UCN source at periodic pulsed reactor

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

Sino-Russia meeting on frontiers of neutron scattering (SRNS-2024)

October 8–11, 2024, Ekaterinburg

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

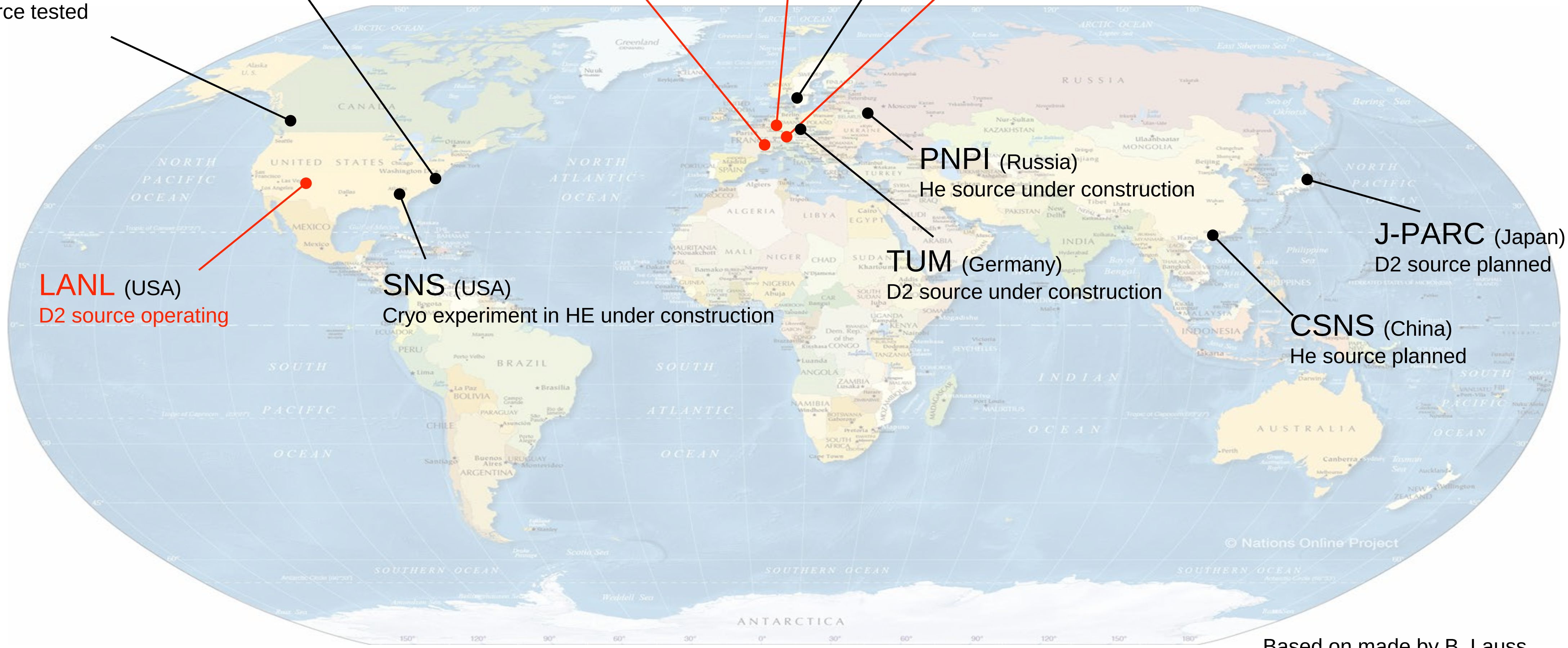
Measurement of angular correlation coefficients of neutron beta decay

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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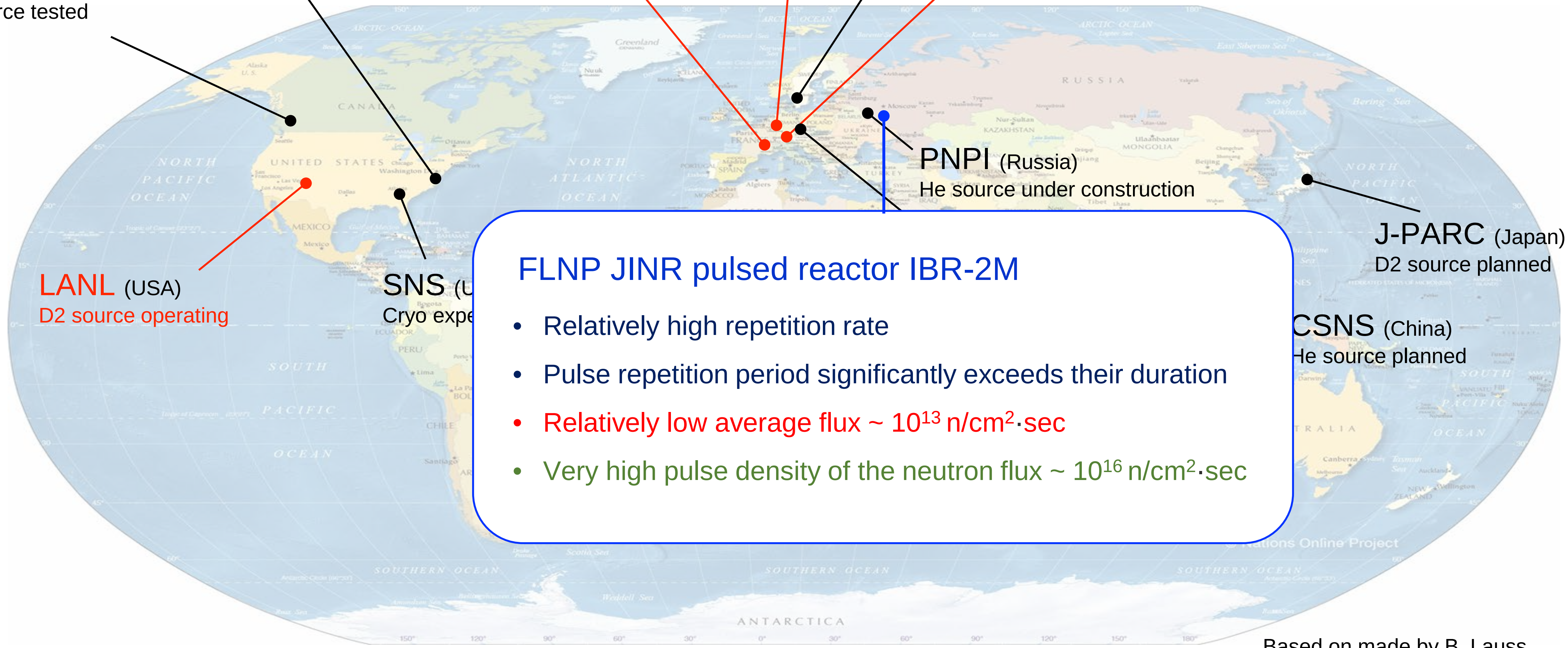


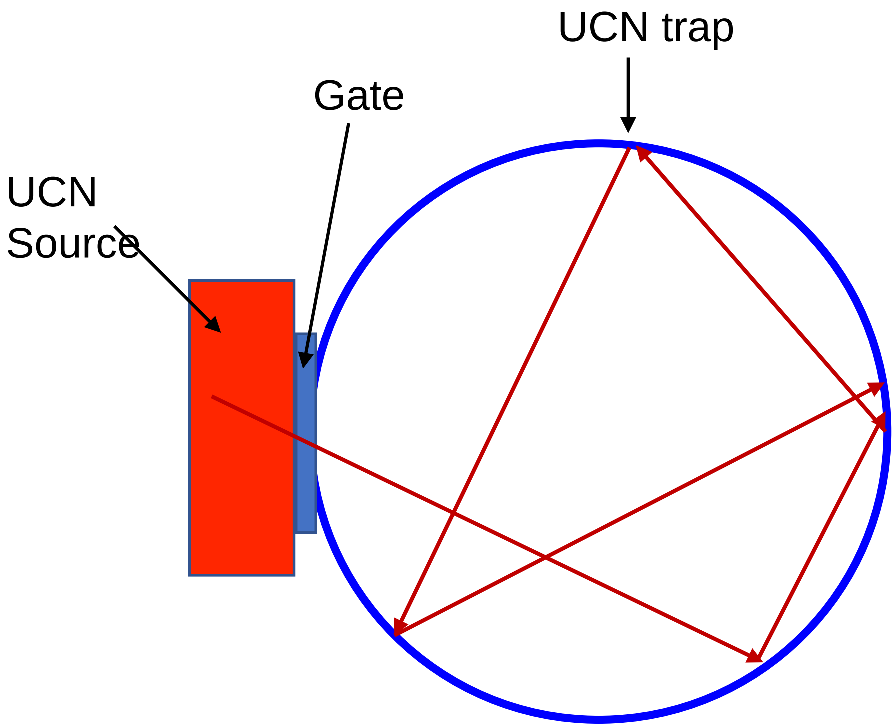
FLNP JINR pulsed reactor IBR-2M

- 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

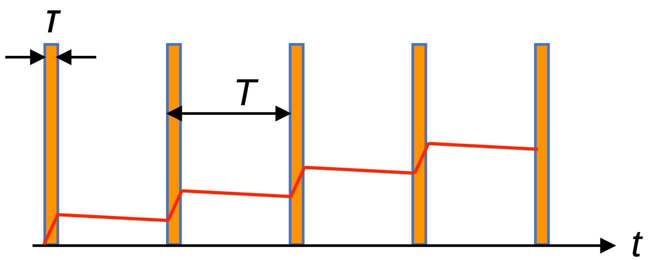
Based on made by B. Lauss

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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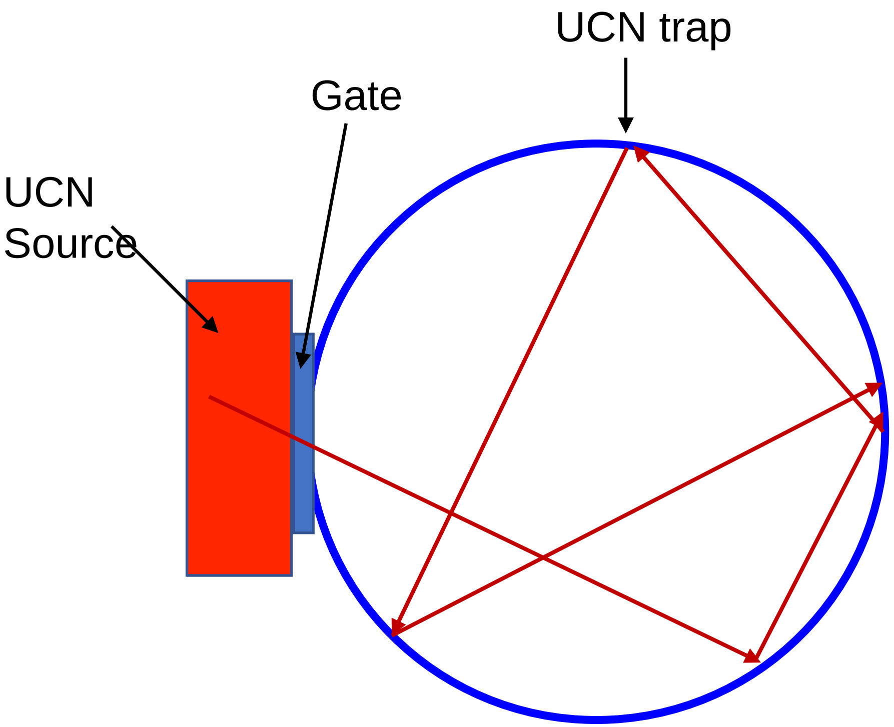

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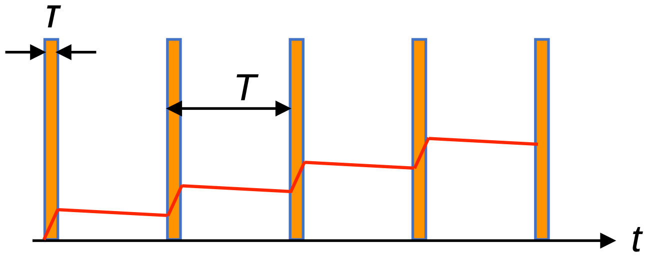

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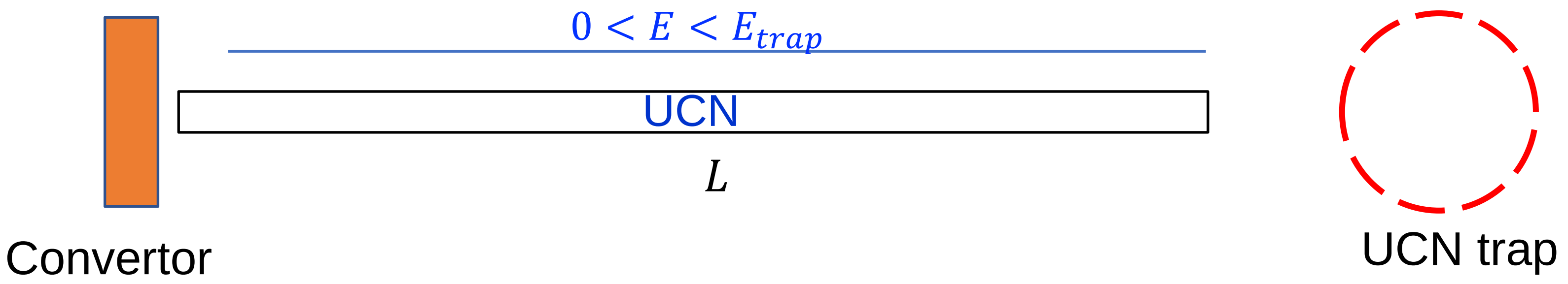
The trap is remote from the moderator due to the presence of biological shielding

