Measuring the Charge of the Neutron using a Time-Of-Flight Neutron Grating Interferometer

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Motivation - Charge of the Neutron

$Q_n = 0?$

Current value : $Q_n = (-0{,}4 \pm 1{,}1) \cdot 10^{-21} e$ [1].

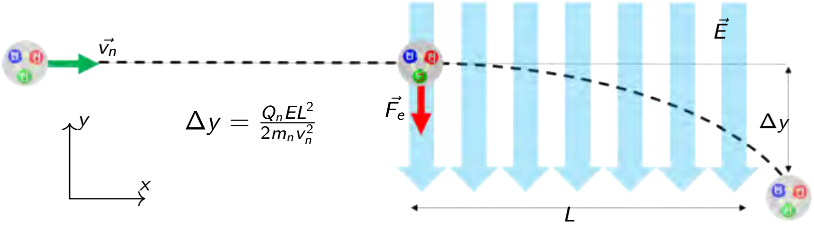
Important consequences for precise tests of fundamental physical laws:

- Even though Q_n is small, charge quantization and neutrality of atoms is under debate.
- Has Q_n the same value for bound and free neutrons?
- Charge conservation prohibits neutron - antineutron oscillation if $Q_n \neq 0$.

Here: Application of a cold neutron beam deflection measurement.

[1] Baumann et al., Phys. Rev. D37,3017(1988)

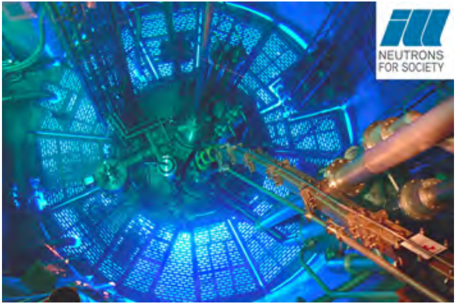
Introduction - Measuring the Charge of the Neutron

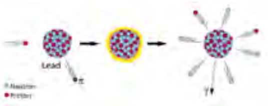


- Goal: Improvement by two orders of magnitude.
- Task: Deflection measurement on the picometer scale![2]

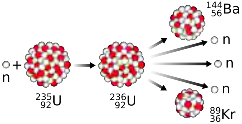
[2] Piegsa, Phys. Rev. C 98, 045503 (2018)

Introduction - Production of Neutrons





spallation



fission

Introduction - Energy Range of the Neutrons

	produced neutrons	cold neutrons	ultra cold neutrons
temperature [K]	1000	10	10^{-8}
energy [eV]	> 1	10^{-3}	10^{-7}
velocity [$\mathrm{m\,s^{-1}}$]	2200	800	5
wavelength [Å]	2	5	800

- Cooling the neutrons to the desired energy.
- Very Low energy for storage experiments (UCN).
- Low energy for interference experiments (CN).

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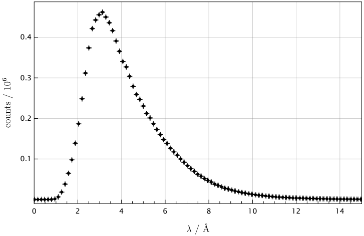

Spectrum of the cold neutron beam at *SINQ, PSI*.

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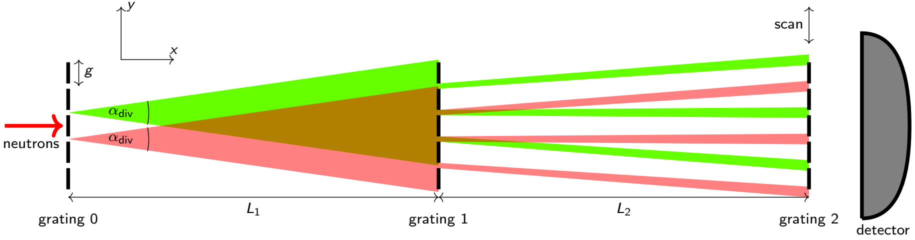
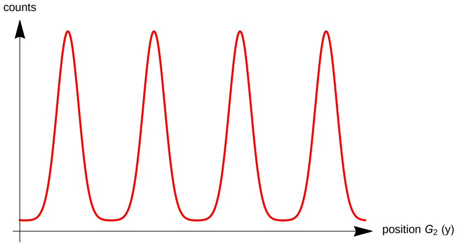
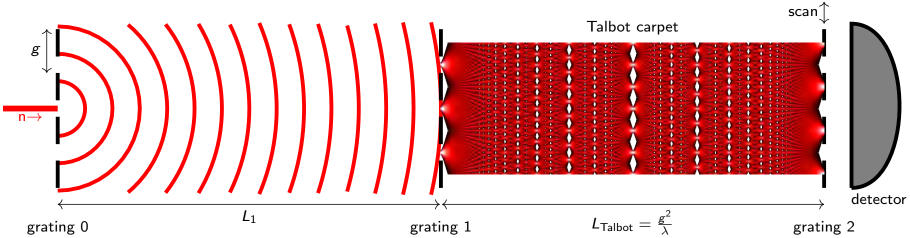
Principle - Geometric Case



