National Research Centre «Kurchatov Institute»
PETERSBERG NUCLEAR PHYSICS INSTITUTE

DEVELOPMENT AND IMPLEMENTATION OF TECHNOLOGIES FOR A NEW ULTRACOLD NEUTRON SOURCES BASED ON SUPERFLUID HELIUM

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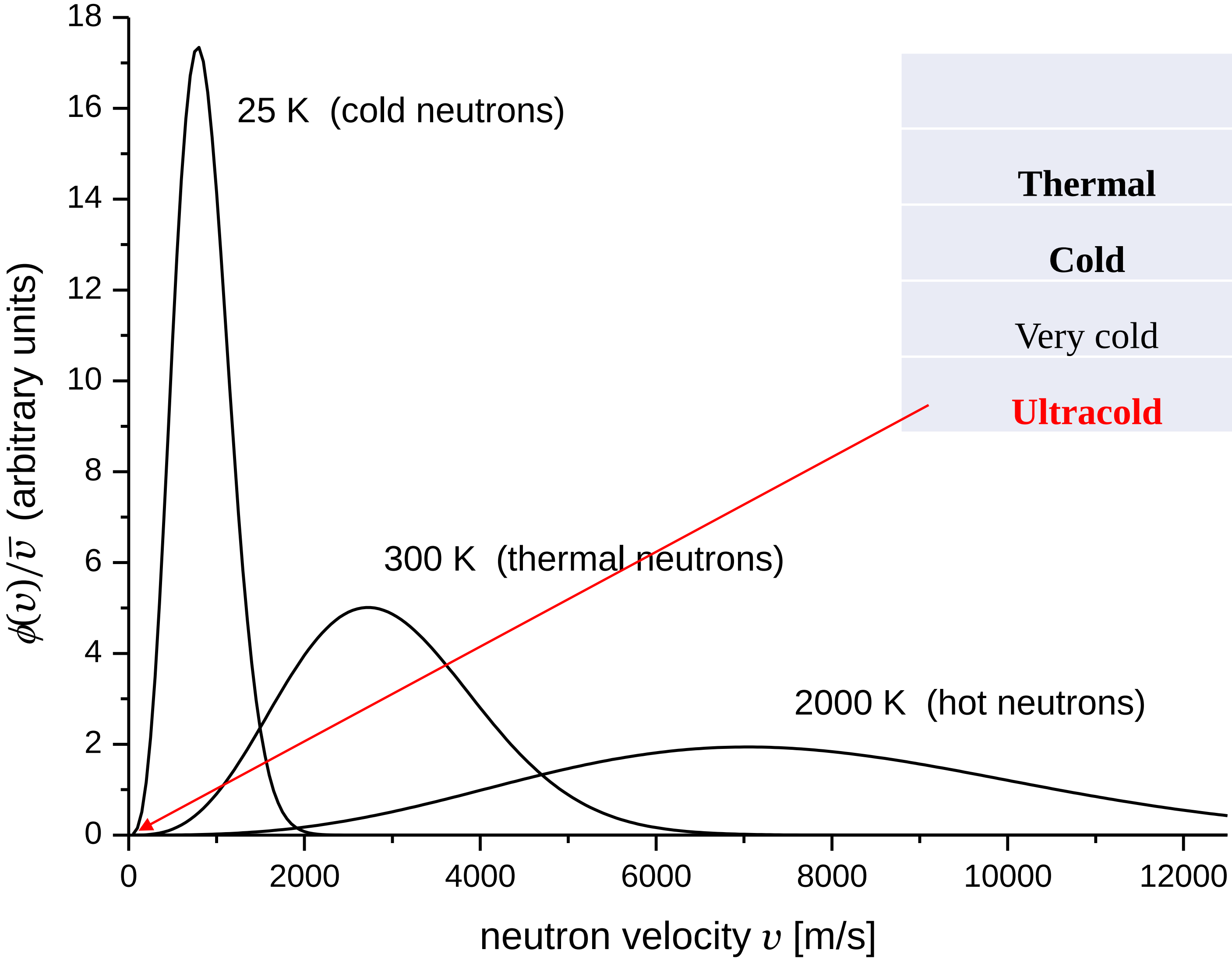
ICPPA
The 7th international conference on particle physics and astrophysics

ULTRACOLD NEUTRONS

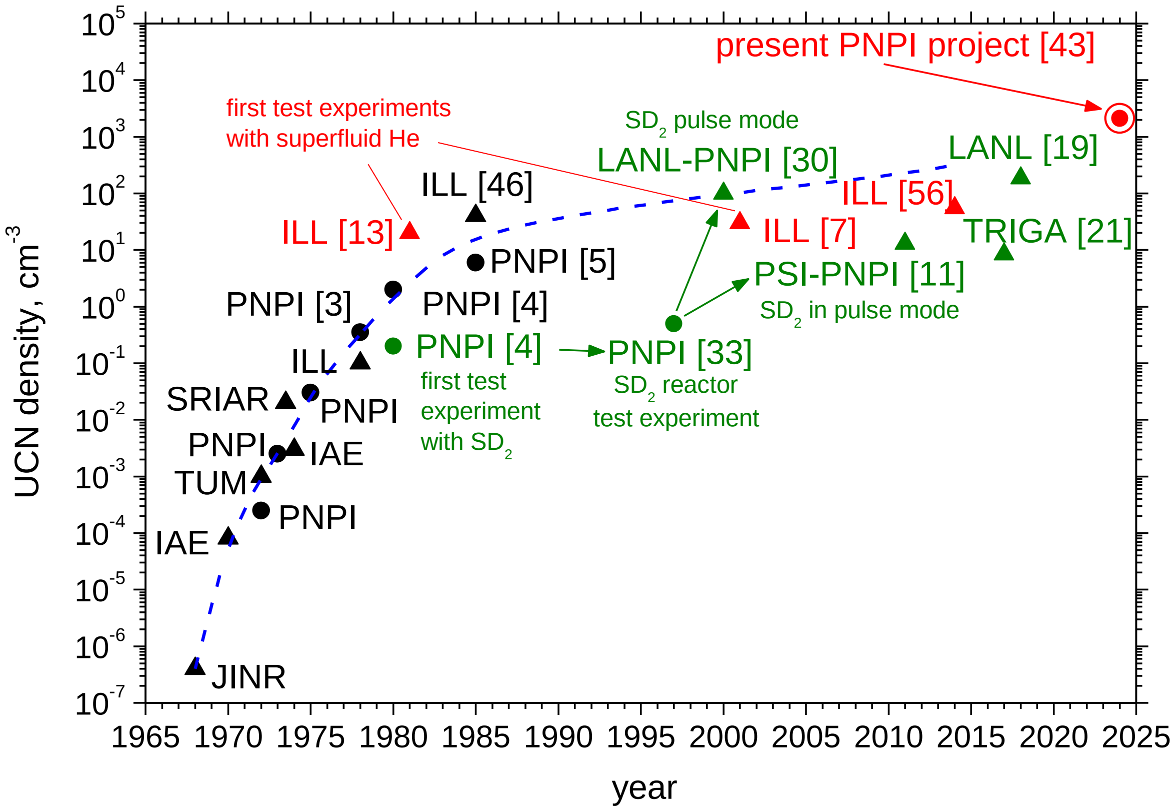


	Energy, eV	**Energy, К**	**Velocity, m/s**
Thermal	$5 \cdot 10^{-3} \div 0,5$	$6000 \div 50$	$9,8 \cdot 10^{2} \div 9,8 \cdot 10^{3}$
Cold	$10^{-4} \div 5 \cdot 10^{-3}$	$50 \div 1$	$1,4 \cdot 10^{2} \div 9,8 \cdot 10^{2}$
Very cold	$10^{-7} \div 10^{-4}$	$1 \div 10^{-3}$	$4,4 \div 140$
Ultracold	**$\sim 10^{-7}$**	**10^{-3}**	**~4,4**

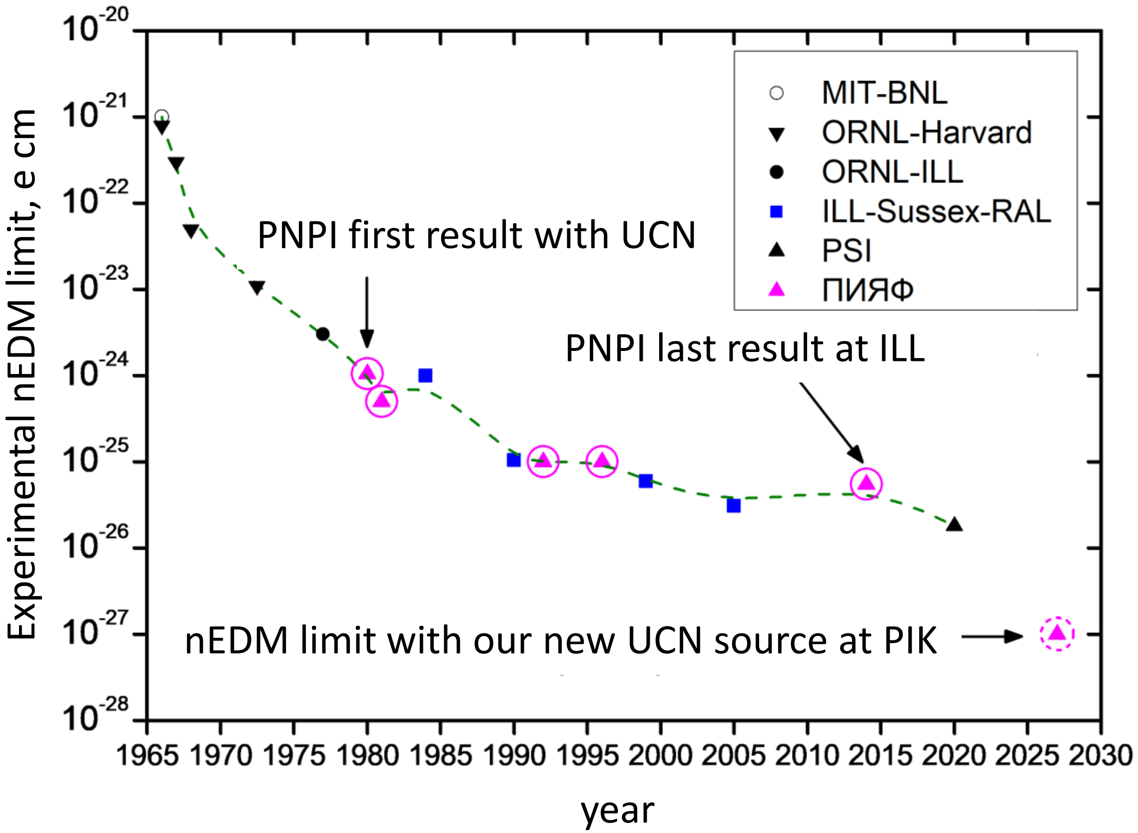
Ultracold neutrons have the property of being reflected from any matter at any angle of incidence, so they can be stored in material traps for tens and hundreds of seconds..

