$$J = B_0 \cdot L + B_0 \frac{r^2}{2D}$$

$$\Delta J / J = \frac{r^2}{2DL}$$

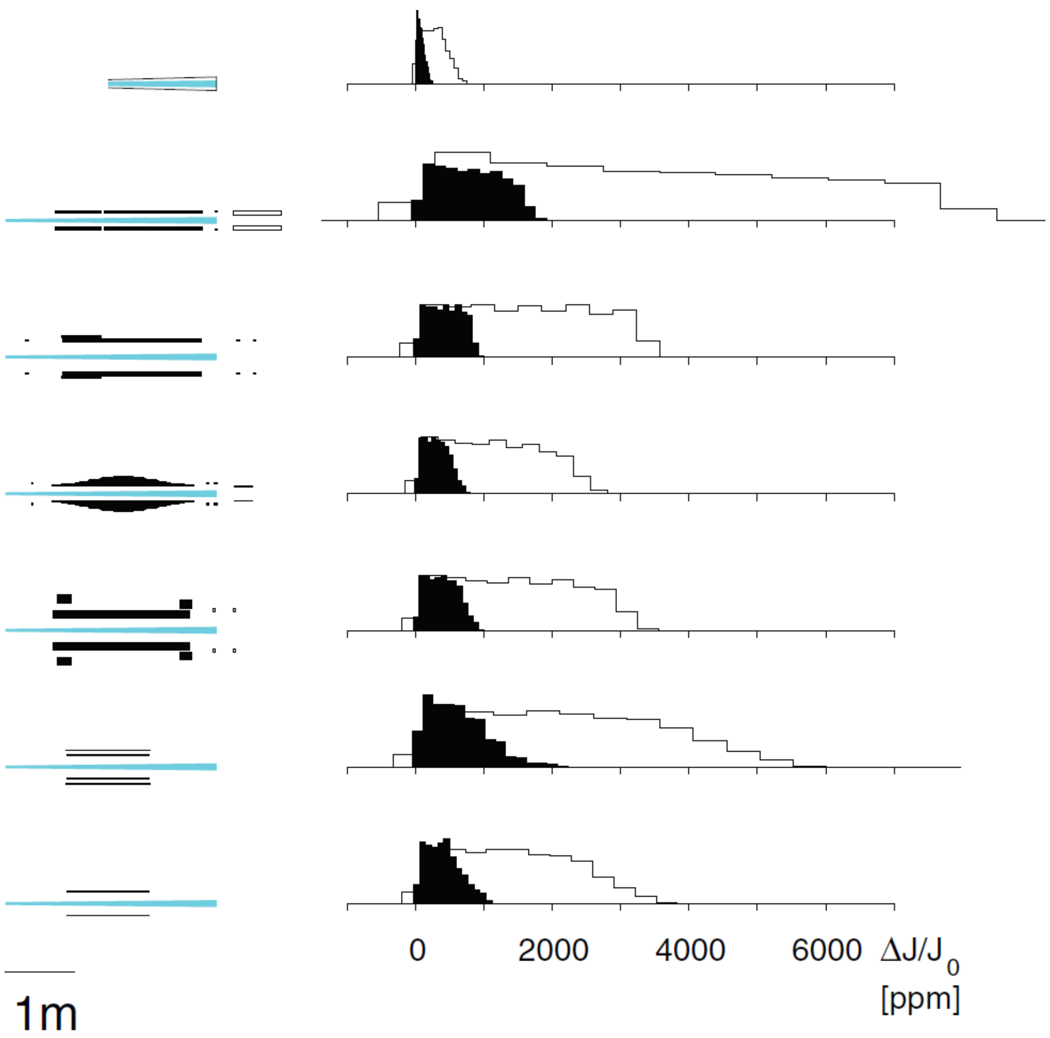
how to improve the homogeneity

1. make field transitions soft -> *Optimal field shape (Claude Zeyen)*
   $B \sim \cos^2(L)$
2. correction coils

3. new technologies (*Longitudinal spin echo*)

comparing coil designs (S. Pasini, JCNS)

d_{beam}: 4 ->10 (20)cm



uniform

IN11

IN15

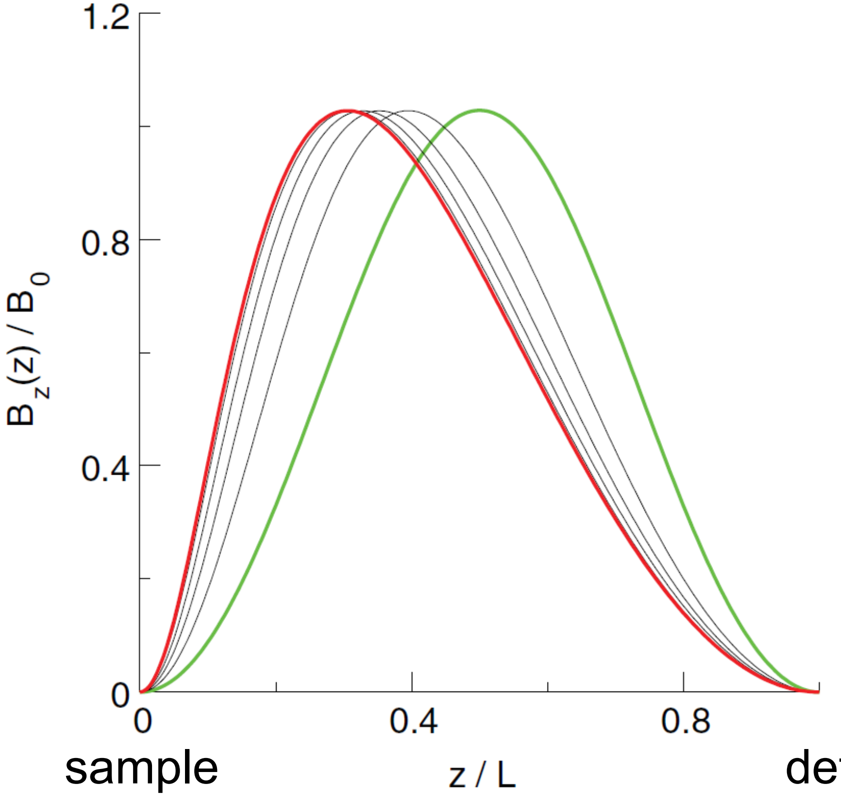
optimal shape (Tokai)

Jülich NSE (FRM II, NIST)

Jülich – SNS compensated

Jülich – SNS inner coil

optimal shape

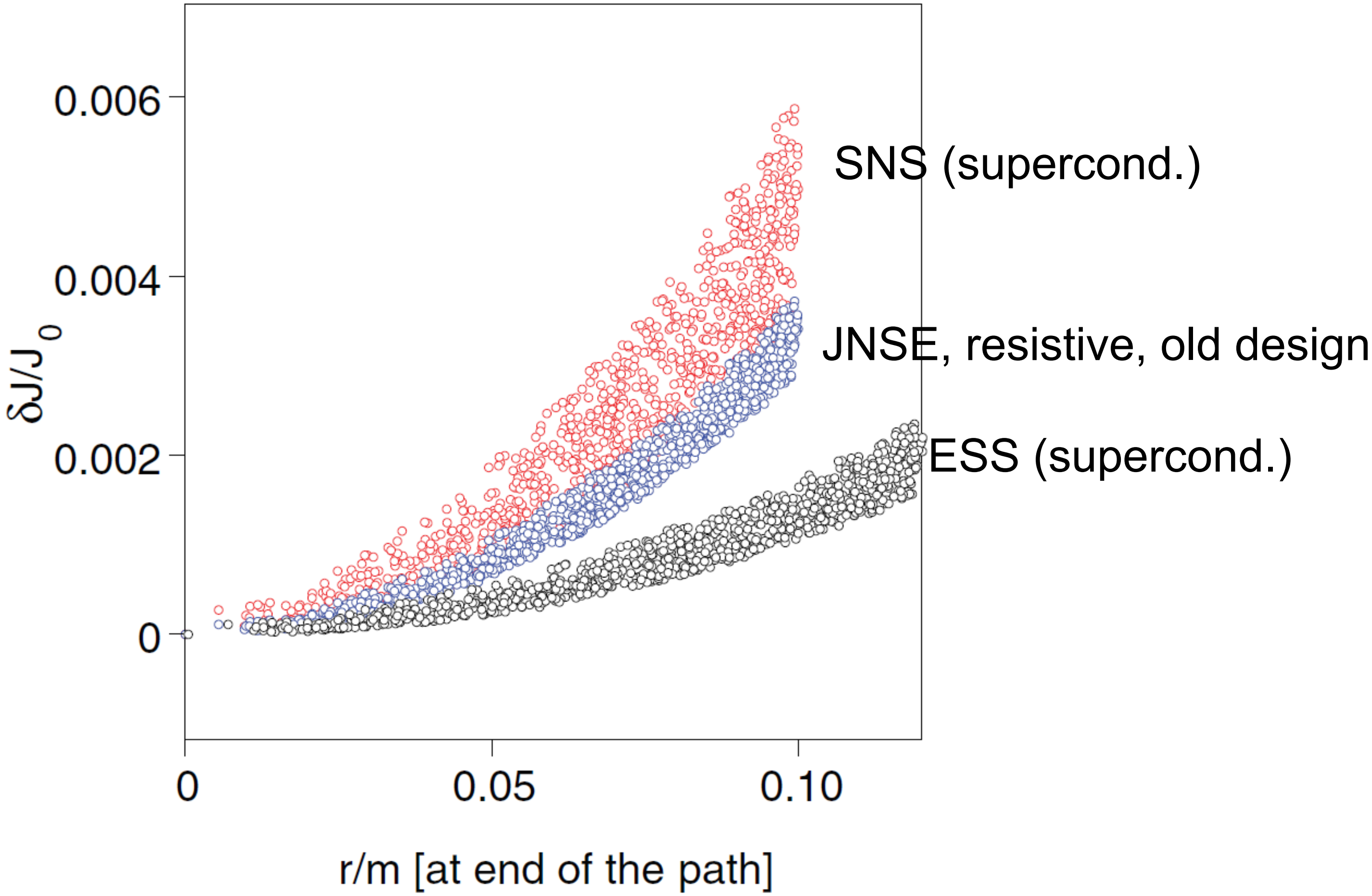


sample detector

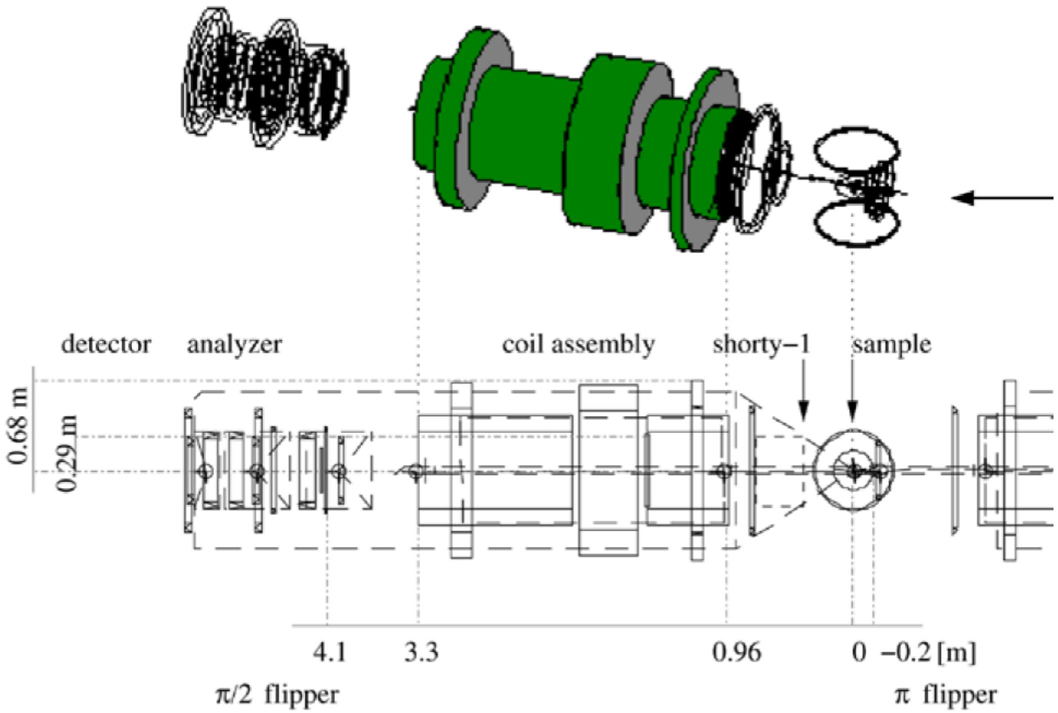
(detector diameter 4-40cm)

S. Pasini, Meas. Sci. Tech. 26, 035501 (2015)

Jülich instruments

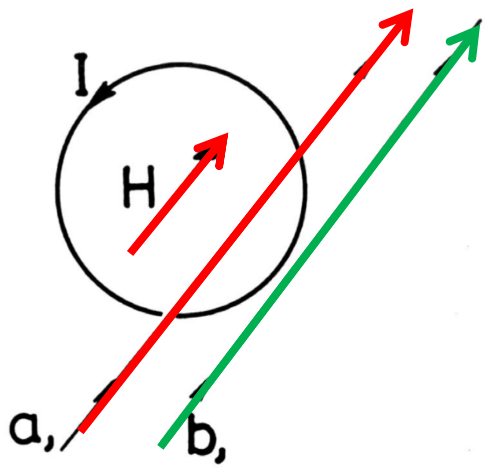


ESS spin echo (SC)



correction element: Fresnel coil

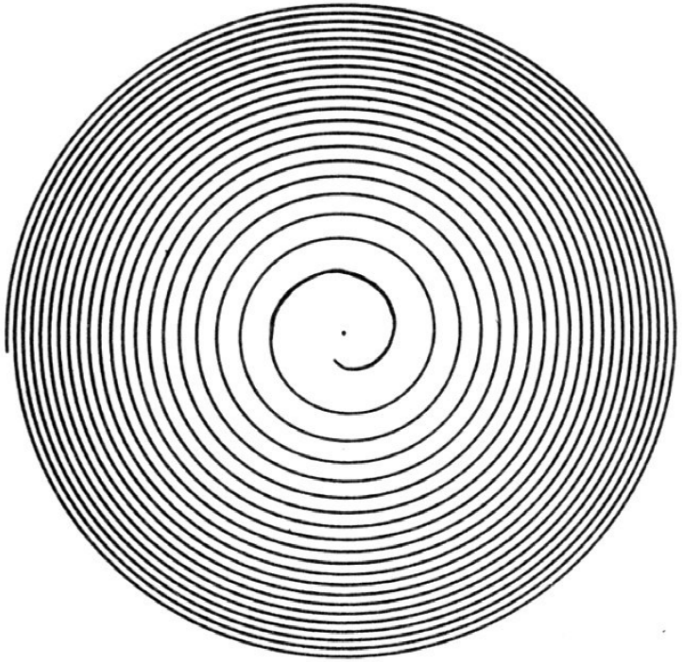
solution: subtract J ~ r^2
-> generate quadratic current density



$$\oint \boldsymbol{H}\, ds = I$$

add strong field || axis:

