Diffraction enhanced experiments for Particle Physics

Michael Jentschel, Hartmut Lemmel, Valery Nesvizhevsky,

NEUTRONS
FOR SOCIETY

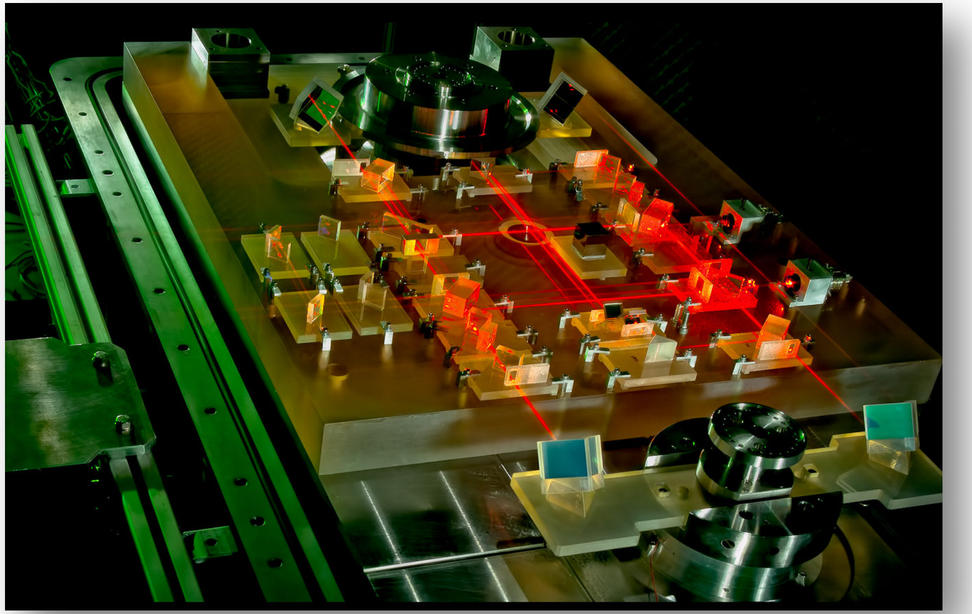
Why diffraction?

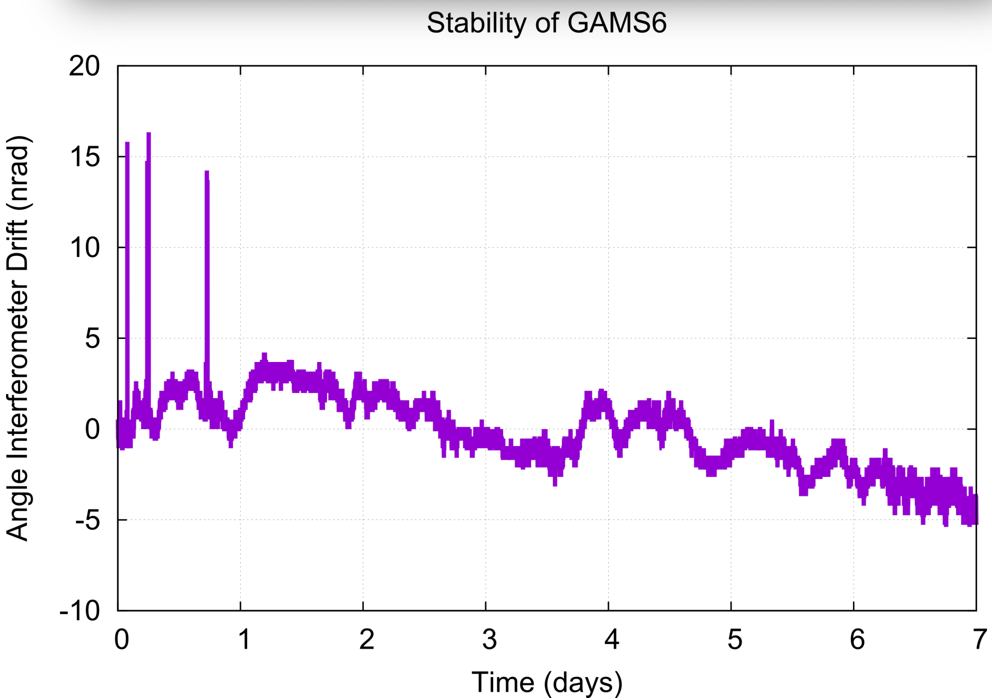
Perfect Crystal Diffraction:

Phase space filter

Sets up correlations

Beam optics





Why diffraction?

<u>Perfect Crystal Diffraction:</u>

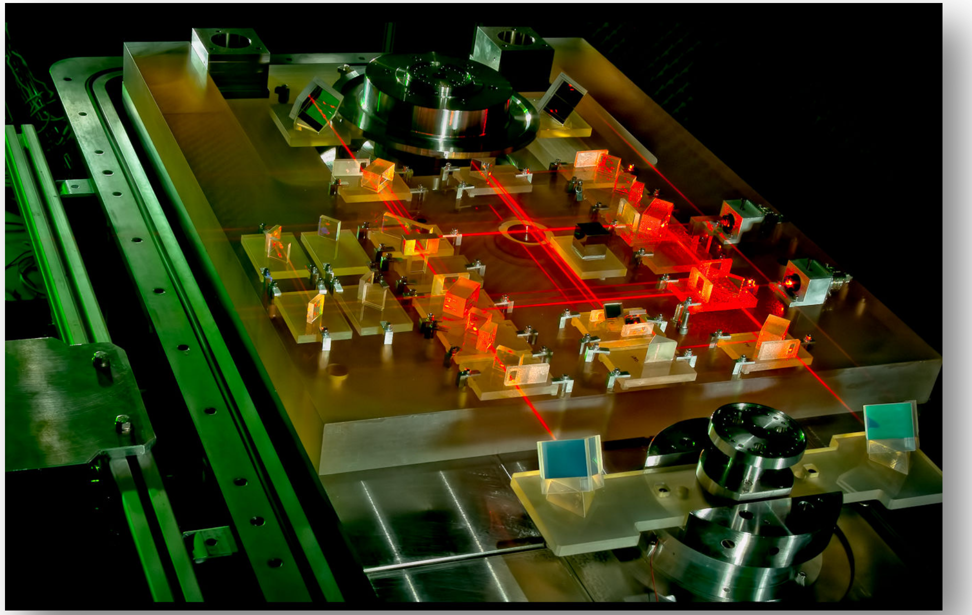
Phase space filter

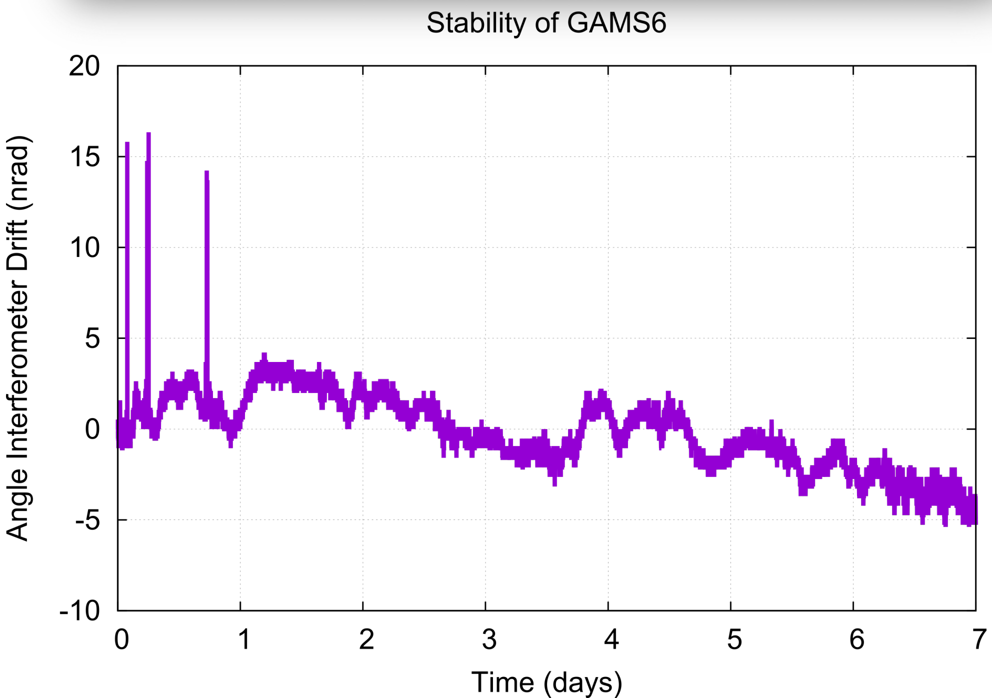
Sets up correlations

Beam optics

<u>Outline:</u>

- Diffraction of perfect crystals
- Towards a split crystal interferometer
- Diffraction enhanced measurements

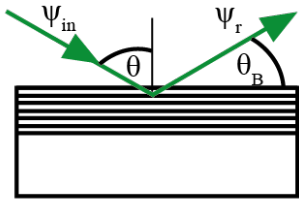


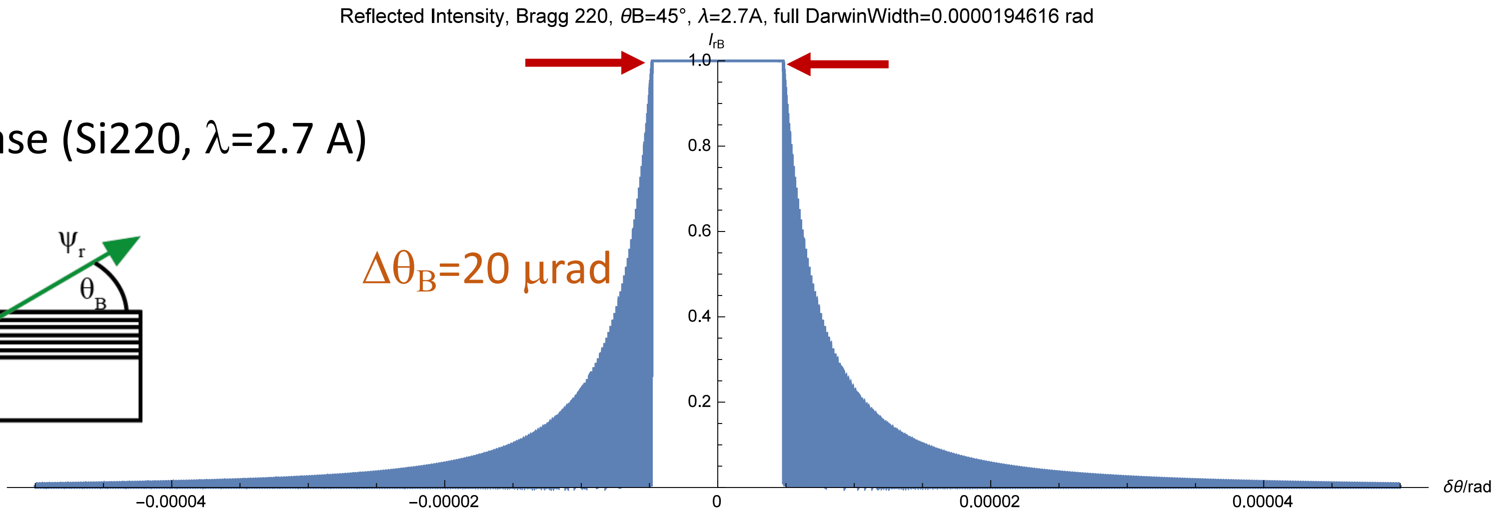


Dynamical diffraction theory

Bragg case (Si220, λ=2.7 A)

Bragg:

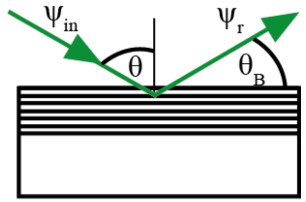


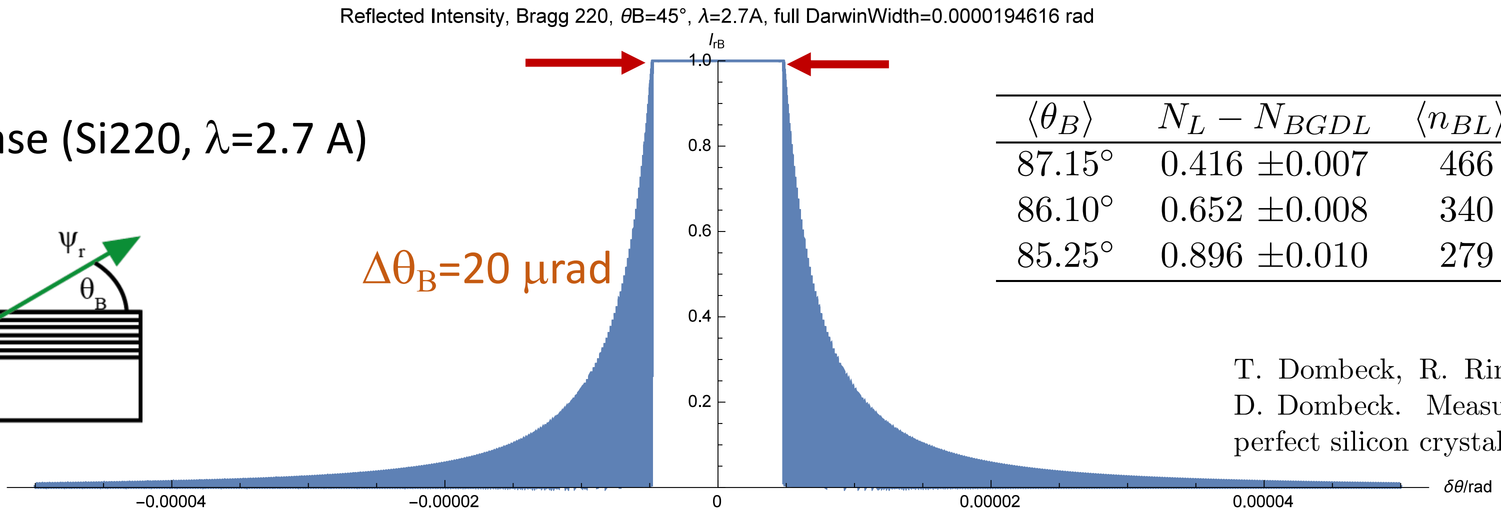


Dynamical diffraction theory

Bragg case (Si220, λ=2.7 A)

Bragg:





$\langle\theta_B\rangle$	$N_L - N_{BGDL}$	$\langle n_{BL}\rangle$	$N_S - N_{BGDS}$	$\langle N_{BS}\rangle$	R	δR
87.15°	0.416 ±0.007	466	0.420±0.007	116	0.999973	±0.000070
86.10°	0.652 ±0.008	340	0.656±0.008	85	0.999976	±0.000070
85.25°	0.896 ±0.010	279	0.900±0.012	70	0.999979	±0.000085

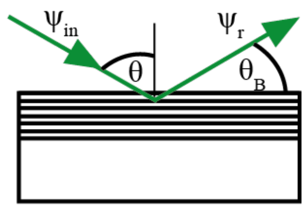
λ=1.92 A

T. Dombeck, R. Ringo, D.D. Koetke, H. Kaiser, K. Schoen, S.A. Werner, and D. Dombeck. Measurement of the neutron reflectivity for bragg reflections off a perfect silicon crystal. *Physical Review A*, 64(053607), 2001.

