Superconducting magnetic system for gradient spin-flipper with a strong magnetic field

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A.A. Popov, A.I. Frank, G.V. Kulin, V.A. Kurylev, K.S. Osipenko, M.A. Zakharov

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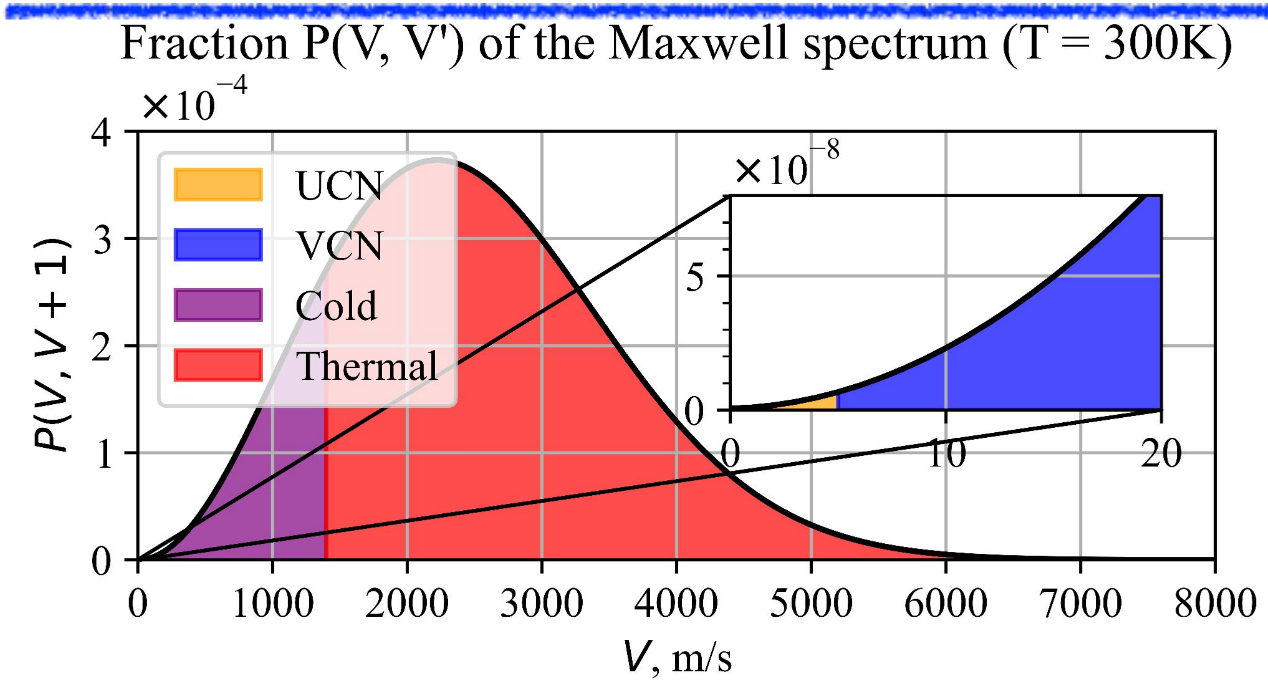
Ultracold neutrons



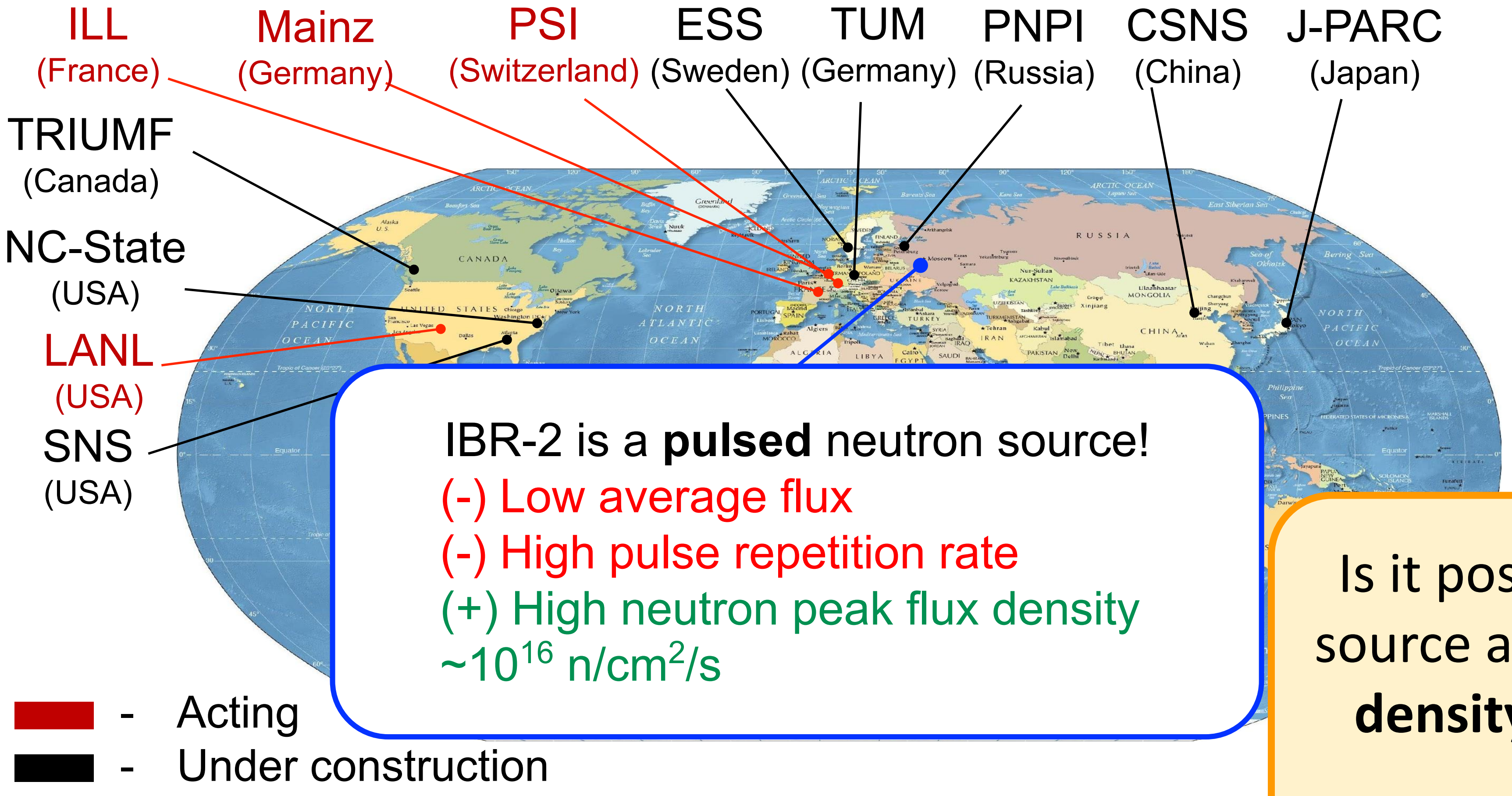
Effective potential for neutron-matter interaction:
$U = (2\pi\hbar^2/m)\rho b$,
ρ - amount of nuclei per unit volume,
b - coherent scattering length

Neutrons	Energy (eV)	fraction at the Maxwell spectrum (300 K)
Ultracold (UCN)	**$< 10^{-7}$**	**$\sim 10^{-8}$**
Very cold (VCN)	10^{-7} - 10^{-4}	$\sim 10^{-4}$
Cold	10^{-4} - 10^{-2}	~0.14
Thermal	$>10^{-2}$	~0.85

Ultracold neutrons reflect from material by any angle of incidence

UCN can be accumulated in material traps

UCN Sources



IBR-2 is a **pulsed** neutron source!

