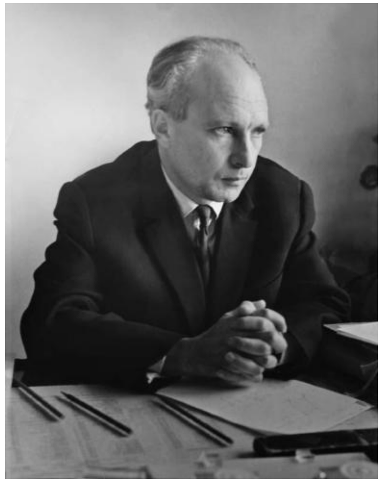
# Development of the concept of an ultracold neutron source at IBR-2 pulsed reactor

**Project leaders:** V.N. Shvetsov, G.V. Kulin

**Deputy leader (scientific supervisor):** A.I. Frank

# The FLNP contribution to world research with UCN



F.L. Shapiro, V.I. Lushchikov, A.V. Strelkov, Yu.N. Pokotilovski

V.K. Ignatovich

Письма в ЖЭТФ

Т. 9 1969 Вып. 1

1969

30

НАБЛЮДЕНИЕ УЛЬТРАХОЛОДНЫХ НЕЙТРОНОВ

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

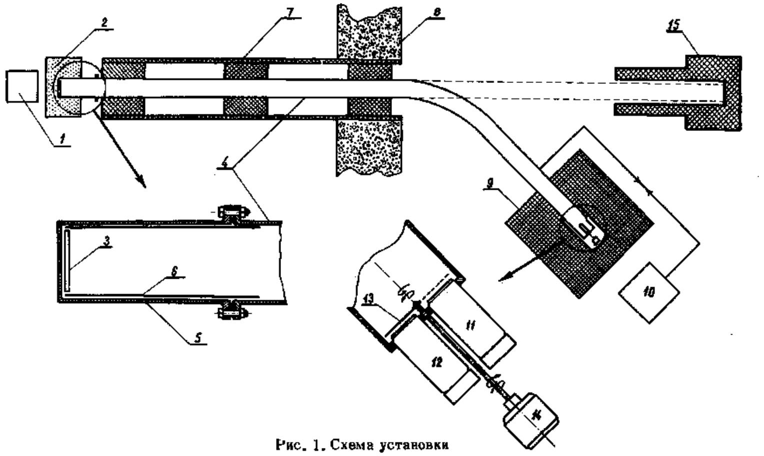


Рис. 1. Схема установки

*Выход ультрахолодных нейтронов из замедлителей* 211

**1. МЕТОД РАСЧЕТА**

Рассмотрим плоский конвертор, расположенный внутри горизонтального канала УХН (рис. 143). За счет полного отражения по каналу могут распространяться все выходящие из конвертора нейтроны с энергией

$$E < U_{\text{ст}} \equiv (4\hbar^2/m)\pi n_{\text{ст}} b_{\text{ст}}$$

($n_{\text{ст}}$ — плотность ядер и $b_{\text{ст}}$ — когерентная длина рассеяния нейтронов для материала стенки канала, $m$ — масса нейтрона; для медных стенок $U_{\text{ст}} \approx \approx 1{,}7 \cdot 10^{-7}$ *эв*). Поток нейтронов с энергией в интервале от $E$ до $E + dE$,

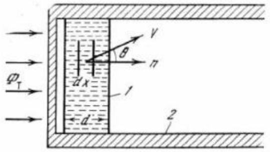


**Рис. 143.** Схема начального участка нейтроновода УХН

1 — конвертор УХН, облучаемый изотропным потоком нейтронов;
2 — вакуумный нейтроновод

выходящий с 1 $см^2$ конвертора толщиной $d$, можно записать в виде

$$\Phi(E)\,dE = dE\int_0^\infty \Phi_{\text{т}}(E')\,n_{\text{к}}\sigma(E' \to E)\,dE' \int_0^d dx \int_0^{\pi/2} W(E, x, \theta)\,\frac{2\pi \sin\theta d\theta}{4\pi}. \qquad (1)$$

*Водяной и гидридциркониевый конверторы ультрахолодных нейтронов* 223

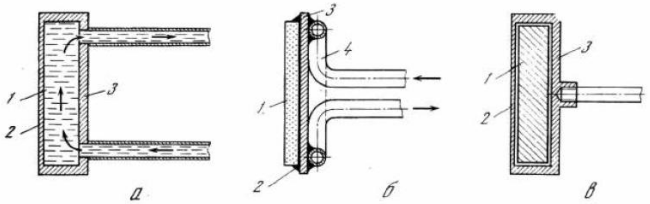
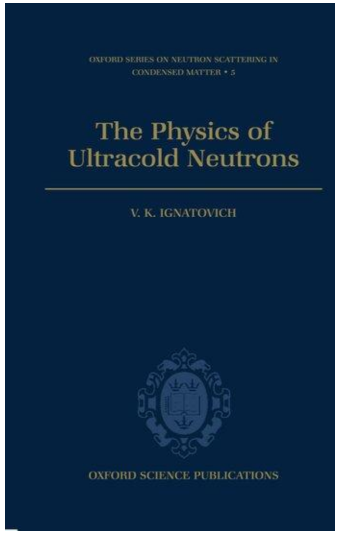


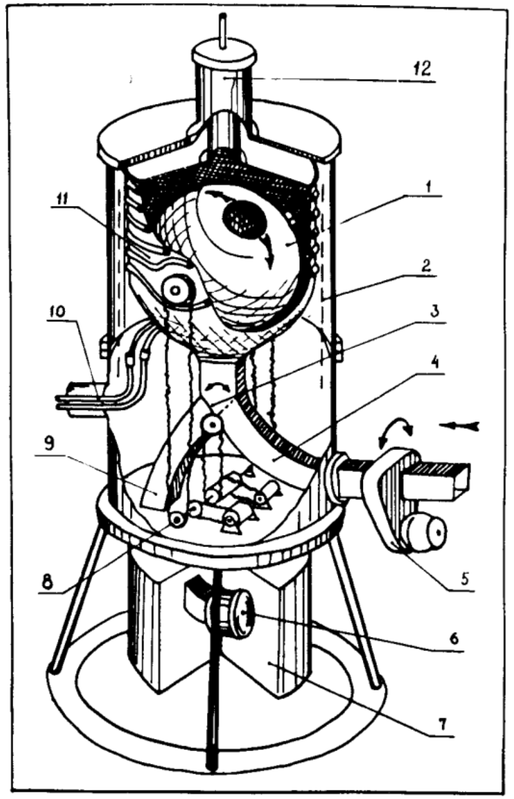
**Рис. 149.** Схема конвертора УХН

*а* — водяной конвертор с алюминиевым окном: 1 — вода; 2 — алюминиевое окно 0,25 *мм*; 3 — алюминиевый корпус; *б* — гидридциркониевый конвертор: 1 — гидрид циркония; 2 — оловянный припой; 3 — медная подложка; 4 — трубки охлаждения; *в* — магниевый конвертор: 1 — магний; 2 — алюминиевое окно 0,25 *мм*; 3 — алюминиевый корпус




1986

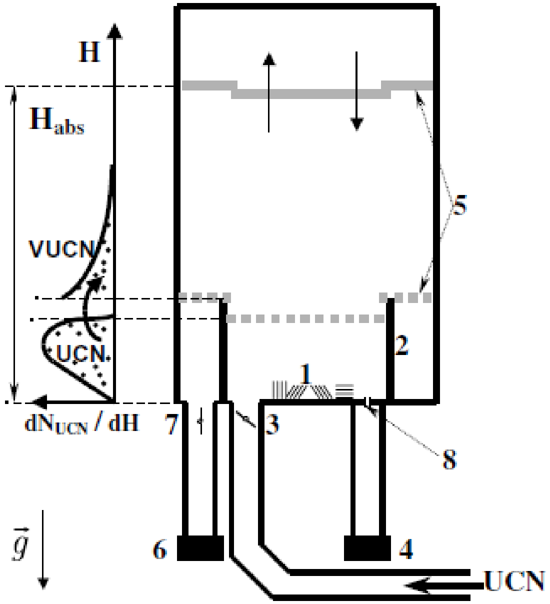
## Measurement of the betta decay constant (1990 – 1992)




$\tau_n = 888{,}4 \pm 3{,}3$ *Nesvizhevski et al. JETP, (1992)*

The work served as the beginning of a new stage of precision measurements of the decay constant

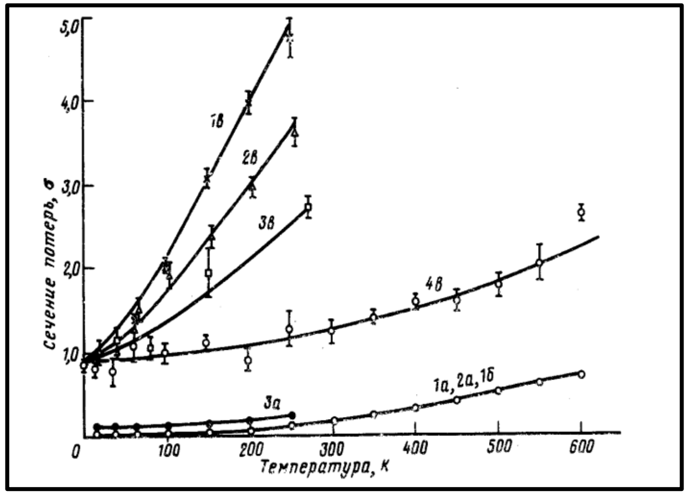
## Processes of small energy transfers during UCN storage



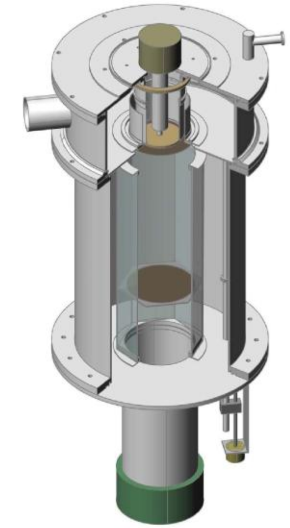

*Geltenbort, Nesvizhevsky, Kartashov et al. JETP Letters, (1999),*
*Nesvizhevsky, Lychagin, Muzychka et al. Phys. Lett. B (2000)*
*Kartashov, Lychagin, Muzychka et al. Int. J. Nanoscience (2007)*
*Cherniavsky, Lychagin, Muzychka et al. Eur. Phys. J. C (2019)*

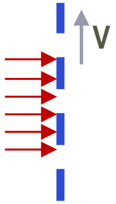
Anomaly in the UCN storage inside beryllium traps - **the nature of the anomalous absorption during reflection remains unnown**

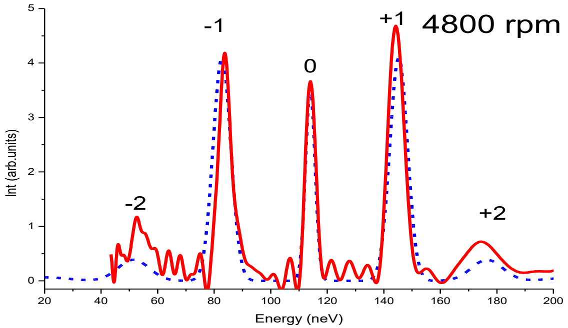
*Alfimenkov et al. JETP Letters, (1992)*

