

# **NEUTRON MODERATORS AT EUROPEAN SPALLATION SOURCE**

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Alan Takibayev  
European Spallation Source ERIC  
Lund | Sweden

# ESS OVERVIEW

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## WHY NEUTRONS?

Neutrons are very useful for probing materials:

- Neutrons are neutral, interact with electrons rather weakly, and, therefore, are highly penetrating;
- Neutrons interact with nuclei rather strongly and can distinguish between isotopes;
- Neutrons can be "cooled down" to wavelengths (i. e. energies) similar to atomic spacing.

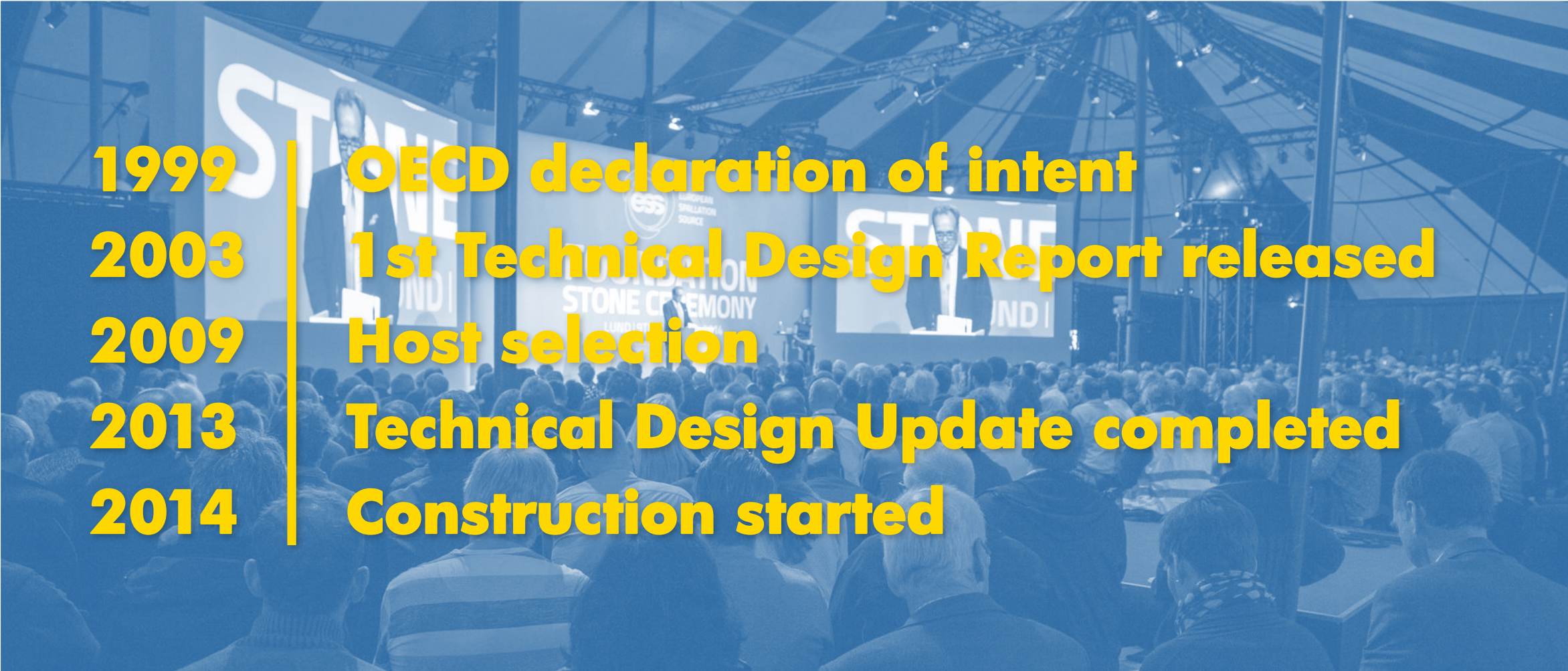
## HOW TO GET NEUTRONS?

Neutrons can be produced in a variety of ways: fission, fusion, spallation, stripping, etc. Currently, two types of facilities are capable of producing neutrons at an industrial scale:

- Nuclear reactors,
- Spallation neutron sources.

# SELECTED NEUTRON SOURCES AROUND THE WORLD



- 
- 1999** | **OECD declaration of intent**
  - 2003** | **1st Technical Design Report released**
  - 2009** | **Host selection**
  - 2013** | **Technical Design Update completed**
  - 2014** | **Construction started**