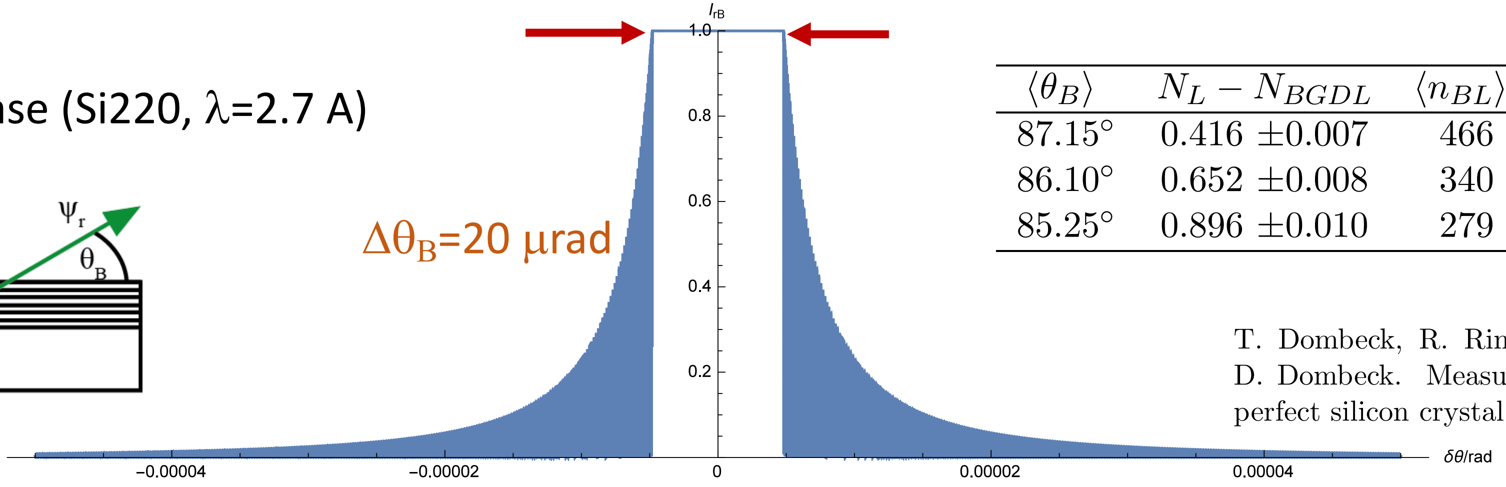
Dynamical diffraction theory

Bragg case (Si220, λ=2.7 A)

Bragg:



Reflected Intensity, Bragg 220, θB=45°, λ=2.7A, full DarwinWidth=0.0000194616 rad



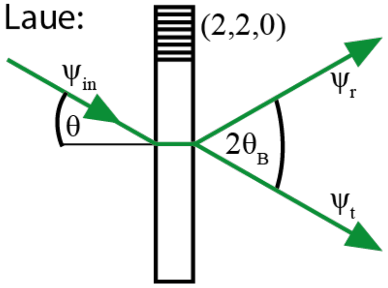
$\langle\theta_B\rangle$	$N_L - N_{BGDL}$	$\langle n_{BL}\rangle$	$N_S - N_{BGDS}$	$\langle N_{BS}\rangle$	R	δR
87.15°	0.416 ±0.007	466	0.420±0.007	116	0.999973	±0.000070
86.10°	0.652 ±0.008	340	0.656±0.008	85	0.999976	±0.000070
85.25°	0.896 ±0.010	279	0.900±0.012	70	0.999979	±0.000085

λ=1.92 A

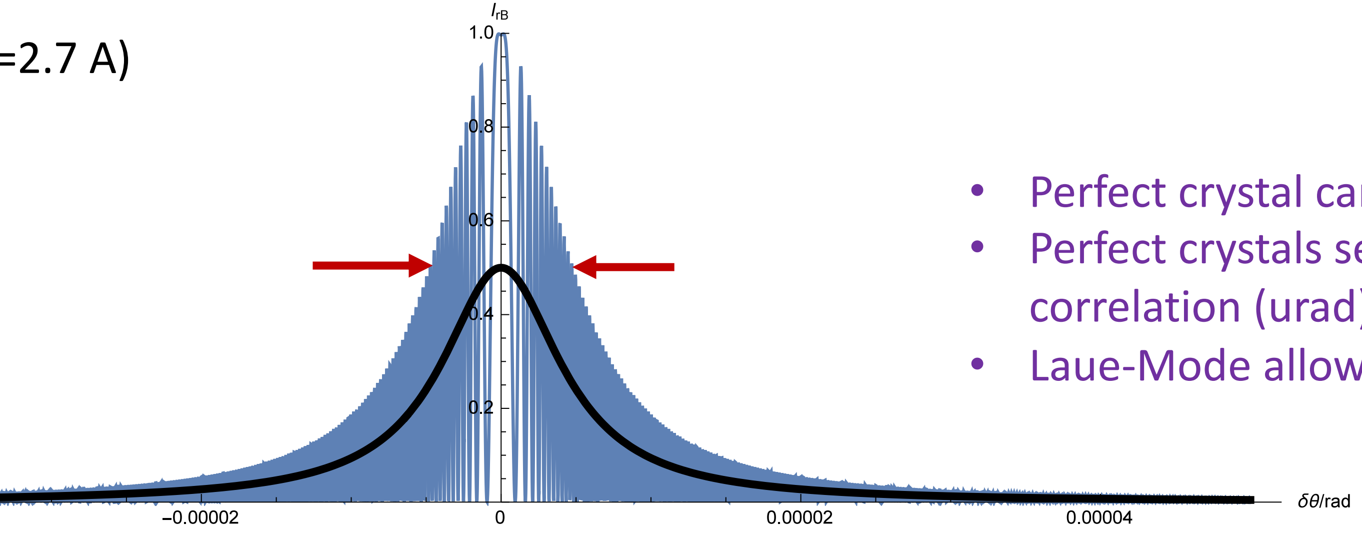
T. Dombeck, R. Ringo, D.D. Koetke, H. Kaiser, K. Schoen, S.A. Werner, and D. Dombeck. Measurement of the neutron reflectivity for bragg reflections off a perfect silicon crystal. *Physical Review A*, 64(053607), 2001.

Laue case (Si220, λ=2.7 A)

Laue:

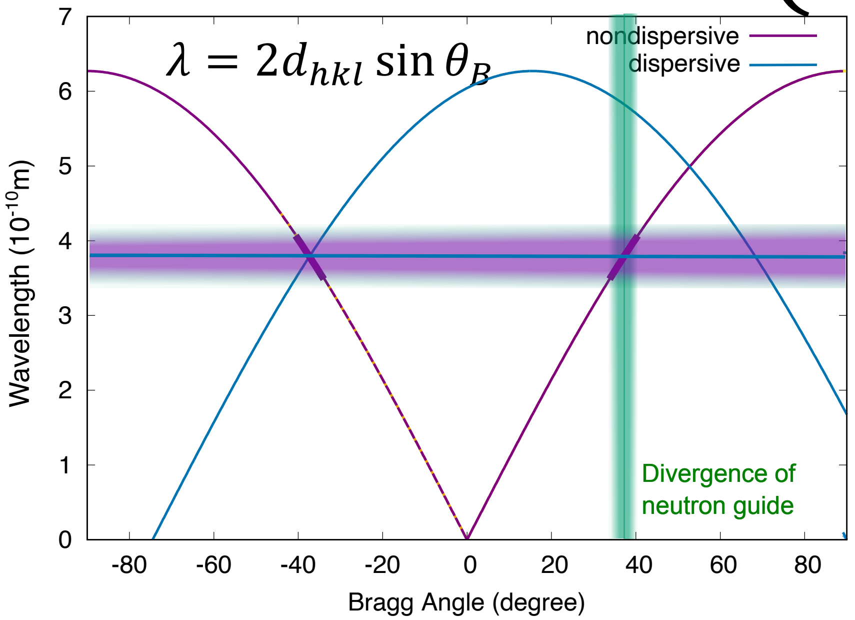


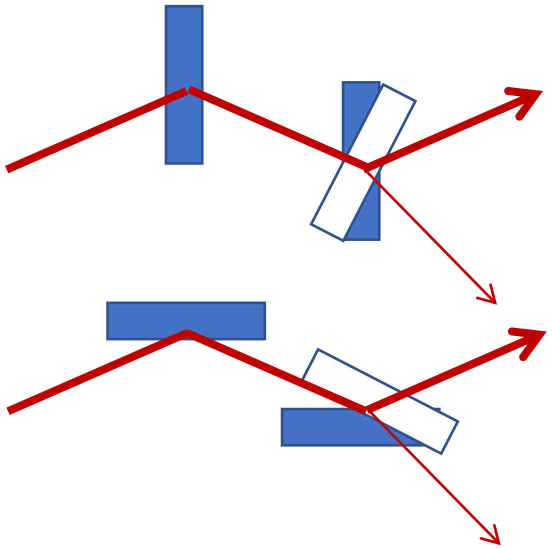
Reflected Intensity, Laue 220, θB=45°, λ=2.7A, full DarwinWidth=0.0000194616 rad



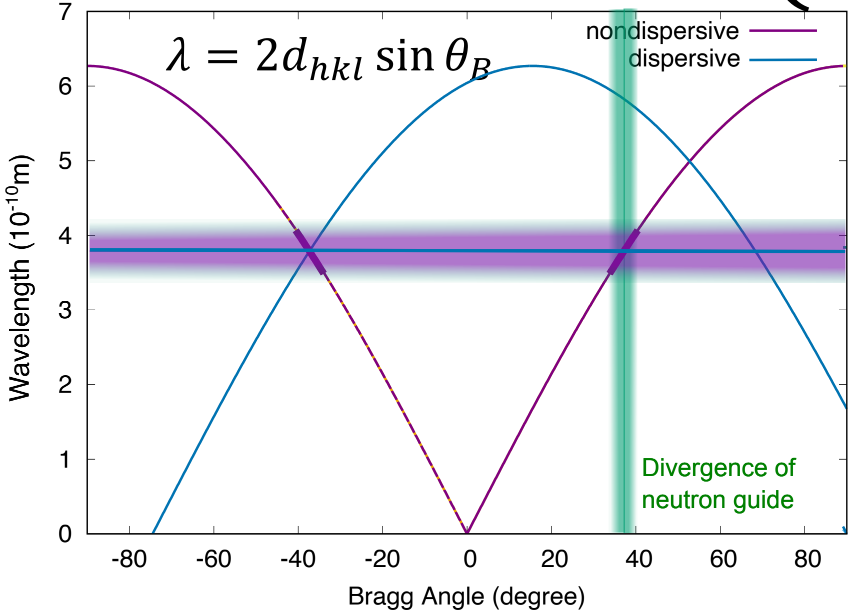
- Perfect crystal can achieve very high reflectivity
- Perfect crystals sets very sensitive angular correlation (urad)
- Laue-Mode allows 50% beam splitter

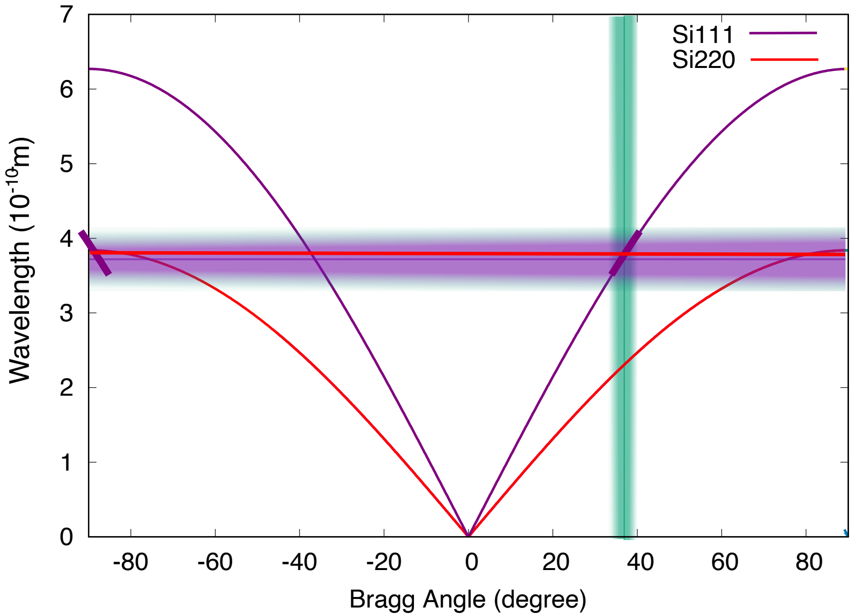
Correlations: $\lambda\,(\theta); \lambda\,(t)$

