JOINT INSTITUTE FOR NUCLEAR RESEARCH

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Research of neutron transportation through neutron guide tubes and magnetic fields of the UCN source at the pulsed reactor

Based on master's dissertation

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Dubna

Special thanks to
A.I.Frank - supervisor
G.V.Kulin - consultant
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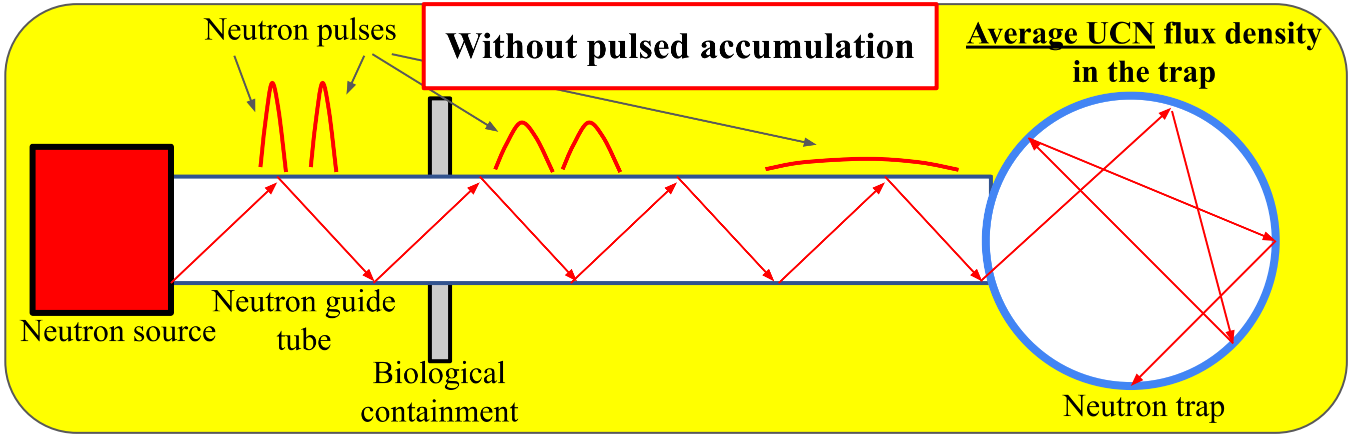
A.Y.Nezvanov - reviewer

Motivation

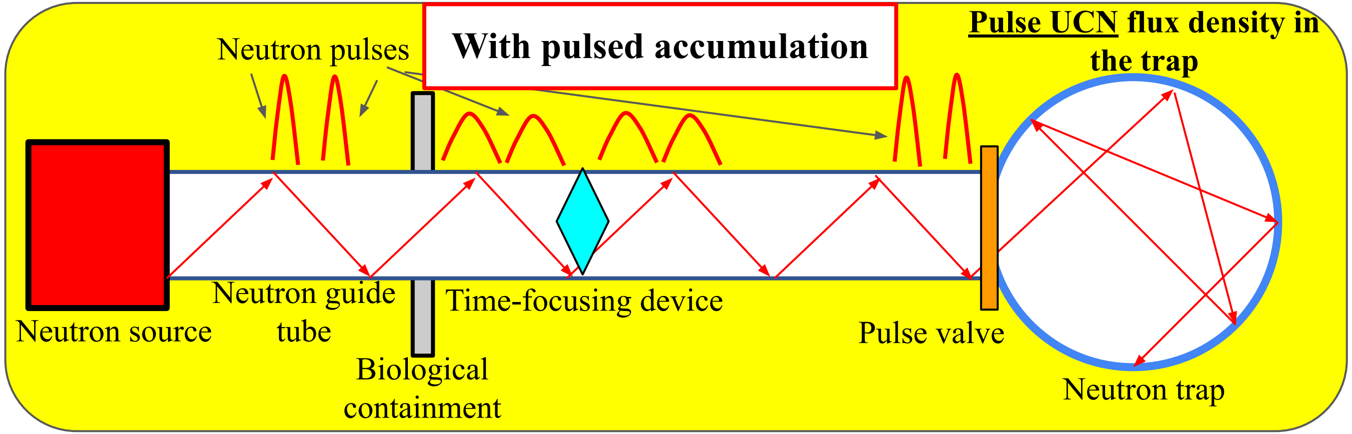
1) To introduce you the problem of the UCN source on a pulsed reactor

2) To show you my contribution to problem solving

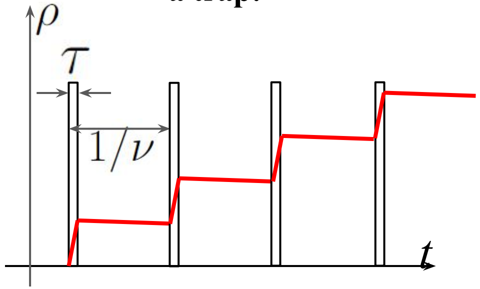
Concept of UCN Source on pulsed reactor



To experimental installations



Pulsed neutron accumulation in a trap:

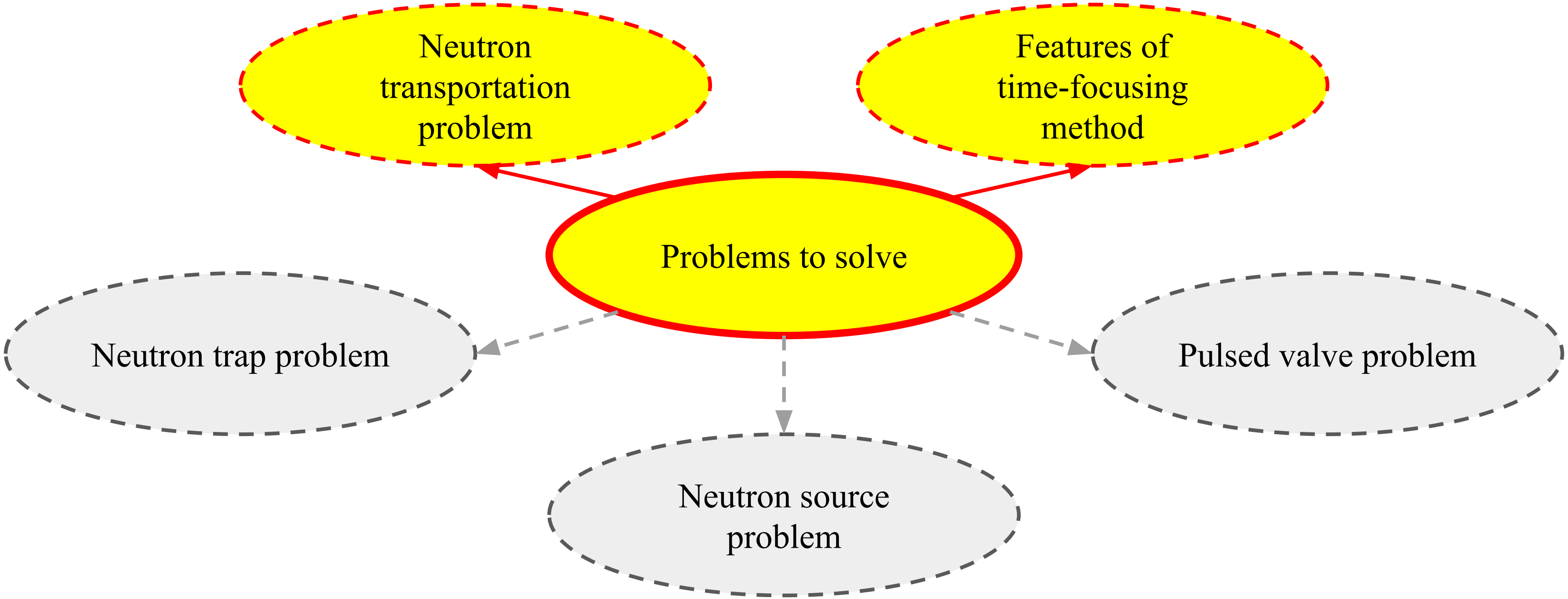


ρ neutron flux density in a trap
ν - pulse rate
τ - pulse duration

Pulsed reactor feature:
its **pulse** flux density is greater than **average** flux density

[1] Ф.Л. Шапиро, ЭЧАЯ, **2**, 4, 975 (1972).
[2] A.I. Frank *et al.*, *Phys. Part. Nuclei* 53, 33 (2022).

Barriers for pulse accumulation with time-focusing device



Neutron transportation problem

Guide tube defects

Macroscopic waveness

- Measurement methodology wasn't found

Microscopic roughness

- Well known measurement methodology (AFM)
- Well known experimentally proved scattering theory [3] (MR-model)

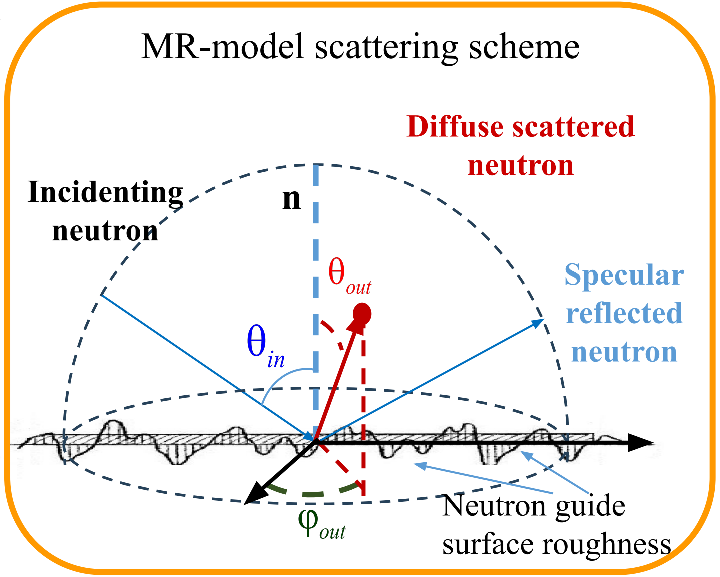
Mean square amplitude of roughness less than 5 nm for neutrons with Velocity less than 50 m/s

Lead to

Non specular changing velocity direction

Leads to

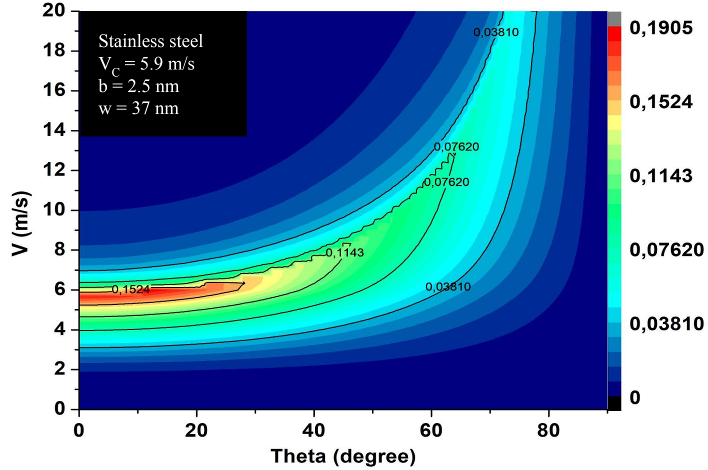
Transportation losses

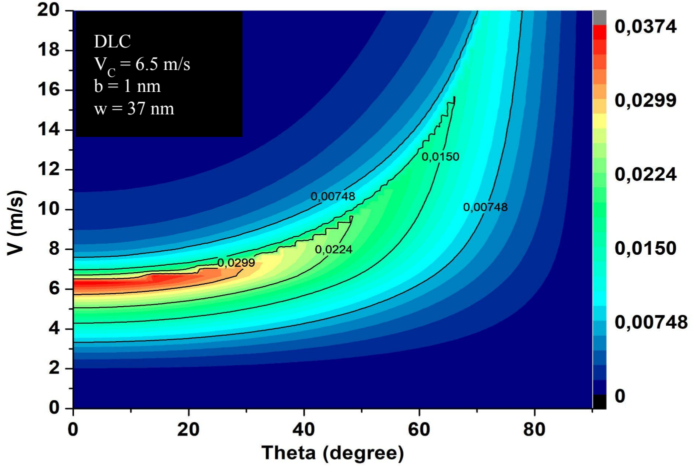


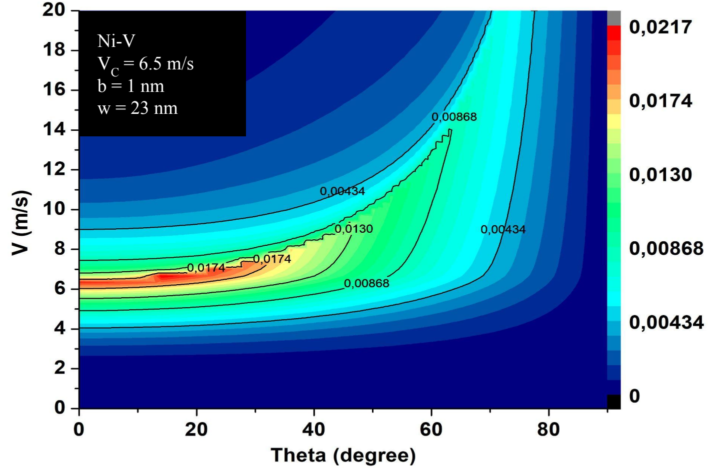
It is necessary to evaluate the transmission of neutron guide tubes at least with roughness

[3] A. Steyerl Effect of surface roughness on the total reflexion and transmission of slow neutrons., *Z. Physik*, **254**, 169 (1972)

Probabilities of the diffuse scattering for different materials depending on the angle of incidence and neutron velocity in MR-model







Material	b, nm	w, nm	V_C, m/s
Stainless steel	2.5	37	5.9
DLC	1	37	6.5
Ni-V	1	23	6.5

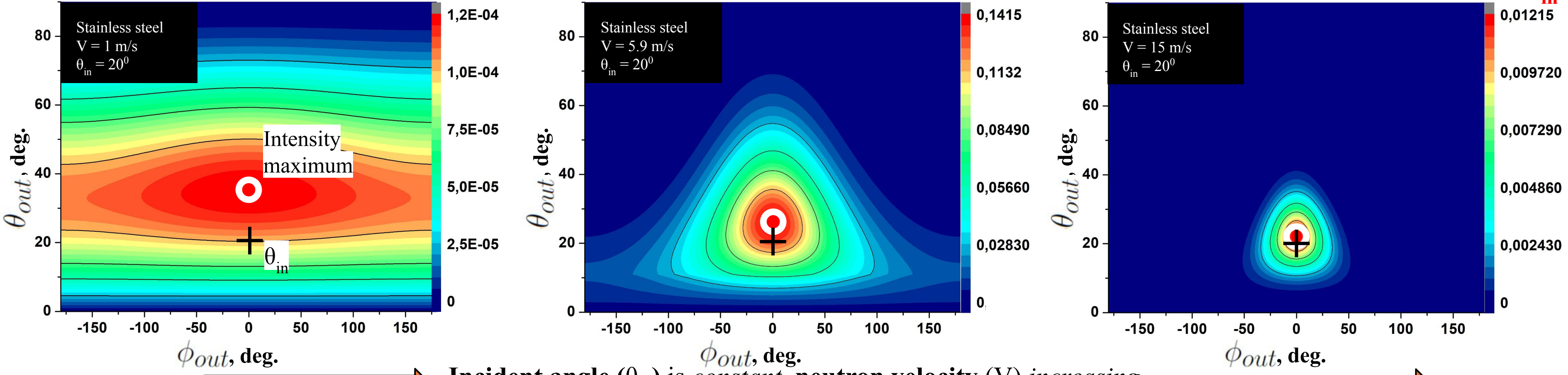
Material parameters

b – mean square roughness amplitude

w – correlation length of roughness distribution

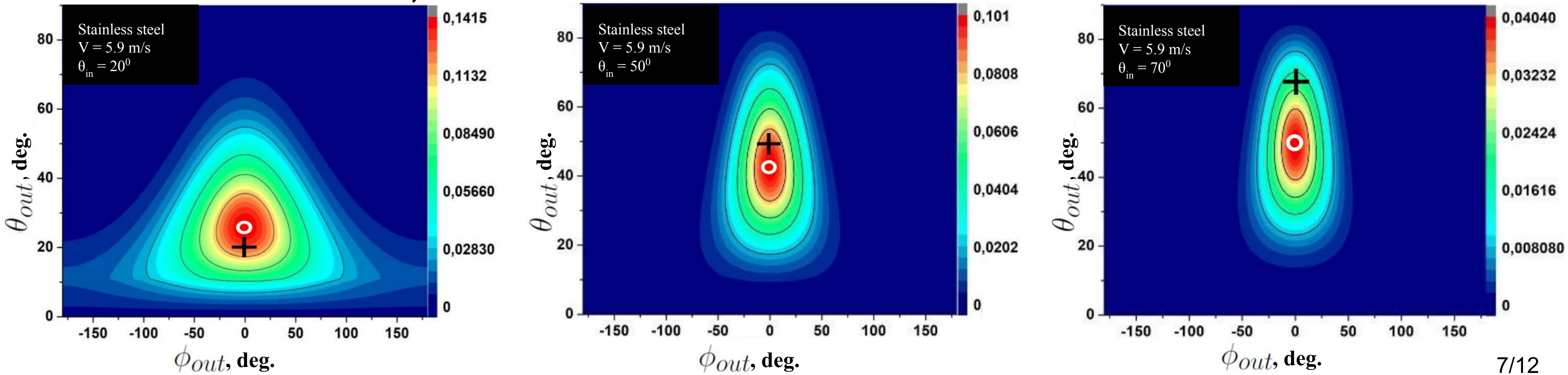
V_C - material critical velocity

Angular distribution intensity of neutrons during diffuse reflection depending on velocity V and angle of incidence θ_{in}

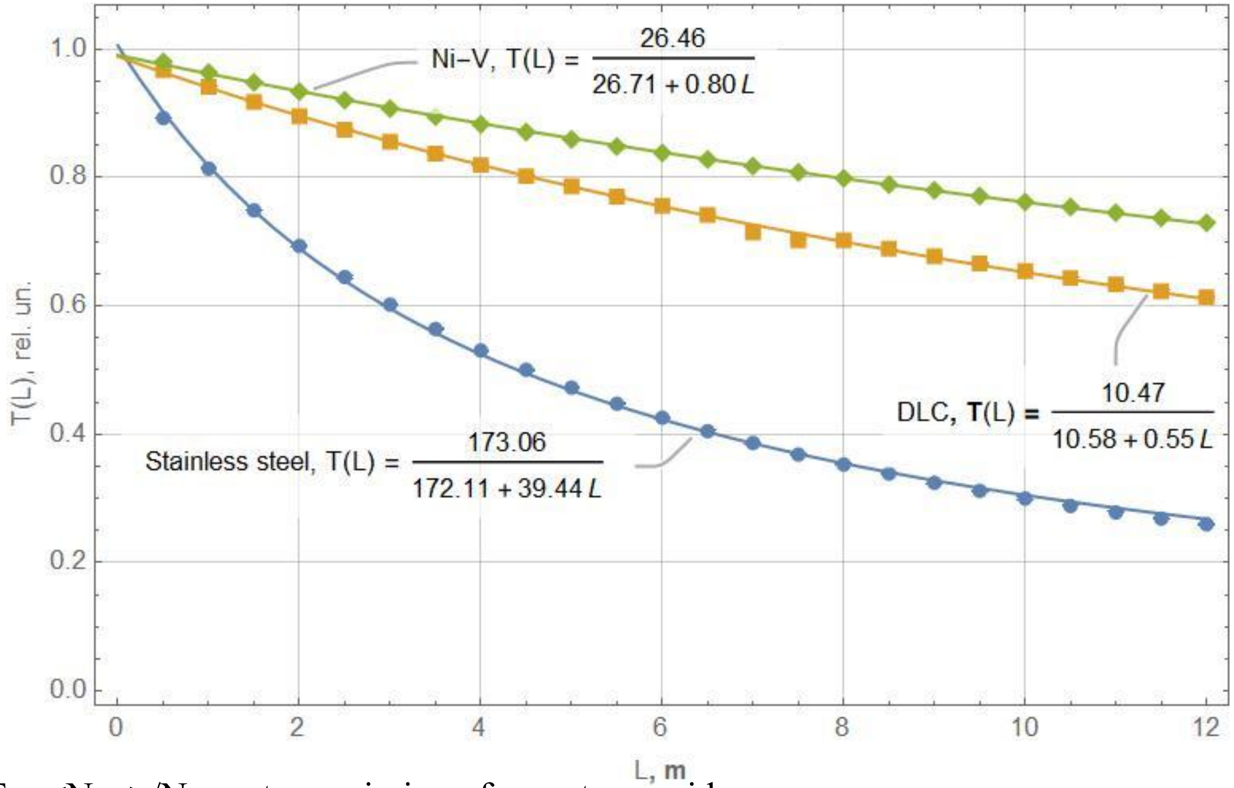


Incident angle (θ_{in}) is *constant*, **neutron velocity** (V) *increasing*

Incident angle (θ_{in}) increasing, **neutron velocity** (V) is *constant*



Dependence of the transmission of a neutron guide tube on its length in MR-model



Starting velocity distribution:

$V_z^{start} = 15$ m/s

$V_{xy}^{start} \in [0; V_c]$

Guide tube geometrical parameters:

Radius = 0.04 m

$L \in [0.5; 12]$ m

Material	*b*, nm	*w*, nm	V_C, m/s
Stainless steel	2.5	37	5.9
DLC	1	37	6.5
Ni-V	1	23	6.5

$T = \langle N_{end} \rangle / N_{start}$ - transmission of a neutron guide,

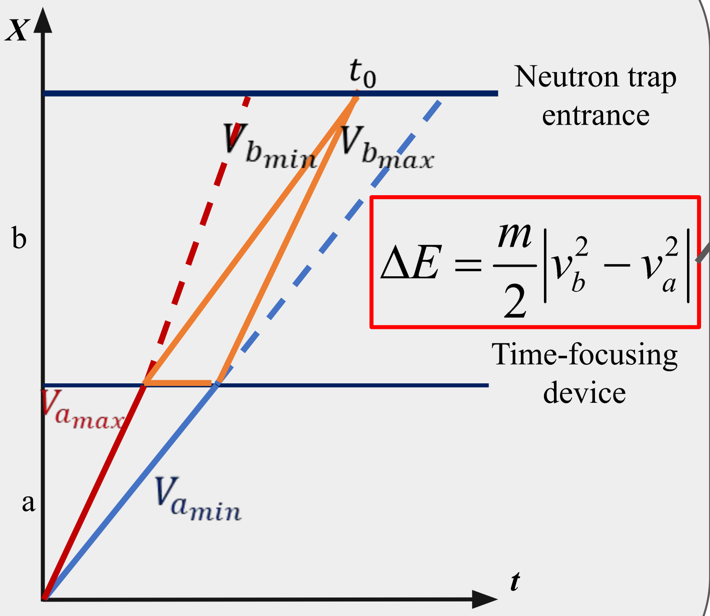
N_{end} - neutron amount in the end of calculations,

N_{start} - neutron amount in the start of calculation,

L - guide tube length.

Focusing method using an adiabatic spin flipper

The idea of focusing method [4]



Time-length diagram of the neutron flight

$$U(x,y,z) = \pm\mu\left|B(x,y,z)\right|$$

$$\Delta E = \pm 2\mu\left|B(x,y,z)\right|$$

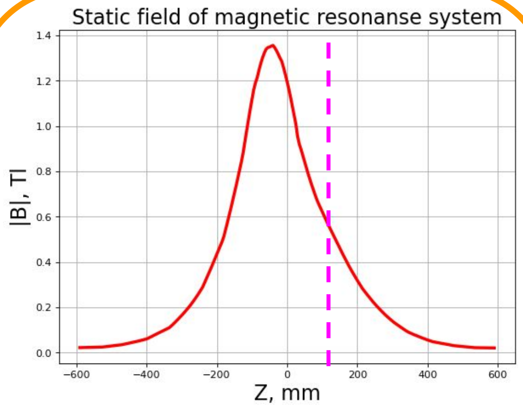
$$\vec{F} = \vec{\nabla} U(x,y,z)$$

$$\vec{\nabla}\vec{B} = 0$$

Besides the longitudinal gradients, there are radial gradients

Increasing of longitudinal velocity spectre **wideness**

Increasing of the time of flight dispersion



Energy changing happening only in small area, but **changing of velocity** comes during all along the way through magnet system

The idea is proposed:

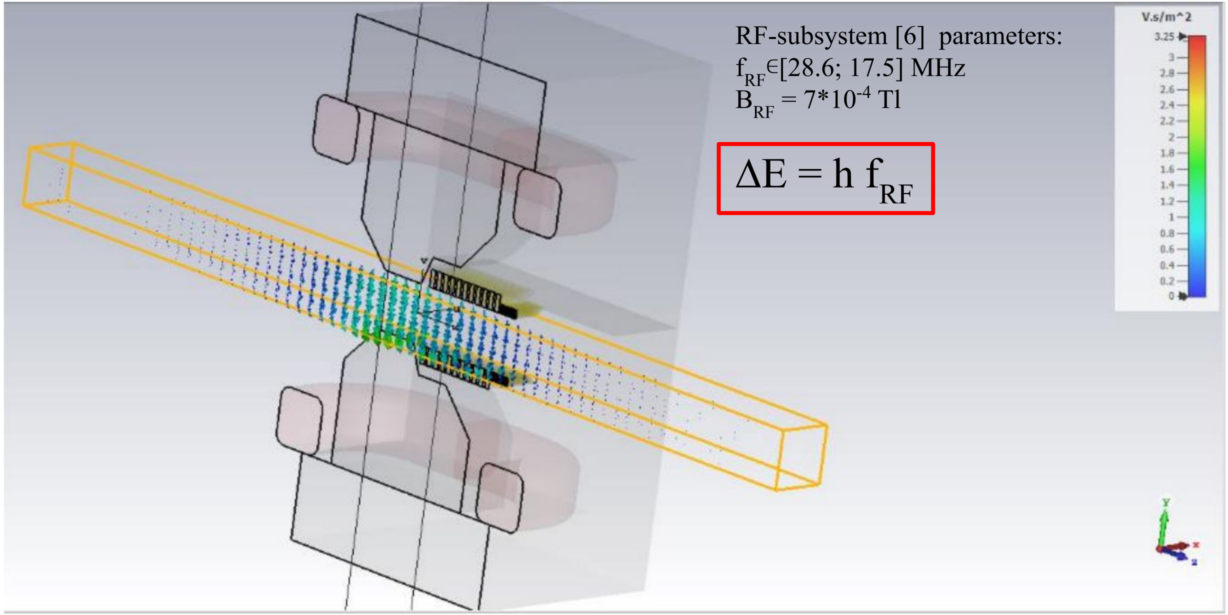
[4] Frank A. I., Gahler R. Time Focusing of Neutrons //April 2000 Physics of Atomic Nuclei 63(4):545-547.

The method has been experimentally tested:

[5] Arimoto Y., Gertenbort P., Imajo S., etl Demonstration of focusing by a neutron accelerator// PHYSICAL REVIEW A 86, 023843 (2012).

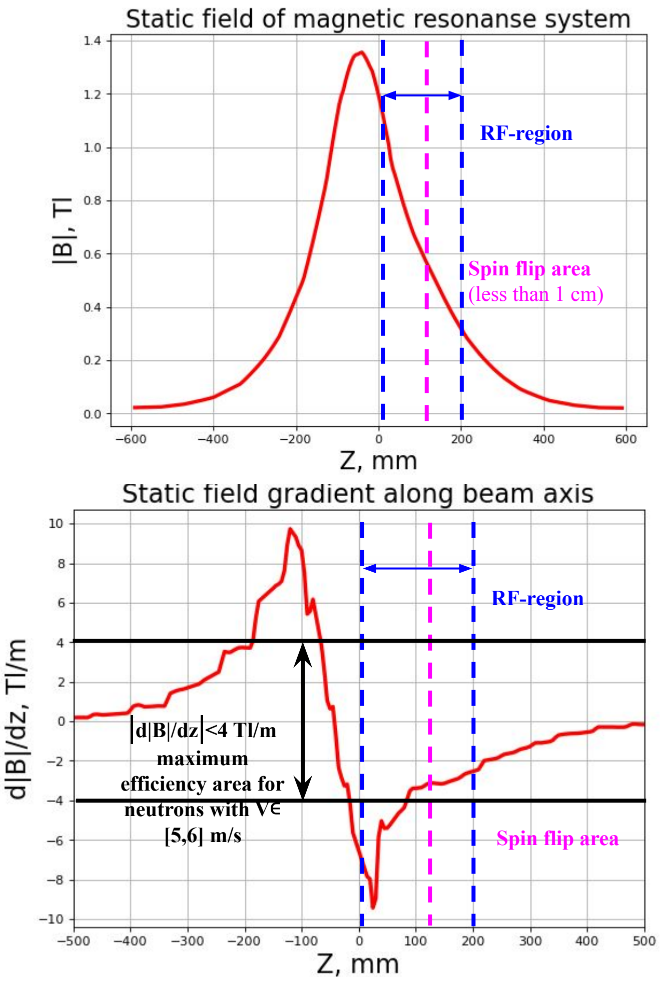
Magnetic resonance system

Picture of magnet [6] from CST Studio



RF-subsystem [6] parameters:
$f_{RF} \in [28.6; 17.5]$ MHz
$B_{RF} = 7*10^{-4}$ Tl

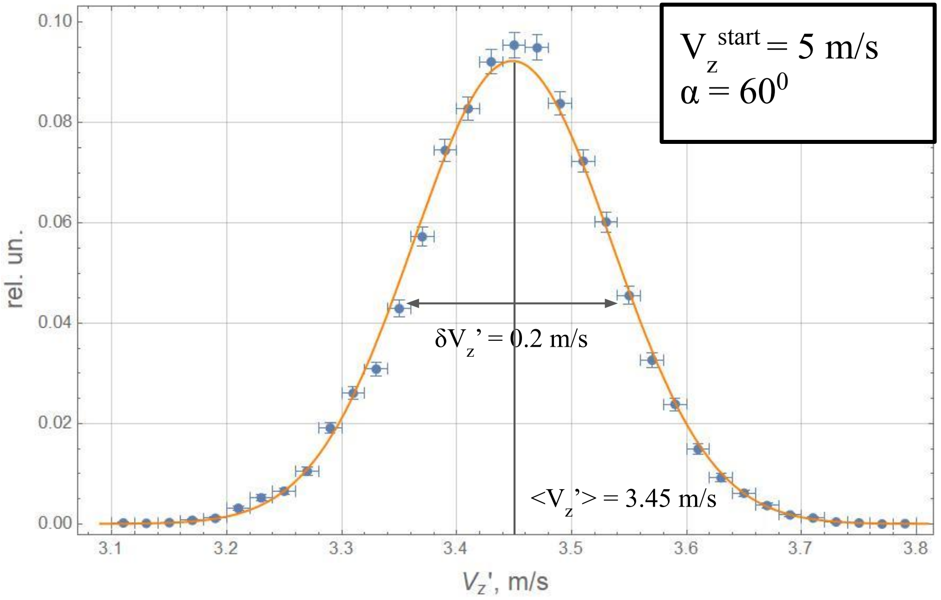
$$\Delta E = h f_{RF}$$

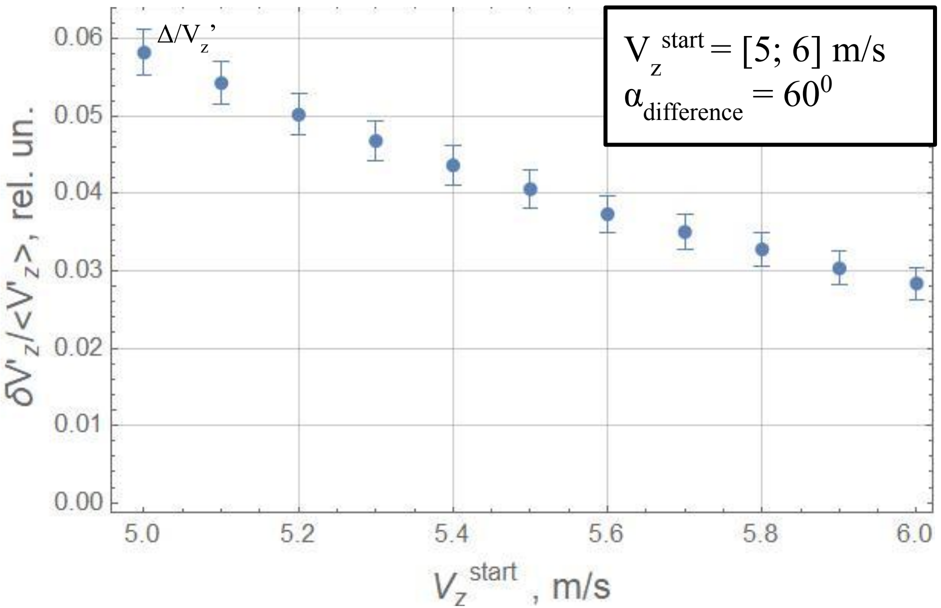


It is necessary to evaluate the dispersion of the longitudinal velocity spectrum after passing through the magnetic resonance system

[6] Y. Arimoto, T. Yoshioka, H. M. Shimizu, et al. Longitudinal-gradient magnet for time focusing of ultra-cold neutrons// Physics Procedia 17 (2011) 20–29.

Dispersion of the longitudinal velocity spectrum after exiting the magnetic resonance system depending on the fixed longitudinal velocity before entering the system





V_z^{start} - fixed starting longitudinal velocity

V_z' - neutron longitudinal velocity after exiting magnetic system

$\delta V_z'$ - FWHM of longitudinal velocity distribution after exiting magnetic system

$\langle V_z' \rangle$ - mean of longitudinal velocity distribution after exiting magnetic system

α - beam divergence

$\Delta = 0.01$ m/s - calculation method error

$$\frac{\delta T}{T} = \frac{\delta V}{V}$$

Main results

1) A software product has been created that allows to evaluate the small roughness effect on the neutron guide tube transmission.

2) Transmission curves were obtained for the most popular neutron guide tube materials: stainless steel, DLC, Ni-V.

3) A software product has been created that allows to estimate the longitudinal velocity spectrum distribution after passing through a magnetic resonance system.

4) An estimate of the blurring of the longitudinal velocity spectrum after passing through a magnetic resonance system is obtained.

Thanks!

Additional materials

Micro-roughness neutron scattering

The probability of diffuse scattering at angles θ, φ is determined by the expression from [3]:

$$I(\theta_{out},\phi_{out}) = \frac{k_c^4}{4\cos(\theta_{in})}|S(\theta_{in})|^2|S(\theta_{out})|^2F(\theta_{in},\theta_{out},\phi_{out})$$

$$S(\theta) = \frac{2\cos(\theta)}{\cos(\theta)+\sqrt{\cos^2(\theta)-k_c^2/k^2}}$$

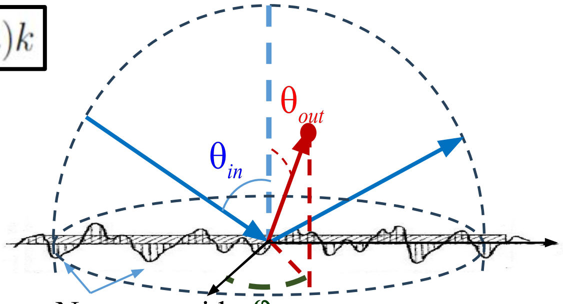
$$F(\theta_{in},\theta_{out},\phi_{out}) = \frac{b^2w^2}{2\pi}exp\left(-\frac{\zeta^2w^2}{2}\right)$$

$$\zeta^2 = k^2\left(\sin^2(\theta_{in})+\sin^2(\theta_{out})-2\sin(\theta_{in})\sin(\theta_{out})\cos(\phi_{out})\right)$$

b – mean square roughness amplitude
w – correlation length of roughness distribution

The existing model of neutron scattering on roughnesses (MR-model)describes non-specular scattering on small roughnesses in a large range of angles.
Criterion of applicability: $kb \ll 1$

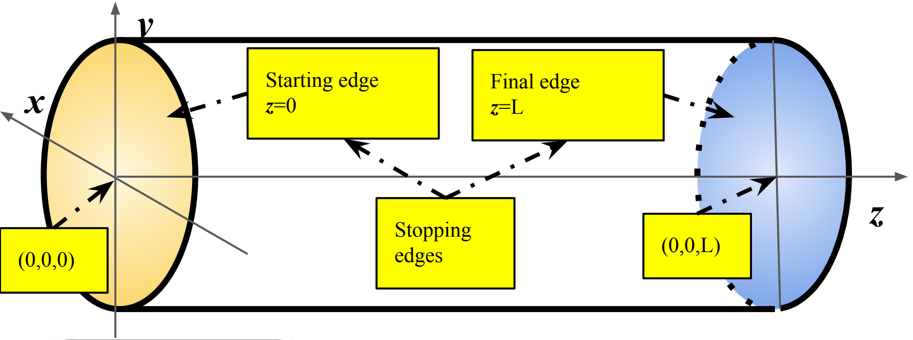
$V = (\hbar/m)k$

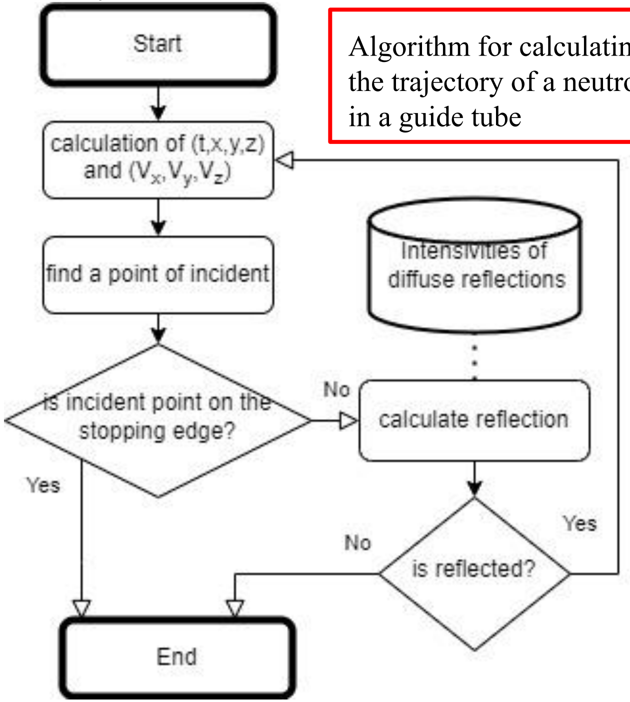


It is necessary to evaluate the transmission of neutron guides with roughness

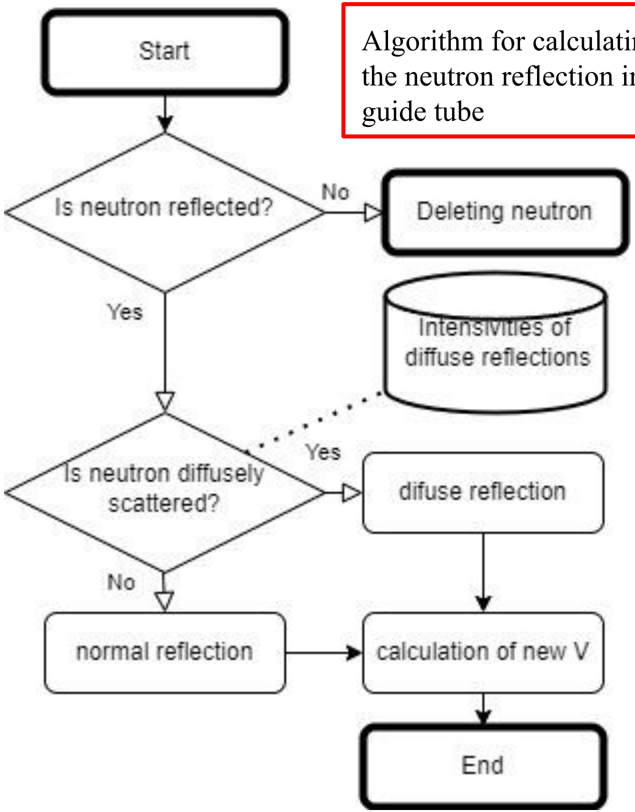
[3] A. Steyerl Effect of surface roughness on the total reflexion and transmission of slow neutrons., Z. Physik, **254**, 169 (1972)

Model of neutron movement in a guide tube



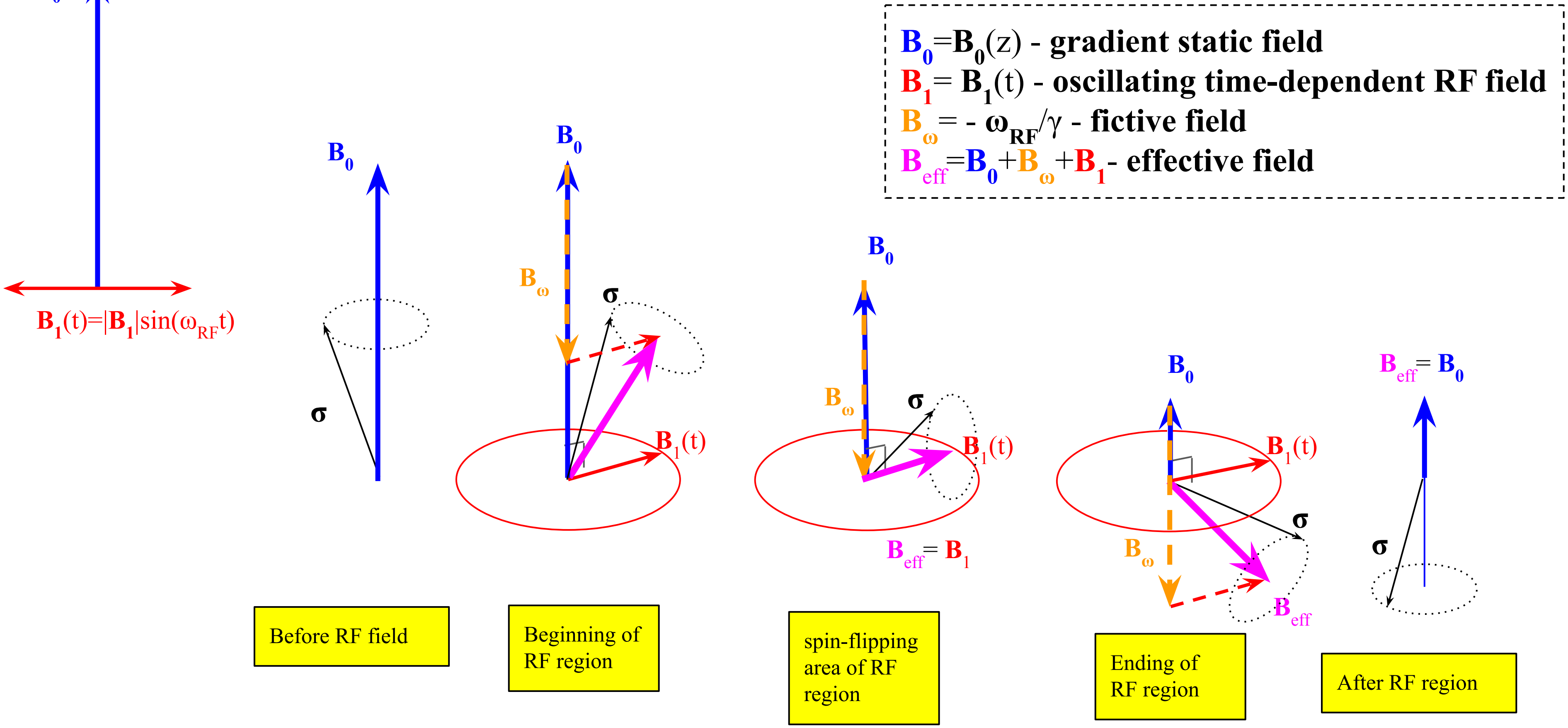


Algorithm for calculating the trajectory of a neutron in a guide tube



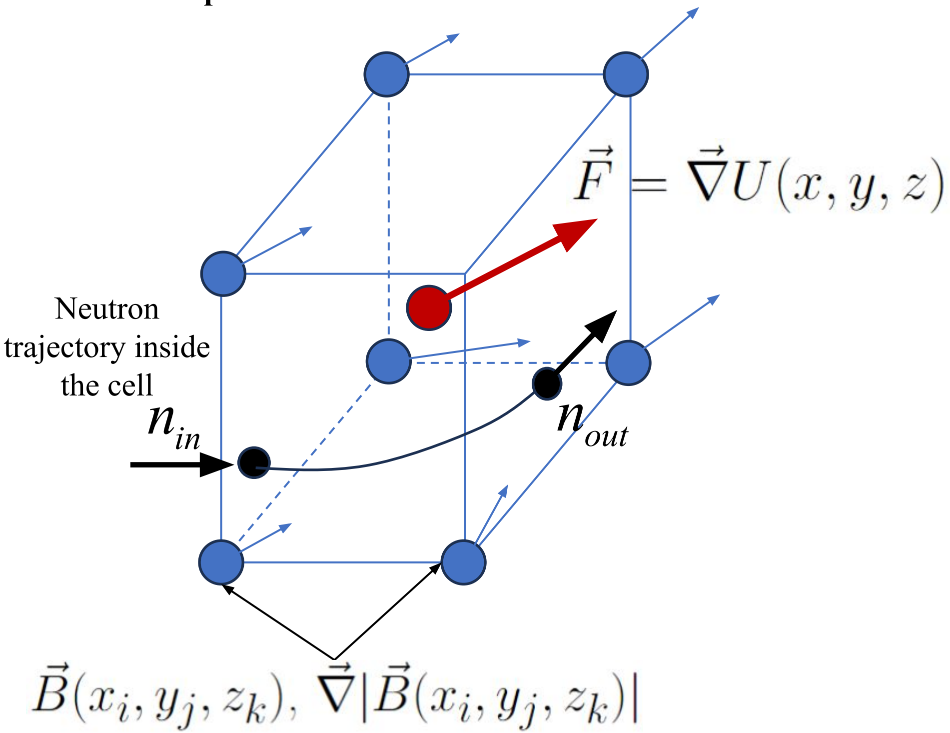
Algorithm for calculating the neutron reflection in a guide tube

Polarization evolution in magnetic resonance system



Model of neutron movement in a magnetic resonance system

Schematic representation of the movement of a neutron in a cell:



Model basements:

1) The magnetic field in the model is specified by a **three-dimensional grid** with magnetic field strengths at the nodes.

2) The model assumes movement in a magnetic field as movement through **small cells**, the gradient inside is close to constant.

3) **Reflection** from the neutron guide tube is considered **specular**.

4) A spin flip occurs when neutron passes through a certain cross section determined from the outside.