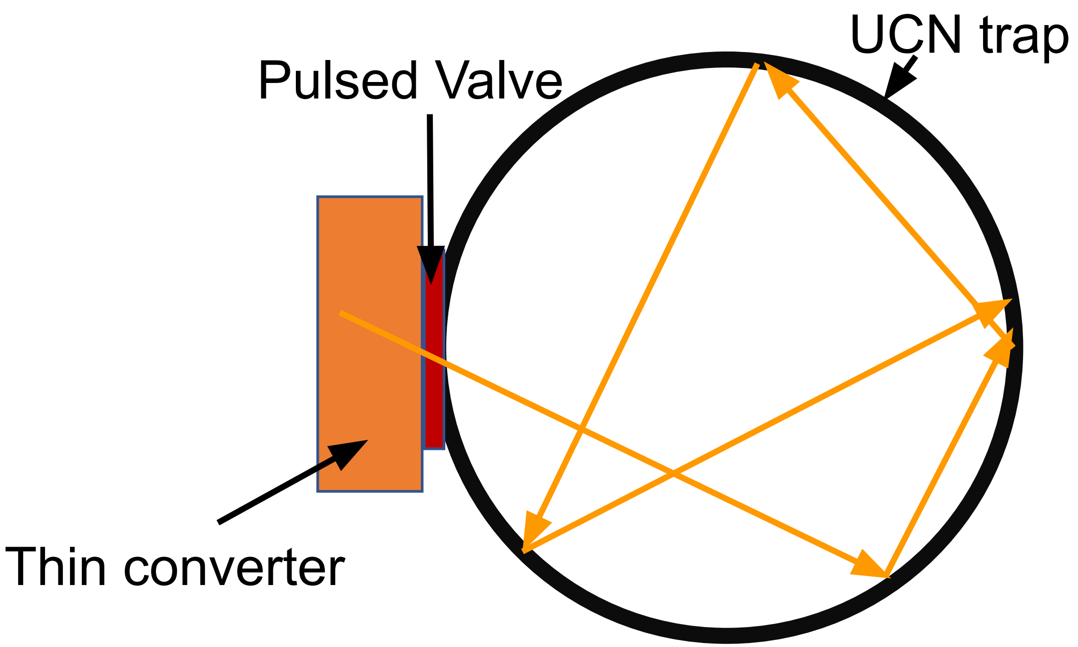
(-) Low average flux

(-) High pulse repetition rate

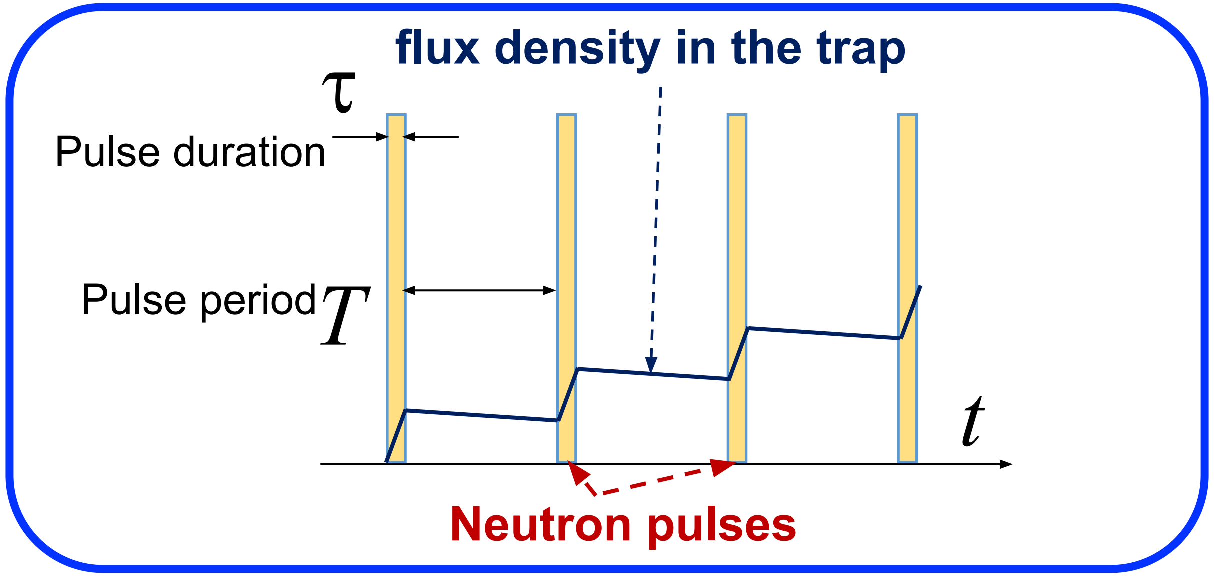
(+) High neutron peak flux density $\sim 10^{16}$ n/cm^2/s

Is it possible to create the UCN source at IBR-2 **using a peak flux density** instead of an average flux density?

The idea of UCN source at a pulsed reactor



$$0 < E_n < E_{trap} \approx 250 \text{ neV}$$



The increasing of the neutron flux in the trap due to pulsed filling of the trap

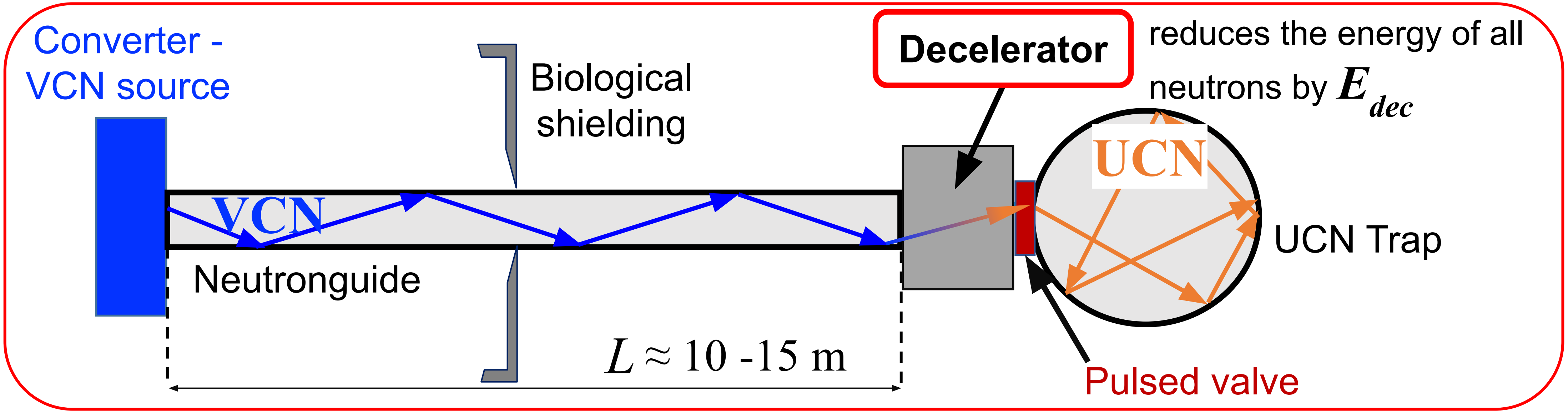
The main idea is effective **pulsed accumulation** of UCN in the trap

$$g = \frac{ST}{S\tau + \Sigma\mu T}$$

S - area of the trap entrance
Σ - area of the UCN trap surface
μ - probability of UCN lost
τ - bunch duration at the trap entrance
T - pulse period

$$g \rightarrow 10 \div 10^2$$

Concept of the UCN source



Before the **decelerator:**

$E_{dec} < E_n < E_{dec} + E_{trap}$

At the **decelerator:**

$E_n \rightarrow E_n - E_{dec}$

After the **decelerator:**

$0 < E_n < E_{trap}$

$$\delta t/t = \delta V/V = \delta E/(2E) = E_{trap}/2E_{dec}$$
$$\delta E \ll E \Rightarrow \delta t \ll T$$

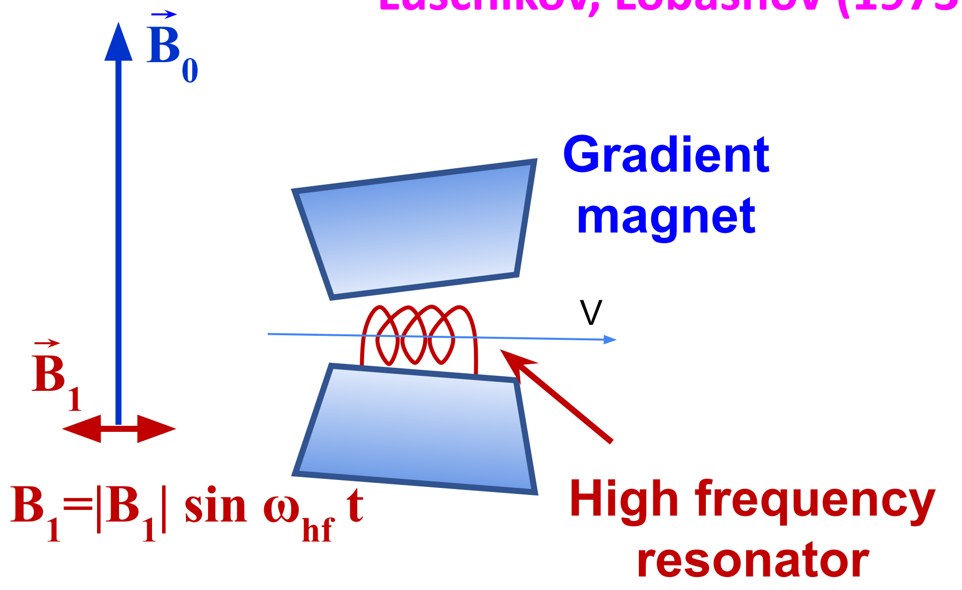
The flux of neutrons, which can be trapped after strong ($E_{dec} \gg E_{trap}$) deceleration, has a **pulsed structure**