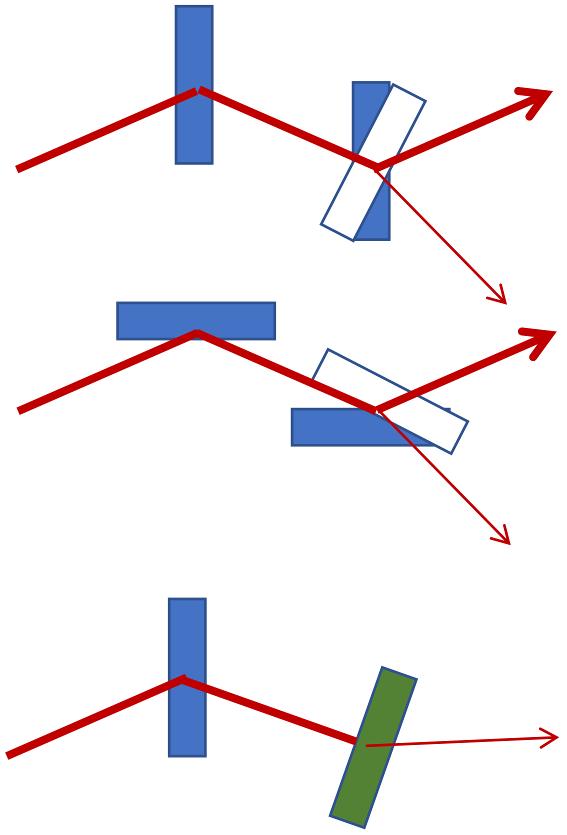




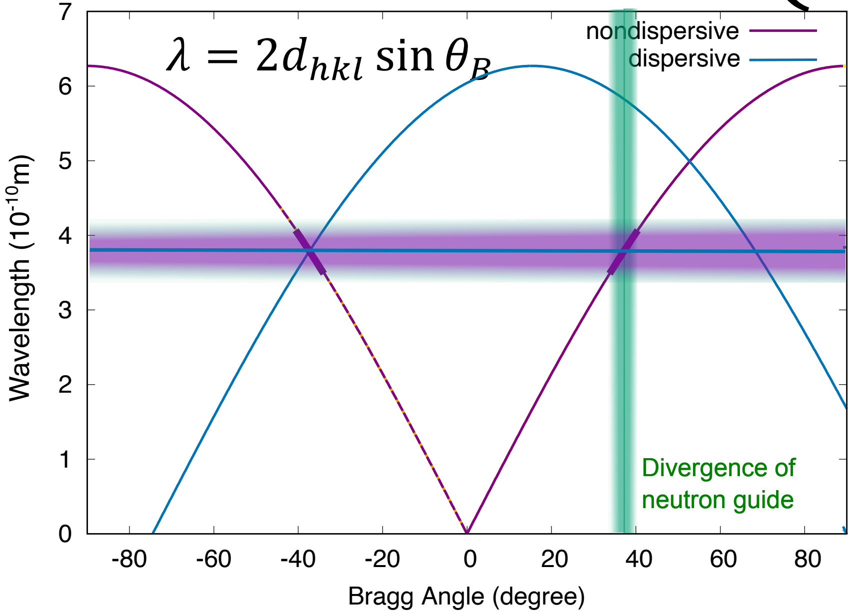
Correlations: $\lambda(\theta); \lambda(t)$

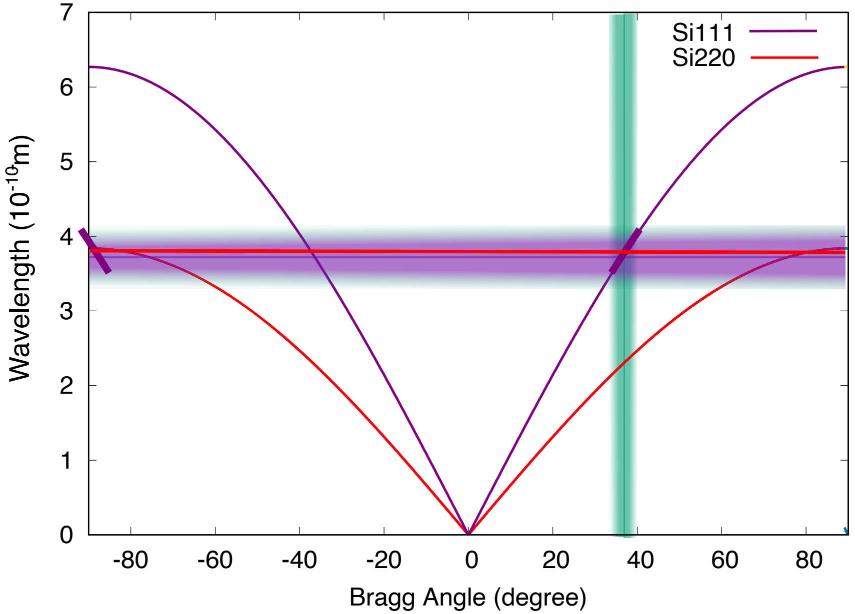


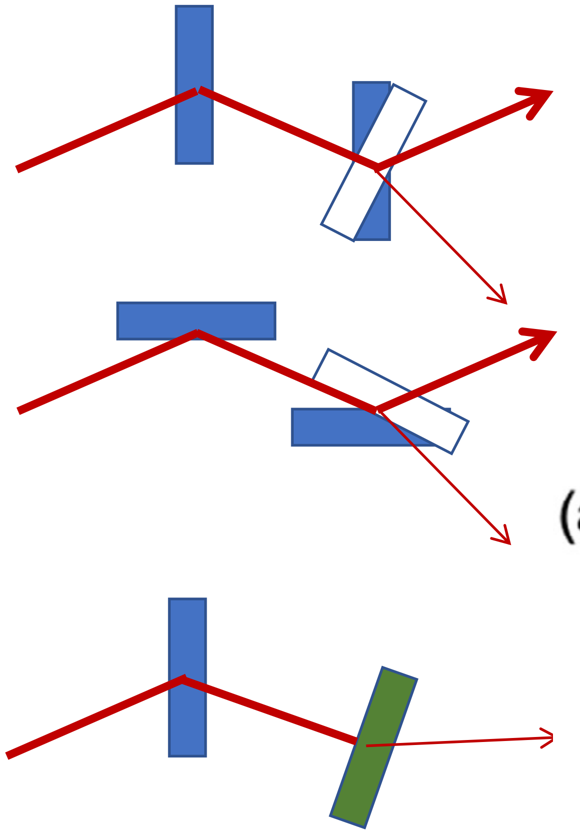




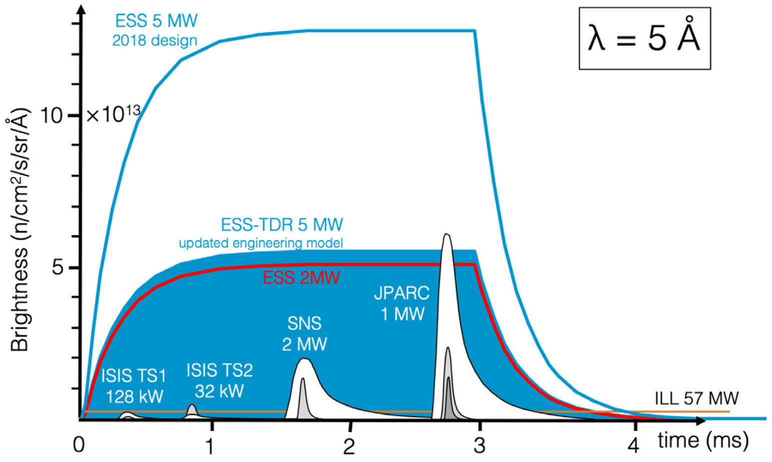
Correlations: $\lambda\,(\theta); \lambda\,(t)$



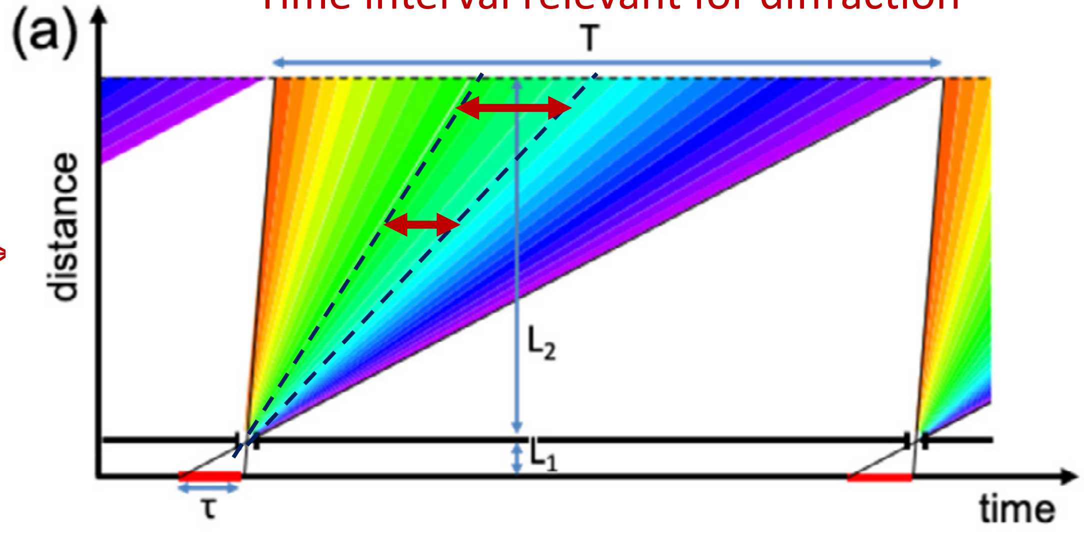




Time of flight: $\lambda\,(t) =$

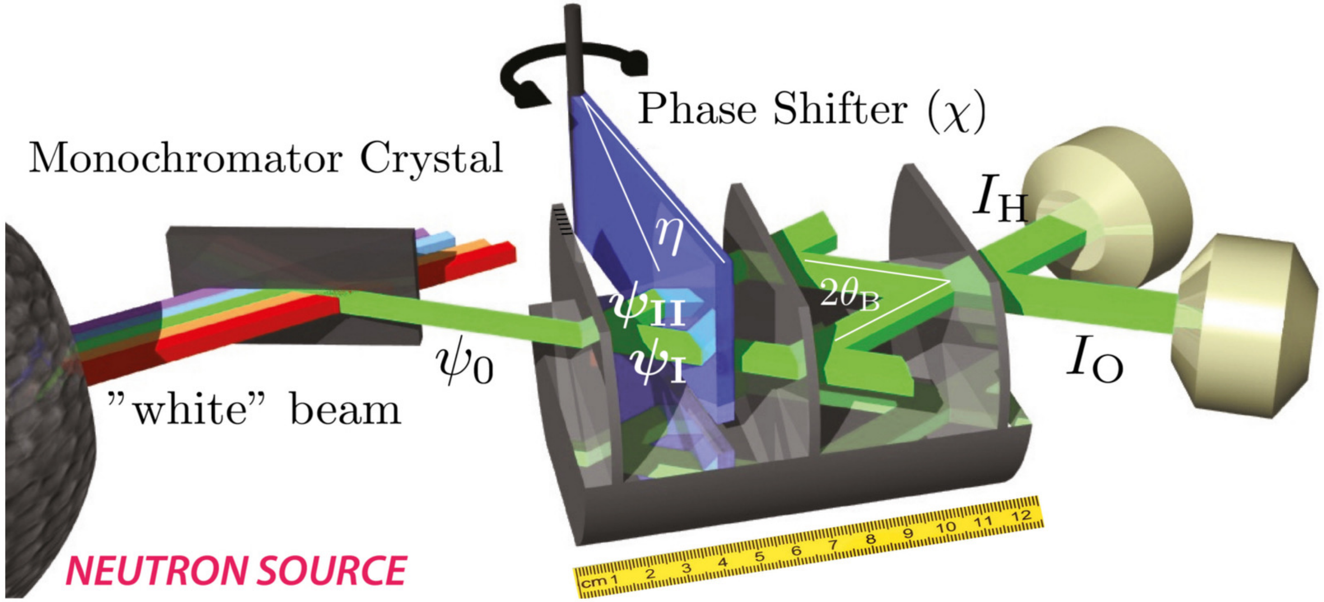


Time interval relevant for diffraction

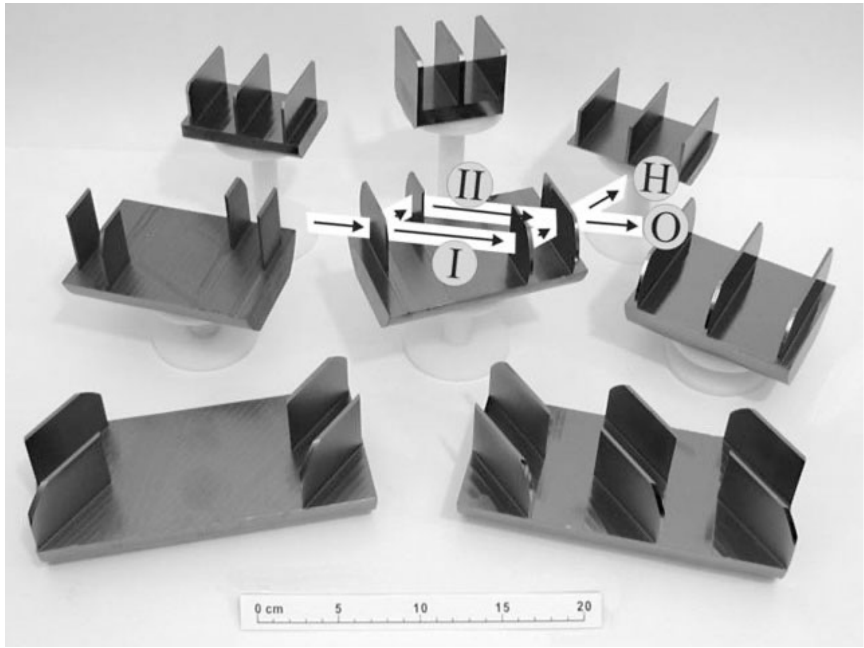


guide divergence ~ 10^{-3} rad, θ=45° T=T/785 (~ 10^{-6}s)

