NRC «KURCHATOV INSTITUTE»

PETERSBURG NUCLEAR PHYSICS INSTITUTE

ADVANCED COLD NEUTRON SOURCES AT THE REACTOR PIK :

(STATUS AND DEVELOPMENT PROSPECTS)

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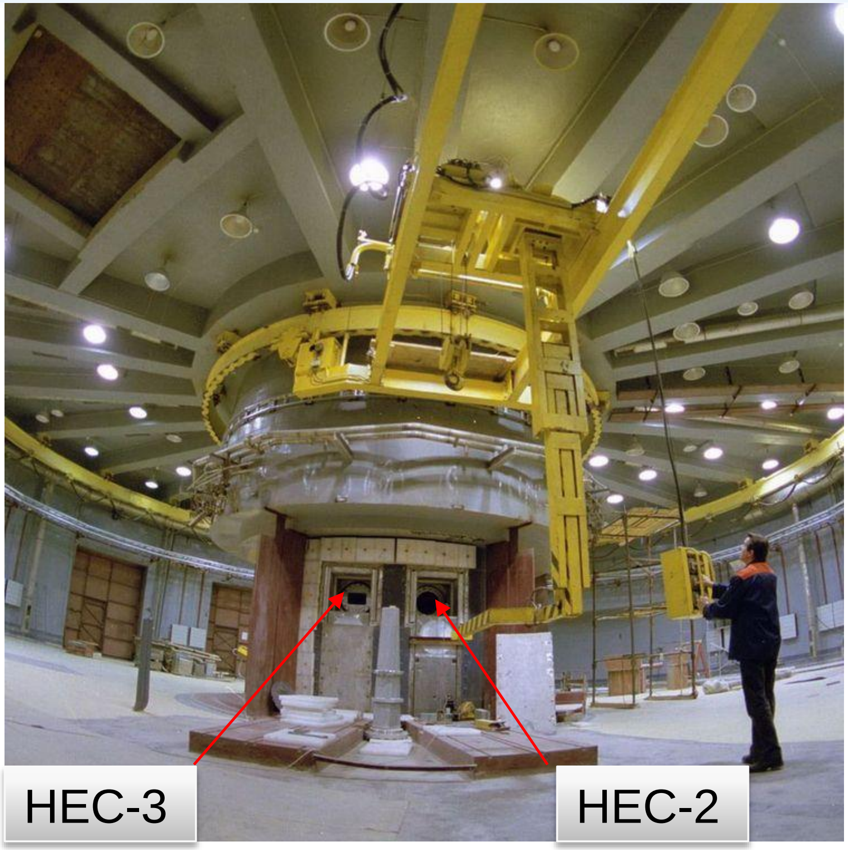
Sino-Russia meeting SRNS-2024

8-11 October 2024

HIGH-FLUX REACTOR PIK



100 MW power

D_2O reflector

Thermal neutron flux density in the reflector - about

$1.2*10^{15}$ $n*cm^{-2}*s^{-1}$

Fuel in the copper-beryllium matrix: UO_2, 90% enrichment

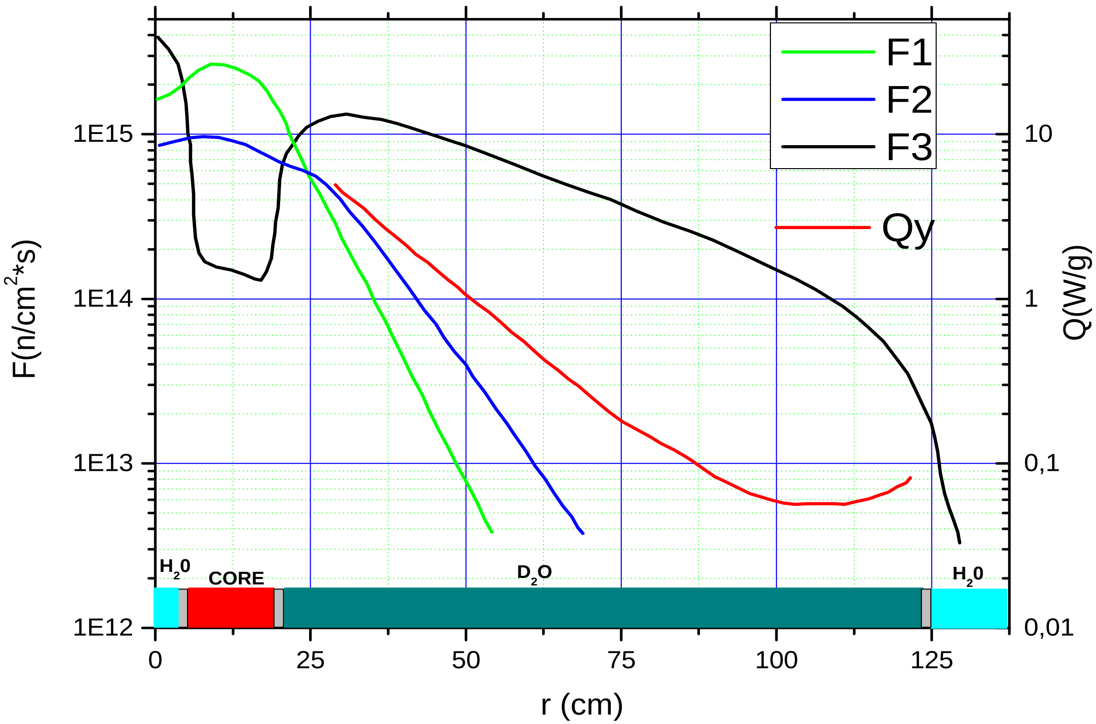
1 - central channel;
10 - horizontal experimental channels;
(3 - through channels)
6 - inclined experimental channels;
6 - vertical experimental channels.

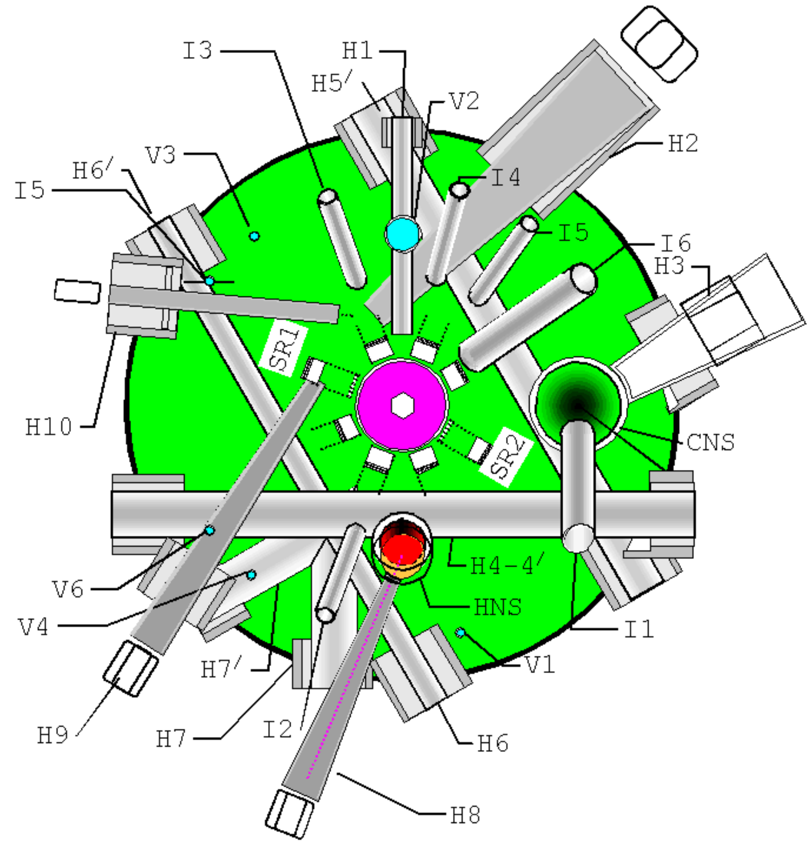
PNPI got the final approval from regulatory bodies for start-up of the new high-flux beam reactor PIK and got a license for operation during the following 5 years.

The first criticality of PIK reactor on February 2011

Reactor full power is expected on 2026-2027

Distribution of unperturbed neutron fluxes F and heat load Qγ in the reactor at 100MW





Reactor Neutron Beams layout

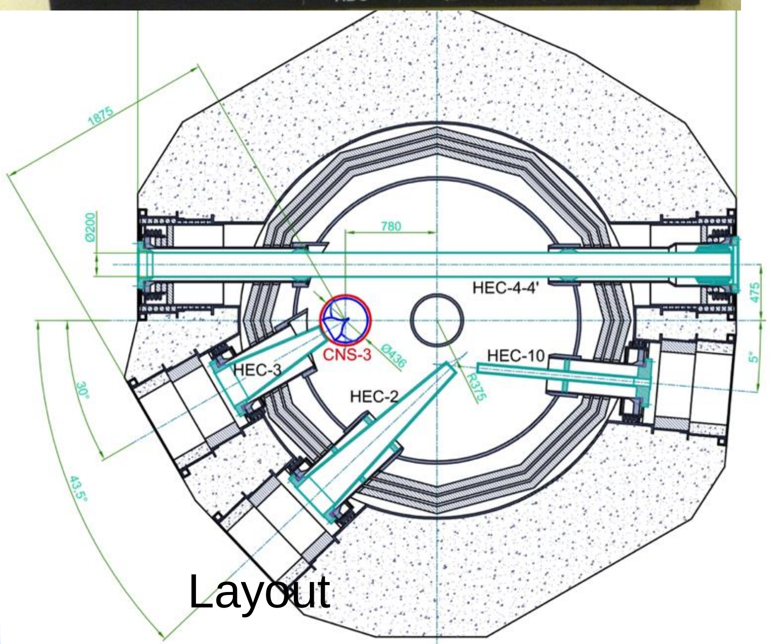
F1 - Flux density of fast neutrons E > 5 keV.

F2 - Flux density of epithermal neutrons
5 keV > E > 0.6 eV.

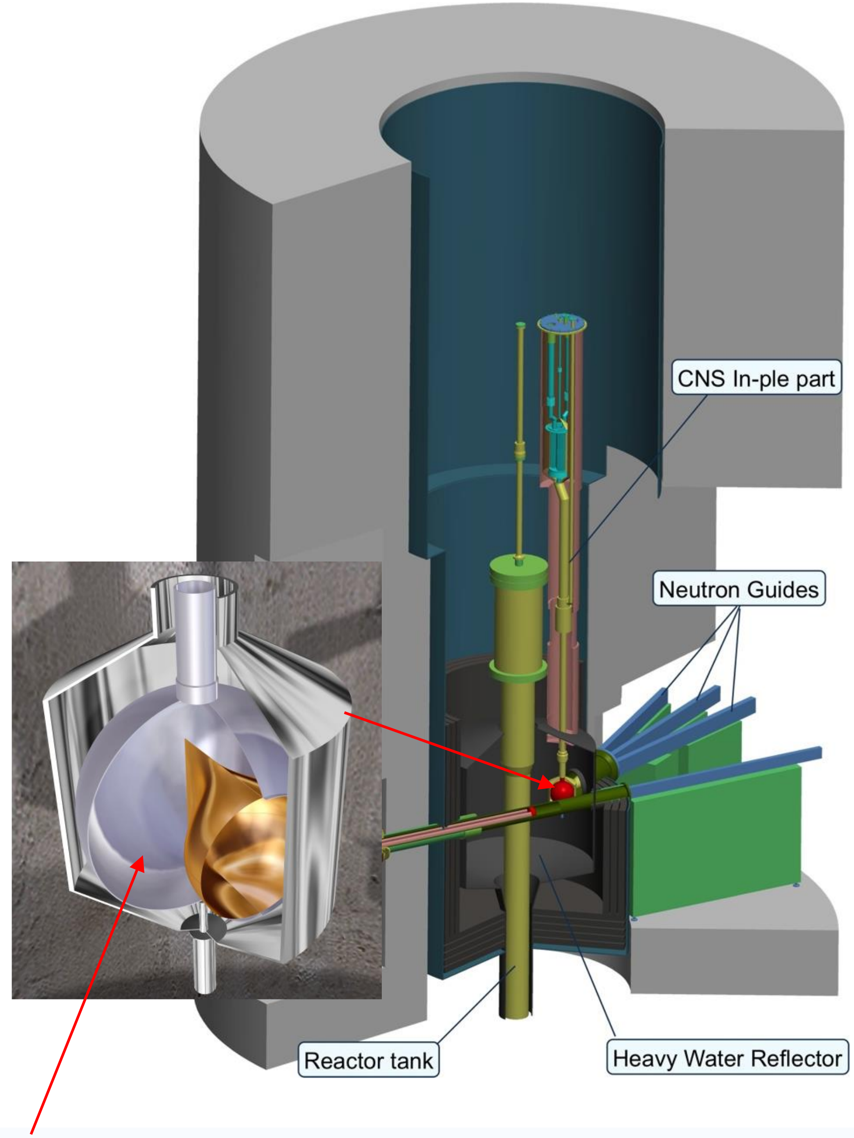
F3 - Flux density of thermal neutrons E < 0.6 eV.