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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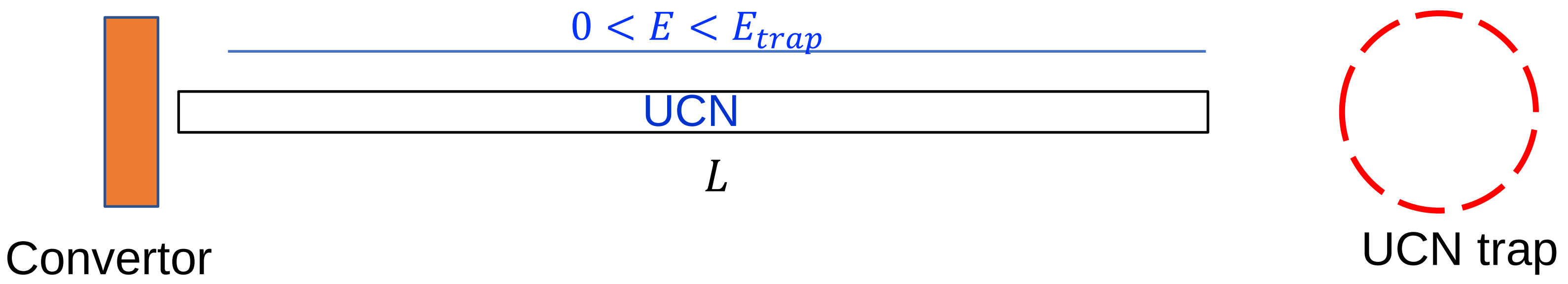

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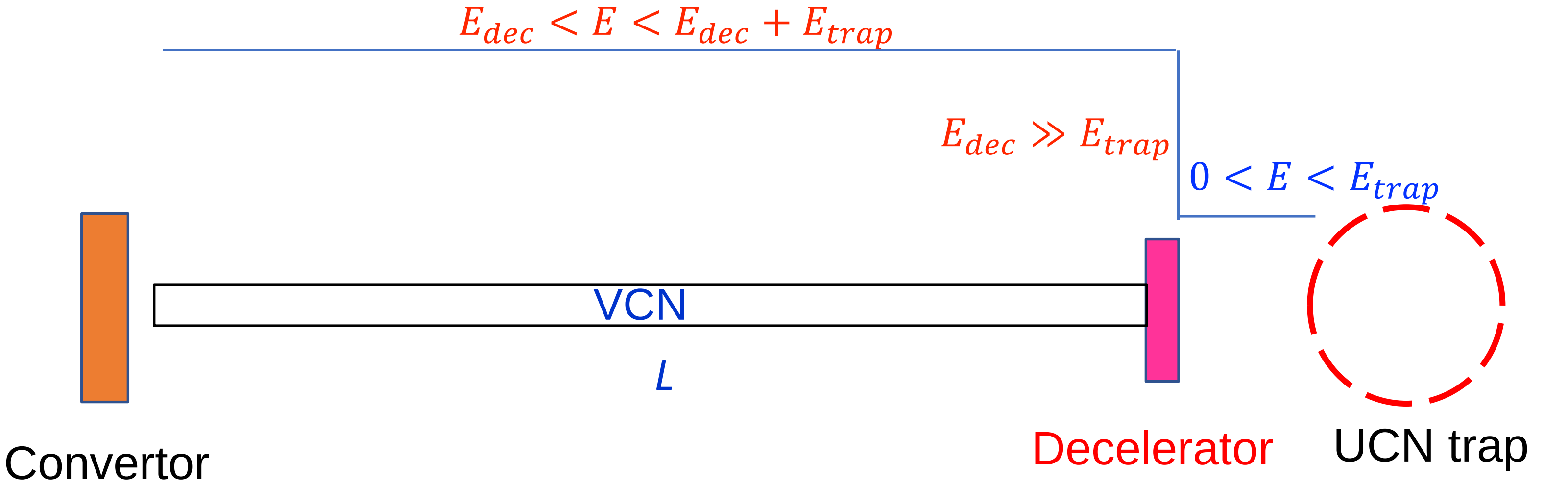
Frank, A.I., Kulin, G.V., Zakharov, M.A. Phys. Part. Nuclei Lett. 20, 664–667



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

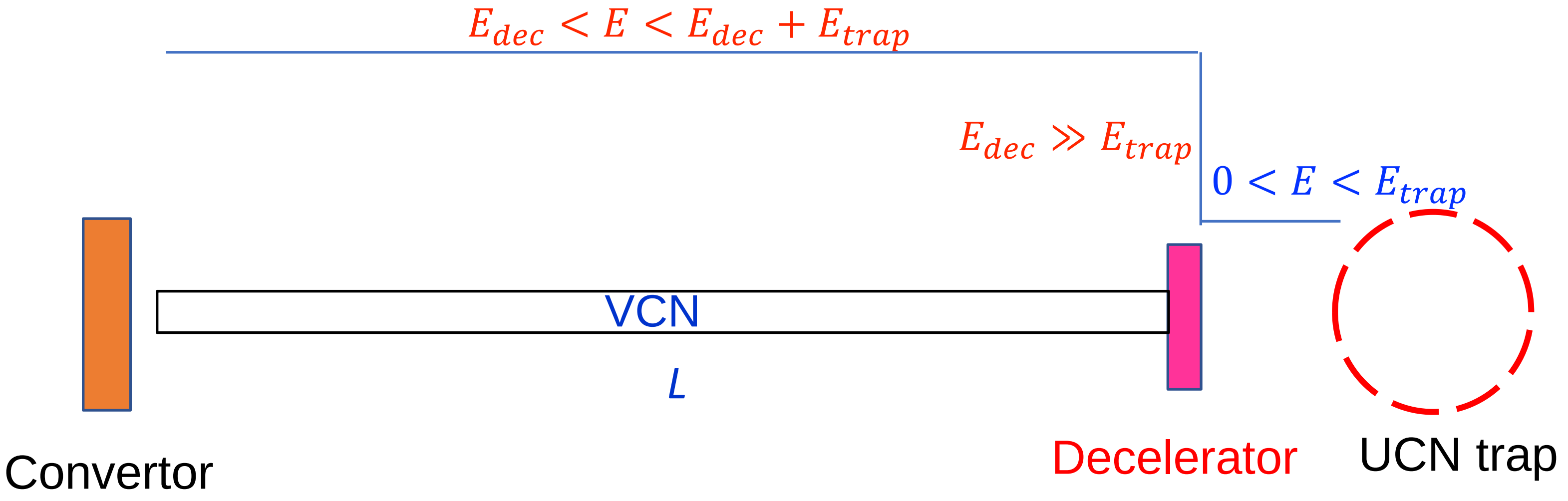
$$t \simeq \frac{L}{\sqrt{E_{dec}/2m}}$$

$$\delta t \ll T$$

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

Pumping option of the pulsed source – decelerator

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



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

$$\delta t \ll T$$

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

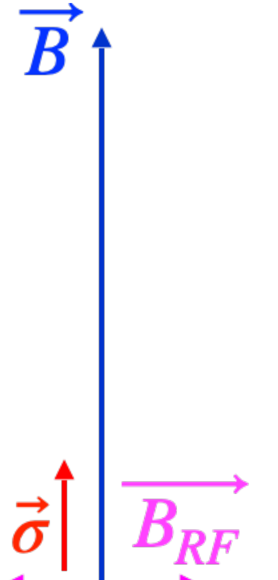
✓ The pulse structure of the "useful" neutrons is remain, but the pulse duration at the entrance to the trap exceeds the initial one.

✓ 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

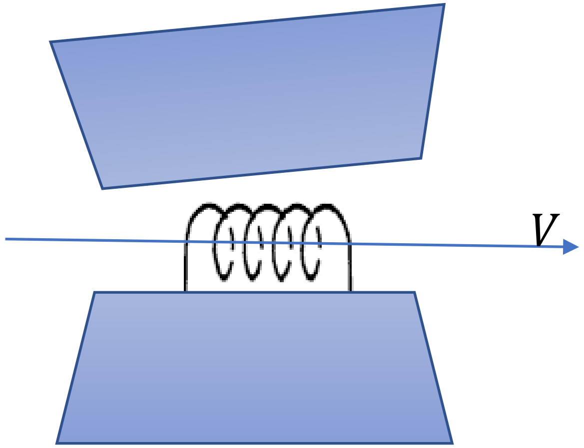
✓Since “useful” neutrons covers a small part of the VCN spectrum, such a source can simultaneously serve as a source of UCN and VCN

Decelerator — broadband gradient (adiabatic) spin flipper

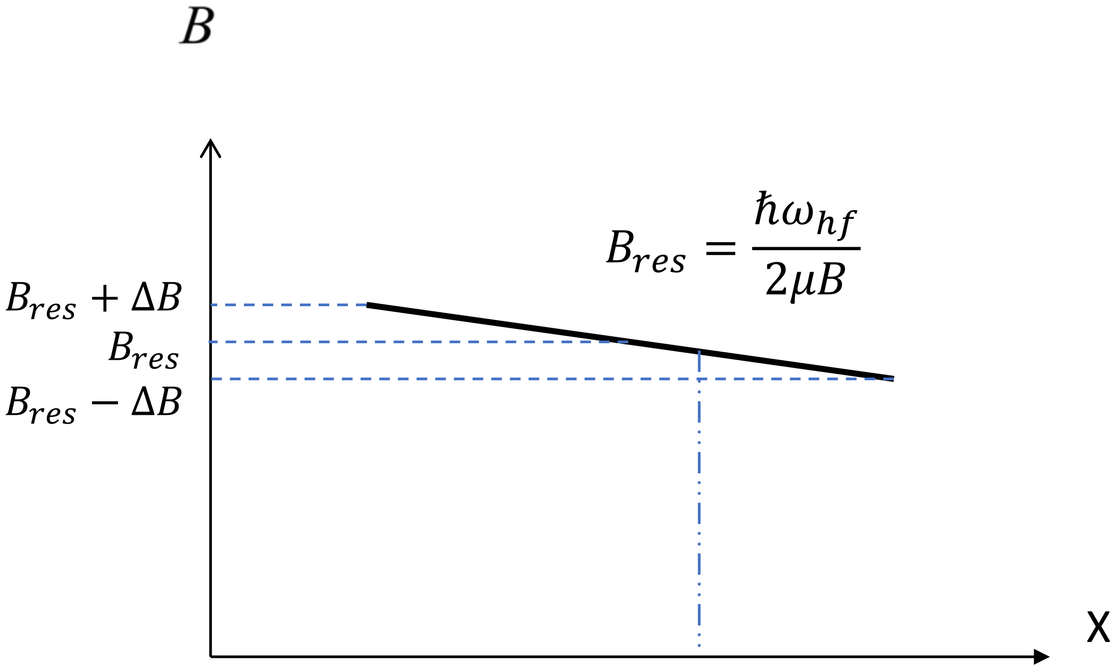
G. M. Drabkin and R. A. Zhitnikov. Sov. Phys. JETP, 11, 729 (1960) — Proposed to use spin-flip of neutrons in a non-uniform magnetic field to obtain “supercold” neutrons



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



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



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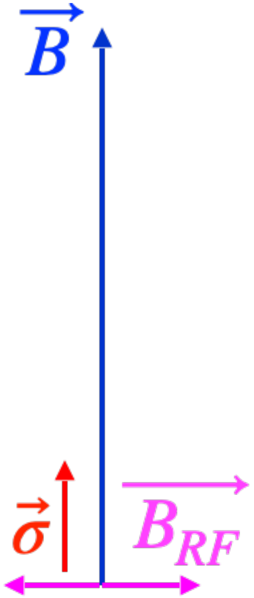

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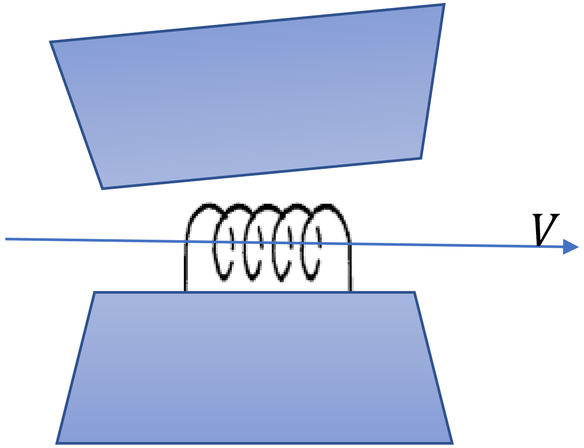