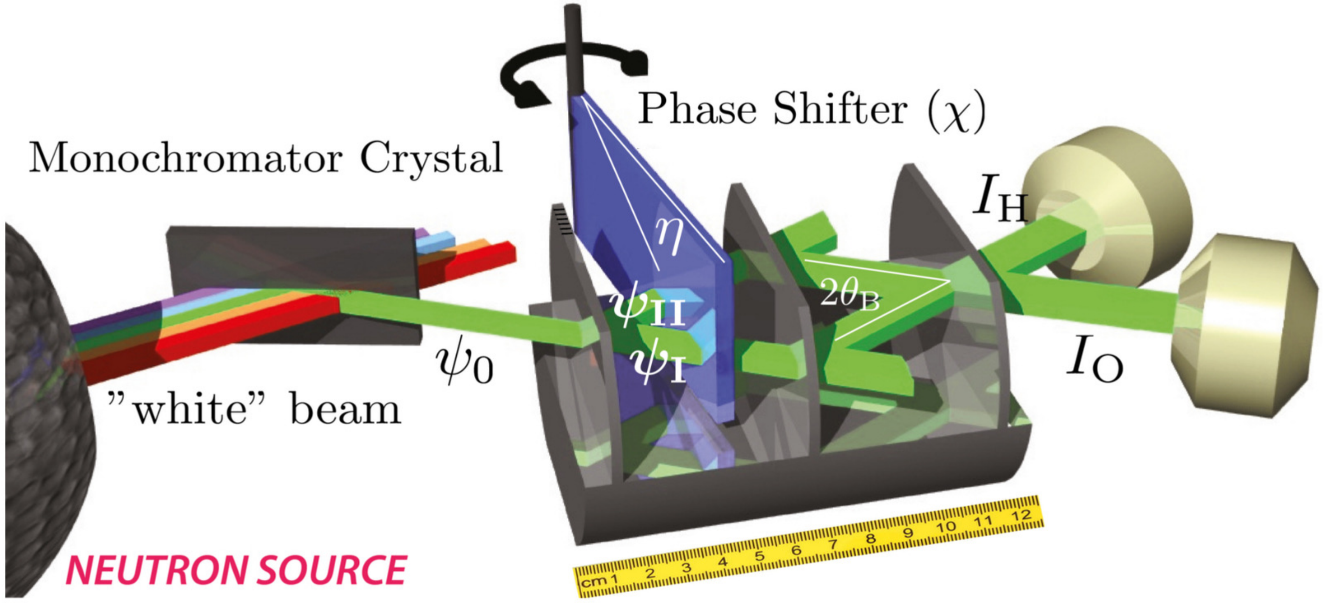
Thermal Neutron Interferometry



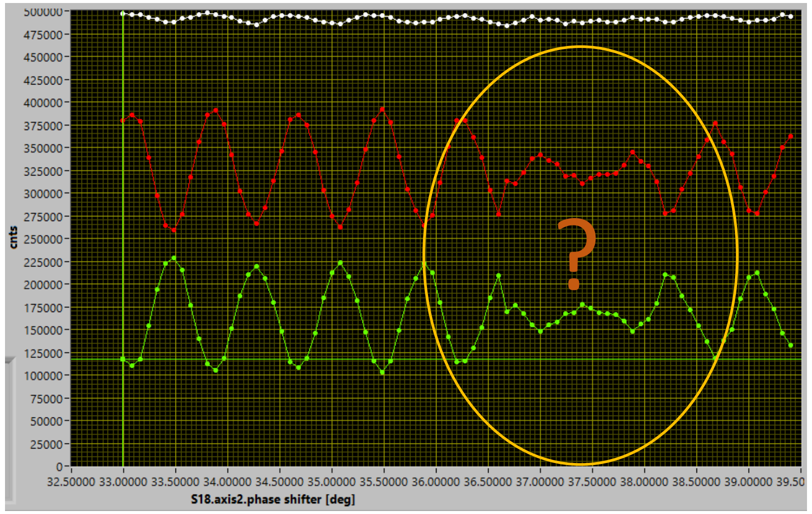
Monochromator: perfect single crystal Si220 in Bragg
Interferometer: solid Si block, Si220, non-dispersive geometry

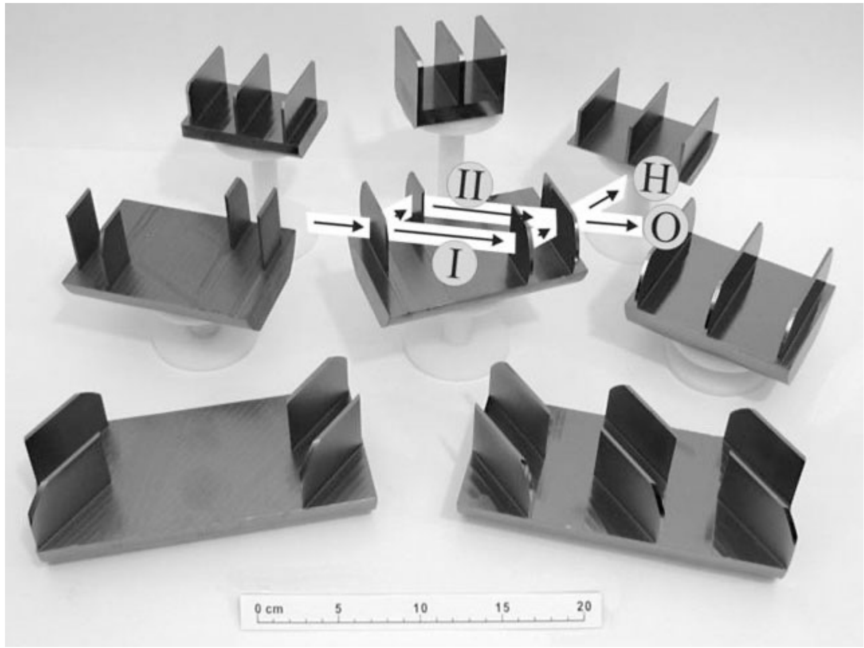


Thermal Neutron Interferometry



Monochromator: perfect single crystal Si220 in Bragg
Interferometer: solid Si block, Si220, non-dispersive geometry

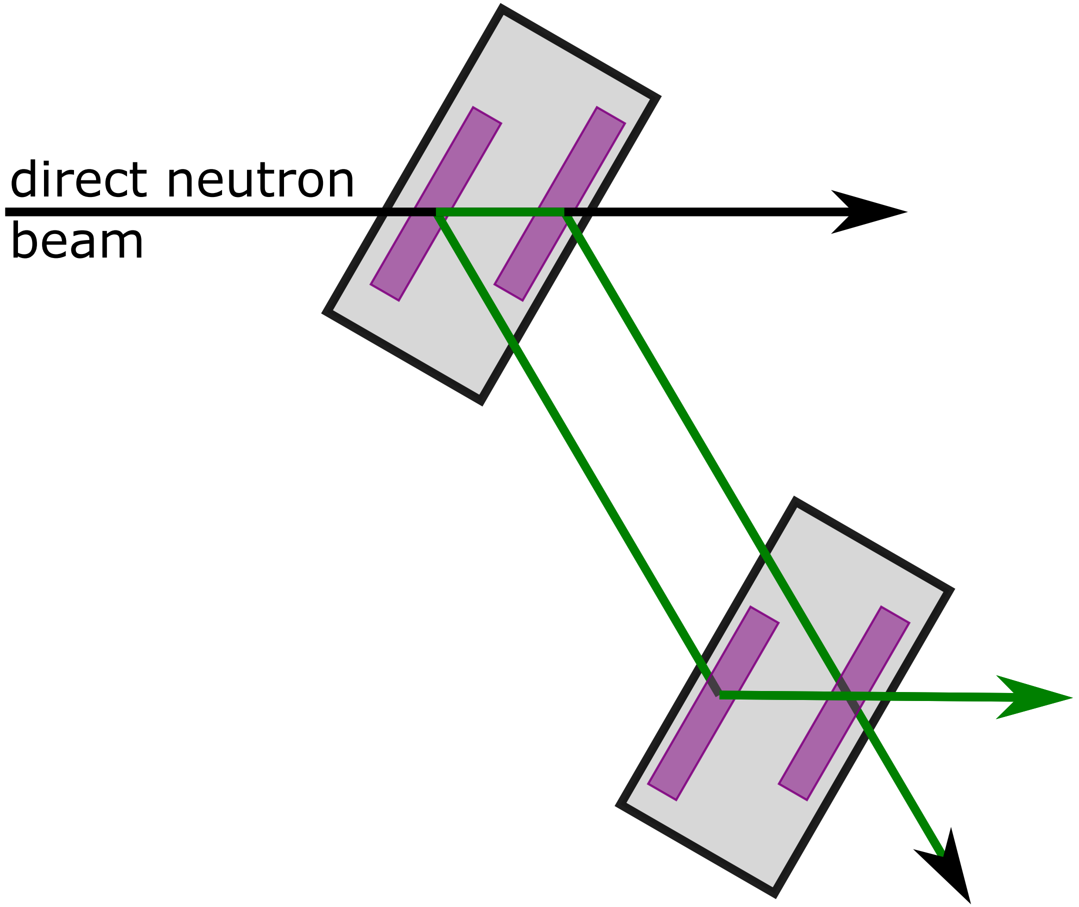


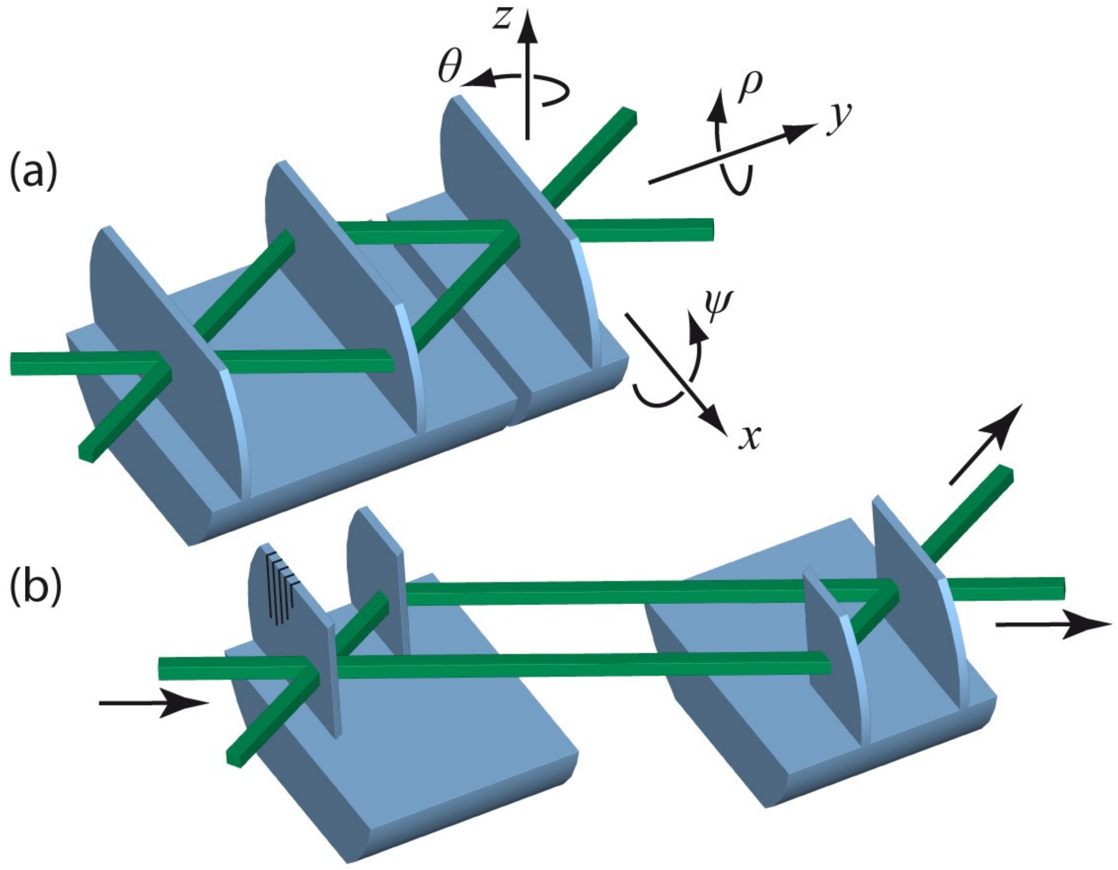


Main problem:

- limited size
  - limited sample
  - Limited sensitivity
- Sensitivity to environement
- limited flexibility

