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Preliminary conceptual design of the high-intensity ultracold neutrons source at the WWR-K reactor

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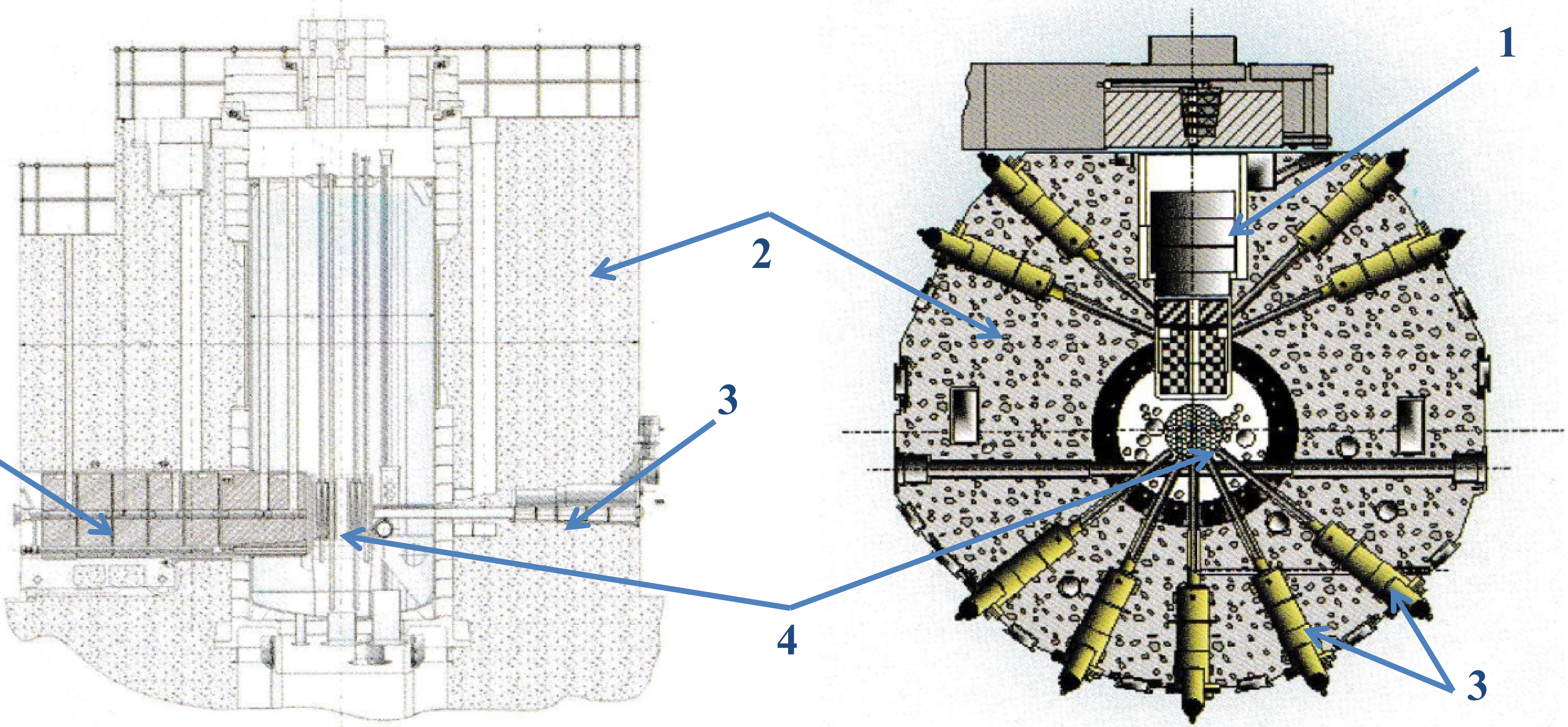
Main physical characteristics of the WWR-K reactor

Parameters	Value
Rated power, MW	6
Fuel composition	Uranium dioxide
U-235 enrichment, %	19.7
Neutron moderator/reflector	Light water and beryllium
Coolant	Light water
Reactor core height, mm	600
Reactor core diameter, mm	720
Maximum flux density of thermal neutrons in the center of the reactor core, $n/cm^2 \cdot s$	$2.2 \cdot 10^{14}$
Thermal column	Big size
Very large area for infrastructure for the source and experimental installations	

WWR-K Reactor

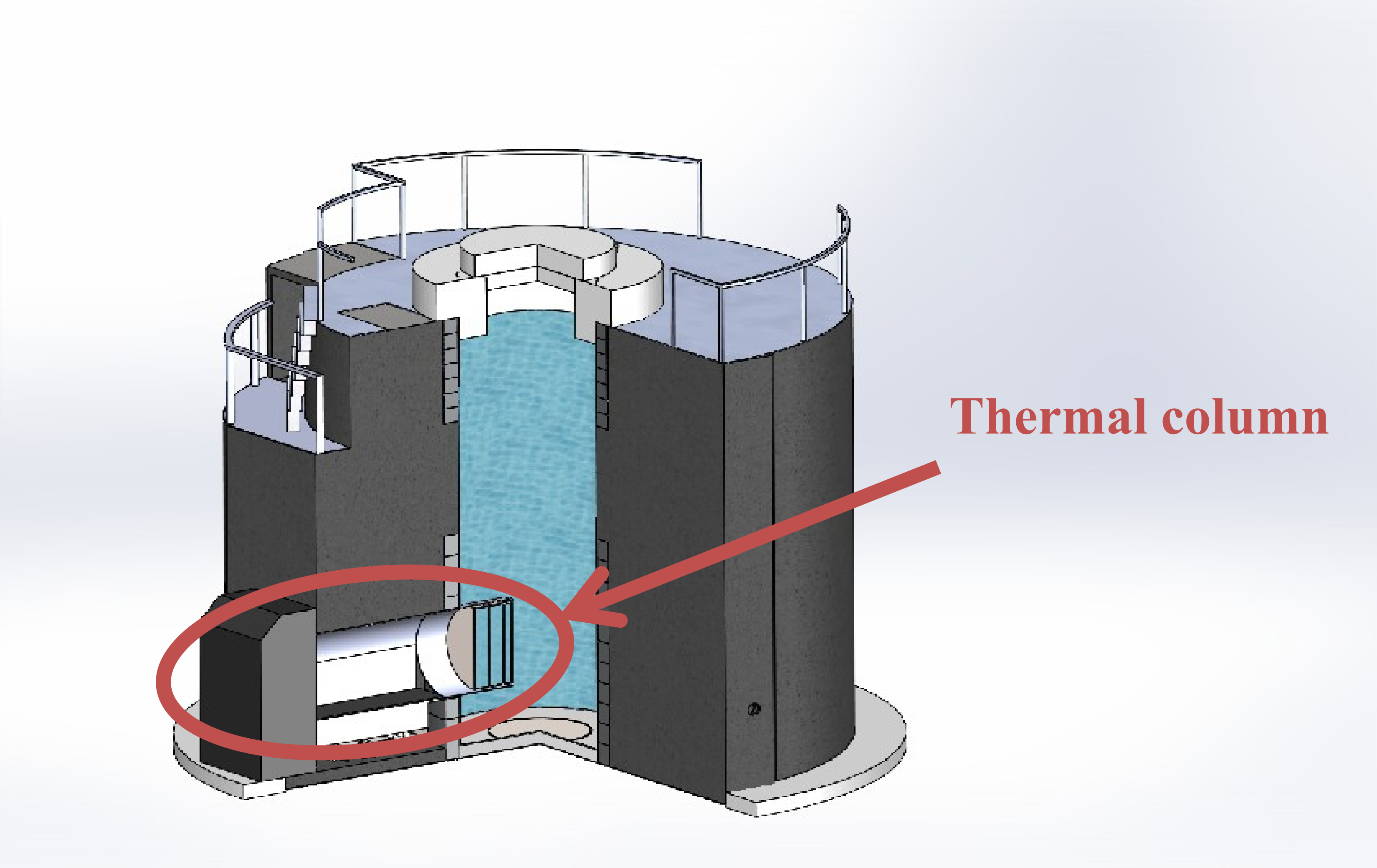
Thermal column



Cutaway drawing of the WWR-K reactor

1 – Thermal column **2 – Biological shield,** **3 – Horizontal channel,** **4 – Reactor core,**