CNS HEC-3 layout at PIK reactor (level +2100 mm)
1989 year

каналы	нейтроноводы	поток на выходе из нейтроновода	длина волны нейтронов, соответствующая максимуму интенсивности в спектре	длина нейтроновода
		$N \cdot 10^9 n/cm^2 \cdot S$	λ	m
ГЭК 3 холодные нейтроны	HB 3	1,4	~5,0	27,1
	HB 4	1,2	~5,0	36,7
	HB 5	1,1	~5,0	46,3
ГЭК 2 тепловые нейтроны	HB 7	1,1	~1,7	41,5
	HB 8	1,2	~1,5	51,0
	HB 9	1,2	~1,3	65,5



Layout



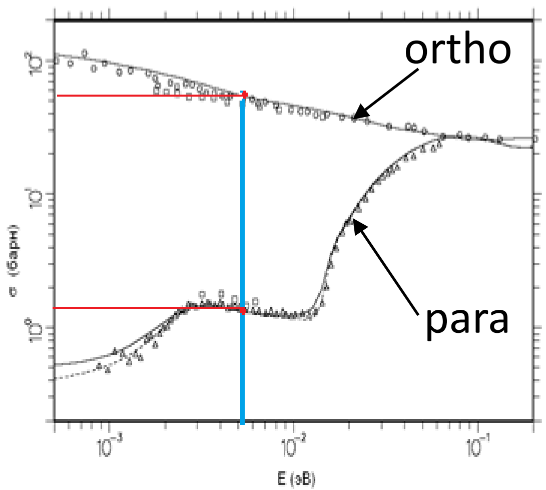
Moderator chamber

CNS design key points

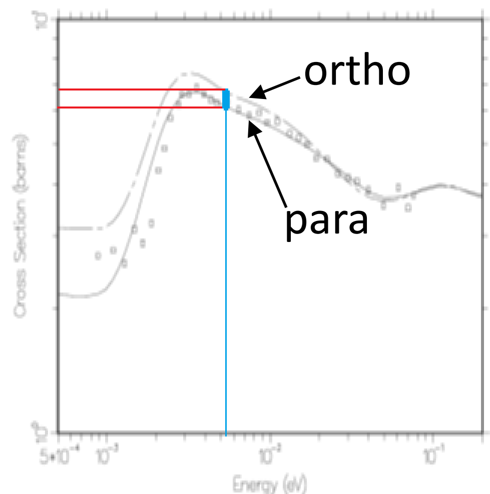
- **Neutron calculation**
  - ✓ CNS neutron performances (moderator and MC shape optimization, brightness, CN flux density, heat load)
- **Thermal-hydraulic calculation**
  - ✓ Moderator temperature, heat removal, CNS elements temperature
- **Stress analysis**
  - ✓ Stresses in CNS in-pile part at working condition
- **Safety analysis report (SAR)**
  - ✓ Hydrogen and Nuclear safety

Cross-sections of inelastic scattering of neutrons on H and D

H_2



D_2



$\lambda = 4$ Å $\longrightarrow$ $E \cong 5.1$ meV

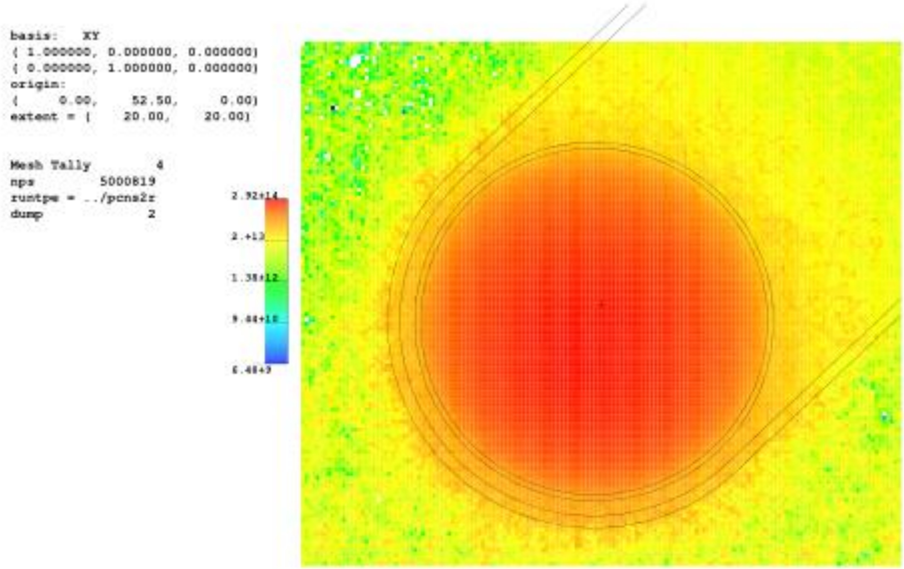
$\sigma_{para} \cong 1.5$ b $\rightarrow$ $l \cong \mathbf{16}$ cm

$\sigma_{ortho} \cong 55$ b $\rightarrow$ $l \cong \mathbf{0.4}$ cm

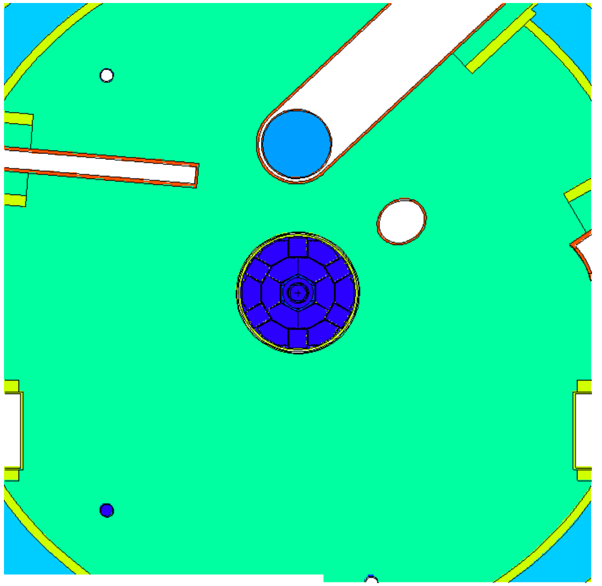
$\sigma_{ortho} \cong 7$ b $\rightarrow$ $l \cong \mathbf{2.9}$ cm

$\sigma_{para} \cong 6$ b $\rightarrow$ $l \cong \mathbf{3.3}$ cm

Flux field for cold neutrons. LD_2 chamber

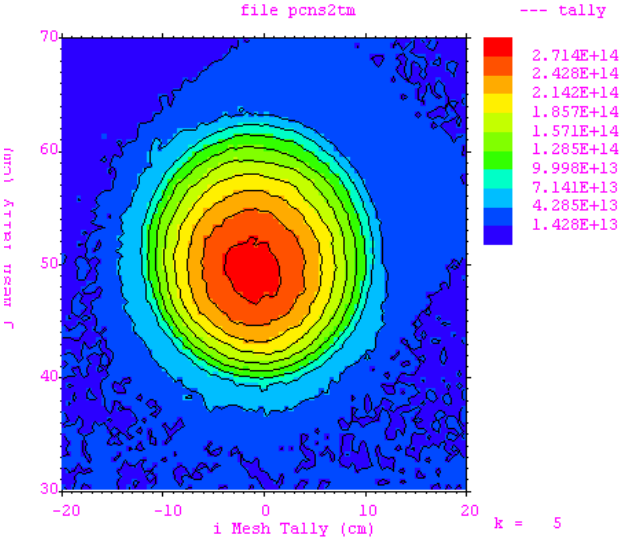


Distance to the reactor Core - 514mm



R=11.6 cm

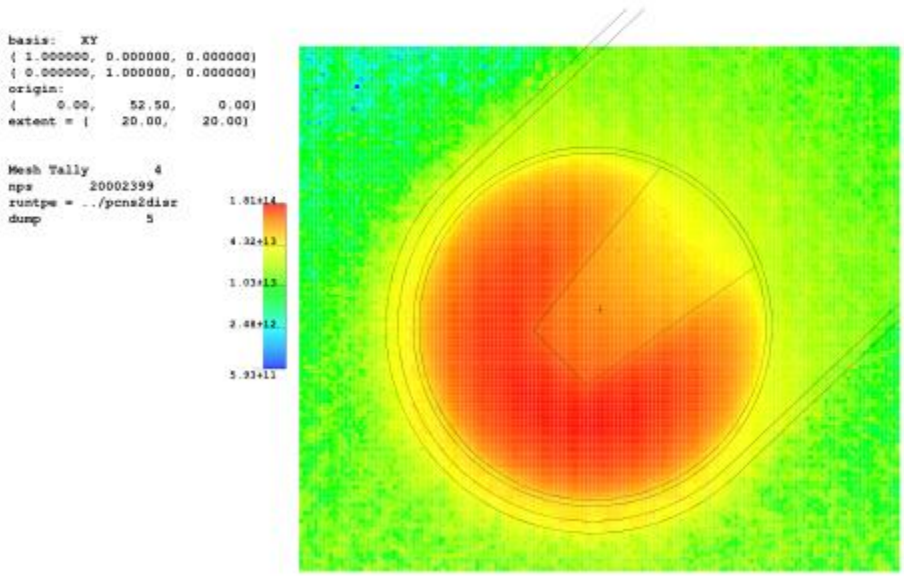
V=6.5 l

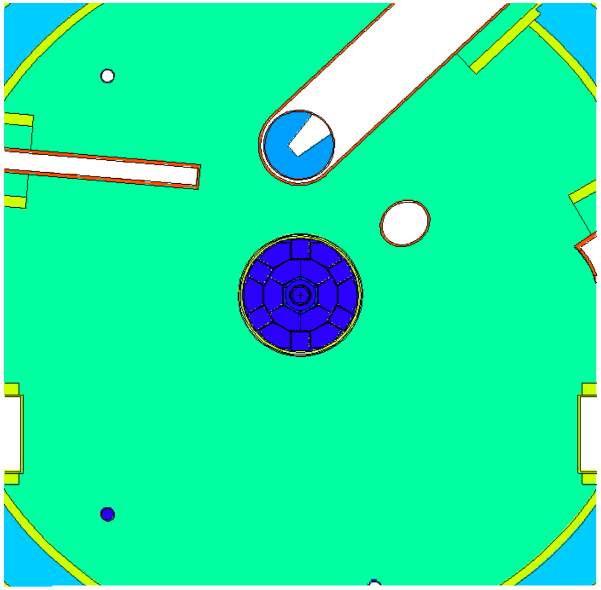


Cold neutrons λ > 4 Å.

$\Phi_{cold\ max} = 2.92 \cdot 10^{14}\ cm^{-2}s^{-1}$

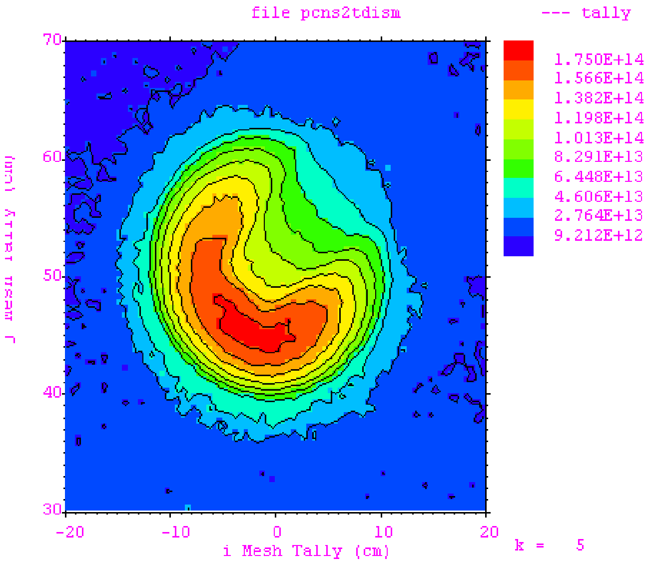
Using displacer for increasing the flux of cold neutrons released from the chamber into the channel





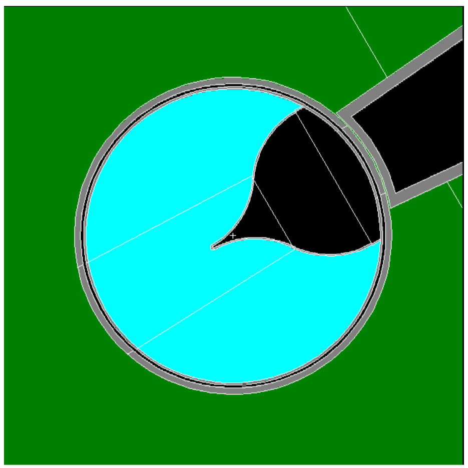
$$\Phi_{cold\ max} = 1.81 \cdot 10^{14}\ cm^{-2}s^{-1}$$

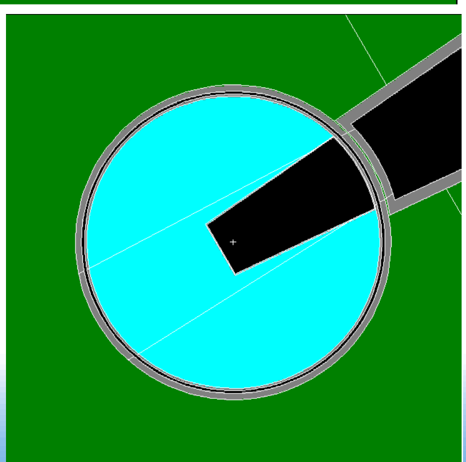
38% decrease comparing to chamber without displacer