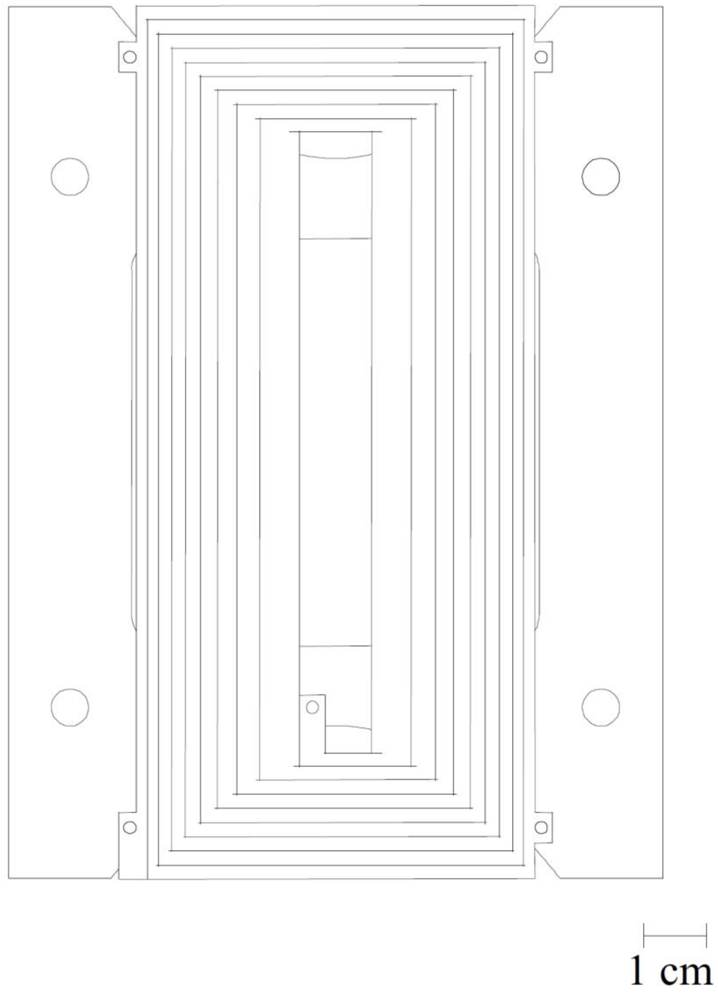
Fresnel coil



problem: current density, heat transport

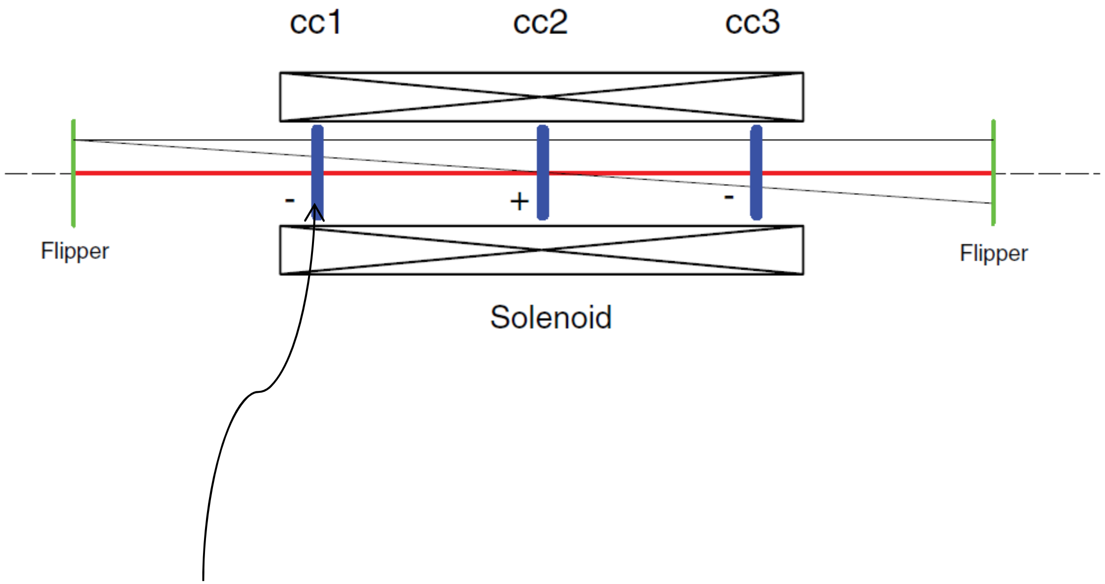
Phythagoras coils

2 crossed coils: $r^2 = x^2 + y^2$



idea: U. Schmidt, B. Boehm, Heidelber

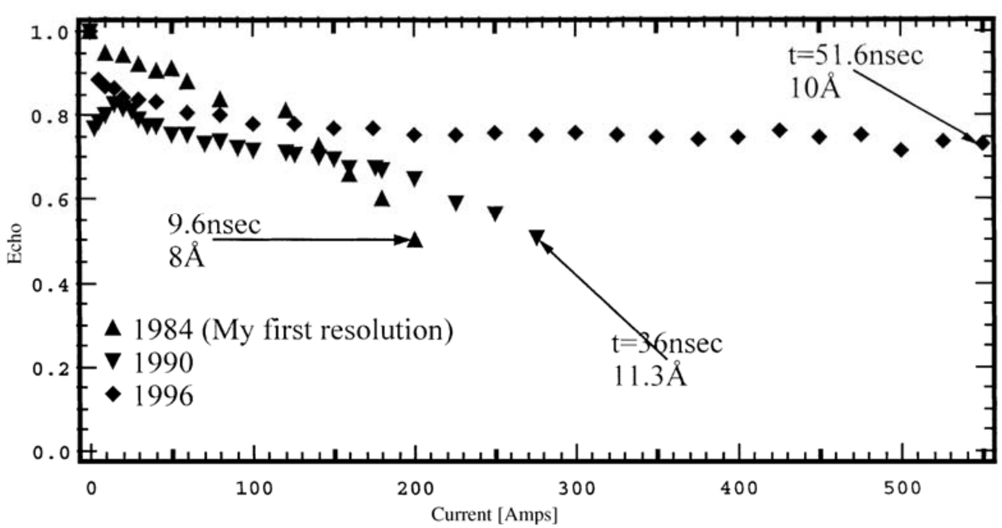
full correction -> 3 coils

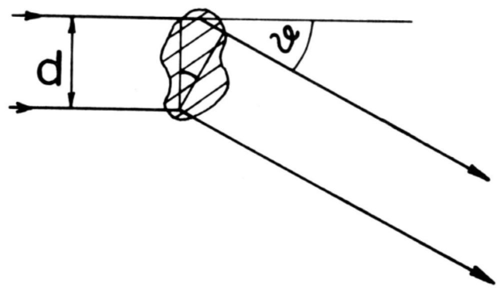


Fresnel or Pythagoras

resolution curves IN11

B. Farago / Physica B 267–268 (1999) 270–276





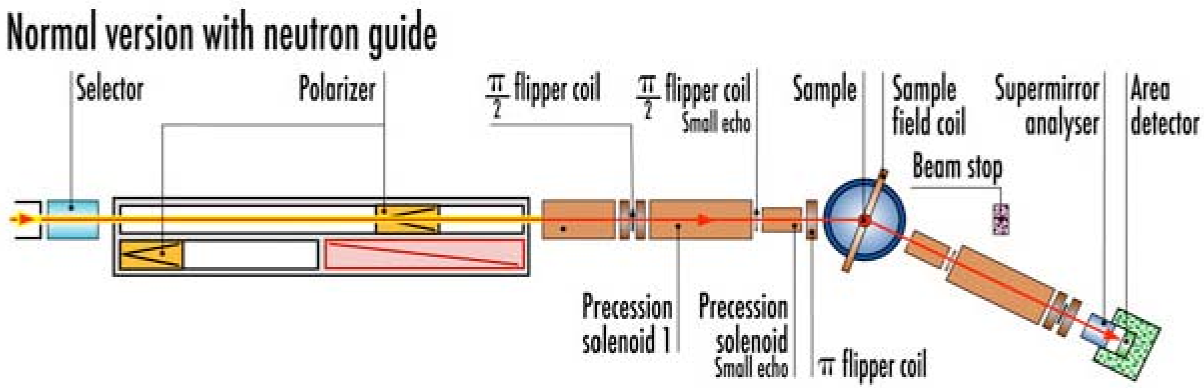
Farago, Physica B267, 270 (1999)

NSE instruments

IN15 (ILL)

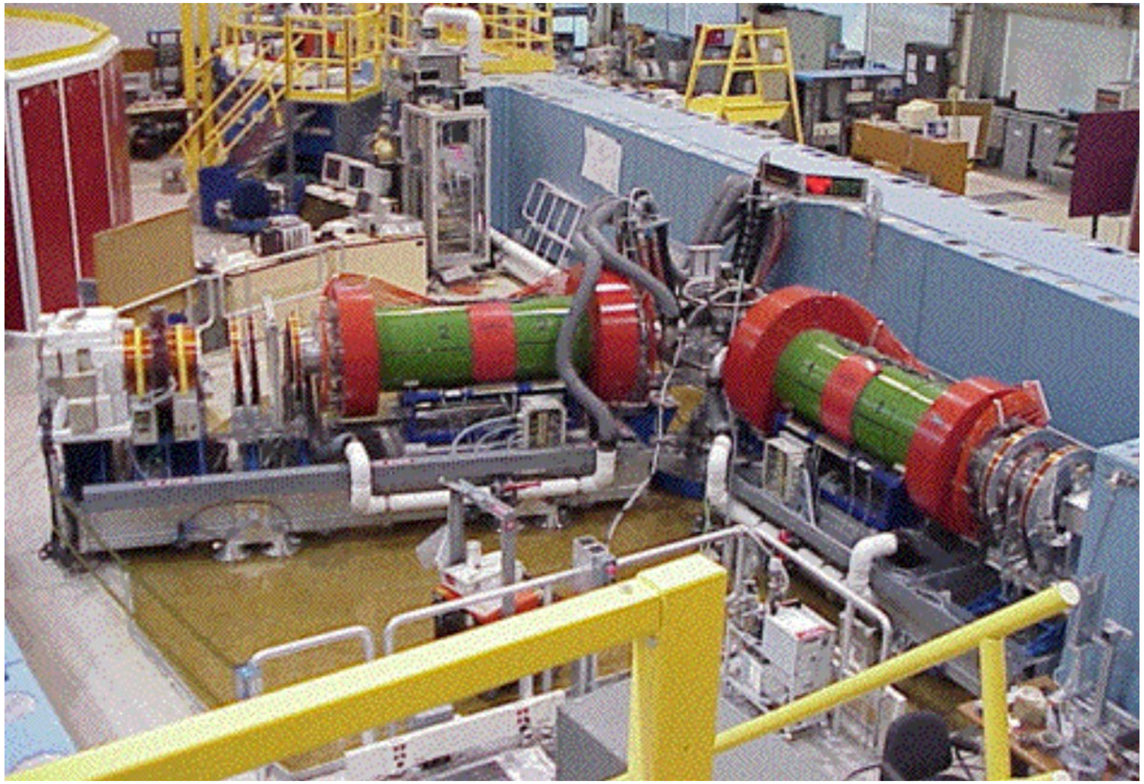
400ns, 25Å

IN15 layout


Normal version with neutron guide
Selector
Polarizer
$\frac{\pi}{2}$ flipper coil
$\frac{\pi}{2}$ flipper coil Small echo
Sample
Sample field coil
Supermirror analyser
Area detector
Beam stop
Precession solenoid 1
Precession solenoid Small echo
π flipper coil

