Plan to search for nnbar at WWR-M reactor

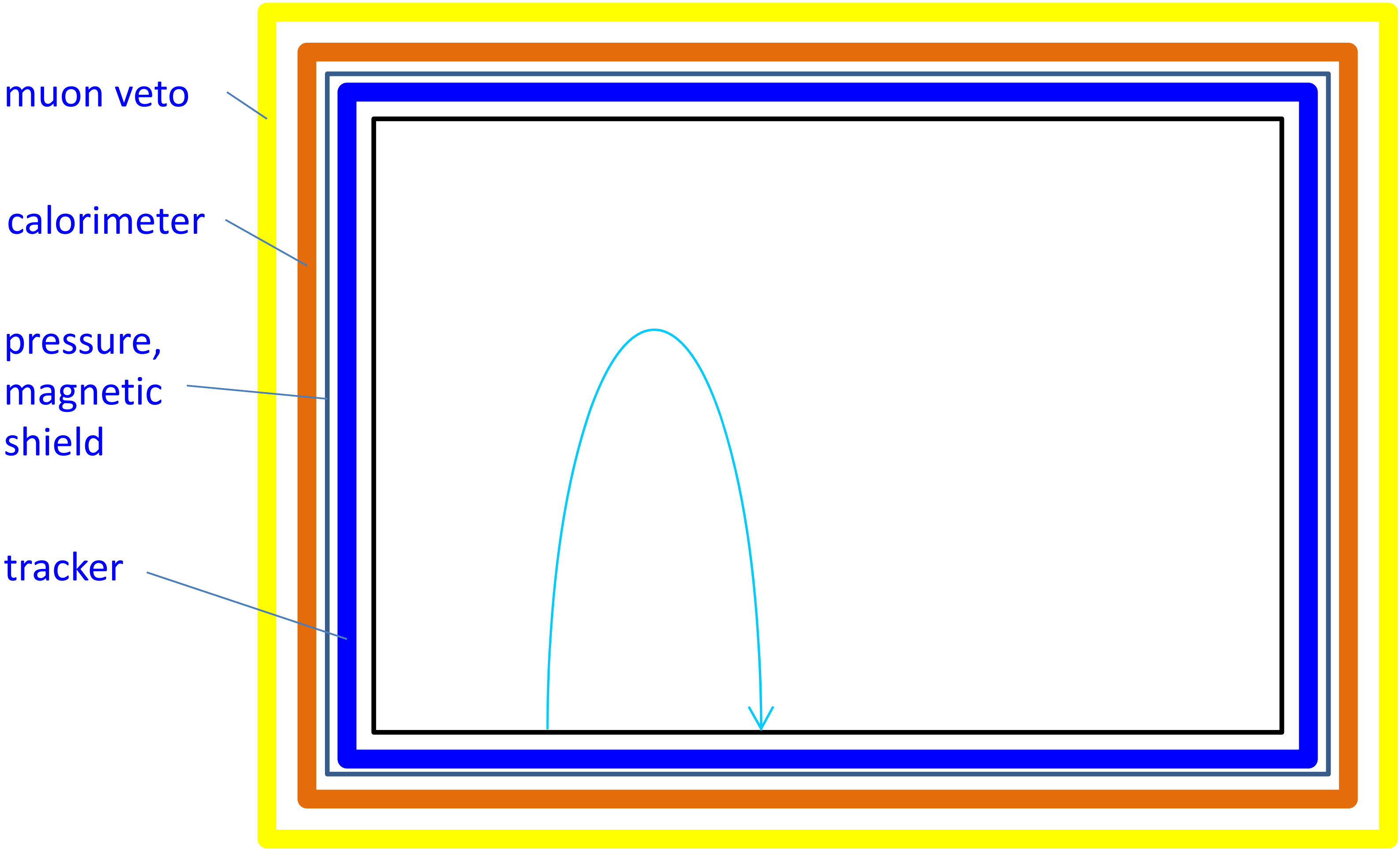
A. Fomin

A. Serebrov, O. Zherebtsov, M. Chaikovskii, A. Murashkin,
E. Leonova, O. Fedorova, V. Ivochkin, V. Lyamkin,
D. Prudnikov, A. Chechkin

PNPI, Gatchina, Russia

INT Workshop INT-17-69W
Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis
October 23 - 27, 2017

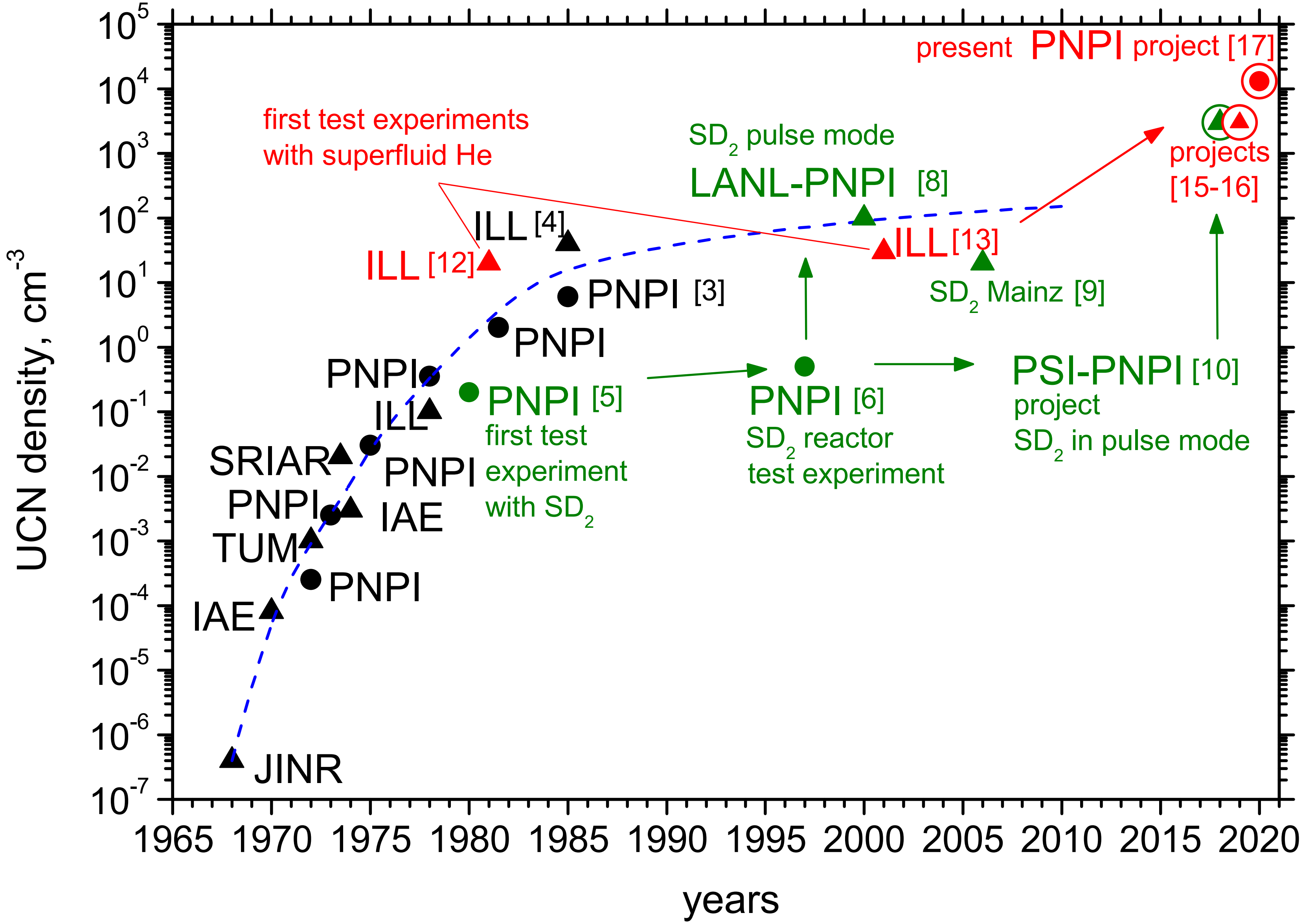
NNbar via UCN



$N\cdot t^2$ – discovery potential

Storage trap: height 2.5 m, $v_{boundary}$ = 6.8 m/s, diffusion 90 %, abs. in walls $3\cdot10^{-5}$

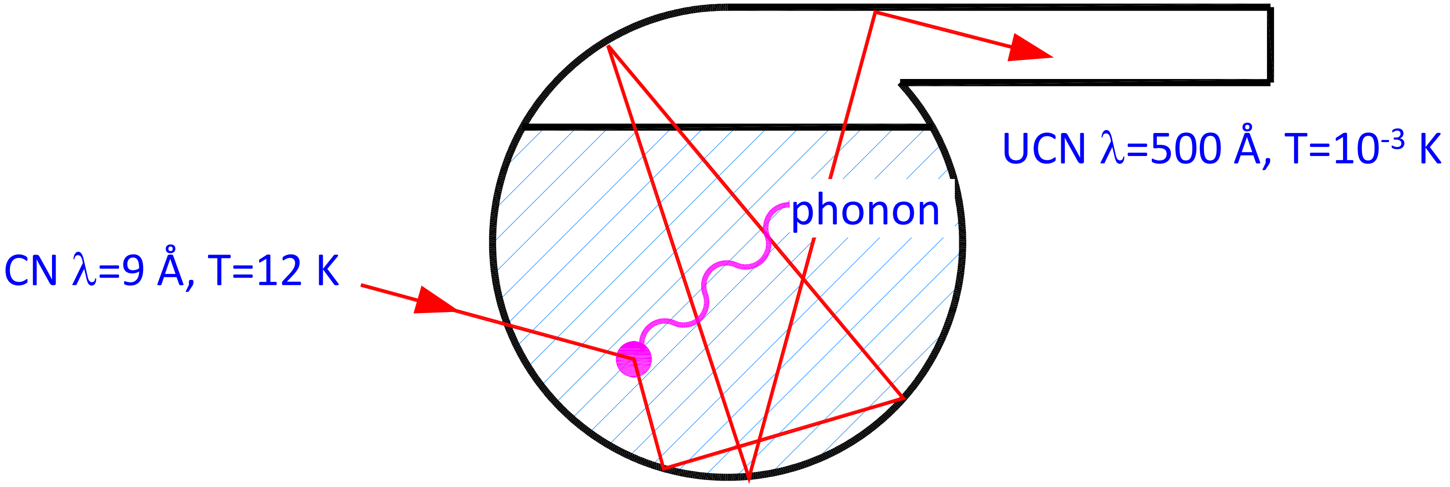
Progress of UCN sources



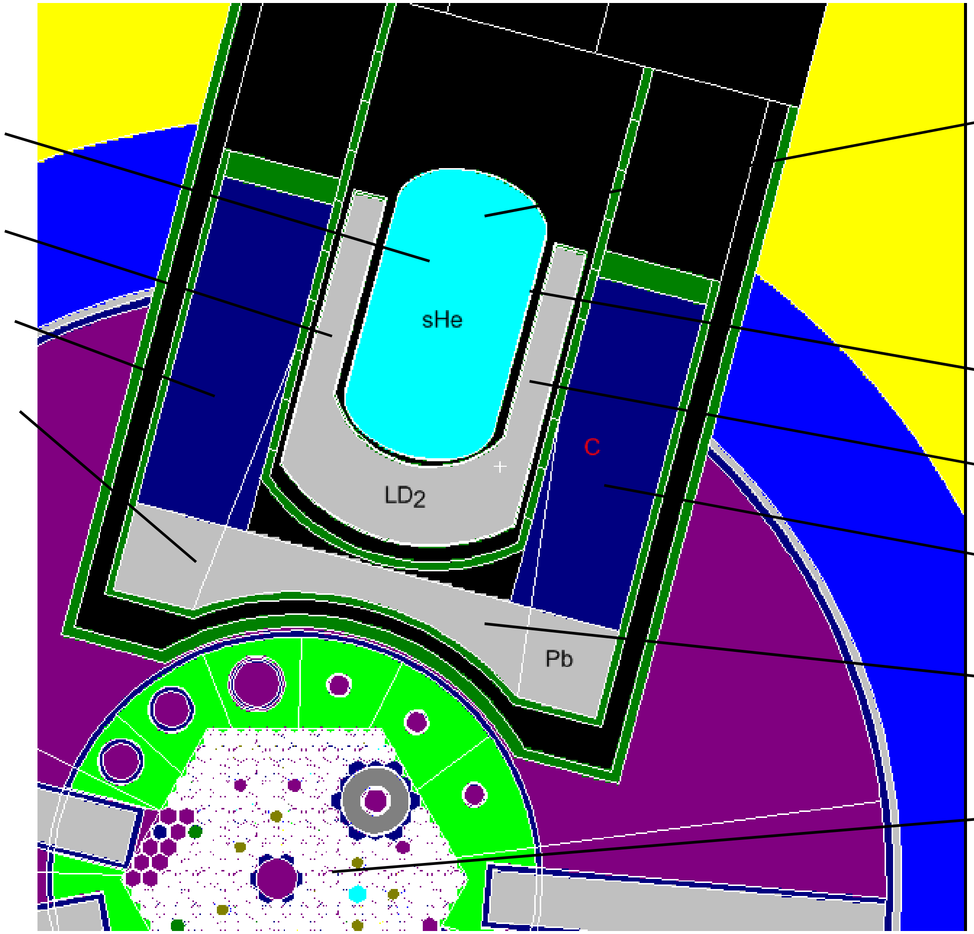
Principle of a source

UCNs are generated in helium from cold neutrons of 9 Å wavelength (12 K energy). It is correspond with phonon energy: cold neutron produces phonon, practically stops and becomes an ultracold one. UCN can "live" in superfluid helium for tens or hundreds of seconds until a phonon be captured.

Cold neutrons (9 Å) penetrate through the wall of a trap, but ultracold neutrons (500 Å) are reflected, that is why UCN can be accumulated up to the density defined by the time of storage in the trap filled with superfluid helium.



MCNP neutron flux calculation results and heat generation in thermal column of WWR-M reactor at 15 MW



He T=1.2 K

LD_2 T=20 K

C T=300 K

Pb T=300 K

$\Phi=4.5\cdot10^{12}$ n/(cm^{2}s)

$\Phi(\lambda=9$ A$)=3\cdot10^{10}$ n/(cm^{2}sA)