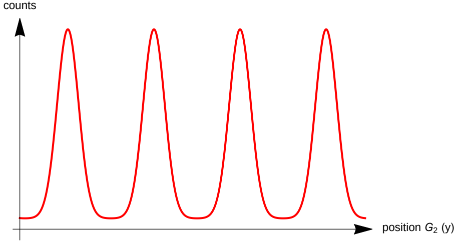
- G_0 and G_1 are acting as collimator.
- Spacial resolution of the detector is too low.
- G_2 needed as analyzer grating.



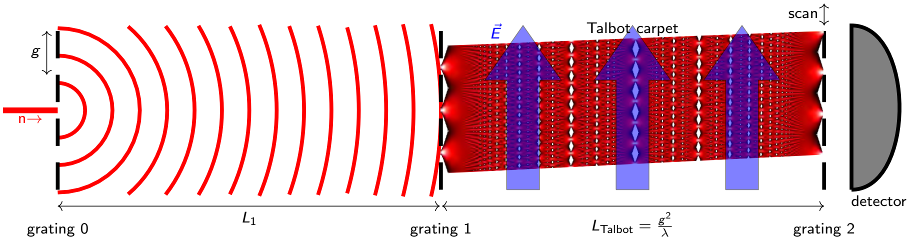
Principle - Diffraction Case



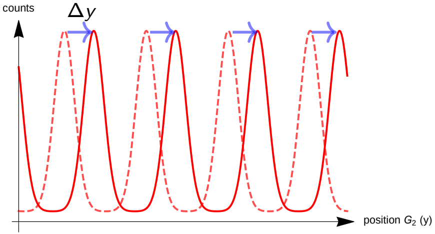
- Diffraction has to be considered.
- G_0 produce coherent line source.
- G_1 as diffraction grating.
- G_2 needed as analyzer grating.



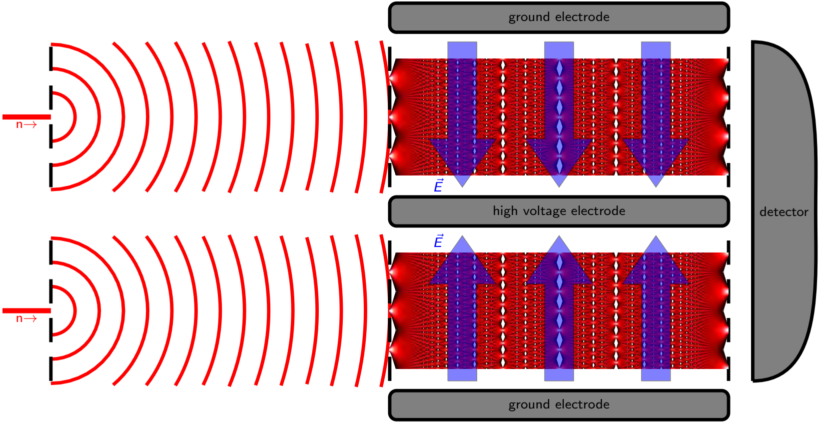
Principle - Charge Measurement



- Apply an electric field $\vec{E}$.
- If $Q_n \neq 0$ this induces a shift Δy of the pattern.
- $Q_n = \frac{2 m_n v_n^2 \Delta y}{E L^2}$



Principle - Two Beam Method



- Separate the neutron beam into two parts.
- Applying an electric field with inverted polarity using a central high voltage electrode.
- Taking the difference between left and right spot in order to compensate for global drifts.

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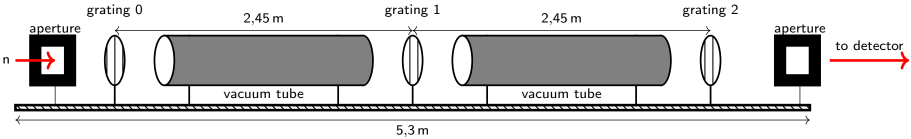
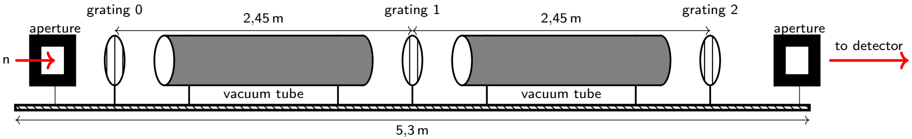
Setup - Overview