Idea of a split crystal interferometer



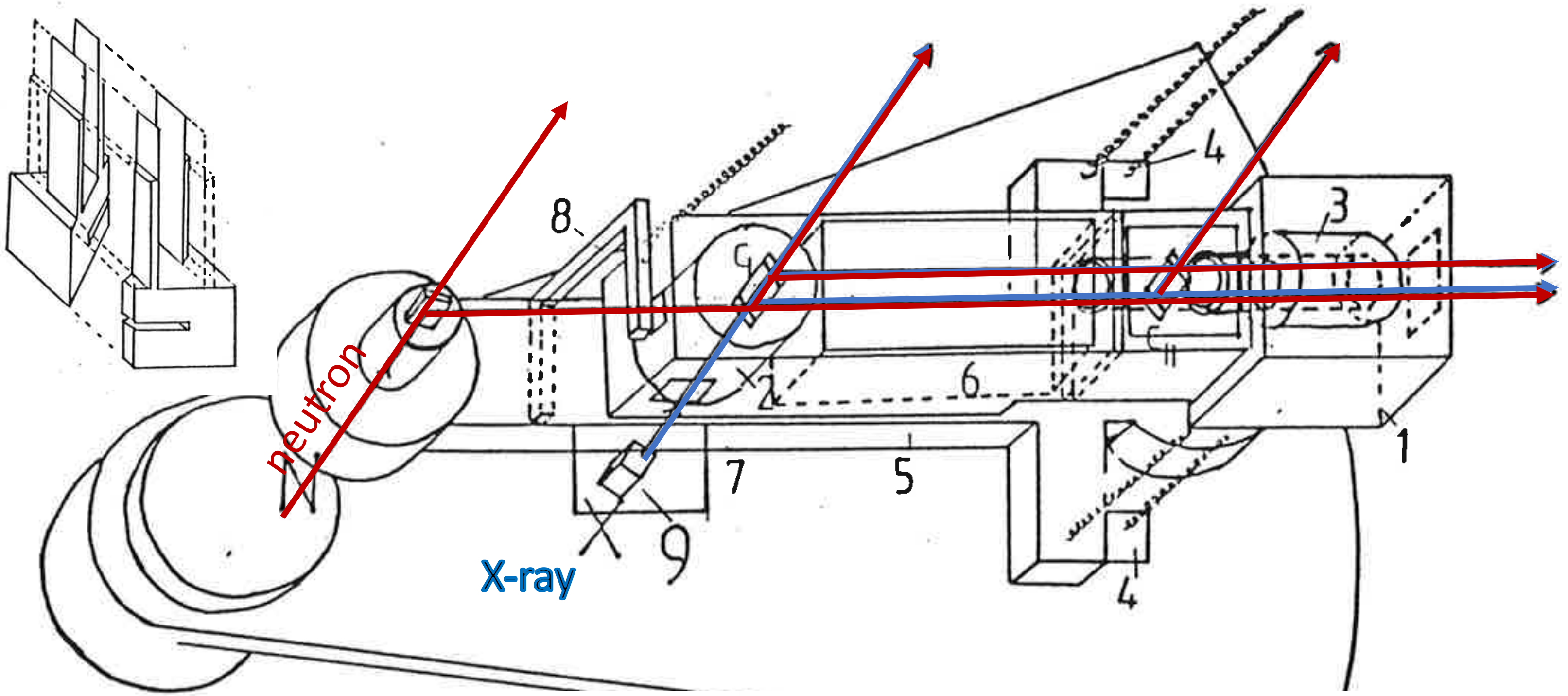


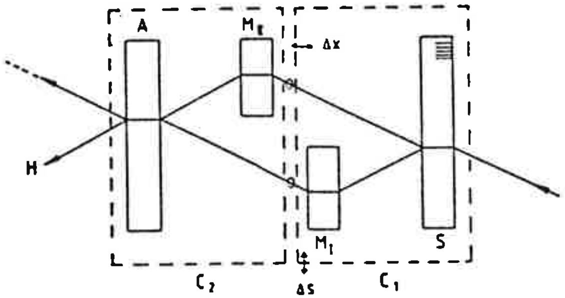
Attempt to build split crystal interferometer

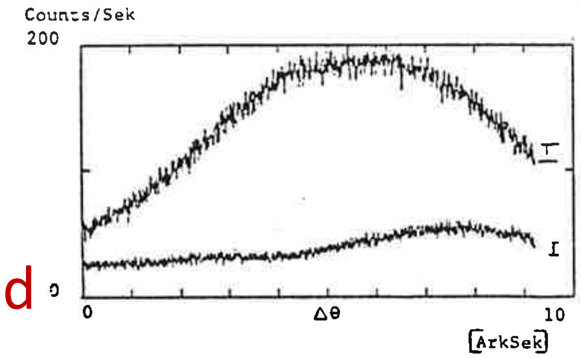
AUFBAU UND MESSUNGEN
MIT DEM
ZWEIKRISTALL-RÖNTGEN-NEUTRONEN-INTERFEROMETER

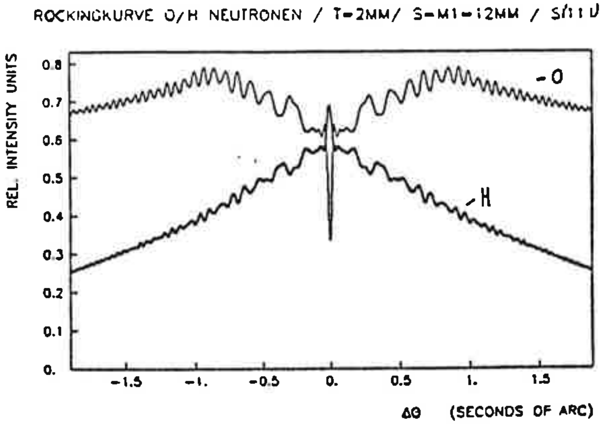
Dissertation
zur Erlangung des Doktorgrades
der Naturwissenschaften
der Abteilung Physik der Universität Dortmund

vorgelegt von
HUBERT UEBBING
1991





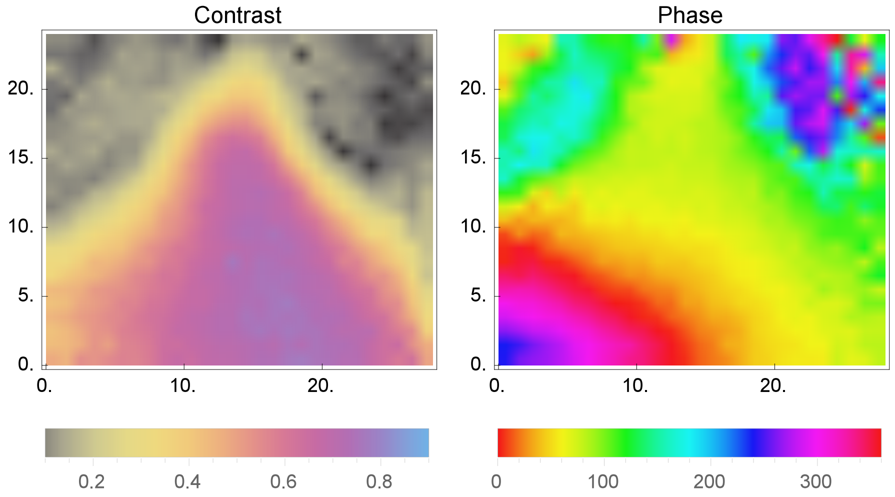


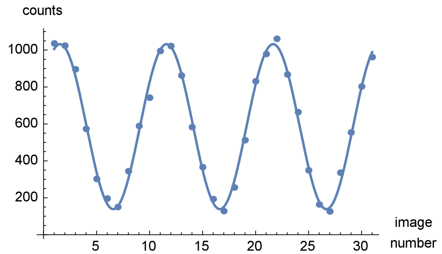


No interference was achieved -> Project stopped

Loss of coherence?

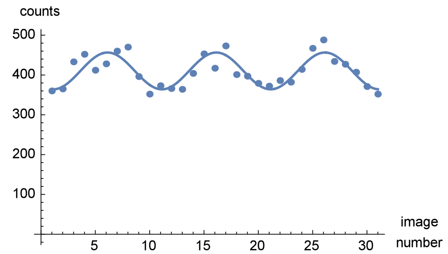
Spatial distribution of phase





x=16, y=3

contr=0.763348
offs=585.248
phase=34.462°
period=10.0527

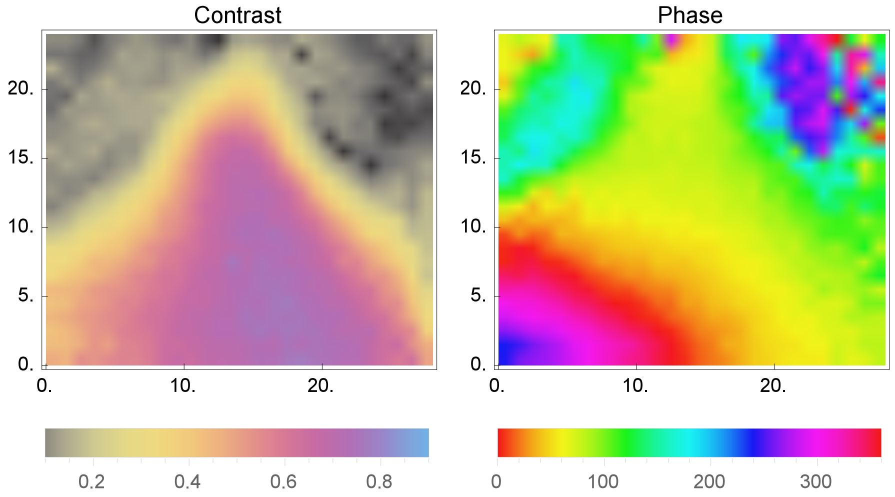


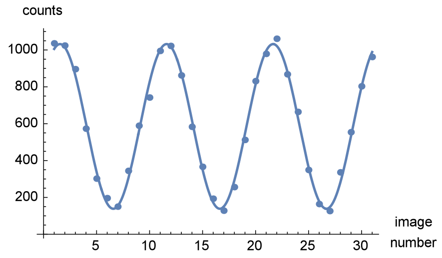
x=20, y=20

contr=0.112618
offs=410.212
phase=229.404°
period=10.0034

Loss of coherence?

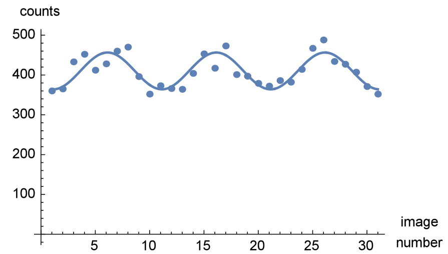
Spatial distribution of phase





x=16, y=3

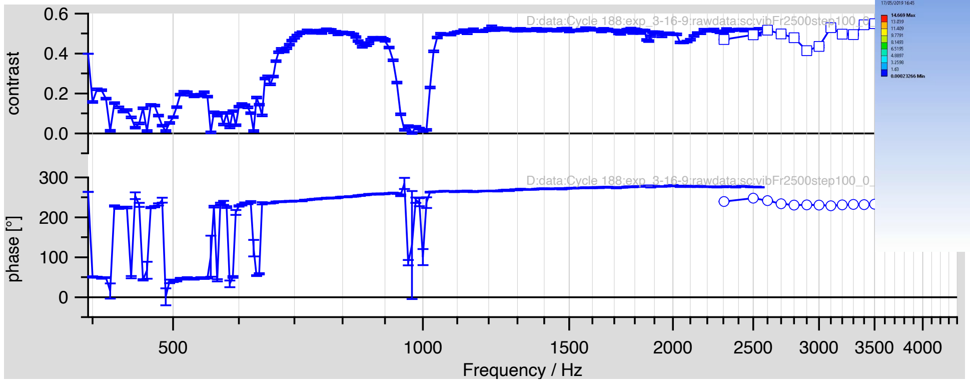
contr=0.763348
offs=585.248
phase=34.462°
period=10.0527

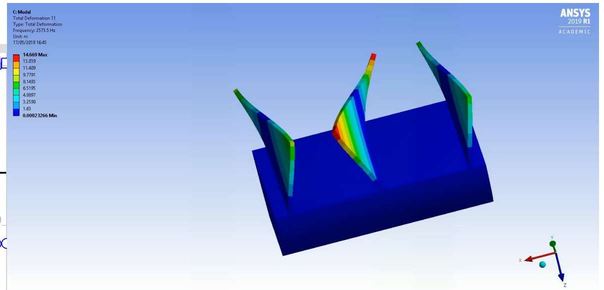


x=20, y=20

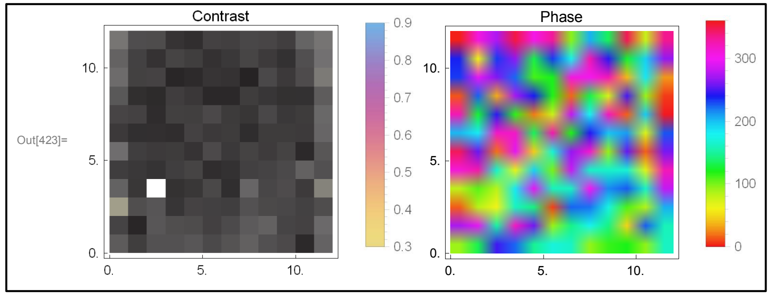
contr=0.112618
offs=410.212
phase=229.404°
period=10.0034

Temporal distribution of phase
(neutron is 1 x10^{-4} s within interferometer)