$Q_{He}=6$ W

19 W

Al, $Q_{Al}=13$ W

LD_2, $Q_{LD2+Al}=100$ W

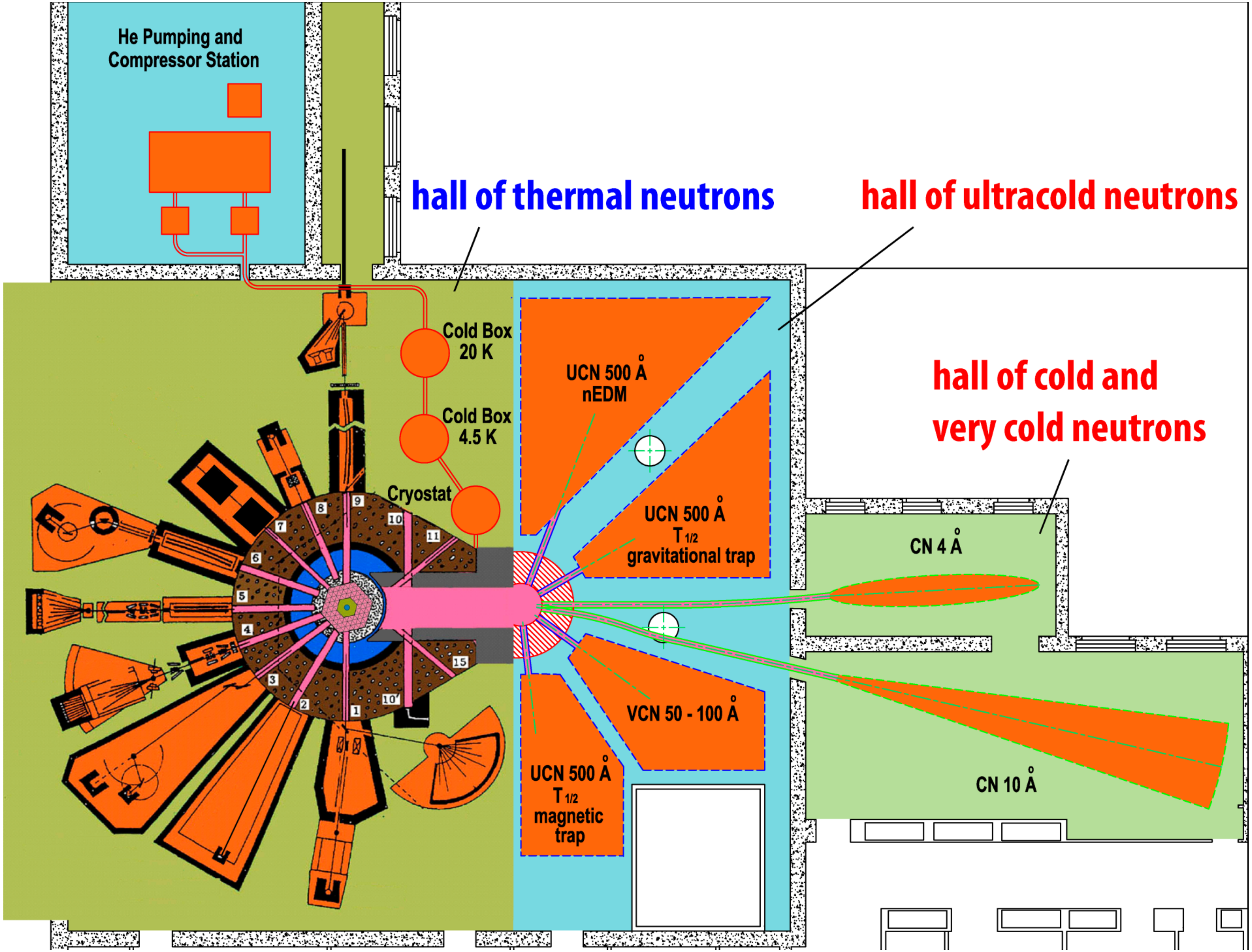
C, $Q_C=700$ W

Pb, $Q_{Pb}=15$ кW

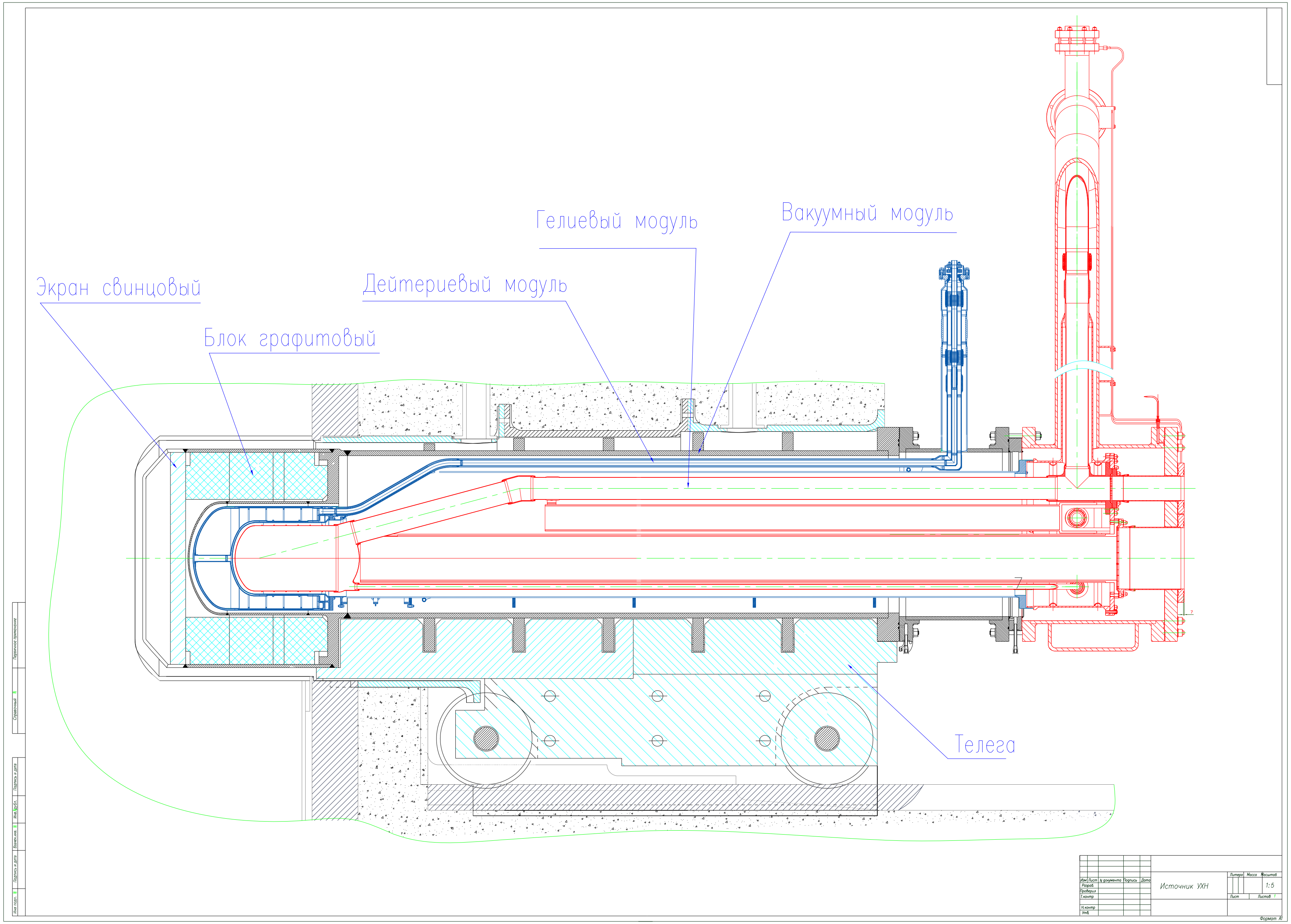
$\Phi=10^{14}$ n/(cm^{2}s)

Q=15 MW

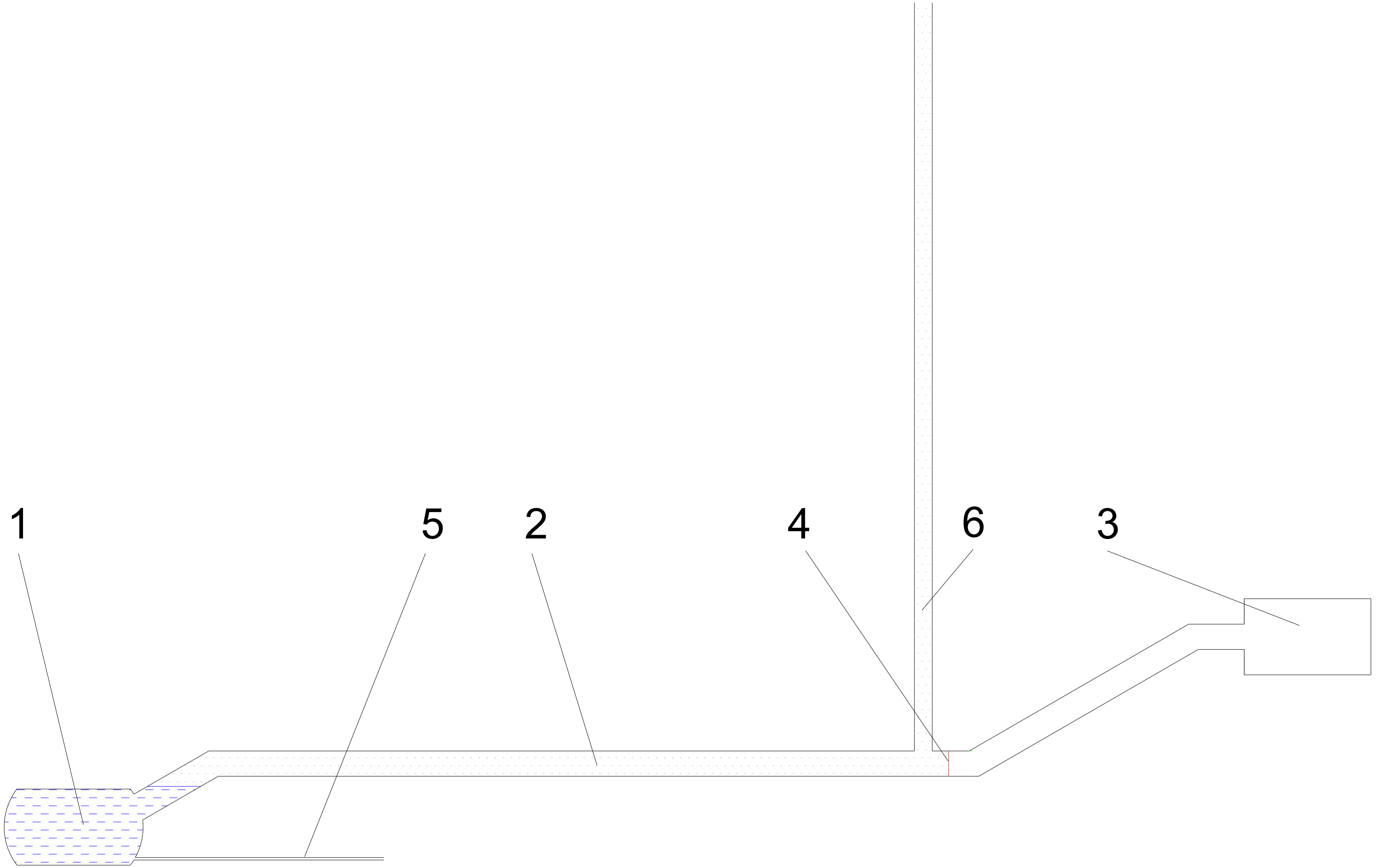
Project of UCN source at reactor WWR-M (PNPI, Gatchina)



UCN source inside the thermal column of the WWR-M reactor

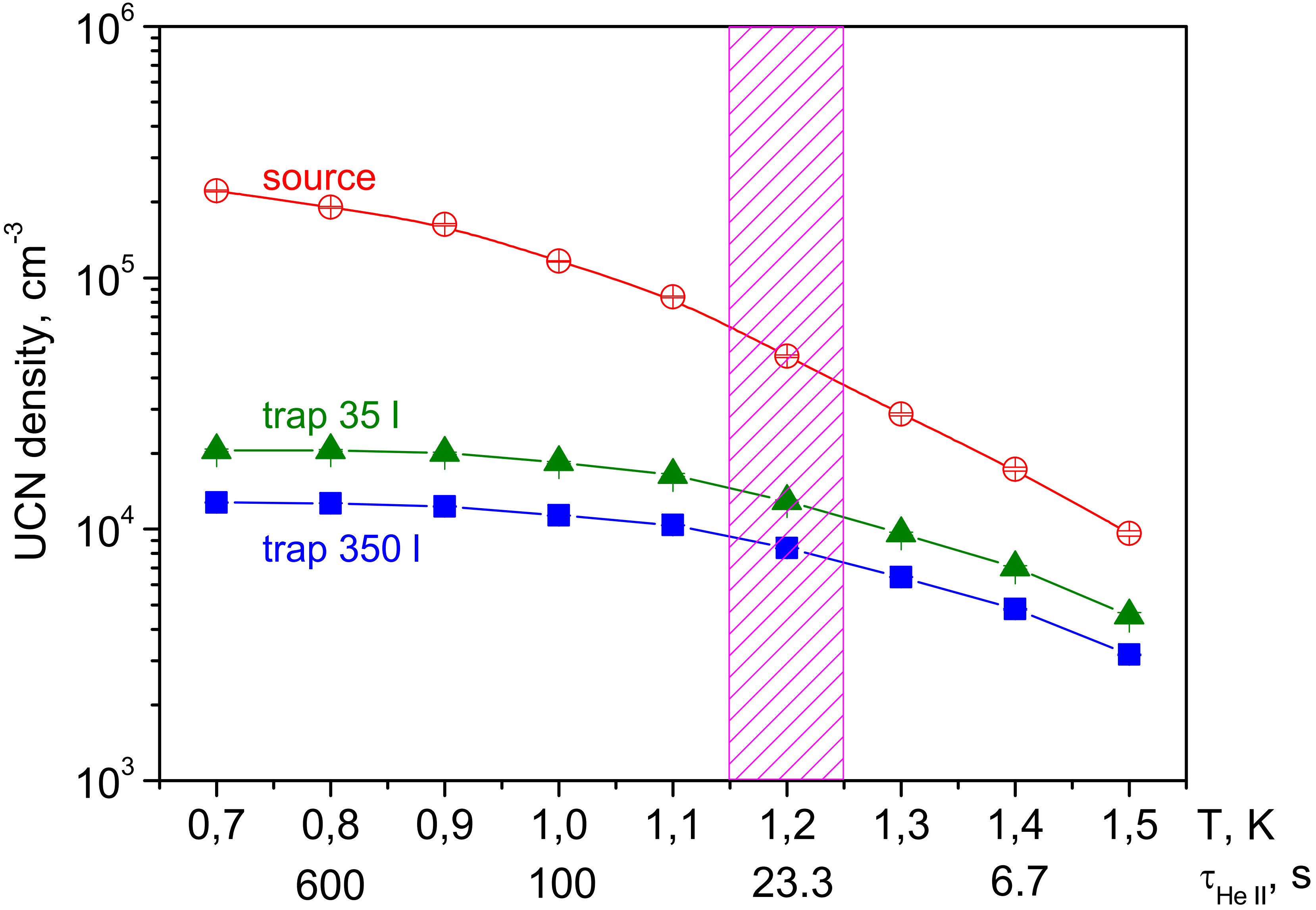


MC model of the source



(*1*) source chamber; (*2*) neutron guide; (*3*) UCN trap; (*4*) membrane in front of the inlet to the UCN trap;(*5*) pipe for filling the chamber; (*6*) pipeline for evacuation of the chamber (UCN gravitational shutter)

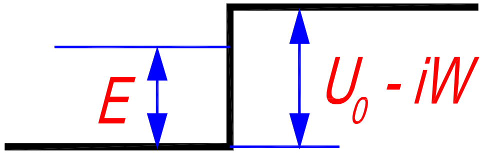
UCN density



Production of the source 10^8 UCN/s.

What is the probability for UCÑ to be reflected?

$$\tilde{R} = \left| \frac{1 - \sqrt{1 - \frac{\tilde{U}_0}{\tilde{E}_\perp}(1 - i\tilde{\eta})}}{1 + \sqrt{1 - \frac{\tilde{U}_0}{\tilde{E}_\perp}(1 - i\tilde{\eta})}} \right|^2$$

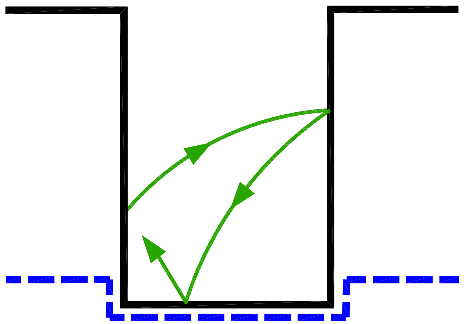


$$\tilde{U} = \tilde{U}_0 - i\tilde{W} \qquad \tilde{\eta} = \frac{\tilde{W}}{\tilde{U}_0}$$

We can consider two cases:

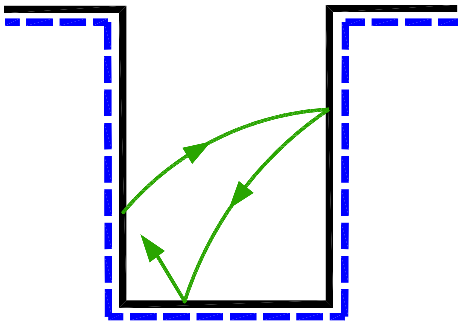
1. $\tilde{R} = 0$

   (pessimistic case)



2. $\tilde{R} = \tilde{R}\,(\eta = 0.2) \approx 0.8$

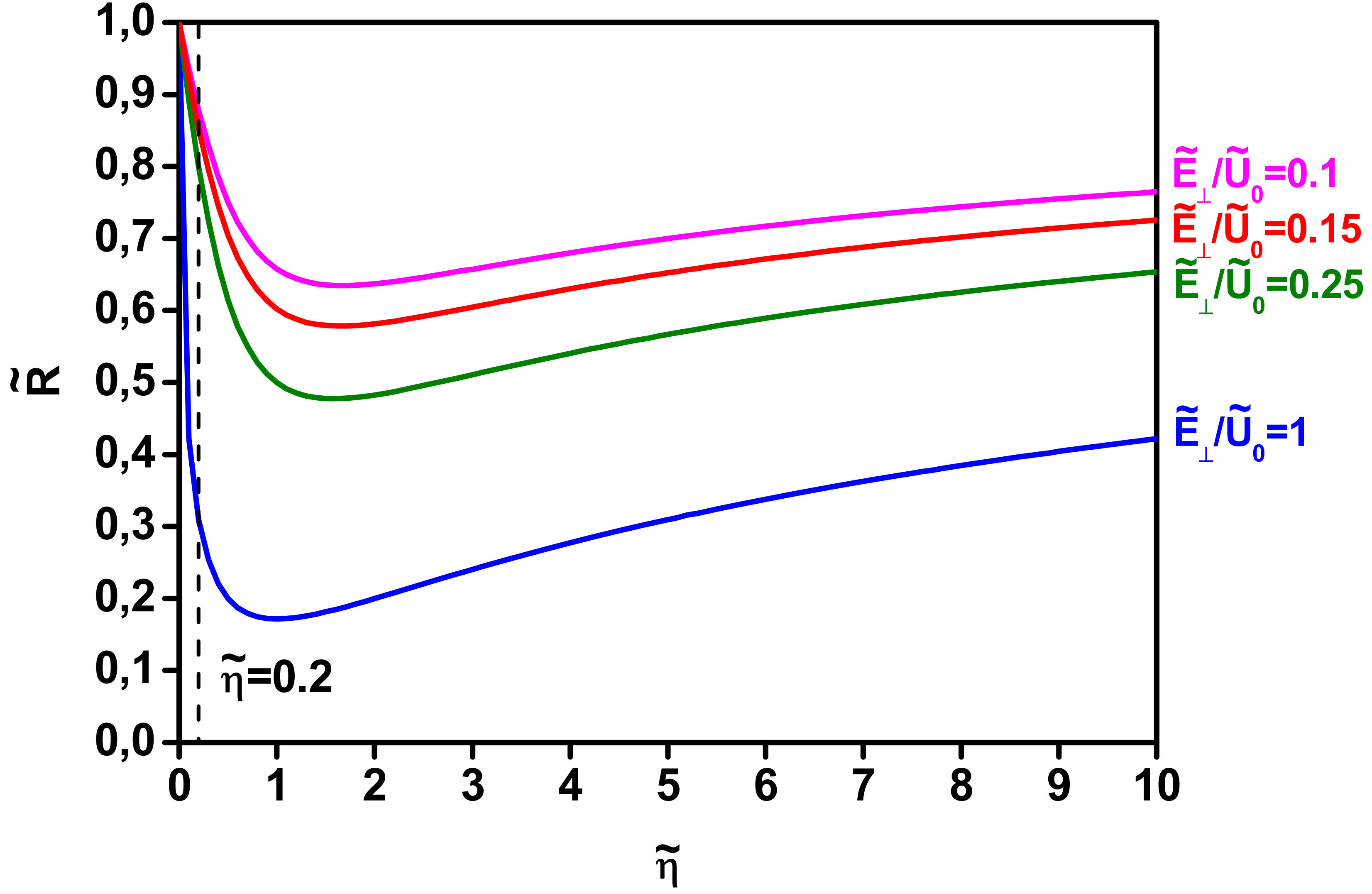
   (optimistic case)