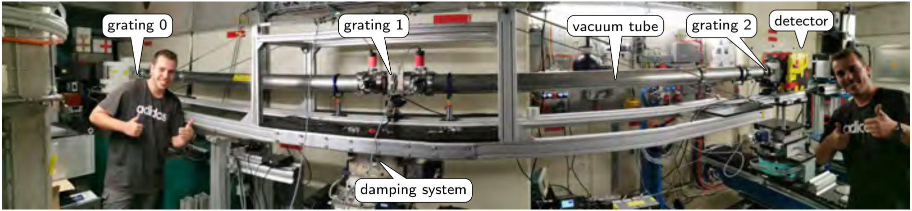


Scheme of the interferometer setup as it was used at the *Paul Scherrer Institute* (August 2022)

Setup - Overview

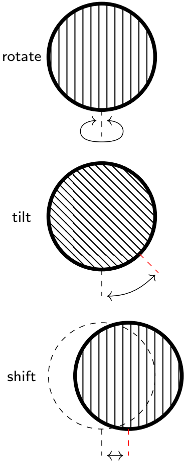


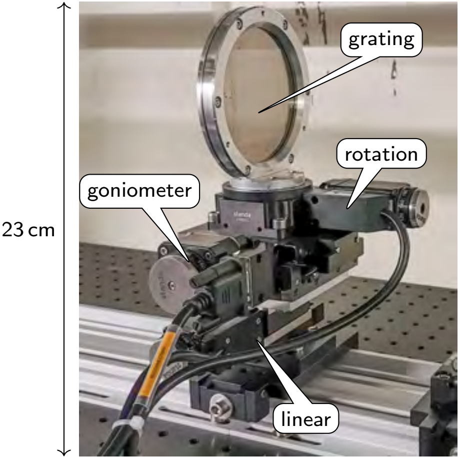
Scheme of the interferometer setup as it was used at the *Paul Scherrer Institute* (August 2022)



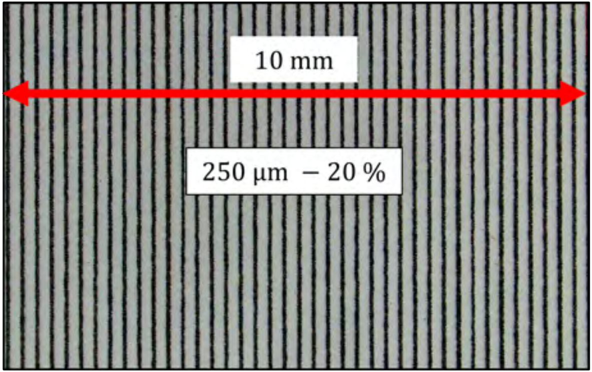
Setup - Stages

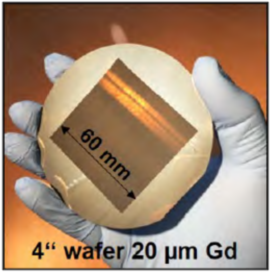
Adjusting rotation, tilt angle, and translation remotely.





Setup - Gratings

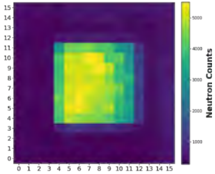




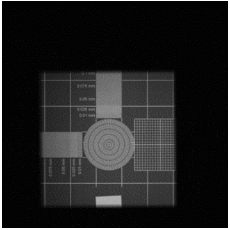
- Gd coated sapphire wavers (20 µm and 30 µm layer thickness).
- Engraved with a laser.
- Grating constant from $g = 25\,\mu\text{m}$ to $g = 250\,\mu\text{m}$.

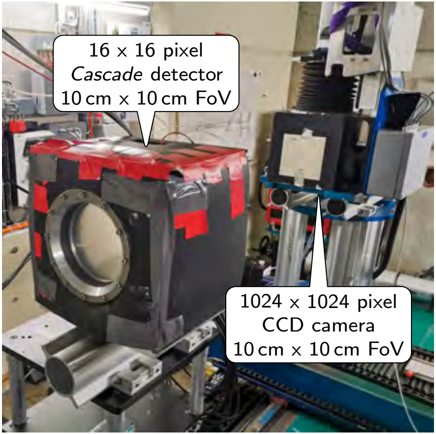
Setup - Detectors

High statistics



High resolution





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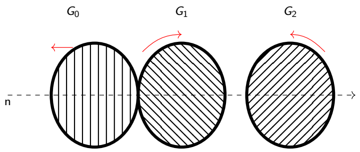
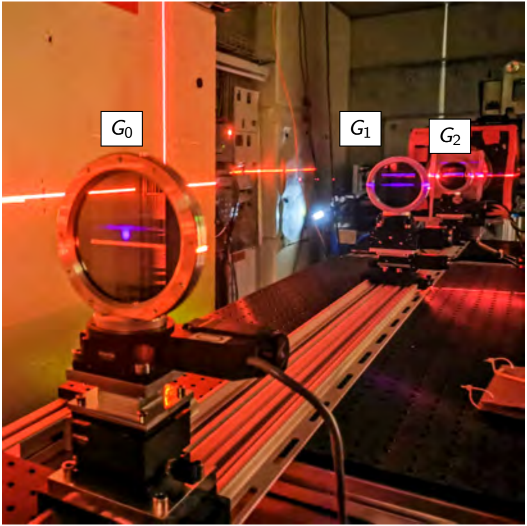
Alignment - Optical

