The concept of an UCN source for a periodic pulsed reactor

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

ISINN-29

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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

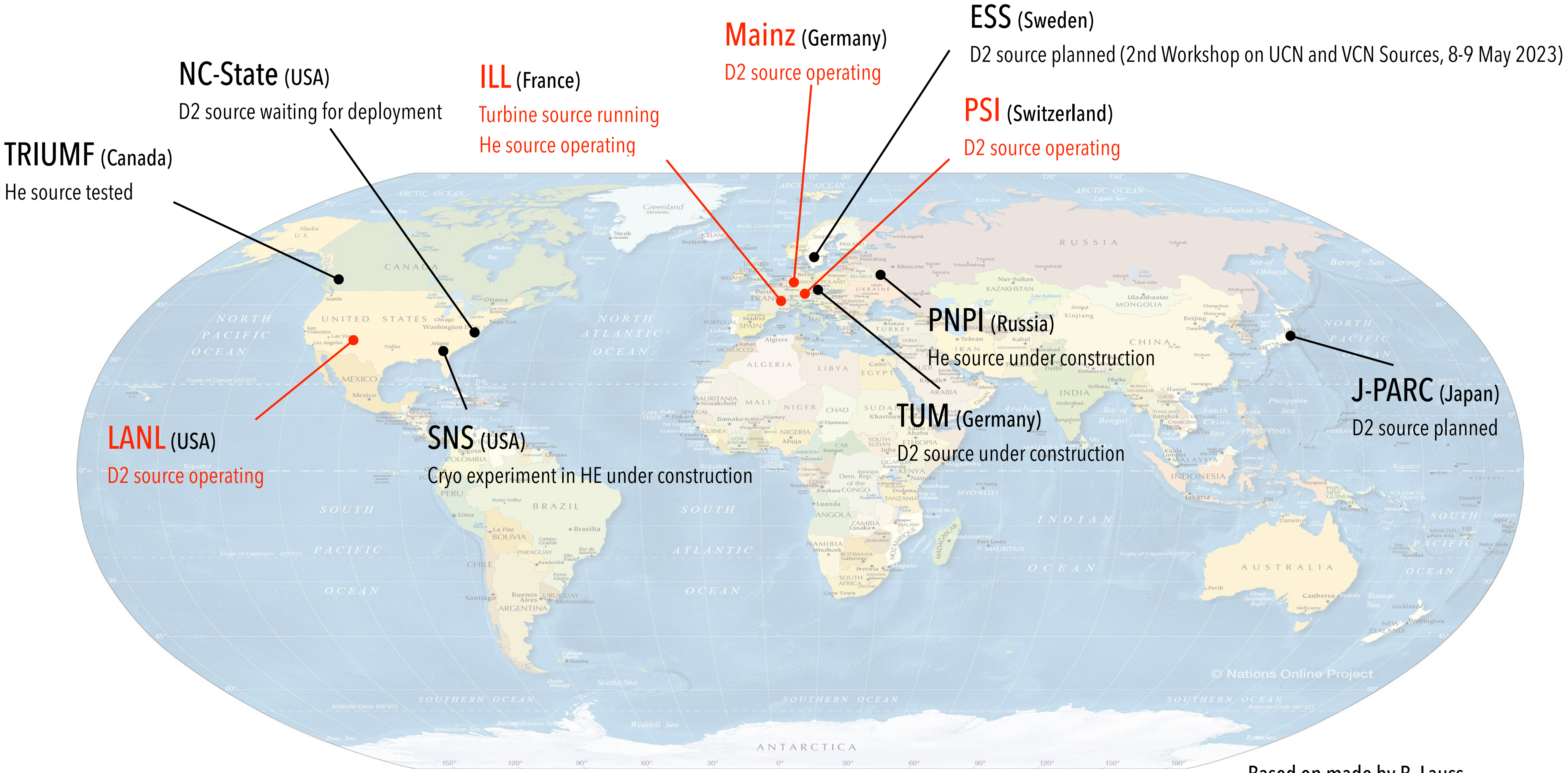
Measurement of angular correlation coefficients of neutron beta decay

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

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

Письма в ЖЭТФ

Т. 9 1969 Вып. 1

30

НАБЛЮДЕНИЕ УЛЬТРАХОЛОДНЫХ НЕЙТРОНОВ

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

1969

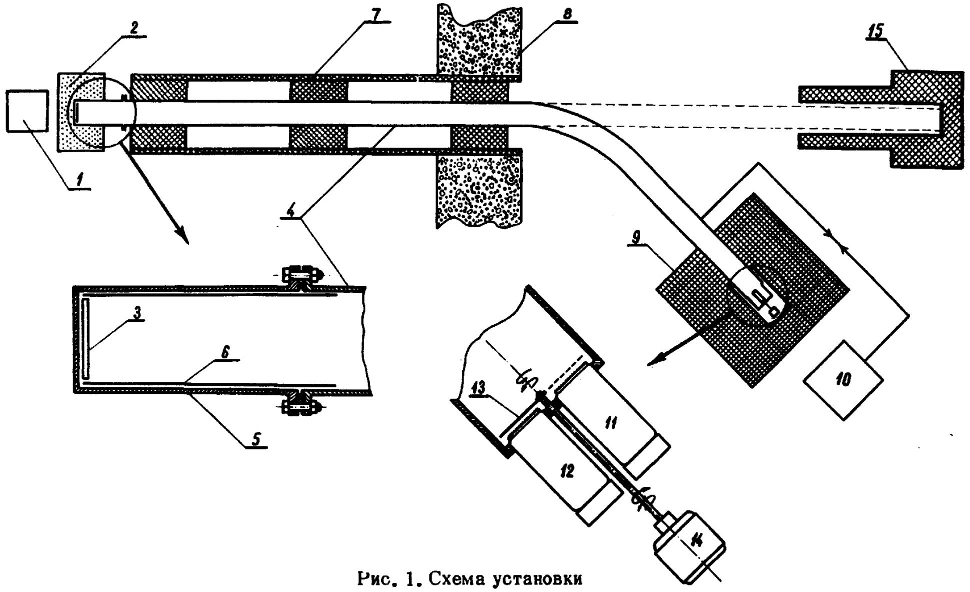
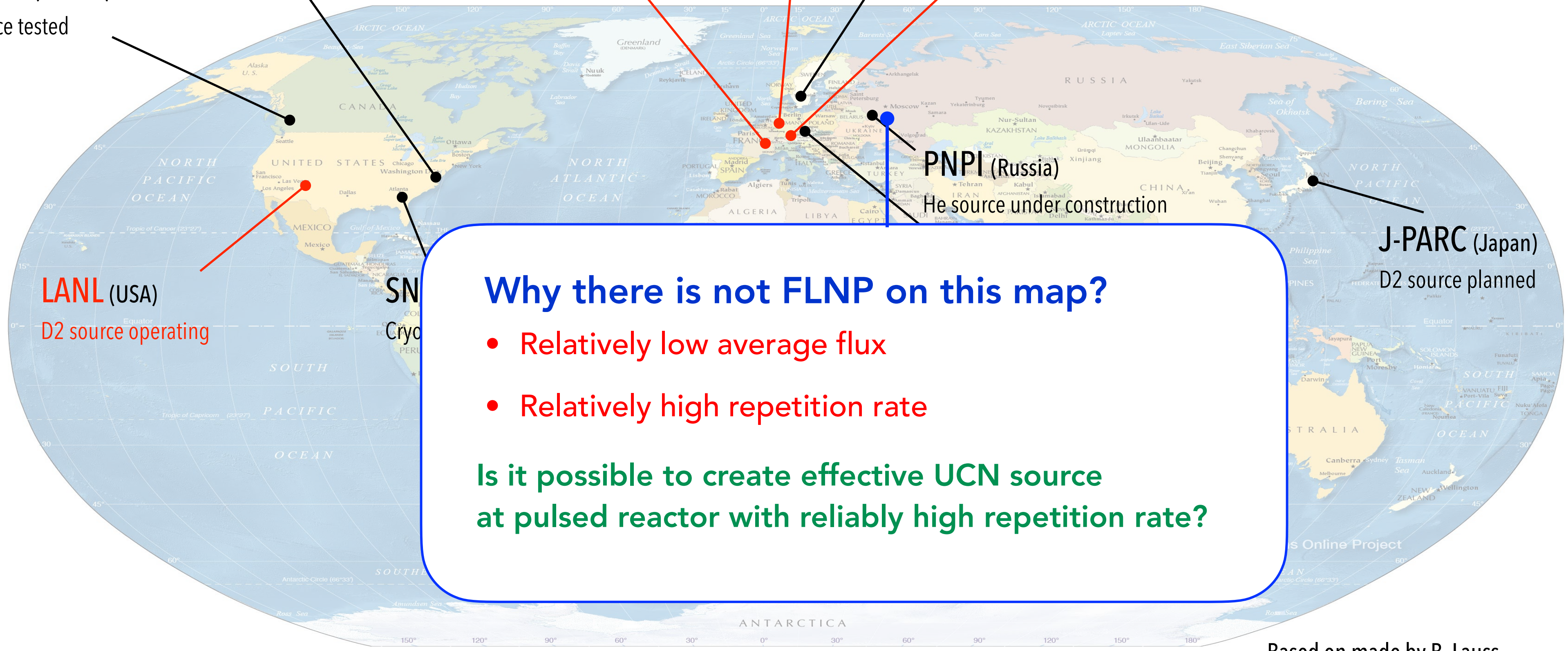


Рис. 1. Схема установки

Ultra Cold Neutron sources



Why there is not FLNP on this map?

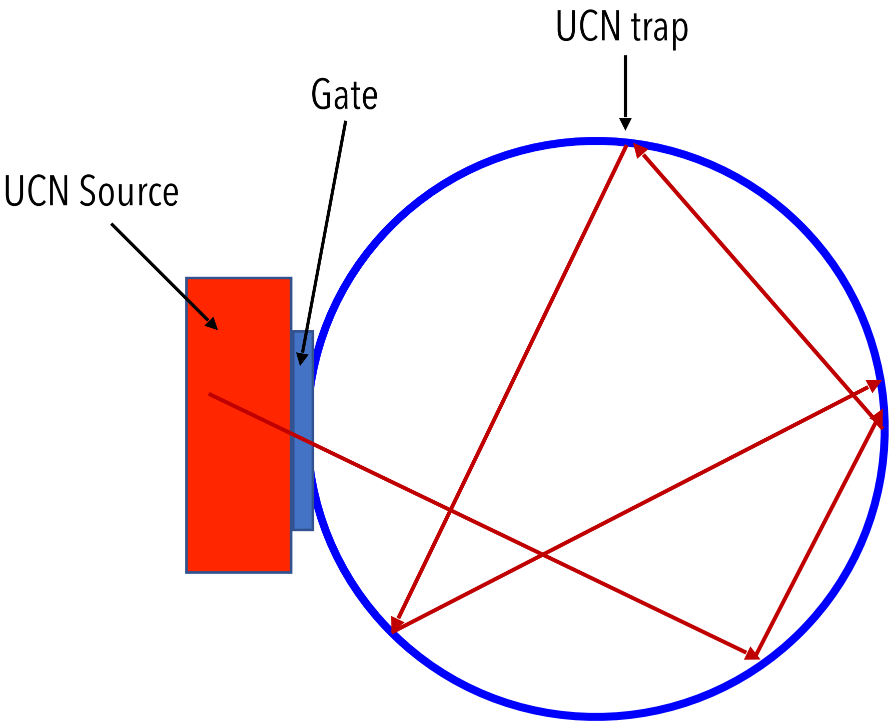
- Relatively low average flux
- Relatively high repetition rate

Is it possible to create effective UCN source at pulsed reactor with reliably high repetition rate?