Potential location of the UCN source at the WWR-K reactor



3D model of the WWR-K reactor

- **Diameter: 1 m**
- **Close to the reactor active core**

Concept of UCN production in helium at very low temperatures

R. Golub and J. M. Pendlebury, Phys. Lett, A53, 133 (1975)

Initial concept

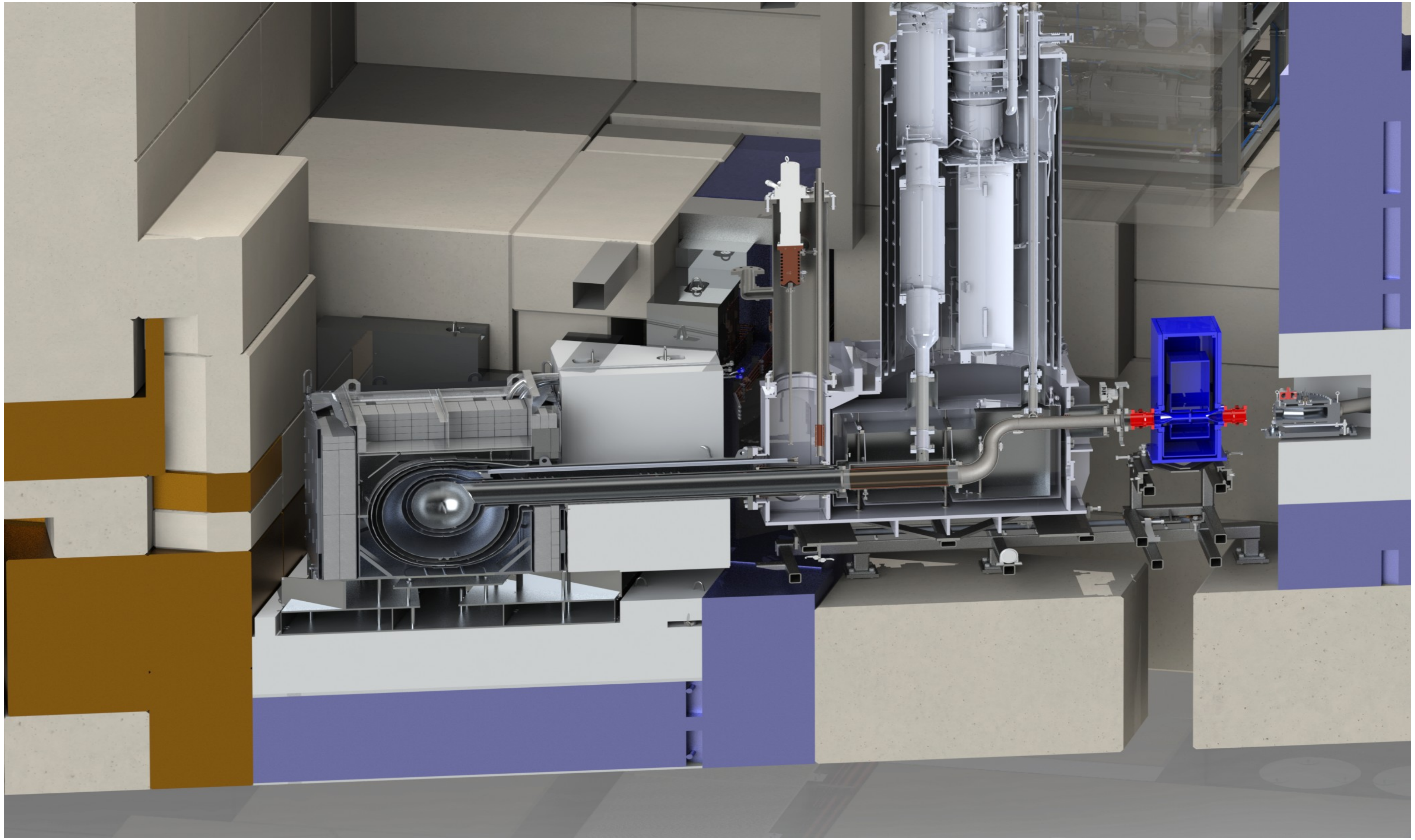
- In the initial concept, helium was in the heavy water, and to reduce heat load it needed to be protected.
- Protect helium from gamma rays using a lead sheild.

The advantages of this concept:

1. 4π angular distribution of parent neutrons to increase their total flux
2. Long-term accumulation of neutron children due to a decrease in helium temperature

TUCAN spallation source based He-II UCN source:

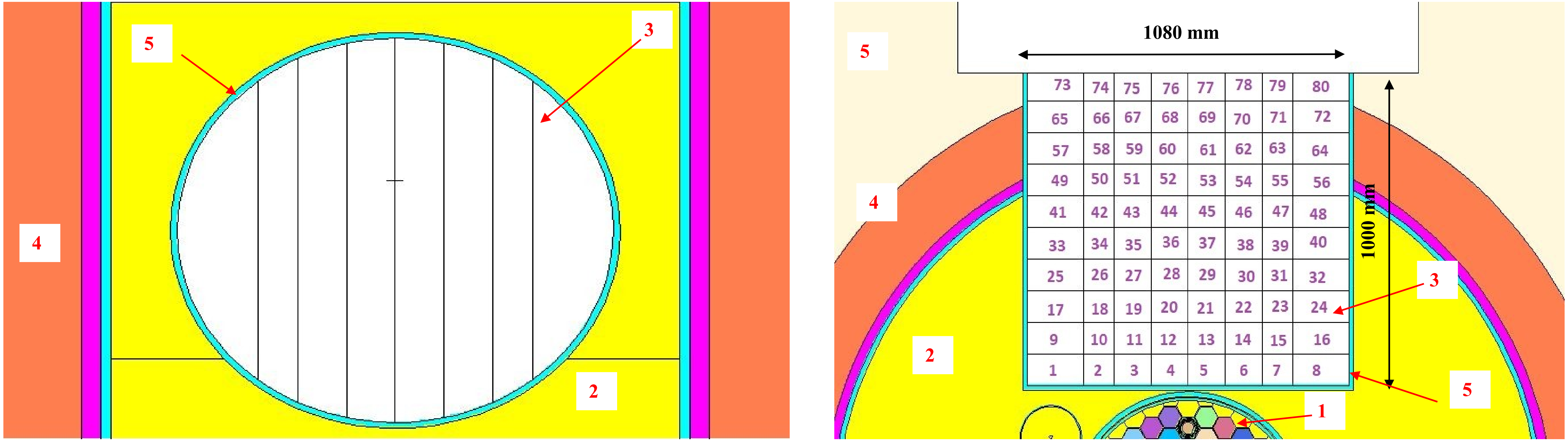
The closest implementation of the initial concept



Courtsey, Picker Ruediger

Calculation of the spatial distribution of neutron flux density

To develop a technical design based on this concept, we need to calculate the flux of neutrons and gamma quanta depending on the energy-coordinates and various materials that we want to place in the thermal column of the reactor



(a) (b)

Vertical (a) and horizontal (b) sections of the mathematical model of the WWR-K reactor: 1 – reactor core, 2 – water, 3 – thermal column, 4 – cast iron protection, 5 – heavy concrete, 5 – 2 mm thick Al wall

