JOINT INSTITUTE
FOR NUCLEAR RESEARCH

FRANK LABORATORY
OF NEUTRON PHYSICS

To the UCN source at periodic pulsed reactor

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

F.L.Shapiro, V.I..Luschikov.A.V. Strelkov and Yu.N. Pokotilovsky

Письма в ЖЭТФ

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НАБЛЮДЕНИЕ УЛЬТРАХОЛОДНЫХ НЕЙТРОНОВ

В.И.Лущиков, Ю.Н.Покотиловский, А.В.Стрелков, Ф.Л.Шапиро

1969

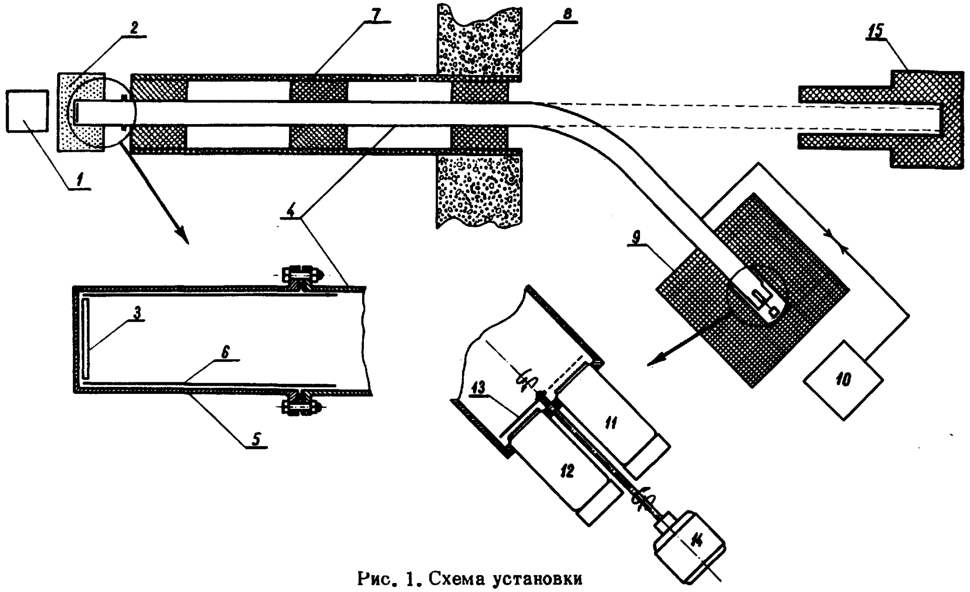


Рис. 1. Схема установки

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(A)
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	(10-100) ×10-3	120-1000	4-1
Resonant	>1		< 0.1

UCNs are important tools for:

Search for the neutron EDM

Measurement of the neutron lifetime

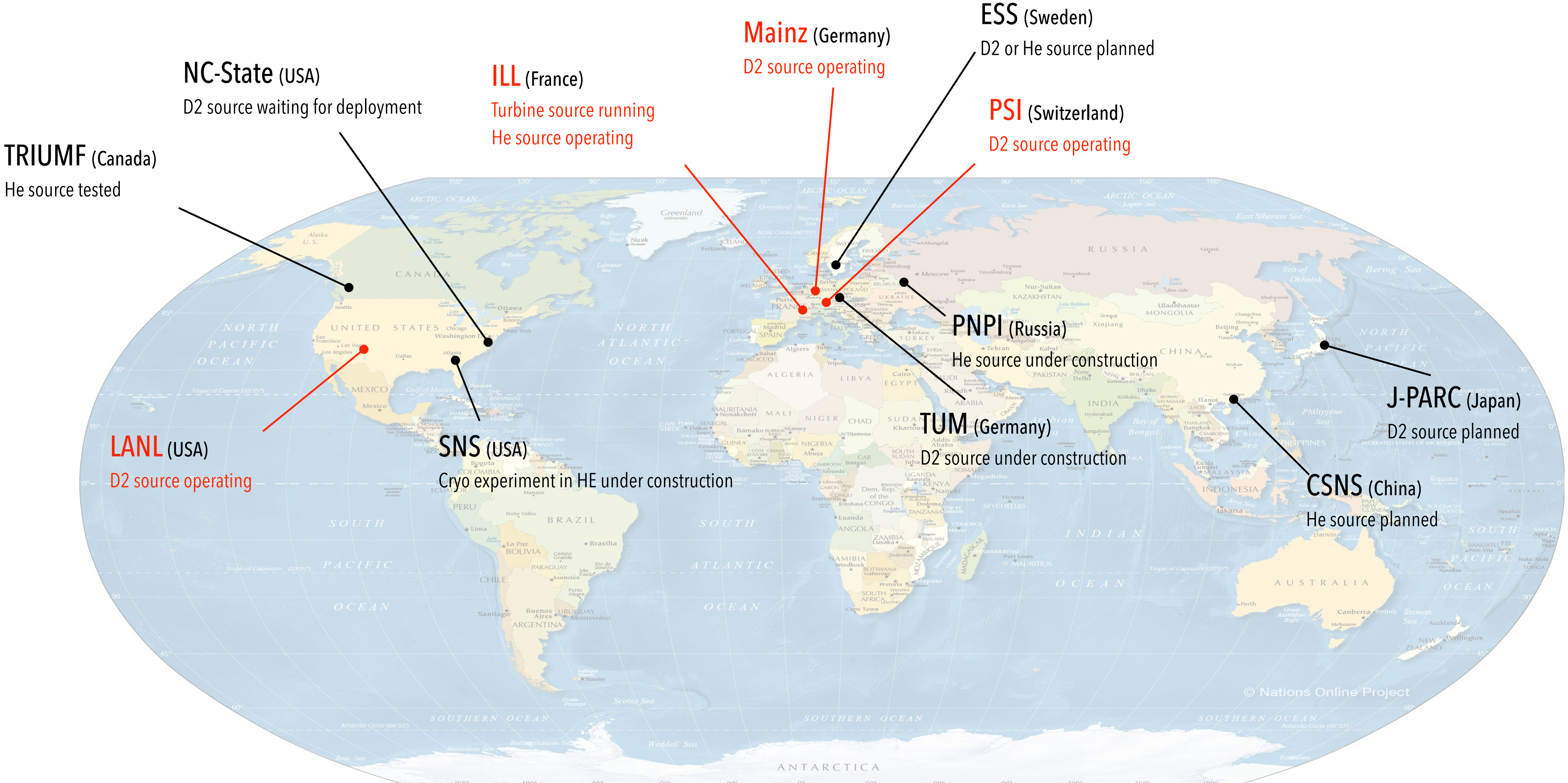
Measurement of angular correlation coefficients of neutron beta decay

Search for neutron-antineutron oscillations

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

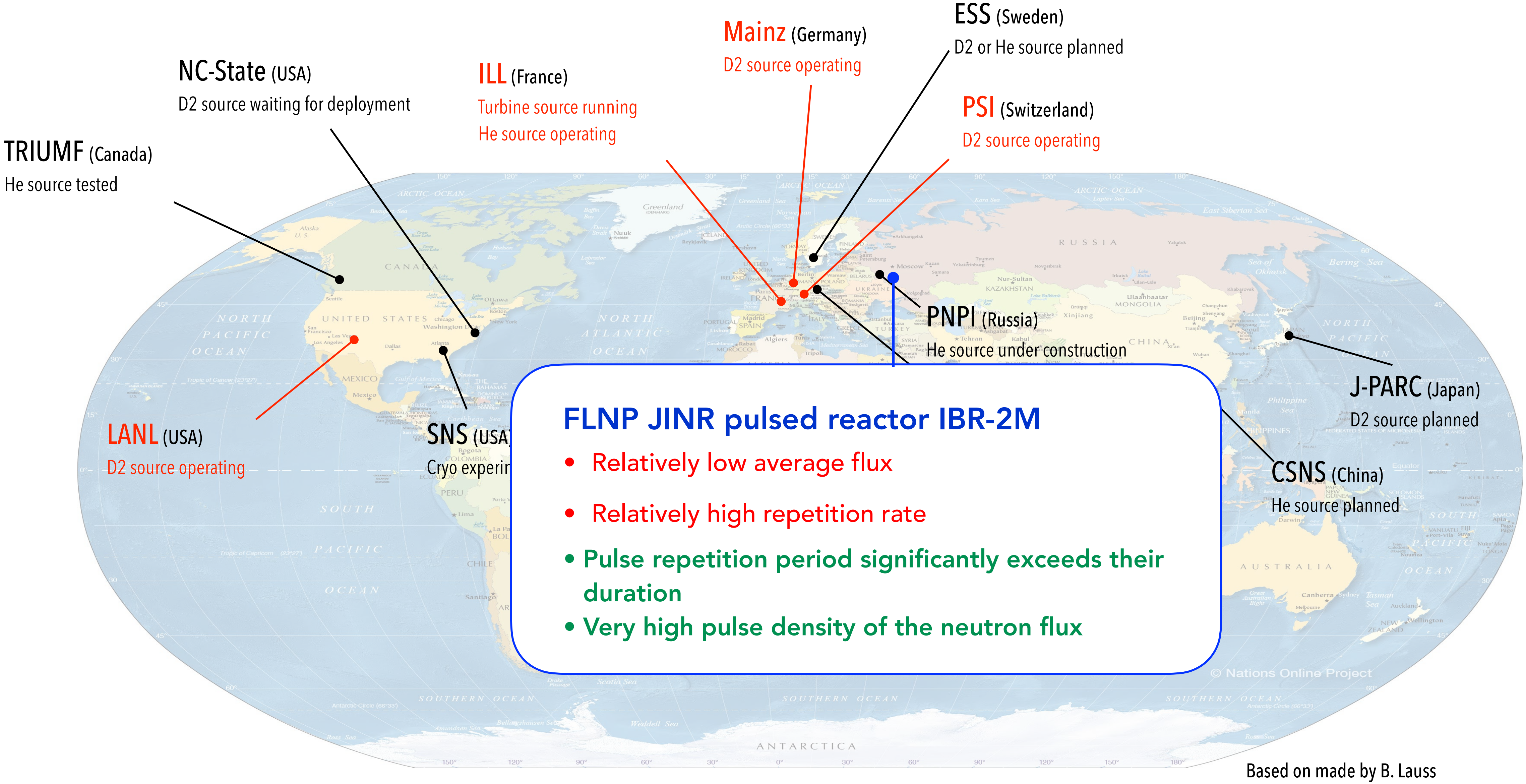
Non-stationary quantum mechanics and neutron optics

Ultra Cold Neutron sources



Based on made by B. Lauss

Ultra Cold Neutron sources



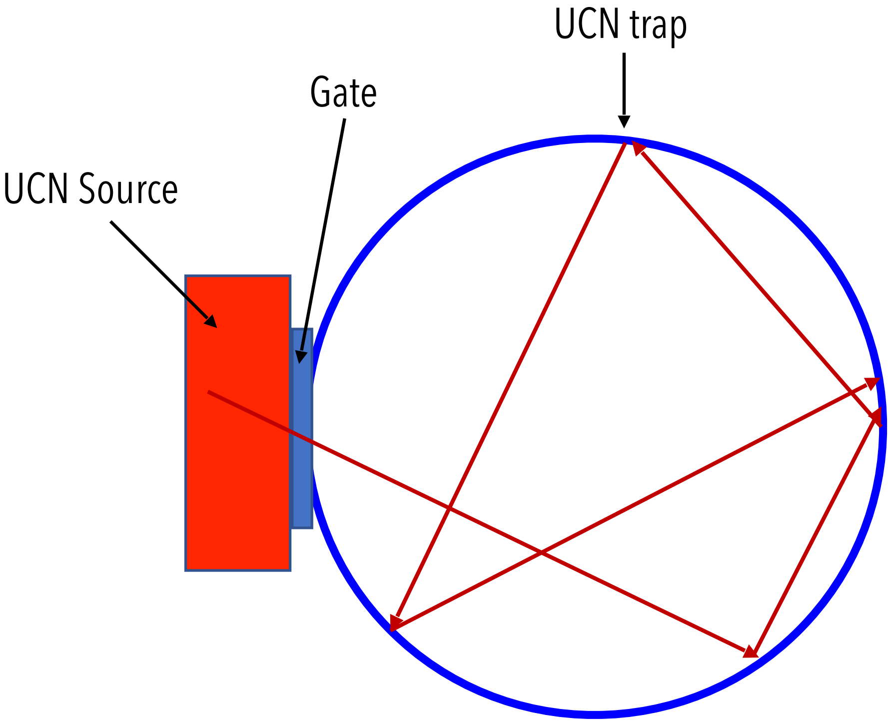
FLNP JINR pulsed reactor IBR-2M

- Relatively low average flux
- Relatively high repetition rate
- Pulse repetition period significantly exceeds their duration
- Very high pulse density of the neutron flux

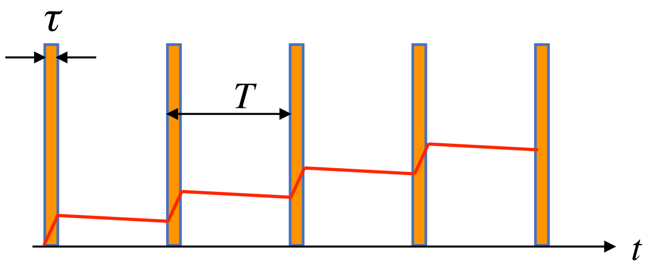
Based on made by B. Lauss

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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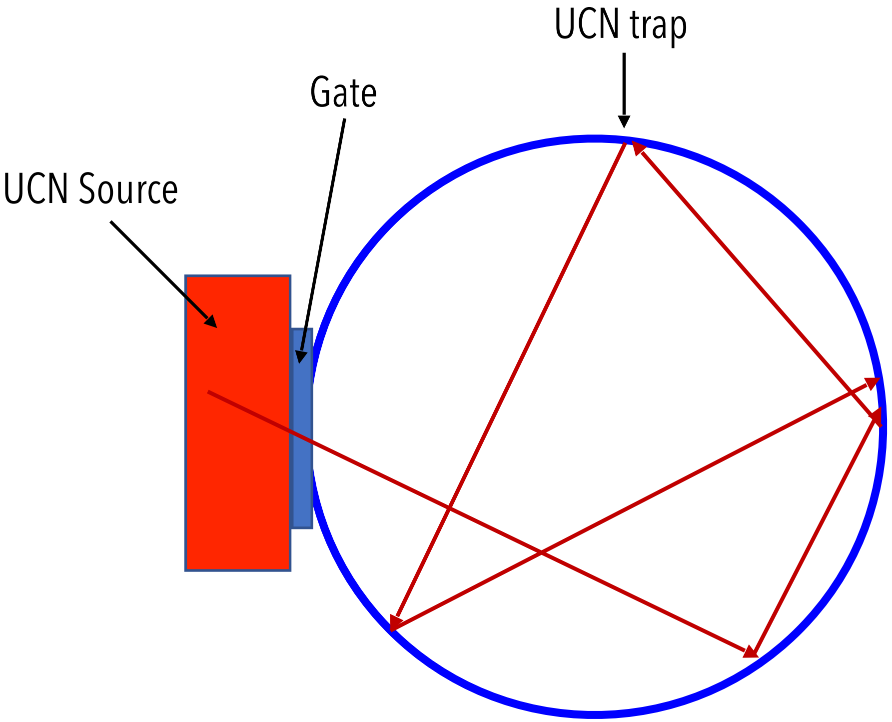

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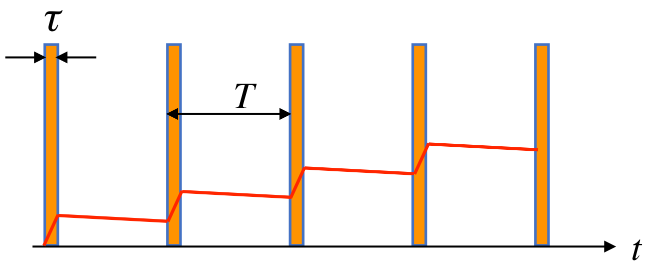

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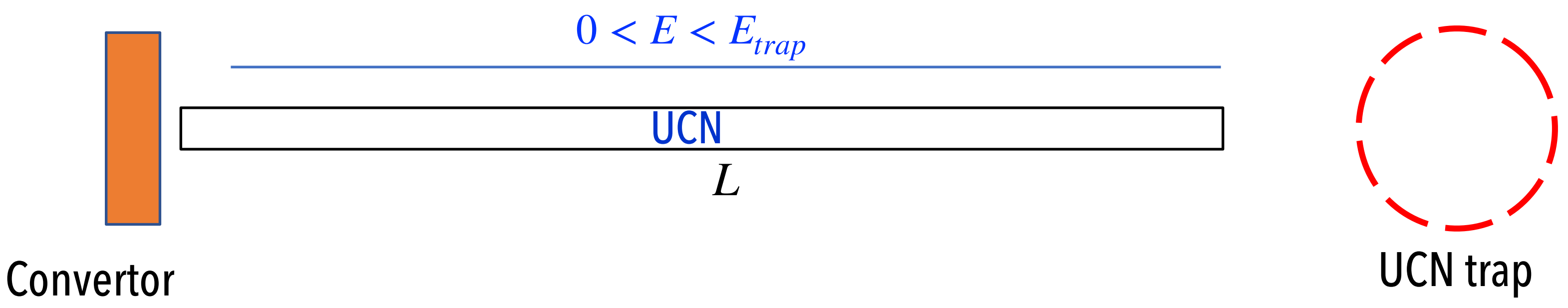
The trap is remote from the moderator due to the presence of biological shielding

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



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

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

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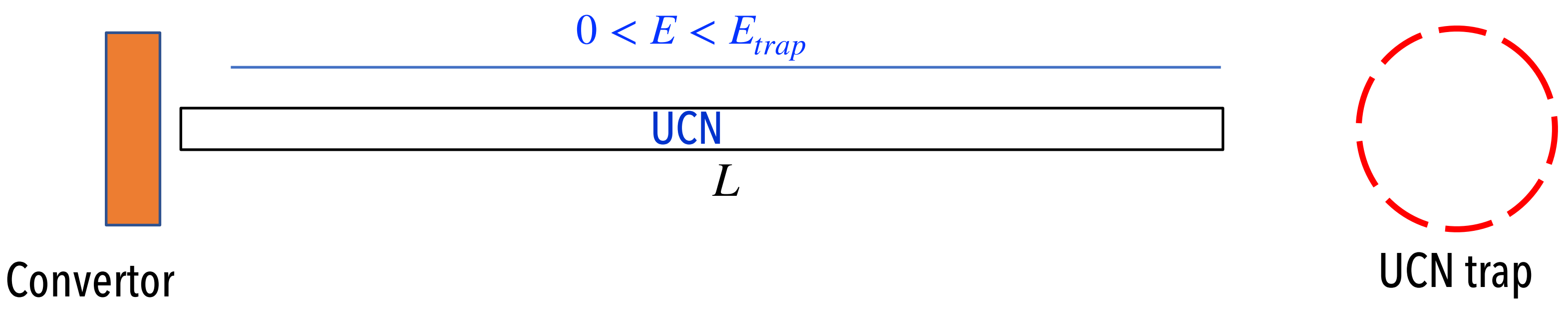