MOTIVATION

- Over the past 20 years, there has been no progress in increasing the density of ultracold neutrons
- Highly efficient cryogenic methods by using **LD2** or **sD2** have been mastered
- For further progress, it is proposed to **use superfluid helium** to obtain UCN
- Progress in the development of UCN sources is holding back progress in researches



World progress in increasing the UCN density



Progress in lowering the upper limit on the neutron EDM

UCN PRODUCTION

Neutron source → E = 300 K n → Pre-moderator T = 20 K → E = 12 K n → UCN convertor T = 1 K → E = 10^{-3} K n

$$\rho_{UCN} = P\tau$$

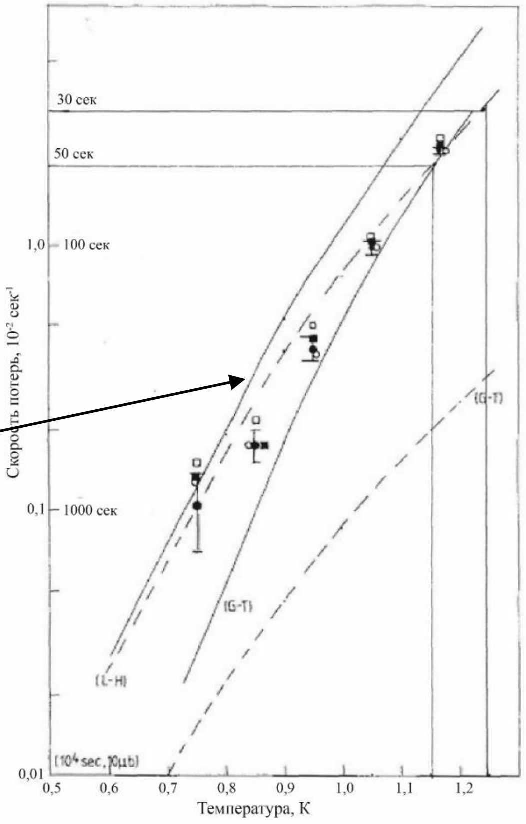
$$\tau^{-1} = \tau^{-1}_{\beta} + \tau^{-1}_{capture} + \tau^{-1}_{wall\ losses} + \tau^{-1}_{upscattering}$$

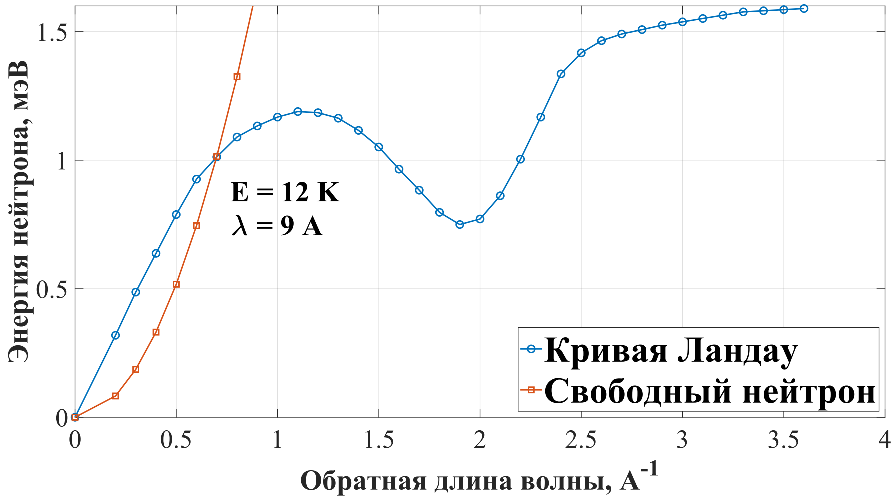
τ_{decay} = const

$\tau_{capture} \rightarrow He^3/He^4$

$\tau_{wall\ losses} \rightarrow$ coating → 42 c

$\tau_{upscattering} \rightarrow T_{He}$





$E_{нач}$=12 K → $E_{УХН} \approx 10^{-3}$ K

λ=9 Å

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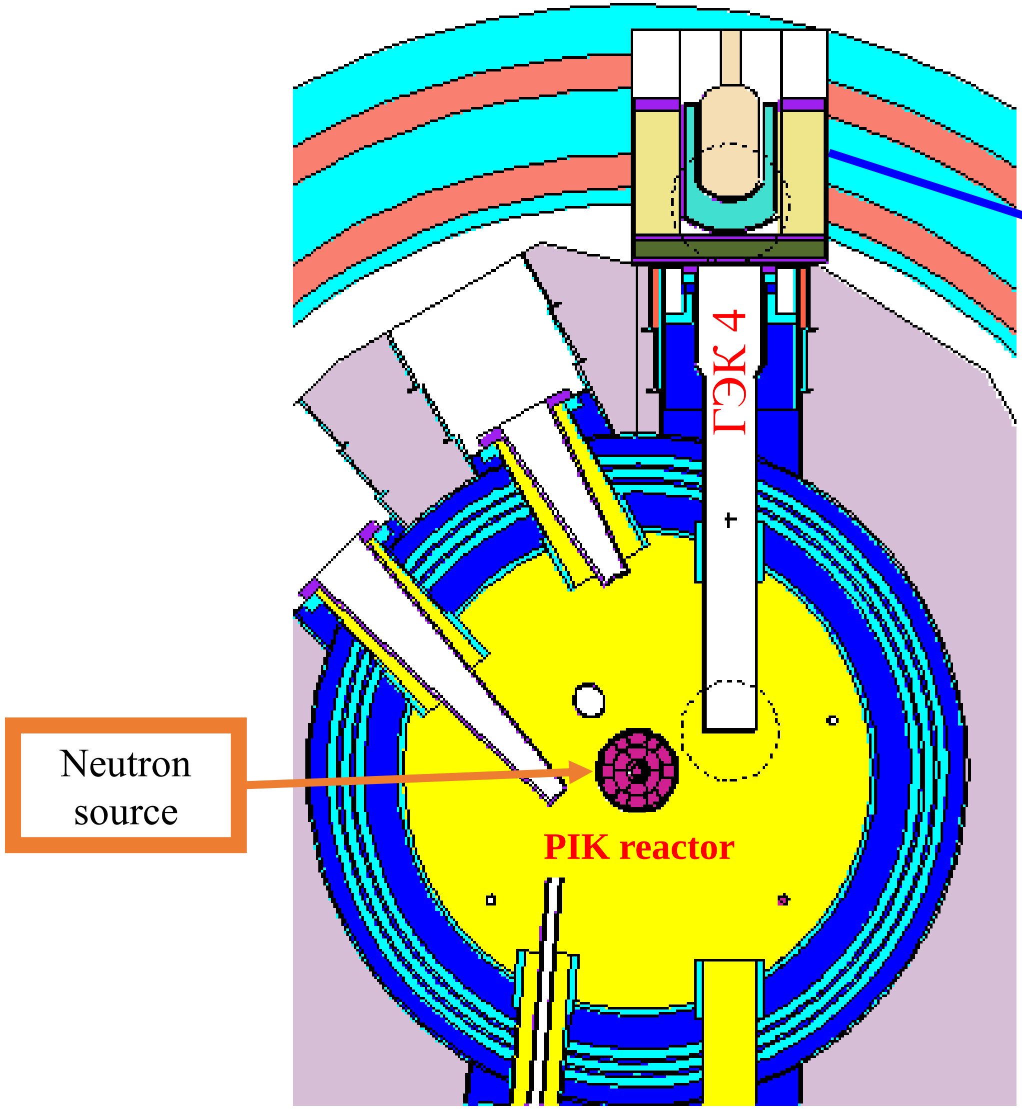
* ЖЭТФ, 1946, 16, 391; J. Phys. USSR, 1945, 9, 461.

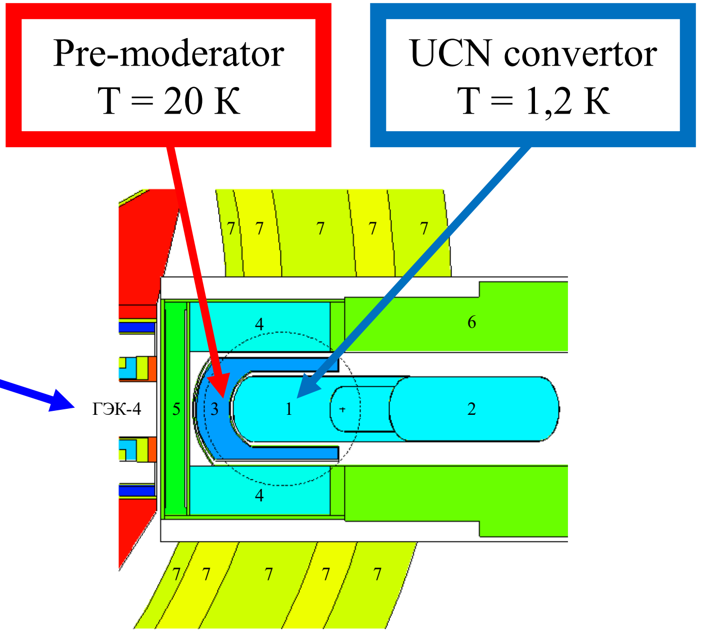
MCNP CALCULATIONS OF THE UCN SOURCE FOR PIK