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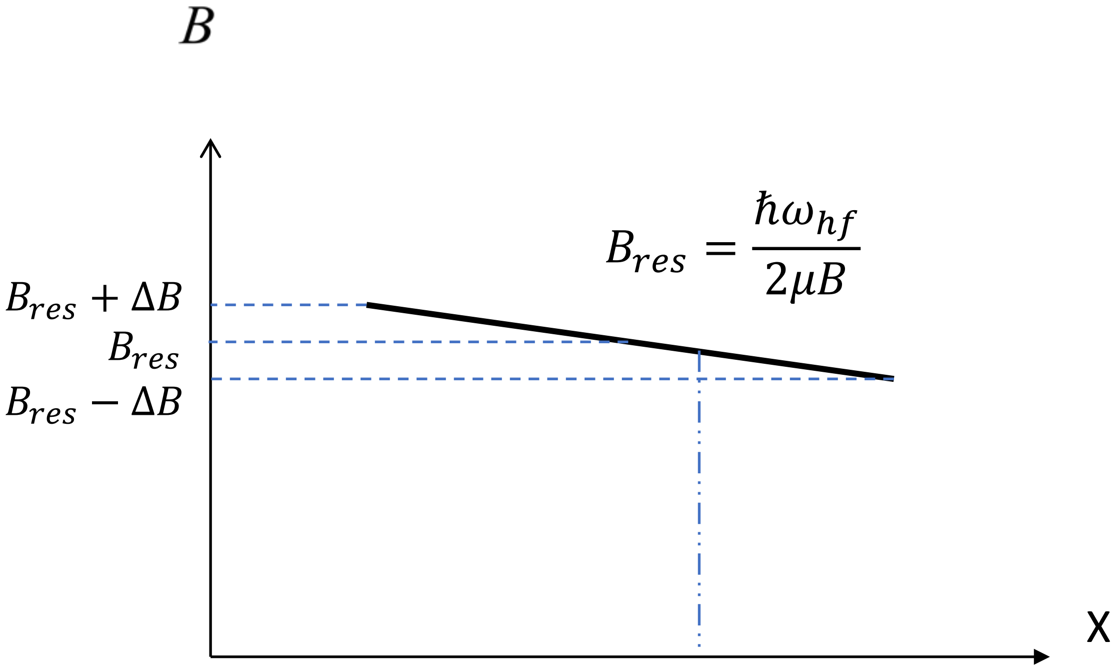

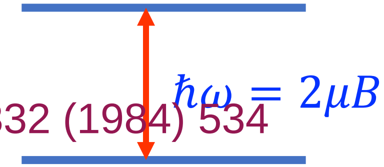

$\Delta E = 2\mu B = \hbar\omega$

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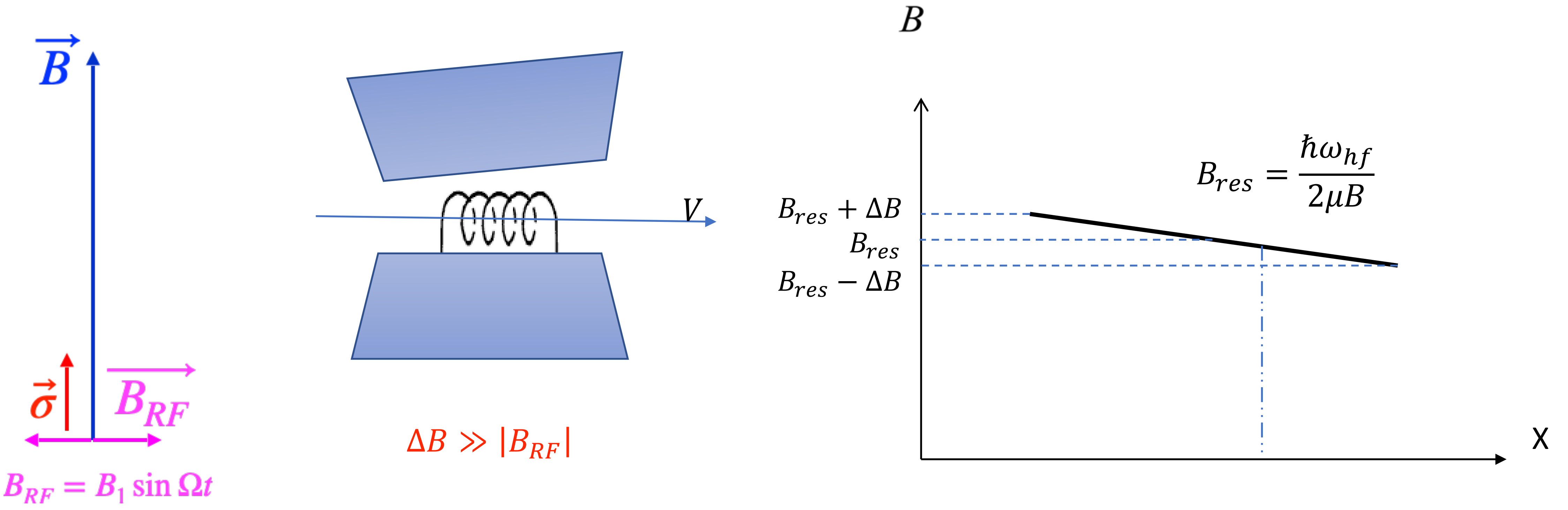


to decelerate a neutron at a speed of 20 m/s to a speed of 5 m/s

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

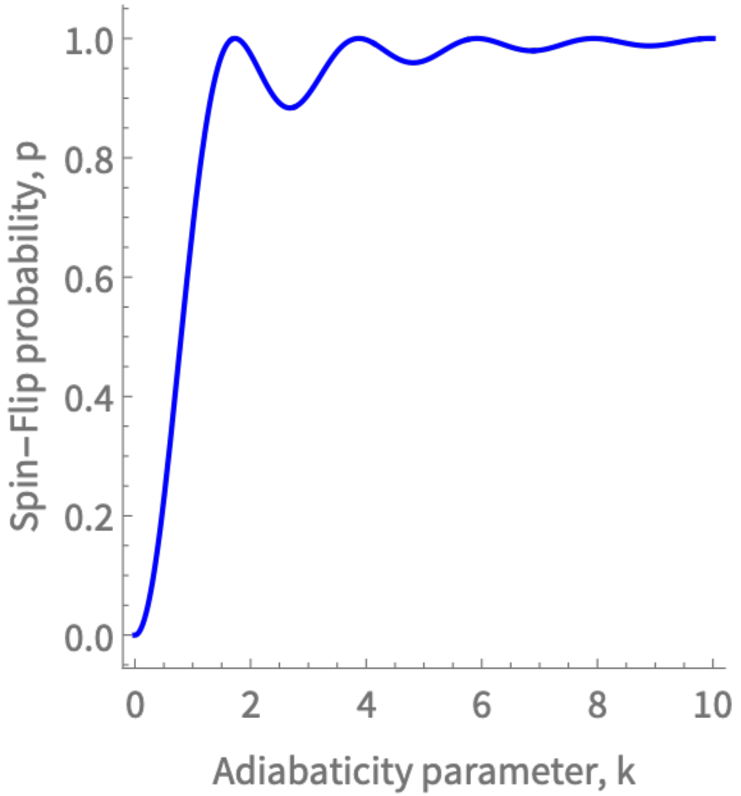
Parameters of adiabatic spin flipper

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

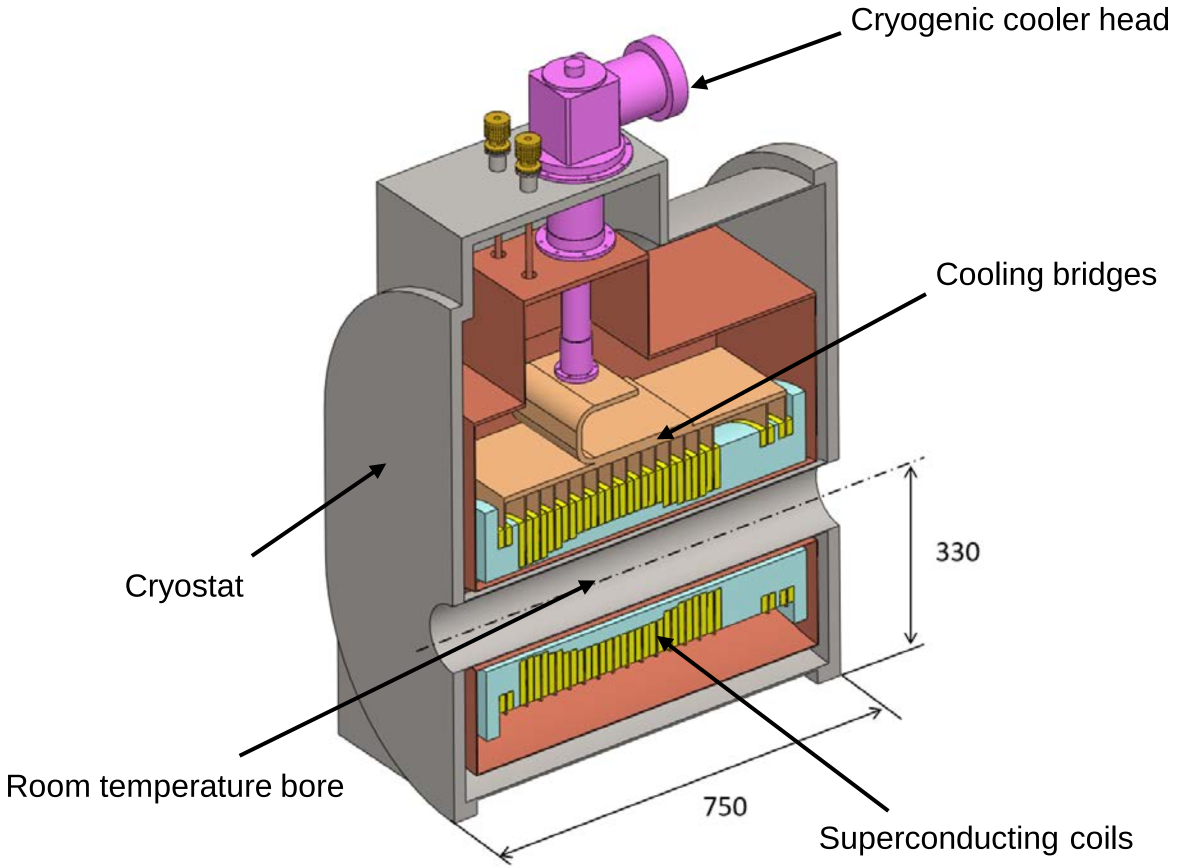
at $k = 4$ and $V = 16 m/s$ $\longrightarrow$ $B_1^2 > \frac{dB}{dz} \cdot (2.86 \times 10^{-7})$