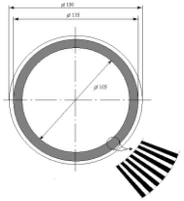


# Nonstationary neutron diffraction at moving grating (1991 – 2019 )





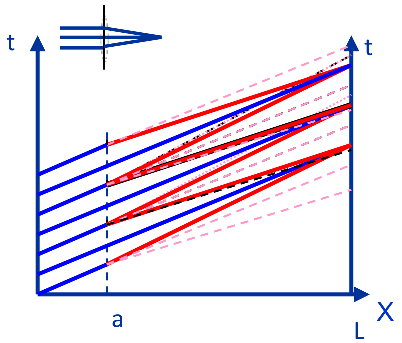



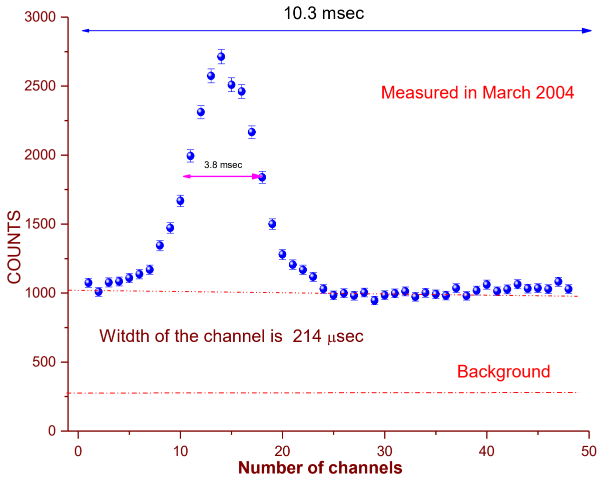



*A.I.Frank, V.G.Nosov. Phys. Lett. A (1994)*
*A.I.Frank et al. Physics Letters A (2003)*
*G.V. Kulin et al. Phys. Rev. A (2016)*
*Г. В. Кулин, и др. ЖЭТФ (2019)*

## Time focusing of neutrons

*Balashov et. al . Physica B (2004)*



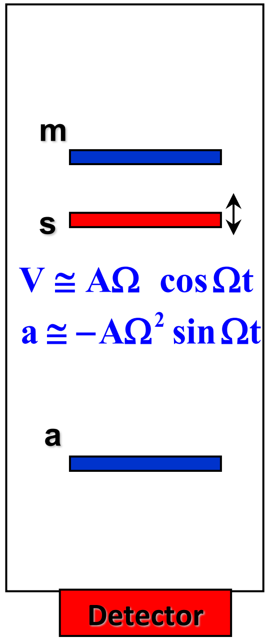

# Discovery of an accelerating matter effect

**The change in neutron energy after passing through an accelerating sample**

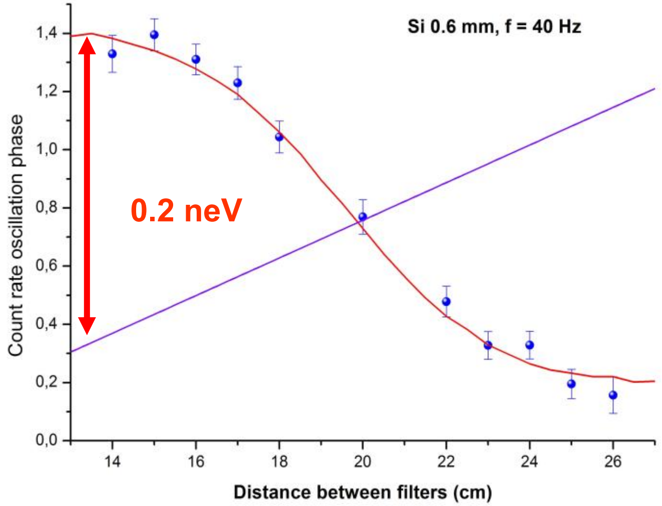
$$\Delta E = mad\left(\frac{1-n}{n}\right)$$

$a$ is a sample acceleration

**Kowalsky-Nosov-Frank**




**Count rate oscillation phase in the dependance on the position of the monochromator**

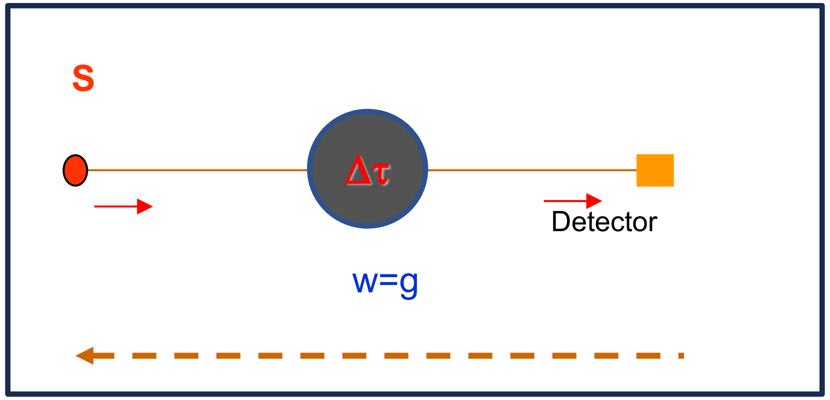



$$\Delta E \cong -KmA\Omega^2 L\left(\frac{1}{n}-1\right)\sin\Omega t \qquad K = 0.94 \pm 0.06$$

*A.I. Frank, P.Geltenbort, G.V.Kulin, et al, Phys. At. Nuclei, 71 (2008) 1656.*

# Scientific program at a future UCN Source

# Verification of the theoretical prediction of the validity of the concept of Acceleration effect in the quantum sector

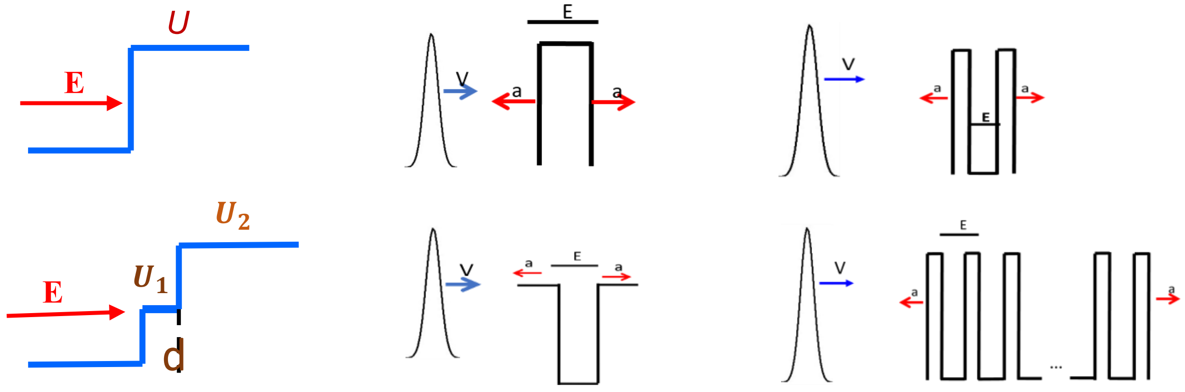



## Acceleration Effect as a consequence of the equivalence principle

Any object that scatters a wave or transmits a signal shifts wave frequency if it is moving with acceleration.

$$\boxed{\Delta\omega = kw\Delta\tau}$$

*A.I. Frank. Physics-Uspeckhi, 63, 500-502 (2020)*




*M.A. Zakharov, G.V. Kulin, A.I. Frank. Eur. Phys. J. D (2021)*

In all cases, the energy of the wave packet changed in qualitative agreement with $\Delta\omega = kw\Delta\tau$, where Δτ is the interaction time (group delay time)

**The acceleration effect must occur in quantum phenomena, and this result is awaiting experimental confirmation.**

# Development of a new approach to gravitational resonance spectroscopy

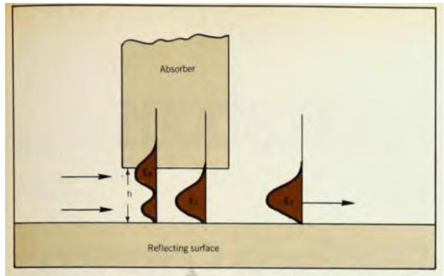
## Prediction of motion quantization in a gravitational field

# Ultracold neutrons

Neutrons with energies around one hundred nanoelectron volts
can be extracted from reactors and stored for up to 400 seconds—long enough
to encourage a search for the neutron electric dipole moment.

V. I. Luschikov

Physics Today **30**, 6, 42 (1977);

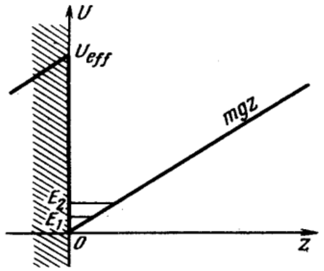


**The "flow" of ultracold neutrons along a horizontal plane.** The slot height $h$ is about 20 microns. Note that only neutrons with vertical-motion energy $E_1$ (the first energy level) pass through; this energy $E_1$ is $1.4 \times 10^{-12}$ eV. The wavefunction for the next state, $E_2$ ($=2.45 \times 10^{-12}$ eV) rises about 10 microns higher than that for $E_1$. Figure 7

*Письма в ЖЭТФ, том 28, вып. 9, стр. 607 – 609* *5 ноября 1978 г.*

КВАНТОВЫЕ ЭФФЕКТЫ
ПРИ ХРАНЕНИИ УЛЬТРАХОЛОДНЫХ НЕЙТРОНОВ НА ПЛОСКОСТИ

*В.И. Лущиков, А.И. Франк*




**Quantum states of neutrons in the Earth's gravitational field**

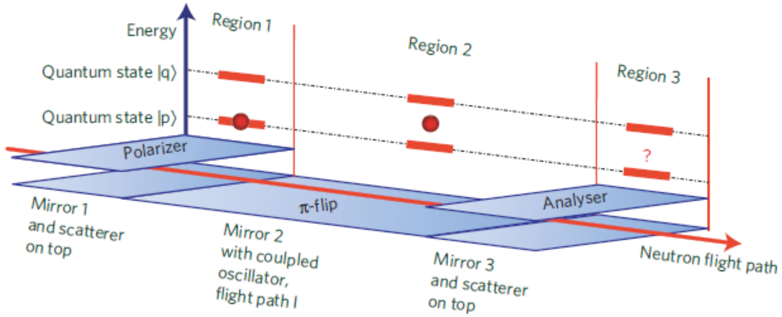
**Valery V. Nesvizhevsky*, Hans G. Börner*, Alexander K. Petukhov*, Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†, Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡ & Alexander V. Strelkov§**

Nature 415, 42 (2002) 298

**Realization of a gravity-resonance-spectroscopy technique**

Tobias Jenke[1], Peter Geltenbort[2], Hartmut Lemmel[1,2] and Hartmut Abele[1,3,4]*

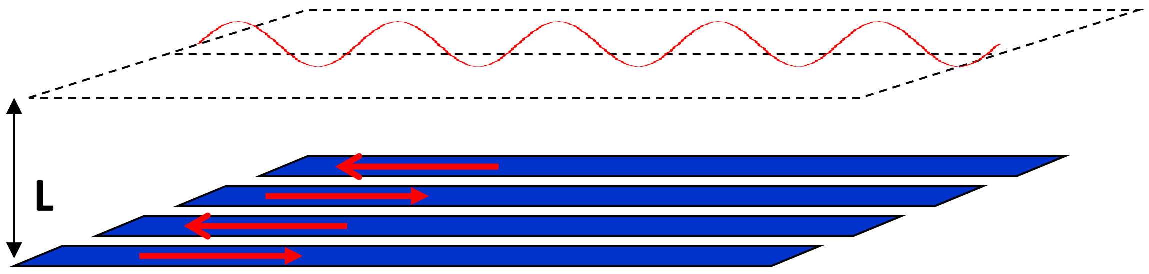
Nature Physics (2011)