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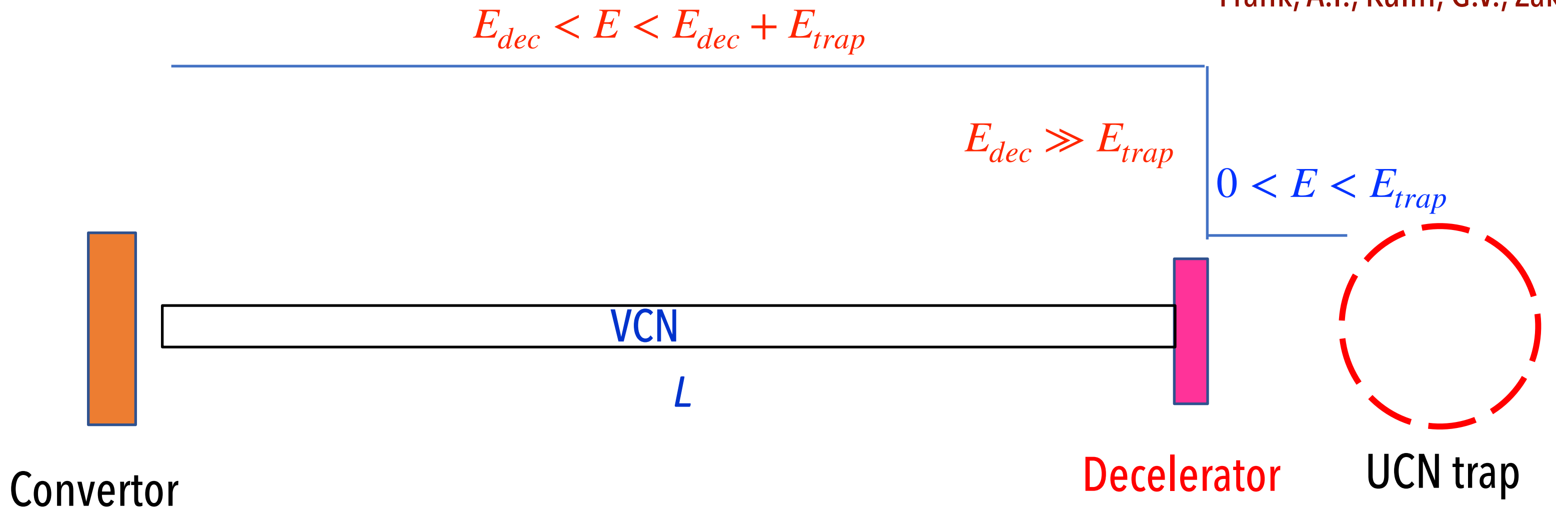


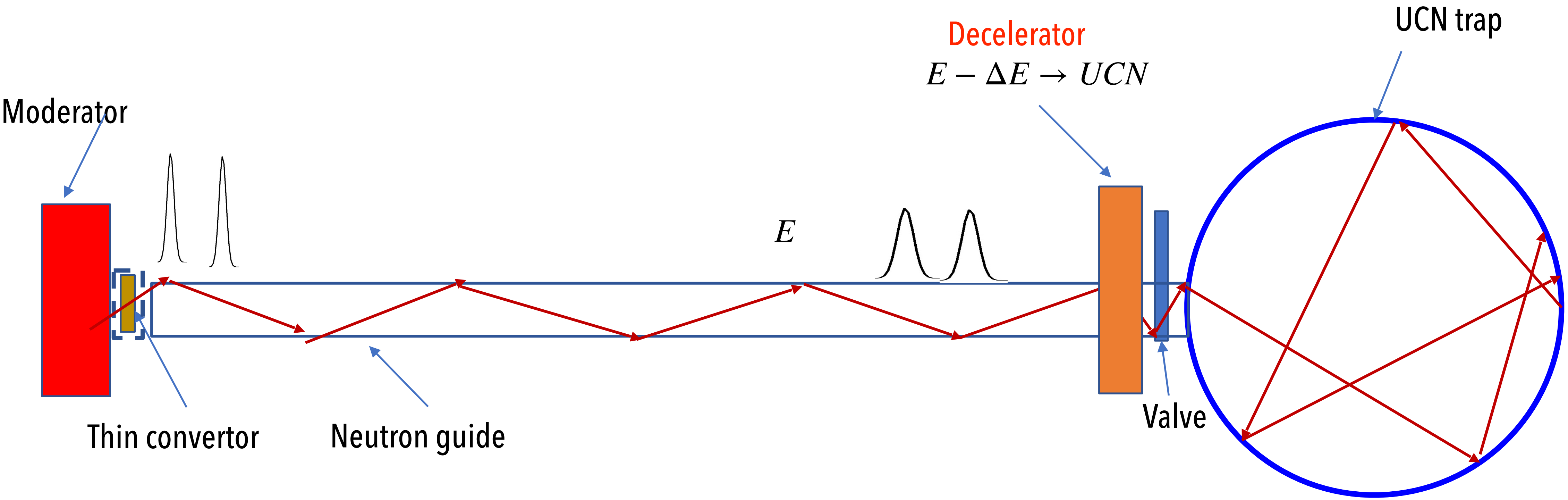
$$\frac{\delta t}{t} = \frac{\delta V}{V} = \frac{\delta E}{2E} = \frac{E_{trap}}{2E_{dec}} \ll 1$$

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

$$\delta t \ll T$$

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

Pumping option of the pulsed source – decelerator

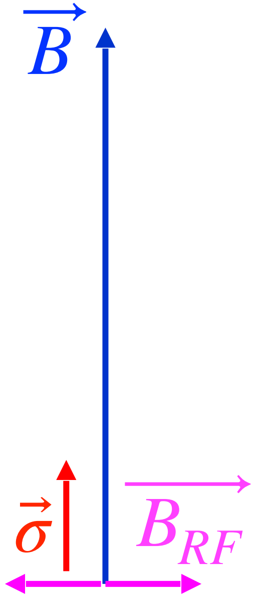


During deceleration, all neutrons change their energy by the same value

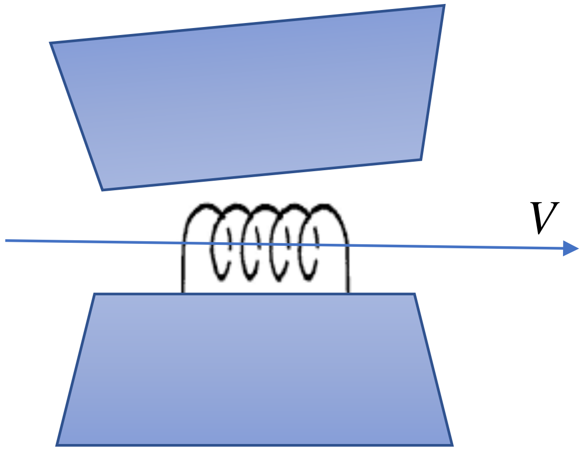
✓ The extraction of neutrons with higher speeds than that of the UCN from the moderator converter provides better conditions for the transportation of neutrons and allows the use of a more efficient converter

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

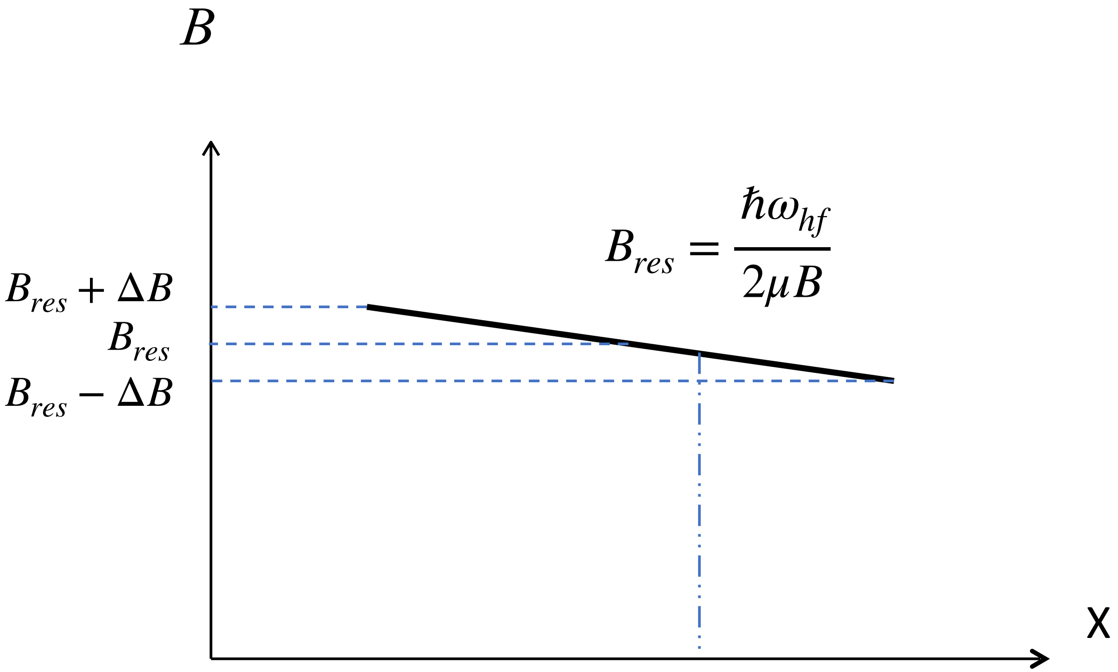
Decelerator — broadband gradient (adiabatic) spin flipper



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



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



G. M. Drabkin and r. A. Zhitnikov. Sov. Phys. JETP, 11, 729 (1960).
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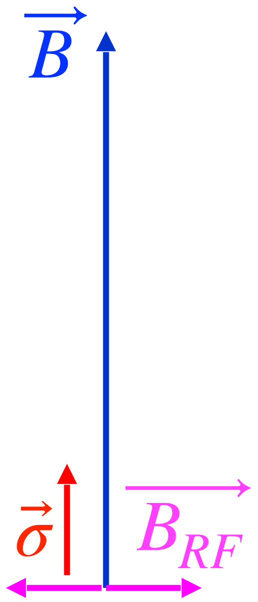

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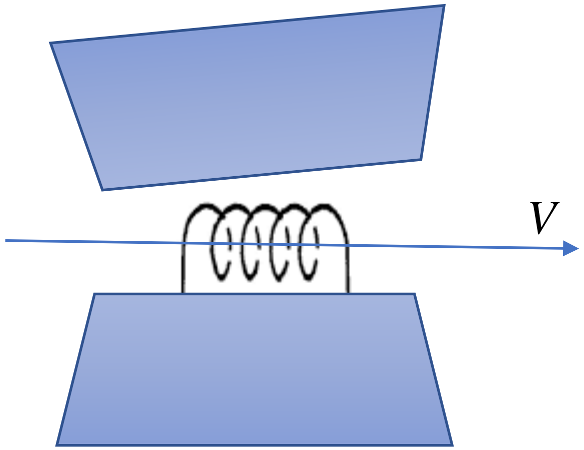

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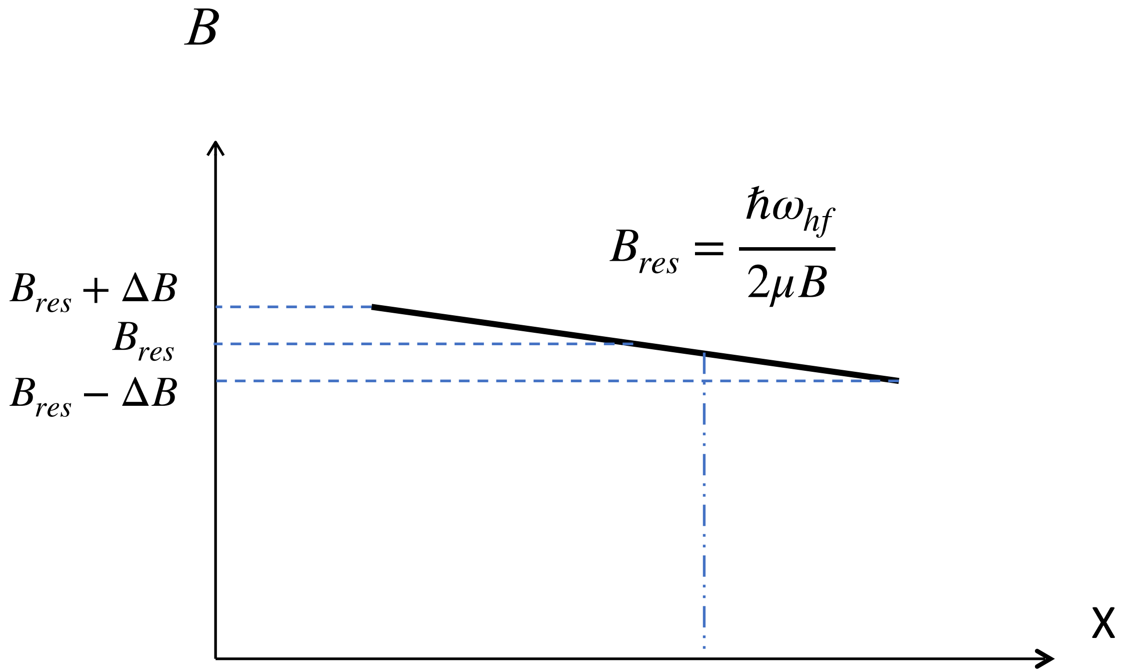

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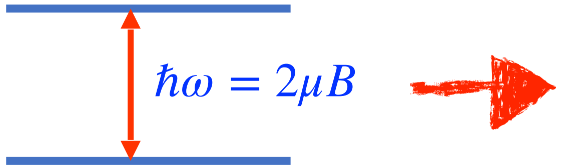
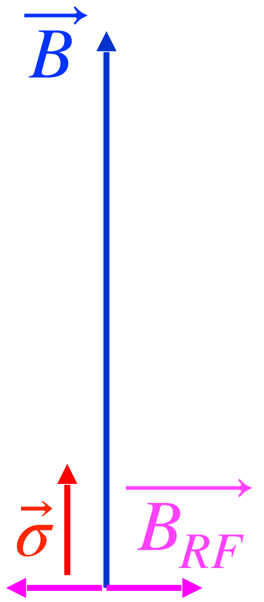


$\Delta E = 2\mu B = \hbar\omega$

Decelerator — broadband gradient (adiabatic) spin flipper



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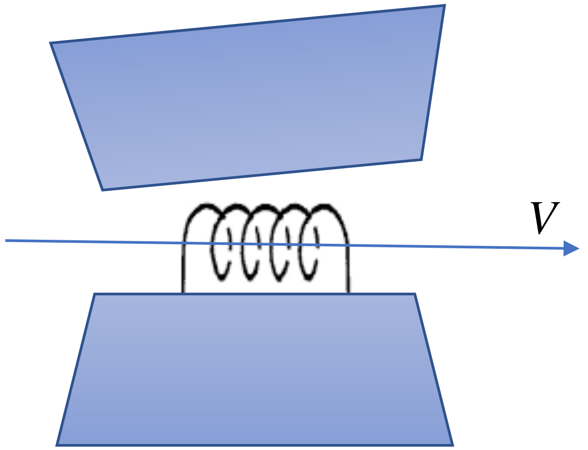

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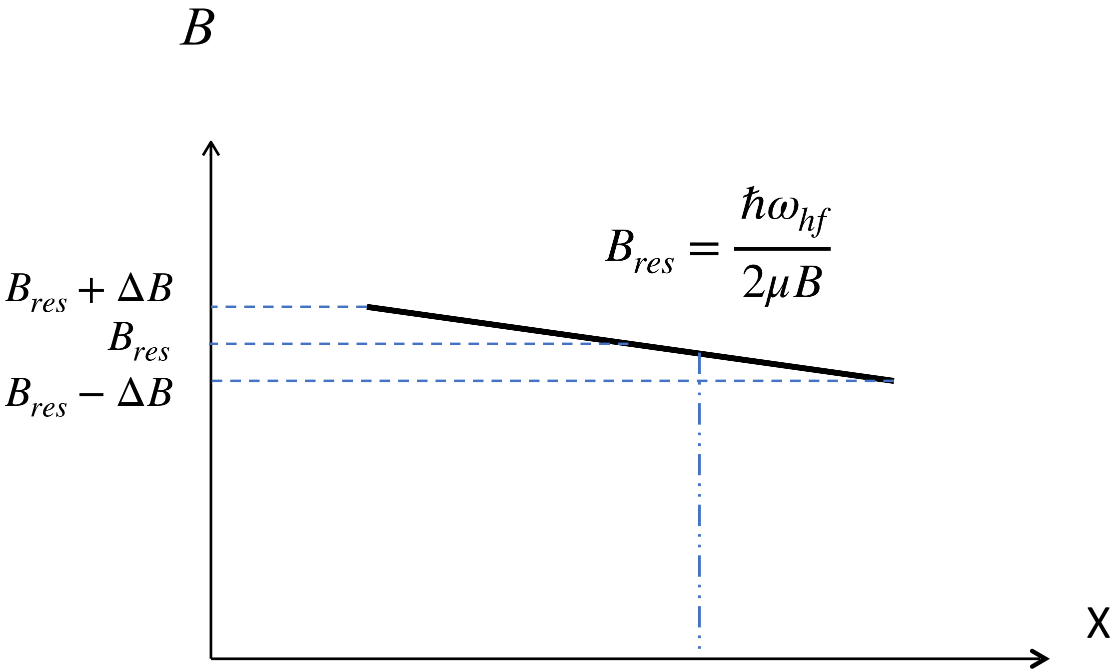


to decelerate a neutron at a speed of 20 m/s to a speed of 5 m/s

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

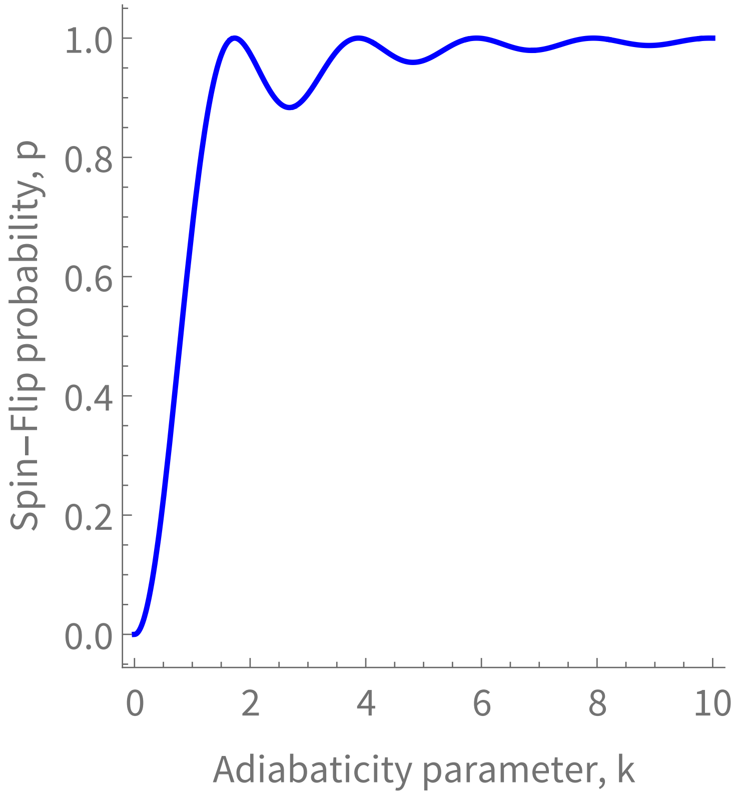
Parameters of adiabatic spin flipper

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

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

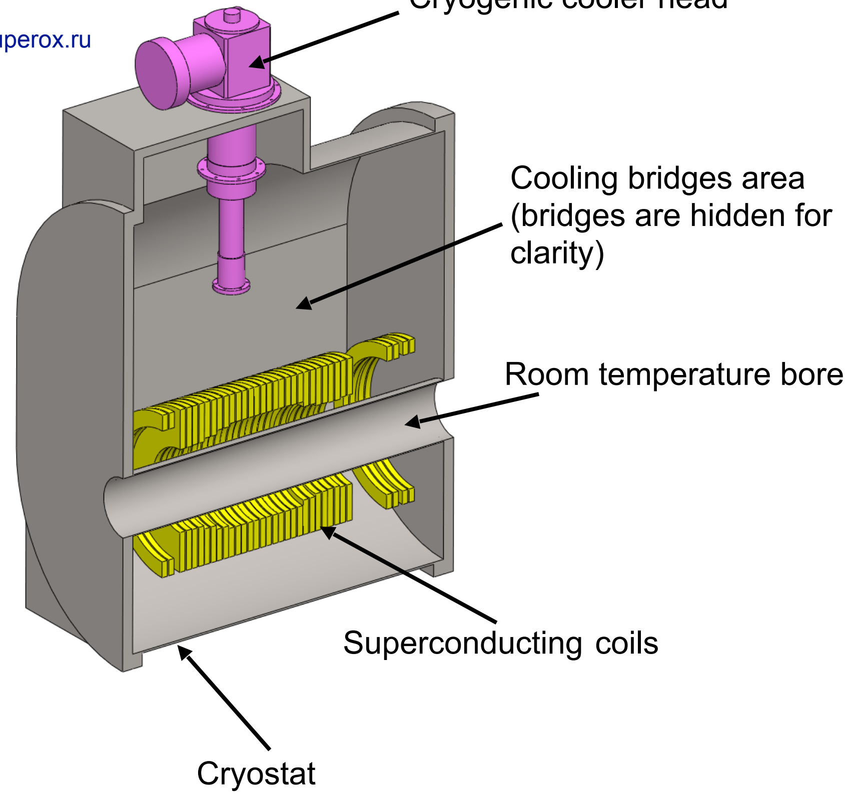
For gradient of magnetic field 1.5 T/m ⟶ $B_1 \geq 0.7$ mT