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



Stationary gradient field – superconducting solenoid

Stationary magnet design

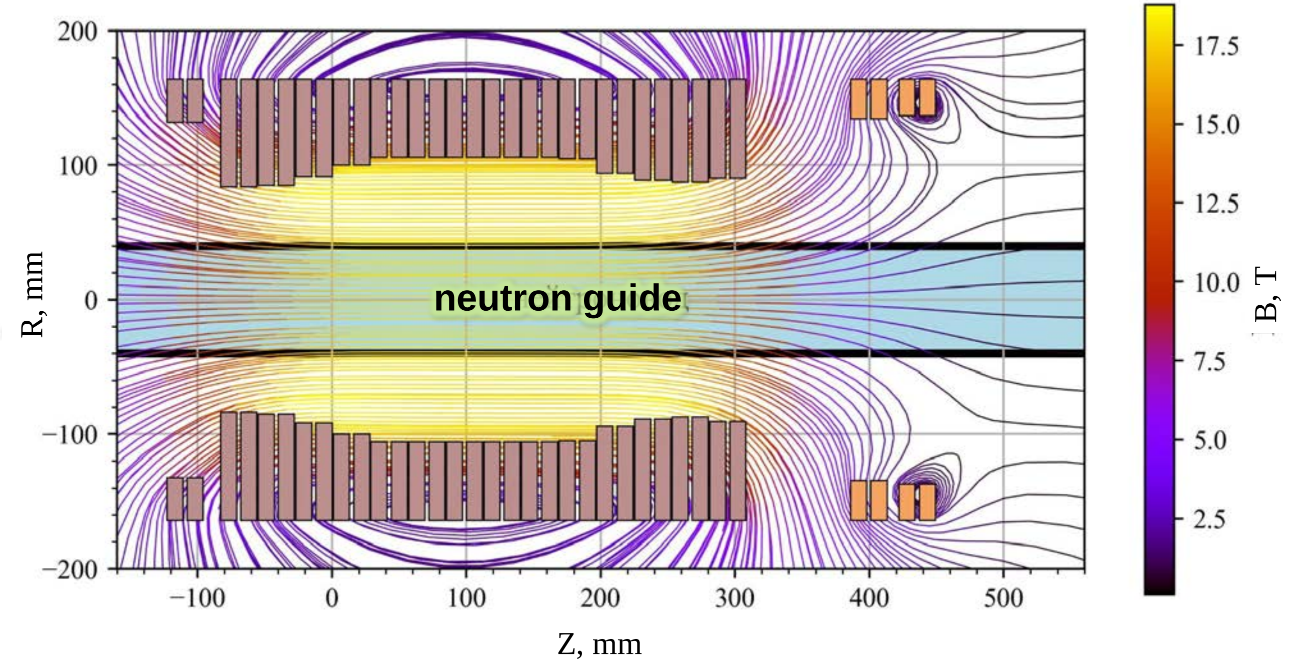


Technical specifications

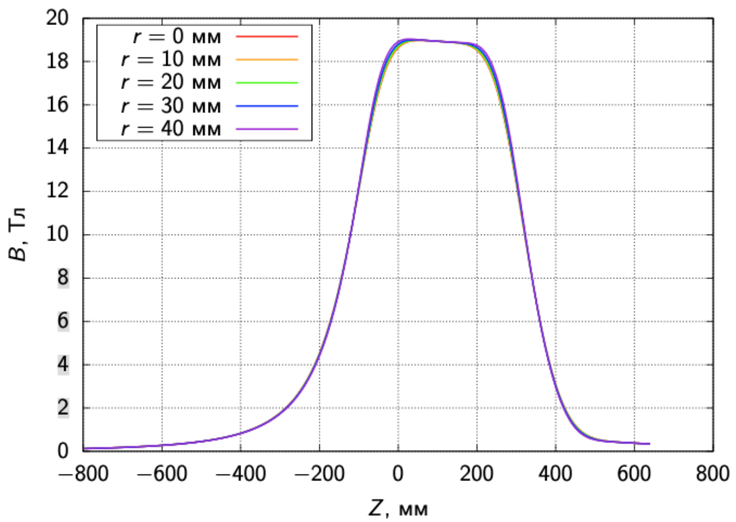
Magnetic field (peak)	20 T
Bore diameter	120 mm
Bore type	Room temperature
Dimensions **Length** **Width** **Height**	 750 mm 660 mm 1250 mm
Mass (including cryostat, magnet and cooling head)	Less than 1000 kg
Power supply	3-phase 380 V
Consumption	16 kW nominal 30 kW during cooldown)
Magnet wire	Second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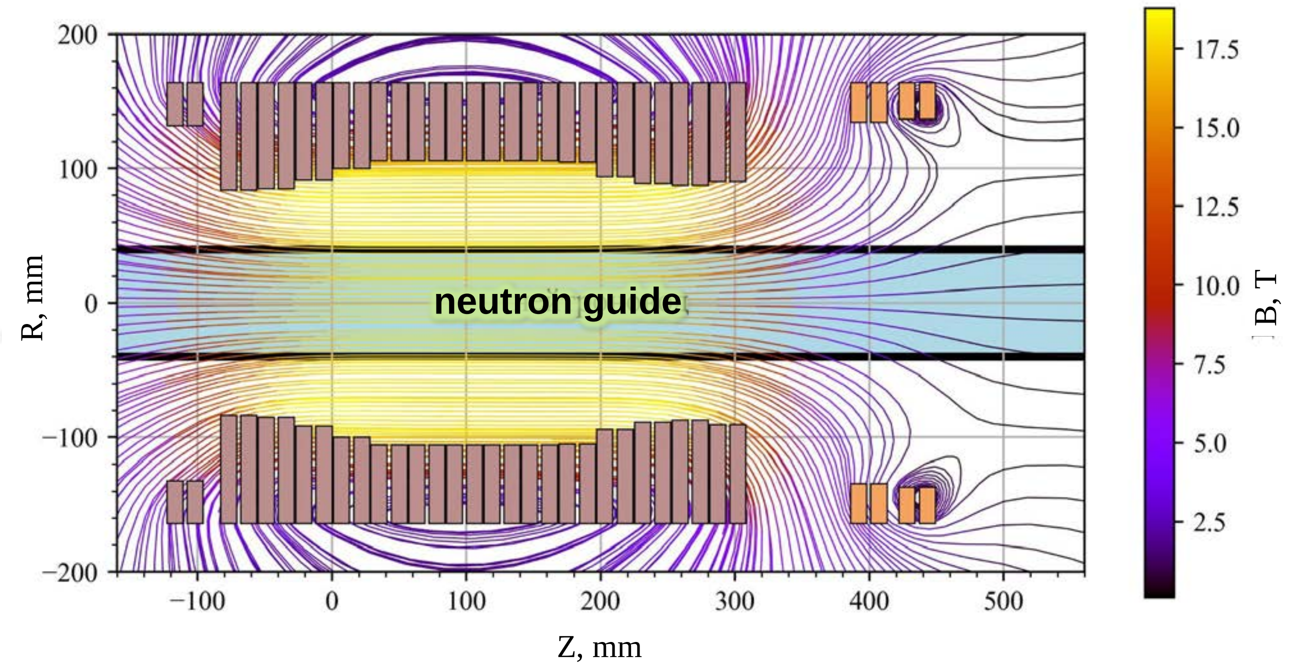

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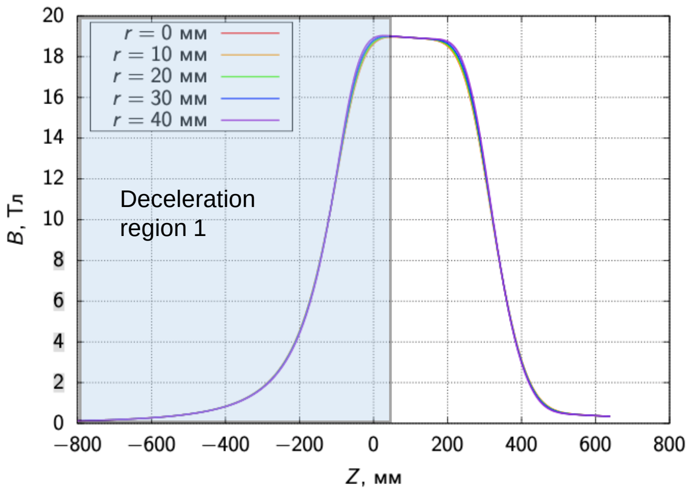

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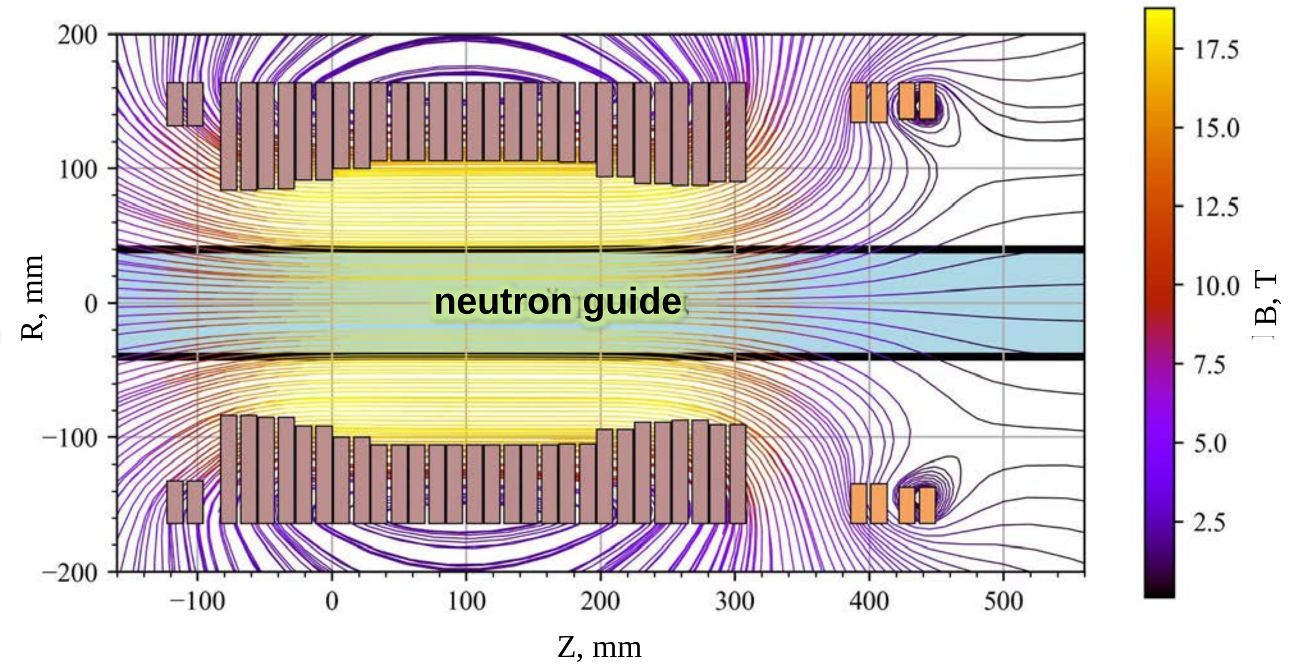

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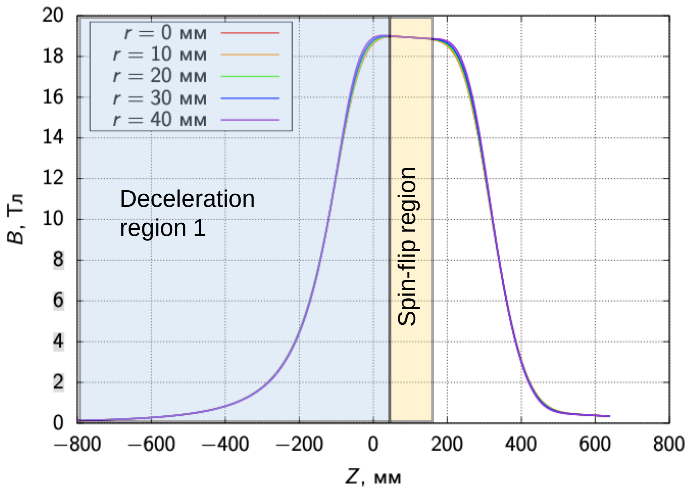

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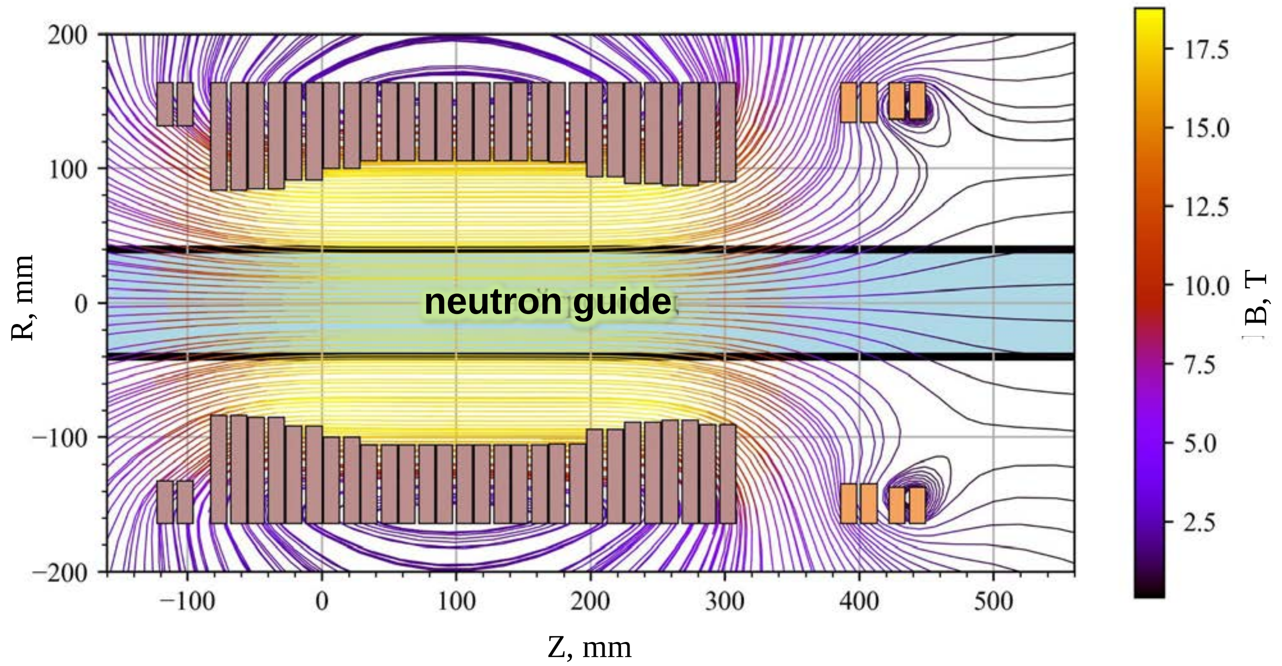

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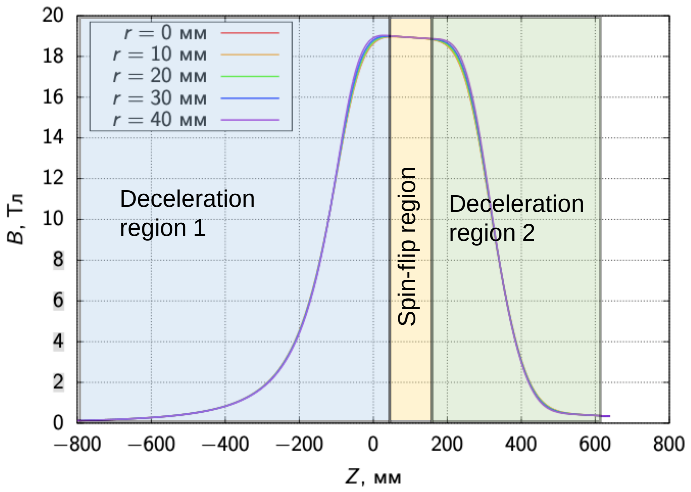