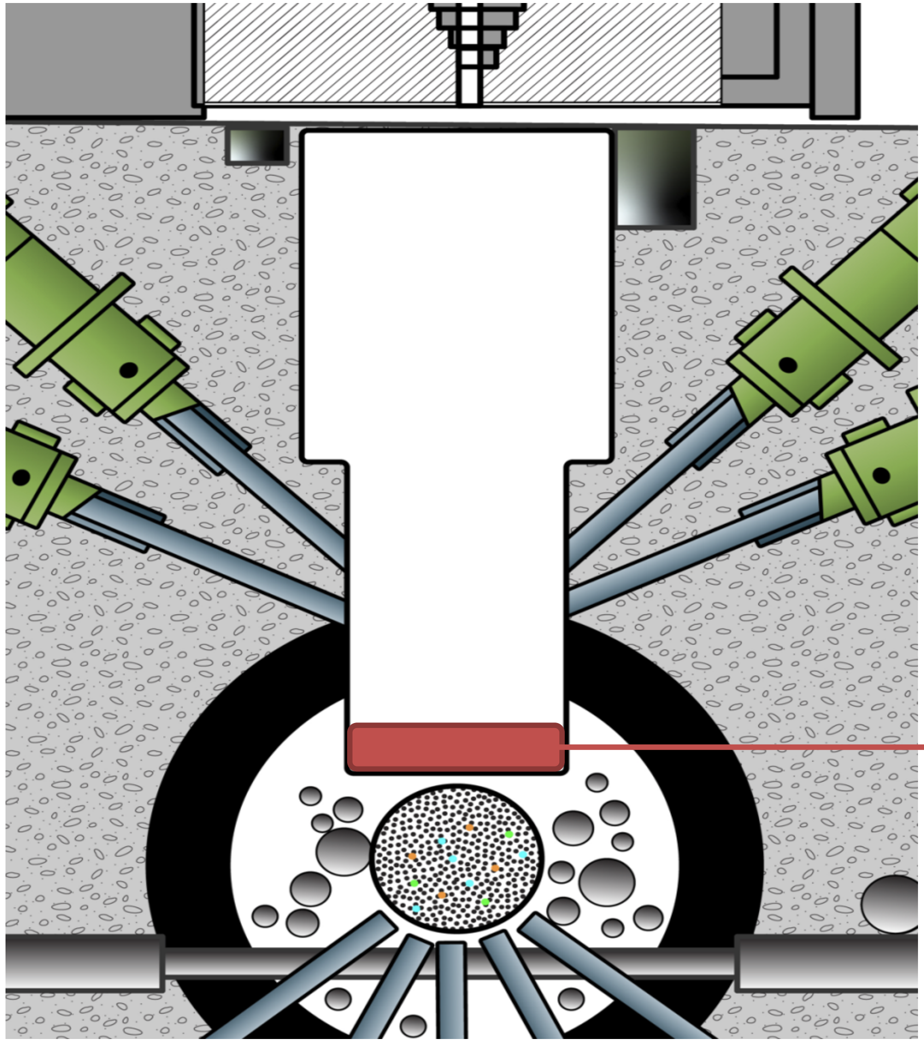
Spatial distribution of parent neutron flux density

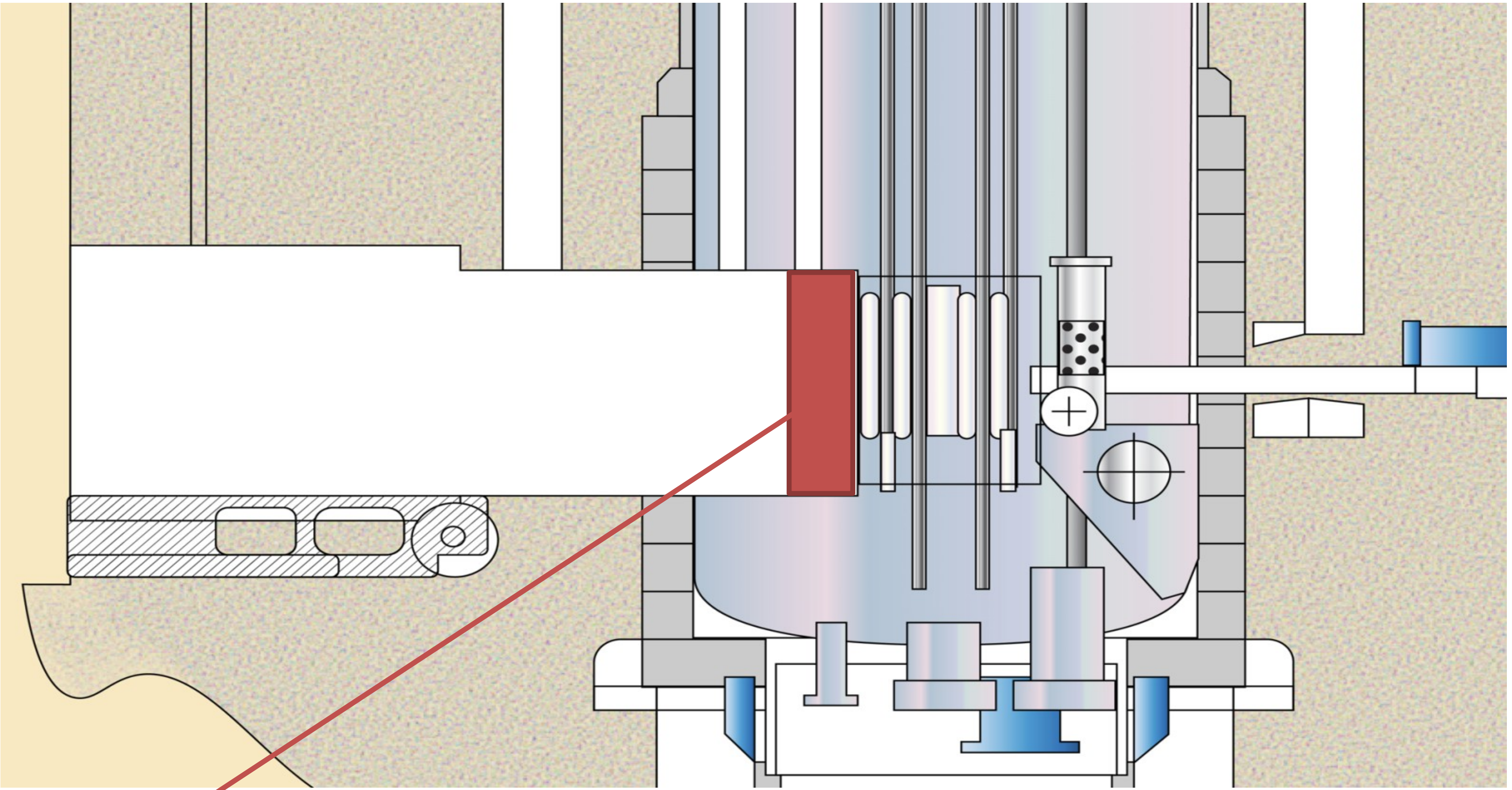
$n/cm^2 \cdot s$

$1.93 \cdot 10^{11}$							$1.91 \cdot 10^{11}$
$2.88 \cdot 10^{11}$							$2.89 \cdot 10^{11}$
$4.19 \cdot 10^{11}$							$4.23 \cdot 10^{11}$
$3.44 \cdot 10^{11}$							$3.45 \cdot 10^{11}$
$4.19 \cdot 10^{11}$			Thermal column				$4.23 \cdot 10^{11}$
$4.68 \cdot 10^{11}$							$4.77 \cdot 10^{11}$
$4.95 \cdot 10^{11}$							$5.06 \cdot 10^{11}$
$4.90 \cdot 10^{11}$							$5 \cdot 10^{11}$
$4.43 \cdot 10^{11}$							$4.49 \cdot 10^{11}$
$3.57 \cdot 10^{11}$	$4.84 \cdot 10^{11}$	$7.62 \cdot 10^{11}$	$1.19 \cdot 10^{12}$	$1.21 \cdot 10^{12}$	$7.91 \cdot 10^{11}$	$5.02 \cdot 10^{11}$	$3.61 \cdot 10^{11}$

