



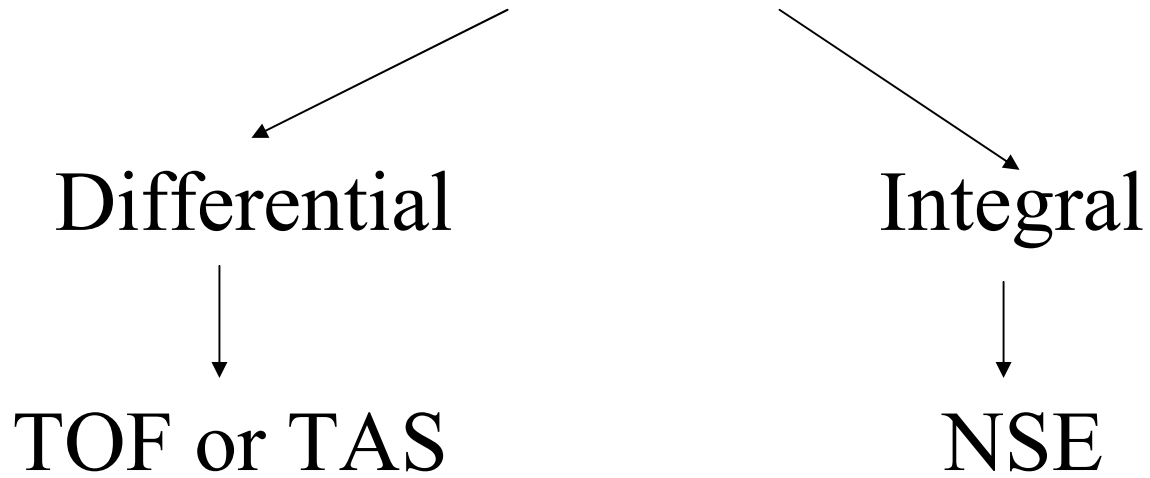
# A new instrumentation for VCN spectroscopy

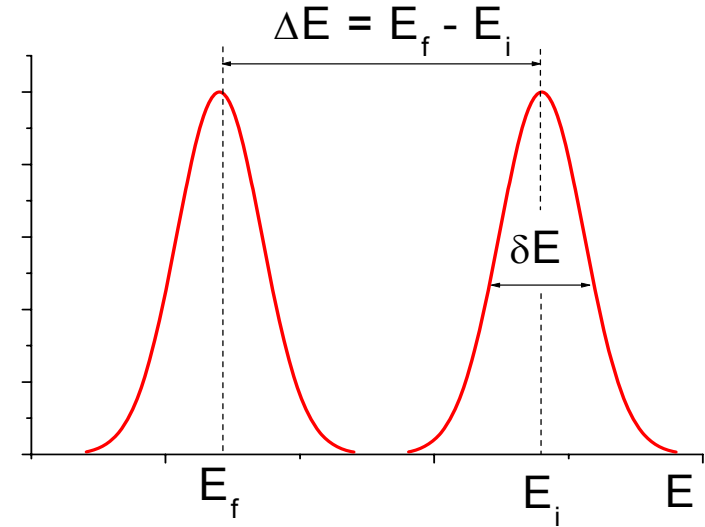
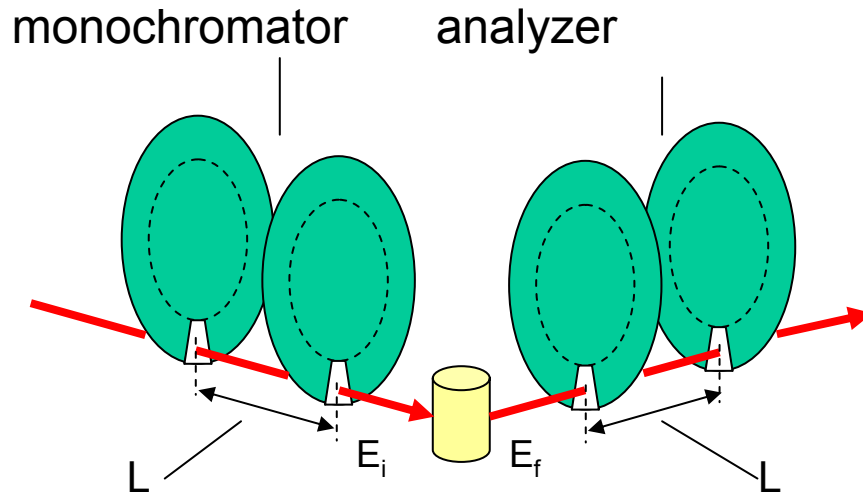
*Alexander Ioffe*