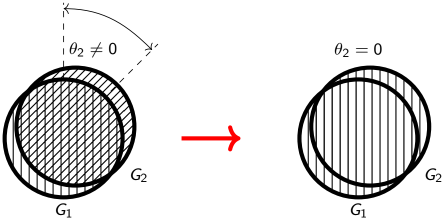
Alignment with laser



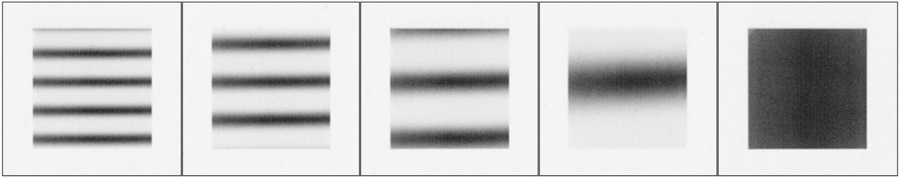


Alignment - Neutron

Alignment with Neutrons



Pictures taken with CCD camera.



$\theta_2 = 1.2°$ $\theta_2 = 0.9°$ $\theta_2 = 0.6°$ $\theta_2 = 0.3°$ $\theta_2 = 0°$

Scanning the tilt angle θ_2 between Grating 1 and Grating 2.

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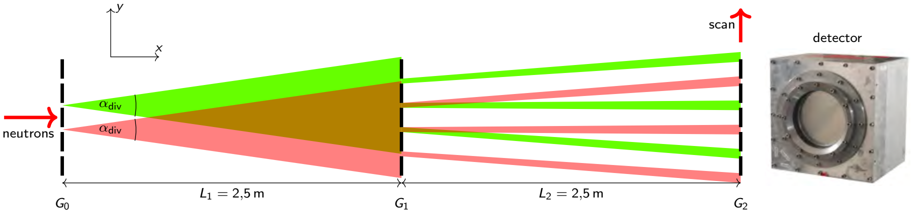
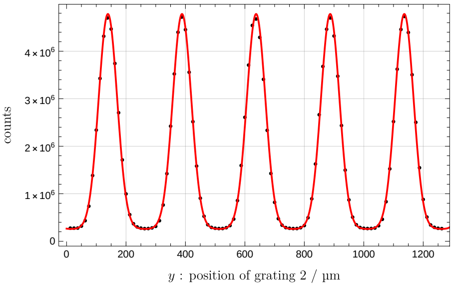
Measurements - Visibility - Ballistic Case



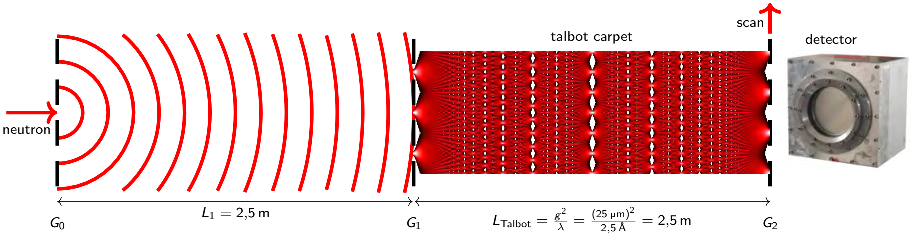
$$G_0 = G_1 = G_2 = 250\,\mu\mathrm{m}, 20\,\%\ \mathrm{dc},\ 30\,\mu\mathrm{m}\ \mathrm{Gd}$$

Visibility of modulation:

$$\eta = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} = 89{,}9\,\%$$



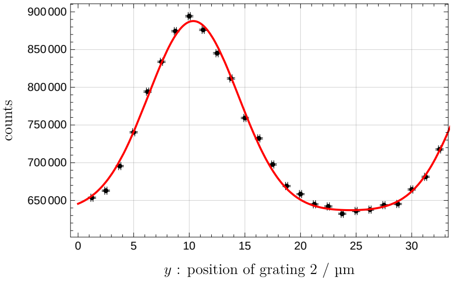
Measurements - Visibility - Diffraction Case



