CREMLIN PLUS

Connecting Russian and European Measures for Large-scale Research Infrastructures

HighNess

Progress Towards very Cold Neutron Sources

L. Zanini

Moderators and Neutron Optics SC of WP3 (CREMLINplus)

Based on contributions from HighNESS/CREMLINplus project members

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072.

Are times mature to develope a VCN source?

- There are recent progresses in Europe that indicate real possibilities for a VCN source, with respect to previous workshops at ORNL (2005/2016):
- Novel materials are proposed as possible candidates for VCN production (converters from CN to VCN)
- Advanced reflectors for VCN, i.e. nanodiamonds, to transport and reflector long wavelenght neutrons, have been extensively studied.
- Development of numerical tools (thermal scattering librairies to simulate VCN moderators and reflectors, including materials for which improved cross sections are needed, such as solid D2)
- EU-funded CREMLINplus and HighNESS projects include the study of VCN source including prototype experiments, and design for existing facilities (ESS, JINR, PIK?)

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VCN neutrons are roughly defined in the range 20-100Å

	λ (nm)	T_n (K)
thermal	0.18	300
cold	0.5	30-100
very cold	> 1.5	< 4
ultra cold	> 50	"0.002"

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Very cold neutrons are useful for everyone:

(O. Zimmer, ENS2019 workshop)

Neutron scattering community:

For pulsed VCN sources, the following gains can be assumed for resolution and intensity:

	resolution at fixed geometry	Intensity at fixed resolution
SANS	λ^{-1}	λ^{0}
Reflectometry	λ^{-1}	λ^{2}
TOF-INS	λ^{-3}	λ^{2}
NSE	λ^{-3}	λ^{2}-λ^{4}

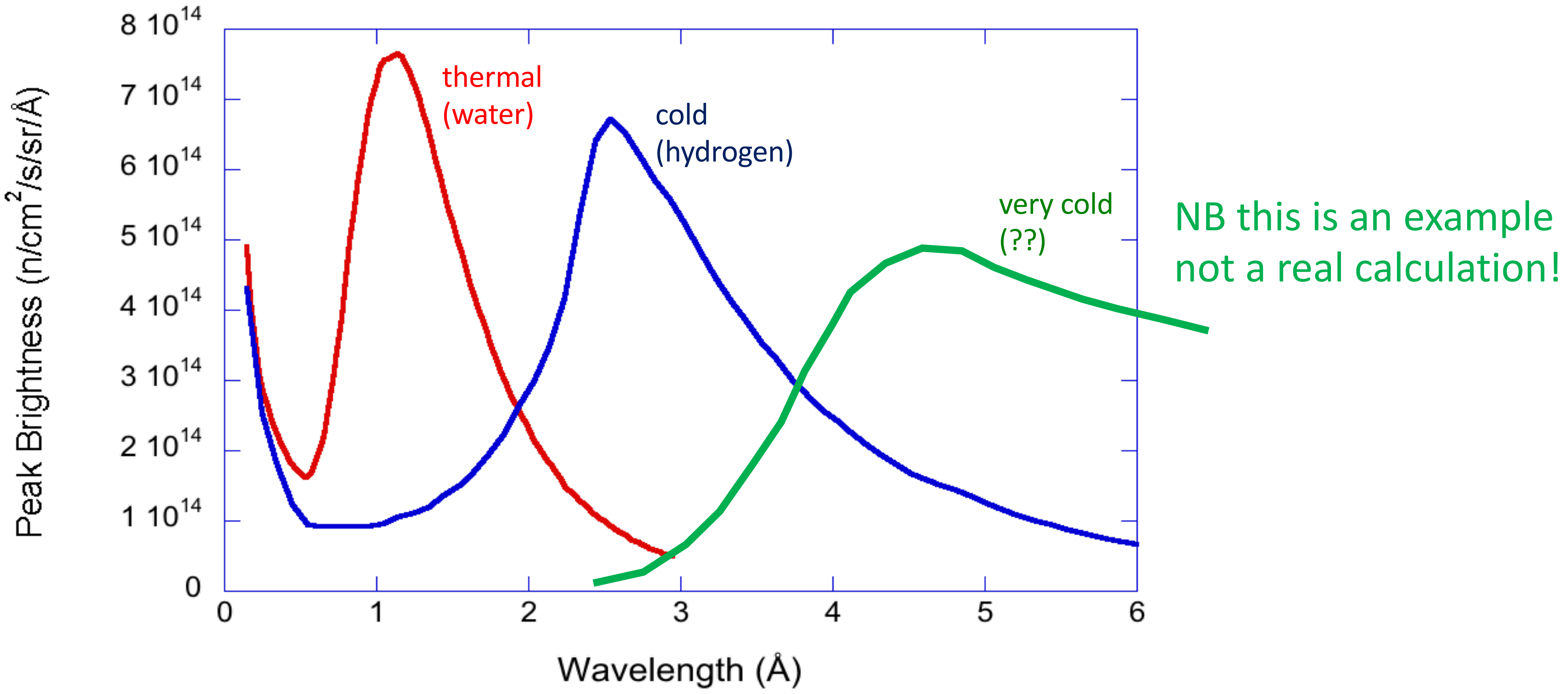
From proceedings of workshop on application of a VCN source at Argonne, 2005

Particle physics community:

Counting statistics improvements e.g. for

- neutron-antineutron oscillation experiment
- beam neutron EDM experiments

This project has r
research and inn



For increase of VCN there are two possibilities:

1. Enhancement of the cold tail of the LD2 via quasi-specular reflection from nanodiamonds or other reflectors
2. Development of a dedicated VCN moderator material

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Task 3.3 in CREMLINplus: development of a VCN source

Project time scale: February 2020-January 2024.

GOALS

- Study of converter (cold-> VCN) materials
- Coupling of VCN converter with nanodiamond reflectors to improve VCN yields
- Design and prototype experiment of a VCN source

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Task 3.3 in CREMLINplus

Task 3.3: Development of advanced Very Cold Neutron Source (ILL, NRC KI-PNPI, JINR, PTI, UCA, UNIMIB, ESS) M1-M48

Plan, technical developments ongoing

- S(q.w) and transmission measurements for new converter material
- VCN production calculations for various converters (solid deuterium, liquids hydrogen,…)
- Investigation of nanodiamond podwers
- Choice of technology of manufacture of nanodiamond powders
- Conceptual design of nanodiamond reflector to be employed in VCN source prototype
- Manufacture of reflector components
- Cryostat design and manufacturing
- Development of VCN selector
- Experiment
- Calculations of various configurations of VCN sources for real neutron sources (ESS, PIK,…)

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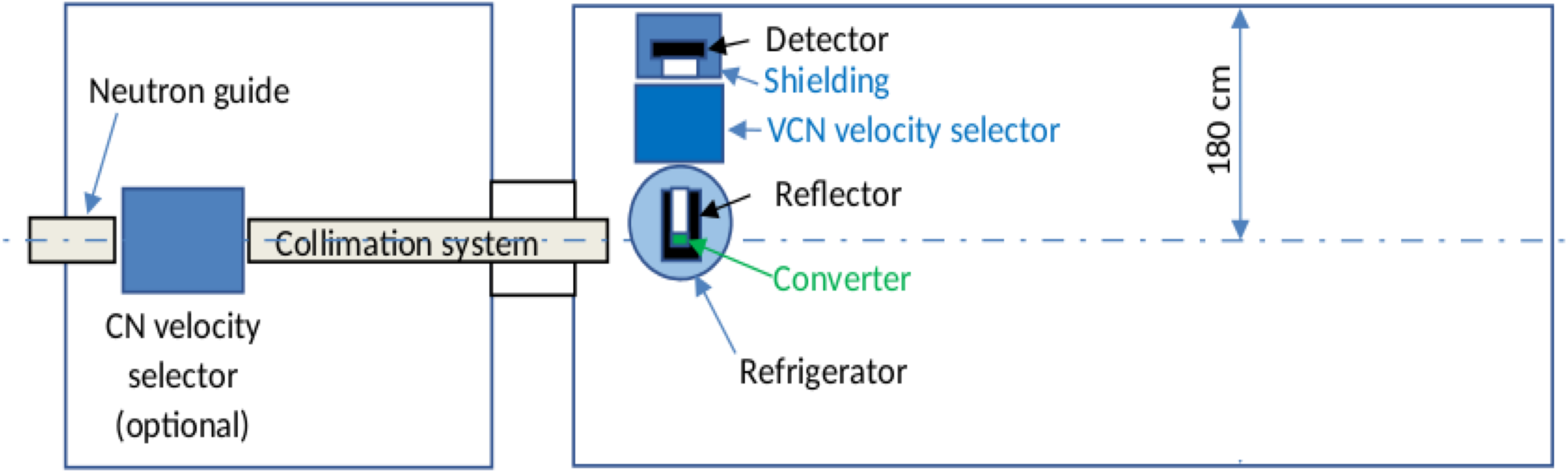
Schematic figure of CREMLIN experiment



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VCN yields, materials under study

GOALS
- Determine yields of VCN from candidate converter materials, including the effects of ND reflectors
- Determine best converter material for prototype experiment to be performed at PF1B/ILL

	Material	Temperature	Density (g/cm³)
converter	Solid deuterium	5 K	0.2059
converter	Liquid parahydrogen	14 K	0.071
converter	Liquid orthohydrogen	14 K	0.071
converter	Solid methane	22 K	0.5
reflector	Magnesium-hydride	20 K	0.5 (bulk density)
reflector	Nanodiamond	296 K	0.6 (bulk density)

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Modeling of nanodiamonds in MCNP

- A simple model for SANS as described by Granada [Granada, J. Rolando, J. Ignacio Márquez Damián, and Christian Helman. ”Studies on reflector materials for cold neutrons.” EPJ Web of Conferences, 231, 04002 (2020)]:
  - Bragg scattering and inelastic scattering are modeled using an ACE file produced with NJOY-Ncrystal
  - SANS is modeled with a piecewise power function that approximates the S(Q) measured by Teshigawara [Teshigawara, M., Y. et al. ”Measurement of neutron scattering cross section of nano-diamond with particle diameter of approximately 5 nm in energy range of 0.2 meV to 100 meV.” Nucl. Instr. and Meth. A, 929, 113 (2019)]

- The parameters for this function are stored in the ACE file, and a modified version of the Monte Carlo code reads these parameters and sample the outgoing direction.

- The modification was implemented in MCNP 6.2, PHITS 3.21 and OpenMC.

[J. I. Márquez Damián et al., Nuclear Data Development at the ESS, UCANS-web 2020]

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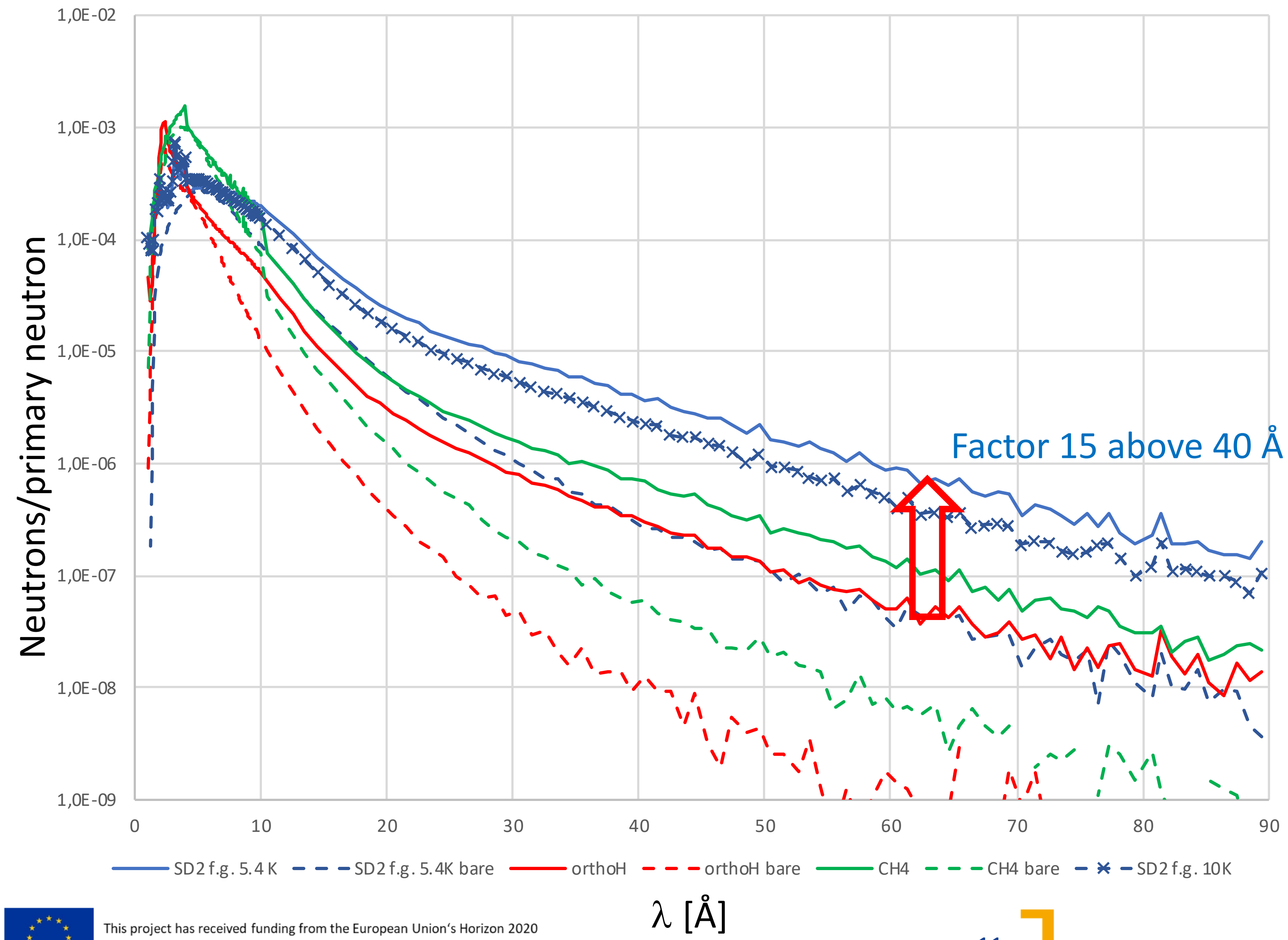
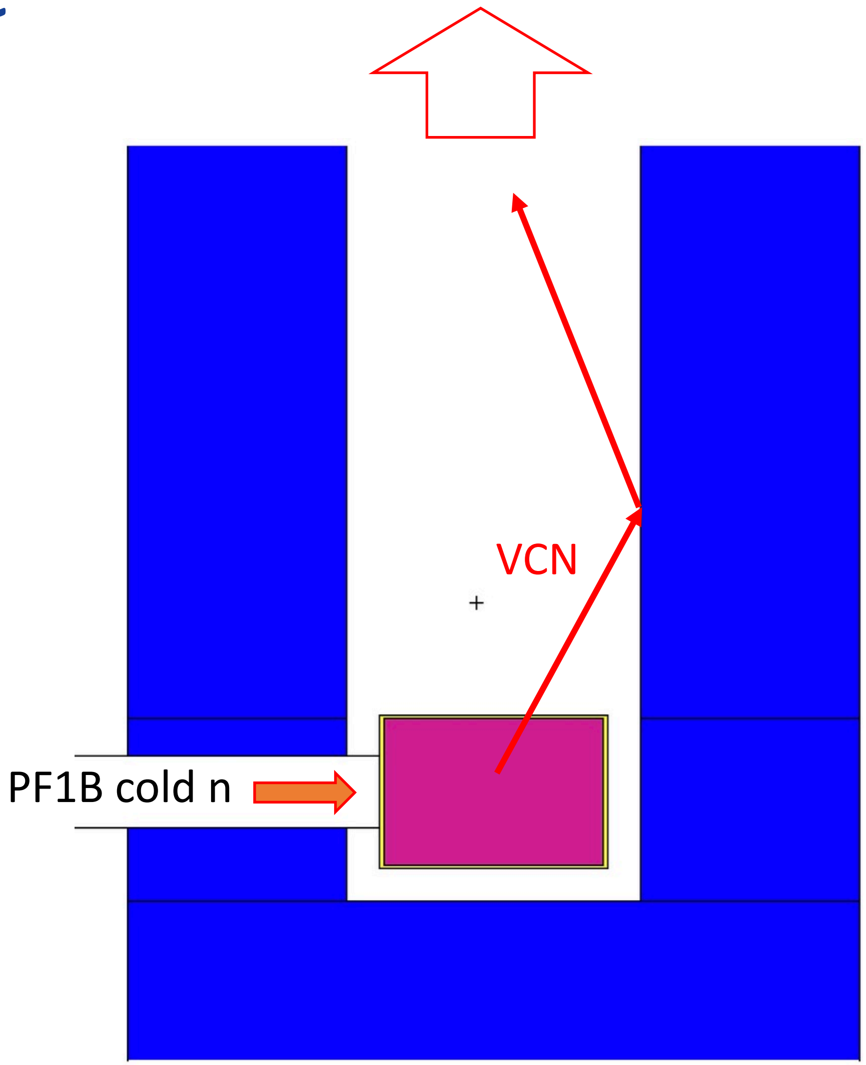
Effect of ND reflector on flux increase





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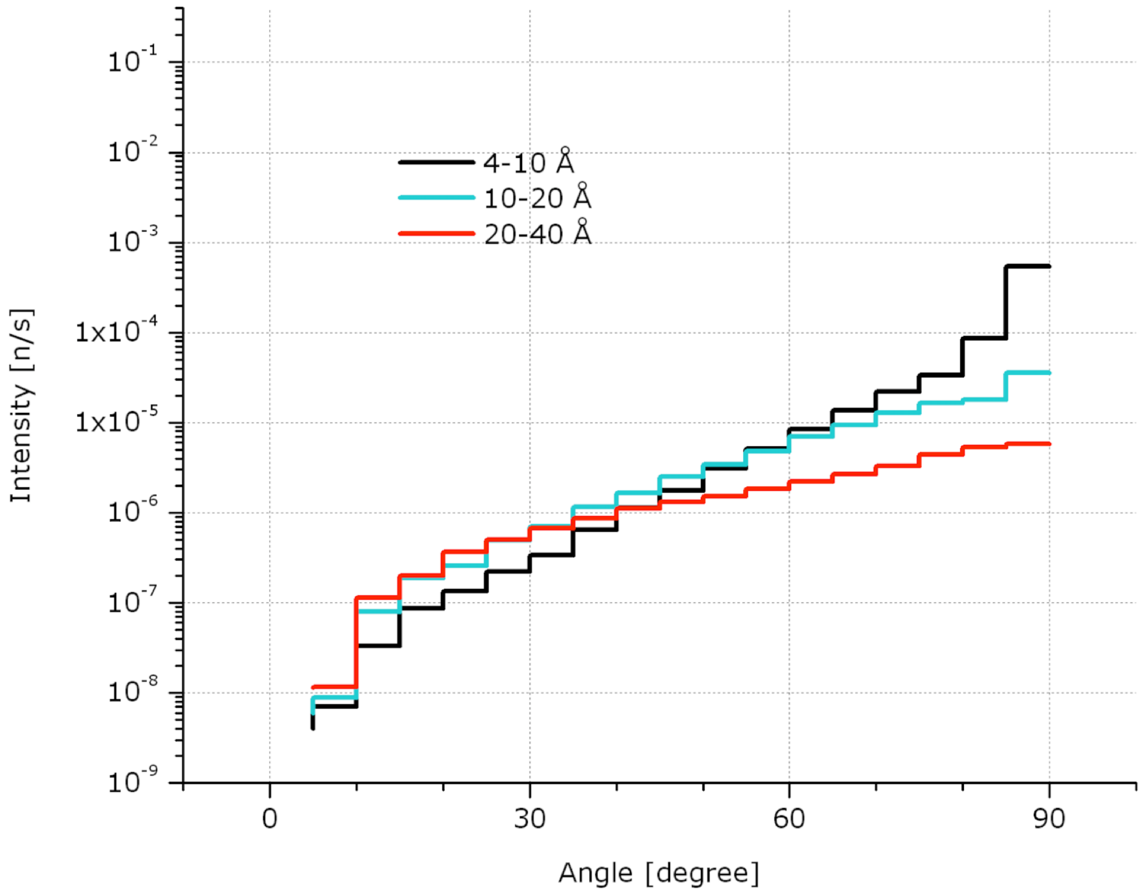
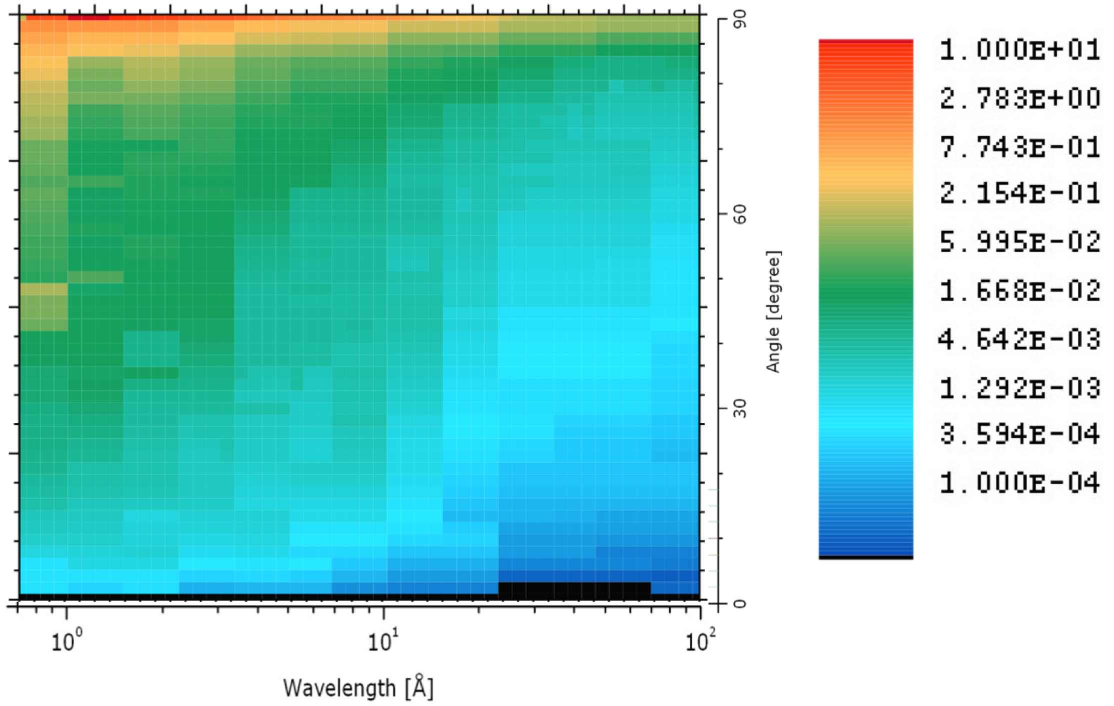
Angular histogram (orthodeuterium converter and nanodiamond reflector)

Simulation with existing SD2 cross section used and generic ILL cold spectrum





The colder neutrons are less collimated as expected

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Status on VCN yields

- With nanodiamond around the converter and nanodiamond tube, we can reach >10 times increase in intensity comparing with the bare case
- The effect is larger for smaller converters (about 3 cm diameter), even though larger converters deliver more VCNs

NEXT STEPS

- For more reliable results, especially above 40 Å, **we have identified the need for improved solid deuterium cross sections**
- Simulations with different ND types will be added in the course of the project
- Neutron spectra and count rates of the prototype experiment will be calculated

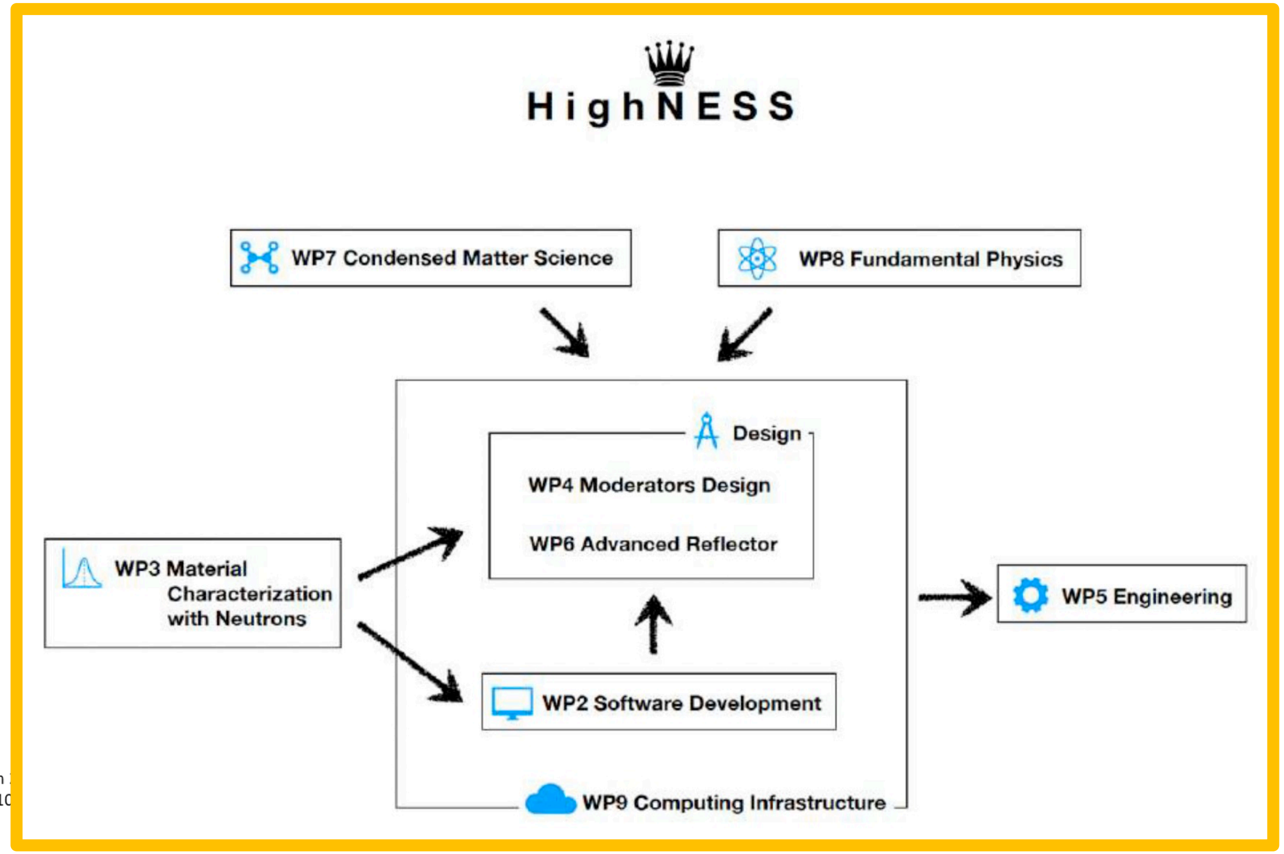
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072.

The HighNESS project at ESS, started October 2020

The HighNESS project (3 MEURO funded by the European Commission) has as purpose the development of the new source that will be installed at ESS >2030
The new source will be composed by Liquid deuterium moderator that will serve a UCN moderator and a VCN source using advanced reflectors.
Conceptual Design Report expected by the end of 2023

Project time scale: October 2021-September 2023.

8 EU Institutes,
7 countries,
34 people presently involved



This project has received funding from the European Union's Horizon
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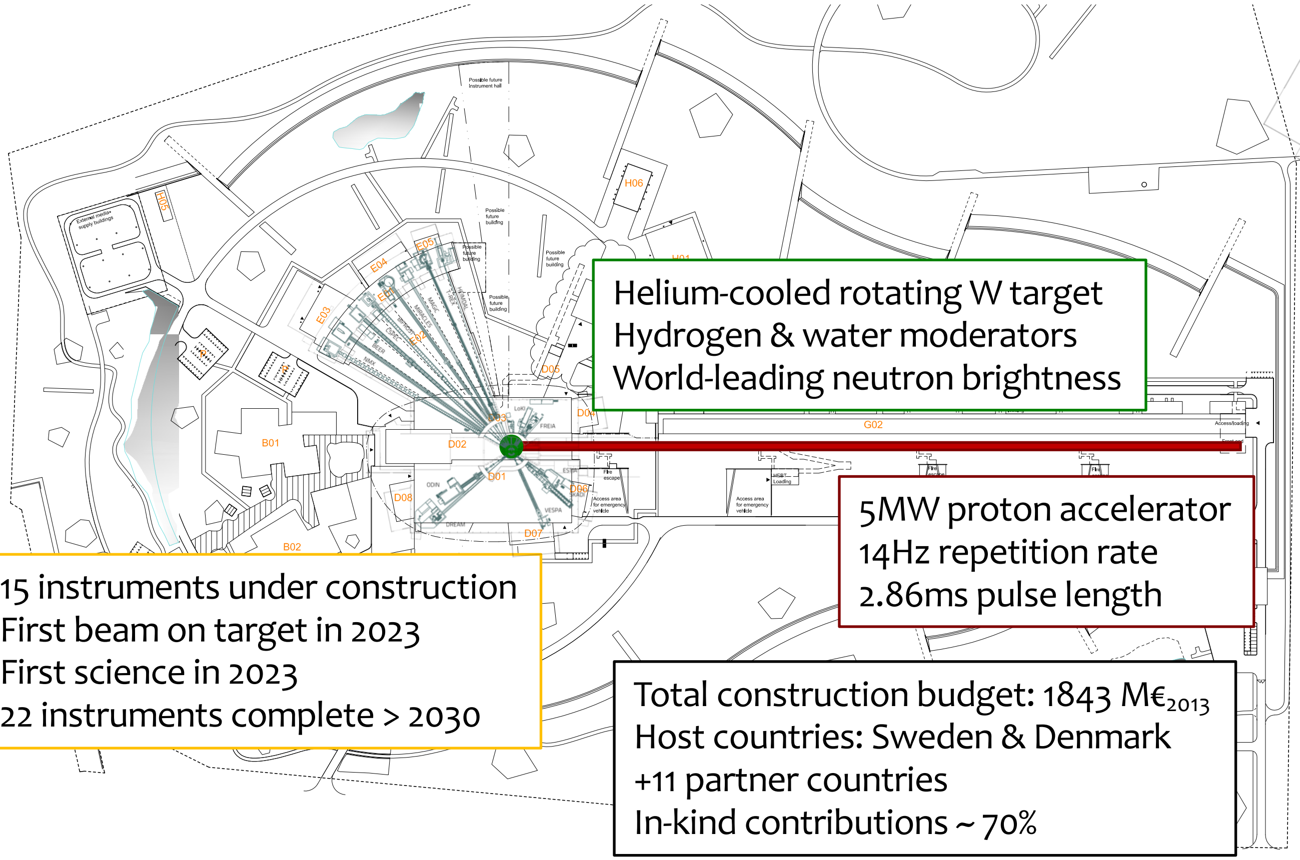
HighNess

The European Spallation Source

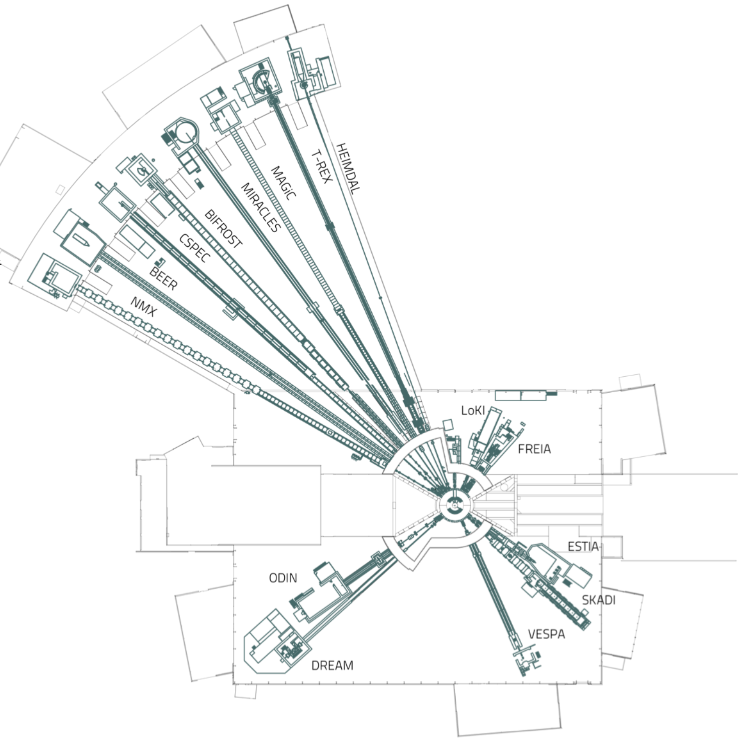


Helium-cooled rotating W target
Hydrogen & water moderators
World-leading neutron brightness

5MW proton accelerator
14Hz repetition rate
2.86ms pulse length

15 instruments under construction
First beam on target in 2023
First science in 2023
22 instruments complete > 2030

Total construction budget: 1843 M€$_{2013}$
Host countries: Sweden & Denmark
+11 partner countries
In-kind contributions ~ 70%



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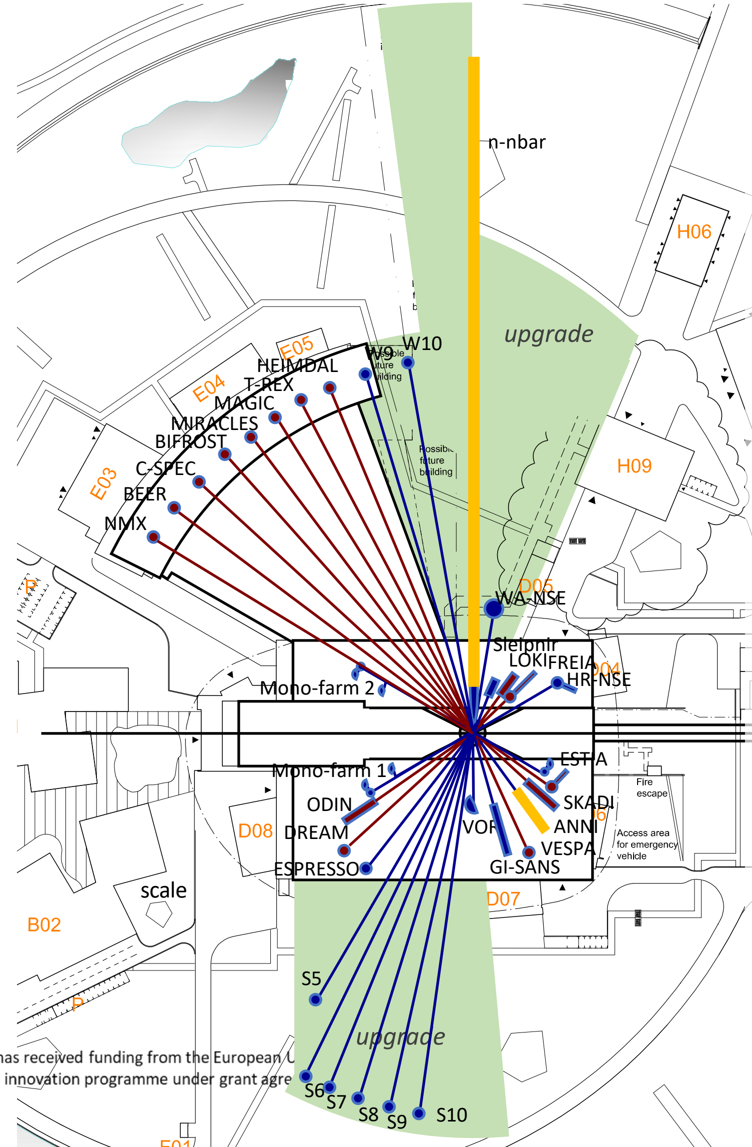
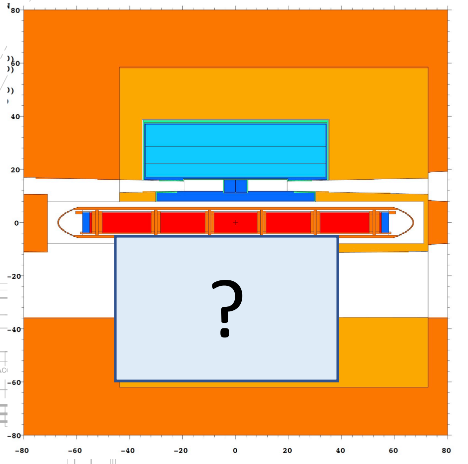
HighNESS will designs the lower moderator for the ESS upgrade



- Primary upgrade path: more instruments
- 42 beamports with ~6° separation
- Upgrade areas
- ~80% beamport use
  - 60% for short instruments
  - 100% for long instruments
- >1 instrument on some beamports?
  - Monochromator instruments?
- 35-40 instruments possible
- Lower moderator not yet defined
  - All initial instruments view upper moderator
  - But all beamports can view both moderators



This project has received funding from the European U
research and innovation programme under grant agre

HighNess

Three sources: CN, VCN,UCN will be designed for ESS

Main source

UCN

VCN

Description of work

Task 4.1 Definition of Figures of Merit.
Figures of merit will be defined for the following moderator sources: cold neutrons from the D2 moderator; Very cold neutrons from the D2 moderator. Cold neutron flux to feed the UCN converter. The figure of merit will be defined following iterative work with WPs 6-8. **ESS,** DTU, ILL (M1-12)

Task 4.2. Neutronic study of the D2 moderator.
The D2 moderator placed right below the target is the core of the HighNESS moderator system. The neutronic optimization will study the shape, dimensions, and location of the moderator. Heat load will be calculated. In iteration with WP5 the moderator will be designed. **ESS,** DTU, Mirrotron (M1-18)

Task 4.3. Neutronic study of in-beam UCN.
The neutronic design of a UCN converter placed at the monolith exit will be performed. Study will include the geometry of the D2 moderator previously defined as an outcome of Task 4.2. It will also include transport of cold neutrons from the D2 surface to the UCN converter via nanodiamonds and other reflector materials studied in WP3. **ESS**, ILL (M13-30)

Task 4.4. Neutronic study of in-pile UCN.
In parallel with Task 4.3, the study of a UCN source placed inside the ESS monolith, at a certain distance from the D2 moderator, will be performed. The neutronic design will be performed in iteration with WP5, concerning the engineering requirements particular the cooling of the system), and with WP8, concerning the design of the moderator and the extraction of the ultra-cold neutrons. **ESS**, ILL (M13-30)

Task 4.5. Neutronic design of a VCN source. Task done in conjunction with WP5 and WP6. It consists of an iterative work where the D2 is coupled with advanced reflectors studied in WP6 to provide an enhancement of the long wavelength tail of the D2 moderators. **ESS**, DTU, ILL, Mirrotron (M13-34)

Task 4.6. Neutronic design of conceptual VCN source. Based on the studies performed in WP2, WP3 and WP6, a conceptual design of a dedicated VCN source will be performed. **ESS**, DTU, ILL, Mirrotron (M19-34)

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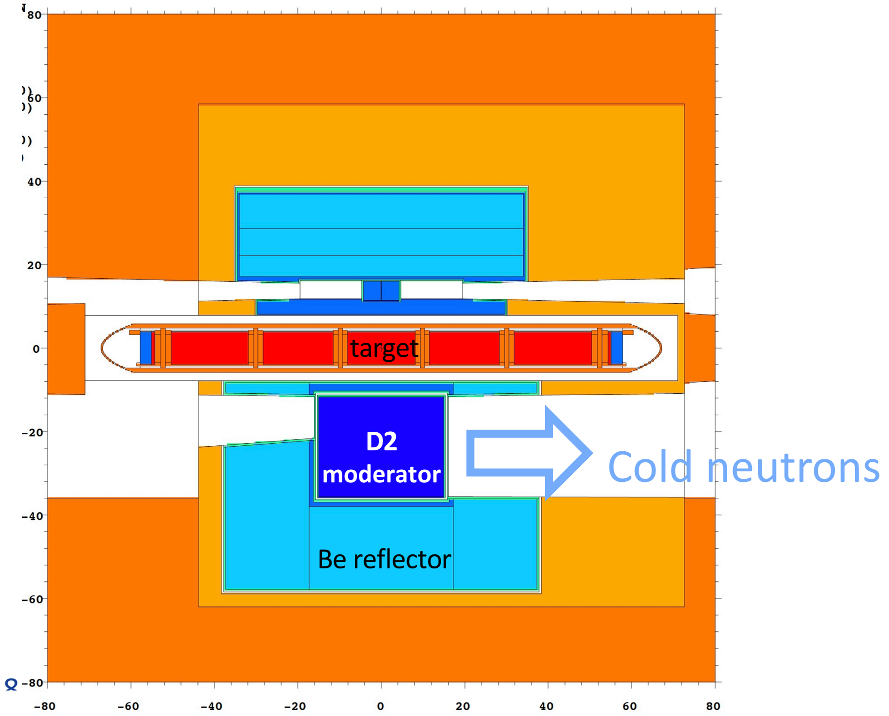
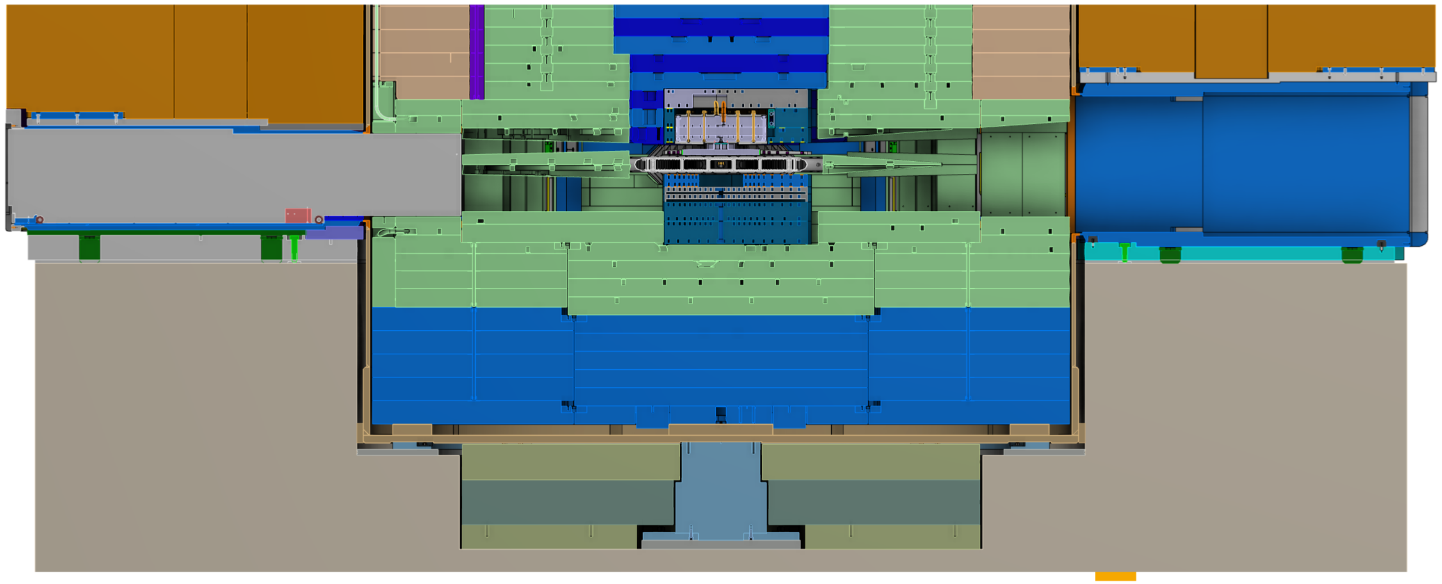
MCNP model of the cold moderator

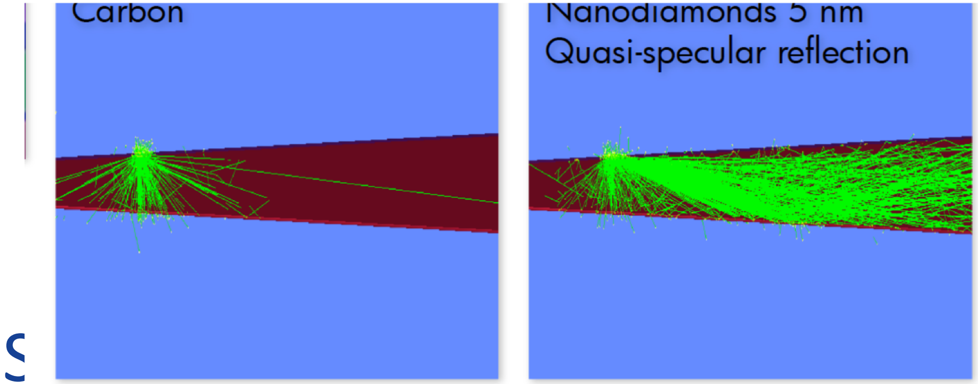
Source (Moderator):

It determines the number of cold neutrons emitted by the source



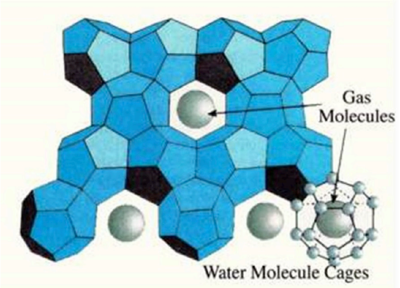


VCN options in HighNESS



(M. Jamalipour)

- Two options are considered for a VCN in HighNESS
- first option, including engineering: use of advanced reflector (most likely nanodiamonds) to reflect the colder tail of the large LD2 moderator.
  - Experiment on prototype experiment of advanced reflector in program at Budapest Research Center.
- Use of material for VCN production (no eng.)
  - Novel material candidate: deuterated clathrate hydrates
  - Additional options: solid deuterium



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New converter material: deuterated clathrate hydrates

- O. Zimmer, Phys. Rev. C **93**, 035503 (2016)
- Proposed for VCN moderation
- Use of particle spins for cooling
- Paramagnetic at liquid-He temperatures
- Measurement of S(q,omega) for various clathrates within HighNESS

Solid oxygen is antiferromagnetic at low T (dispersion and dangerous)

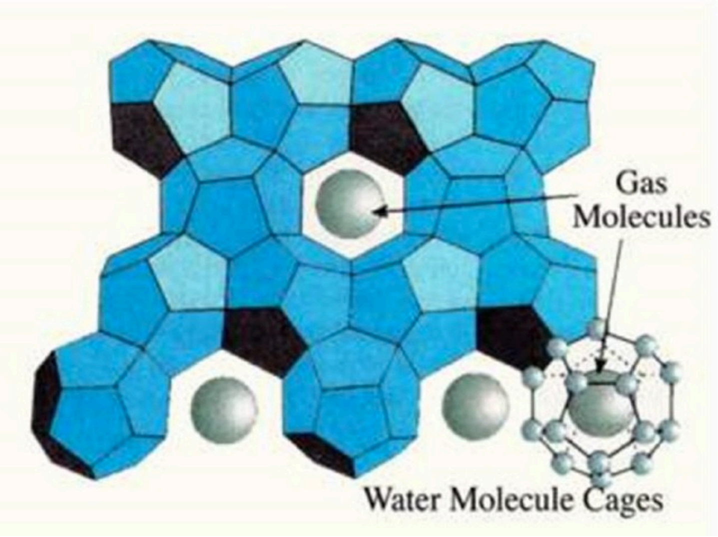
O_2 hydrate clathrate:

O_2 density $\approx 4.2 \times 10^{21}$/ccm (90 % cage filling)

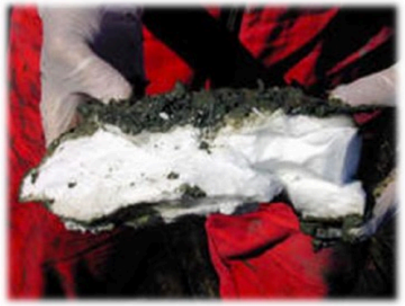
$\rightarrow$ stays paramagnetic at liquid-He temperatures

$\rightarrow$ metastable (not explosive)

$\rightarrow$ neutron survival > 0.1 s if fully deuterated



Methane hydrate clathrate



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Advanced reflectors of interest

- **Nanodiamonds** are suitable for use as a quasi-specular reflector for cold and very cold neutrons (CNs and VCNs) and are expected to be an asset for a beam extraction channel at the exit of the moderator. Used as a reflector material around the LD2 moderator or around a separate VCN source, they are expected to enhance the yield of VCNs.
- **Graphite intercalation compounds** and **MgH2** both show great promise as potential CN and VCN reflector materials. They are potentially useable for enhancing the VCN brightness of moderators.
- **clathrate hydrides** could also be used for reflection of cold and very cold neutrons .

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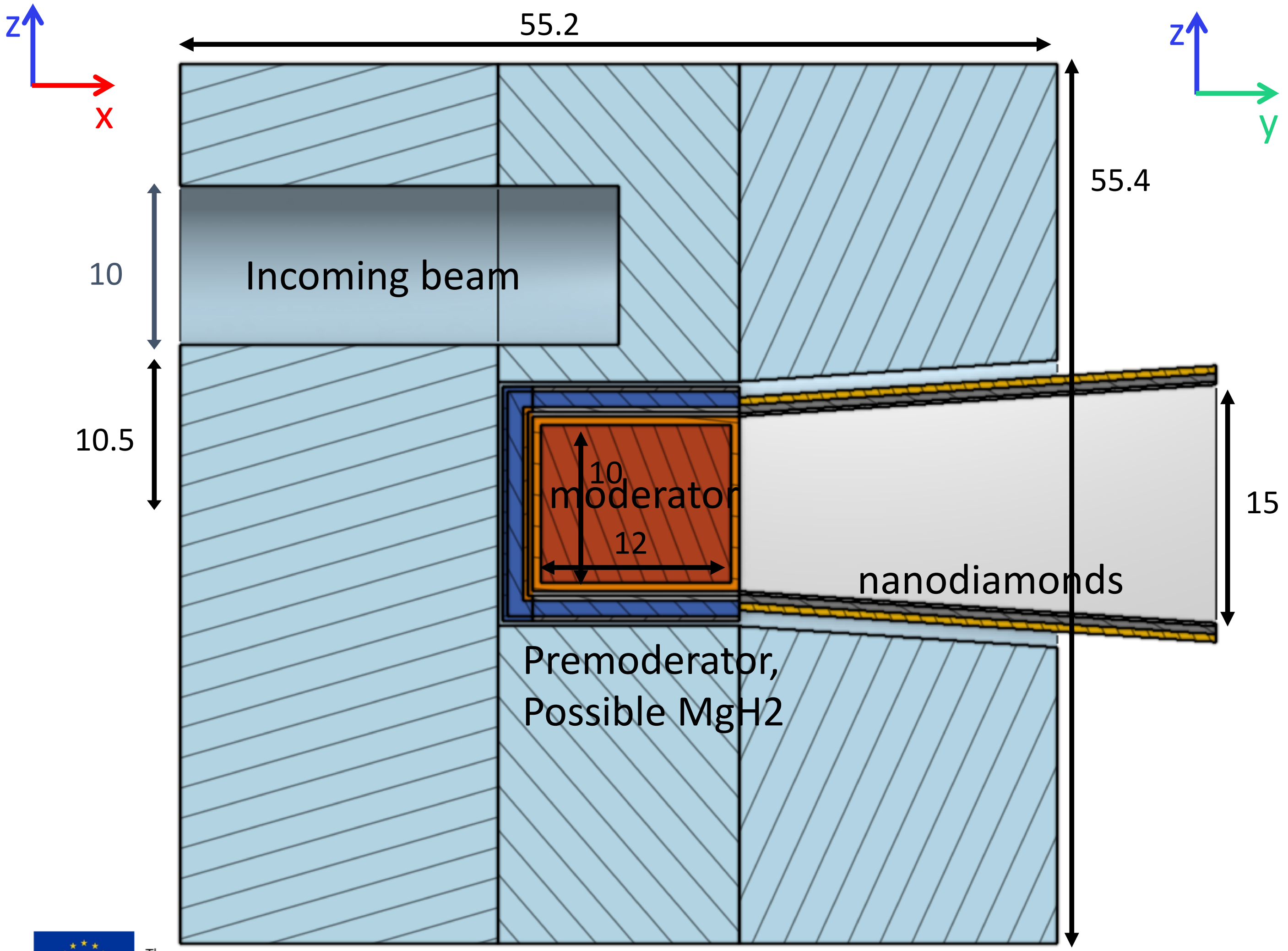
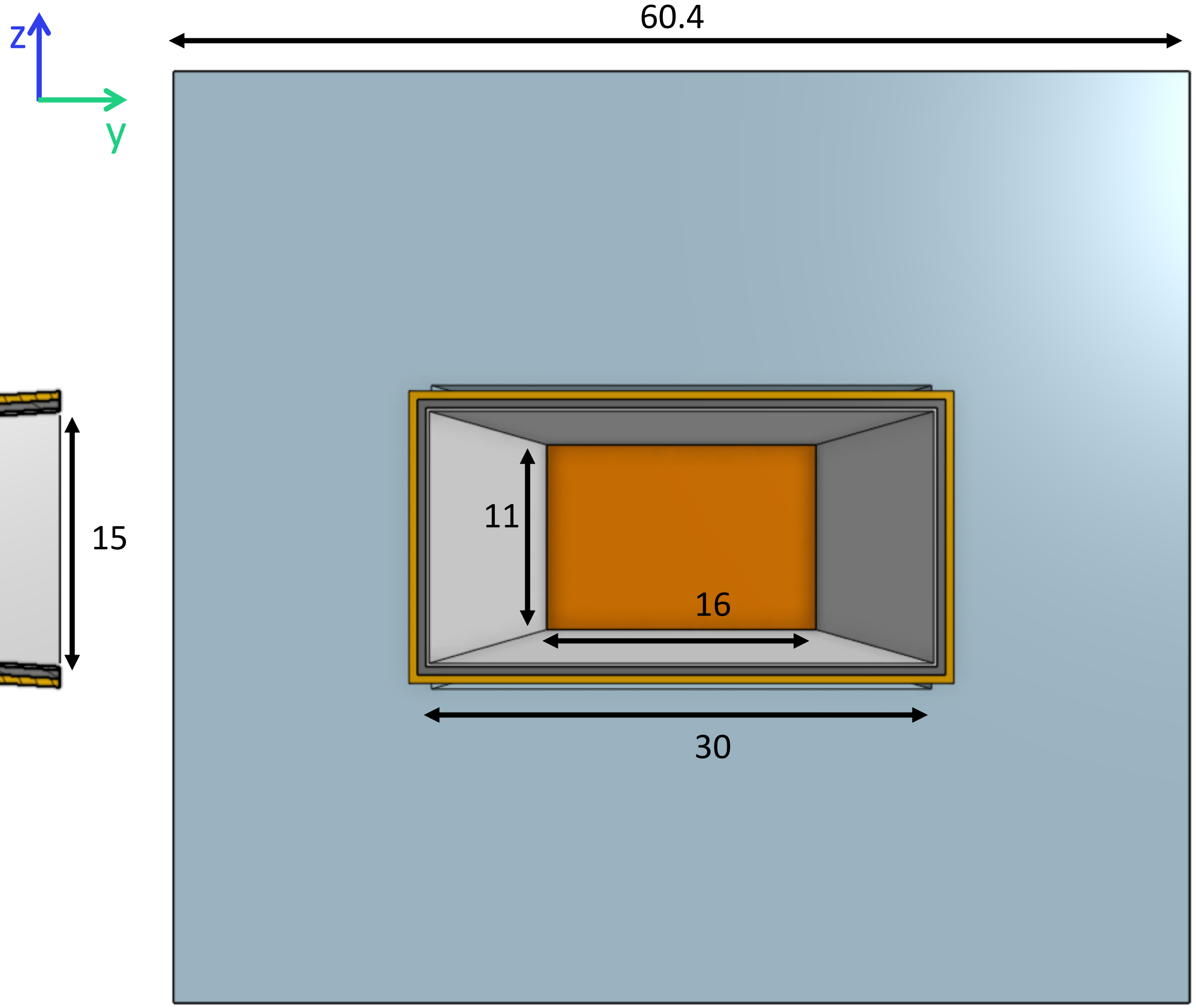
Modelling of possible Budapest experiment (N. Rizzi, DTU) goal: test advanced reflectors





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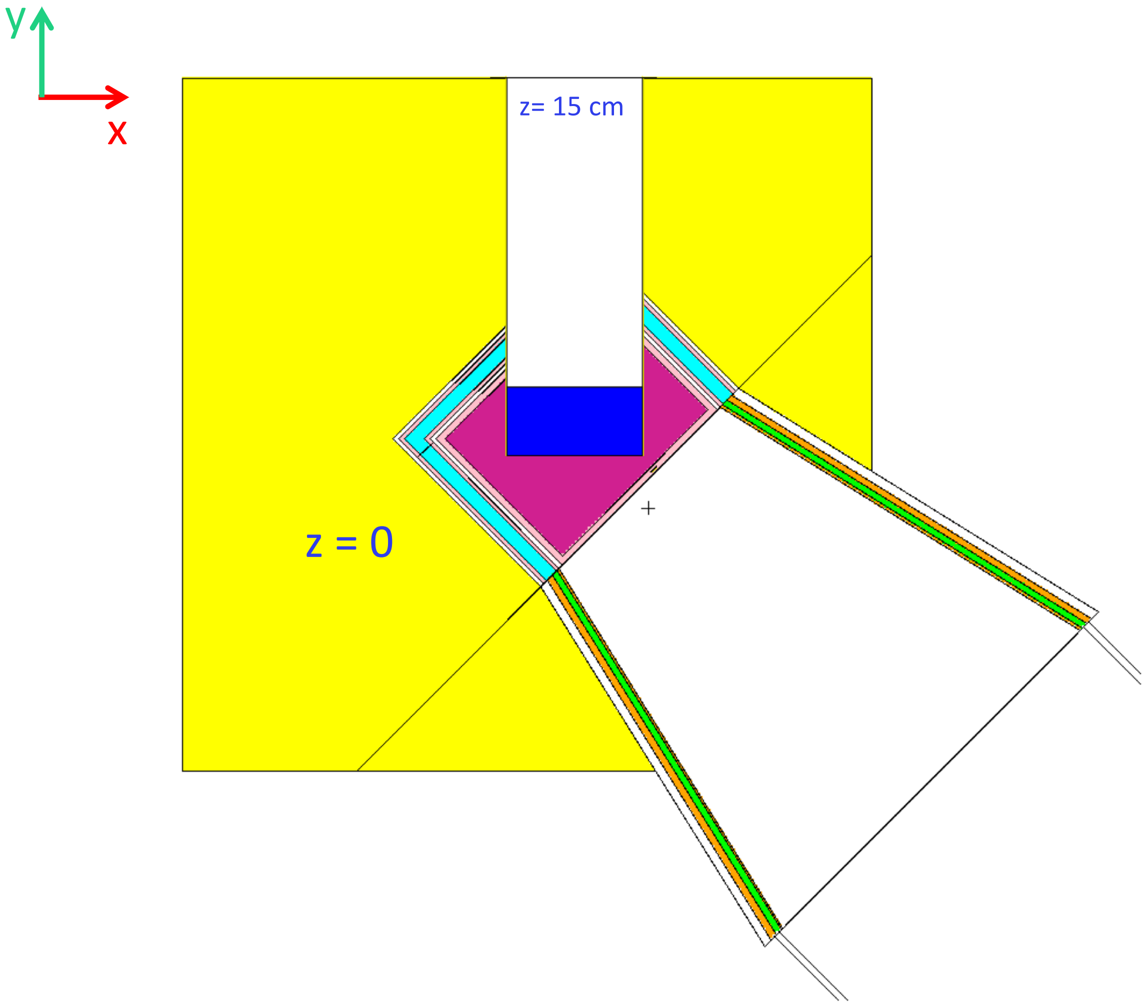
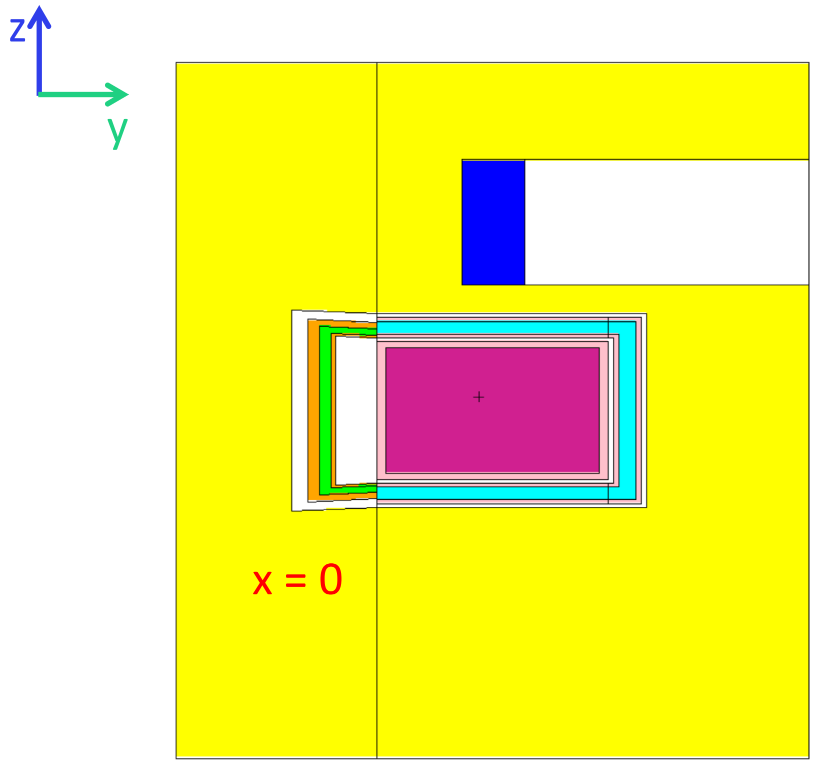
research and innovation programme under grant agreement No. 871072.

MCNP Geometry 45° degree + Be disk





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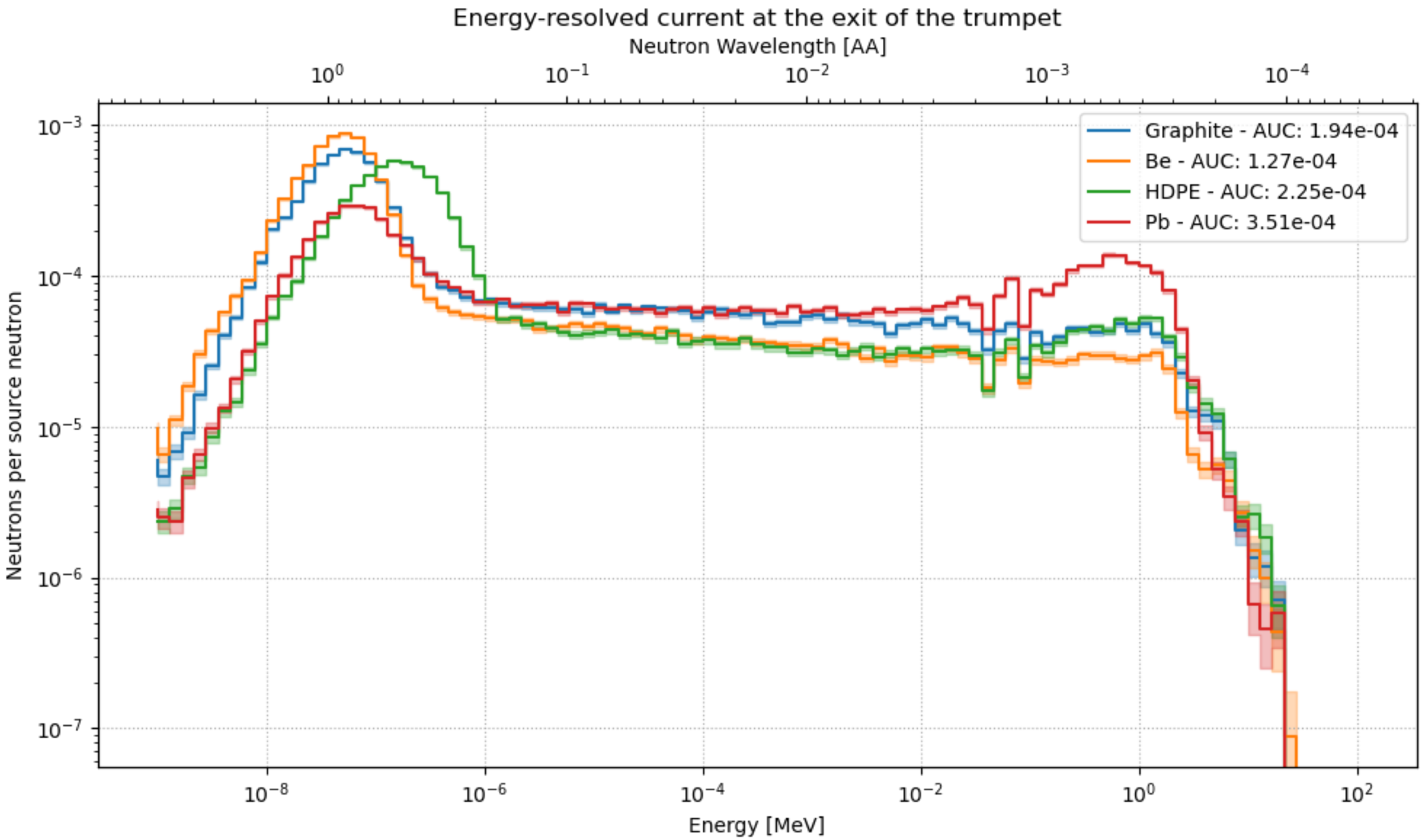
D_2

Example of calculated spectra



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HighNESS workshop on UCN/VCN @ESS

- We plan to hold a workshop at ESS in late 2021/beginning 2022 focused on the following tasks:
- Discuss recent advances in UCN and VCN research
- Discuss options and ideas for a UCN source at ESS
- Discuss options and ideas for a VCN source at ESS
- The time of the workshop is chosen so that it will have a direct impact on the HighNESS project, where the moderator design has focused so far on the main liquid D2 moderator.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072.