Stationary gradient field – superconducting solenoid

Preliminary magnet design

Designed by SuperOx LLC / www.superox.ru

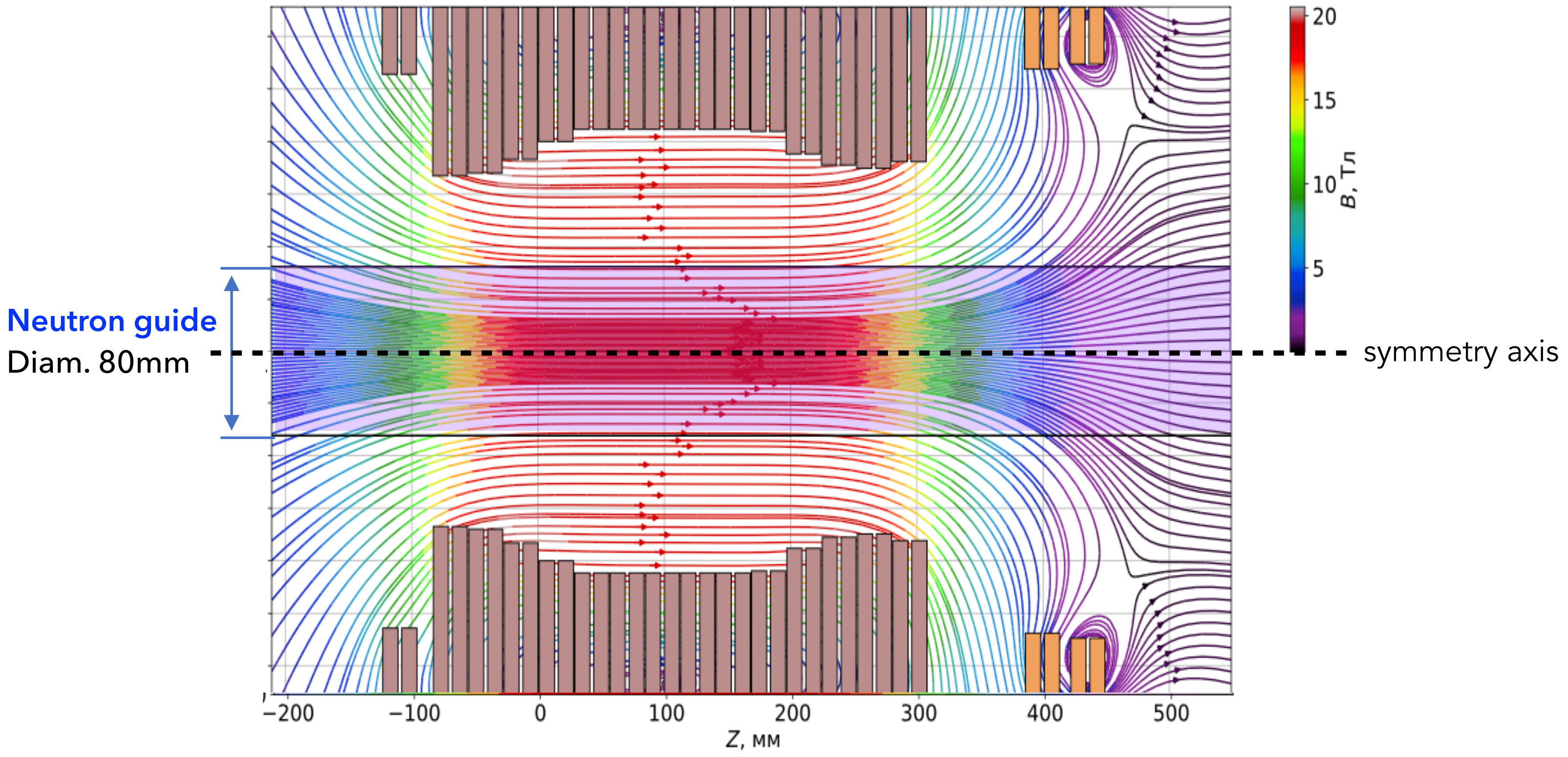


Technical specifications

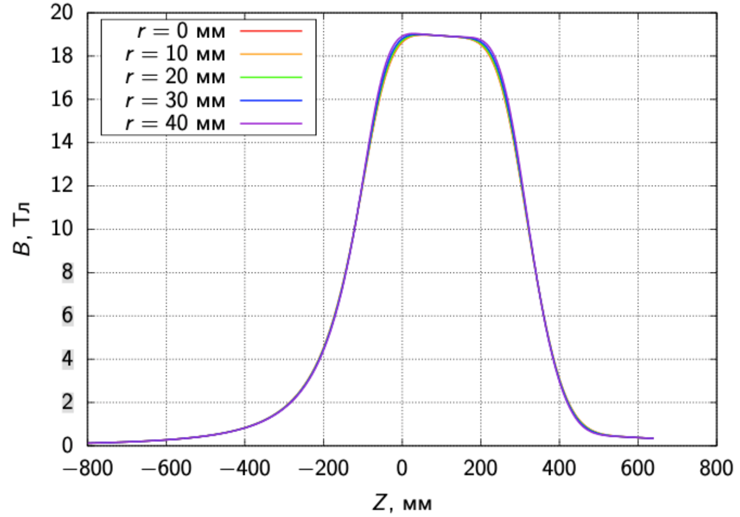
Magnetic field (peak)	20 T
Bore diameter	120 mm
Bore type	Room temperature
Dimensions **Length** **Width** **Height**	 750 mm 660 mm 1250 mm
Mass (including cryostat, magnet and cooling head)	Less than 1000 kg
Power supply	3-phase 380 V
Consumption	16 kW nominal 30 kW during cooldown)
Magnet wire	Second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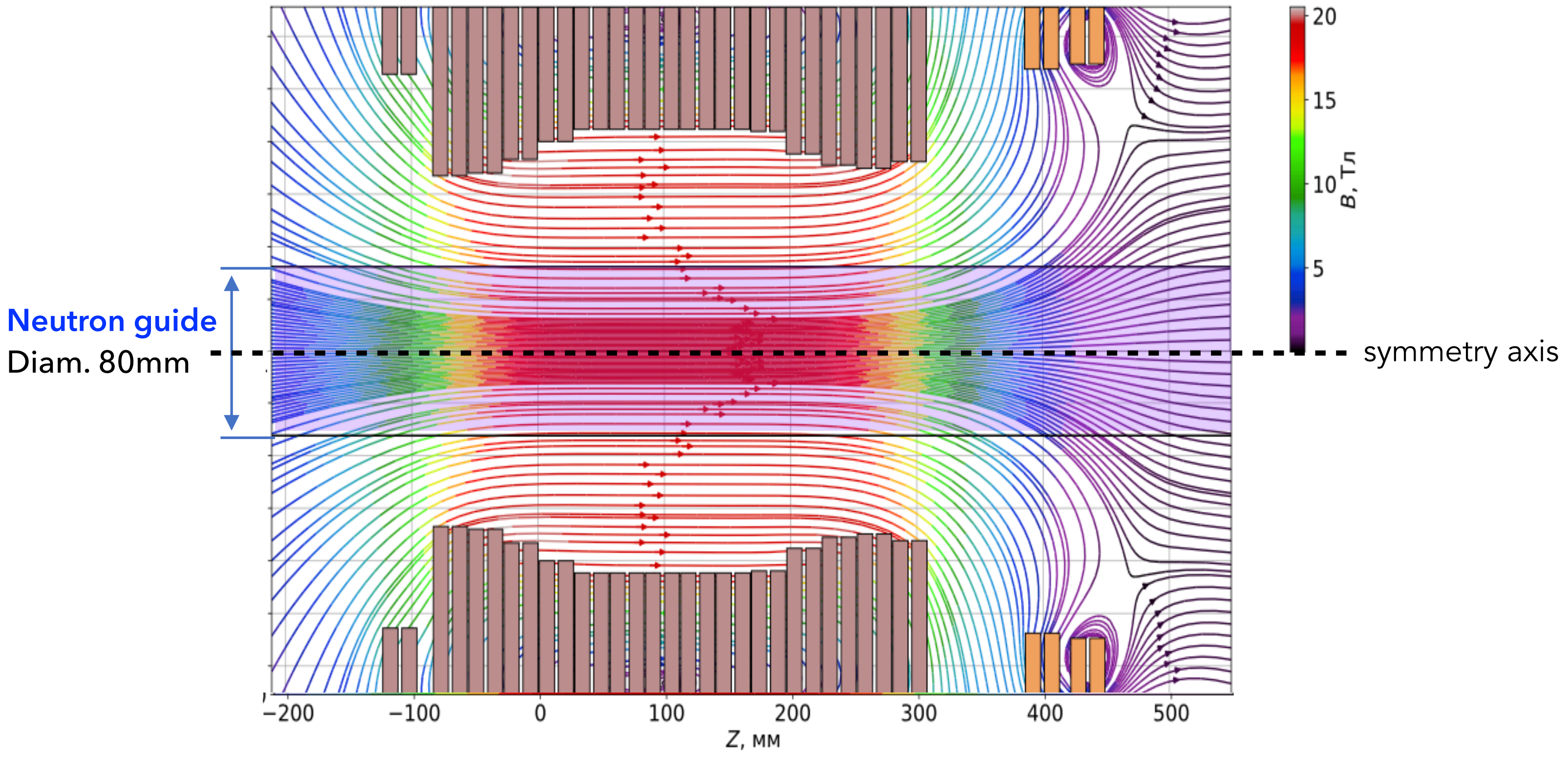

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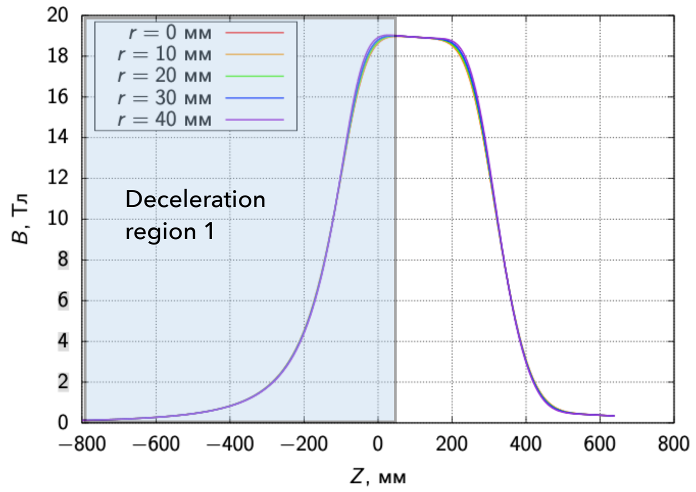

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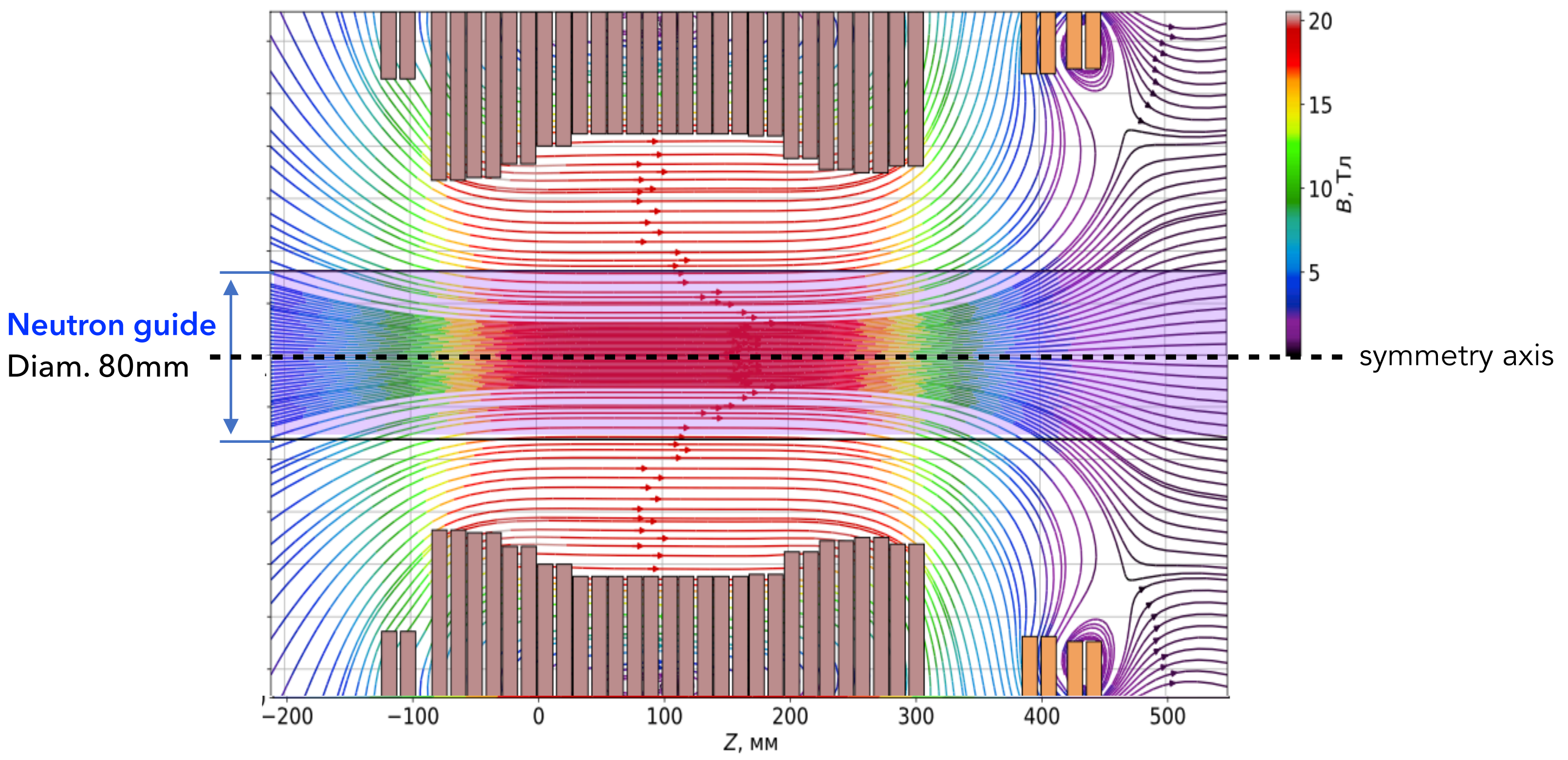

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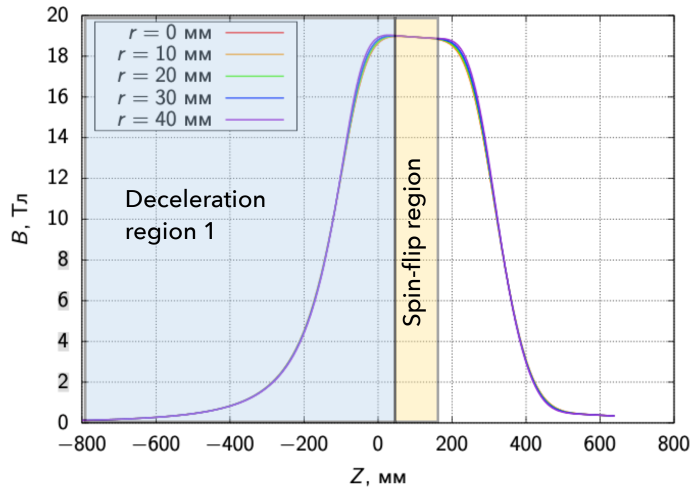
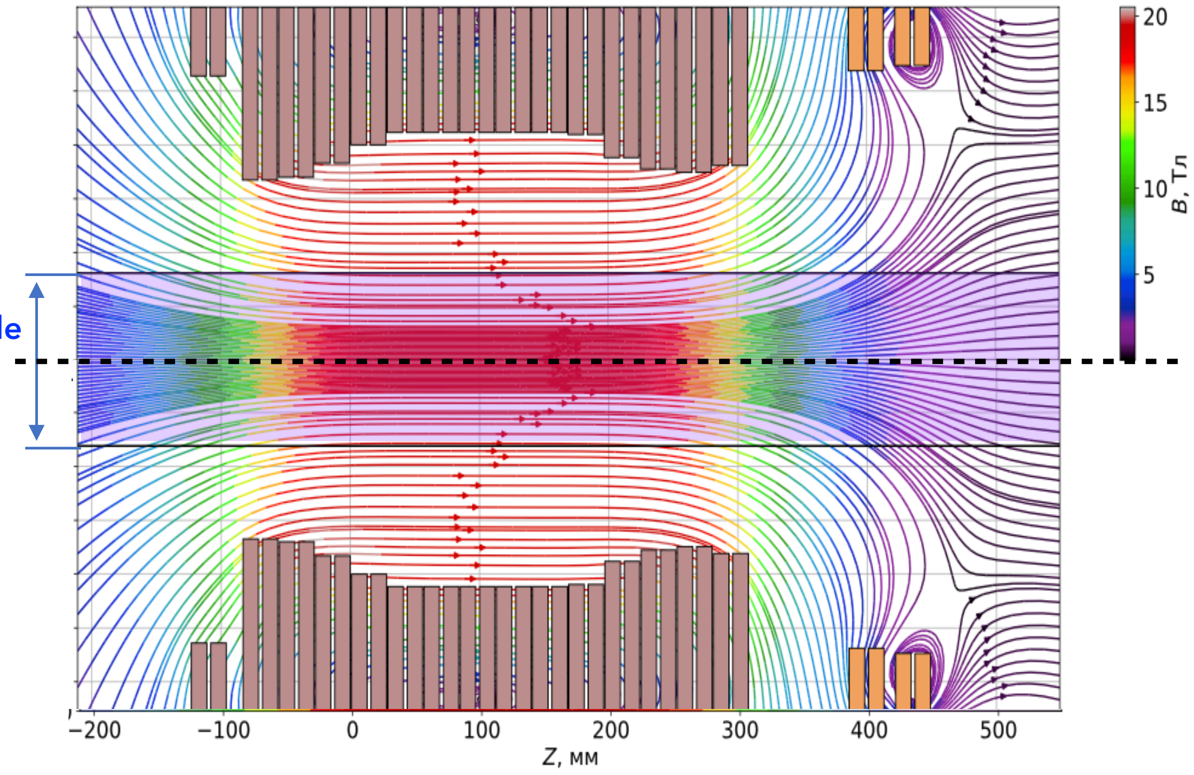