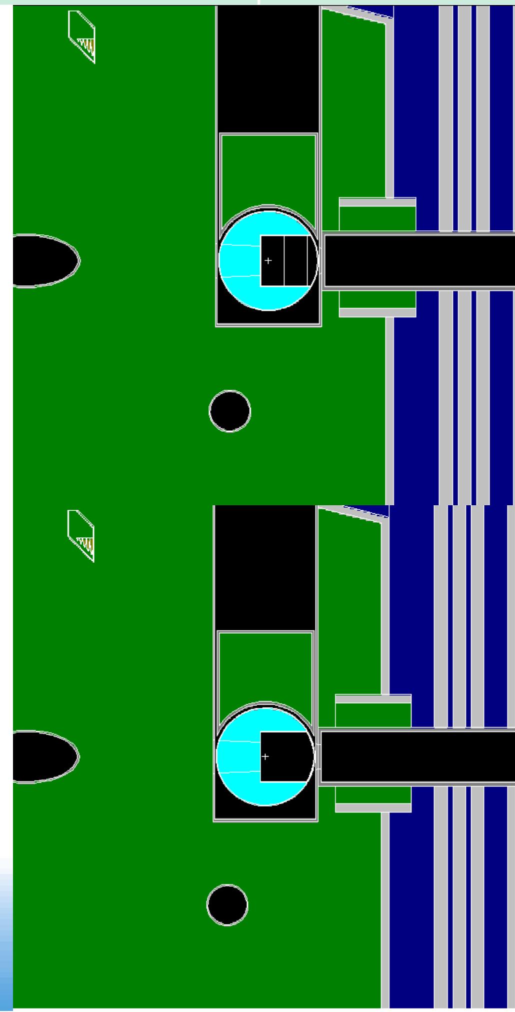


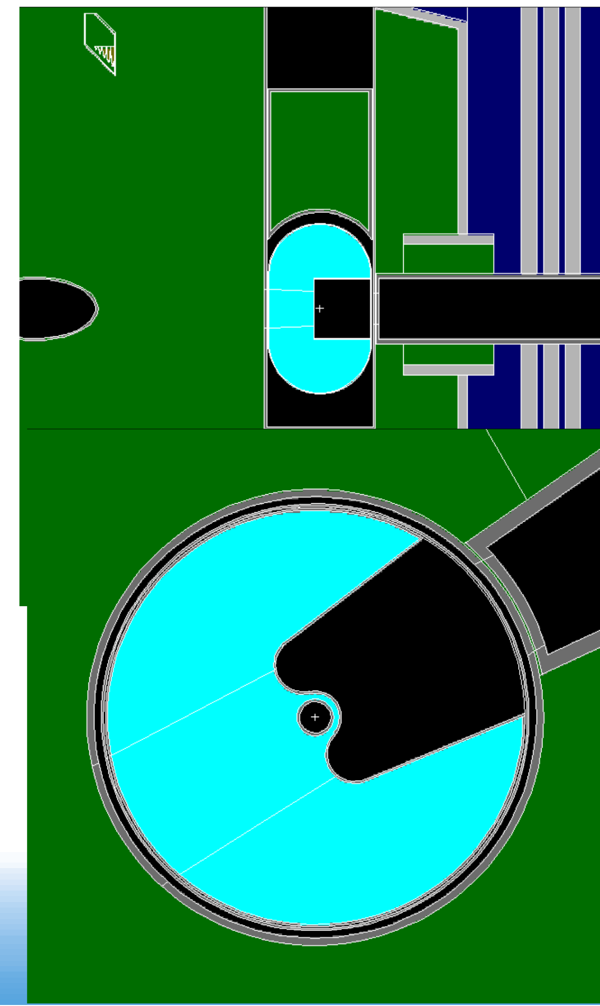
Neutron optimization calculation

Volume, liters	Ver. channel inner diameter, mm
10	284
20	352
30	400

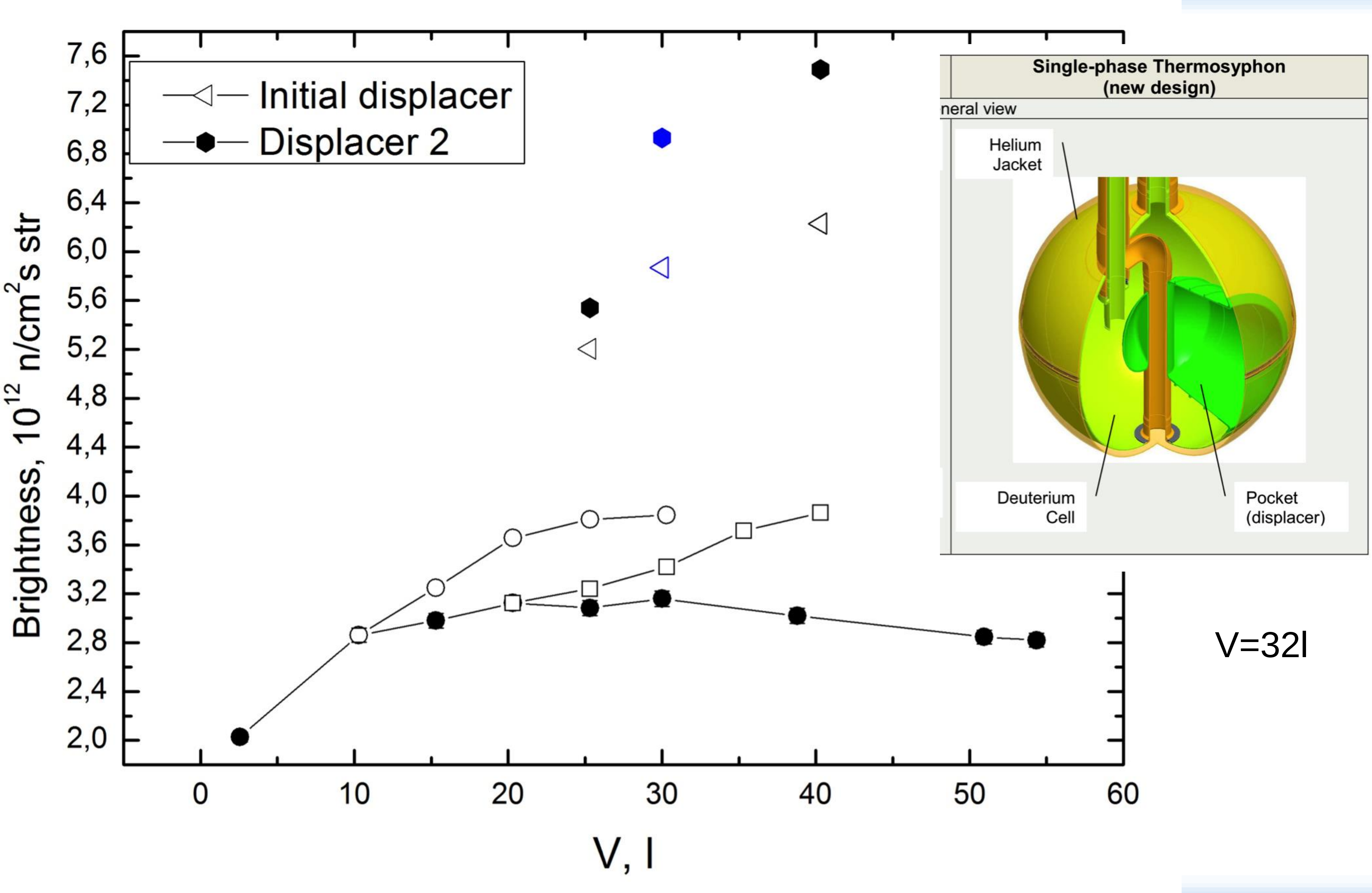






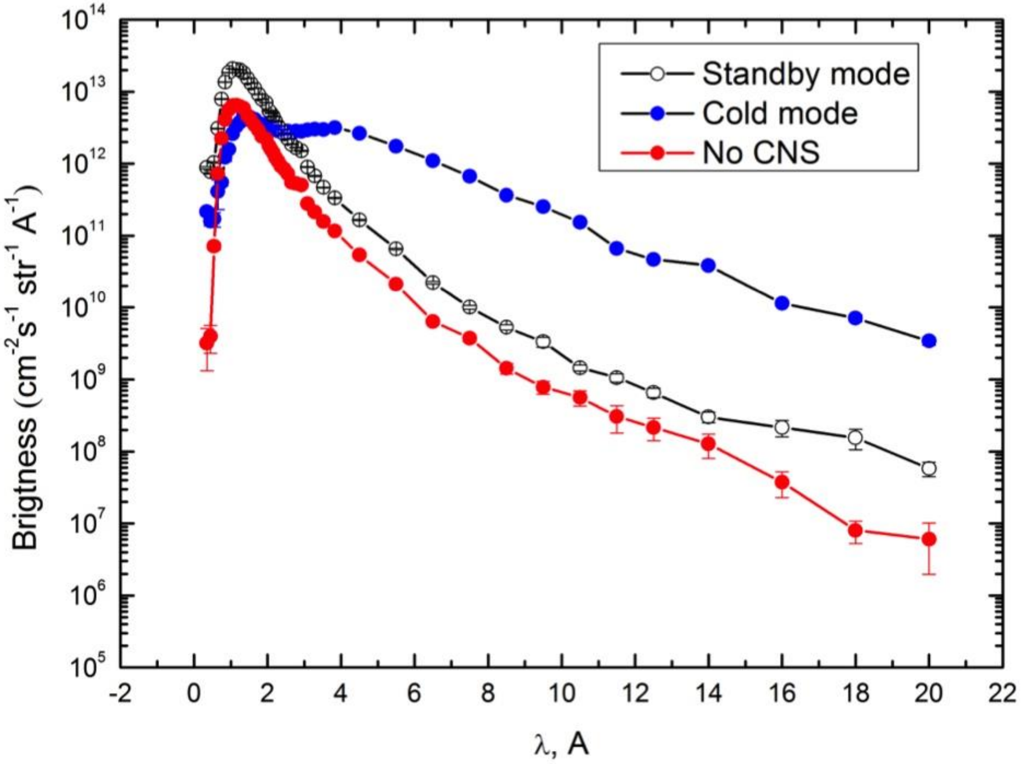


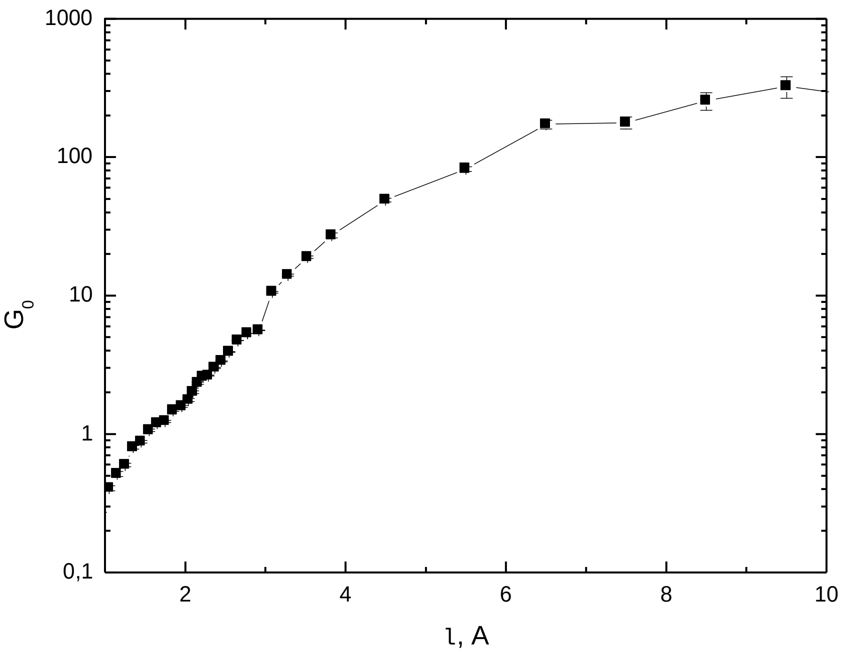
Brightness for different CNS volume



V=32l

CNS HEC-3 brightness and Gain





Gain

$7.4*10^{12}$ n cm^{-2} s^{-1} sr^{-1}

Heat load

		CNS Chamber (Al)	CNS LD_2	Displacer	Pipes (Al) Z<100 cm	Pipes Center. (Al)	Pipes (LD_2) Z<100 cm
m, g		3544	4182	640	2273	232	258
Δ*E*, W	n+γ	2001(15)	1882(15)	323(5)	451(7)	130(2)	43(1)
	β	1128(6)		251(3)	169(2)	110(1)	
Total by components		3129(21)	1882(15)	574(8)	620(9)	240(3)	43(1)
Total CNS, W		**6488**					
Δ*E*, W/g	n+γ	0,565	0,450	0,505	0,199	0,560	0,167
	β	0,318		0,392	0,074	0,474	
Specific heat load		**0,883**	**0,450**	0,897	0,263	1,034	0,167