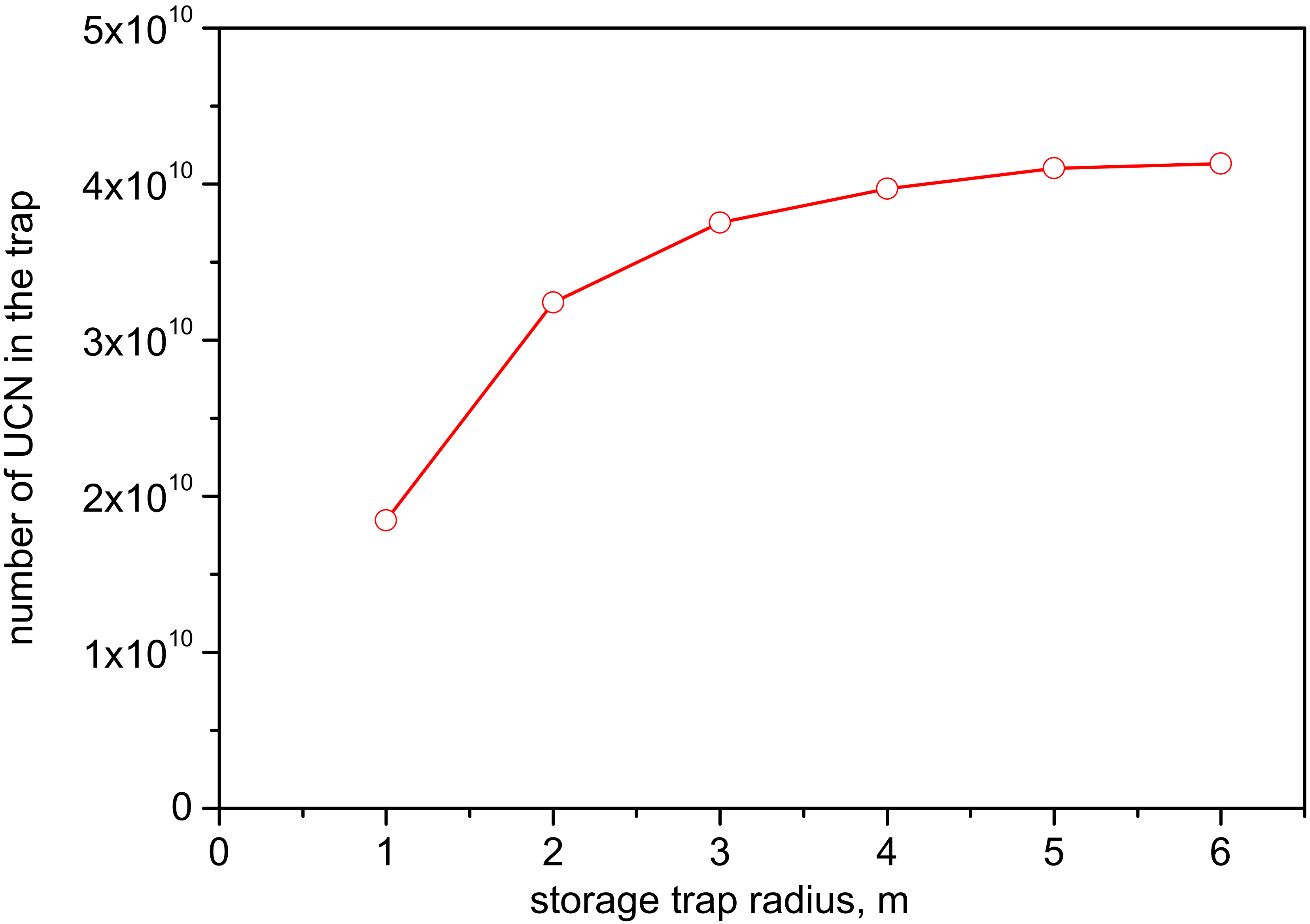
$U_0 - iW$ for n ———

$\tilde{U}_0 - i\tilde{W}$ for $\tilde{n}$ - - -

Reflection coefficient for UCÑ

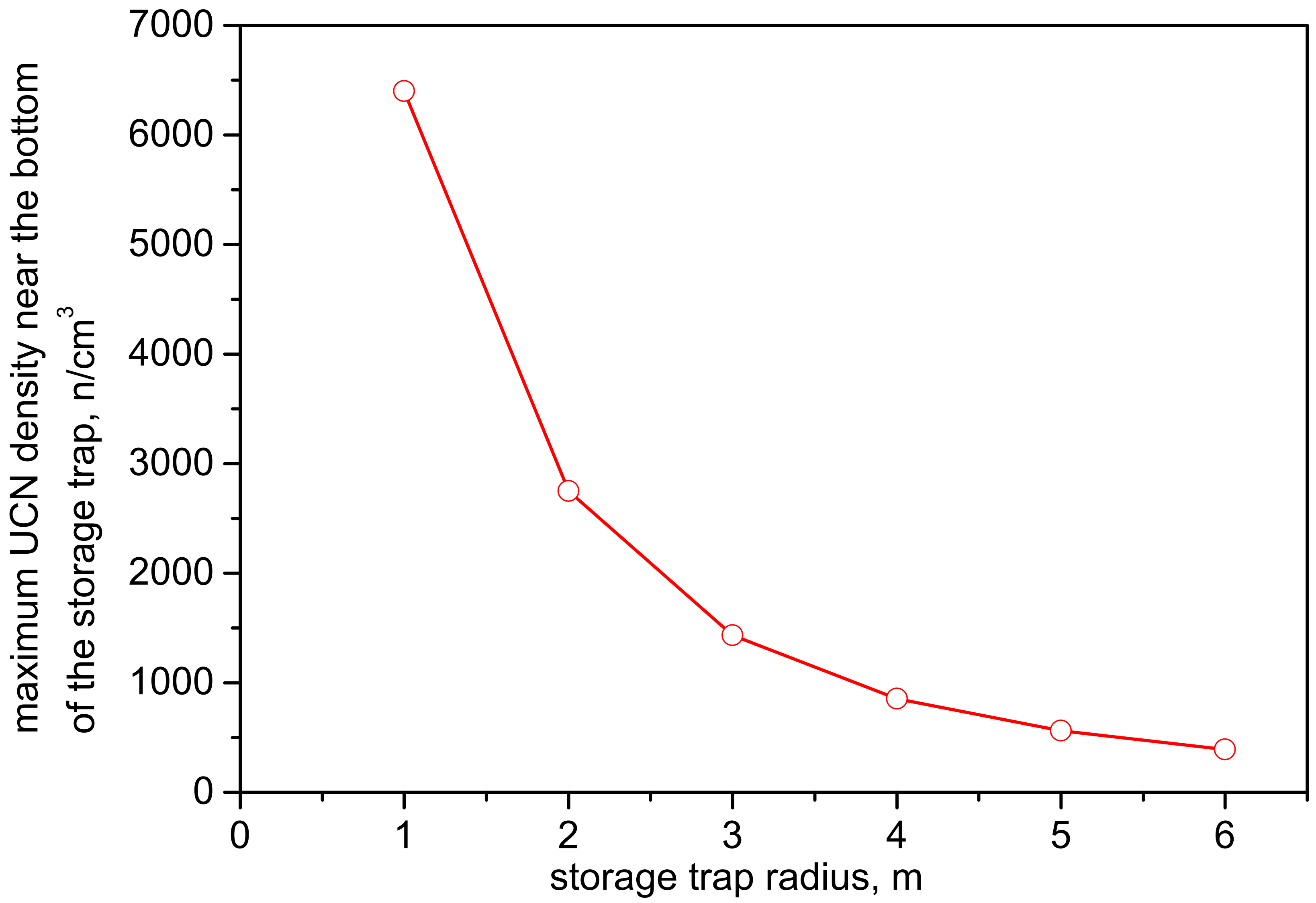


UCN number in the trap for different storage trap radius



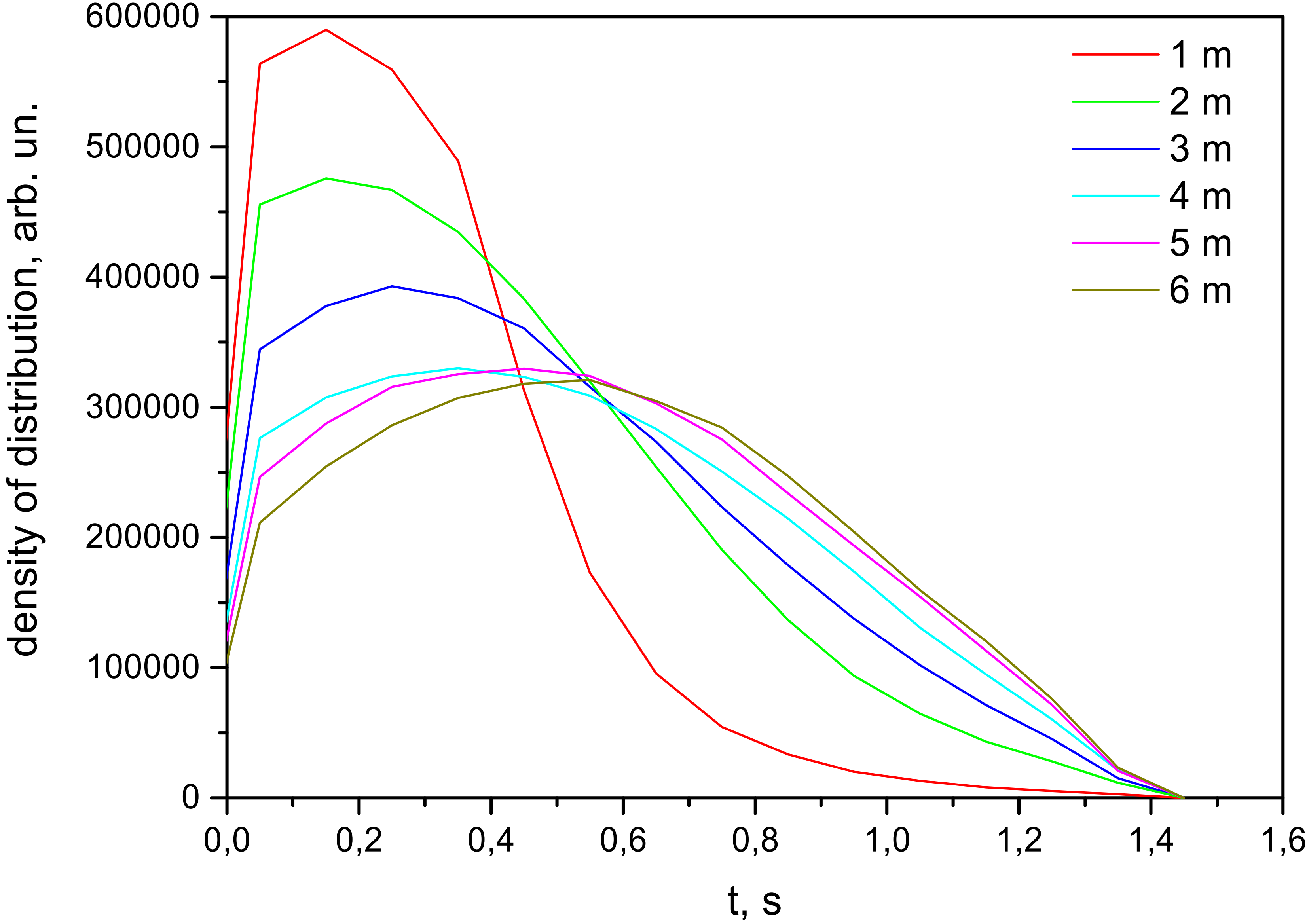
Storage trap: height 2.5 m, $v_{boundary}$ = 6.8 m/s, diffusion 90 %, abs. in walls $3 \cdot 10^{-5}$

UCN density for different storage trap radius



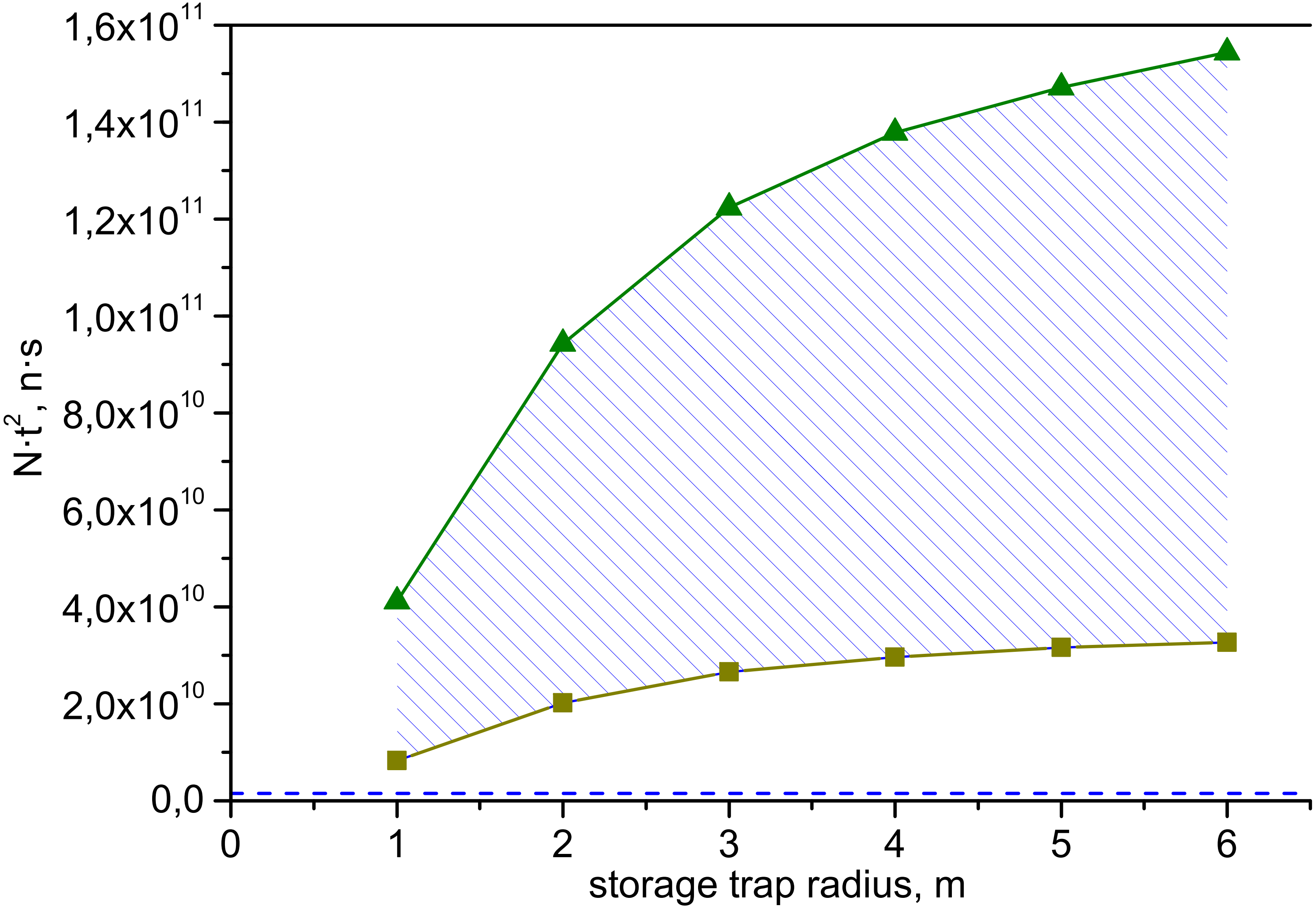
Storage trap: height 2.5 m, $v_{boundary}$ = 6.8 m/s, diffusion 90 %, abs. in walls $3 \cdot 10^{-5}$

UCN time of flight for different storage trap radius



Storage trap: height 2.5 m, $v_{boundary}$ = 6.8 m/s, diffusion 90 %, abs. in walls $3 \cdot 10^{-5}$

$N \cdot t^2$ for different storage trap radius



Storage trap: height 2.5 m, $v_{boundary}$ = 6.8 m/s, diffusion 90 %, abs. in walls $3 \cdot 10^{-5}$

Oscillation period

$$\tau_{n\tilde{n}} = \sqrt{\frac{(N \cdot t^2) \cdot T \cdot \varepsilon}{\tilde{N}}}$$