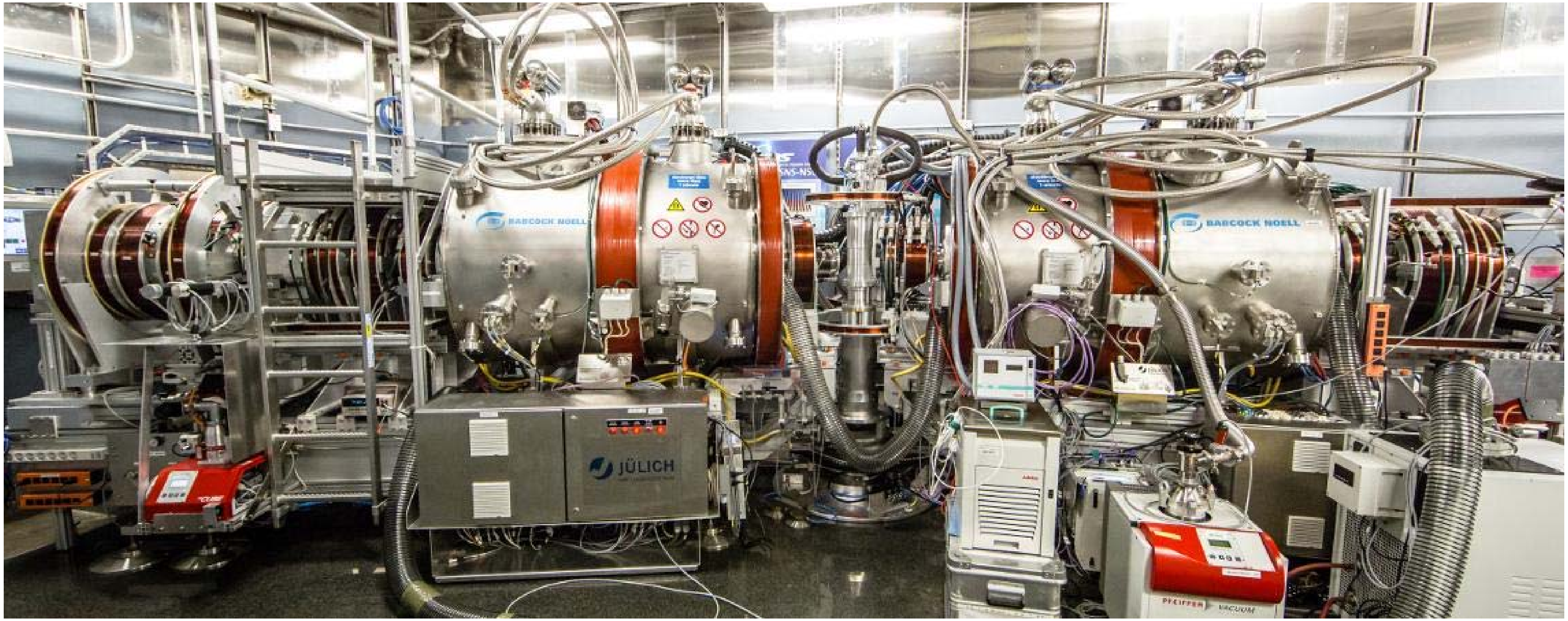
NSE Tokai JRR3

Jülich NSE (NIST and FRM II)



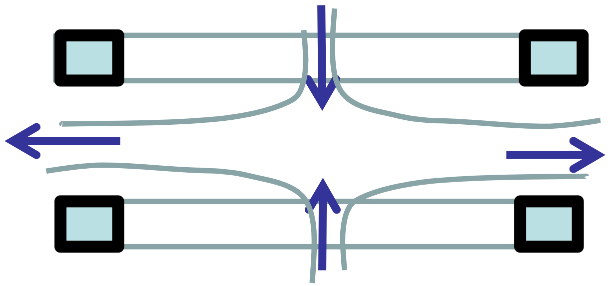
100ns

Jülich NSE SNS



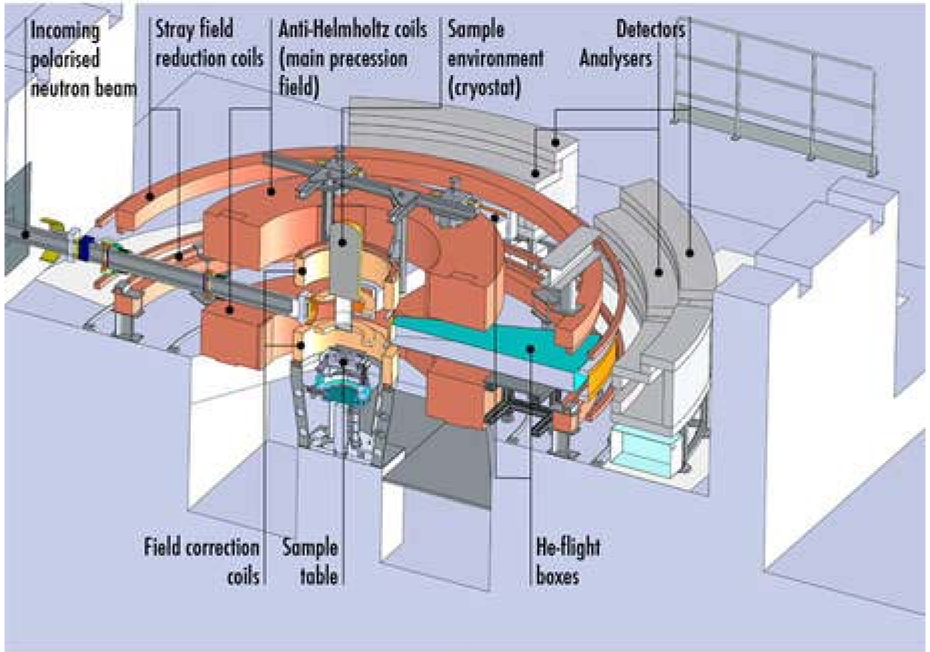
- superconductiong coils, low fringe fields
- mu-metal chamber

SPAN (HZB, Pappas, Mezei))

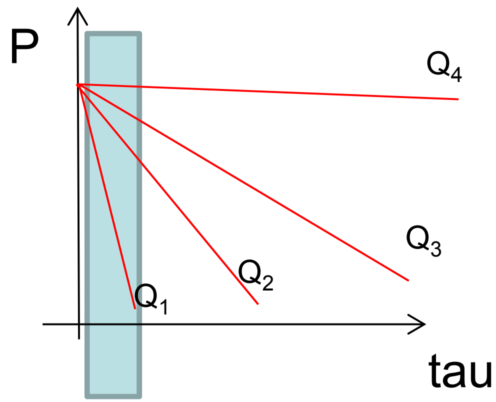


multi-angle analysis

WASP (ILL)

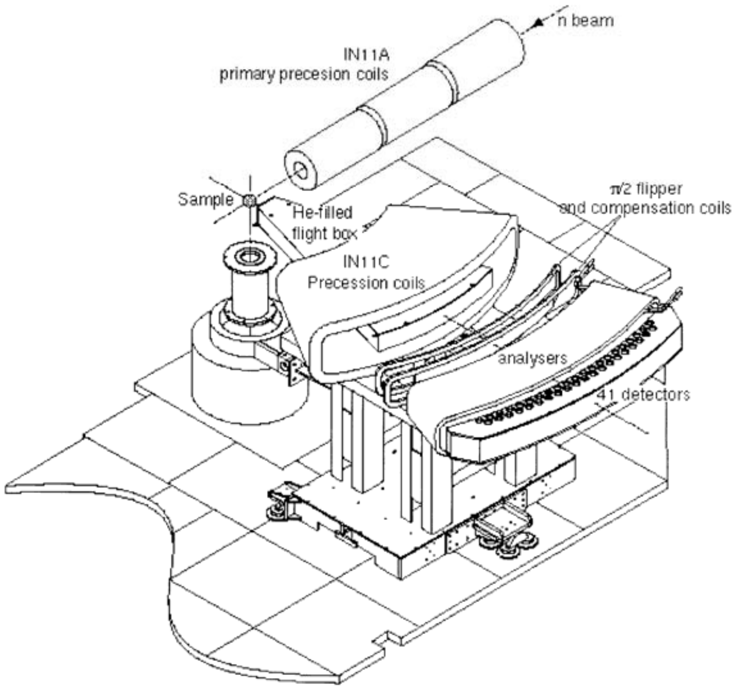


50ns @ 10Å



IN11c

B. Farago / Physica B 267–268 (1999) 270–276



1ns @ 5.3Å

NRSE: spin echo based on RF spin flippers

- linewidths of excitations (phonons, magnons)

- Larmor diffraction

conventional triple axis spectrometer

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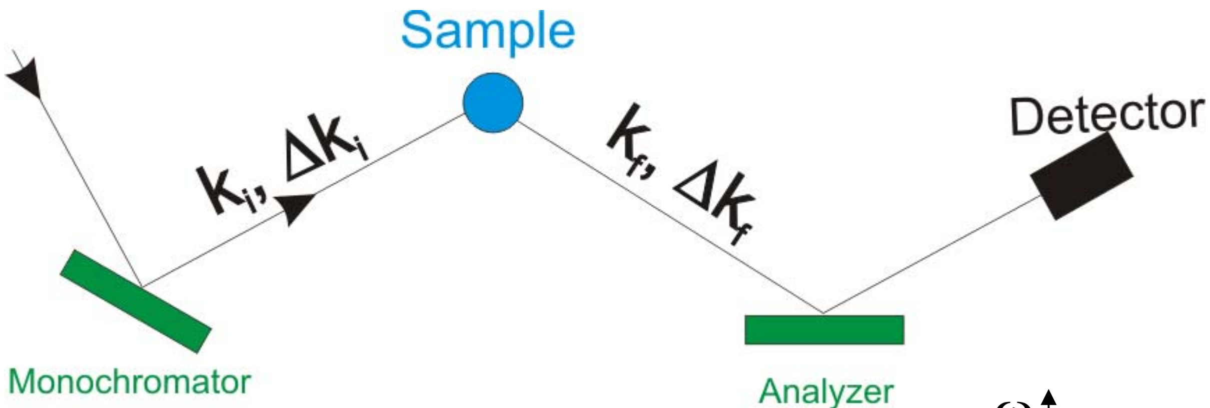
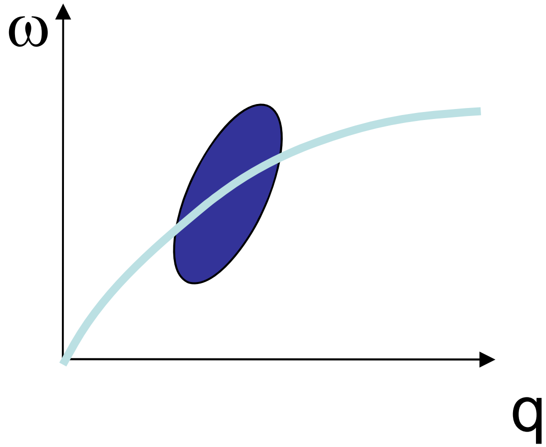
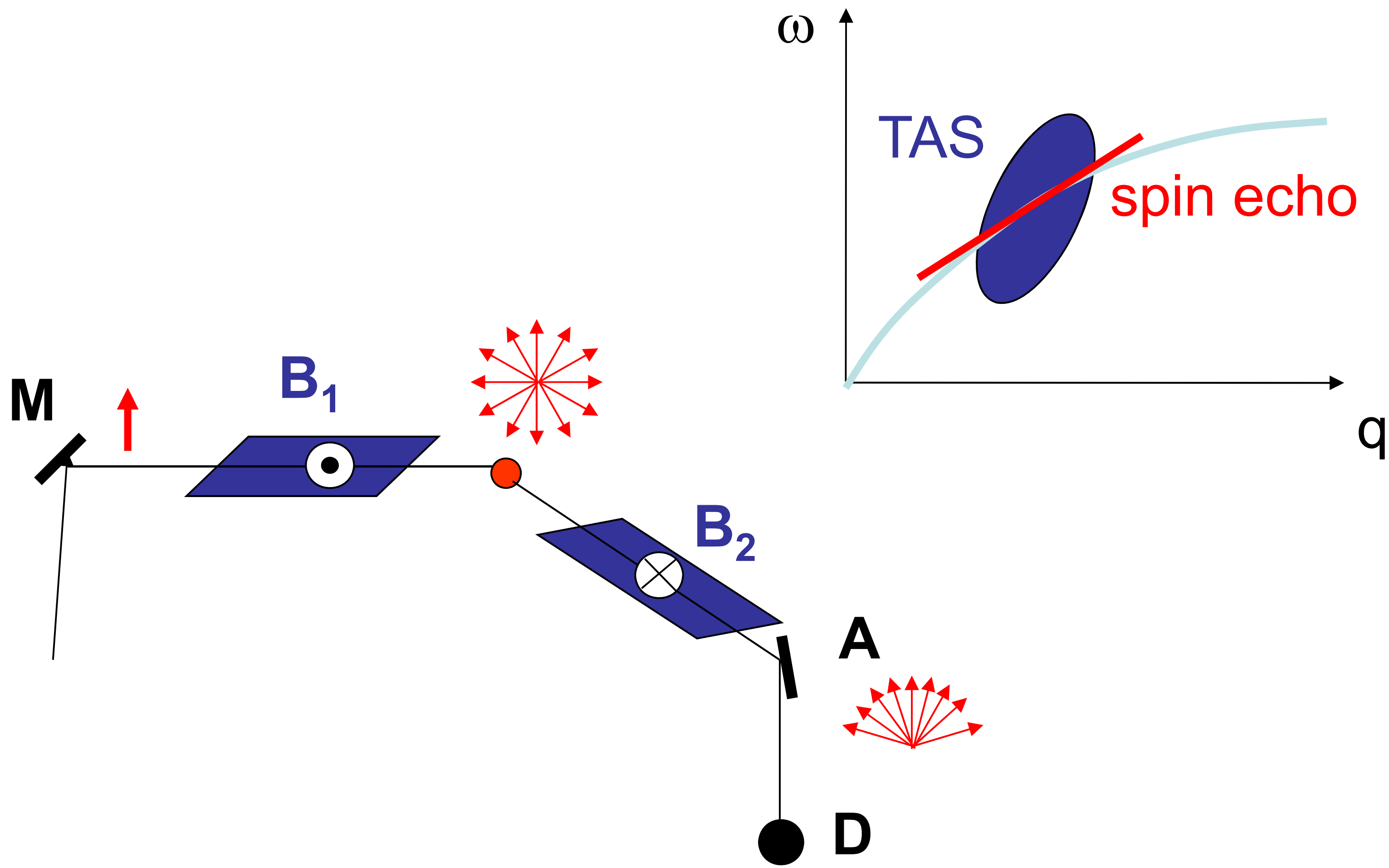




