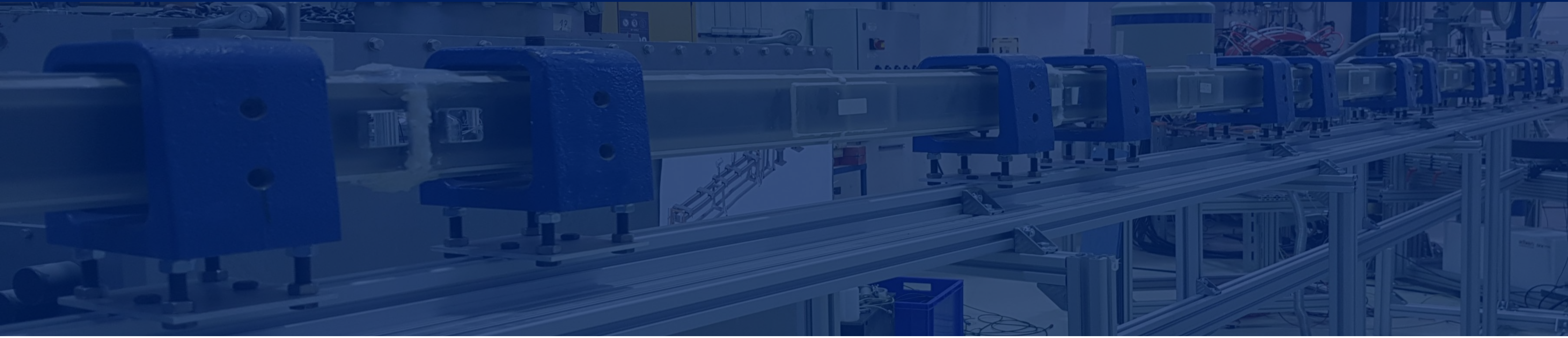
CONCEPTUAL DRAFT FOR A HE-II BASED ULTRA COLD NEUTRON SOURCE IN THE MODERATOR COOLING BLOCK

9.5.2023 I Mathias Strothmann



m.strothmann@fz-juelich.de

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Mitglied der Helmholtz-Gemeinschaft

HighNess JÜLICH Forschungszentrum

OVERVIEW

- How to create ultra cold neutrons (UCN)
- MCNP Simulation results for an ESS UCN source
- Experimental investigation of He-II
- Conclusion of results & outlook

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

OVERVIEW

- How to create ultra cold neutrons (UCN)
- MCNP Simulation results for an ESS UCN source
- Experimental investigation of He-II
- Conclusion of results & outlook

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

OVERVIEW

- **How to create ultra cold neutrons (UCN)**
- MCNP Simulation results for an ESS UCN source
- Experimental investigation of He-II
- Conclusion of results & outlook

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Suitable materials for an UCN source

- In general the absorption cross-section increases with lower neutron energies
- Low capture cross-section more important for UCN gain then high elastic scattering cross-section

→ Just a few materials are suitable for UCN applications

Isotope	
^{2}H (Deuterium)	✓ Low absorption cross section but high elastic scattering cross section × Solid at ultra cold temperatures × Extended safety measures needed (high flammable gas)
^{4}He	✓ In phase II condensed (He-II) super thermal moderation properties ✓ No neutron capturing ✓ Inert × He-II is super fluid → Elaborate sealing needed × ^{3}He contaminants can significantly reduce the UCN gain
^{12}C	✓ No isotope separation needed (>98% abundance)
^{15}N	× Natural abundance to low → Isotope separated highly expensive
^{16}O	✓ No isotope separation needed (>99% abundance)
^{208}Pb	× Isotopic pure highly expensive (>1650$/g)

^{1}H has a high capture cross-section!

→ Contaminations in a material are decreasing the UCN gain massively

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Suitable materials for an UCN source – superfluid He-II

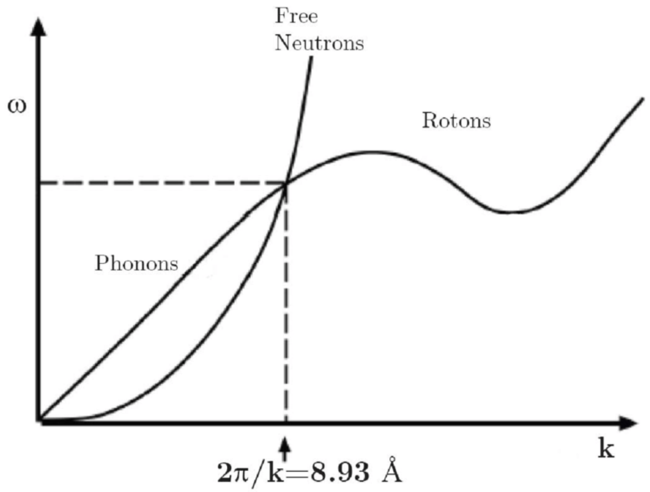
- Phase transistion from liquid ^{4}He in superfluid phase (He-II) at **2,17K**
- Plainly simple temperature reduction of L^{4}He bath by pressure reduction:

Bath temperature:	4,2 K	→	1,6 K
Pressure:	1000 mbar	→	7,6 mbar
Bath filling	100 %	→	58 %

[1]

Superthermal process:

- High energy transfer for **~8,9 Å** neutrons to He-II (in just one interaction directly to UCN)
  → Premoderation should be optimised for high 8,9 Å gain
- Energy transfer to a „thermal reservoir“ in He-II (system not in thermal equilibrium)
  → Effective UCN temperature can be lower then He-II temperature
- Upscattering Process is suppresed
- He-II has the highest known thermal conductivity
  → Heat is directly transfered to surounding surface



[2]

→ **He-II is a good choice for an UCN converter**

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

[1] C. Haberstroh – Flüssigheliumversorgung, TUDPress, 2010
[2] J. Yoder - Measurement of wall relaxation times of polarised ^{3}He in bulk: Liquid ^{4}He for the neutron electric dipole moment experiment. Diss. University of Ilinois, 2010

OVERVIEW

- How to create ultra cold neutrons (UCN)
- **MCNP Simulation results for an ESS UCN source**
- Experimental investigation of He-II
- Conclusion of results & outlook

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

UCN source concept design

Concept 1:

- UCN converter based on

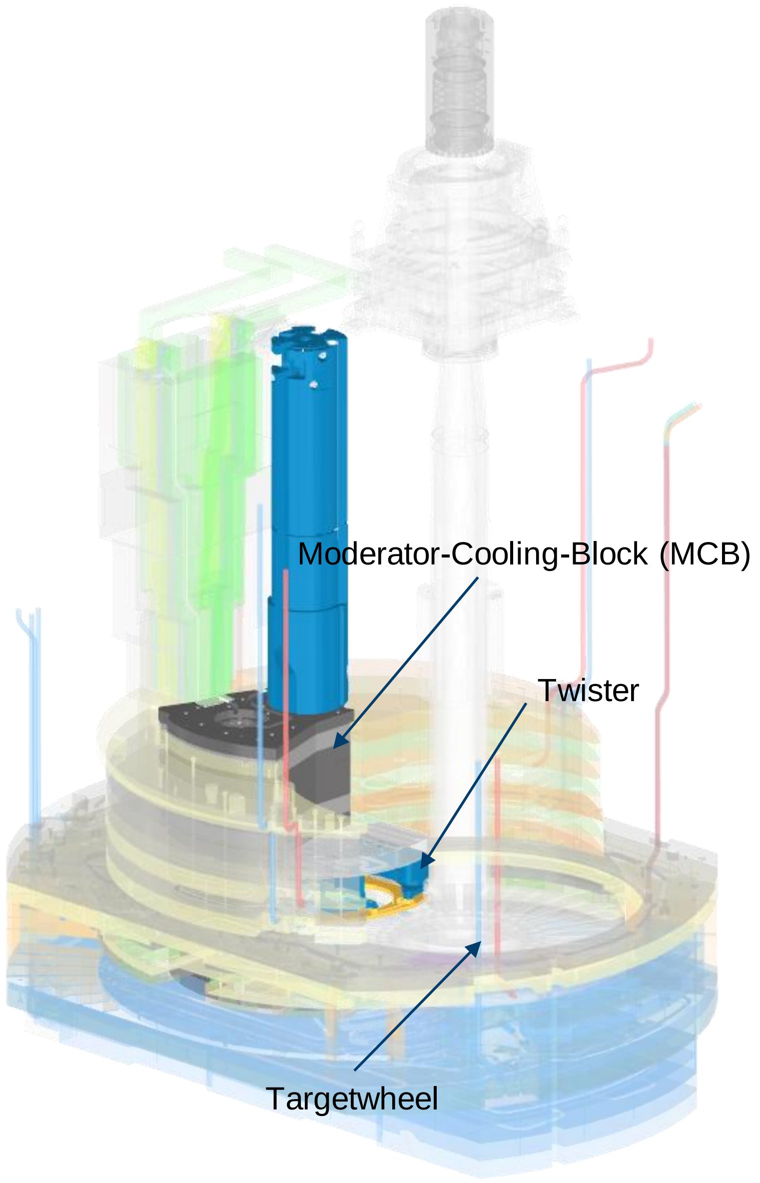
  3 stage coaxial design

- Converter medium: ^{4}He-II
- Location: Moderator-Cooling-Block (MCB)

2 origin design:

1. Moderation of fast neutrons in thermal and cold moderator shell
2. Neutron guide optimised für 8,9Å neutrons from VCN moderator to He-II converter

- Guiding of UCN:
  - ➢ Option 1: Vertical
  - ➢ Option 2: Horizontal through beamport



HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

UCN source concept design

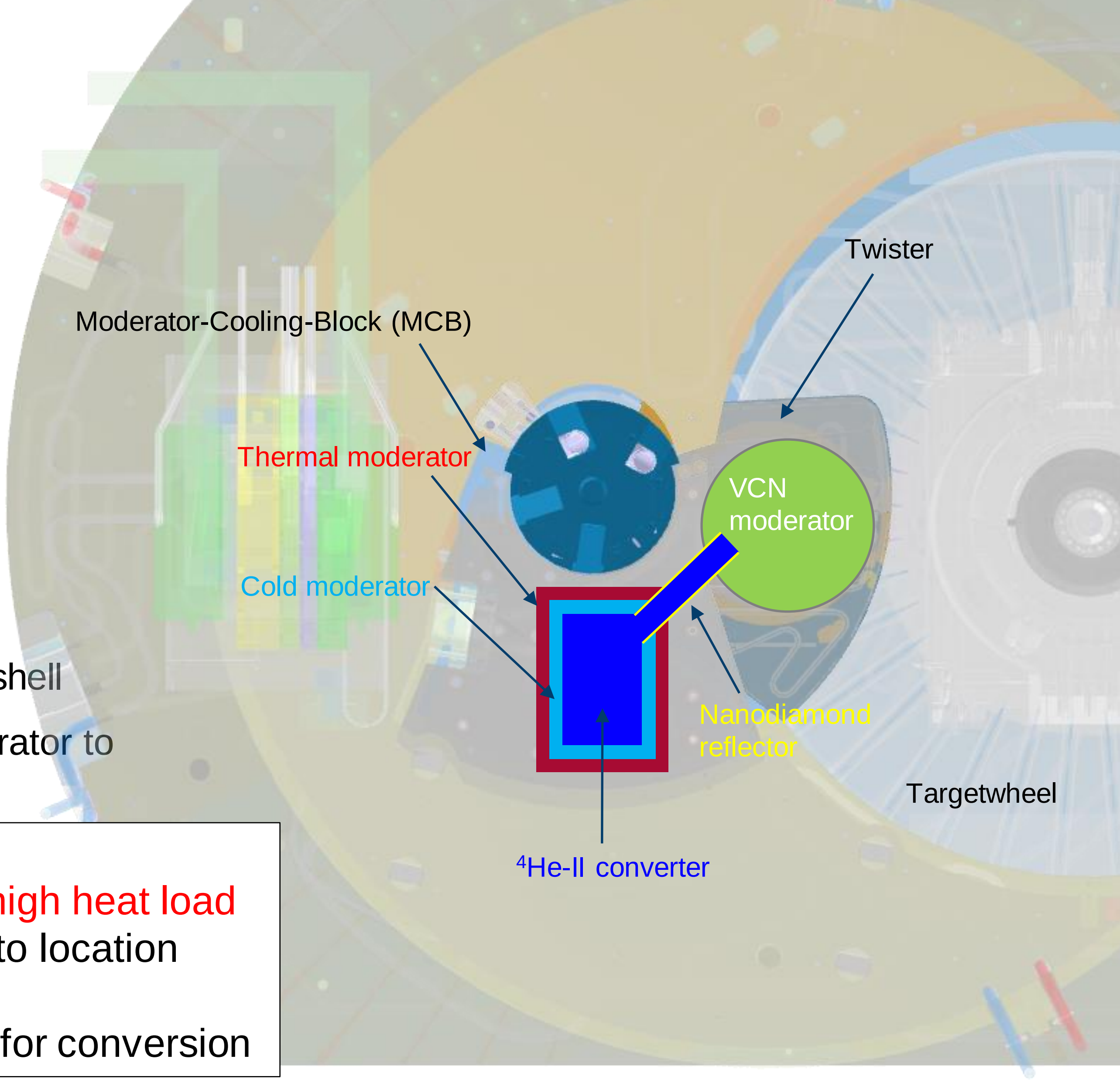
Concept 1:

- UCN converter based on

  3 stage coaxial design
- Converter medium: ^{4}He-II
- Location: Moderator-Cooling-Block (MCB)

2 origin design:

1. Moderation of fast neutrons in thermal and cold moderator shell
2. Neutron guide optimised für 8,9Å neutrons from VCN moderator to He-II converter



Advantages of MCB location:
- Close to spallation center → high neutron flux but also high heat load
- Supply with different coolants (H_2O, LD_2) already close to location
- Shielding blocks can be replaced by UCN source
- LD_2 moderator close → cold neutrons can be extracted for conversion

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

UCN source concept design

MCNP simulation model – Calculation of UCN production rate

- UCN production rate P_{UCN} [cm^{-3} s^{-1}] figure of merit of UCN source

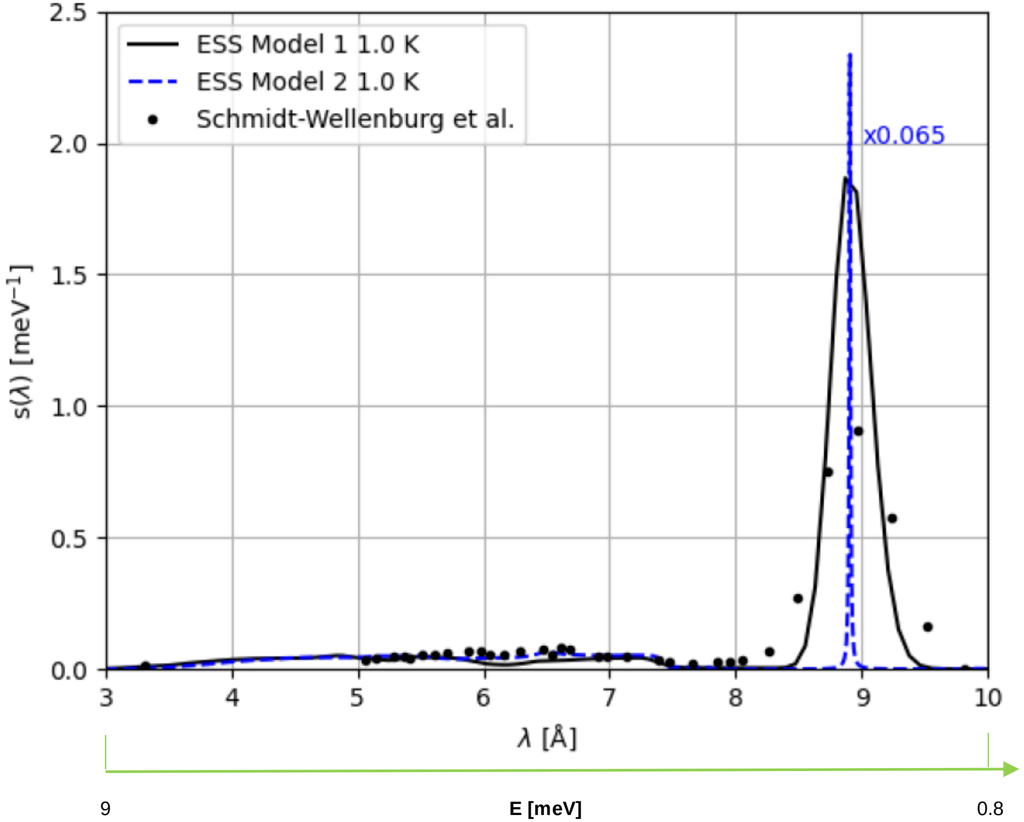
  → UCNs can not be transported directly with MCNP:

$$P_{UCN}(V_c) = N\,\sigma V_c \frac{k_c}{3\pi} \int_0^\infty \frac{d\phi}{d\lambda} s(\lambda)\lambda\, d\lambda$$

[4]

With

V_C:	UCN potential
N:	Number of density of ^4He atoms
K_C:	Cut of wavenumber for UCNs
σ:	Bound atom cross section of ^4He



HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

HighNess JÜLICH Forschungszentrum

[4] Schmidt-Wellenburg et al. - Ultra cold neutron production by multiphonon processes in superfluid helium under pressure – Nuclear Instruments and Methods in Physics Research A, 2009

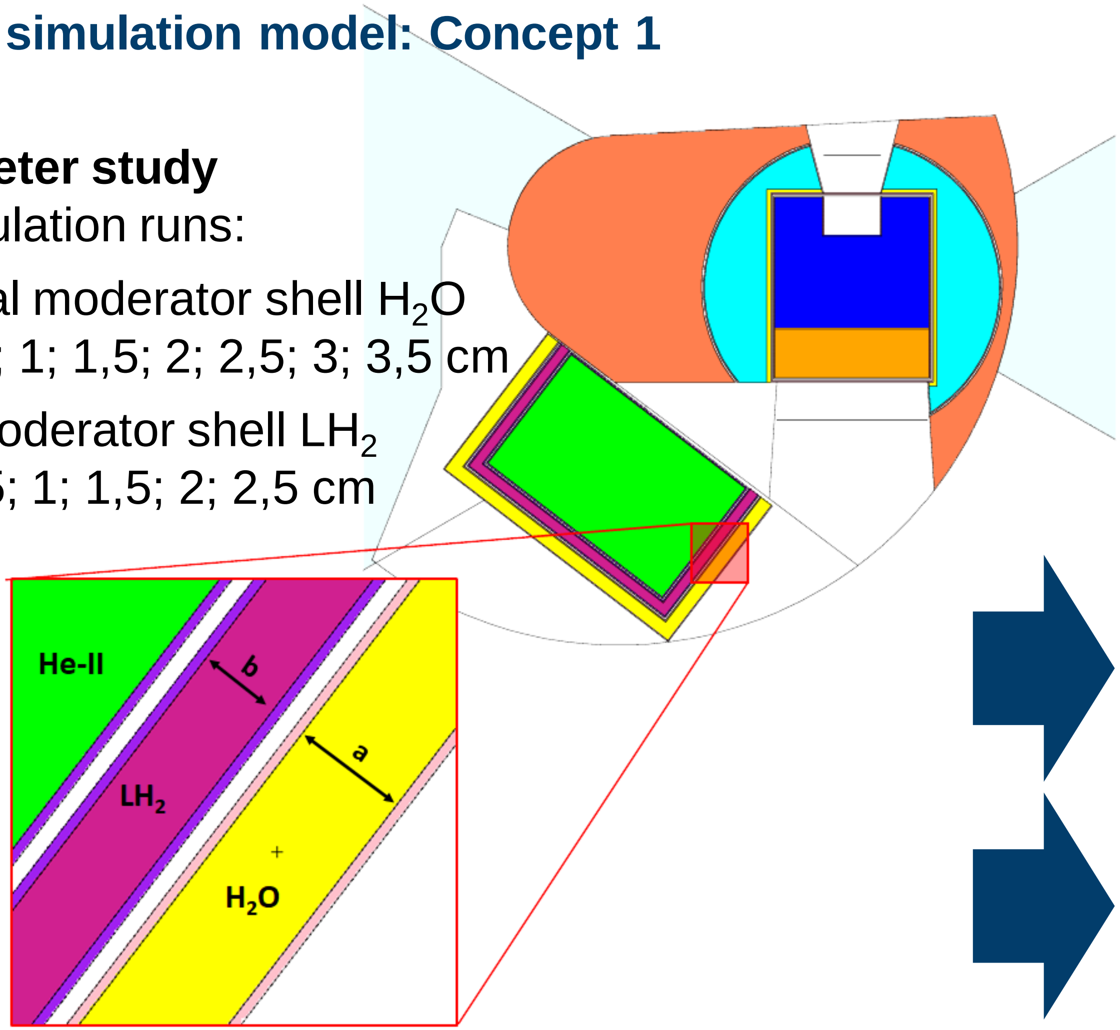
UCN source concept design

MCNP simulation model: Concept 1

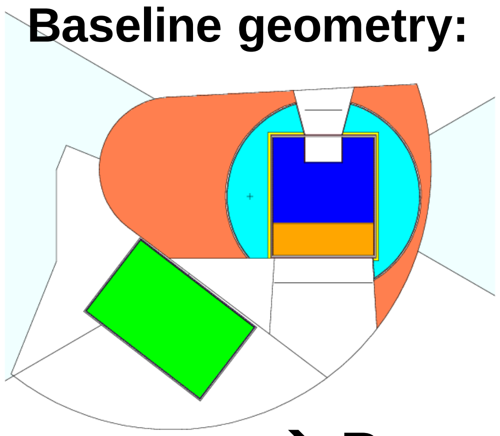
Parameter study
25 simulation runs:

Thermal moderator shell H_2O
a = 1,5; 1; 1,5; 2; 2,5; 3; 3,5 cm

Cold moderator shell LH_2
b = 0,5; 1; 1,5; 2; 2,5 cm

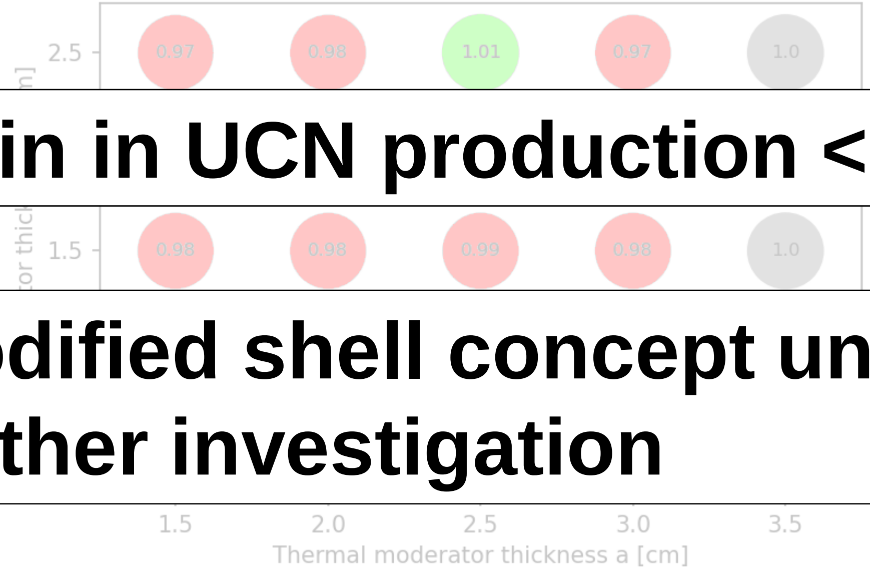


Baseline geometry:



Al 6061-T6 vessel
3mm wall size filled with
He-II @ 1K
$V_{He\text{-}II}$ = 24233 cm³

→ P_{UCN} = 2.16E+03 cm^{-3} s^{-1}



Gain in UCN production < 2%

Modified shell concept under further investigation

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

HighNess JÜLICH Forschungszentrum

UCN source concept design

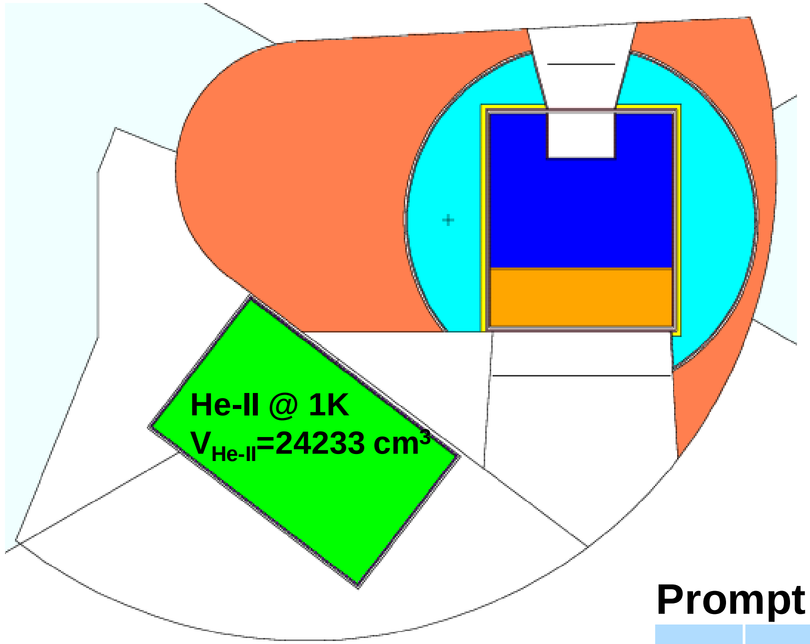
MCNP simulation model: Concept 2

Concept 2: „Plain & simple"

→ Aluminium vessel with minimized wall thickness

→ Maximized He-II volume

→ Passive He-II heatpipe design designated to remove heatload from UCN source



→ P_{UCN} = 2.16E+3 cm^{-3} s^{-1}

Additional factors for high performance:

→ Purification of ^{4}He-II (reduction of contaminants ^{3}He, H_2)

→ Coating of inner walls:

High Pseudo-Fermi potential of coating material compared to UCN energy needed → **^{58}Ni**

Prompt heat load (5 MW p-beam):

	Al	He-II	Σ
γ	173 W	84 W	256 W
n	11 W	61 W	71 W
			328 W

Experimental investigations of He-II planned at Forschungszentrum Jülich

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

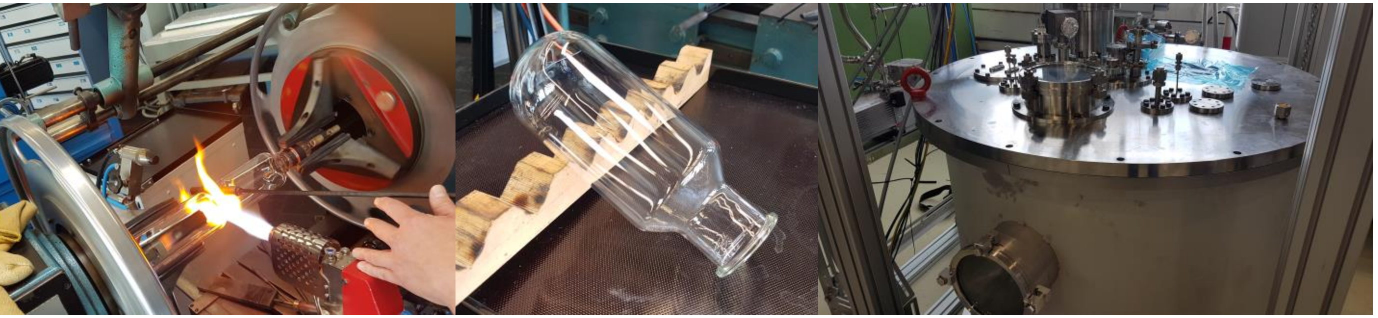
OVERVIEW

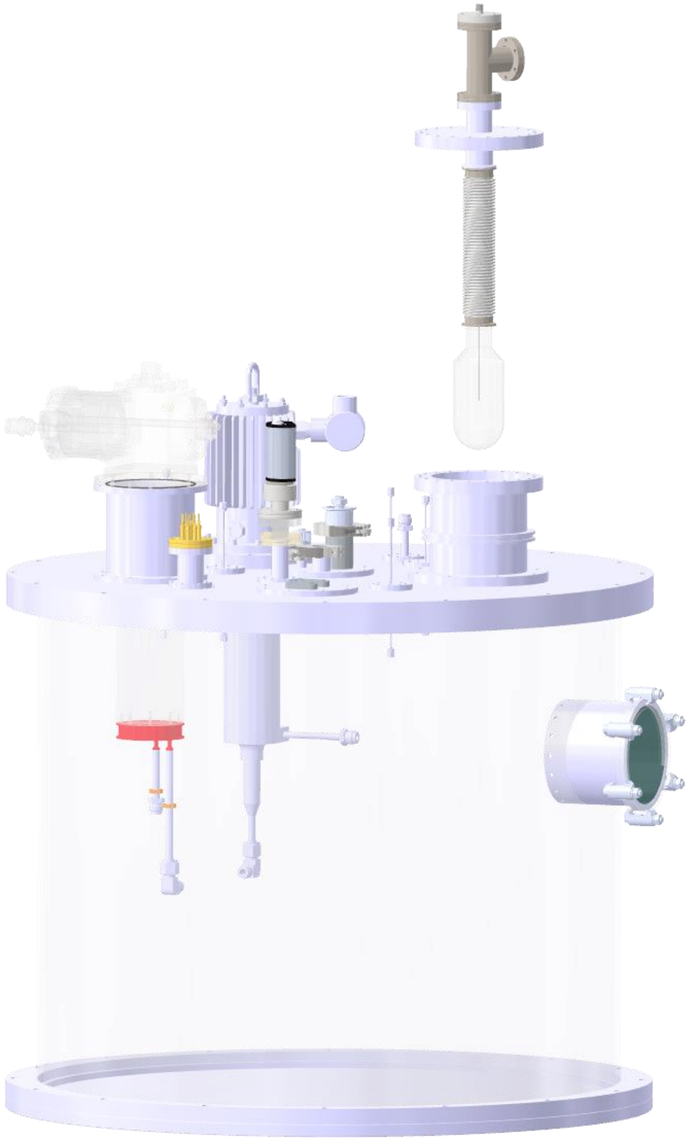
- How to create ultra cold neutrons (UCN)
- MCNP Simulation results for an ESS UCN source
- **Experimental investigation of He-II**
- Conclusion of results & outlook

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Experimental investigation of He-II properties

- Glass-cryostate for visual investigation of the ^{4}He-I to ^{4}He-II phase-change
- Filling of glass vessel by connection to Helium dewar
- Cooling of ^{4}He bath from 4,2K to 1,6K by pressure reduction with vacuum pump to induce phase-change
- Investigating phase stability by applying heat load into the center of the bath

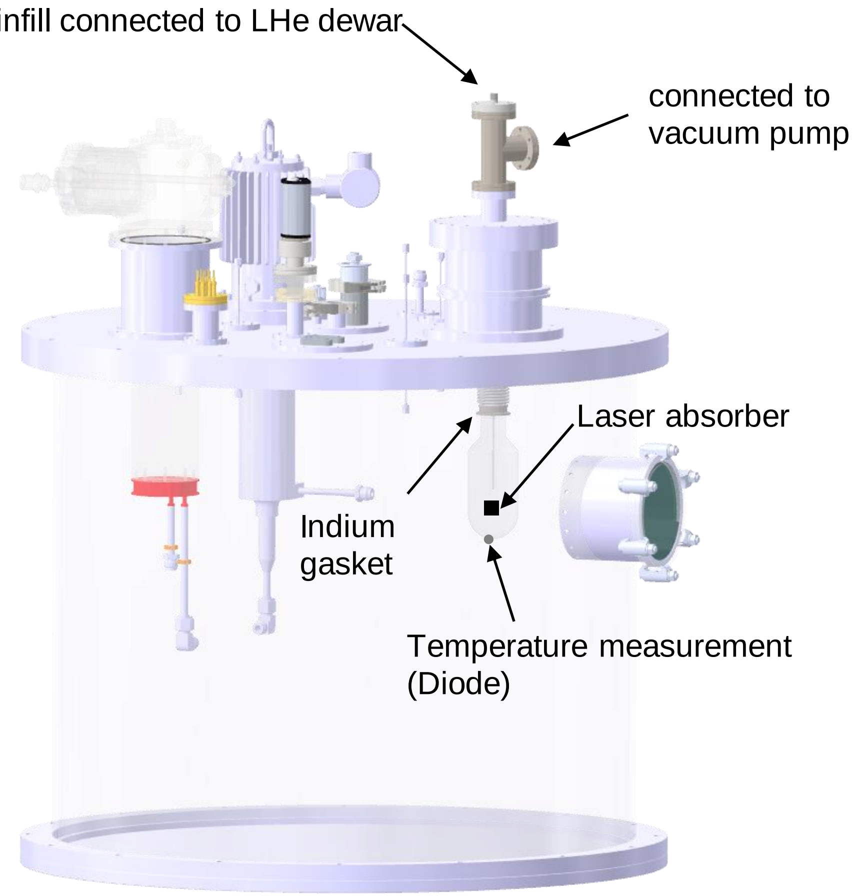


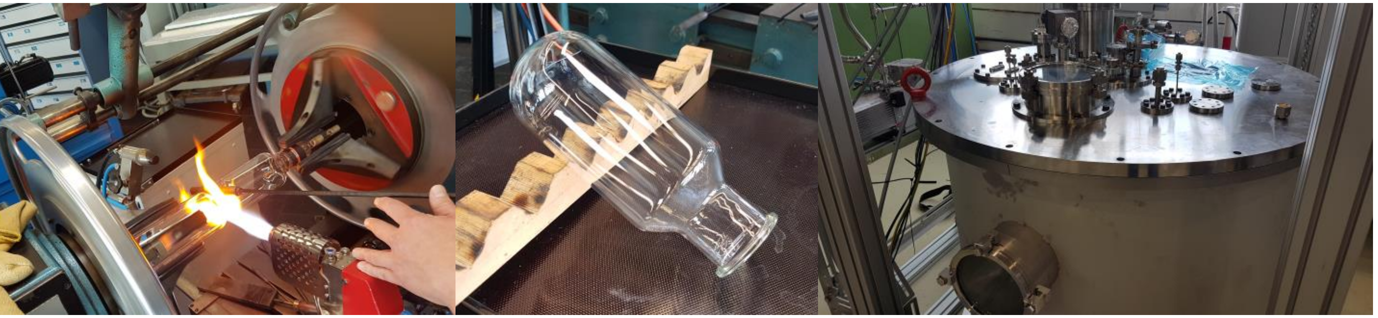


HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Experimental investigation of He-II properties

- Glass-cryostate for visual investigation of the ^{4}He-I to ^{4}He-II phase-change
- Filling of glass vessel by connection to Helium dewar
- Cooling of ^{4}He bath from 4,2K to 1,6K by pressure reduction with vacuum pump to induce phase-change
- Investigating phase stability by applying heat load into the center of the bath

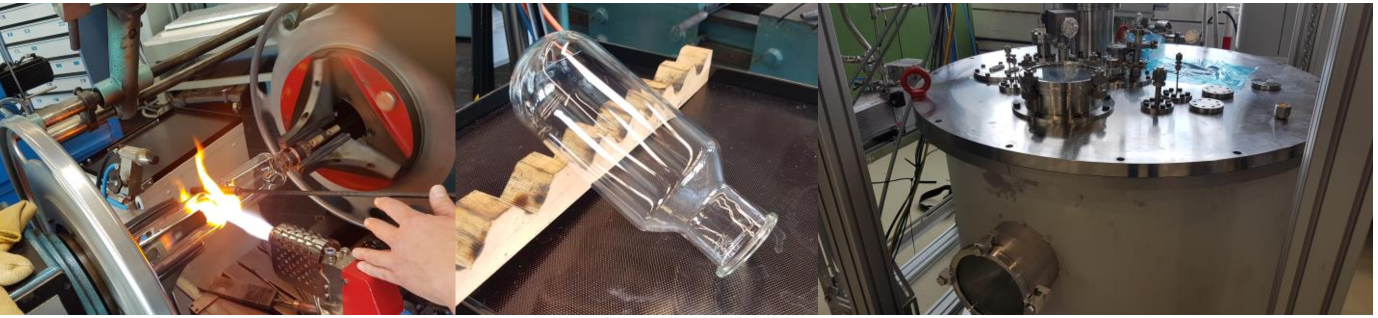




HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Experimental investigation of He-II properties

- Glass-cryostate for visual investigation of the ^{4}He-I to ^{4}He-II phase-change
- Filling of glass vessel by connection to Helium dewar
- Cooling of ^{4}He bath from 4,2K to 1,6K by pressure reduction with vacuum pump to induce phase-change
- Investigating phase stability by applying heat load into the center of the bath



Bath temperature:	4,2 K
Pressure:	1000 mbar
Bath filling	100 %

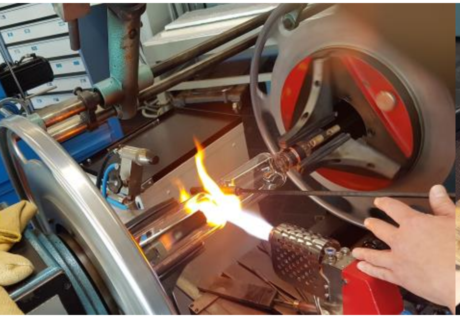
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

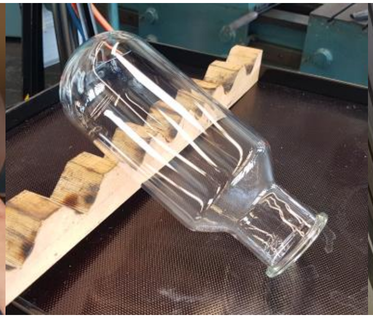
Experimental investigation of He-II properties

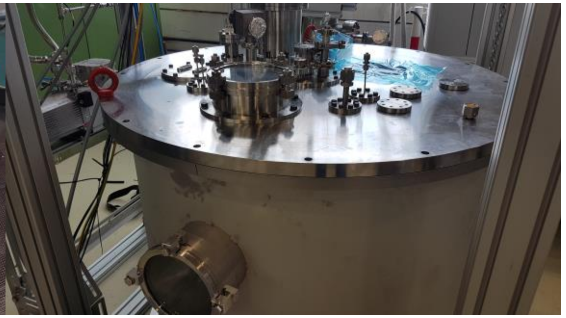
- Glass-cryostate for visual investigation of the ^{4}He-I to ^{4}He-II phase-change
- Filling of glass vessel by connection to Helium dewar
- Cooling of ^{4}He bath from 4,2K to 1,6K by pressure reduction with vacuum pump to induce phase-change
- Investigating phase stability by applying heat load into the center of the bath

Bath temperature:	1,6 K
Pressure:	7,6 mbar
Bath filling	58 %

Phase II



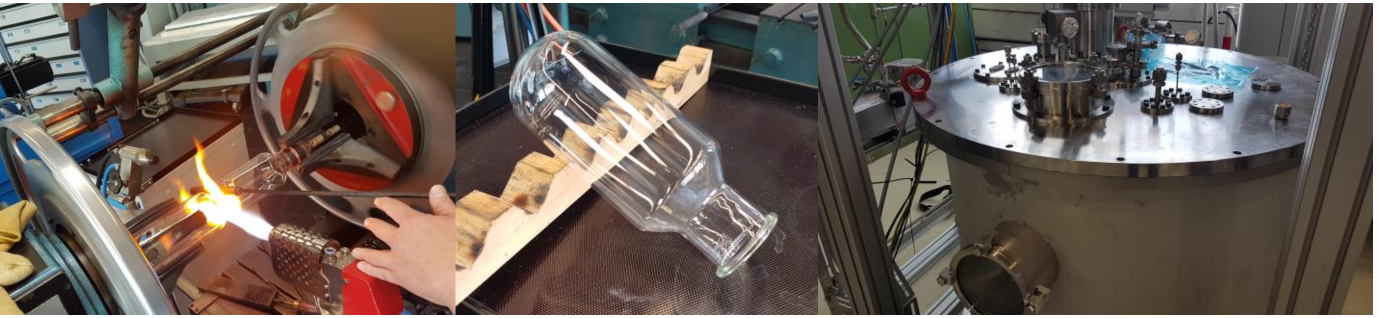


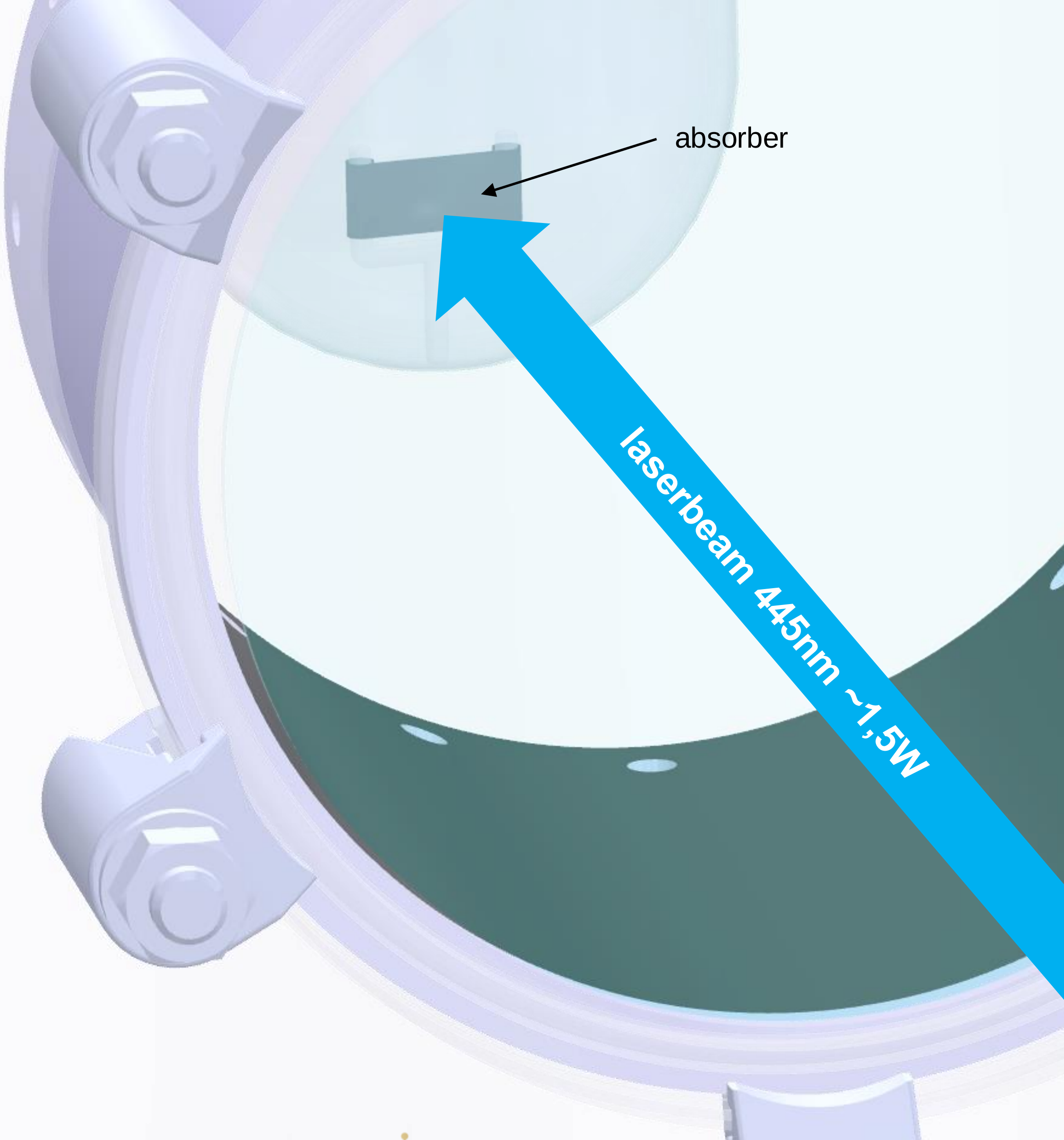


HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Experimental investigation of He-II properties

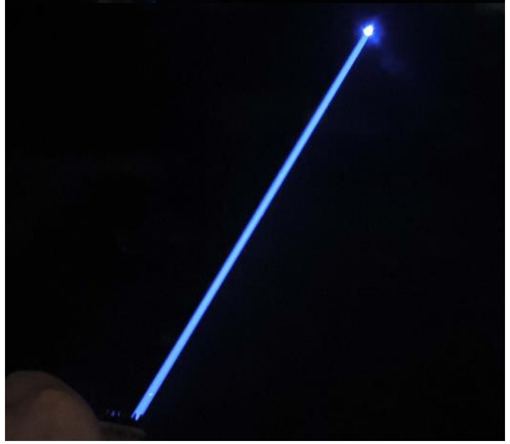
- Glass-cryostate for visual investigation of the ^{4}He-I to ^{4}He-II phase-change
- Filling of glass vessel by connection to Helium dewar
- Cooling of ^{4}He bath from 4,2K to 1,6K by pressure reduction with vacuum pump to induce phase-change
- Investigating phase stability by applying heat load into the center of the bath





HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Experimental investigation of He-II properties



Laser for apply of heat load into the He-II volume:

1,5W @ 445nm

- Low absorption in the glas vessel → heat deposition into the absorber in the center of the He-II bath
- Focus optics allows beam broadening to ~10x3mm on absorber → Power density max. ~ 50mW/mm^2
- Focused (~0,2x0,01mm) → power density max. ~160W/mm^2

Power control in two ways:

→ Continious wave power reduction with gray filters

→ Pulse width modulation to reduce average power of beam

→ Simulation of pulse structure of ESS proton beam possible

➡ Flexible setup to taylor the laser beam in regard to the expected heat loads (MCNP) for an experimental simulation of the ESS conditions

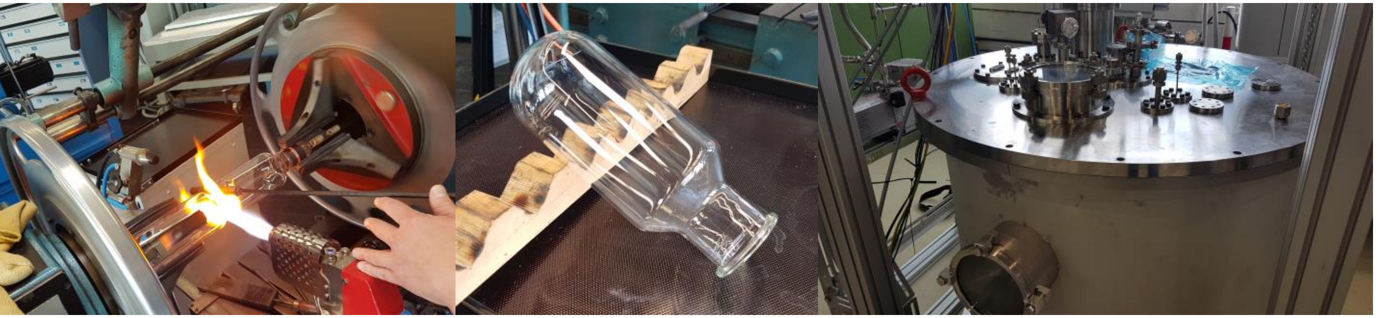
HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

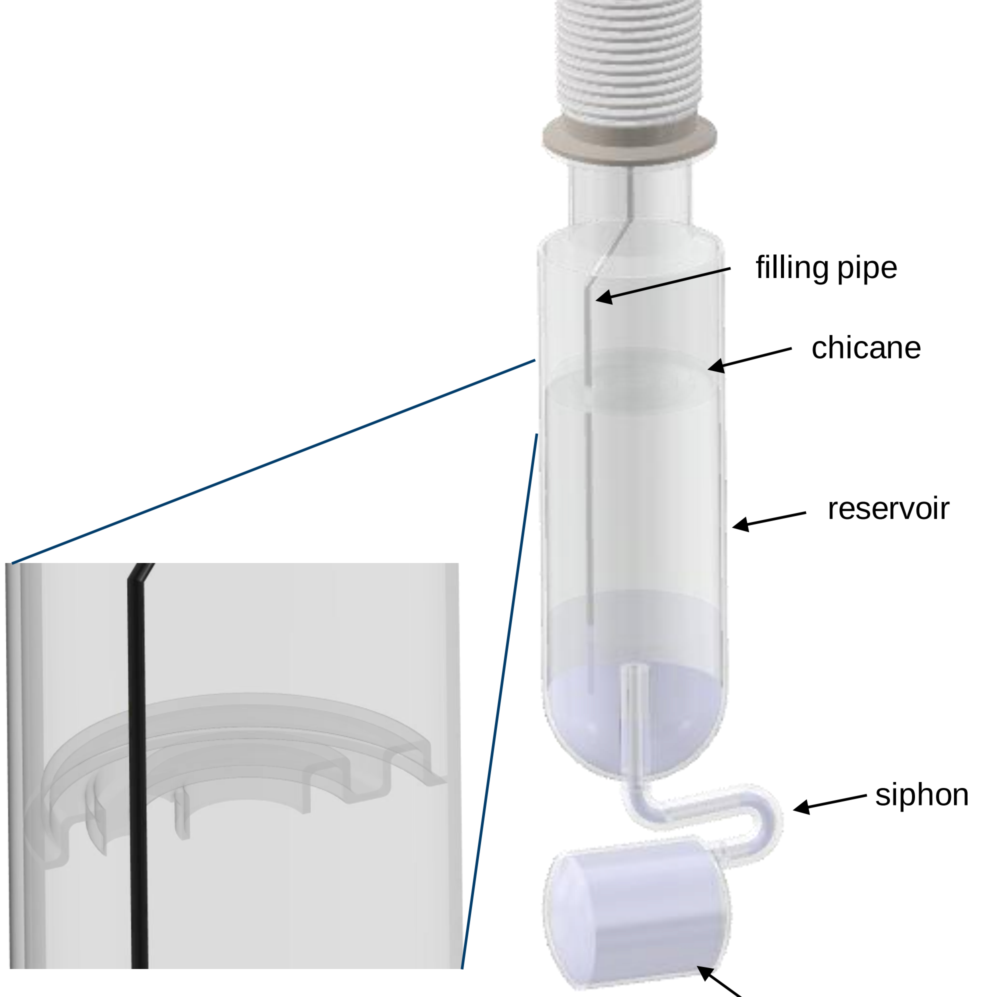
Experimental investigation of He-II properties

Second version of glass vessel:

→ Investigation of mixing behaviour He-I <-> He-II

→ Investigation of limits for heat transport through limited cross section area





HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

OVERVIEW

- How to create ultra cold neutrons (UCN)
- MCNP Simulation results for an ESS UCN source
- Experimental investigation of He-II
- **Conclusion of results & outlook**

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Results

- 3 stage coaxial UCN source design based on He-II as conversion medium has been evaluated in MCNP

  → Coaxial shell design is not effient to increase the UCN production rate

→ **Best option** is a **„plain and simple“ design**:

  → Aluminium vessel with minimized wall thickness

  → Maximized He-II volume

  → Passive He-II heatpipe design to remove heatload from UCN source

Outlook

- Experimental investigations on He-II regarding:
  - Phase stability
  - Heat conductivity

  → Experimental simulation of ESS conditions based on MCNP simulation results (expected heatload, pulse structure):
    - Heatload deposition in the center of He-II volume
    - Heatload deposition in the vessel walls
    - Limits for crossection area for heat transport through He-II

HighNESS is funded by the European Union Framework Programme for Research and Innovation Horizon 2020, under grant agreement 951782

Thank you for your attention!