Neutron source

Pre-moderator
T = 20 К

UCN convertor
T = 1,2 К



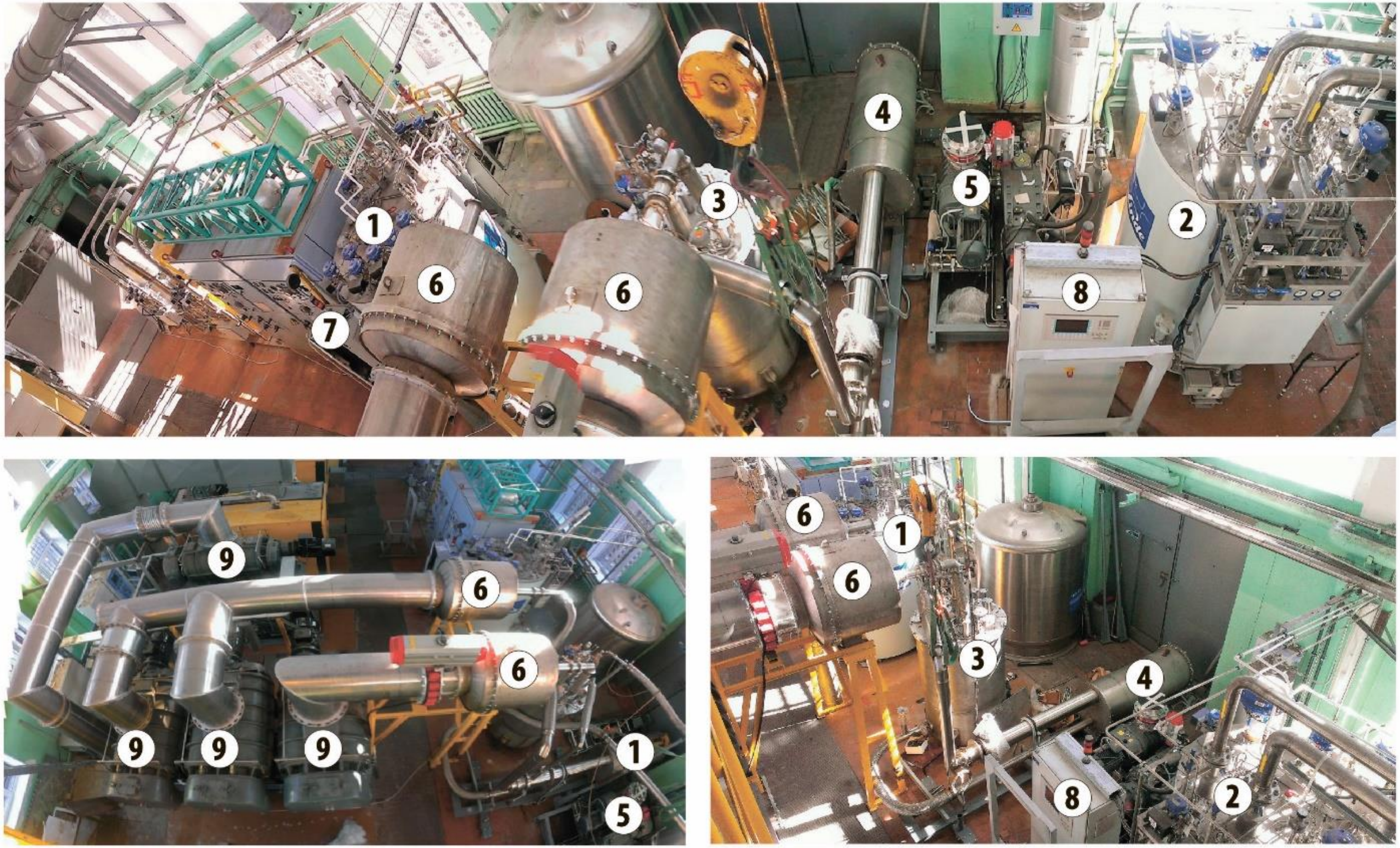
Parametr	Value
Converter temperature, К	1,1-1,2
Thermal neutron flux, $cm^{-2}s^{-1}$	$2,8\cdot10^{10}$ (±2,7%)
9 Å neutron flux, $cm^{-2}s^{-1}$ $Å^{-1}$	$5\cdot10^{8}$ (± 5%)
UCN density at EDM spectrometr, cm^{-3}	**$2,0\cdot10^{2}$**
He-II heat influx, W	3,85 (± 7%)
D2 heat influx, W	10,7 (± 4%)
Lead shiel heat influx, W	267 (± 3%)

TECHNOLOGIES FOR A NEW ULTRACOLD NEUTRON SOURCES BASED ON SUPERFLUID HELIUM

$$\tau^{-1}_{\mathrm{UCN}} = \tau^{-1}_{\beta} + \tau^{-1}_{\mathrm{upscattering}} + \tau^{-1}_{\mathrm{wall\ losses}} + \tau^{-1}_{\mathrm{capture}}$$

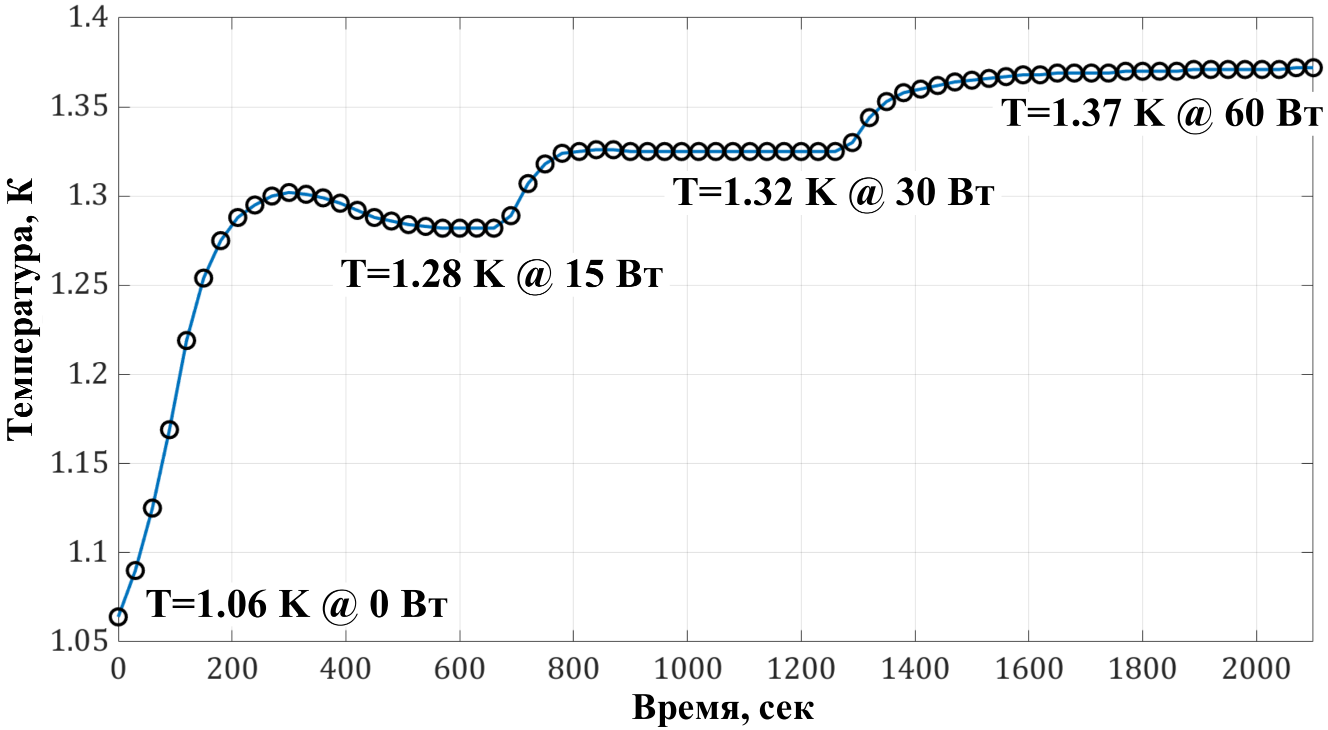
1. **Production and maintenance of superfluid helium at 1 K under reactor heat inflows**
2. **Design of the UCN source and the technological complex for maintaining its operating parameters**
3. **Calculation and design of heat exchangers for ultra-low temperatures**
4. **Manufacturing of UCN neutron guides with high neutron reflection boundary velocity (coated by ^{58}Ni)**
5. **Isotopically pure helium to eliminate the neutron-absorbing isotope ^{3}He**

FULLSCALE UCNS MODEL



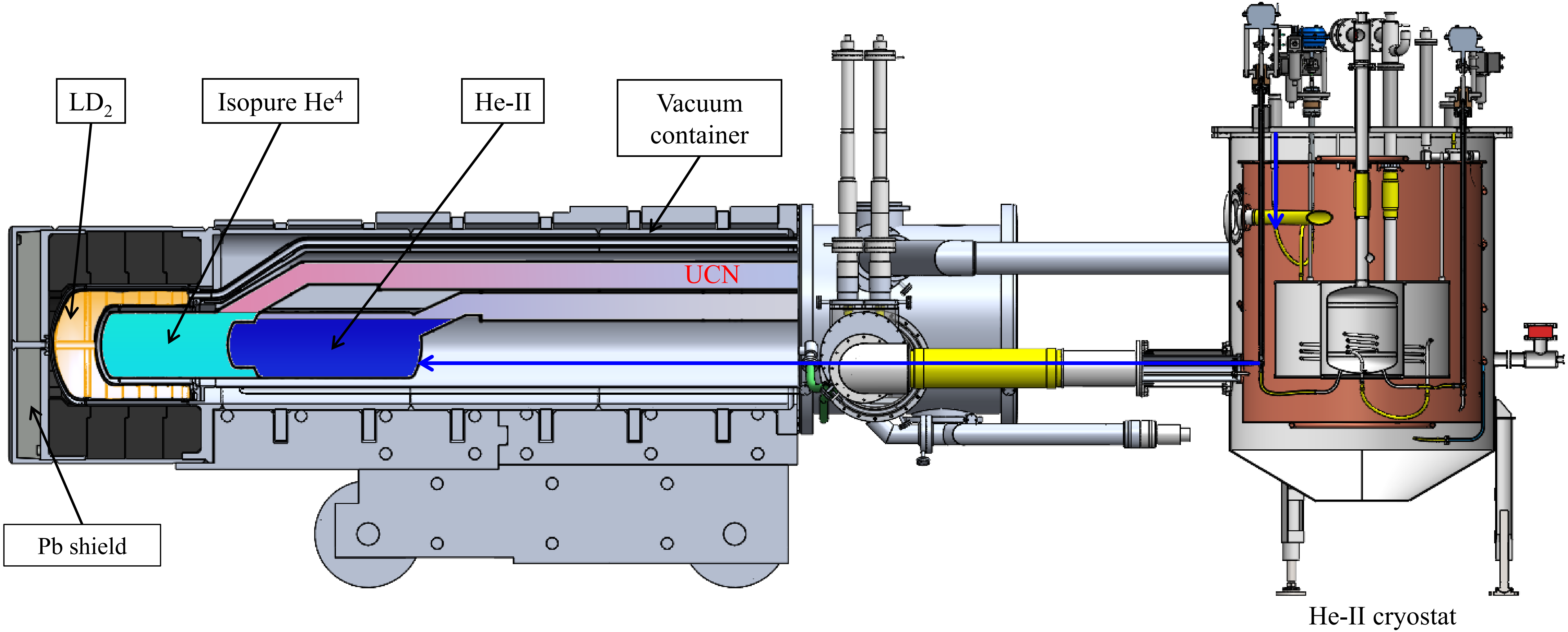
CREATION OF FULLSCALE UCNS MODEL

HEAT LOAD TESTS



- **The possibility of maintaining helium in the superfluid state under thermal loads up to 60 W was experimentally checked**
- **The possibility of installing a UCN source on the fission reactor was experimentally substantiated**