**Precision gravity spectroscopy at the level of $10^{-15}$ eV**

# Development of a new approach to gravitational resonance spectroscopy

## Storage on a magnetic mirror

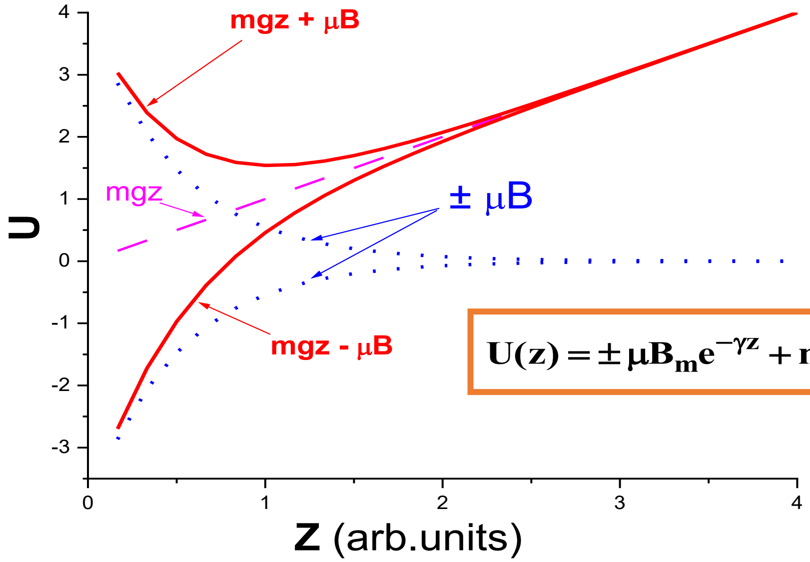



*A. I. Frank, V. G. Nosov. JETP Letters, 79, (2004) 313–315.*

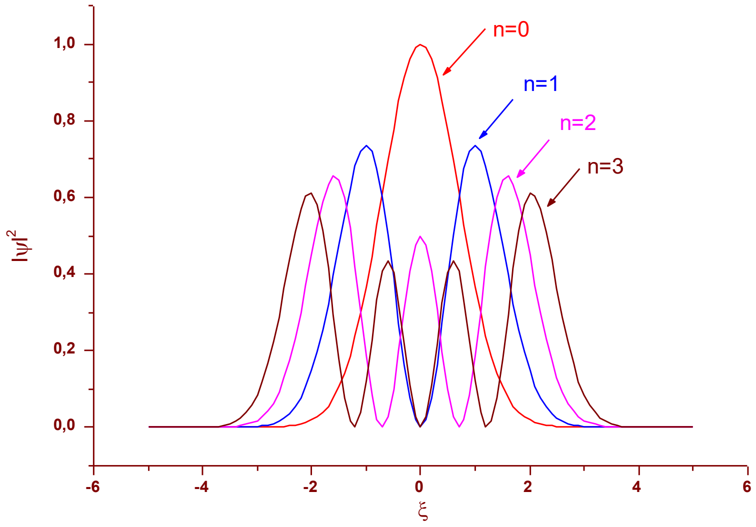
## Magnetic suspension condition

$$\left(B_0 = B_m e^{-\gamma L}\right) \qquad \gamma \mu B_m e^{-\gamma L} = mg,$$

$$\boxed{\gamma = \frac{mg}{\mu B_0}} \qquad \boxed{\omega = \sqrt{\frac{C}{m}} = \sqrt{\frac{mg^2}{\mu B_0}}}$$



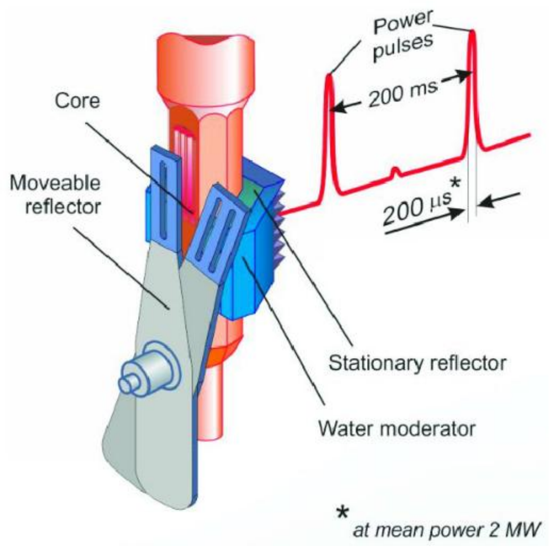

$$\boxed{U(z) = \pm \mu B_m e^{-\gamma z} + mgz}$$



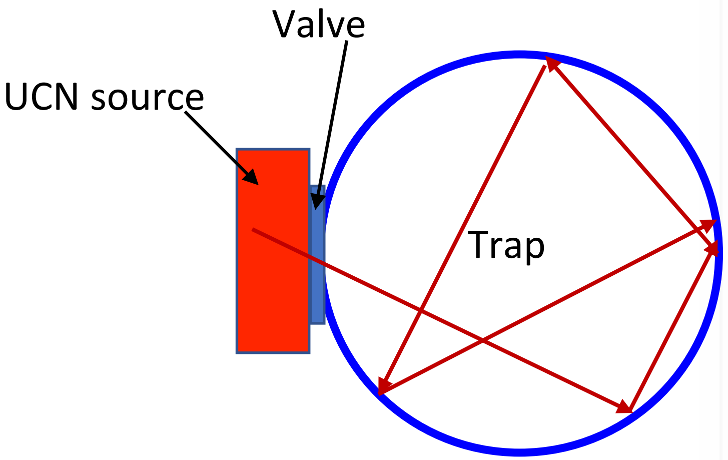
# Project of the UCN Source at FLNP JINR

# FLNP JINR pulsed source + pulsed accumulation of UCN in Trap

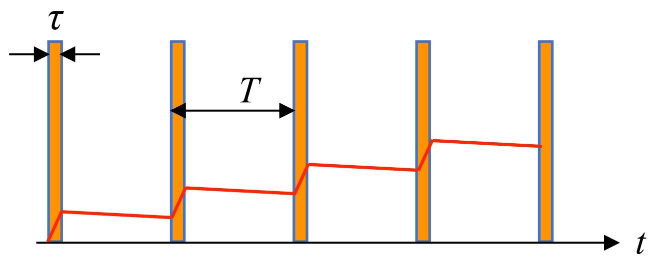
**IBR-2 pulsed reactor**




- Pulse frequency **5 Hz** (Period **0.2 s**)
- Pulse duration **350-500 µs**
- Average thermal flux density **~ $10^{13}$ см$^{-2}$·с$^{-1}$**
- Pulse thermal flux density **~ $10^{16}$ см$^{-2}$·с$^{-1}$**




F.L. Shapiro, 1972

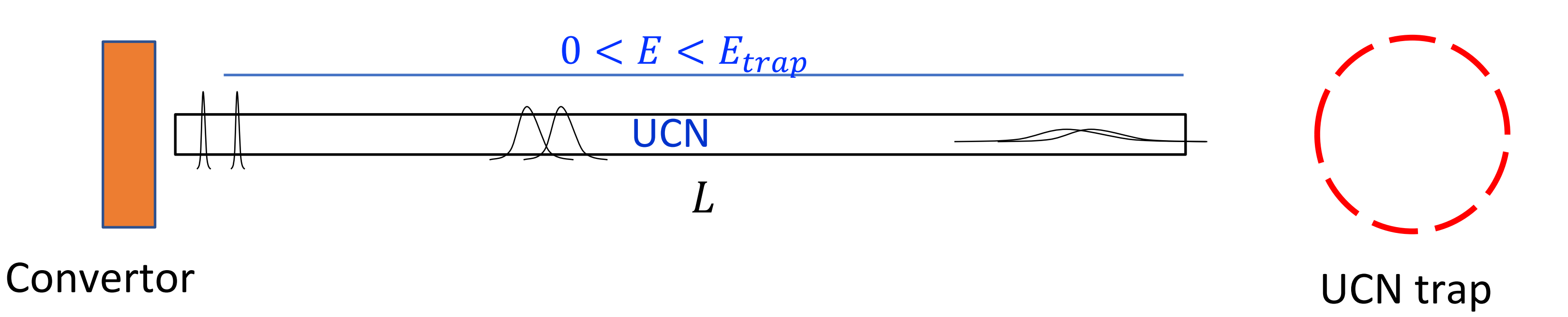



An approach is to fill the UCN trap only during the pulse and to efficiently isolate it the rest of the time.

In the case of relatively small losses, the equilibrium flux of UCNs in the trap can significantly exceed the time-averaged flux at its entrance.

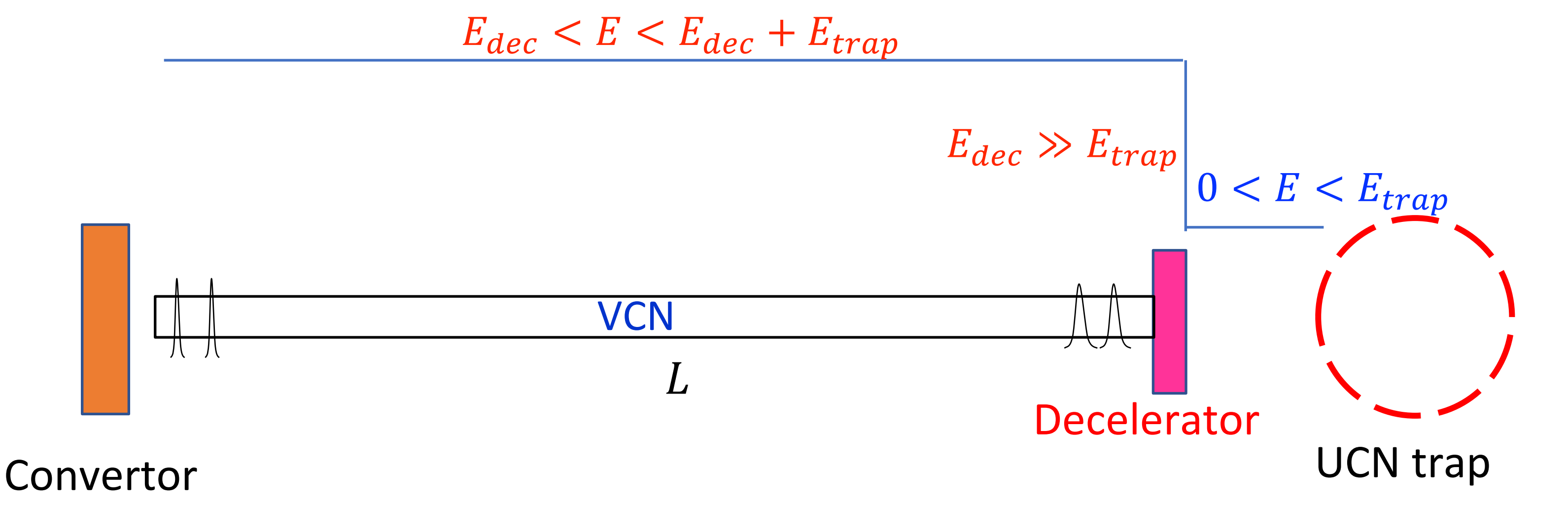
**Due to the biological shielding, the trap is distant from the moderator-convertor**

# 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




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

$$t \simeq \frac{L}{\sqrt{E_{dec}/2m}} \rightarrow \delta t \ll T$$

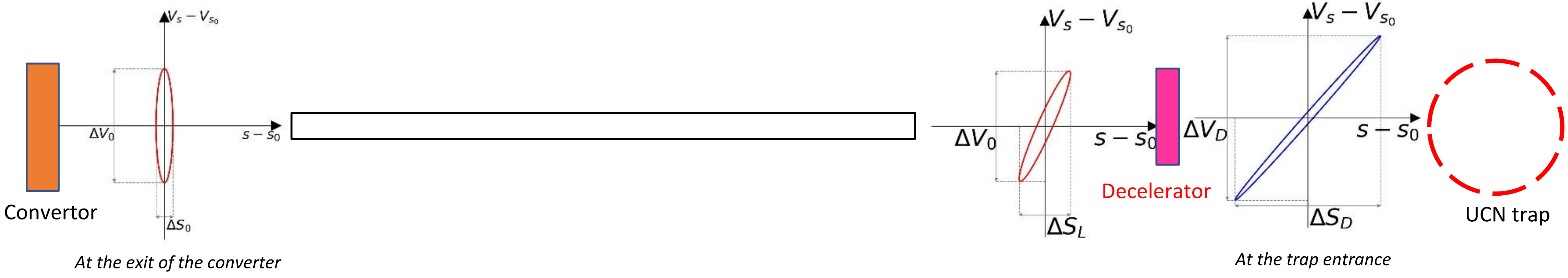
The flux of neutrons, which can be trapped after deceleration, has a pulsed struct

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

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

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

<u>Neutron pulse evolution phase portrait</u>




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

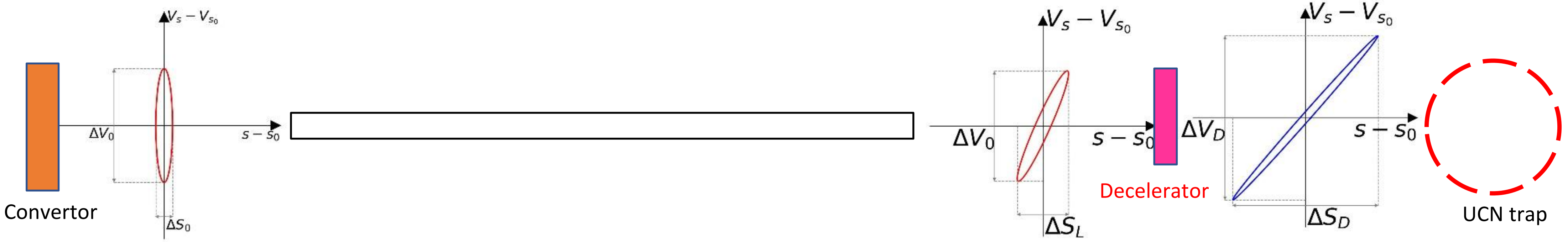
The deceleration process is not instant !