Reactor core

Optimization the flux density parent neutron

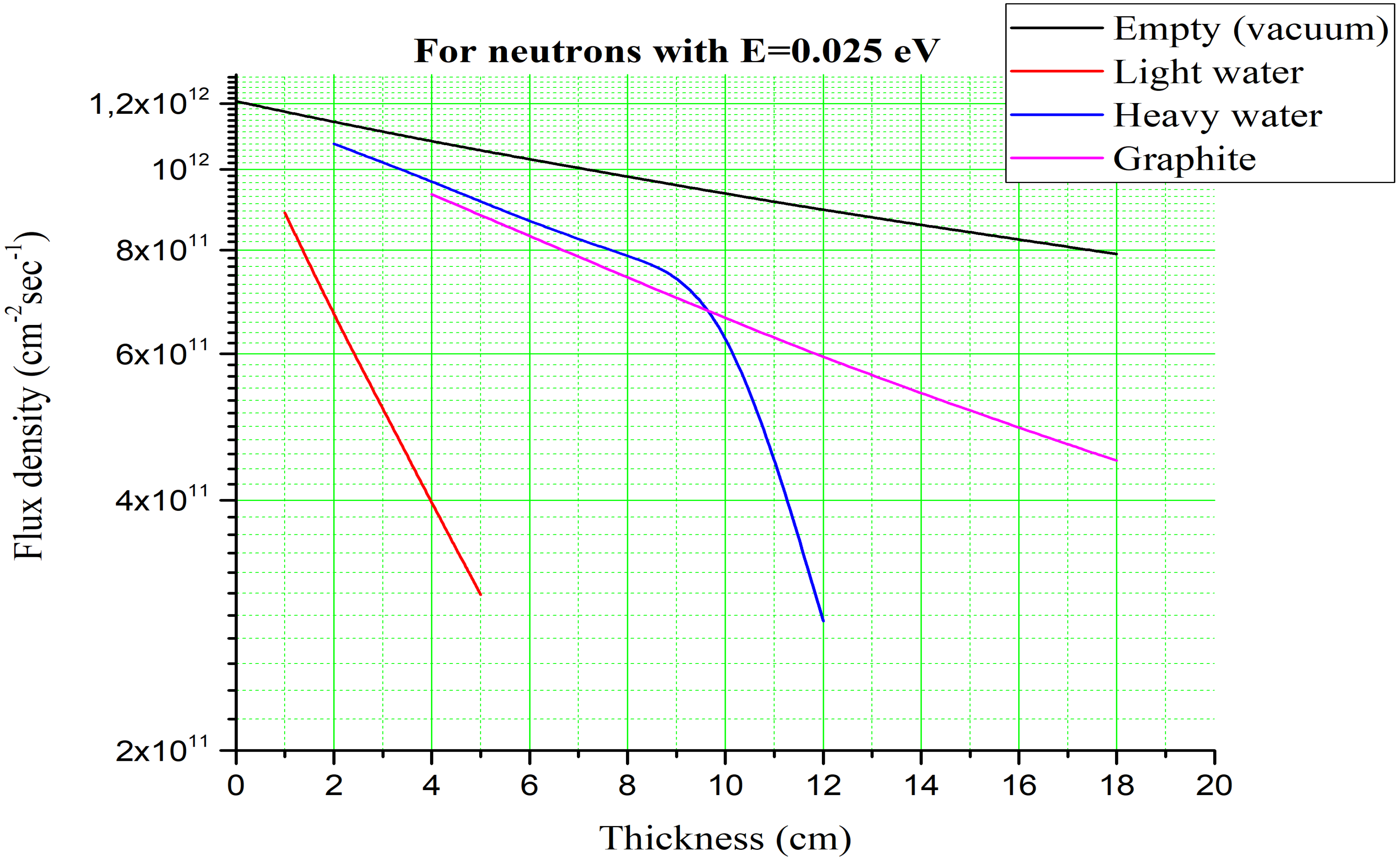




Neutron moderator

Consider an empty (vacuum) thermal column.
Place a flat layer of the neutron moderator from the water H_2O, heavy water D_2O and graphite C on the front wall of it .

Thermal neutron flux density on front wall of the thermal column for different type of neutron moderator

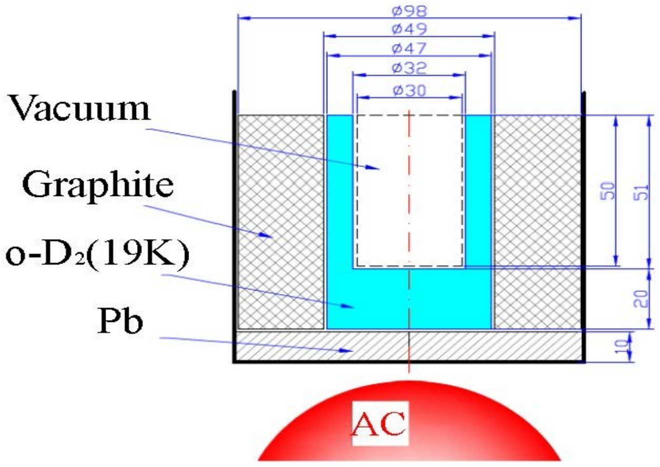


The maximum thermal neutron flux is extracted in empty (vacuum) thermal column.

Several options of optimizations

We are considering technical possibilities

Different materials and geometries: shielding, moderator and reflector



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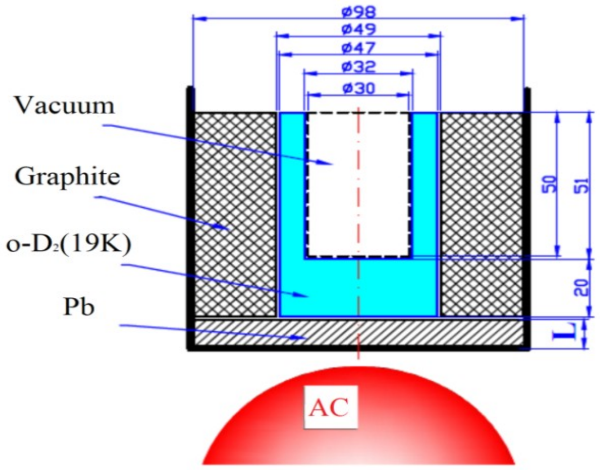

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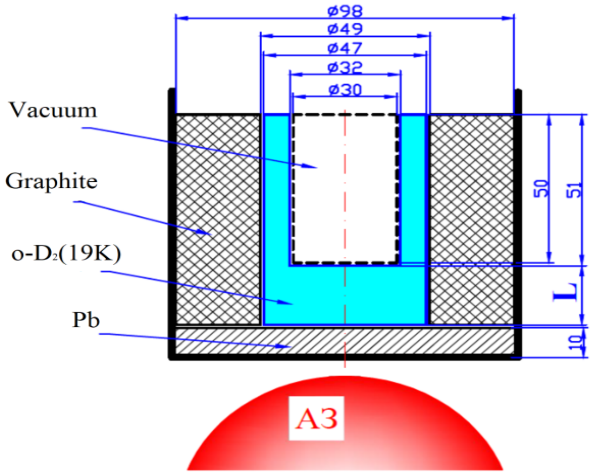