Heat load in CNS with light water neutron reflector

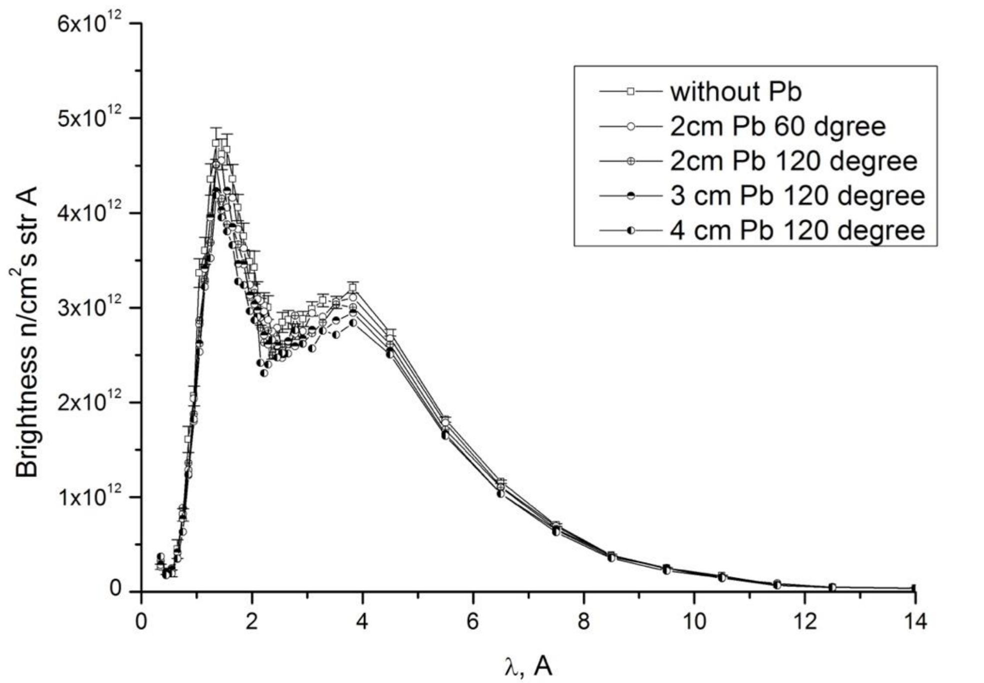
6165 W - Start-up reactor core

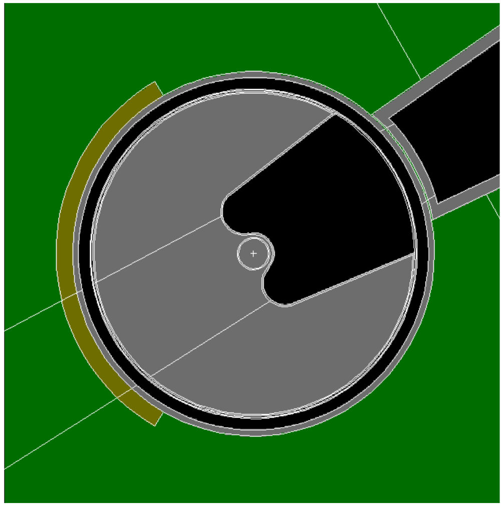
5590 W - Full loaded reactor core

3220 W - CNS in “warm” mode

Old CNS – heat load **4,0 -5,0 kW**

Differential brightness for different lead shielding





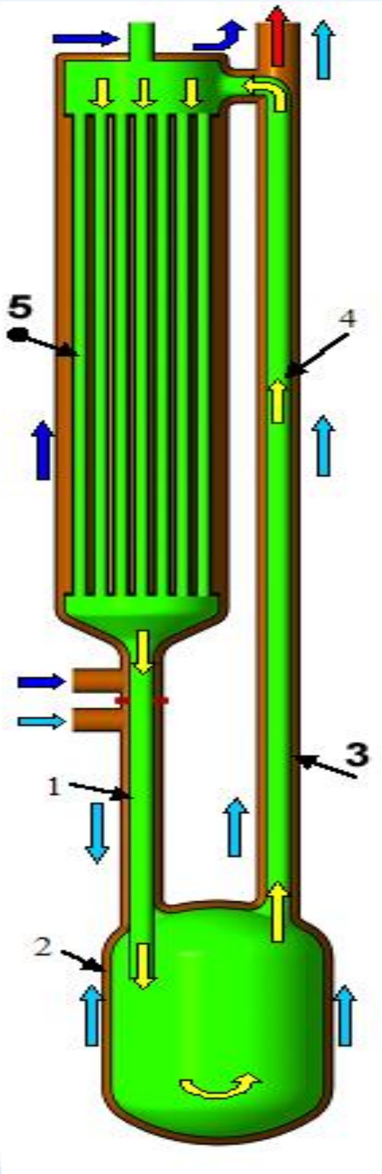
Integral brightness and heat load (Pb)

Lead thickness, cm	Brightness, n/cm²s str	Reduction, %	Heat load, W	Reduction, %
0	7.42 10^{12}		6488	
2	**7.06 10^{12}**	**5**	**5201**	**20**
3	6.86 10^{12}	7,5	4900	24,5
4	6.71 10^{12}	9,5	4703	27,5

CNS comparative parameters

Параметр	ANSTO	PNPI	ILL (V / H)
Reactor power, MW	20	100 (ver. ГЭК-3)	57
Thermal neutron flux at CNS location, n $cm^{-2}c^{-1}$	$1{,}65{*}10^{14}$	$4{,}0\ 10^{14}$	$4{,}6x10^{14}$ / $8x10^{14}$
Cold neutron flux at reactor face, *λ > 4Å,* n $cm^{-2}c^{-1}$	**(1,8-2,5) 10^{10}**	**$6{,}0\ 10^{10}$**	**$\sim 10^{10}/4\times10^{10}$ *)** ***) Capture flux**
Cold neutron flux at neutron guide hall, λ > 4Å, n $cm^{-2}c^{-1}$	**$6{,}4\ 10^{9}$**	**$\approx 10^{10}$**	**$5{,}4\ 10^{8}$**, (H18) **$5{,}4\ 10^{9}$**, (H17) **$5{,}0\ 10^{6}$** , (H14)
Moderator	LD_2	LD_2	LD_2
Moderator Temperature, К	23	19,5-25	25/25
Moderator chamber volume, l	20	24	20/6
Total heat load, kW	4-5	6,5-7,1	6/3
CNS standby mode	yes	yes	no

Principal layout of thermosiphon



1, 3, 4 – heat exchanger (pipe in pipe) ;

2 – CNS chamber;

5 – heat exchanger with jacket and counter-flow of helium.

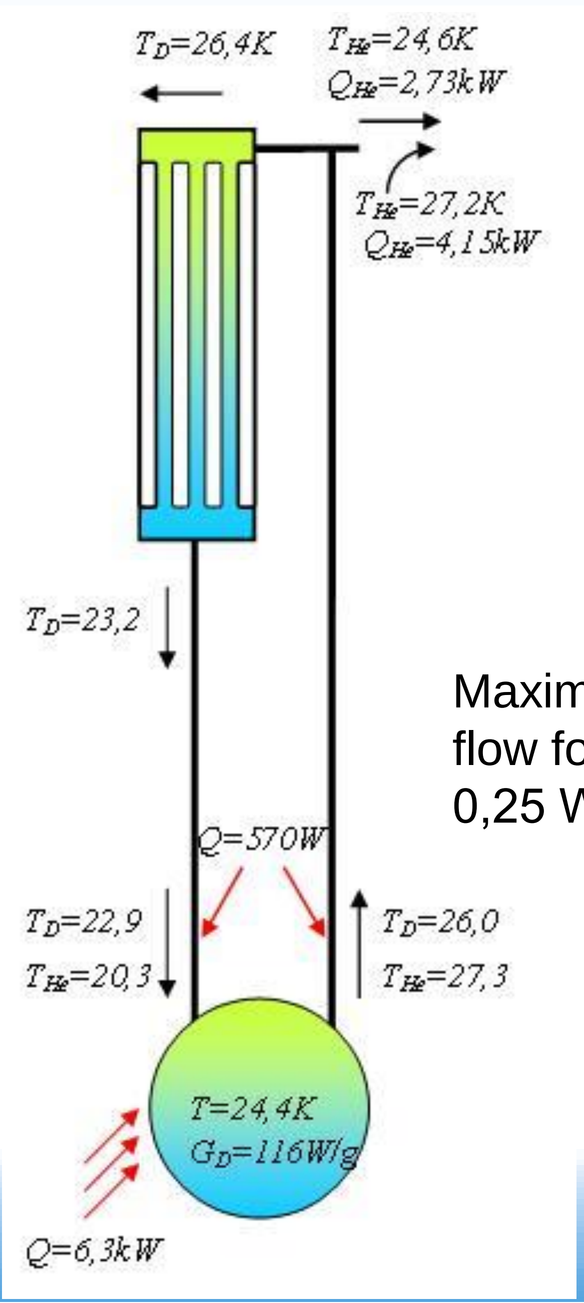
Flow of liquid deuterium

Flow of helium through the heat exchanger

Flow of helium through the deuterium chamber

Flow of helium to cryogenic system

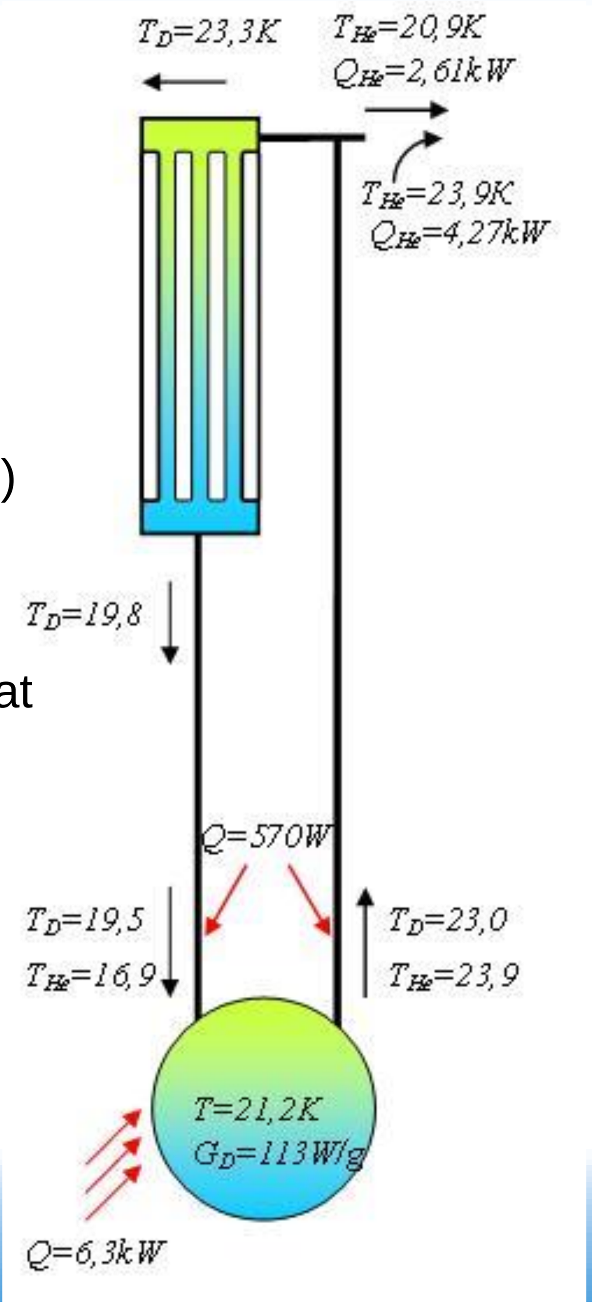
Heat remove principle



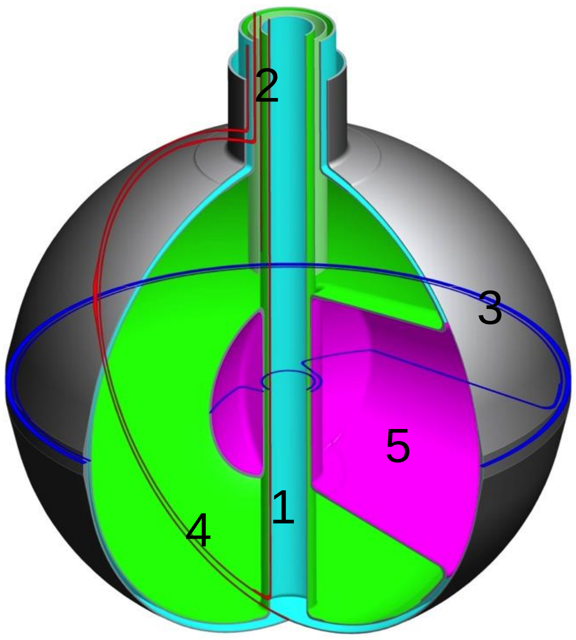
$Q=K*F*\Delta T$
$K=1/(1/\alpha_1+1/\alpha_2)$

5,6 W/cm²

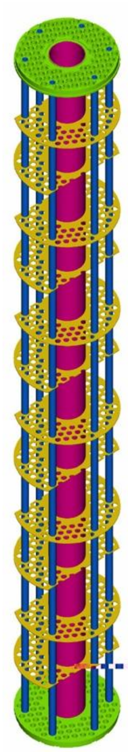
Maximum value of heat flow for direct cooling 0,25 W/cm^2



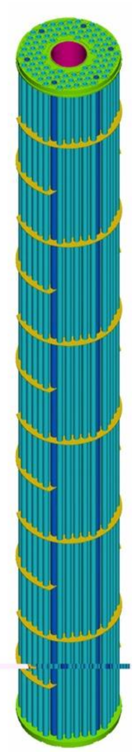
Chamber and Heat Exchanger



Deuterium chamber
1 – Helium supply tube
2 – Supply pipes
3 – Helium case
4 – Deuterium chamber
5 – Cavity (displacer)



1



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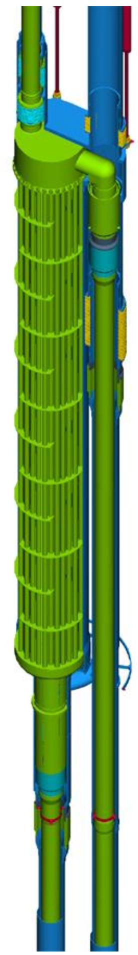