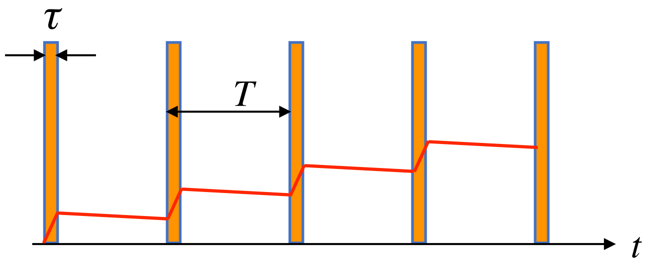
Based on made by B. Lauss

Pulse source and UCN pumping in a trap

F.Shapiro, 1972



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



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

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

S – *active convertor area*

Σ – *area of the trap*

μ – *probability of the UCN lost*

Pumping option of the pulsed source – time lens

The trap is remote from the moderator due to the presence of biological shielding → the spread of the UCN flight times will exceed the intervals between pulse

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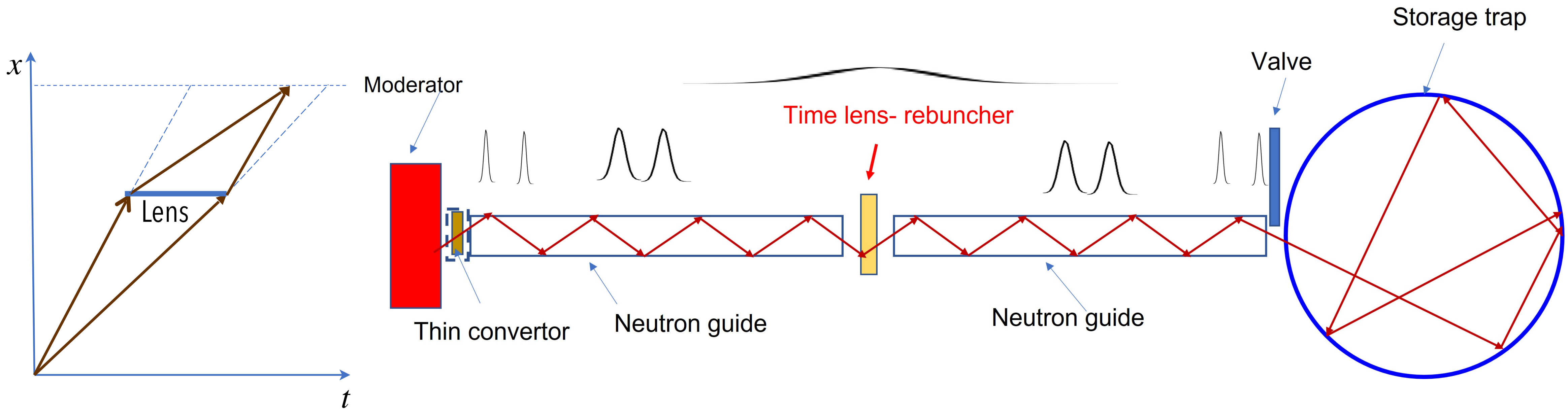
Solution: Time lens which forms a time image of the source directly near the trap



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

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

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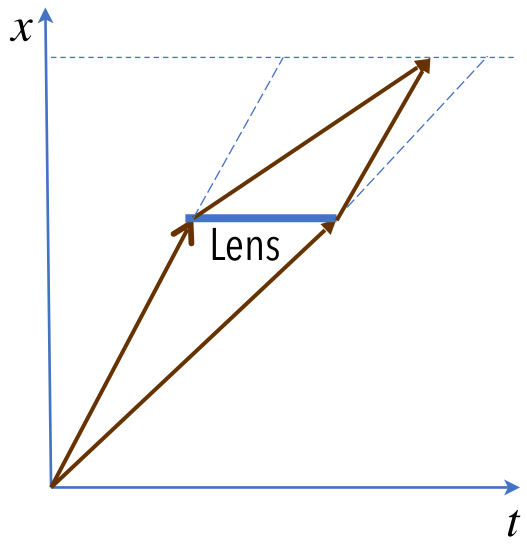

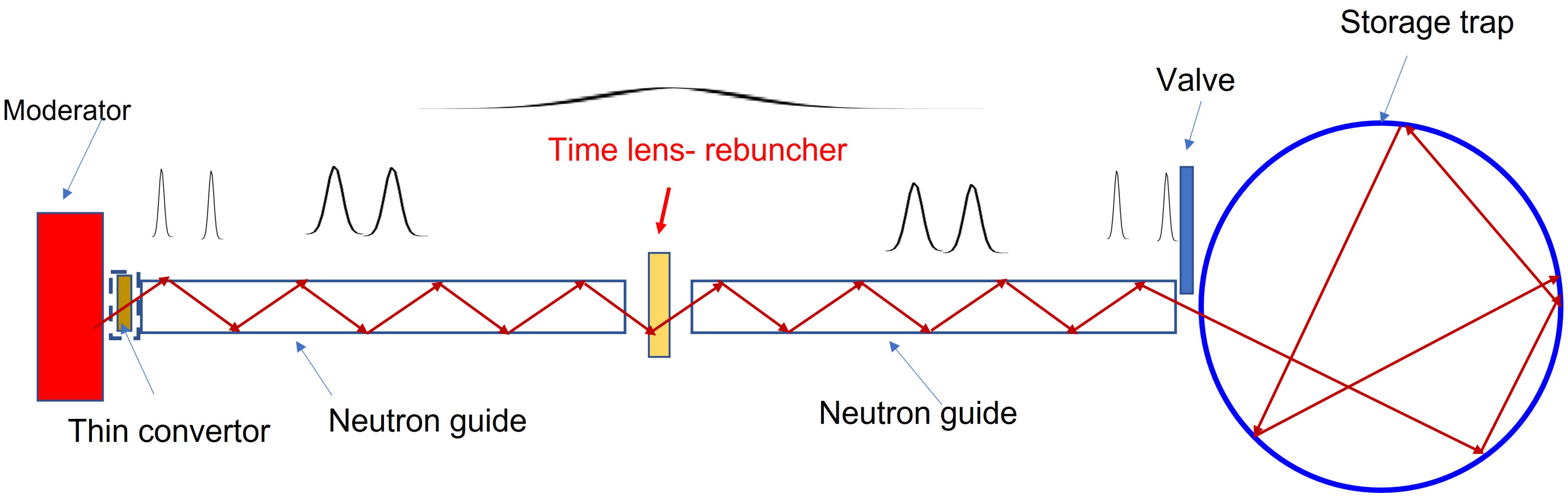

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Time lens – set of diffraction gratings

G.V. Kulin, A.I. Frank, N.V. Rebrova, M.A. Zakharov **ISINN-28, Physics of Particles and Nuclei 53 (2022) 33-44**

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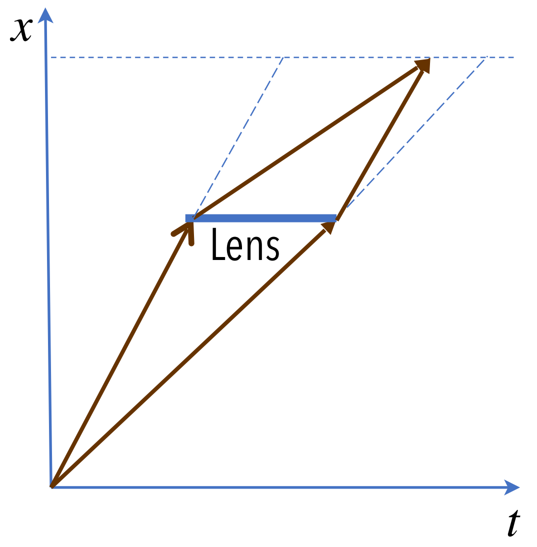

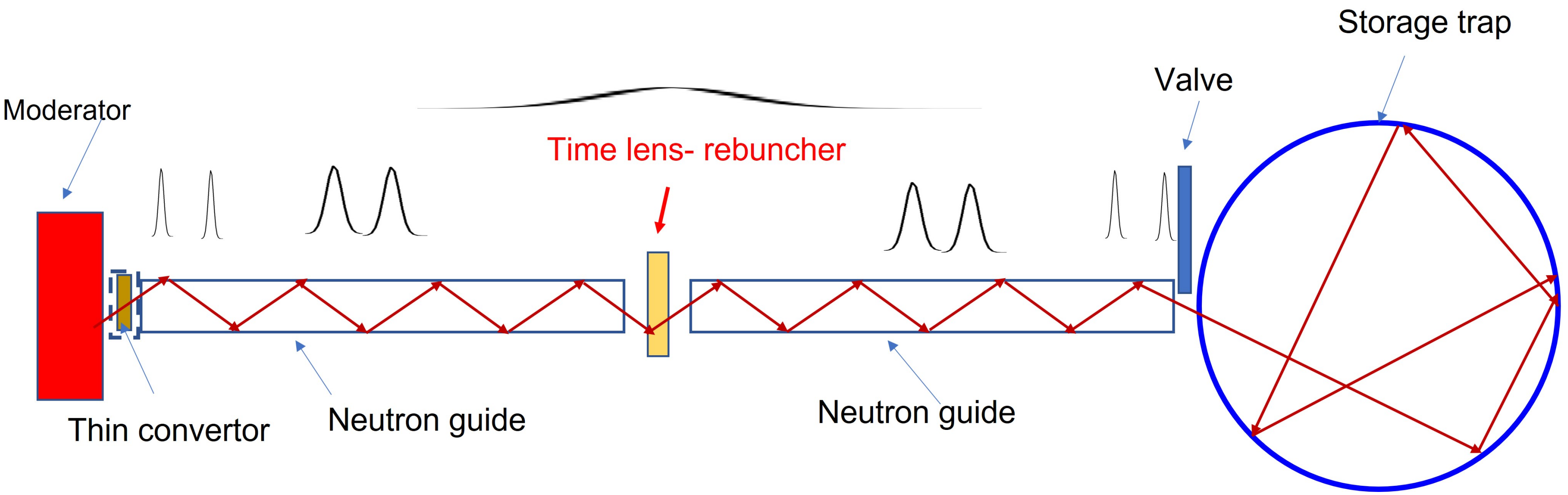

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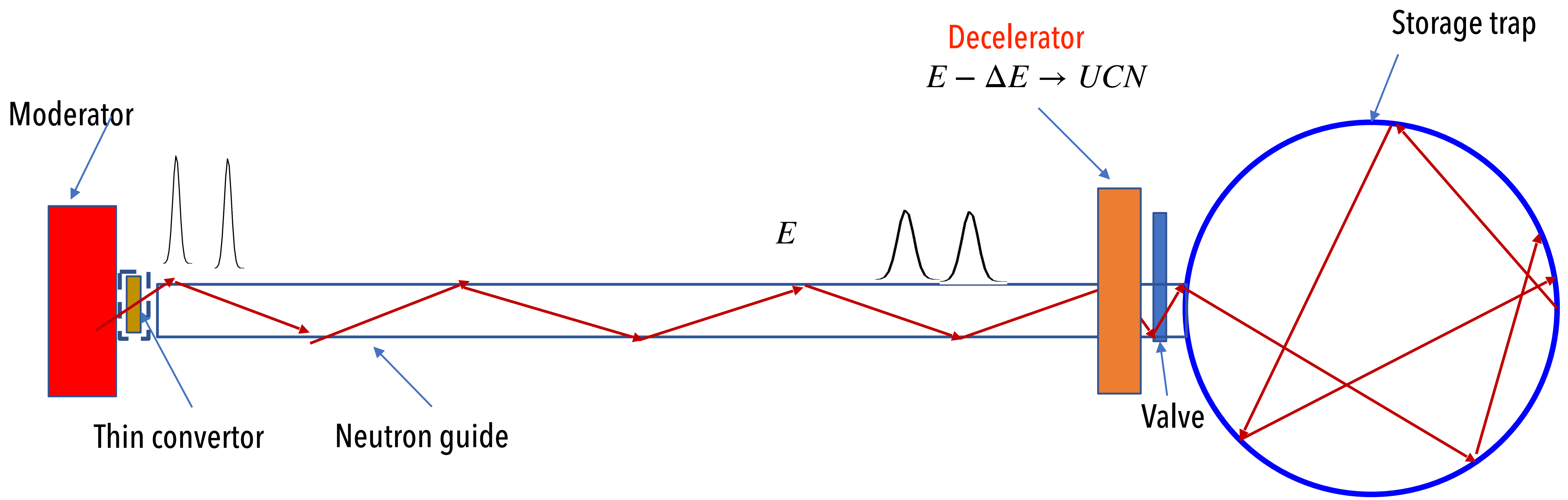
it is not known how to implement this technically