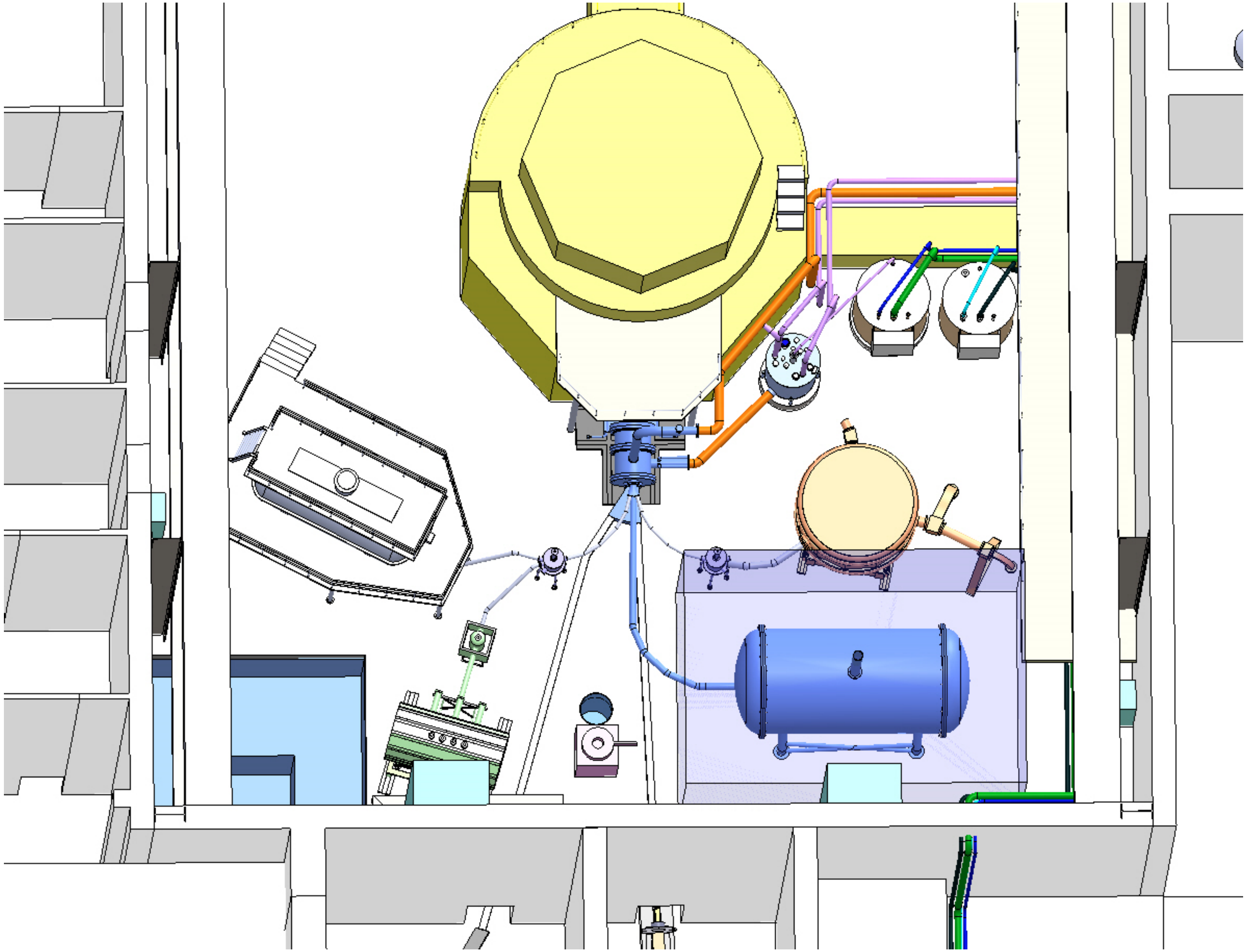
$$T \sim 3\ years$$

$$\varepsilon = 0.9$$

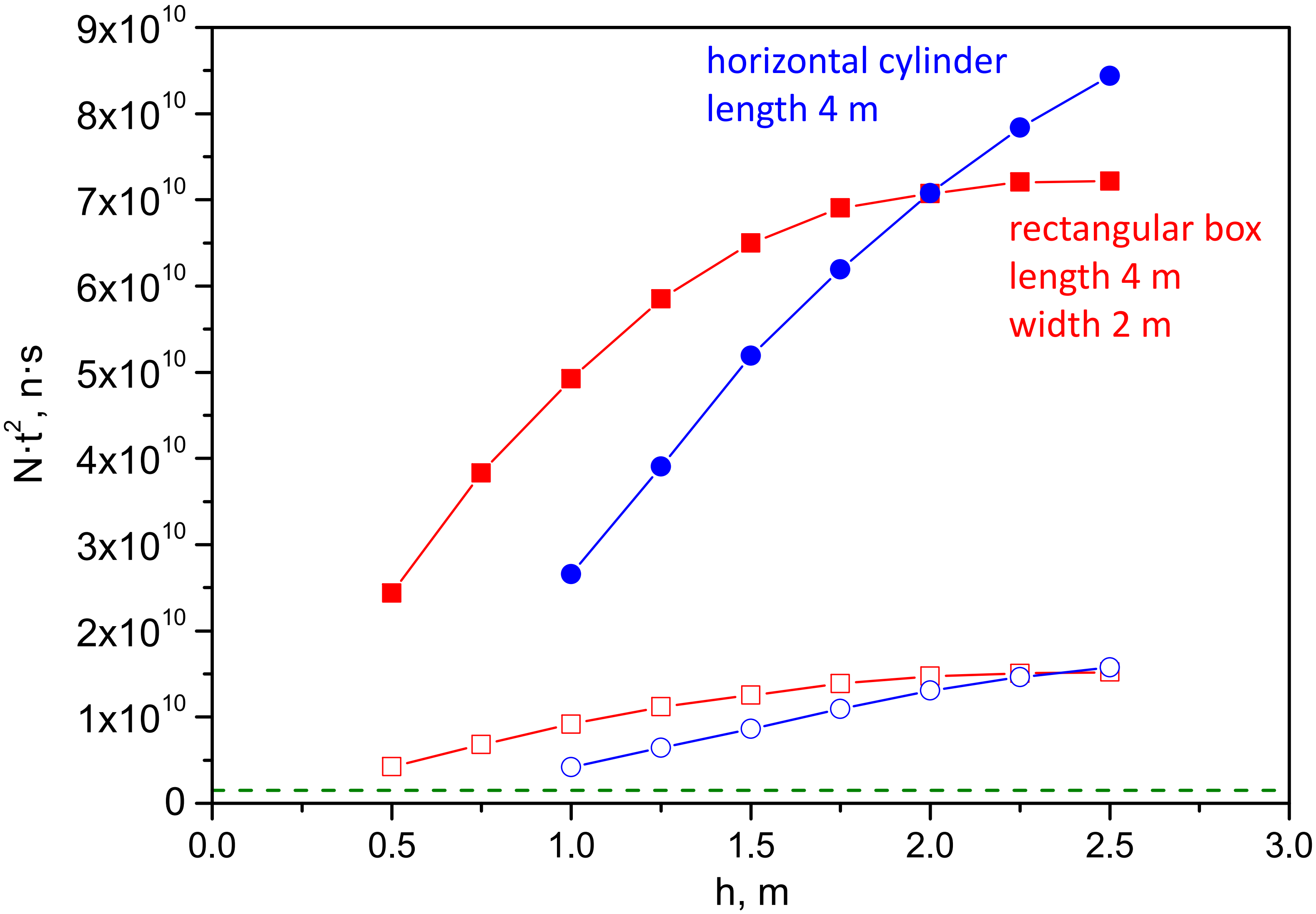
$\tilde{N} = 0$ **(** ≤ 2.3 **at 90% CL)**

$\tau_{n\tilde{n}} \geq (1 \div 2) \cdot 10^9$ **s (90% CL)**

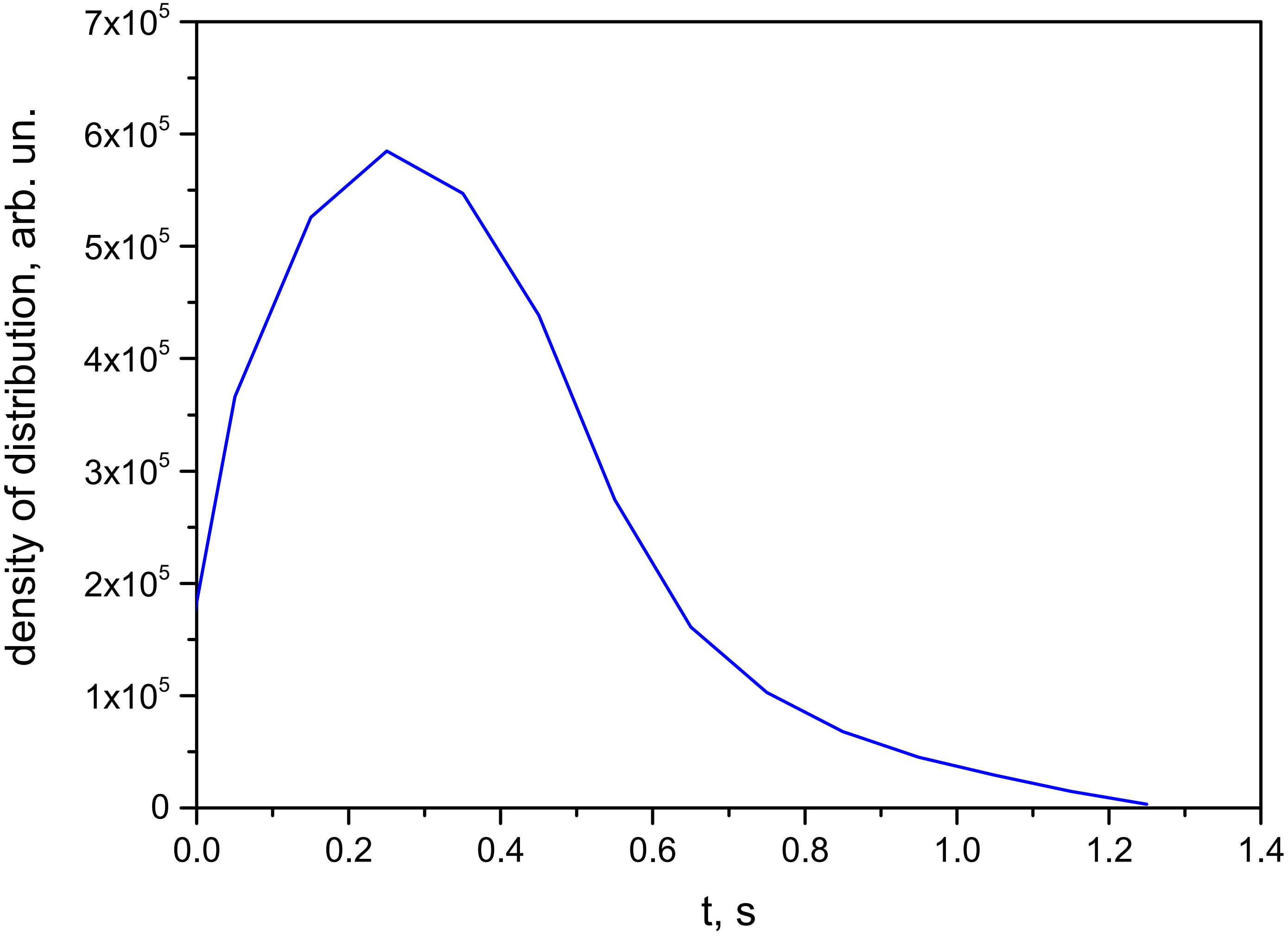
UCN facilities at reactor WWR-M



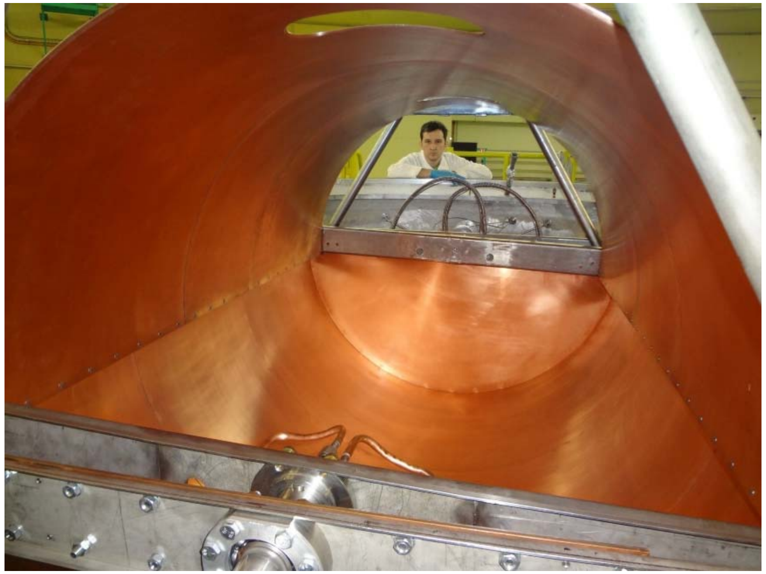
$N \cdot t^2$ for different storage trap height



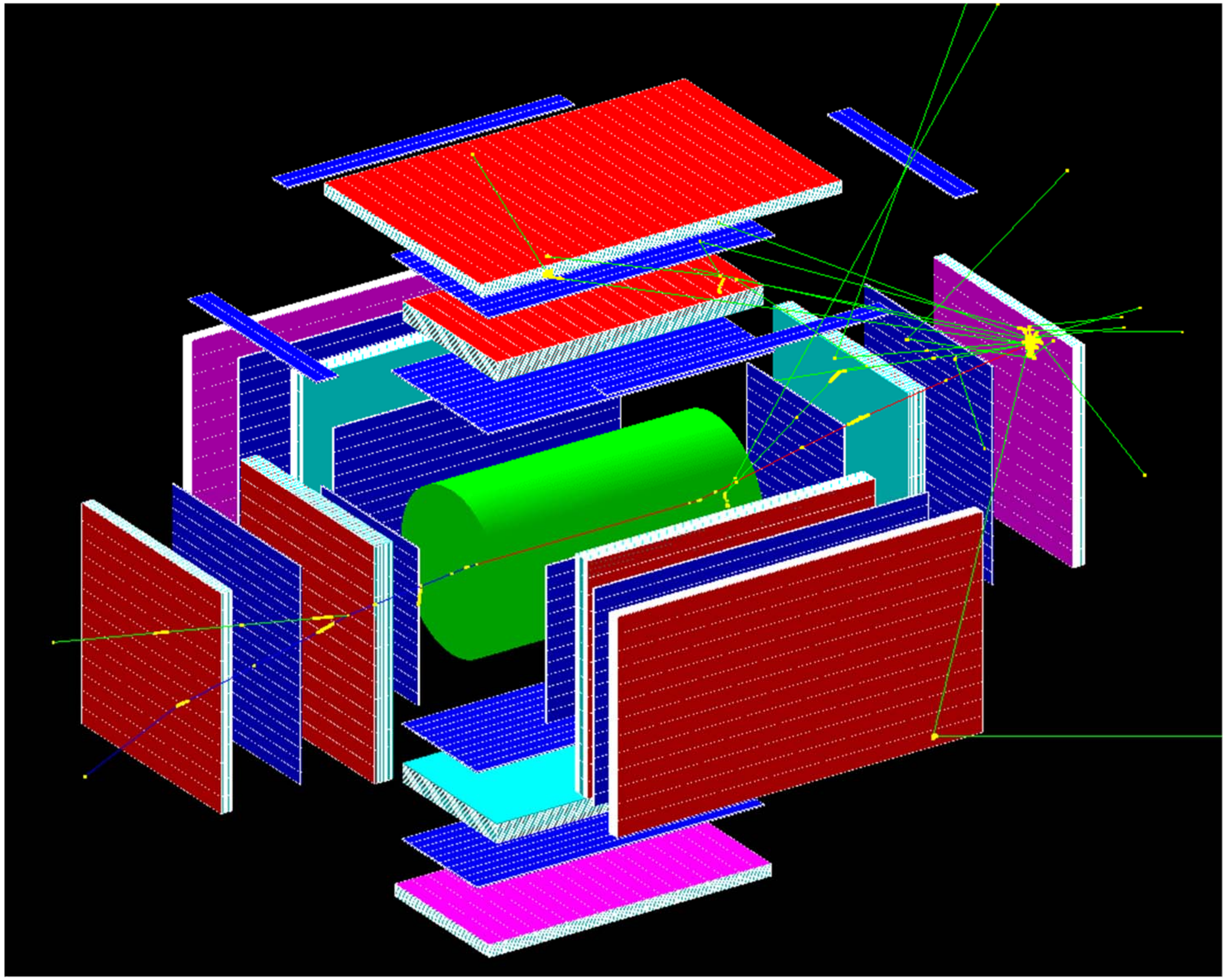
Time of flight distribution



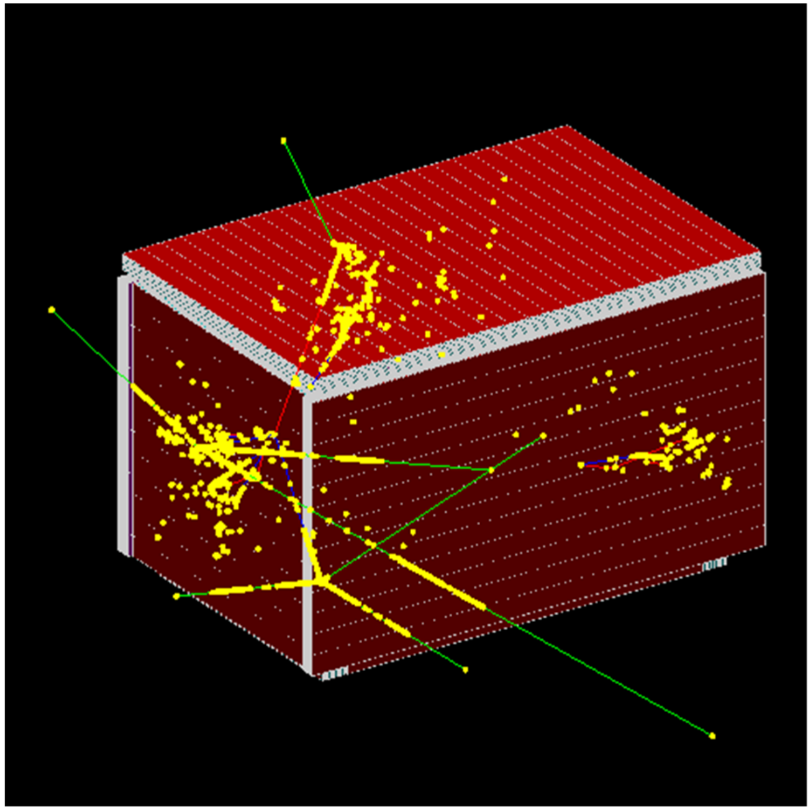
Big gravitational trap
for neutron lifetime measurement