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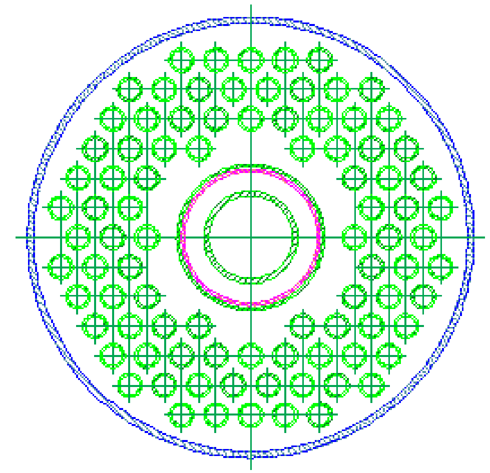
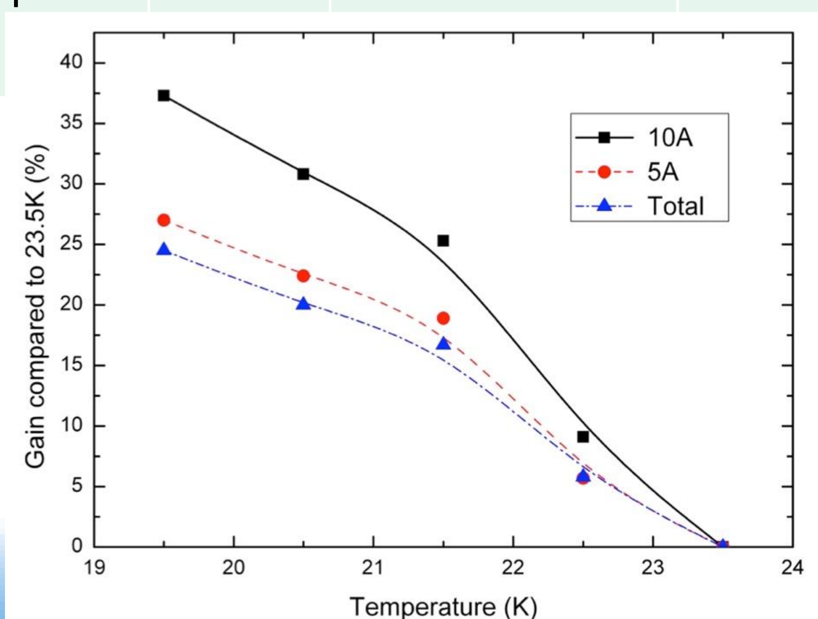


4

Heat exchanger
1 – without case and pipes
2 – without case
3 – general view
4 – cross-section

Main parameters of thermosiphon

He flow rate, g/s	LD_2 flow, g/s	LD_2 max. temperature, К	Aver. LD_2 Temperature in chamber, К	Min. Temperature LD_2, К	He inlet temp., К	Pressure D_2, bar
100+100	113	23,3	21,2	**19,5**	16,0	1,4
100+100	116	26,4	24,4	22,9	19,0	2,9



T_{boil}= 25-26 К
at saturation pressure 1,45 -1,9 bar

Main CNS components

I – CNS Support tube

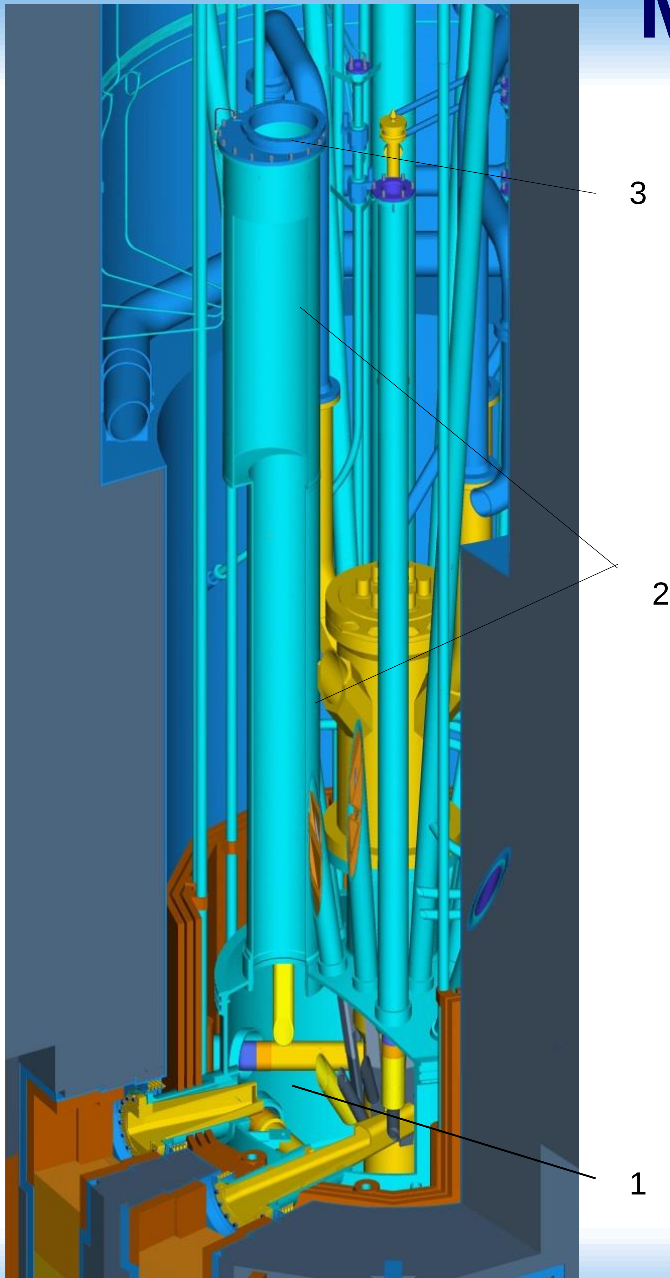
1 - Reactor tank

2 - Connecting branch PIK 00.020 (support pipe)