Stationary gradient field – superconducting solenoid

Neutron guide
Diam. 80mm



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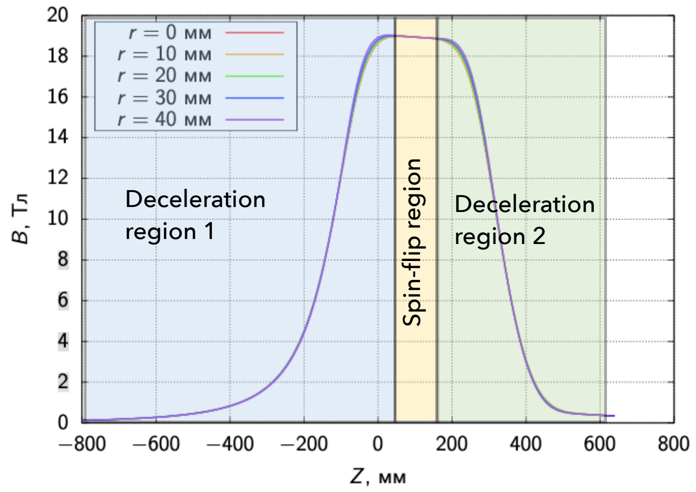

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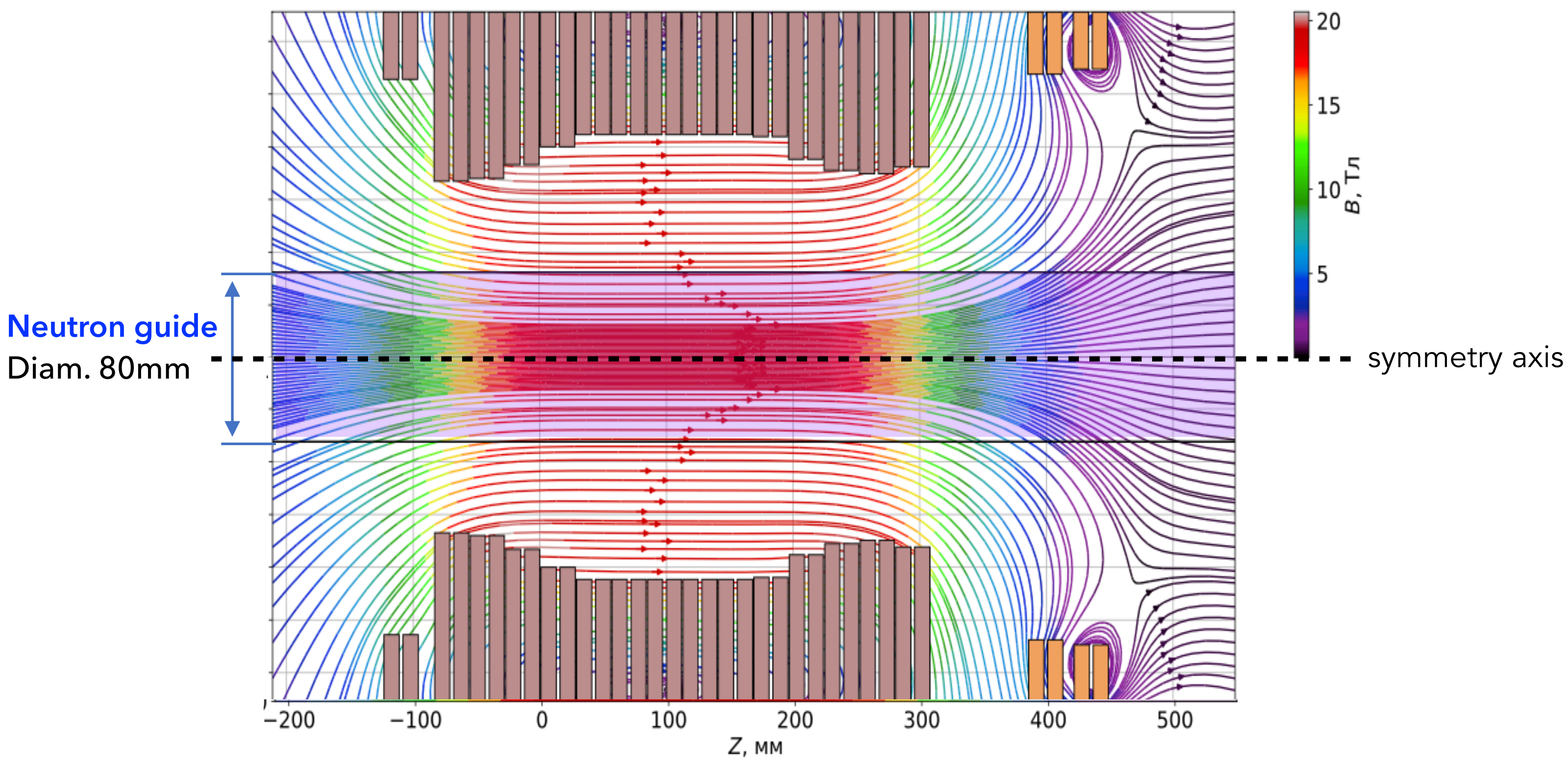

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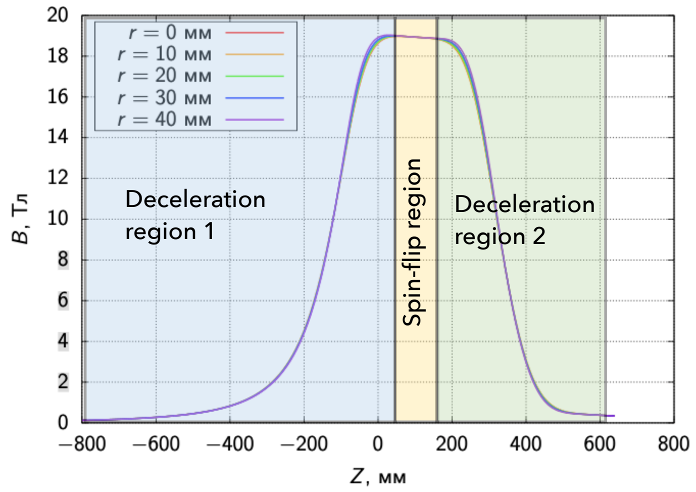
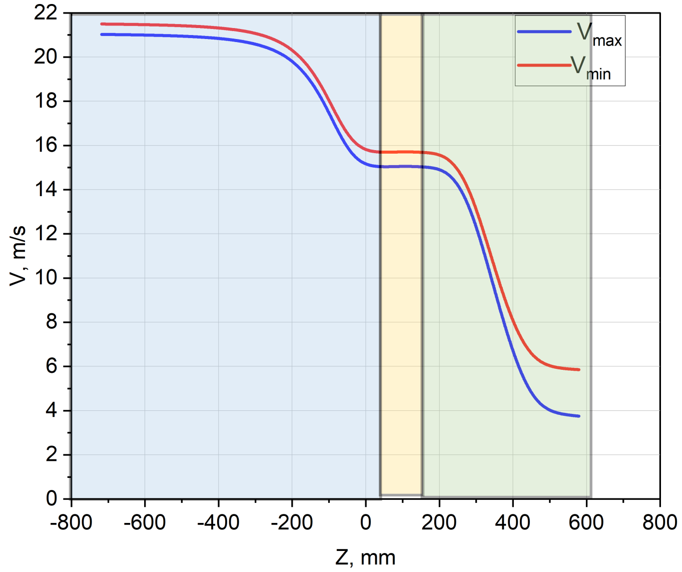
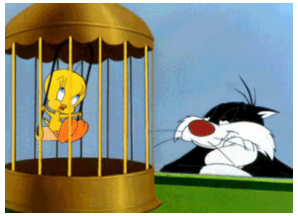


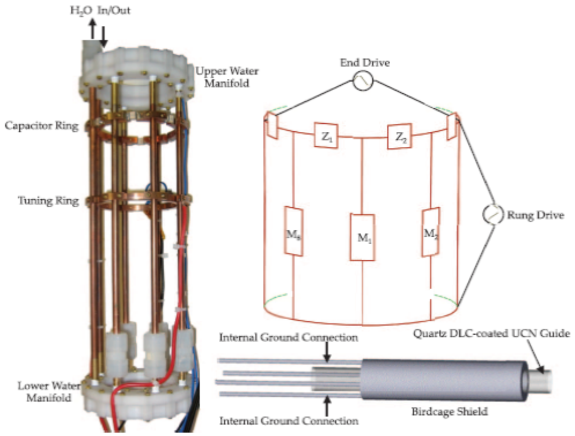


High frequency resonator



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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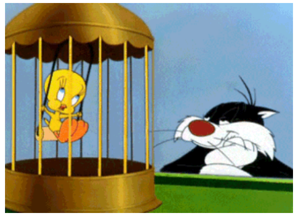

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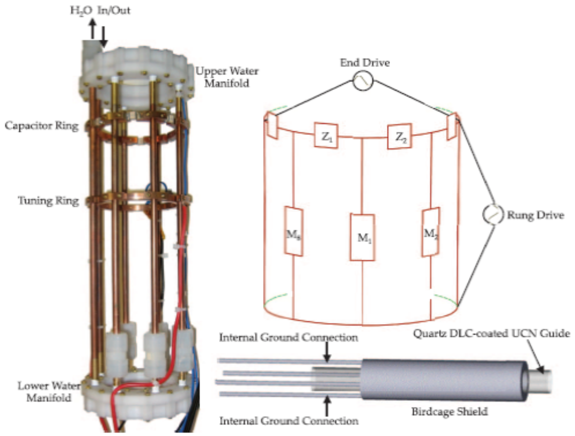

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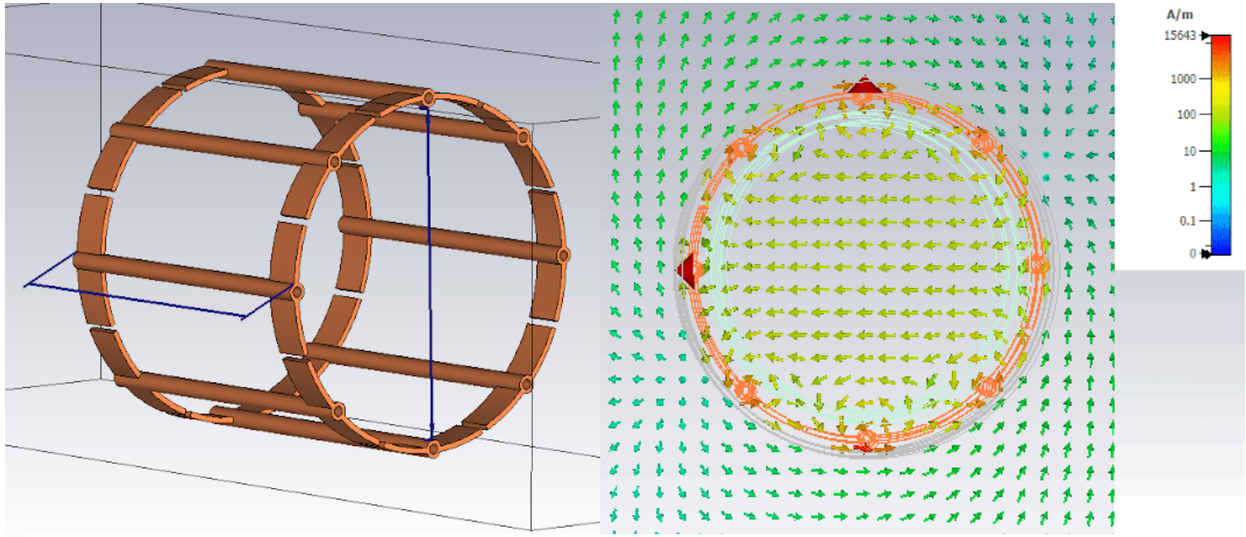
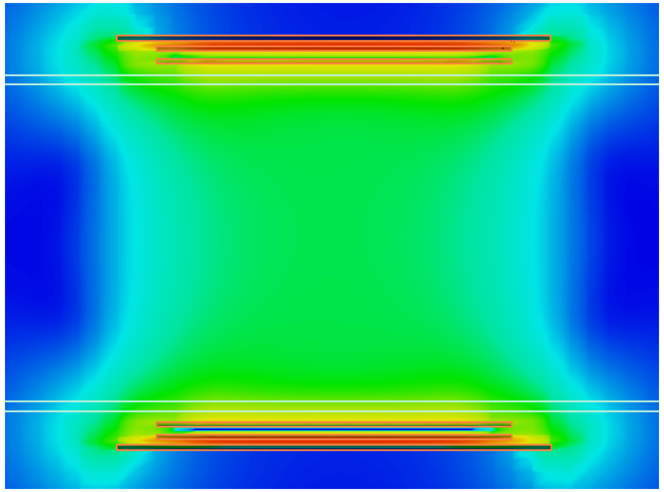
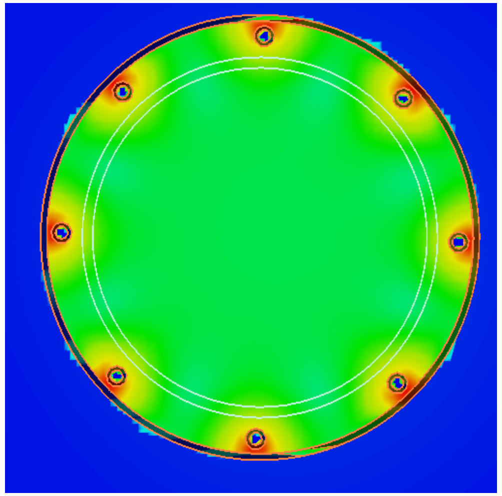


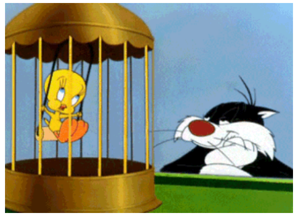




Q-factor $\approx 10^3$, $B_1 = 0.7$ mT, $f = 500$ MHz, Input power ≈ 4 kW

! The resonator will operate during the pulse only

High frequency resonator



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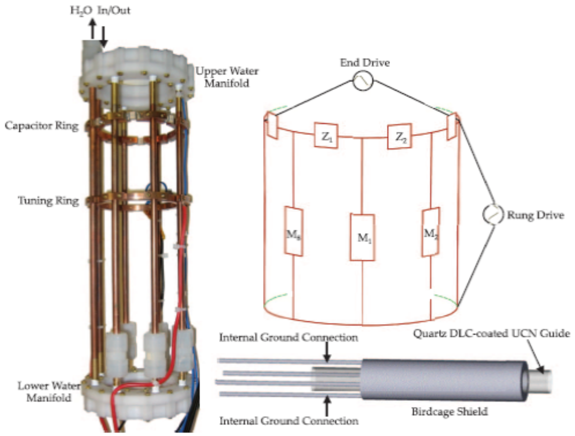

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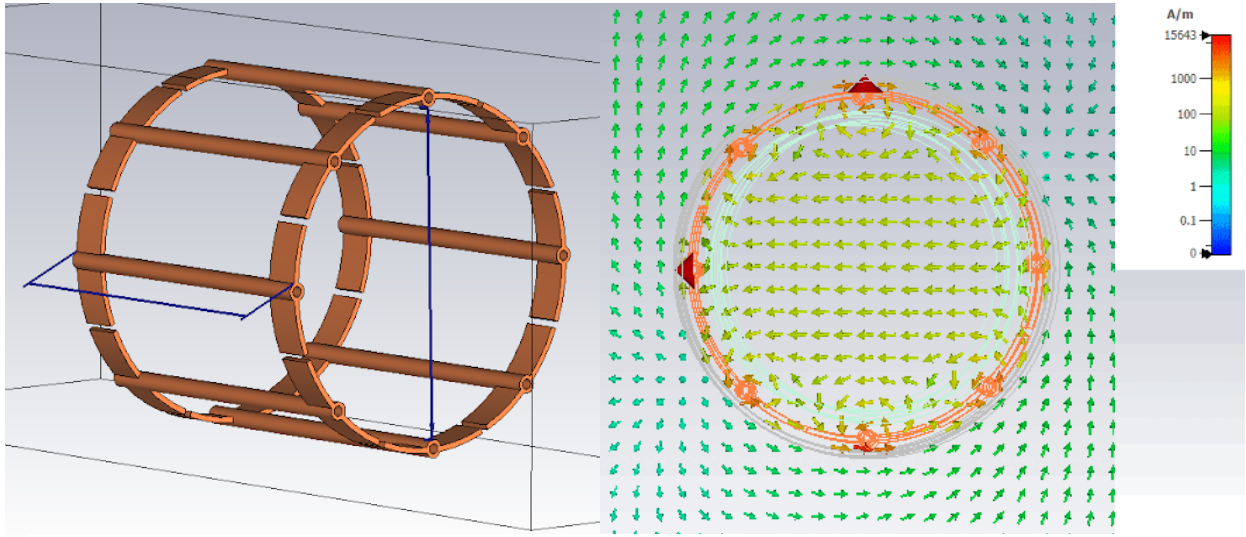