Pumping option of the pulsed source – decelerator

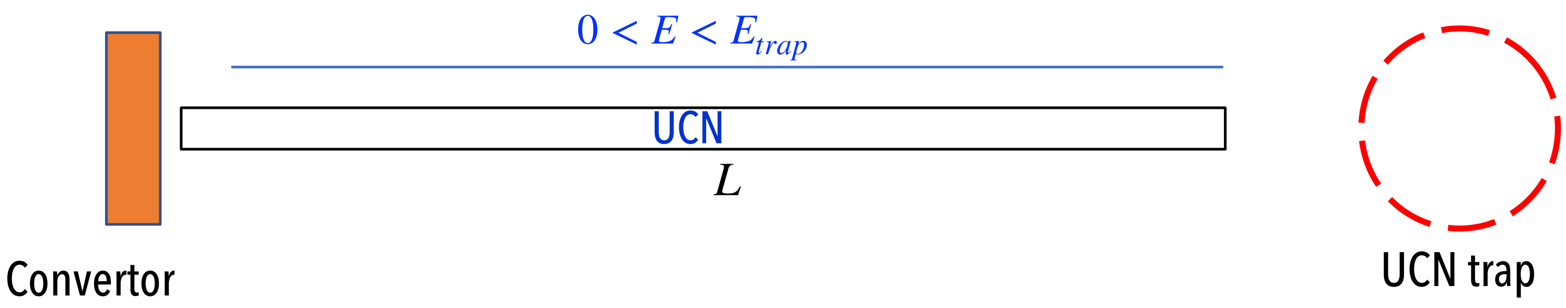


During deceleration, all neutrons change their energy by the same value

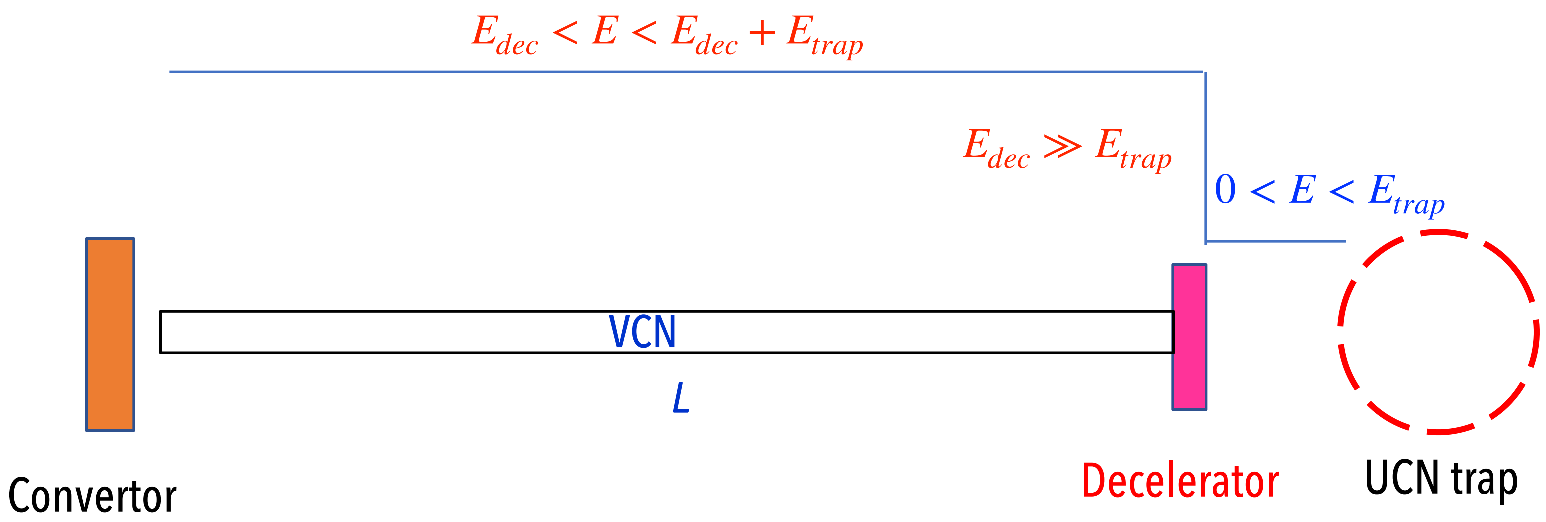
✓ The extraction of neutrons with higher speeds than that of the UCN from the moderator converter provides better conditions for the transportation of neutrons and allows the use of a more efficient converter

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

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



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



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

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

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

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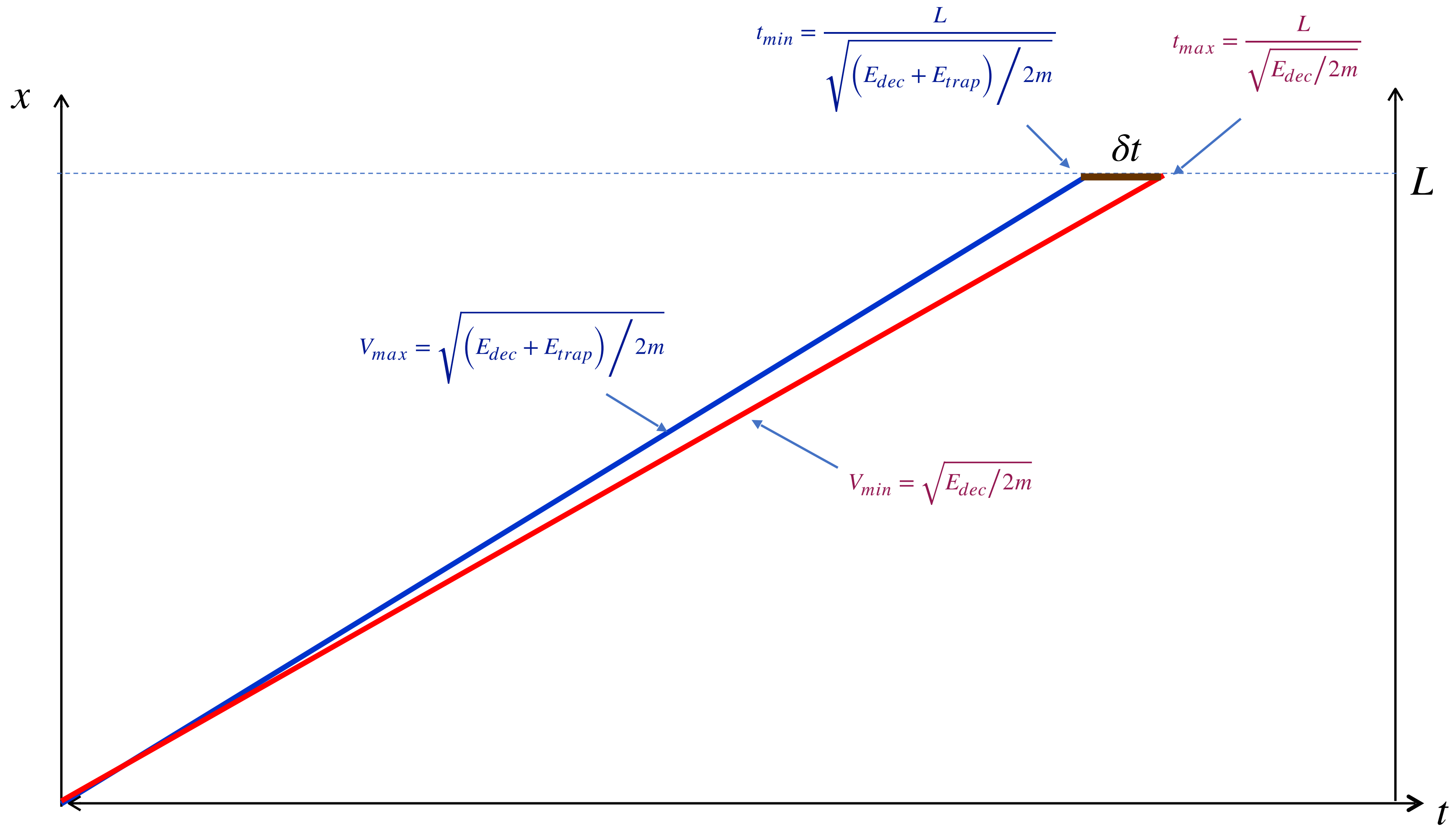

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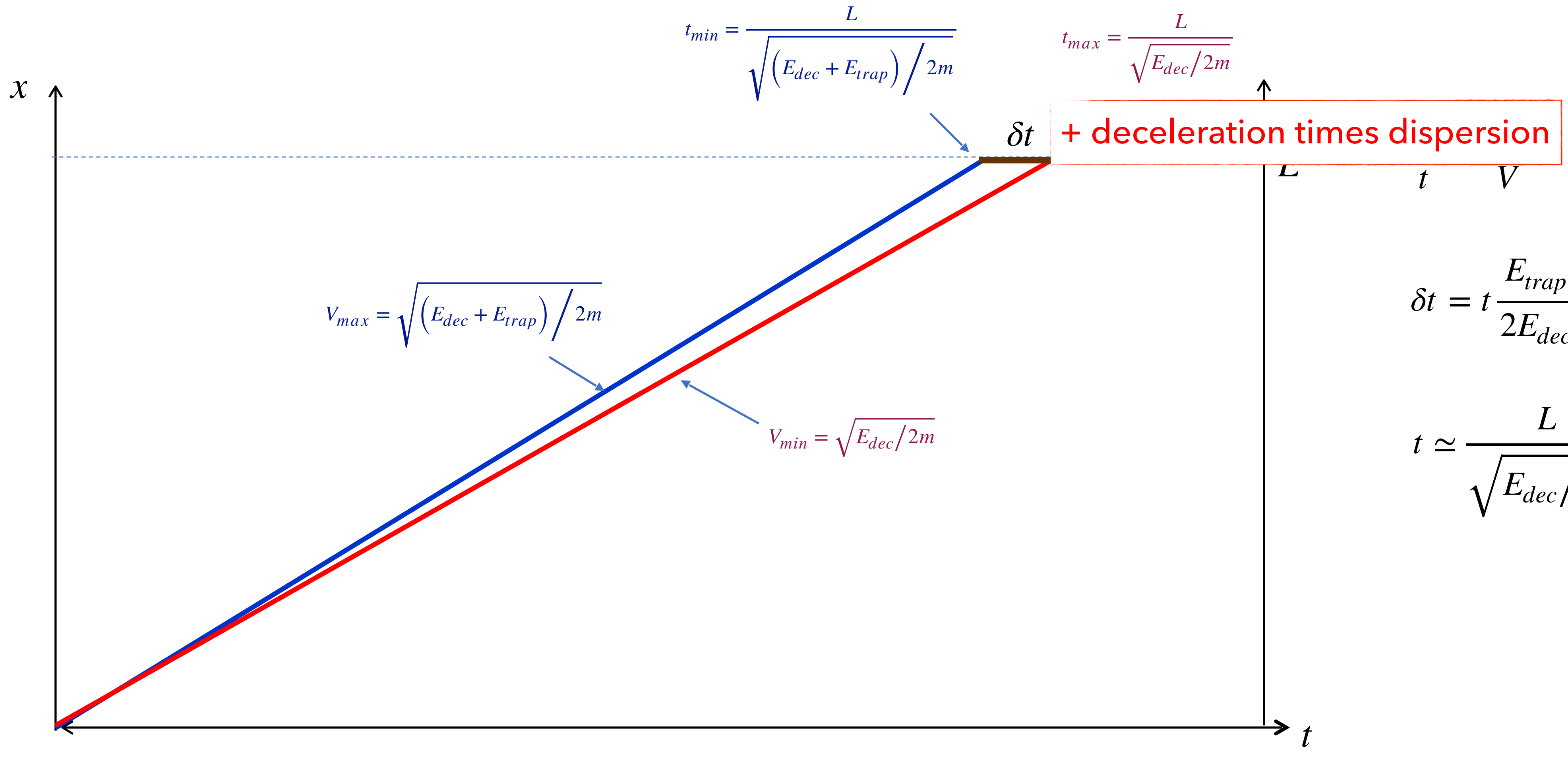