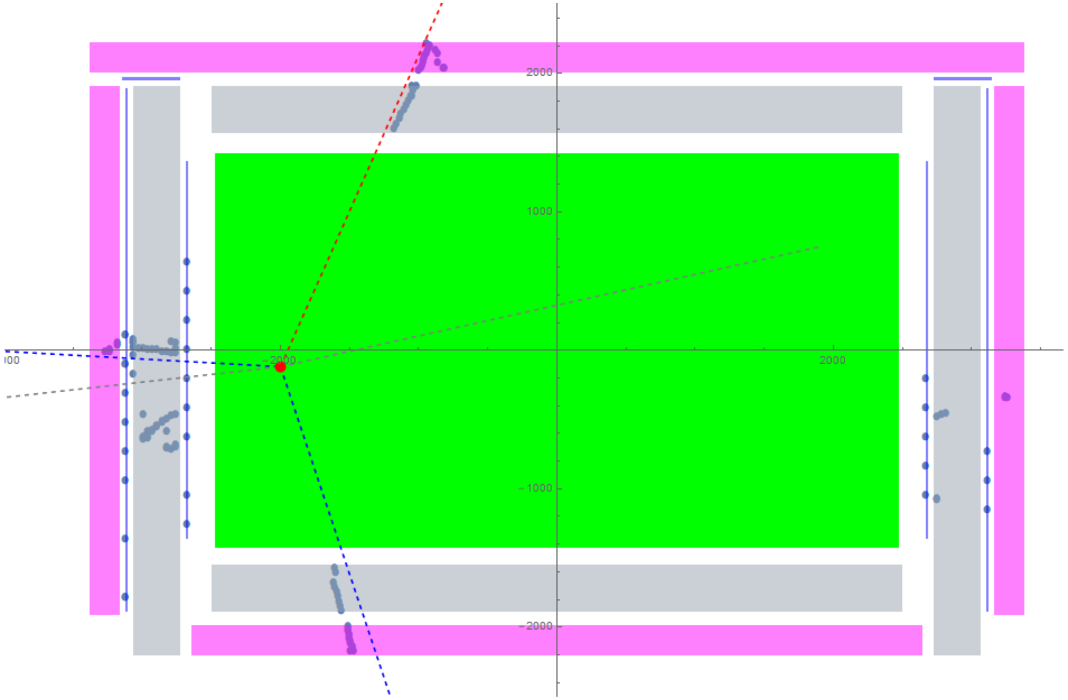


GEANT4 simulation

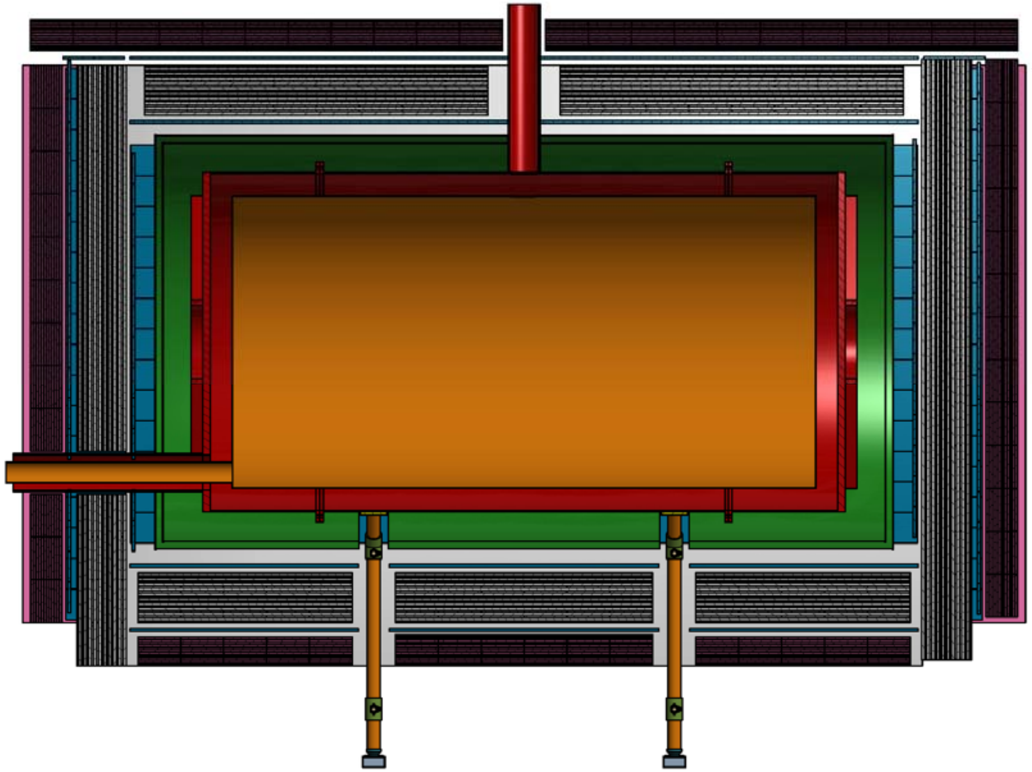


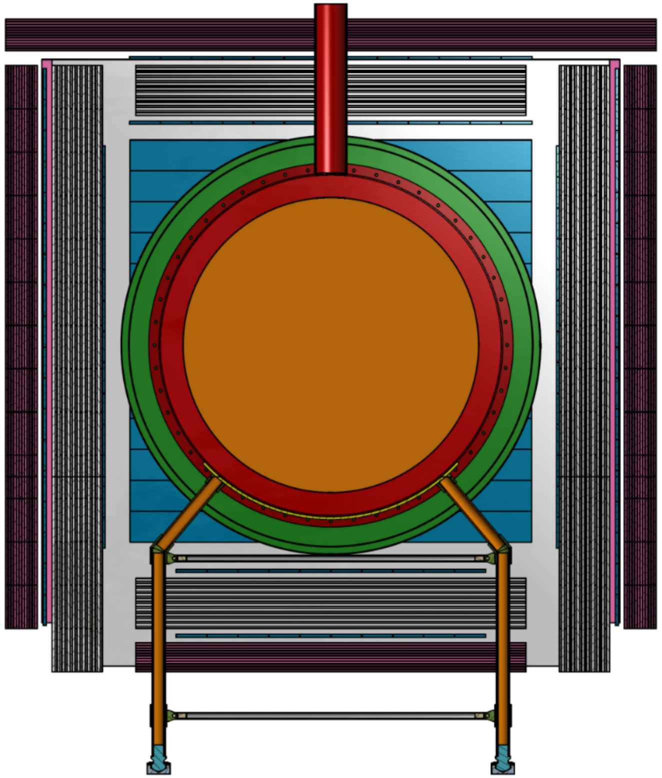
GEANT4 simulation



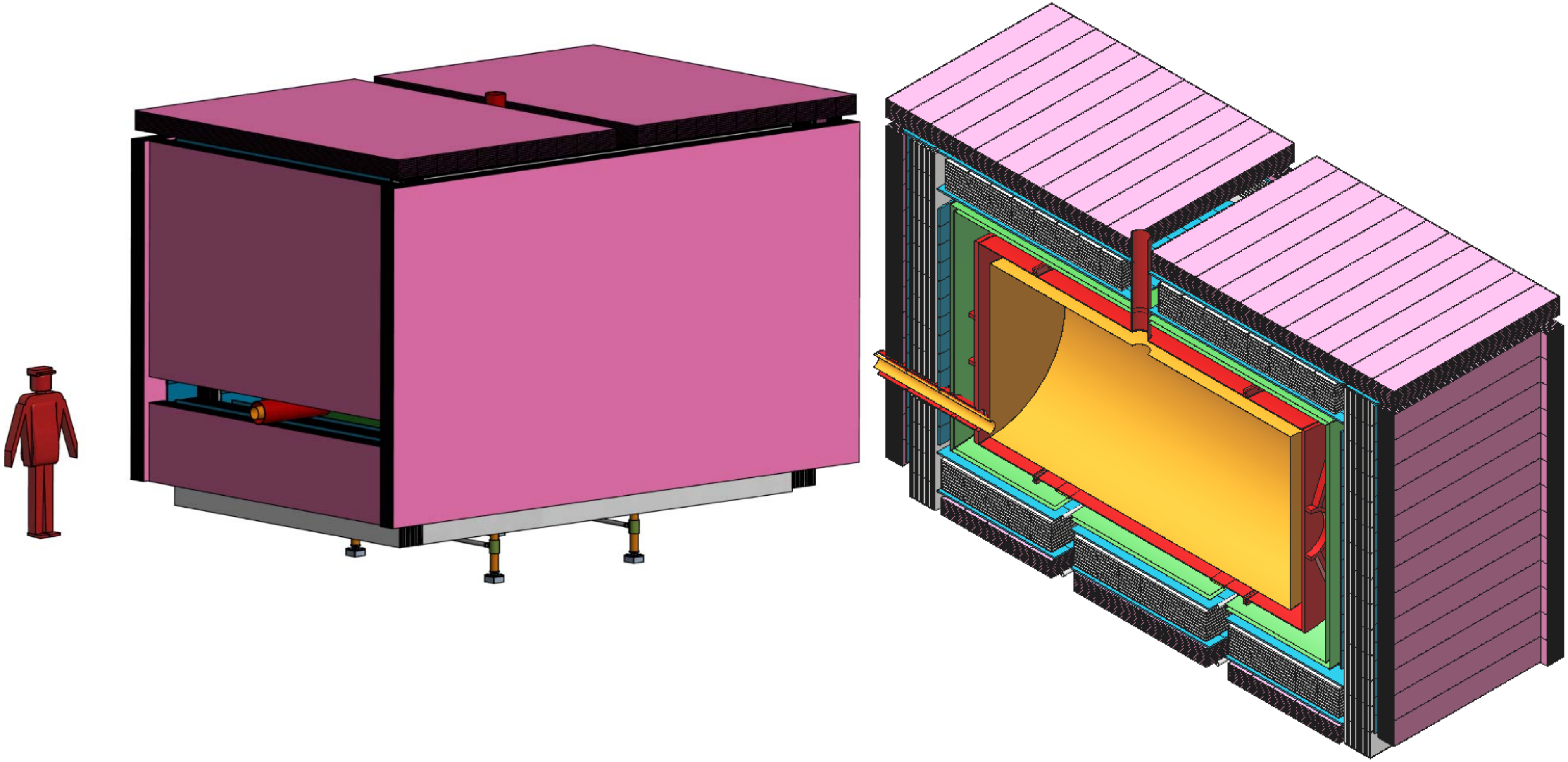


Design of the setup





Design of the setup



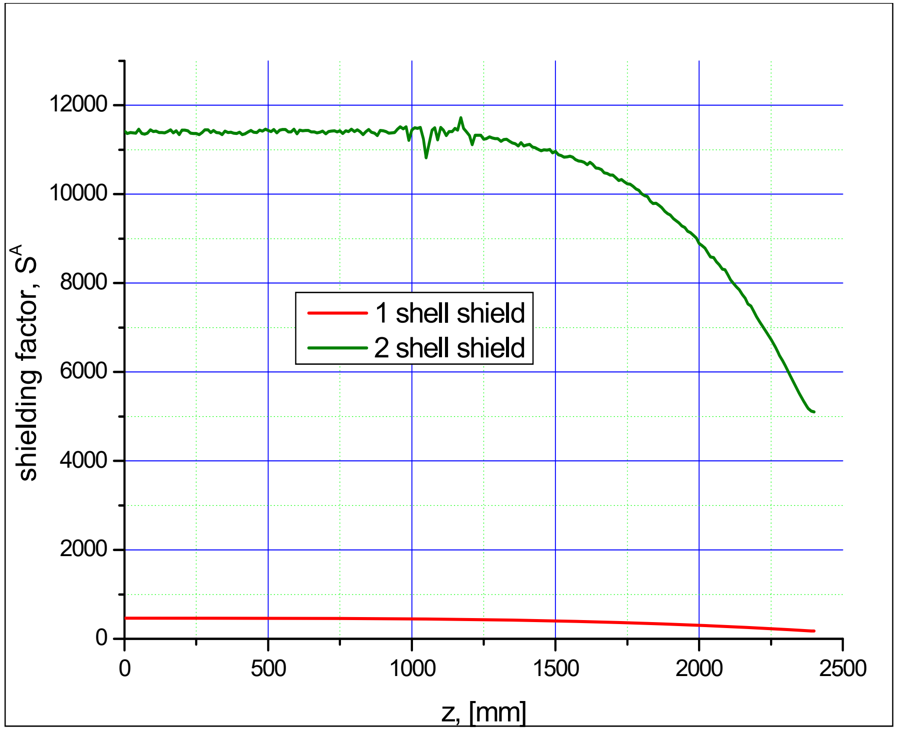
Magnetic shielding

Residual magnetic field: $B < 1\,nT$ is needed
External magnetic field of Earth: $B \sim 10^4 nT$
Required shielding factor: $S \sim 10^4$

It is planned to use μ-metal from the manufacturer Vakuumschmelze (Gamburg) with a thickness of 1.5 mm
Magnetic properties of this metal after thermal processing:
$\mu_{in} = 50000$ (*initial magnetic permeability*);
$\mu_{max} = 250000$ (*maximum magnetic permeability*);
$B_{sat} = 0.8\,T$ (*saturation induction*).

Axial magnetic shielding

Numerical calculation of the static axial shielding factor



Static shielding factor for μ-metal after demagnetization procedure.
The soft “Radia” (ESRF Grenoble) was used for numerical calculation.

Analytical calculation of the static and dynamic axial shielding factor

$S_A = 1 + 4\left(\left.[\ln(2p)-1]\right/ p^2\right) S_T$ – *expression for computing a single–layer screen.*

$S_T = \frac{\mu d}{D}$ – *transverse shielding factor a single–layer screen.*

$p = L/D > 1$ – *the ratio of the length/diameter of the screen.*

$\mu_{in} = 50000$ – *for calculation dynamic shielding factor;*

$\mu_{eff} = 2 \times 10^6$ – *for calculation static shielding factor (after demagnetization μ-metal).*

$S^A = 1 + S_1^A + S_2^A + S_1^A S_2^A \left(1 - L_1/L_2\right)$ – *expression for computing a two–layer screen*

S_i^A – *shielding factor for i shell*; $2 < L/D < 10$ – *the ratio of the length/diameter of the screen*

the results are presented in the table

PNPI (project)					
1 shell shield			2 shell shield ($\Delta R = \Delta L = 100$ mm)		
dynamic	static	Active compensation rate	dynamic	static	Active compensation rate
~16	~600	~300	~45	~14200	~100

Analytical calculation of the static and dynamic transverse shielding factor

$S^T = 1 + S_1^T + S_2^T + S_1^T S_2^T \left(1 - {R_1}^2/{R_2}^2\right)$ – *expression for computing a two–layer screen.*

$S_i^T = (\mu_i d_i)/D_i$ – *transverse shielding factor for i layer.*

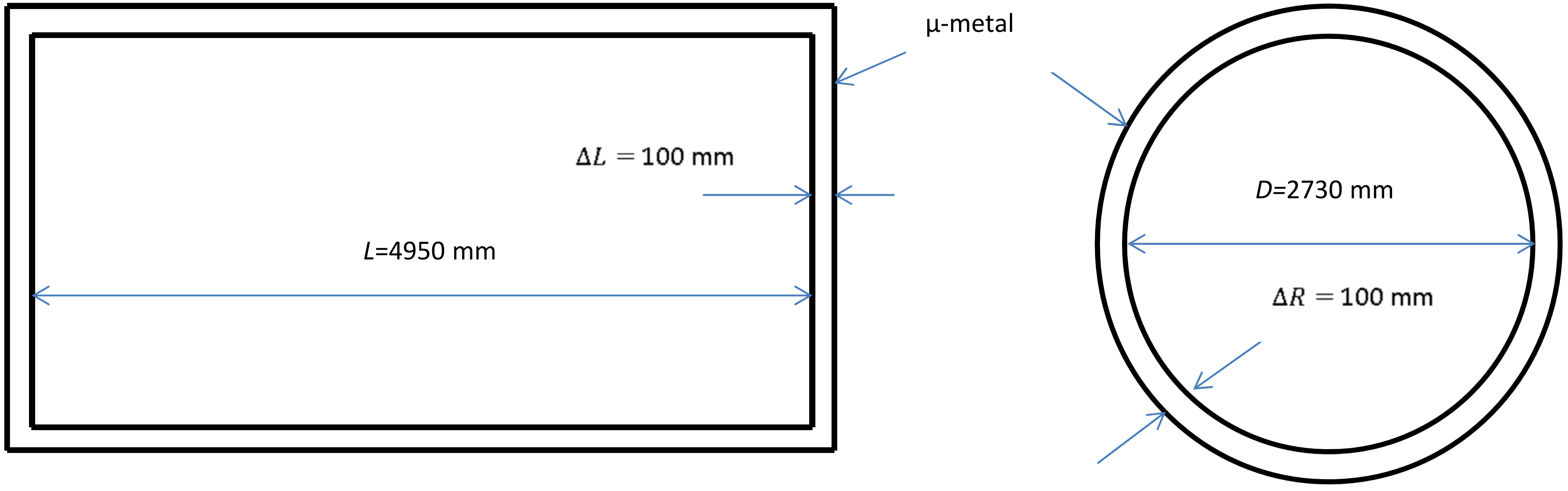
To ensure good shielding ($B < 1\ nT$), active compensation the external field is required.