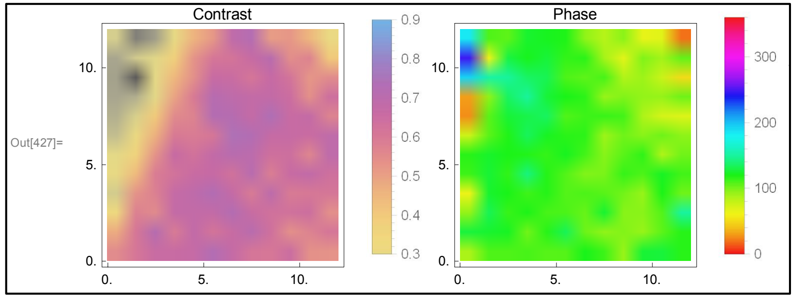


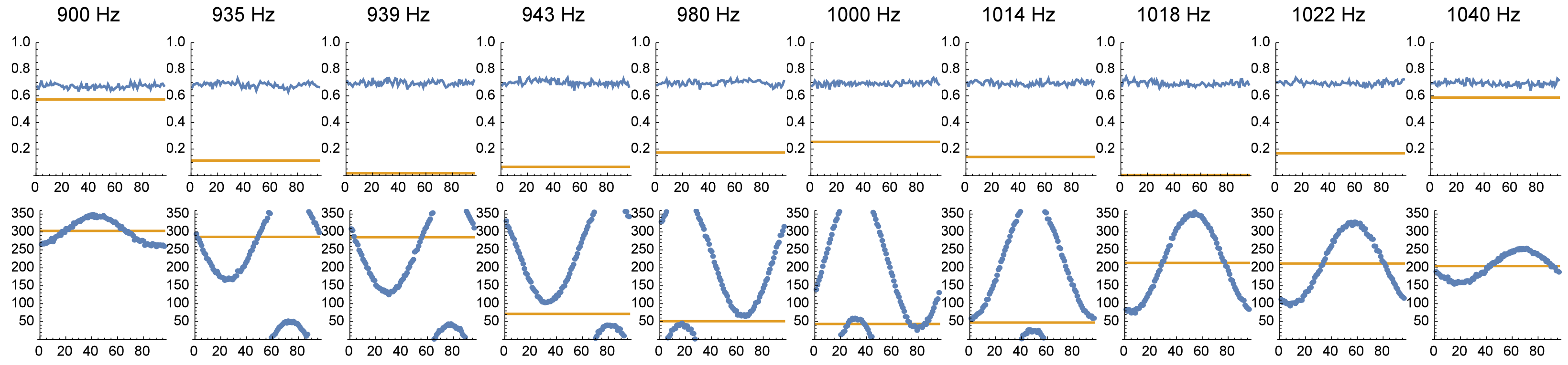


Phase/contrast time integrated



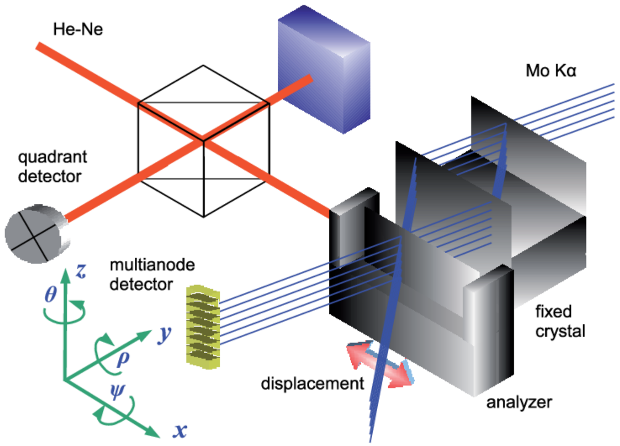
Phase/contrast time binned

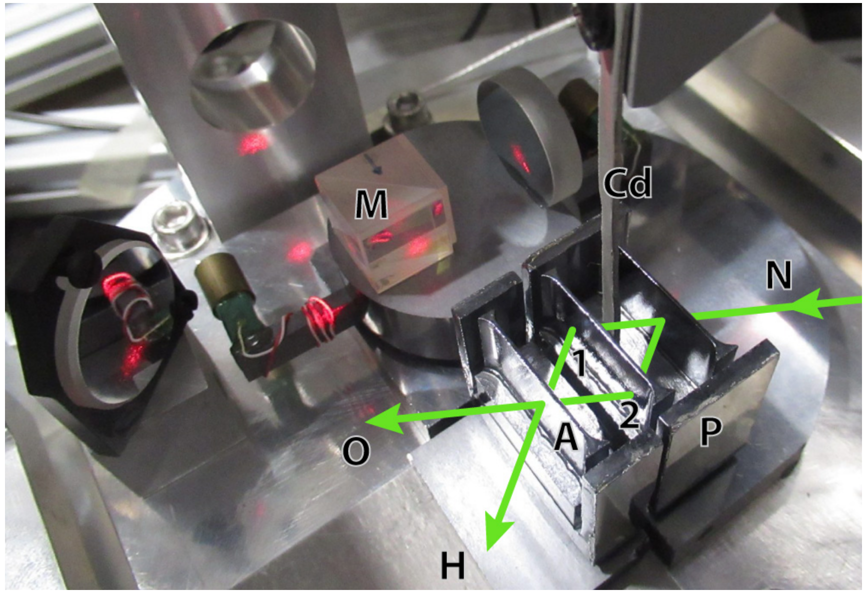


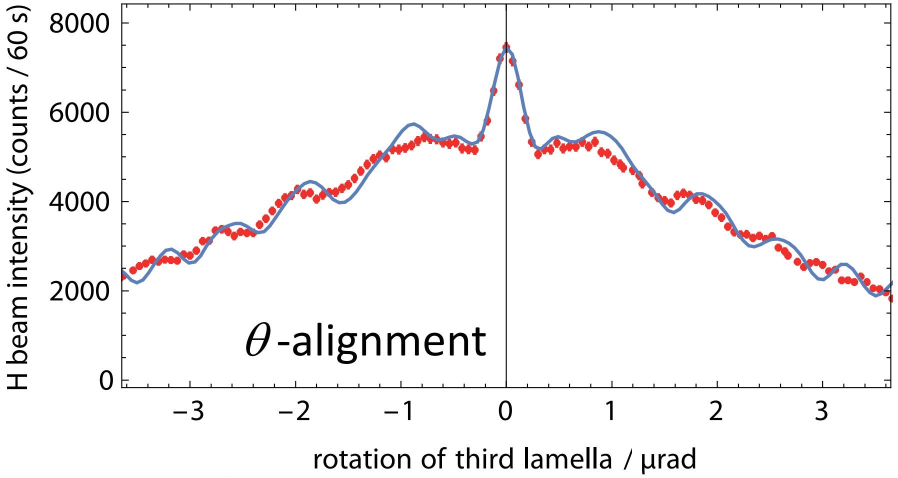


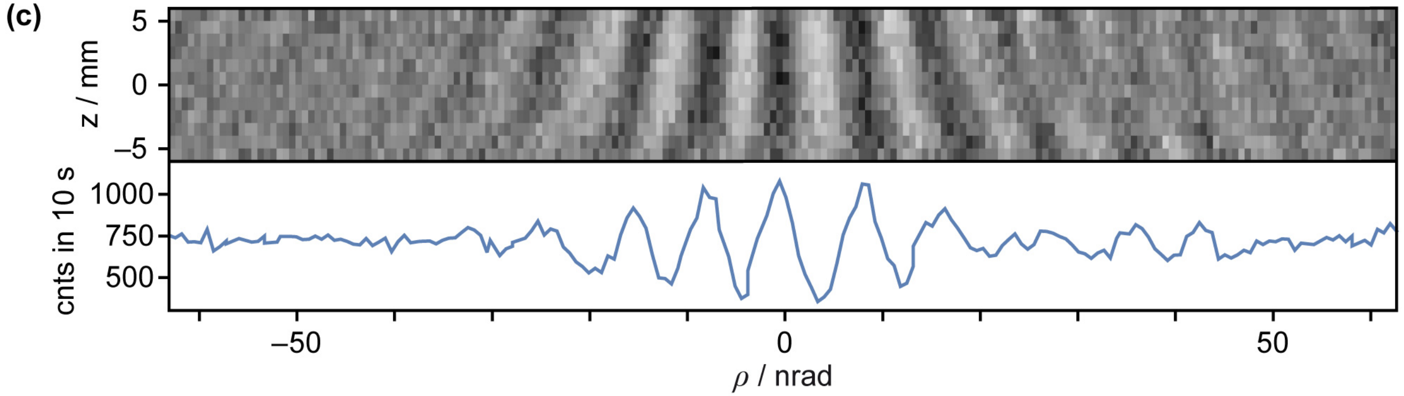
New attempt of a split crystal

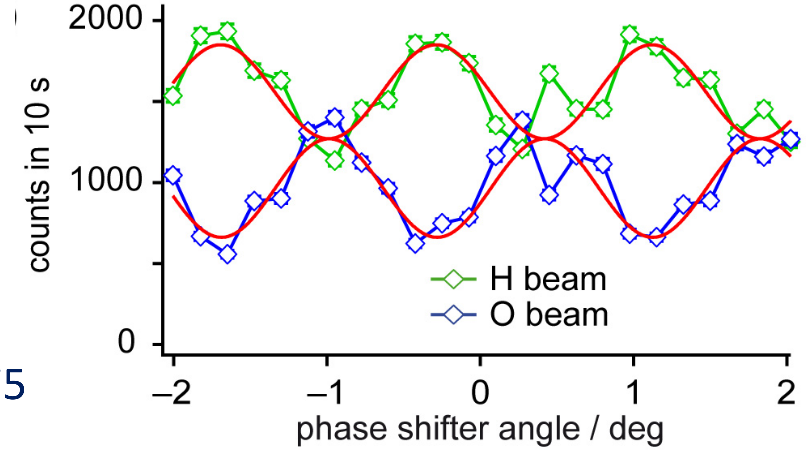
IOP Institute of Physics DEUTSCHE PHYSIK

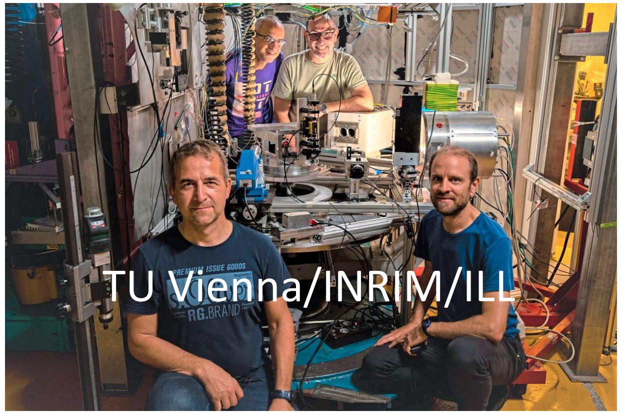






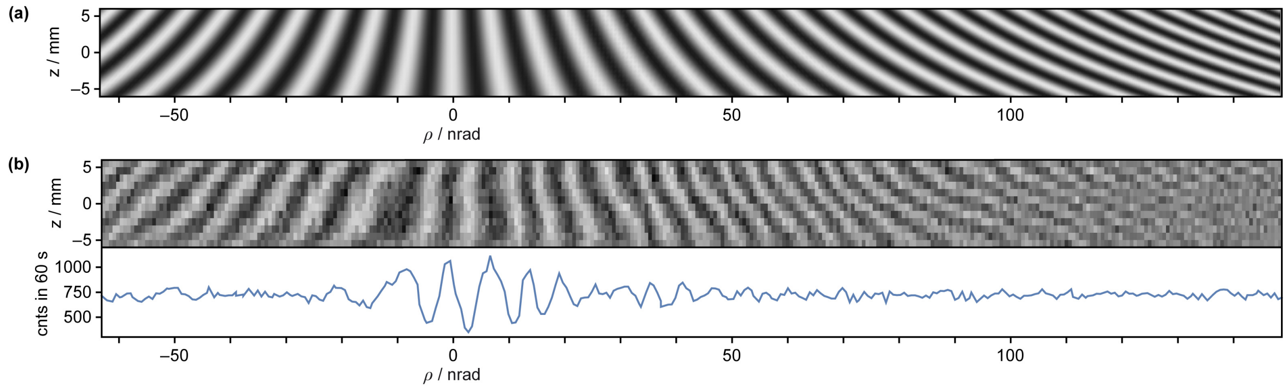




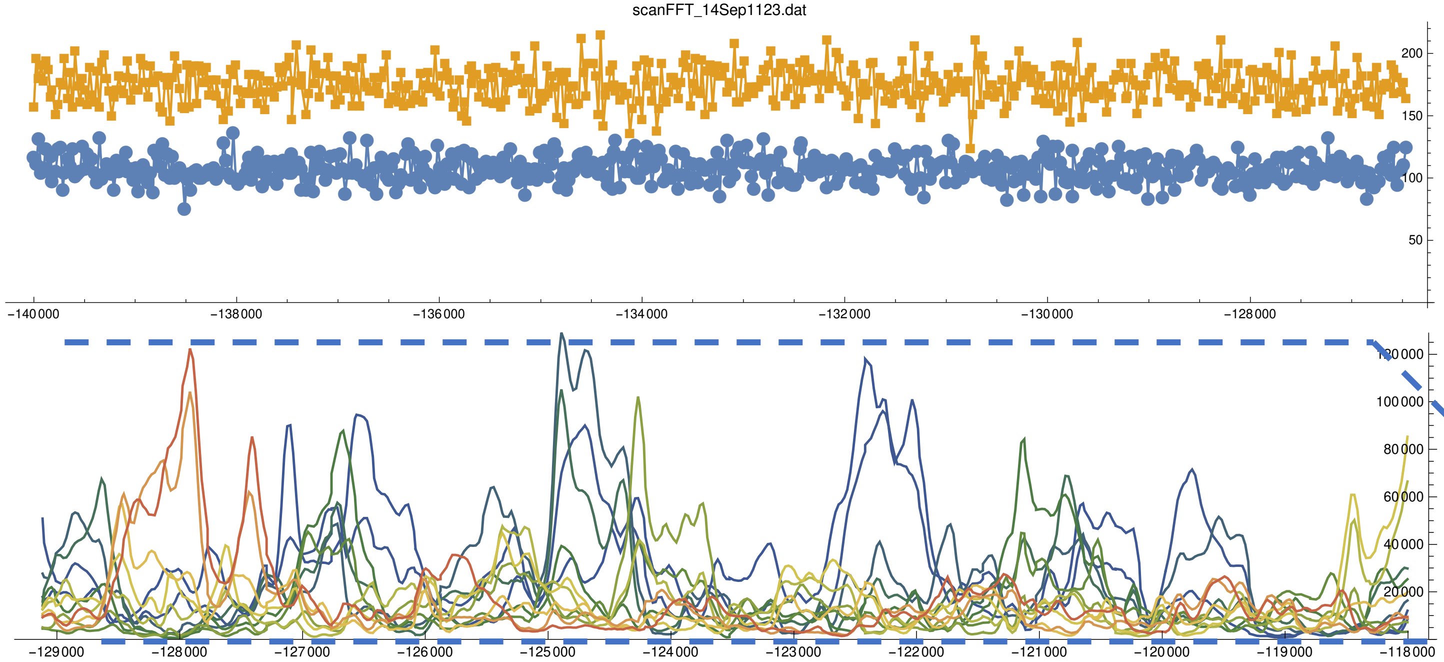


H. Lemmel et al., Journ. Appl. Cryst. 55 (2022) 870 -875

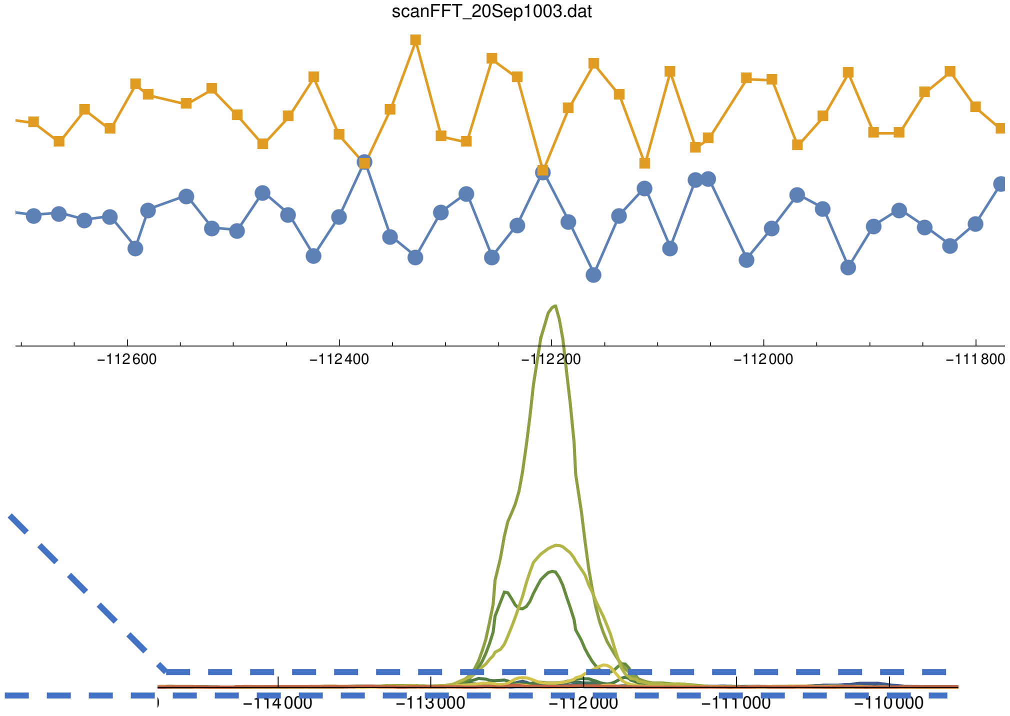
How to get to nrad with neutrons?