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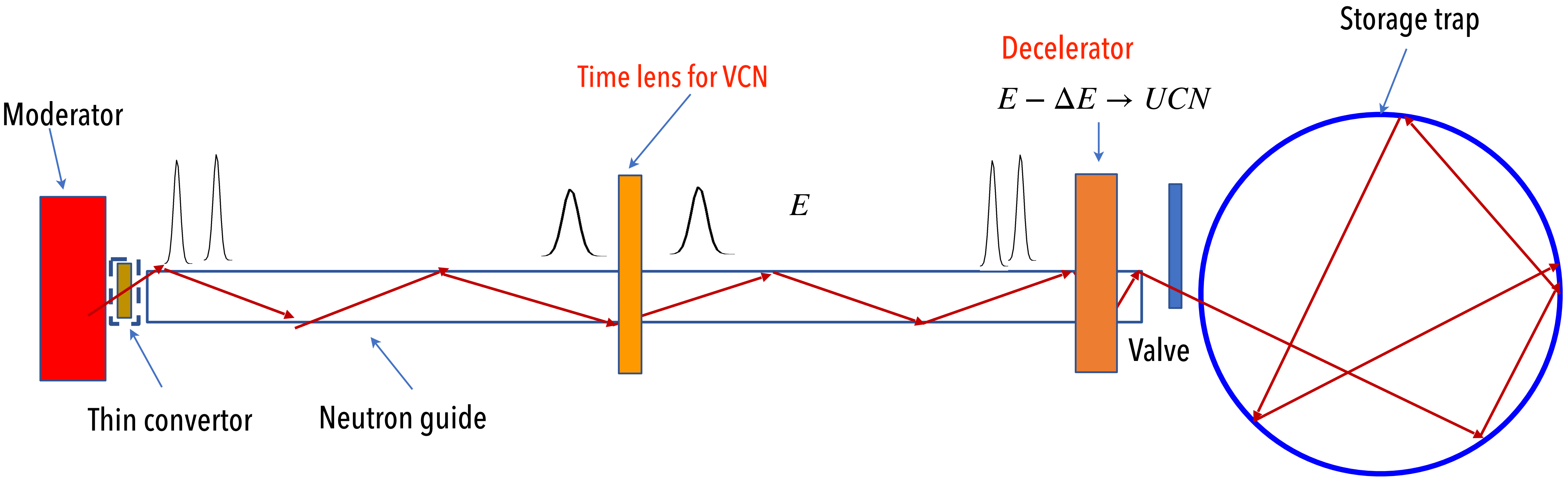
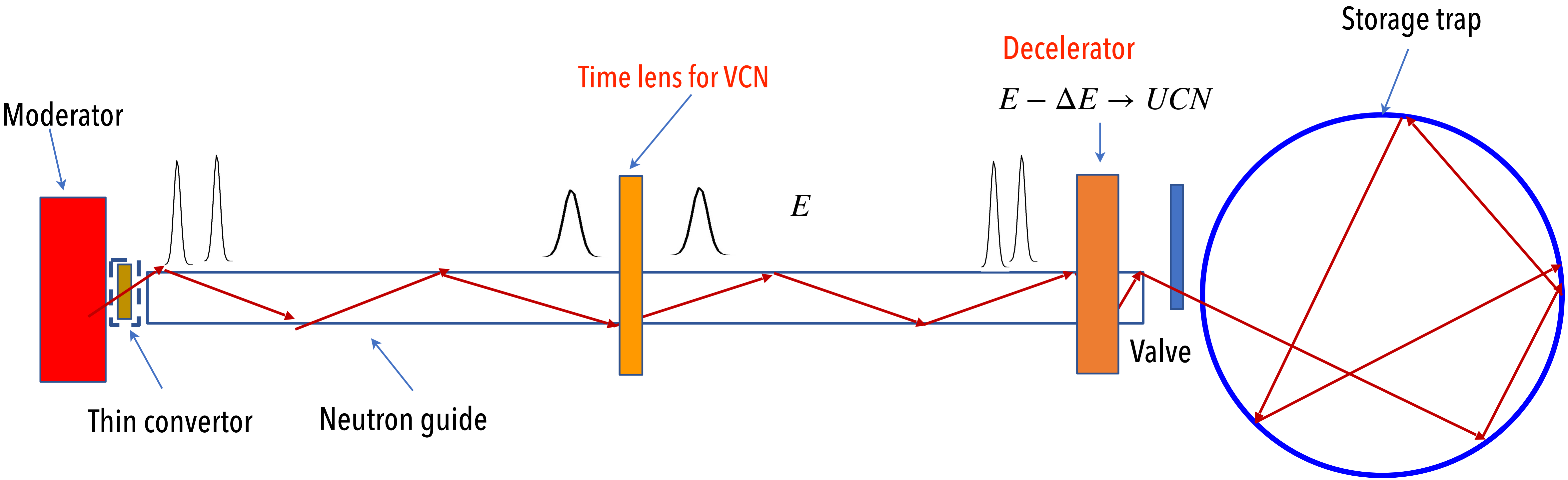
Time lens to minimise the bunch duration at the Decelerator



Lens has to operate with VCN

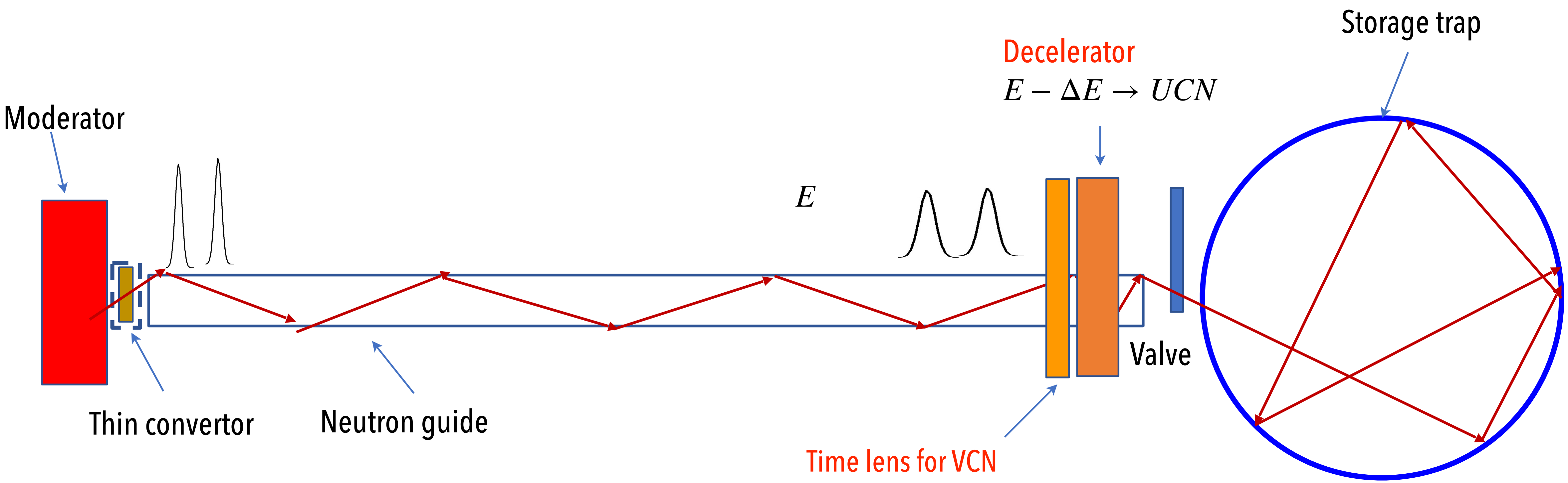
Time lens to minimise the bunch duration at the Decelerator



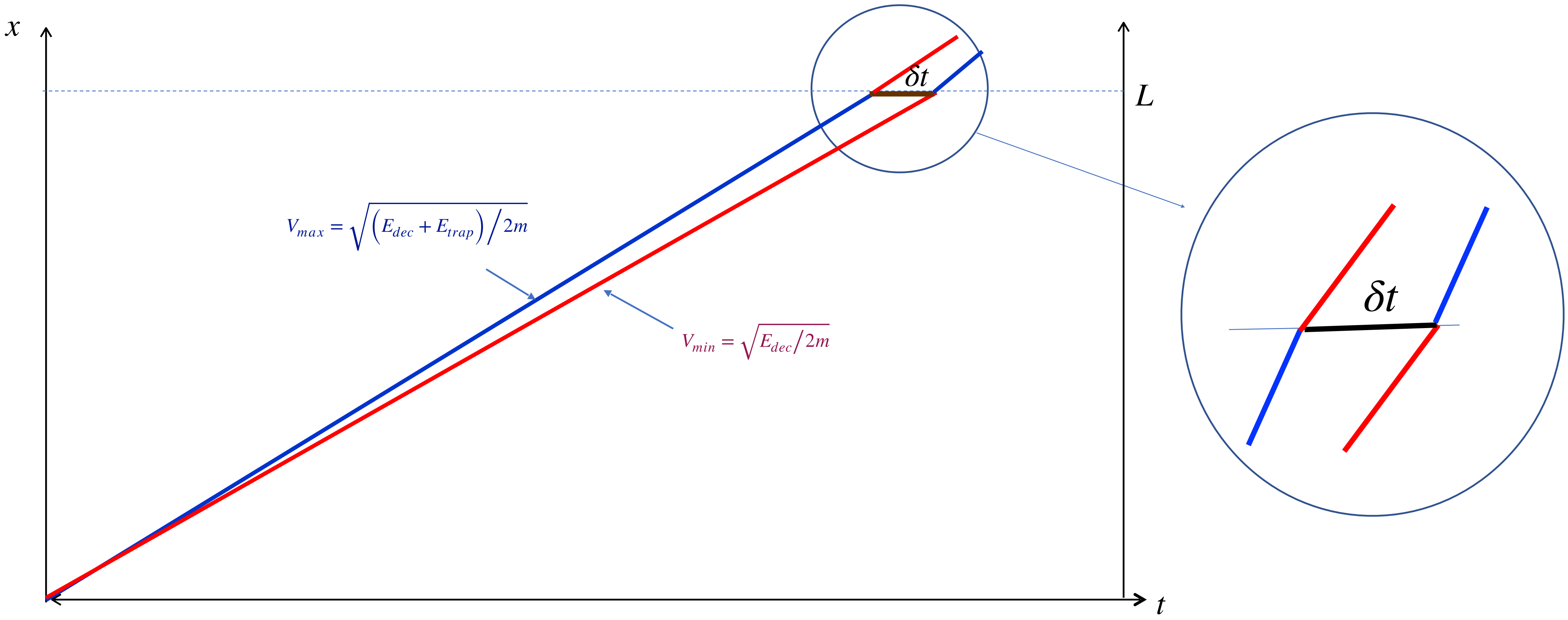
Lens has to operate with VCN

! Problem of deceleration times dispersion still remains

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



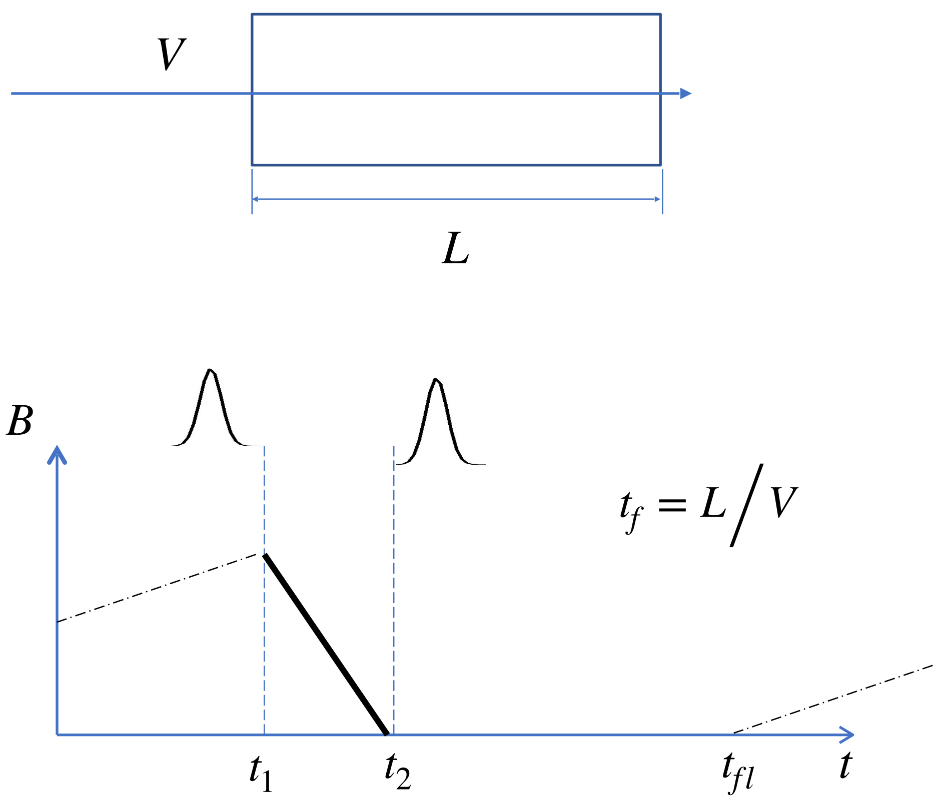
The time lens inverts the velocities in order to partially compensate the dispersion of the time of subsequent deceleration