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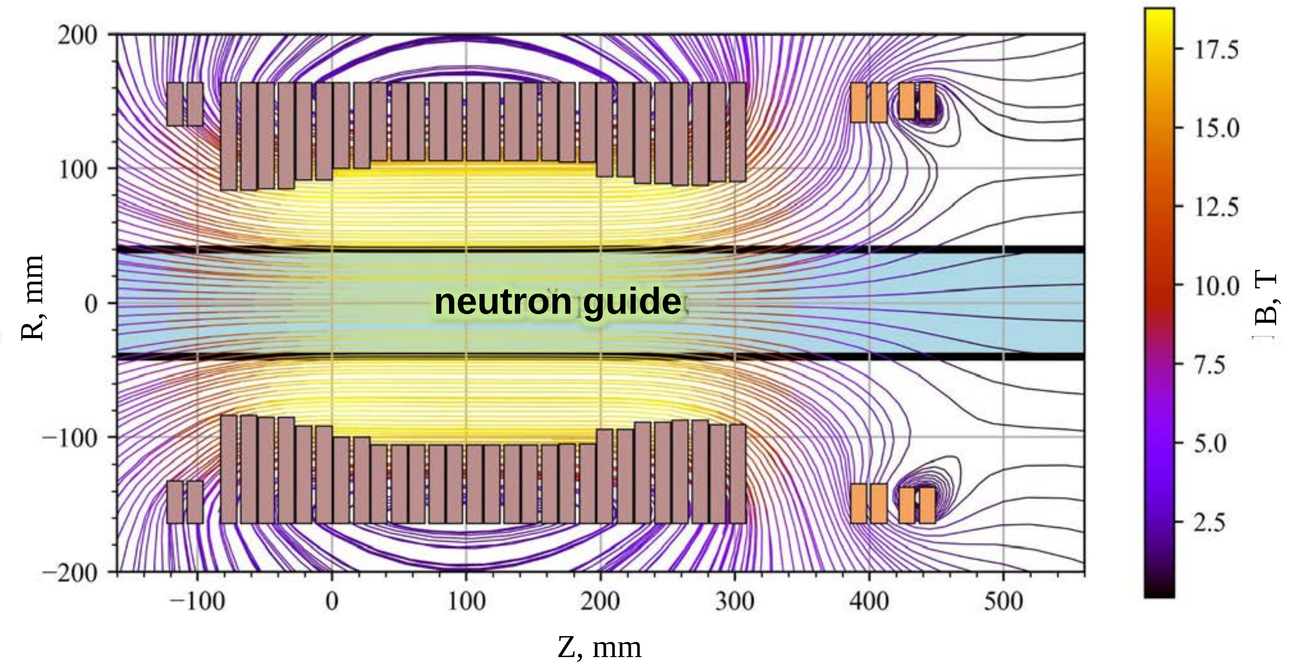

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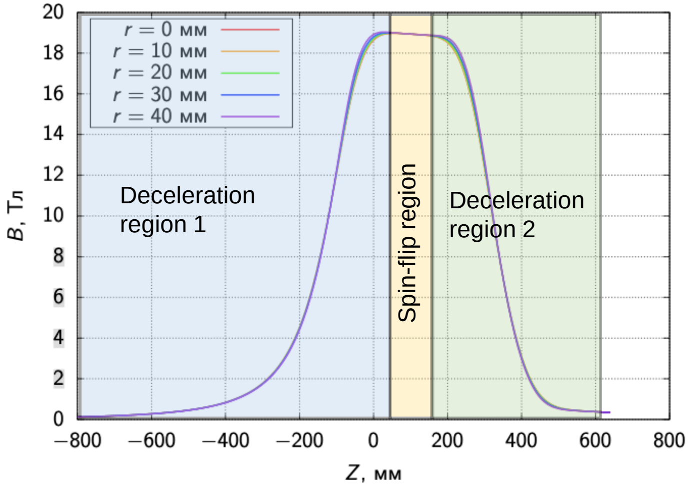
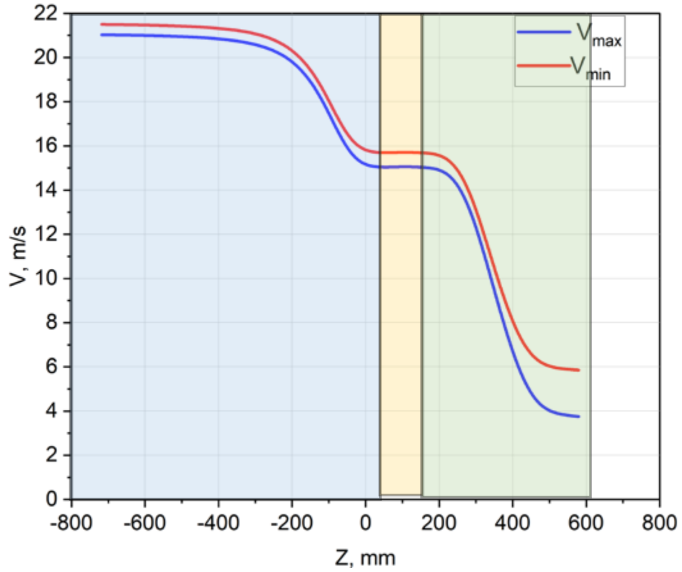
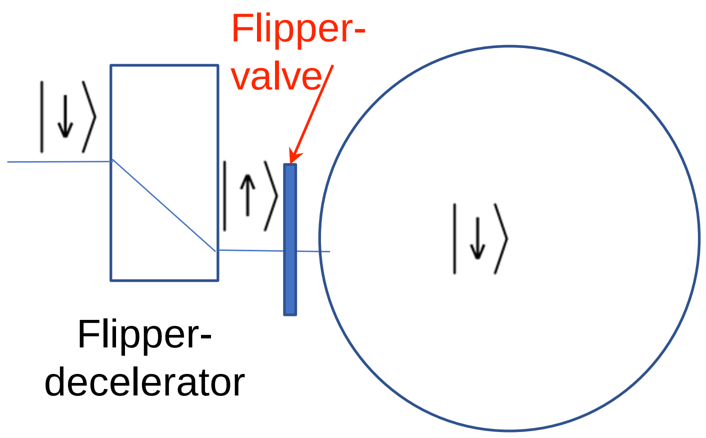
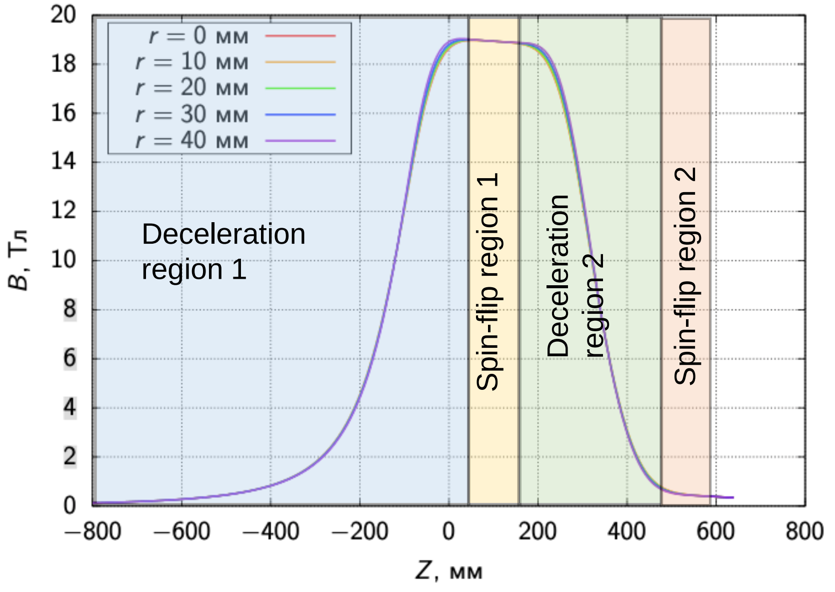




Pulsed valve

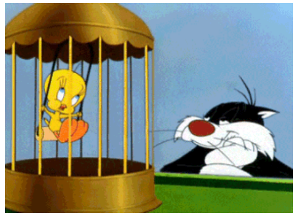
As a valve it is considered to use a gradient spin flipper, located in the area of decreasing of the flipper-decelerator field. Approximately in the 0.1-0.2T field





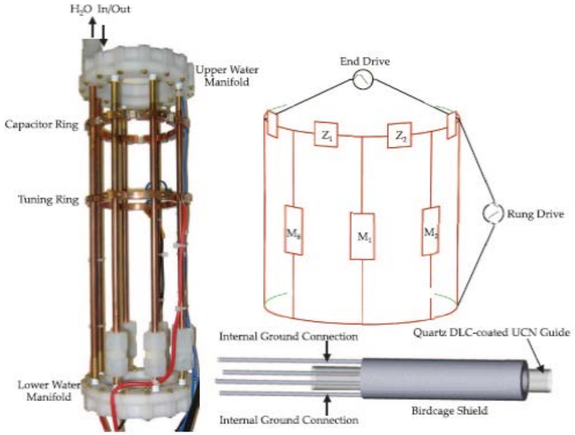
- Spin of polarised neutrons stored in the trap is oriented in such a way that the magnetic field of the flipper-decelerator is a barrier for them
- The high frequency of the flipper is applied only during the time of the arrival of the bunch. During this time, it passes neutrons in both directions

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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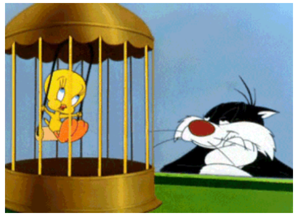

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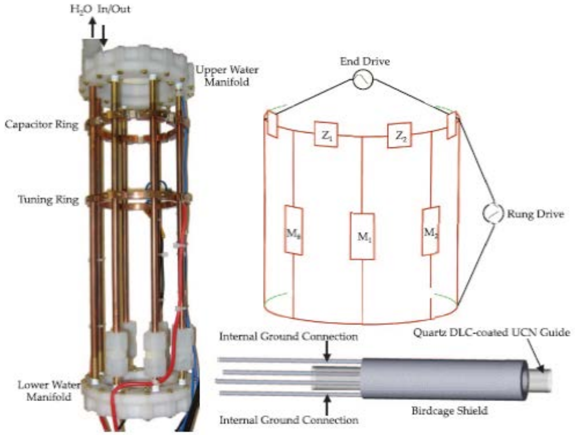

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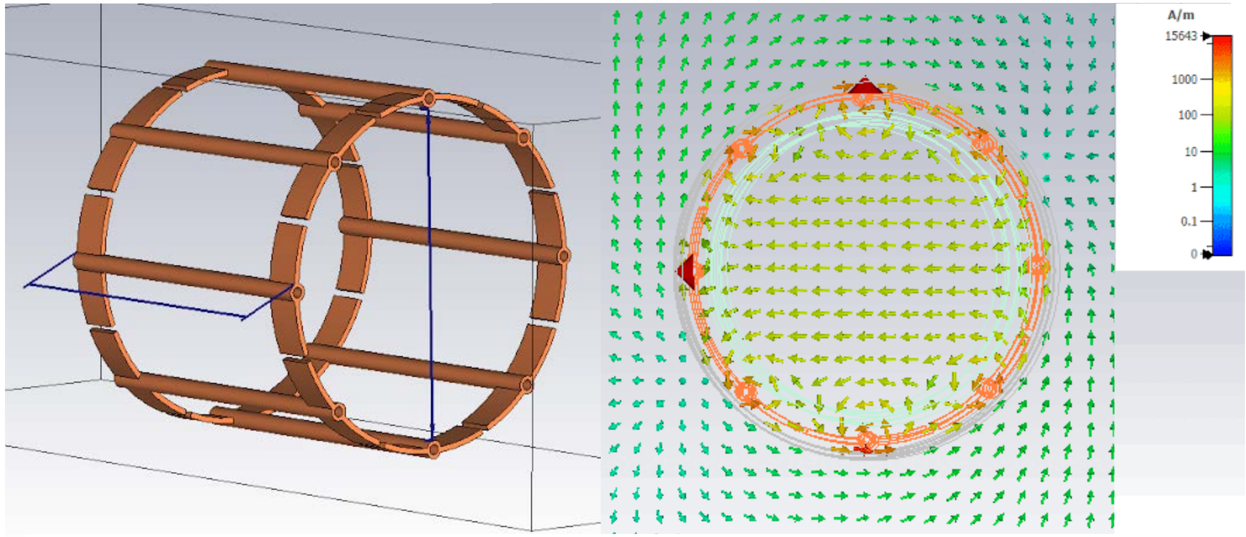
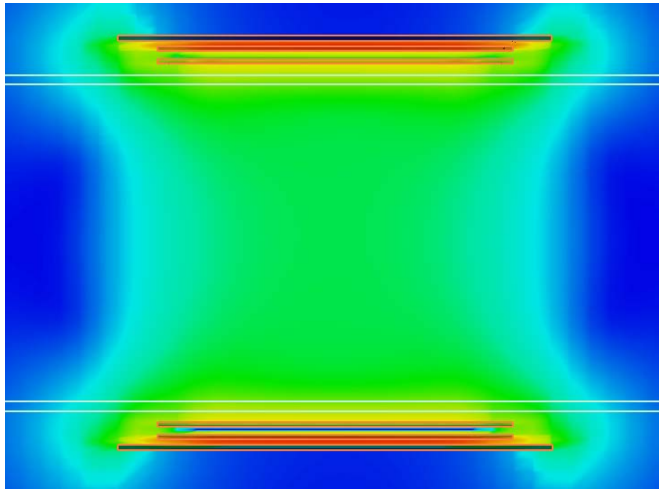
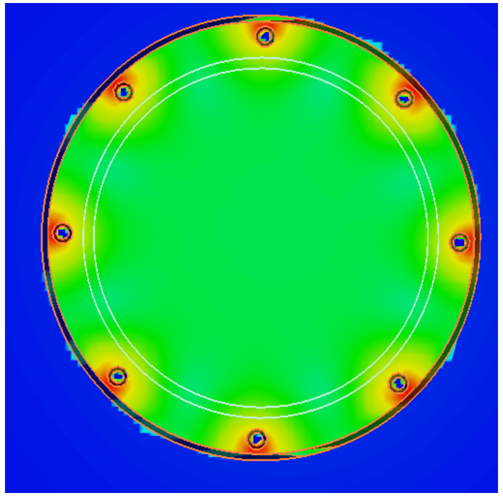