LOW TEMPERATURE PART



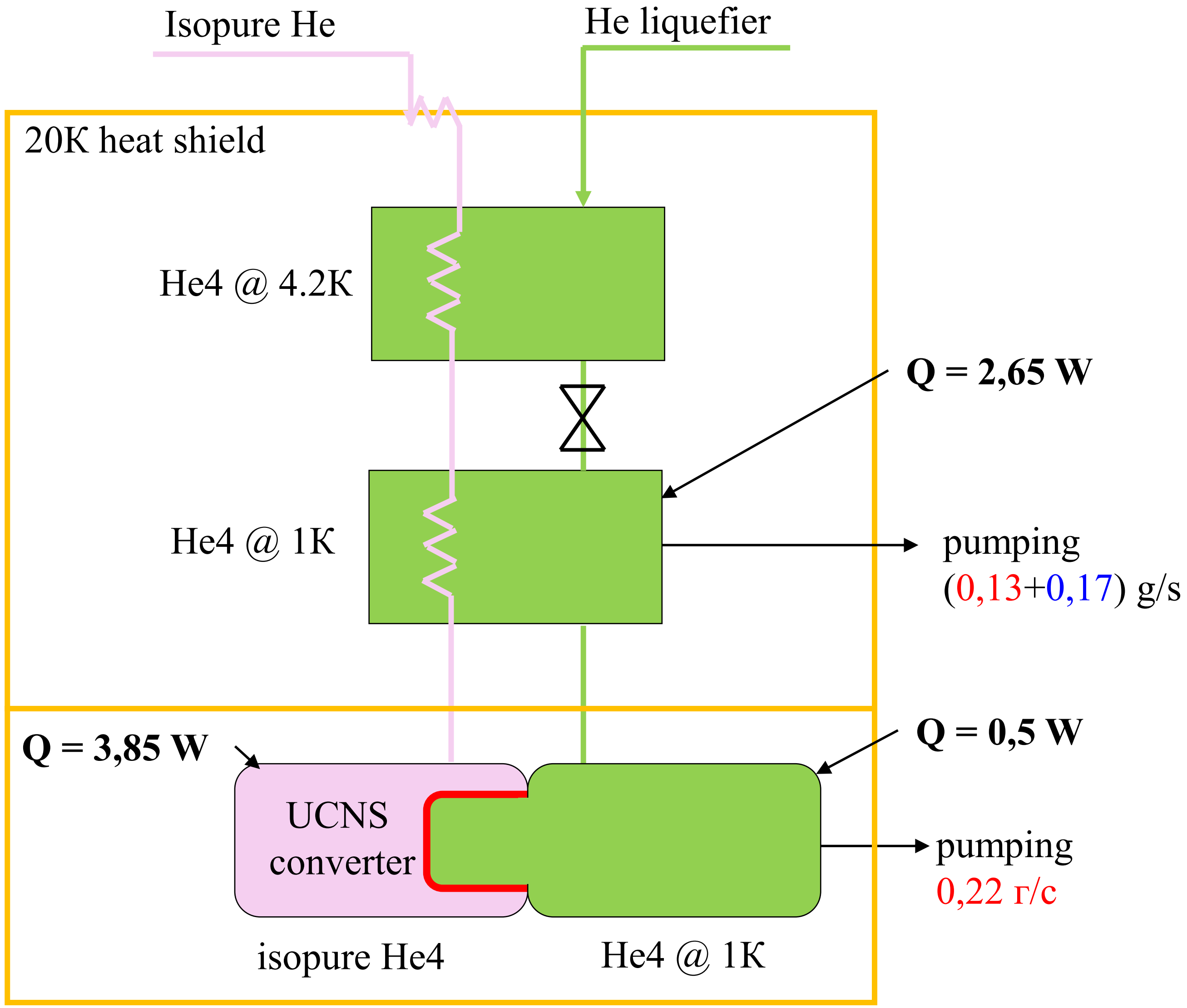
☐ Liquid D_2
- Volume: 60 l
- Temperature: 19-24 K

☐ Isopure Helium
- Volume: 35 l
- Temperature ~1.2 K

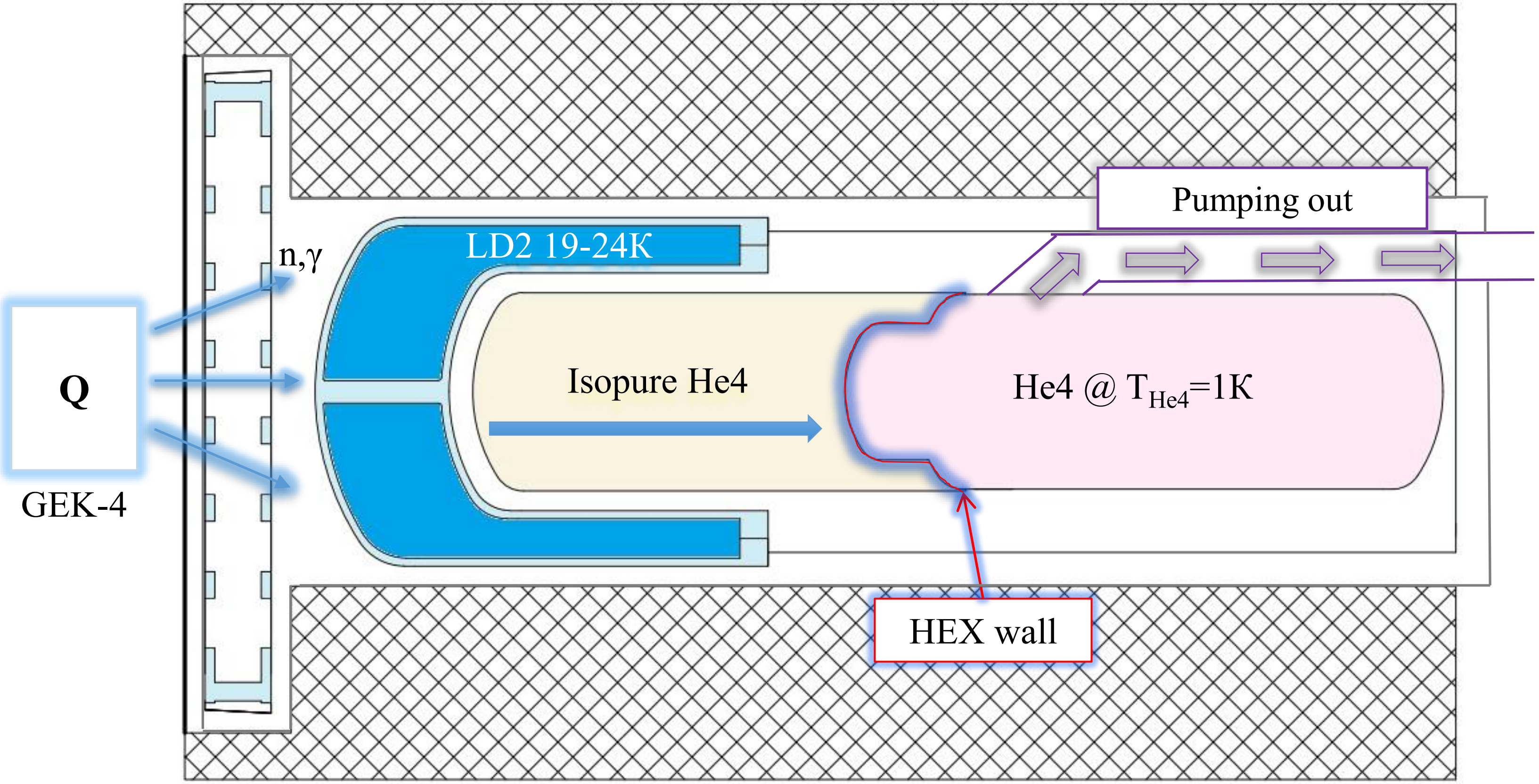
☐ Normal He
- Volume: 50 l
- Temperature ~1.0 K

HELIUM COOLING SYSTEM

- Heat load at He4@1K: **7 W**
- Required helium pumping performance
  - To compensate for heat load: 0,35 g/s
  - To lower helium temperature down to 1K: 0,17 g/s
  - P_{He4} = 40 Pa
- He4 mass flow: **0,52 g/s (15 l/h liquid)**
- HEX area: 2200 cm^2