Then slower the neutrons, then more time they spend on deceleration

$$\delta t_{trap} = \delta t_{transp.} + \delta\tau_{dec} \text{ (deceleration time dispersion)}$$

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

Neutron beam phase portrait w/o compensation

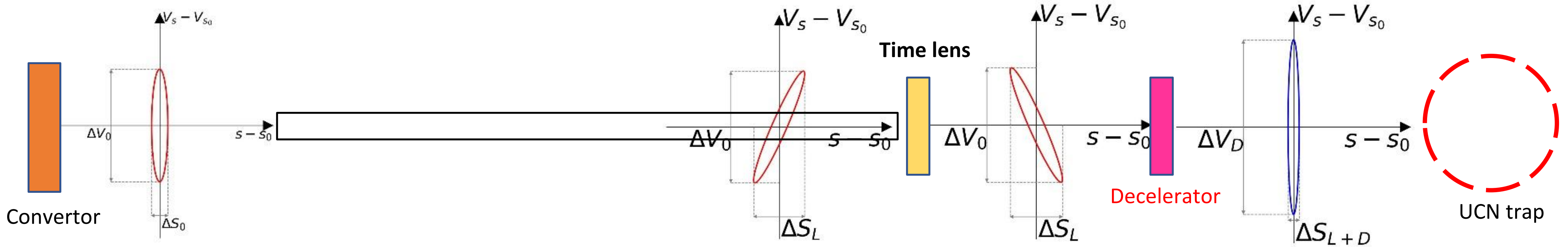



*At the exit of the converter*

*At the trap entrance*

$$\delta t_{trap} = \delta t_{transp.} + \delta\tau_{dec}$$

Neutron beam phase portrait in the ideal compensation case




*At the exit of the converter*

*Before lens*

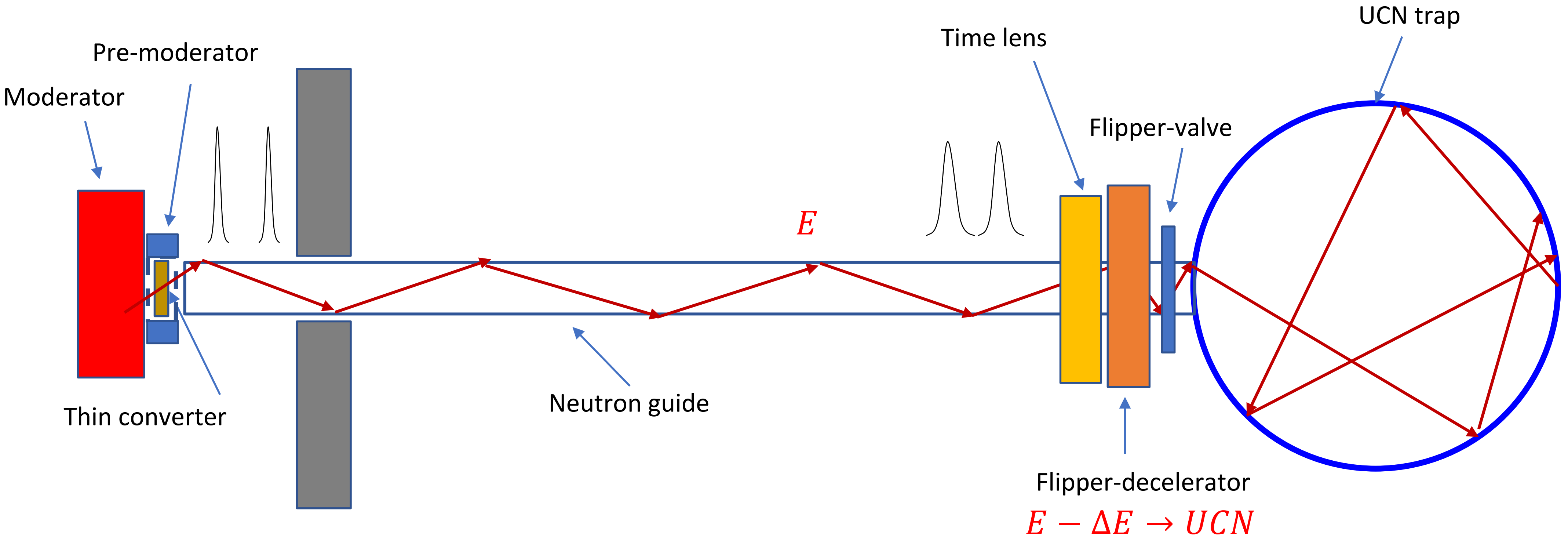
*After lens*

*At the trap entrance*

$$\delta t_{trap} = \delta t_{transp.} - \delta\tau_{dec}$$

# Schematic of the projected UCN source @ IBR-2 reactor

A.I. Frank, G.V. Kulin, M.A. Zakharov et al. PEPAN 56 (2025)

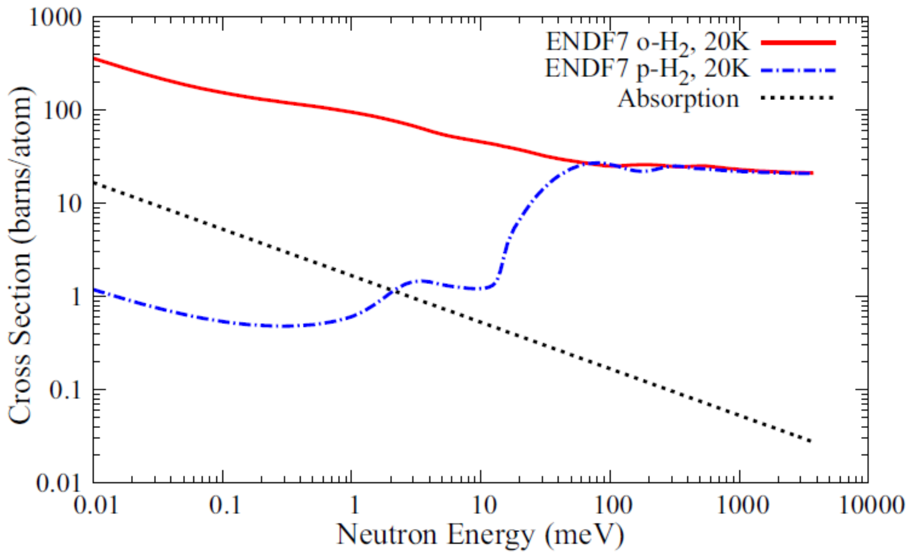



UCN Source @ IBR-2 reactor 3rd channel

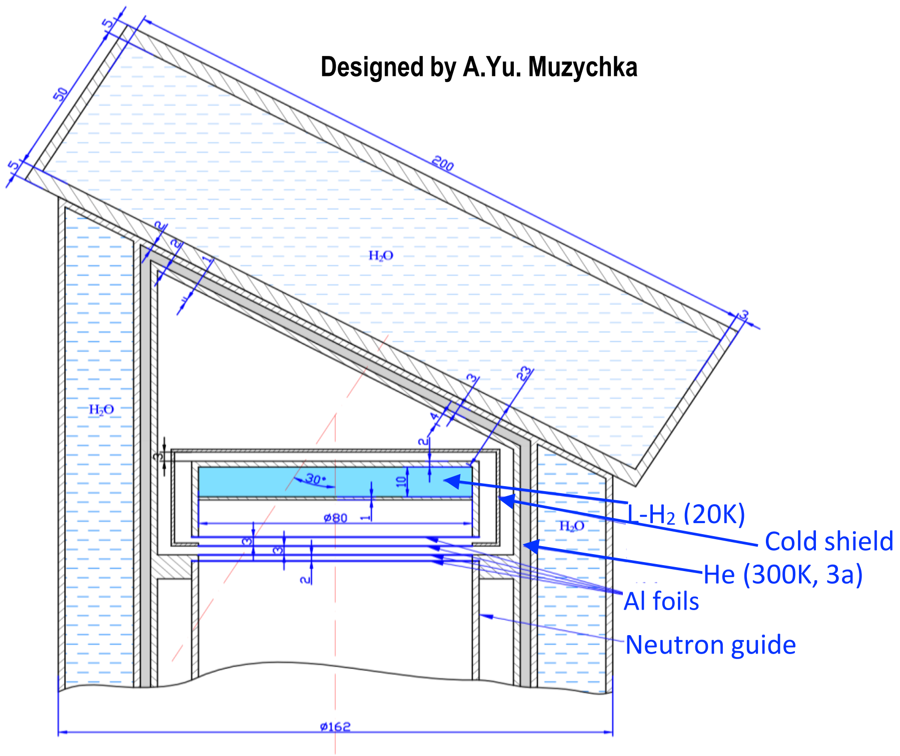
# Convertor

The basic variant assumes that the convertor will be a thin chamber with $LH_2$

Scattering cross section on $H_2$




VCN flux gain factor: **40**

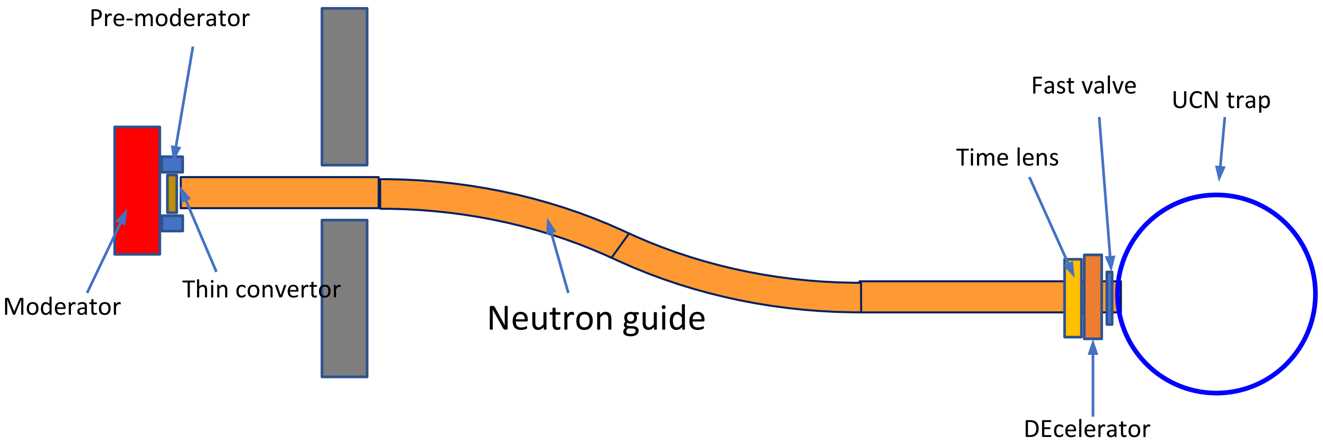



$LH_2$ convertor volume: **≈ 50 – 70ml**

$LH_2$ convertor weight: **≈ 3.5 - 5 g**

**Additional water moderator** Increases thermal neutron flux at the convertor by 3 times

# Neutron guide




Length: 13-15 m

Two bend sections with a curvature radius of about 20 m

S-shaped guide:

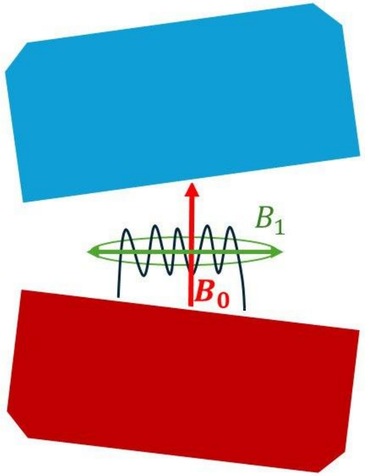
- significantly reduce the background of neutrons with velocities higher than 200 m/s
- geometry doesn't affect to time pulse shape

**Rather high requirements to the neutron guide inner surface:**

- The small micro-roughnesses should ensure transmittance at the level of tens of percent
- Permissible level of shape defects (waviness) should ensure equality of monochromatic neutron flight time at the level of 2-3 ms.