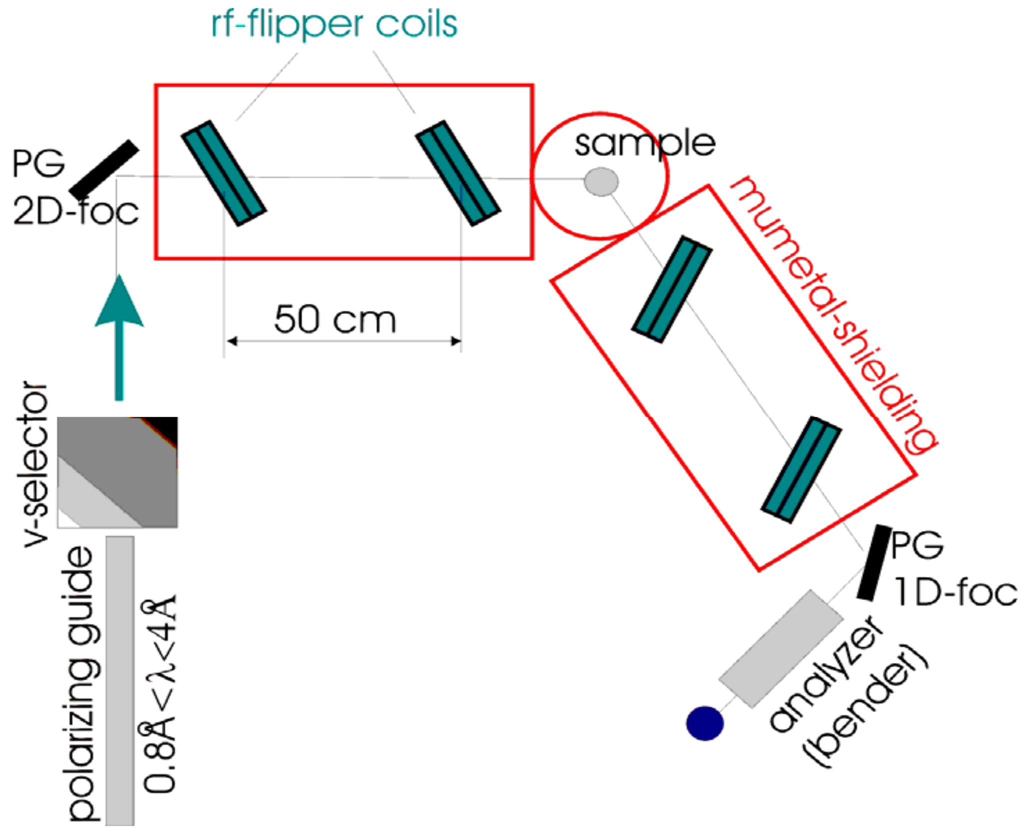
excitation energy: <100meV
energy resolution: typ. 10% resolution ~ 1/intensity

-> not sufficient to resolve linewidths

solution Mezei 1977: spin echo + TAS
tilted coil technique



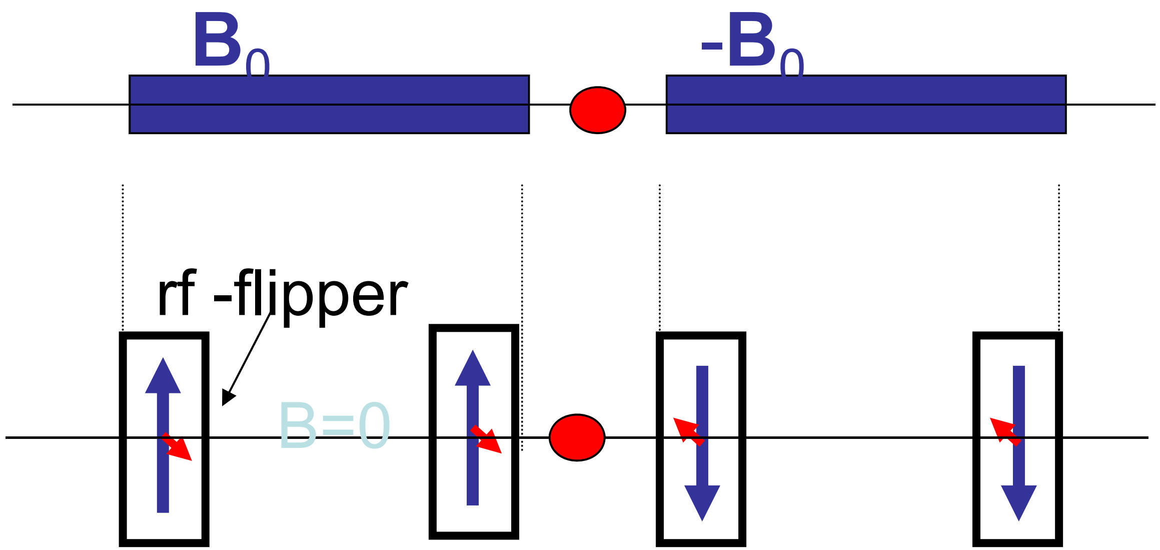
TRISP at the FRM II (NRSE)



optimized for lifetime measurements of dispersing excitations

- excitation energy <50meV (thermal beam)
- resolution 1-100μeV

NRSE (neutron resonance SE)



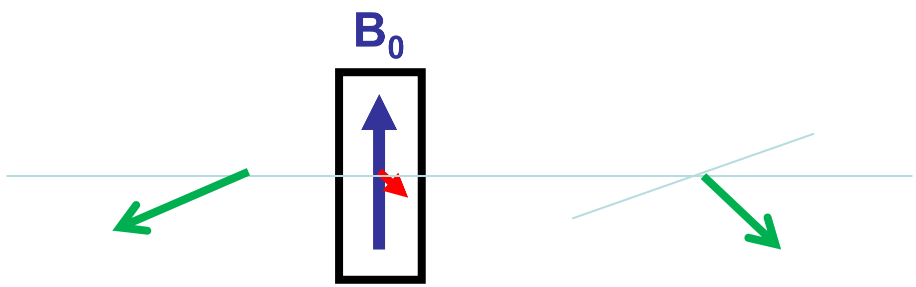
+ NRSE:

- precise field boundaries (windings of rf –flipper)
- high stability (RF oszill. vs. large DC coil)
- no stray fields (*bootstrap* coils)
- mu-metal shield possible
- dispersive excitations (phonons, magnons)

+ NSE:

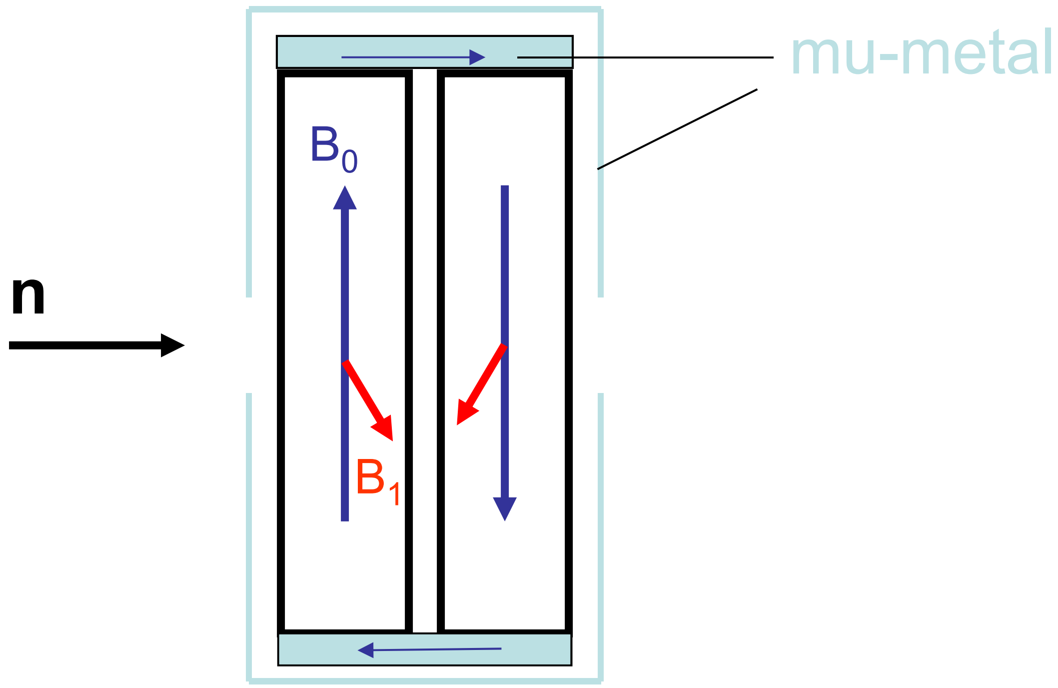
- better resolution for quasielastic small *Q*
- multidetector setups

RF flipper



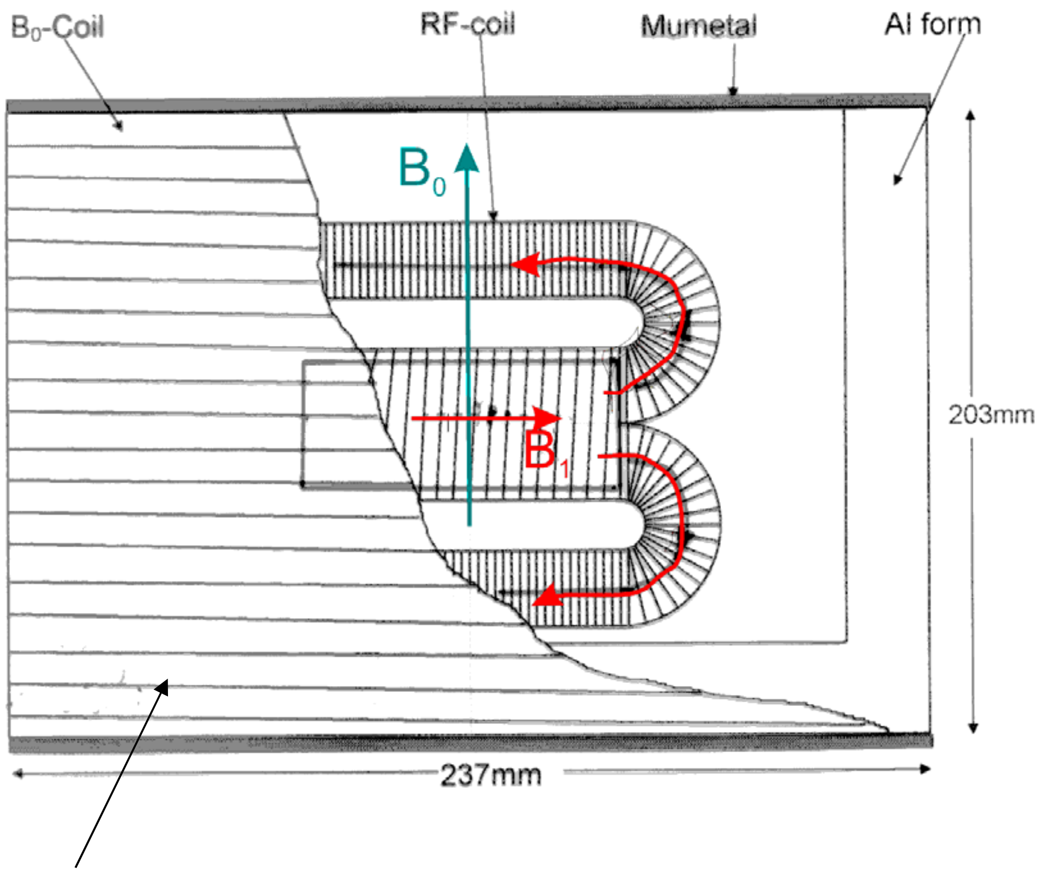
$$\phi = 2\gamma B_0 t - \phi_0$$

RF spin flipper (*bootstrap* coil)



effective field: $4B_0$

TRISP

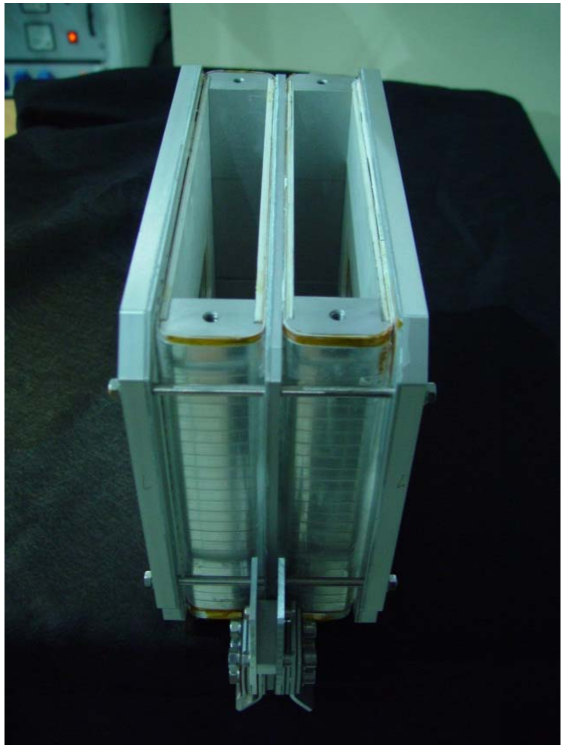


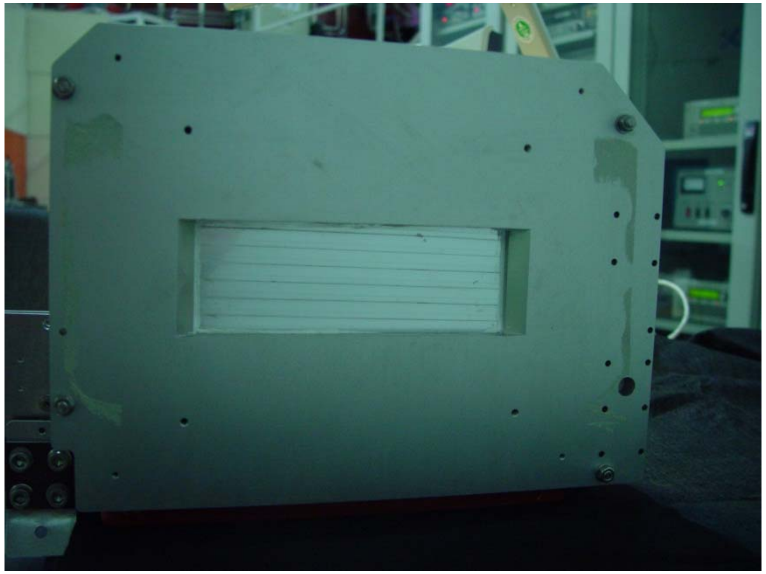
Al-tape (anodized)