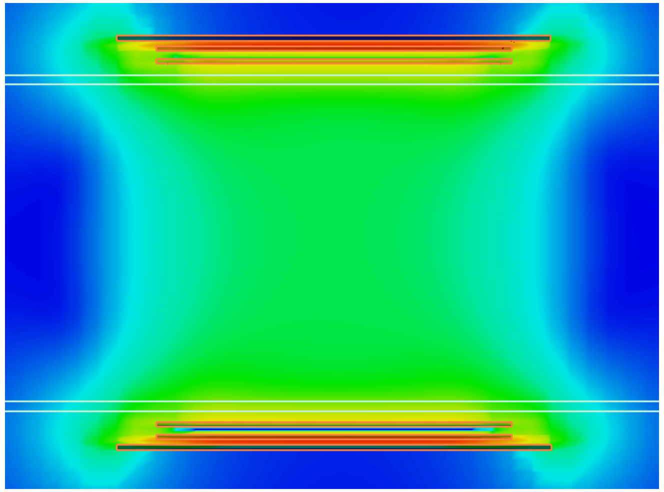

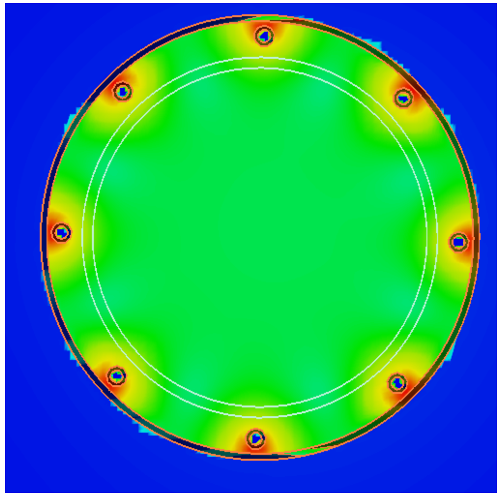

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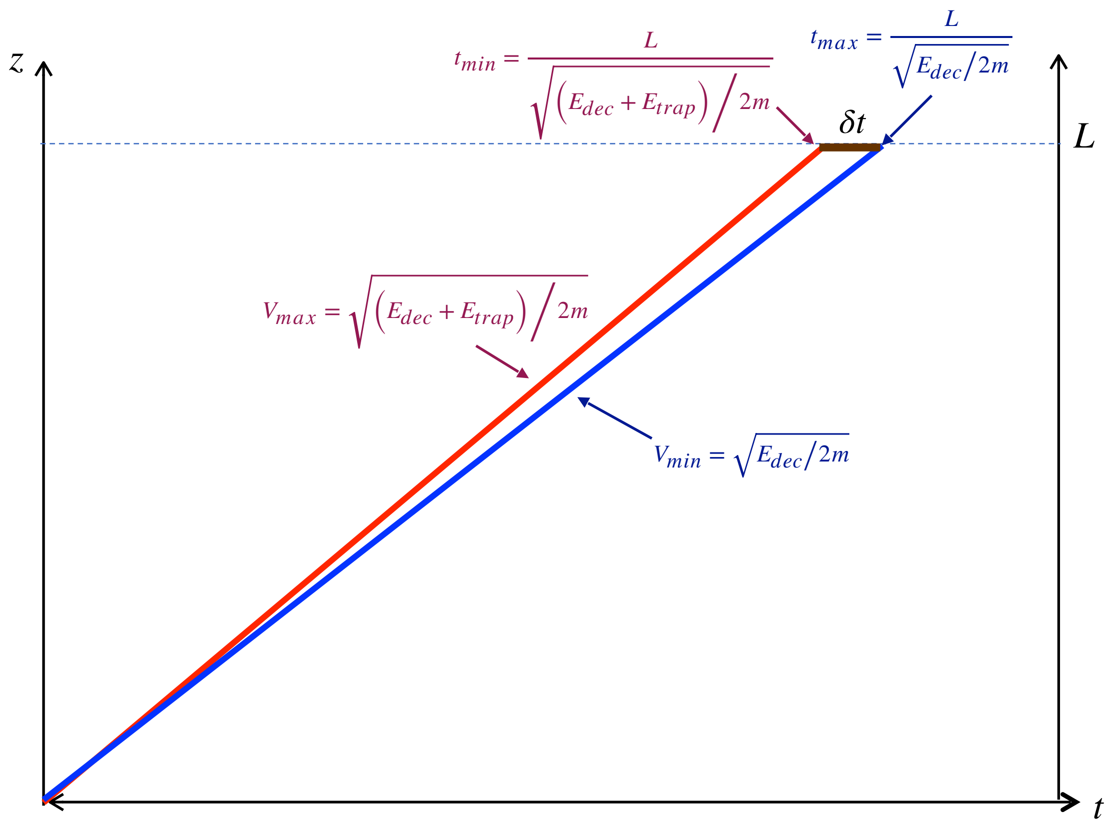

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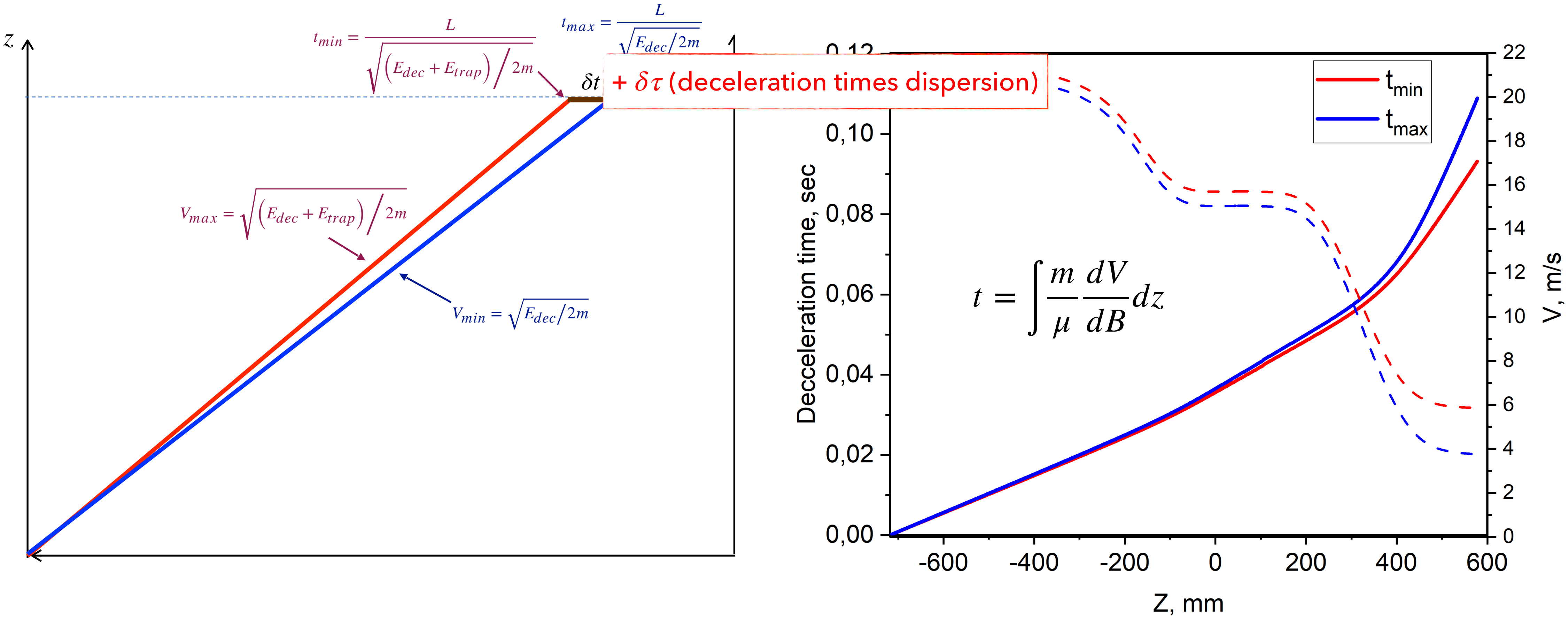
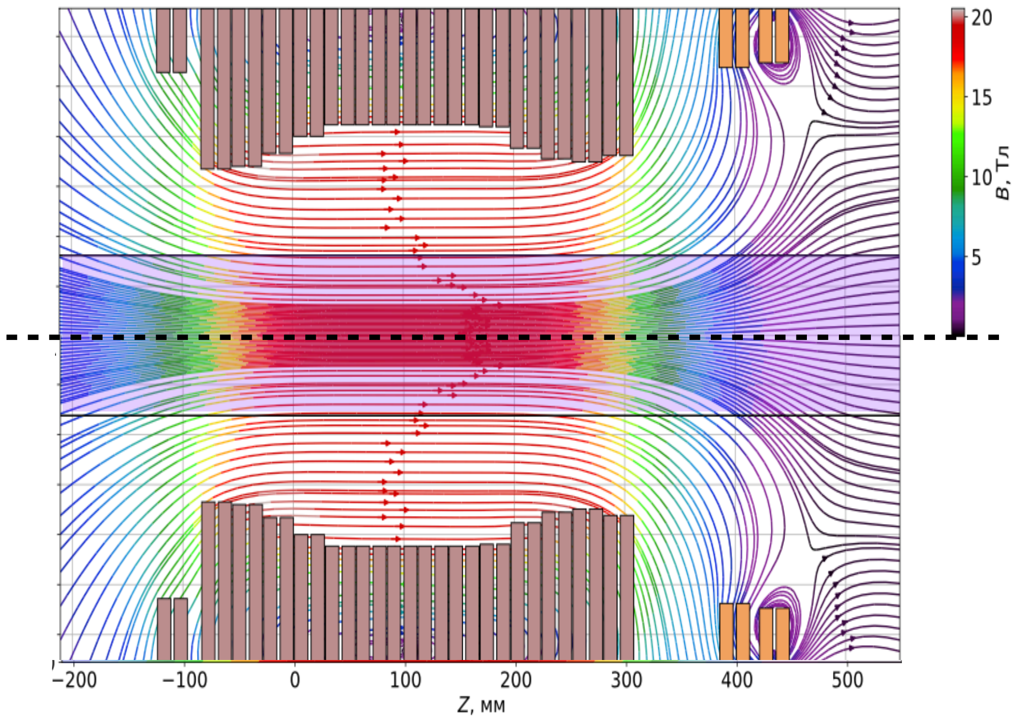
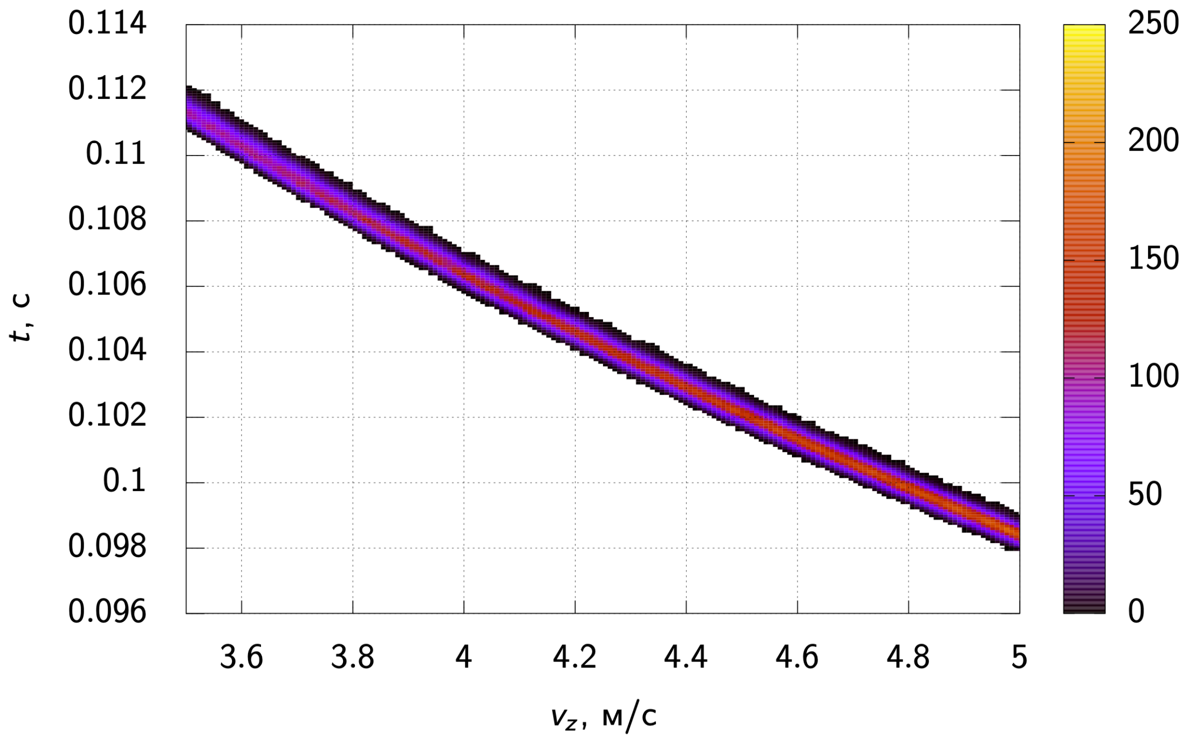


The slower the neutrons, the more time they spend on deceleration

Dispersion of deceleration times



rectangular neutron guide: 60 mm×60 mm



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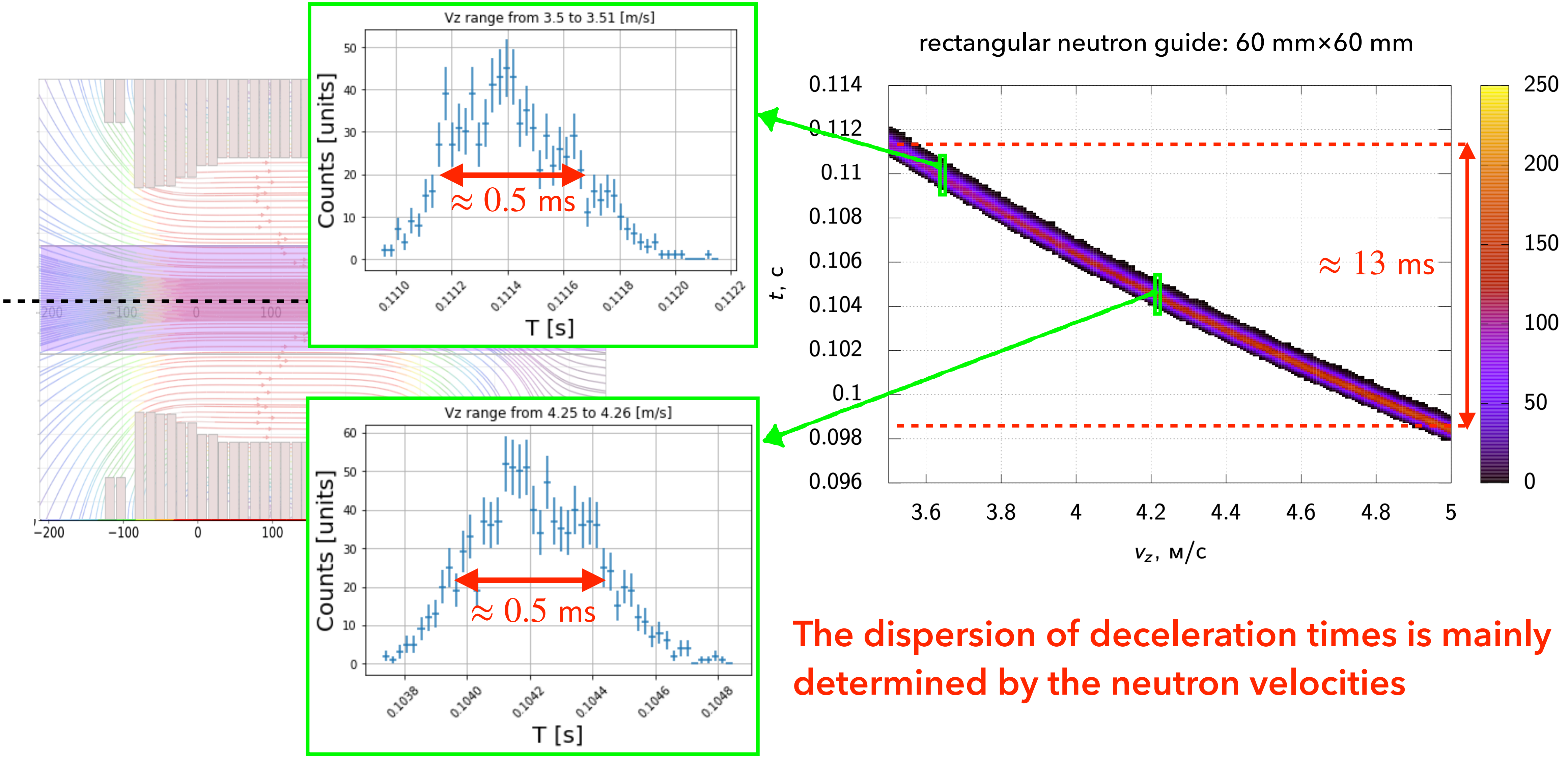
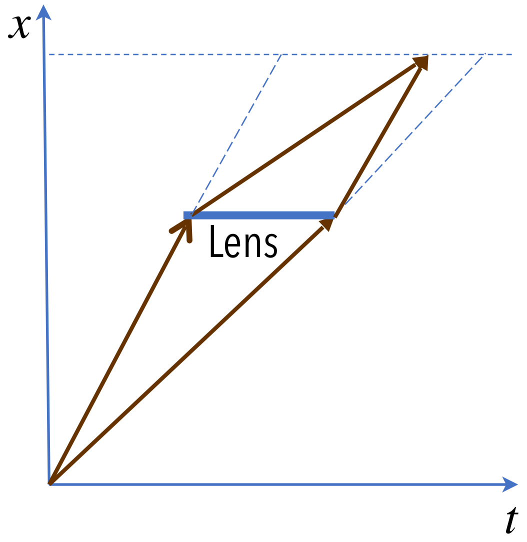
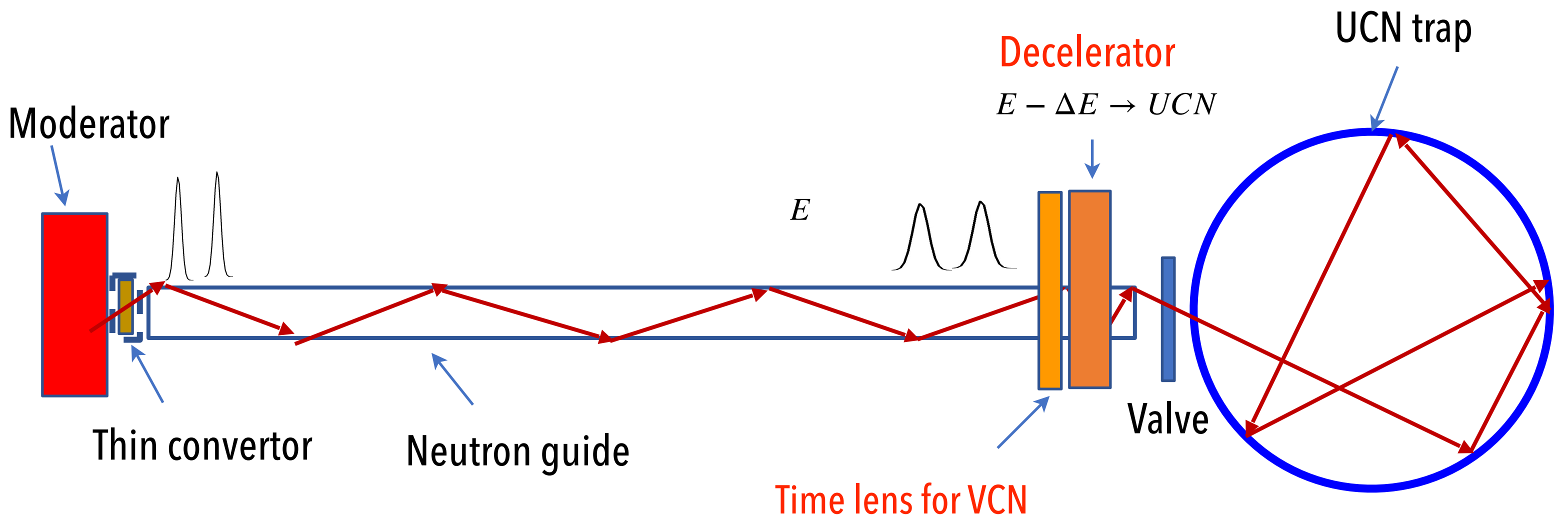


The dispersion of deceleration times is mainly determined by the neutron velocities

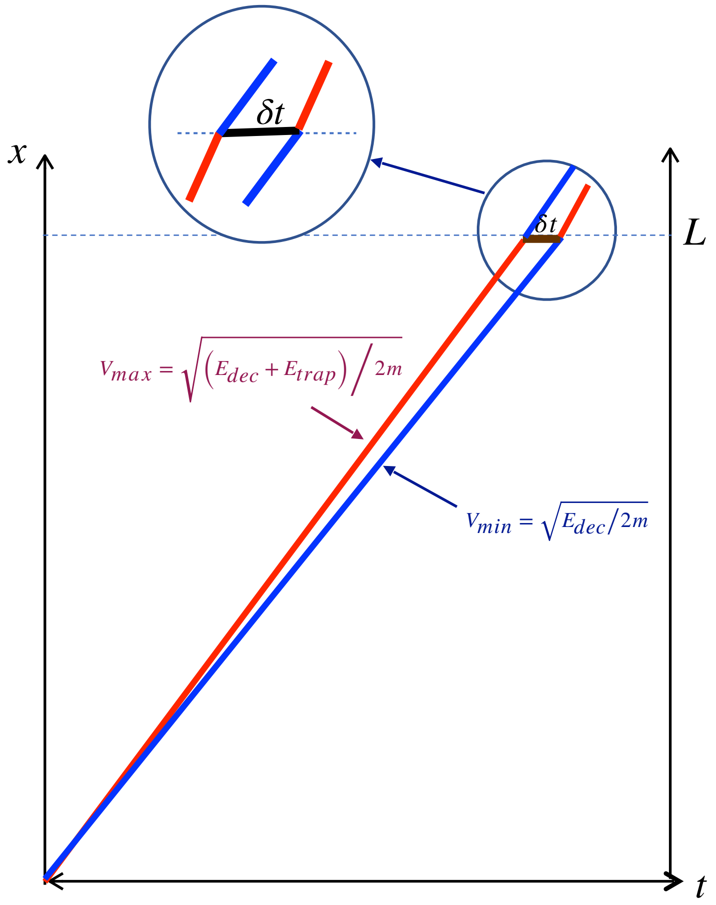
Time lens to compensate deceleration times dispersion



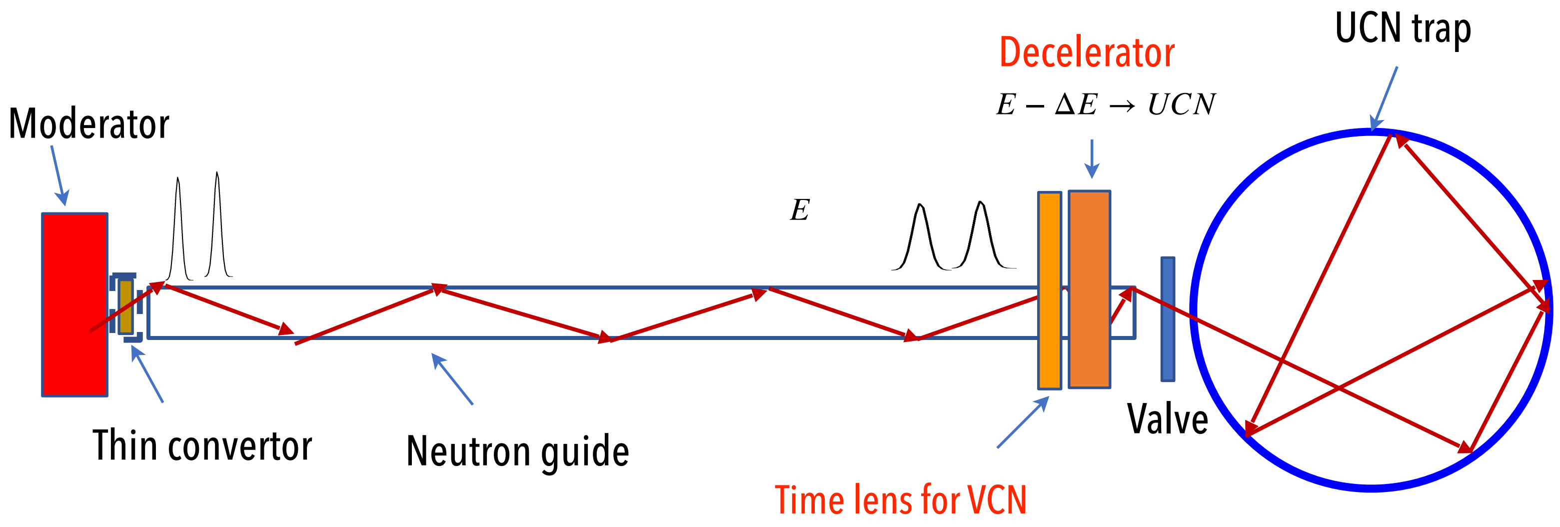
A.I. Frank and Gähler, ISINN-4, Dubna, 1996
A.I. Frank and R. Gähler. Phys. At. Nuc. 63, 545 (2000).



Time lens to compensate deceleration times dispersion



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



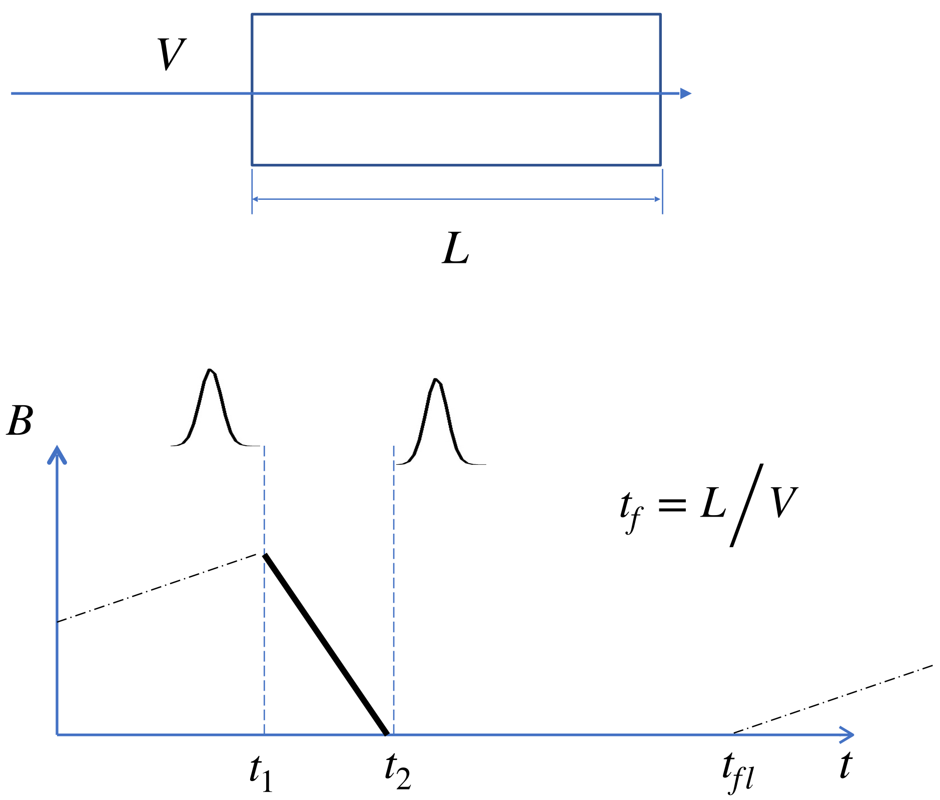
The time lens inverts the velocities in order to partially compensate the dispersion of the time of subsequent deceleration and to minimise bunch duration at the trap entrance

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

A time-dependent magnetic field lens

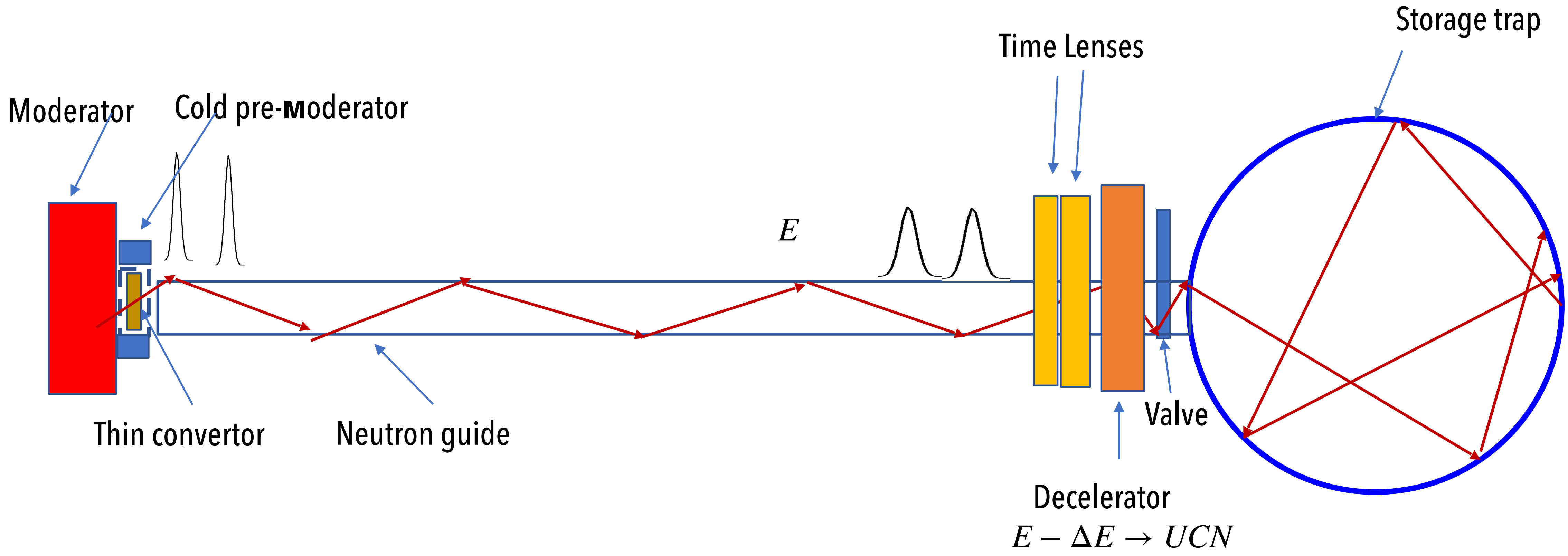
Neutrons change their energy when passing a homogeneous in space time-varying magnetic field

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



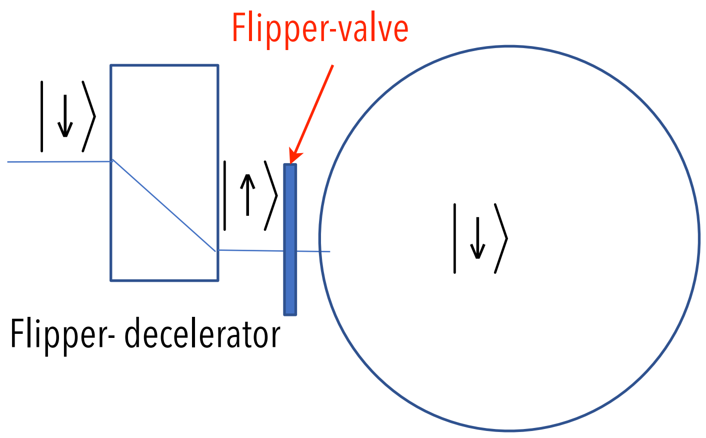
Time of flight of the bunch	$\Delta t = t_2 - t_1 \approx 10 - 15$ ms
Neutron velocity	$V \approx 20$ m/s
Lens length	$L \approx 40$ cm
Time of flight of the lens	$t_{fl} = 20$ ms
Repetition period	$T = 200$ ms
Magnetic field	$B = 1.5$ T

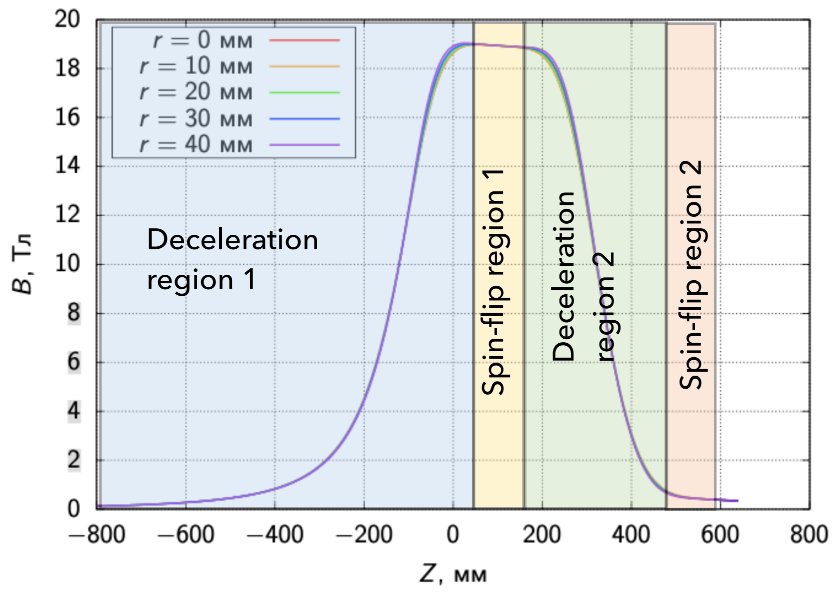
Most probable conception of UCN source @ periodic pulsed reactor



Pulsed valve

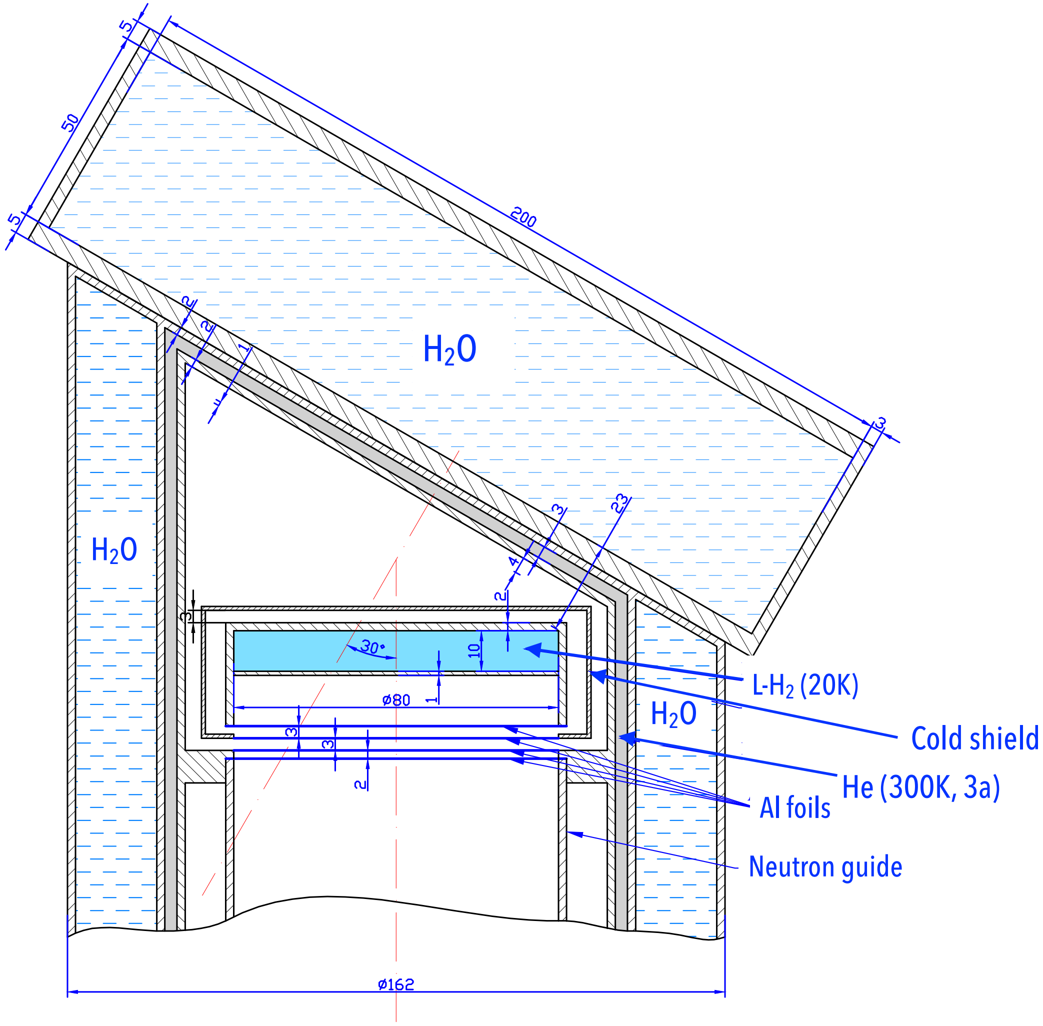
As a valve it is considered to use a gradient spin flipper, located in the area of decreasing of the flipper-decelerator field. Approximately in the 0.1-0.2T field





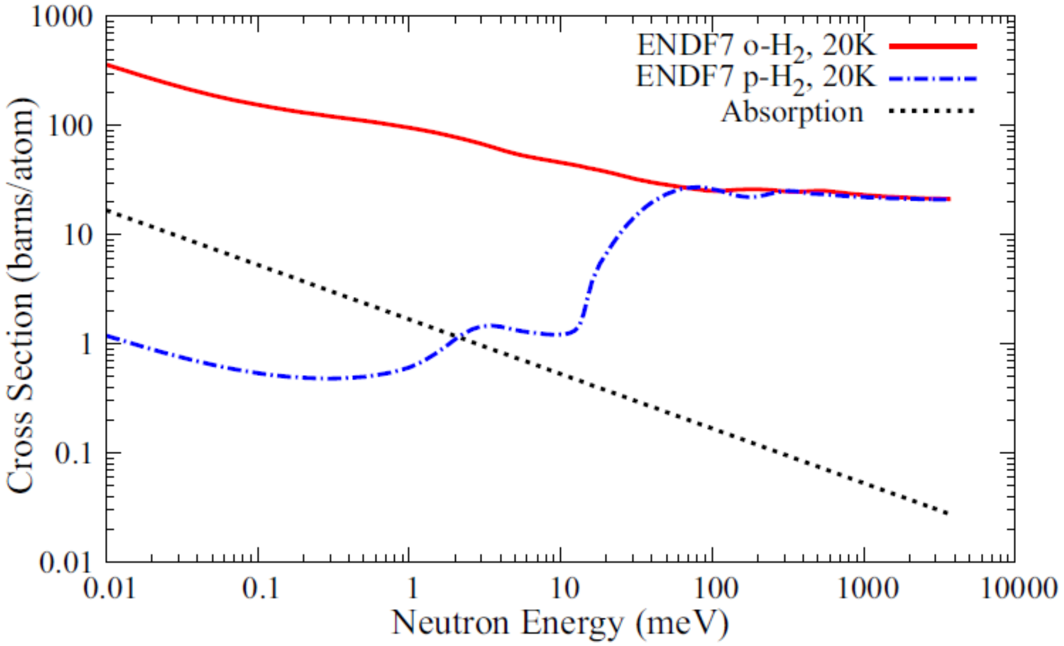
- Spin of polarised neutrons stored in the trap is oriented in such a way that the magnetic field of the flipper-decelerator is a barrier for them
- The high frequency of the flipper is applied only during the time of the arrival of the bunch. During this time, it passes neutrons in both directions

Liquid H_2 converter

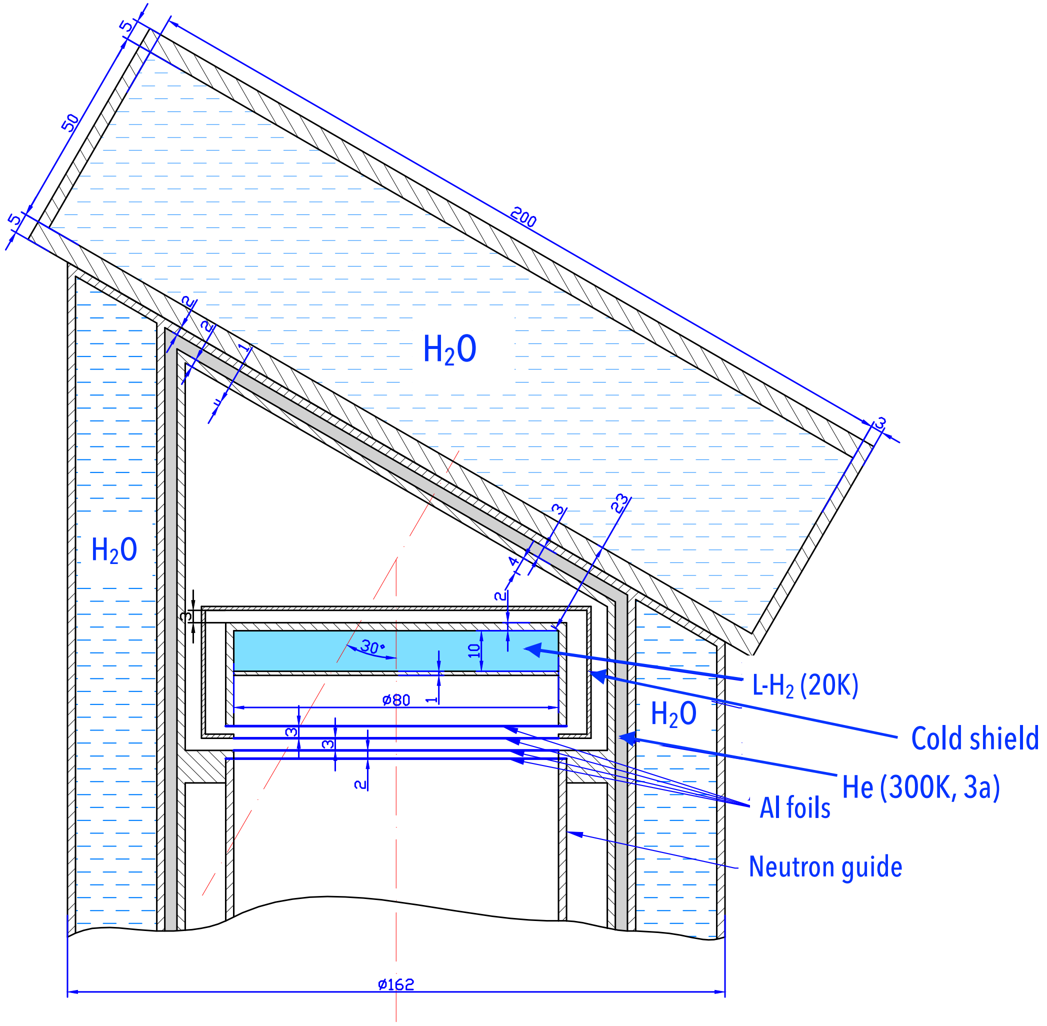


Designed by A.Yu. Muzychka

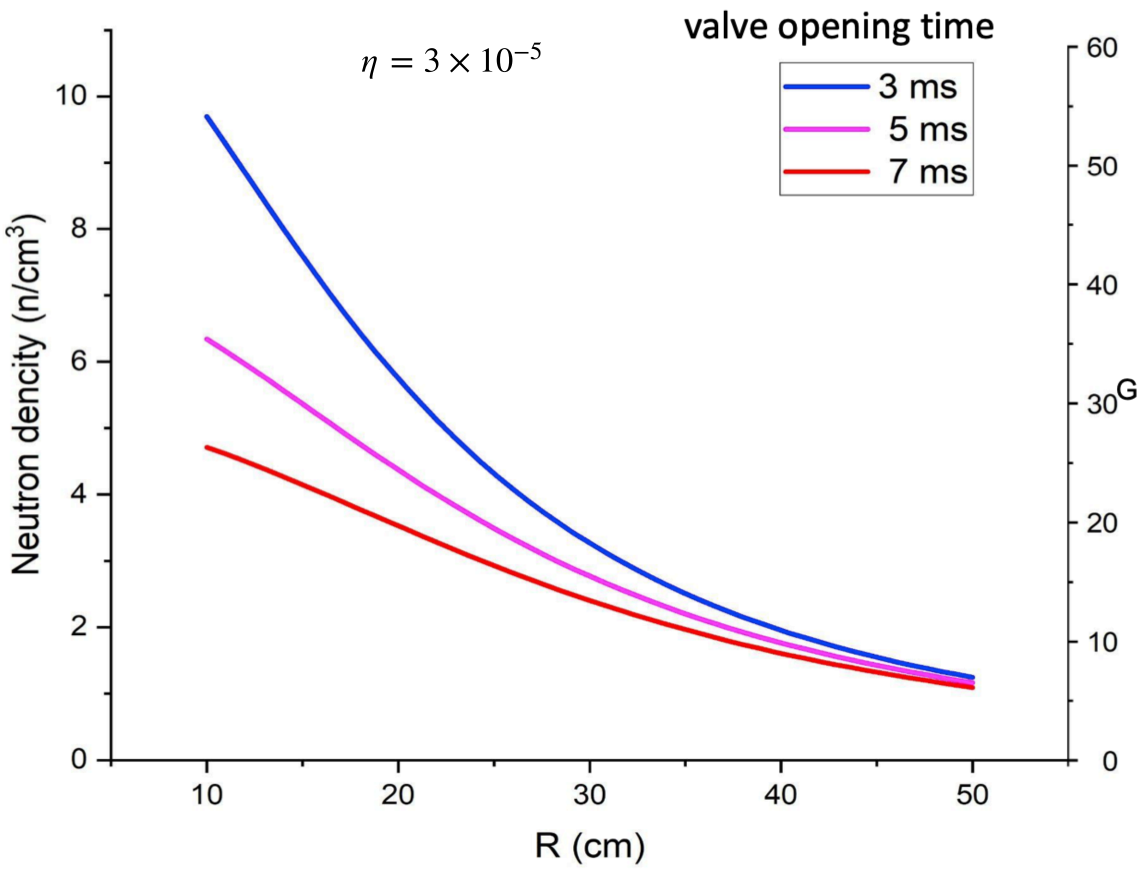
Scattering cross Section on H_2



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

Thanks for the discussions to V.N. Shvetsov, E.V. Lychagin, A. Yu. Muzychka, A.N. Chernikov, S.V. Gurskiy, S.V. Mironov and V.I. Bodnarchuk.

Special thanks to the staff of SuperOx company K.A. Baburin and V.I. Shcherbakov.

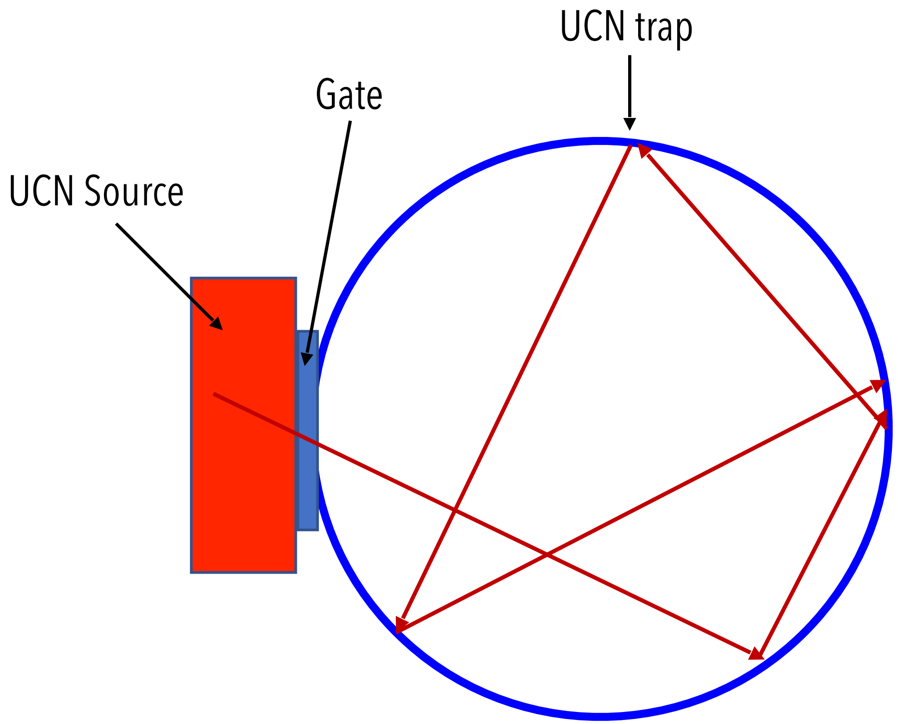
Thank you for your attention!!!

Parameters and results of calculation

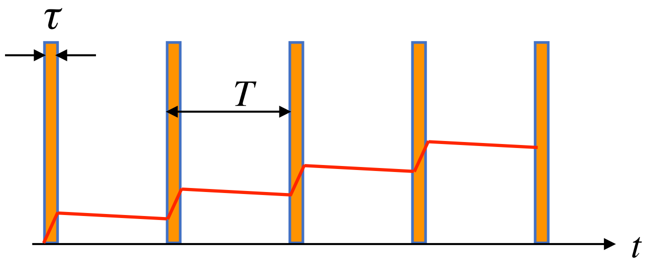
The boundary velocity of the neutron guide	5.9 m/s
Correlation length of the roughness	37 nm
The boundary velocity of the trap	6.9
Neutron guide transmission (NiV guide, losses only due to roughness)	0.78
Coefficient of losses in material the trap	3×10^{-5}
Velocity aperture of the lens	3.75 - 5.5 m/s
Pulse repetition period	200 ms
Pulse duration at the entrance to the trap	7-15 ms
Flux of thermal neutrons in the converter area	2×10^{12} n/cm²s
UCN flux (V<6.9 m/s) at a temperature of the spectrum of 400 K and G=1	14 n/cm²s
The fraction of the neutron flux captured by the neutron guide	0.62
The fraction of the flux transmitted by the lens	0.34
Full efficiency of the flux transmission without taking into account absorption in the neutron guide and pulse broadening due to the guide waviness	$0.78\times0.62\times0.34\times0.5=0.08$

Pulse source and UCN pumping in a trap

F.Shapiro, 1972



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



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

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

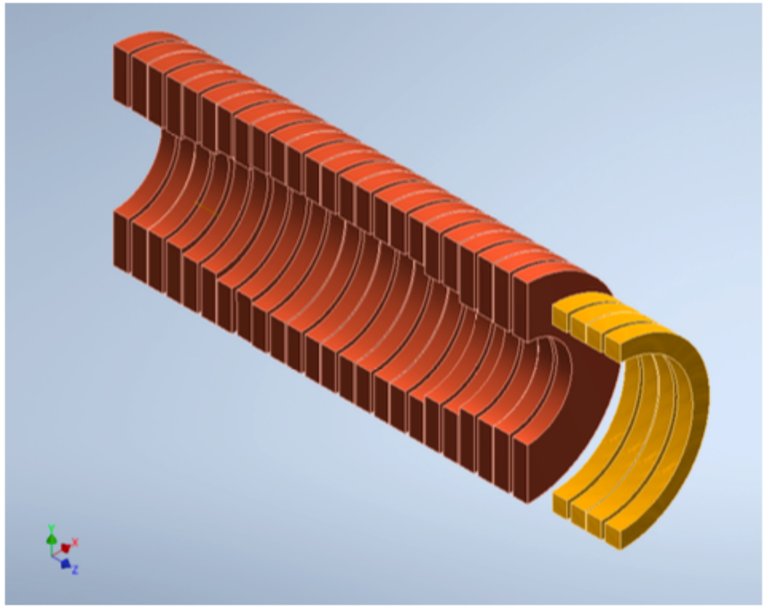
S – *active convertor area*

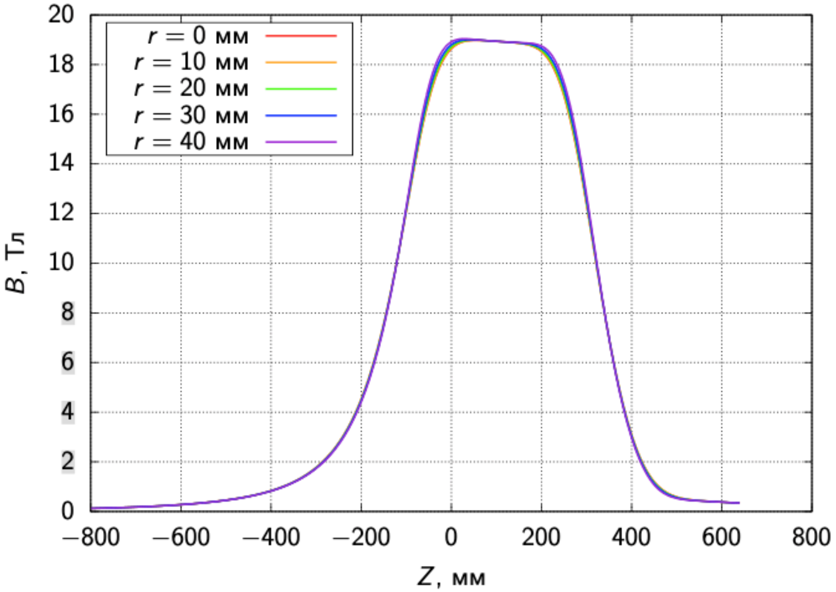
Σ – *area of the trap*

μ – *probability of the UCN lost*

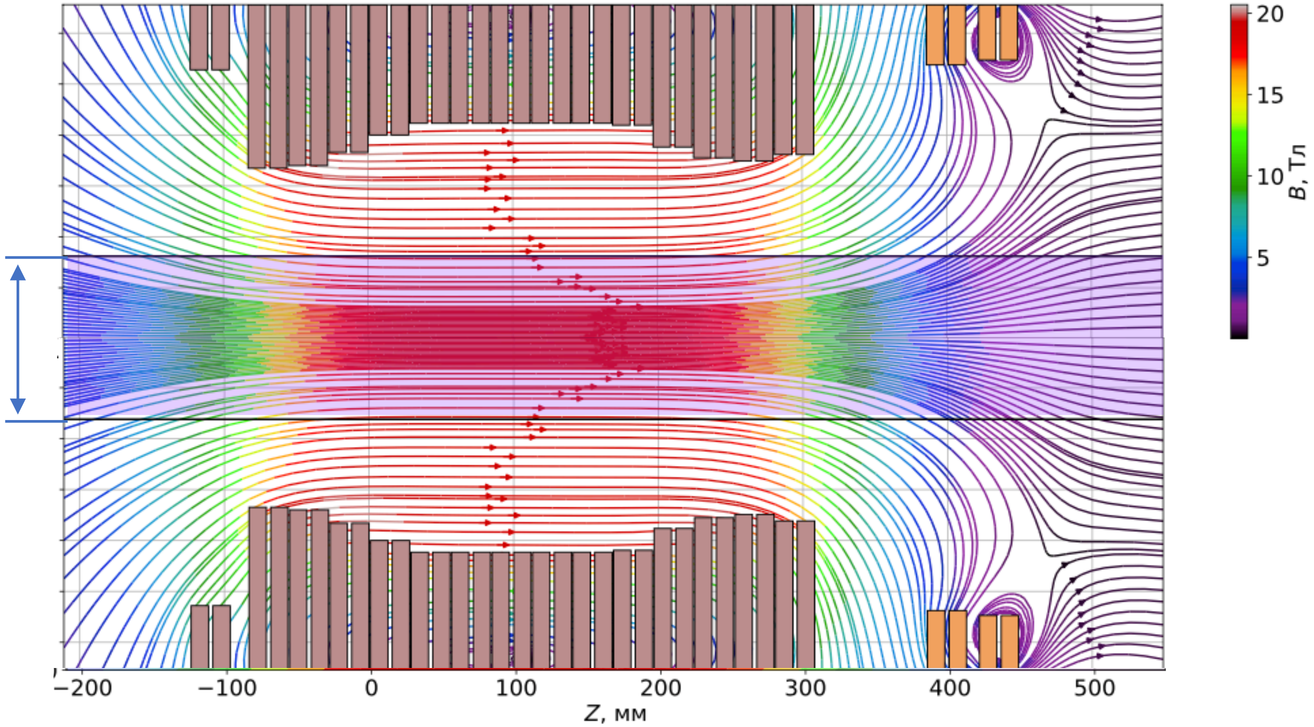
γ is gain factor which is ratio of pulse flux density accumulating in trap to flux density accumulating in trap from stationary source of average power

Stationary gradient field – 20T superconducting solenoid

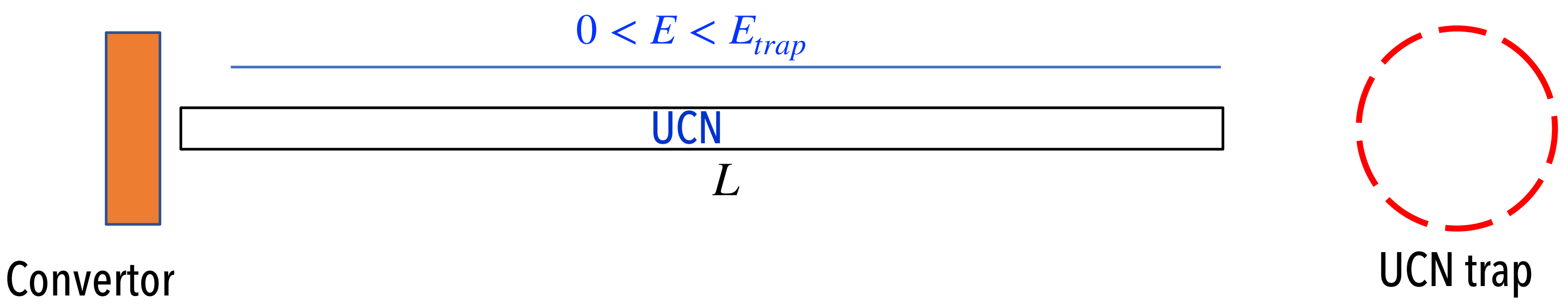




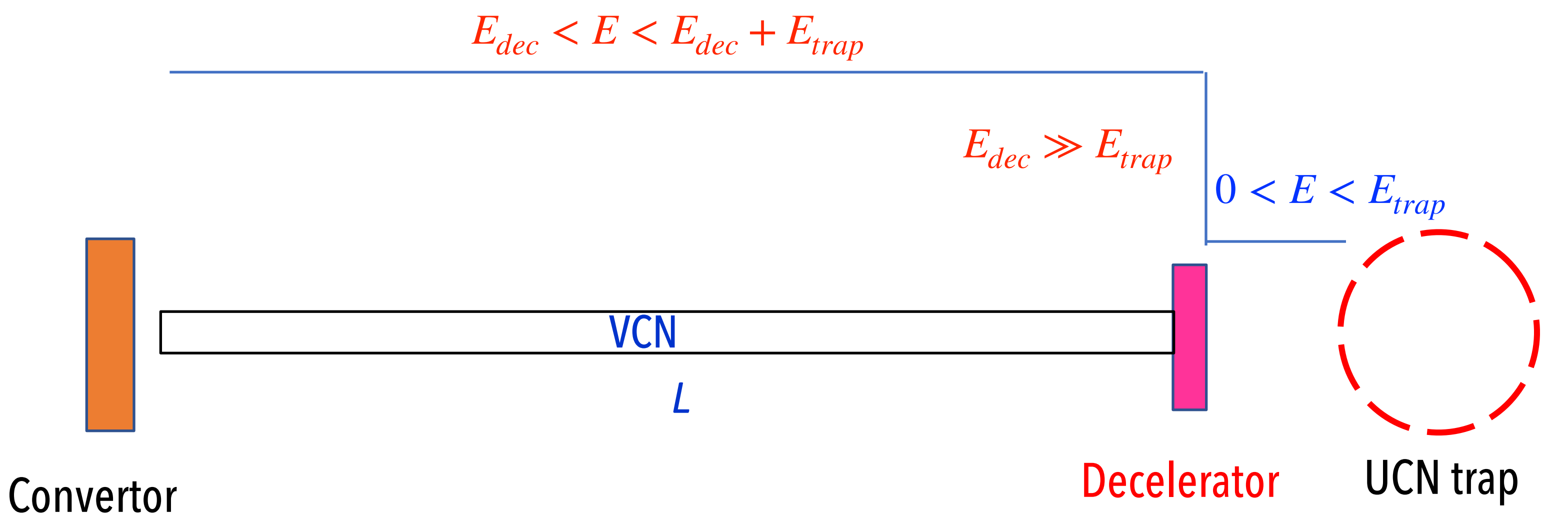
Neutron guide
Diam. 80mm



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



$$\Phi_1 = n\int_0^{\sqrt{E_{trap}/2m}} V_z dV_z = n\frac{E_{trap}}{2m}$$



$$\Phi_2 = n\int_{\sqrt{E_{trap}/2m}}^{\sqrt{(E_{trap}+E_{dec})/2m}} V_z dV_z = n\frac{E_{trap}}{2m}$$

$$\Phi_1 = \Phi_2$$

Assumptions:

- the deceleration time is the same for all neutrons
- converters and transport conditions are identical

Neutron rebunching – magneto-resonant change of a neutron energy

Physics of Atomic Nuclei, Vol. 63, No. 4, 2000, pp. 545–547. Translated from Yadernaya Fizika, Vol. 63, No. 4, 2000, pp. 605–608.

IN MEMORIAM
OF F. L. SHAPIRO

Time Focusing of Neutrons

A. I. Frank* and R. Gähler[1)]
Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia
Received October 14, 1999

Abstract—The possibility of time focusing for very slow neutrons is considered. This focusing may prove very useful in solving the problem of accumulating ultracold neutrons in a trap that are generated by a pulsed source. Diffraction at a phase grating moving across a beam or resonance neutron-spin flip is proposed to implement time-controlled changes in the neutron energy. © 2000 MAIK *"Nauka/Interperiodica"*.

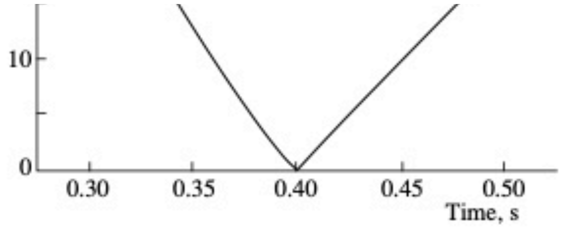


Fig. 2. Frequency of a quantum modulator as a function of time after the source burst.

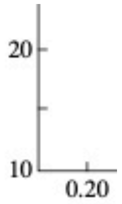


Fig. 3. Ma... moderatio...

Another attractive possibility is based on resonance neutron-spin flip in a magnetic field [10]. Upon traversing a volume where there are a slowly changing field $B(t)$ and a radio-frequency field orthogonal to it and where the resonance condition ensuring spin flip is permanently satisfied, neutrons change energy by $\hbar\omega_r(t)$, where $\omega_r(t)$ is the frequency of the radio-frequency field.

A. I. Fra... for stimula... here and so...

1. F. L. Sh... p. 229.

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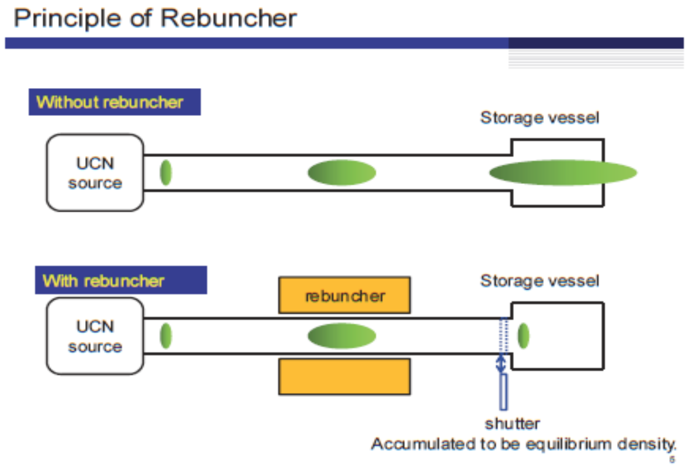
Physics Procedia 17 (2011) 20–29
Physics Procedia
Physics of Fundamental Symmetries and Interactions – PSI2010

Longitudinal-gradient magnet for time focusing of ultra-cold neutrons

Y. Arimoto[a], T. Yoshioka[a], H. M. Shimizu[a], K. Mishima[a], T. Ino[a], K. Taketani[a], S. Muto[a], M. Kitaguchi[b], S. Imajo[c], Y. Iwashita[d], S. Yamashita[e], Y. Kamiya[e], A. Yoshimi[f], K. Asahi[g], T. Shima[h], K. Sakai[i]



PHYSICAL REVIEW A **86**, 023843 (2012)

Demonstration of focusing by a neutron accelerator

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Department of Physics, Kyoto University, Kitashirakawa, Kyoto 606-8502, Japan

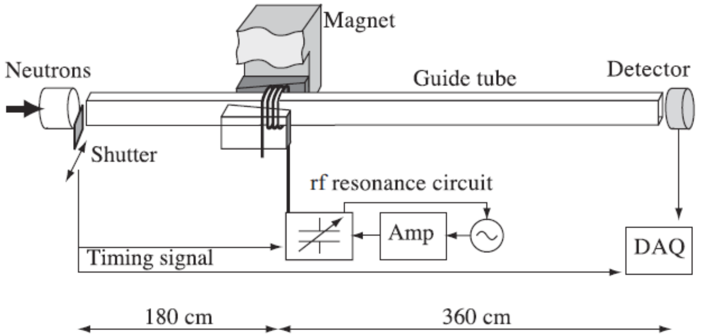
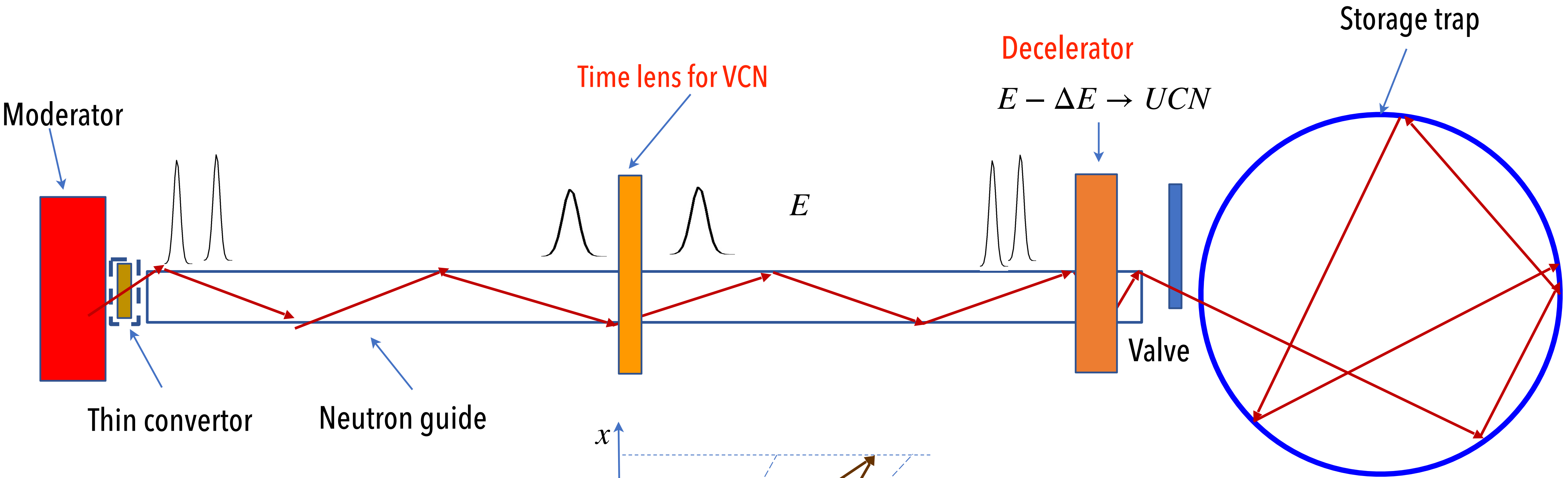
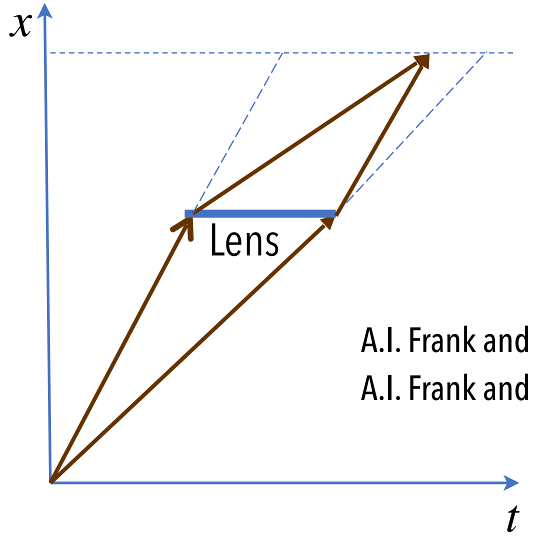


FIG. 2. Experimental setup. The neutron accelerator is installed in the middle of the guide tube. The rf and data acquisition systems are synchronized with the shutter operation.

Time lens to minimise the bunch duration at the Decelerator

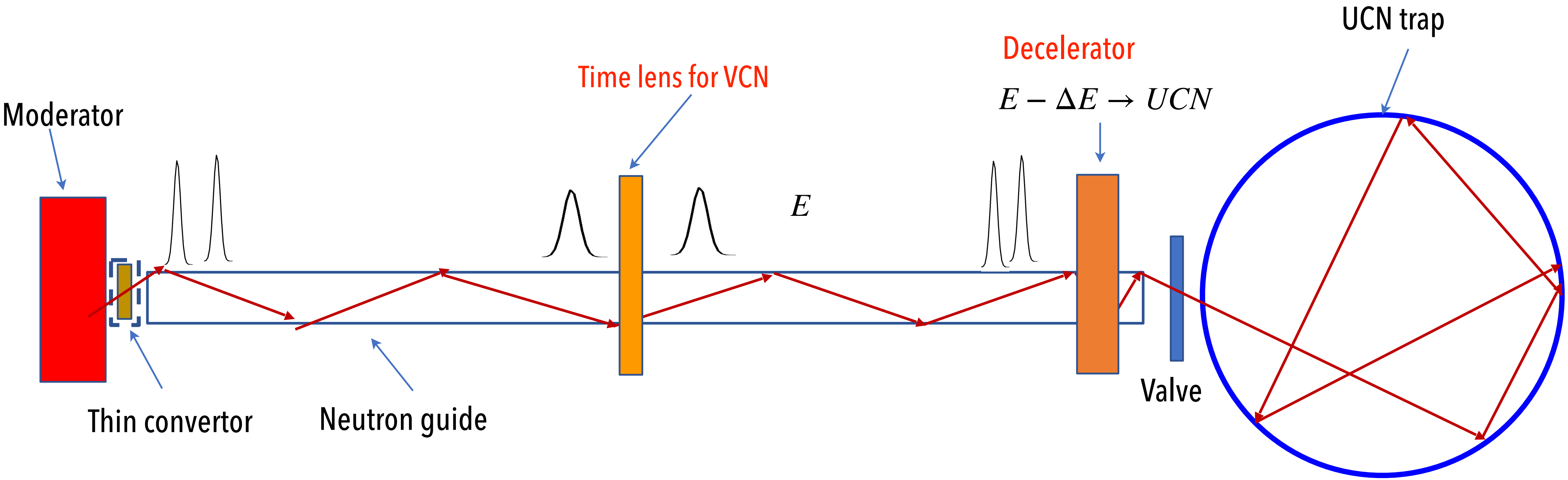




A.I. Frank and Gähler, ISINN-4, Dubna, 1996

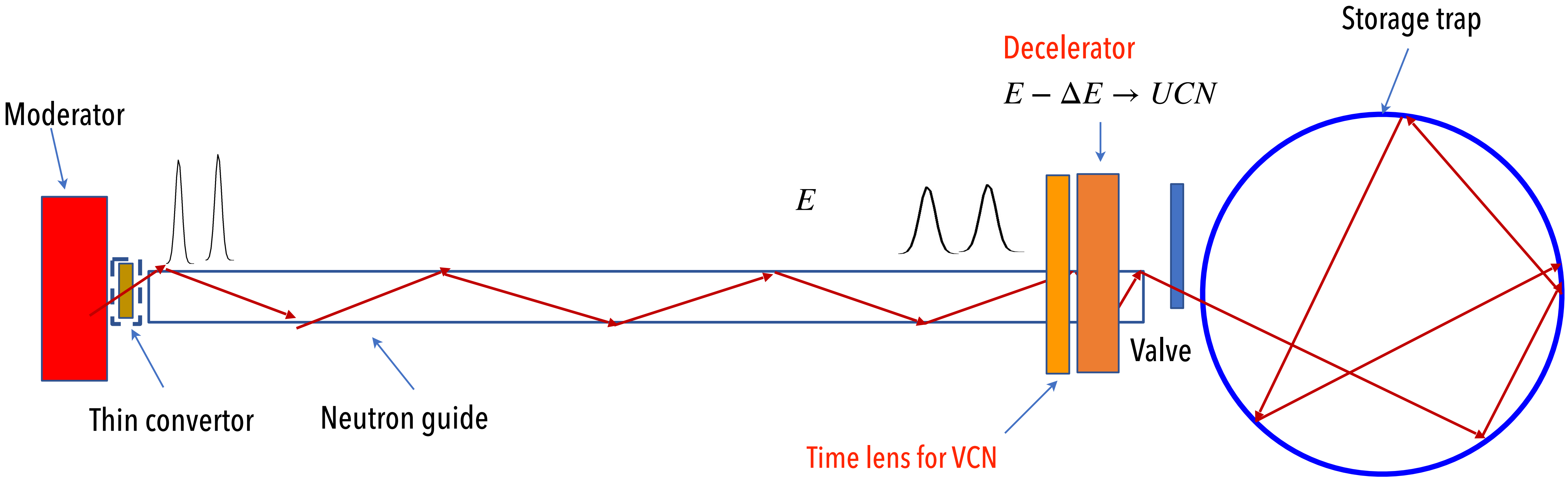
A.I. Frank and R. Gähler. Phys. At. Nuc. 63, 545 (2000).

Time lens to minimise the bunch duration at the Decelerator



! Problem of deceleration times dispersion still remains

Time lens to compensate deceleration times dispersion and to minimise bunch duration at the trap entrance



Main parameters of the source

1.	Converter	Undefined
3	Channel length	15 m
4	Diameter of the neutron guide	8 cm (limited by the diameter of the "warm" area of the flipper-decelerator)
5	Flipper-decelerator	Adiabatic
6	Magnetic system of the flipper-decelerator	Superconducting solenoid with a magnetic field of 15T
7	High frequency resonator	Birdcage type resonator with a frequency of 430 Mhz and a Q-factor of about 500
8	Inverting lens	Neil-Rauch type lens with a magnetic field of 1.5T
9	Pulsed valve	Adiabatic (?) spin flipper in the residual field 0.1-0.2T of the flipper-decelerator
10	Storage volume	The size is not defined. Most likely with a DLC coating
11	Duration of the bunch of "useful" neutrons at the entrance to the flipper-decelerator	T1. It is determined by the length of the channel, the value of the magnetic field of the flipper-decelerator and the spectrum of stored UCNs
12	The dispersion of the deceleration time	T2
13	Duration of the bunch at the trap entrance	The goal value is 10 ms. Determined by the time difference T2-T1

Problems

1. The choice of a converter and, possibly, a pre-moderator.
2. The problem of neutron transport with conservation of the longitudinal velocity component. The problem of waviness.
3. A trap with a low probability of loss and depolarization
4. Optimisation of the flipper in order to reduce the deceleration time dispersion and, as a consequence, the duration of the bunch

To the UCN source at periodic pulsed reactor

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