**The choice of material and design of the neutron guide will be done by results of especially performed experiments**

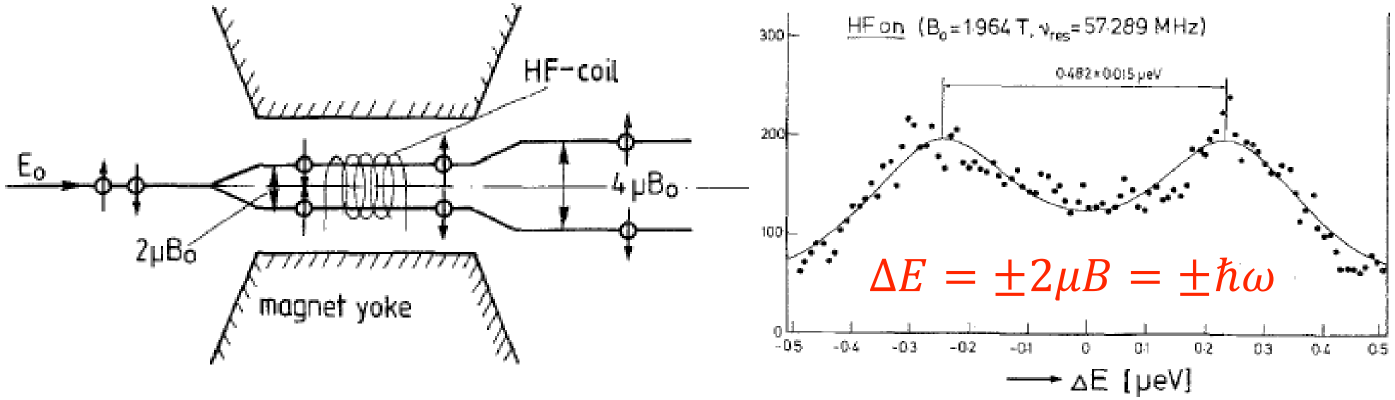
# Decelerator — gradient spin-flipper



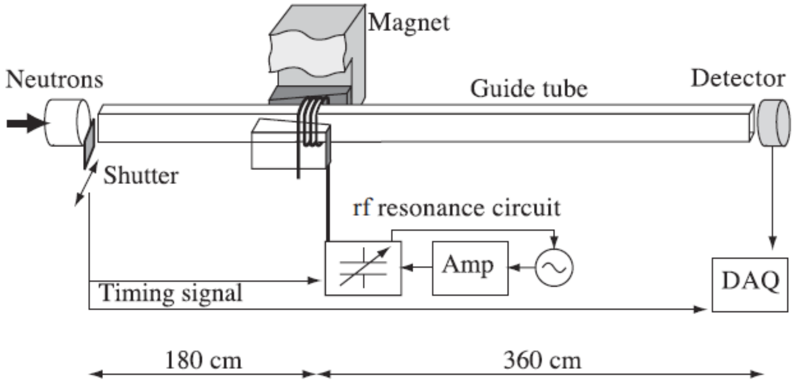

- V.I. Luschikov, Yu.V. Taran. NIM 228 (1984) 159
- A.N. Bazhenov, V.M . Lobashev, A.N. Pirozhkov and V.N. Slusar. NIM A332 (1984) 534
- S .V. Grigoriev, A.I. Okorokov, V.V. Runov. NIM A384 (1997) 451

Nonstationary spin flip in a magnetic field as a method of producing "supercold" neutrons — *G. M. Drabkin, R. A. Zhitnikov. Sov. Phys. JETP (1960)*

Neutron energy change at resonant spin-flip - *B. Alefeld et al., Zeit. für Phys. B (1981)*

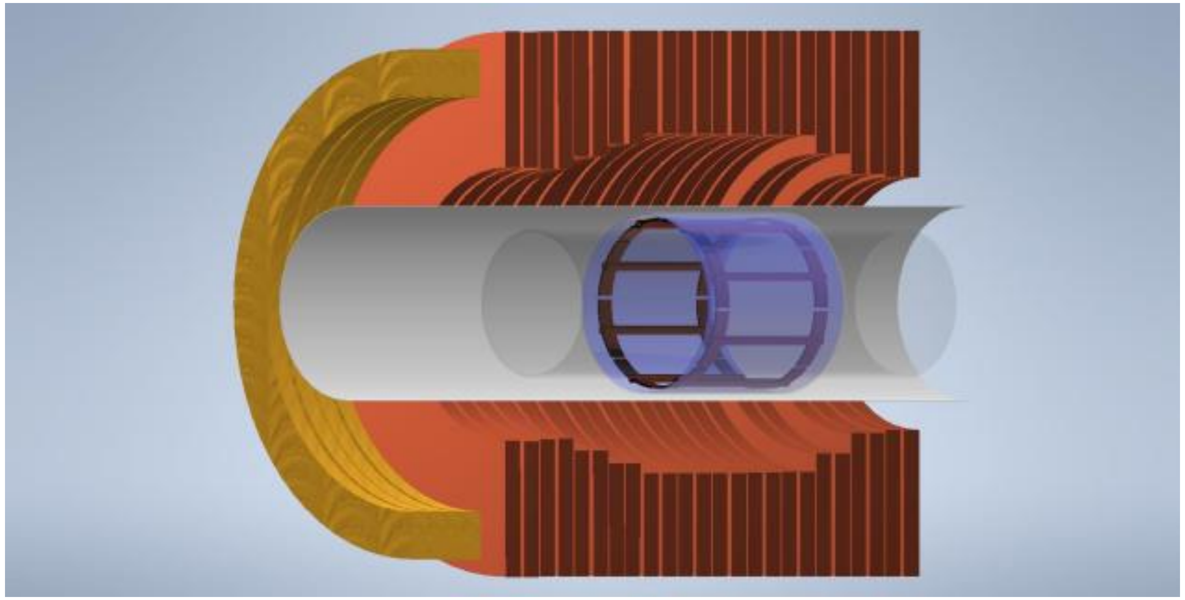



Gradient spin-flipper for UCN time focusing - *Arimoto et al. Prys.Rev. A (2012)*



# Decelerator — gradient spin-flipper

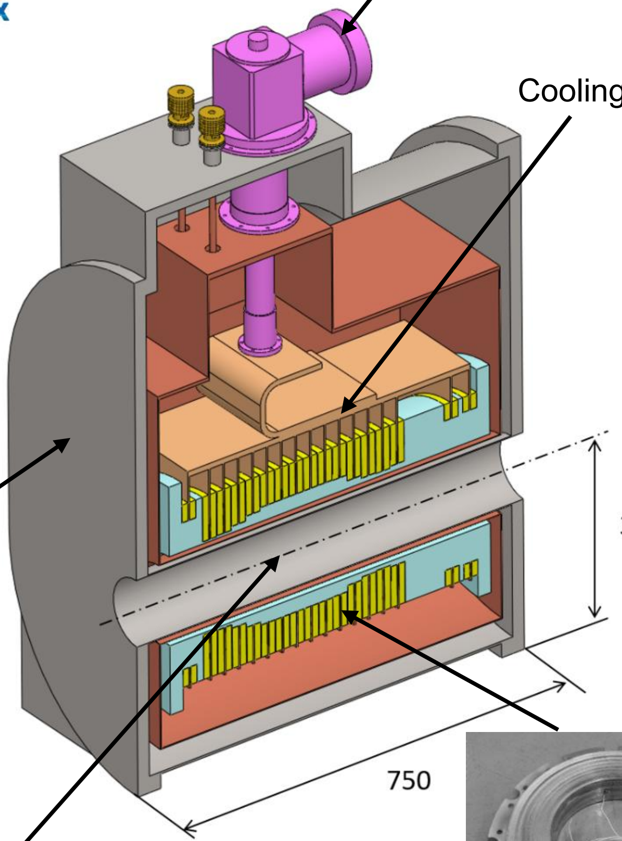
It is desirable that the magnetic system forming the stationary field, as well as the HF resonator, have cylindrical symmetry.



$$B = \frac{\Delta E}{2\mu} \approx 20\,T \qquad \Delta E \approx 2.4\,\mu eV \qquad f = \frac{\omega}{2\pi} \approx 520\,MHz$$

It allows to slow down VCNs with velocities of 20 m/s to UCNs with velocities of 5 m/s

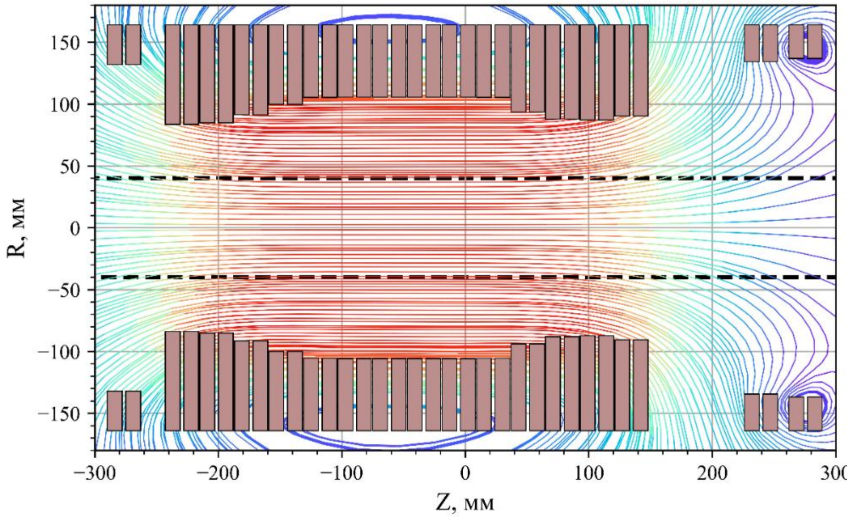
# Decelerator — gradient spin-flipper



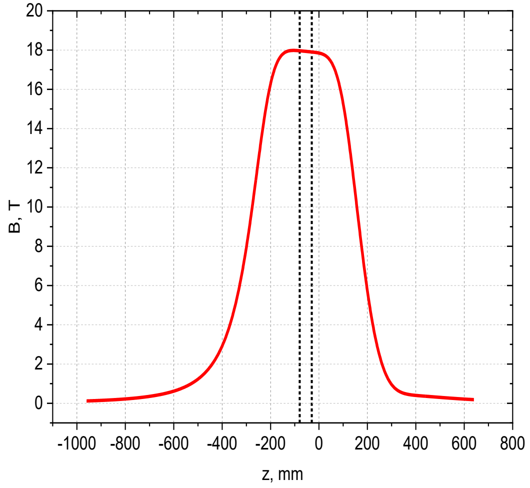

Pancake made from HTS tape
(a flat, double coil)

