Diffraction-grating VCN interferometry
and
experimental search for neutron electric charge

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MLZ is a cooperation between:

HighNESS UCN/VCN Workshop
May 9-10 2023

Contents:

1. I will not discuss "why" to measure q_n, just "how" to measure.
2. Earlier attempts and current experimental limit q_n .
3. Interferometrical approach using grating interferometers.
4. VCN grating interferometer in gravitational field, specific requirements .
5. Experiment on neutron charge quest at ESS.

Previous experiments and limits on neutron charge q_n

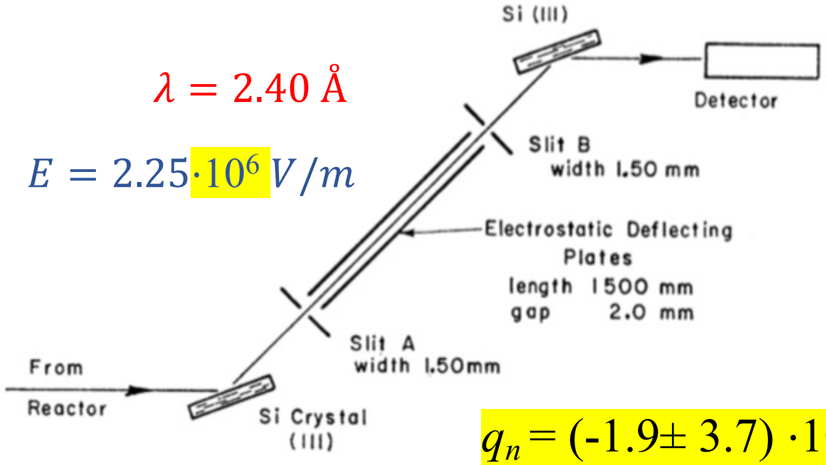
PHYSICAL REVIEW VOLUME 153, NUMBER 5 25 JANUARY 1967

Experimental Limit for the Neutron Charge*

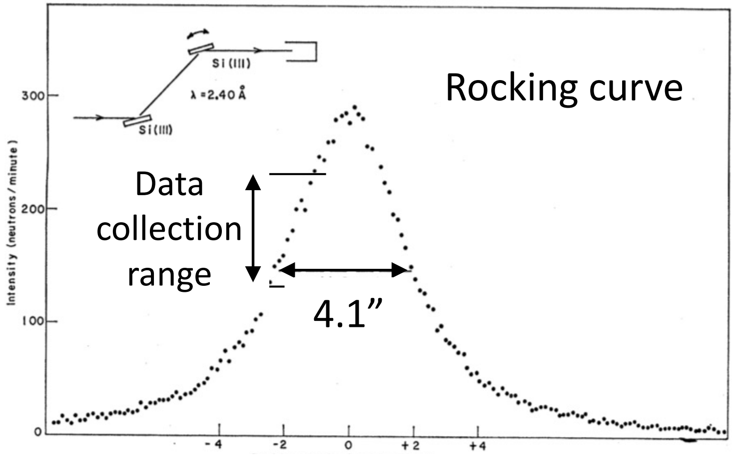
C. G. SHULL, K. W. BILLMAN, AND F. A. WEDGWOOD†

$\lambda = 2.40$ Å

$E = 2.25 \cdot 10^6\ V/m$



$q_n = (-1.9 \pm 3.7) \cdot 10^{-18}\ e$ (CI 68%)

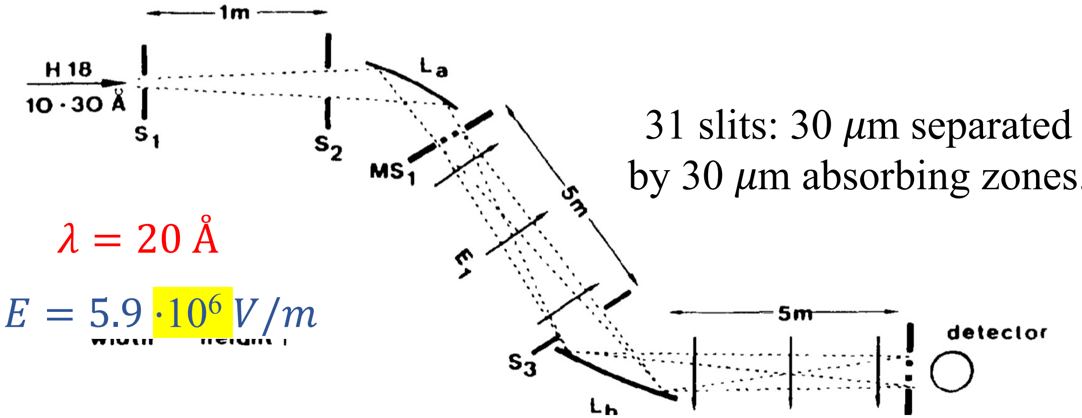


Rocking angle (sec of arc)

PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Experimental limit for the charge of the free neutron

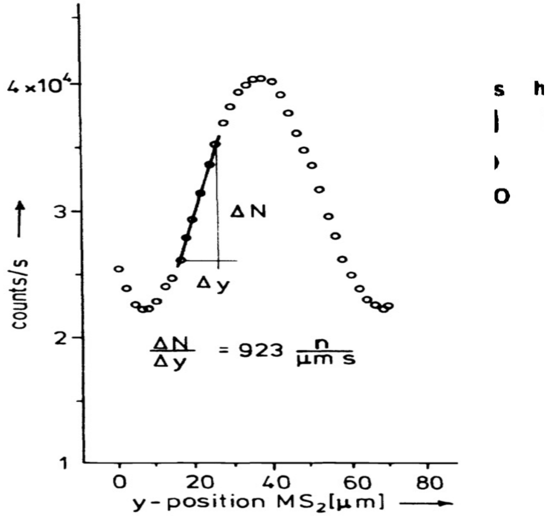
R. Gähler, J. Kalus, W. Mampe

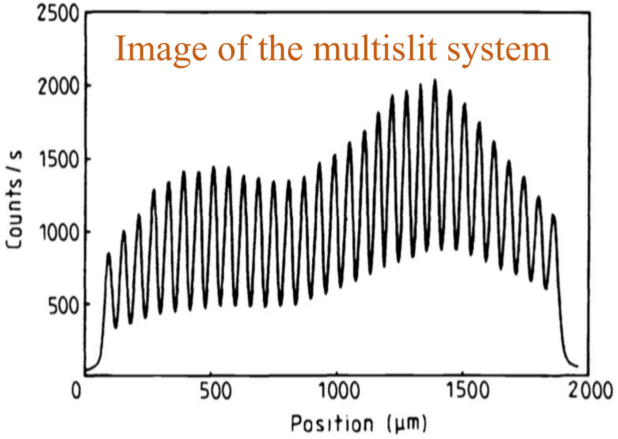


31 slits: 30 μm separated by 30 μm absorbing zones.

$\lambda = 20$ Å

$E = 5.9 \cdot 10^6\ V/m$

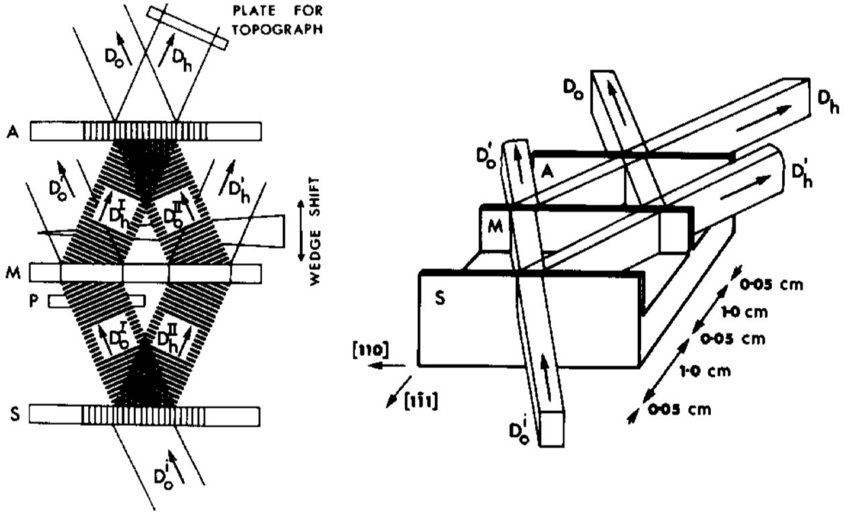




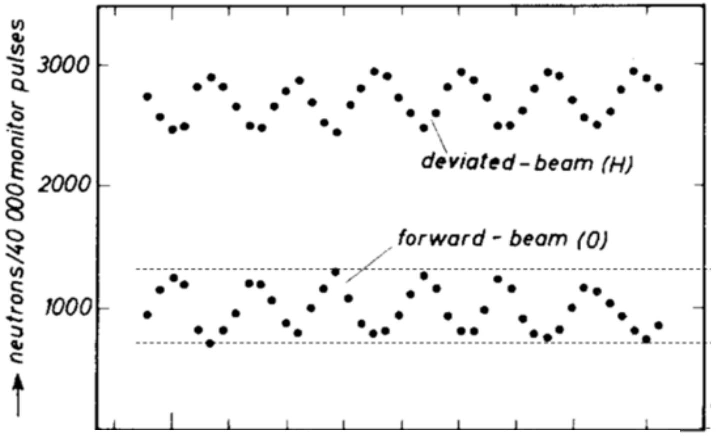
$q_n = (-0.4 \pm 1.1) \cdot 10^{-21}\ e$ (CI 68%)

Perfect crystal neutron interferometer

Perfect crystal neutron LLL interferometer



Introduced phase shift $(\Delta\varphi)$ between beams in the NI



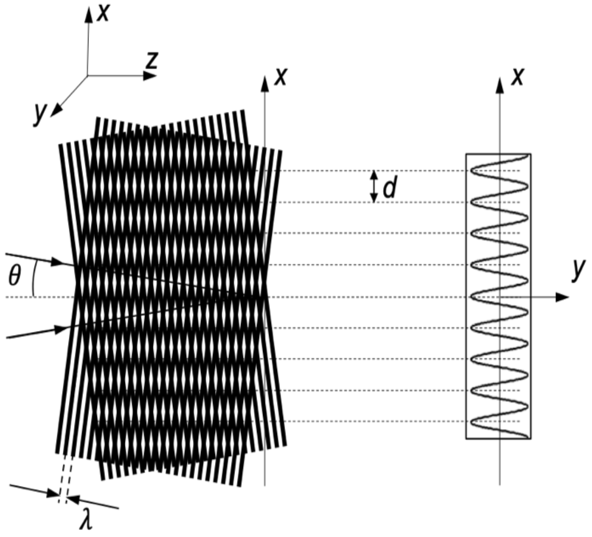
Phase shift $(\Delta\varphi)$ between beams in NI

$$I_{\mathrm{H}}(\Delta\varphi) = B - \mathrm{A}\cos(\Delta\varphi)$$

Swapping intensity between O- and H-beams

$$I_{\mathrm{O}}(\Delta\varphi) = \mathrm{V}(1 + \cos(\Delta\varphi))$$

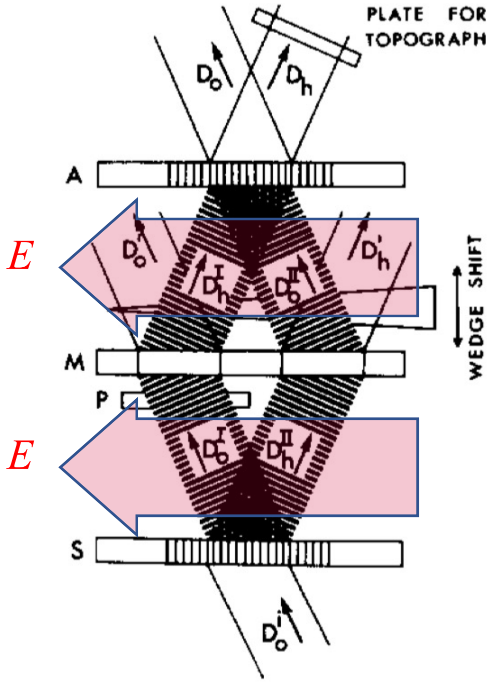
H. Rauch et al., 1974



Alternatively:

- crossing coherent waves produce interference pattern of period d
- these interference fringes are superimposed with crystal lattice (d) => Moiré effect (fringes)
- $\Delta\varphi$ results in the lateral shift of interference fringes w.r.t. crystal lattice
- this leads to oscillations of Moiré fringes, i.e. oscillations of recorded intensity

Gedanken experiment with crystal interferometer: q_n

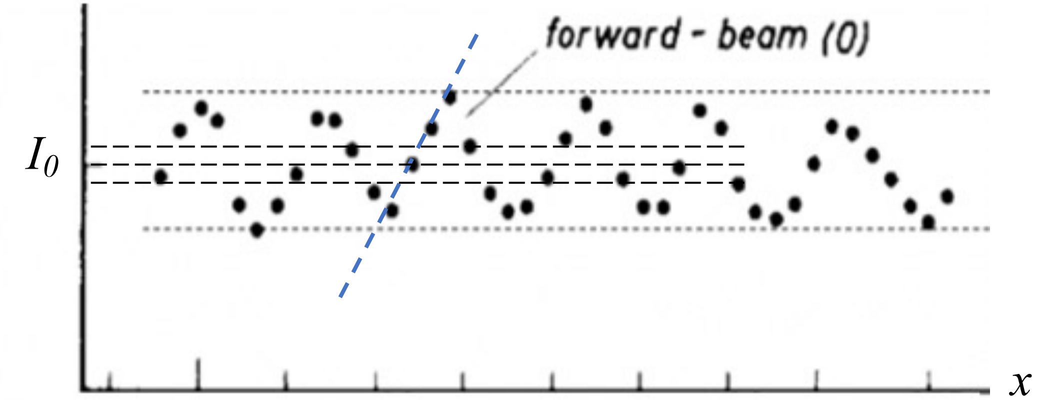


Electric field across neutron beams => shift of interference pattern:

$$\Delta x = \frac{1}{2} qE \left(\frac{L}{v}\right)^2 = \frac{1}{2} qE \left(\frac{L}{h} m\lambda\right)^2 \sim qEL^2\lambda^2$$

$$I(\Delta x) = I_0 V \left(1 + \cos \frac{2\pi}{d} \Delta x\right)$$

--> Shift by d (lattice spacing) corresponds to full intensity oscillation

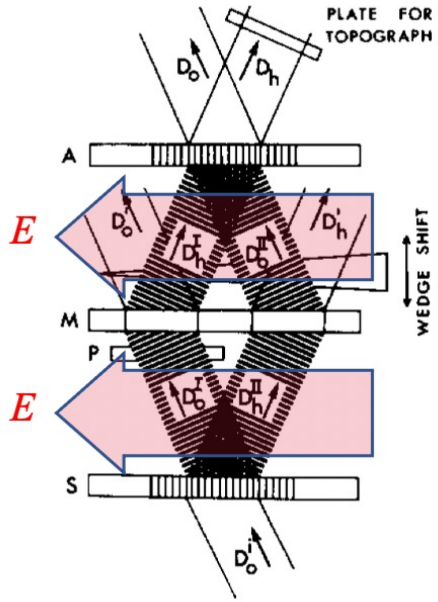


$$q = \frac{\sqrt{2}\, d}{\pi \sqrt{I_0}} \frac{1.5}{V\ E\ L^2\ \lambda^2} \left(\frac{h}{m}\right)^2$$

For E = 60 kV/cm, L = 5cm, λ=2 Å, d=1.92 Å $\quad q_n \geq 3 \cdot 10^{-20}\, e$ (CI 90%) in 100 days

Important: $q \sim \frac{d}{\sqrt{I_0} E\ L^2\ \lambda^2}$ - this is a kind of FOM

Neutron interferometer with larger length and wavelength



$$q_n \sim \frac{d}{\sqrt{I_0}E\,L^2\,\lambda^2}$$

Now imagine we can modify our interferometer towards larger length and wavelength, however with corresponding increase of d.

Scaling to VCN:

λ: 2 Å -> 20 Å => x10^2 L: 5 cm -> 5 m => x10^4	x	d: 2 Å -> 1 μm => x $(2 \cdot 10^{-4})$ $I_0 : \sqrt{\lambda^{-5}}$ => x $(3 \cdot 10^{-3})$	x	Thermal to cold neutron source: x 15

Total gain about 10 => one can put a harder limit on q_n

However, for cold neutrons one should use other than the Laue diffraction coherent splitting of neutron waves

(Very) cold neutrons: coherent beam splitting

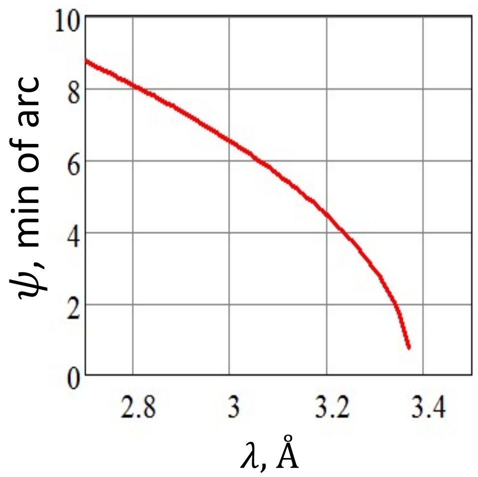
For cold neutrons one should employ other than the Laue diffraction coherent splitting of neutron waves: diffraction on periodical structures (gratings) or reflection from semi-transparent coatings.

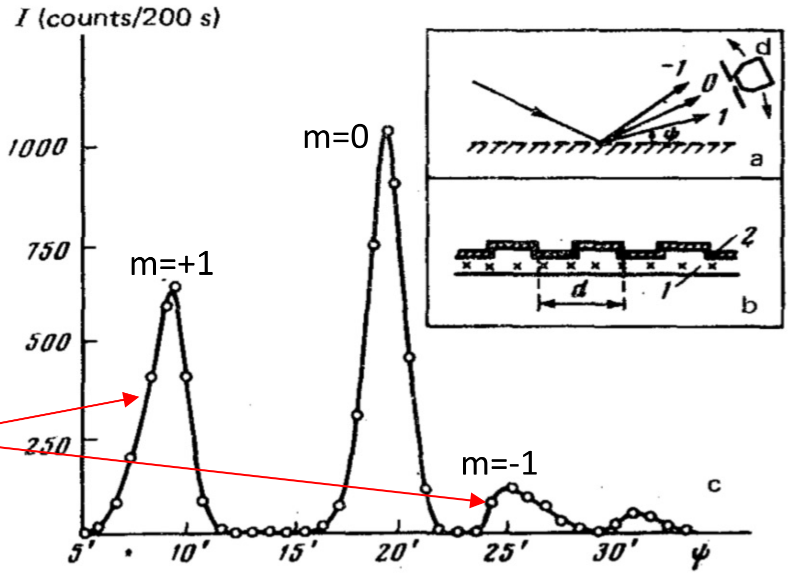
<u>Effective neutron diffraction gratings: modulated surface relief</u>

A.Ioffe et al, JETP letters 33, 374 (1981)

$d = 21\ \mu\text{m} \quad \lambda = 2.7\ \text{Å}, \quad \Delta\lambda/\lambda = 32\%$ (Ni mirror)

Diffraction efficiency:
m=+1 ≈ 5%
m=0 ≈ 7.5%



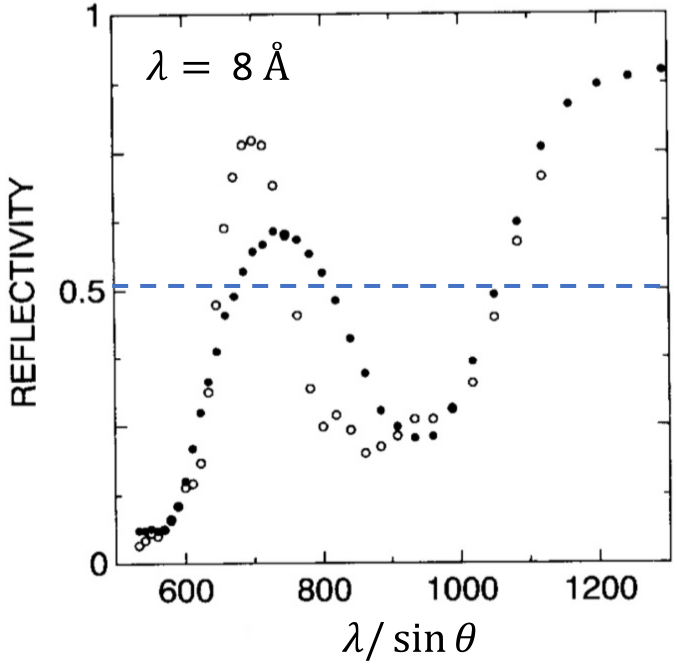


Note asymmetry: spectrum of incident beam => spectroscopy

<u>Coherent beam splitter</u>

*T. Ebisawa et al, NIM A **344**, 597 (1994)*

V-Ti multilayer mirror with spacing d=360 Å



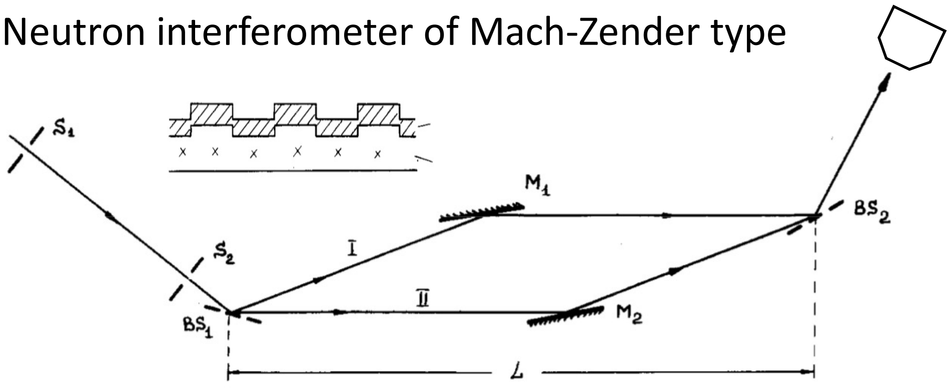
Cold neutron interferometers

Volume 111, number 7 PHYSICS LETTERS 30 September 1985

TEST OF A DIFFRACTION GRATING NEUTRON INTERFEROMETER

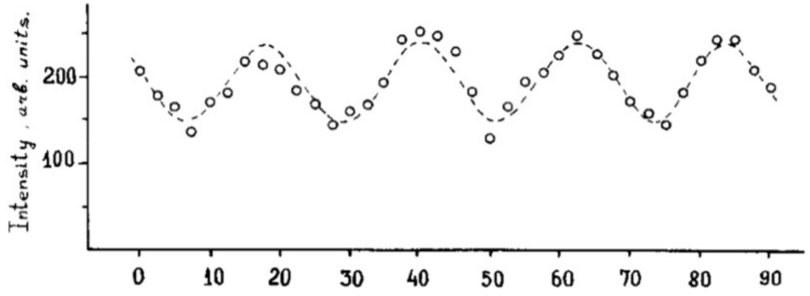
A.I. IOFFE, V.S. ZABIYAKIN and G.M. DRABKIN

Neutron interferometer of Mach-Zender type



Moire pattern with a period d :