$$Active\ compensation\ rate = \frac{External\ field}{Residual\ field}$$

the results are presented in the table

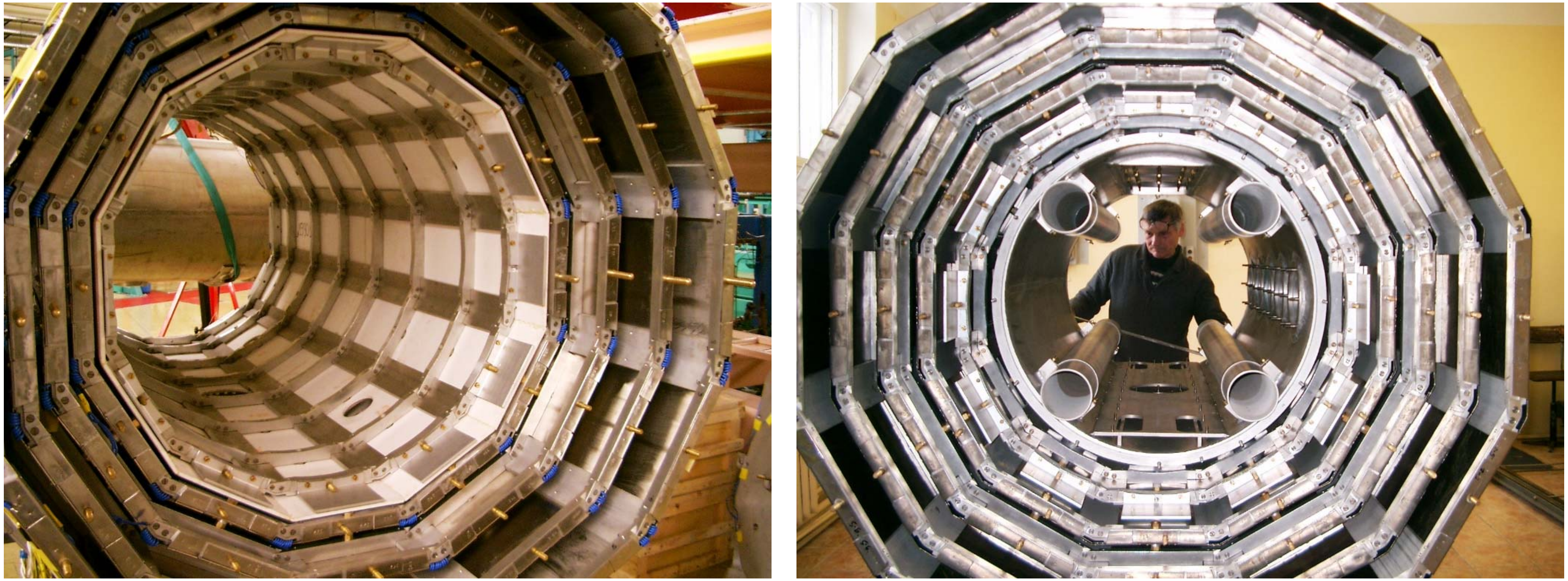
PNPI (project)					
1 shell shield			2 shell shield ($\Delta R = \Delta L = 100$ mm)		
dynamic	static	Active compensation rate	dynamic	static	Active compensation rate
~30	~1100	~150	~150	~150000	~20

The final configuration of our magnetic shield

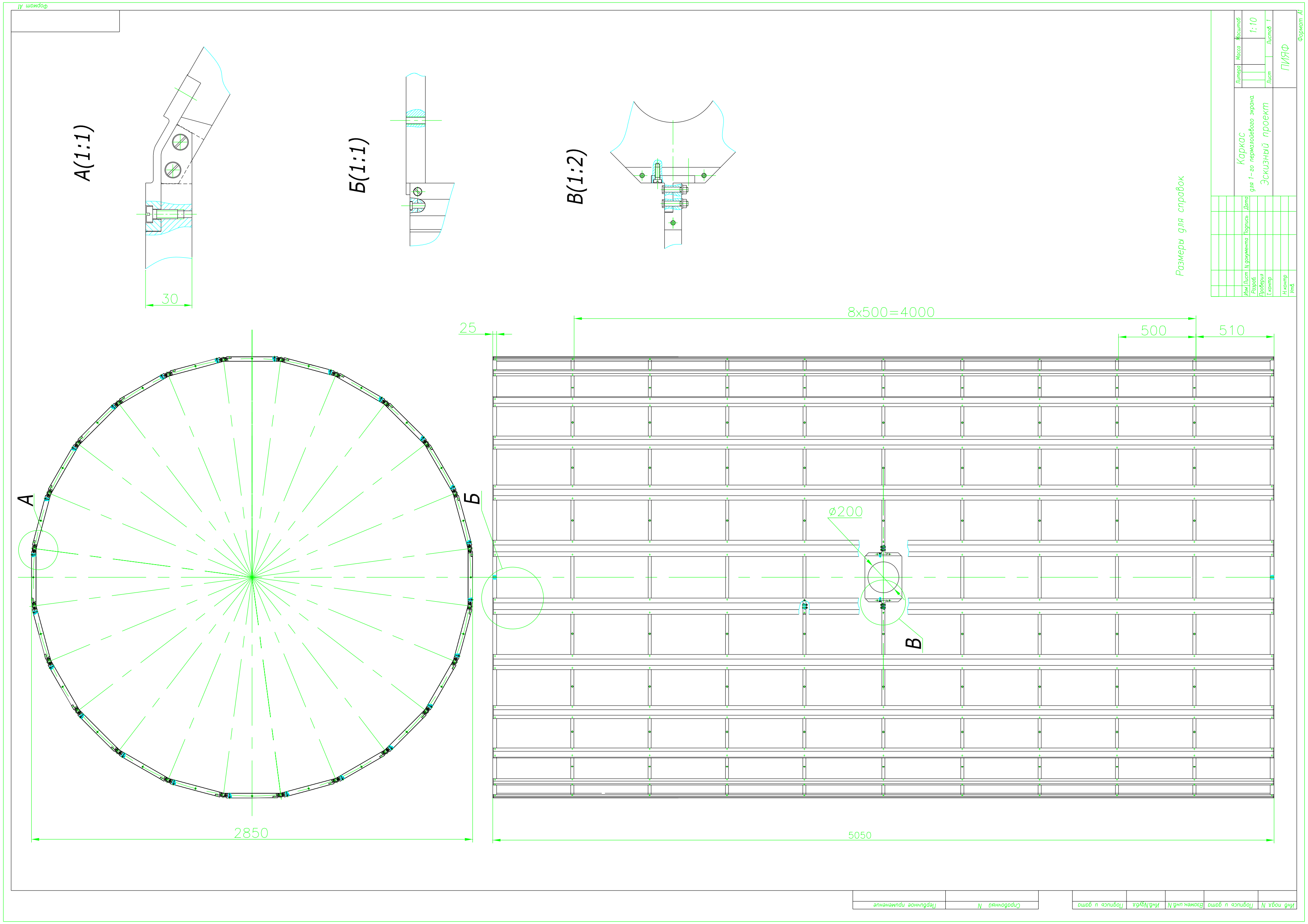


thickness of μ-metal - 1.5 mm

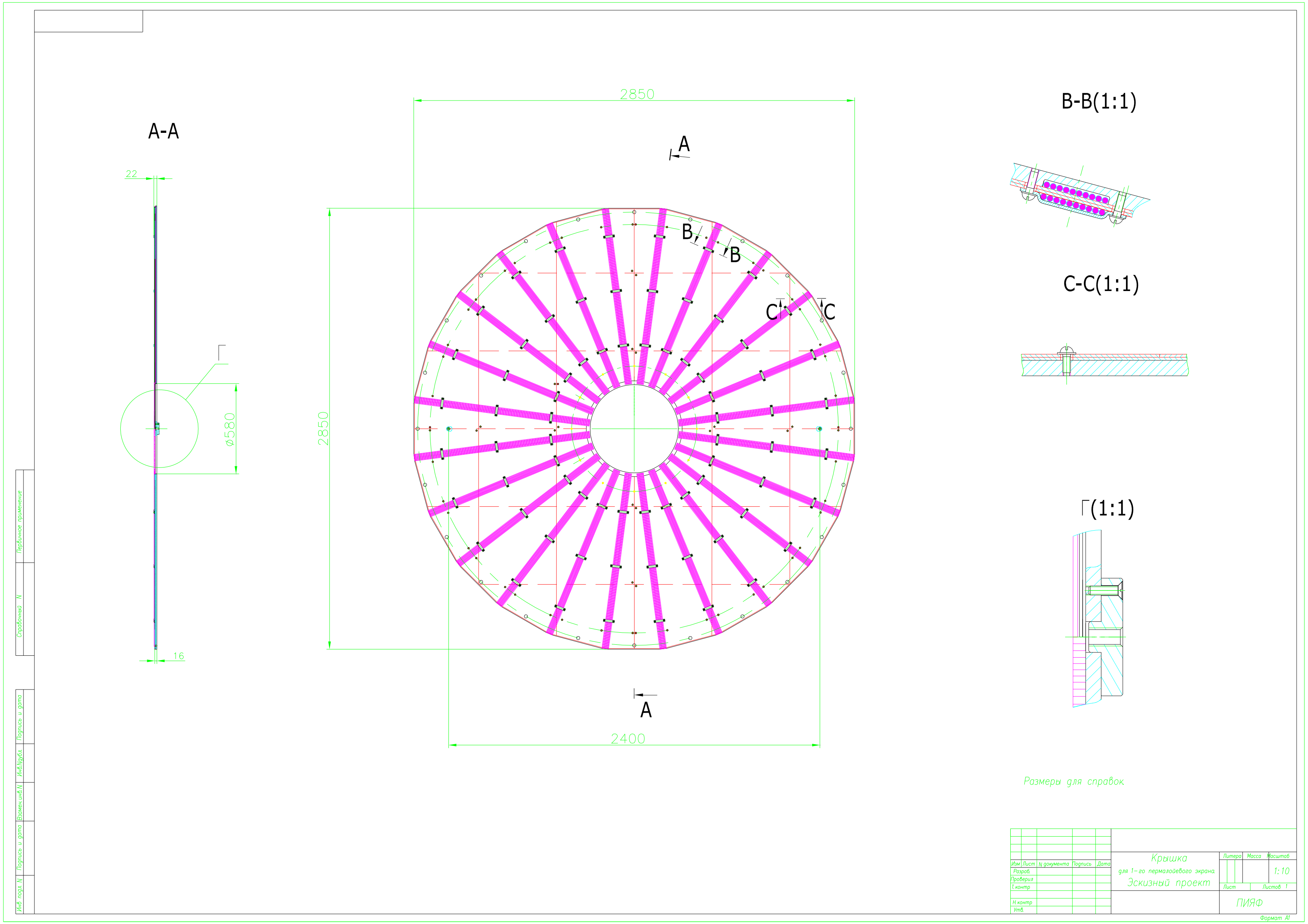
Magnetic shielding of multi-chamber EDM spectrometer