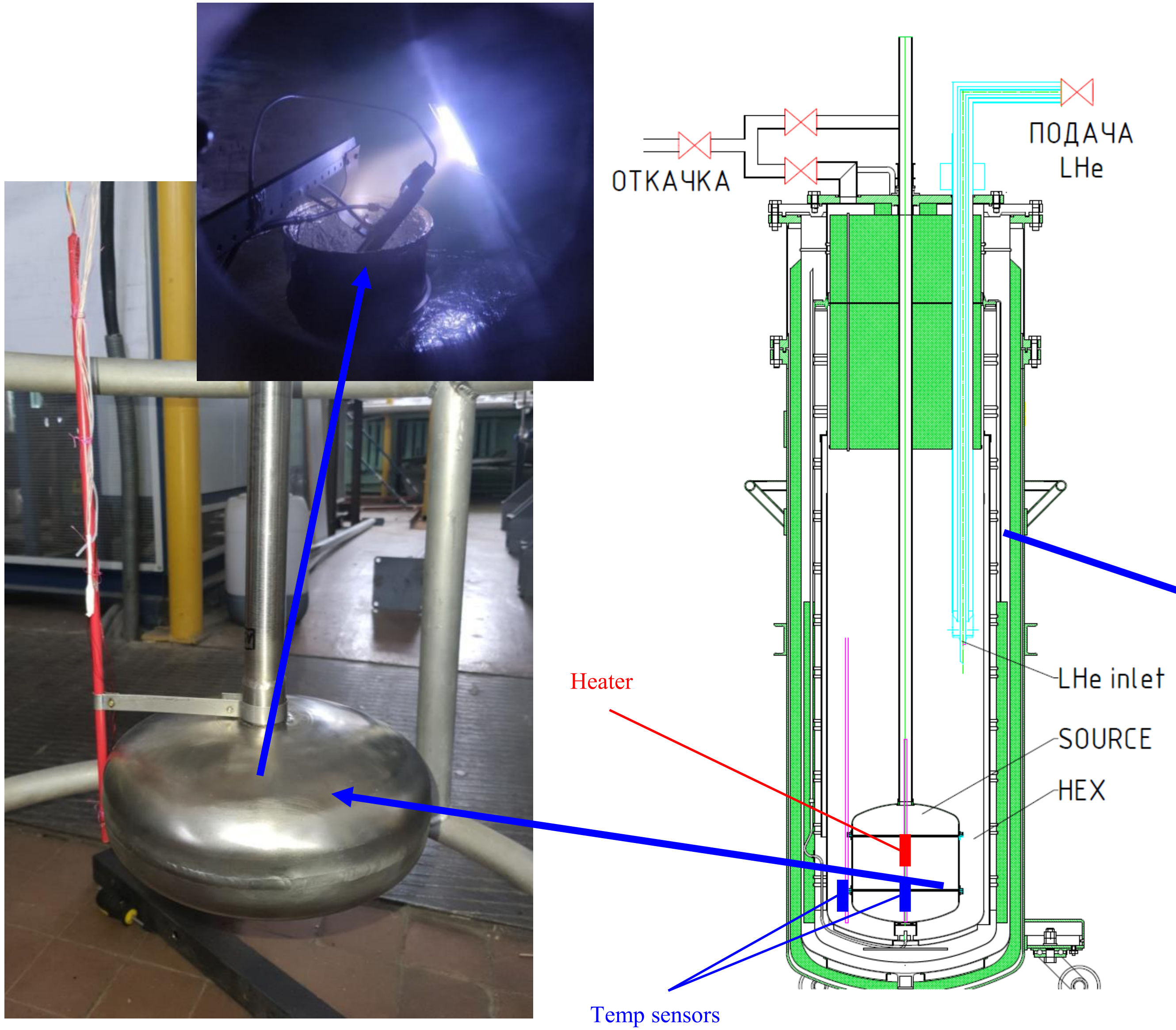
HEAT REMOVAL FROM HELIUM CONVERTER

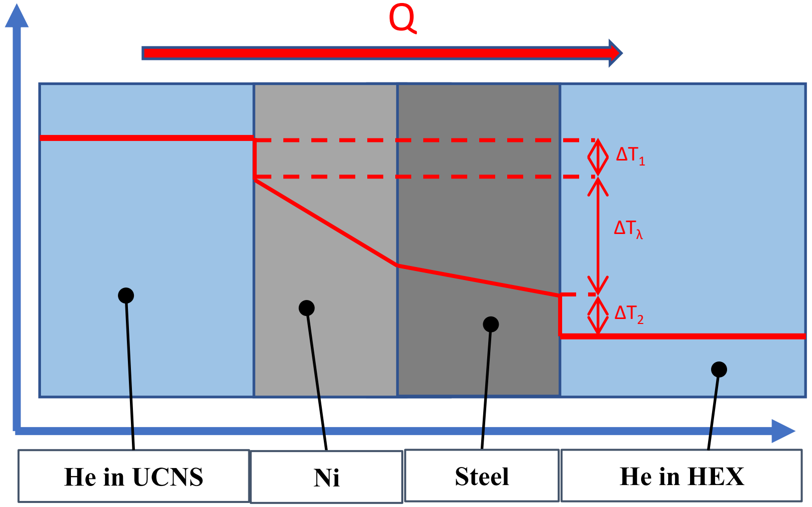


$$T_{UCNS} = \underset{\substack{\uparrow \\ \text{He4 pump perf.}}}{T_{He4}} + \underbrace{\Delta T_{He4\text{-steel}} + \Delta T_{Ni\text{-HeII}}}_{\text{Kapitza Conductance}} + \underset{\substack{\uparrow \\ \text{Wall heat Conductance}}}{\Delta T_{\lambda}} + \Delta T_{\text{к}} \leftarrow \text{Temperature difference in isotopically pure helium}$$

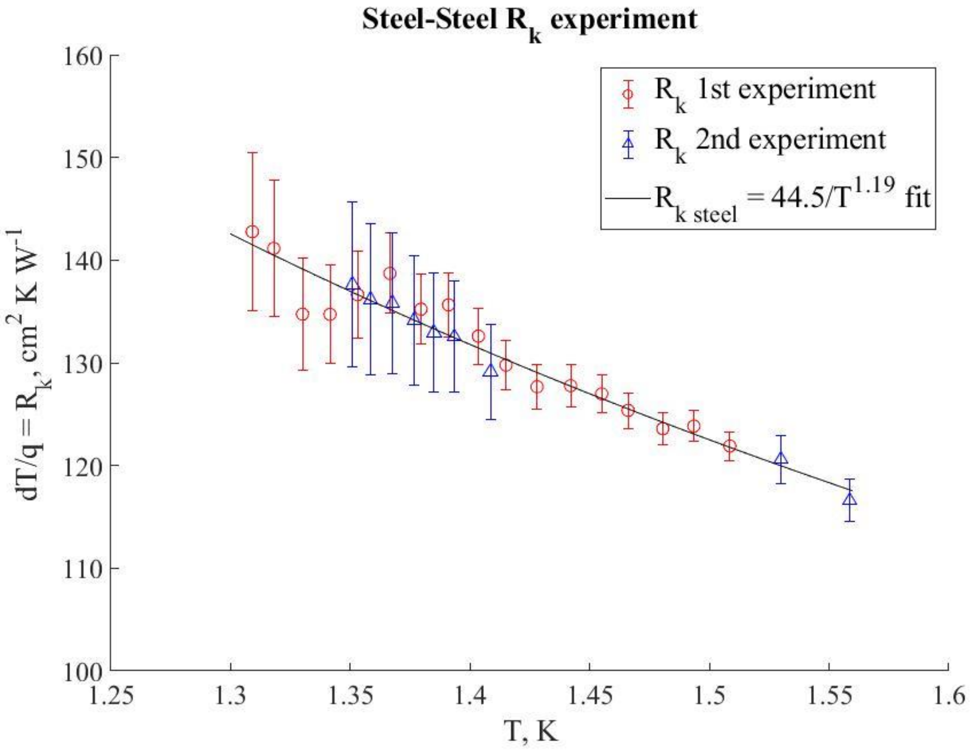
T_{UCNS} – UCNS convernet temperature, K; T_{He4} – He4 temperature at the HEX, K; $\Delta T_{He4\text{-Fe}}$, $\Delta T_{Ni\text{-HeII}}$ – Kapitza Conductance at He-steel and He-Ni, K; ΔT_{λ} – temperature gradient due to thermal resistance of the HEX wall, K; ΔTк – temperature gradient due to heat transfer in He-II, K.

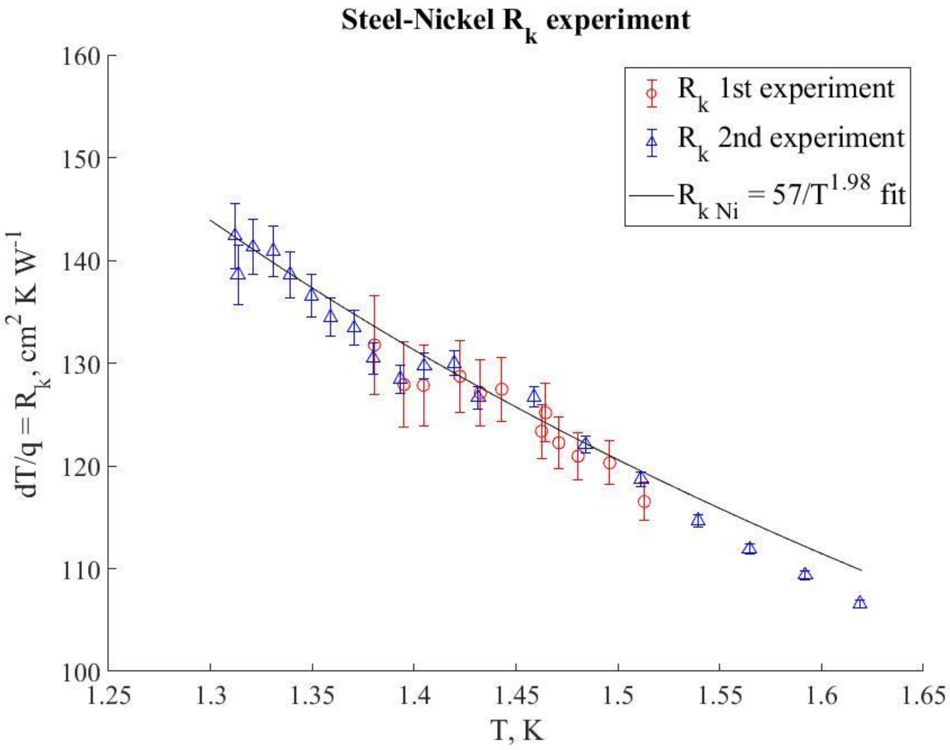
KAPITZA CONDUCTANCE MEASURMENT EXPERIMENT





KAPITZA CONDUCTANCE MEASURMENT RESULTS





$$h_{k,steel} = \frac{2}{\frac{S\Delta T}{Q_p} - \frac{\delta}{\lambda}} \qquad h_{k,Ni} = \frac{1}{\frac{S\Delta T}{Q_p} - \frac{\delta}{\lambda} - \frac{1}{h_{k,steel}}}$$

- **$h_{k,steel} \sim 224 * T^{1.2}$ [W/m²K]**
- **$h_{k,Ni} \sim 175 * T^{1.98}$ [W/m²K]**