$\lambda = 3.15$ Å $d = 21\ \mu$m



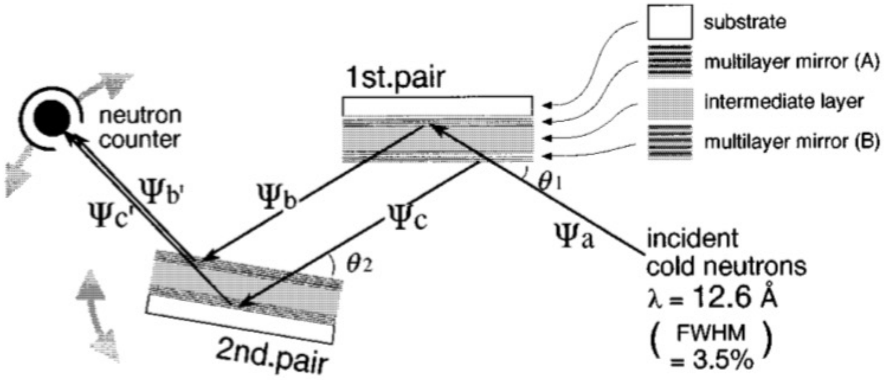
Lateral shift of BS_2, μm

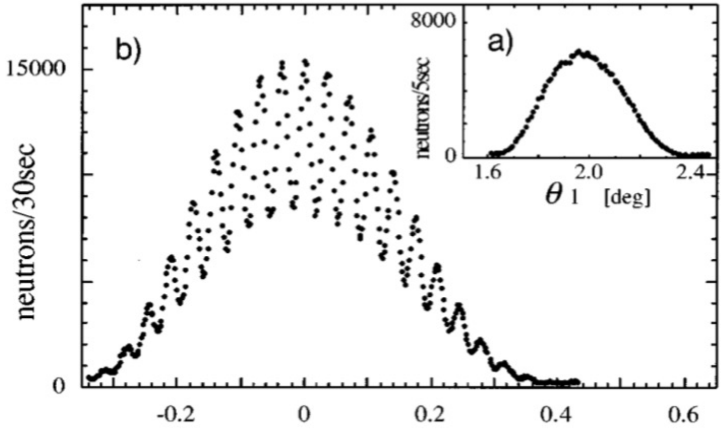
PHYSICAL REVIEW A VOLUME 54, NUMBER 1 JULY 1996

Interferometer for cold neutrons using multilayer mirrors

Haruhiko Funahashi,[1,*] Toru Ebisawa,[1] Tomohito Haseyama,[2] Masahiro Hino,[3] Akira Masaike,[2] Yoshié Otake,[4]

*Idea: T. Ebisawa et al, NIM A **344**, 597 (1994)*

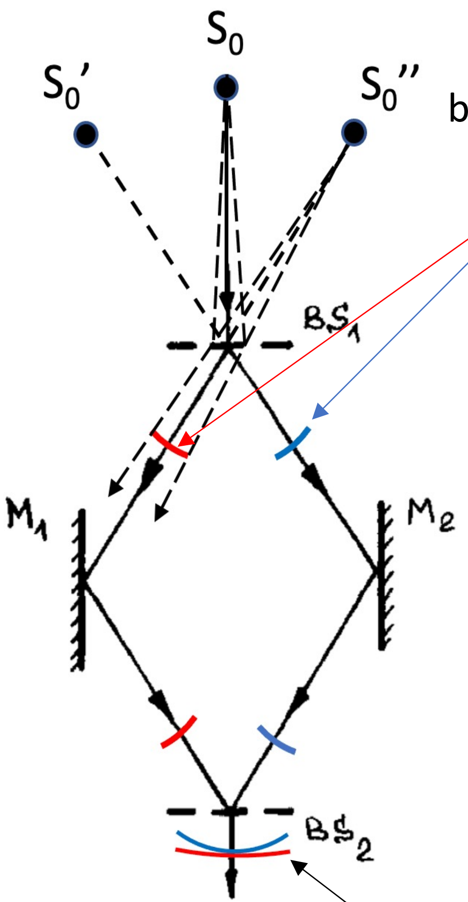




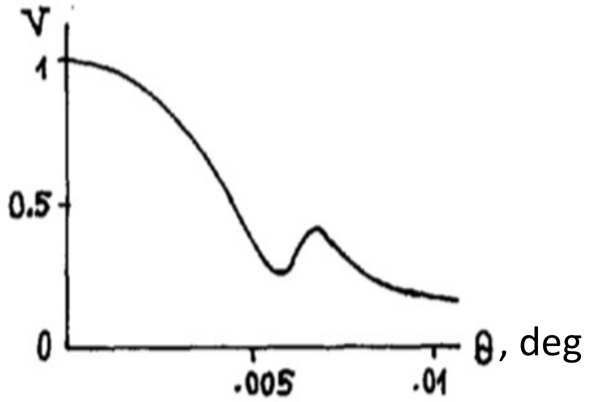
Angle between first and second pairs

See also presentation of H. Shimizu at 1st UCN/VCN workshop

3- grating interferometers



Spherical incident wavefronts diffracted by periodic structures are principally aberrated, but non-identical for m=1 and m=-1.



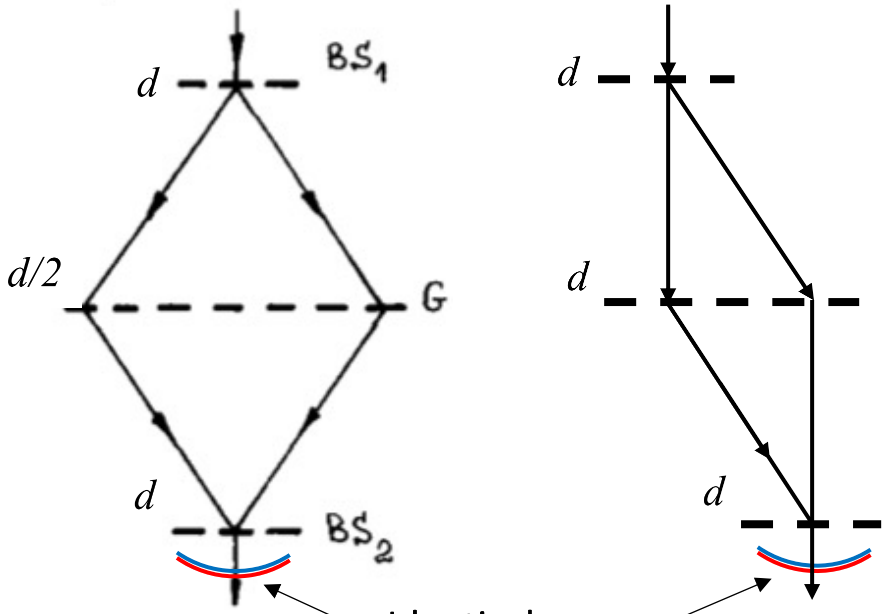
=> Strong requirements to incident beam divergence
⇒ Bad for neutrons in general; unfeasible for VCN

Interference of two non-indentical waves:
=> non-constant period of the interference pattern
=> amplitude modulation over the beam cross-section
=> low visibility V

Unavoidable different aberrations in interfering beams:
=> add complimenting aberrations for equalization.

Deflection --> Diffraction: gratings instead of mirrors

3-grating interferometers

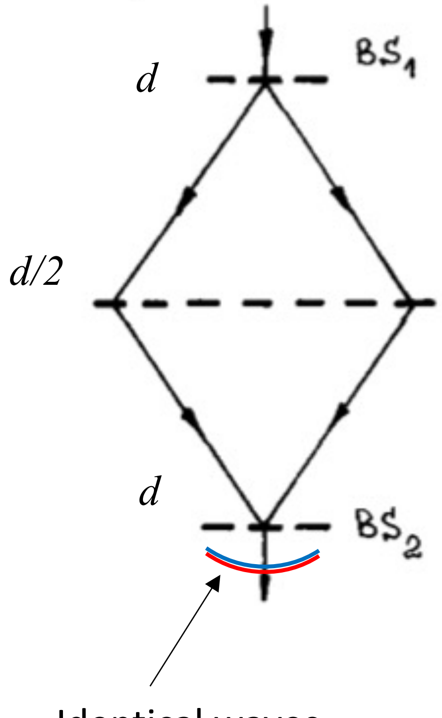


Identical waves

Aberration analysis shows that now interfering wavefronts are distorted identically and V=1:
=> no requirements to incident beam divergence

A.Ioffe, Physica B 174 (1991) 385.

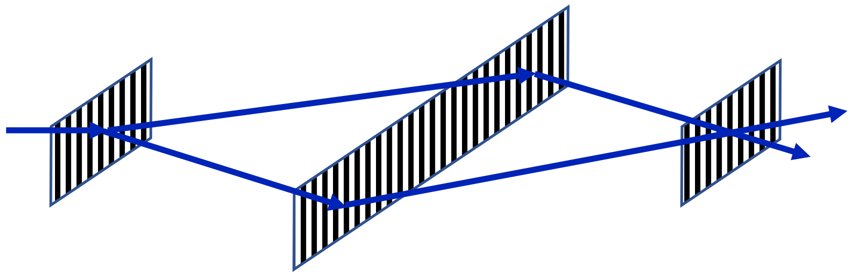
Diffraction grating interferometers



This is not the Talbot interferometer: Talbot effect is a near-field diffraction effect, where the self-imaging of periodic objects (gratings) **requires spatially coherent illumination.**

Here: the imaging of a grating by a second grating **regardless of the coherence of the source.**

- First shown by first-order diffraction theory (i.e. without accounting for aberrations): (*B.Chang, R.Alferness, E.Leith (Apll. Opt. 14 (1975) 1569*) .
- Aberration analysis (higher-orders diffraction theory): full compensation of aberrations => interfering waves are identical (*A.Ioffe, NIM A268 (1988) 169*).



Such interferometer works regardless of the source coherence, i.e. for non-monochromatic and non-collimated neutron beam!

Transition to neutrons:
refraction index of vacuum in gravitational field ≠ 1.

(*I.M Frank, A.I Frank, JETP Lett.* ***28*** *(1978) 515*)

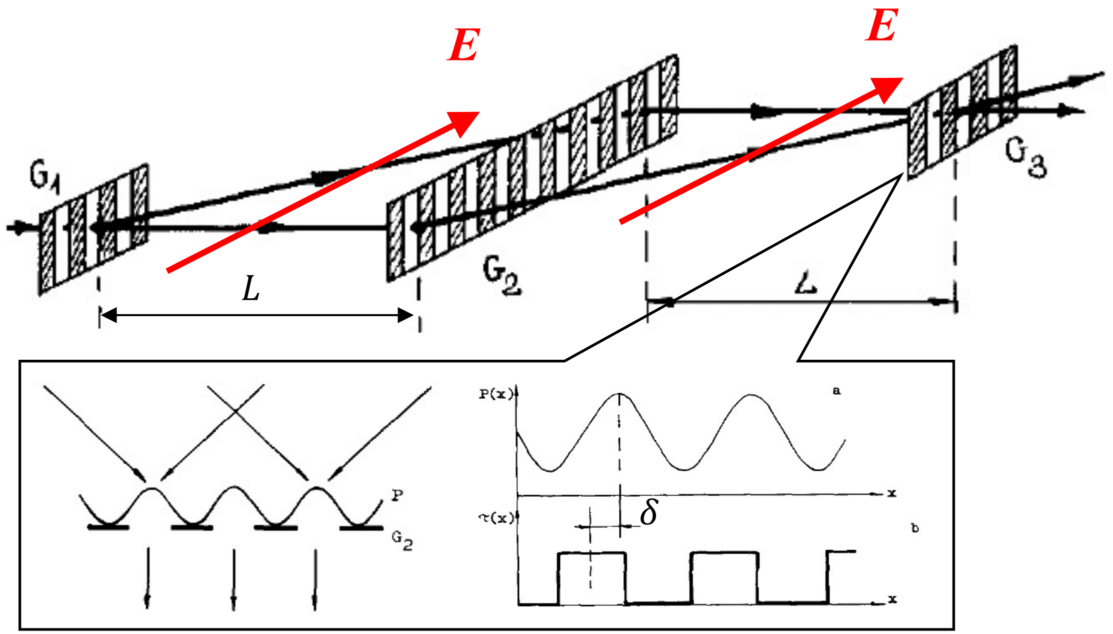
$$n = \sqrt{1 - 2gz\left(\frac{m_n}{h}\right)^2 \lambda^2}$$

=>

As neutrons propagate on parabolic trajectories, vacuum has non-linear refraction index. This is not trivial, will be discussed later.