T - pulse period, t -flight time, δt - variance of the flight time at the trap entrance,
E_n- energies of neutrons, which can be trapped after strong deceleration

Decelerator – gradient (adiabatic) spin-flipper

Scheme of the first adiabatic spin-flipper

Luschikov, Lobashov (1973)



A spin flip in a combination of stationary and nonstationary magnetic fields **leads to a change in energy**

Drabkin, Zhitnikov (1960)

$$\Delta E = \hbar\omega_{hf} = 2\mu B_0$$

$\omega_{hf} = \omega_L = \gamma B_0$ - resonance condition

ω_L - angular velocity of Larmor precession at B_0 field

μ = 60.31 neV/Tl - the magnetic moment of a neutron

$\gamma = 1.83*10^8$ rad Tl^{-1} sec^{-1} - the gyromagnetic ratio of a neutron

Splinflip probability at adiabatic spin-flippers

Adiabaticity parameter ***k***:

$$k = \omega_L/\omega_B = \frac{\gamma B_1^{\,2}}{(\partial|B_0|/\partial z)\, V}$$

p> 0.99, when k >4

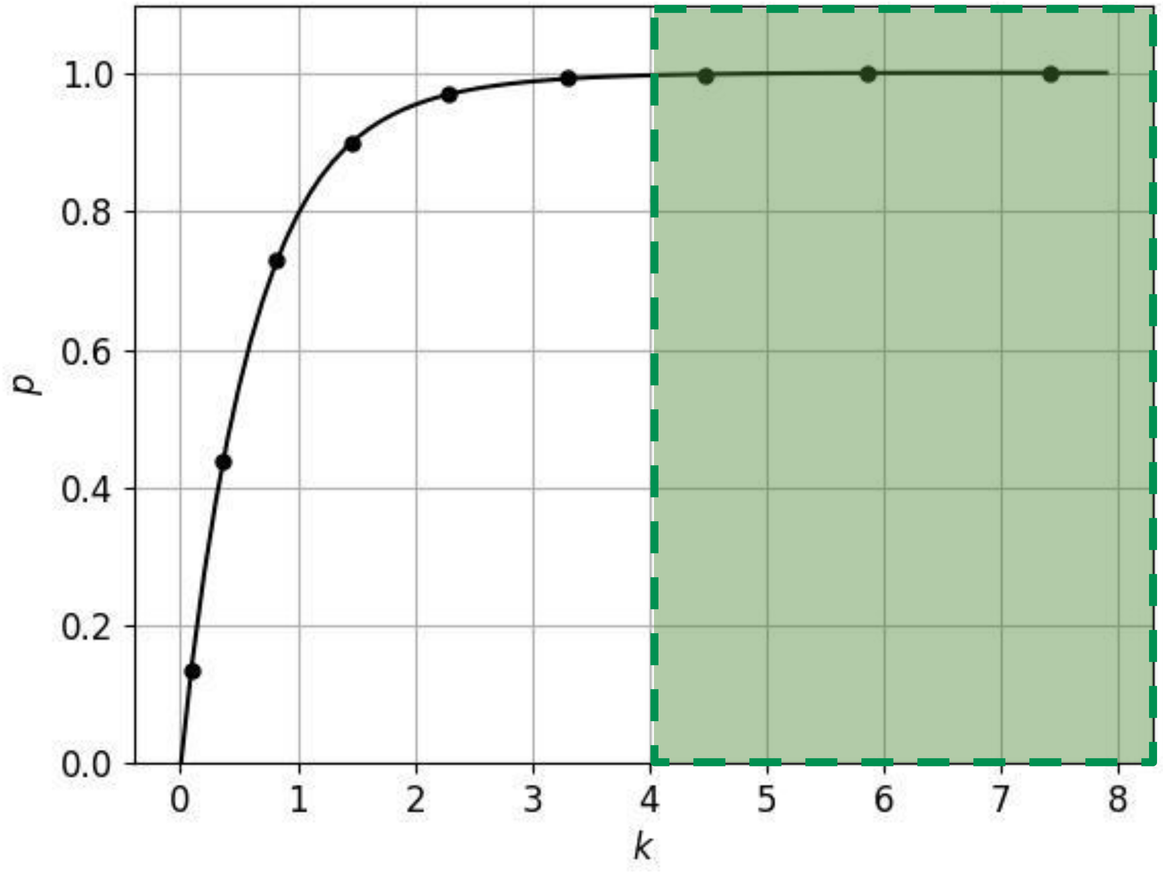
ω_B - angular velocity of field B in neutron coordinate system

V - neutron velocity

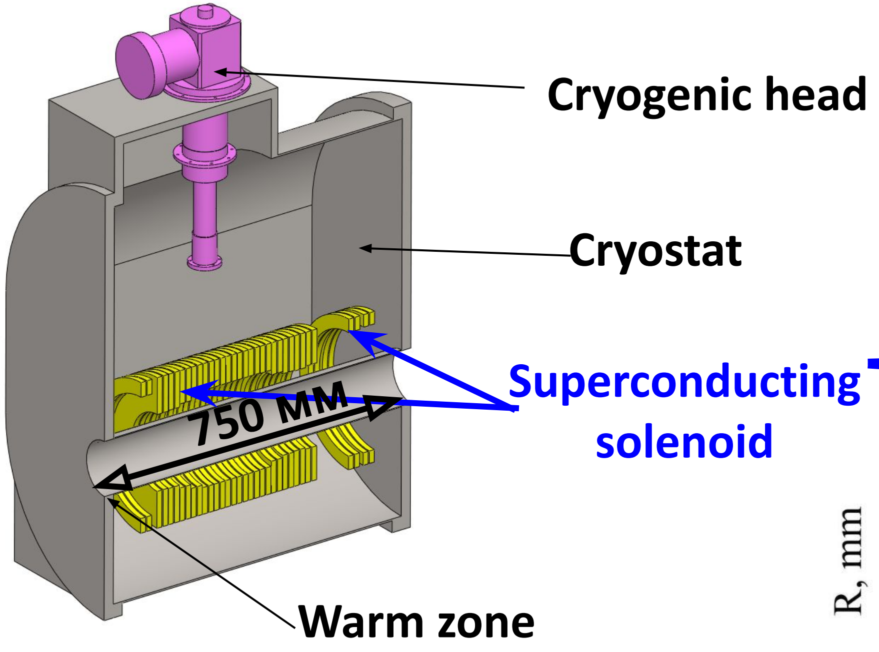
B_0 - stationary gradient field

B_1 - rotating HF field

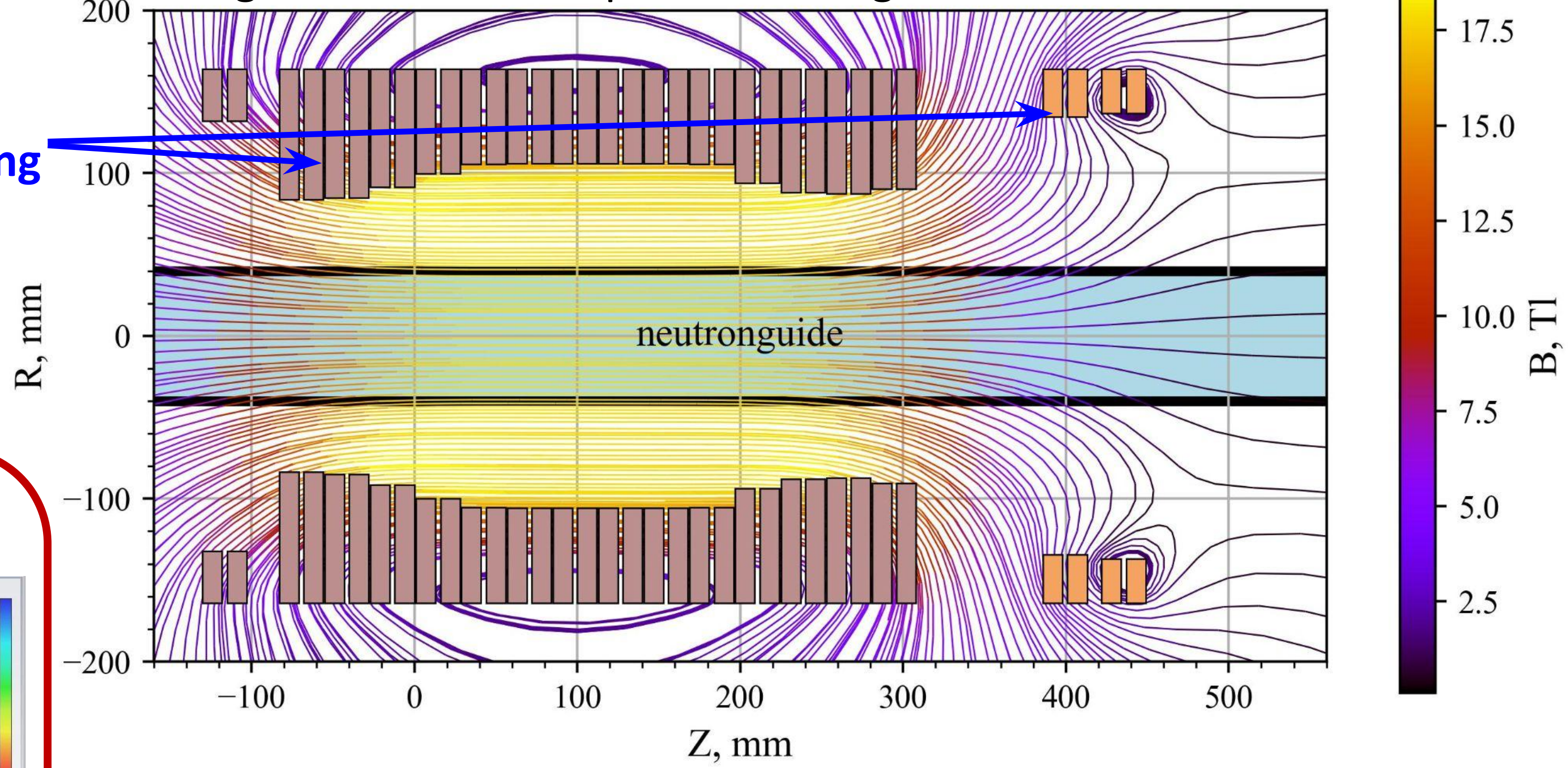
Spinflip probability ***p*** in dependence of adiabaticity parameter ***k***



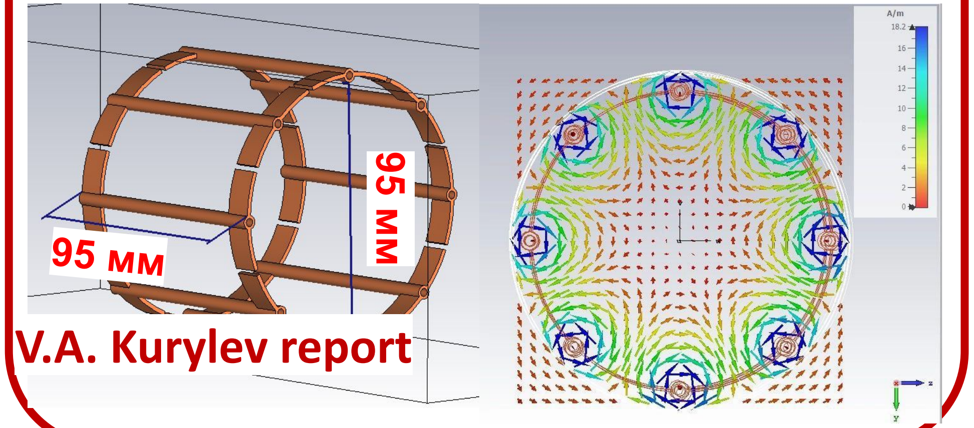
The design of the flipper-decelerator



Magnetic lines of a superconducting solenoid:



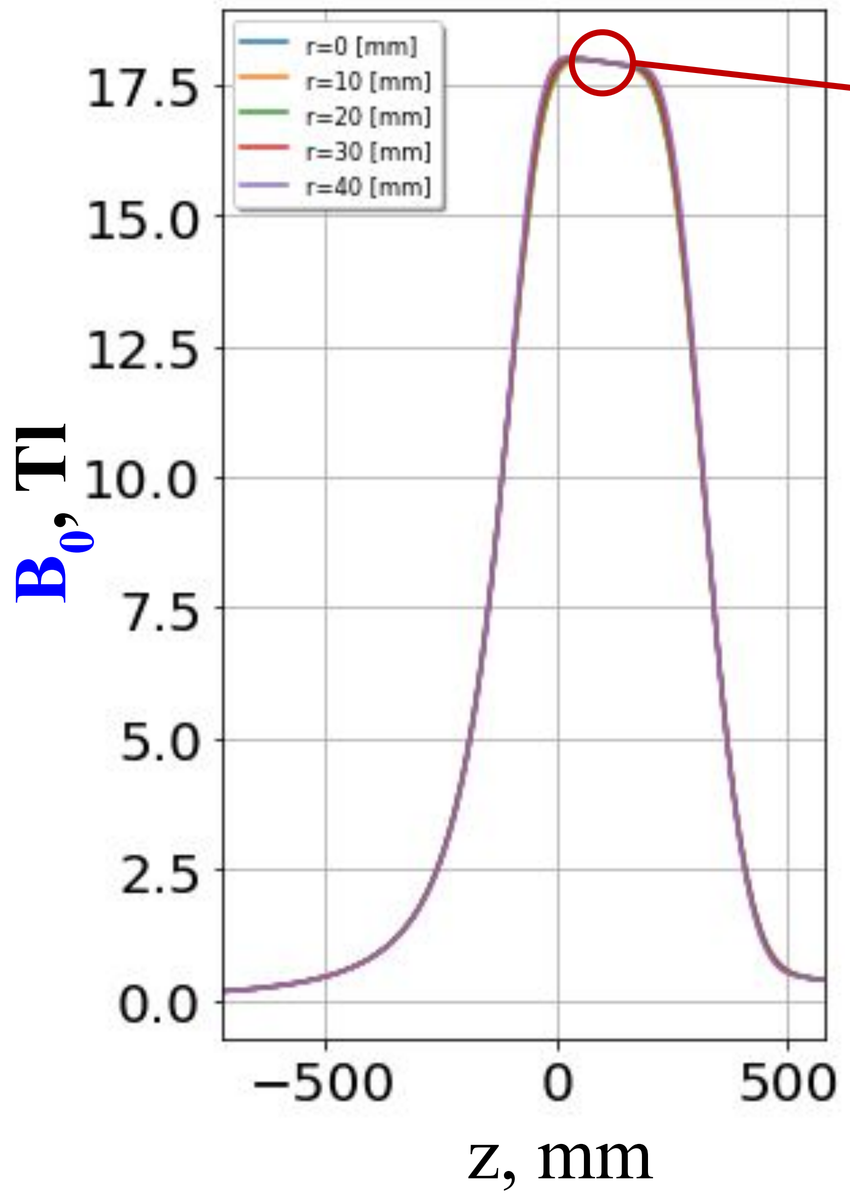
HF-resonator “Birdcage”

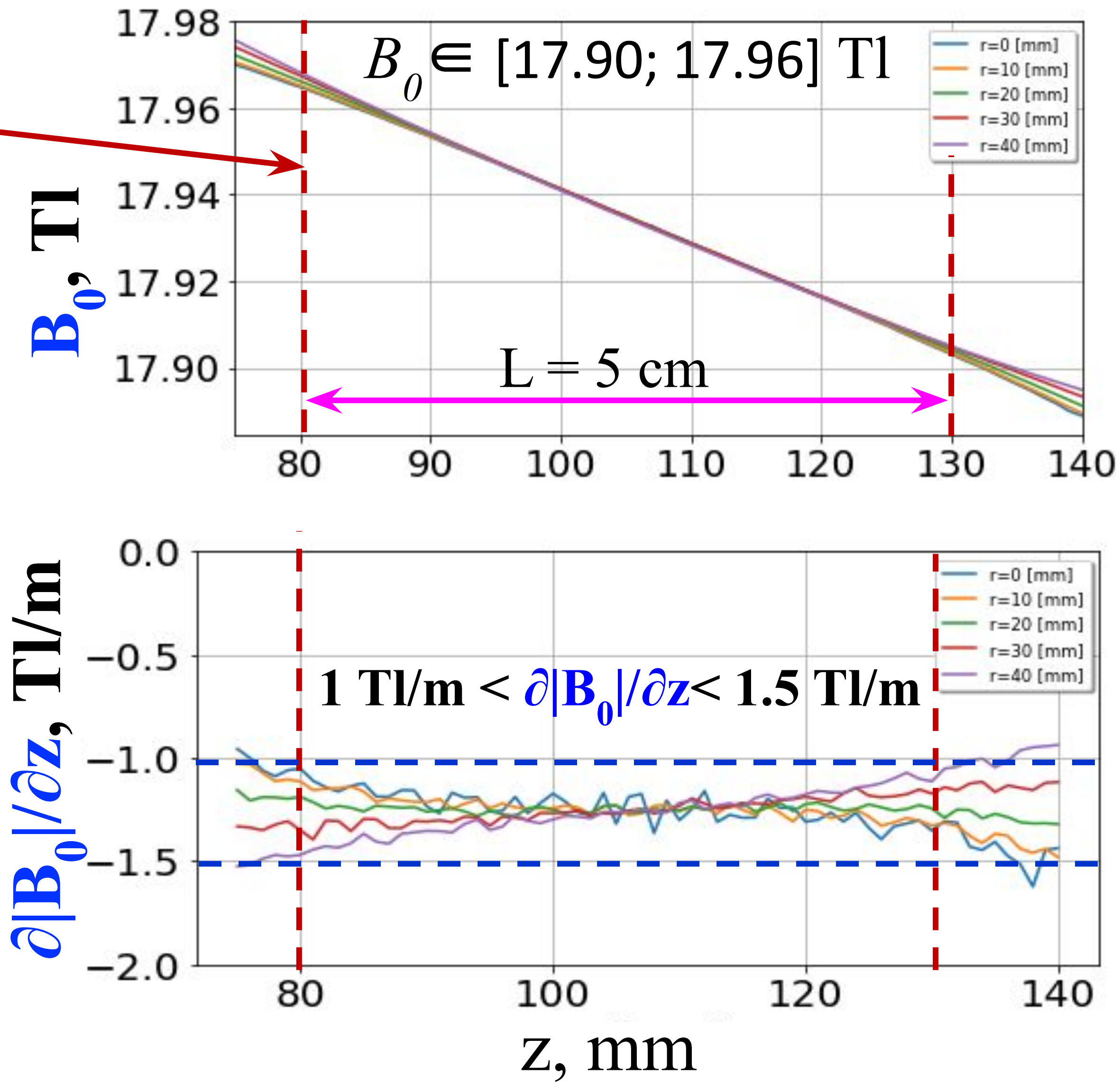


$B_1 > 0.7$ mTl
$f = \omega/2\pi = 524$ MHz

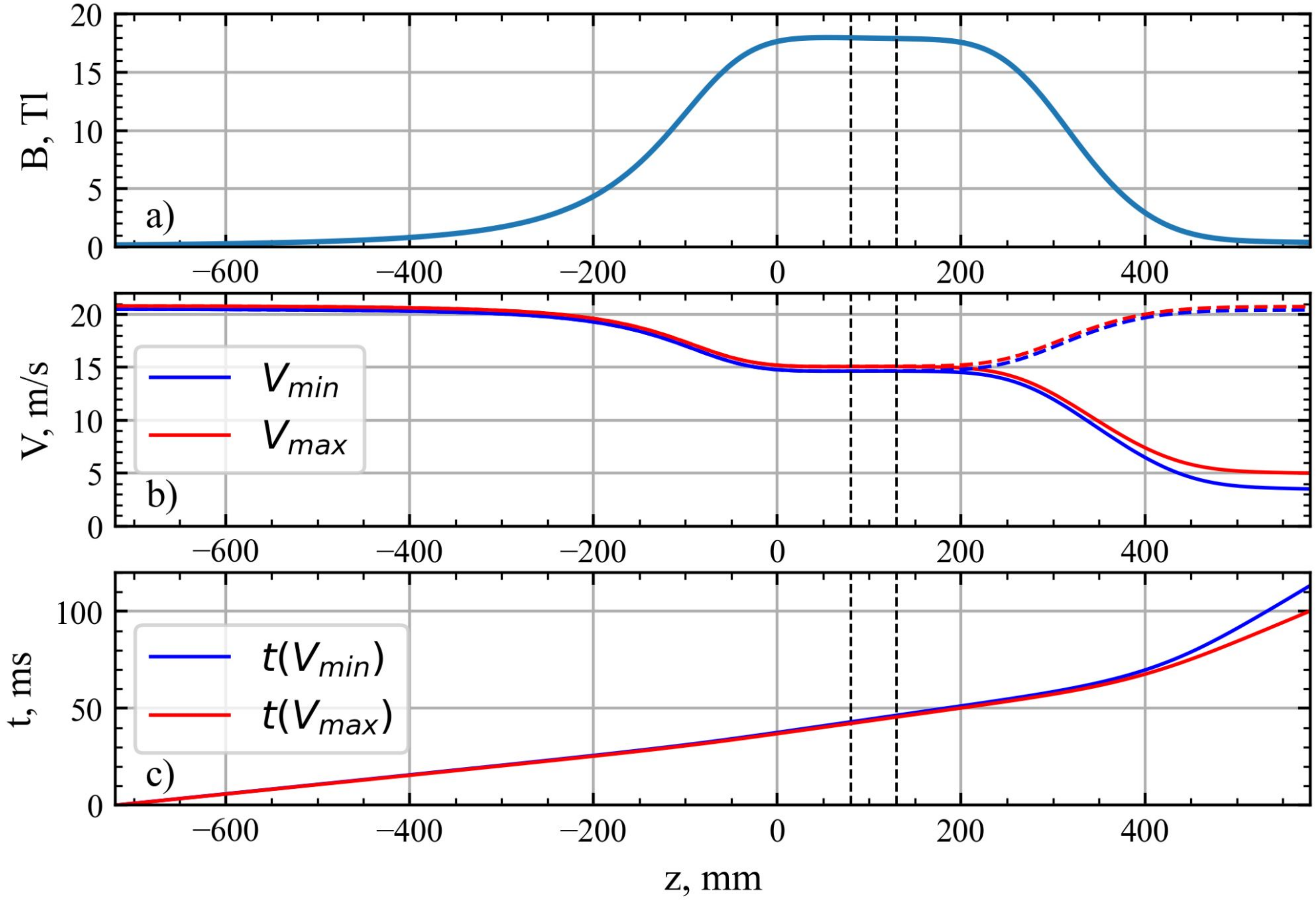
$B_0 = 18$ Tl, $\Delta E = 2.2\ \mu eV$
$1\ Tl/m < \partial|B_0|/\partial z < 1.5\ Tl/m$

Magnetic fields of the superconducting magnet





Neutrons in a strong magnetic field



a) Field $\mathbf{B_0}$ distribution along z-axis
b) Neutron velocity evolution in field $\mathbf{B_0}$ along z-axis
c) Neutron deceleration time evolution along z-axis

The full energy change occurs only over a small area, but **the velocity change occurs throughout the entire path inside the magnetic field**

The results of the MC-analysis of the magnetic system*

Bunch depolarisation

$< \mathbf{0.1\%}, \ \omega_L/\omega_B > 10^4$

Flipper efficiency

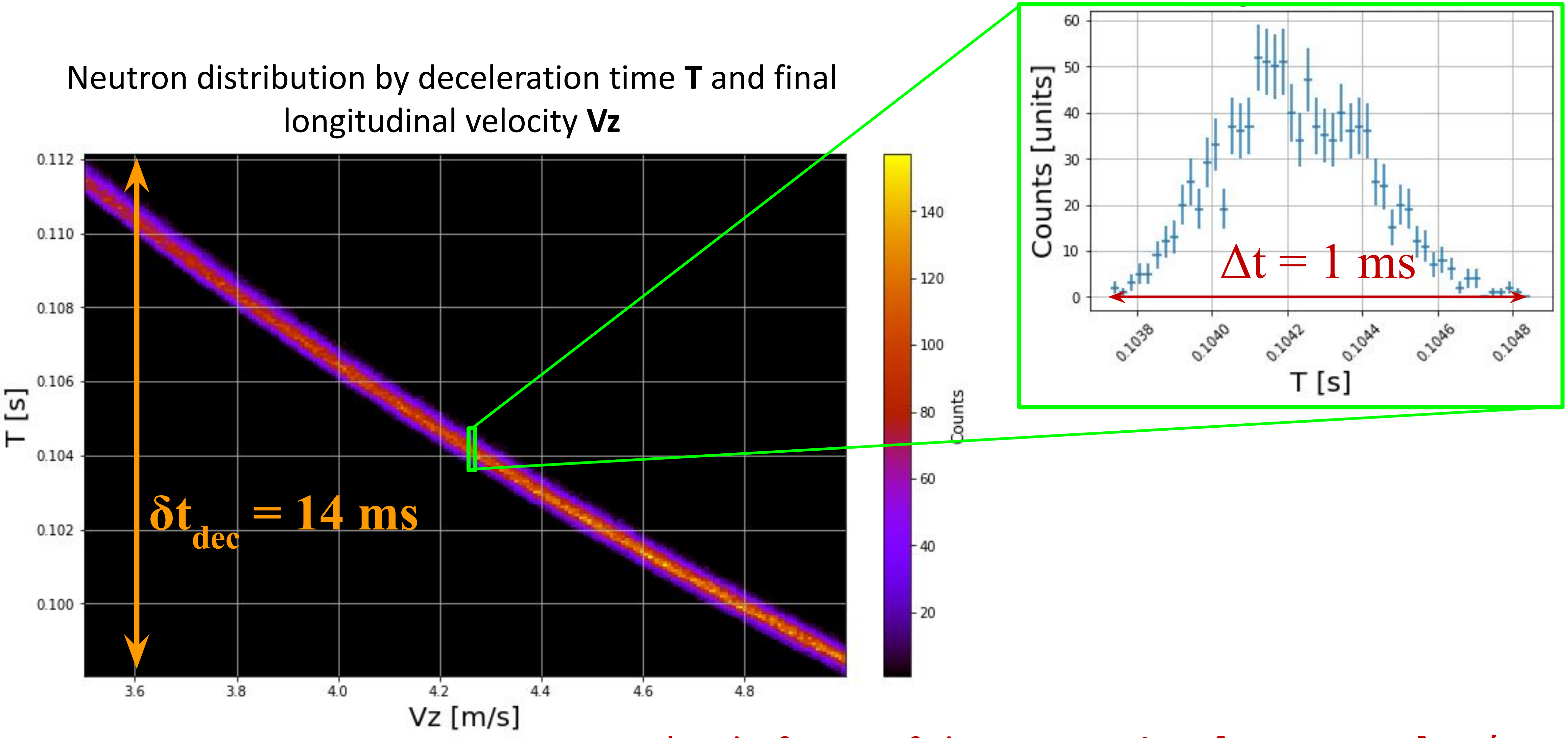
Spinflip probability **>** 0.99

*only for useful neutrons! V∈[20.9; 21.2] m/s

The results of the MC-analysis of the magnetic system*

Deceleration time

Neutron distribution by deceleration time **T** and final longitudinal velocity **Vz**

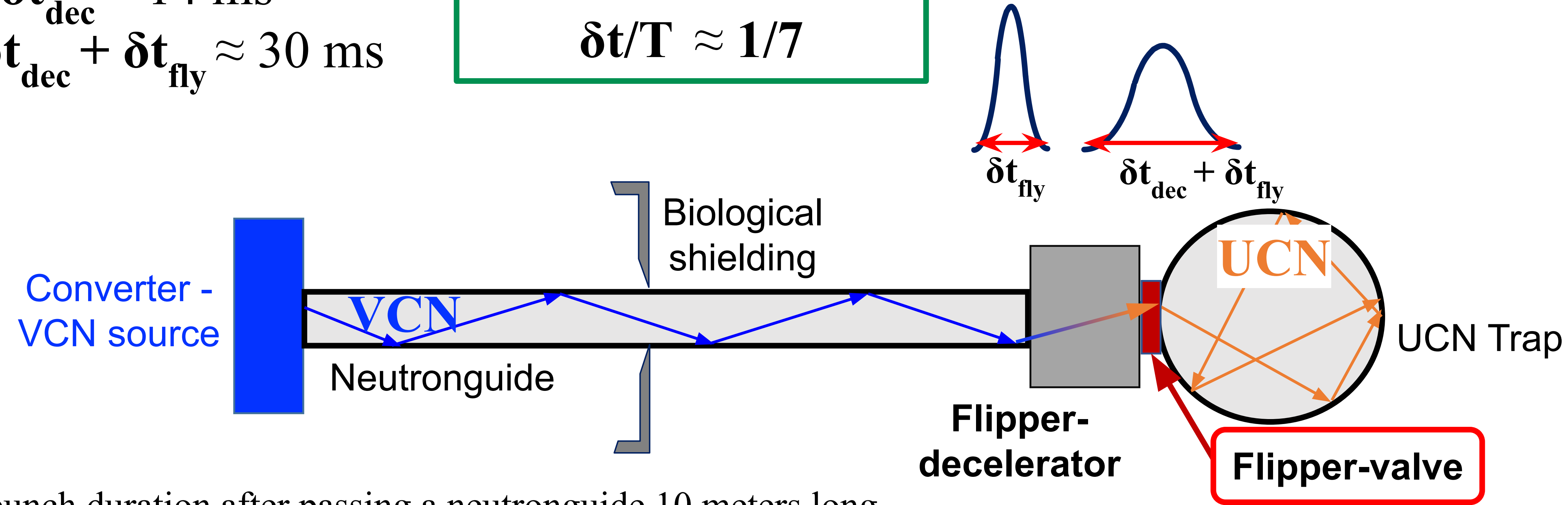


*only for useful neutrons! V∈[20.9; 21.2] m/s

The possibility of a pulsed accumulation

$$\delta t_{fly} \approx 15 \text{ ms}$$
$$\delta t_{dec} \approx 14 \text{ ms}$$
$$\delta t \approx \delta t_{dec} + \delta t_{fly} \approx 30 \text{ ms}$$

$$\delta t \ll T = 200 \text{ ms}$$
$$\delta t/T \approx 1/7$$



δt_{fly} - VCN bunch duration after passing a neutronguide 10 meters long
δt_{dec} - VCN bunch duration after passing flipper-decelerator,
δt - full VCN bunch duration,
T - pulse period.

Pulsed accumulation is **possible**!

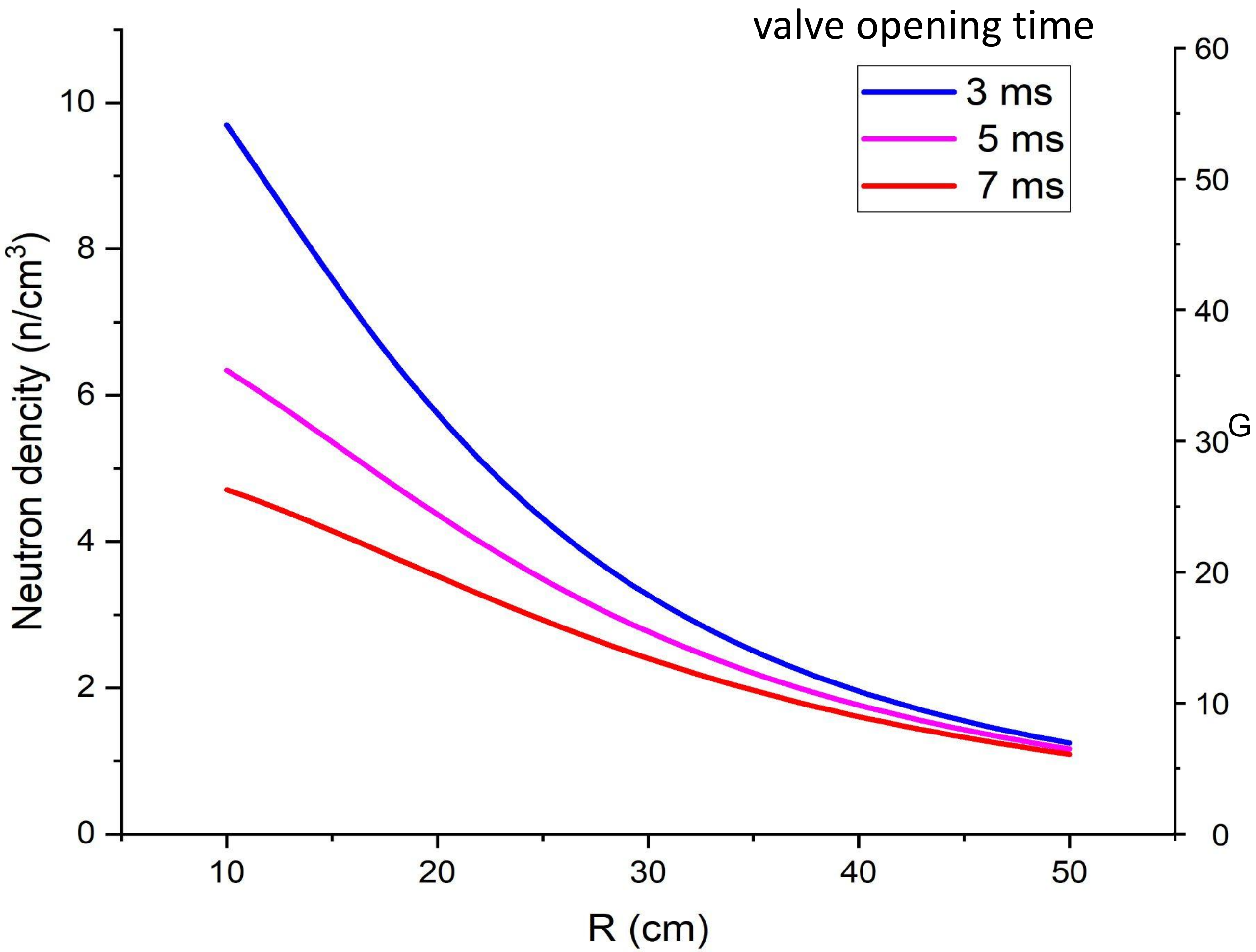
Summary

- A primary design of the superconducting gradient solenoid for a UCN source has been developed

- It was shown:
- The flipper efficiency is better than 99 %
- The variance of the deceleration time $\boldsymbol{\delta t_{dec}}$ = 14 ms.
- **Using flipper-decelerator allows one to implement the idea of effective pulsed accumulation.**

Additional materials

Neutron density in a spherical UCN trap (liquid H_2 converter)

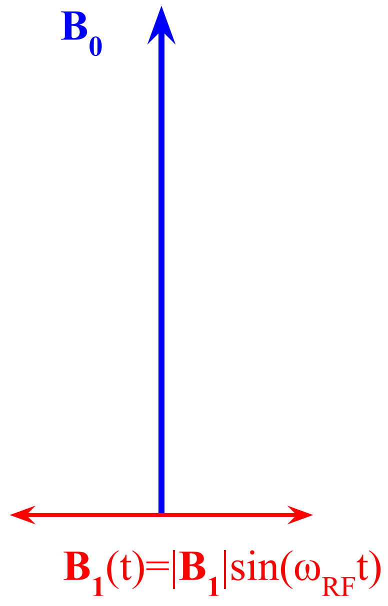


Neutron density depending on the UCN trap radius

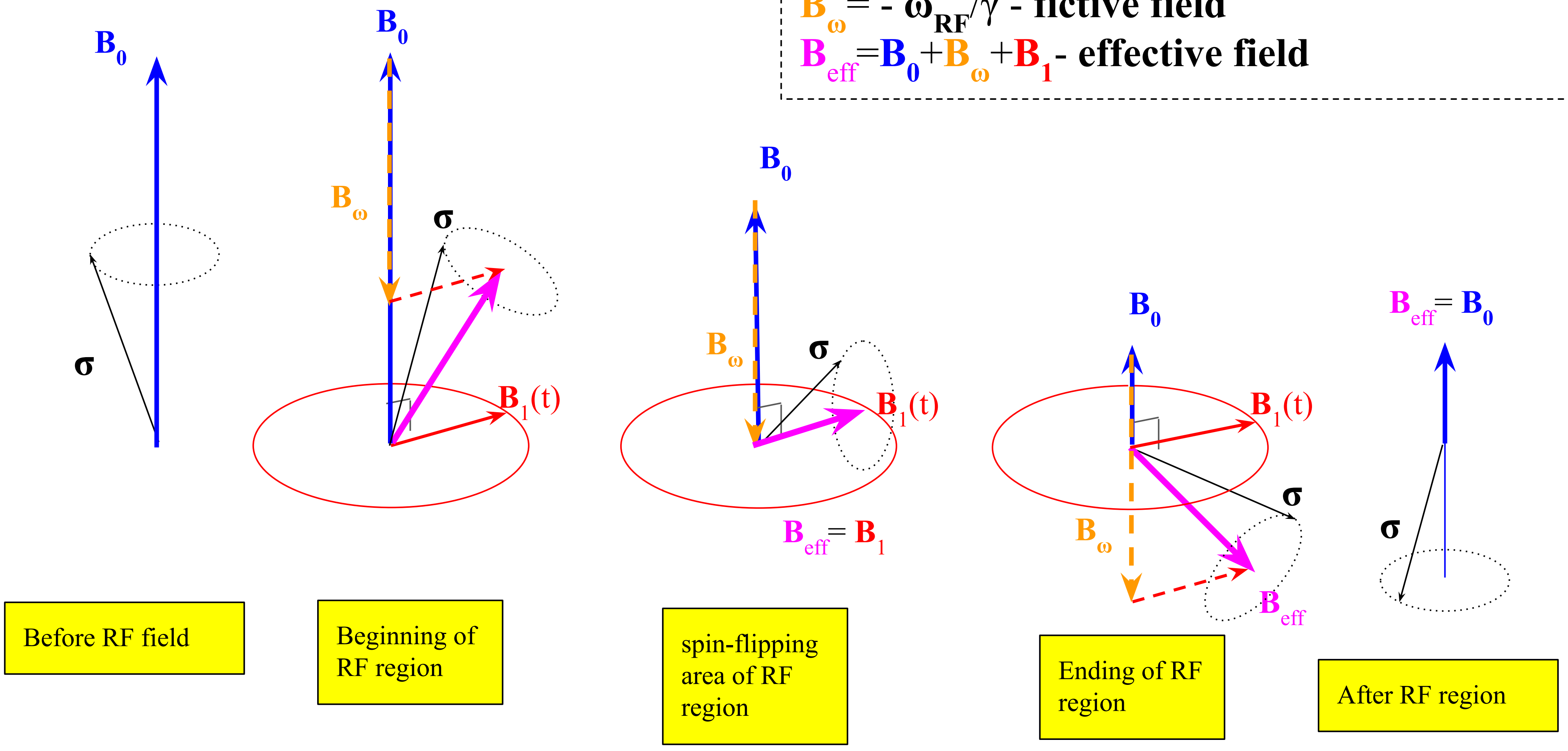
G is the ratio of the flux in the trap to the average flux at the trap entrance

For more effective converter, like **solid D_2**, the neutron density can be increased by **30** times

Polarization evolution in magnetic resonance system

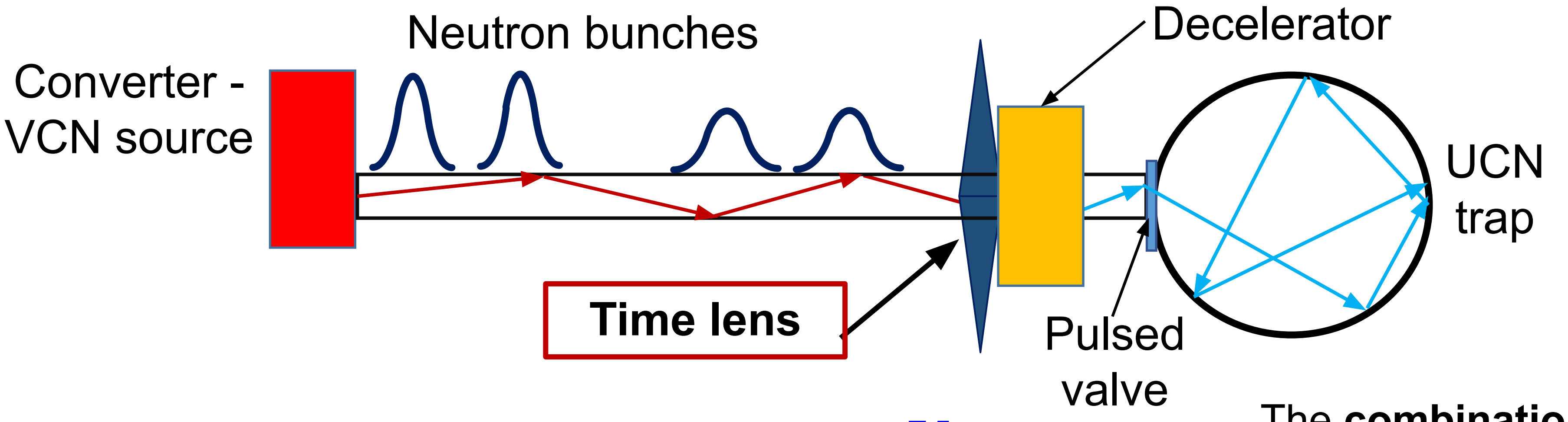


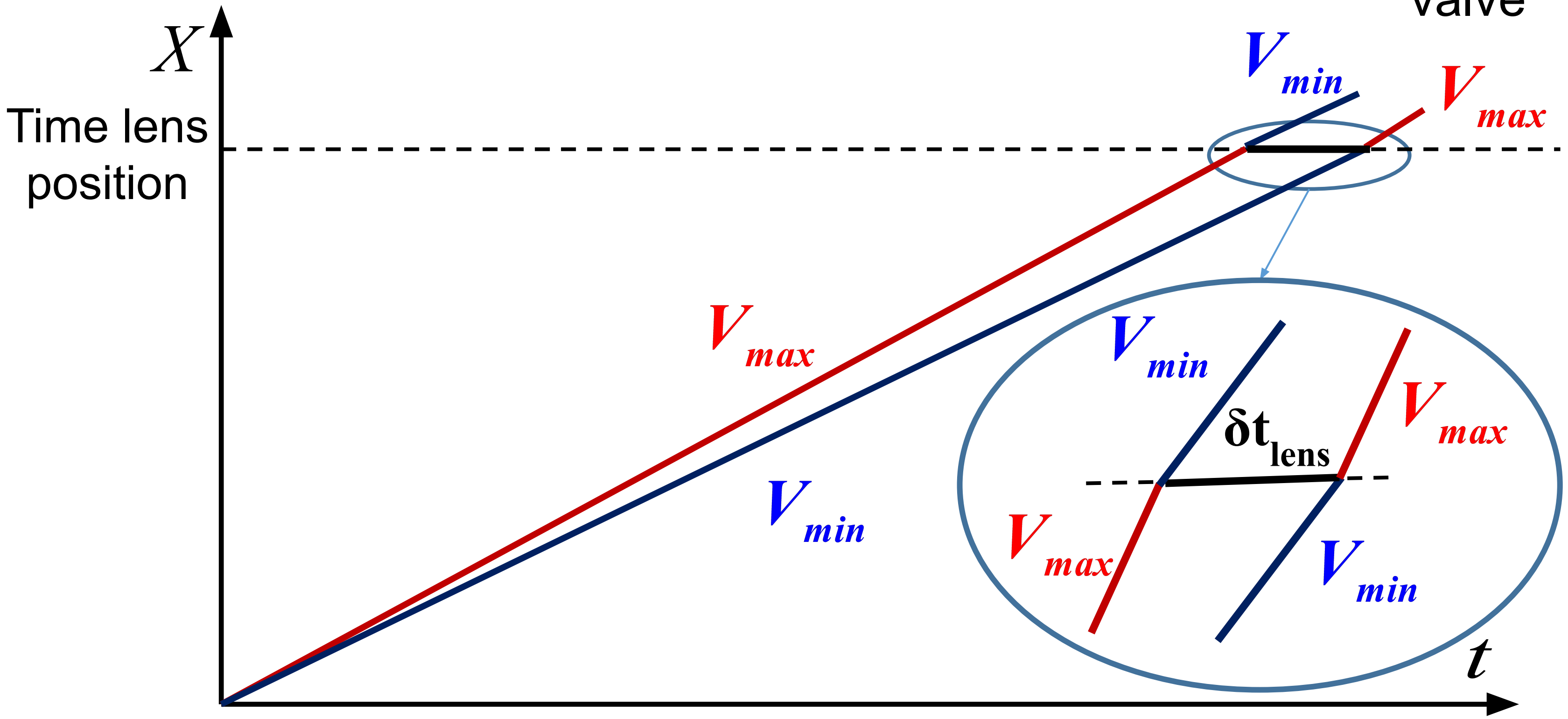
$B_0 = B_0(z)$ - gradient static field
$B_1 = B_1(t)$ - oscillating time-dependent RF field
$B_\omega = -\omega_{RF}/\gamma$ - fictive field
$B_{eff} = B_0 + B_\omega + B_1$ - effective field



Time lens

Work in progress





The **combination** of the *time lens* and the *decelerator* allows to minimize **bunch duration**

$$\delta t \approx \delta t_{dec} - \delta t_{lens}$$

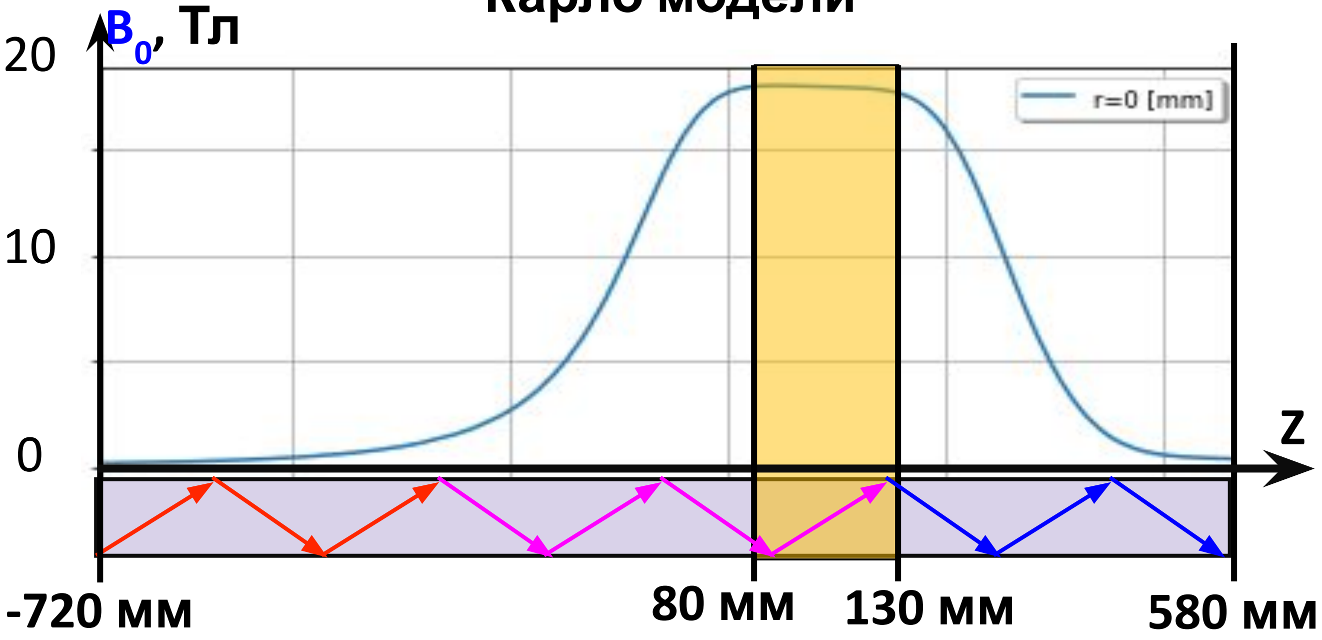
$$\delta t \ll \delta t_{dec} \approx \delta t_{lens}$$

δt_{lens} - flight time dispersion

δt_{dec} - deceleration time dispersion

Монте-Карло модель движения нейтрона в магнитной резонансной системе

Рис.: Схема области расчета Монте-Карло модели



Основные положения модели:

1) Магнитное поле в модели задается **трехмерной сеткой** с известной напряженностью магнитного поля в узлах. **Шаг сетки - 1 мм.**
2) Градиент магнитного поля определяется внутри модели.
3) Движение осуществляется через ячейки с постоянным градиентом магнитного поля.
4) **Отражение** от стенок нейтроновода считается зеркальным.

$\mathbf{F} = \nabla(\boldsymbol{\mu},\mathbf{B})$ - уравнение движения нейтрона

$d\boldsymbol{\mu}/dt = \gamma[\boldsymbol{\mu},\mathbf{B}]$ - уравнение прецессии спина

- Сечение нейтроновода 6 см x 6 см
- Длина области 1.3 м