Development of the high-brightness HEC-2 cold neutron source at the reactor PIK

V. A. Mityukhlyaev, M.S. Onegin

Physical properties of LH_2

Melting temperature* ,K	13.9
Boiling temperature*, K	20.4
Rotational energy level excitation (0 →1), meV	14.7
Vibrational energy level ΔE, meV	546
Free scattering cross-section	
incoherent, barn	20.052
coherent, barn	0.397

*) Standart conditions

Physical properties of LD_2

Melting temperature* ,K	18.62
Boiling temperature*, K	23.67
Rotational energy level excitation (0 →1), meV	7.4
Vibrational energy level ΔE, meV	386
Free scattering cross-section	
incoherent, barn	0.907
coherent, barn	2.489

*) Standart conditions

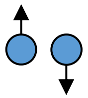
$$\sigma^{H}_{(n,\gamma)} = 0.332\frac{v_0}{v}$$

$$\sigma^{D}_{(n,\gamma)} = 0.000506\frac{v_0}{v}$$

$$v_0 = 2200\ м/с$$

$s_H = 1/2$

H_2



Ground state: L=0, S=0 - para

Antisymmetric spin arrangement

Excited state: L=1, S=1 - ortho

Normal condition (T=293 K):

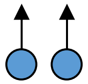
Ortho:para = 3:1

T=20,3 K

Ortho:para = 0.2:99.8

$s_D = 1$

D_2



Ground state: L=0, S=0,2 - ortho

Symmetric spin arrangement

Excited state: L=1, S=1 - para

Normal condition (T=293 K):

Ortho:para = 2:1

T=20 K

Ortho:para = 98.1:1.9

n + p,d Scattering

$s_n = s_p = 1/2$

$$J - \ \ channel\ spin = \ \boldsymbol{s_n} + \boldsymbol{s_p} + \boldsymbol{l}$$

Cold neutrons: $\boldsymbol{l} = 0$ $\qquad$ $\boldsymbol{J} = 0{,}1$

$$\psi(\mathbf{r})\Big|_{r>r_0} = e^{\mathrm{i}\mathbf{k}_0\mathbf{r}} - a\frac{e^{ikr}}{r}$$

Scattering length

$$a_+ = a_t \ \text{-}\ J = 1$$
$$a_- = a_s \ \text{-}\ J = 0$$

$$a_{coh} = \frac{I+1}{2I+1}a_+ + \frac{I}{2I+1}a_-$$

$$a_{inc} = |a_+ - a_-|\frac{\sqrt{I(I+1)}}{2I+1}$$

$^1_1$H - *I=1/2*

$a_+ = 5.424 \pm 0.003$ fm

$a_- = -23.749 \pm 0.008$ fm

$a_{coh} = -1.869$ fm

$a_{inc} = 12.632$ fm

$^1_1$D - *I=1*

$a_+ = 6.34 \pm 0.02$ fm

$a_- = 0.65 \pm 0.03$ fm

$a_{coh} = 4.44$ fm

$a_{inc} = 2.68$ fm

We can only make scattering on H_2 and D_2.

Schwinger J., Teller E. Phys. Rev. **52**, 286 (1937)

Fermi pseudopotential

$$V(\mathbf{r},\mathbf{R}_1,\mathbf{R}_2)=\frac{2\pi h^2}{m}\sum_{i=1}^{2}\left[a'_{i,coh}+\frac{2(a'_{i,+}-a'_{i,-})}{2I_i+1}\mathbf{s}_i\sigma\right]\delta(\mathbf{r}-\mathbf{R}_i)$$

$$a'_{+,-}=\left(1+\frac{m}{M}\right)a_{+,-}$$

Born approximation is applicable.

$$\frac{d\sigma_{n,l\to n',l'}}{d\Omega}=\frac{4}{9}\frac{p}{p_0}\cdot c_{S\to S'}\times$$

$$\frac{1}{2l+1}\sum_{m,m'}\left|\int\exp\left\{\frac{i(\mathbf{p}_0-\mathbf{p})\mathbf{R}}{2h}\right\}\Phi^*_{n',l',m'}(\mathbf{R})\Phi_{n,l,m}(\mathbf{R})d\mathbf{R}\right|^2$$

$l,l'-even: S,S'=0$
$l,l'-odd: S,S'=1$

$$c_{0\to0}=3(a_++a_-)^2$$

$$c_{0\to1}=3(a_+-a_-)^2$$

$$c_{1\to1}=(3a_++a_-)^2+2(a_+-a_-)^2$$

$$c_{1\to0}=(a_+-a_-)^2$$

$$E_{n,\min}=0.0137\left[l'(l'+1)-l(l+1)\right]+0.819(n'-n)\quad[\text{eV}]$$

For H_2 E_{Qinel}=0.0274 eV

Young and Koppel theory of inelastic scattering on H_2 and D_2 (Phys.Rev. **135**, 3A p.A603, (1964))

$$\sigma(E \to E', \mu) = \frac{\sigma_b}{2kT}\sqrt{\frac{E'}{E}}S(\alpha, \beta) \qquad \alpha = \frac{E' + E - 2\sqrt{EE'}\mu}{AkT}; \quad A = M/m_n \qquad \beta = \frac{E' - E}{kT}$$

$$S_{para}(\alpha,\beta) = \sum_{J=0,2,4...} P_J \times \frac{4\pi}{\sigma_b}\left[A_{para}\sum_{J'=0,2,4...} + B_{para}\sum_{J'=1,3,5...}\right](2J'+1) \times S_f(w\alpha, \beta+\beta_{JJ'}) \times \sum_{\ell=|J'-J|}^{J'+J} 4j_\ell^2(y)C^2(J,J',l;00)$$

$$S_{ortho}(\alpha,\beta) = \sum_{J=1,3,5...} P_J \times \frac{4\pi}{\sigma_b}\left[A_{ortho}\sum_{J'=0,2,4...} + B_{ortho}\sum_{J'=1,3,5...}\right](2J'+1) \times S_f(w\alpha, \beta+\beta_{JJ'}) \times \sum_{\ell=|J'-J|}^{J'+J} 4j_\ell^2(y)C^2(J,J',l;00)$$

$$\beta_{JJ'} = (E'_J - E_J)/kT$$
$$y = (a/2)\sqrt{MkT\alpha}$$

$$w = \begin{cases} \frac{1}{2} - \mathrm{H}_2 \\ \frac{1}{4} - \mathrm{D}_2 \end{cases}$$

$$\sigma_b = 4\pi\left(a_c^2 + a_i^2\right)$$

$$S_f(\alpha,-\beta) = \frac{1}{\sqrt{4\pi\alpha}}\exp\left[-\frac{(\alpha-\beta)^2}{4\alpha}\right]$$
$$S_f(\alpha,\beta) = e^{-\beta}S_f(\alpha,-\beta)$$