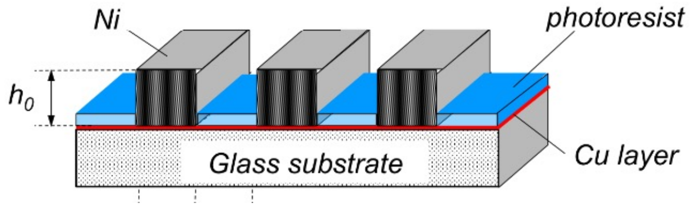
VCN diffraction grating interferometer for search of q_n

Electric field applied across interferometer beams



$$I(\Delta x) = I_0\, V\left(1 + \cos\frac{2\pi}{d}\,\delta\right)$$

Phase diffraction gratings: surface relief



d = 3.3 μm
h_0 =1.7 μm: phase shift π for λ= 20 Å

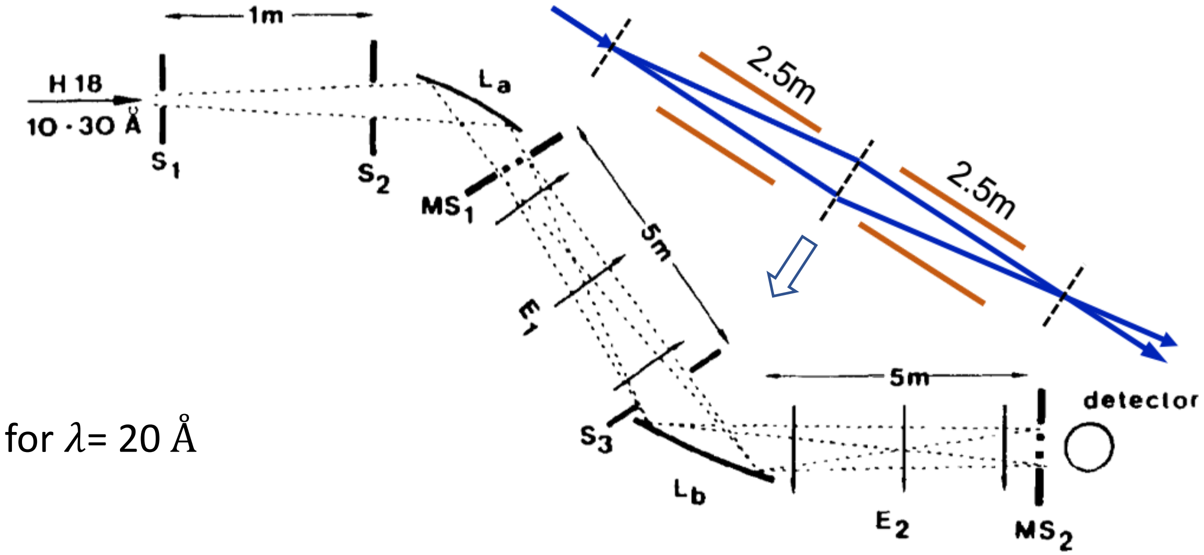
A. Ioffe, NIM A228 (1984) 141; NIM A268 (1988) 169.

$$\delta = \frac{1}{2} qE \left(\frac{L}{h} m\lambda\right)^2 \qquad q = \frac{\sqrt{2}\, d}{\pi\sqrt{I_0}} \frac{1.5}{E\, L^2 \lambda^2} \left(\frac{h}{m}\right)^2$$

1987- proposal to ILL (accepted, but was not materialized):
to use the same setup at H18 as for previous q_n experiment:

I_0 = 200 n/s , λ= (20 ±0.15) Å, E =60 kV/cm, L =5 m

$q_n \geq 2 \cdot 10^{-22}\, e$ in 60 days - order of magnitude improvement

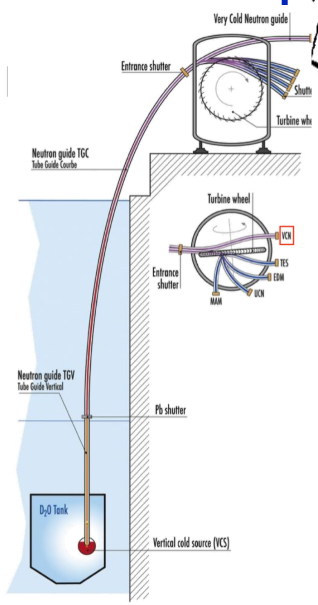


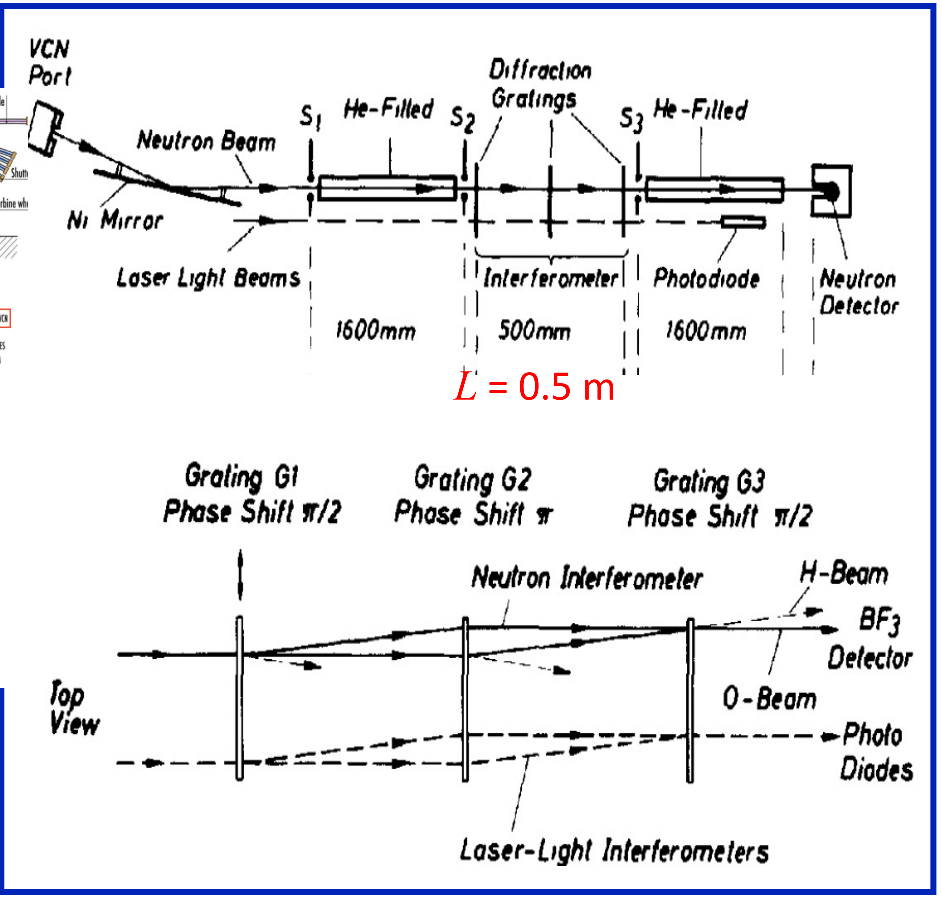
First realization of VCN diffraction grating interferometer

Volume 140, number 7,8 PHYSICS LETTERS A 9 October 1989

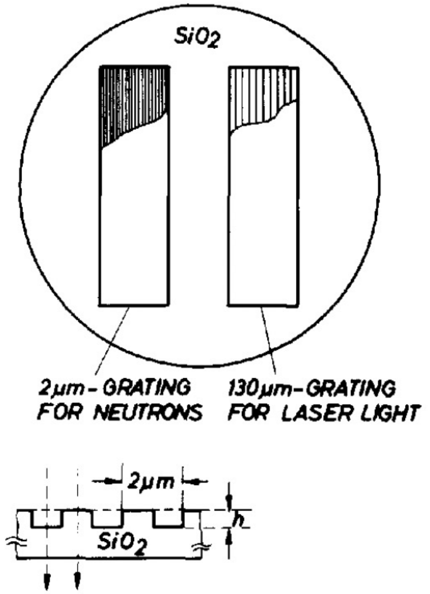
A PHASE-GRATING INTERFEROMETER FOR VERY COLD NEUTRONS

M.Gruber, K.Eder, A.Zeilinger, R.Gähler, W.Mampe



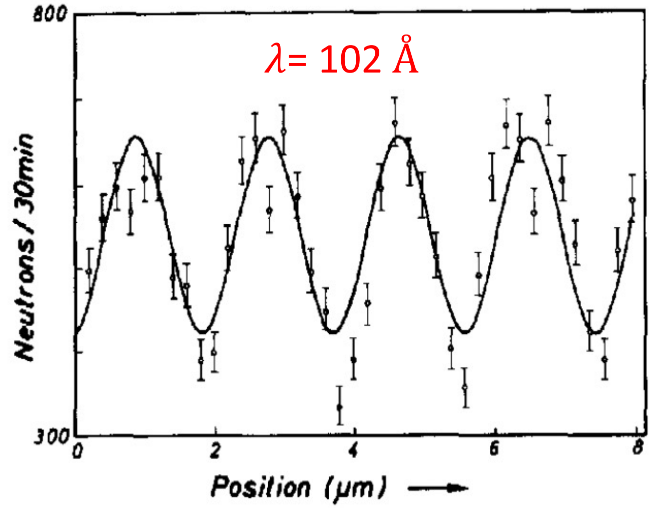


Phase diffraction gratings:



d = 2 μm

Interference pattern: obtained by translation of G_1 along its surface.



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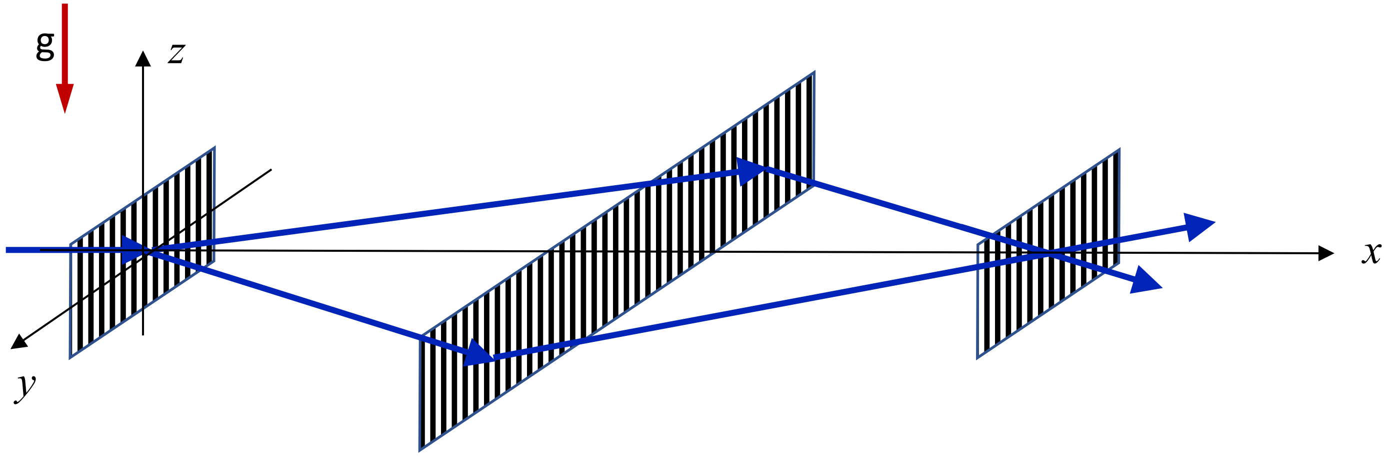
VCN diffraction grating interferometers in gravitational field



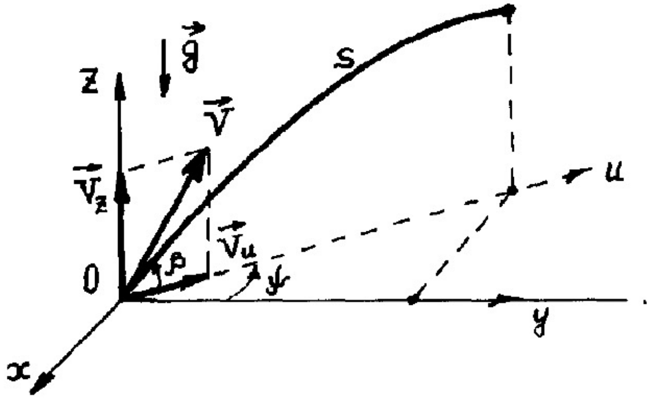
Refraction index of vacuum in gravitational field
(*I.M Frank, A.I Frank, JETP Lett.* ***28*** *(1978) 515*)

$$n = \sqrt{1 - 2gz\left(\frac{m_n}{h}\right)^2 \lambda^2}$$

Neutrons propagate on parabolic trajectories,
i.e. in the media with non-linear refraction index.