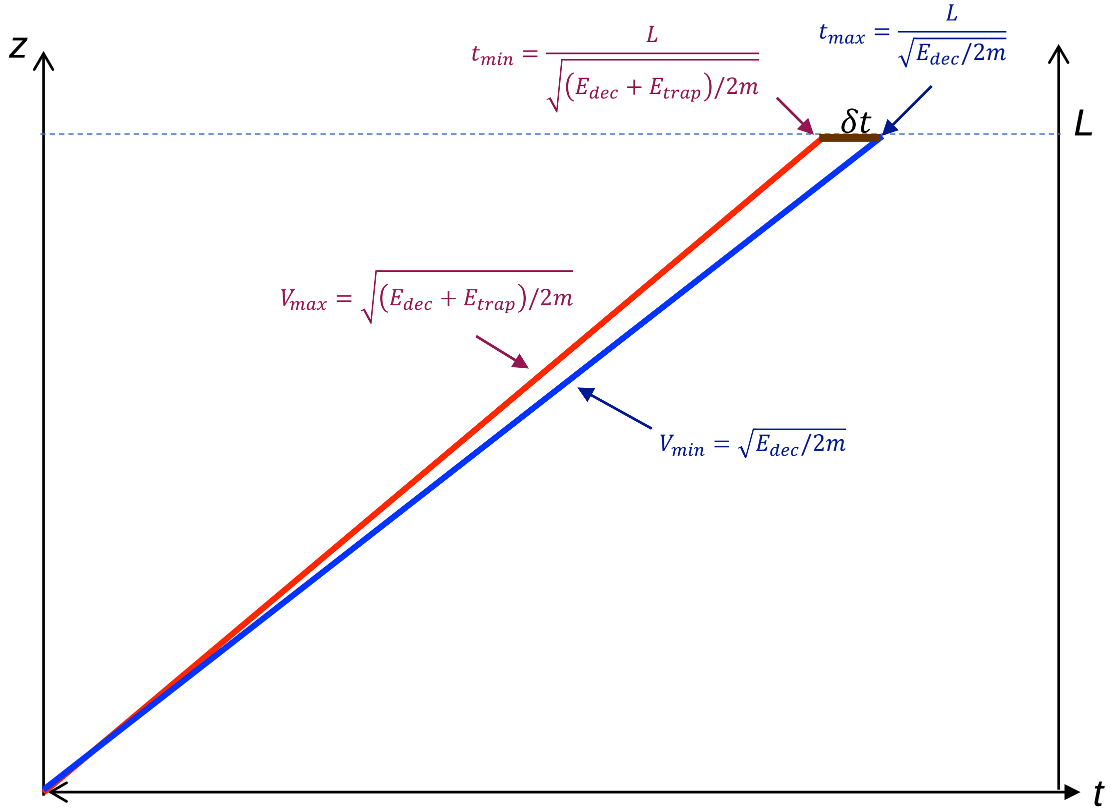


Q-factor≈ 10^3, $B_1 = 0.7\,mT$, $f = 500\,MHz$, Input power ≈ $4\,kW$

! 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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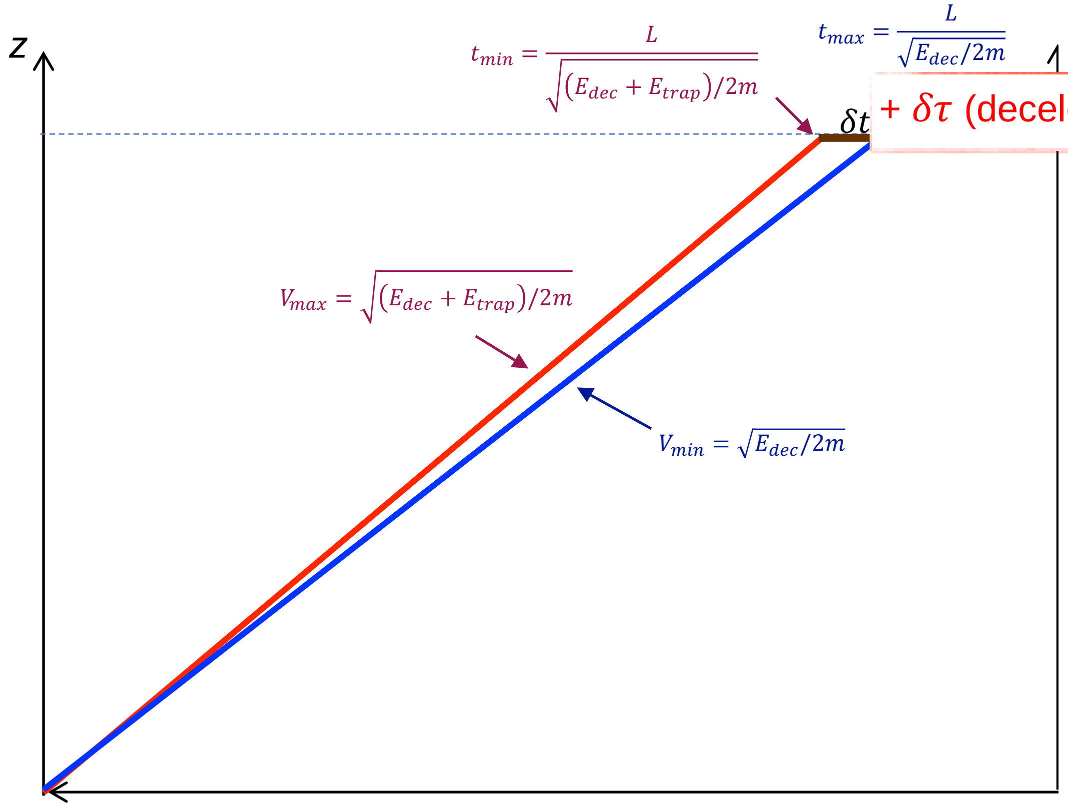
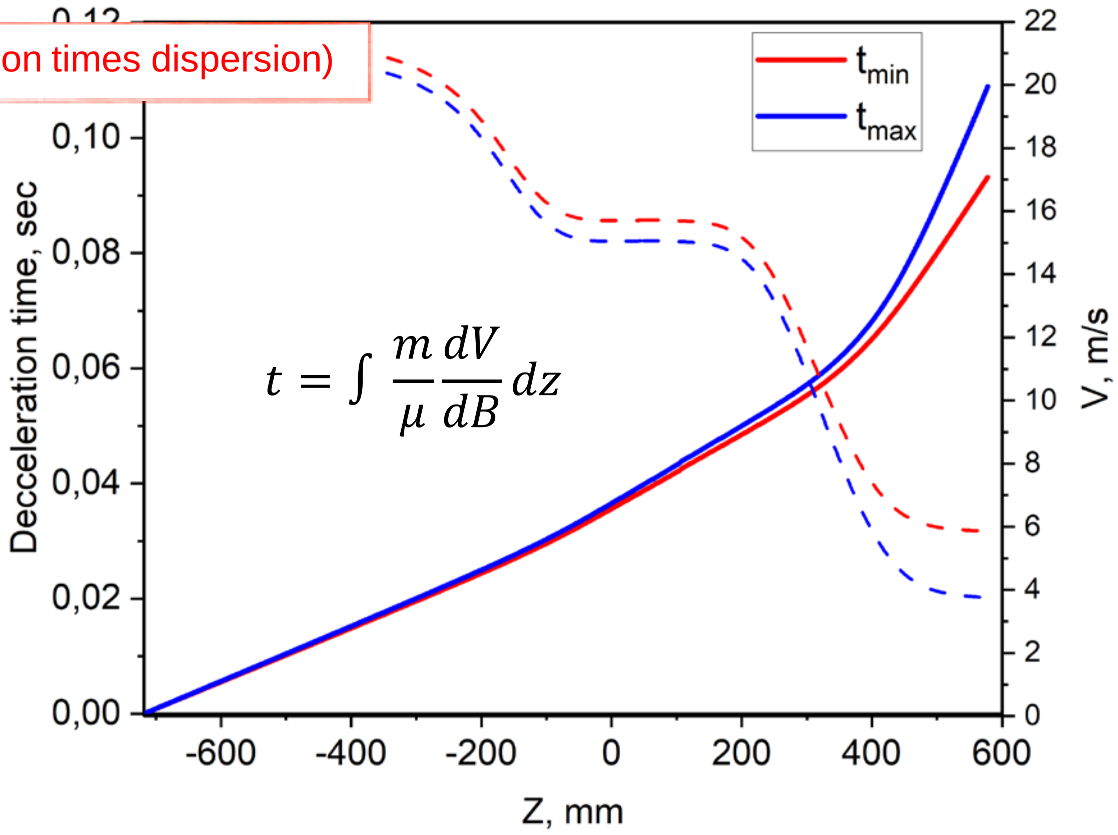
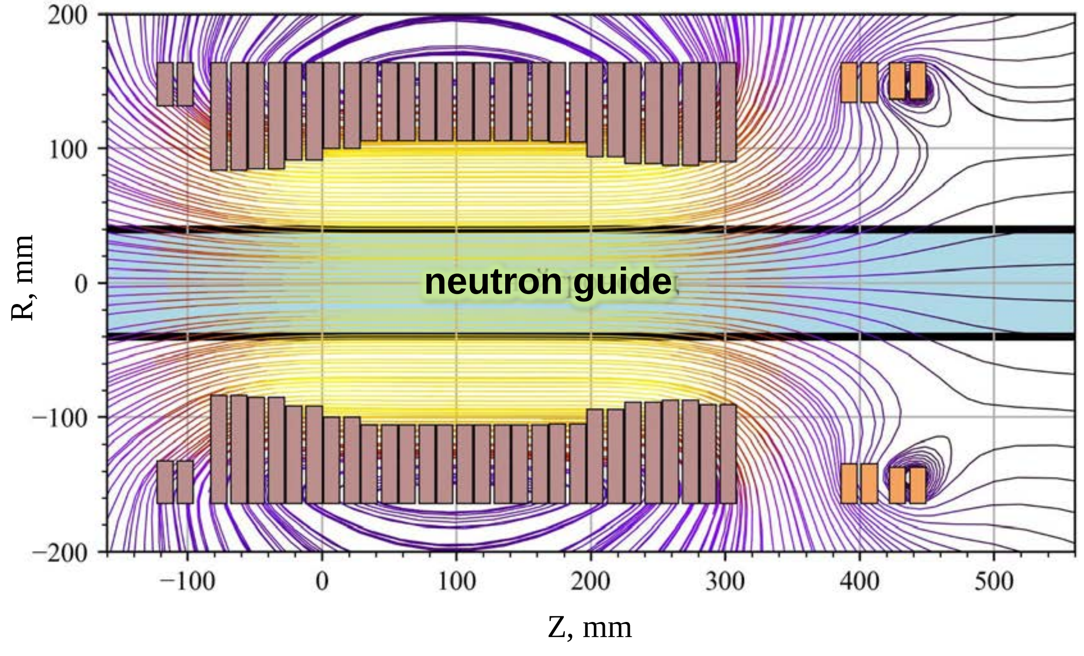