Conclusions

- Strong activities in Europe on VCN supported by two EU programs CREMLINplus (2020-24) and HighNESS (2020-23) are in progress
- There are promising materials for VCN production and reflection
- Additional use of advanced reflectors such as nanodiamondsis very promising

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Progress with high brightness moderator tasks at the Budapest Neutron Centre

Construction of a moderator test facility in an external beam position at the Budapest Research Reactor

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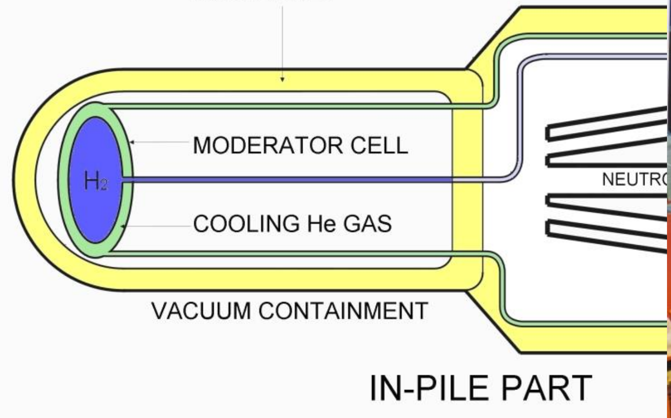
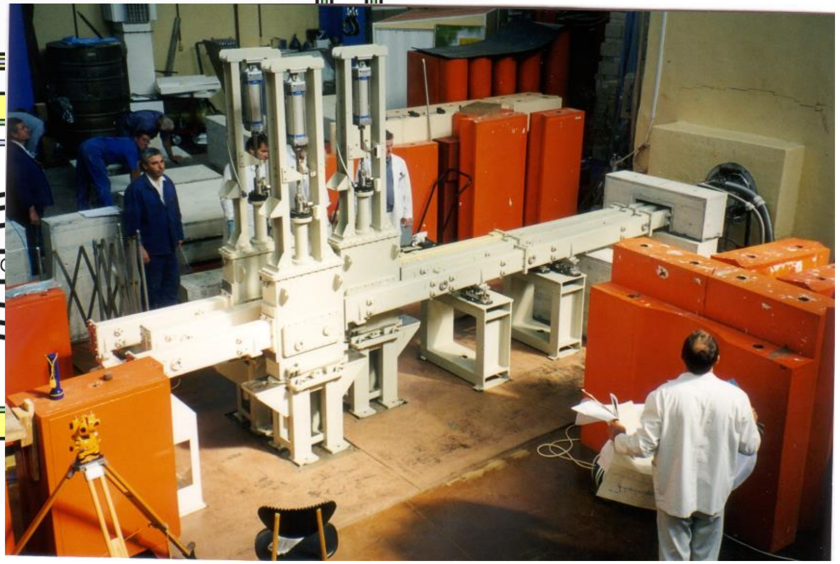
Budapest Neutron Centre

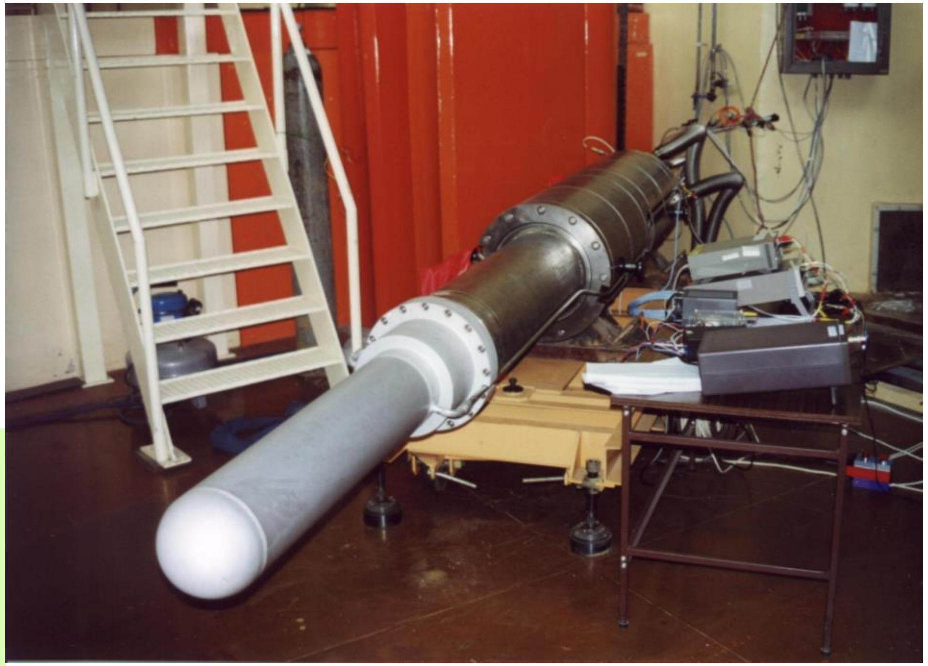
The primary goal of the BNC project is the refurbishment and upgrade of the cold neutron source (CNS) commissioned in 2000. (Collaboration of PNPI and BNC, assisted by IAEA)

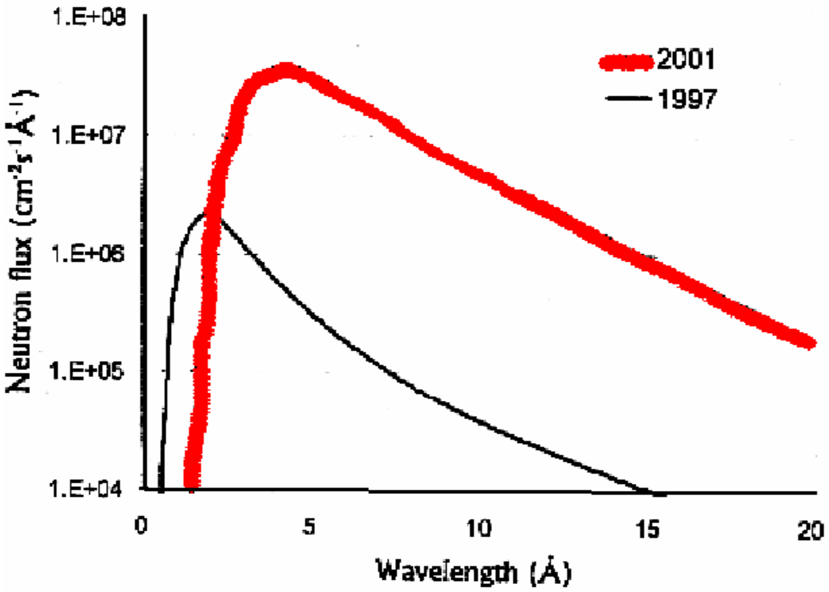
‚Volume' moderator of 480 ml liquid hydrogen at 18K





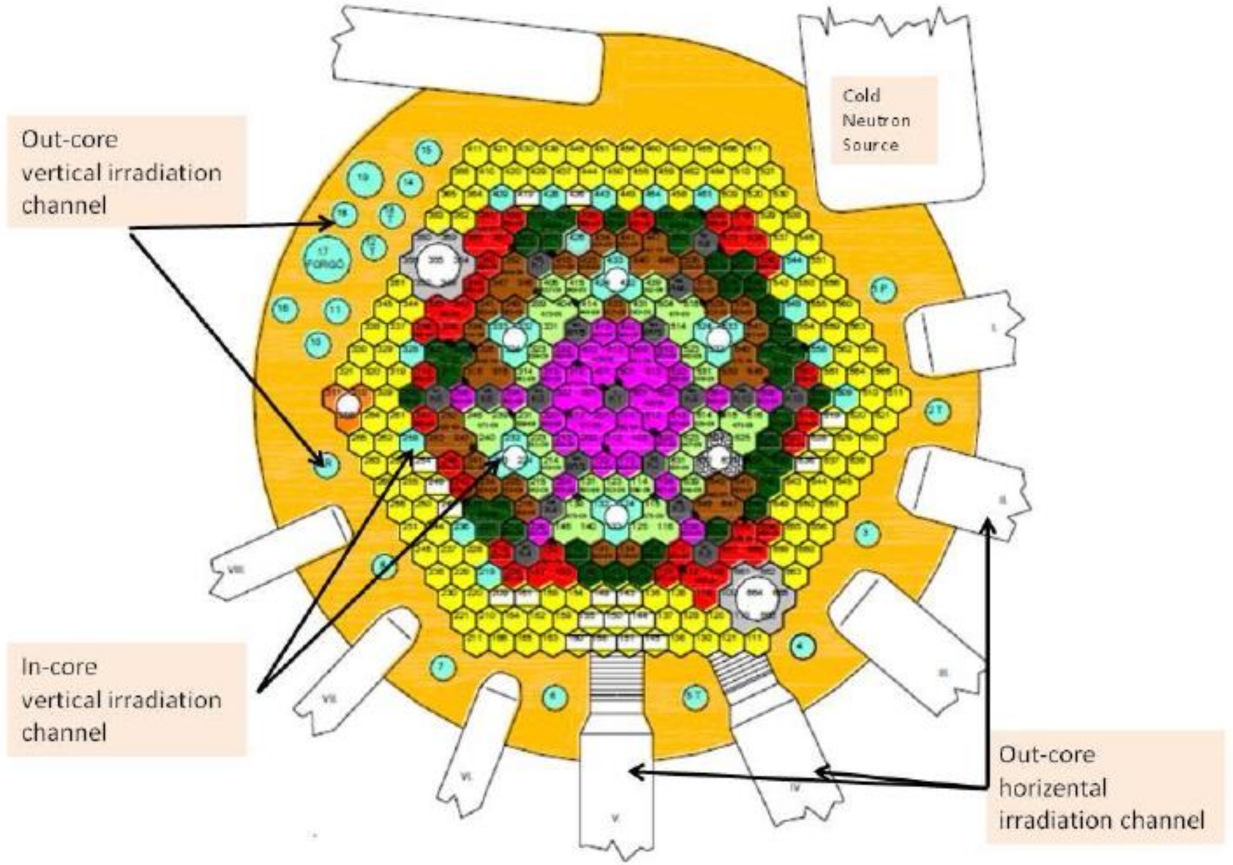
Installation of the cold source and 3 supermirror neutron guides in 1999. A similar action is planned for 2022-2023.





The aim of the CNS project is to apply the low-dimensional moderator (LDM) concept for enhanced source brightness.

- Preliminary MCNPX modelling has shown that the low dimension type ***bare moderator*** cell has twice as high neutron brightness than the existing thick moderator cell (Ø140 x 40 mm)
- *The parameter of the low dimension type bare moderator* cell is varied in the following ranges: radius 10-25 mm, length 90-180 mm. The moderator cells are supposed to be filled with pure p-hydrogen during the optimization.
- Application of pre-moderators could increase the neutron brightness for low dimension moderator cell by 6-8 %. The material of pre-moderator was light- and heavy water.
- When the p-hydrogen ratio is less than 90% the volume moderator cell has better neutronics properties.
- The experimental verification of the model calculations is foreseen by constructing a moderator test facility in an external beam position at the Budapest Research Reactor.

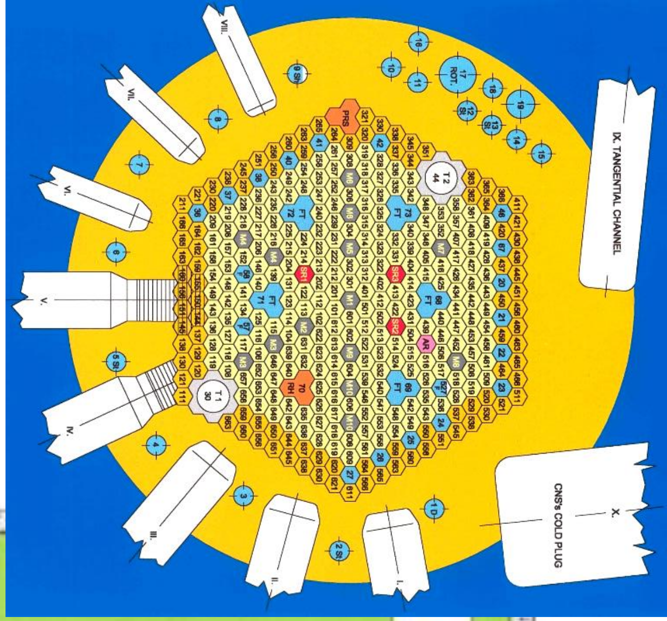


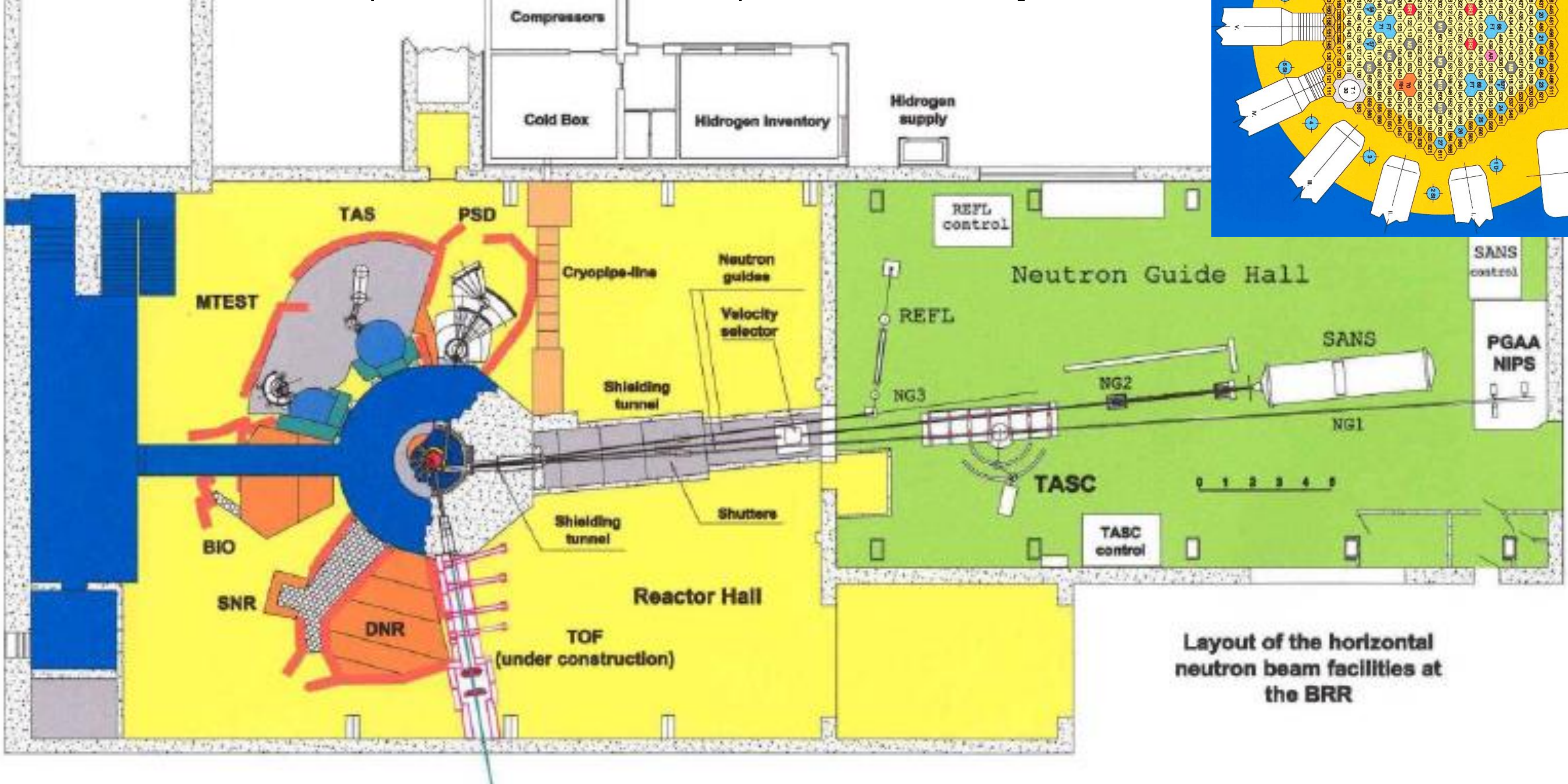
The cold neutron test facility (CMTF) is expected to be realised and utilised within the Cremlin+ project in 2021-2022 and by the end of 2024, respectively. Additional BNC tasks:

- Development of accelerator-based compact neutron sources (CANS) (e.g. LvB at Martonvásár), and transition from reactor (BRR) to CANS e.g. from 2027.
- To provide user services for projects of significant CNS developments in the world (PIK, NIST, SNS2, ESS2, HBS, etc.).
- Refurbishment of beamlines at BRR: Channel 5 (BIO station) and channel 3 to be be made suitable for high-dose irradiations - this can meet such increasing needs, as to irradiate elements of space electronics and fusion experiments.

The following tasks have been performed in the first project period.

- Channel #4 has been selected for the installation of the CMTF.
- Accurate survey of the 3-4-5 channel environment, its representation in a 3D blueprint
- Detailed elaboration and placement of our CMTF components in 3D drawings.



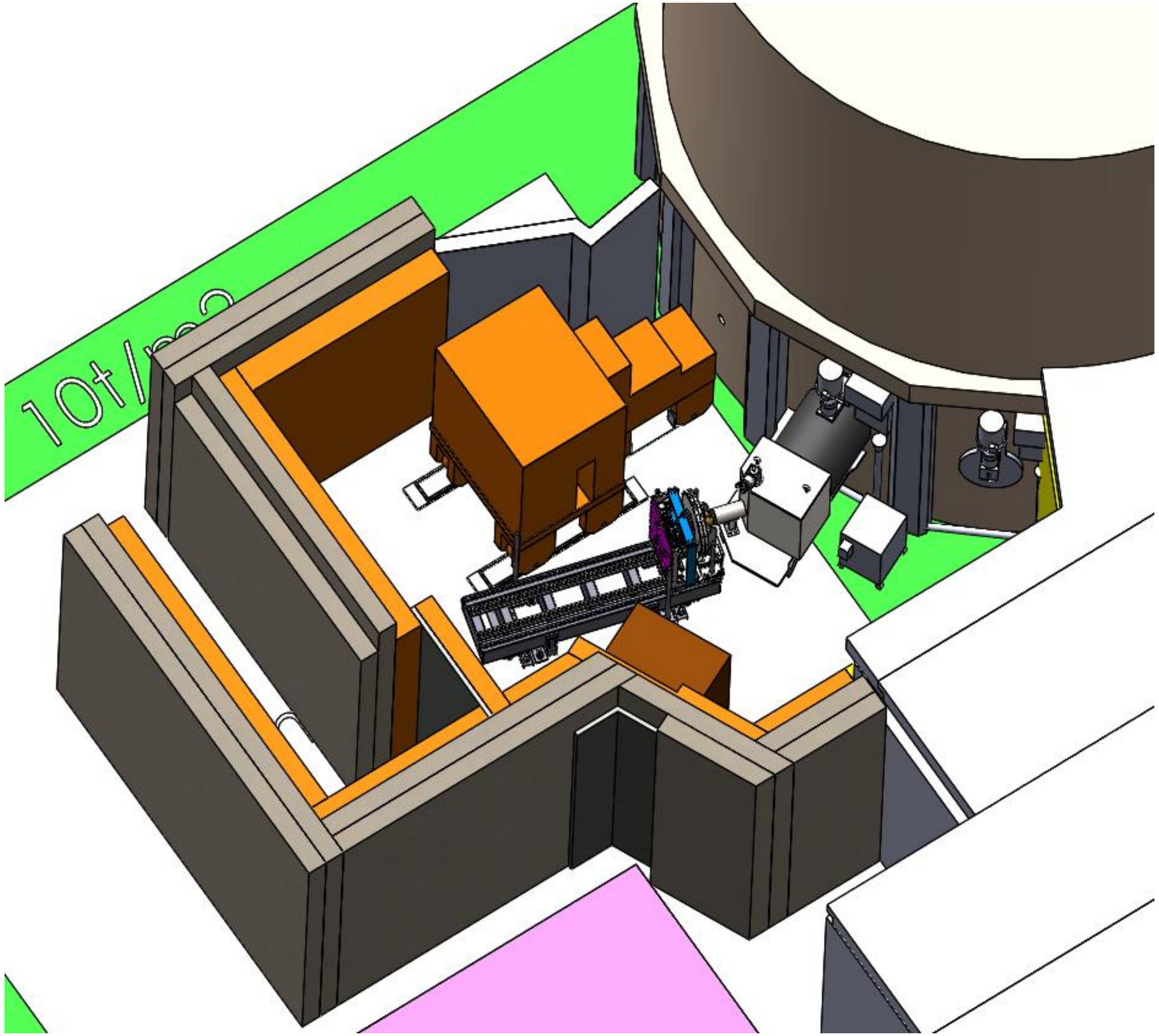


Layout of the horizontal neutron beam facilities at the BRR

The following tasks have been performed in the first project period.

- Channel #4 has been selected for the installation of the CMTF.
- Accurate survey of the 3-4-5 channel environment, its representation in a 3D blueprint
- Detailed elaboration and placement of our CMTF components in 3D drawings.

Channel #5 (right from the MTES instrument with blue monochromator shielding) and channel #4 (on the right) are epithermal neutron beams with 100 mm diameter (dismounting August 2020)

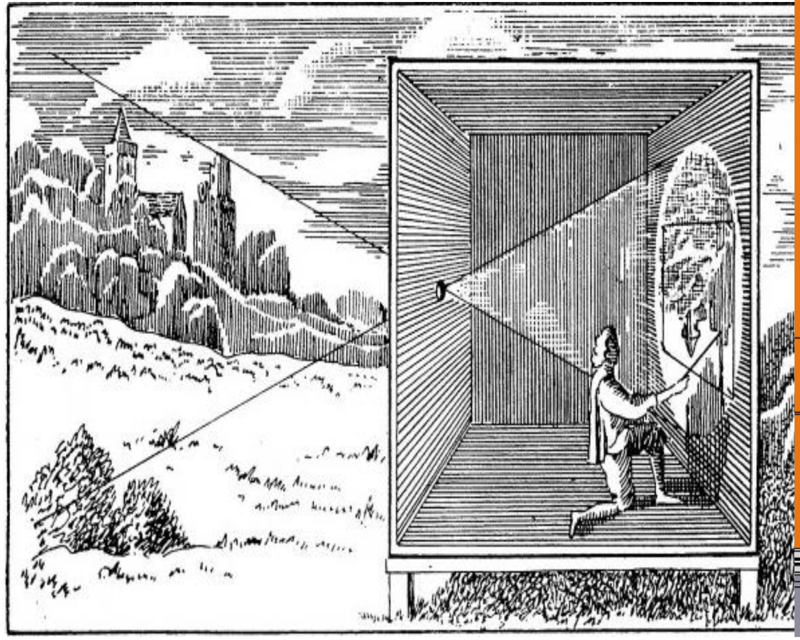


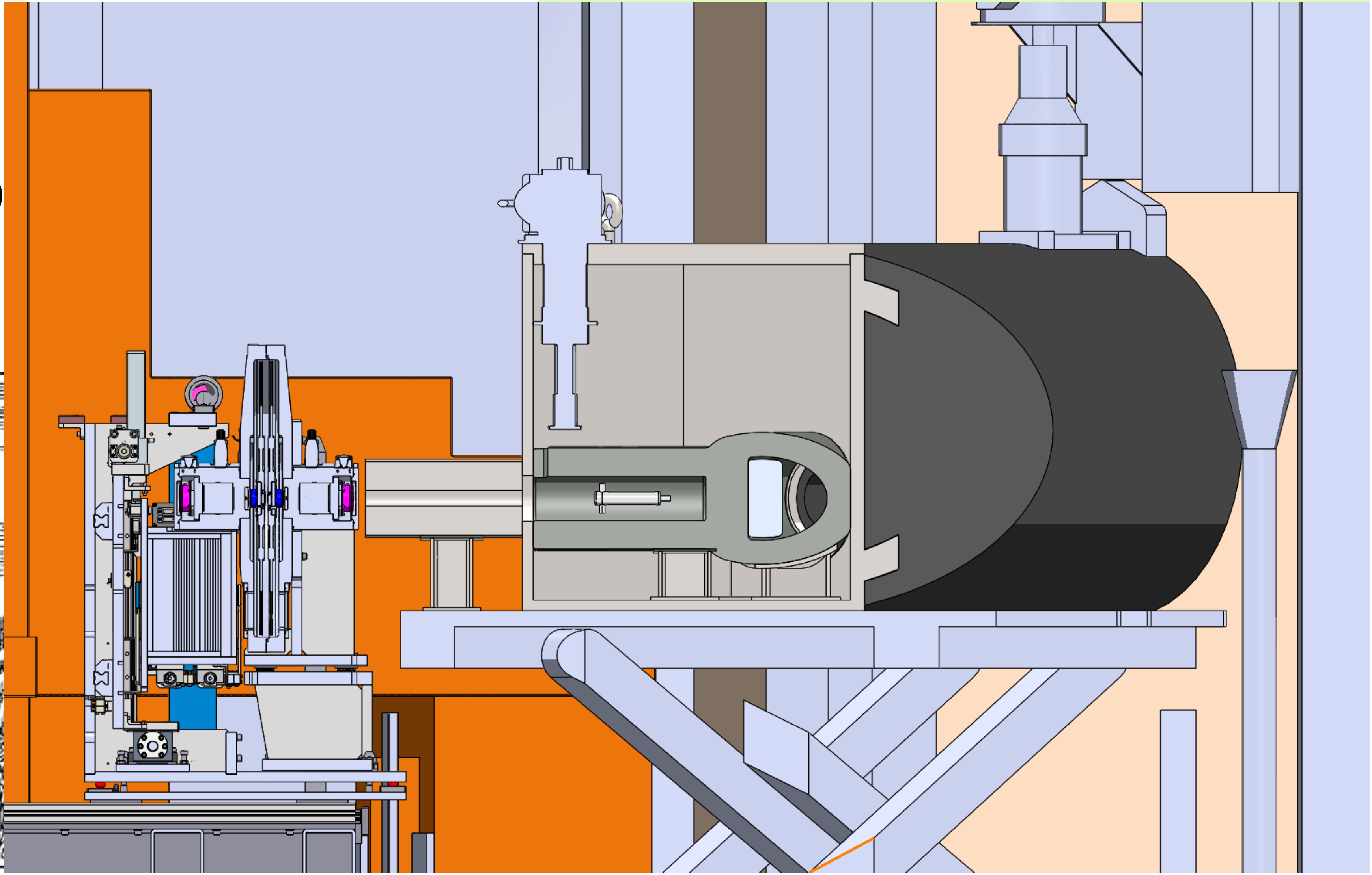
Cremlin+ Task 3.1 status at BNC:
CMTF realisation is in progress

CMTF major components:

- Beam take-off/Collimator
- Premoderator/reflector box
- Cryostat – cryo-cooler
- Compressor
- Hydrogen generator
- Pin-hole camera device („Kukucska")
- Biological shielding
- CMTF control system

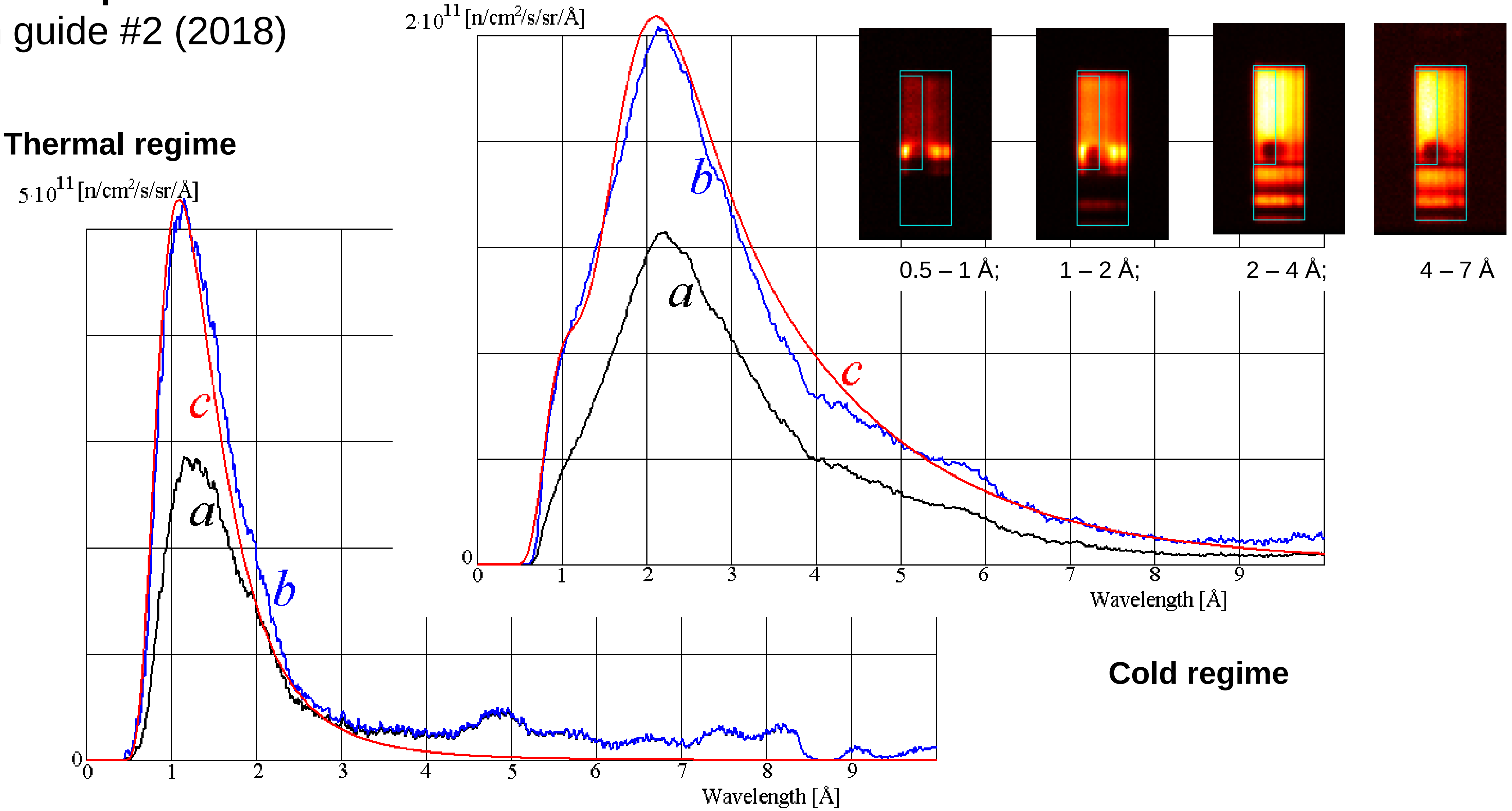
Cold Moderator Test Facility (CMTF)
BRR Channels #4





BNC moderator spectrum

Cold neutron guide #2 (2018)



a) detected flux distribution

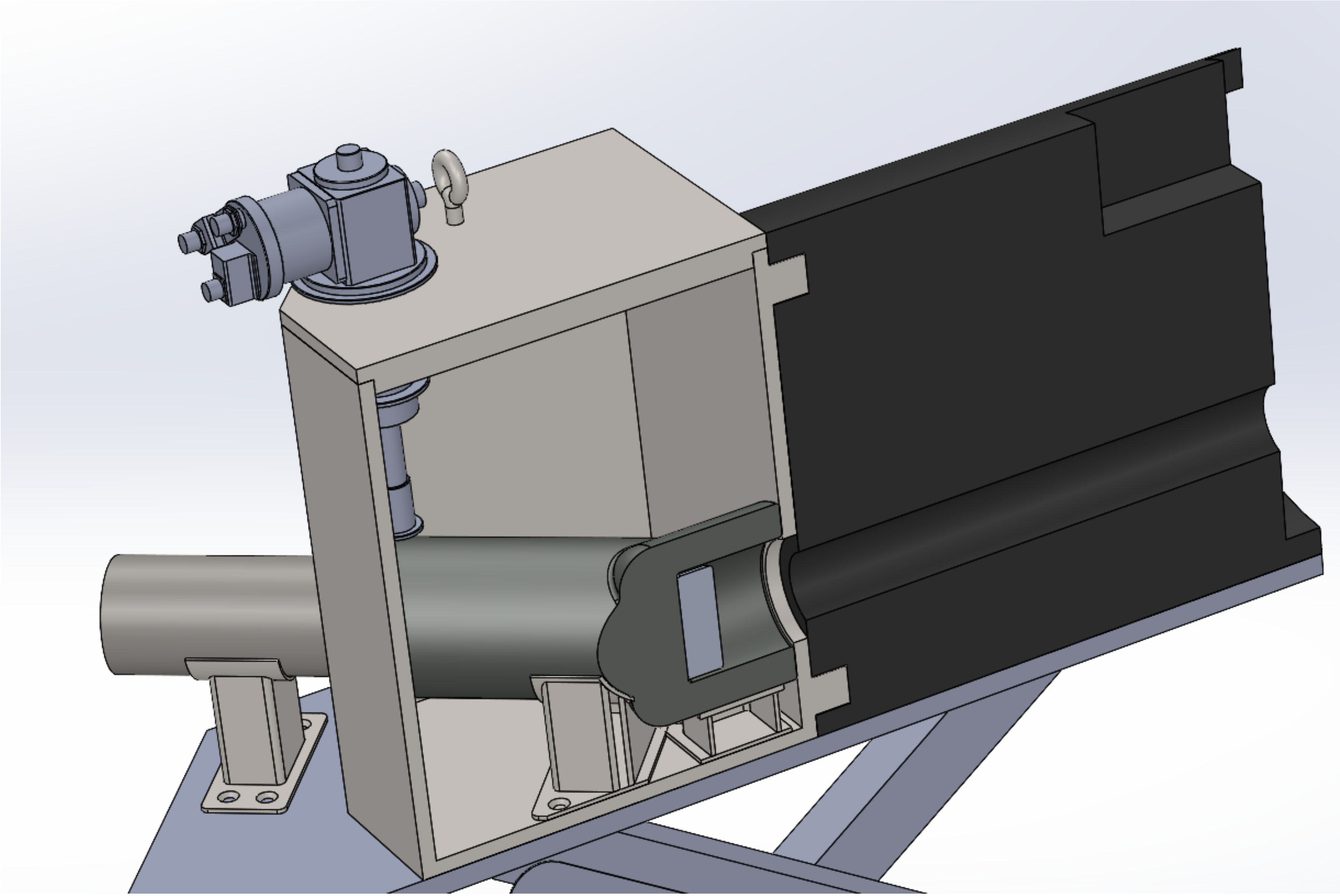
b) spectrum corrected for detector gas absorption efficiency

c) Maxwell-Boltzmann fit

- thermal: T = 320 K (reactor pool trmperature); total flux 5.6 E11 n/cm^2/s/sr
- cold: T_1 = 20 K, Φ_1 = 0.9 E11 n/cm^2/s/sr; T_2 = 80 K, Φ_2 = 4 E11 n/cm^2/s/sr; T_3 = 320 K, Φ_3 = 1.1 E11 n/cm^2/s/sr;

CMTF component details:

- Beam take-off/Collimator
- Premoderator/reflector box
- Cryostat – cryo-cooler
- Compressor
- Hydrogen generator
- Pin-hole camera device („Kukucska”)
- Biological shielding
- CMTF control system



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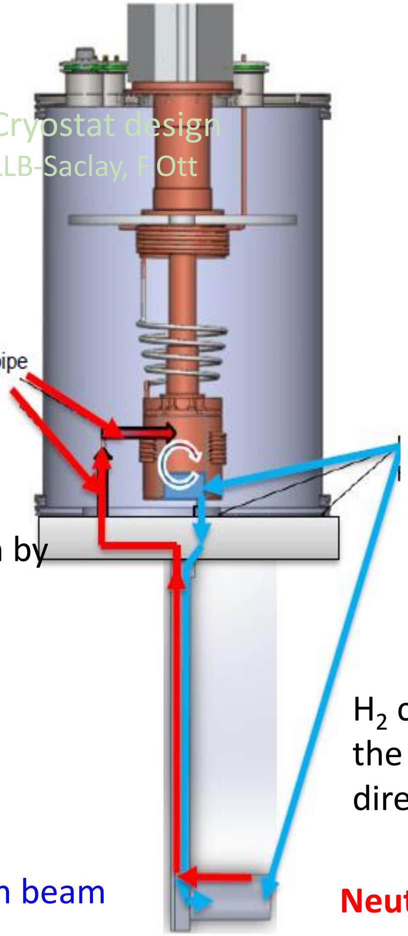
Closed cycle refregerator 10K, 20W



Liquid H2 evaporation in the pipe
Circulation ensured by Δp

H_2 condensation by thermosiphon?

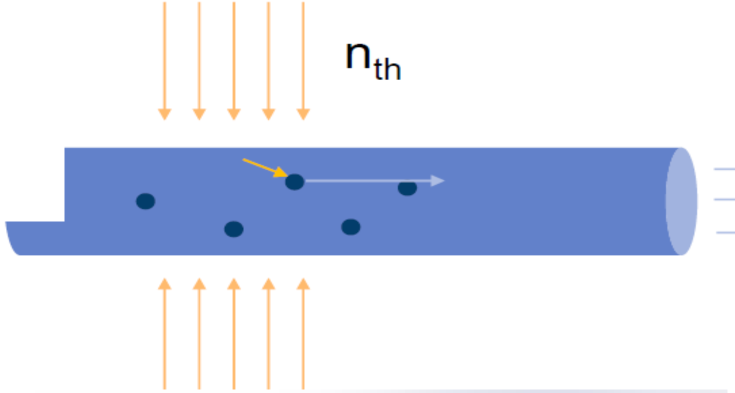
H_2 condensation in the moderator cell by direct He cooling?

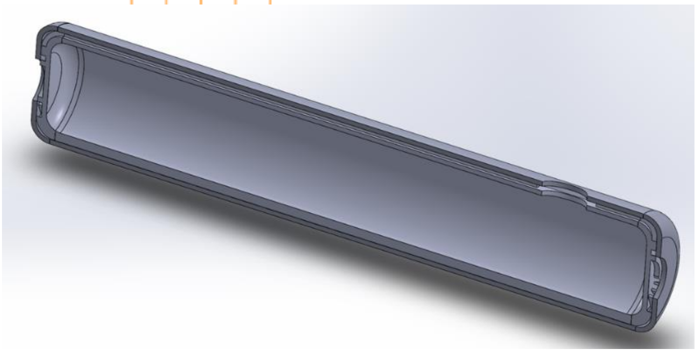
Cold neutron beam

Neutron beam from reactor

Moderator tube
Ø25 x 150 mm

Sumitomo
http://www.shicryogenics.com/products/specialty-cryocoolers/rdk-500b/
RDK-500B 20K Cryocooler Series





Conceptual design and engineering version of the moderator vessel

CMTF component details:

- Beam take-off/Collimator
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- CMTF control system
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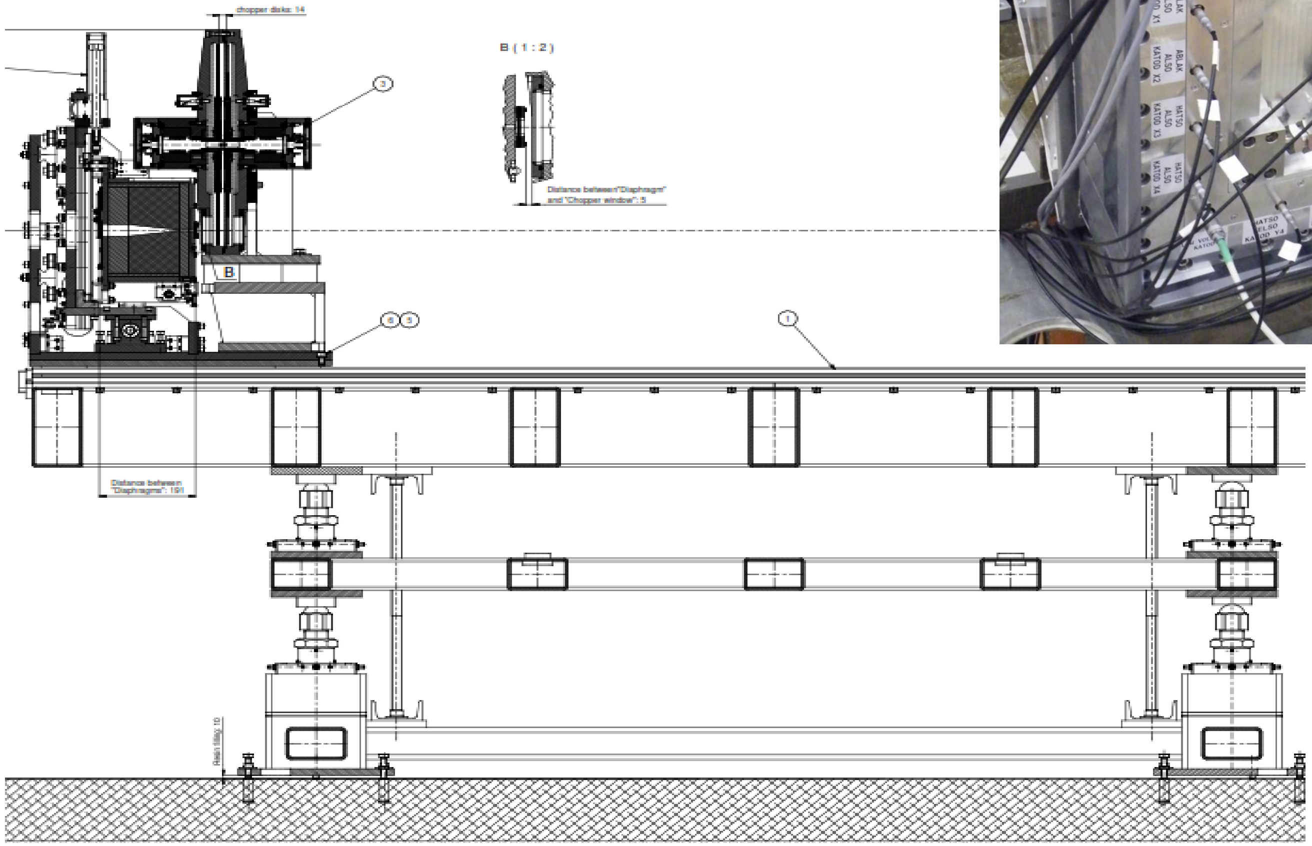
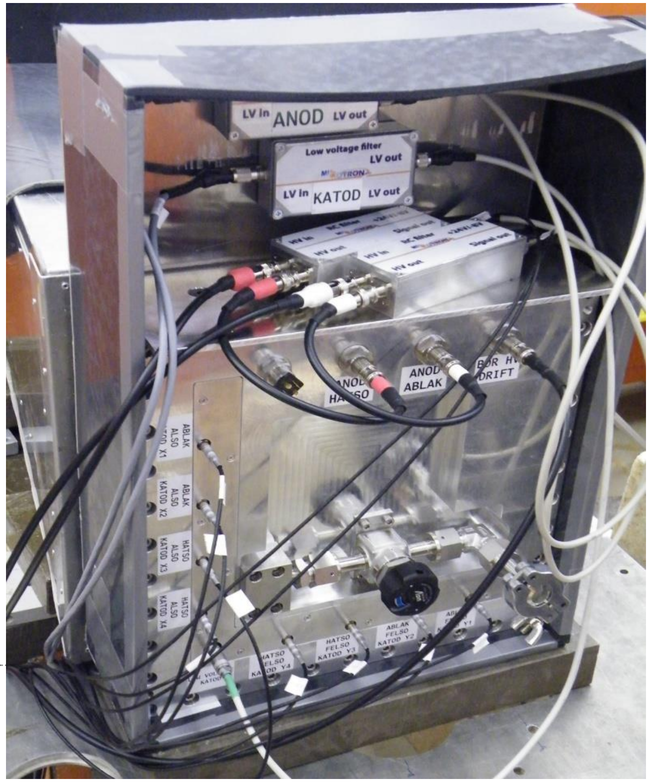


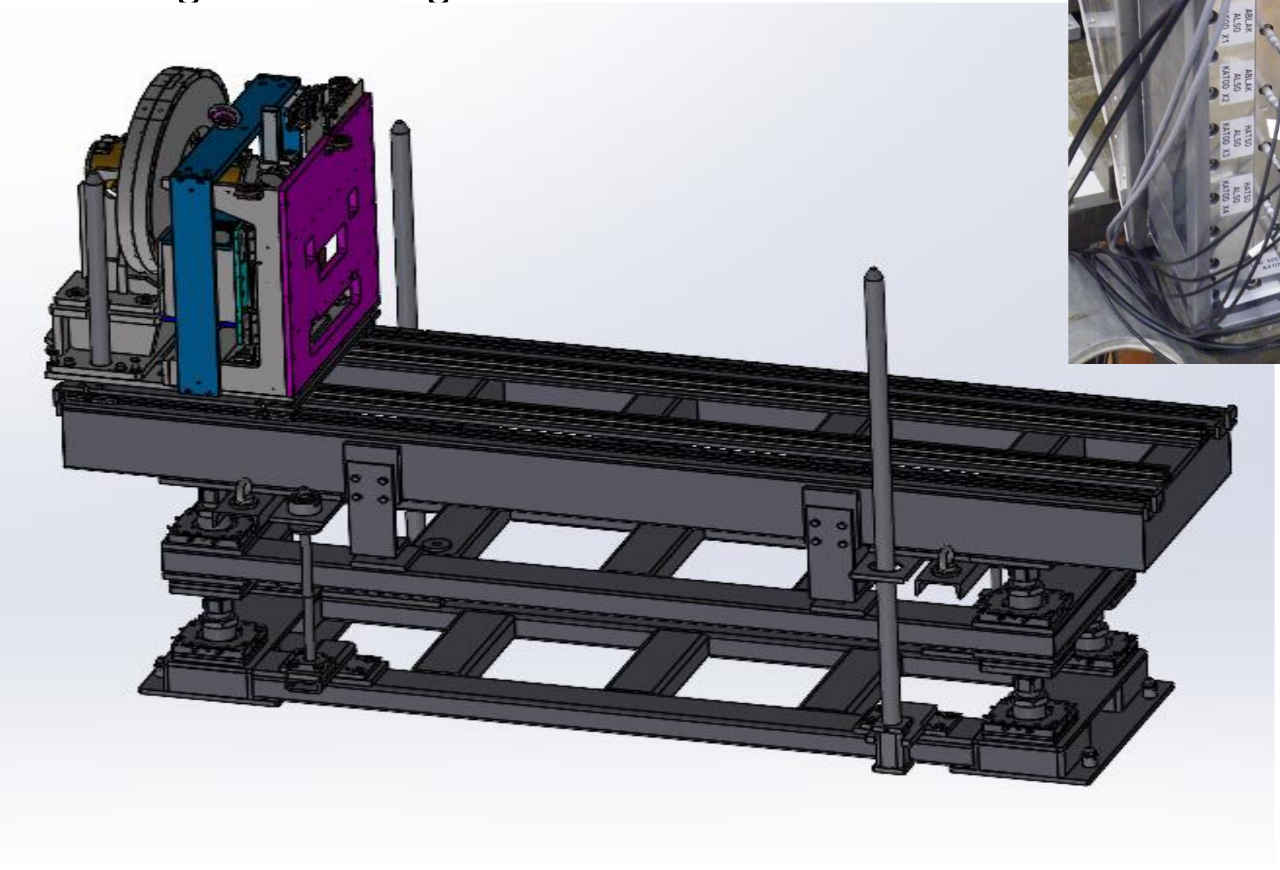
Pinhole-camera TOF neutron brightness measuring device



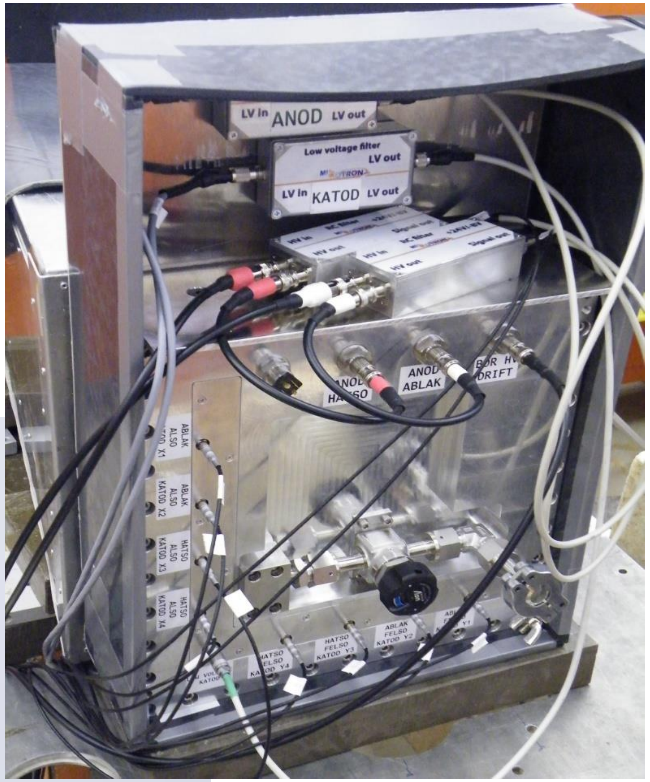
A camera-obscura principle device was developed and built within the BrightnESS project. This mashine will be installed at channel #4 as a part of the CMTF

CMTF component details:

- Beam take-off/Collimator
- Premoderator/reflector box
- Cryostat – cryo-cooler
- Compressor
- Hydrogen generator
- Pin-hole camera device („Kukucska”)
- CMTF control system
- Biological shielding