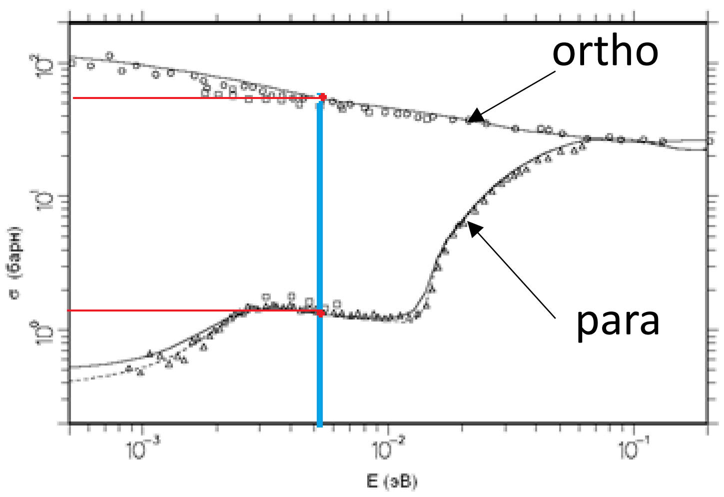
a_c - coherent scattering length
a_i - incoherent scattering length

a – interatomic distance in the molecule

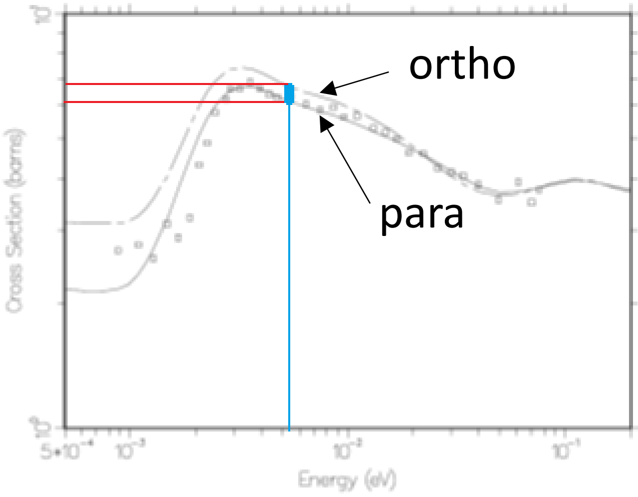
	A (even)	*B* (odd)
H para	a_c^2	a_i^2
H ortho	$a_c^2/3$	$a_c^2+2a_i^2/3$
D para	$3a_i^2/4$	$a_c^2+a_i^2/4$
D ortho	$a_c^2+5a_i^2/8$	$3a_i^2/8$

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

H_2



D_2



$\lambda = 4$ Å → $E \cong 5.1$ meV

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

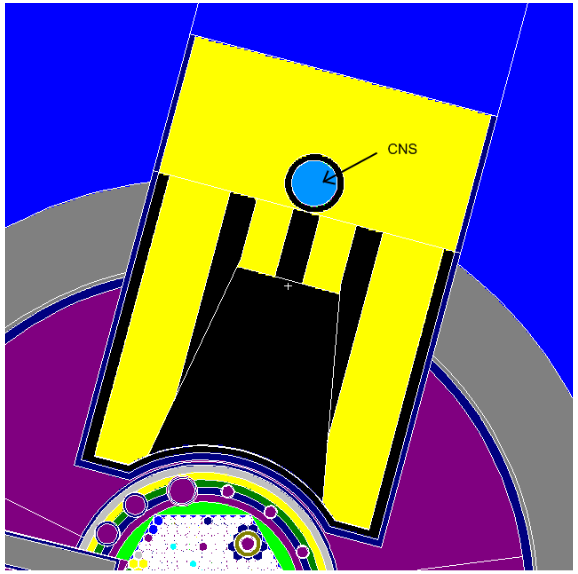
$\sigma_{ortho} \cong 55$ b → $l \cong \mathbf{0.4}$ cm

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

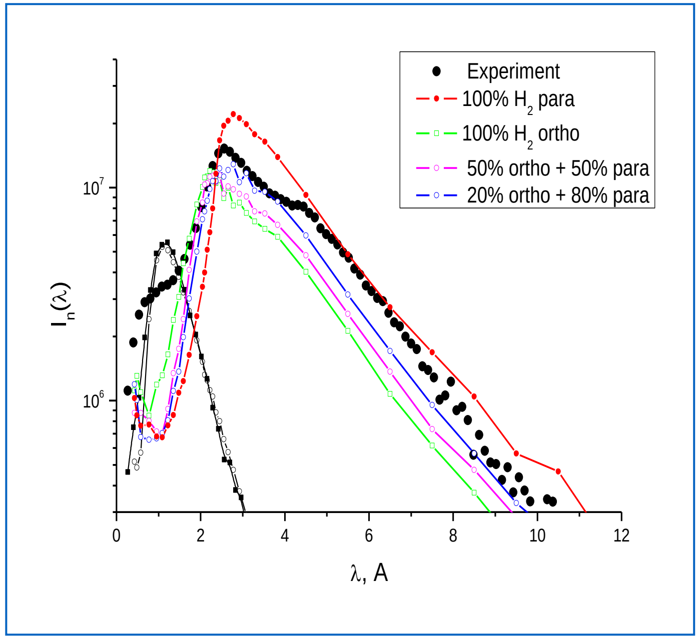
$\sigma_{para} \cong 6$ b → $l \cong \mathbf{3.3}$ cm

Chamber of 6L volume was situated in the reactor Thermal Column

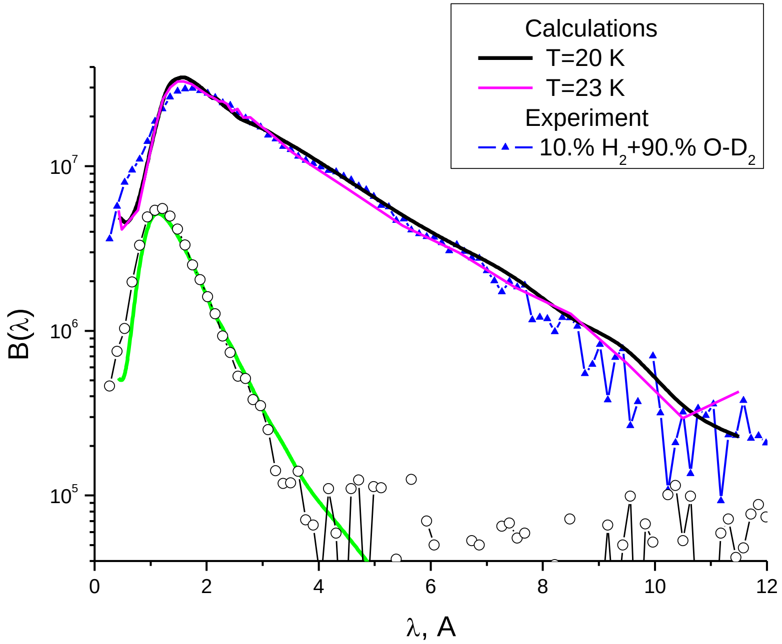
A.P. Serebrov, V.A. Mityukhlyaev, A.A. Zakharov et al