A time-dependent magnetic field lens

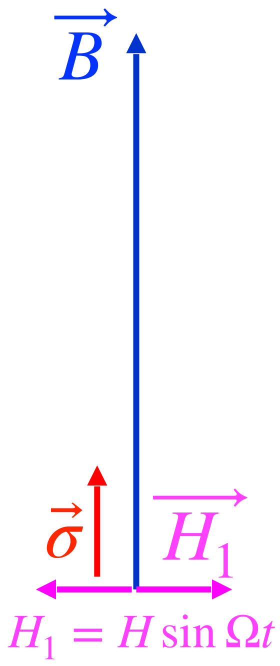
Neutrons change their energy when passing a homogeneous in space time-varying magnetic field

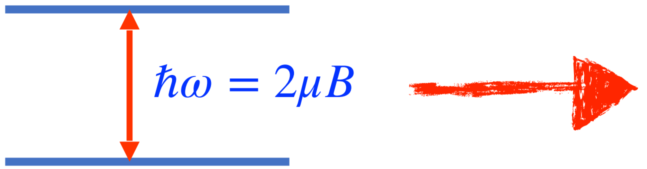
L.Niel, H.Rauch, Z. Phys.B. – Condensed Matter 74, 133 (1989)



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

Resonant spin flip as a transition between spin states





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

$$\omega_{hf} = \omega_L = \frac{2\mu B}{\hbar}$$

$$\omega_L = \gamma |B|$$

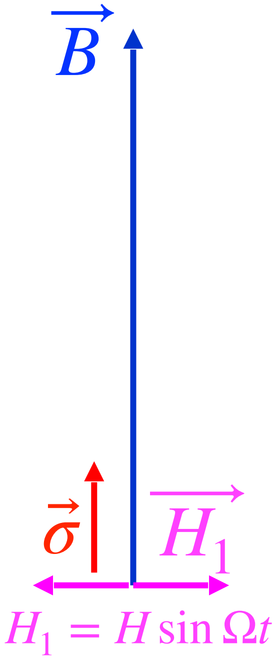
$$\mu = 60.31 \text{ neV/T}$$

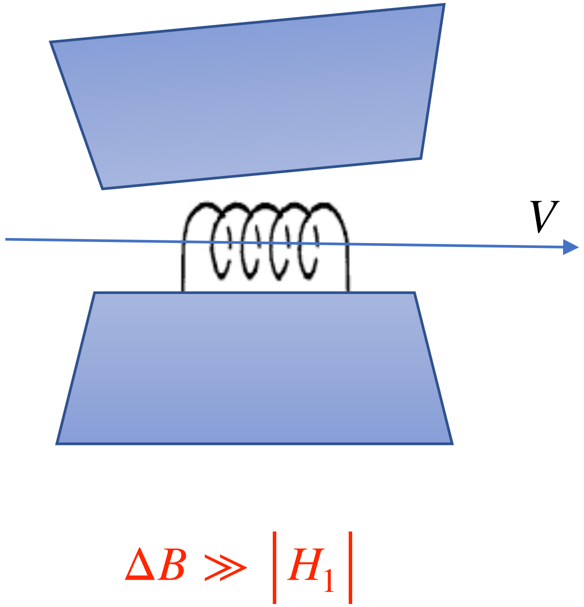
$$\gamma = 1.83 \times 10^8 \text{ rad} \cdot \text{s}^{-1} \cdot \text{T}^{-1}$$

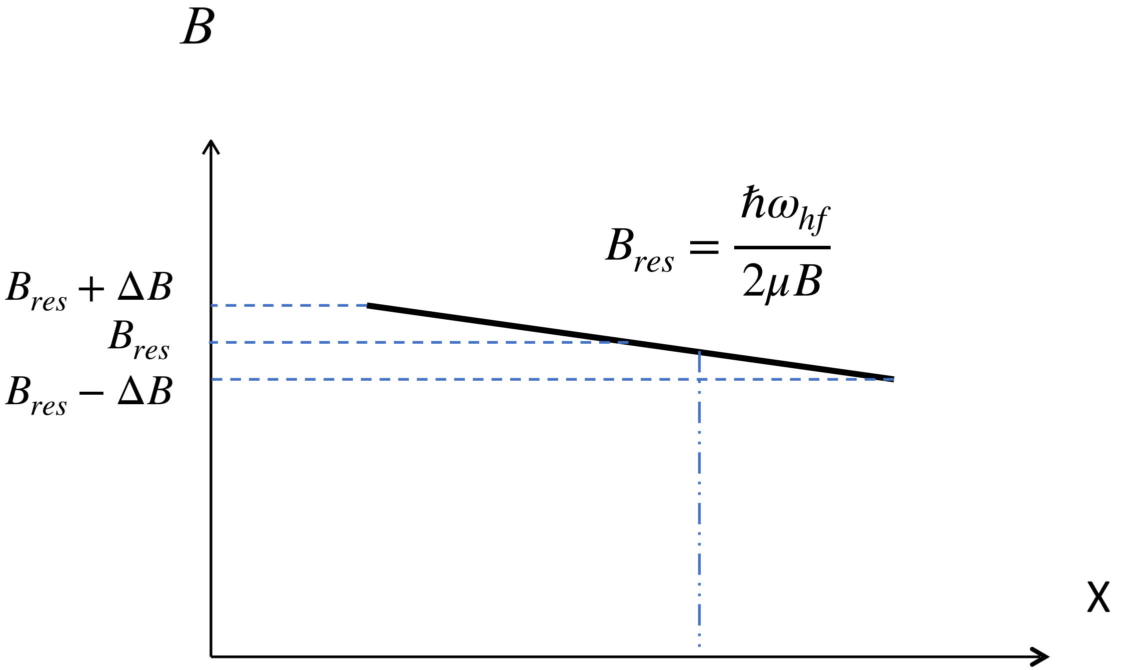
to decelerate a neutron at a speed of 20 m/s to a speed of 5 m/s

$$\Delta E \approx 2\ \mu\text{eV} \quad B = \frac{\Delta E}{2\mu} = 15\text{ T} \quad f = \frac{\omega}{2\pi} \approx 435\text{ MHz}$$

Decelerator — broadband gradient (adiabatic) spin flipper





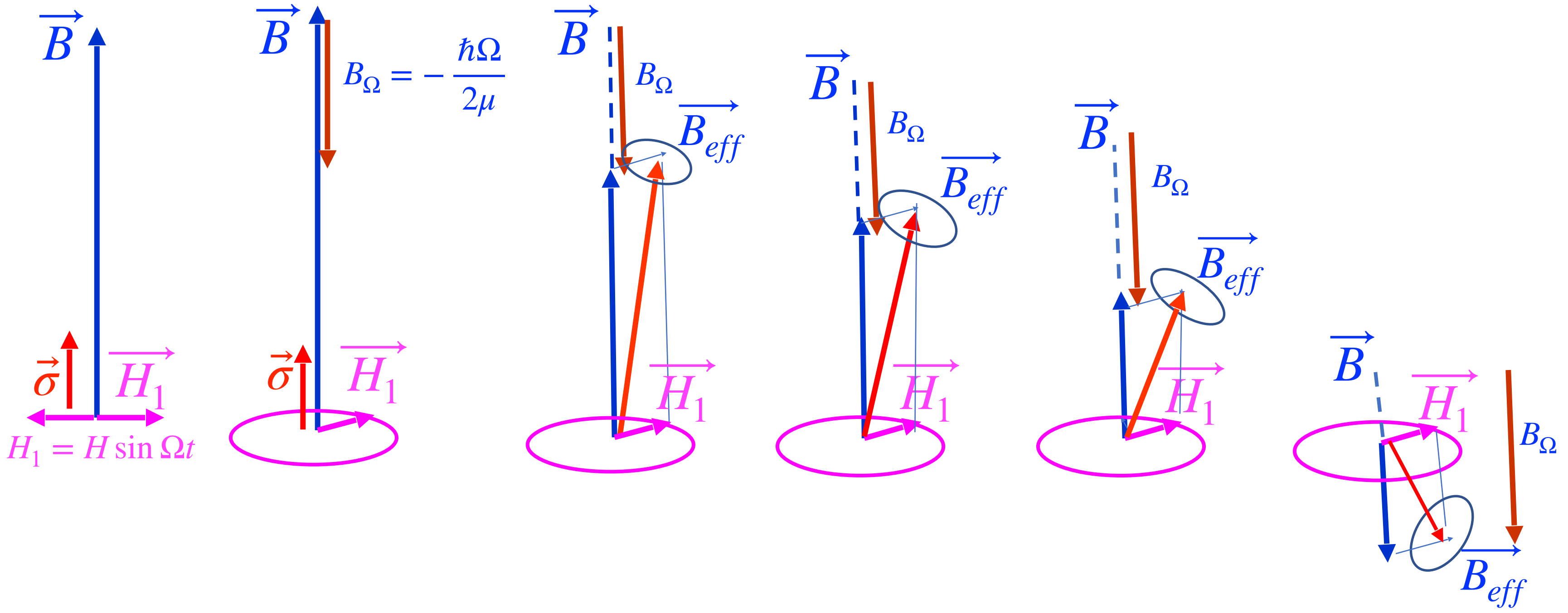


V.I.Luschikov, Yu.V.Taran. NIM 228 (1984) 159

A.N. Bazhenov, V.M . Lobashev, A.N. Pirozhkov and V.N. Slusar. NIM A332 (1984) 534

S .V. Grigoriev *, A.I. Okorokov, V.V. Runov. NIM A384 (1997) 451

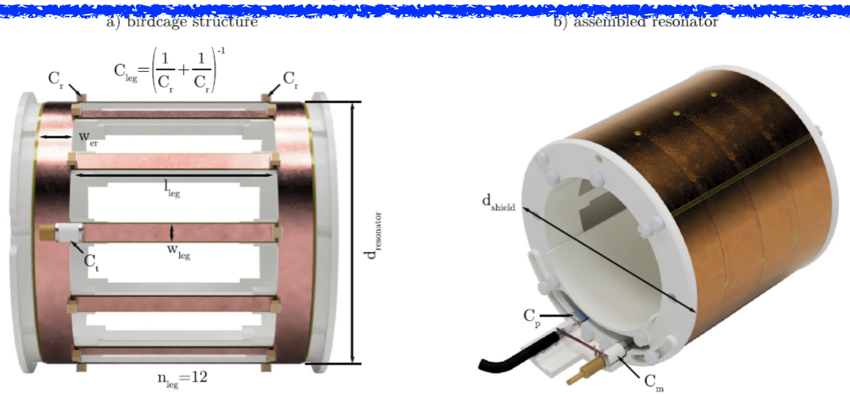
The evolution of spin is determined by the sum of B_Ω and the external fields B and H_1

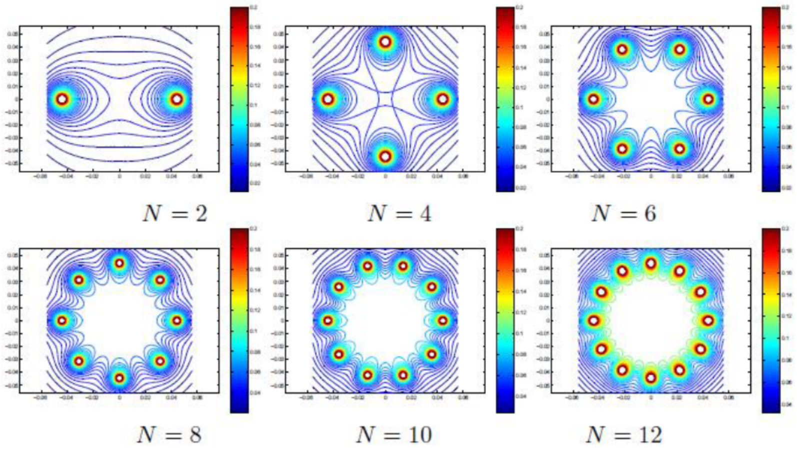


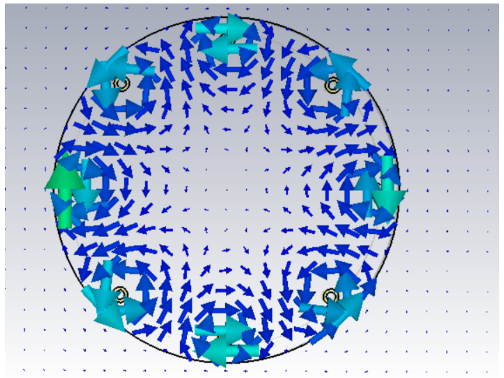
The neutron spin "follows" the total B_{eff} field formed by this differential field $B - B_\Omega$ and the constant field H_1.