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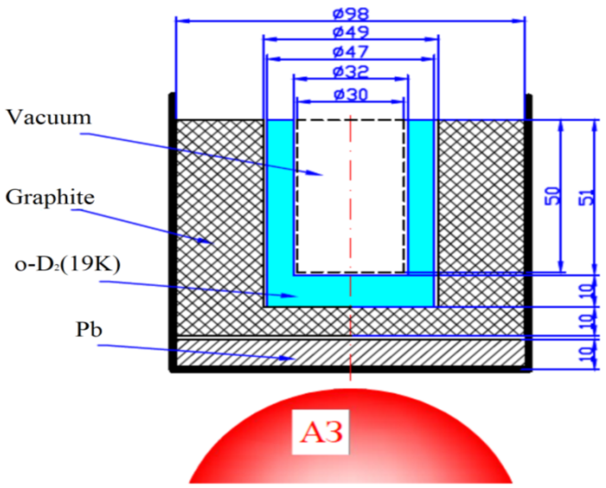
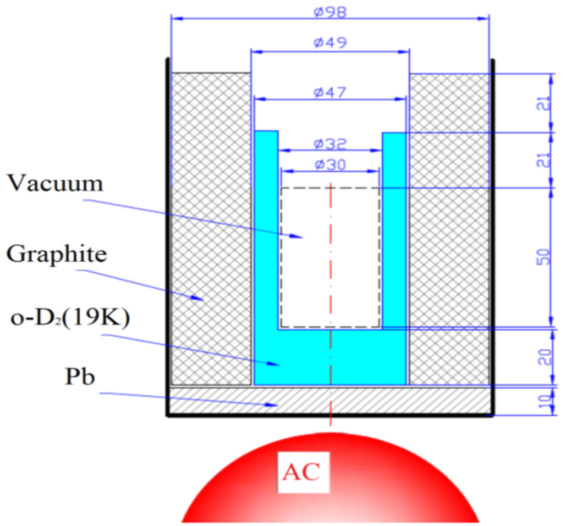


3-1.



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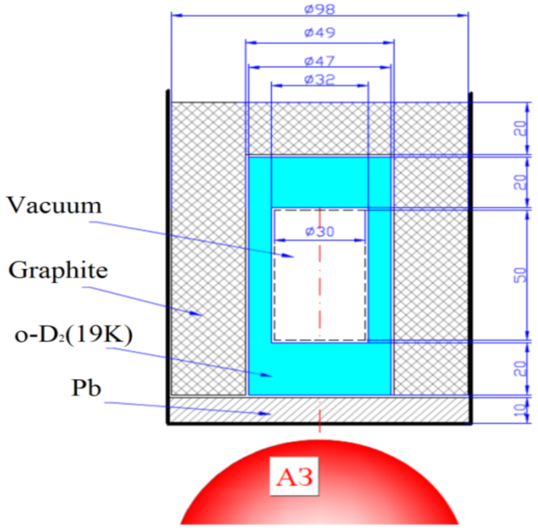
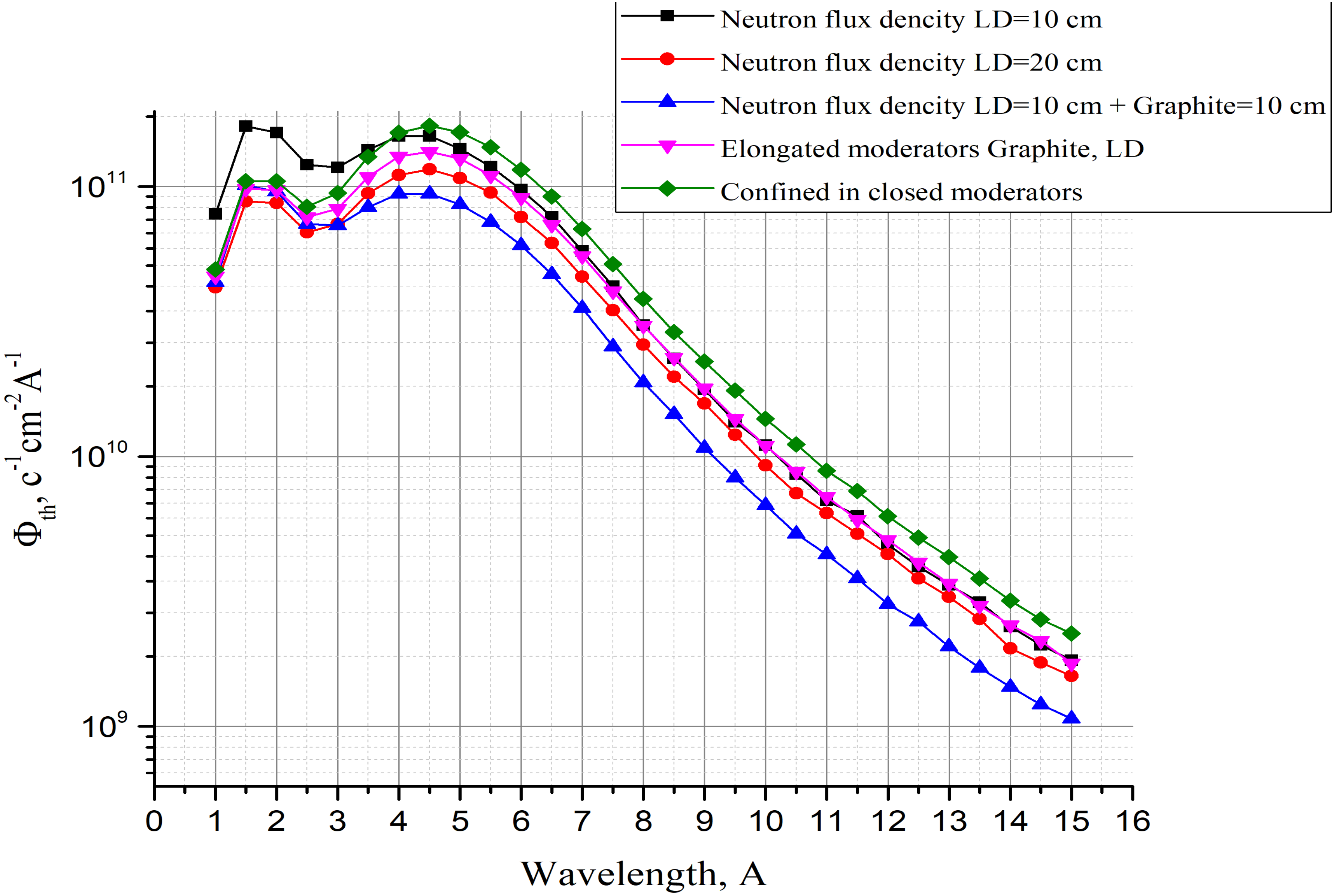


3-3.

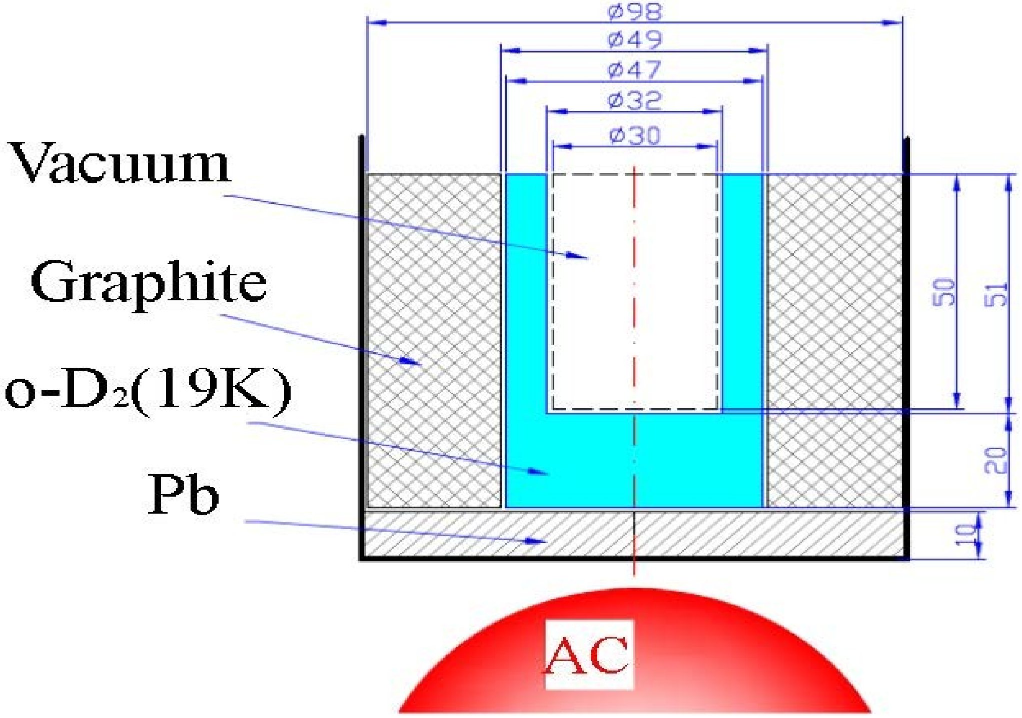
Calculation of the parent neutron flux density