Quasi-classical approximation: calculations of the phase of neutron wave, propagating over classical trajectory

A.Ioffe, NIM A268 (1988) 169.



$$z = -\frac{gu^2}{2V_u^2} + \frac{V_z}{V_u} u \,.$$

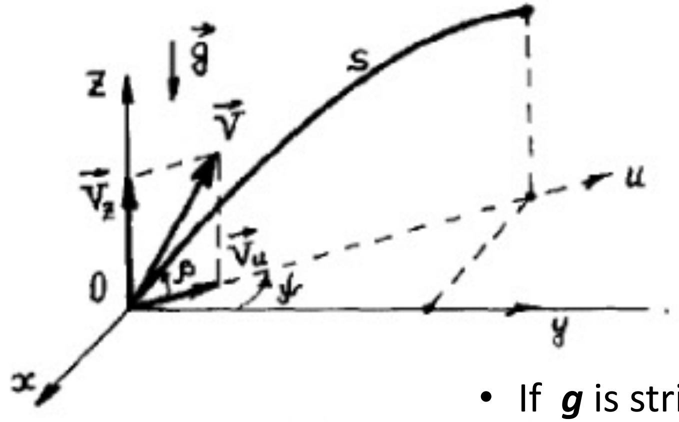
$$\lambda(u) = \frac{h}{m_n}\left[V_u^2 + \left(V_z - \frac{gu}{V_u}\right)^2\right]^{-1/2}$$

Gravitational phase shift:

$$\Phi = \int_0^{u_L} \frac{2\pi}{\lambda(u)} \sqrt{1 + \left(\frac{dz}{dx}\right)^2}\, du,$$

$$\varphi(u) = \frac{m_n}{\hbar}\left[uV_u + \frac{V_z^3}{3g} - \frac{V_u^3}{3g}\left(\tan\beta - \frac{gu}{V_u^2}\right)^3\right],$$

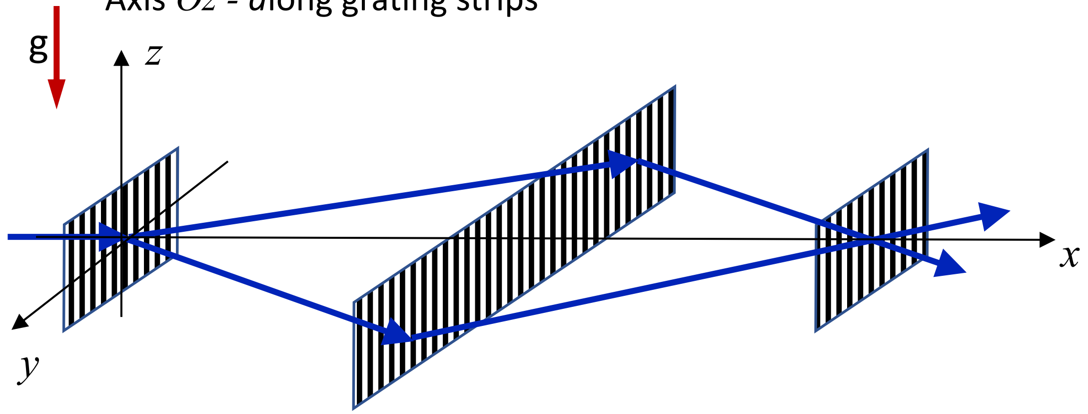
VCN grating interferometers in gravitational field

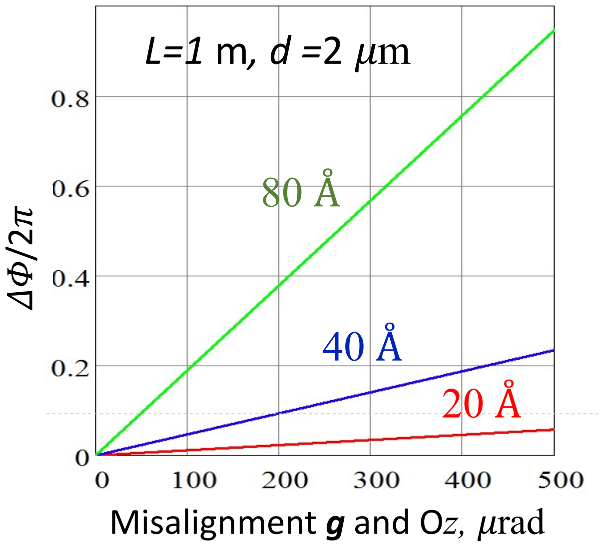


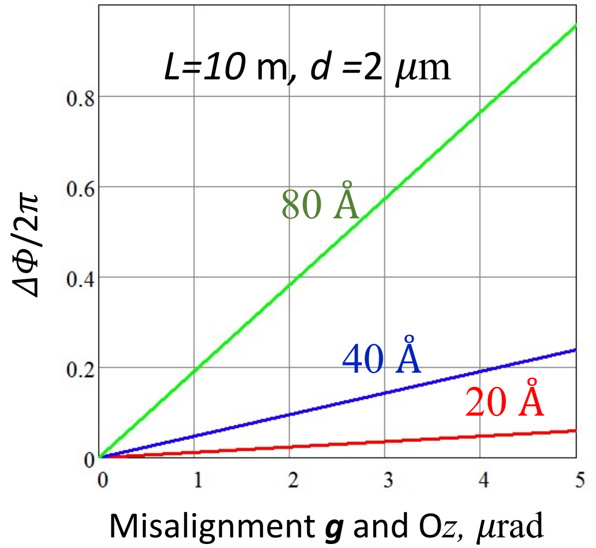
$$\Phi(u) = \frac{m_n}{\hbar}\left[uV_u + \frac{V_Z^3}{3g} - \frac{V_u^3}{3g}\left(\tan\beta - \frac{gu}{V_u^2}\right)^3\right],$$

Calculating the velocity components immediately after diffraction, it is possible to calculate the phase shift of neutron wave during its following propagation.

- If ***g*** is strictly parallel to O*z* (grating strips), gravitational potentials for both sub-beams are equal (symmetry).
- Violation of this symmetry leads to neutron trajectories rising to different heights => phase difference.



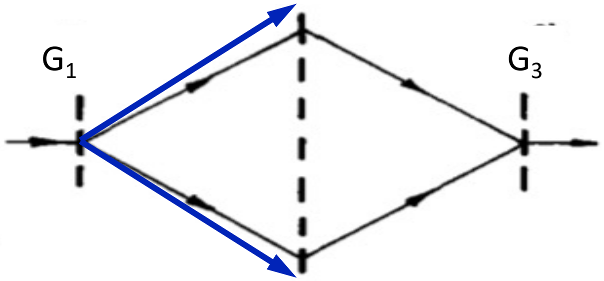




A challenge for the use of VCN !

Symmetric 4-grating interferometer

Sagnac effect

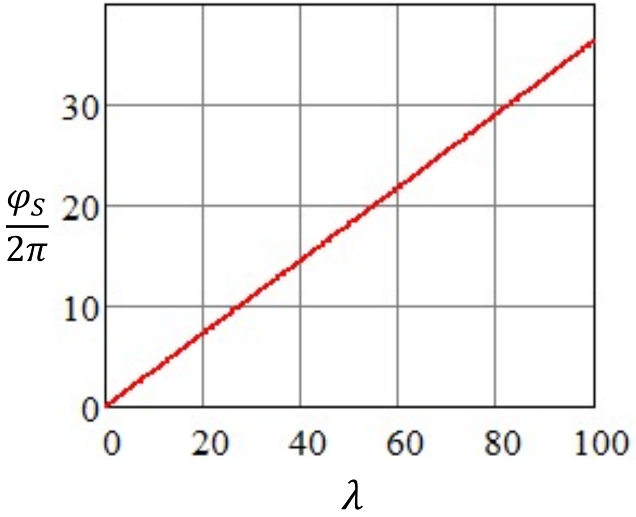


(+) for VCN: aberration-free, V=100% for full incoherent illumination
(-) for VCN: requires μrad alignment relative **g**
(-) parasitic Sagnac effect

$$\varphi_S = \frac{2m_n}{\hbar}(\boldsymbol{\omega}\cdot\boldsymbol{A}) = \frac{2m_n}{\hbar}\omega_0 A \sin\theta_1,$$

$\omega_0 = 7.29 \cdot 10^{-5}\ s^{-1}$ angular velocity (Earth's rotation)

$\theta_1 \approx 56°$ - latitude angle (Lund)



$A = \frac{\lambda}{d}\frac{L}{2}$ area enclosed by interfering beams

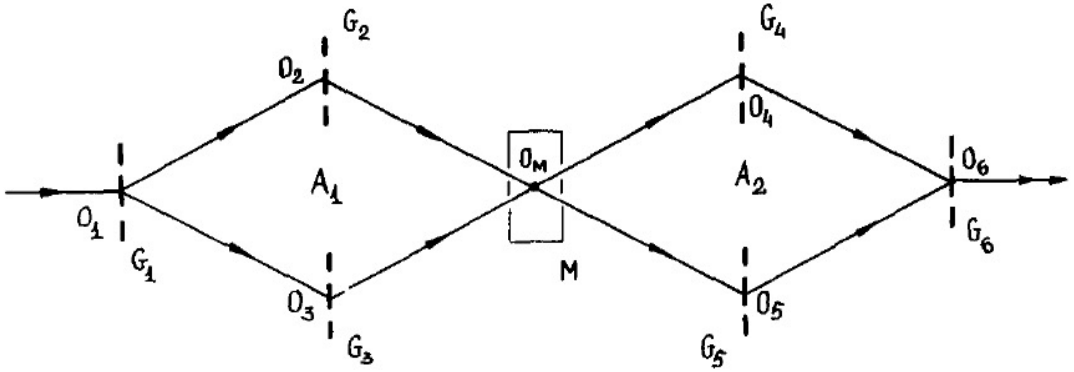
$\Delta\lambda \to \Delta A$ Scatter in λ

$$\Delta\varphi_S \sim \Delta A = \frac{\Delta\lambda}{\lambda}A = 0.1A$$

For $\Delta\varphi_S > \pi/2$ interference fringes are washed out.