no coherence C(t) Poisson distributed -> noise in FFT

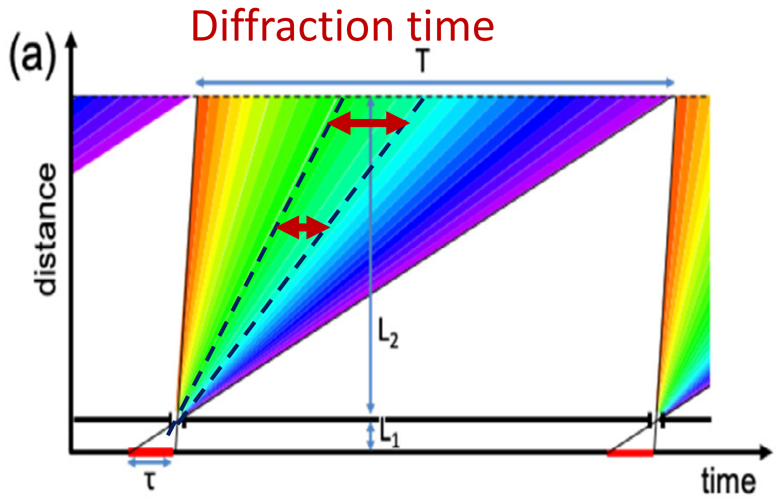


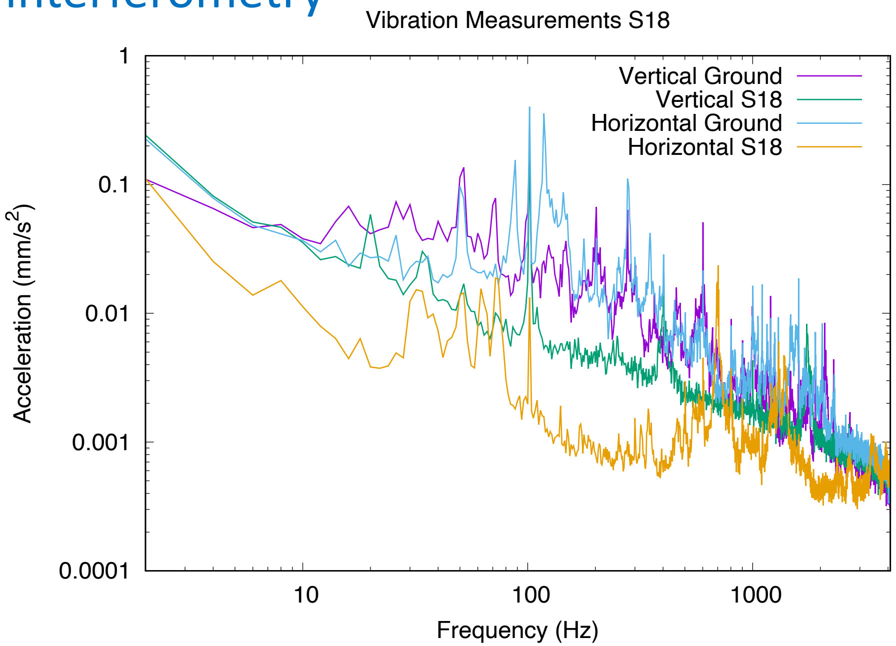
interference -> Peak in FFT

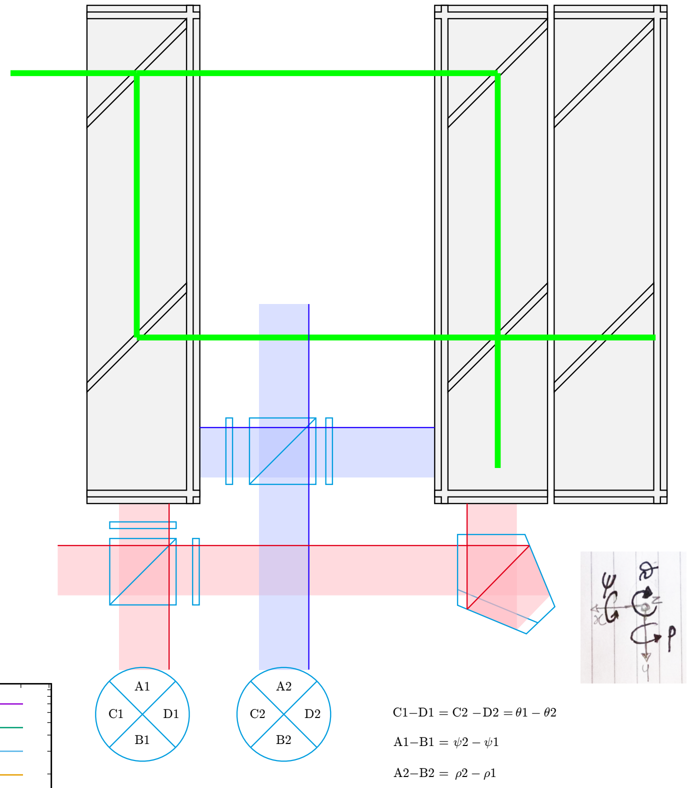


Project combined Optical, X-ray and Neutron interferometry

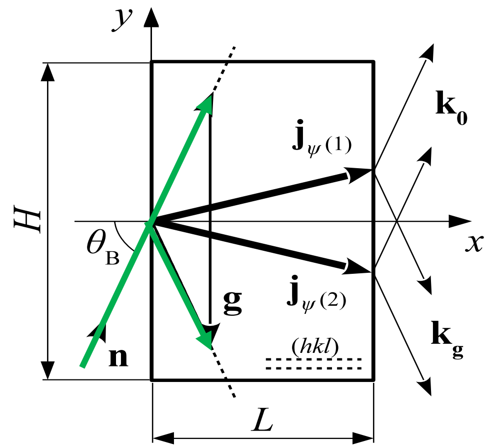
- Probing different interactions, different time scales, different length scales within one device
  - X-rays: 10^8 m/s, electromagnetic interaction (local electron density), wavelength 10^{-10}m
  - Neutrons: 10^3 m/s, strong interaction, spin, wavelength 10^{-10}m
  - Light: 10^8 m/s, electromagnetic interaction (integrated electron density), wavelength 10^{-7} m
- ESS: interesting source for Neutron interferometry







Diffraction around $\theta_B = \pi/2$



$$\psi^{(1)}(\mathbf{r}) = \cos\gamma\, e^{i\mathbf{k}^{(1)}\mathbf{r}} + \sin\gamma\, e^{i[\mathbf{k}^{(1)}+\mathbf{g}]\mathbf{r}},$$
$$\psi^{(2)}(\mathbf{r}) = -\sin\gamma\, e^{i\mathbf{k}^{(2)}\mathbf{r}} + \cos\gamma\, e^{i[\mathbf{k}^{(2)}+\mathbf{g}]\mathbf{r}}.$$

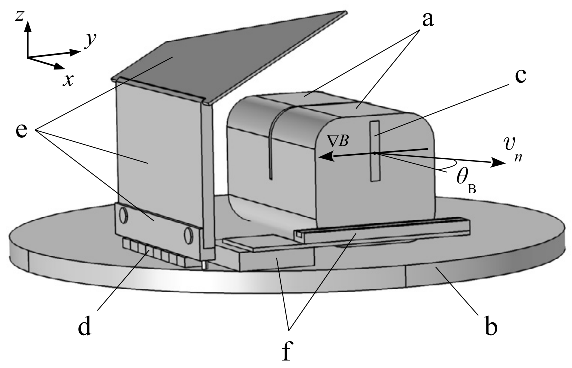
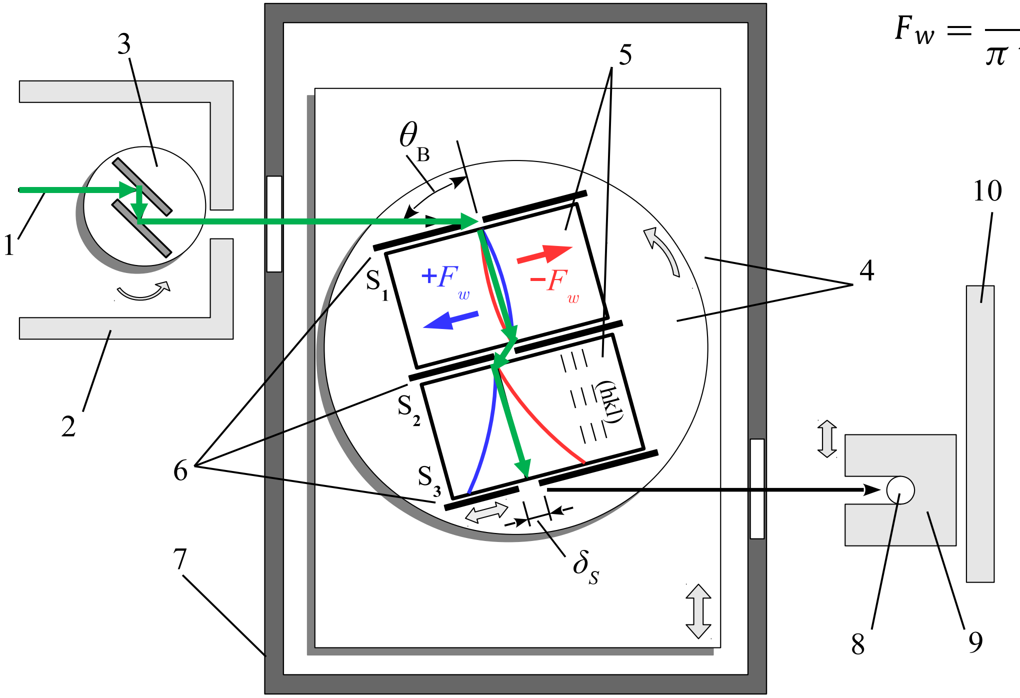


Fig. 3. Schematic view on probing silicon crystal and magnetic field guide: a – probing silicon crystal, b – rotation stage (also part of field guide), c – neutron beam exit area, d – permanent magnets, e – magnetic field guide, f – piezomotor positioner of exit slit S_3 (slit is not shown).

$$F_w = \frac{m_0 d}{\pi \tan^2\theta_B}\cdot\frac{2E_n}{L^2}\cdot\delta_s \equiv \frac{1}{K_e}\cdot\frac{2E_n}{L^2}\cdot\delta_s$$

Amplification coefficient: $K_e^{(220)} = \dfrac{\pi\tan^2\theta_B}{m_0 d} = 2.1\cdot 10^5\cdot\tan^2\theta_B$ ~10^7

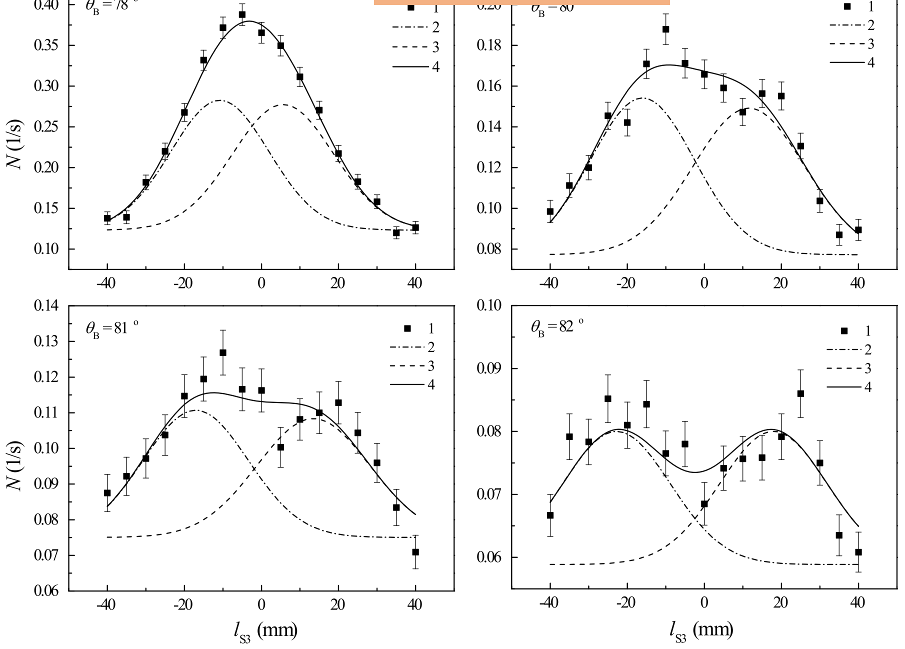


$$\frac{\partial B}{\partial y} = \frac{2E_n}{\mu K_e^{(220)} L^2}\cdot\frac{\Delta_{exp}}{2}$$