*Jülich Centre for Neutron Science,  
Forschungszentrum Jülich, Germany*

VCN Workshop, PSI, 13-14 February 2006

# Spectroscopy methods





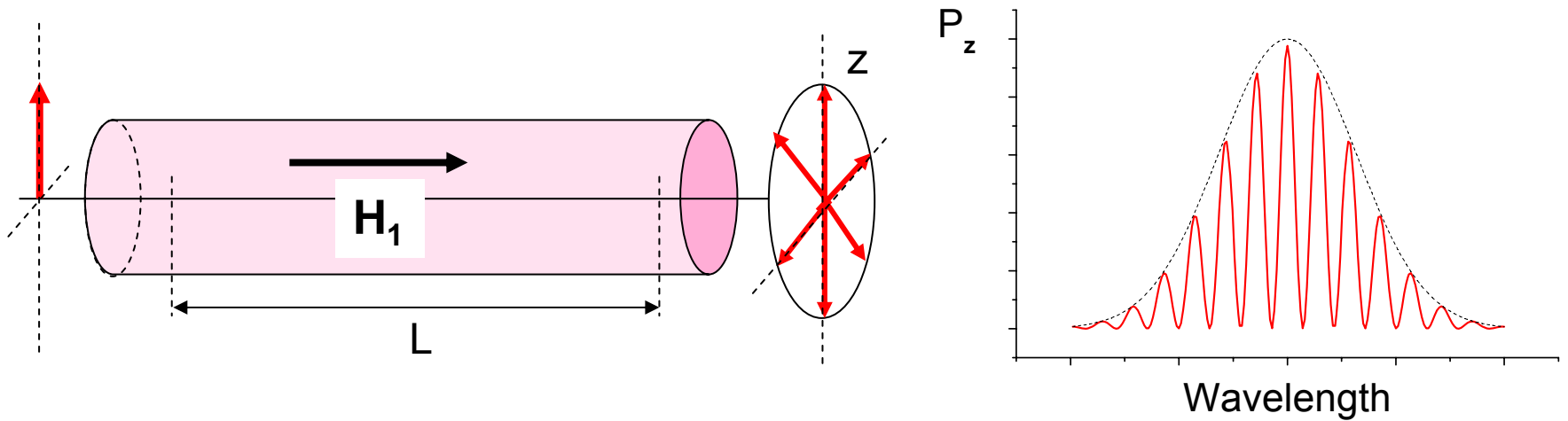
Classical neutron spectroscopy:  
the neutron crowd - neutrons in the beam are indistinguishable.

Energy exchange = the difference of two well-defined mean energies:

$$\Delta E = E_f - E_i$$

High E-resolution → very well defined  $E_i$  &  $E_f$ , i.e. small  $\delta E$  →  
 → low intensity: **not an option for VCN spectrometry**

# Larmor clock: neutron spin precession in magnetic field



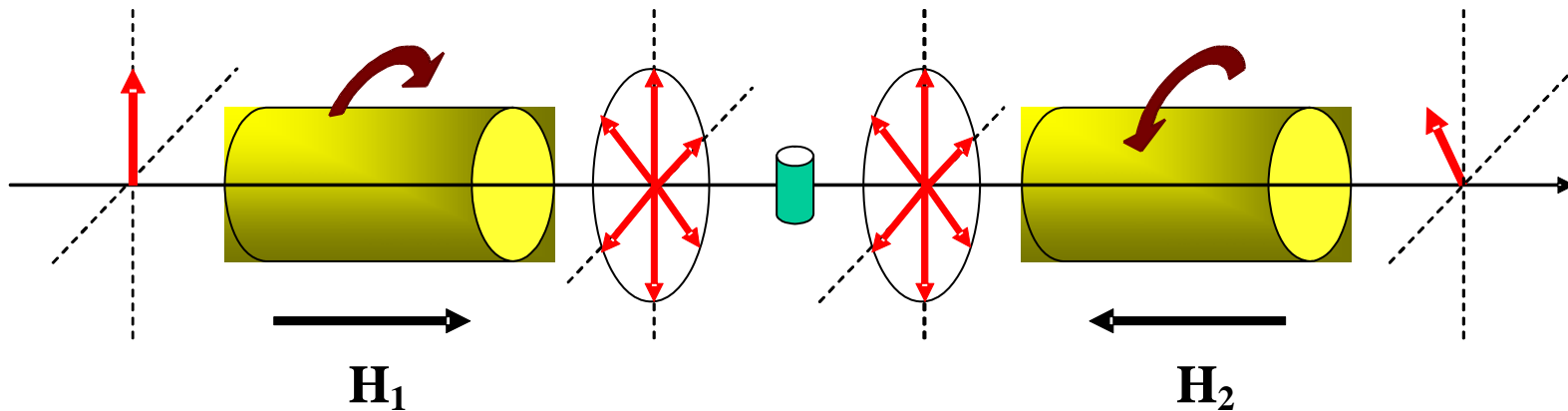
The Larmor clock position depends only on  $\lambda$ : 
$$\varphi = \omega_L \frac{L}{v_n} = \gamma B L \frac{m_n \lambda}{h}$$

Individualization of neutrons:  
each neutron in the beam has its own label

This is the wavelength (speed) encoding - Larmor labelling:  
the speed of every neutron is coded by its spin direction

# Encoder-decoder combination

Neutron spin echo spectrometer is the encoder-decoder combination:  
Larmor clocks go forward before and back after the sample.



$$\varphi = \omega_L \left[ \frac{L}{V_f} - \frac{L}{V_i} \right] = \gamma B L \frac{m_n}{h} \Delta \lambda \propto \Delta E \quad - \text{one directly measures } \Delta E$$

Indeed, no monochromator/analyzer  $\rightarrow$  no corresponding intensity losses  
 $\rightarrow$  very small  $\Delta E$  achievable.

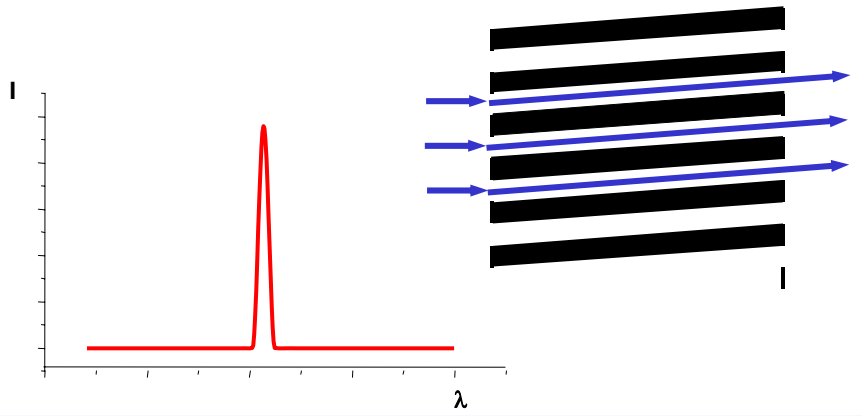
**Conclusion:** the crucial part of a NSE spectrometer  
being the  $\lambda$  (speed) encoder