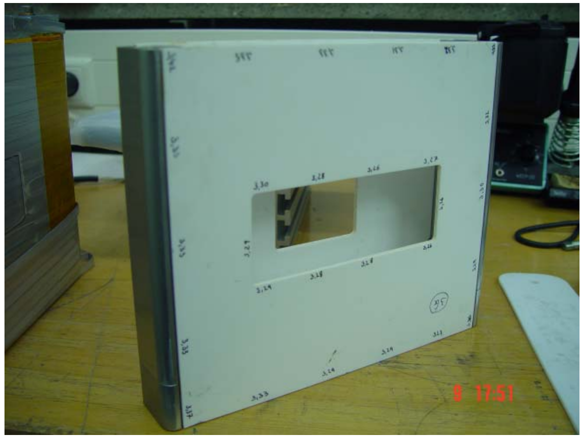
- Al tape 8x0.5mm²
- B_0 300G, P=1kW

rf flipper TRISP

MAX-PLANCK-GESELLSCHAFT



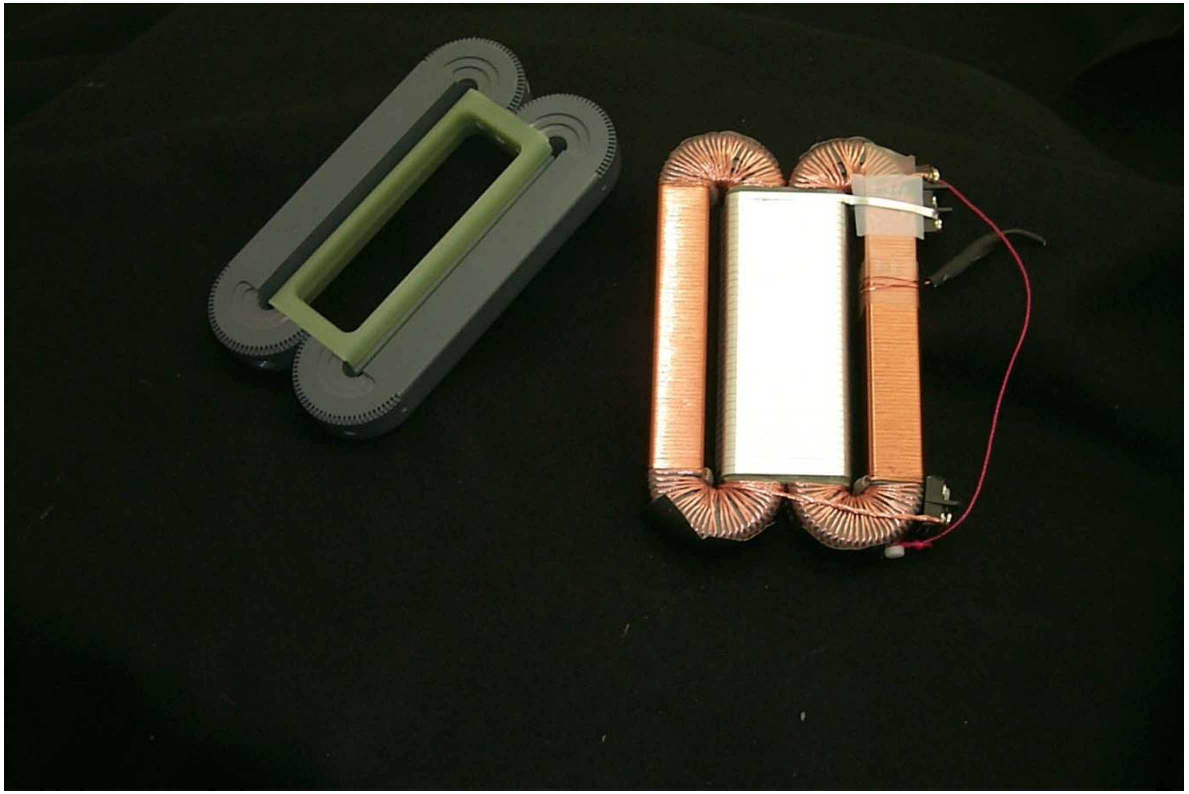




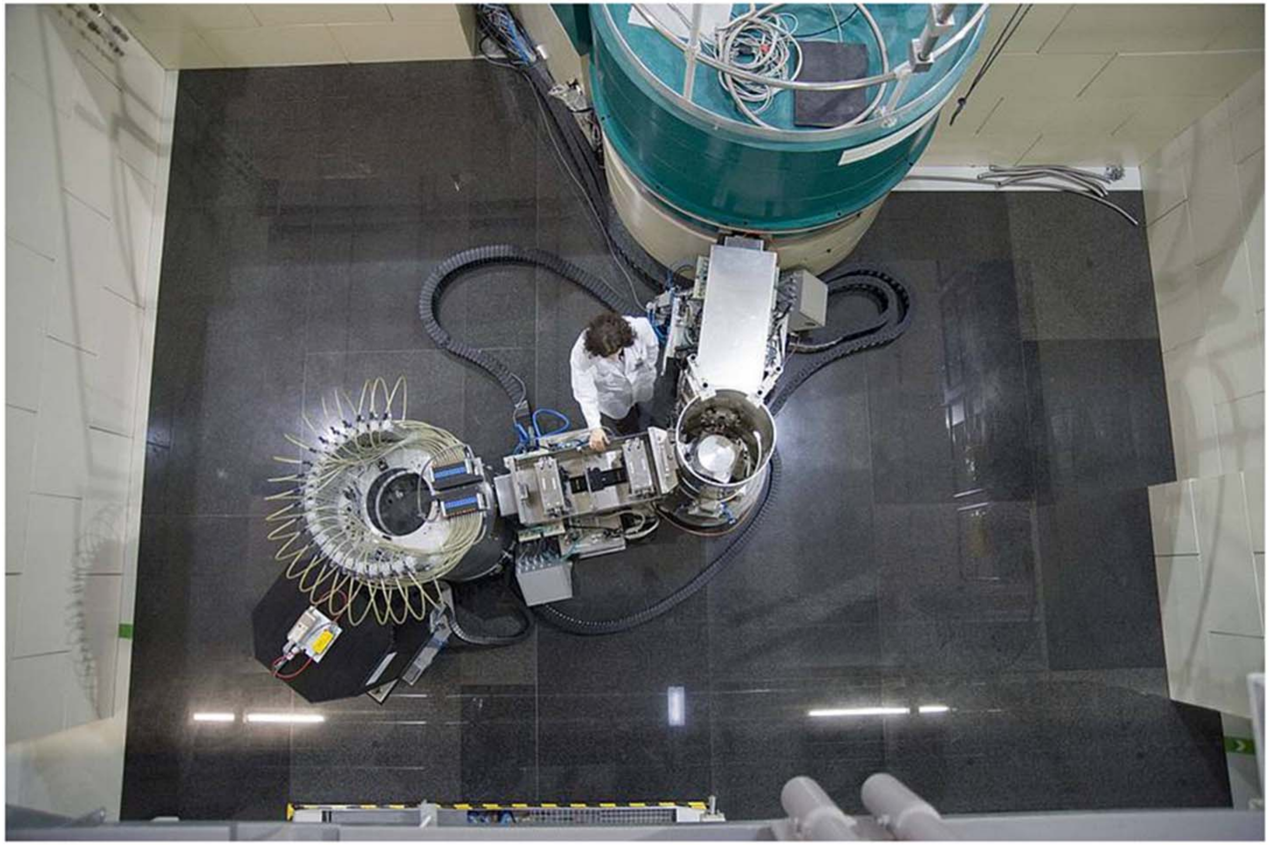
+ precise surface
+ low stray field
- small angle scattering

TRISP

MAX-PLANCK-GESELLSCHAFT



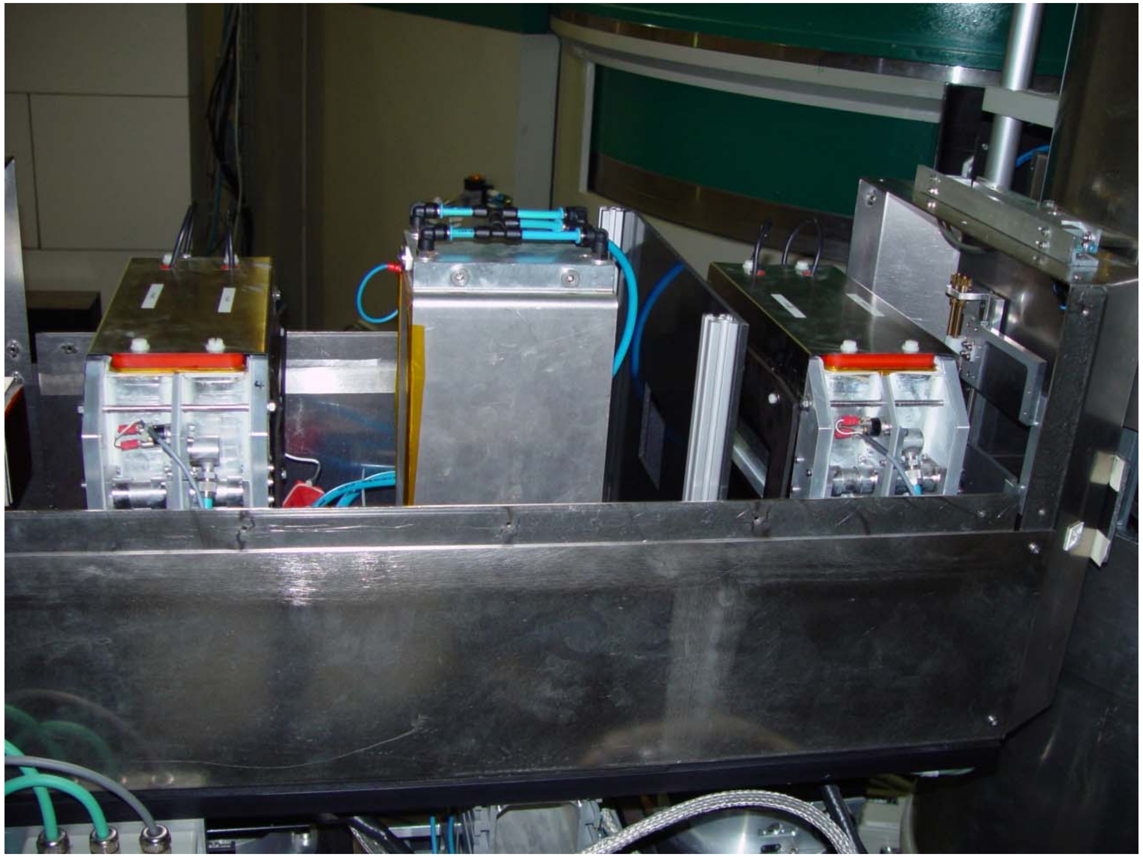
TRISP (FRM II)



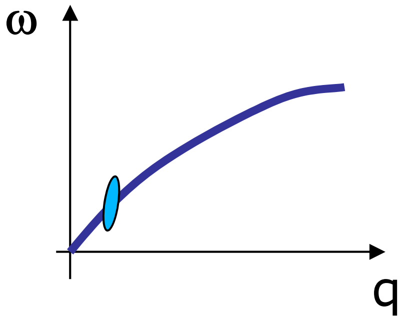
mu-metal: 2mm, 1 layer -> shielding factor 100