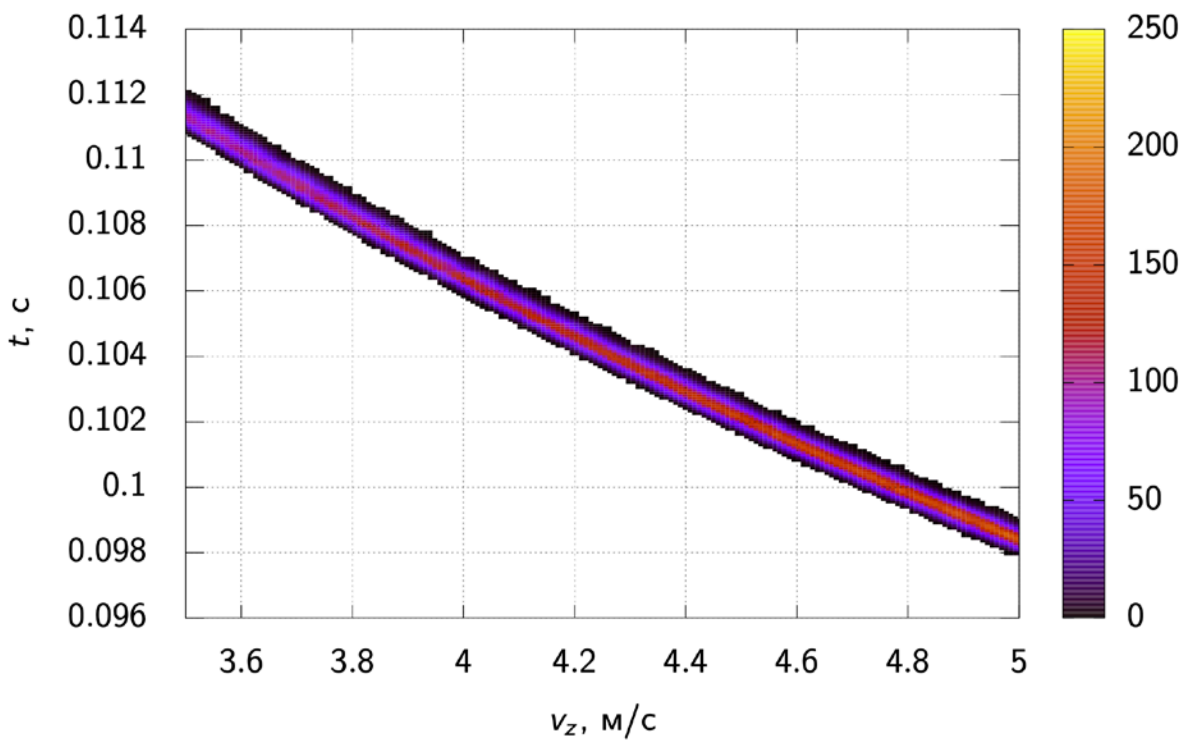


The slower the neutrons, the more time they spend on deceleration

Dispersion of deceleration times



rectangular neutron guide: 60 mm×60 mm



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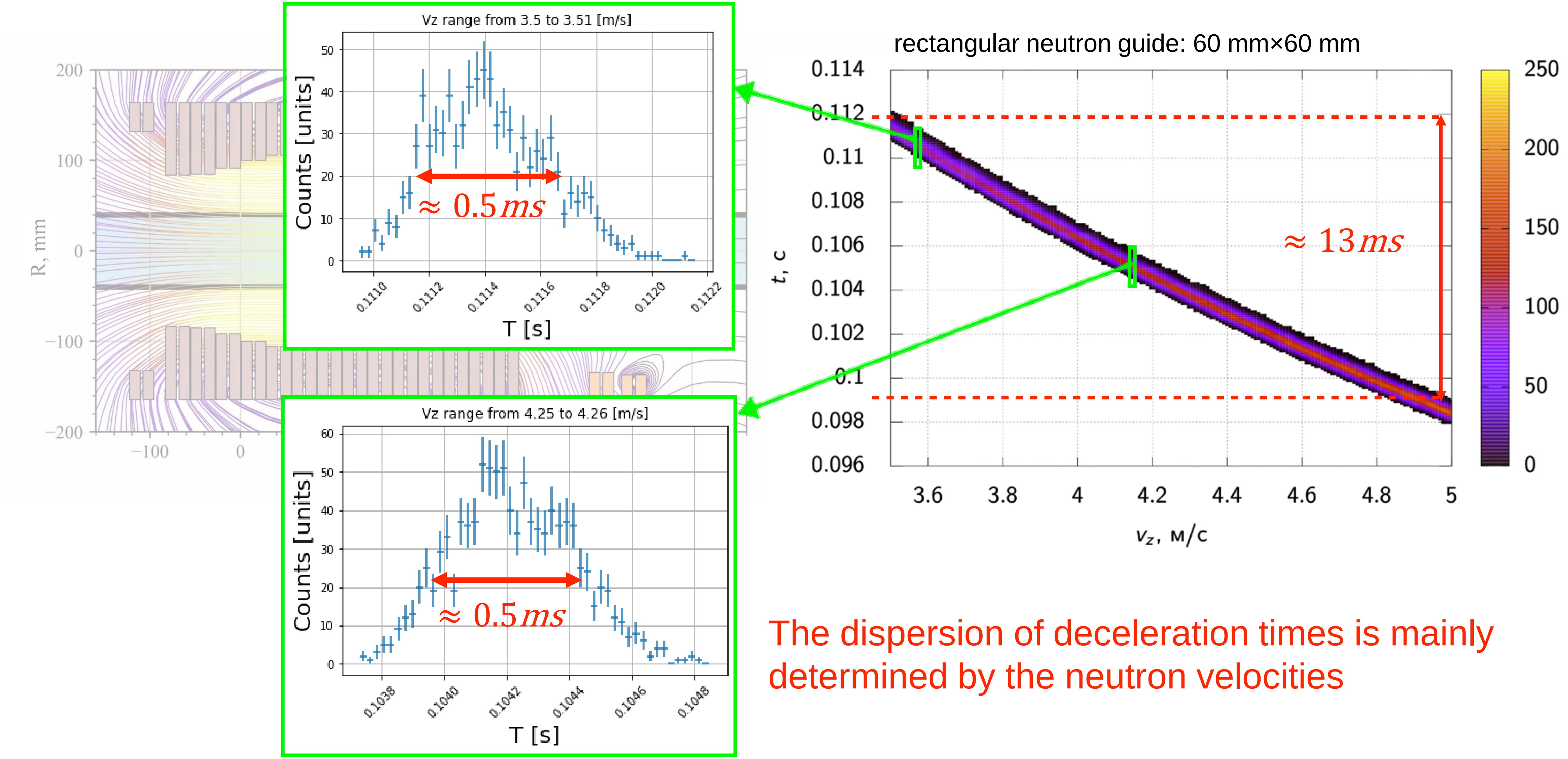
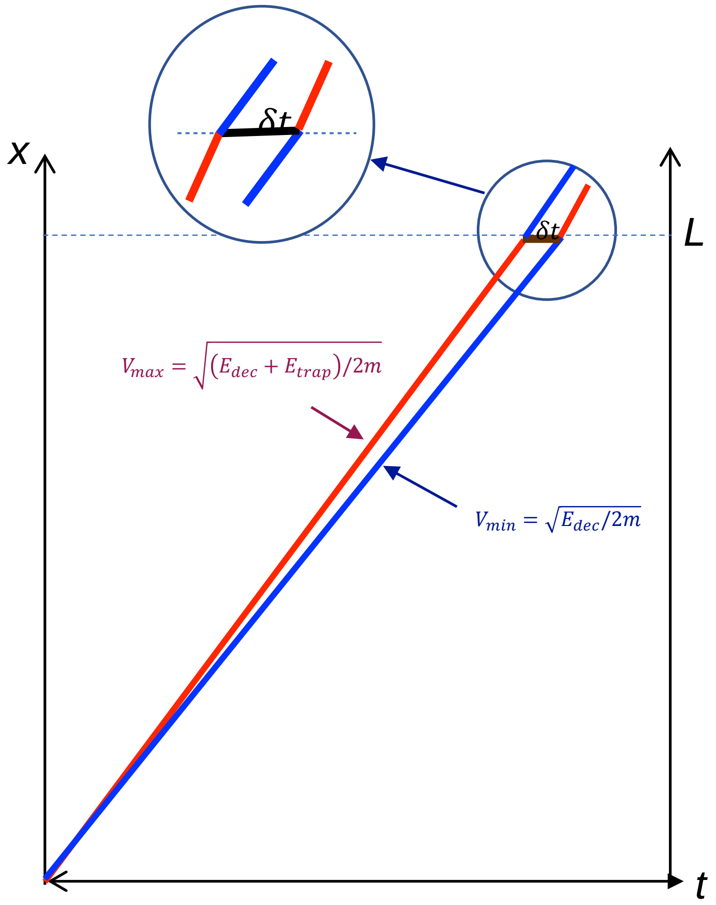


The dispersion of deceleration times is mainly determined by the neutron velocities

”Velocity invertor” to compensate deceleration times dispersion



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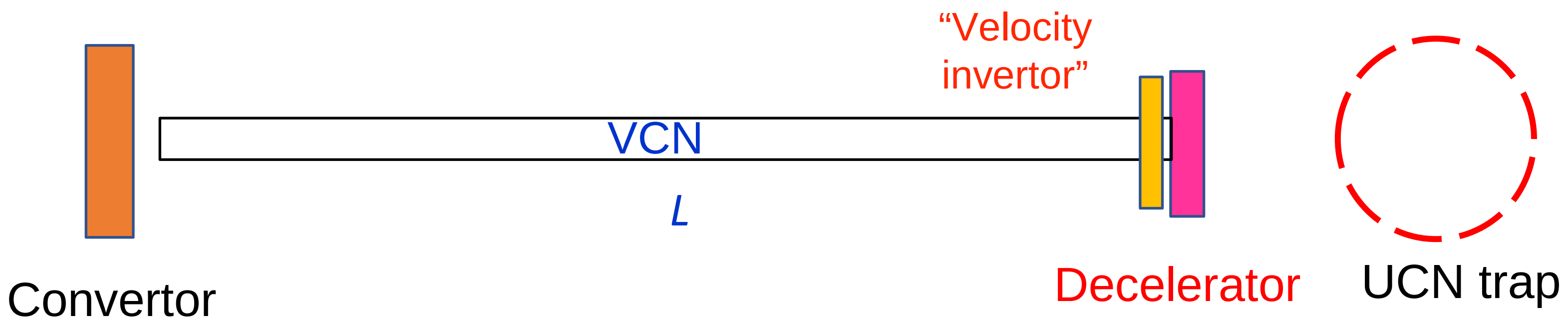


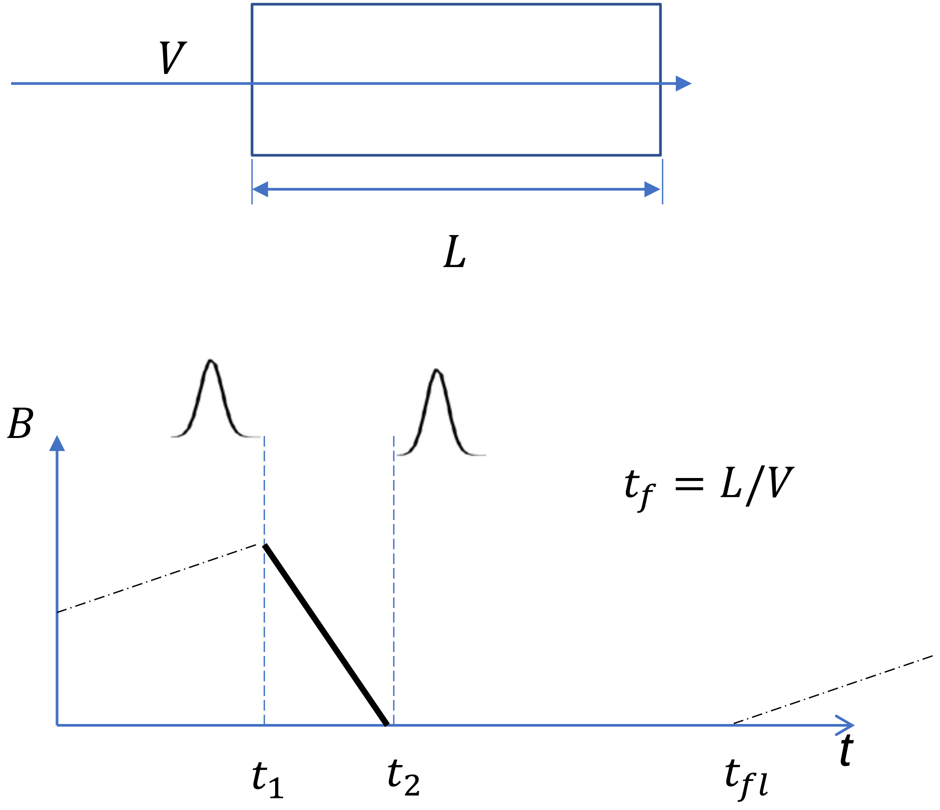
“velocity invertor” inverts neutron velocities in order to partially compensate the dispersion of the time of subsequent deceleration and to minimise bunch duration at the trap entrance

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

A time-dependent magnetic field invertor

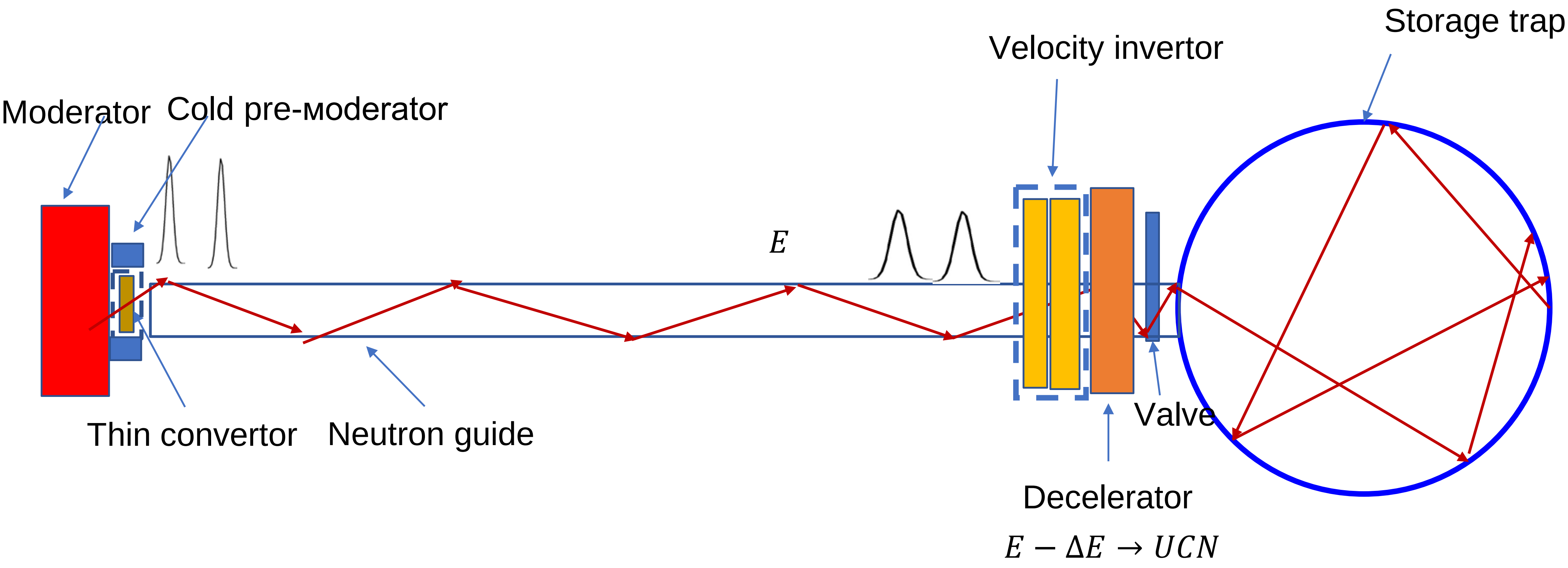
Neutrons change their energy when passing a homogeneous in space time-varying magnetic field