Brightness of chamber filled with LH_2



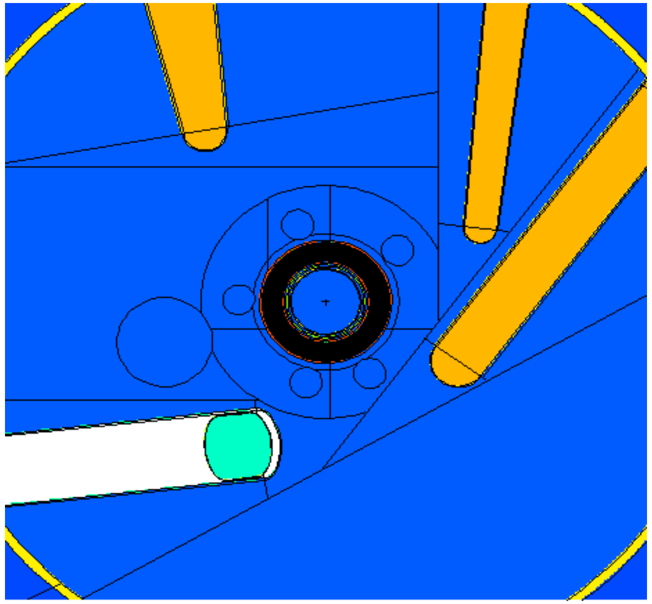
Brightness of chamber filled with LD_2



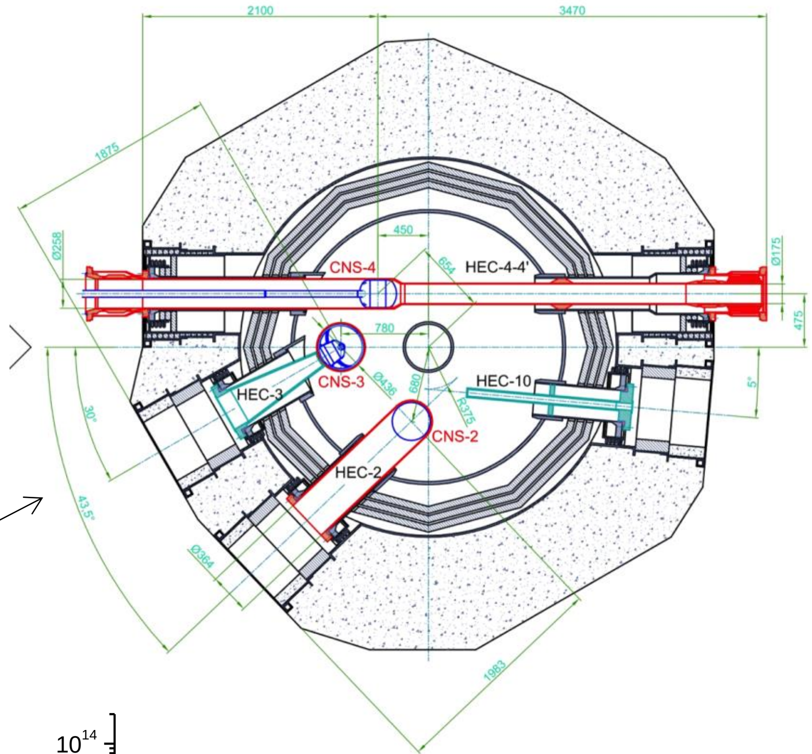
General conclusion:

CNS of large volume filled with LD_2 is more effective then chamber filled with LH_2 in mix spin state.

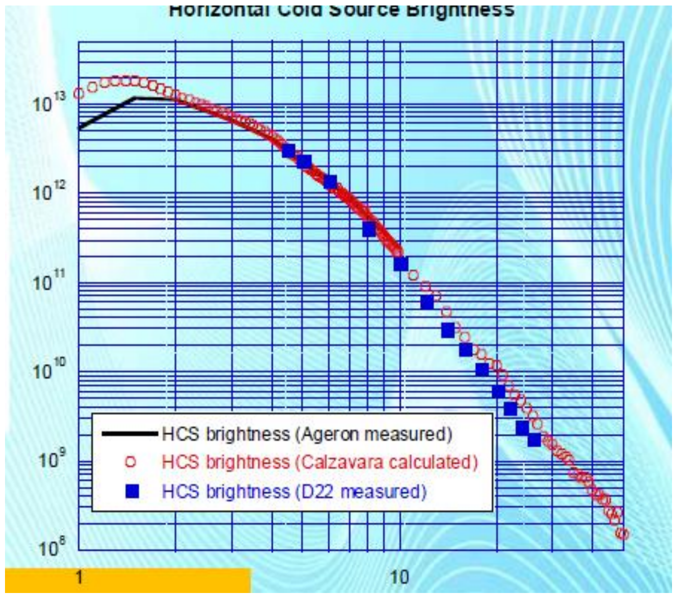
D_2 liquid CNS-2 (project)



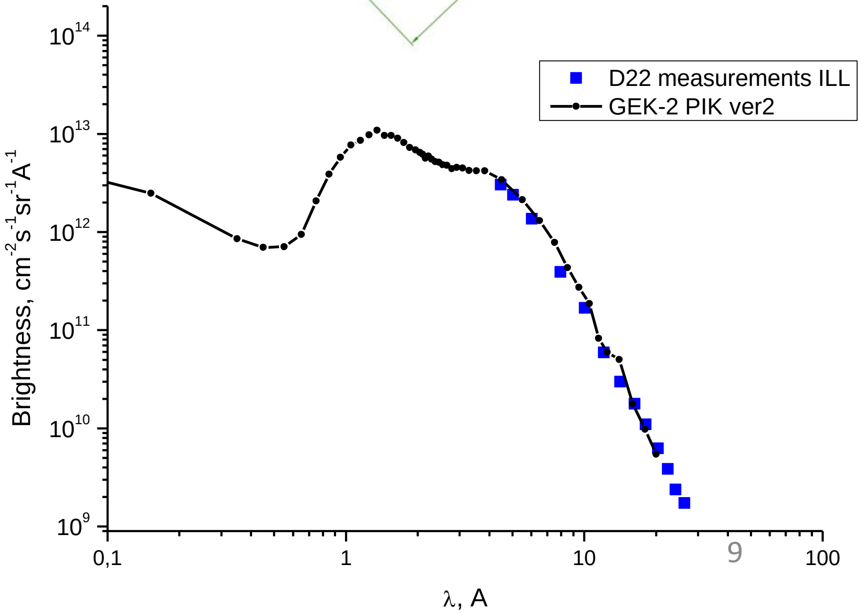
ILL Horizontal cold source
V = 5.2 l



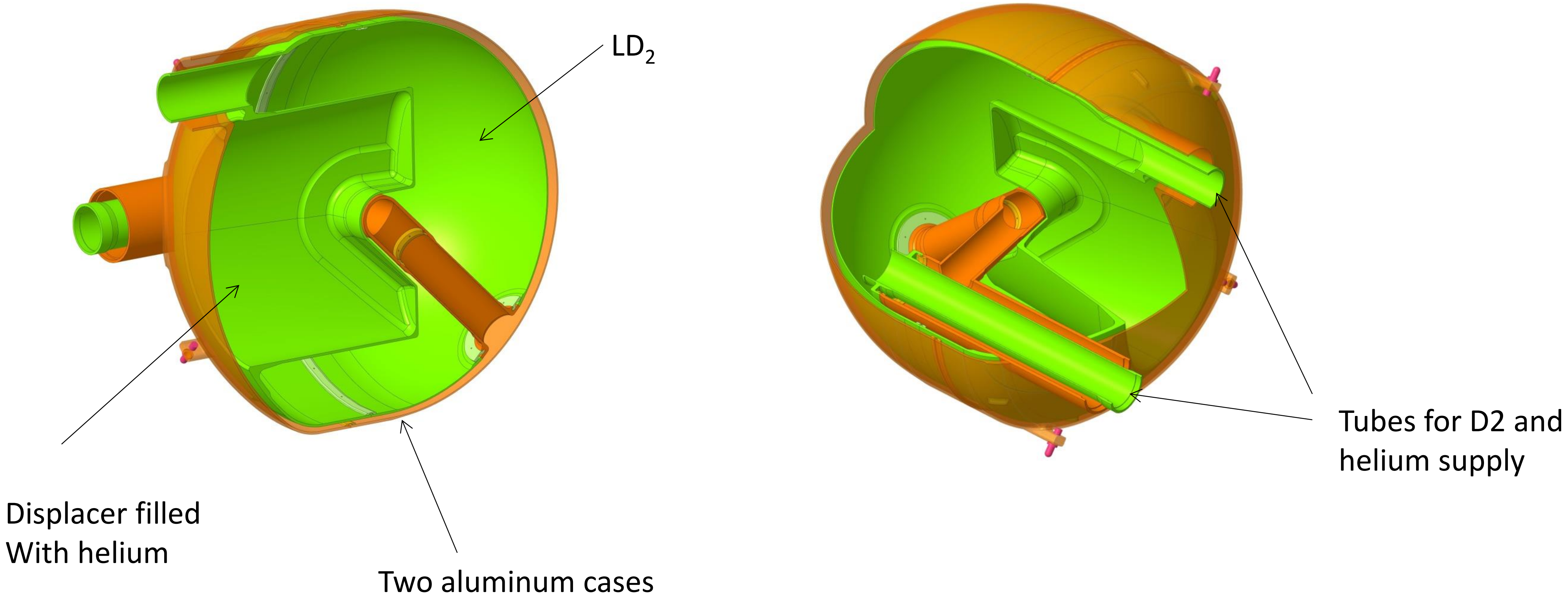
PNPI Cold neutron source 2
V = 14.8 l
Size - ø330 x 370
Channel of maximal
diameter – 380 mm