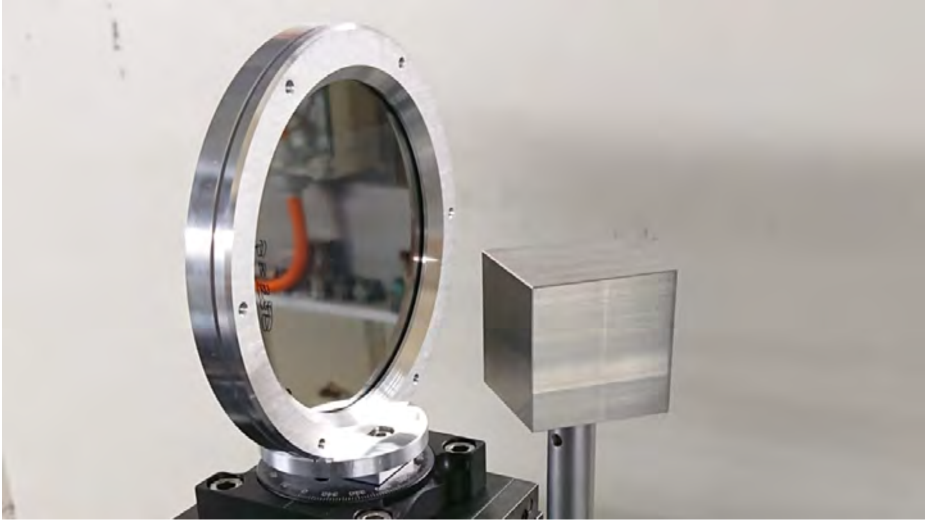
$$G_0 = G_1 = G_2 = 25\,\mu\mathrm{m}, 20\,\%\ \mathrm{dc},\ 30\,\mu\mathrm{m}\ \mathrm{Gd}$$

Visibility of modulation:

$$\eta = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} = 16{,}5\,\%$$



Measurements - Probing Beam Deflections



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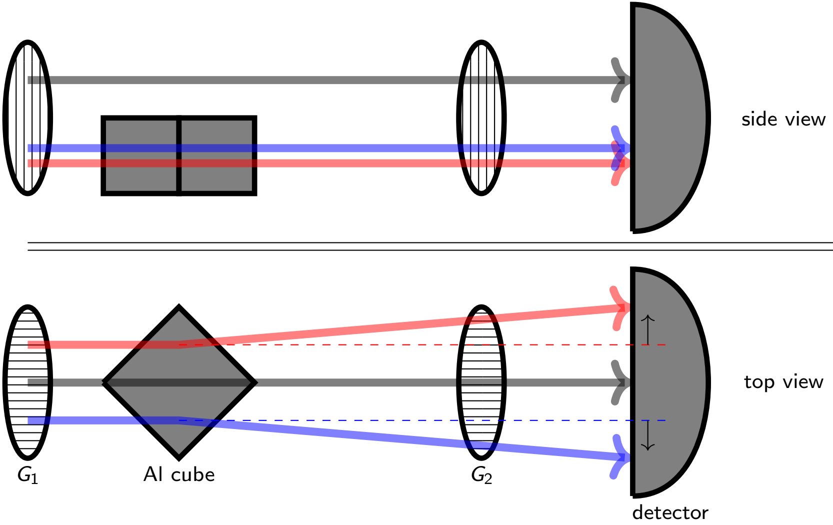
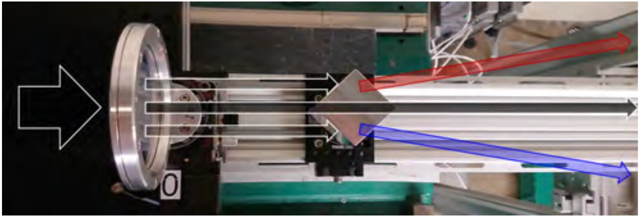
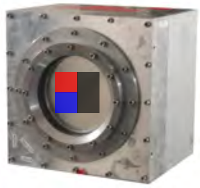
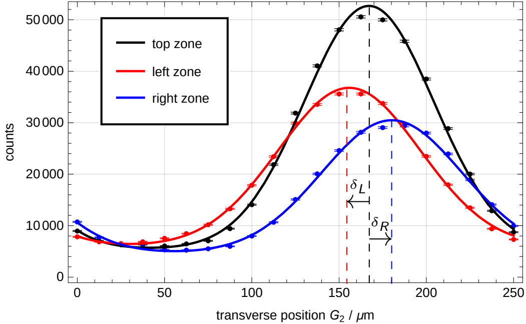


Measurements - Probing Beam Deflections





- Performing a scan with G_2.
- Left zone shifted by $\delta_L \approx -10\,\mu\text{m}$.
- Right zone shifted by $\delta_R \approx 10\,\mu\text{m}$.