A. A. Popov et. al.
arXiv:2503.10878 [physics.ins-det]

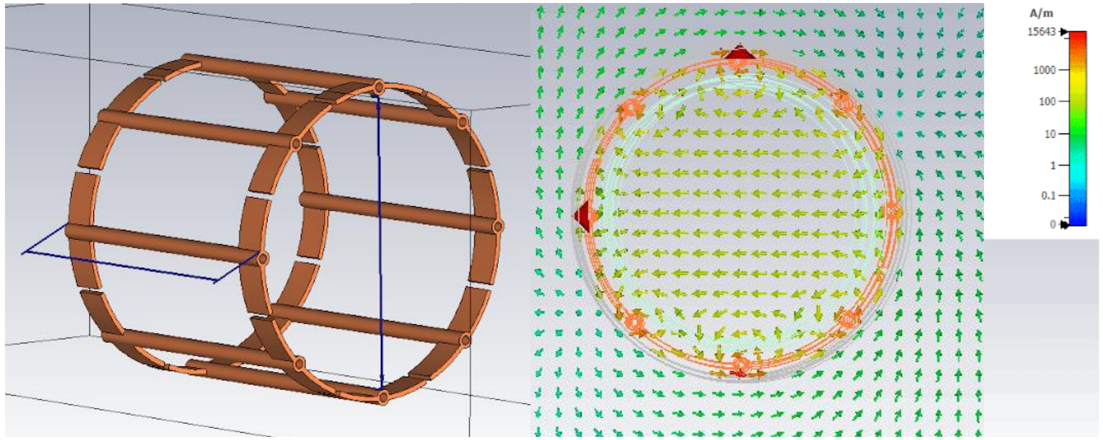
## Stationary gradient magnet



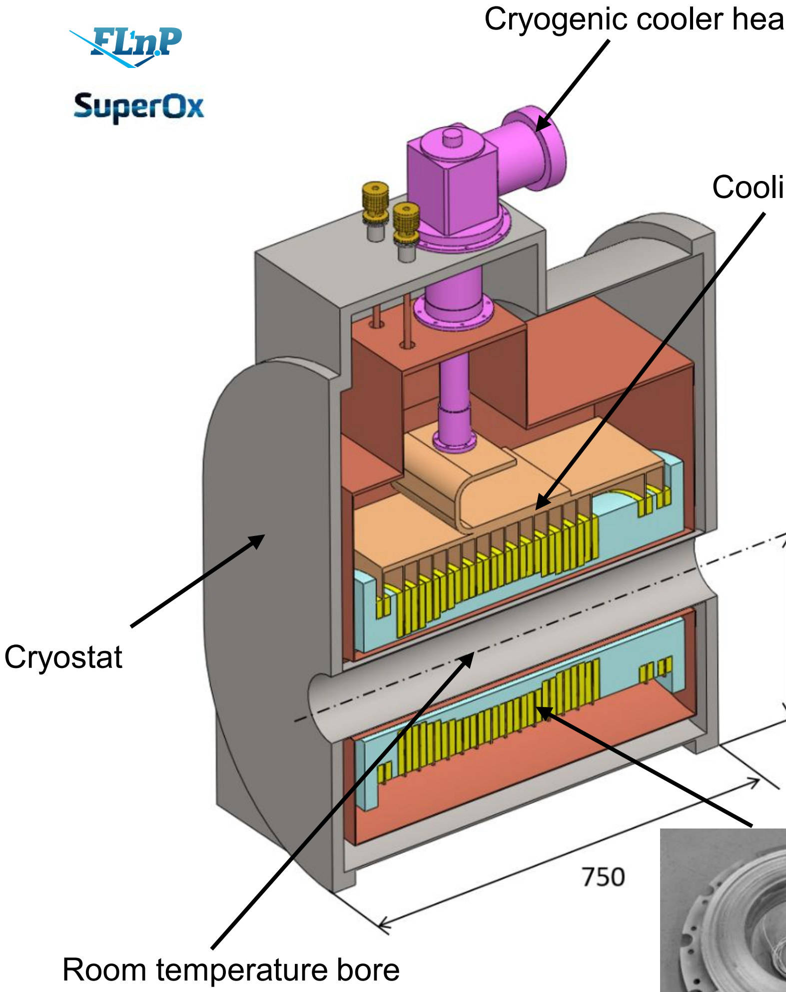

Magnetic field profile along Z-axis

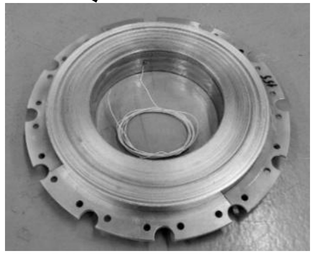



## Birdcage type HF resonator



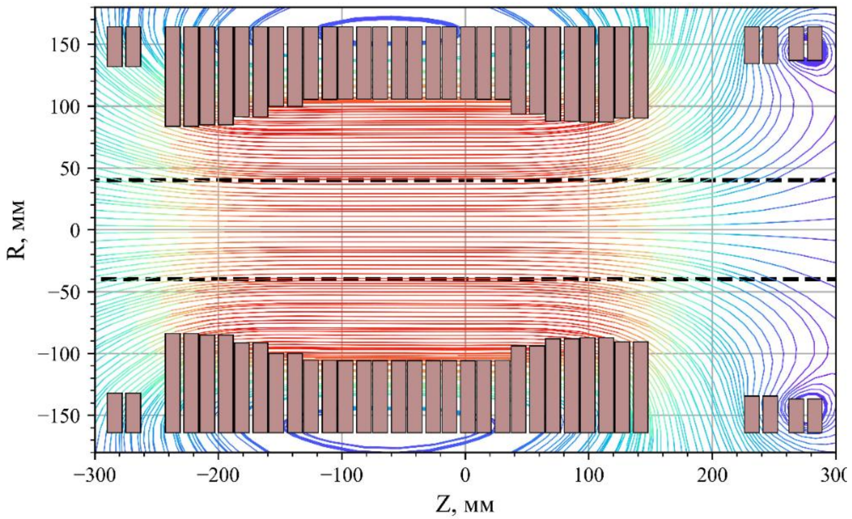
# Decelerator — gradient spin-flipper

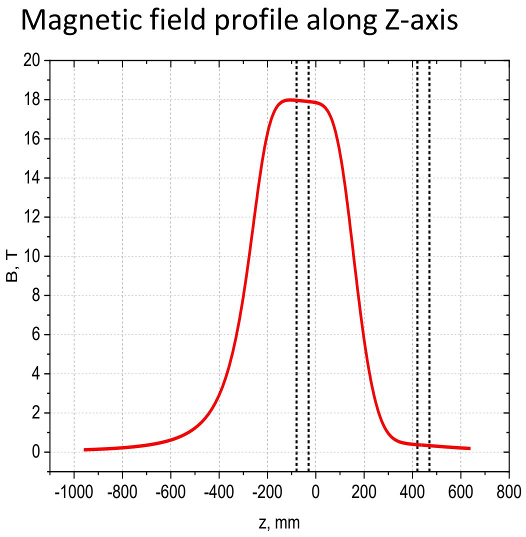


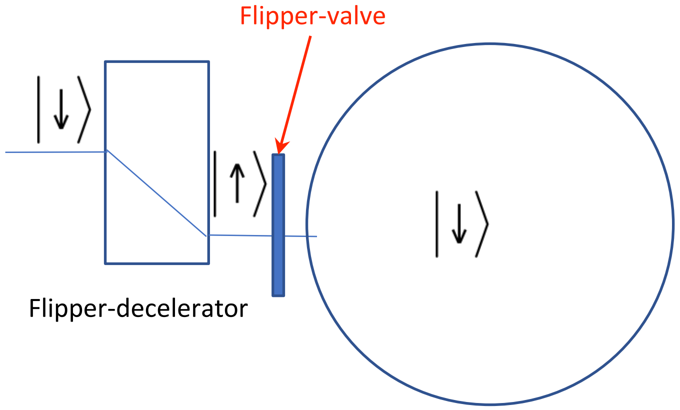
Pancake made from HTS tape
(a flat, double coil)

A. A. Popov et. al.
arXiv:2503.10878 [physics.ins-det]




The valve is a gradient spin–flipper located in the area of decreasing of the flipper-decelerator field. Approximately in the 0.3-0.4T field

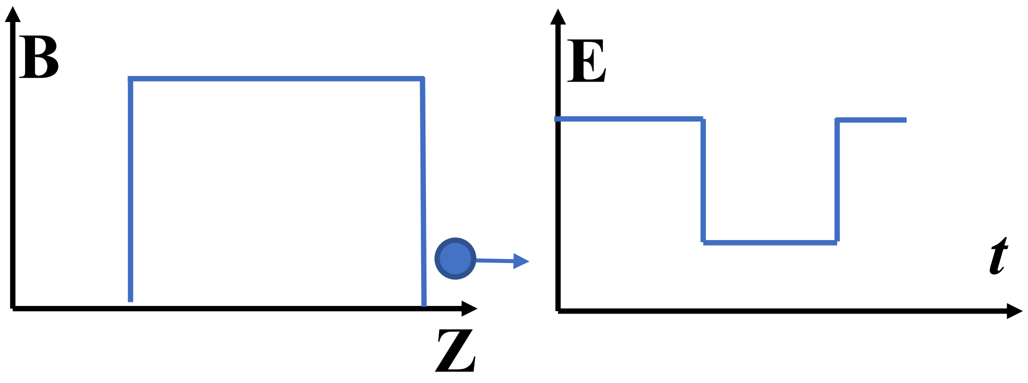


# Physics principals of time lens action

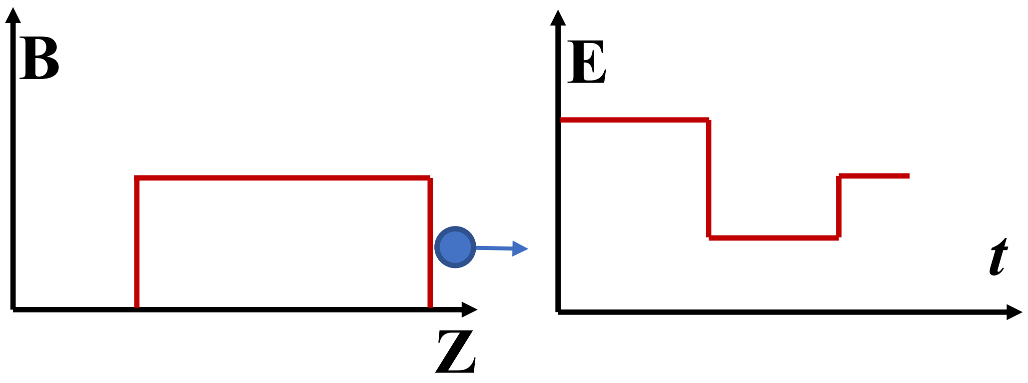
**the functional principle of time lens is based on the magnetic field variation in a certain space region during the neutron time of flight in this region**

L.Niel, H.Rauch, *Acceleration, deceleration and monochromatization of neutrons in time dependent magnetic fields*. Z. Phys.B. – Condensed Matter 74, 133 (1989)

***Passing through stationary magnetic field.***




***Passing through magnetic field, which changed its strength during the time when neutron inside this field***



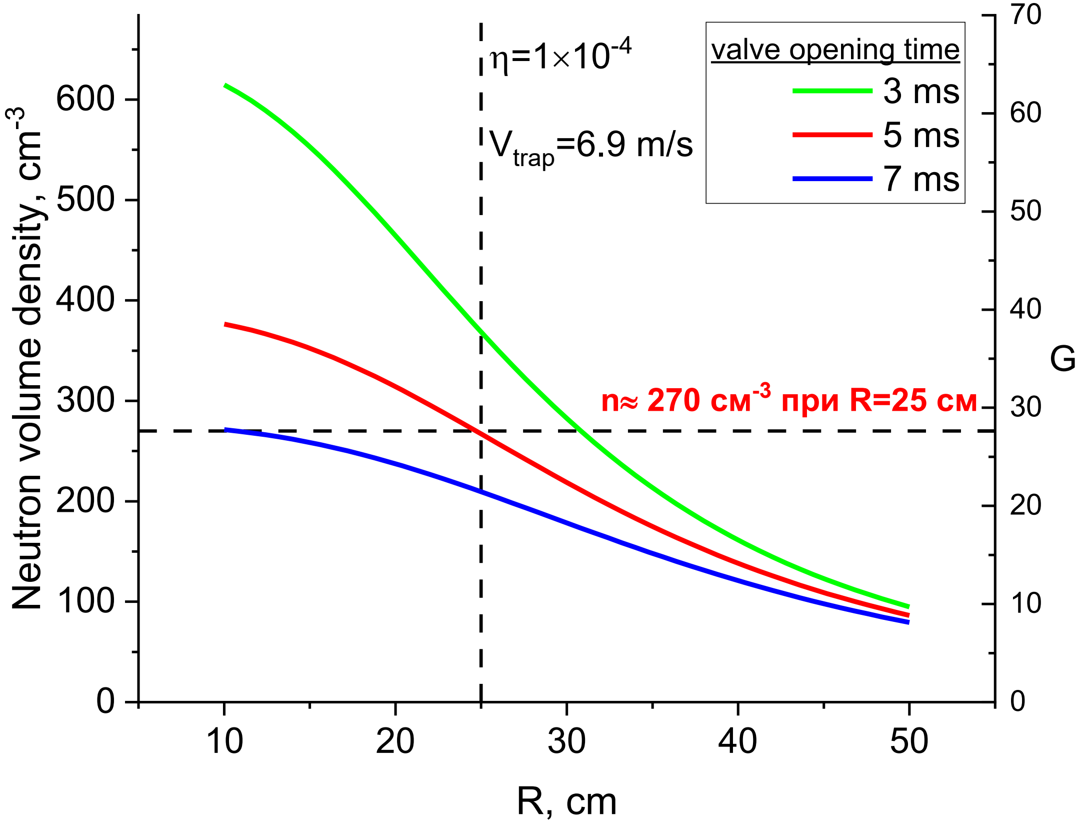

The energy transferred by the lens $\Delta E = \mu\Delta B$ is defined by the variation value of the magnetic field $\Delta B$ during the residence time of the neutron.