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



HEK-2 - CNS-2, LD_2 chamber. Project “Pribornaya basa”



Para-hydrogen for high-brilliant cold neutron sources

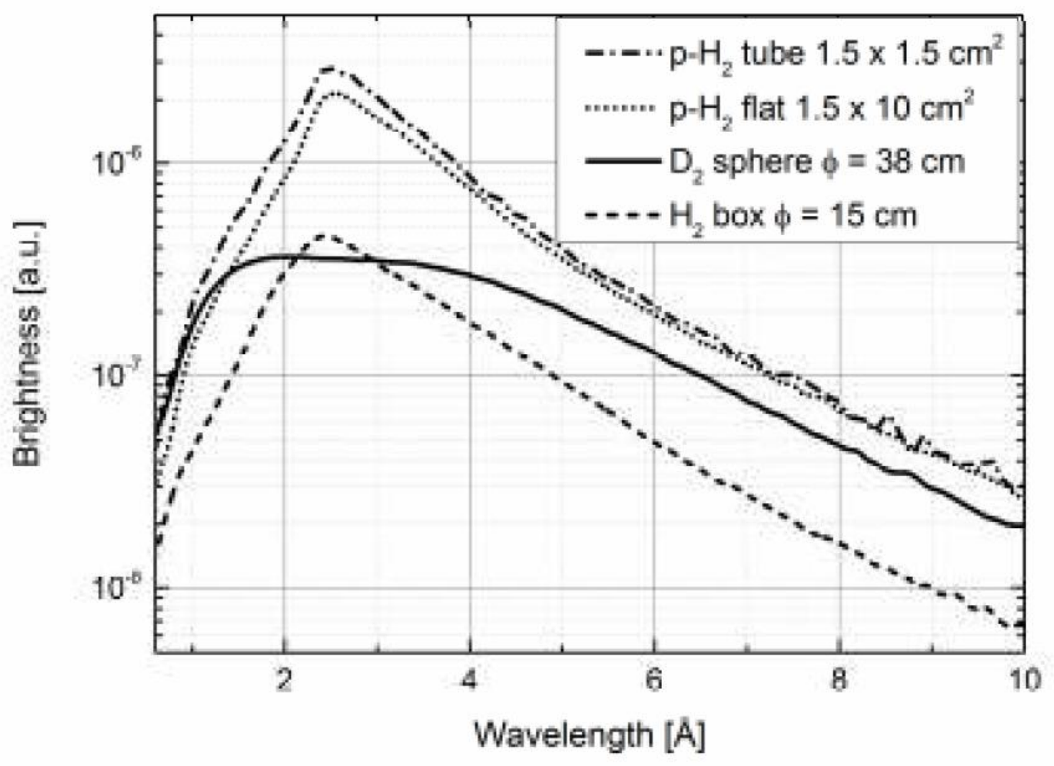
Low dimensional neutron moderators for enhanced source brightness

Ferenc Mezei[1,2], Luca Zanini[1], Alan Takibayev[1], Konstantin Batkov[1], Esben Klinkby[1,3], Eric Pitcher[1] and Troels Schönfeldt[1,3]

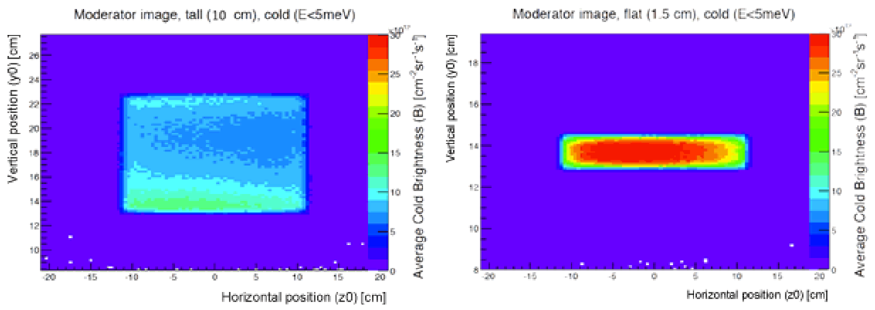
[1]European Spallation Source, ESS AB, PO BOX 176, 22100 Lund, Sweden
[2]Hungarian Academy of Sciences, Wigner RCF, 1525 Budapest, Pf. 49, Hungary
[3]DTU Nutech, Technical University of Denmark, DTU Risø Campus, 4000 Roskilde, Denmark

Corresponding Author: F. Mezei, European Spallation Source ESS AB, PO BOX 176, 22100 Lund, Sweden, e-mail: ferenc.mezei@esss.se, Tel:+46 72 179 2039

(2014). *J. Neutron Res*. 17, 101–105.

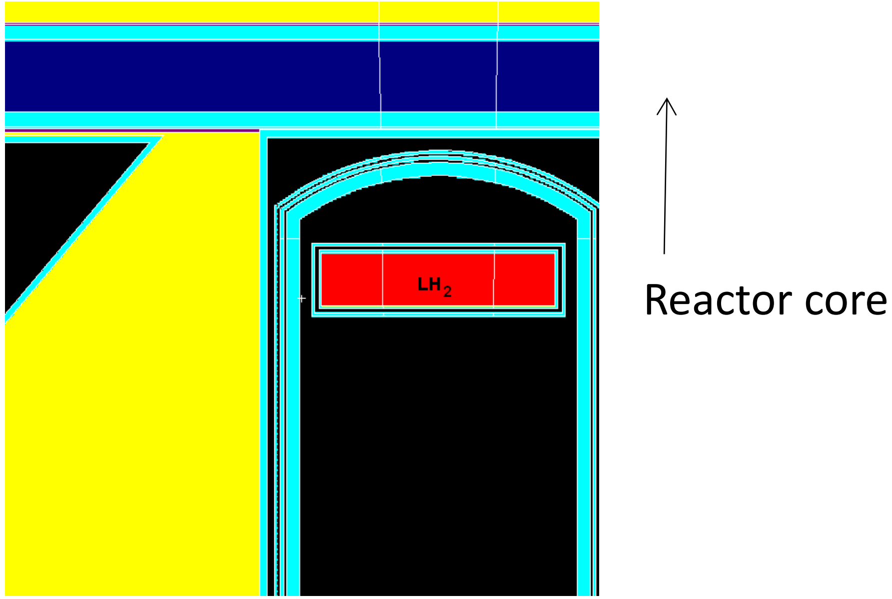


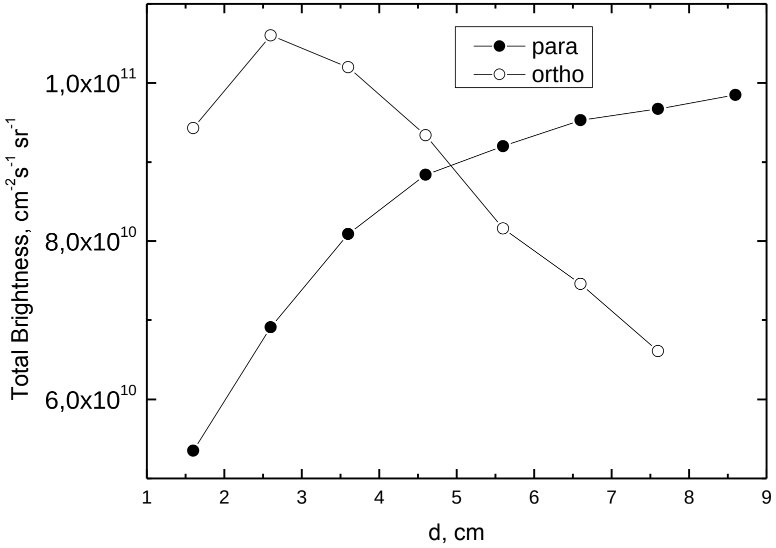
Para-hydrogen is more convenient for spallation sources
Low-dimensional Para-hydrogen CN source is plan to use on ESS.