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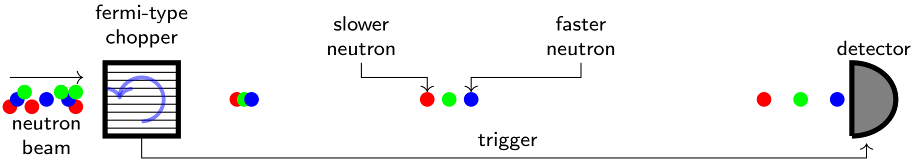
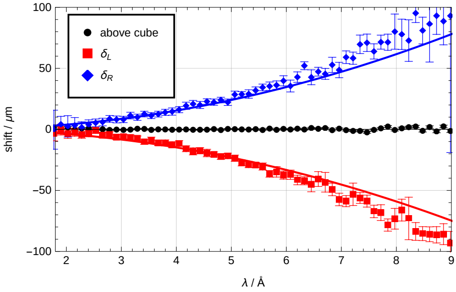


- Time-of-Flight measurement
- Wavelength dependent deflections δ_L, δ_R



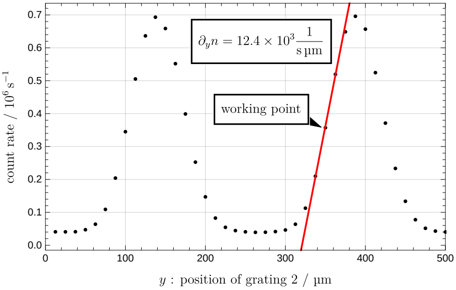
Measurements - Stability

How stable is the setup?

Measurements - Stability

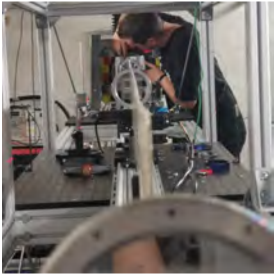
Long time measurement at the most sensitive point (working point).

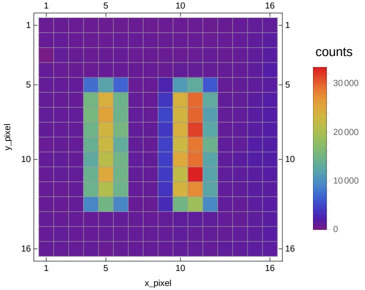
- Drive G_2 to the working point.
- Calibration count rate $\leftrightarrow$ position.



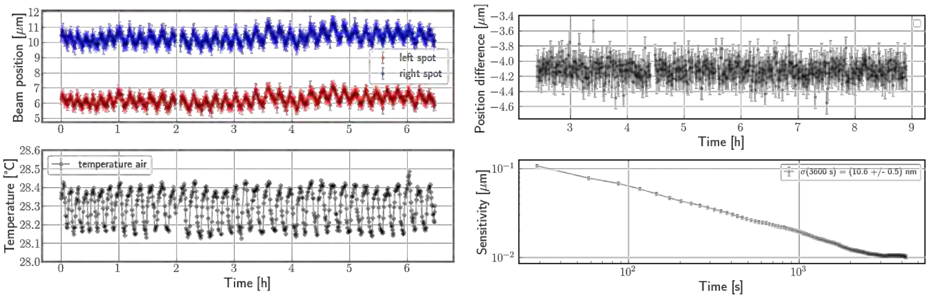
Measurements - Stability

Two beam method



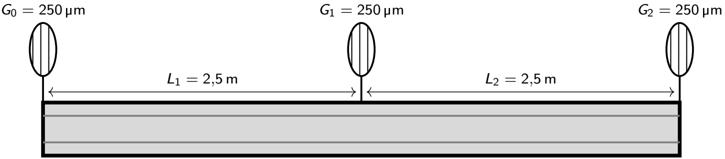


Measurements - Stability



- Periodical temperature fluctuations observed at the beamline.
- Changes in temperature observable in neutron data.
- Taking the difference of the left and right spot in order to get rid of this systematic effect.

Measurements - Sensitivity



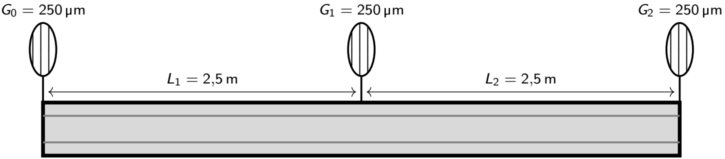
Sensitivity of charge measurement:

$$\sigma(Q_n) = \frac{4\pi\hbar^2 G_2}{\eta m_n E L_2^2 \lambda^2 \sqrt{N}}$$

- η: visibility
- N: number of neutron counts
- m_n: mass of the neutron
- E: electric field
- λ: wavelength

Baumann: $(-0{,}4 \pm 1{,}1) \cdot 10^{-21} e$

Measurements - Sensitivity



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- η: visibility
- N: number of neutron counts
- m_n: mass of the neutron
- E: electric field
- λ: wavelength