Comparison of options for the UCN source

Options	h(Pb), cm	h(L-D_2),cm	Moderators	P_{UCN}, n/s (dJ/dλ (9Å), n/cm²/s/Å)	$Q_{L\text{-}He}$, W		
					n	γ	Tot
1.	10	20	Short	$2,48\cdot 10^7$ $(1,54\cdot 10^{10})$	1,2	2,0	3,2
2-1.	7	20	Short	$3,15\cdot 10^7$ $(1,96\cdot 10^{10})$	1,44	4,35	5,8
2-1.	15	20	Short	$1,69\cdot 10^7$ $(1,05\cdot 10^{10})$	0,65	0,88	1,53
2-2.	10	10	Short	$2,87\cdot 10^7$ $(1,78\cdot 10^{10})$	3,13	2,28	5,4
2-2.	10	30	Short	$1,85\cdot 10^7$ $(1,15\cdot 10^{10})$	0,57	1,55	2,1
3-1.	10	10+10(Graph.)	Short	$1,73\cdot 10^7$ $(1,076\cdot 10^{10})$	1,05	1,46	2,5
3-2.	10	20	Long	$2,88\cdot 10^7$ $(1,79\cdot 10^{10})$	1,2	2,0	3,2
3-3.	10	20	Closed	$3,62\cdot 10^7$ $(2,25\cdot 10^{10})$	1,2	2,0	3,2

Calculation of the cold neutrons flux density



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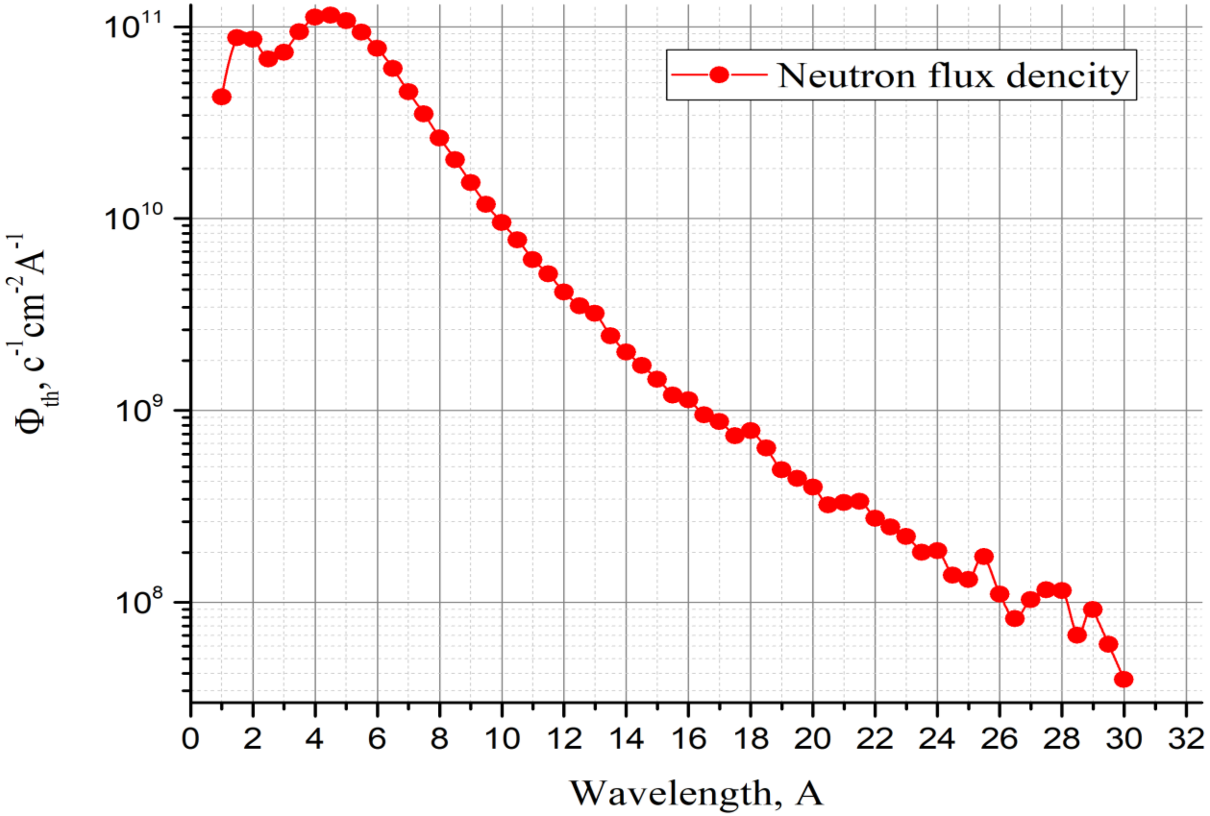
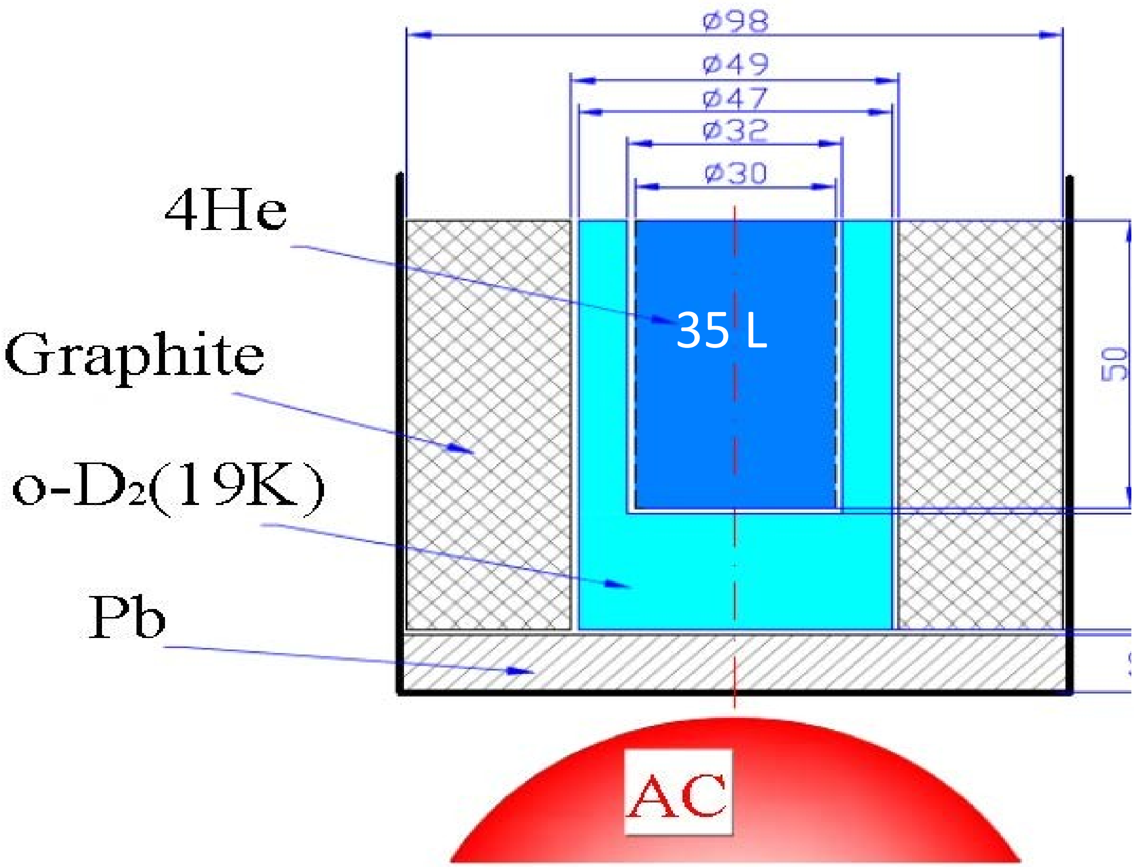


A precise calculation performed using the MCNP program shows that in a hemispherical layer of liquid deuterium 20 cm thick, the flux density of cold neutrons with a wavelength of 9 Å is $\boldsymbol{\Phi_c(9\text{Å}) = 1.54 \cdot 10^{10} cm^{-2} s^{-1} \text{Å}^{-1}}$.