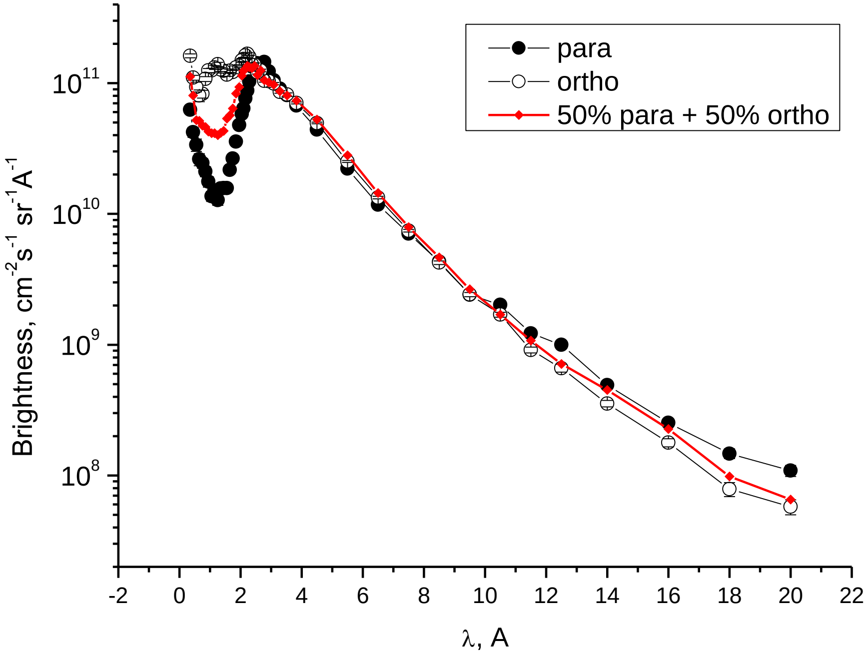


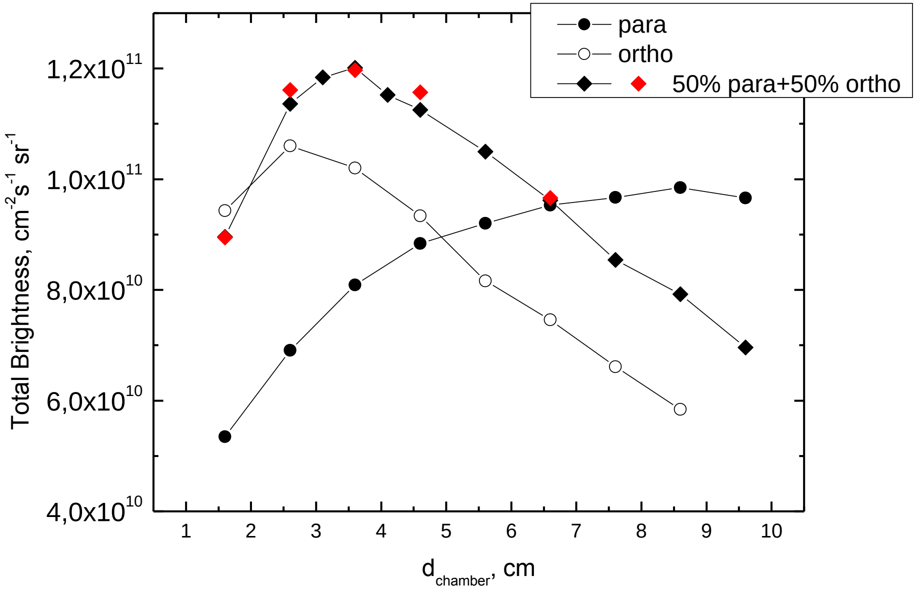
Computer simulation for J_PARC source

Liquid hydrogen chamber optimization for the reactor IR-8

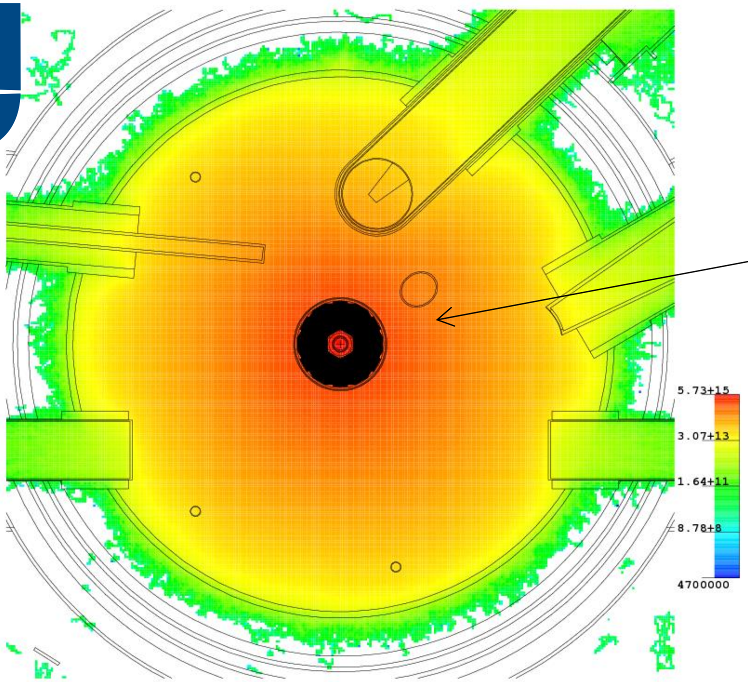






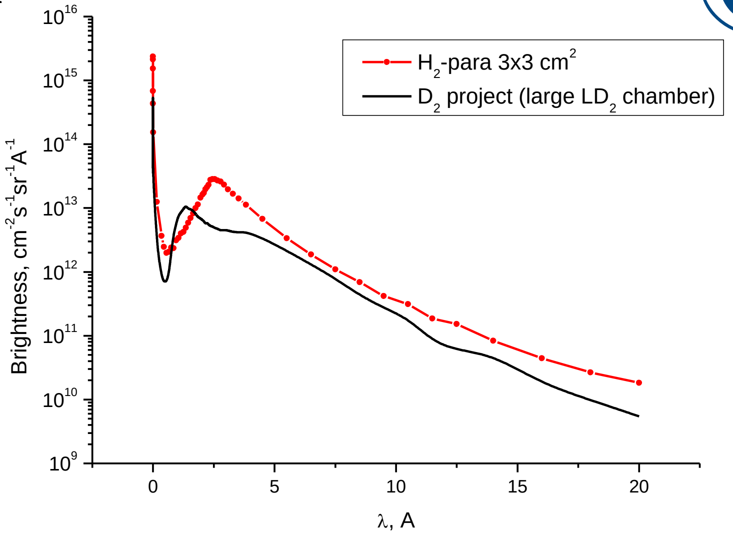


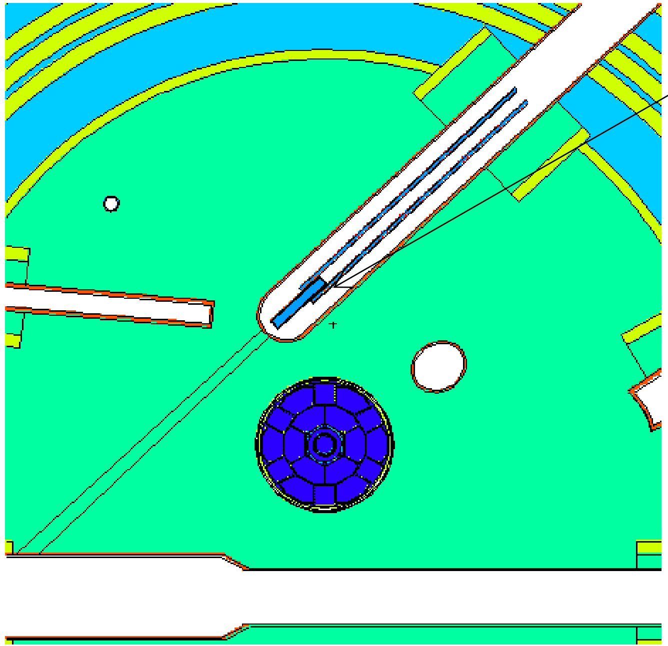
Comparison of para-hydrogen and Liquid deuterium sources



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

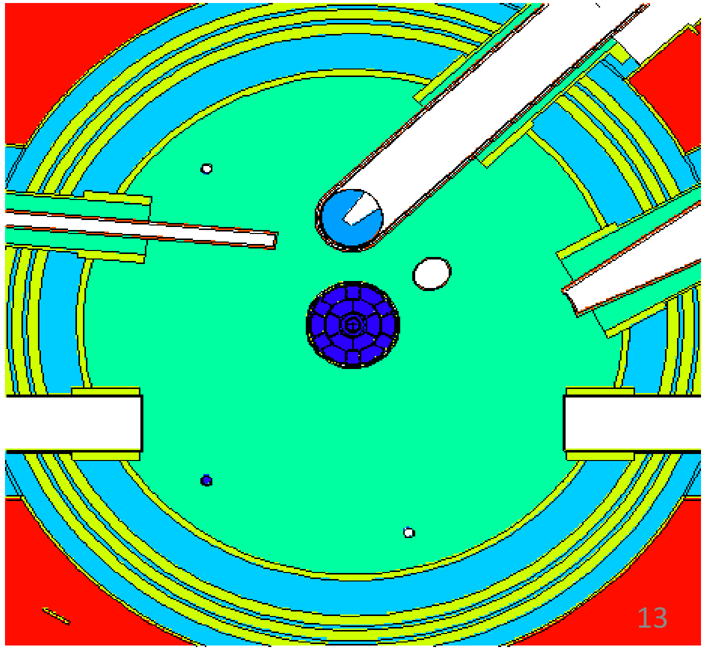
The problem of heat release



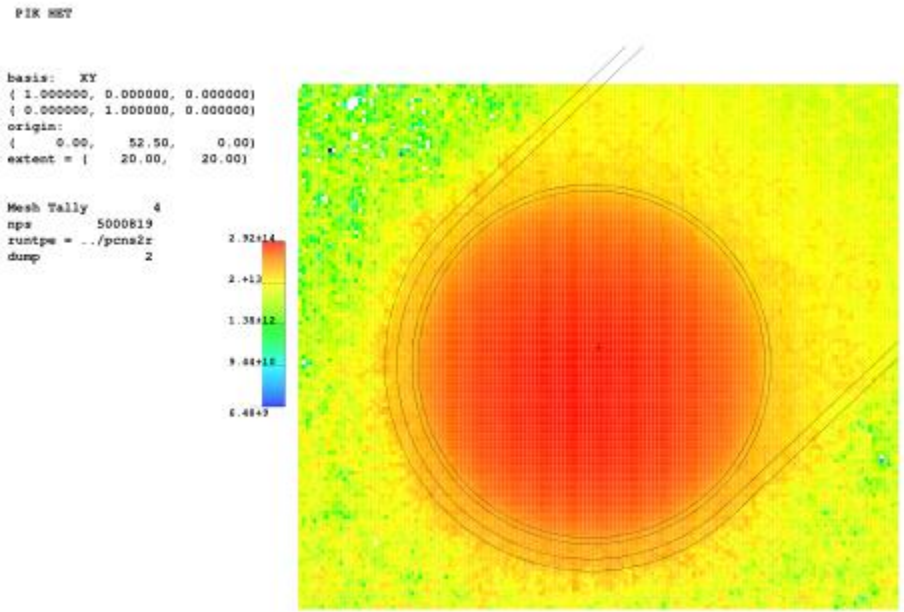


Para hydrogen source in HEC-2
F.Mezei, A.Ioffe, E.Vezhlev et al suggestion

Chamber size: 30x30x200 mm^3



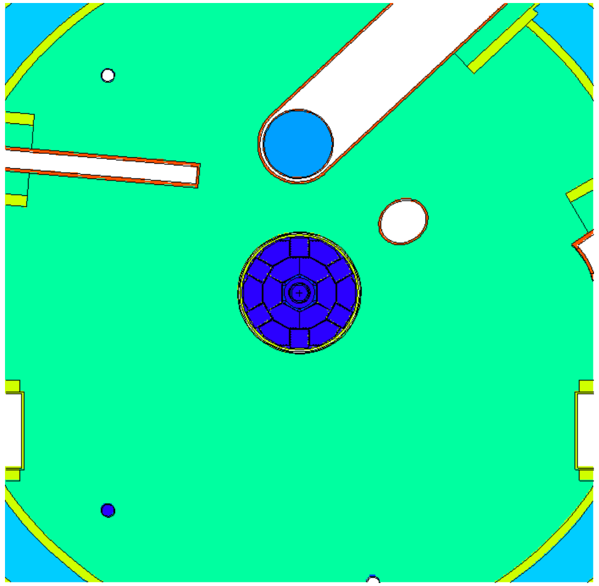
Flux field for cold neutrons. LD_2 chamber



R=11.6 cm

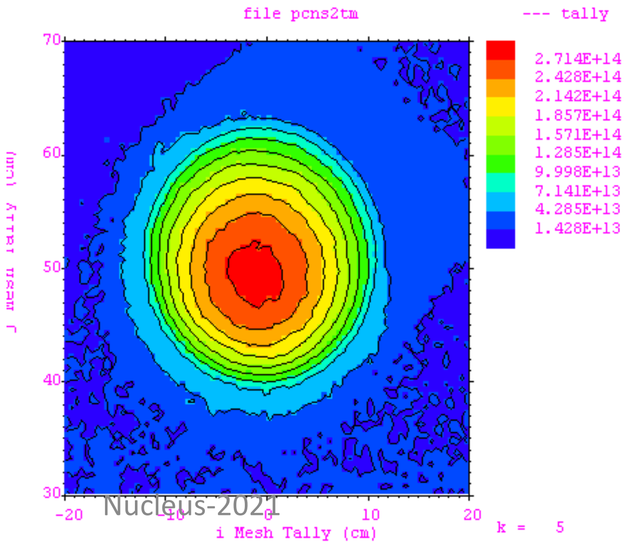
V=6.5 l

Distance to the core - 514 mm

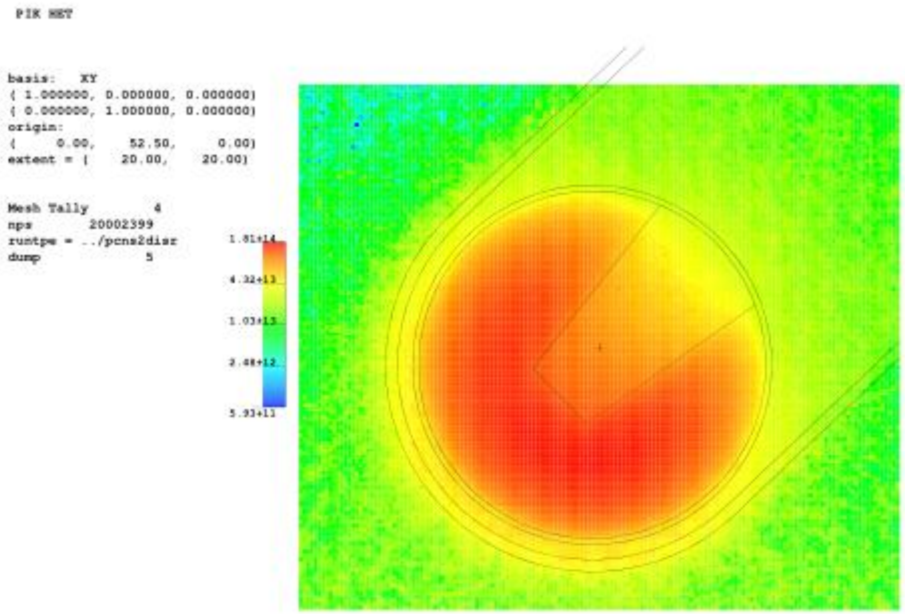


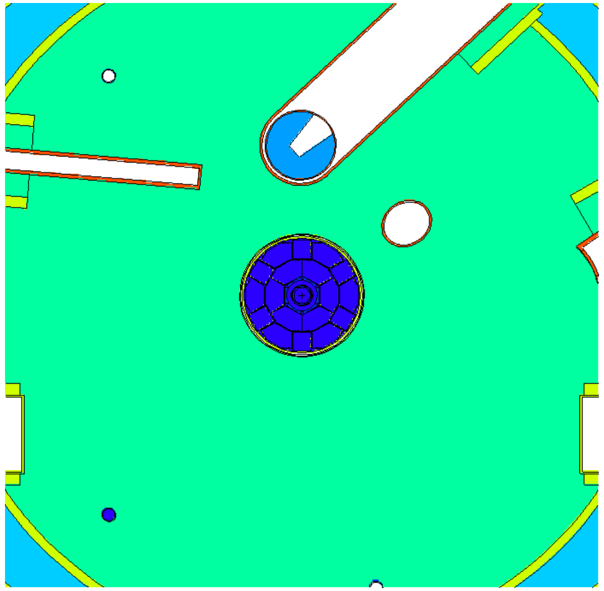
Cold neutrons λ > 4 Å.

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

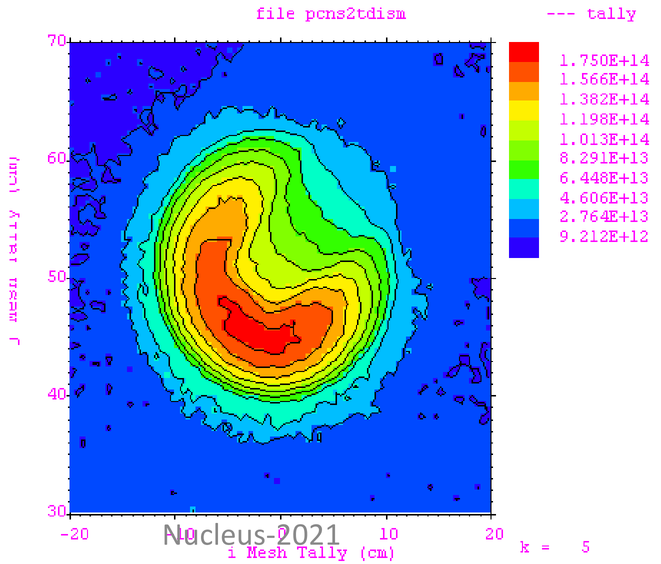


Using displacer for increasing the flux of cold neutrons released from the chamber into the channel





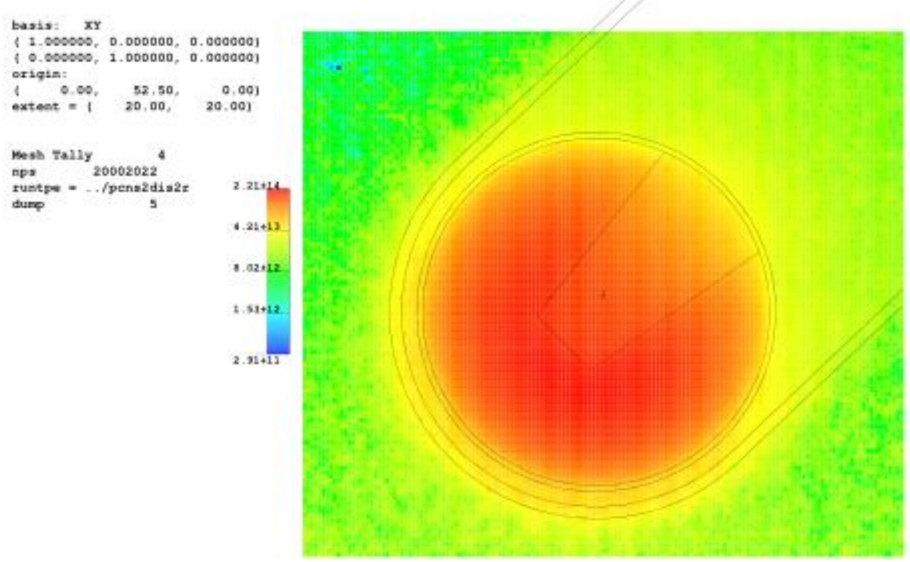
$\Phi_{cold\ max} = 1.81 \cdot 10^{14}\ cm^{-2}s^{-1}$