$\eta = 89{,}9\,\%$, $\lambda = 4{,}2\,\text{Å}$, neutron rate $= 317\,\text{kHz}$

If an electric field of $E = 100\,\text{kV}\,\text{cm}^{-1}$ would be applied (Electrodes under construction):

$$\boxed{\sigma(Q_n) = 8{,}1 \cdot 10^{-20}\,e/\sqrt{\text{day}}}$$

Baumann: $(-0{,}4 \pm 1{,}1) \cdot 10^{-21}\,e$

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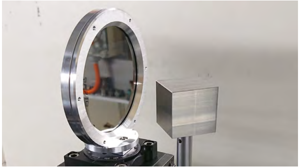
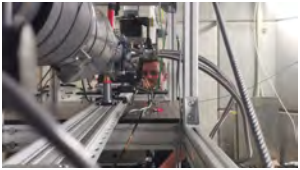
Summary

- Several setups characterized so far ✓
- Developed efficient alignment technique ✓
- Two beam method tested ✓
- Effect of external temperature fluctuations analyzed ✓
- Beam deflections observed (Proof of principle with Al prism) ✓





Outlook

- Next beam time in November at the *ILL* in Grenoble.
- Electrodes will be installed for the first time.
- First measurement of the charge of the neutron (not competitive).

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Ultimate goal: Measuring at the *ESS* in Lundt, Schweden.
Estimation:

- Chopped, high intensity neutron beam.
- Measurement time of 100 days.
- Length of the setup of 10 m.
- Electric field of $100\,\mathrm{kV\,cm^{-1}}$

$$\sigma(Q_n) \approx 10^{-23} e$$

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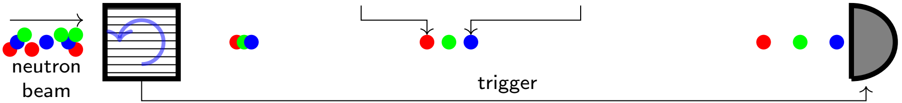
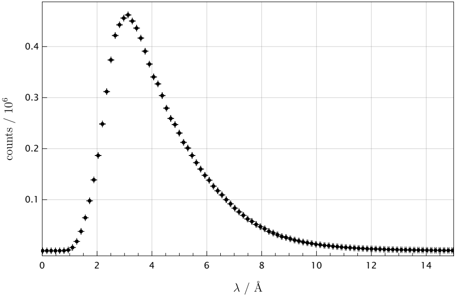
Appendix

Appendix

Principle - Time of Flight

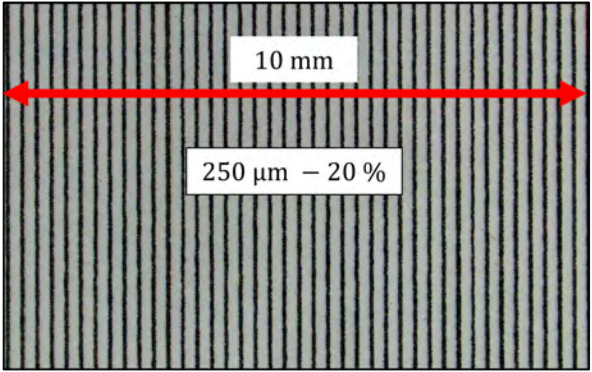


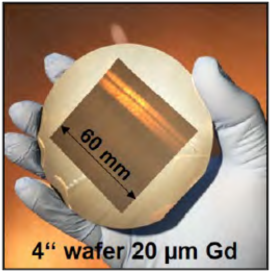
- Spectrum of the neutron beam in general non monochromatic.
- Using a fermi-type chopper to get time (wavelength) information.
- Maxwell distributed energy of the neutrons.



Time-of-flight spectrum of the cold neutron beam at *SINQ*, *PSI*.

Absorption Gratings - Properties

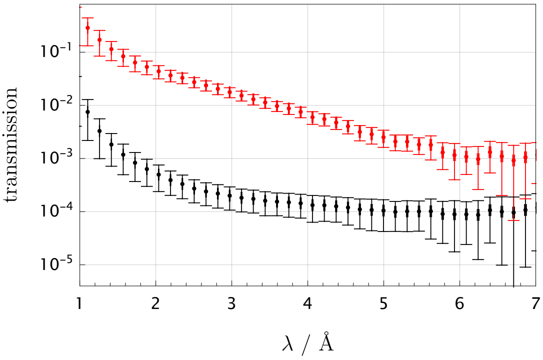




- Gd coated sapphire wavers (25 µm and 30 µm layer thickness).
- Engraved with a laser.
- Grating constant from $g = 25\,\mu\text{m}$ to $g = 250\,\mu\text{m}$.