After the rotating field is turned off, the neutron spin is inverted relative to the true field B

High frequency resonator







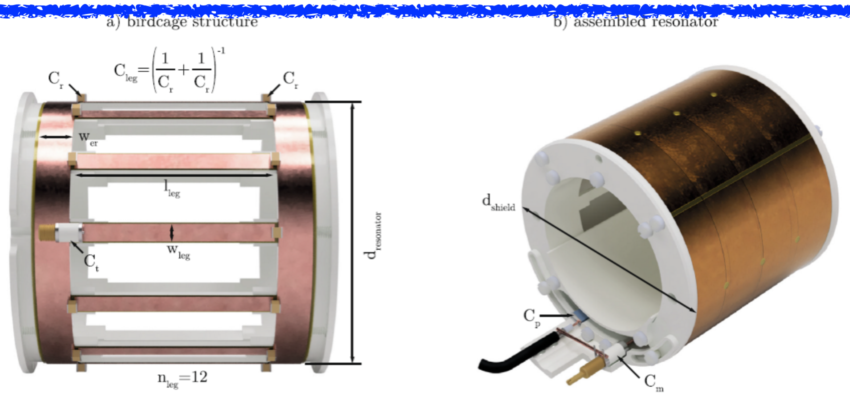
P.Kemper, J.Thöming, E. Kustermann. HardwareX, **12** (2022) e00326

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.
- Has an excellent Q-factor and rather small thermal losses.

The calculation of a birdcage type resonator with an operating frequency of 435 MHz is in progress

High frequency resonator



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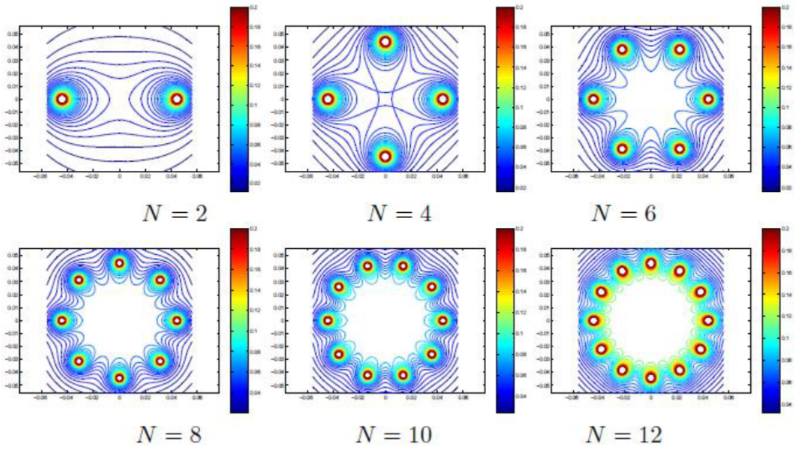

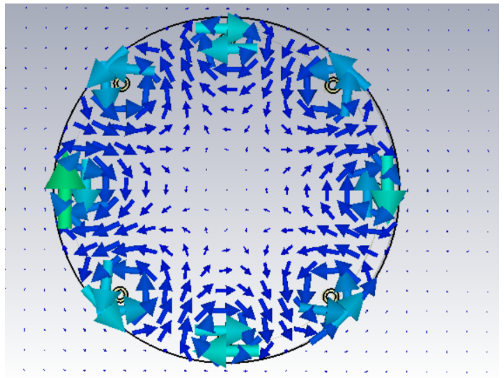

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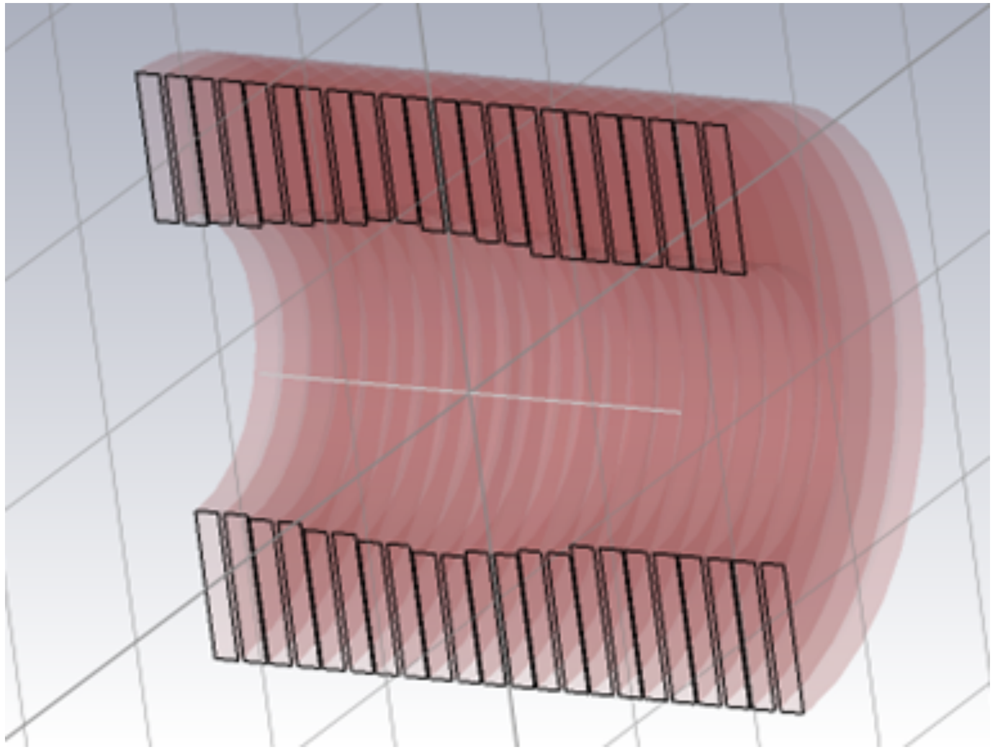
For more details, see poster of Vladimir Kurylev

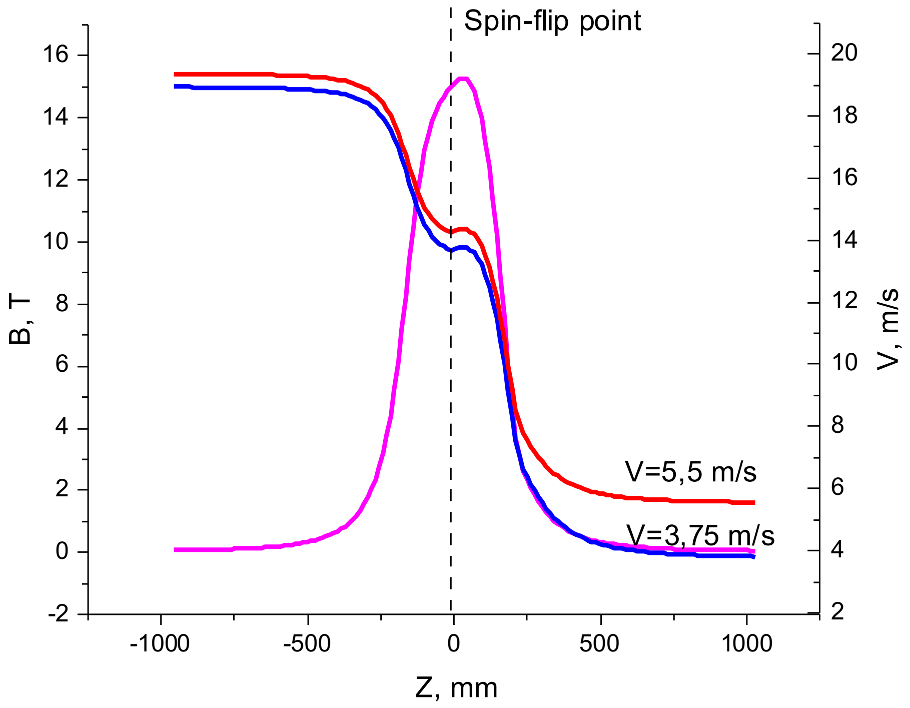
The calculation of a birdcage type resonator with an operating frequency of 435 MHz is in progress

Stationary gradient field – 15T superconducting solenoid

HTS magnet (preliminary design of SuperOx company)