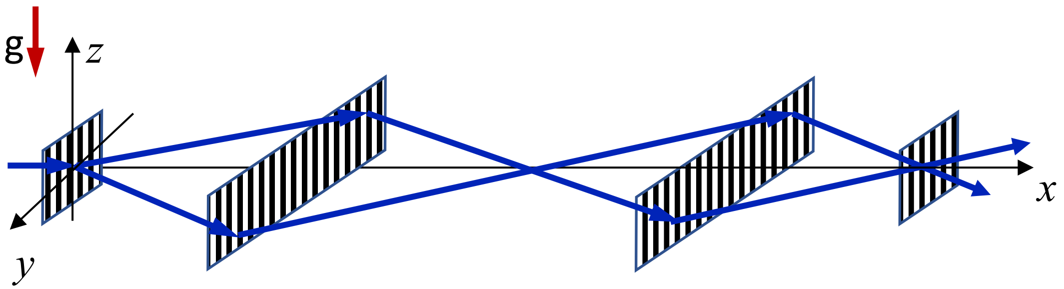
Symmetric 4-grating interferometer

A.Ioffe, NIM A268 (1988) 169.



$A_1 = A_2$ (symmetry) => Complete compensation of Sagnac phase shift

Also complete compensation of gravitational phase difference

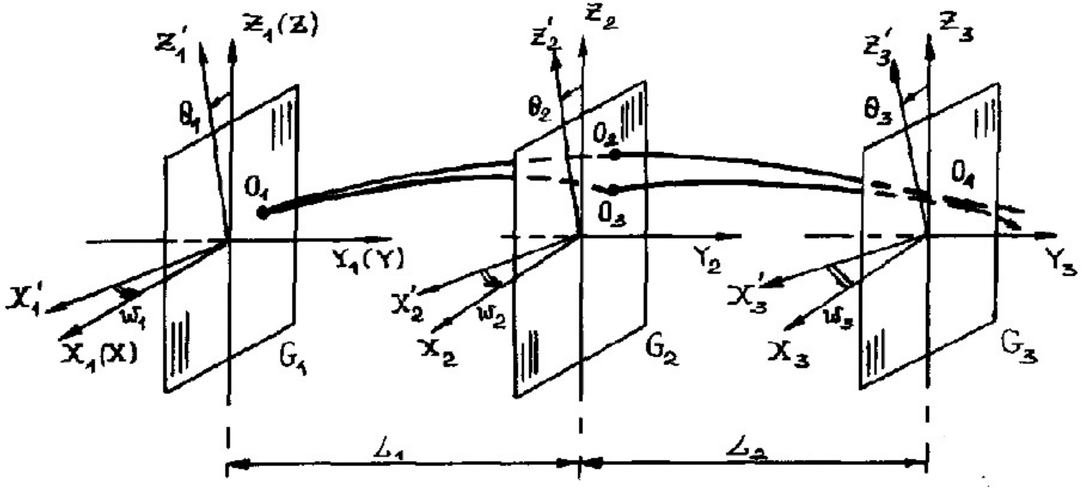


Not for free: one more grating - additional intensity losses

VCN grating interferometer: adjustment

Ray tracing (not Monte Carlo): regular grid defined by Shannon-Kotelnikov theorem, rather than random grid.

Non-parallelism of grating planes



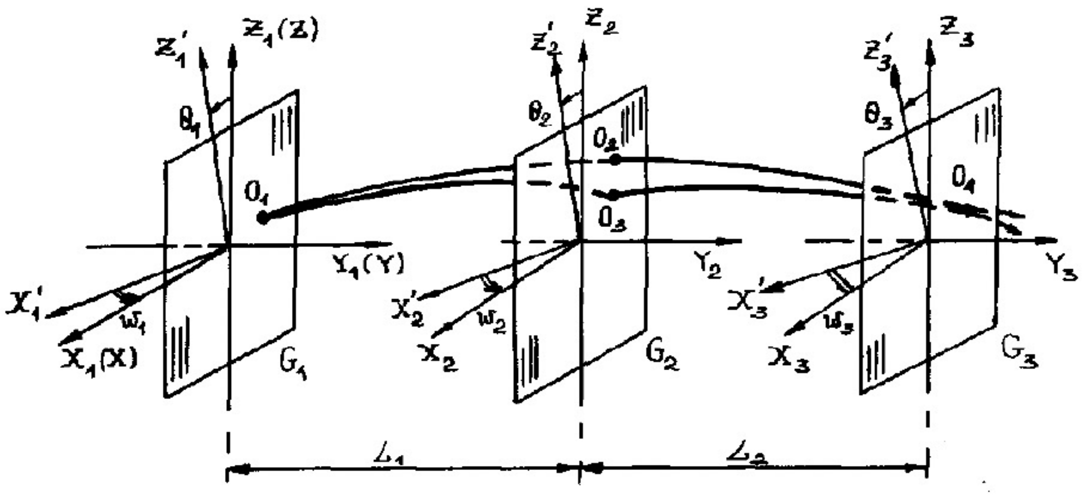
For each ray (neutron) and both interferometer arms:

1. Vector V of initial neutron velocity is defined in the laboratory frame XYZ (OZ parallel **g**)
2. Components of V are transformed to coordinate frame of grating G_1 by the Eulerian rotational matrix
3. Velocity vector components after diffraction are determined from diffraction grating equation.
4. Phase shift $\Phi(u)$ for propagation over path to G_2 is calculated.

$$\Phi(u) = \frac{m_n}{\hbar}\left[uV_u + \frac{V_Z^3}{3g} - \frac{V_u^3}{3g}\left(\tan\beta - \frac{gu}{V_u^2}\right)^3\right],$$

VCN grating interferometer: adjustment

Ray tracing (not MC): regular grid defined by Shannon-Kotelnikov theorem , rather than random grid.



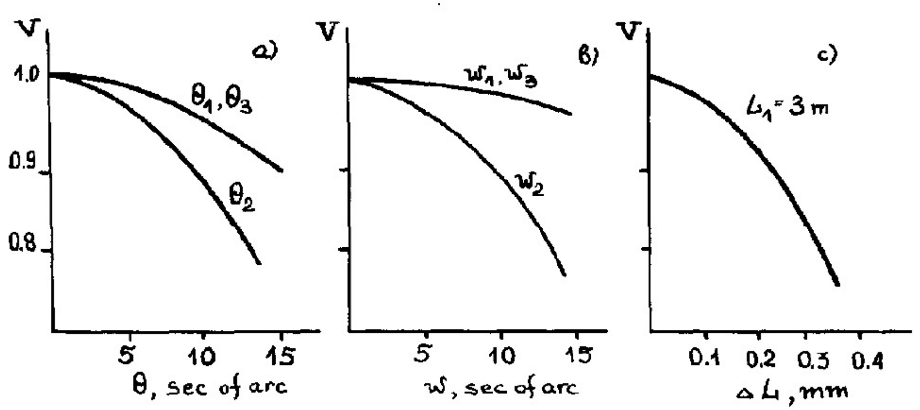
Non-parallelism of grating planes leads to:

- Path difference and spatial separation between interfering rays after diffraction on grating G_3
- Appearance of interference fringes in the output beam cross-section => reduced visibility.
- Visibility defines requirements to adjustment accuracy

Dependences of Visibility on misalignment

For L=6m, λ= 100 Å:
angular accuracy < 10" , $\Delta L < 0.15$ mm

Not a complicate technical problem.



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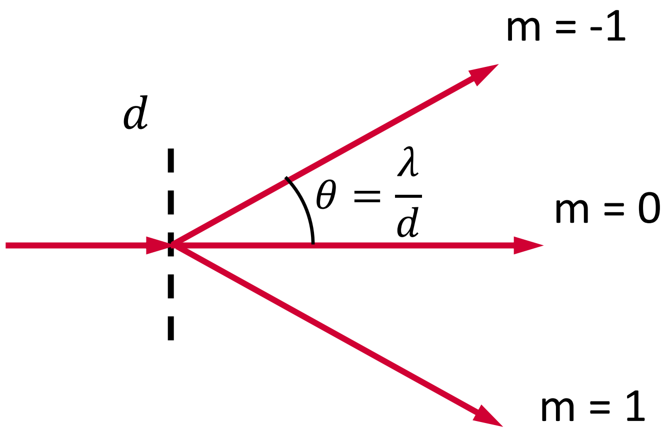
Diffraction gratings for VCNs

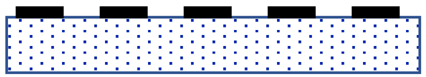


Requirements: small period and high diffraction efficiency

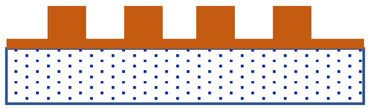
- Photolithographic gratings (stamping in photoresist)
- Holographic photolithographic gratings (interference lithography)
- Holographic nanodiamond-polymer composite gratings (next talk by J.Klepp)

Amplitude gratings

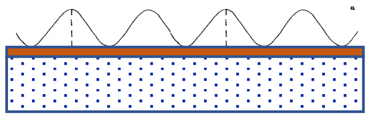
Gd

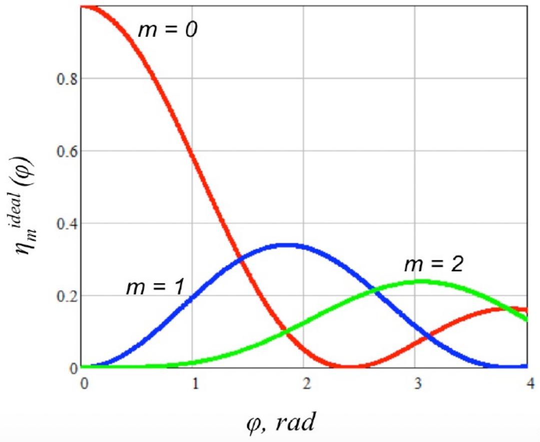


Phase gratings



φ - phase shift





Diffraction efficiency:

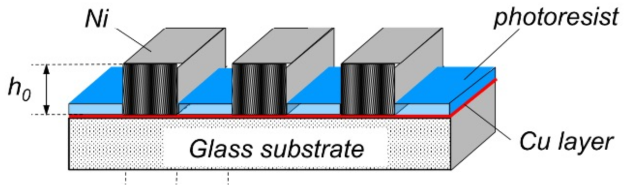
$\eta_m = \frac{1}{\pi^2 m^2}$ $\qquad$ $\eta_m = \frac{4}{\pi^2 m^2} \sin^2(\varphi)$ $\qquad$ $\eta_m = [J_m(\varphi)]^2$

$\eta_1^{max} = 10.1\%$ $\qquad$ $\eta_1^{max} = 40.4\%$ $\qquad$ $\eta_1^{max} = 33.8\%$

Diffraction gratings for VCNs

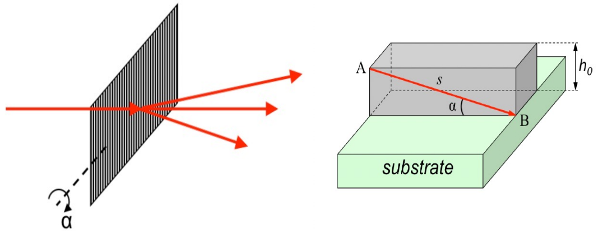
A. Ioffe, V. Pipich, JPS Conf. Proc.22, 011014 (2018)