Pinhole-camera TOF neutron brightness measuring device



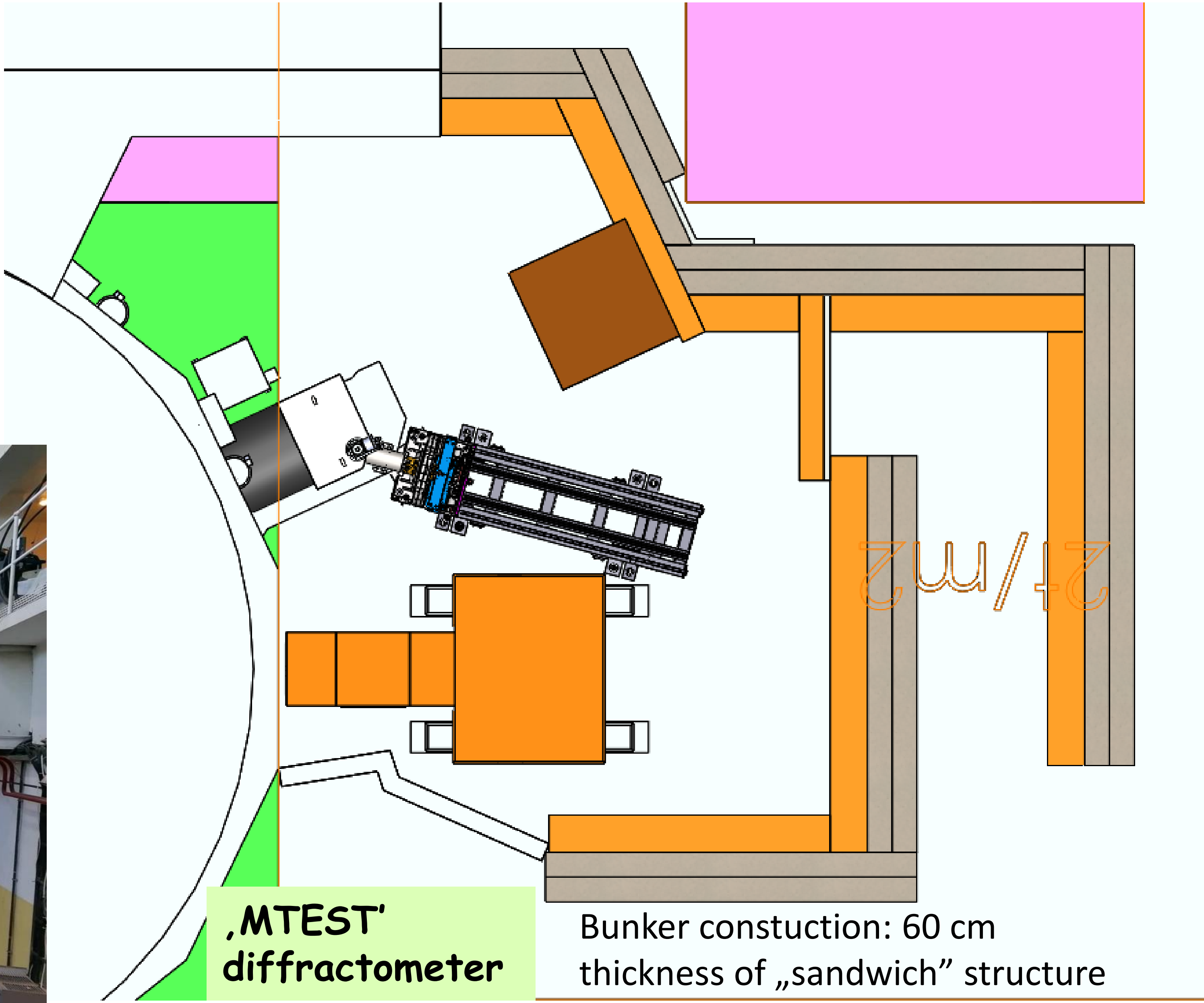
- Pinhole collimation unit, mechanics, choppers, detector built by Mirrotron Ltd.
- Controller* built by BNC Neutron Spectroscopy Dept.
  - 19” crate
  - 4 axes
  - Beckhoff PLC

*ESS-standard

CMTF component details:

- Beam take-off/Collimator
- Premoderator/reflector box
- Cryostat – cryo-cooler
- Compressor
- Hydrogen generator
- Pin-hole camera device („Kukucska”)
- CMTF control system
- **Biological shielding**

‚MTEST' diffractometer



‚MTEST' diffractometer

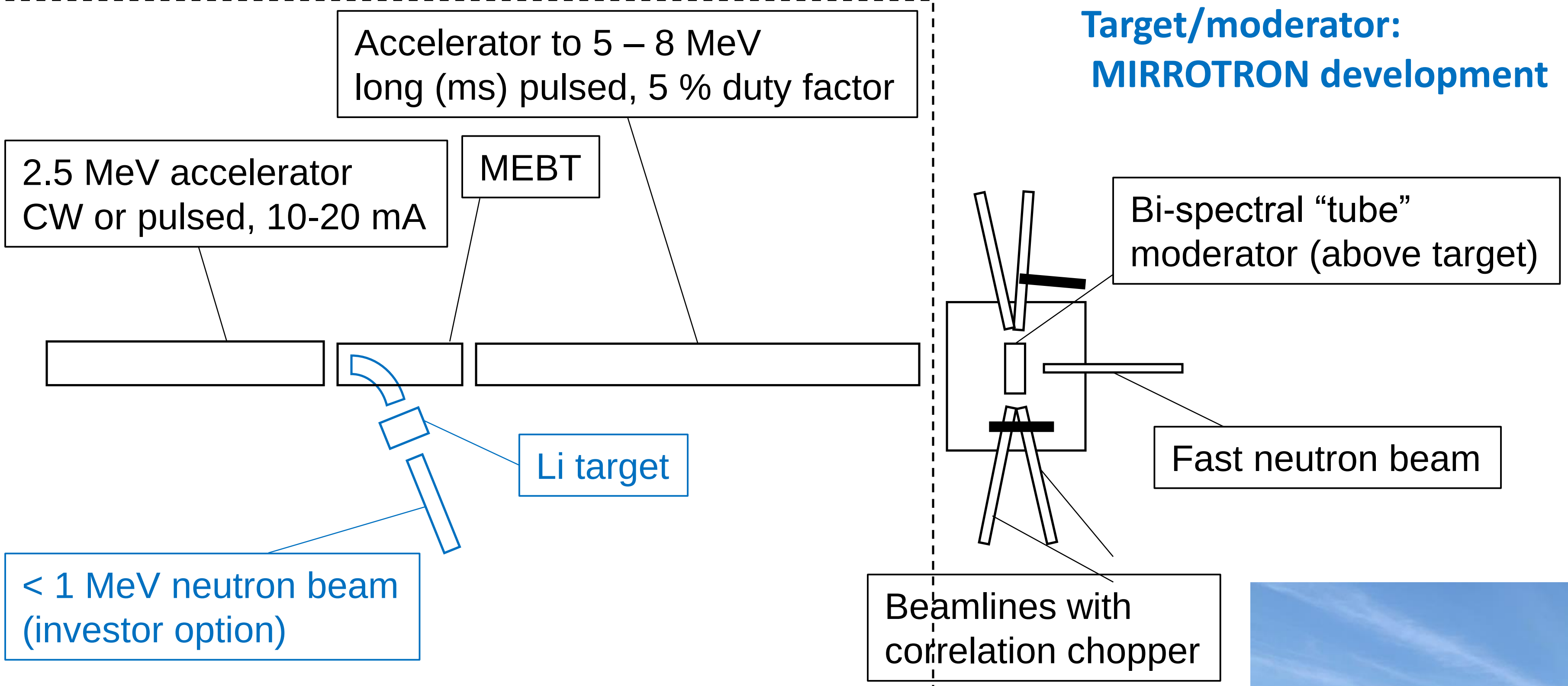
Bunker constuction: 60 cm thickness of „sandwich” structure

MCNPX modelling to reach 1 μS level

The Cold Moderator Test Facility for user services

“LvB” COMPACT NEUTRON SOURCE PROJECT AT MARTONVÁSÁR

Target/moderator: MIRROTRON development



Public procurement tender:

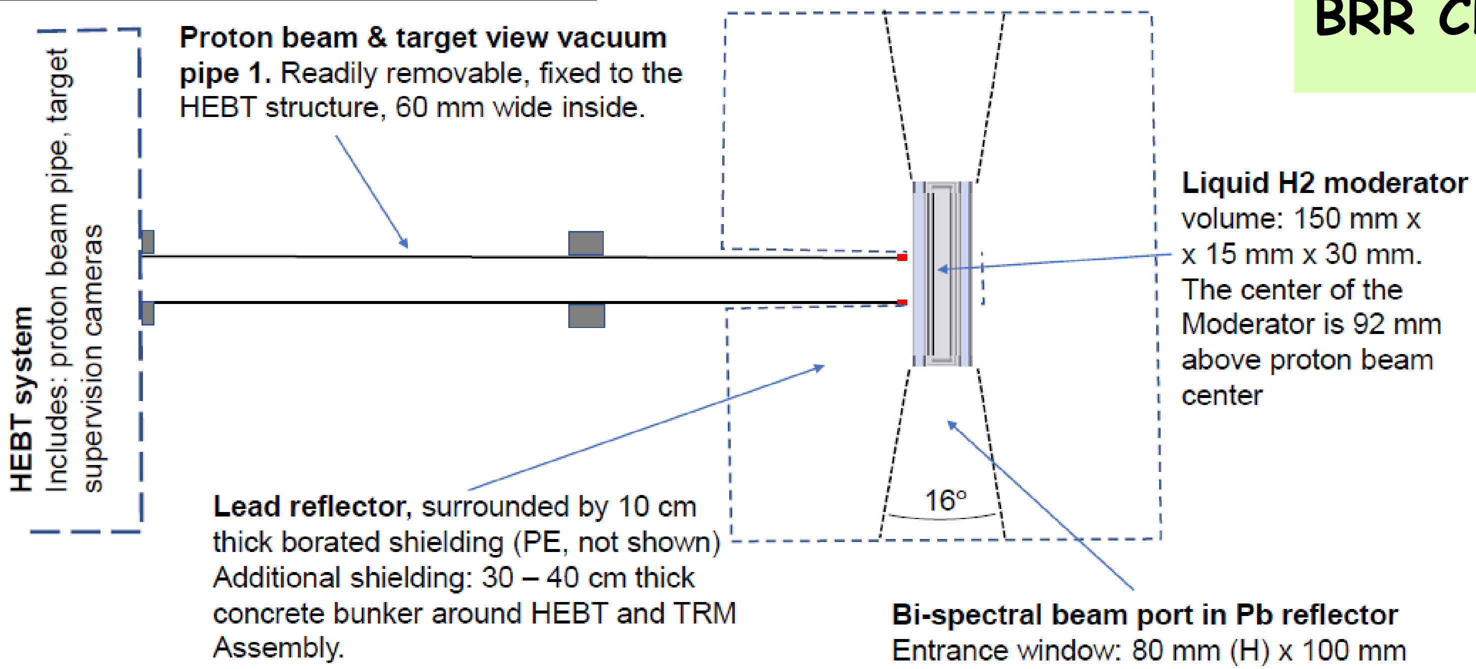
- ion source + LEBT
- 2.5 MeV accelerator (+ MEBT)
- accelerator 5 – 8 MeV (+ HEBT)
- RF amplifier
- integration

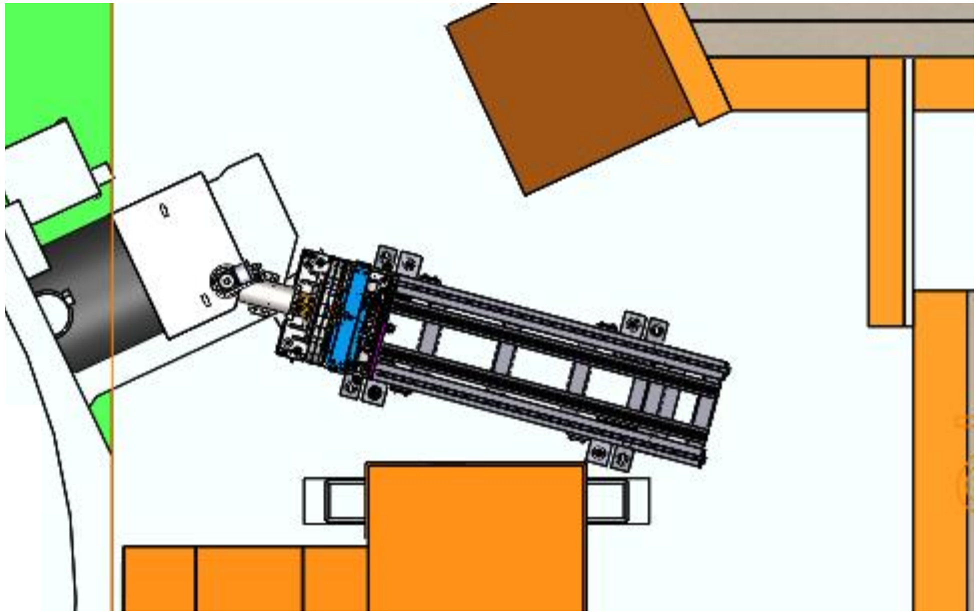
Project completion deadline extended by 15 months:
Public procurement delays + Covid 19

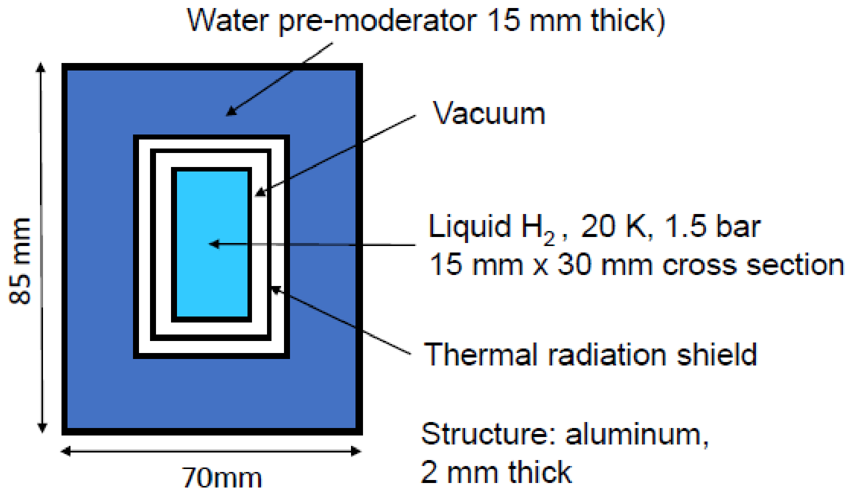
First neutrons in 2022

Cold Moderator Test Facility (CMTF) BRR Channels #4

LvB moderator and reflector
Reference design. Projection to horizontal plane. *(Not to scale!)*







Moderator developed by
MIRROTRON

Major milestones to implement the project for the installation of the Moderator test facility in an external beam position and perform neutron beam measurements:

- Contracting for the hydrogen/moderator vessel system design 2021 Q3
- Contracting for the cryostat design 2021 Q3
- Installation of a pre-moderator (Pb, Be) in the beam of Ch#5 2021 Q3
- Installation of the Pinhole-camera device at Ch#5 2021 Q4
- Contracting for the hydrogen/moderator vessel system fabrication 2021 Q4
- Contracting for the cryostat fabrication 2021 Q3
- Purchase of the cryocooler 2021 Q3
- Biological shielding construction 2021 Q4
- Pinhole camera experiments with thermal beam 2021 Q4
- Installation of the cryostat at Ch#5 2022 Q2
- First test measurements with cold neutrons 2022 Q2
- Various moderator configuration tests with the TBL 2022-24

Staff involved in the project

- László Rosta, project leader
- Laura Draskovics
- Viktor Heirich
- József Janik,
- Péter Kárpáti
- Márton Markó
- Viktor Mészáros
- Zsolt Rithnovszky
- Viktória Sugár
- Alex Szakál
- Tamás Veres

External expert companies

- HNF-Tech Ltd. – Cold source technology
- Mirrotron Ltd. – Neutron optics
- VTLT Ltd. - Cryogenics

NRC «KURCHATOV INSTITUTE»

PETERSBURG NUCLEAR PHYSICS INSTITUTE

COLD NEUTRON SOURCES AT THE REACTOR PIK:

STATUS TO 07. 2021

VICTOR MITYUKHLYAEV

PROJECT «CREMLIN+» WP3 FPH,

Online meeting, 12 July 2021

CREMLIN PLUS

Connecting Russian and European Measures for Large-scale Research Infrastructures

100E buildings and constructions

External Hydrogen and Vacuum systems

Cooling water system

RECONSTRUCTION REACTOR PIK PROJECT (R2)

Main systems of the CNS HEC-3 mock-up complex

	Components and systems	Availability
1	Buildings & construction works	completed
2	Auxiliary systems (electricity, recycled cooling water, instrument air etc.	completed
3	Cryogenic plant (LINDE) mounting is ready	Ready for setting up 17.07.2021
4	External systems (Deuterium, Vacuum, Helium blanketing)	Mounting 70%
5	Mock-up Vacuum containment	Under manufacturing till end of 2021
6	CNS Thermosiphon (Cryogenic vertical insert)	Under manufacturing till end of 2021
7	CNS Protection and control system	Mounting 90 %
8	Cryogenic connected pipelines (TS-Linde)	Under design. Manufacturing end of 2021

Tasks for CNS HEC-3 implementation

- There is necessary make a new project for transfer of the CNS complex equipment from building 100E to building 100A and to the reactor
- Manufacturing of the Vacuum containment for CNS Thermosiphon
- Financial support shall be decided around 1BRub at the beginning 2021???