Radiation heating of a UCN source



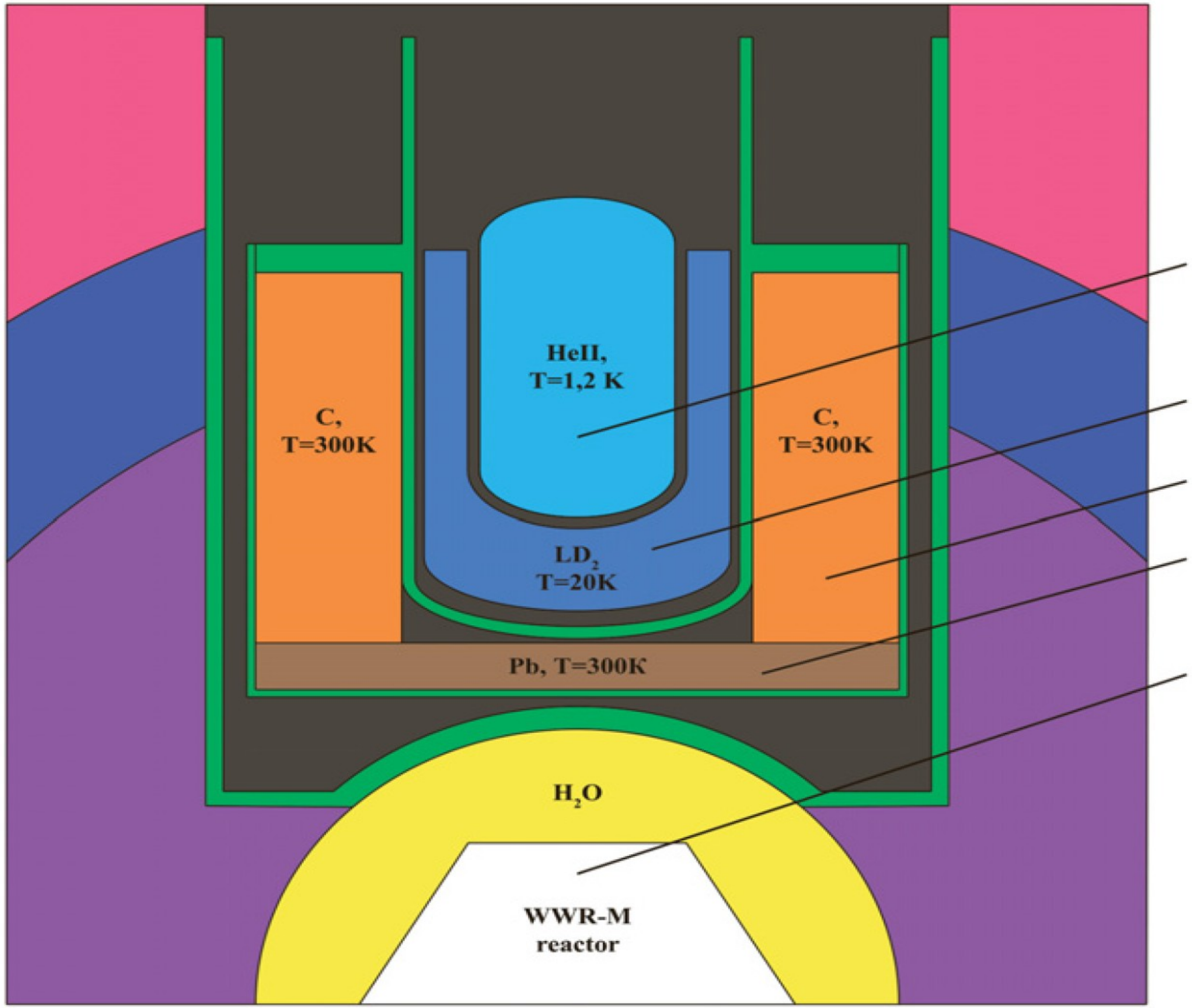
MATERIAL	power distribution [W]	specific power [W/g]
LEAD	14294.2	$1.67 \cdot 10^{-2}$
GRAPHITE	294.2	$4.31 \cdot 10^{-4}$
ORTHO DEUTERIUM	51.1	$3.66 \cdot 10^{-3}$
SUPERFLUID HELIUM	3.2	$6.27 \cdot 10^{-4}$

Calculation was done in the absence of construction materials.
Expected that total radiation heating ~13 W.

It is expected that the Al vessel heating will not exceed 13-3.2 = 9.8 W.

It is planned to use an aluminum-beryllium composite containing up to 70% beryllium. This will reduce the vessel heating to ~ ⅓·9.8 W=2.9 W and the total heat budget to **~ 6.1 W**.

UCN source project at WWR-M reactor at a power of 16 MW



$\rho_{UCN}=10^4$ cm^{-3} (τ=10s)

$\Phi=4.5\cdot10^{12}$ 1/(cm^{2}s)

$\Phi(\lambda=9Å)=3\cdot10^{10}$ 1/(cm^{2}sÅ)