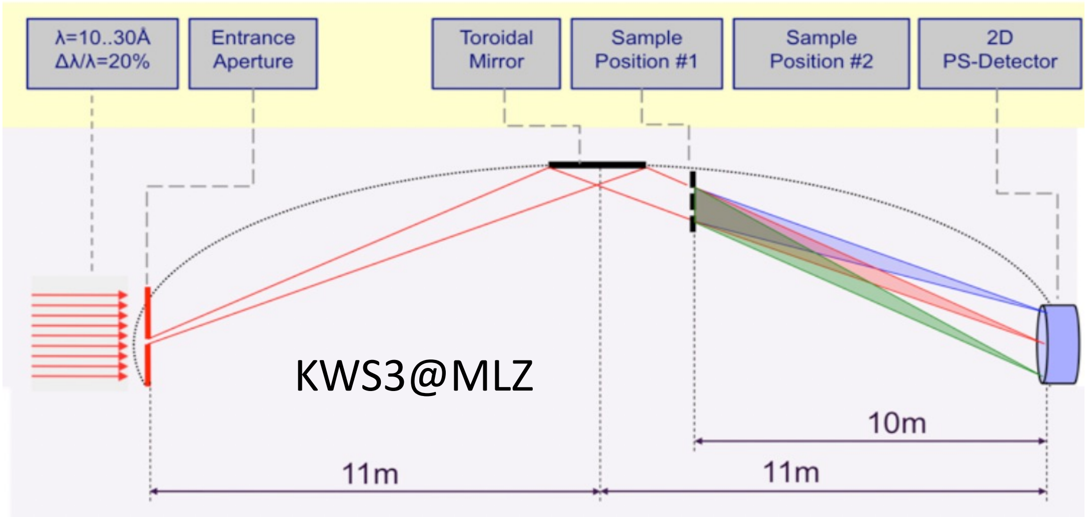
Electrochemical deposition through PR mask

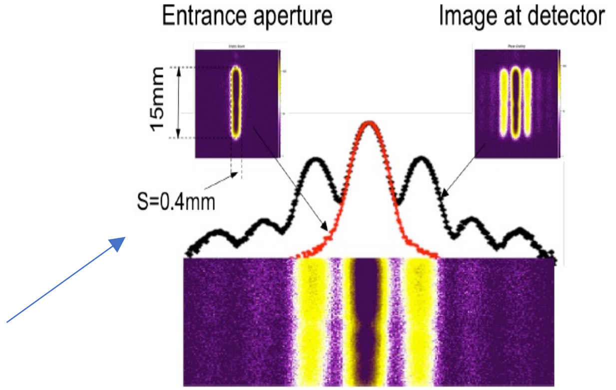


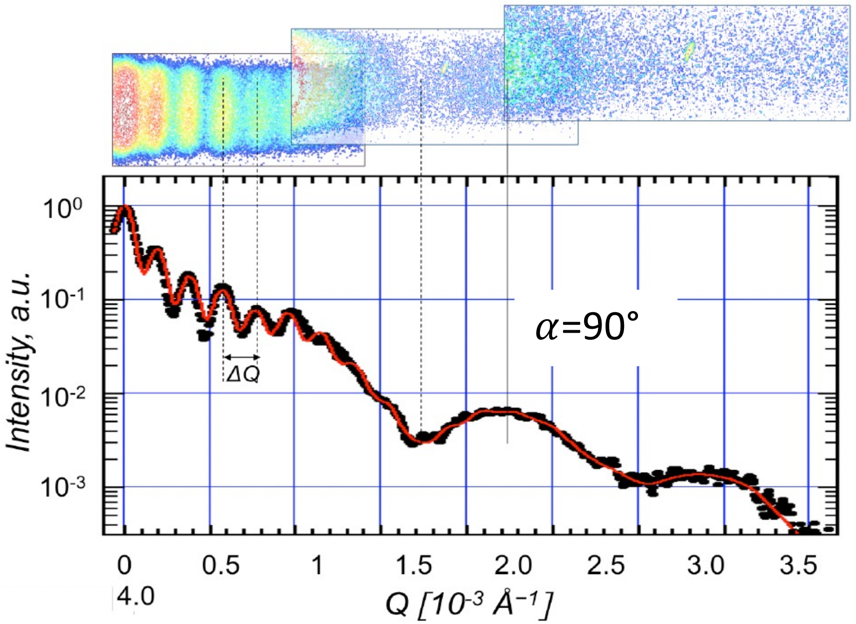
d = 3.3 μm , h_0=1.7 μm
phase shift $\varphi = \pi$ for λ=20 Å
(ILL experiment)

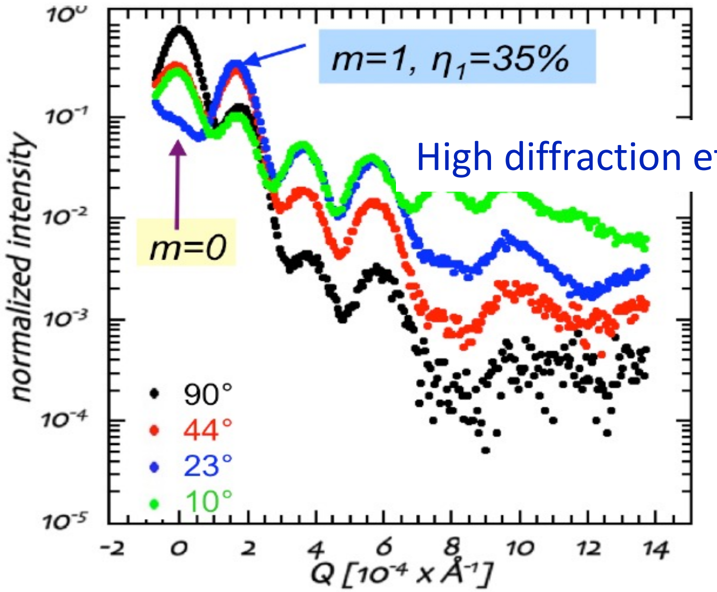
KWS3: λ=12.6 Å $\Rightarrow$ tilt
$\varphi/\sin(\alpha) = \pi$





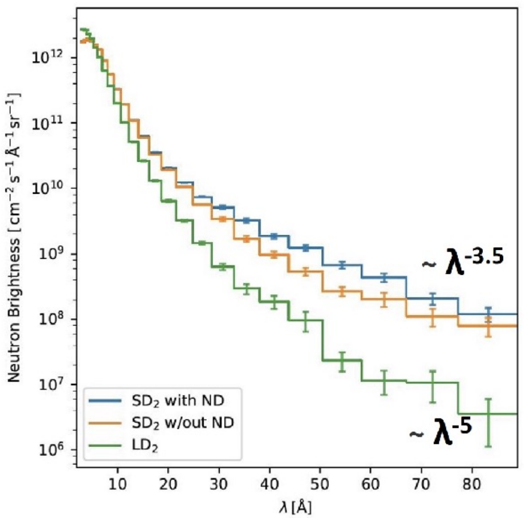


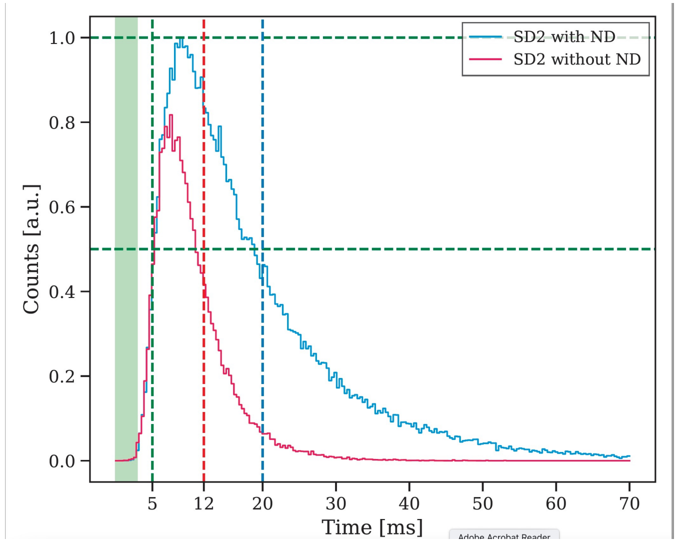




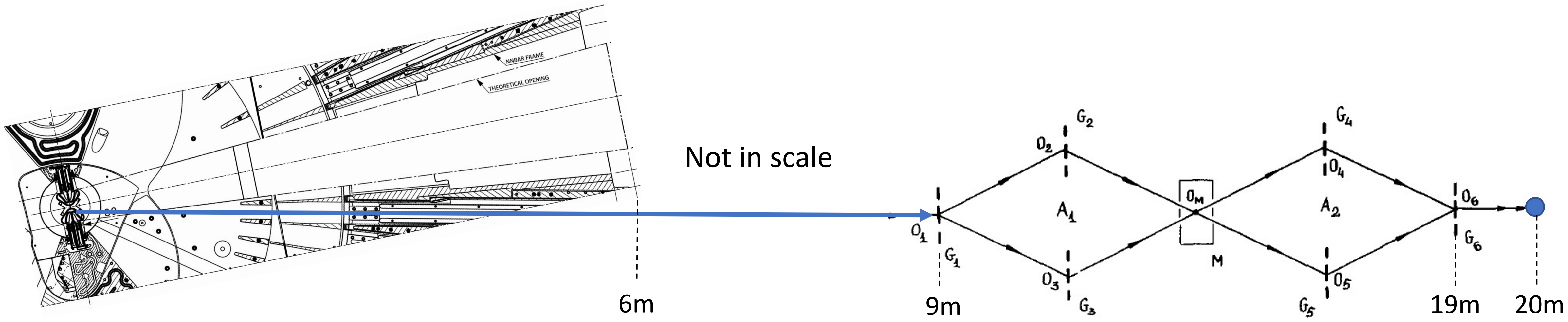
High diffraction efficiency

VCN diffraction grating interferometer at ESS





Data from L. Zanini



Not in scale

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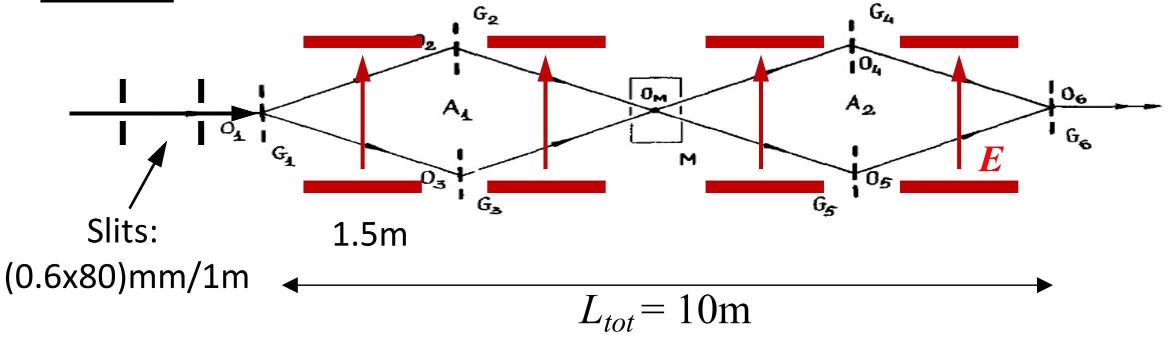
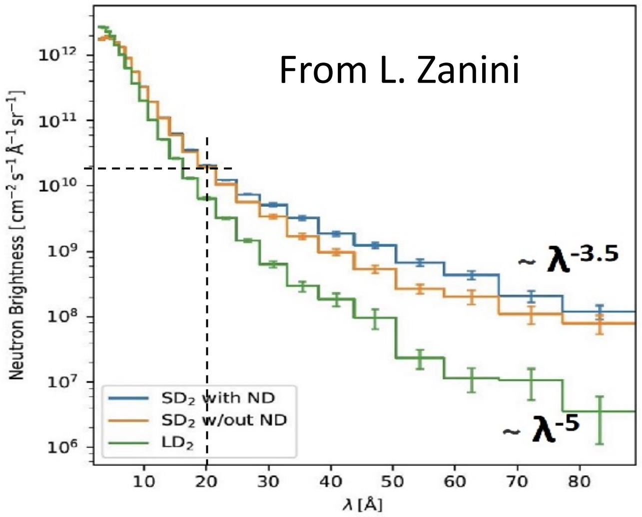
VCN diffraction grating interferometer at ESS: search for q_n

Top view





B (20 Å)= 2 x10^{10}

Expected counting rate:

$I_{rec}(20\ \text{Å}) \approx 4.9 \cdot 10^3$ n/s

$d = 2\ \mu m$
V=50%
E =60 kV/cm
L_E =6m

Beam parameters: the same as at the ILL setup

Beam cross-section: S_{beam} = 0.48 cm^2

Solid angles: ω_x = 0.0006

ω_y = 0.08 (L=10m, last slit is G_4)

$\Delta\lambda = 3956 \cdot T_{rep}/L_{source-det}$ =14 Å

$$q(\lambda) = \frac{\sqrt{2}\, d}{\pi \sqrt{I_{rec}(\lambda)\ 8.64\ 10^4\ N_{days}}} \frac{1.65}{V\ E\ L^2\ \lambda^2} \left(\frac{h}{m}\right)^2$$

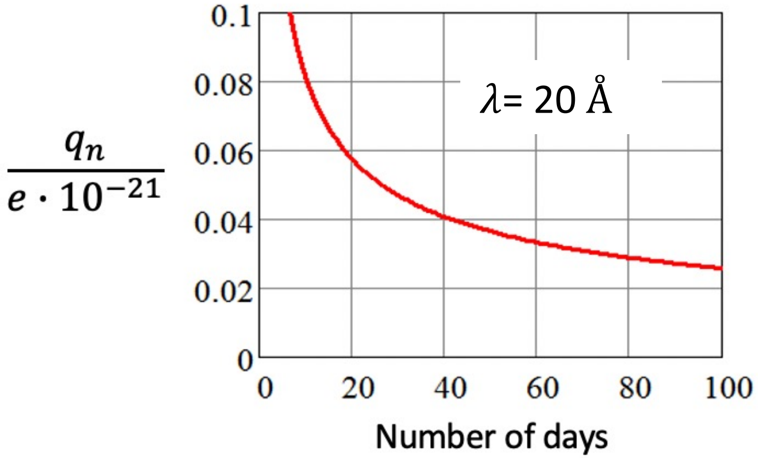
Diffraction efficiency: η^4 =0.008 (η = 30%)

Transmission of substrates (λ= 20 Å) :

Si 4 x 0.07 cm: T_{Si}= 0.93

SiO_2 4 x 0.3 cm: T_{SiO2} = 0.63

$$I_{rec}(\lambda) = B(\lambda)\ S_{beam}\ \omega_x\ \omega_y\ \eta^4\ \Delta\lambda\ T_{SiO2}$$



$q_n \geq 3 \cdot 10^{-23}\ e$ in 80 days (CI 90%)

2 orders of magnitude better, than the present day limit

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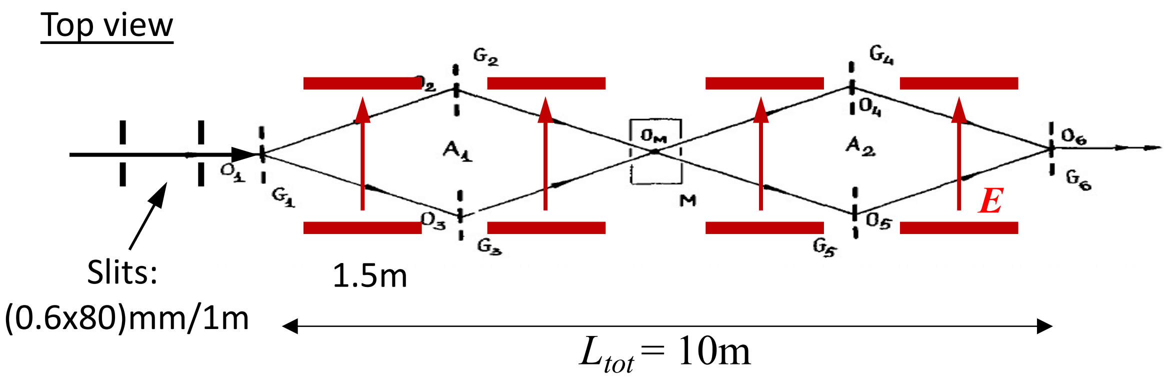
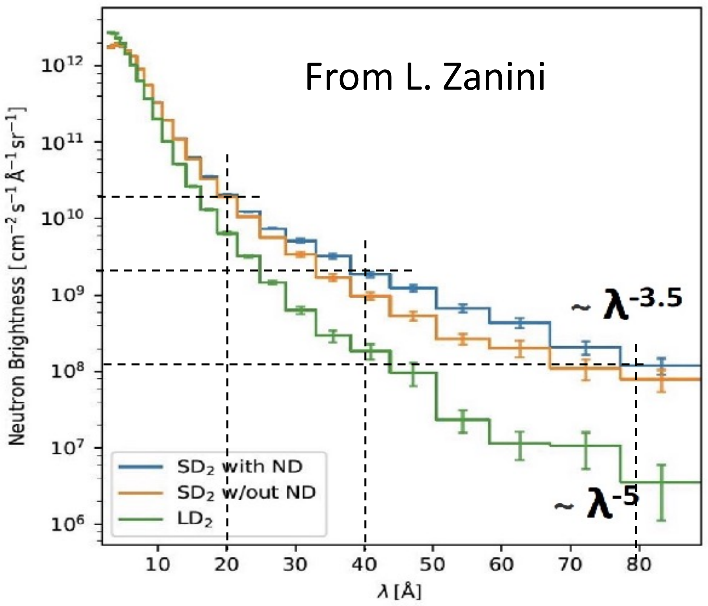
VCN diffraction grating interferometer at ESS: search for q_n





Expected counting rate:

$I_{rec}(20\ \text{Å}) \approx 4.9\cdot 10^3$ n/s

$I_{rec}(40\ \text{Å}) \approx 4.9\cdot 10^2$ n/s

$I_{rec}(80\ \text{Å}) \approx 4\cdot 10^1$ n/s

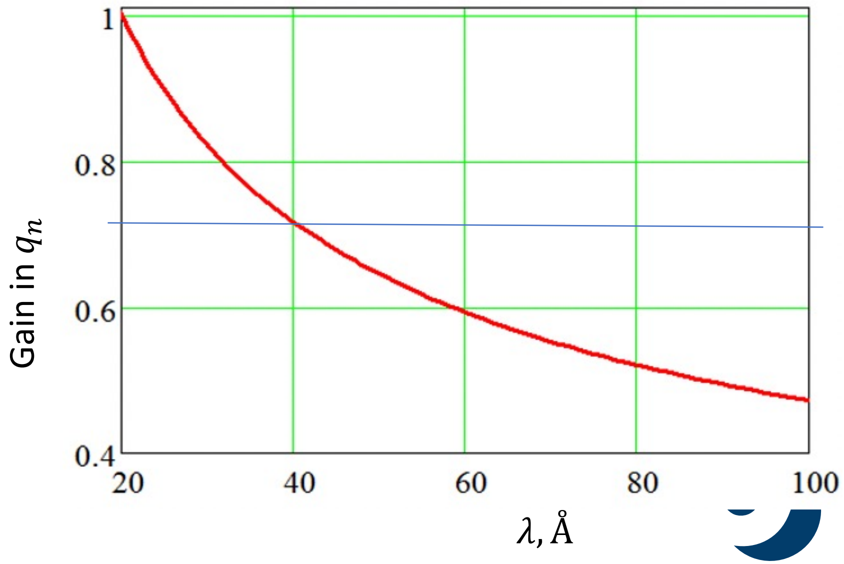
Transition to higher λ : does it make sense?

$$q_n \sim \frac{d}{\sqrt{I_0} E\ L^2\ \lambda^2}$$

LD$_2$: $q_n \sim \dfrac{1}{\lambda^{-2.5}\ \lambda^2} \sim \lambda^{0.5}$ Getting worse

SD$_2$: $q_n \sim \dfrac{1}{\lambda^{-1.75}\ \lambda^2} \sim \lambda^{-0.25}$ Getting better

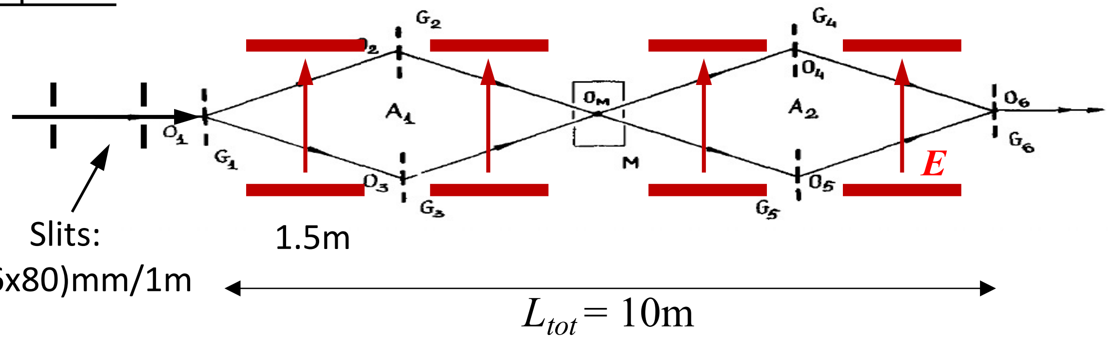
SD$_2$ is a game changer.



Transition from 20 Å to 80 Å gives factor of 2 improvement:

$q_n \geq 1.5 \cdot 10^{-23}\ e$ in 80 days (CI 90%)

Potential for further improvements in search for q_n



$$q_n \sim \frac{d}{\sqrt{I_0}\, E\, L^2\, \lambda^2}$$

Practically, only “free” parameter is grating period d .

Reducing the period d of diffraction gratings to sub-μm:

$\Rightarrow$ direct gain as $q_n \sim d$

$\Rightarrow$ increase of diffraction angle $\theta = \frac{\lambda}{d}$,

therefore gain in incident beam intensity $\sim d^2$:

gain in solid angle $\omega_x \sim d$ (still $\ll \lambda/d$)

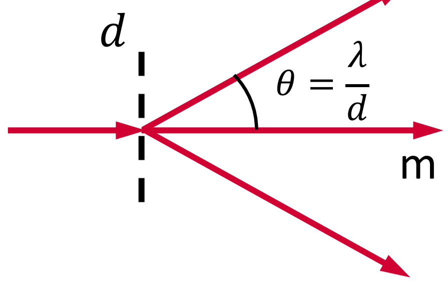
gain in beam cross-section $\sim d$

Overall gain in $q_n \sim d^{-2}$

V=50%, E =60 kV/cm, L_E =6m

Beam parameters:

Beam cross-section: $S_{beam} = 0.48\ cm^2$
Solid angles:
$\omega_x = 0.0006 \ll \lambda/d = 0.005$
$\omega_y = 0.08$ (L=10m, last slit is G_4)
Band: $\Delta\lambda = 14$ Å



d: 2 μm --> 0.5 μm results in additional improvement by an order of magnitude: $q_n \geq 10^{-24}\ e$

=> Holographic (interference) gratings

Conclusion

- Interferometry of cold, especially Very Cold Neutrons (VCN) requires diffraction gratings for effective coherent splitting of neutron waves.
- Diffraction gratings introduce distortions (aberrations) in propagating waves, that however can be compensated in 3-grating neutron interferometer. Such interferometer works regardless of the source coherence, i.e. for **non-monochromatic and non-collimated neutron beams**.
- The Earth gravitational field causes additional aberrations of neutron waves. Moreover, the Earth rotation results in an additional phase shift (Sagnac effect). Each of these makes large VCN interferometers unfeasible.
- Symmetric 4-grating interferometer allows for the full compensation of both above mentioned effects.
- Such interferometer can be used for the neutron charge quest. Being installed at a new high-brilliance VCN source at ESS it will allow to improve the present day experimental limit on neutron charge by 2 orders of magnitude, down to $3 \cdot 10^{-23}$ *e.*
- The use of holographic (interference) gratings with sub-μm period should allow for additional gain of about 10.

Thank you for attention!