In our case: $\Delta B = 1.5\,T,\ \ t \approx 8\,ms$

# UCN density inside a spherical trap (convertor is $LH_2$)

| | |
|---|---|
| **Average thermal flux density at the convertor, $cm^{-2}s^{-1}$** | **3×10$^{13}$** |
| **Flux transmittivity coefficient due to phase volume transformation**<br>• guide boundary velocity **5.35 m/s**,<br>• limitation in longitudinal velocities after deceleration **$3.5\ m/s \le V_z \le 5.5\ m/s$** | **0.26** |
| **VCN transmission of 13 m neutron guide**<br>• only losses due to roughness was taken into account | **0.6** |
| **Gain factor for $LH_2$ convertor** | **40** |
| **Polarized neutrons** | **0.5** |

**UCN volume density inside the trap in dependance on pulse duration at the trap entrance**

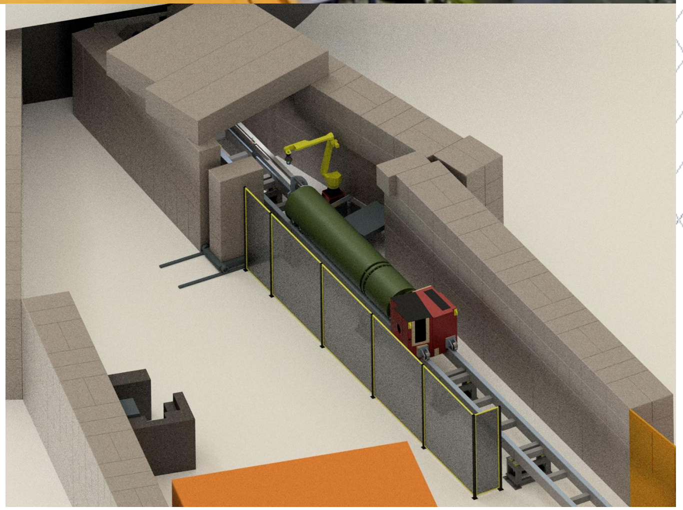


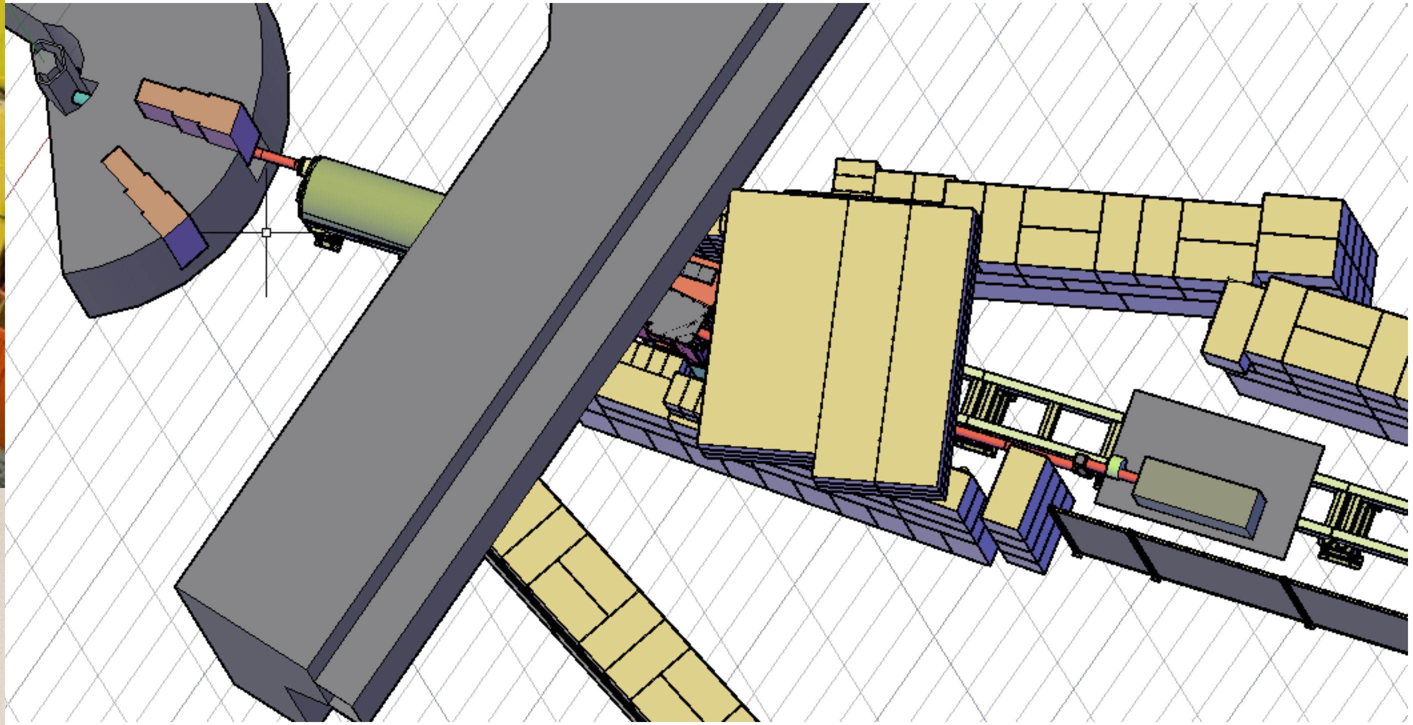

Estimated UCN production rate: ~ 3×10$^5$ s$^{-1}$ (at $V_z$< 7 м/с)

# Scientific and technical challenges have to be solved during project

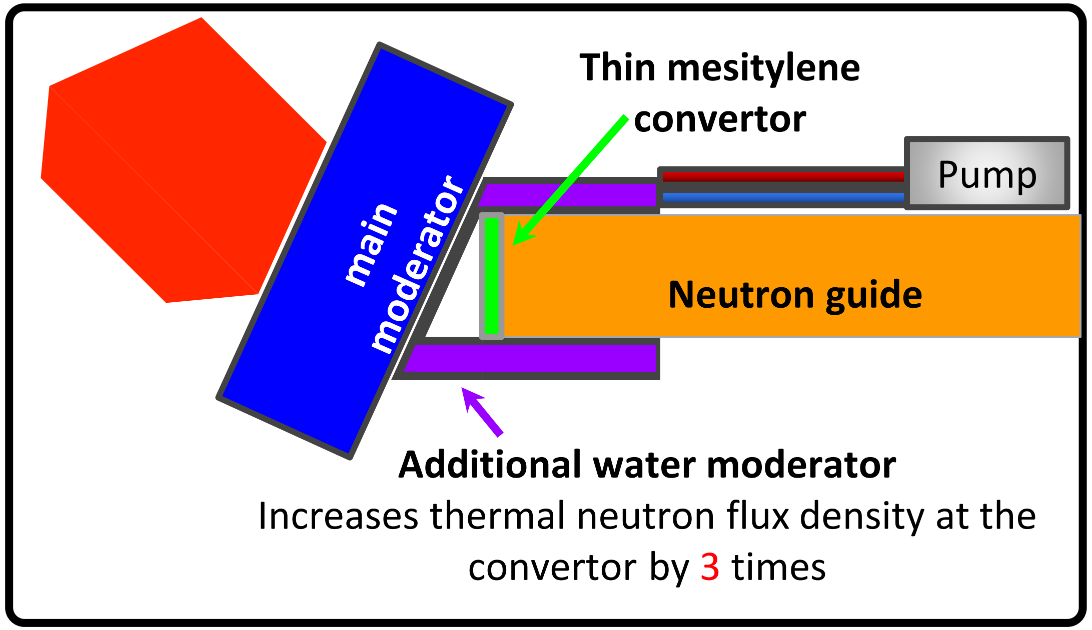
- Construction design and selection of materials for the head section of the beamline with the converter.
- The safety problem concerning the proposed use of a cryogenic, a small volume liquid-hydrogen converter.
- Design of the engineering infrastructure of the source on 3rd channel of IBR-2 reactor.
- Construction design and selection of materials of the neutron guide providing the required time characteristics of VCN transport.
- Construction design, selection of the material and coating of the UCN trap.
- Design of compensating magnetic lens.

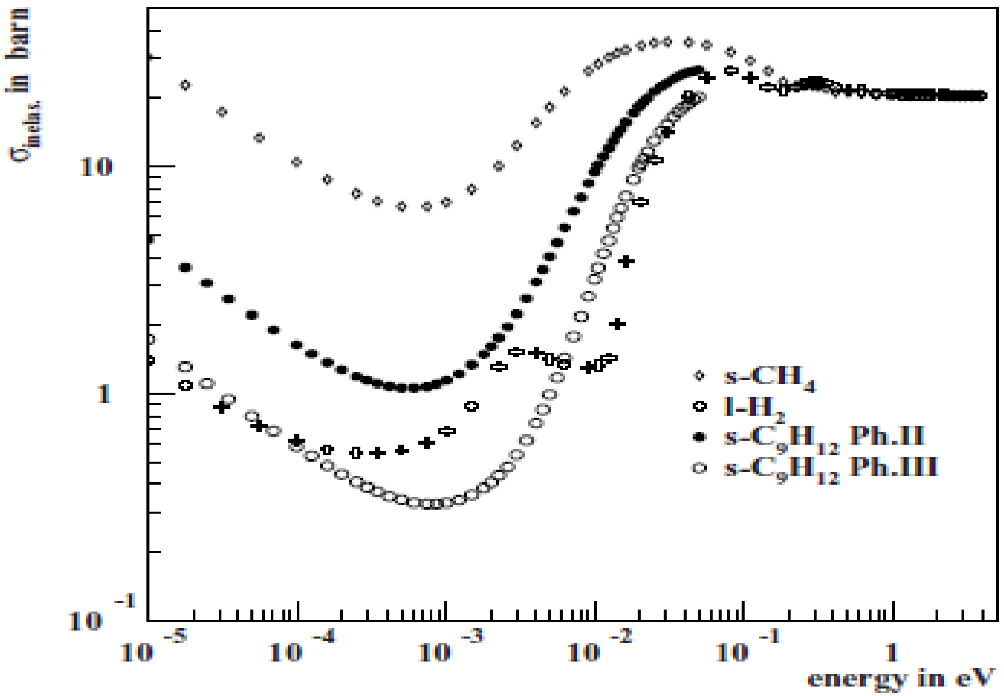
# VCN test facility at 3rd channel of IBR-2 reactor as prototype of the UCN source