T_{He4}= 1 К, Q = 3.8 W

- $\Delta T_{Ni\text{-}He4} = 0.1$ К
- $\Delta T_{steel\text{-}He4} = 0.07$ К
- $\Delta T_{\lambda} = 0.08$ К

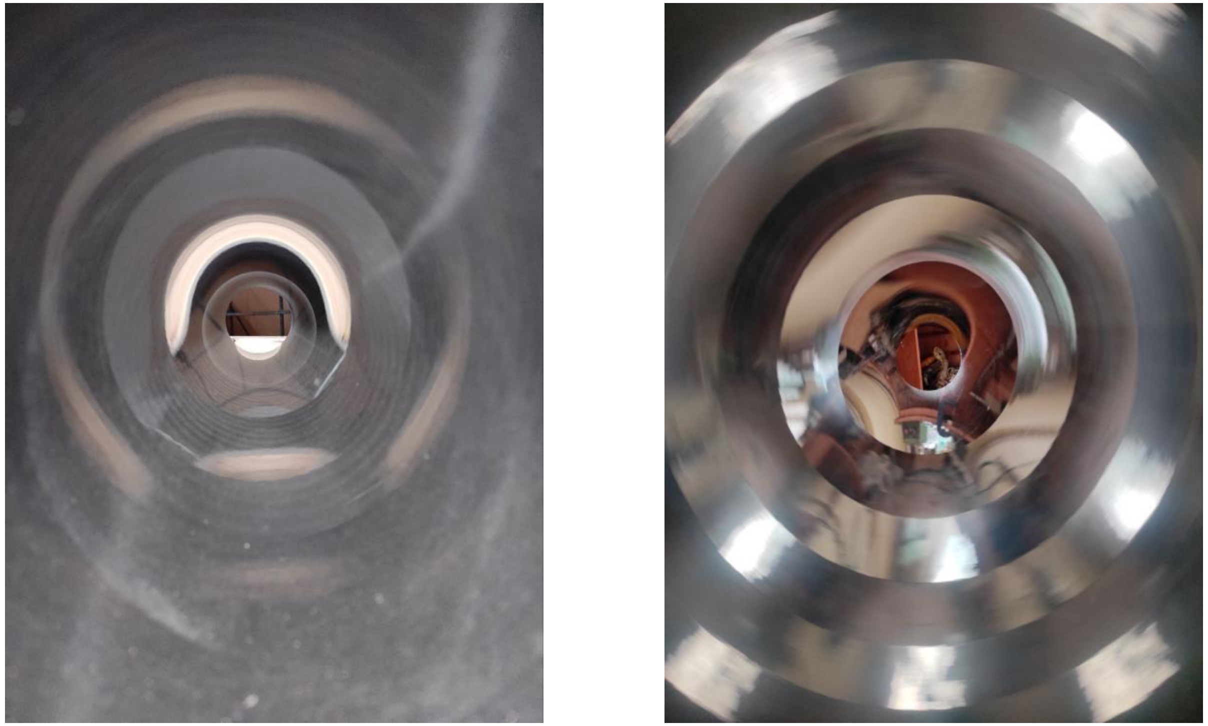
$T_{He\text{-}II}$ = 1.25 К

Can be lowered to 1.2 by using Cu HEX

NEUTRON GUIDES MANUFACTURING

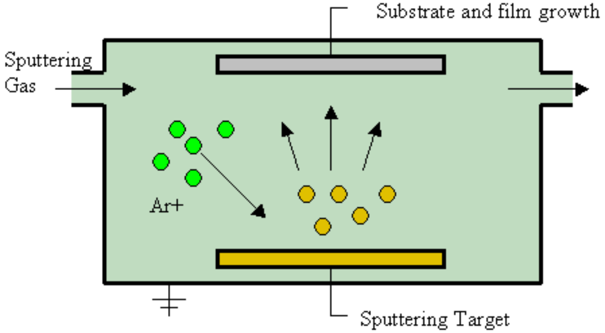
Pipe final polishing machine

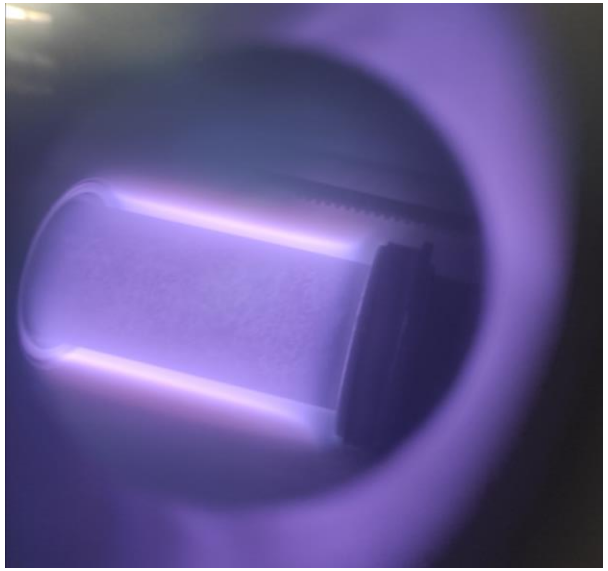
1. Pipe purchasing
2. Obtaining the required (round) geometry
3. Grinding to Ra = 1.6
4. Polishing to Ra = 0.1
5. Final polishing to Ra = 0.025