Absorption Gratings - Transmission Measurement

- Time-of-flight transmission measurements.
- Thicker layers are favorable
- Quality of engraving has to be considered.



Time-of-flight transmission measurement for 20 μm and 30 μm Gd layer coating.

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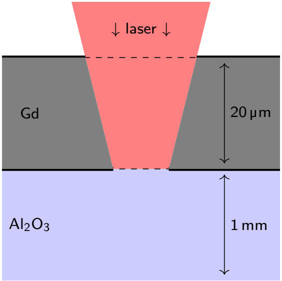
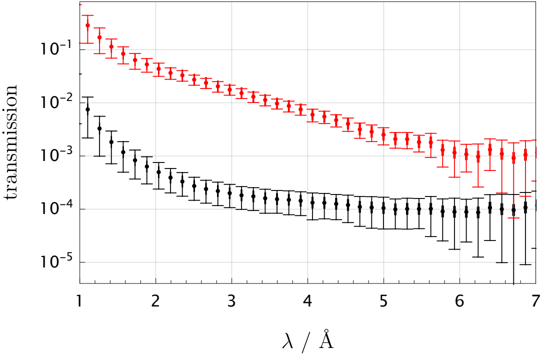
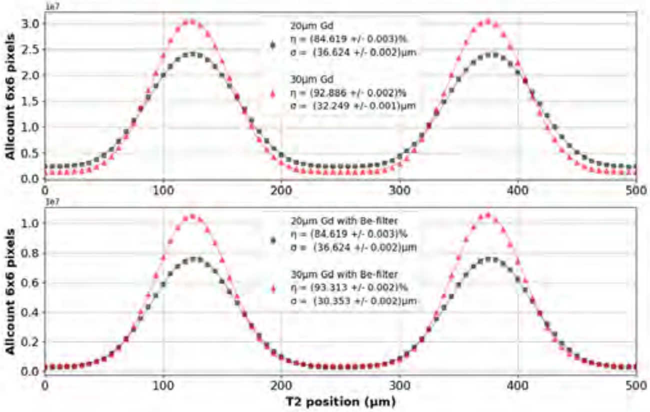




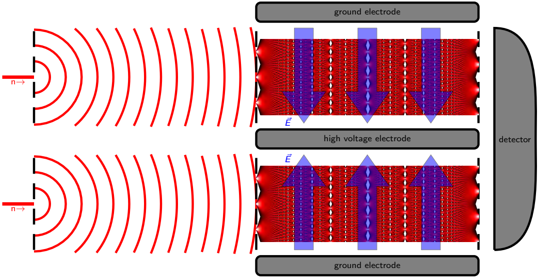
Time-of-flight transmission measurement for 20 µm and 30 µm Gd layer coating.

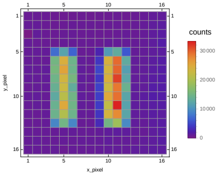
Absorption Gratings - Comparison Layer Thickness



- Transversal scan of G_2 with $g = 250\,\mu m$ grating period and a duty cycle of $20\,\%$.

Setup - Two Beam Method





Measured neutrons with the 16x16 pixel detector.

- Separate the neutron beam into two parts.
- Applying an electric field with inverted polarity using a central high voltage electrode.
- Taking the difference between left and right spot compensates for global drifts.

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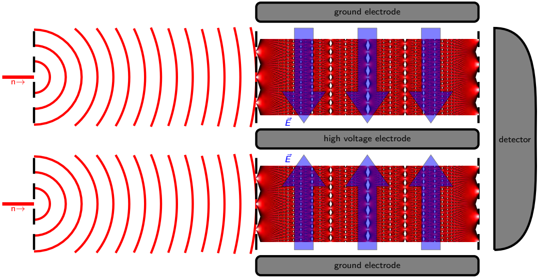

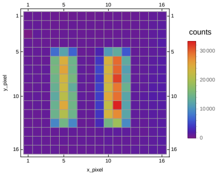

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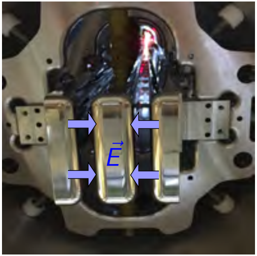
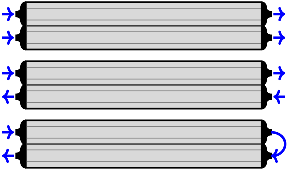


Characterization - Stability

Further investigations in our labs.

Testing different directions of flow:



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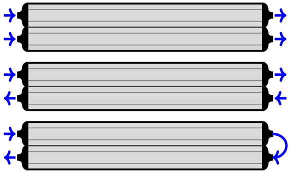

Optical setup with polarizer foils to sense deformations: