UCN source with pulsed accumulation of neutrons in a trap

G.V. Kulin, A.I. Frank, V.N. Shvetsov, V.A. Kurylev, A.A. Popov, K.S. Osipenko, M.A. Zakharov, A.Yu. Muzychka, A.N. Chernikov

Ultra Cold Neutrons

General definition: UCNs are neutrons whose energy is so low that they are reflected under any angle of incidence can be contained in traps

	E (eV)	T (K)	λ(Å)
Ultra cold	$<10^{-7}$	≈ (<) mK	>800
Very cold	$10^{-7} – 10^{-4}$	10^{-2} - 10	800 - 30
Cold	$(0.1\text{-}10)\times10^{-3}$	10-120	30-3
Thermal	$(10\text{-}100) \times10^{-3}$	120-1000	4-1
Resonant	>1		< 0.1

UCNs are important tools for:

Search for the neutron EDM

Measurement of the neutron lifetime

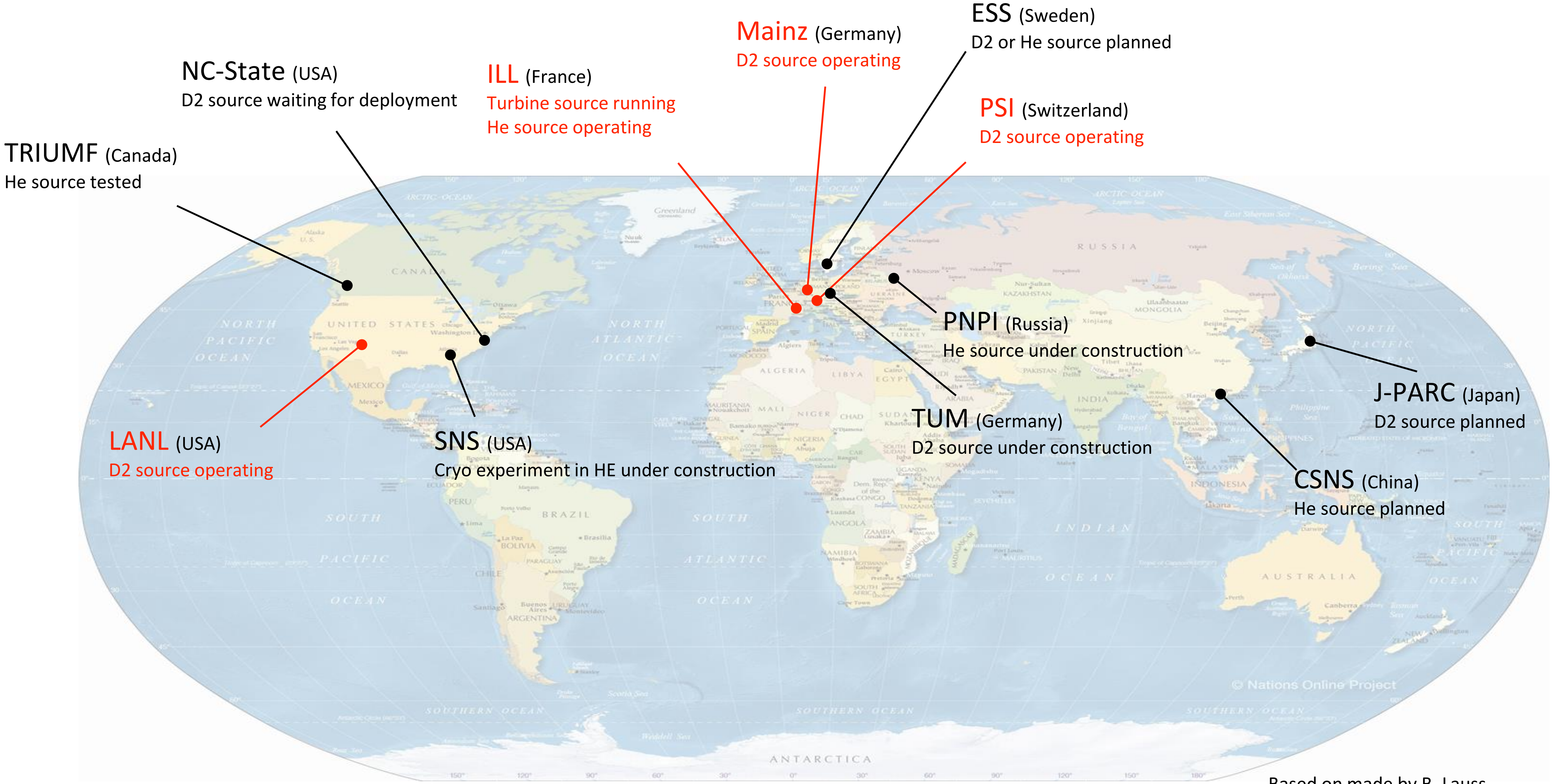
Measurement of angular correlation coefficients of neutron beta decay

Search for neutron-antineutron oscillations

Quantization of neutron states in a gravitational field and search for new interactions

Non-stationary quantum mechanics and neutron optics

Ultra Cold Neutron sources



Based on made by B. Lauss

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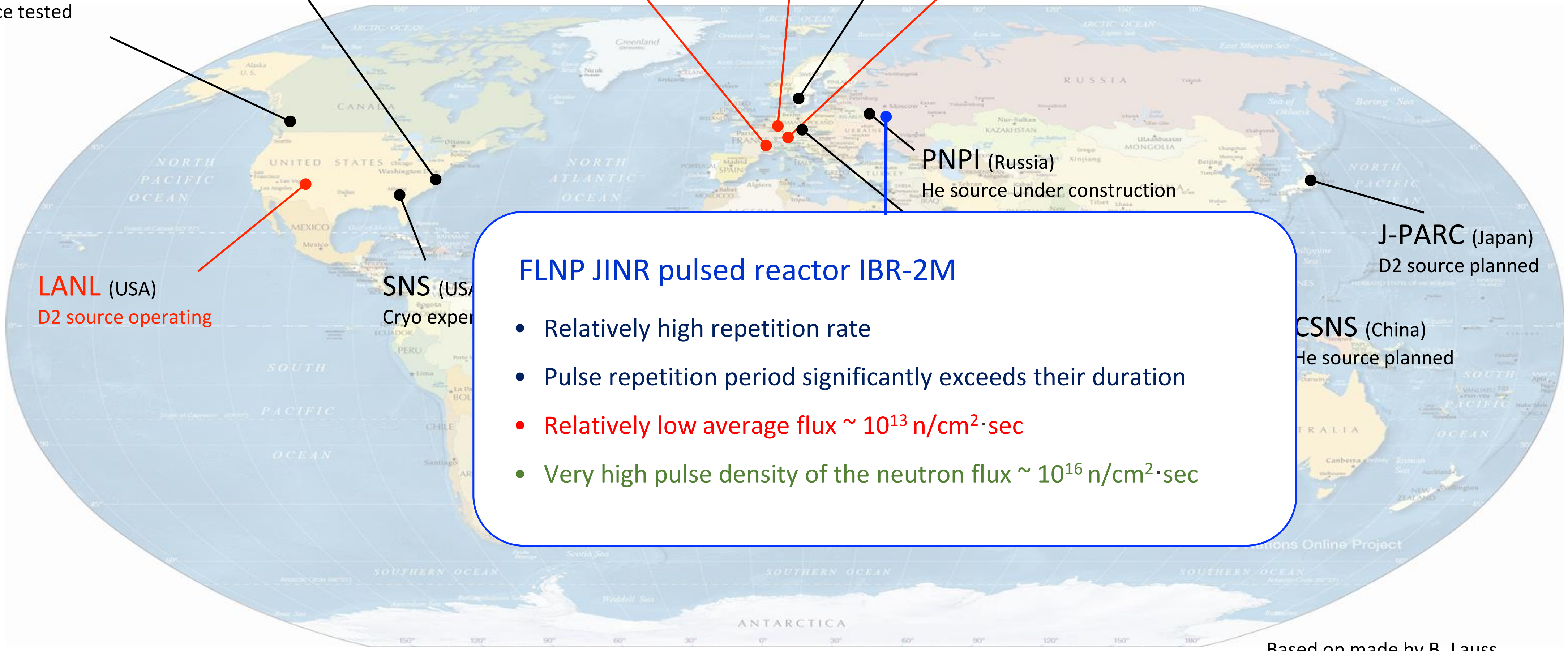


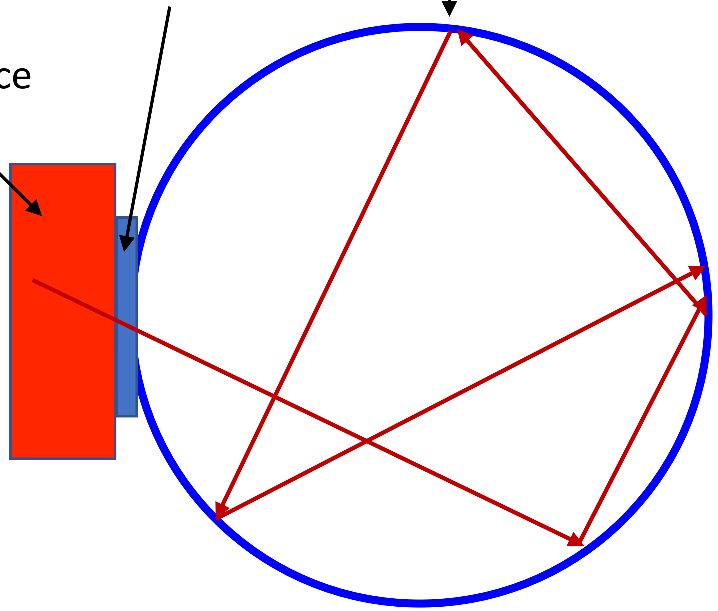
FLNP JINR pulsed reactor IBR-2M

- Relatively high repetition rate
- Pulse repetition period significantly exceeds their duration
- Relatively low average flux ~ 10^{13} n/cm^2·sec
- Very high pulse density of the neutron flux ~ 10^{16} n/cm^2·sec

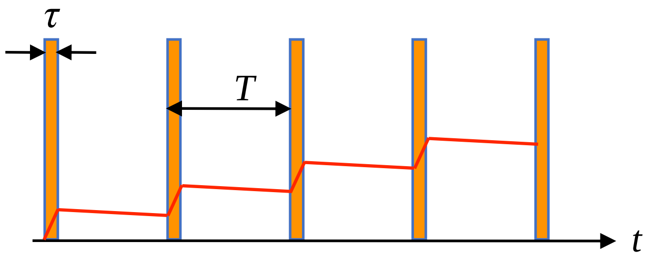
Based on made by B. Lauss

Pulse source and UCN pumping in a trap

F.Shapiro, 1972



$g \to 10^2 \div 10^3$



$$g = 1 + \frac{1 - \frac{\tau_1}{T}}{\frac{\tau_1}{T} + \frac{\Sigma\mu}{S}}$$

$\tau_1 > \tau$ — *chopper opening time*

S — *active convertor area*

Σ — *area of the trap*

μ — *probability of the UCN lost*

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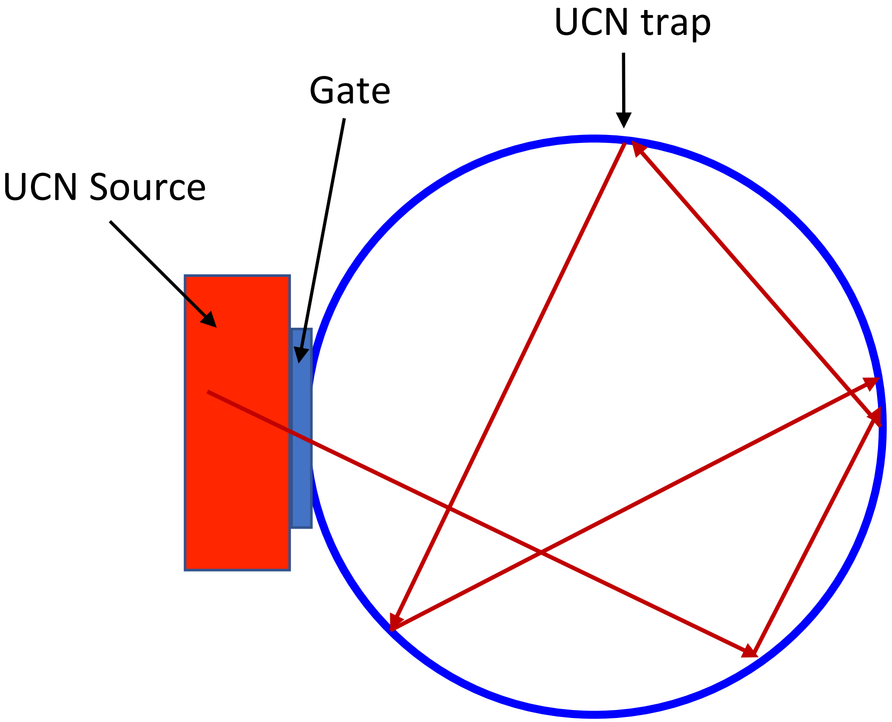

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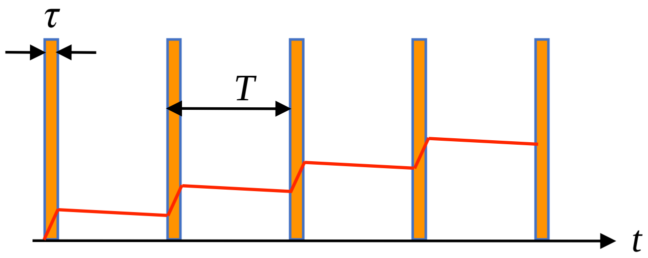

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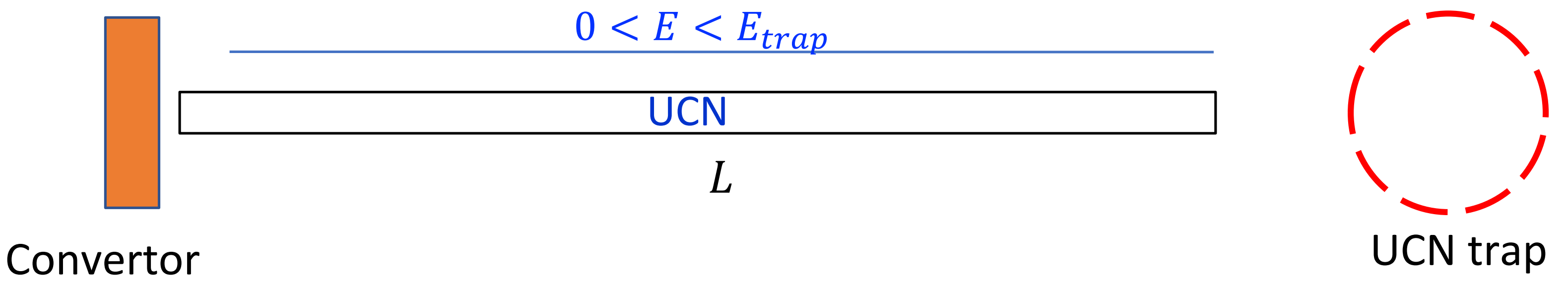
The trap is remote from the moderator due to the presence of biological shielding

Time structure of the beam at the entrance to the UCN trap



$$\delta t \sim t = \frac{L}{\sqrt{E_{trap}/2m}}; \delta t \gg T$$

! The spread of the UCN flight times will exceed the intervals between pulse

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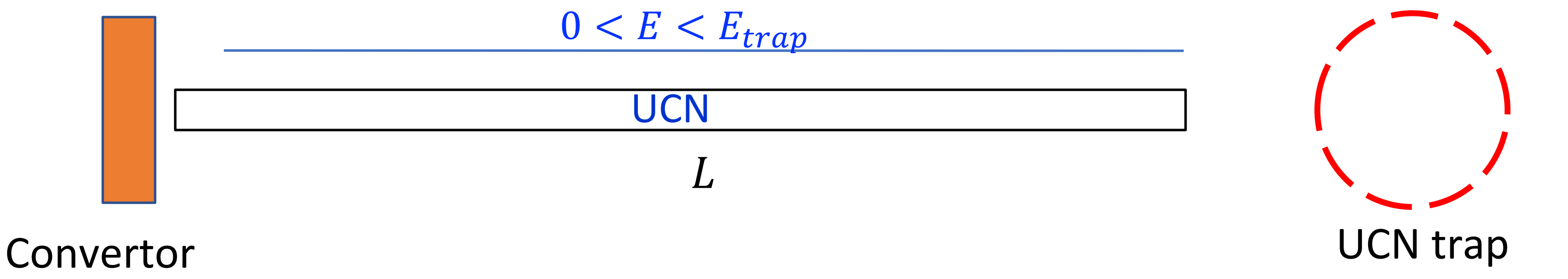

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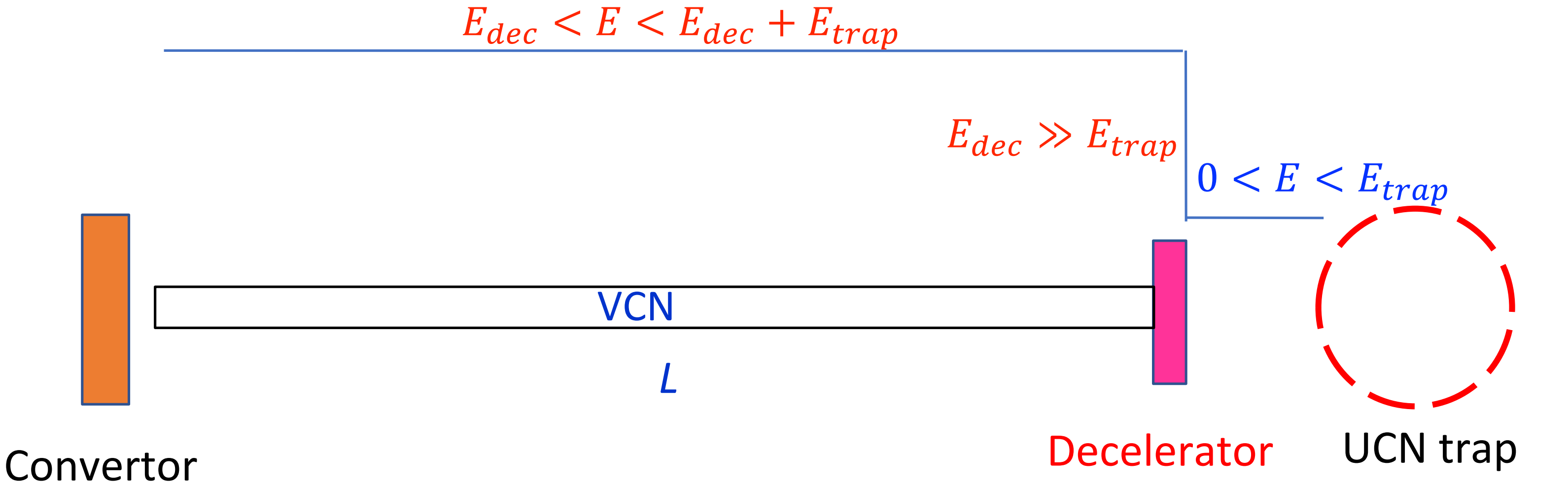
Frank, A.I., Kulin, G.V., Zakharov, M.A. Phys. Part. Nuclei Lett. 20, 664–667 (2023)



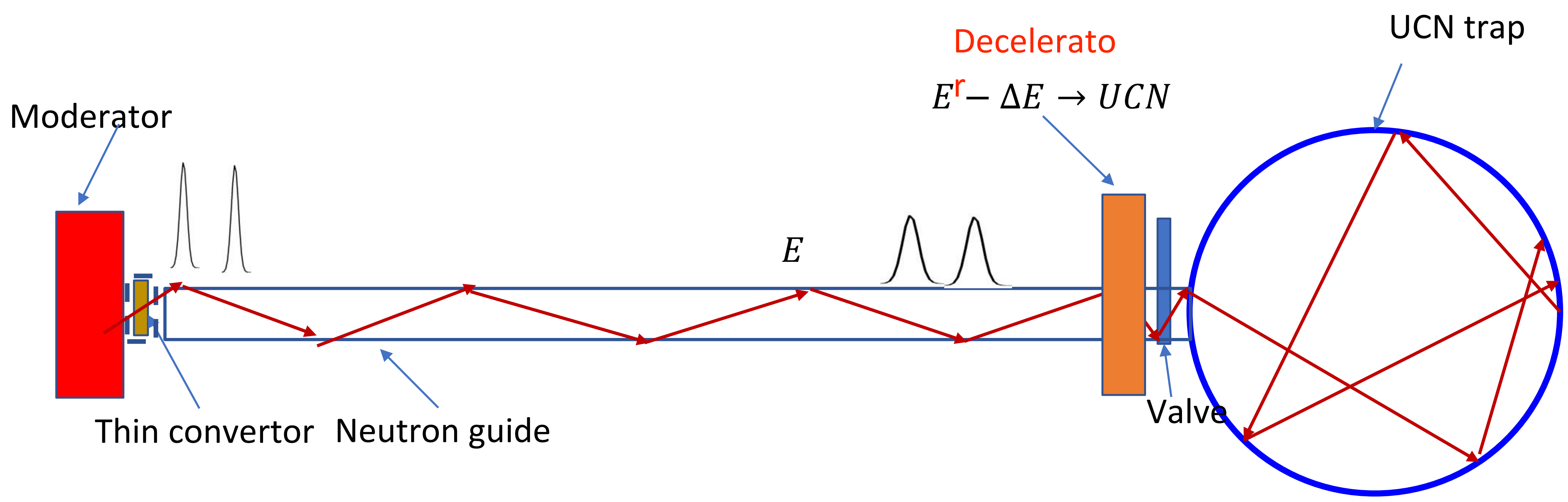
$$\frac{\delta t}{t} = \frac{\delta V}{V} = \frac{\delta E}{2E} = \frac{E_{trap}}{2E_{dec}} \ll 1$$

$$t \simeq \frac{L}{\sqrt{E_{dec}/2m}}$$

$$\delta t \ll T$$

! The flux of neutrons, which can be trapped after deceleration, has a pulsed structure

Pumping option of the pulsed source – decelerator



During deceleration, all neutrons change their energy by the same value

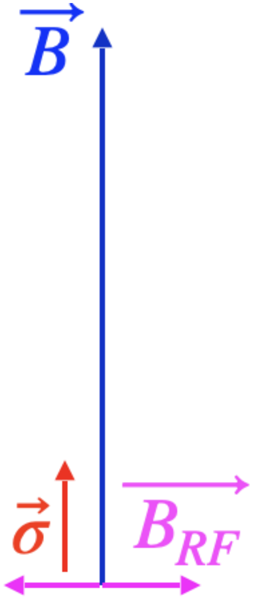
✓ The pulse structure of the "useful" neutrons is remain, but the pulse duration at the entrance to the trap exceeds the initial one.

✓ The extraction of neutrons with higher speeds than that of the UCN from the moderator converter provides better conditions for the transportation of neutrons and allows the use of a more efficient converter

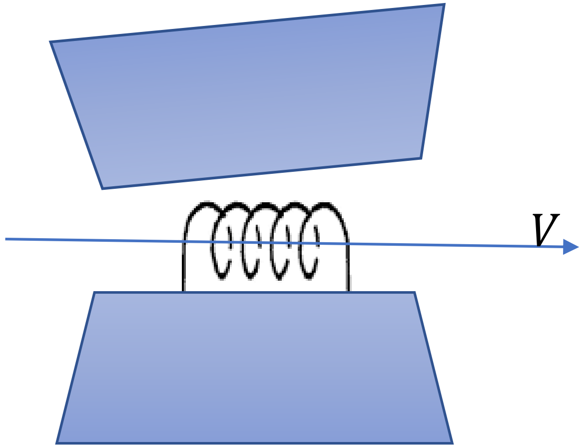
✓Since “useful” neutrons covers a small part of the VCN spectrum, such a source can simultaneously serve as a source of UCN and VCN

Decelerator — broadband gradient (adiabatic) spin flipper

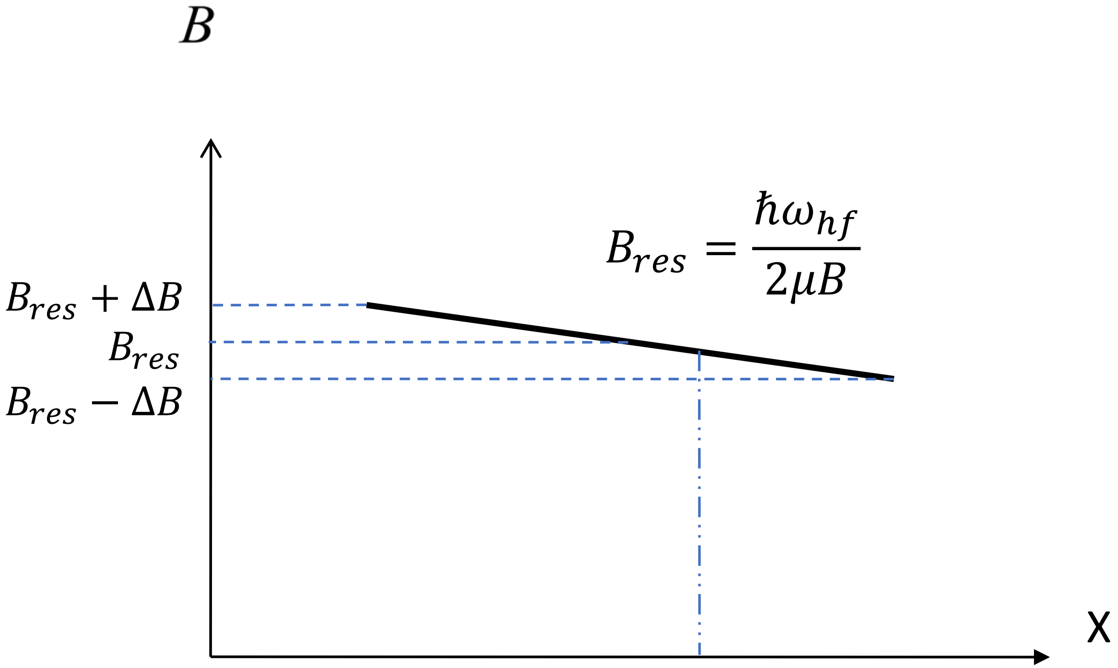
G. M. Drabkin and R. A. Zhitnikov. Sov. Phys. JETP, 11, 729 (1960) — Proposed to use spin-flip of neutrons in a non-uniform (gradient) magnetic field to obtain “supercold” neutrons



$B_{RF} = B_1 \sin \Omega t$



$\Delta B \gg |B_{RF}|$



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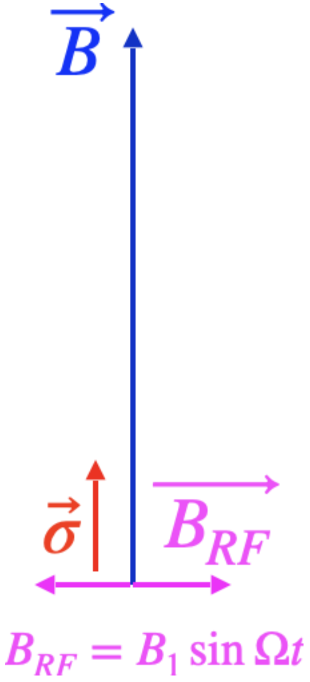

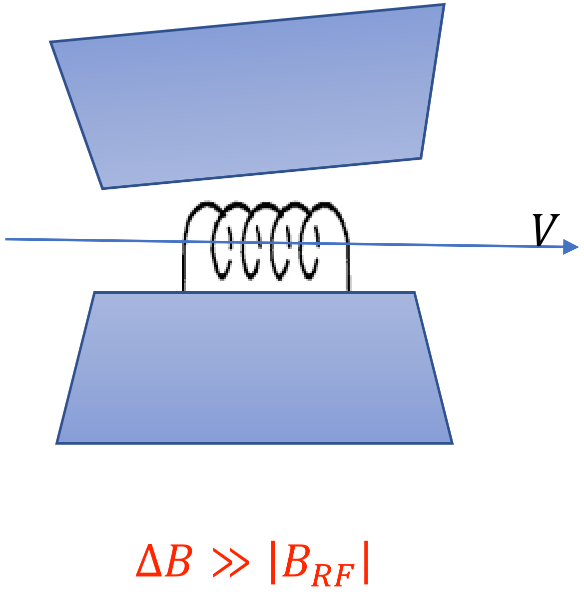

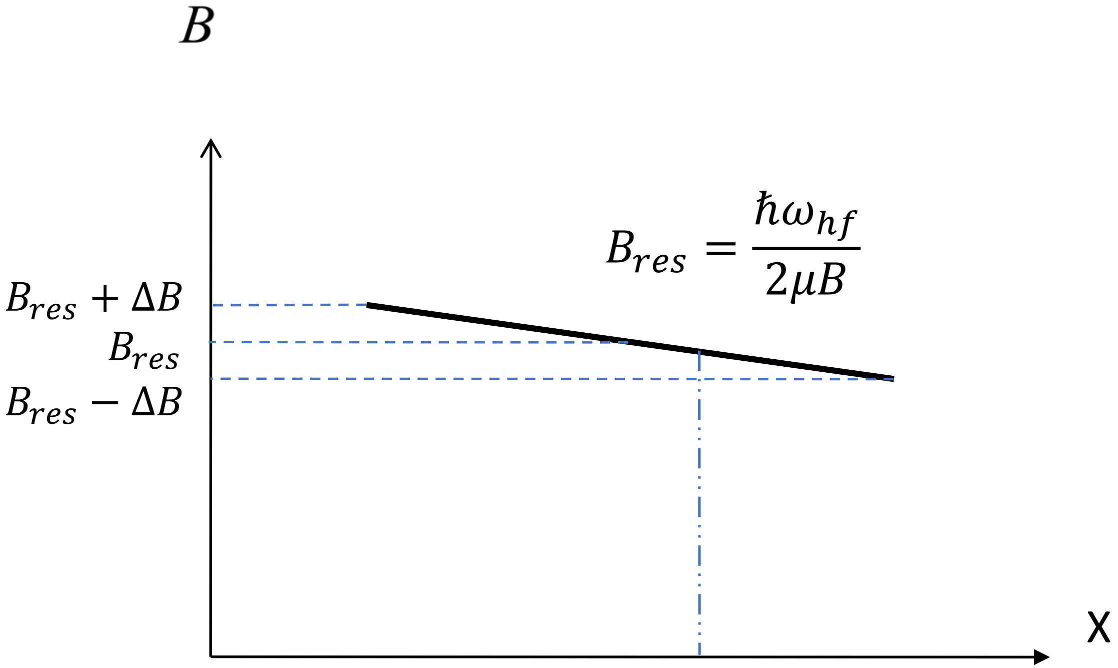

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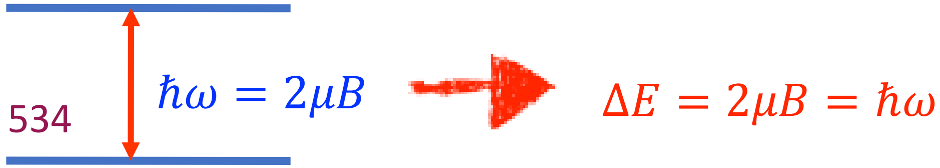

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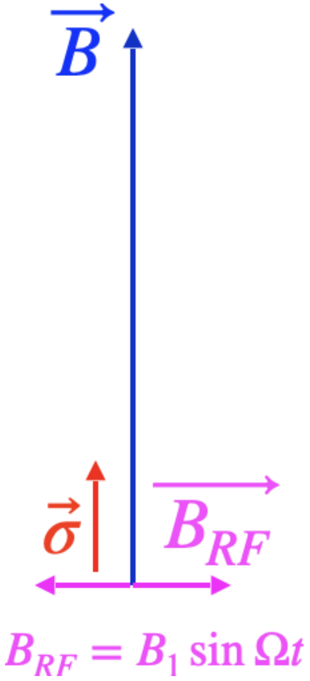
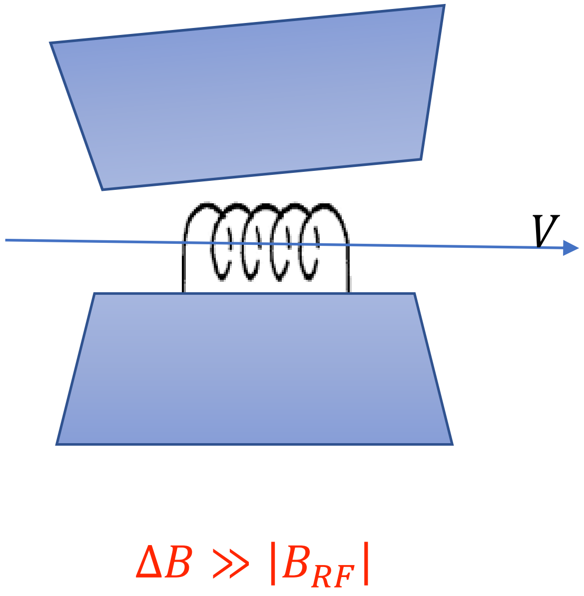
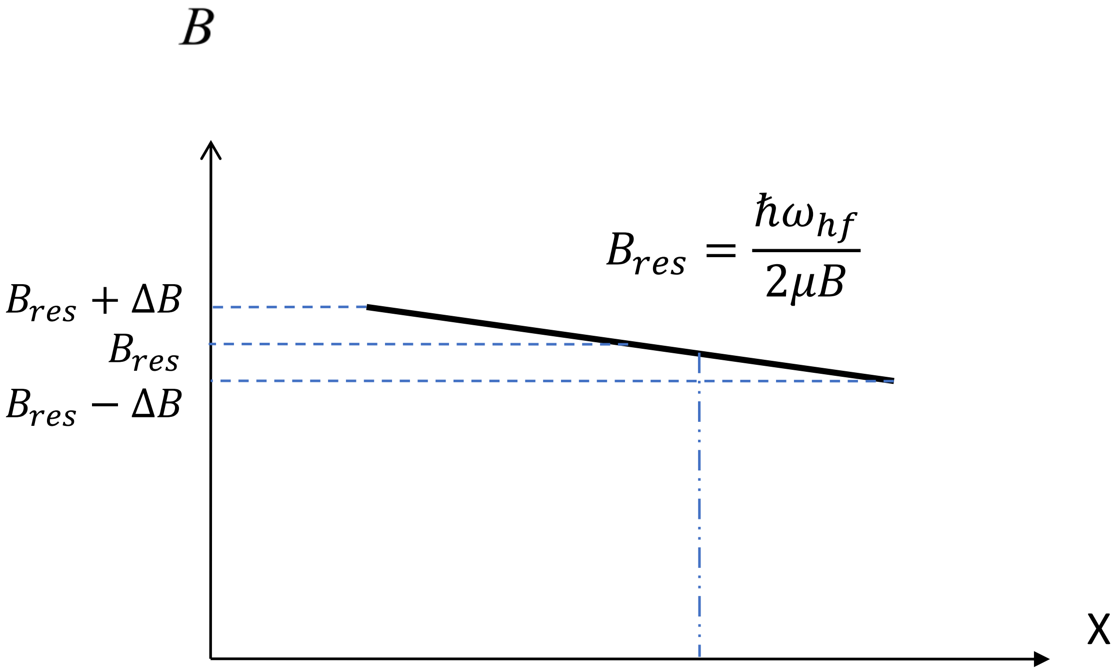






to decelerate a neutron at a speed of 20 m/s to a speed of 5 m/s

$$\Delta E \approx 2.4\mu eV \quad B = \frac{\Delta E}{2\mu} \approx 18\,T \quad f = \frac{\omega}{2\pi} \approx 500\,MHz$$

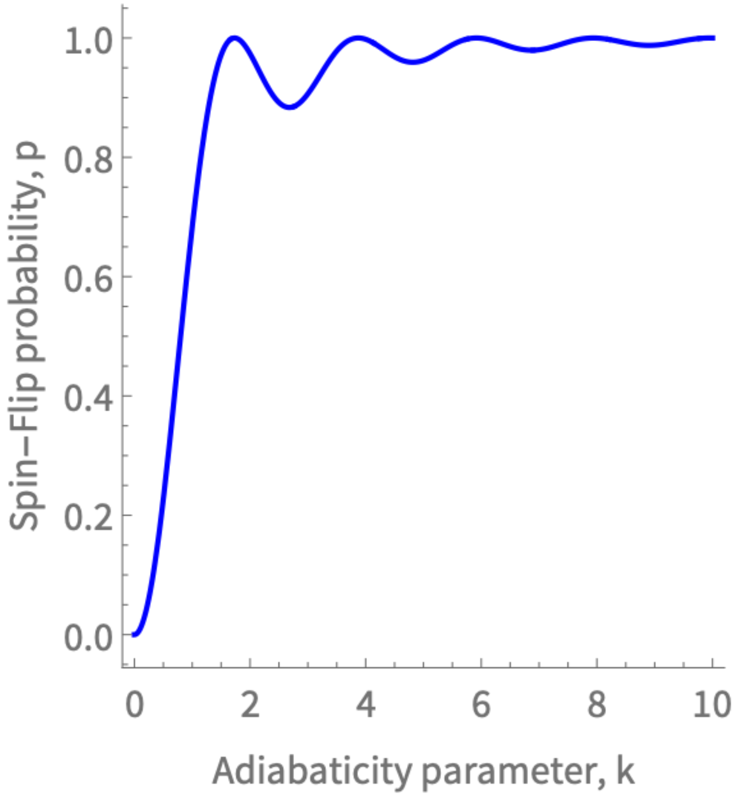
Parameters of adiabatic spin flipper

The adiabaticity parameter $k = \frac{\gamma B_{eff}^2}{\left(\frac{dB}{dz}\right)V}$, where γ is the gyromagnetic ratio of the neutron, V is neutron velocity

Near the resonance point $B \approx B_\Omega$, $B_{eff} \approx B_1$ $\longrightarrow$ $k = \frac{\gamma B_1^2}{\left(\frac{dB}{dz}\right)V}$

at $k = 4$ and $V = 16 m/s$ $\longrightarrow$ $B_1^2 > \frac{dB}{dz} \cdot (2.86 \times 10^{-7})$

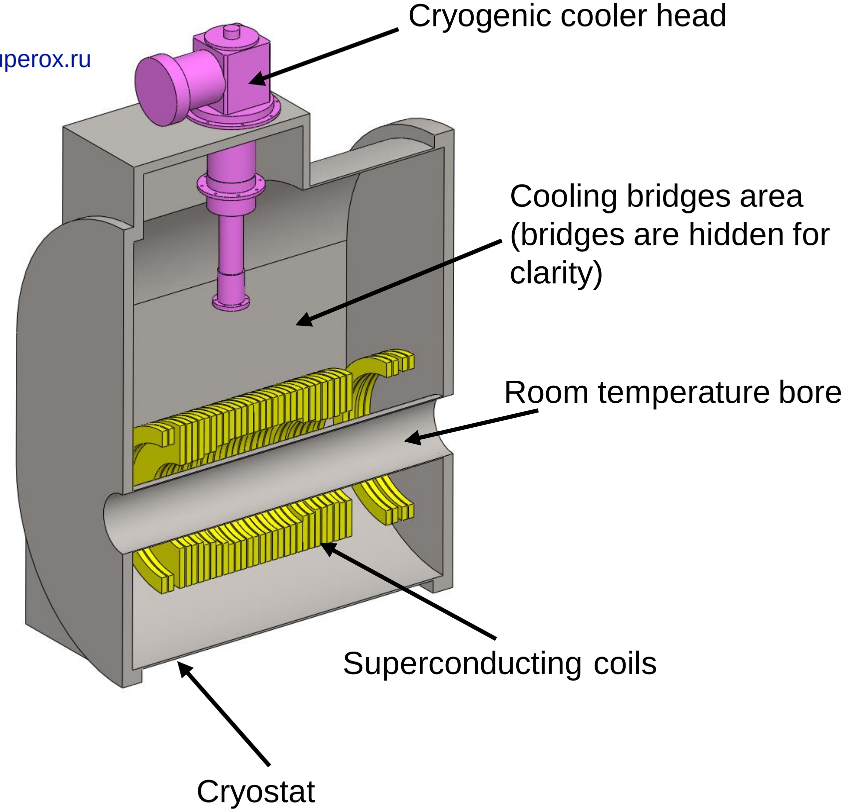
For gradient of magnetic field 1.5 T/m $\longrightarrow$ $B_1 \geq 0.7\, mT$



Stationary gradient field – superconducting solenoid

Preliminary magnet design

Designed by SuperOx LLC / www.superox.ru

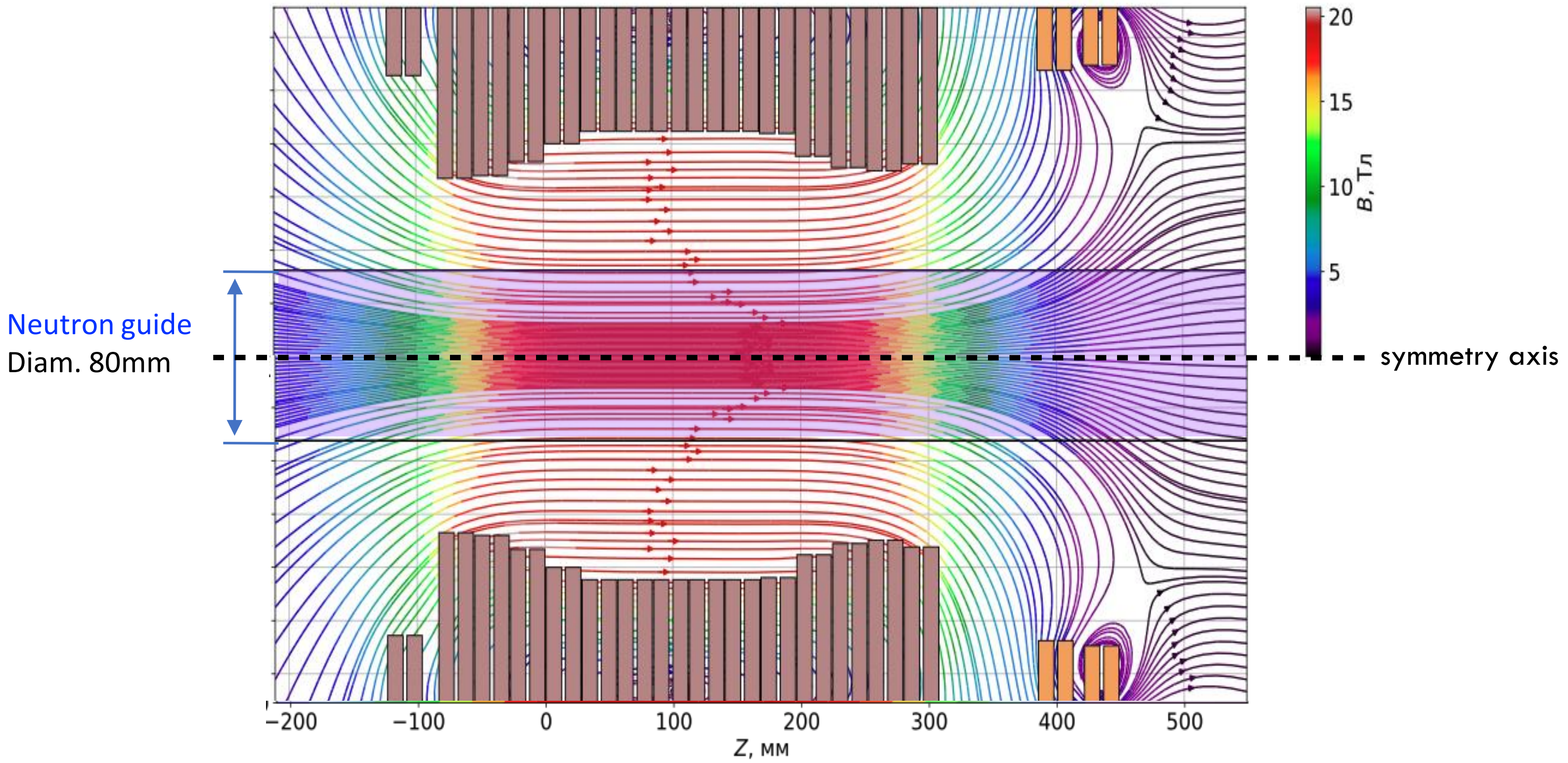


Technical specifications

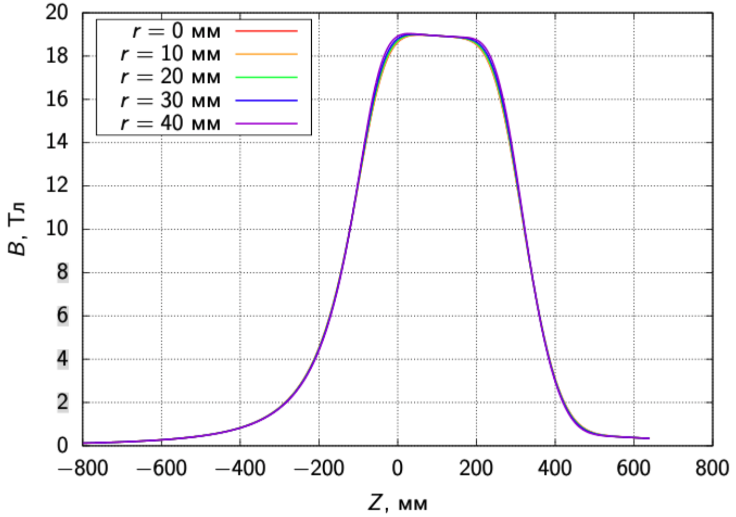
Magnetic field (peak)	20 T
Bore diameter	120 mm
Bore type	Room temperature
Dimensions **Length** **Width** **Height**	 750 mm 660 mm 1250 mm
Mass (including cryostat, magnet and cooling head)	Less than 1000 kg
Power supply	3-phase 380 V
Consumption	16 kW nominal 30 kW during cooldown)
Magnet wire	Second generation high temperature superconductor (YBCO)
Cooling	Indirect (dry-type)

The work on the design of the magnetic system is carried out in co-operation with SuperOx company

Stationary gradient field – superconducting solenoid



Magnetic field profile along Z-axis



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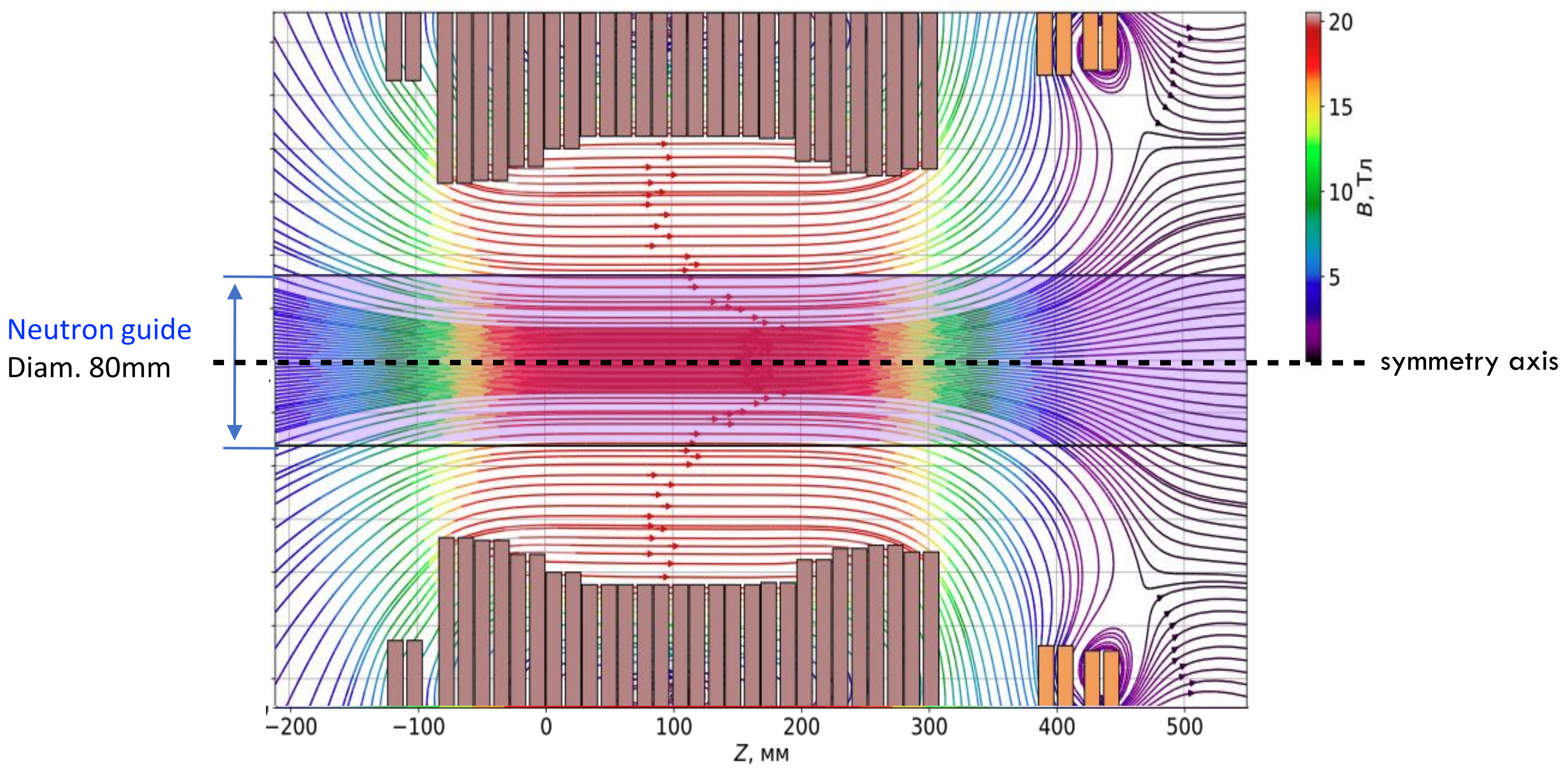

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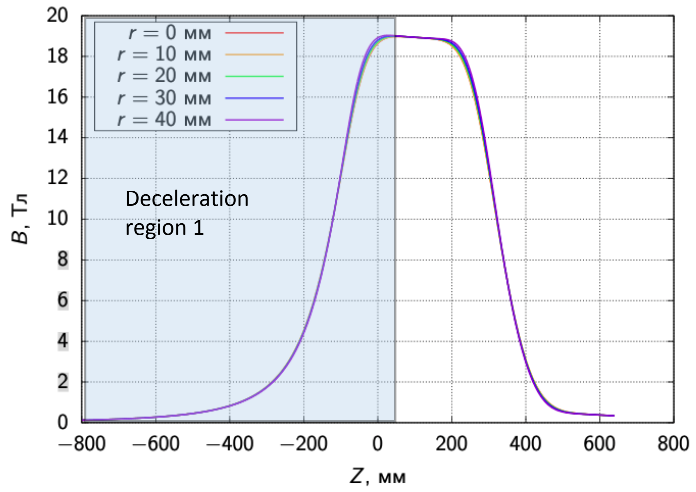
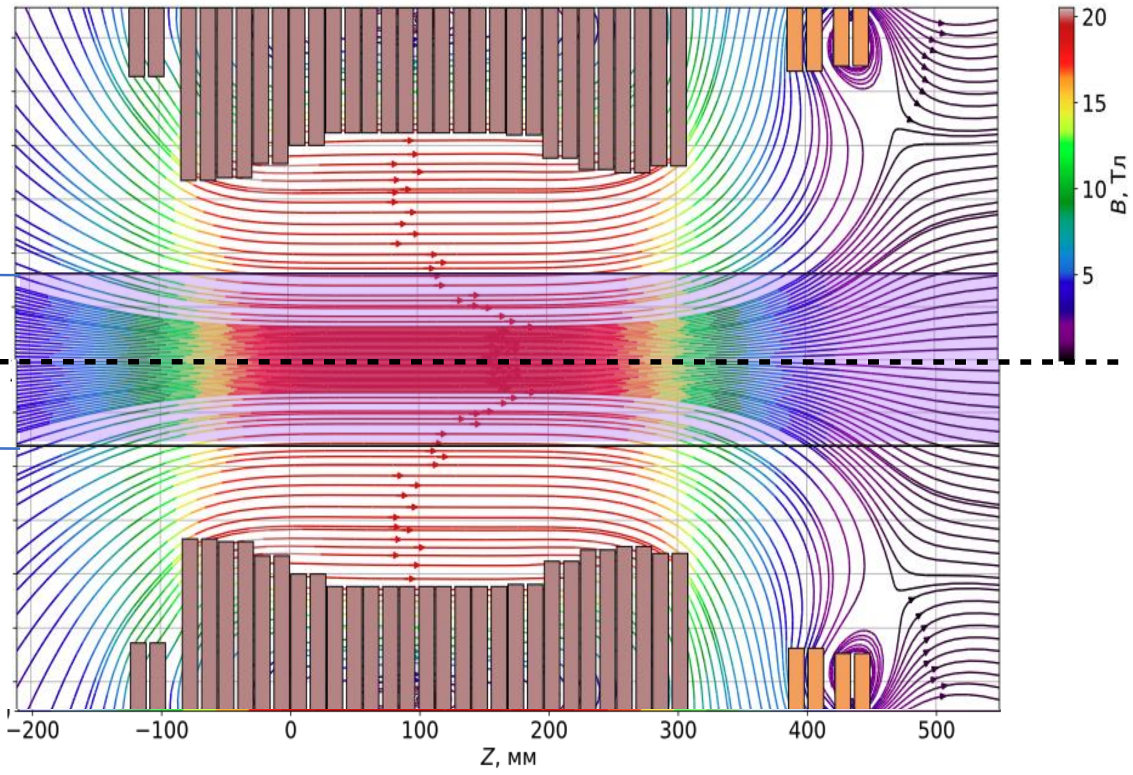


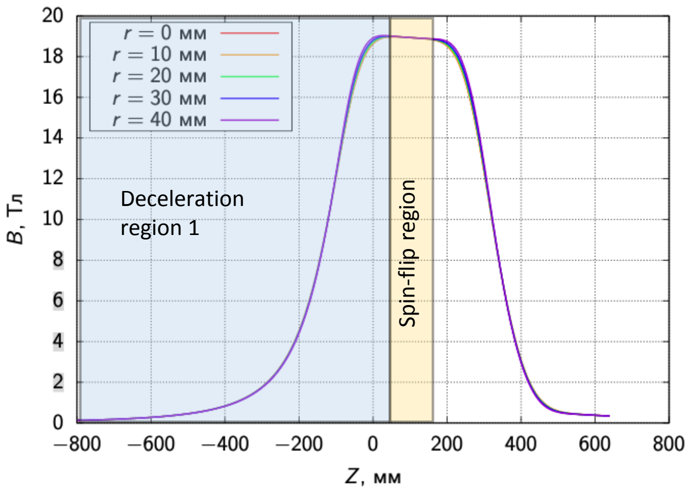
Stationary gradient field – superconducting solenoid

Neutron guide
Diam. 80mm

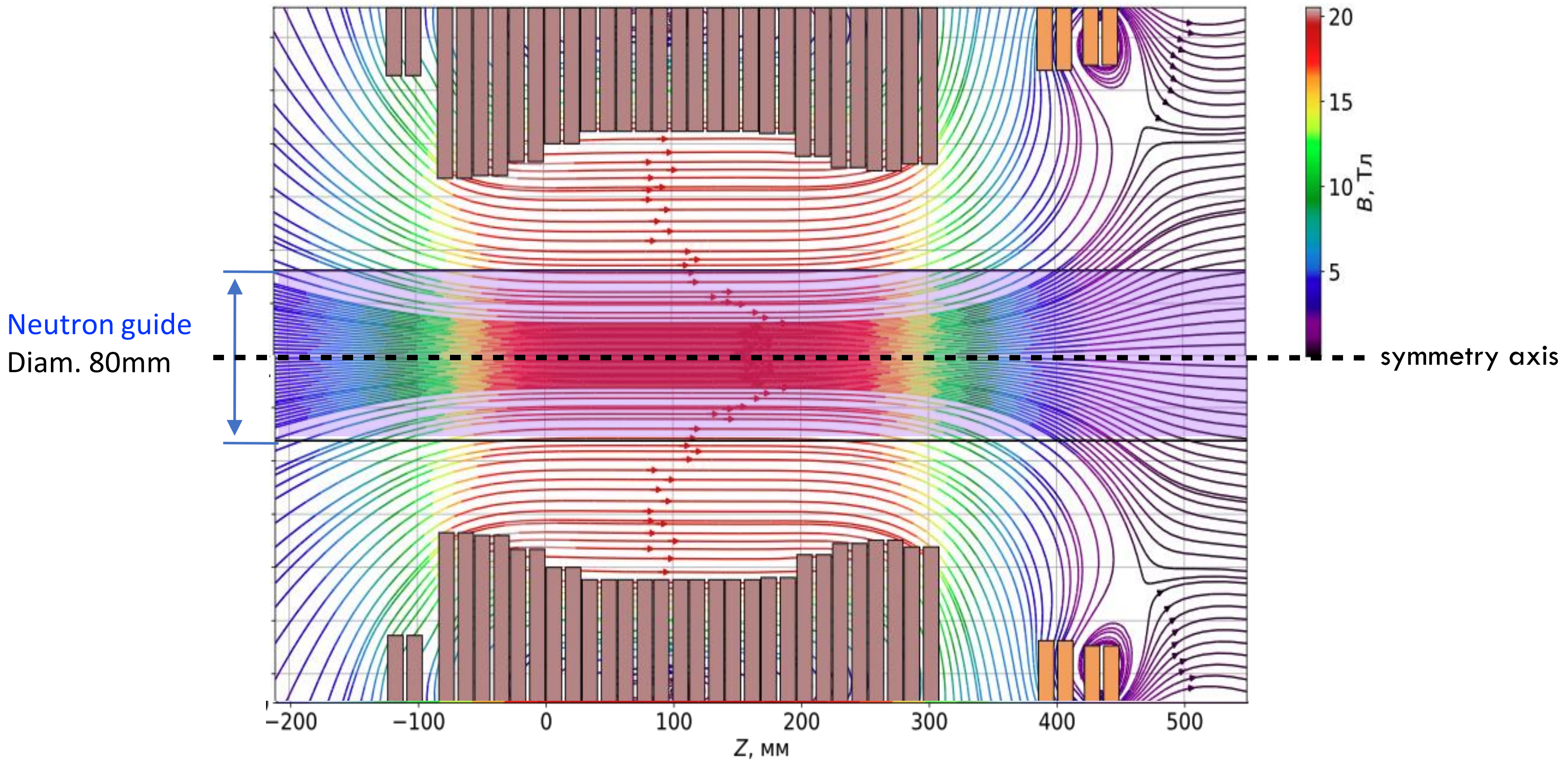


symmetry axis

Magnetic field profile along Z-axis



Stationary gradient field – superconducting solenoid



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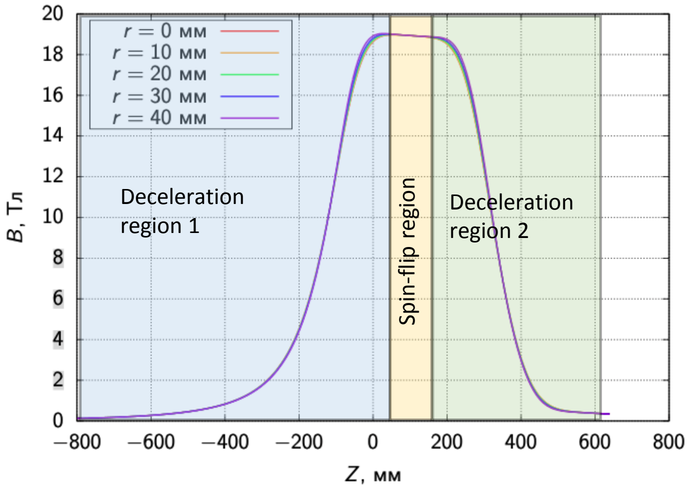

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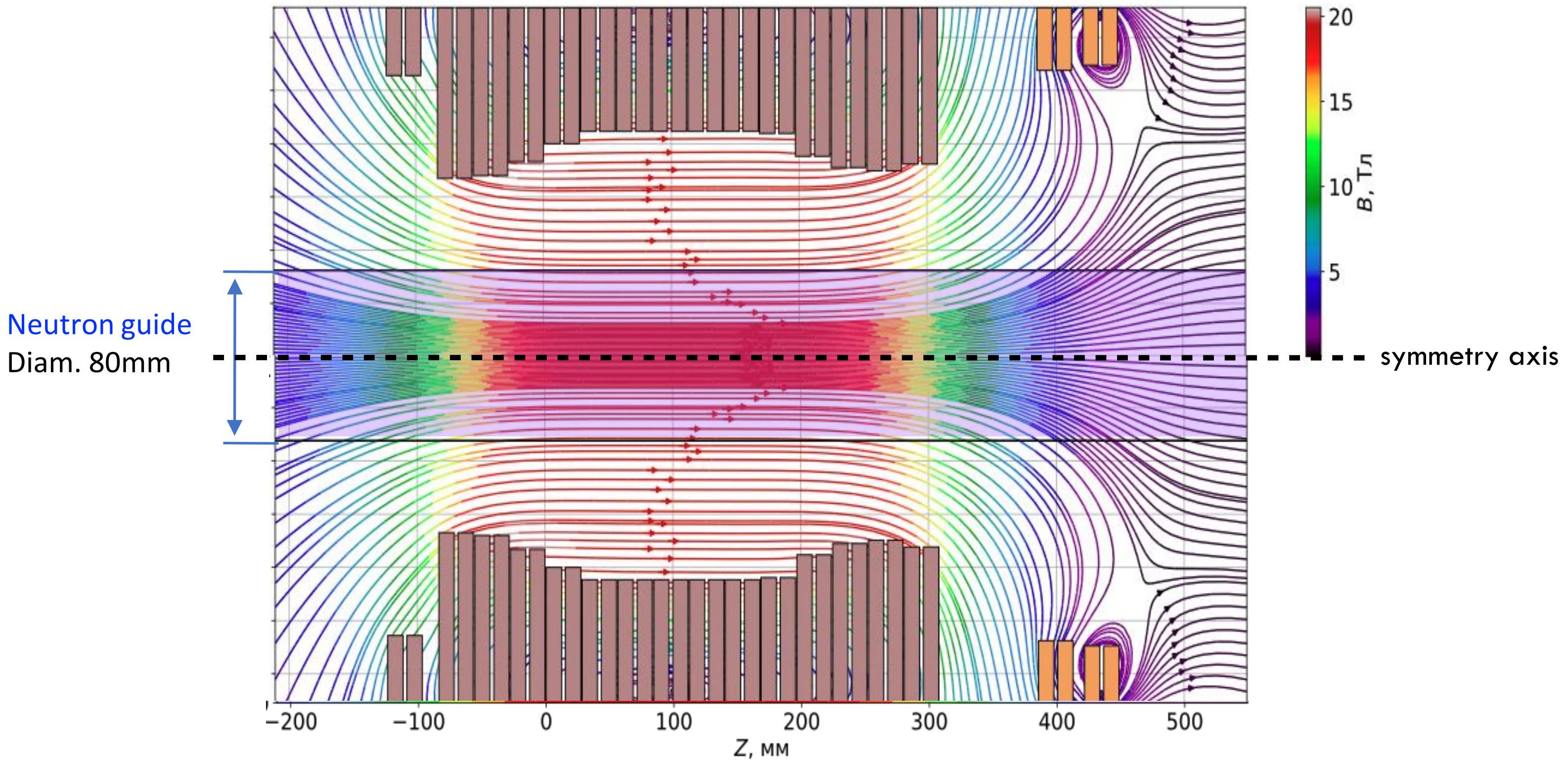

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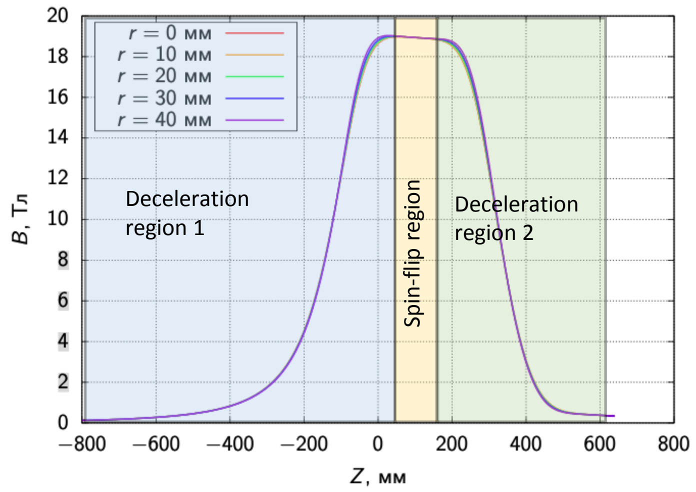
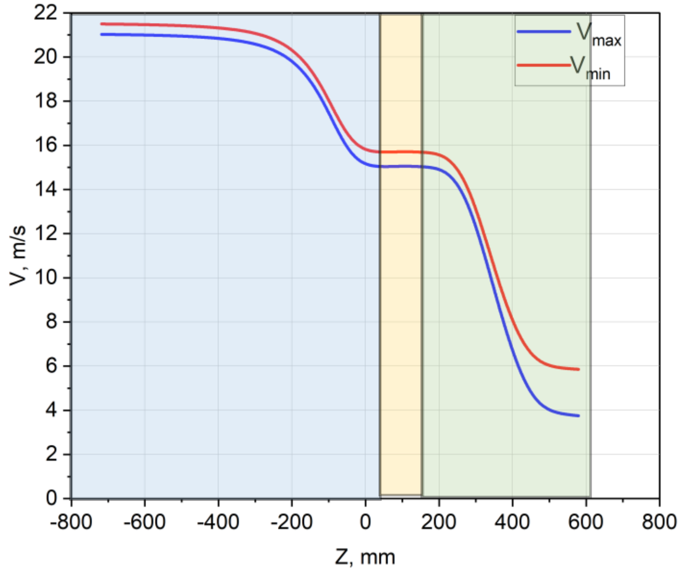
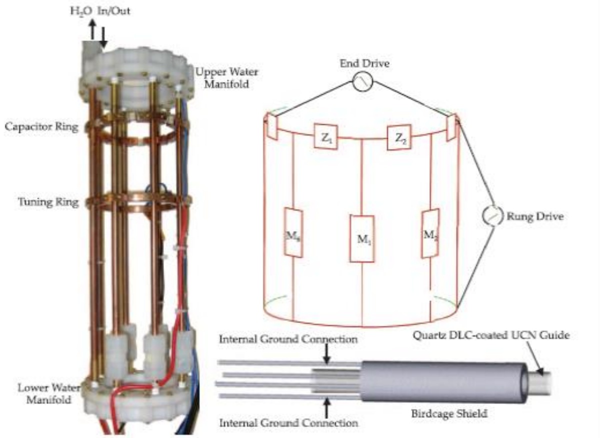




High frequency resonator

The birdcage resonator is a widely used in MRI

- Ability to generate a homogeneous magnetic field over a large volume.
- Allows for a high degree of control over the magnetic field's frequency and amplitude.



Birdcage of UCN spin-flipper (UCNA experiment)

A. T. Holley, L. J. Broussard, J. L. Davis, K. Hickerson, T. M. Ito et al. Rev. Sci. Instrum. 83, 073505 (2012)

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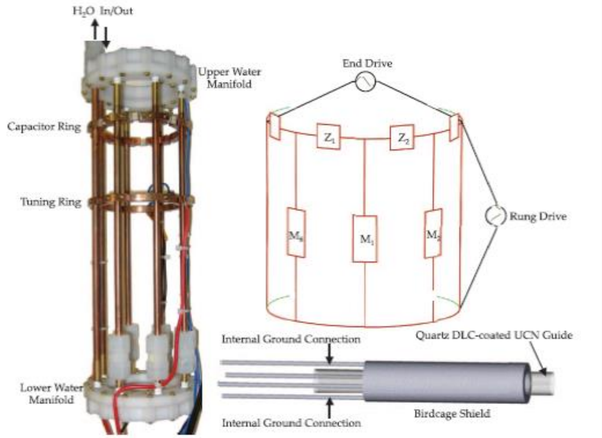

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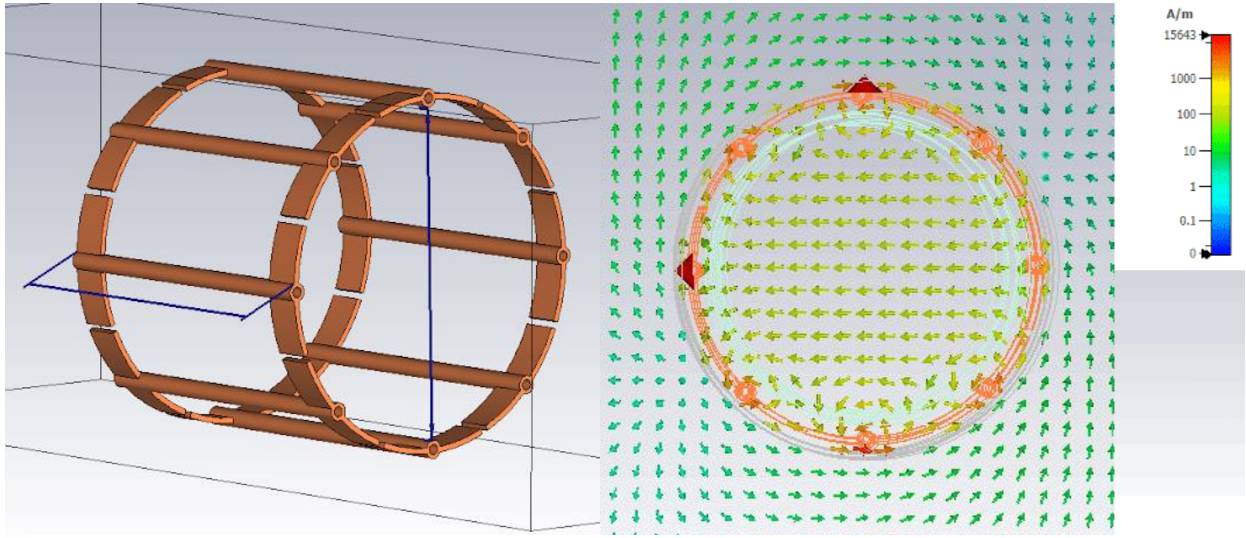
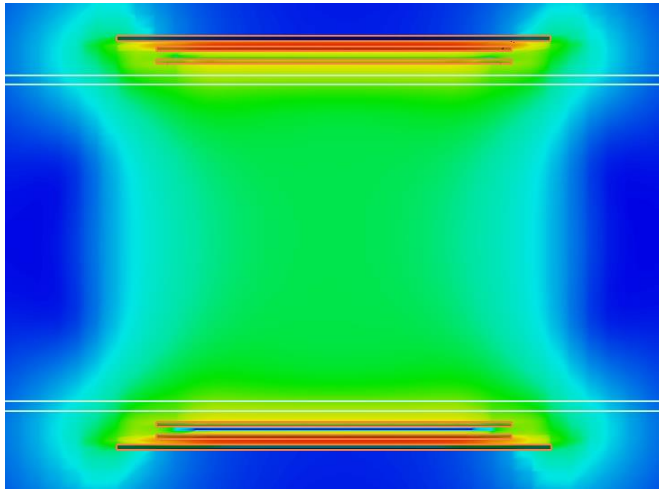
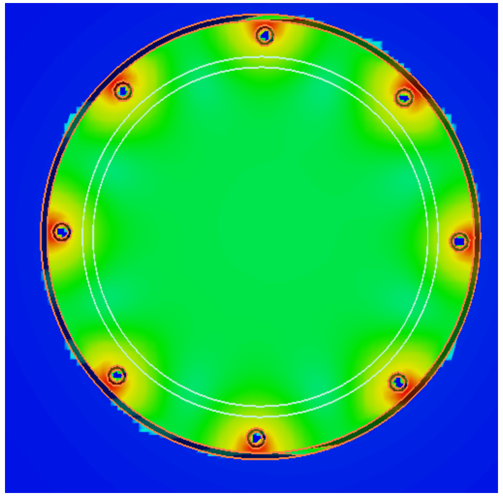




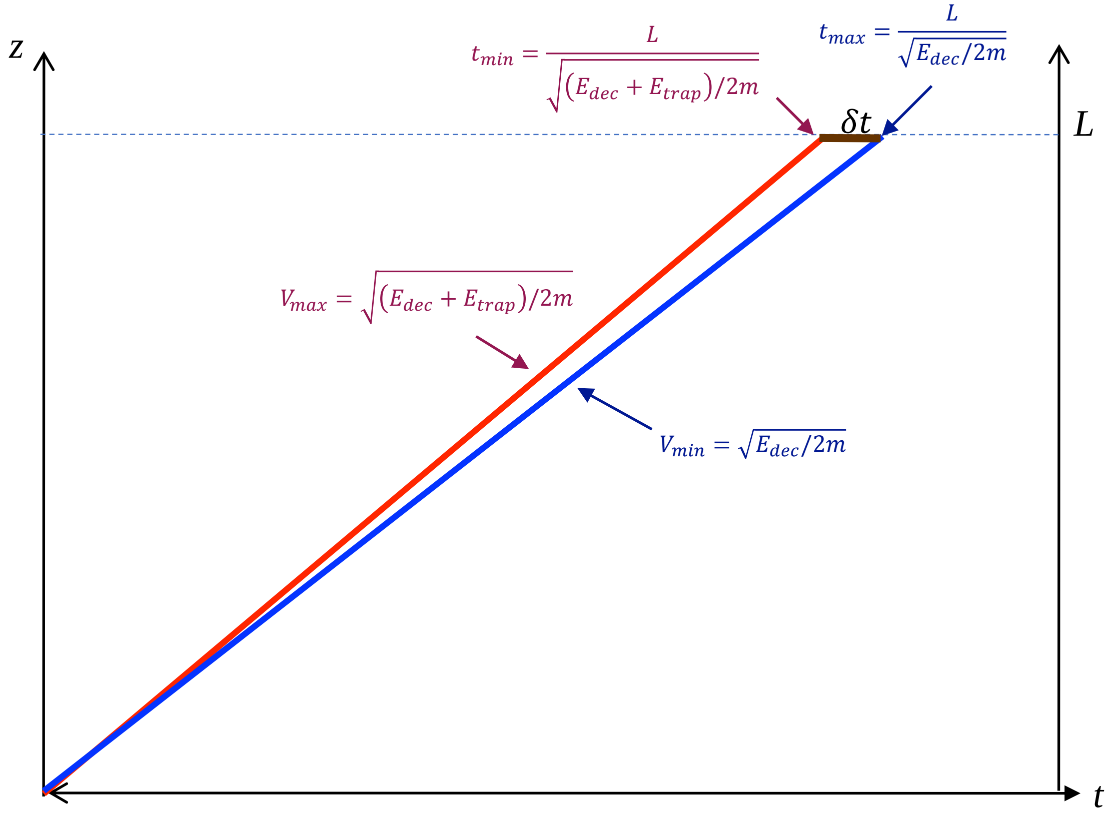


Q-factor$\approx 10^3$, $B_1 = 0.7\,mT$, $f = 500\,MHz$, Input power $\approx 4\,kW$

! The resonator will operate during the pulse only

! The flux of neutrons, which can be trapped after deceleration, has a pulsed structure

! the pulse duration at the entrance to the trap exceeds the initial one



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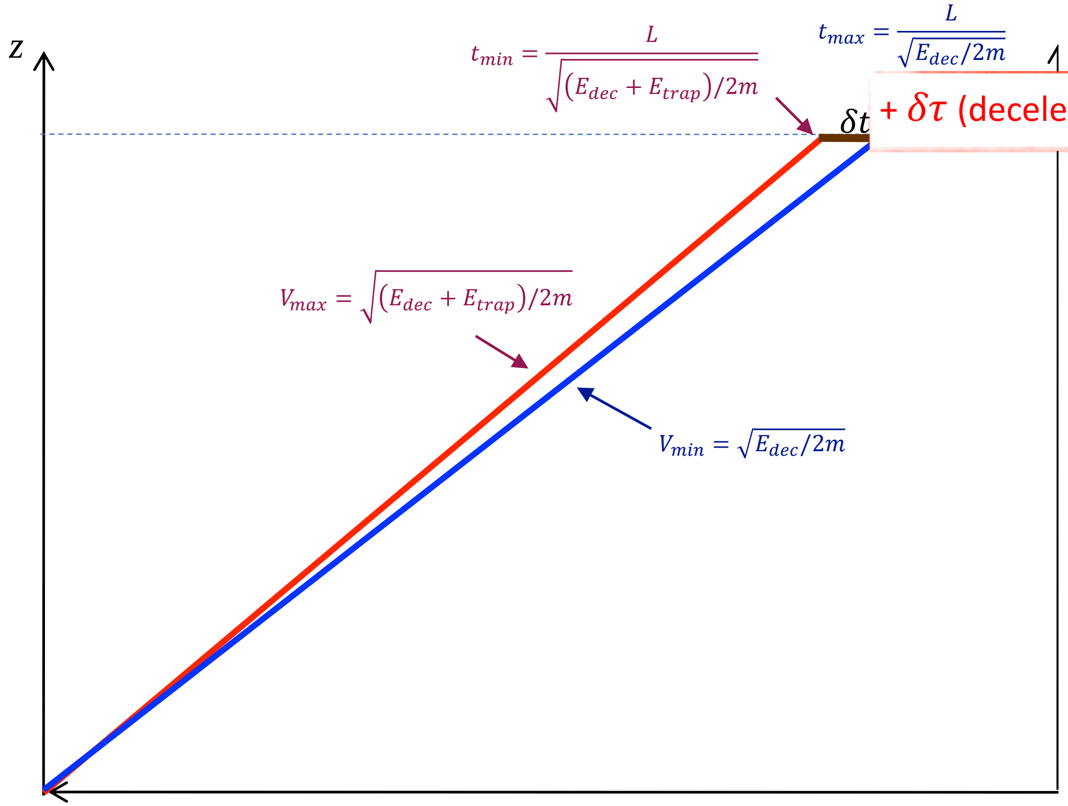
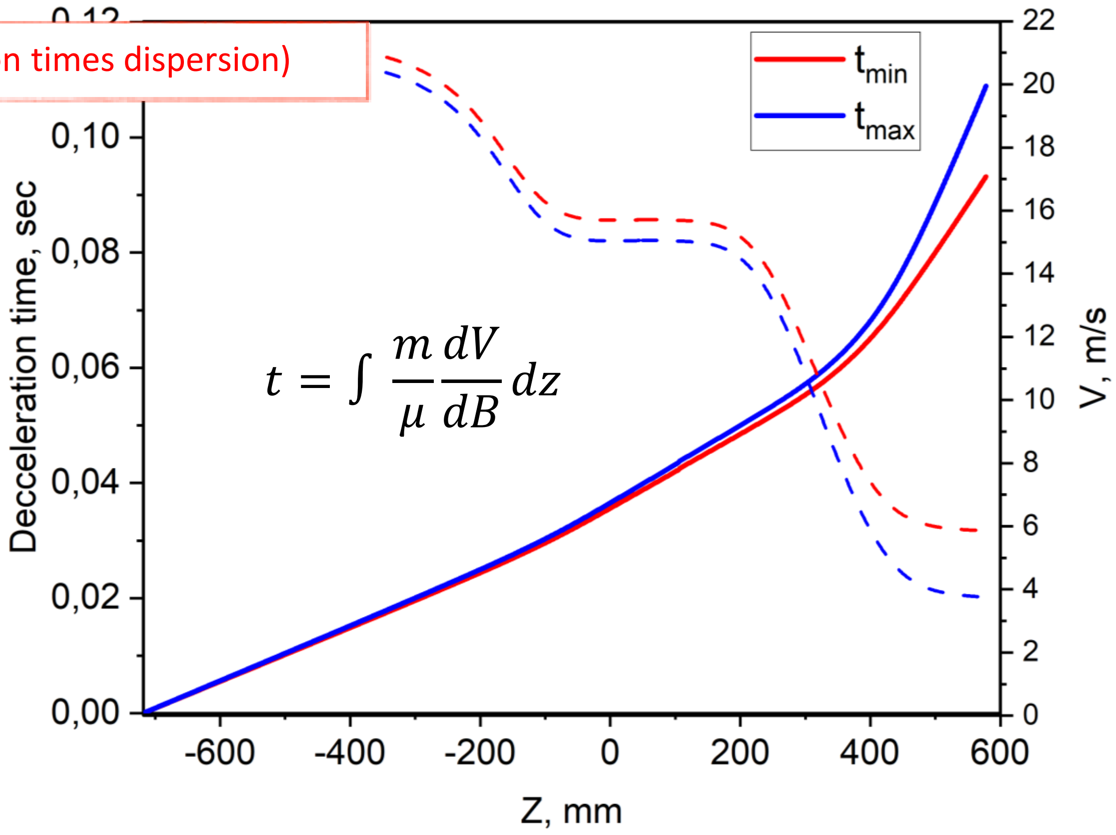
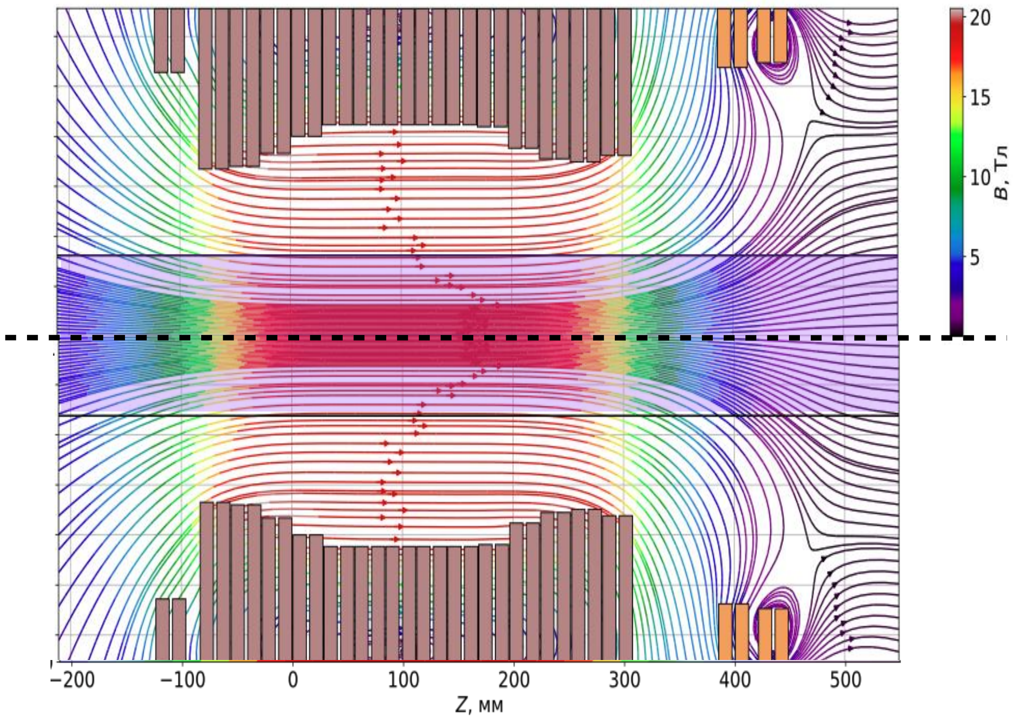


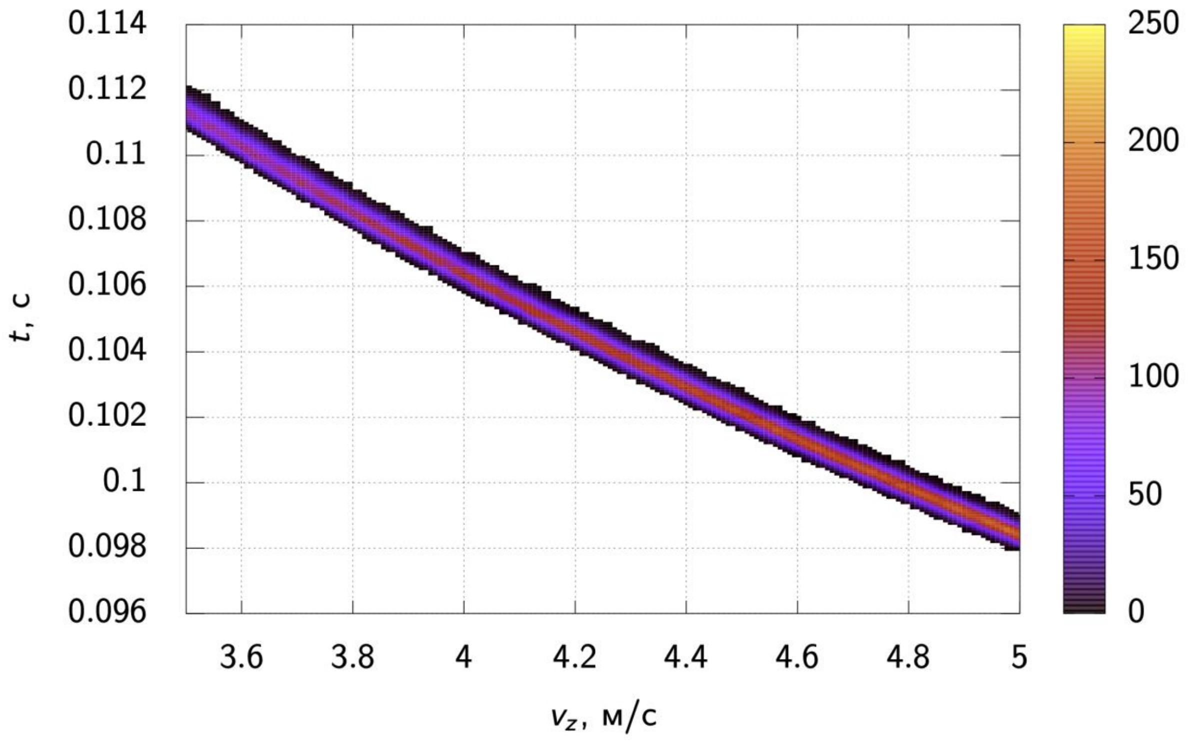


The slower the neutrons, the more time they spend on deceleration

Dispersion of deceleration times



rectangular neutron guide: 60 mm×60 mm



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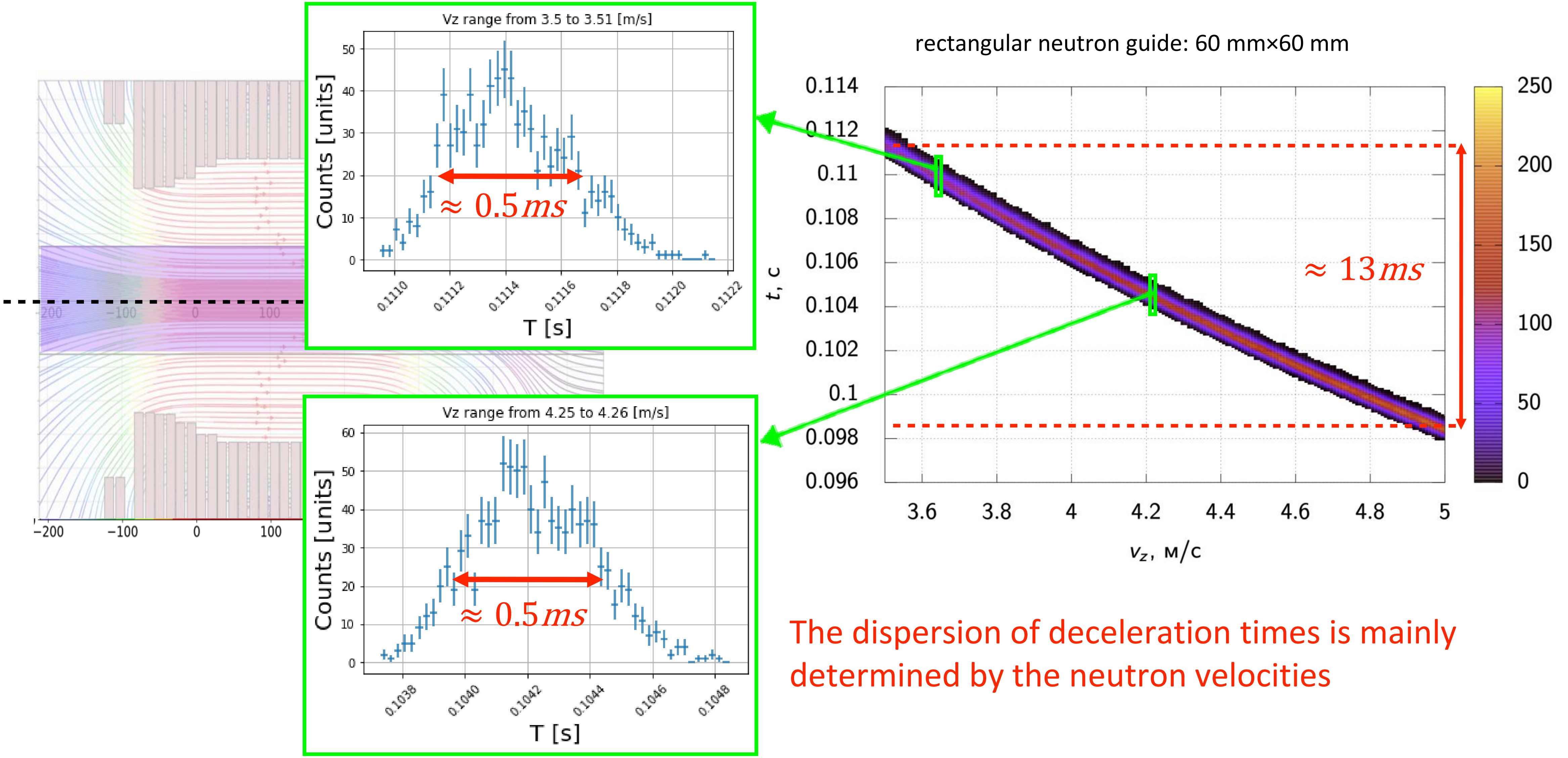
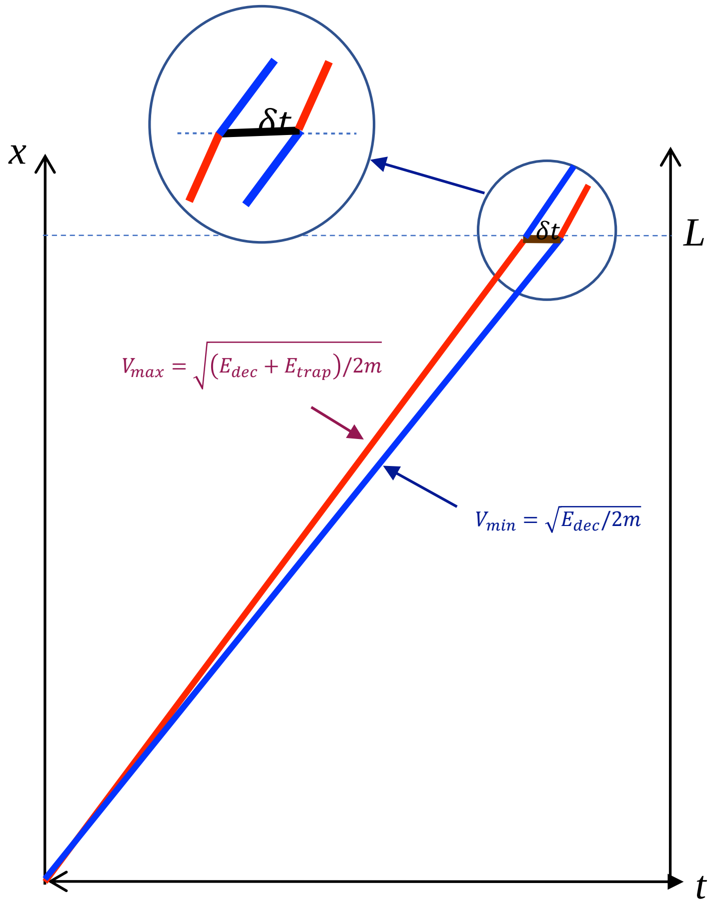


The dispersion of deceleration times is mainly determined by the neutron velocities

"Velocity invertor" to compensate deceleration times dispersion



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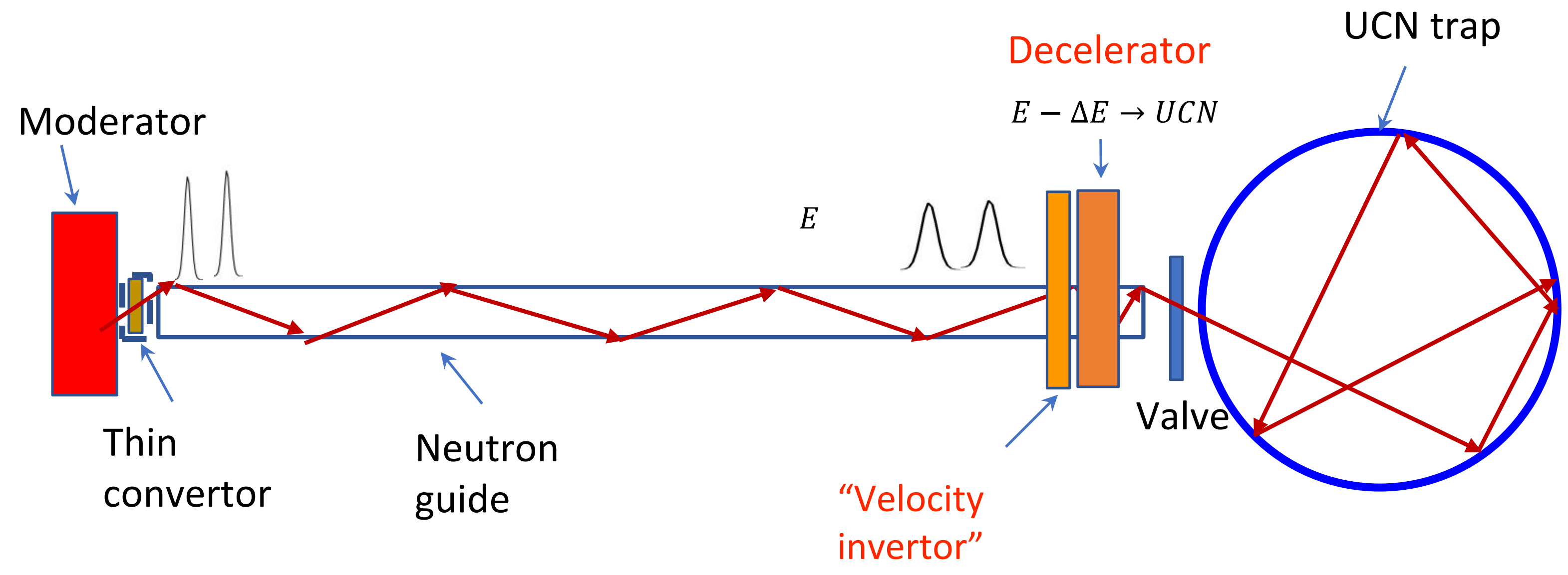


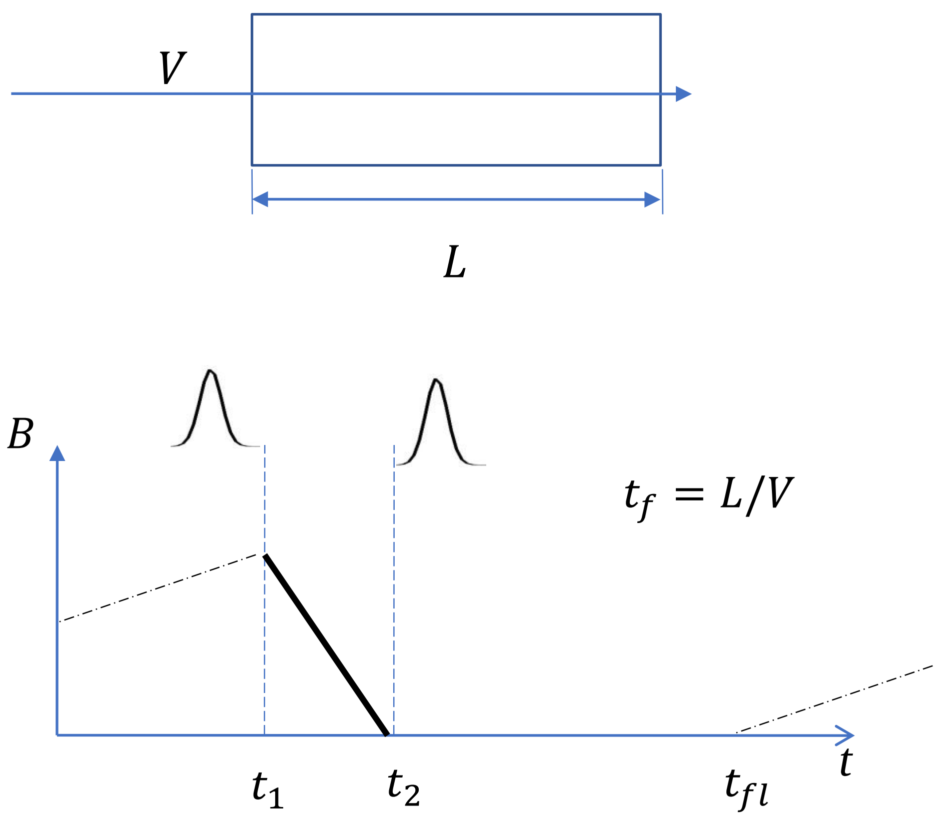
"velocity invertor" inverts neutron velocities in order to partially compensate the dispersion of the time of subsequent deceleration and to minimise bunch duration at the trap entrance

$$\delta t_{trap} = \delta\tau - \delta t$$

A time-dependent magnetic field invertor

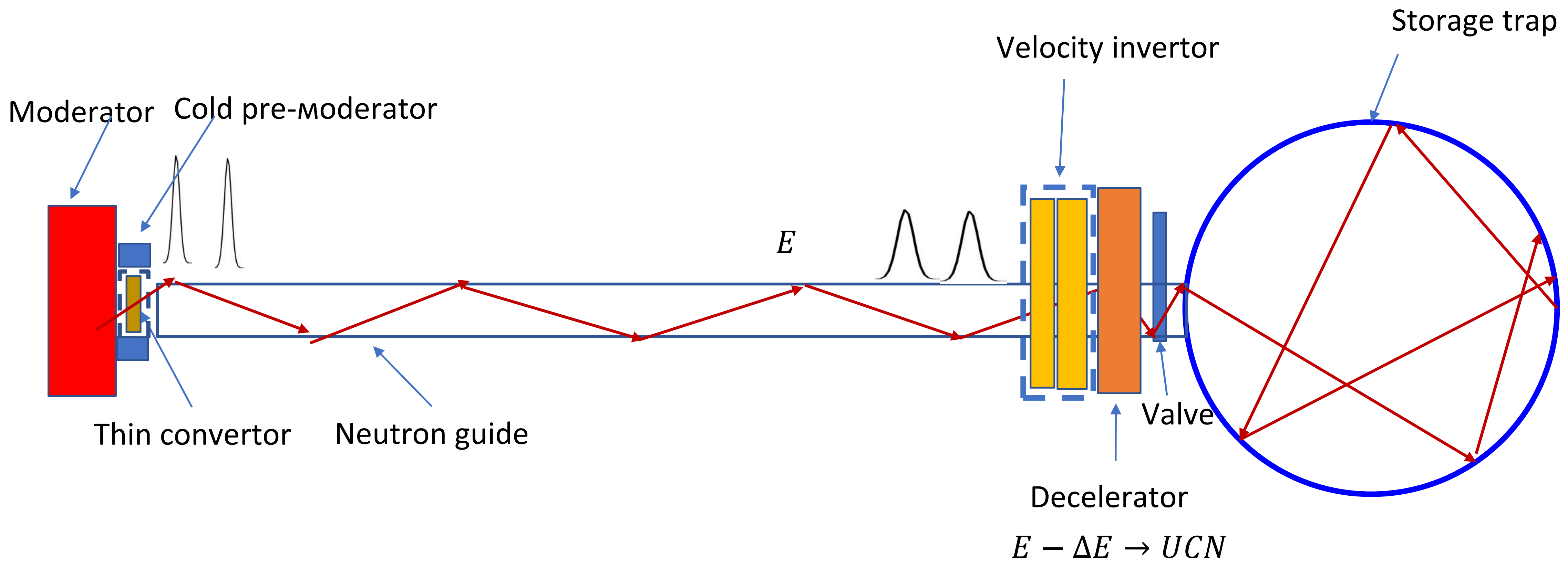
Neutrons change their energy when passing a homogeneous in space time-varying magnetic field

L.Niel, H.Rauch, Z. Phys.B. – Condensed Matter 74, 133 (1989)



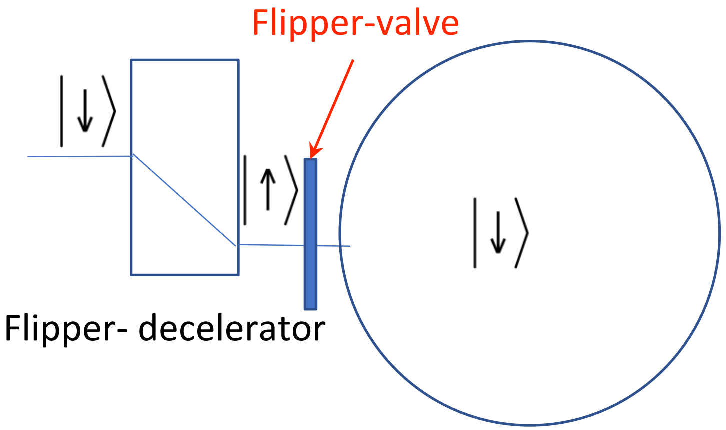
Time of flight of the bunch	$\Delta t = t_2 - t_1 \approx 10 - 15 ms$
Neutron velocity	$V \approx 20 m/s$
Lens length	$L \approx 40 cm$
Time of flight of the lens	$t_{fl} = 20 ms$
Repetition period	$T = 200 ms$
Magnetic field	$B = 1.5\,T$

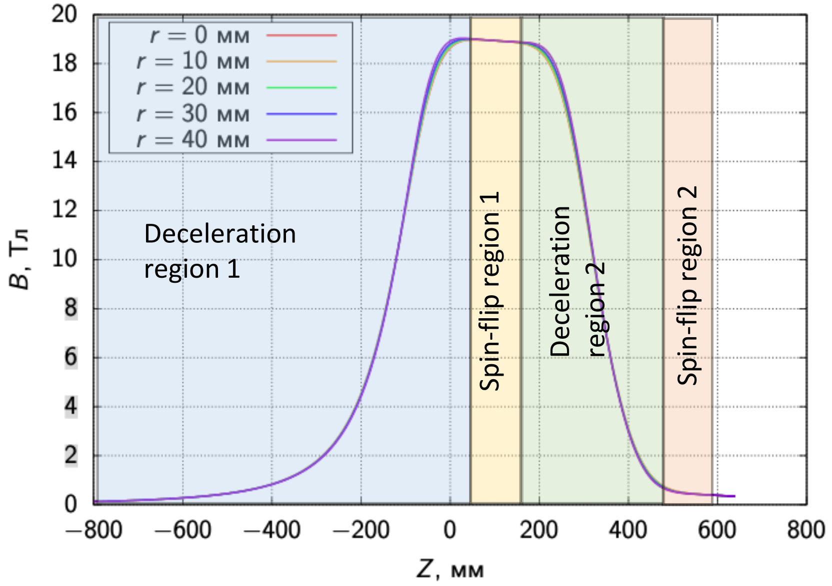
Most probable conception of UCN source @ periodic pulsed reactor



Pulsed valve

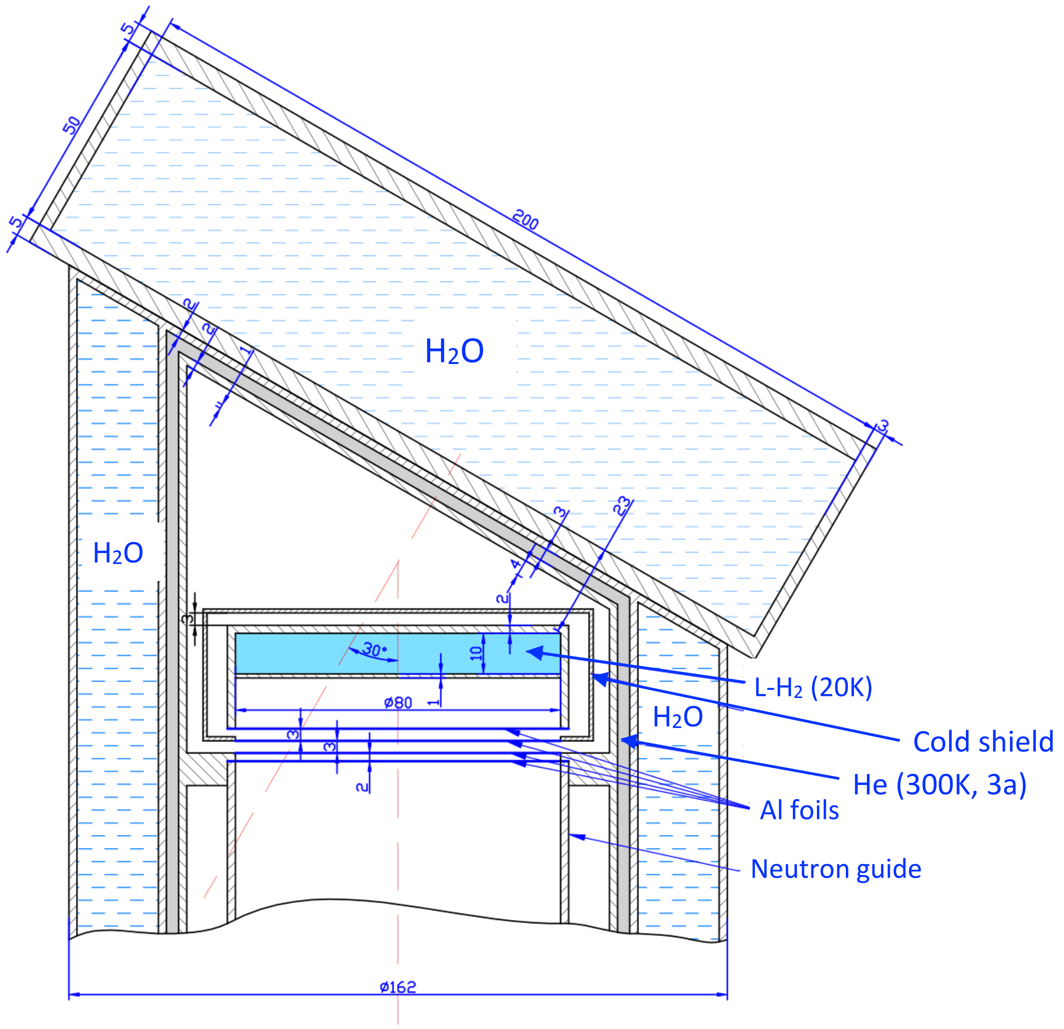
As a valve it is considered to use a gradient spin flipper, located in the area of decreasing of the flipper-decelerator field. Approximately in the 0.1-0.2T field





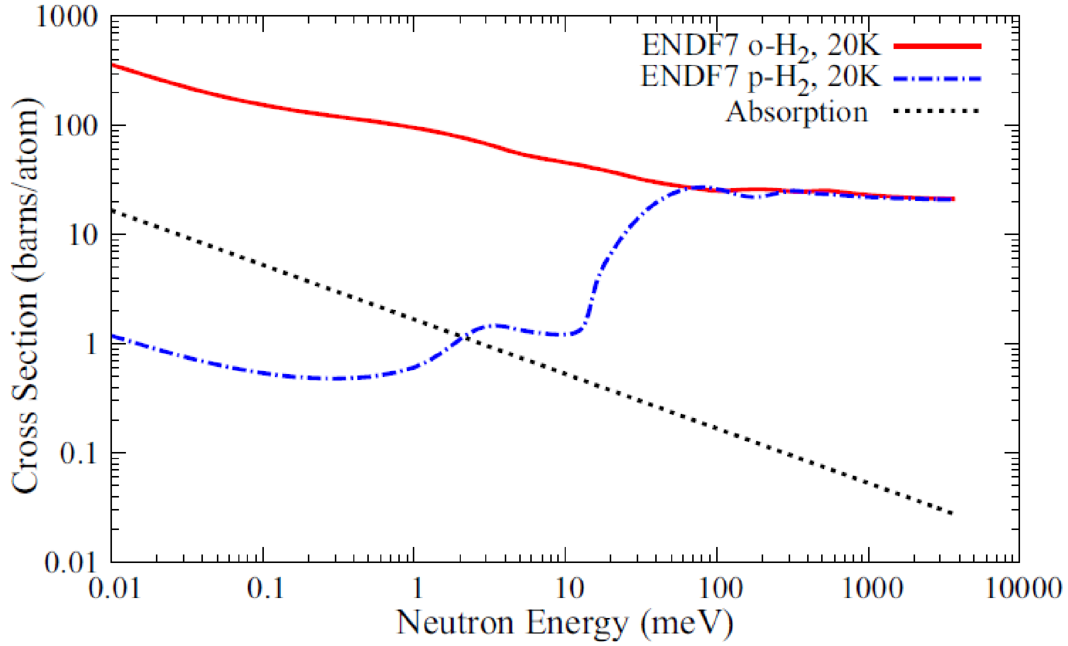
- Spin of polarised neutrons stored in the trap is oriented in such a way that the magnetic field of the flipper-decelerator is a barrier for them
- The high frequency of the flipper is applied only during the time of the arrival of the bunch. During this time, it passes neutrons in both directions

Liquid H_2 converter

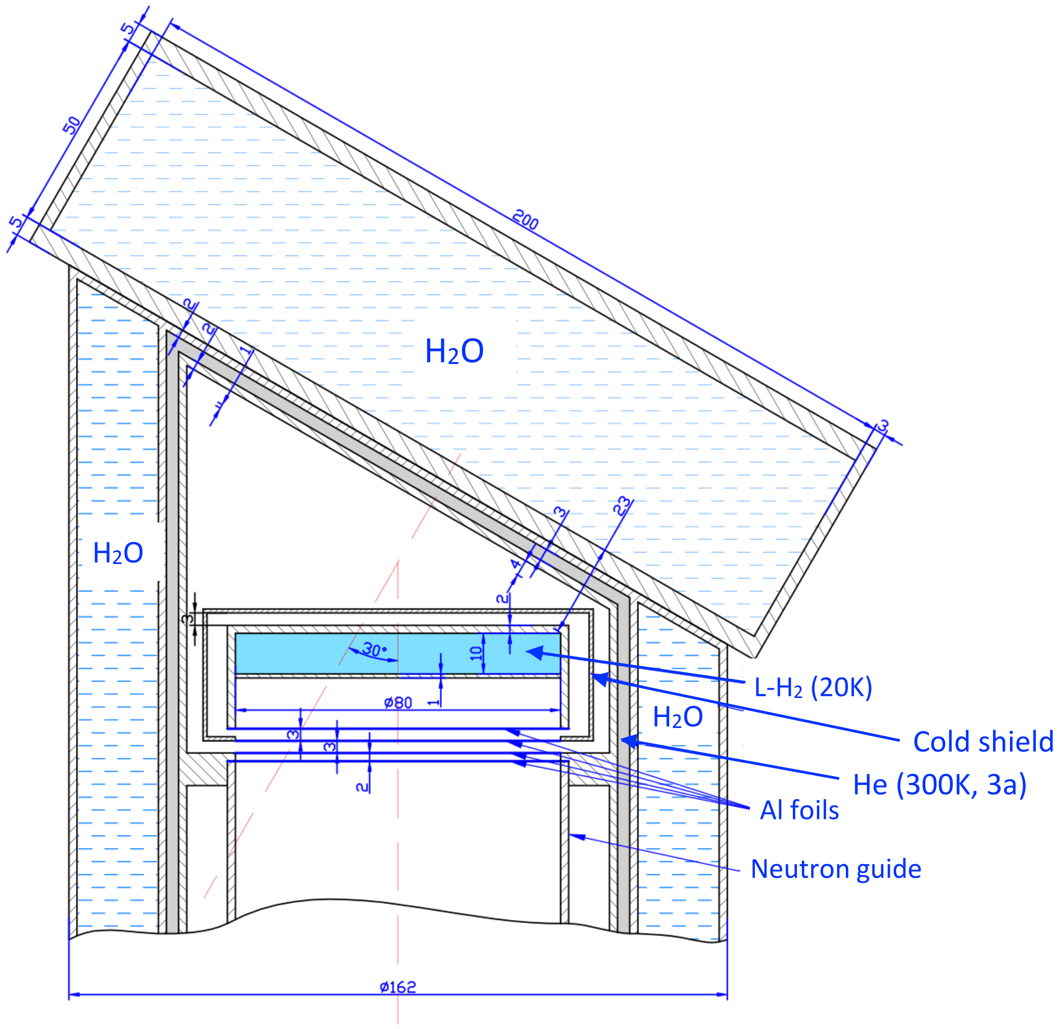


Designed by A.Yu. Muzychka

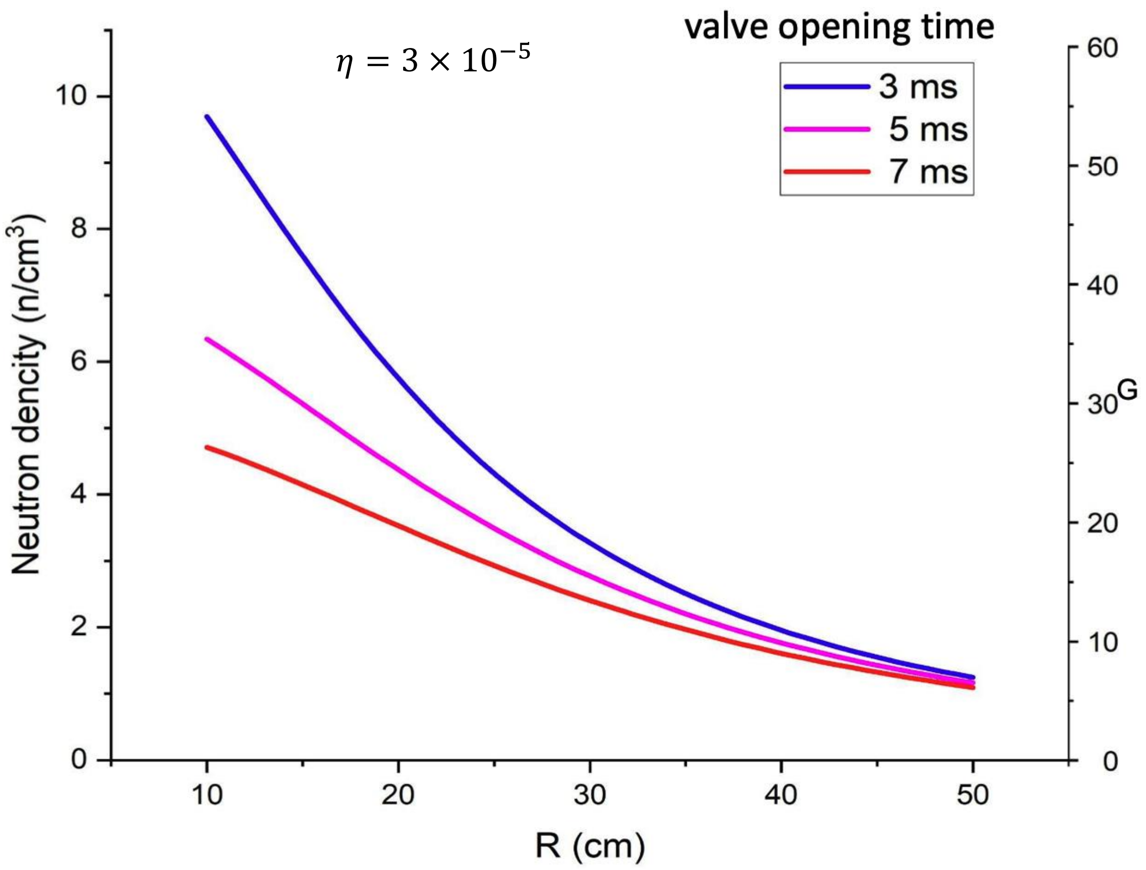
Scattering cross Section on H_2



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



Designed by A.Yu. Muzychka



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

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Thank you for your attention!!!