Q_{He}=19 W
Q_{Al}=18 W
Q_{Tolal}=37 W

Q_{D2}=83 W
Q_{Al}=204 W
Q_{Tolal}=287 W

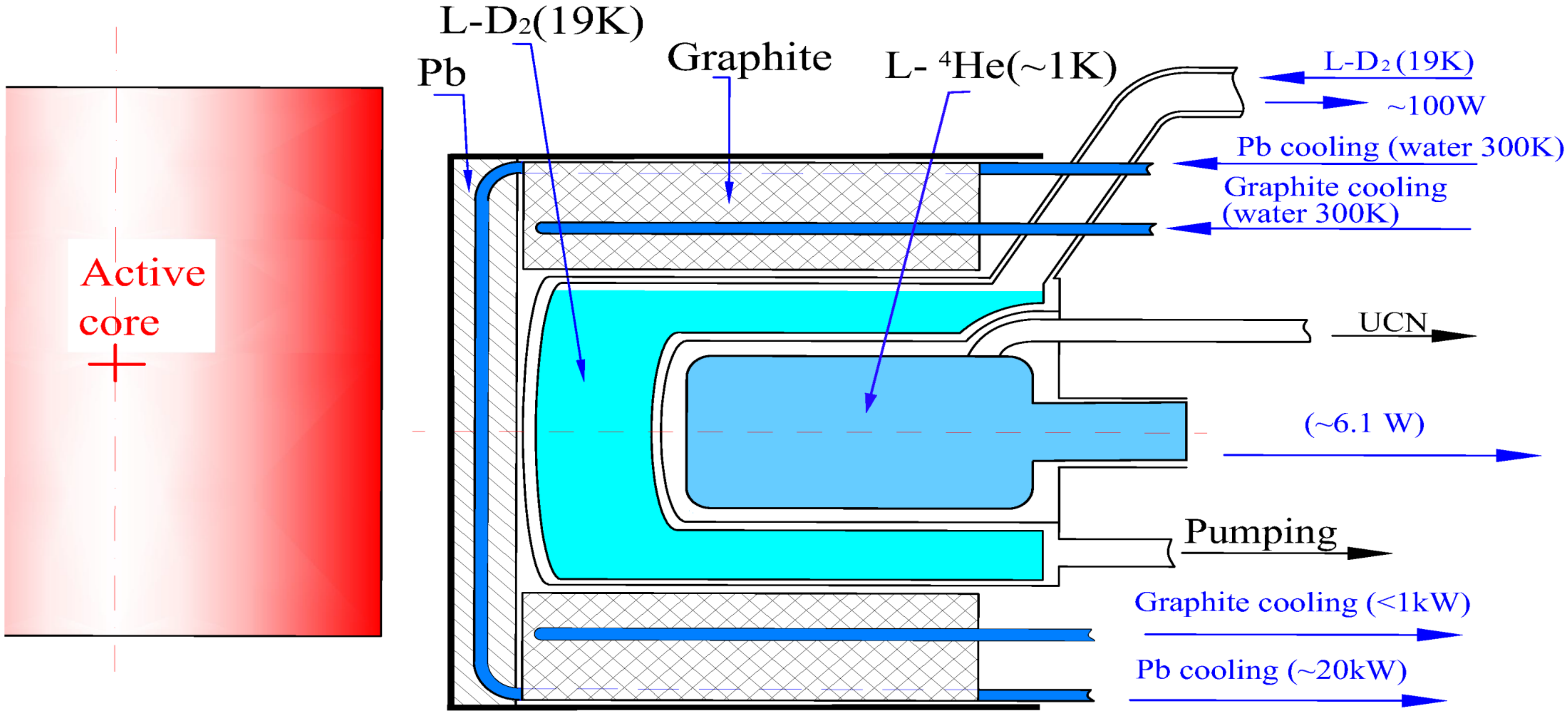
Q=700 W

Q=15 kW

Q=16 MW

EPJ Web of Conferences 219, 10002 (2019)

Basic conceptual design of a high-intensity UCN source



Preliminary UCN Source Parameters

Thermal neutron flux on the front wall of the thermal column

$$\Phi_{th} = 1.21 \cdot 10^{12}\, cm^{-2} s^{-1}$$

Parent neutron flux with wavelength 9 Å in helium chamber

$$\Phi_{c}(9\,\text{Å}) = 1.54 \cdot 10^{10}\, cm^{-2} s^{-1} \mathring{A}^{-1}$$

The storage time of UCN in superfluid helium largely depends on its temperature:

At helium temperature 0.8 K

$$\tau_{He} = 610\,\text{s}$$

At helium temperature 1.15 K

$$\tau_{He} = 50\,\text{s}$$

At helium temperature 1.25 K

$$\tau_{He} = 30\,\text{s}$$

Volume density of UCN in closed helium chamber

At helium temperature 0.8 K

$$\rho_{UCN} = 1.6 \cdot 10^{5}\, UCN/cm^{3}$$

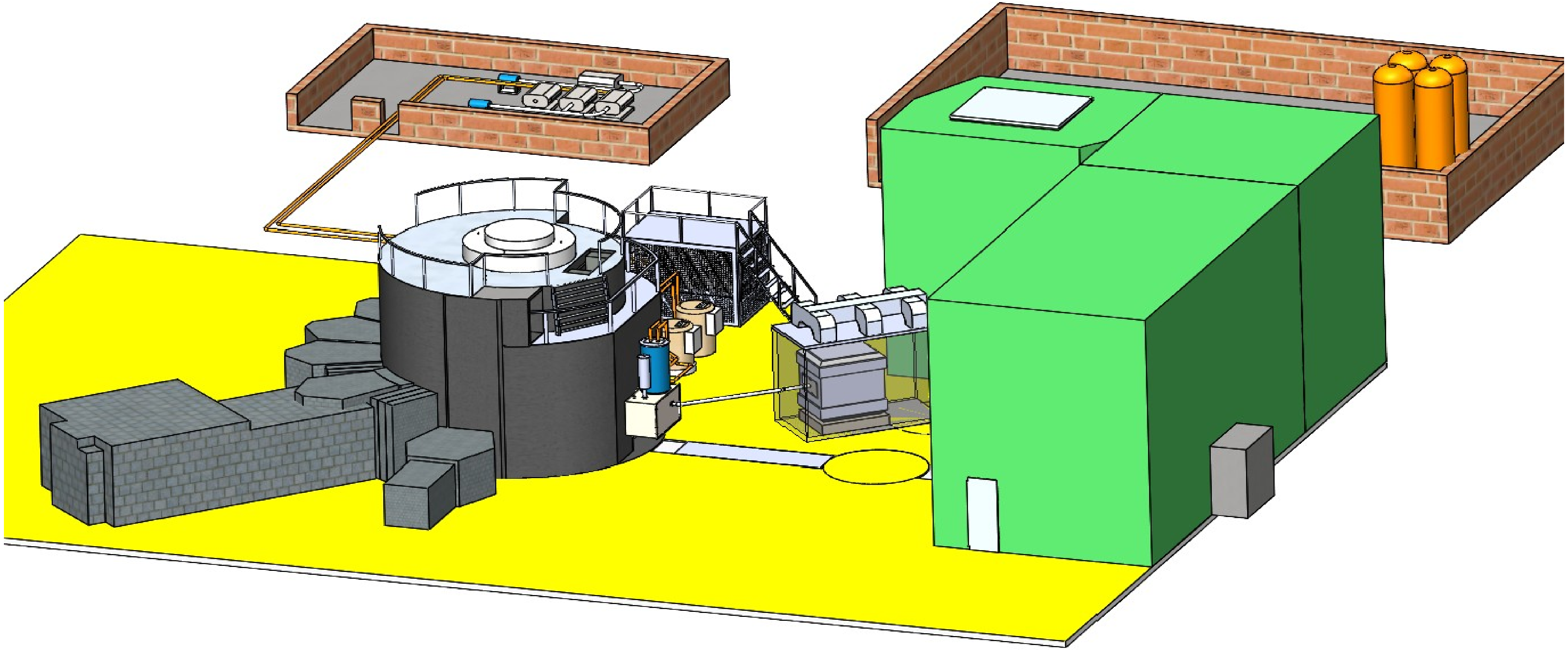
At helium temperature 1.15 K

$$\rho_{UCN} = 3.7 \cdot 10^{4}\, UCN/cm^{3}$$

At helium temperature 1.25 K

$$\rho_{UCN} = 2.4 \cdot 10^{4}\, UCN/cm^{3}$$

Equipment placement plan for the high-intensity UCN source of the WWR-K reactor



Summary

- The thermal column of the 6 MW WWR-K reactor is available for construction of the UCN source with record UCN density.
- The MCNP conceptual design of the UCN source gives good parameters (neutron flux, heat load and UCN density) at different superfluid helium temperatures.
- One of the main tasks is to develop relevant cryogenic systems for operating the UCN source, which will include liquid deuterium cooling loop and He-4/He-3 cryostat for cooling isotopically pure He-4 to below 1K.
- The UCN density $\mathbf{1.6 \cdot 10^5}$ $\boldsymbol{UCN/cm^3}$ will be obtained only if a solution has been found for heat removal of a very high thermal load
- Only by intensive pumping of helium-4 can such a density be obtained. Reliable assessment $\mathbf{2.4 \cdot 10^4}$ $\boldsymbol{UCN/cm^3}$
- And to obtain VCN it is not necessary to cool to low temperatures. Because the accumulation time of UCN is several seconds.

Thank you for your attention!

We welcome more feedback, comments, collaborations from all seminar on-line and off-line participants