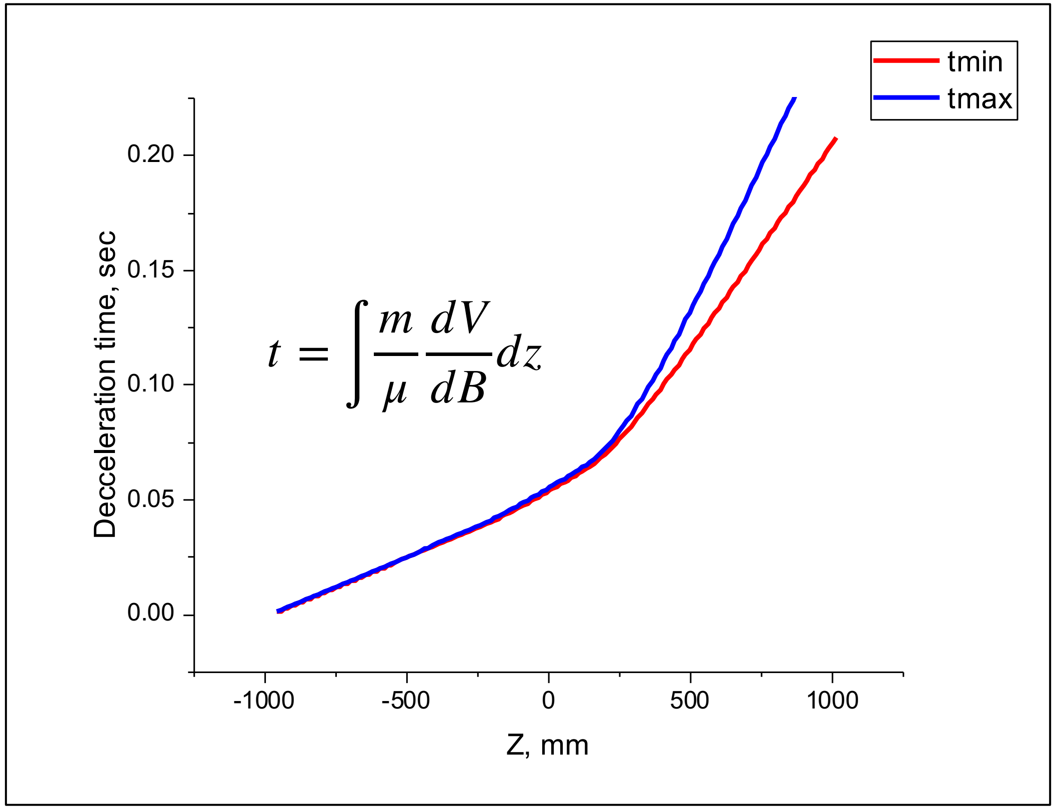


Windings configuration

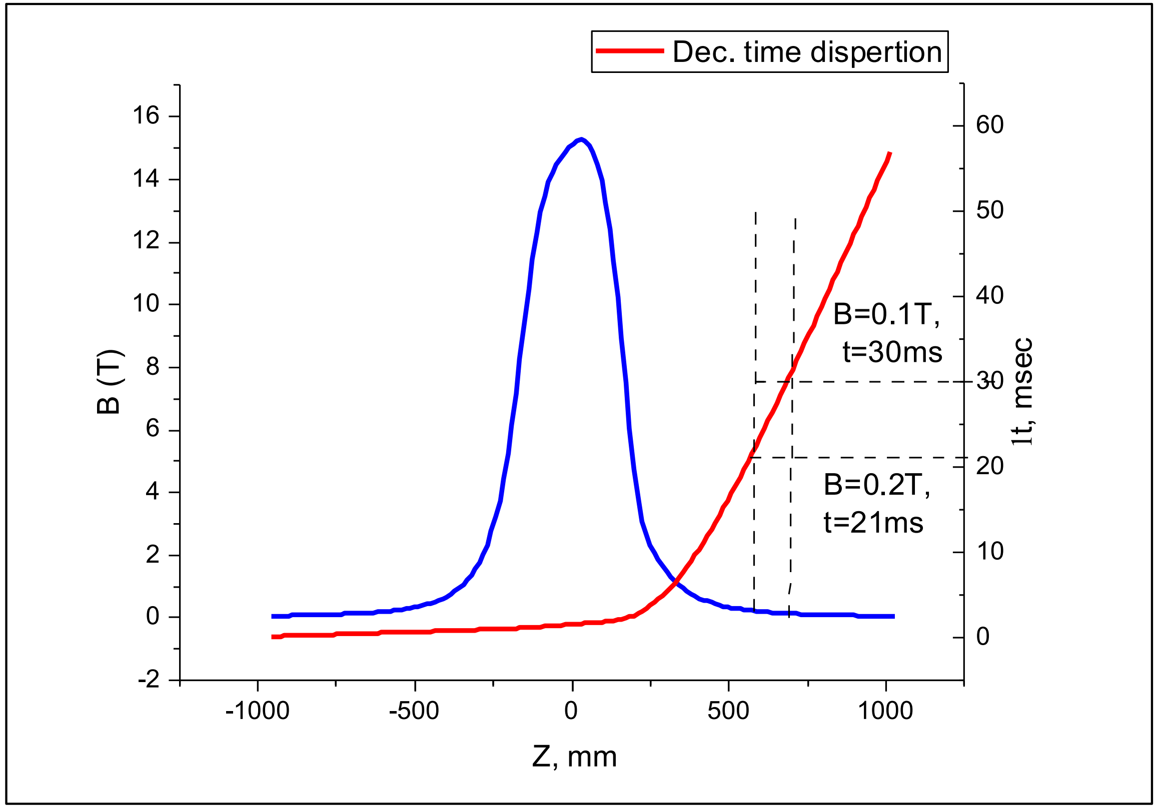


The dependence of the magnetic field and neutron velocities from the coordinate along the axis

Dispersion of deceleration times

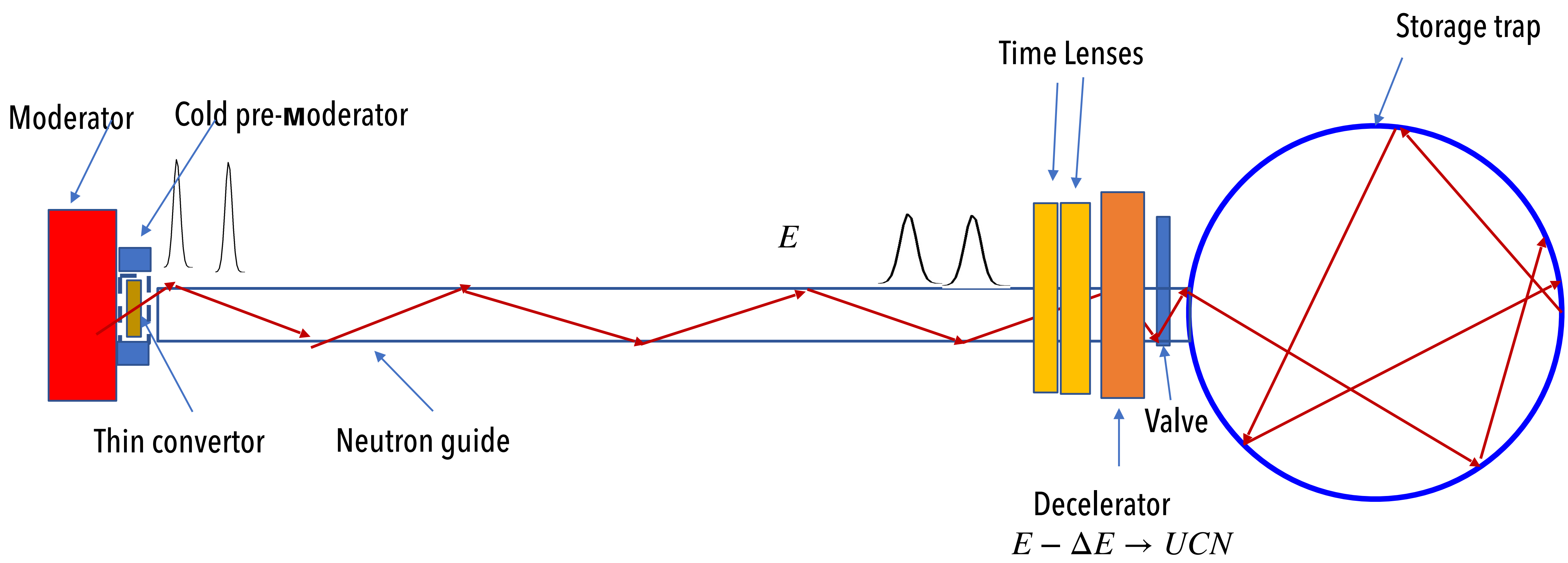


$$t = \int \frac{m}{\mu} \frac{dV}{dB} dz$$



Further optimisation of magnetic field to reduce the dispersion of deceleration times is required

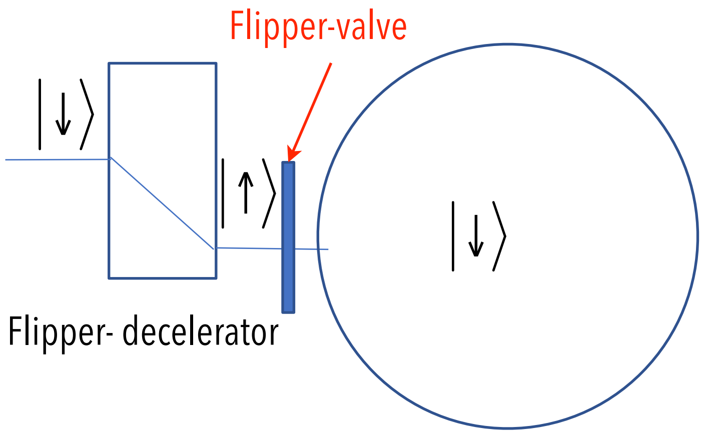
Most probable conception of UCN source @ periodic pulsed reactor



Pulsed valve

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

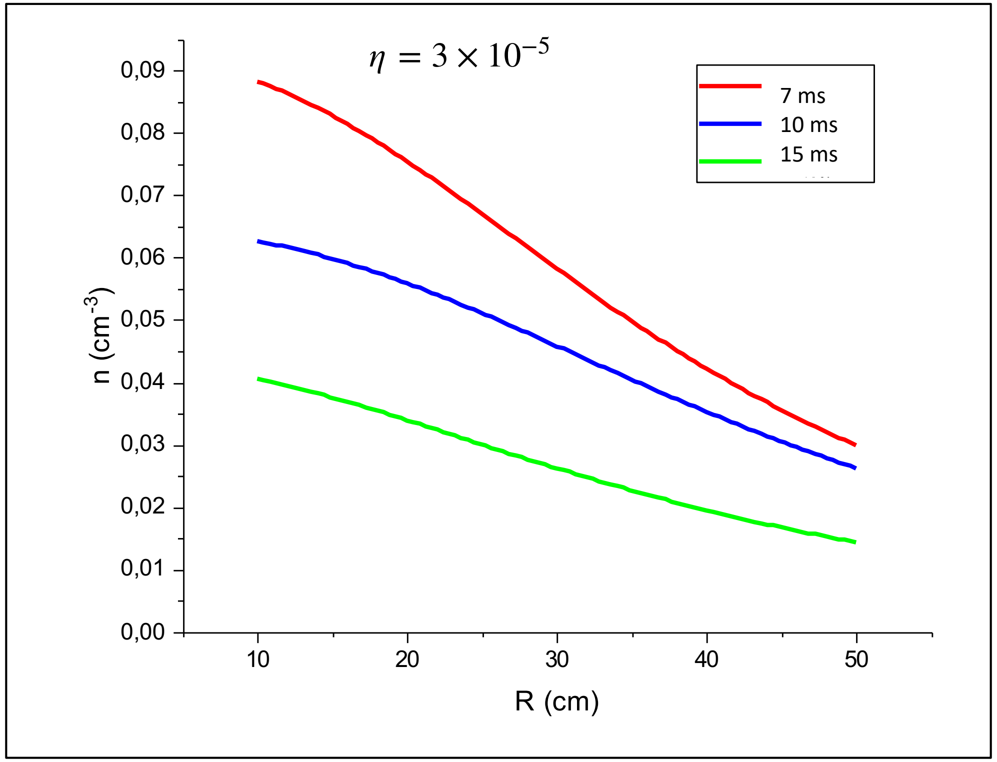
- Spin of polarised neutrons stored in the trap is oriented in such a way that the magnetic field of the flipper-decelerator is a barrier for them
- The high frequency of the flipper is applied only during the time of the arrival of the bunch. During this time, it passes neutrons in both directions

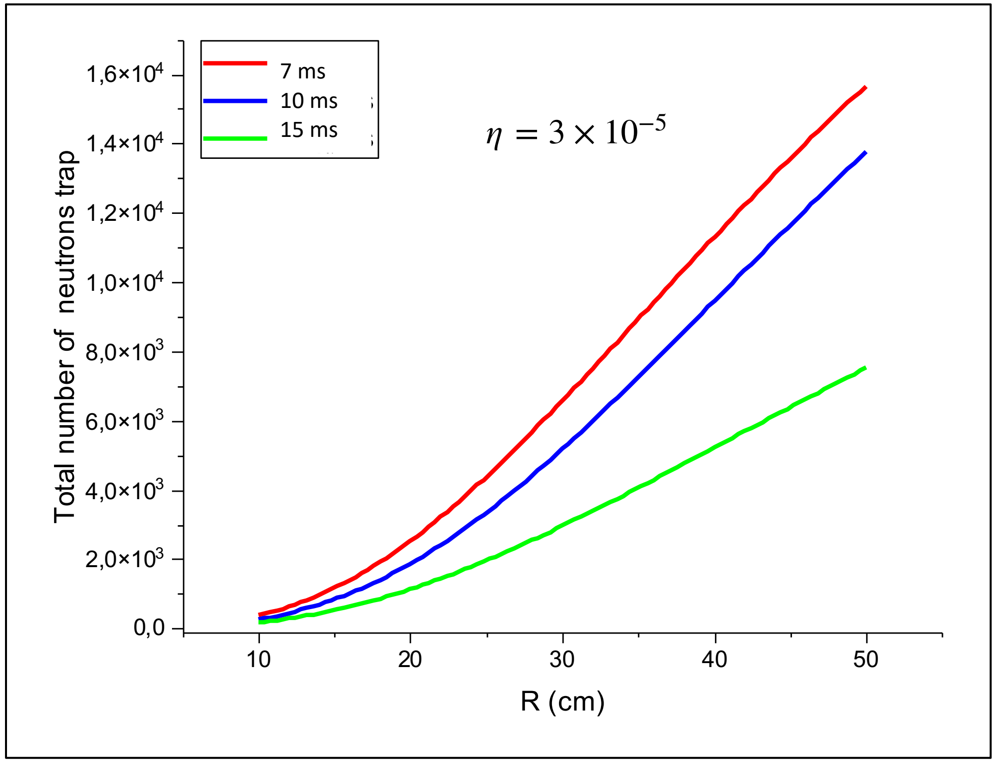


Parameters and results of calculation

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/cm^{2}s
UCN flux (V<6.9 m/s) at a temperature of the spectrum of 400 K and G=1	14 n/cm^{2}s
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	$0.78\times0.62\times0.34\times0.5=0.08$

Density and number of neutrons in a spherical trap ($G = 1$)





For modern converter, such as solid deuterium, the gain factor G can reach the value of 10^3