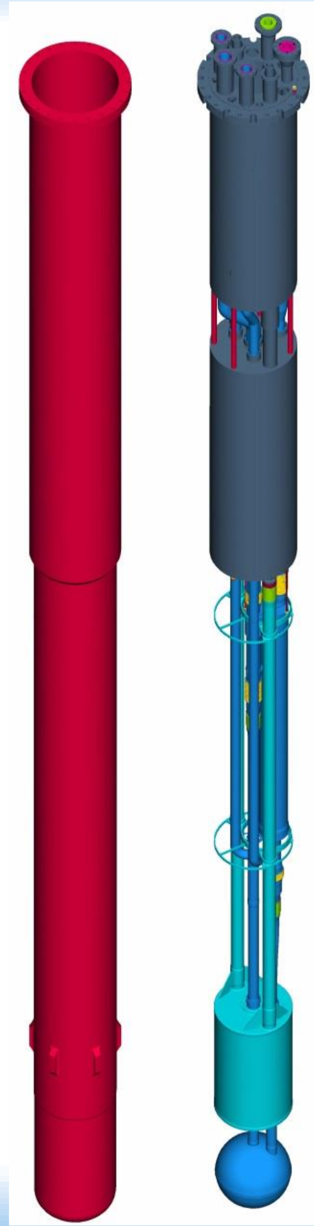
3 - Adapter flange

II – Vacuum containment

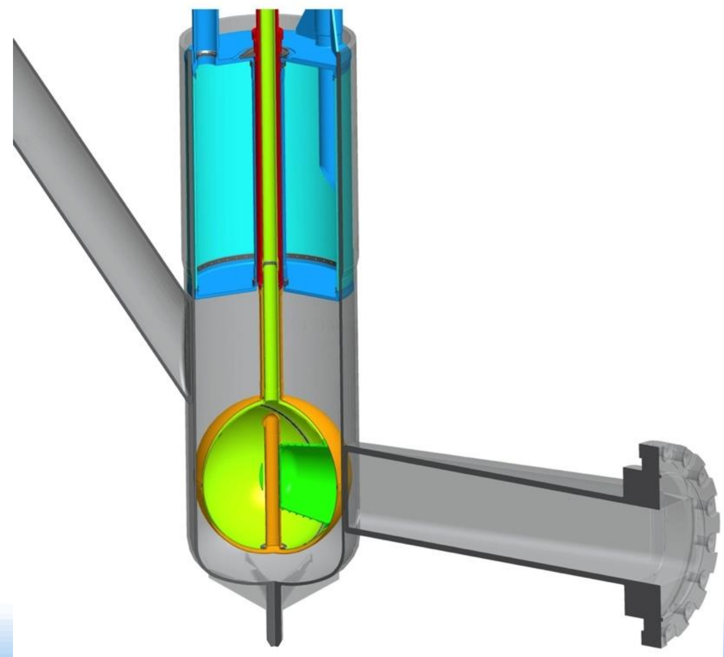
III – Thermosiphon



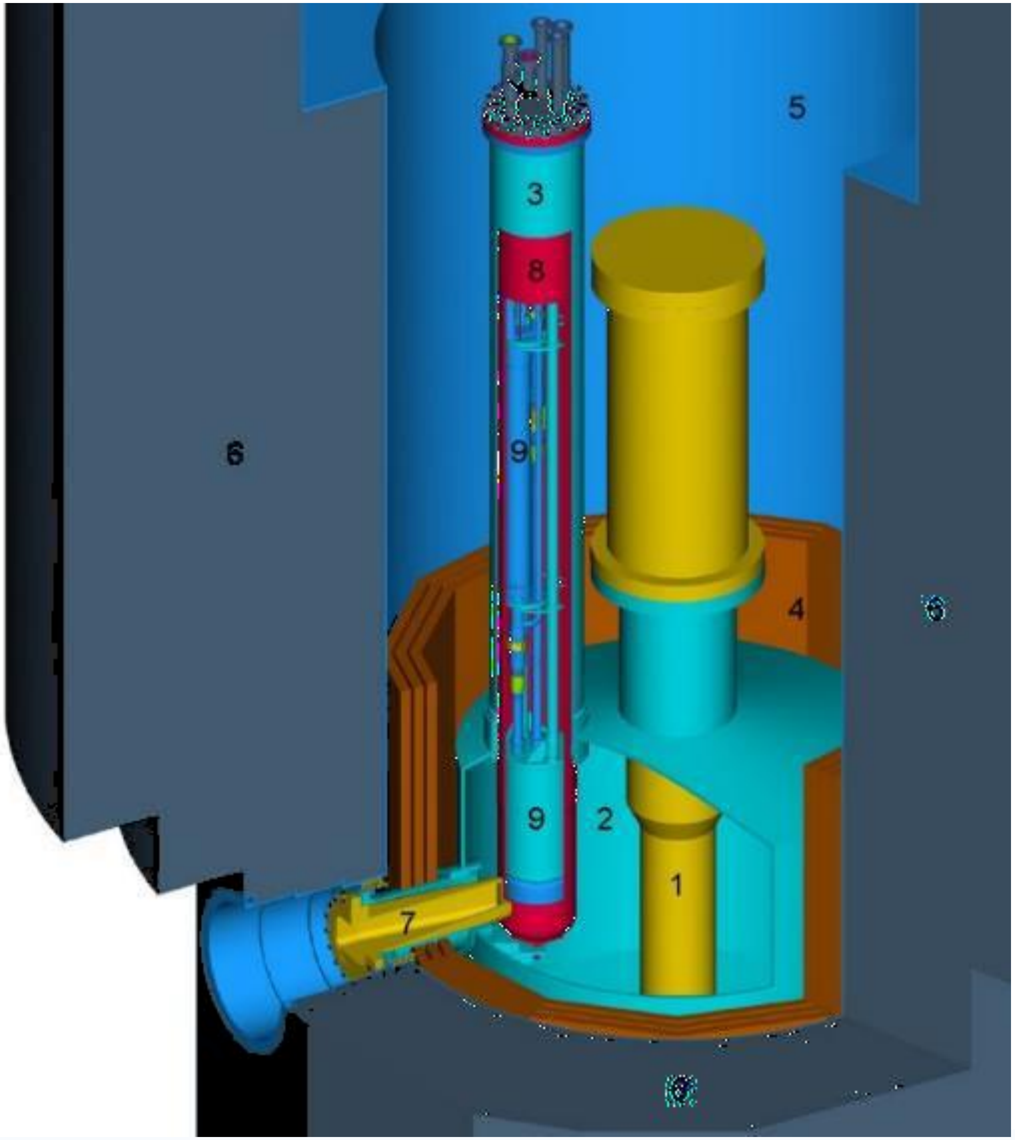
I



II III

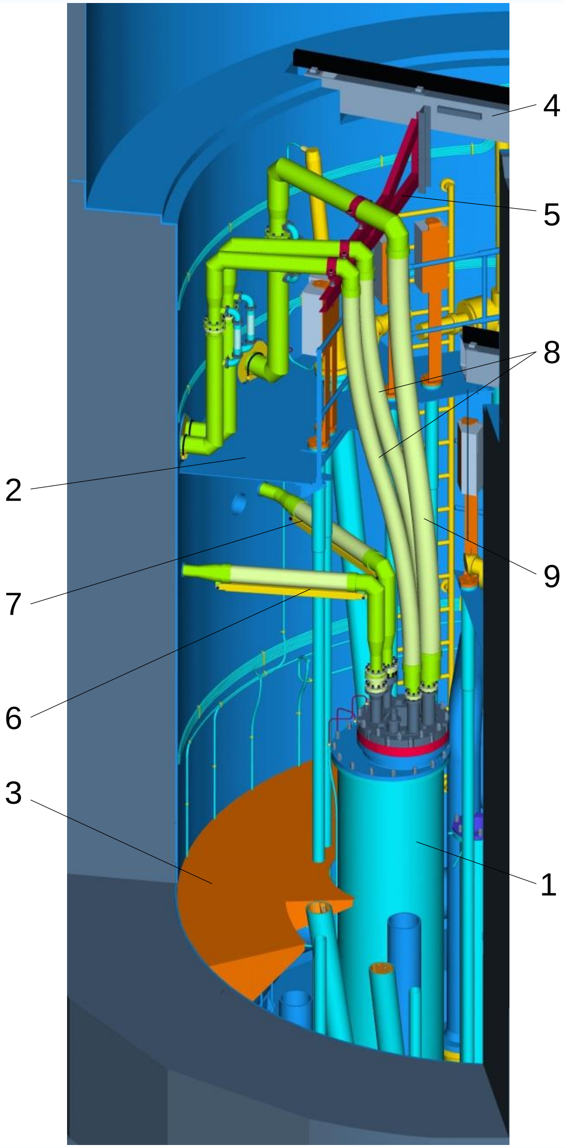


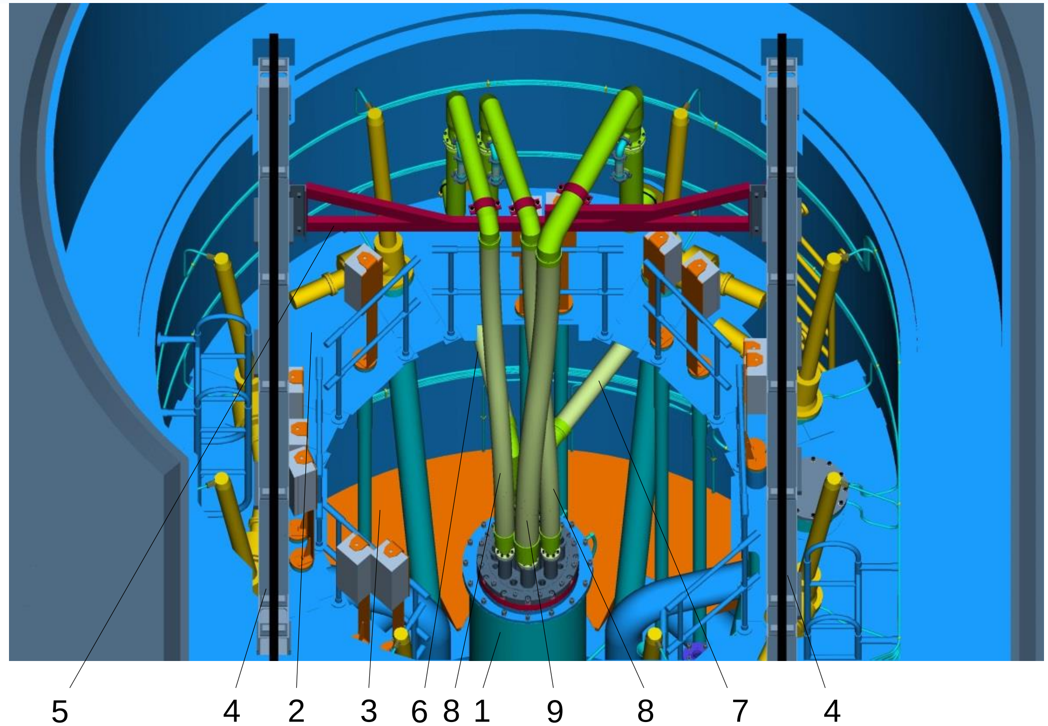
CNS for HEC-3 at reactor PIK (total view)



1 – Core case
2 – Heavy water reflector tank,
3 – Connecting branch PIK 00.020 (support pipe),
4 – Water-concrete shielding,
5 – Steel case of reactor shaft,
6 – Reactor radiation shielding (concrete),
7 – HEC-3 channel,
8 – Vacuum containment,
9 – Thermosiphon.

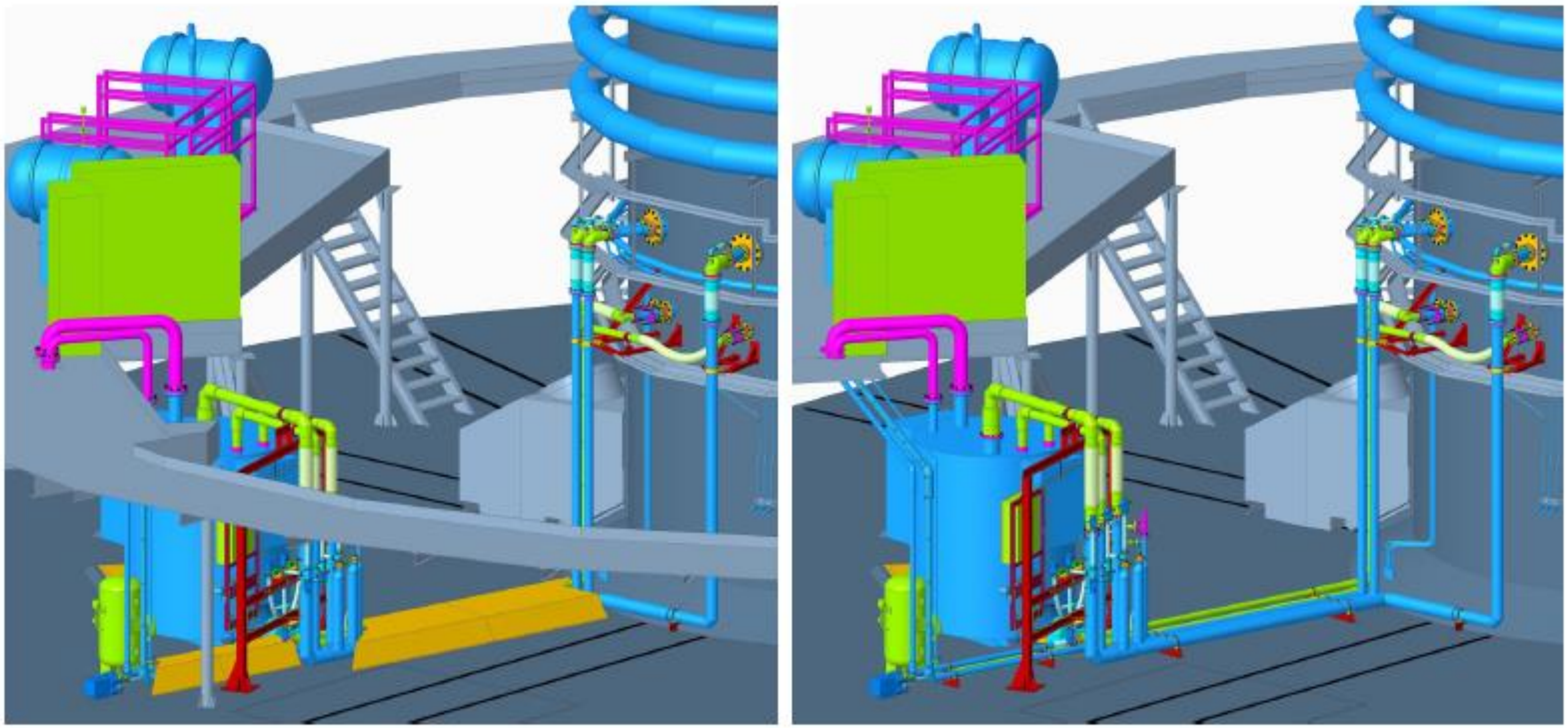
CNS external systems pipes in reactor shaft





1 – Support flange PIK.00.020
2 – Drive platform (level +12080)
3 – Assembly platform (level +9000)
4 – Rail track
5 – Support crossbar
6 – Deuterium pipes
7 – Vacuum pipes
8 – Cryogenic helium pipes (inlet)
9 – Cryogenic helium pipes (outlet)

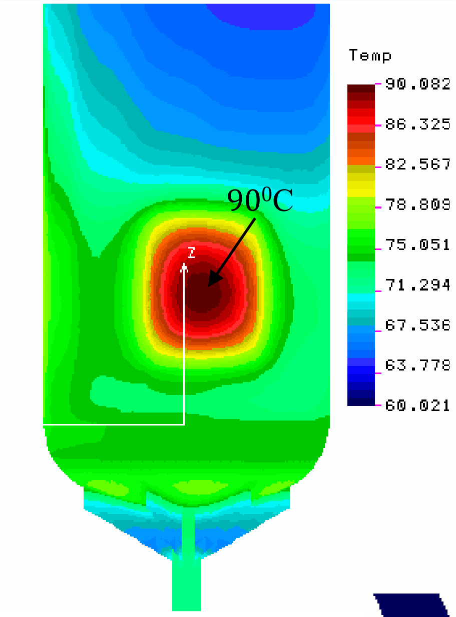
Hall of Inclined channels (+7500 level, upper part +10800)

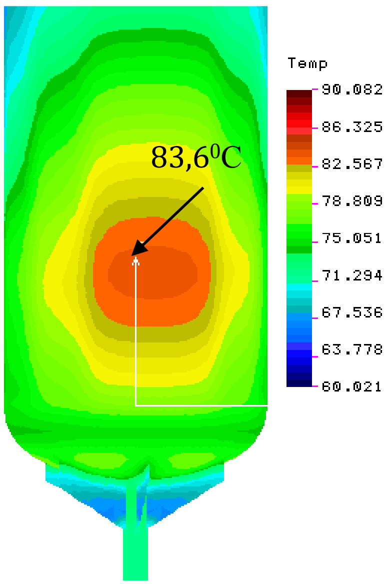


In the heavy water reflector tank. View on HEC-3.

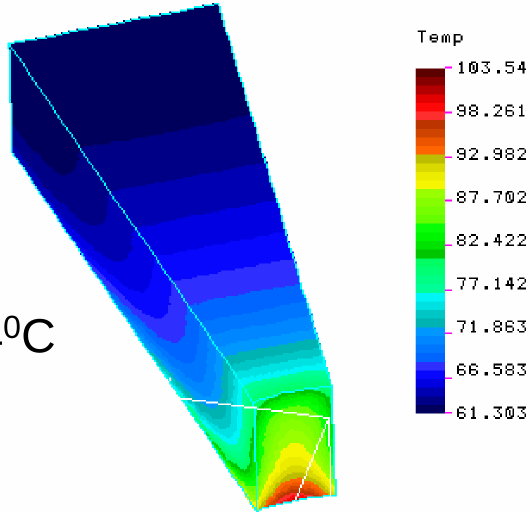
Mockup of the vacuum containment

Temperature of vacuum containment and HEC-3 channel



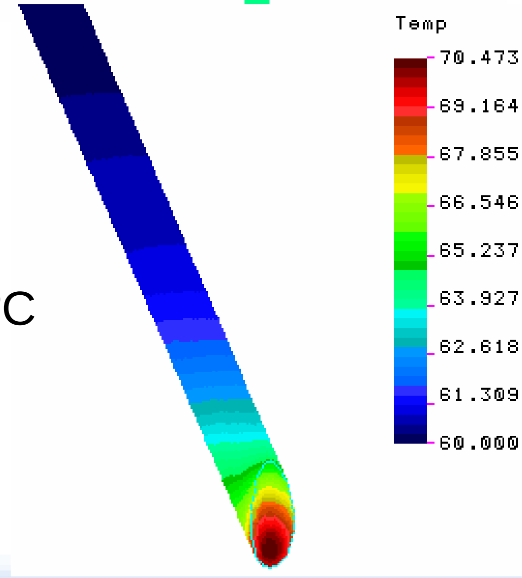


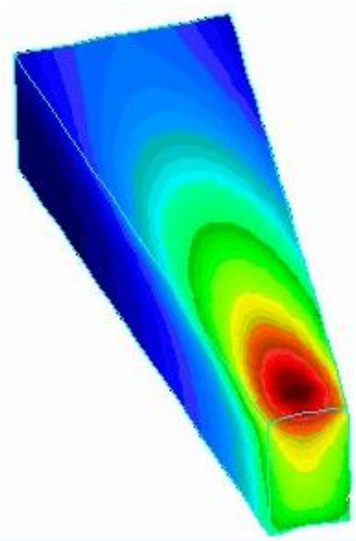
$T_{m3} = 134^0C$



IEC-1, $T_{N1} = 70,5^0C$

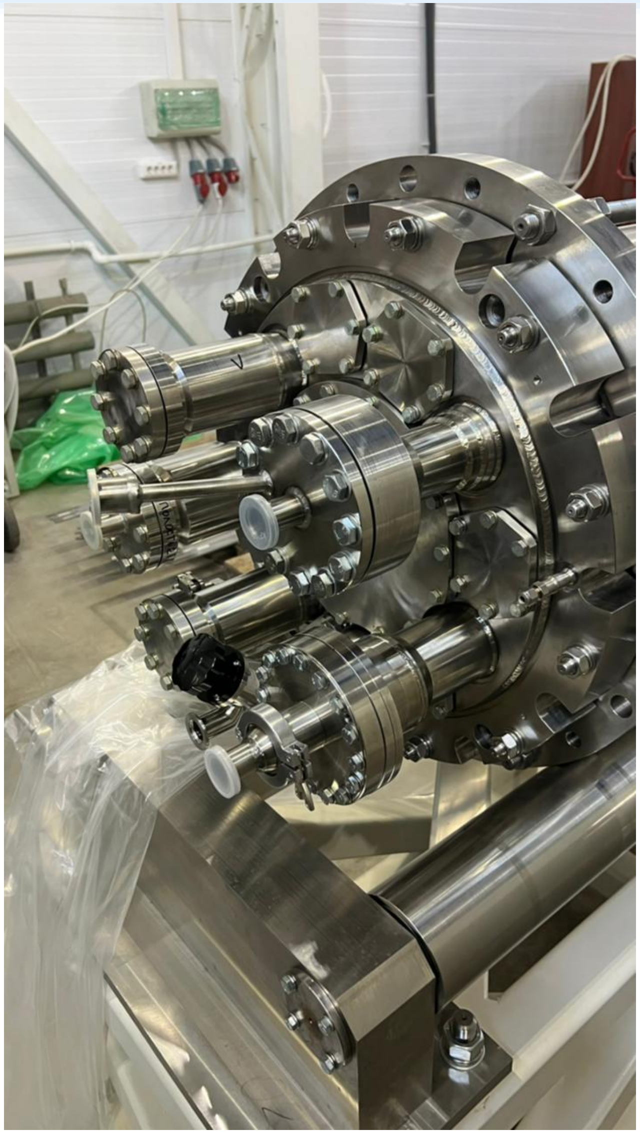
$T_{b3} = 89,5^0C$





400 W/m^{2}K

In-Pile part of CNS HEC-3



Examination of CNS Chamber

Composition of the complex CNS HEC-3

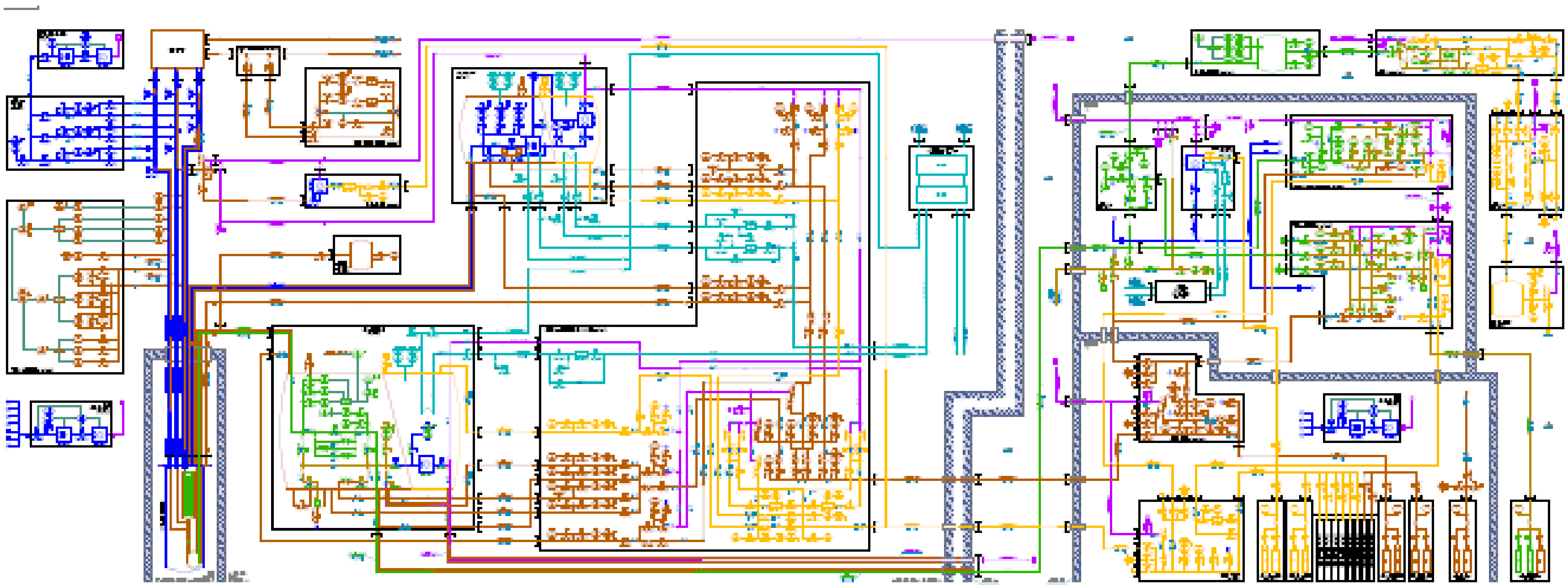
- 1. In-pile part (vacuum containment);
- 2. Cryogenic helium system and cryogenic pipes;
- 3. Deuterium system;
- 4. Vacuum system;
- 5. Protection gaseous system;
- 6. Gas analysis system:
- 7. CNS protection and control system;
- 8. Power supply system;
- 9. Control air system;
- 10. Recycled cooling water system (100E and 100A buildings);
- 11. Gas discharge system.

REACTOR PIK CNS-3 PROJECT

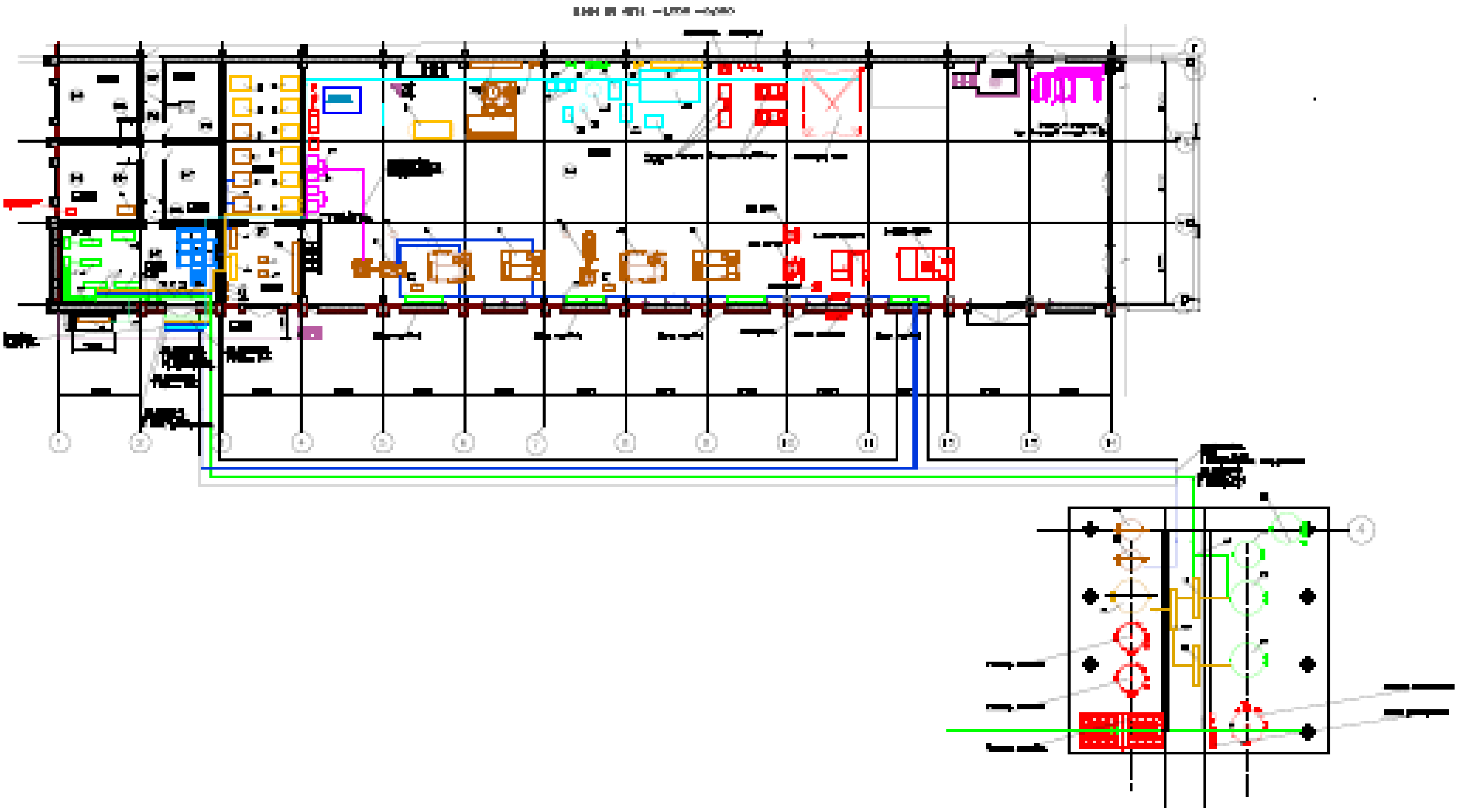
Main systems of the CNS HEC-3 complex

	Components and systems	Availability
1	Buildings & construction works	completed
2	Auxiliary systems (electricity, recycled cooling water, instrument air etc.	Completed 80%
3	Cryogenic plant (LINDE) mounting is ready	Completed 90%
4	External systems (Deuterium, Vacuum, Helium blanketing)	Mounting 70%
5	Vacuum containment	Under manufacturing
6	CNS Thermosiphon (Cryogenic vertical insert)	Completed
7	CNS Protection and control system	Mounting 70 %
8	Cryogenic connected pipelines (TS-Linde)	Completed 50%

Shematic diagram of the CNS complex



Layout of the CNS equipment in the 100E building



CNS systems

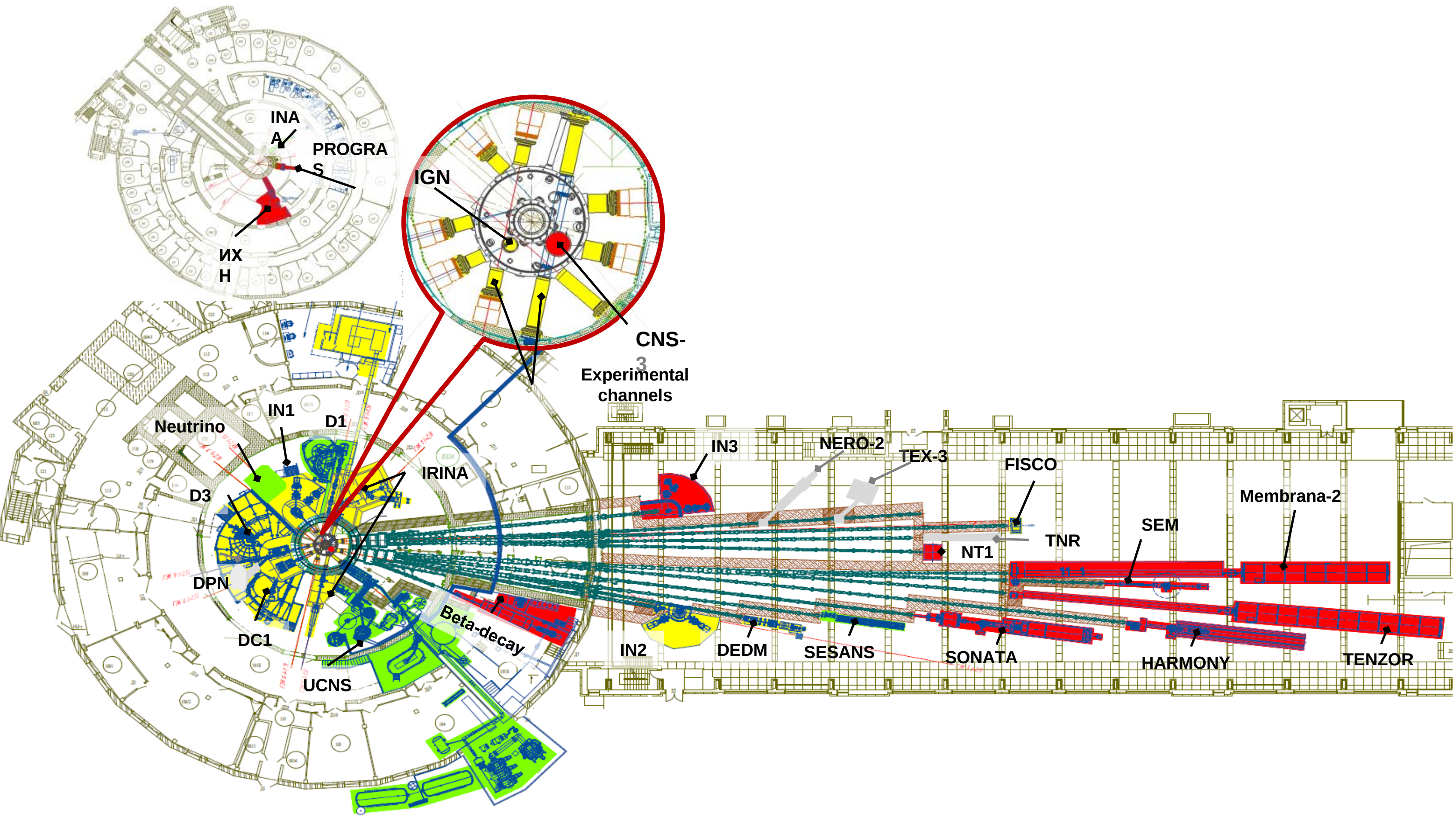
Pipelines between 100A and 100E buildings