- Polarization:  
costs a lot of intensity  
practically prohibits studies of magnetic samples

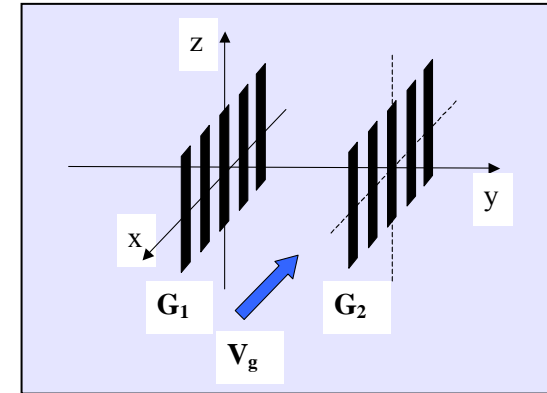
„Neutron Spin Echo Principle“, i.e direct measurements  
of  $(k_i - k_f)$  for non-polarized neutrons?

Neutron Spin Echo without spin =  
= Neutron Speed Echo (NSPE)

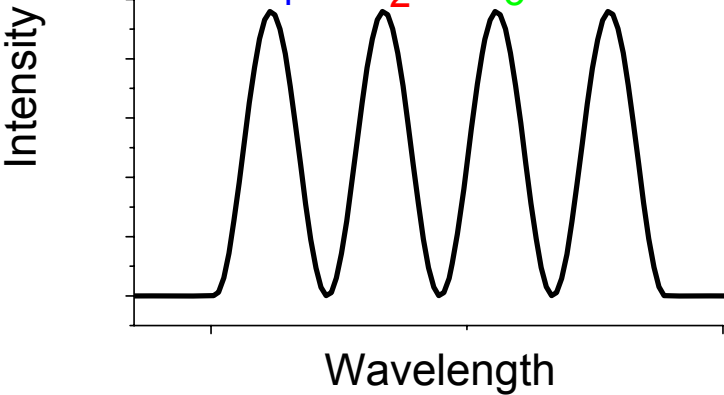
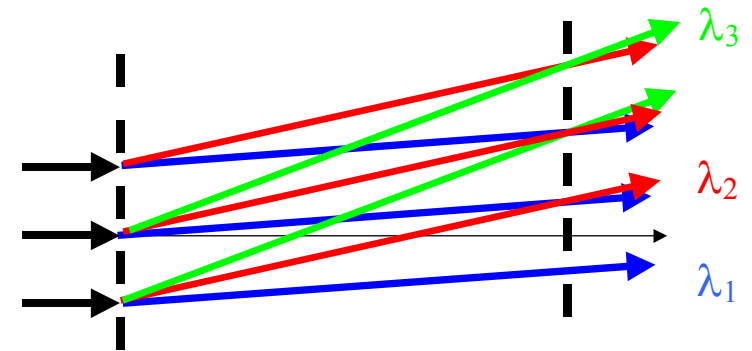
Velocity selector:



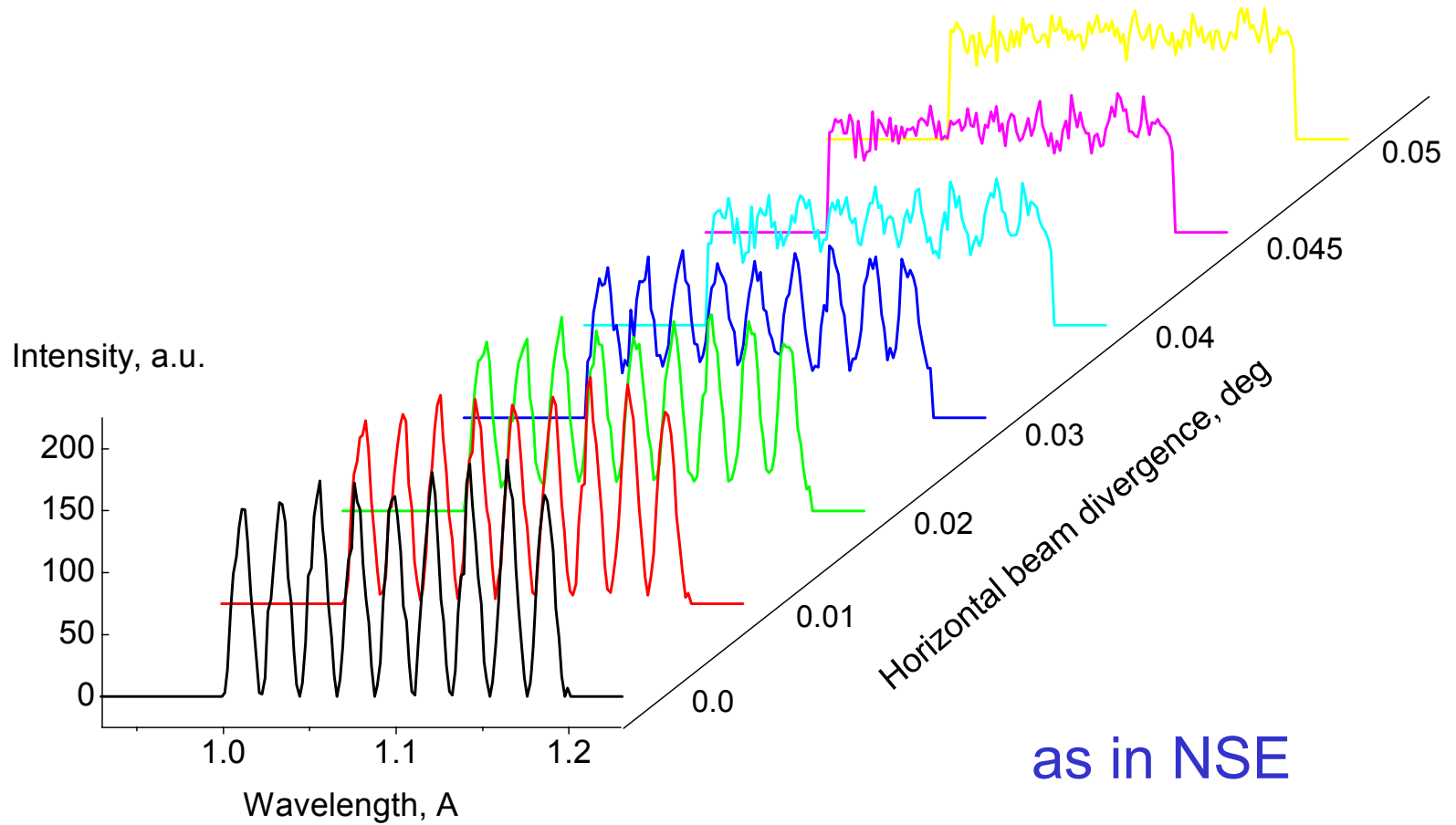
Two moving amplitude structures (gratings) - multiple velocity selector:



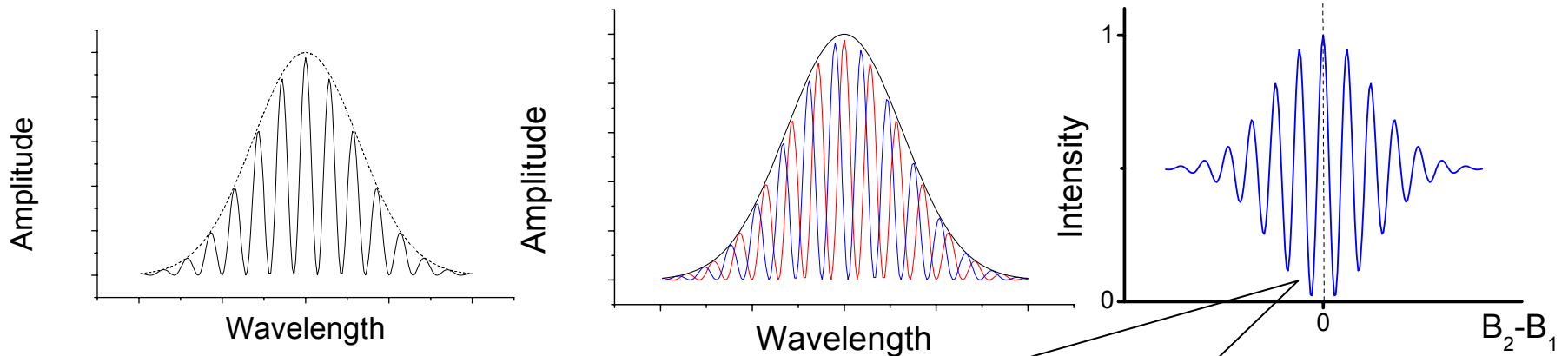
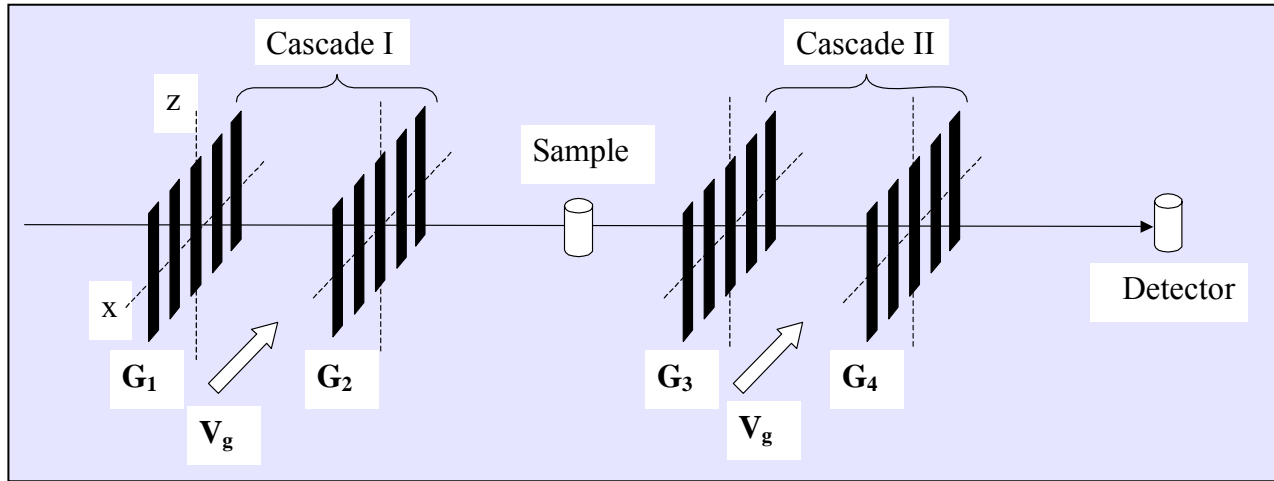
In the moving reference frame:



# Reduction of the modulation depth with the increase of beam divergence

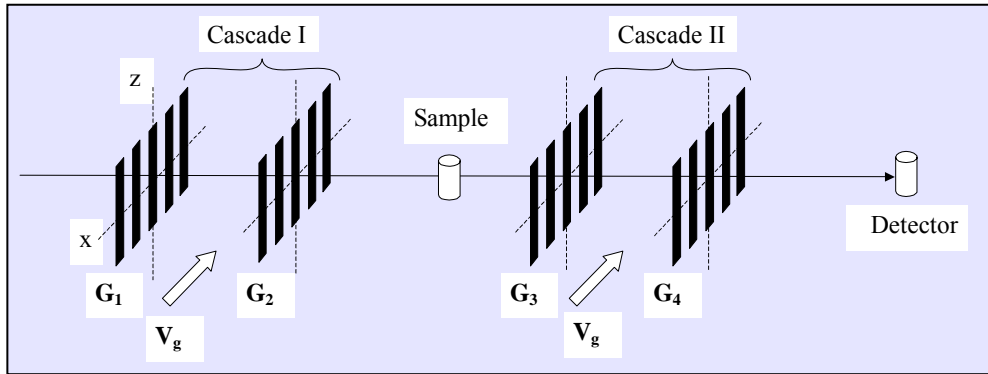


# Restoration of the modulation: NSPE spectrometer



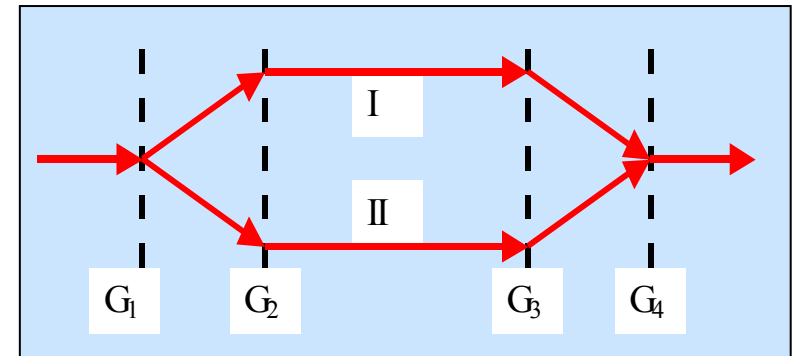
The convolution of velocity spectra results in the recovering of information (like in NSE).

# NSPE spectrometer as interferometer



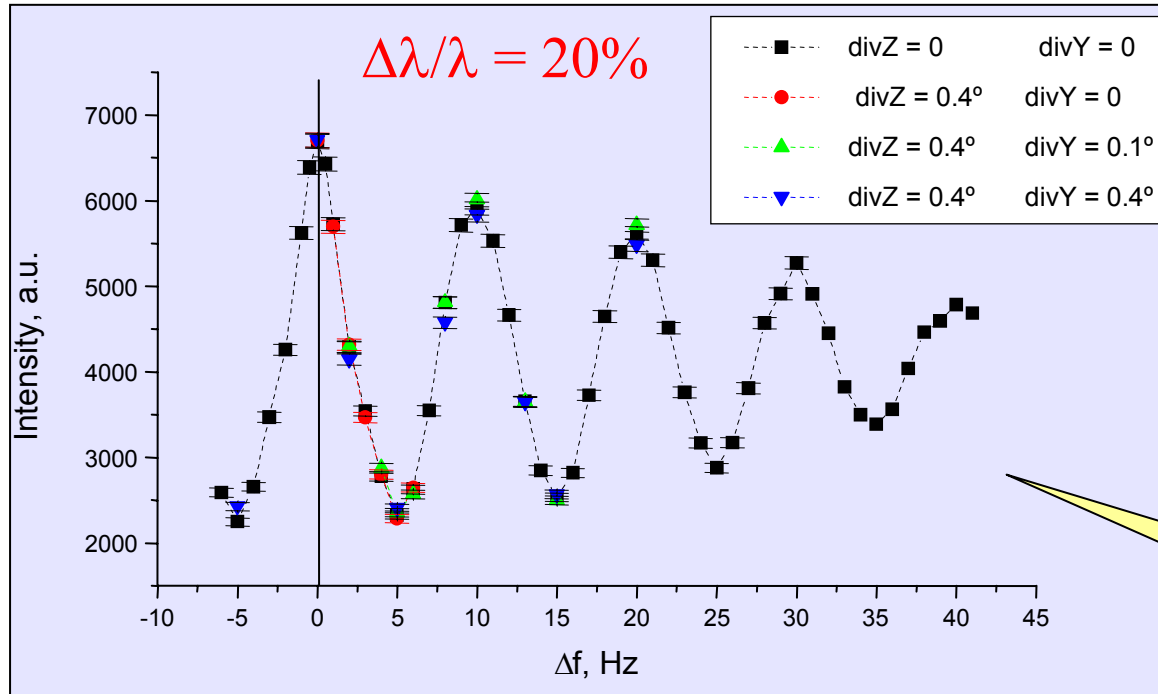
Neutron optics:  
NSPE spectrometer  
is a 4-grating neutron  
interferometer.

Aberration-free scheme:  
such spectrometer should  
operate with **non-collimated**  
and **non-monochromatic**  
incident beam.



It does!

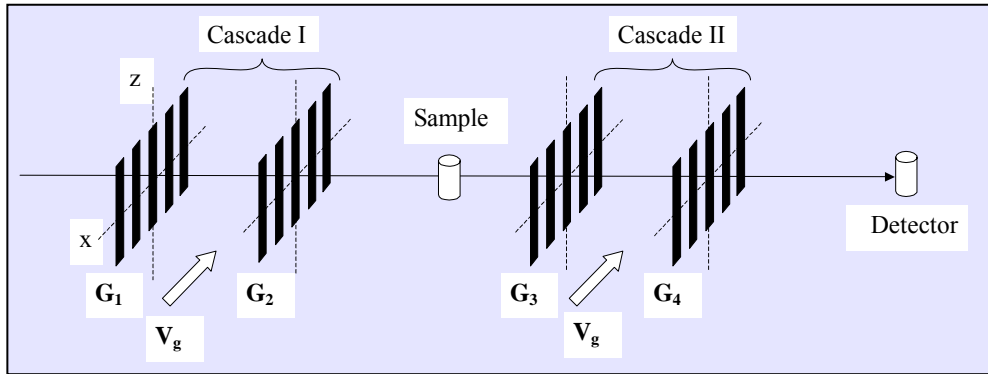
Monte Carlo simulations (VITESS)