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

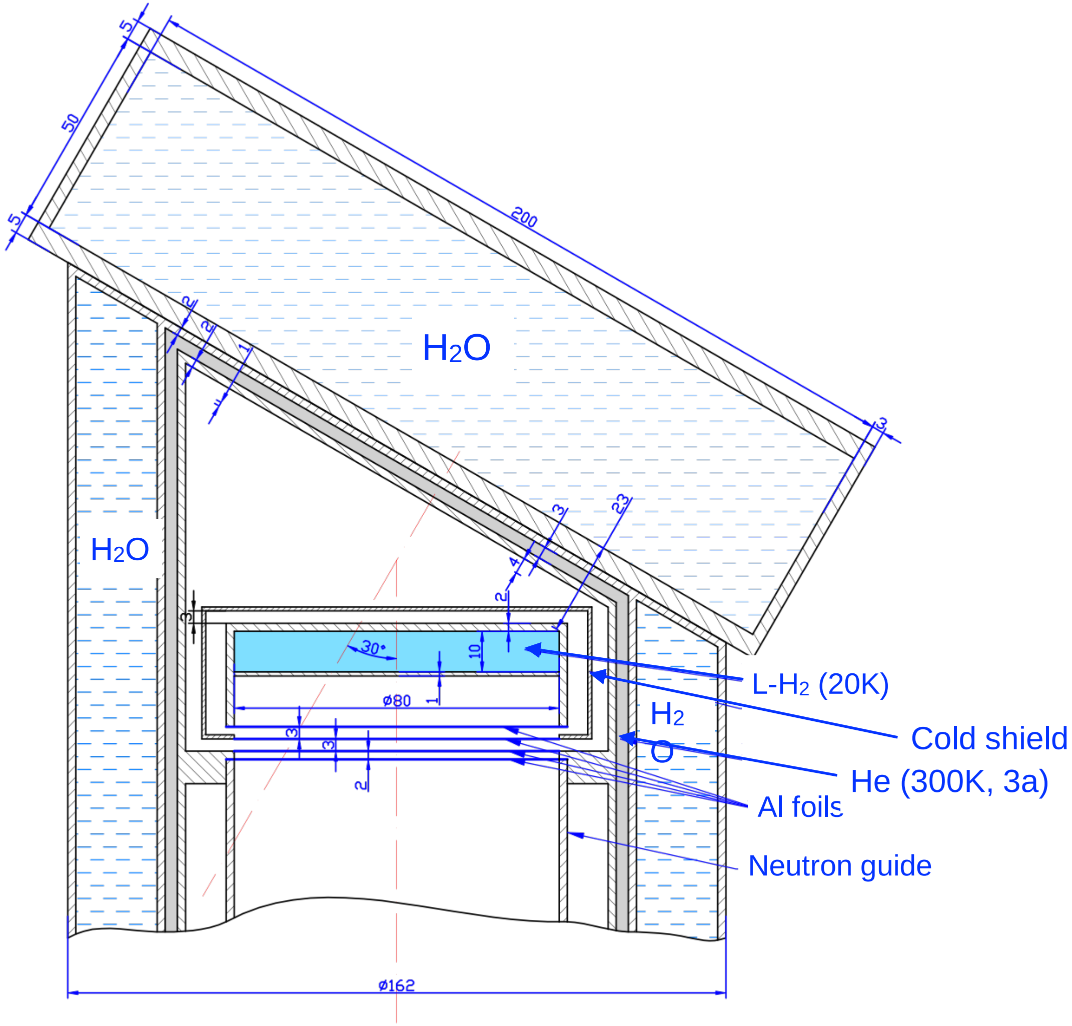


Time of flight of the bunch	$\Delta t = t_2 - t_1 \approx 10 - 15 ms$
Neutron velocity	$V \approx 20 m/s$
Lens length	$L \approx 40 cm$
Time of flight of the lens	$t_{fl} = 20 ms$
Repetition period	$T = 200 ms$
Magnetic field	$B = 1.5 T$

Conception of UCN source @ periodic pulsed reactor

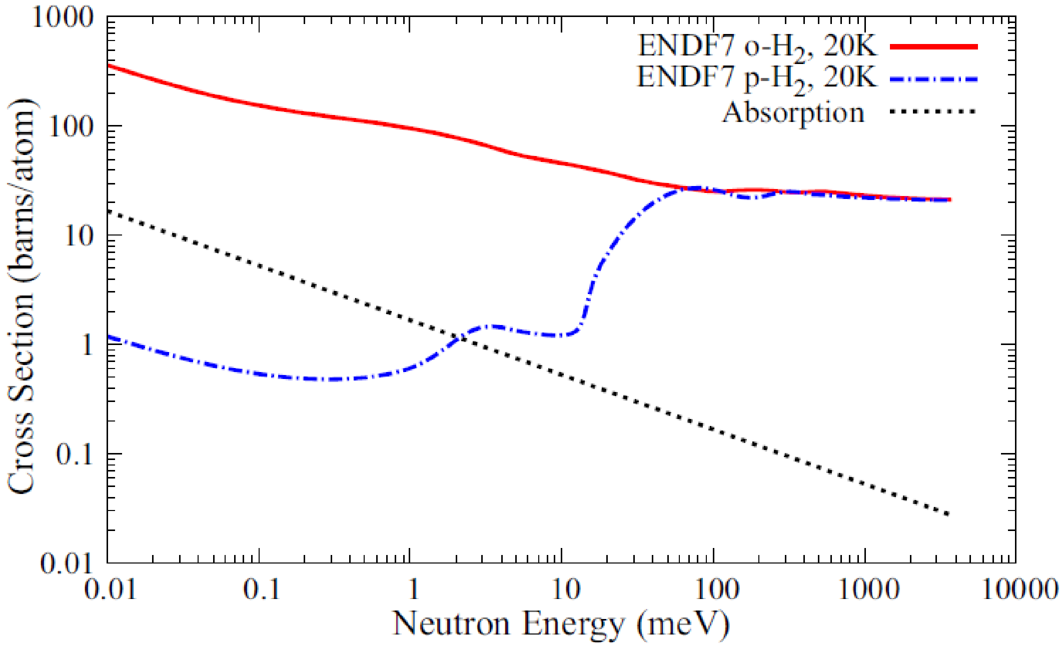


Liquid H_2 converter

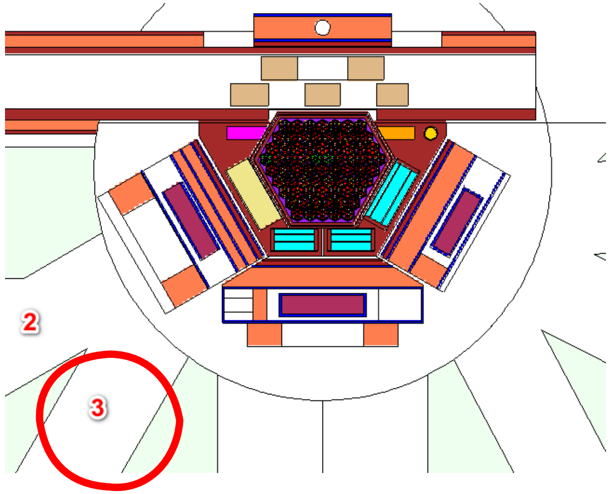


Designed by A.Yu. Muzychka

Scattering cross Section on H_2

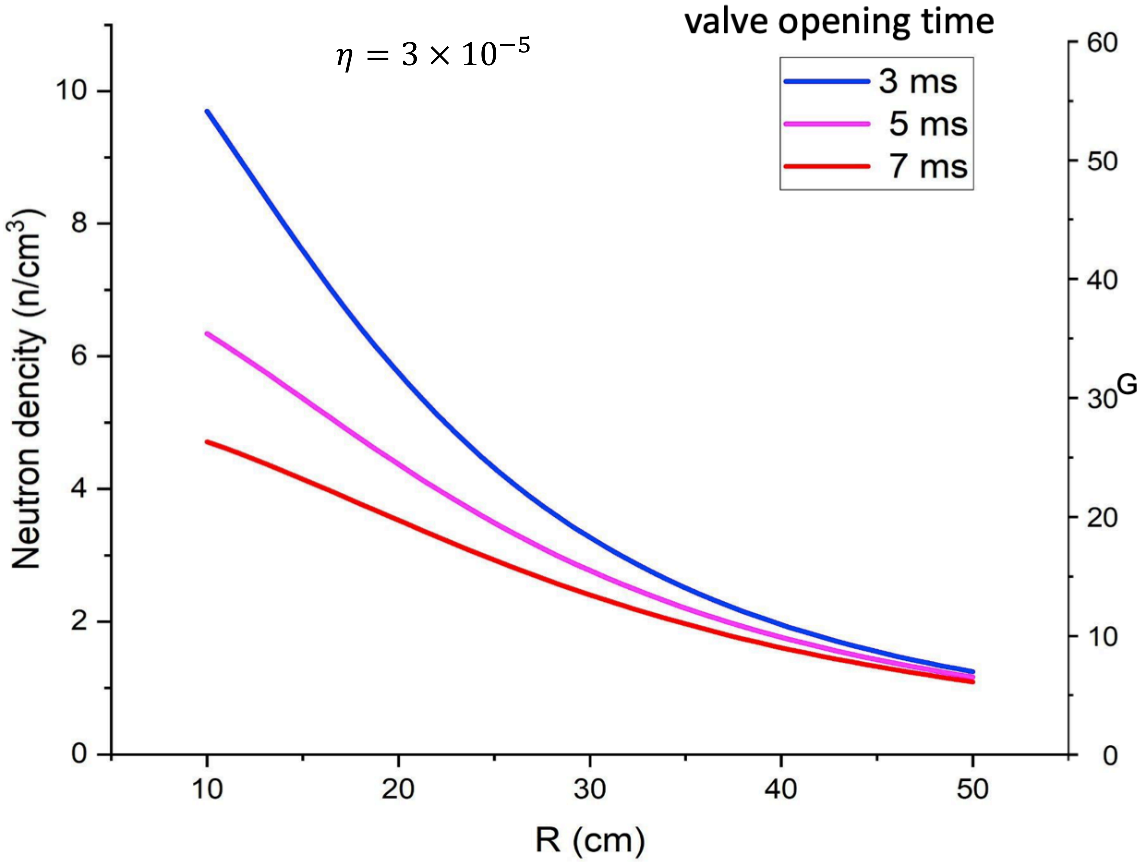


Neutron density in a spherical UCN trap (liquid H_2 converter)

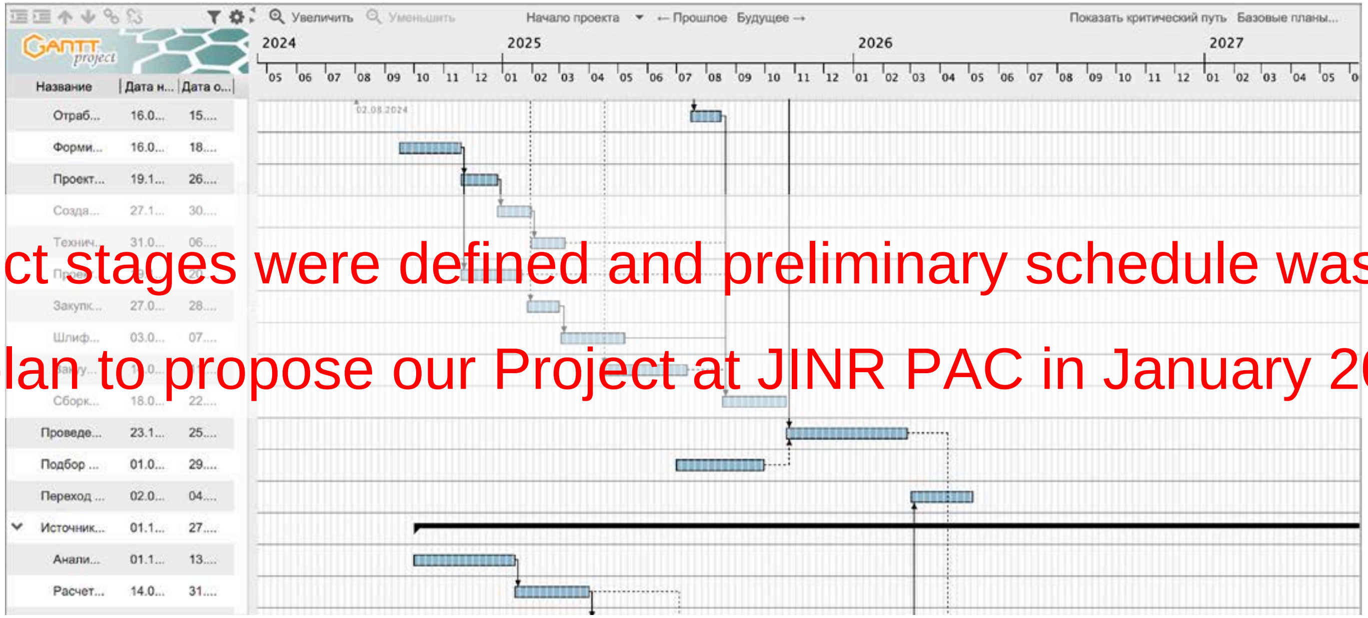


Average flux of thermal neutrons at the surface of the converter	2×10^{12} n/cm^{2}s
The neutron guide boundary velocity	5.9 m/s
The boundary velocity of the trap	6.9 m/s

When calculating neutron guide transmission, only losses due to roughness was taken into account



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



Project stages were defined and preliminary schedule was formed

We plan to propose our Project at JINR PAC in January 2025

Thanks for the discussions to E.V. Lychagin, S.V. Gurskiy, V.V. Kobets, S.V. Mironov and V.I. Bodnarchuk.

Special thanks to the staff of SuperOx LLC, especially to V.I. Shcherbakov.

Thank you for your attention!!!