# VCN test facility – Cold (20K) mesitylene converter



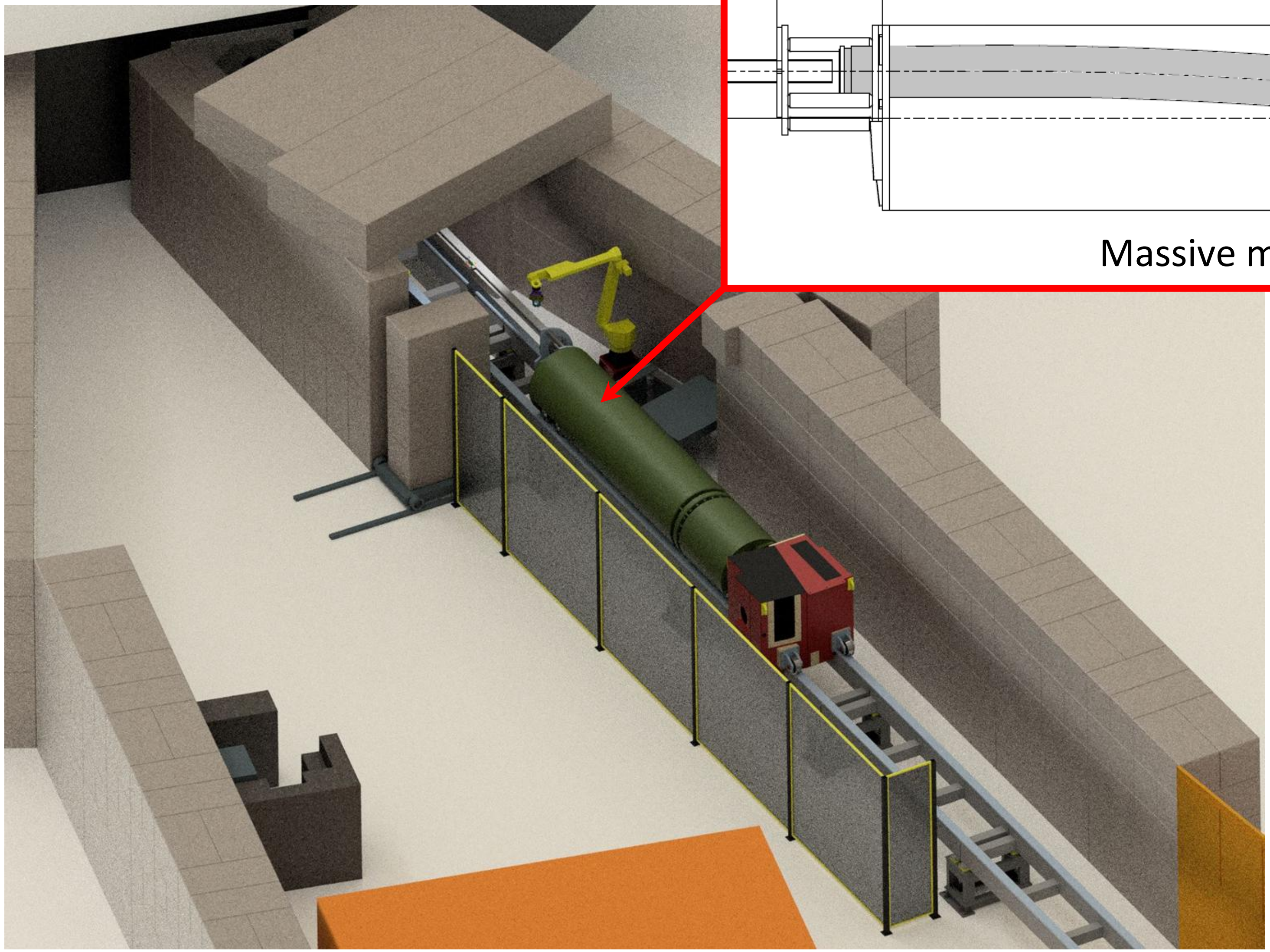



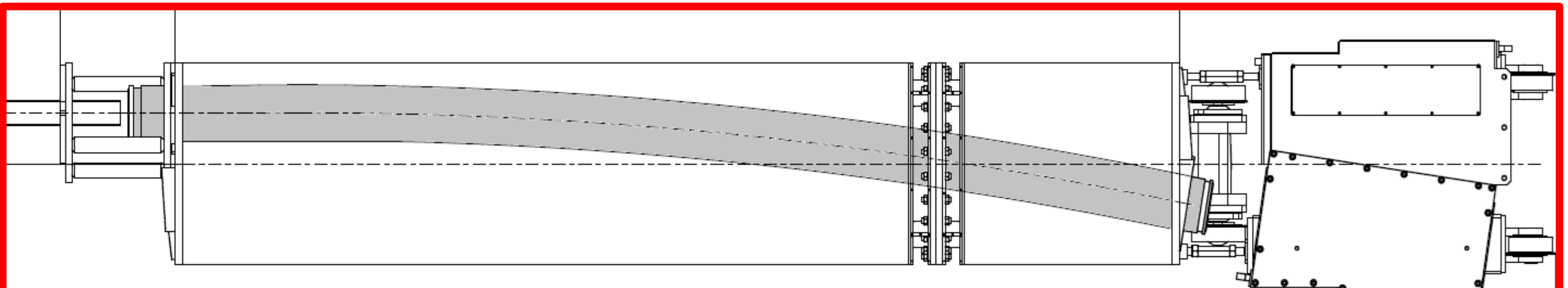

VCN/UCN flux gain factor: **~10**

Mesitylene thickness **~ 1-2 mm (~20ml)**

**The experience of creating this converter will be useful for creating the main source converter**

# VCN test facility – the neutron guide requirements



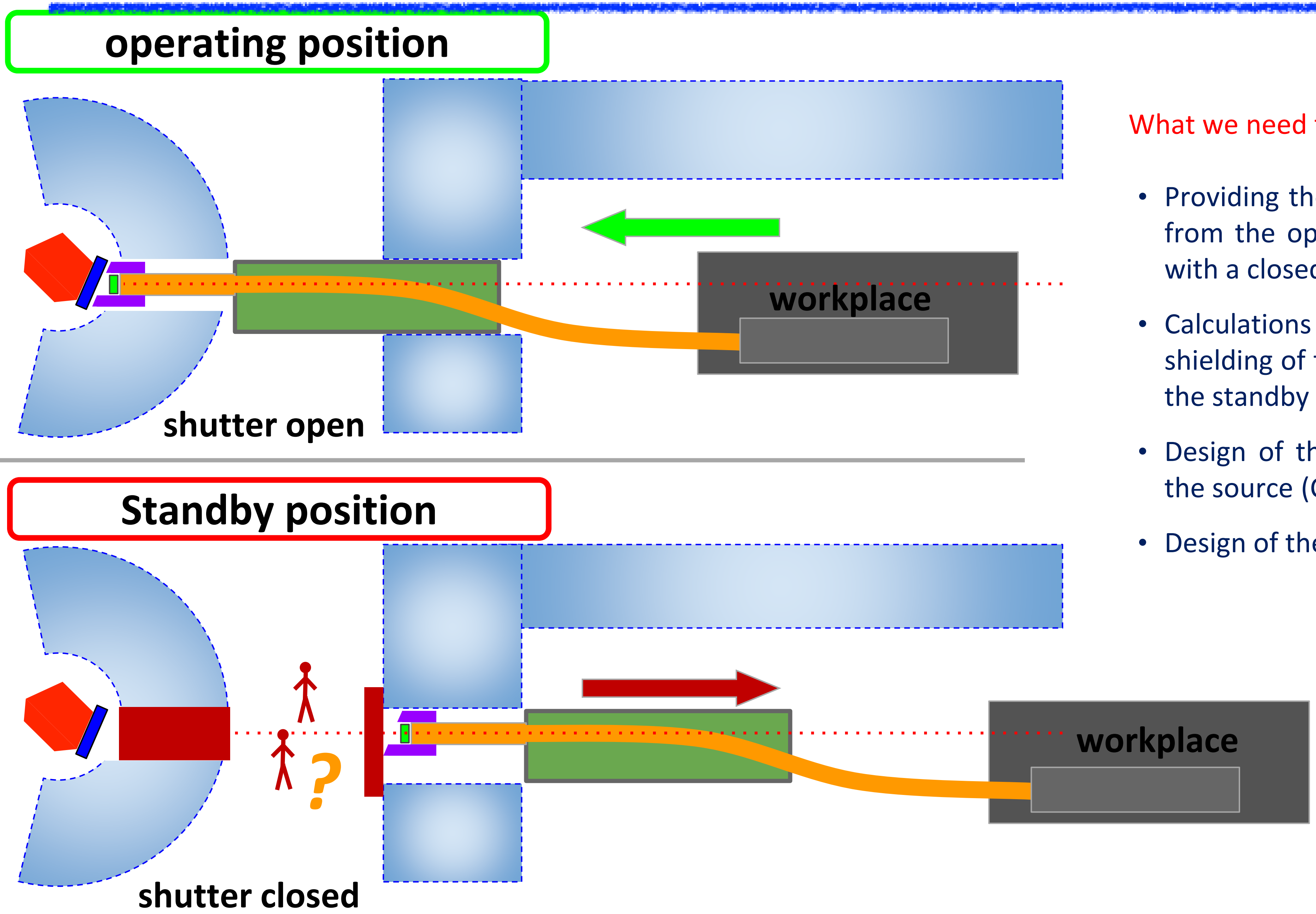


Massive movable shielding (stopper)

The neutron guide for VCN test facility must fit into existing bend tunnel of the movable shielding

An inner surface of the neutron guide will not need to meet as strict requirements as the neutron guide in the planned UCN source.

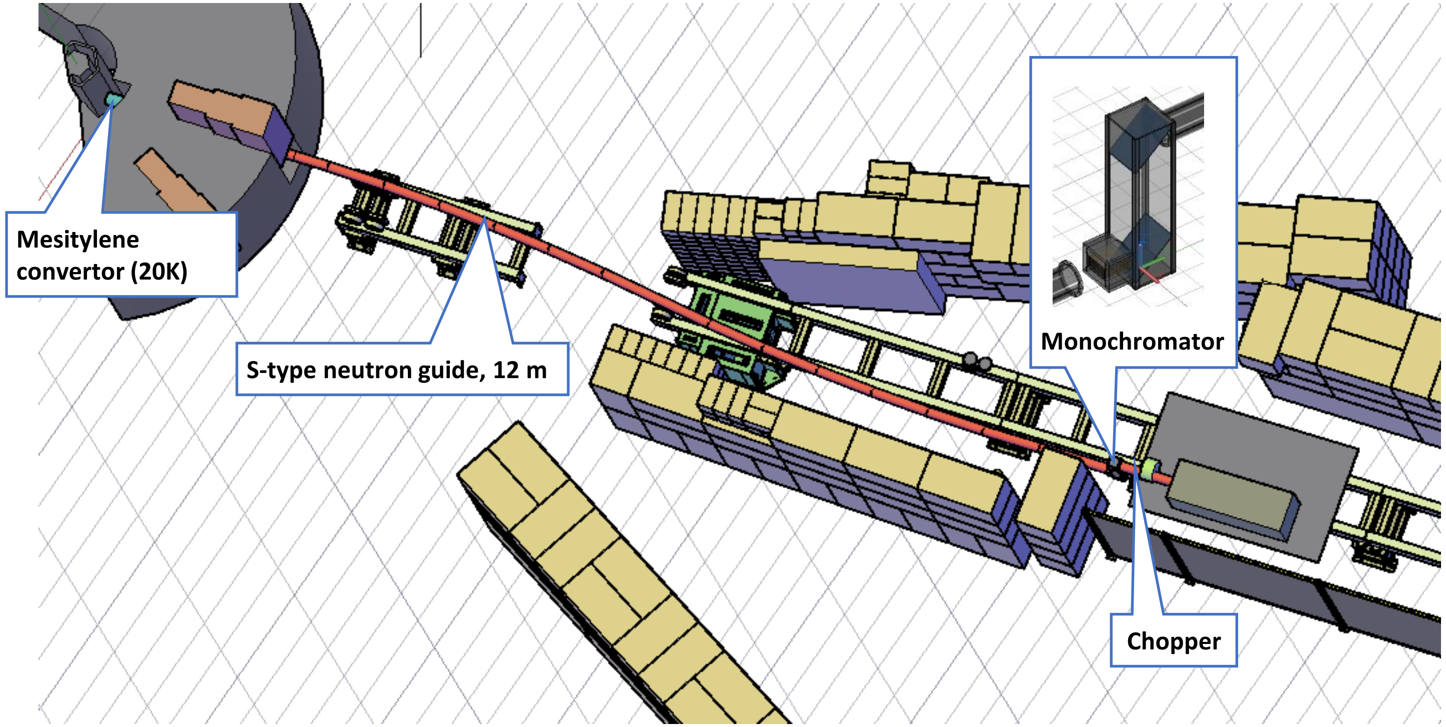
# VCN test facility requrements




What we need to do:

- Providing the possible moving of the source from the operating to the standby position with a closed shutter.
- Calculations and designing radiation shielding of the head part of the beamline in the standby position
- Design of the engineering infrastructure of the source (Cryogenics, Vacuum, …)
- Design of the workplace

# VCN test facility at 3$^{rd}$ channel of IBR-2 reactor as prototype of the UCN source




In main features, the design of the VCN test source will have many similarities with the design of the UCN source.

The construction of VCN test facility will make it possible to verify the correctness of the technical solutions taken to create the projected source, as well as to conduct experimental studies necessary for the UCN Source implementation.

VCN test facility will provide the first practical experience of VCNs and UCNs for an essential part of the newly forming group.

# Thank you for your attention!!!