Neutron Speed  
Echo Signal

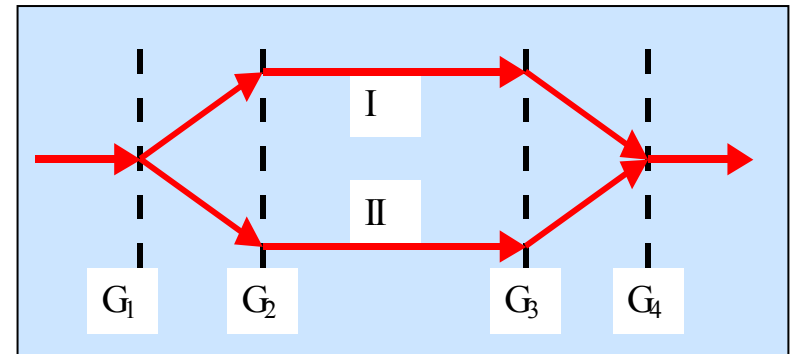
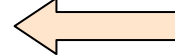
Nor collimation neither monochromatization is required!

# NSPE spectrometer as interferometer



Neutron optics:  
NSPE spectrometer  
is a 4-grating neutron  
interferometer.

Will operate with  
phase gratings as well



	<u>NSE</u>	<u>NSPE</u>
Output signal:	$I \propto \cos^2 \left( 2\pi \gamma B \frac{L}{v_n} \right)$ $I = f(B_2 - B_1)$	$I \propto \cos^2 \left( 2\pi \frac{V_g}{d} \frac{L}{v_n} \right)$ $I = f(V_g^{(2)} - V_g^{(1)})$ $I = f(L_2 - L_1)$
Modulation frequency:	$\omega = \gamma \cdot B$	$\omega = V_g / d$
Number of turns	$\gamma \int_L B ds \quad 7.5 \cdot 10^6 \quad (0.25 \text{ T} \cdot \text{m})$	$\frac{V_g}{d} L \quad 4 \cdot 10^8 \quad (V_g = 400 \text{ m/s}; d = 1 \mu\text{m}, L = 2 \text{ m})$
	Required the use of polarized neutrons	Does not require the use of polarized neutrons

Energy resolution for inelastic scattering:

$$\frac{\Delta E_n}{E_n} = 2 \frac{\Delta V_n}{V_n} = \frac{d}{\pi L} \frac{V_n}{V_g} r$$

$r$  - the accuracy of the NSPE signal 'phase shift' determination

$$V_g = 400 \text{ m/s}, L = 2 \text{ m},$$

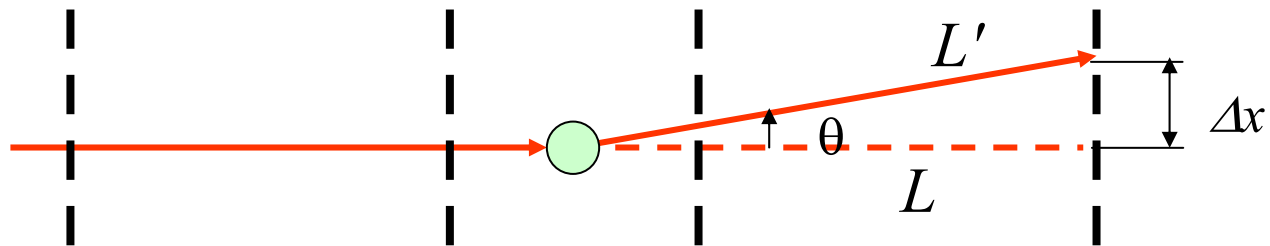
$$d = 1 \text{ } \mu\text{m}, \quad r = 5\%,$$

$$\text{VCN: } V_n = 20 \text{ m/s}, E = 2 \text{ } \mu\text{eV}$$

$$\frac{\Delta E_n}{E_n} = \frac{10^{-6}}{\pi \cdot 2} \cdot \frac{20}{400} \cdot 0.05 = 4 \cdot 10^{-10}$$

$$\Delta E_n \approx 8 \cdot 10^{-16} \approx 1 \text{ feV.}$$

Scattering on a sample:



- Intrinsic problem of NSPE spectroscopy
- Limits the resolution of NSPE spectrometers
- Similar to NRSE: requires a kind of correction elements

„Non-scattering“ sample

- forward scattering
- refraction

- no problems!

$$\Delta E_n \approx 8 \cdot 10^{-16} \approx 1 \text{ feV.}$$

What one can do with such resolution  
and  
„non-scattering“ sample?

## Forward scattering

- EDM - far away ...
- Neutron electric charge  $E = q_n U = 10^{-21} \text{ e} \cdot 100 \text{ kV} = 10^{-16} \text{ eV}$

This is possible: some reserves in the estimate

E.g.:  $r \rightarrow 0.5\%$  : the phase shift of two sinusoidal curves  
as in neutron interferometry.

What's more?

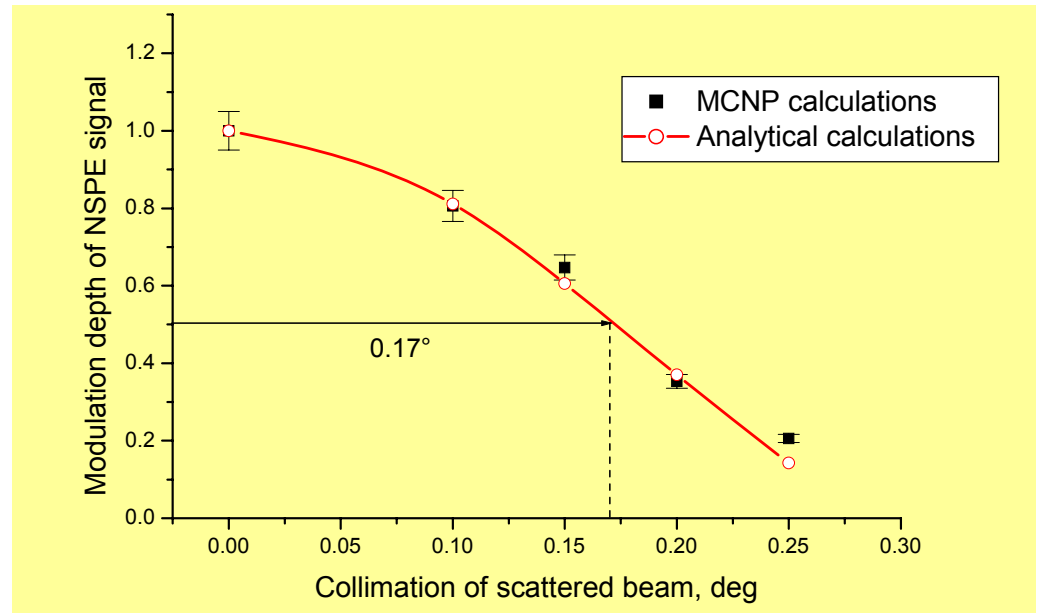
## Refraction ??

Scattering on the sample → reduction of the modulation of the NSPE signal:  $\theta < d/L$

E.g.:  $d/L=0.01$

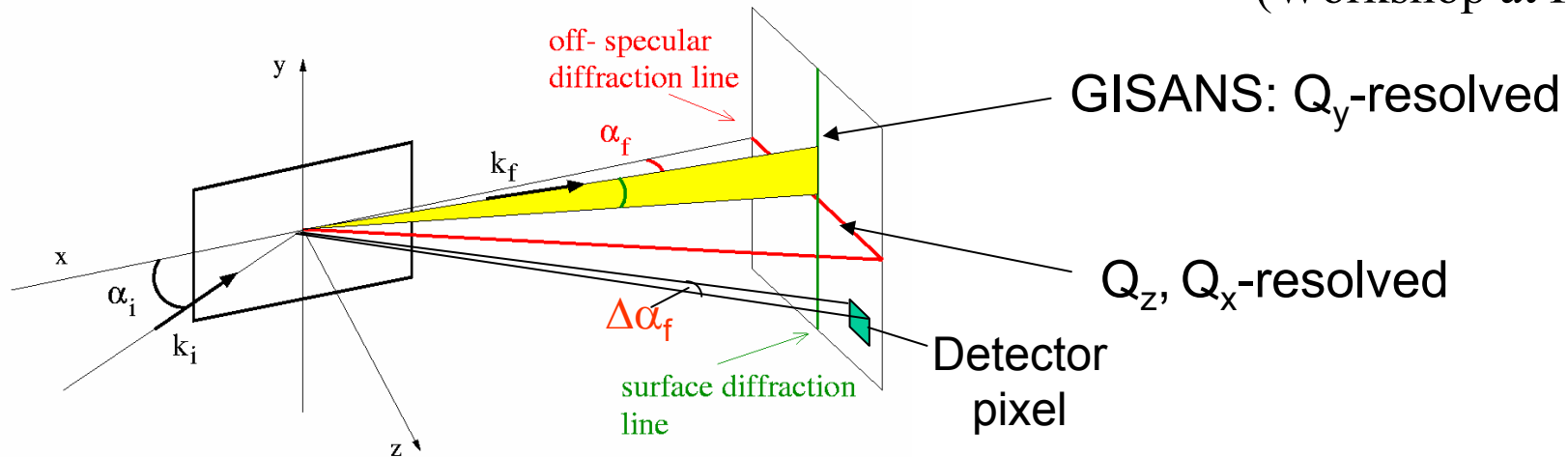


$$\frac{\Delta E_n}{E_n} = \frac{d}{\pi L} \frac{V_n}{V_g} r \rightarrow 10^{-5}$$



- Scattering on the sample impose a limit on the E-resolution
- $\Delta E_n \approx 2 \mu\text{eV} \cdot 10^{-5} \approx 0.01 \text{ neV}$  – is it good?

(Workshop at PSI, 2005)



VCN: larger  $\lambda \rightarrow$  larger  $\alpha_i$  (factor 10)  
 $\rightarrow$  larger beam area  $\rightarrow Q_z = \frac{2\pi}{\lambda} \alpha_i$  - the same as for CN

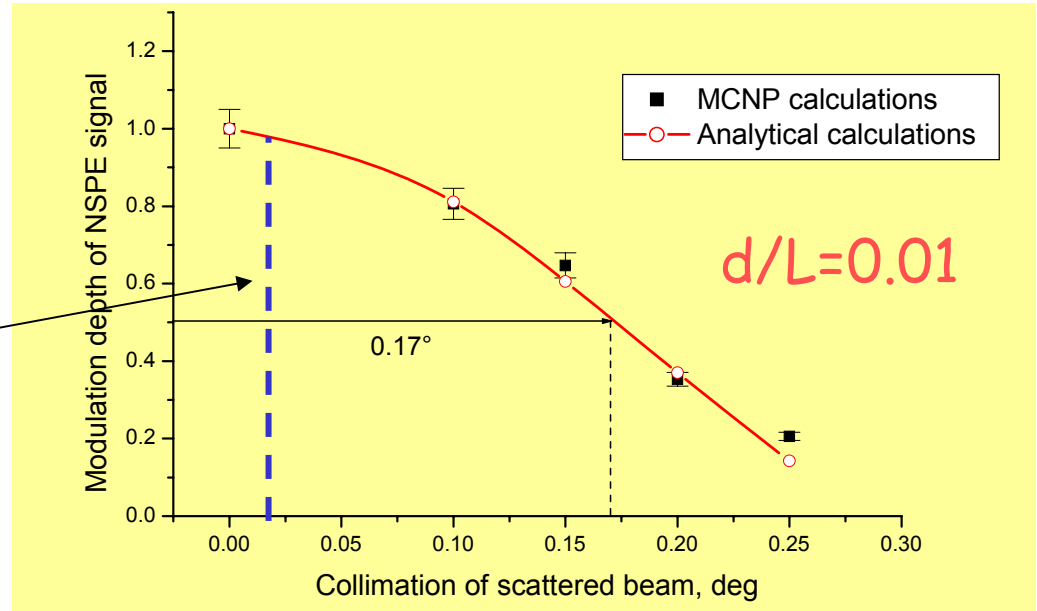
$$\frac{\Delta Q}{Q} = \frac{\Delta \lambda}{\lambda} + \frac{\Delta(\alpha_i)}{\alpha_i} \rightarrow \text{VCN: } \alpha_i = 0.1 \rightarrow \Delta \alpha_i = 0.01$$

$$\Delta \alpha_f = 0.01$$

Effect of scattering?

$\frac{\text{detector pixel}}{\text{detector distance}}$

Negligible!



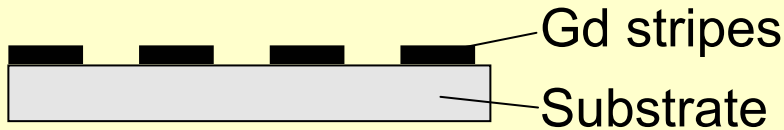
Q-resolution of a reflectometer limits scattering angle at the detector: corresponding E-resolution of NSPE add-on is

$$\Delta E_n \approx 0.01 \text{ neV} \quad - \text{ not bad at all !}$$

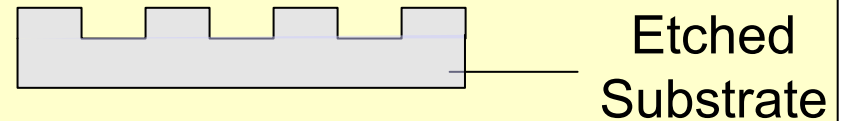
Spin degree of freedom was not used - free hands for separate polarization analysis.

# Gratings

## Amplitude gratings:



## Phase gratings:

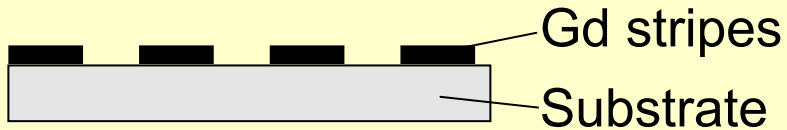


$$h \approx 1500 \text{ \AA}$$

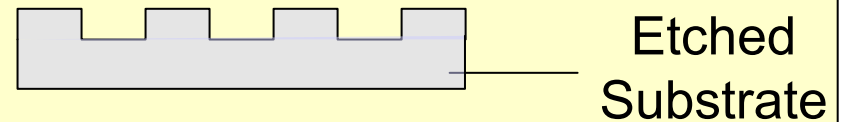
- Intensity losses: for amplitude (absorbing) gratings - 16 times [cf. transmission of polarizing benders -  $\sim (1/6)^2$ ]
- No losses for phase gratings

# Gratings

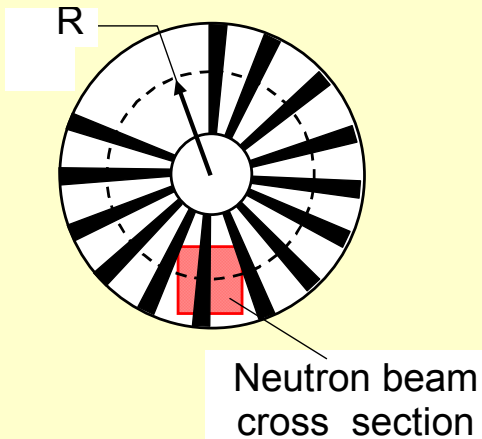
## Amplitude gratings:



## Phase gratings:

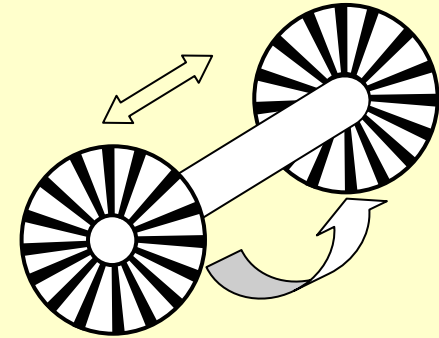


## Radial structures:



$$V_g = \text{const}(R)$$

## Mechanics:



Jülich velocity selector (based upon turbo-vacuum pump) (B.Alefeld, L. Dohmen)

Rotation frequency - up to 400 Hz:

$$V_g = 200 \text{ m/s for } R = 8 \text{ cm}$$

- Neutron Speed Echo Technique - NSE-like, but without spin
- Neutron Speed Echo Technique for VCN - small change in neutron energy,  $\Delta E_n \approx 1 \text{ feV}$ , can be detected.
- Forward scattering/refraction
- Fundamental applications: neutron electric charge, ...?
- Scattering on the sample – imposes limits on E-resolution
- Reflectometry: required Q-resolution limits scattering angle. Corresponding E-resolution of NSPE add-on is  $\Delta E_n \approx 0.01 \text{ neV}$
- Spin degree of freedom was not used - free hands for separate polarization analysis.