3.12 ± 0.09 G/cm

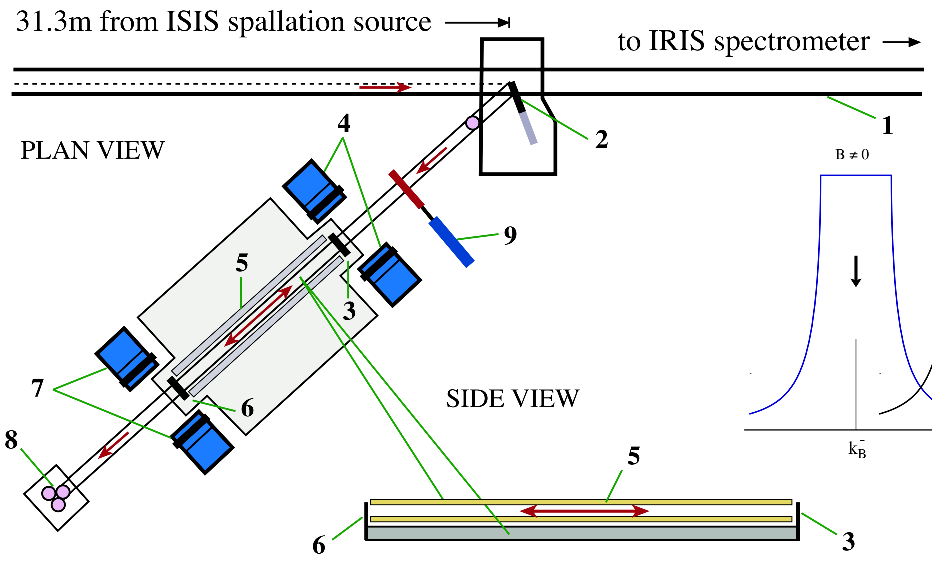
$K_{exp} \sim 2\cdot 10^5 \tan^2\theta_B$

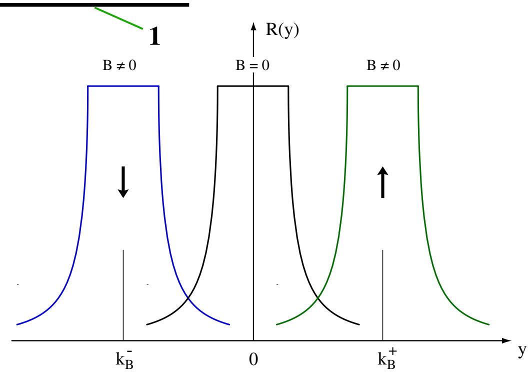
$\theta_B = 78° - 82°$

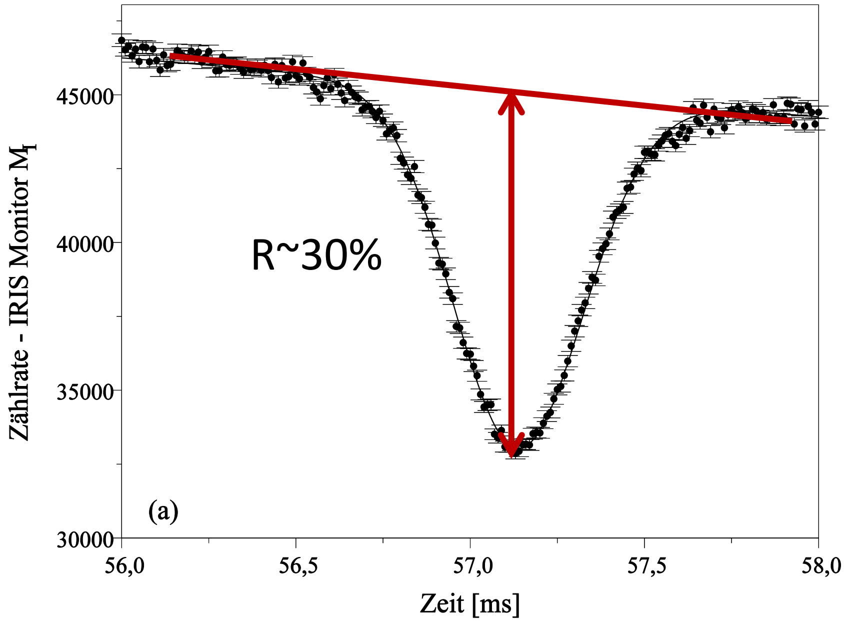


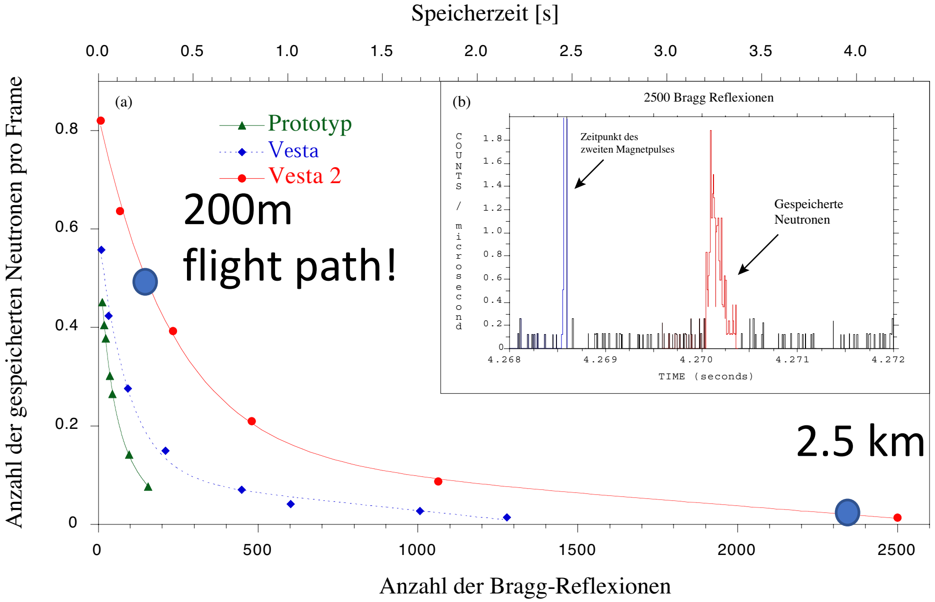
V.V. Voronin et al., Physics Letters B 809 (2020) 135739

Storing neutrons via diffraction









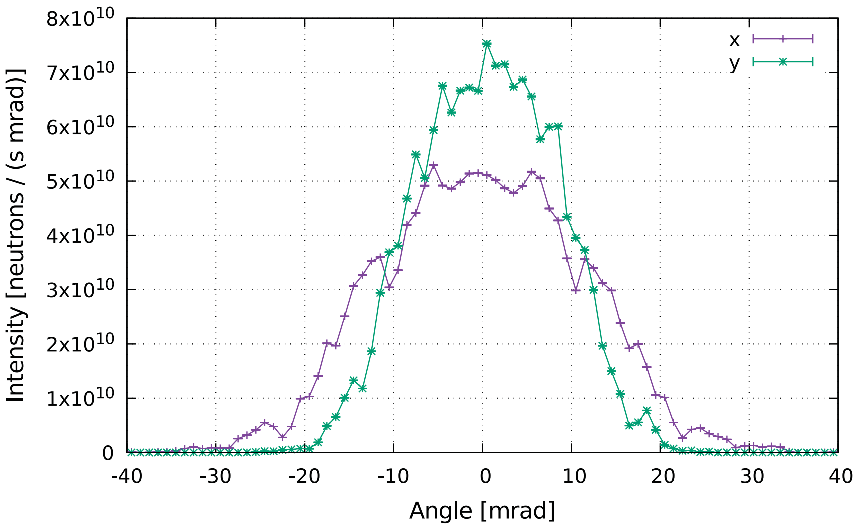
2.5 km flight path!

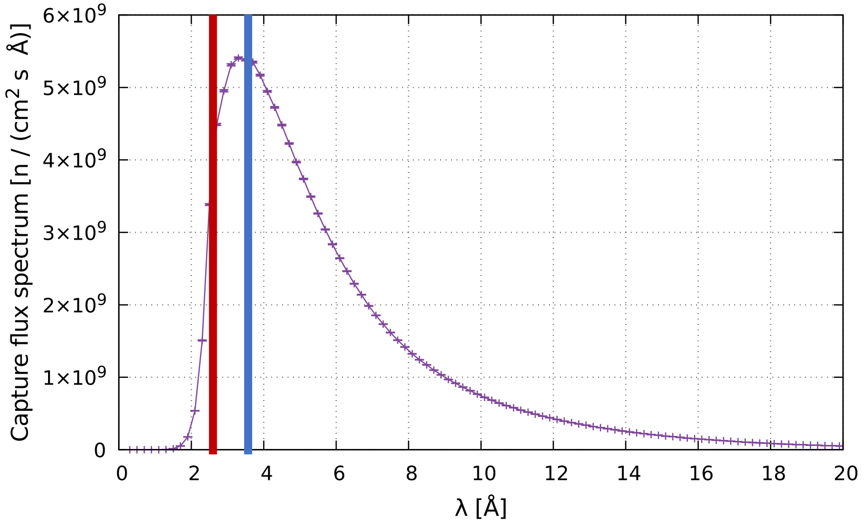
Why revitalizing this setup:

- ISIS beam was not ideal: $3x10^4$ n/s
- Use perfect crystal monochr. (R, T, $\Delta\theta$)
- No need to have monolith:
  - => larger flight distance
  - => no need for pulsed field (all polarization)
- Si220 reflector => 2x better probe of angular deviations

E. Jericha et al. Nucl. Instr. Meth. A 379 (1996) 330
PhD Thesis of E. Jericha, TU Wien
PhD Thesis of N. Jaeckel, TU Wien

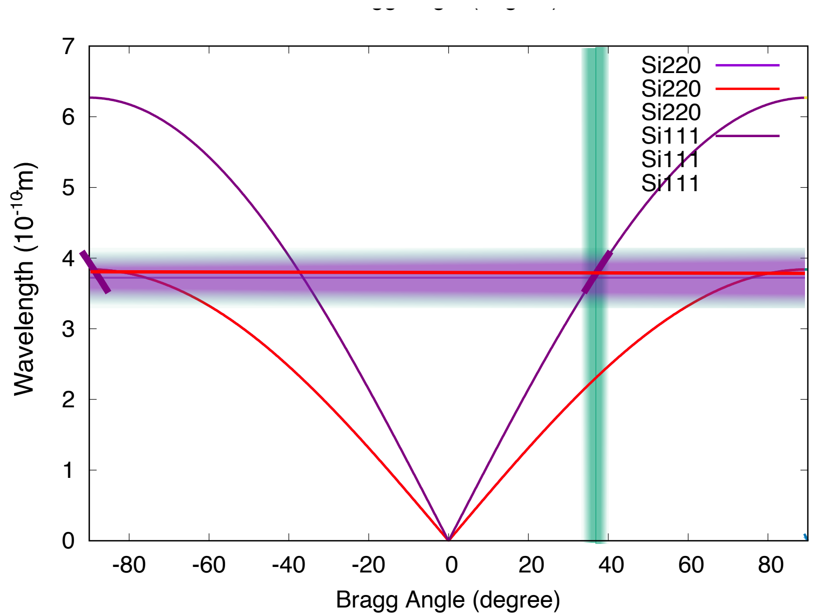
Diffraction based storage @ ANNI



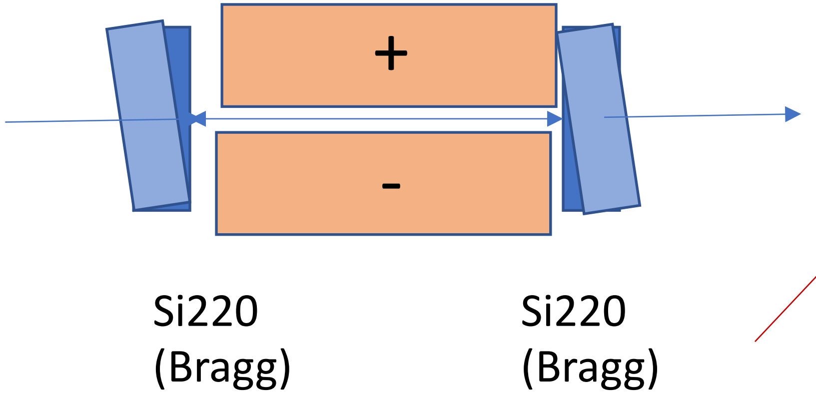


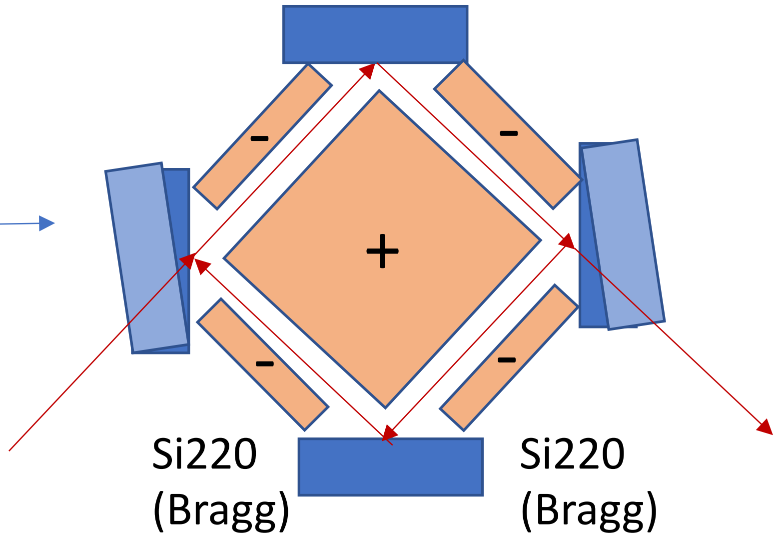
Neutron charge measurement:

Dispersive storage



Non-dispersive storage





Storage opening via 10^{-4} rad kick during Pulse, n x 85 m until next n^{th} pulse.

Measurement of storage time as function of E