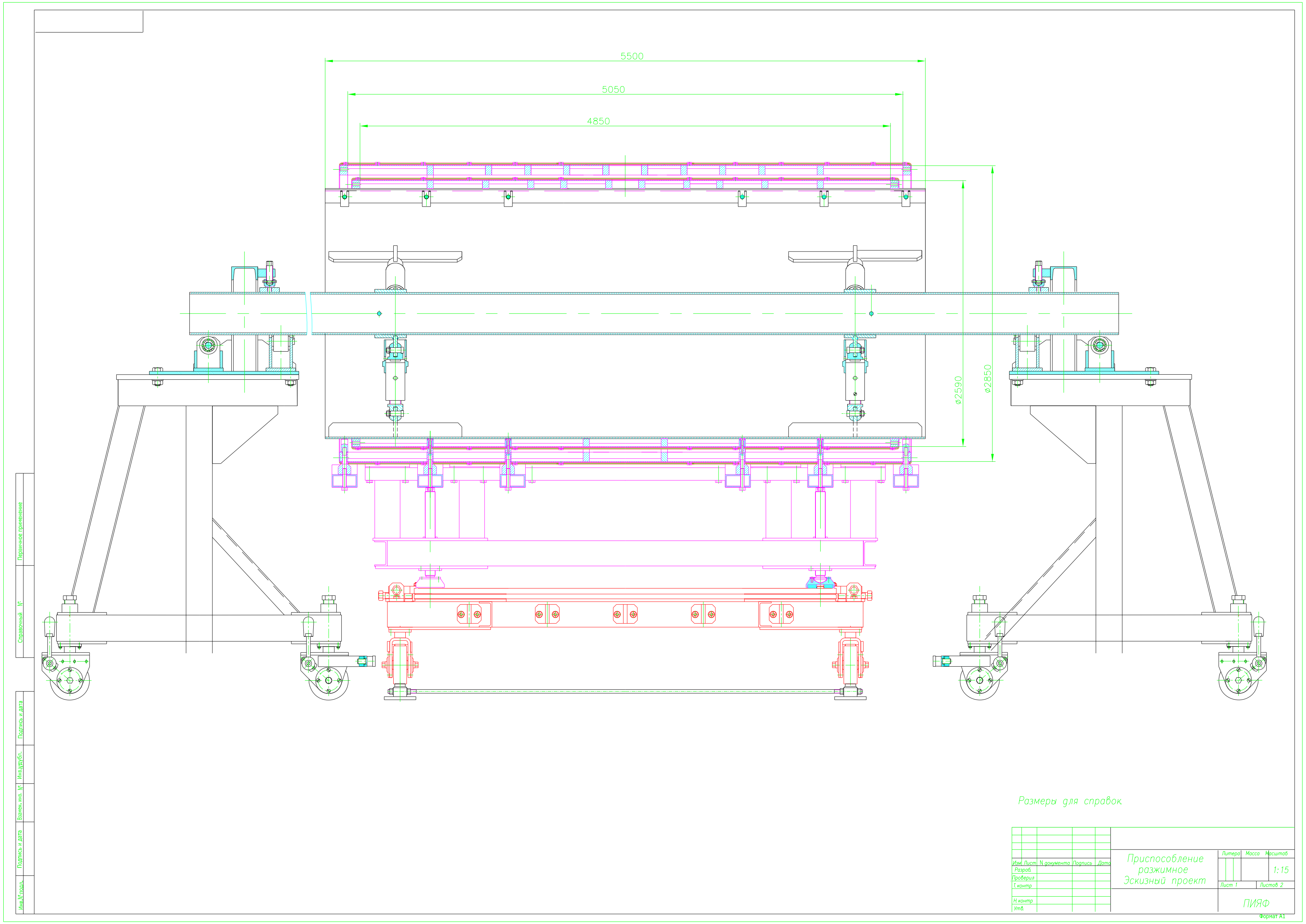
Magnetic shielding



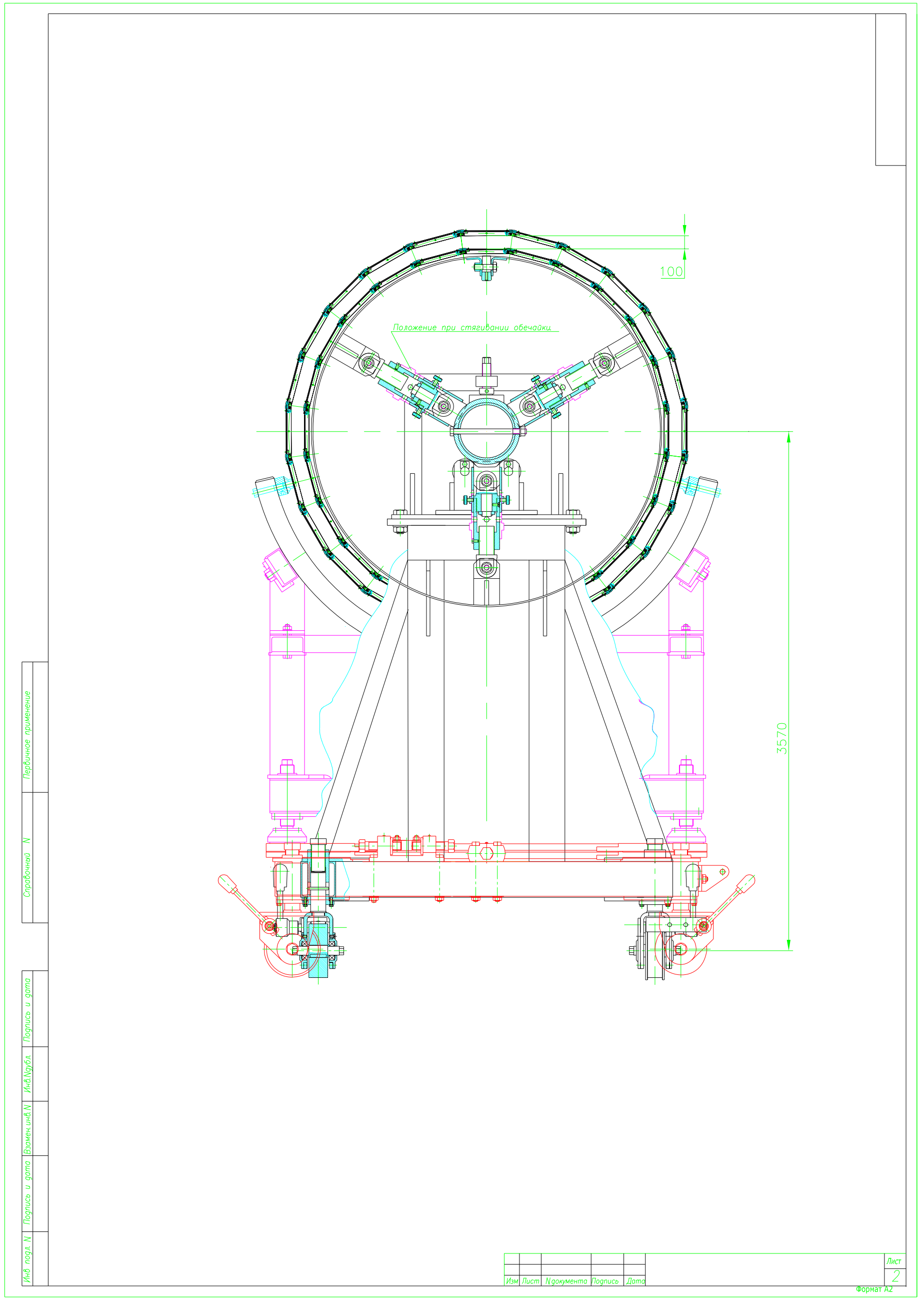
Magnetic shielding



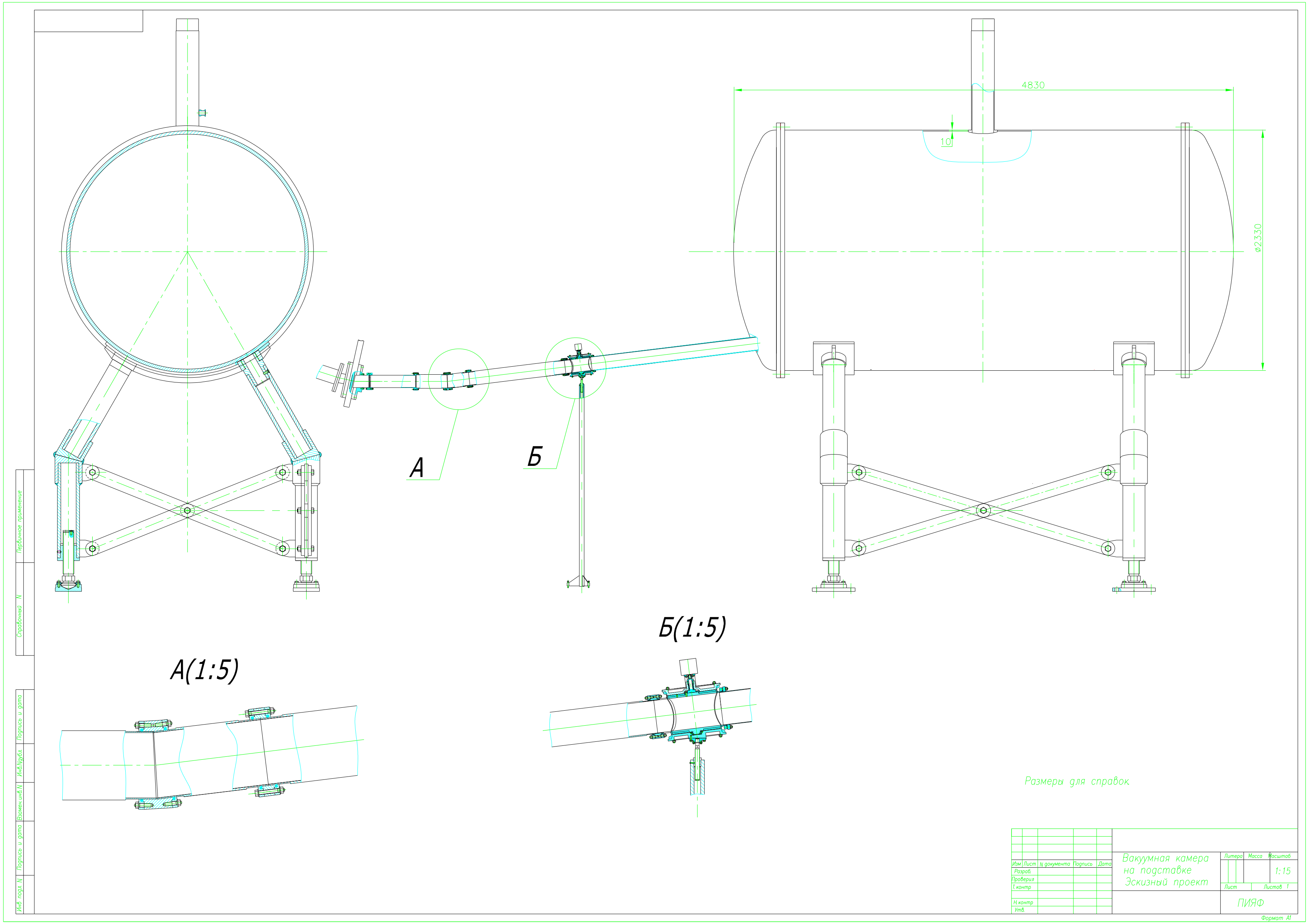
Magnetic shielding assembly



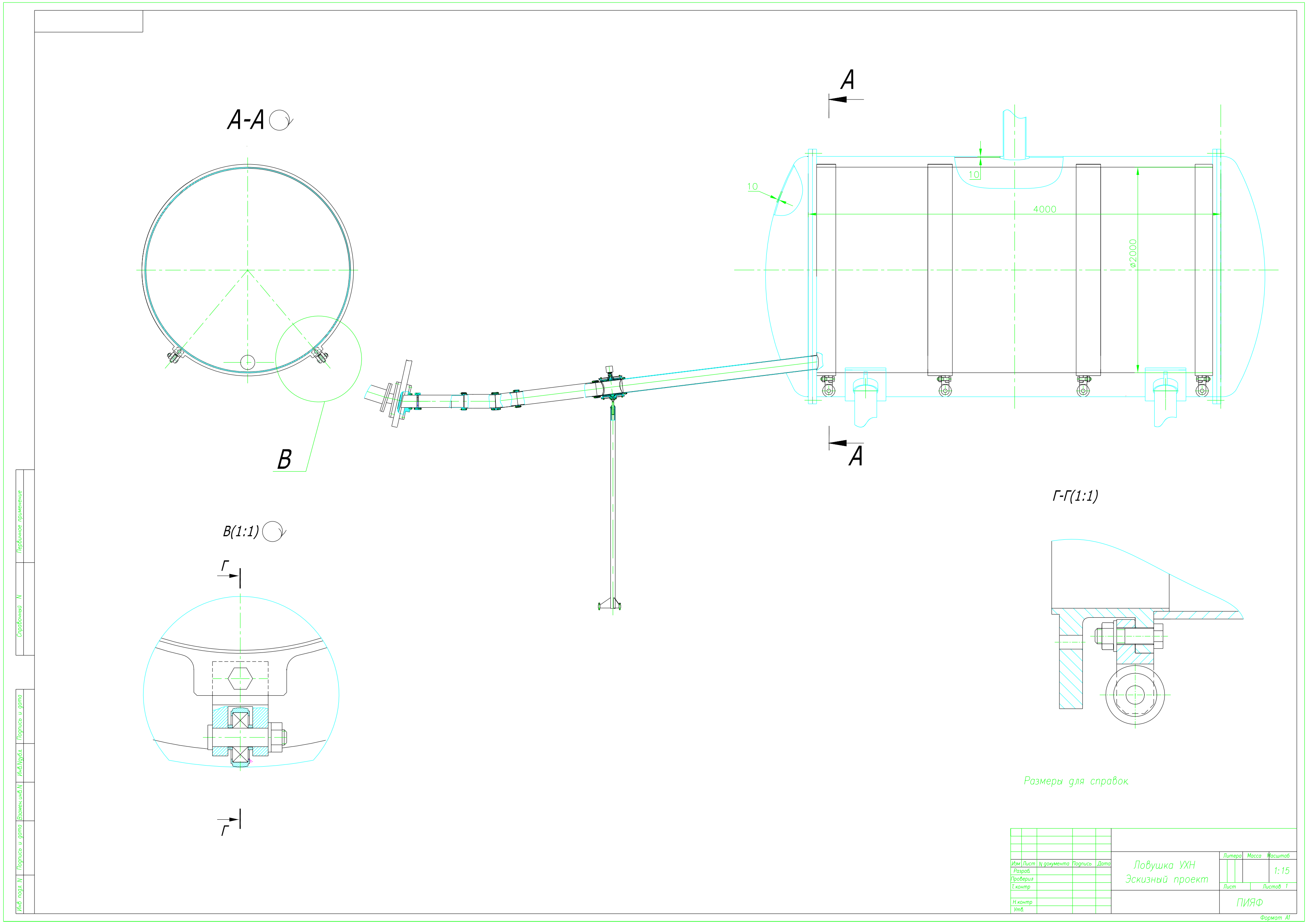
Magnetic shielding assembly



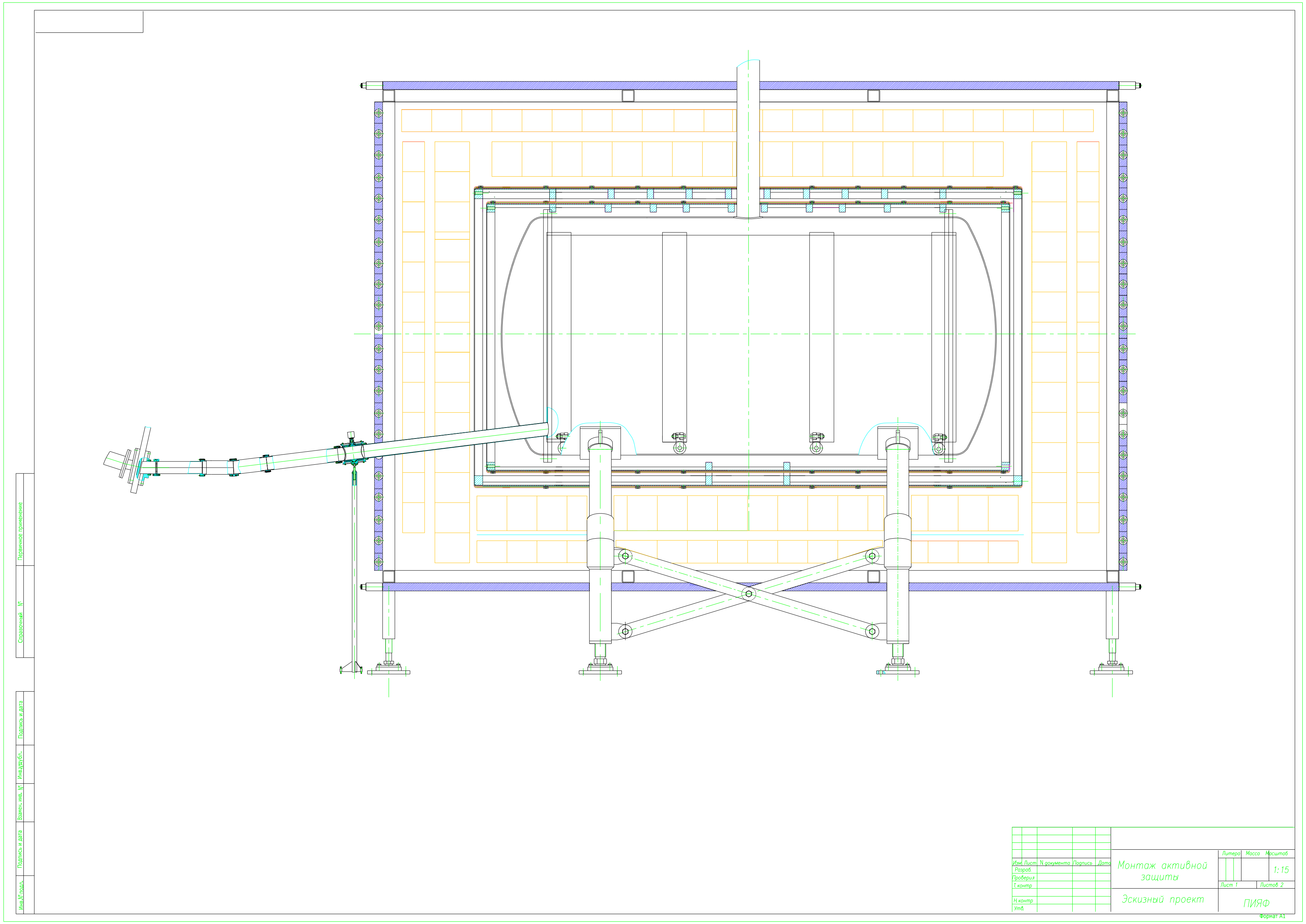
Vacuum chamber



UCN trap


A-A
A
A
10
10
4000
⌀2000
B
B(1:1)
Г
Г
Г-Г(1:1)
Размеры для справок.
Первичное применение
Справочный N
Подпись и дата
Инв.Nдубл.
Взамен.инв.N
Подпись и дата
Инв подл. N
Изм
Лист
N документа
Подпись
Дата
Разраб.
Проверил
Т.контр
Н.контр
Утв.
Ловушка УХН
Эскизный проект
Литера
Масса
Масштаб
1:15
Лист
Листов 1
ПИЯФ
Формат A1

Veto system


Первичное применение
Справочный №
Подпись и дата
Инв. № дубл.
Взам. инв. №
Подпись и дата
Инв. № подл.
Изм
Лист
N документа
Подпись
Дата
Разраб.
Проверил
Т. контр
Н. контр
Утв.
Монтаж активной защиты
Эскизный проект
Литера
Масса
Масштаб
1:15
Лист 1
Листов 2
ПИЯФ
Формат А1

Progress of UCN source at reactor WWR-M

Project leader: A. Serebrov

Cryogenic complex at WWR-M reactor

Hall of the cryogenic equipment

Helium liquefier and refrigerator

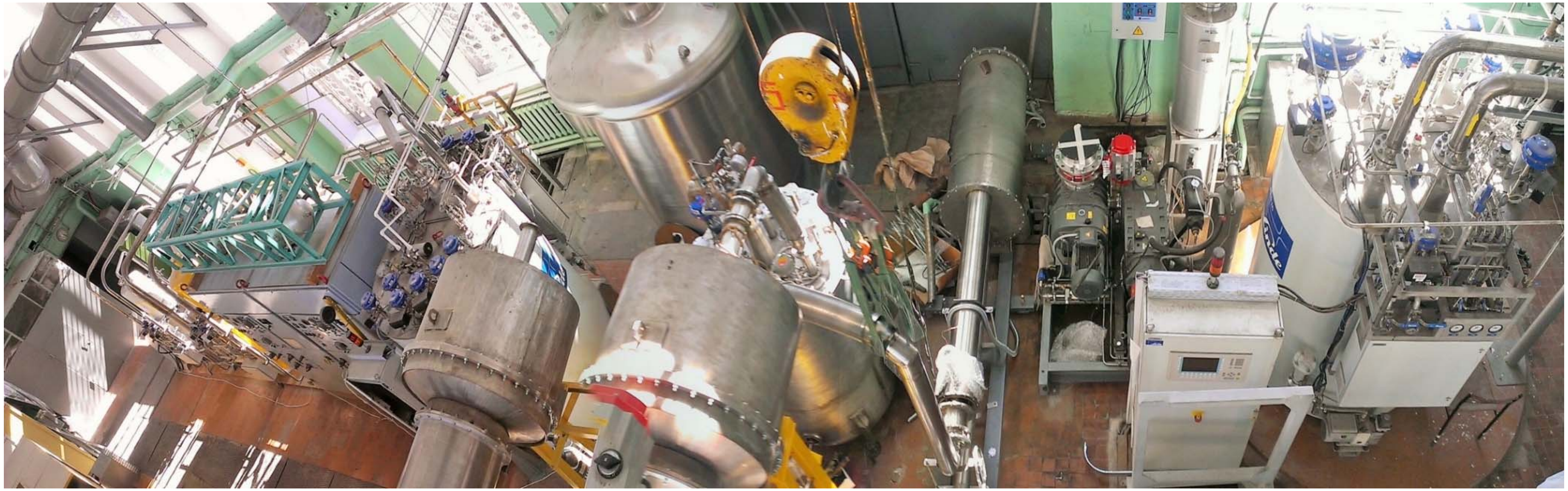
Vacuum equipment

Cryostat

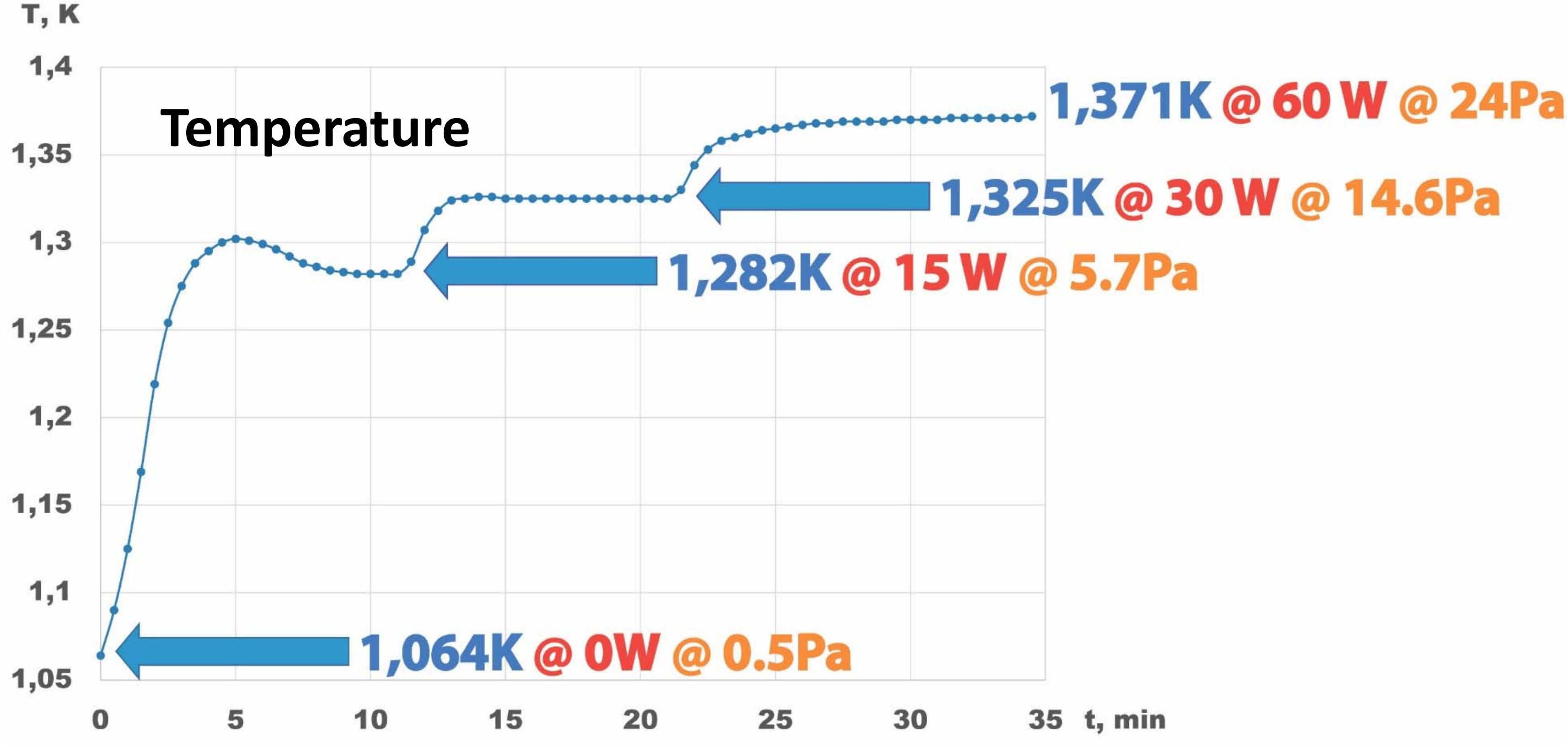
Compressors

Receivers, cryogenic building

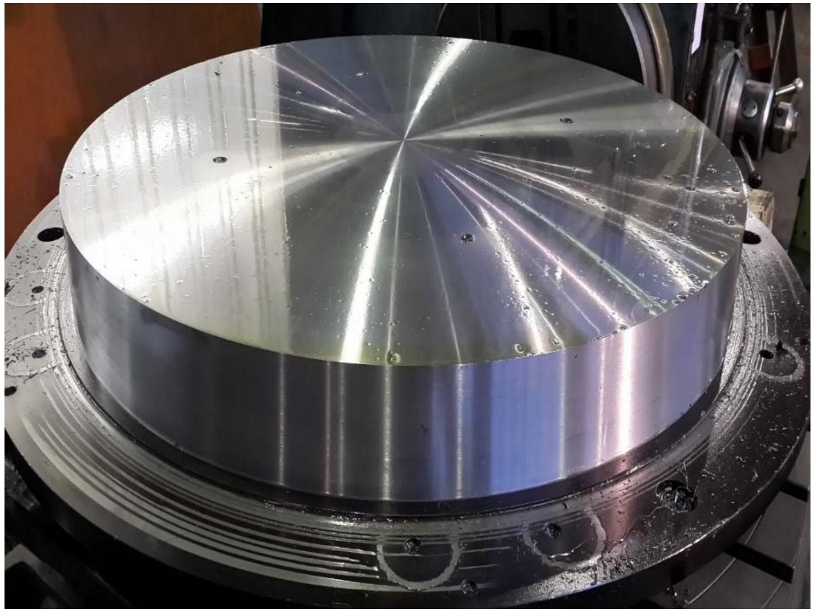
The full-scale technological model of UCN source with superfluid helium is mounted