Linde cryogenic equipment in 100E

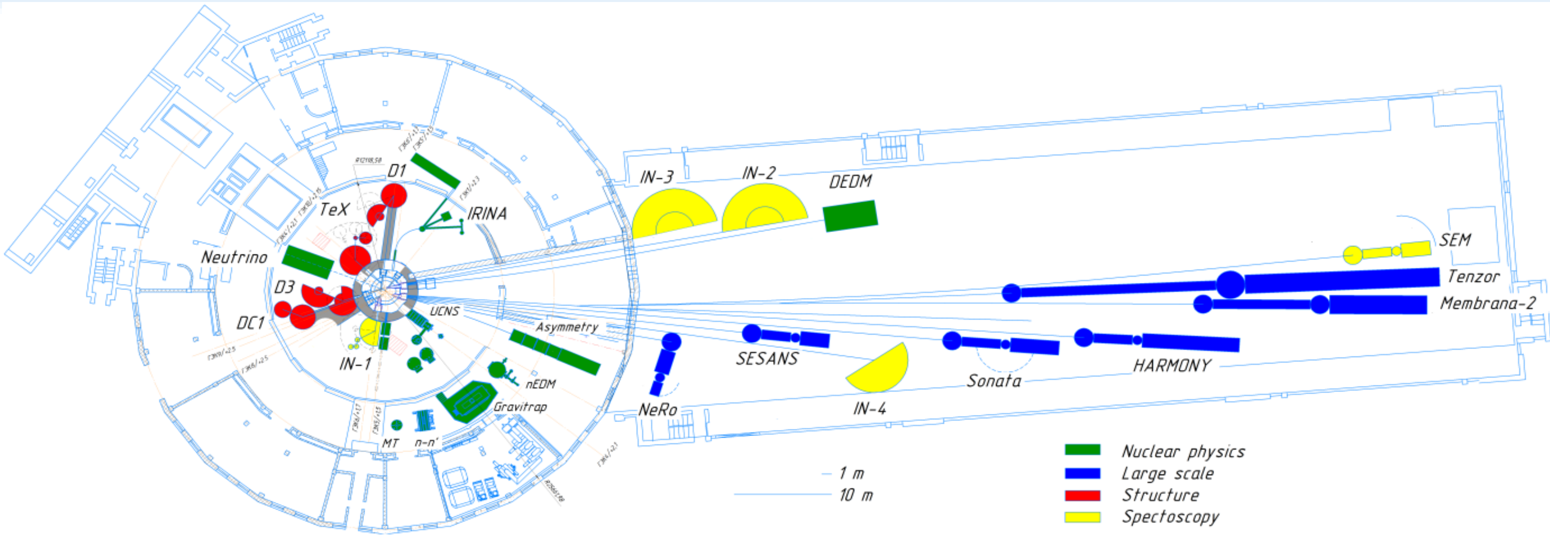
External Hydrogen and Vacuum systems

Cooling water system

Layout of experimental setups in the Inclined and Horizontal halls

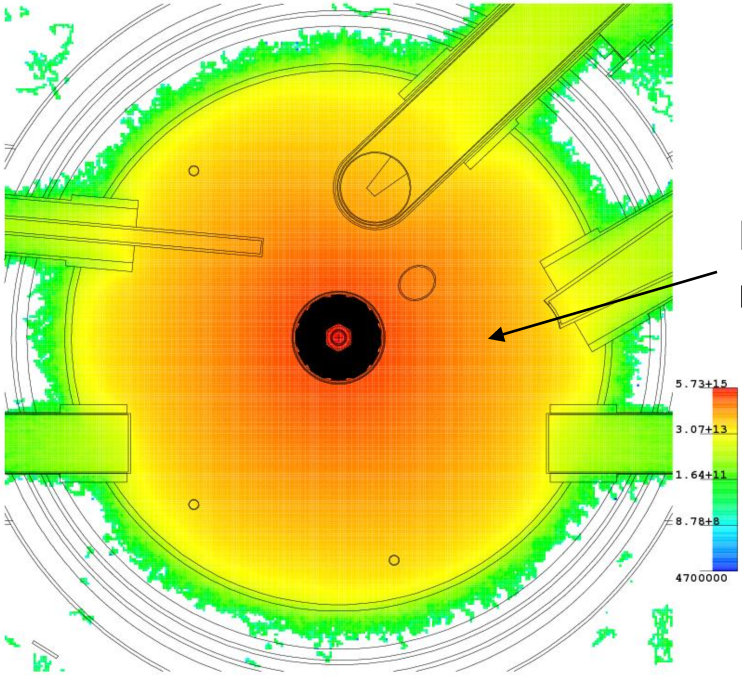


Layout of the main and experimental reactor halls with neutron guide system and neutron stations.

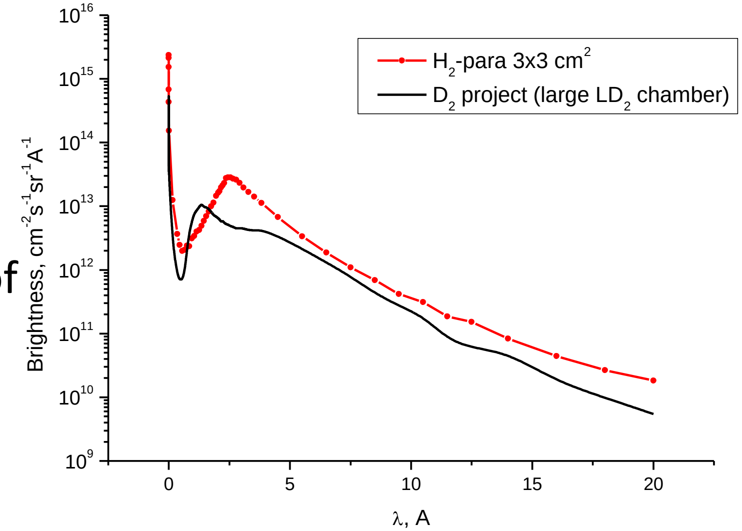


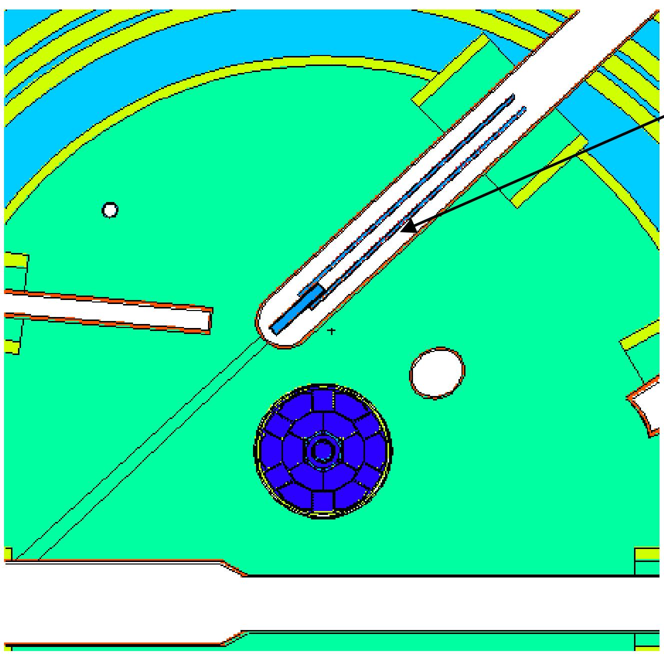
Name	Wavelength range, Å	Beam size at sample position, mm2
1.Reflectometer of polarized neutrons NeRo	1.5	5×50
2. Small angle spin echo SESANS	3.5 - 12	10×10
3. Spectrometer IN-4	2 – 13	30×30
4. Reflectometer Sonata	2 - 20	10×10
5. Reflectometer with vector polarization analyser HARMONY	2 - 20	0.1×100
6. Small angle scattering Membrana-2	4.5 - 20	15×15
7. Small angle diffractometer of polarized neutrons Tenzor	4.5 - 30	30×30
8. Spin echo spectrometer SEM	4.5 - 12	30×60
9. Asymmetry	4 - 12	30×100

Comparison of para-hydrogen and Liquid deuterium sources



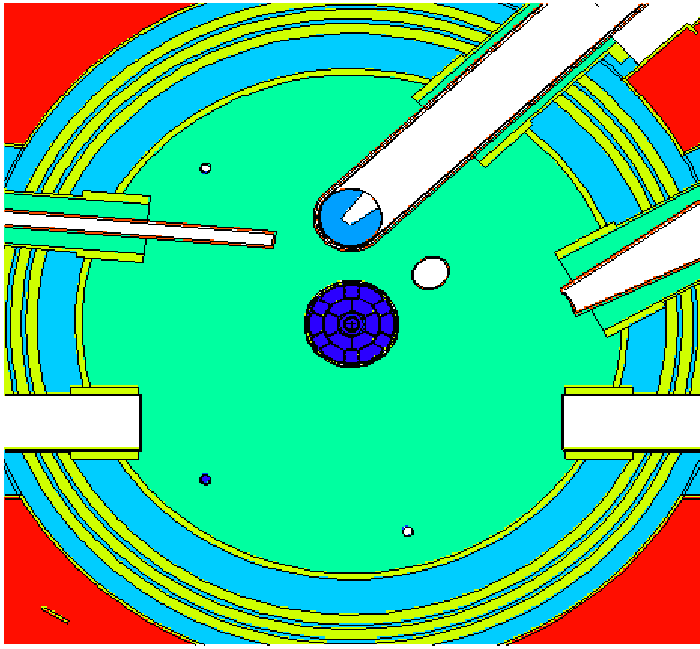
Field of cold neutron flux in heavy water reflector of reactor PIK



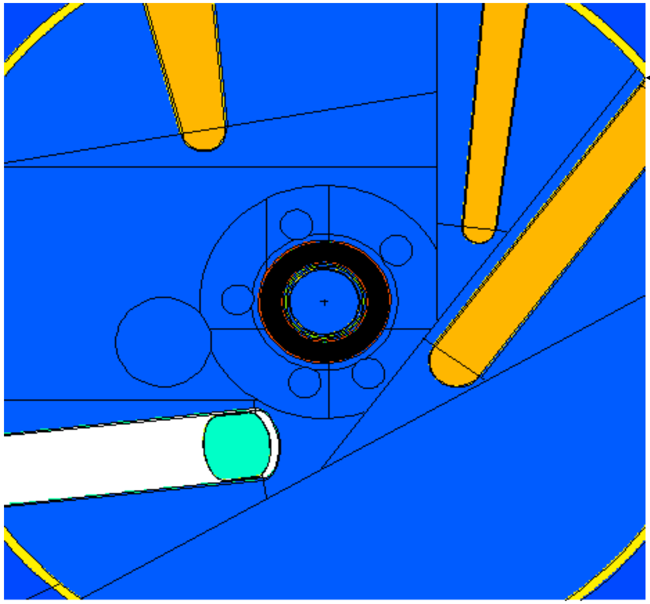


Para hydrogen source in HEC-2 **F.Mezei, A.Ioffe, E.Vezhlev et al suggestion**

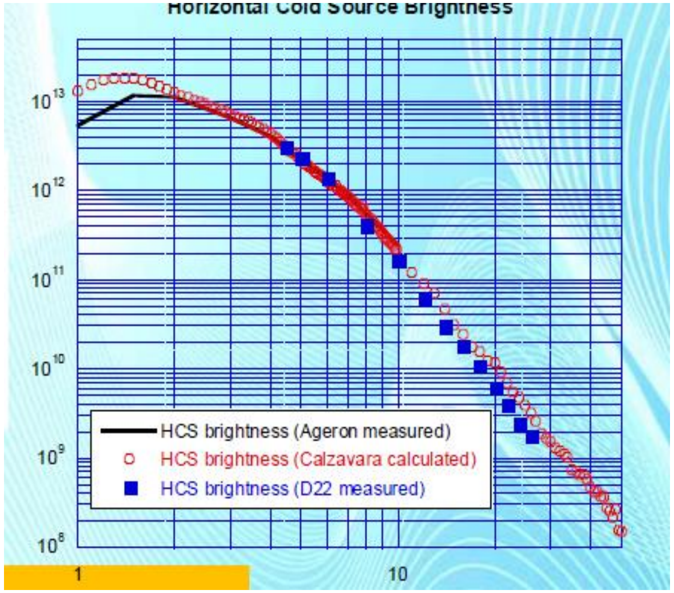
Chamber size: $30x30x200\ mm^3$

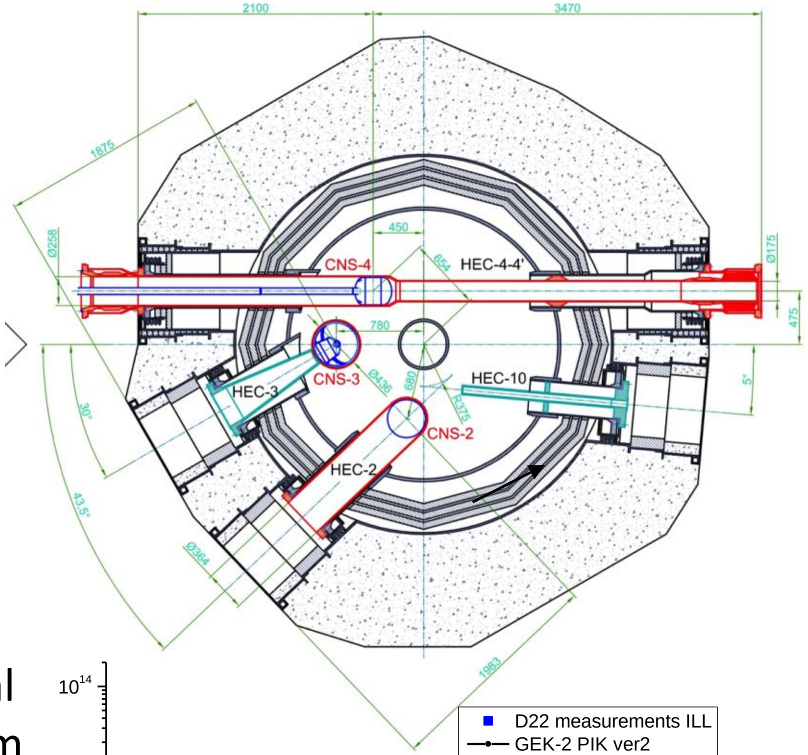


D_2 liquid CNS-2 (project)



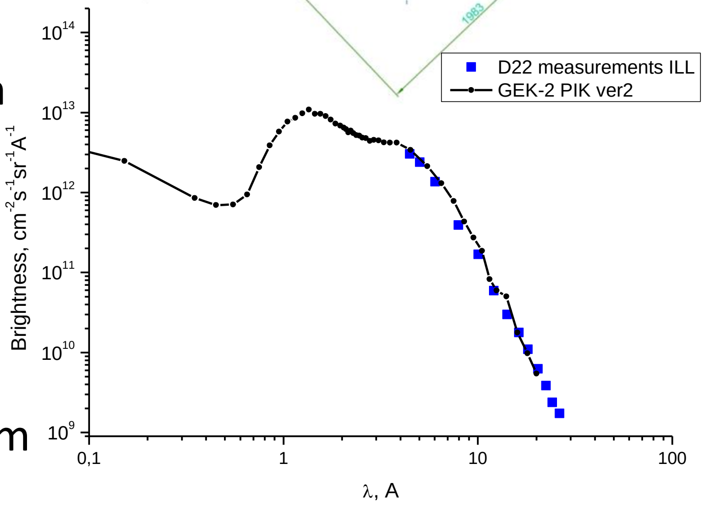
ILL Horizontal cold source
V = 5.2 l





PNPI Cold neutron source 2
V = 14.8 l
Size - ø330 x 370
Channel of maximal diameter – 380 mm

Distance from the centrum of the source to the centrum of the core – 694 mm



Reactor PIK

THANK YOU FOR YOUR ATTENTION!!!!