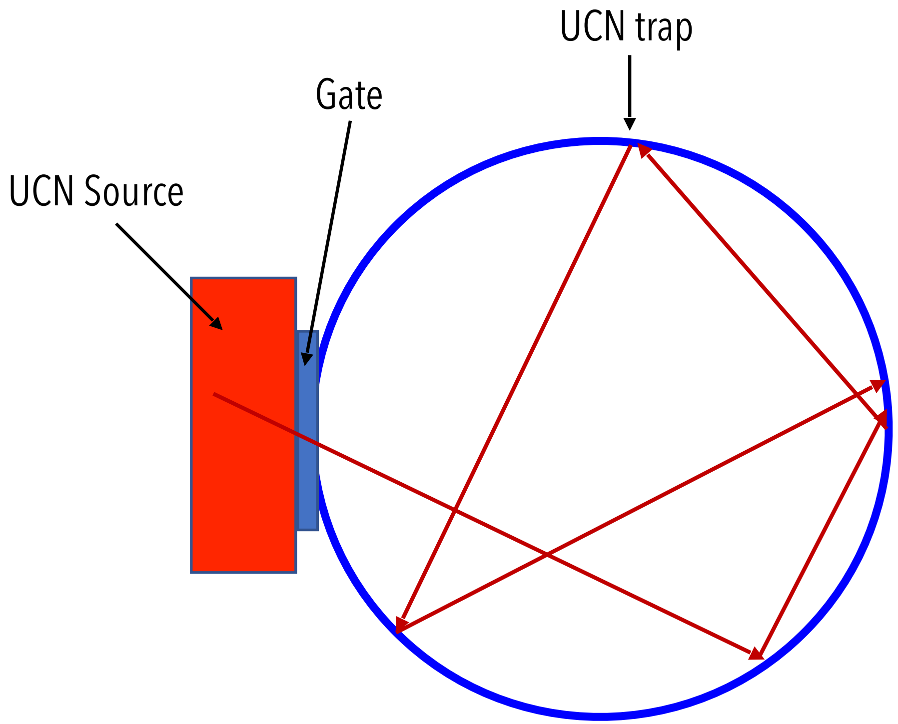
Thanks for the discussions to V.I. Bodnarchuk, O.V. Karamyshev, E.V. Lychagin, A. Yu. Muzychka, M.S. Novikov and A.N. Chernikov.

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

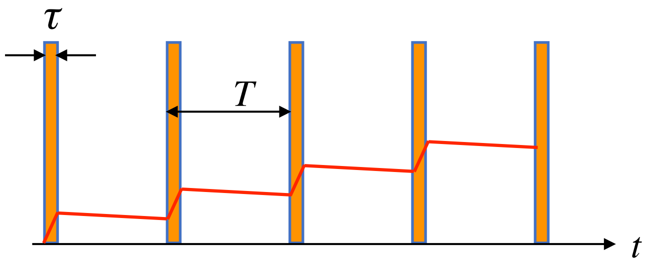
Thank you for your attention!!!

Pulse source and UCN pumping in a trap

F.Shapiro, 1972



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



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

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

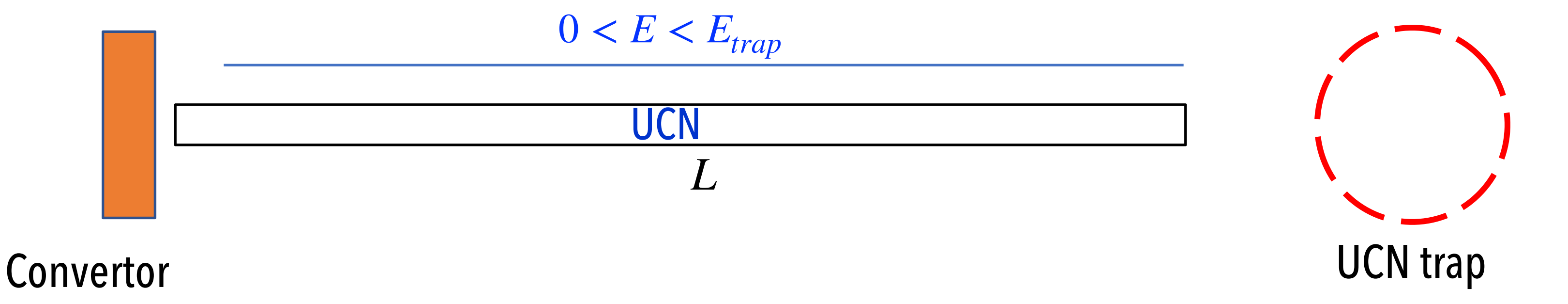
S – *active convertor area*

Σ – *area of the trap*

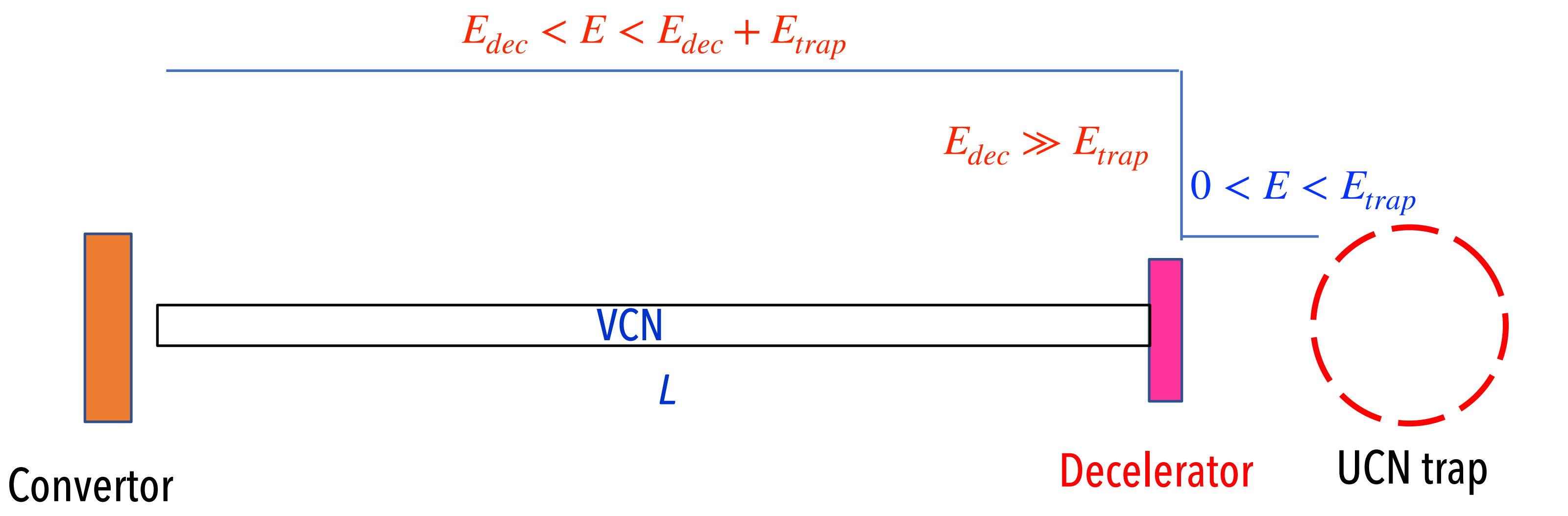
μ – *probability of the UCN lost*

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

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

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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"*.

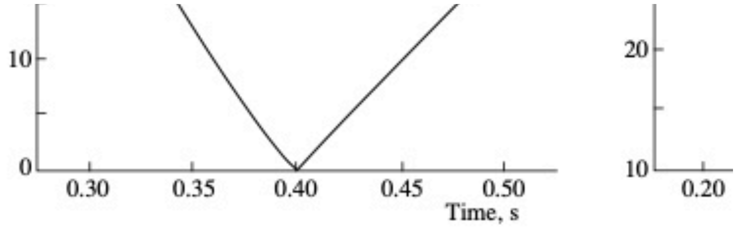

Fig. 2. Frequency of a quantum modulator as a function of time after the source burst.

Fig. 3. Ma
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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.

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

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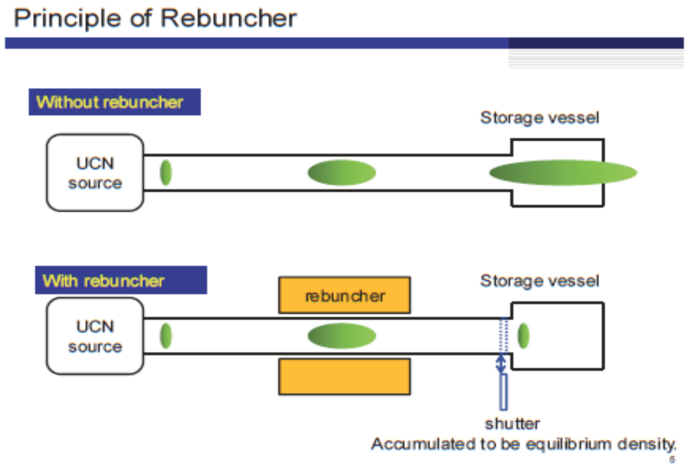

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Demonstration of focusing by a neutron accelerator

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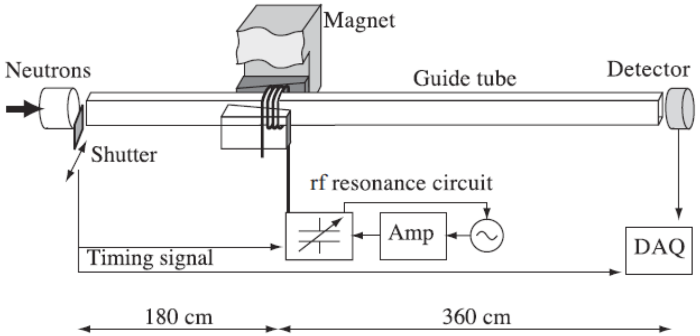


FIG. 2. Experimental setup. The neutron accelerator is installed in the middle of the guide tube. The rf and data acquisition systems are synchronized with the shutter operation.

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

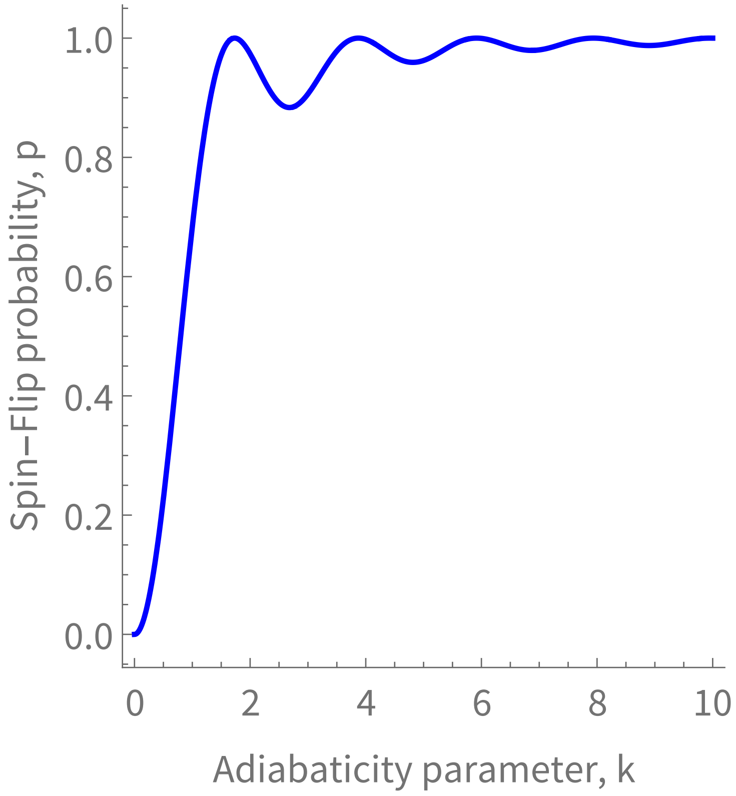
Parameters of adiabatic spin flipper

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 $B \approx B_\Omega$, $B_{eff} \approx H_1 \longrightarrow k = \frac{\gamma H_1^2}{\left(\frac{dB}{dz}\right) V}$

at $k = 4$ and $V = 15$ m/s $\longrightarrow H_1^2 > \frac{dB}{dz} \cdot (3.3 \times 10^{-7})$

For gradient of magnetic field 15T/m $\longrightarrow H_1 \geq 2.2$ mT



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