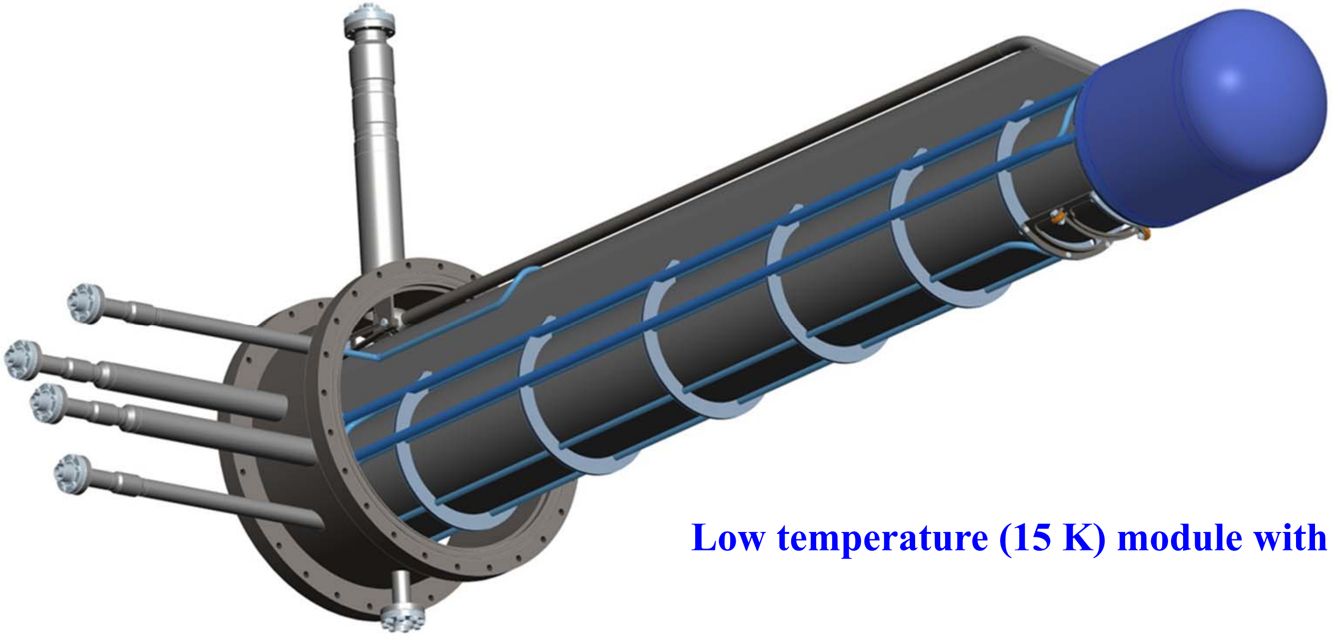
Recent experiment on full-scale model



Vacuum module manufacture



UCN source design / manufacture



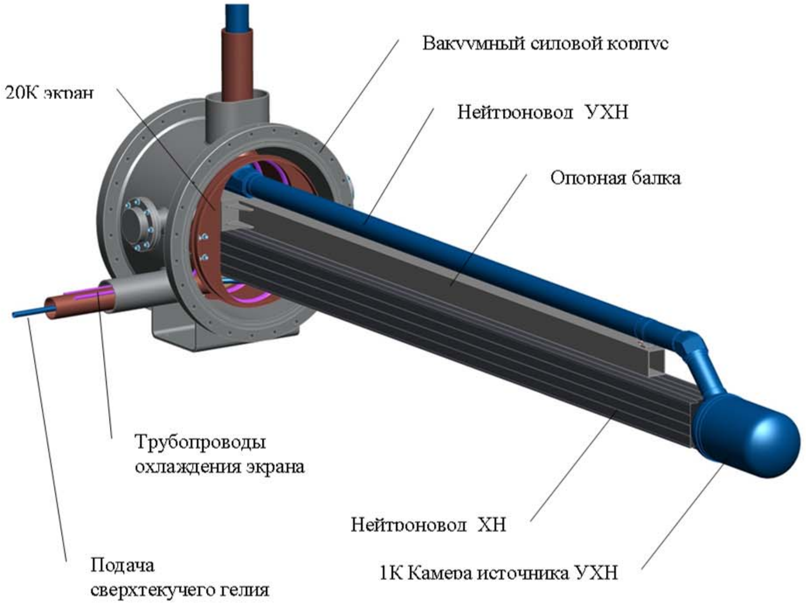
Low temperature (15 K) module with liquid deuterium moderator

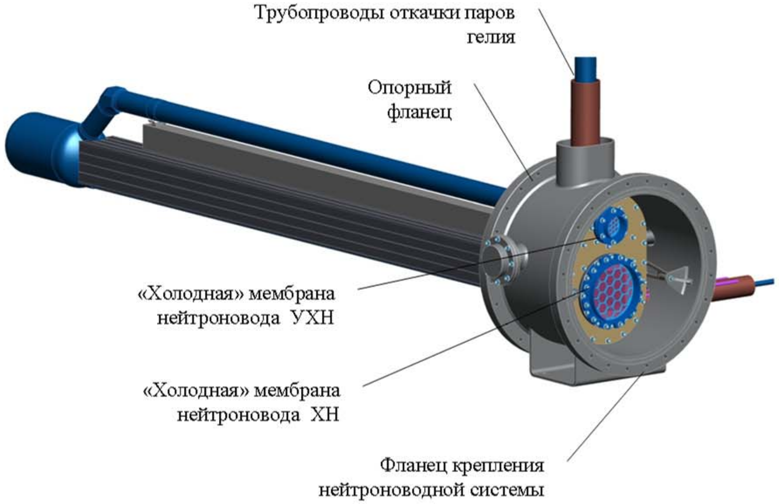
Under construction

X.XX+-0.01
X.XXX+-0.001
ANG.+-0.5

Will be ready till December 2018

UCN source design / manufacture



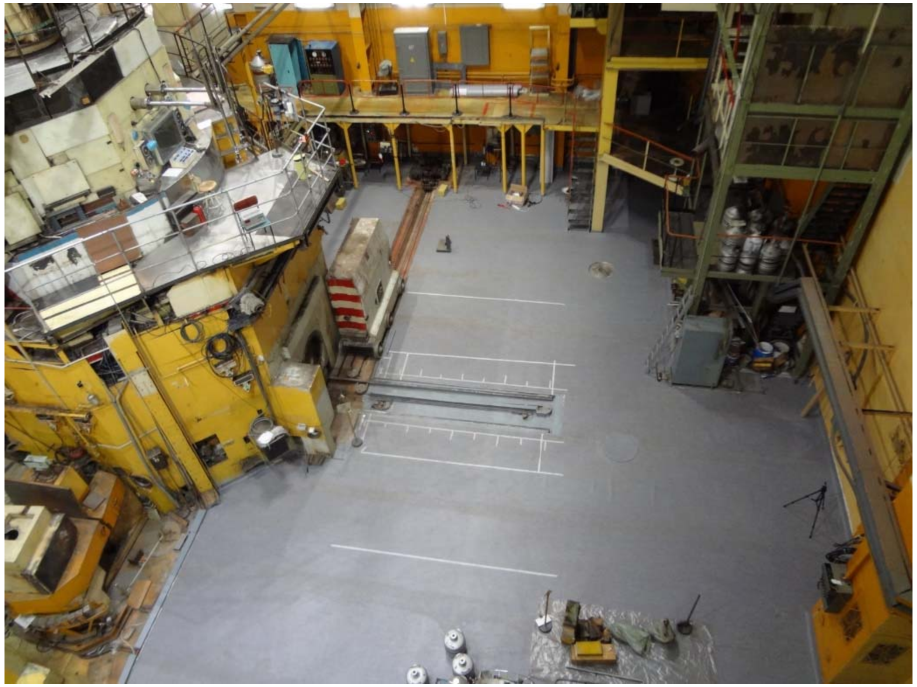


Low temperature (1 K) module with superfluid helium

Under construction

Will be ready till December 2018

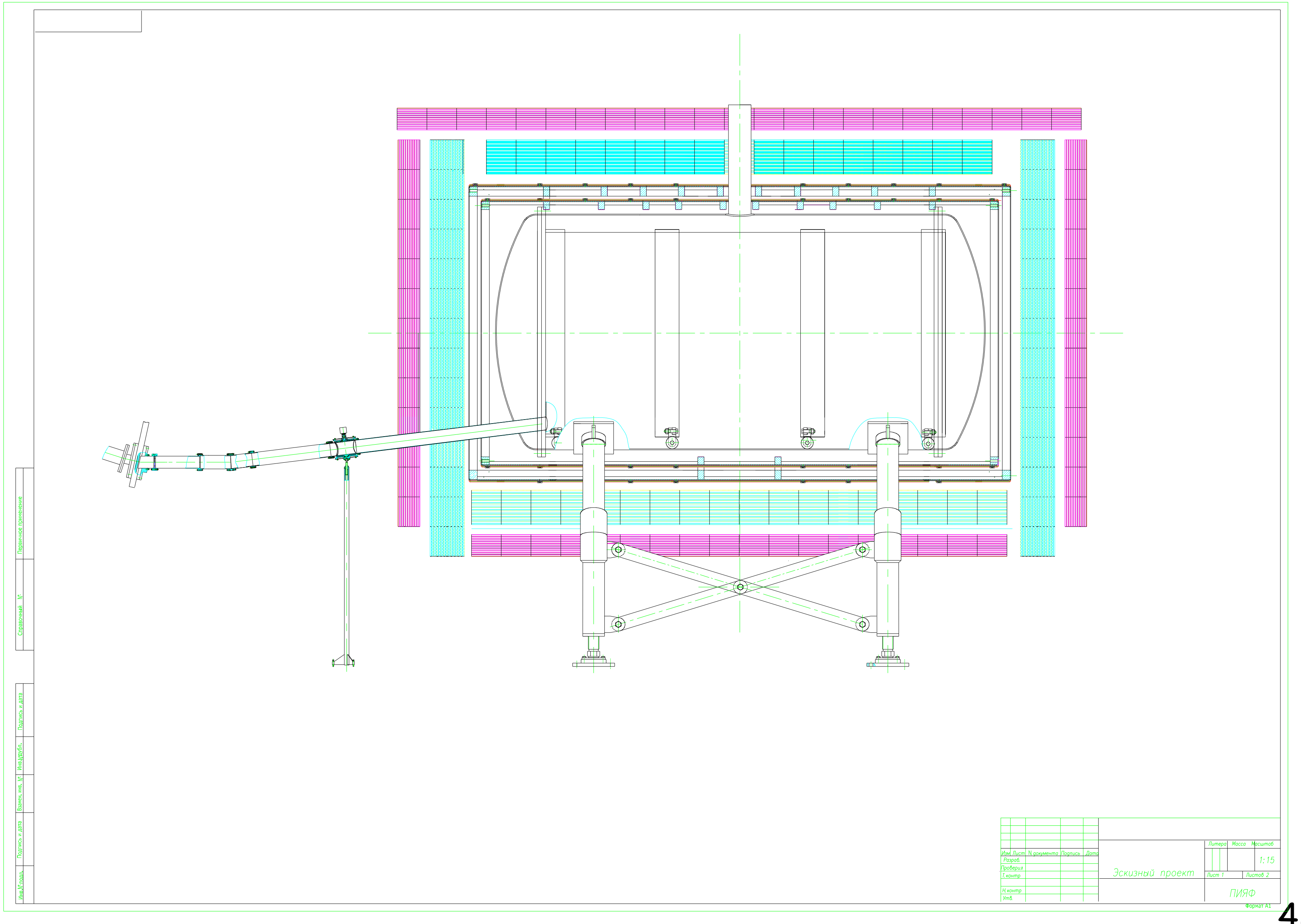
WWR-M reactor thermal column



Thermal column measurements

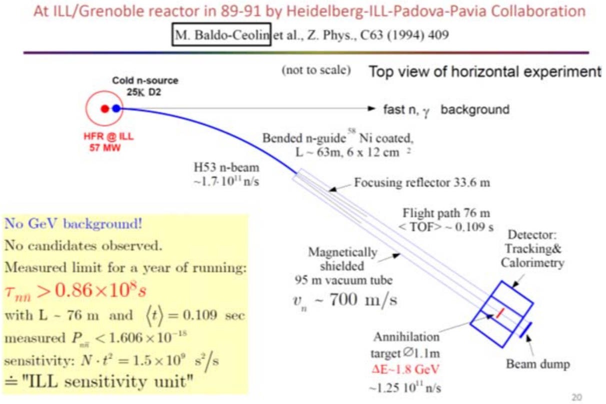
3D scan was done from 7 points
without contacting radioactive thermal column

Design of the setup



Size matters

ILL



At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

M. Baldo-Ceolin et al., Z. Phys., C63 (1994) 409

(not to scale) Top view of horizontal experiment

Cold n-source
25K D2

HFR @ ILL
57 MW

fast n, γ background

Bended n-guide ^{58}Ni coated,
L ~ 63m, 6 x 12 cm ^{2}

H53 n-beam
~1.7·10^{11} n/s

Focusing reflector 33.6 m

Flight path 76 m
< TOF> ~ 0.109 s

Detector:
Tracking&
Calorimetry

Magnetically
shielded
95 m vacuum tube

$v_n \sim 700$ m/s

Annihilation
target ∅1.1m
ΔE~1.8 GeV
~1.25 10^{11} n/s

Beam dump

No GeV background!

No candidates observed.

Measured limit for a year of running:

$\tau_{nn} > 0.86 \times 10^8 s$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

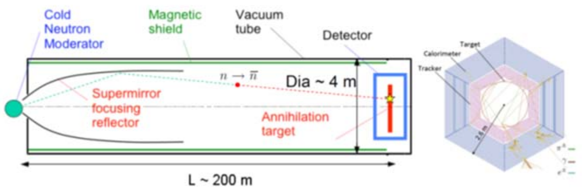
sensitivity: $N \cdot t^2 = 1.5 \times 10^9$ s^2/s

≐ "ILL sensitivity unit"

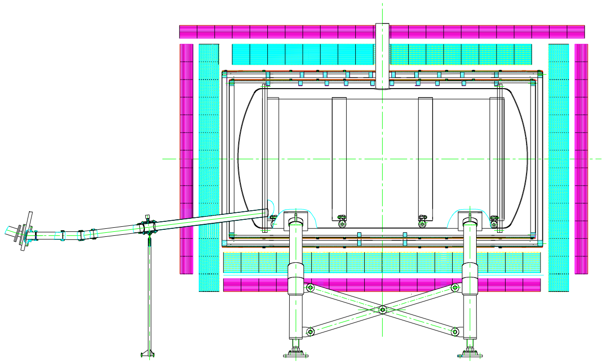
20

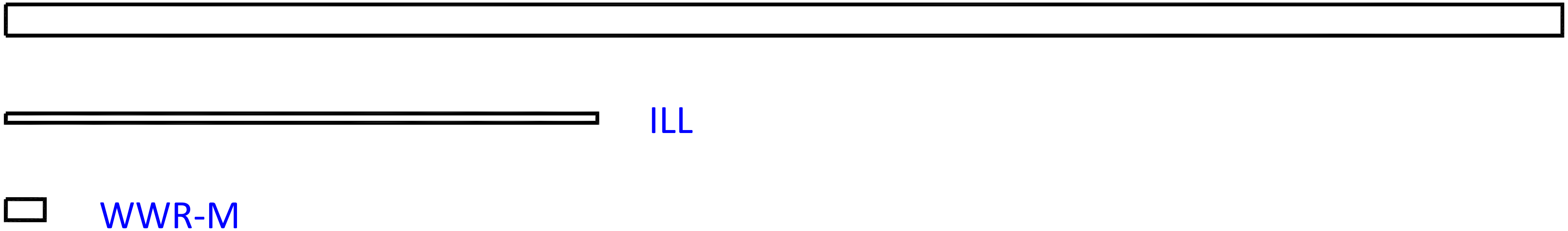
ESS

Scheme of Horizontal N-Nbar experiment
for ESS Neutron Source



WWR-M





ESS

ILL

WWR-M

Conclusion

1. Designed storage trap for NNbar oscillation experiment at reactor WWR-M: horizontal cylinder with diameter 2 m, length 4 m.

2. Increase of the experiment sensitivity is about 10 ÷ 40 times to ILL level.

3. Oscillation period for 3 years:

$$\tau_{n\tilde{n}} \geq (0.7 \div 1.4) \cdot 10^9 \ \mathbf{s\ (90\%\ CL)}$$

The work is supported by the Russian Foundation for Basic Research, grant no.16-02-00778-a.