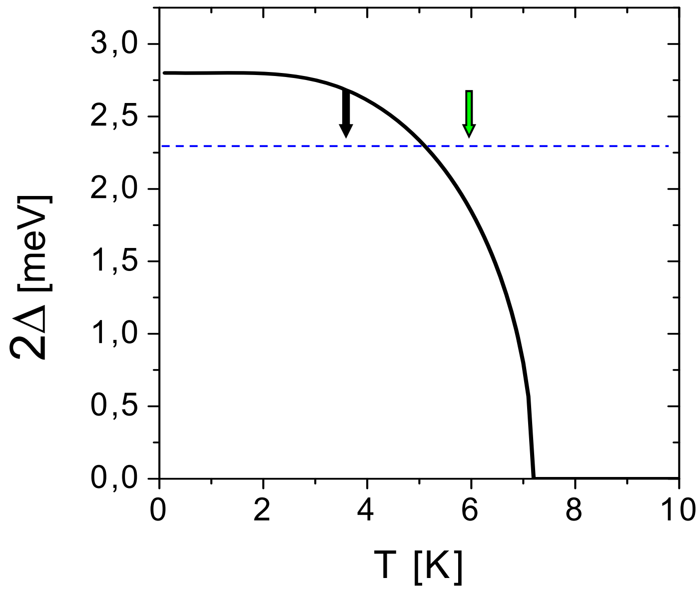
MPI Keimer

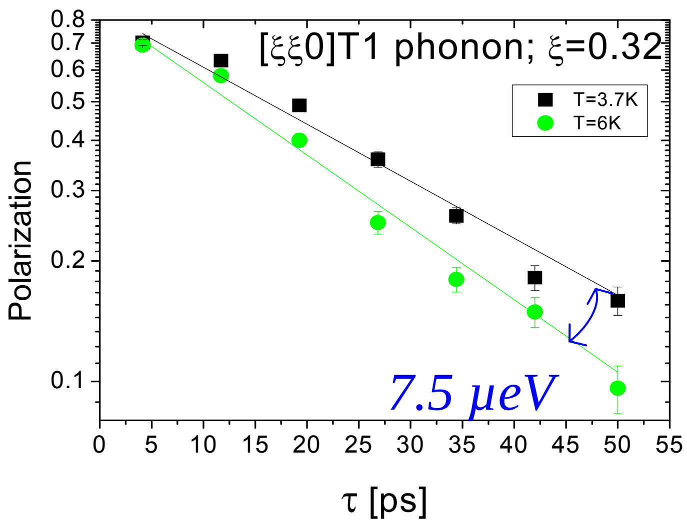
empty



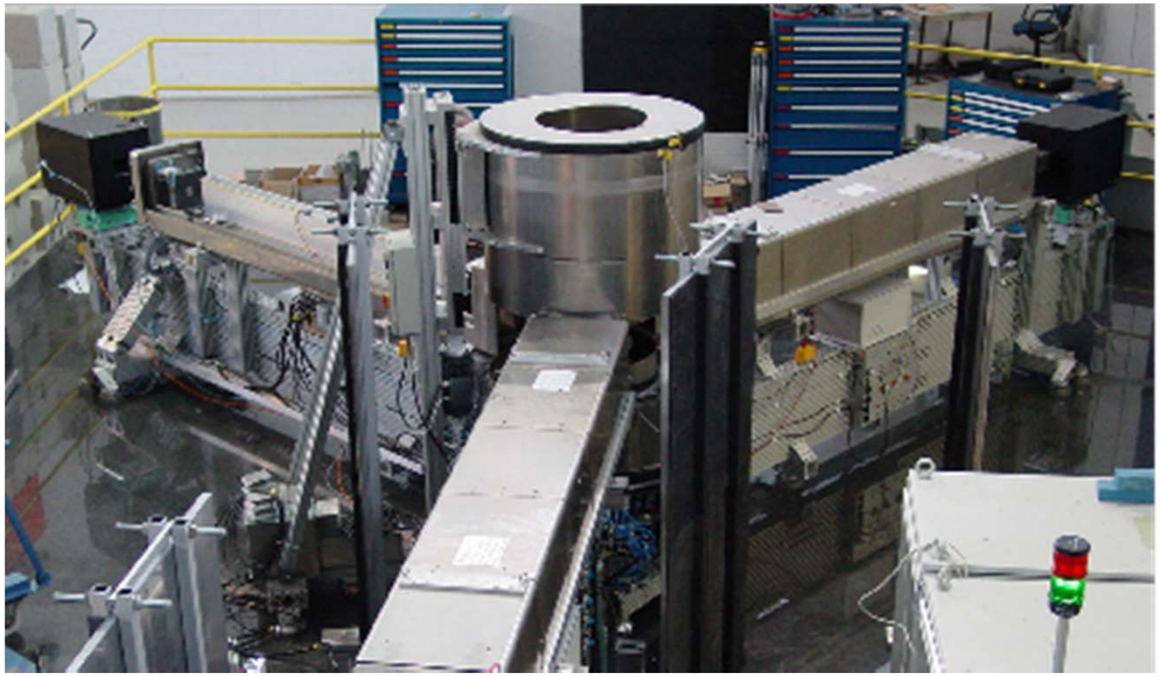
example: e-ph interaction in Pb







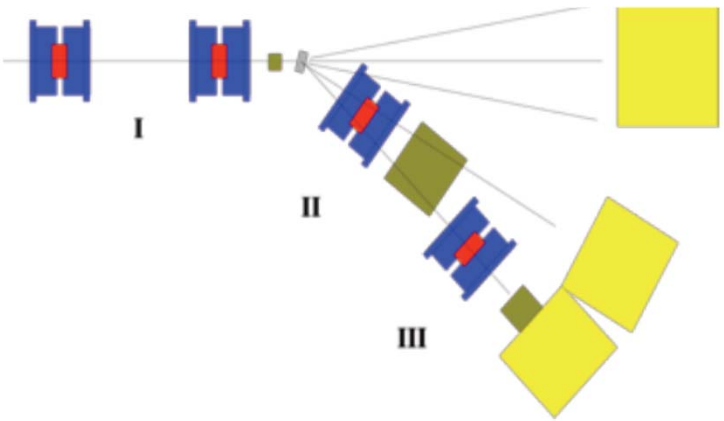
RESEDA (FRM II)



-> quasi elastic
-> 2.5m flight path

W. Häussler, R. Gähler

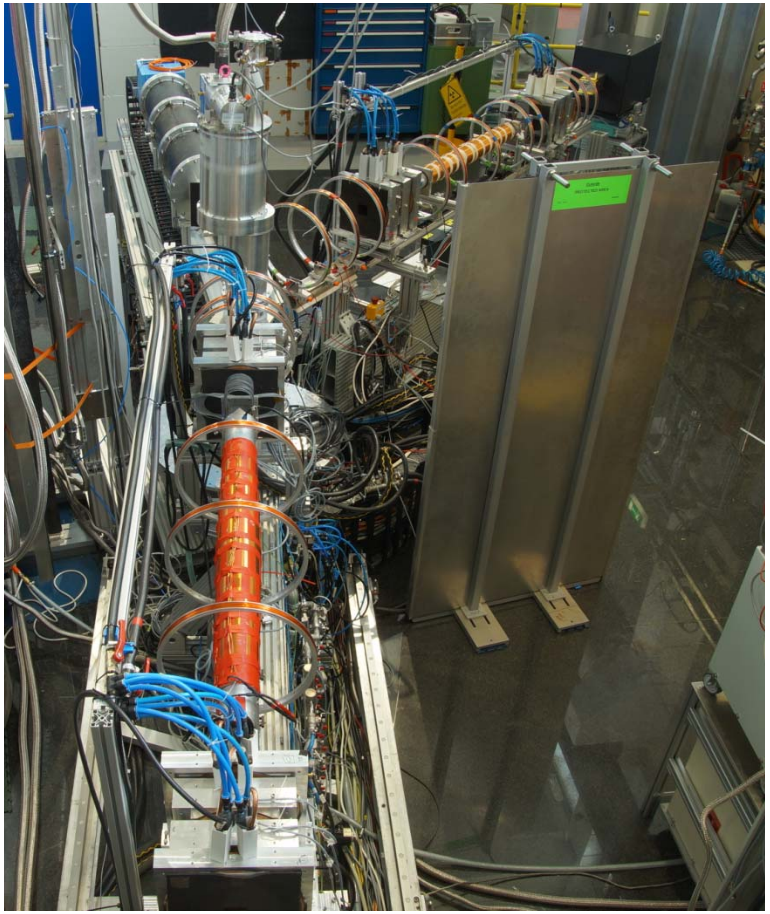
longitudinal NSE



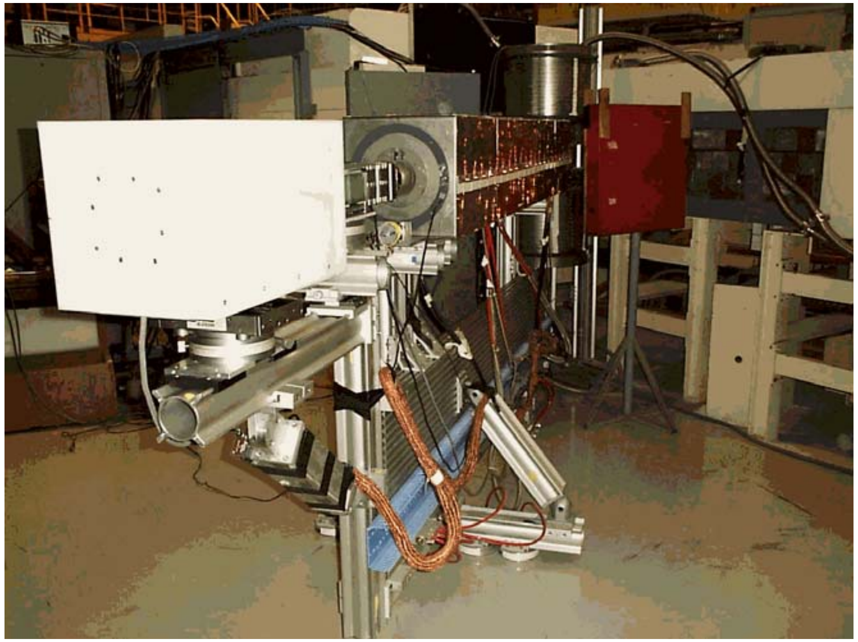
-> very good idea by W. Häußler and U. Schmidt, F. Mezei
(RF flippers, static fields longitudinal)

- small Fresnel correction (20% of NSE -> 5x more field integral)
- focusing possible (low field between coils)
- spin echo mode (4 coils) or MIEZE (2 coils)

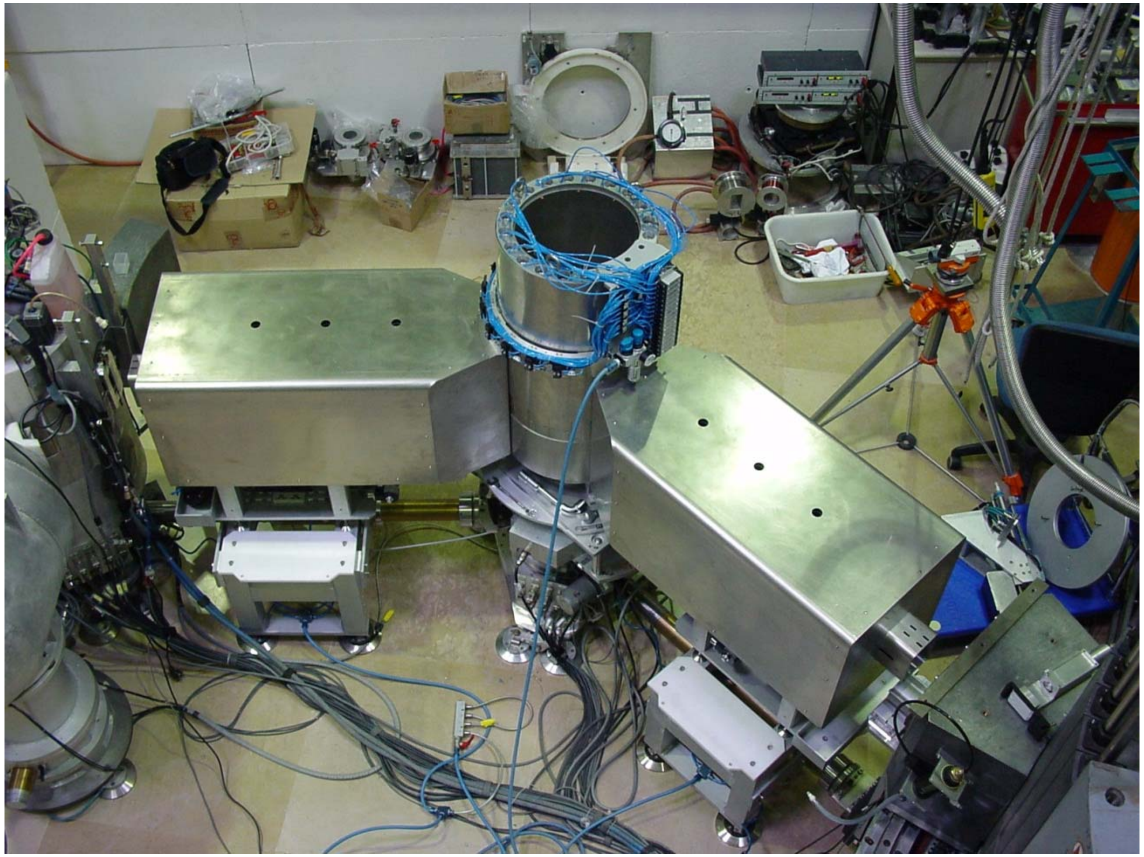
empty



MUSES Saclay



ZETA ILL



Larmor diffraction

Larmor diffraction

LD technique: Rekveldt , 1999
first experiments at FLEX

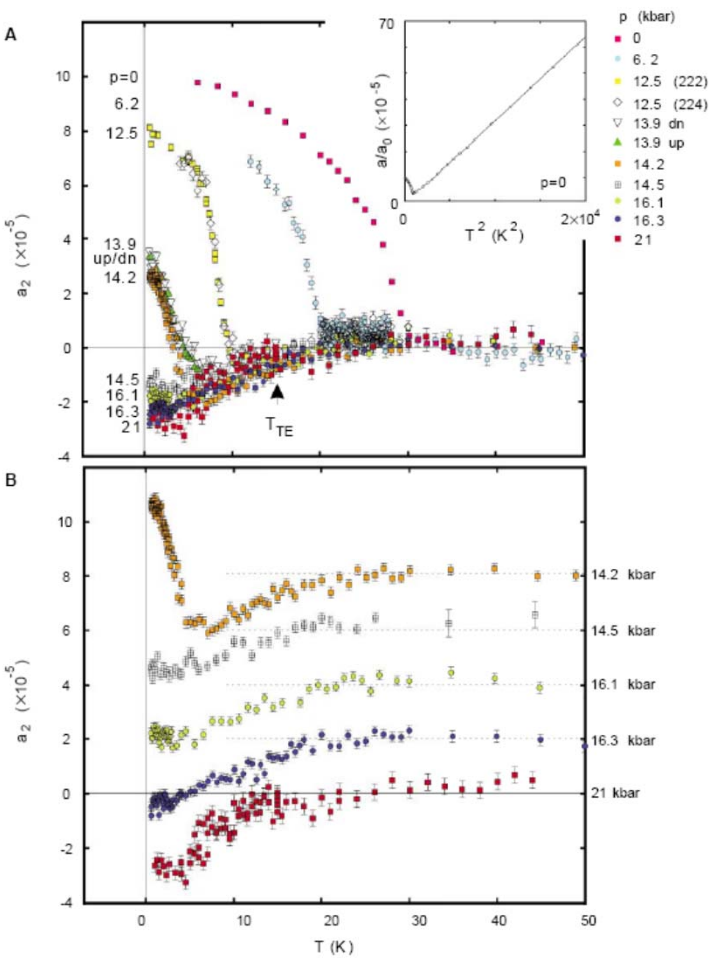
resolution $\Delta d/d = 10^{-6}$

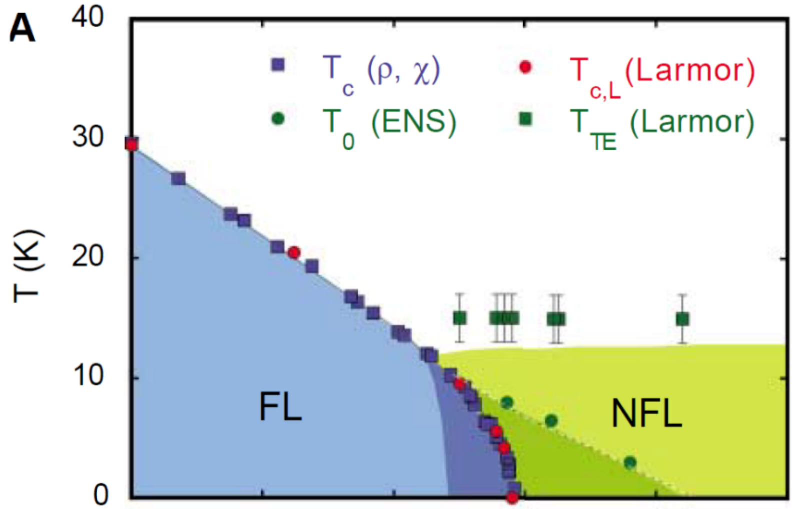
current interest:
- thermal expansion p, low T
- distribution of d-values, peak splitting
- absolute d-values (calibration)