Initial / final state of the neutron guide surface

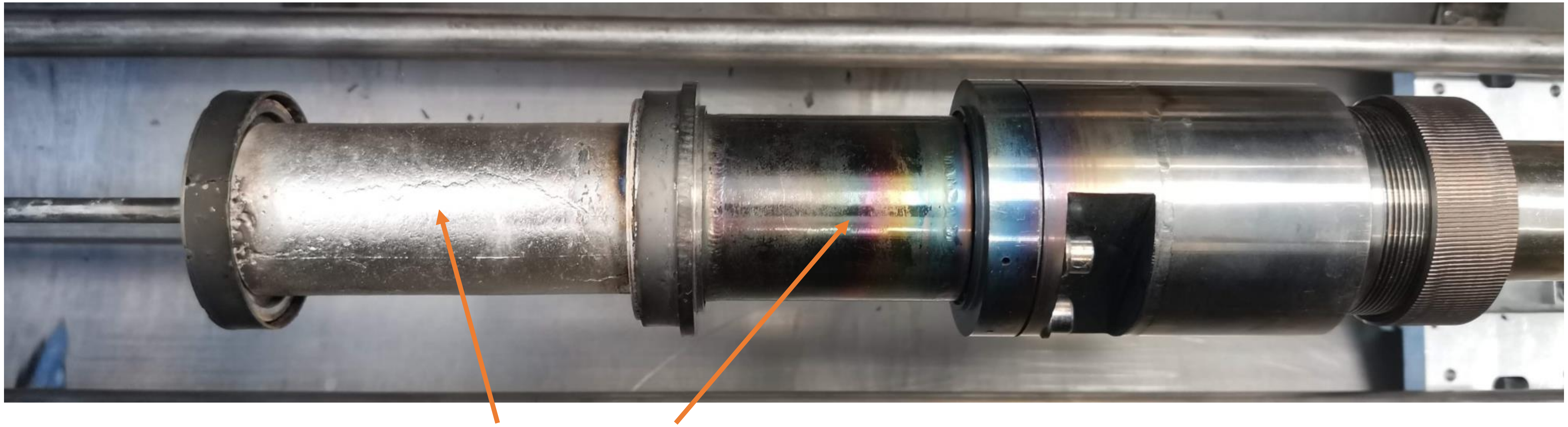
NEUTRON GUIDES COATING



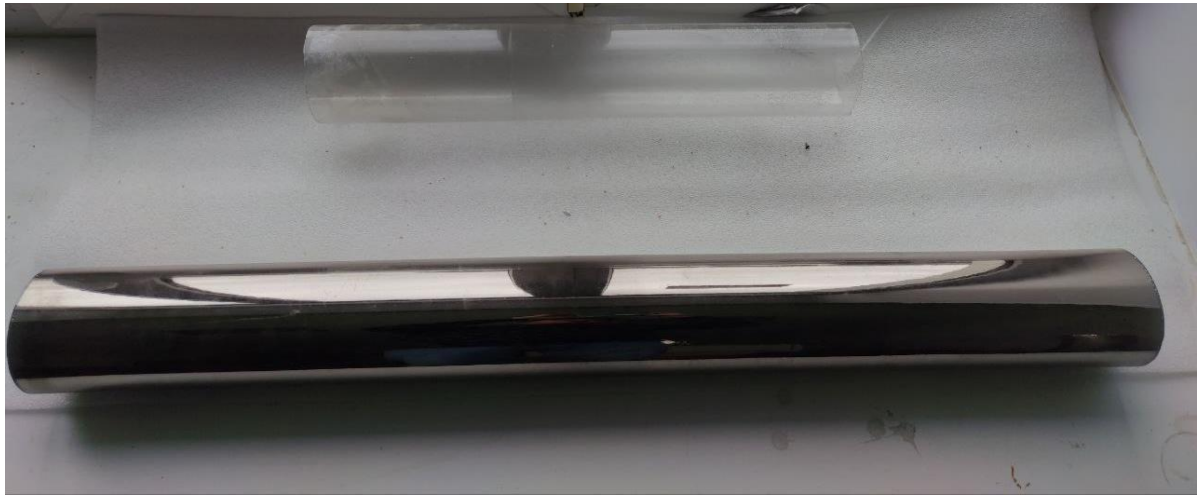


UCN neutron guide coating by ^{58}Ni by using sputter deposition

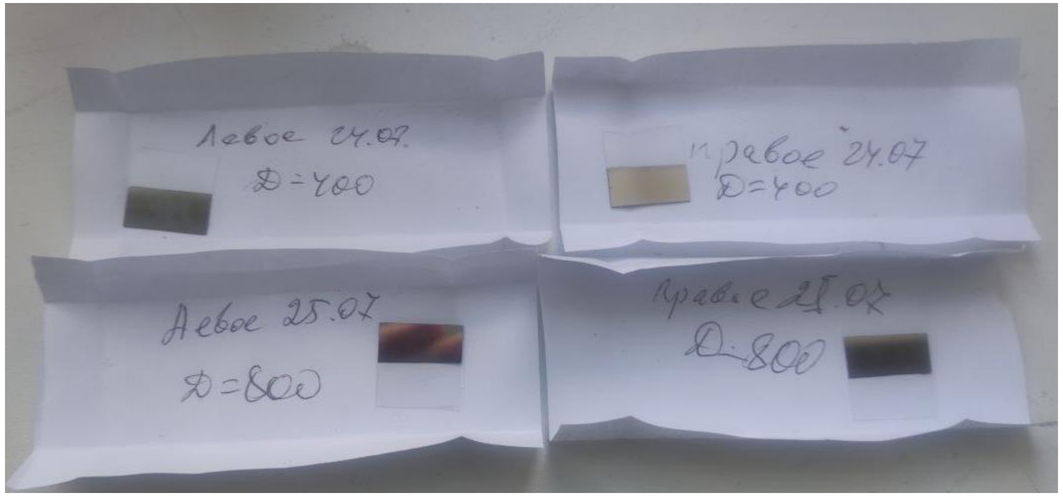
NEUTRON GUIDES MANUFACTURING



Nickel magnetron and ion source for surface pre-cleaning

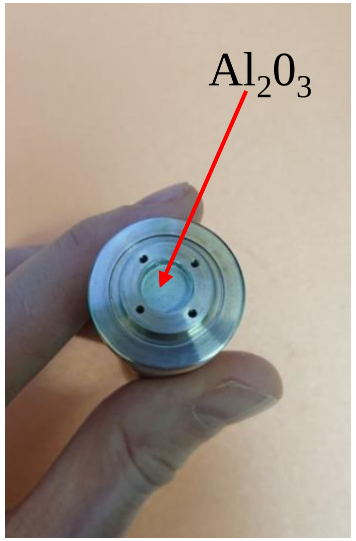


^{58}Ni coated glass pipe compared to a uncoated pipe



Thickness of coated ^{58}Ni is 3000 Å

ISOPURE HELIUM PRODUCTION



$$\tau^{-1}_{\mathrm{UCN}} = \tau^{-1}_{\beta} + \tau^{-1}_{\mathrm{upscattering}} + \boxed{\tau^{-1}_{\mathrm{capture}}} + \tau^{-1}_{\mathrm{wall\ losses}}$$

$$\tau_{\mathrm{capture}} = 30\ ms\ @\ \frac{m_{He3}}{m_{He4}} = 1{,}4 \cdot 10^{-6}$$

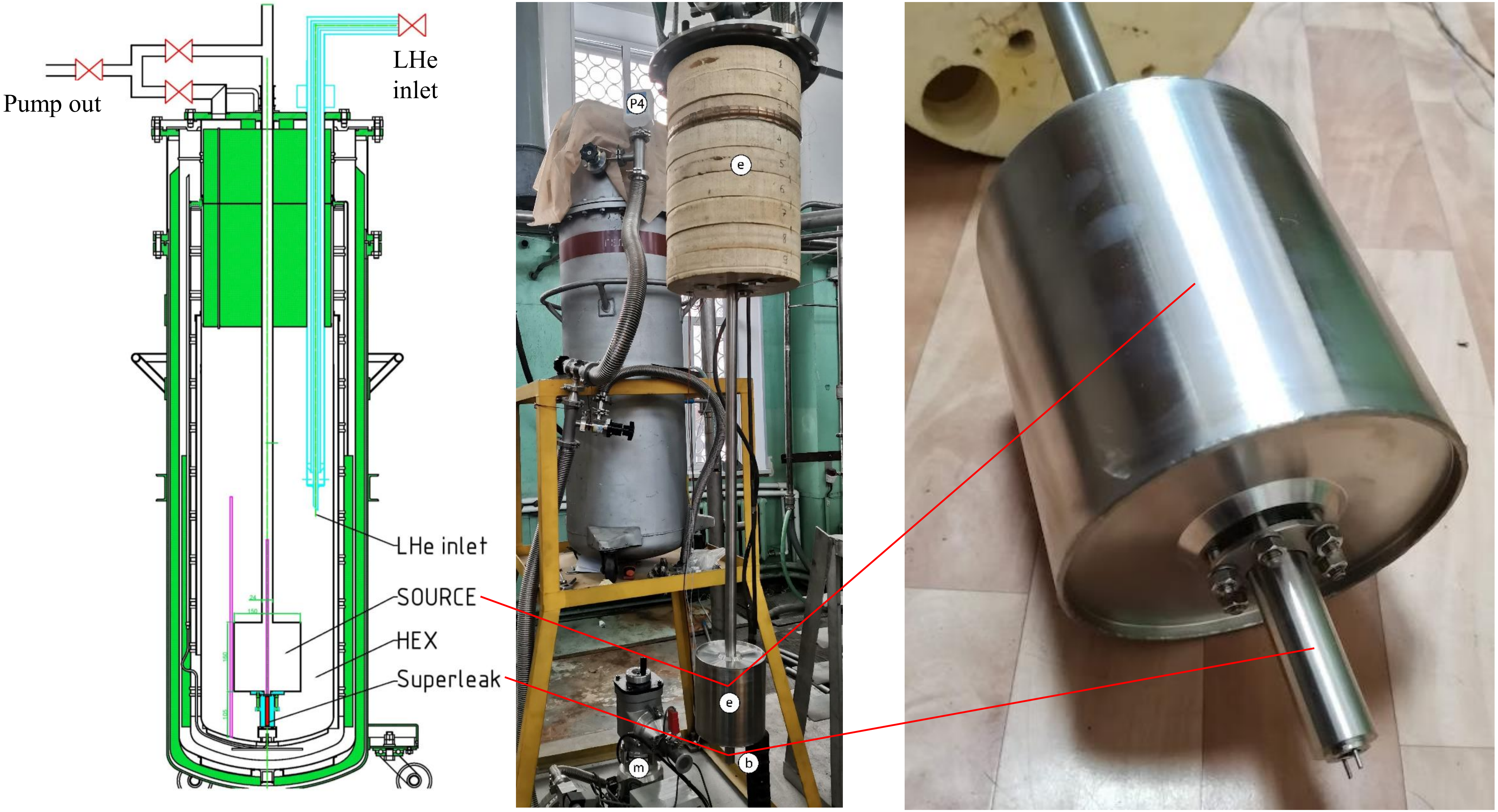
$$\tau_{\mathrm{capture}} = 3\ s\ @\ \frac{m_{He3}}{m_{He4}} = 10^{-8}$$

$$\tau_{\mathrm{capture}} = 350\ s\ @\ \frac{m_{He3}}{m_{He4}} = 10^{-10}$$

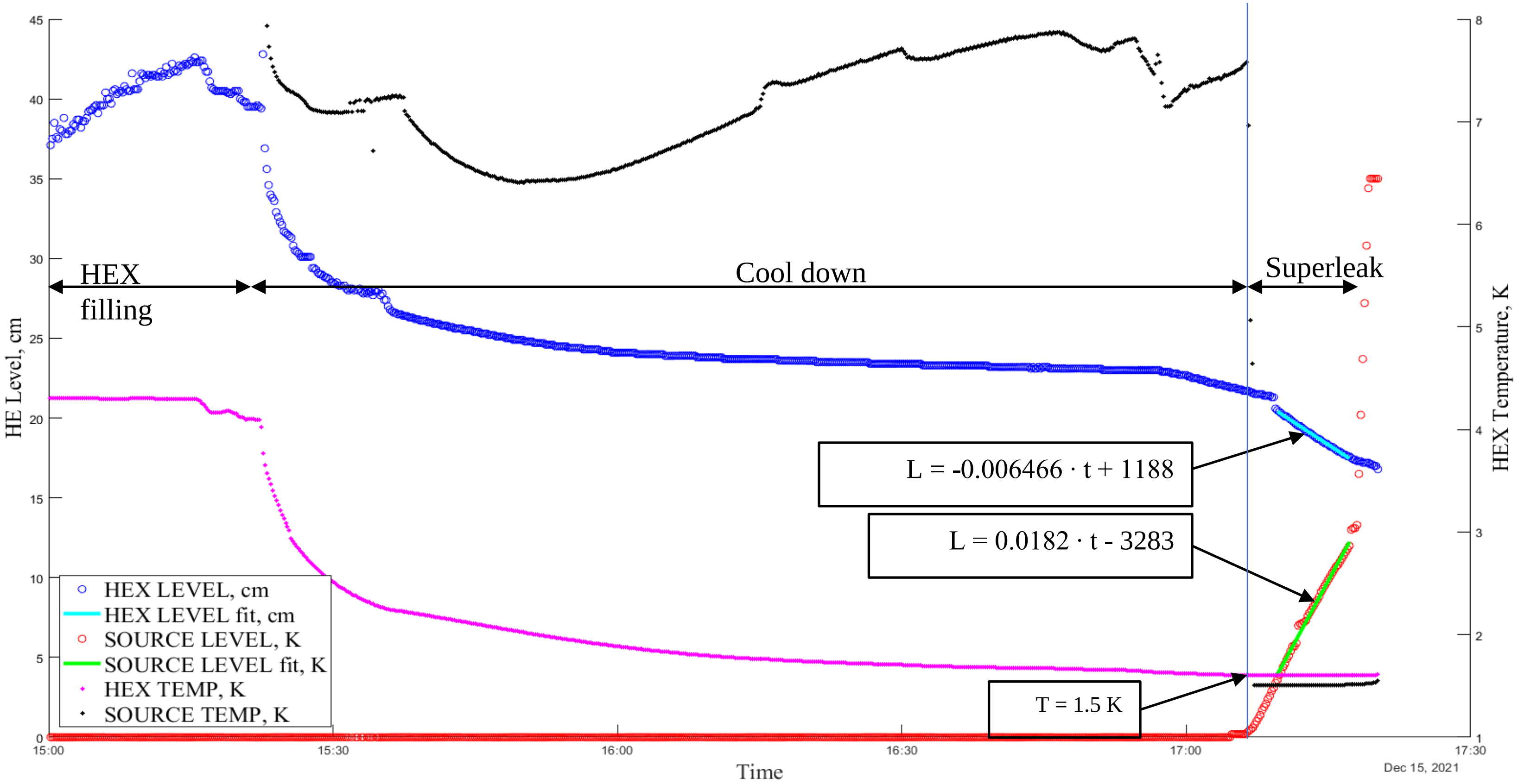
$$\sigma_a(He^3) = 5300\ barn$$

$$\sigma_a(He^4) = 0\ barn$$

ISOPURE HELIUM PRODUCTION



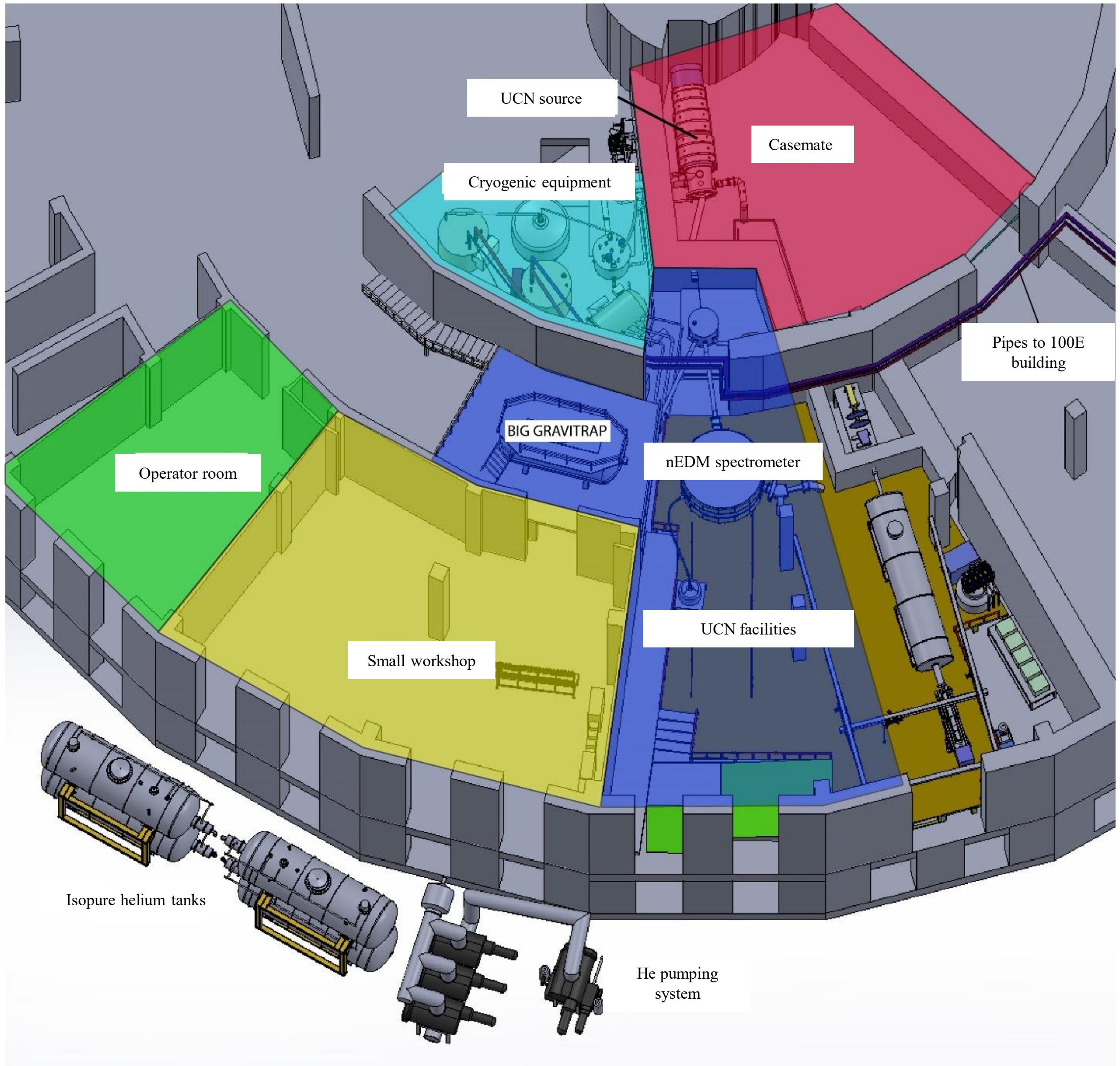
ISOPURE HELIUM PRODUCTION

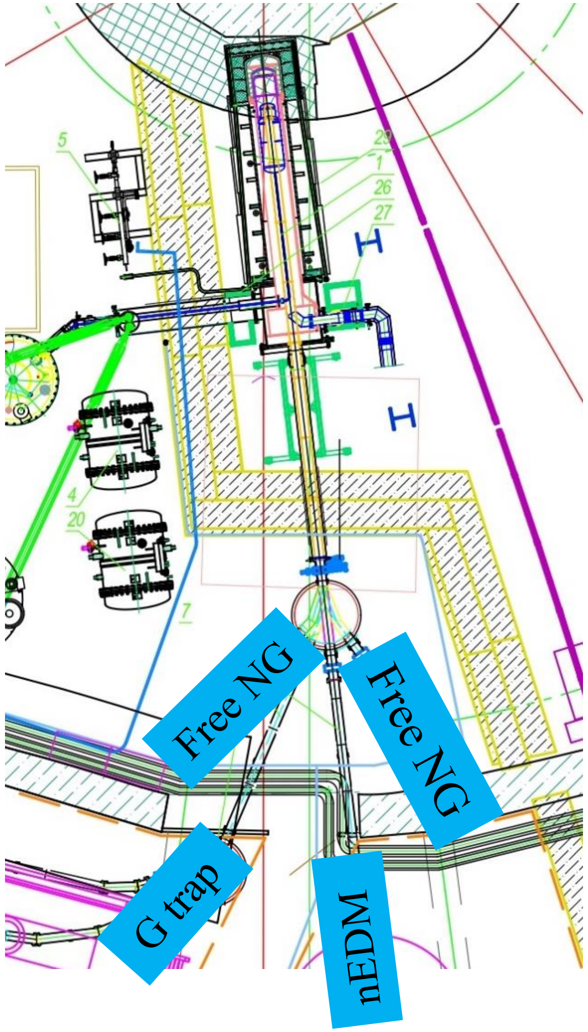


With a filter diameter of 8 mm, the critical flow of superfluid helium through the filter was 1 g/cm^{2}s.

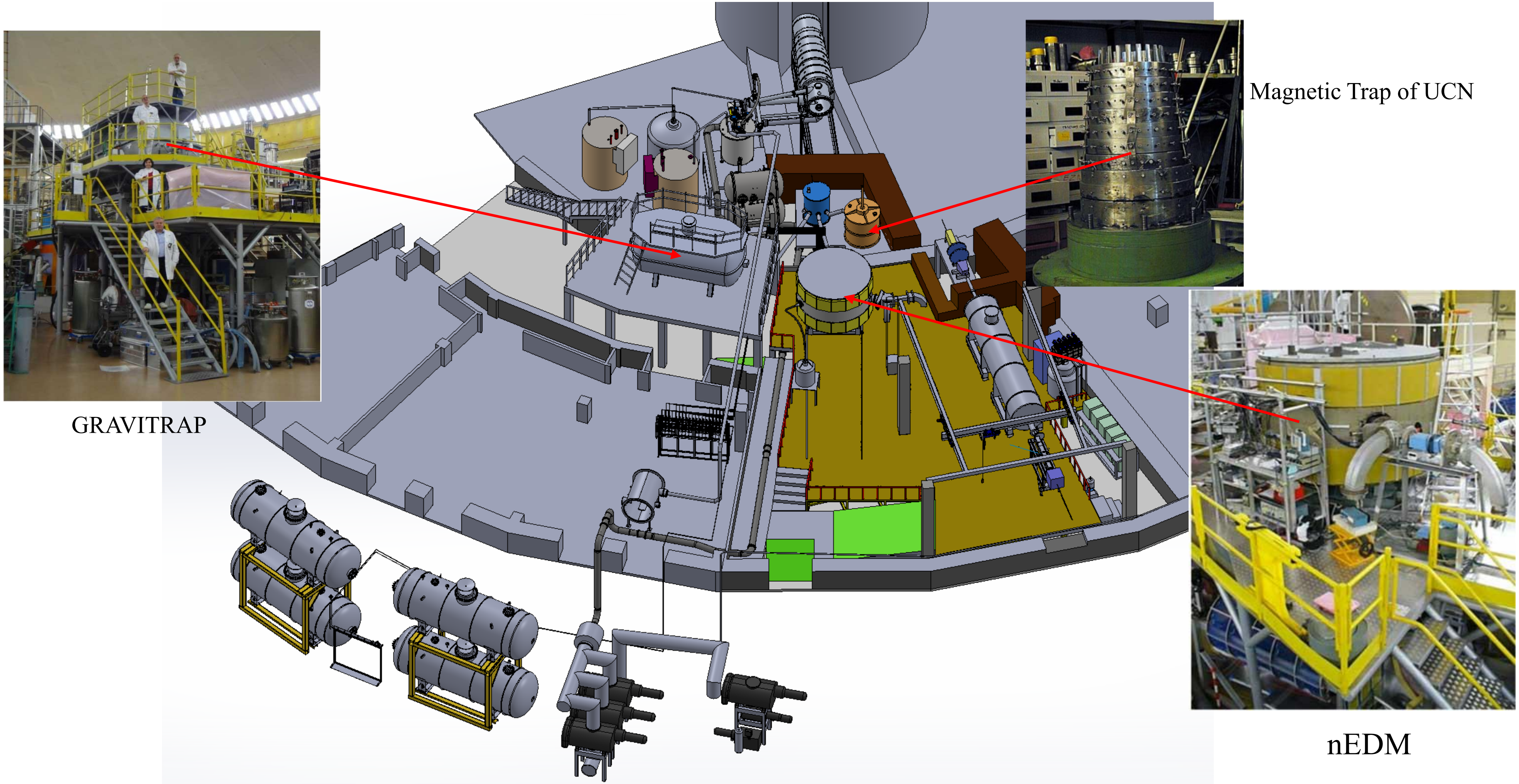
- As a result of 6 launches, 43 m^3 of isotopically pure helium-4 was produced
- Analysis of isotope-pure helium on a HELIX SFT Static Vacuum Mass Spectrometer at the Ilyichev Pacific Oceanological Institute assessed the presence of ^{3}He in purified helium at a level below 10^{-11}

UCN SOURCE LAYOUT





SCIENTIFIC RESEARCH PROGRAM WITH UCN AT THE PIK REACTOR



GRAVITRAP

Magnetic Trap of UCN

nEDM

CRYOGENIC TEST OF UCN SOURCE

THANK YOU FOR YOUR ATTENTION
FROM WHOLE UCNS TEAM