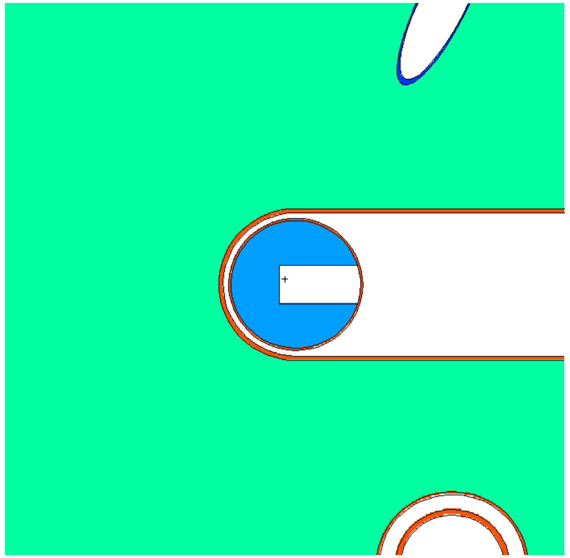


38% decrease comparing to chamber without displacer

Optimization of displacer form

Displacer bottom have square form 60 x 70 mm^2

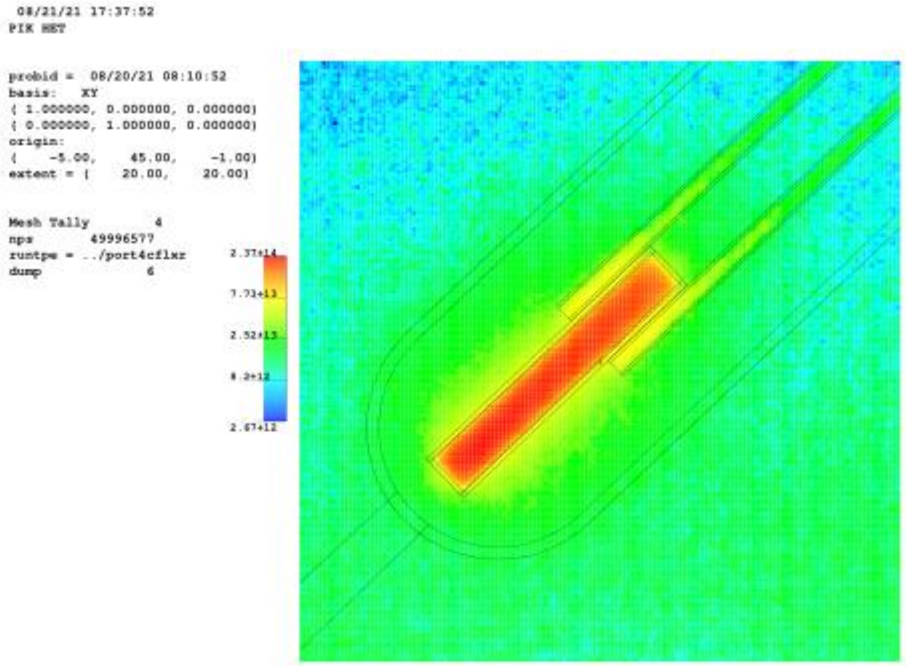


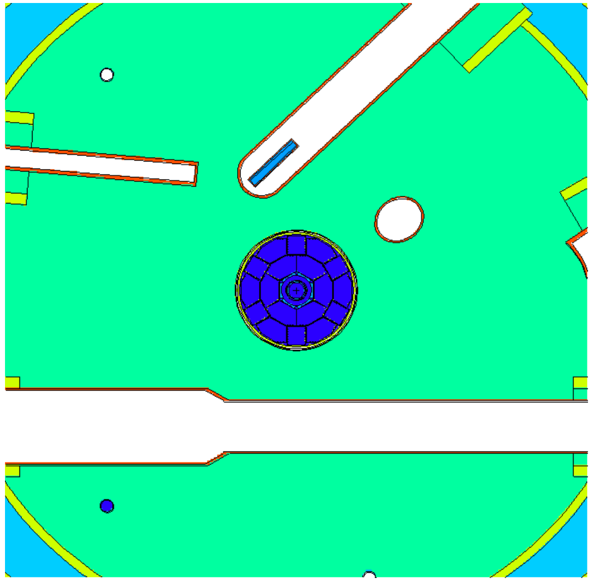


$\Phi_{cold\ max} = 2.21 \cdot 10^{14}\ cm^{-2}s^{-1}$

22% increasing

Ortho hydrogen

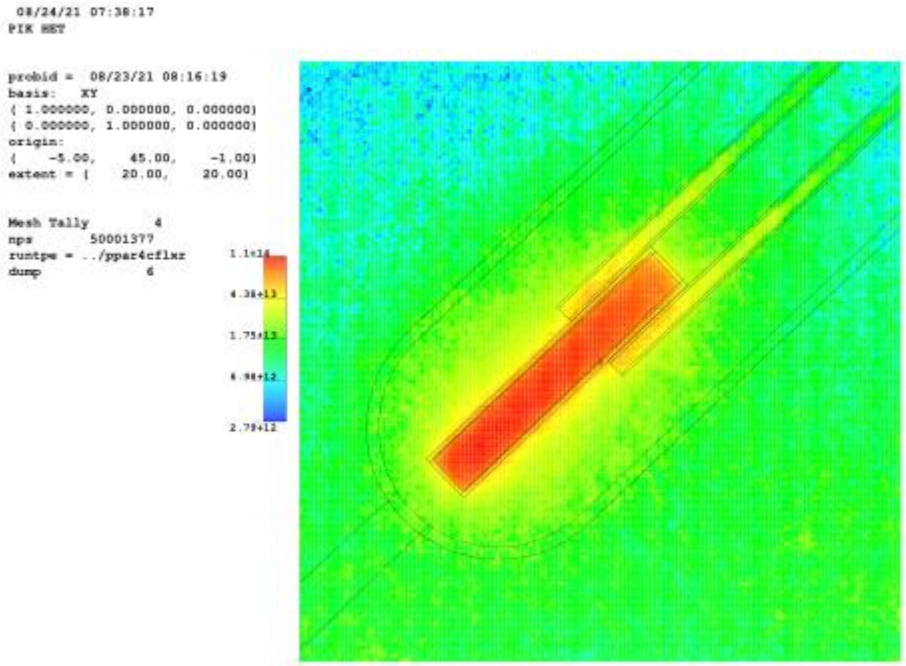




$\Phi_{cold\ max} = 2.37 \cdot 10^{14}\ cm^{-2}s^{-1}$

Due to small mean free path of cold neutrons in ortho- hydrogen this variant is not optimal

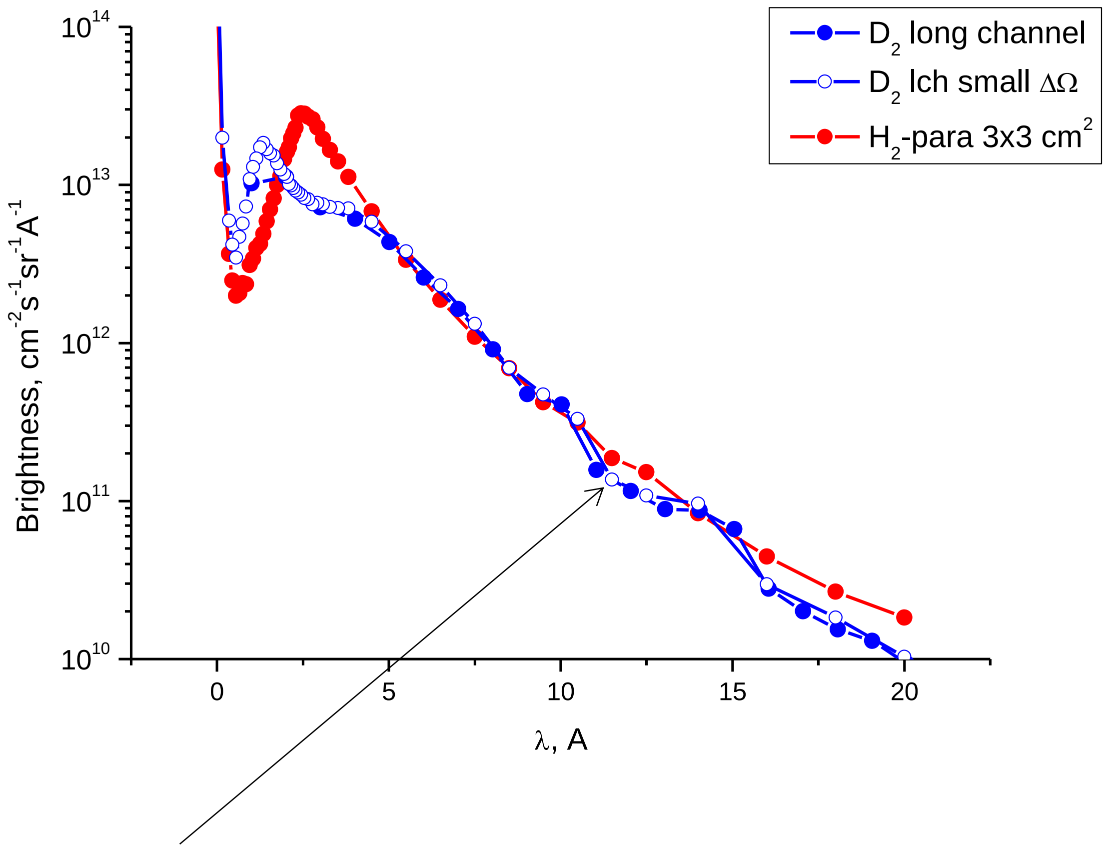
Para hydrogen



$\Phi_{cold\ max} = 1.1 \cdot 10^{14}\ cm^{-2}s^{-1}$

Large free path of cold neutrons in para hydrogen give the opportunity to collect all cold neutrons from the whole chamber length in the direction out of the reactor

Comparison of optimized para-hydrogen and liquid deuterium chambers



Variant	Integral Brightness λ > 4 Å $cm^{-2}\ s^{-1}\ sr^{-1}$
Basic (project)	$9.8 \cdot 10^{12}$
Para-hydrogen	$1.58 \cdot 10^{13}$
LD_2 – long channel	$1.55 \cdot 10^{13}$

Brightness for the LD_2 chamber with 200 mm height displacer

Conclusion and discussion

Para-hydrogen CNS and LD_2 CNS have comparable integral brightnesses of cold neutrons. At the same time there are different pro and contra for these two variants:

Para-hydrogen CNS

Pro

- Smaller heat release
- Small tritium production
- Easer to organize bi-spectral source

Contra

- Needed at least two chambers due to smaller shine surface
- Needings in operational control of the ortho-hydrogen content in the hydrogen contour
- Needings in catalytic conversion of ortho- to para- hydrogen during the CNS operation

Deuterium CNS

Pro

- Large shine surface
- Absence of additional systems
- Considerable background in creation

Contra

- Larger heat release
- Considerable tritium production
- It is more complicated to build bi-spectral source

Thank you for the attention!