dilatometry <-> pressure
high resolution x-ray diffraction (10^{-5}) <-> temperature
neutron diffraction <-> resolution (10^{-4})

motivation: thermal expansion, pressure

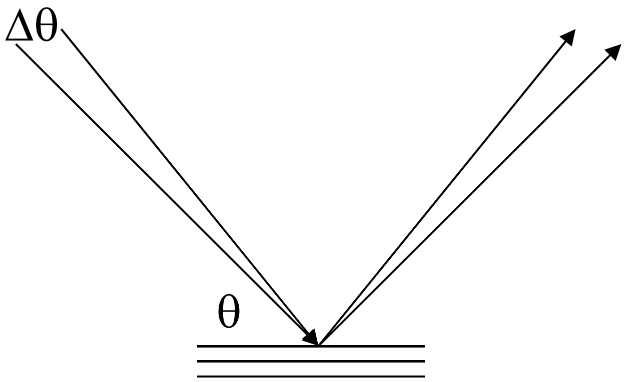
MAX-PLANCK-GESELLSCHAFT





Pfleiderer et al., Science 316, 1871, (2007)

diffraction



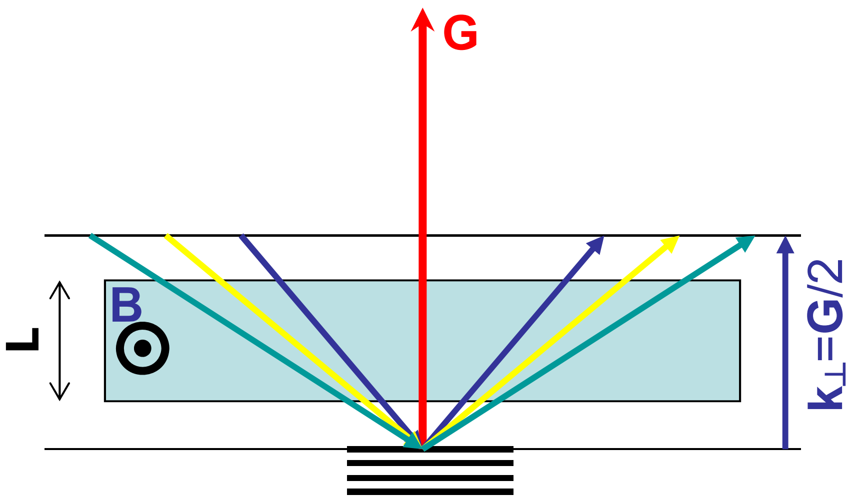
$$\frac{\Delta d}{d} = \frac{\Delta k}{k} + \Delta\theta \cdot \cot\theta$$

resolution=1/intensity

neutron: $\Delta d/d = 10^{-4}$
x-ray: 10^{-5}

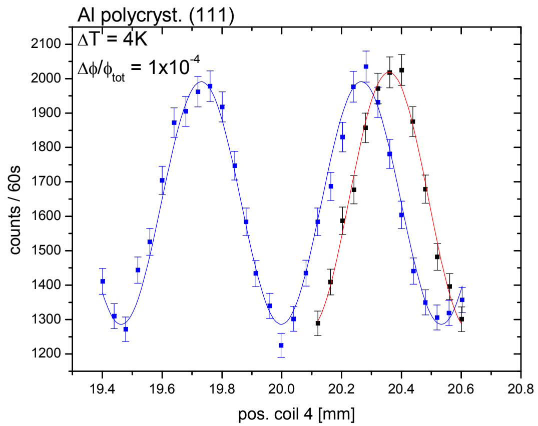
aim: try to measure *d* by a spin echo technique

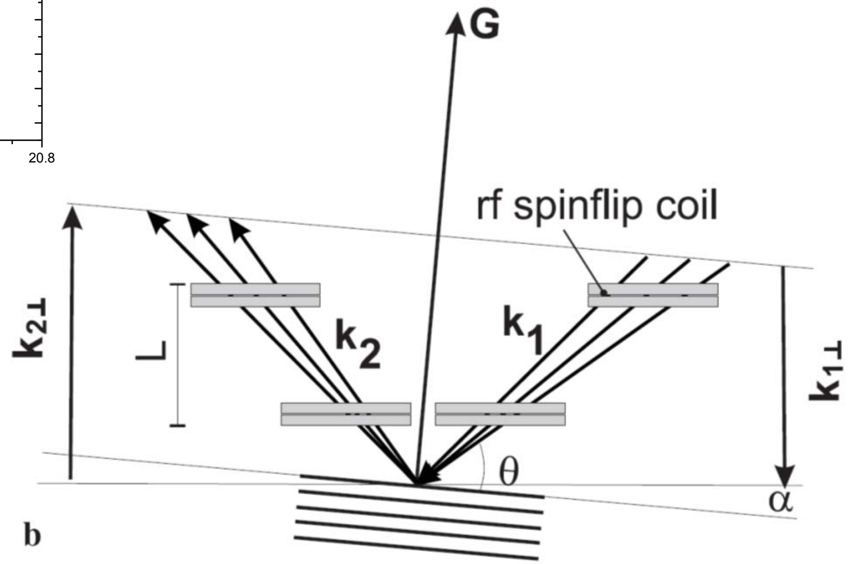
Rekveldt’s solution



$$\phi_{Larmor} = \omega_L \cdot T = \omega_L \cdot \frac{2L}{\mathbf{v}_\perp} = \frac{2\pi\hbar}{m} \cdot \omega_L \cdot L \cdot d$$

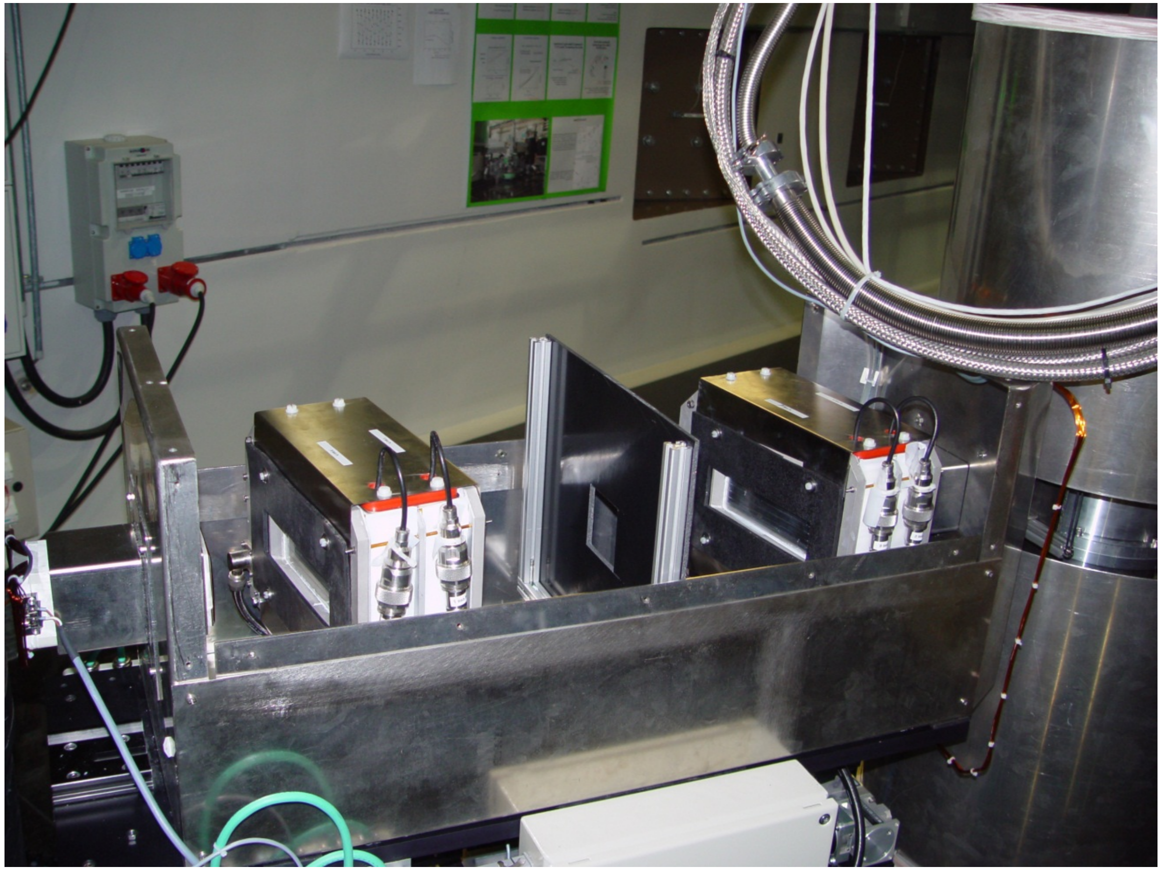
LD using NRSE





$\Delta d/d$ resolution at TRISP: 1.6x10^{-6}


Planck-Institut für Festkörperforschung

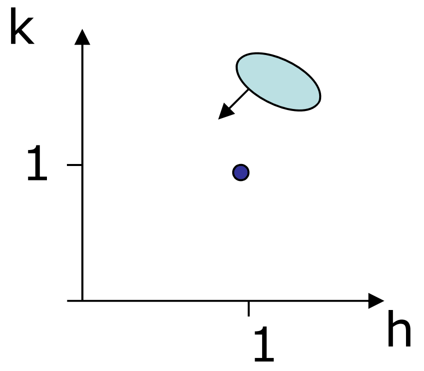


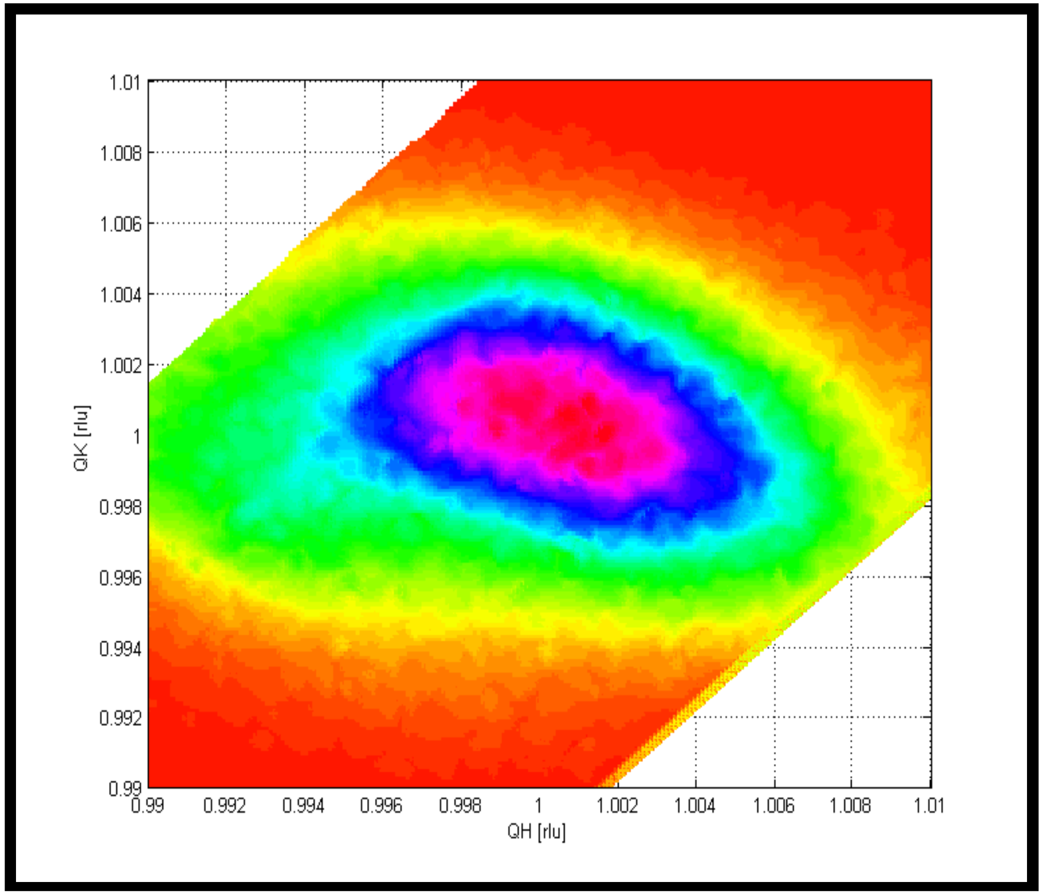
resolution ellipsoid

MAX-PLANCK-GESELLSCHAFT

(110) Bragg reflection
Larmor diffraction (MnF_2)

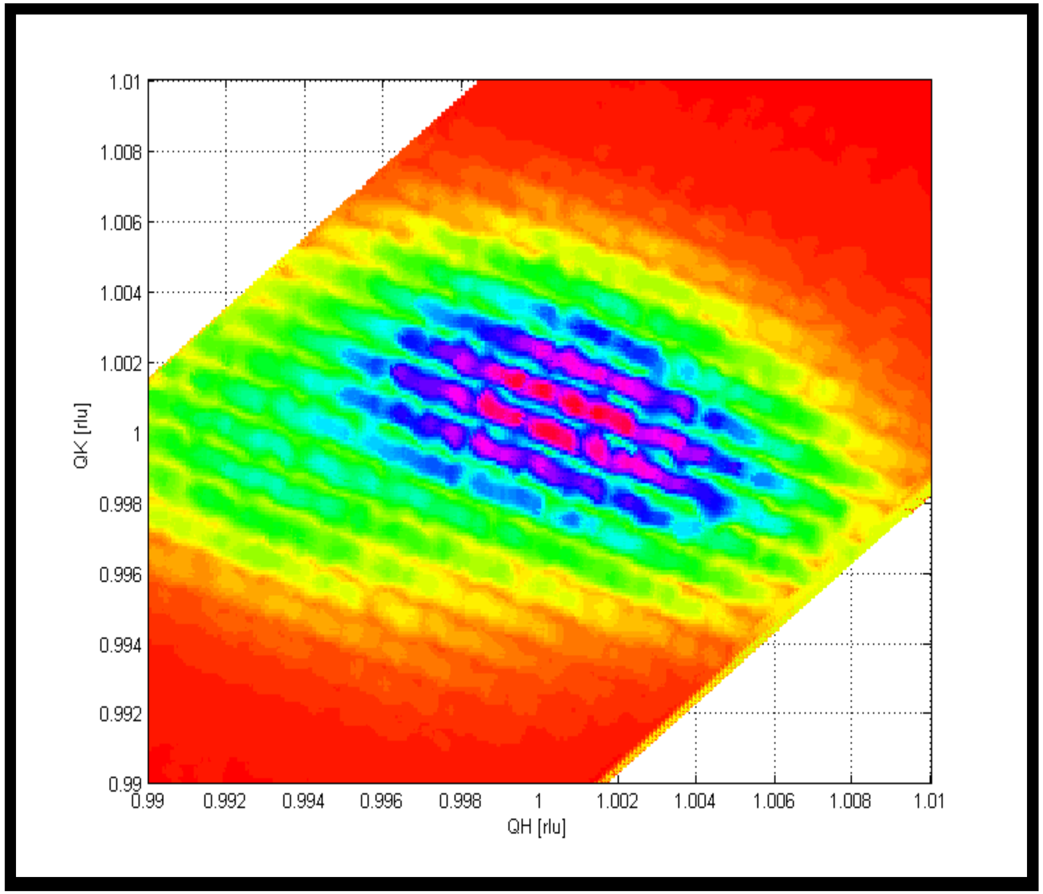
TAS only
NRSE off



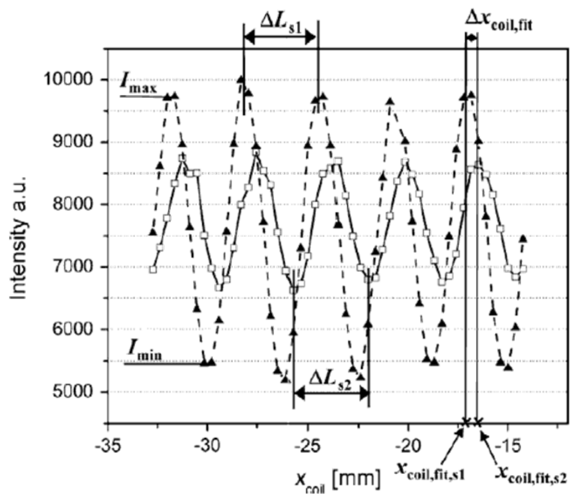


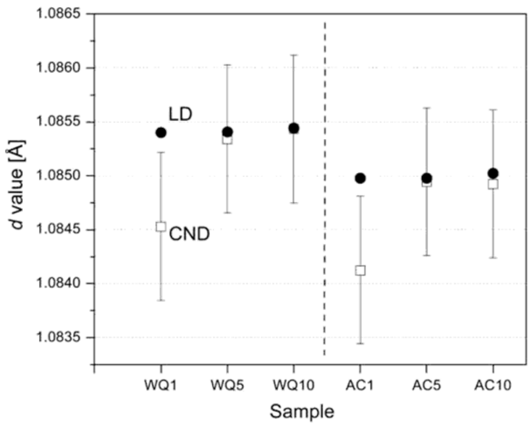
lines of constant Larmor phase

TAS +
NRSE on



materials science: Inconel 718 strain

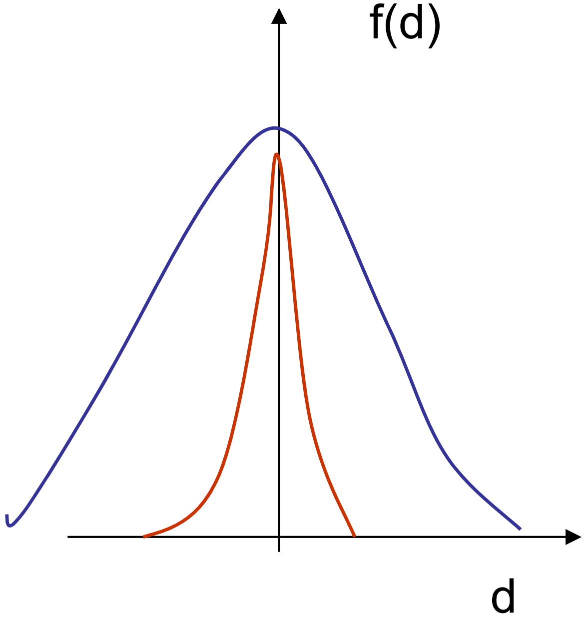


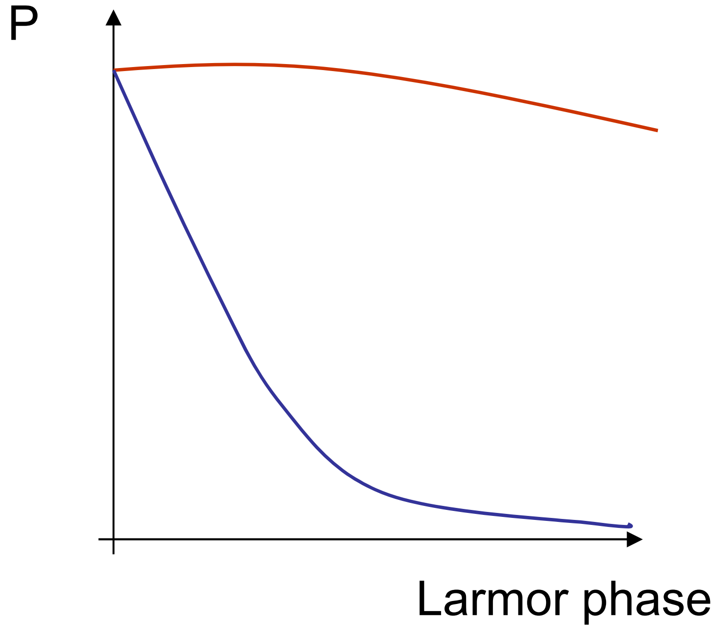


- absolute d
- distributions of d

J. Repper, Acta Materialia 58, 3459 (2010)

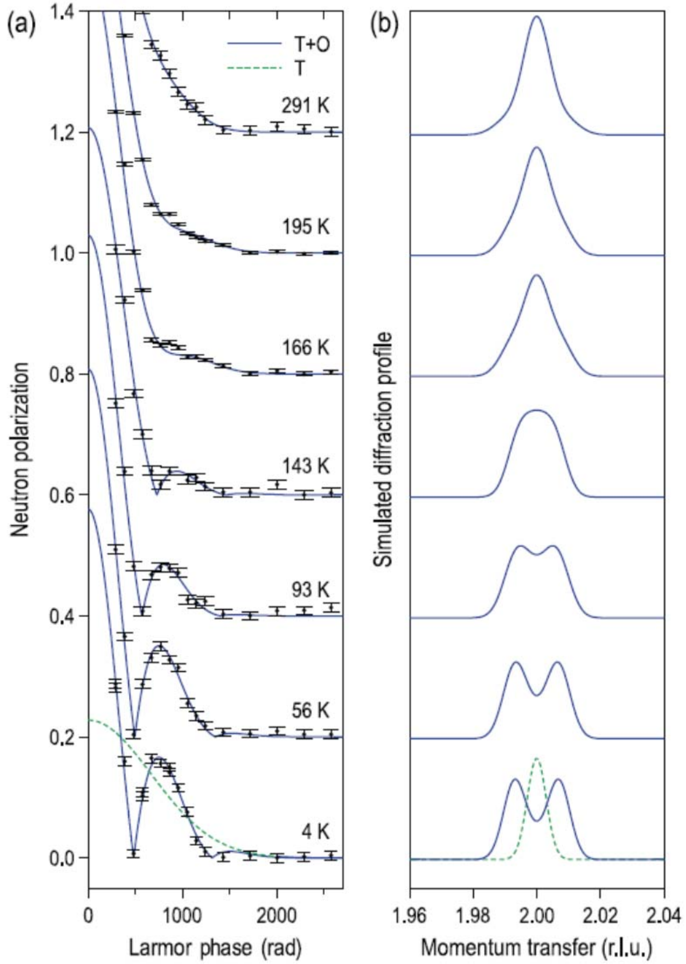
spread of d



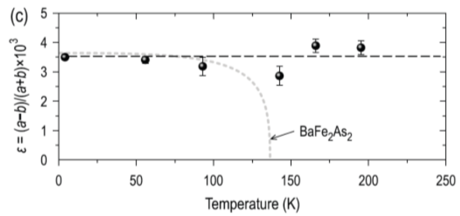


$$P(\Phi) = \int f(d)\cos(d\cdot\Phi)dd$$

peak splitting

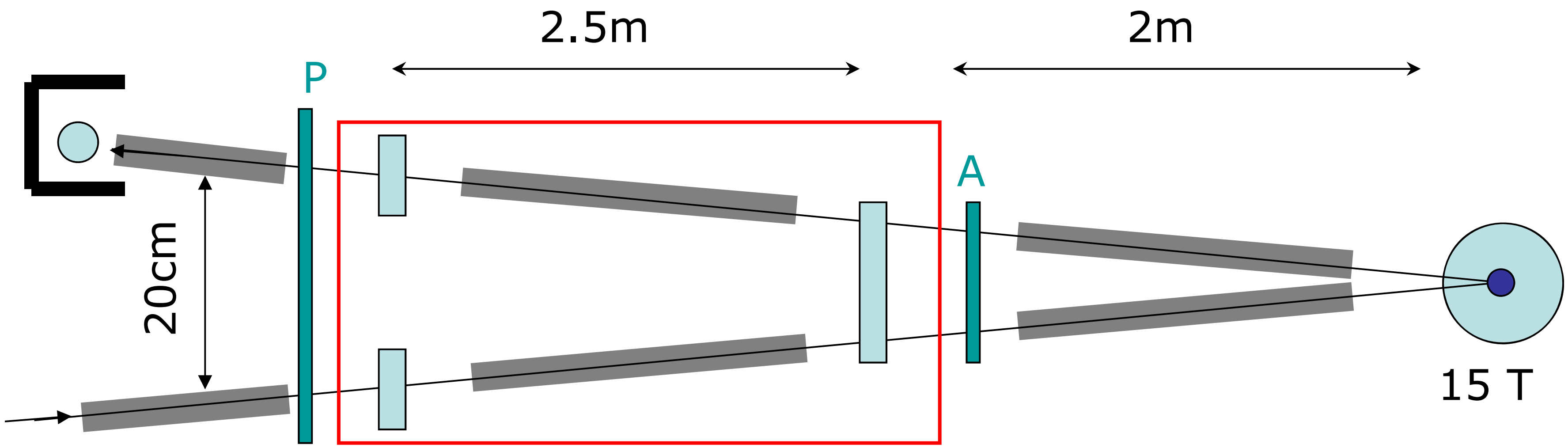


Ba(Fe$_{1-x}$Mn$_x$)As$_2$ (12%)
tetragonal -> orthorombic
(coexistance)



Inosov, Walters, Park et al., PRB **87**, 224425 (2013)

future : a dedicated Larmor diffractometer ?



Gähler: backscattering geometry + Mezei's 'ferromagnetic SE':

- divergent beam (neutron guides and focusing elements)
- compact design
- maximum resolution 10^{-7}

further reading

<u>NSE</u>:

F. Mezei *Neutron spin-echo: new concept in polarized thermal-neutron techniques*, Z. Phys. 255, 146 (1972).

F. Mezei ed., *Neutron Spin Echo*, Lecture notes on physics, Lecture Notes on Physics, Springer Berlin, 1980. (http://dx.doi.org/10.1007/3-540-10004-0)
very good introduction to NSE in this book:
O. Schärpf, *The polarized neutron technique of neutron spin echo*, p. 27.

newer book:
F. Mezei, C. Pappas, T. Gutberlet eds., *Neutron spin echo spectroscopy*, Lecture Notes in Physics 601, Springer 2003.

I. I. Rabi, N. F. Ramsey, J. Schwinger, *Use of Rotating Coordinates in Magnetic Resonance Problems* Rev. Mod. Phys. 26, 167 (1954)

NRSE:
R. Golub, R. Gähler, *A neutron resonance spin echo spectrometer for quasi-elastic and inelastic scattering*, Phys. Lett. A 123, 43 (1987).

R. Gähler, R. Golub, *Neutron resonance spin echo bootstrap method for increasing the effective field,* J. Phys. France 49, 1195 (1988).

Larmor diffraction:
M.T. Rekveldt, T. Keller, R. Golub, *Larmor precession – a technique for high resolution neutron diffraction,* Europhys. Lett. 54, 342 (2001).