# ESS AERIAL VIEW 2017 OCTOBER

<https://europeanspallationsource.se/media-bank>



# ESS AERIAL VIEW 2019 APRIL

<https://europeanspallationsource.se/media-bank>



# ESS AERIAL VIEW 2022 FEBRUARY

<https://europeanspallationsource.se/media-bank>





# ESS LAYOUT

<https://europeanspallationsource.se/media-bank>

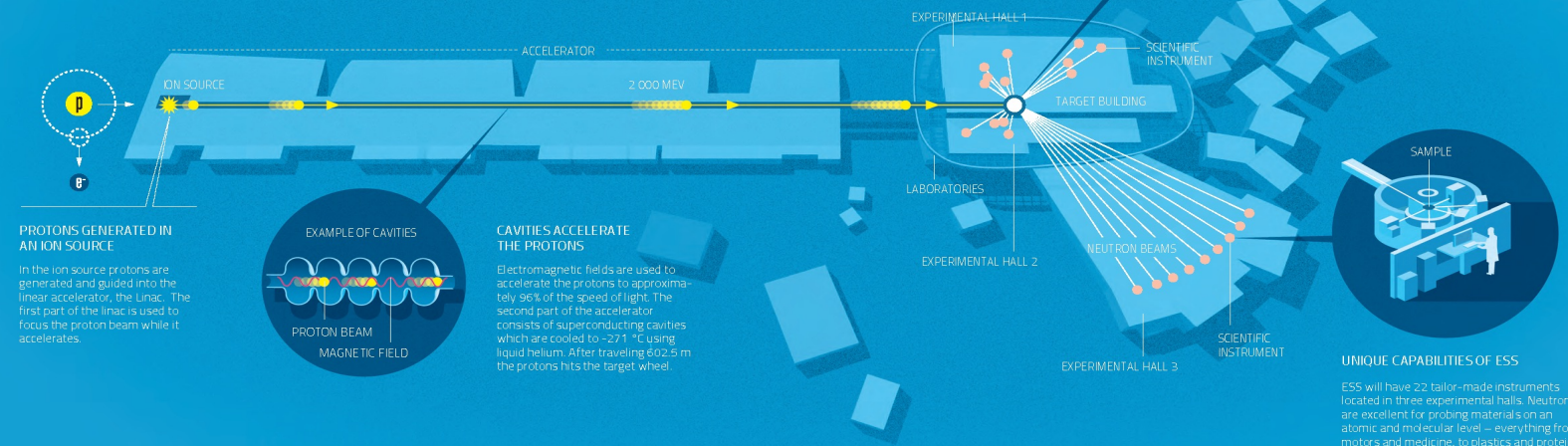
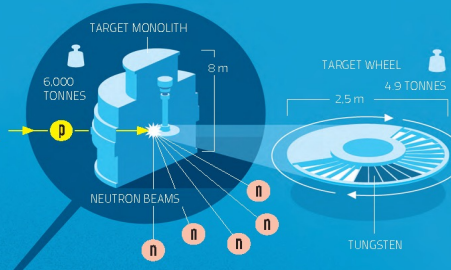
## European Spallation Source

The European Spallation Source (ESS) is a multi-disciplinary research centre based on the world's most powerful neutron source. ESS will give scientists new possibilities in a broad range of research, from life science to engineering materials, from heritage conservation to energy and magnetism. ESS is a pan-European project, with Sweden and Denmark serving as host countries. The main research facility is being built in Lund, Sweden, and the Data Management and Software Centre (DMSC) is located in Copenhagen, Denmark.



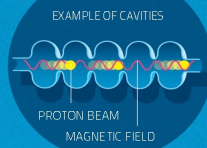
### THE TARGET IS THE NEUTRON SOURCE

When the accelerated protons hit the rotating tungsten target wheel, spallation occurs and neutrons are scattered from the tungsten nucleus. The more neutrons produced and collected in the target, the "brighter" the neutron source. The neutrons are directed through moderators and neutron guides to the scientific instruments where they are used for experiments. The Target monolith consists of the Target wheel, moderators, a cooling system and shielding, and weighs approximately 6,000 tonnes.



### PROTONS GENERATED IN AN ION SOURCE

In the ion source protons are generated and guided into the linear accelerator, the linac. The first part of the linac is used to focus the proton beam while it accelerates.



### CAVITIES ACCELERATE THE PROTONS

Electromagnetic fields are used to accelerate the protons to approximately 96% of the speed of light. The second part of the accelerator consists of superconducting cavities which are cooled to -271 °C using liquid helium. After traveling 602.5 m the protons hit the target wheel.

### TOTAL BUILDING AREA 65 000 m<sup>2</sup>

The ESS facility will be approximately 700 metres in total length. The target building will be 125 metres long and about 30 metres high. The 537-metre-long accelerator tunnel is built underground and covered with soil.

Concrete:	65,000 m <sup>2</sup>
Rebar:	6,000 tonnes
Pipes:	40 km
Cables:	2,000 km
Total volume:	400,000 m <sup>3</sup>

### PILES TO AVOID MOVEMENTS

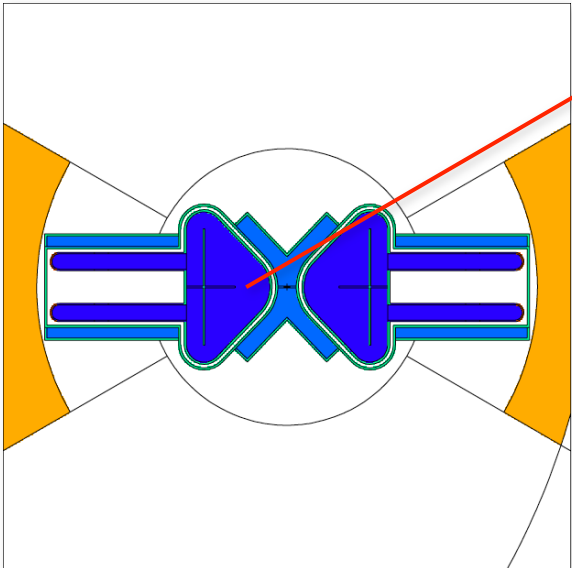
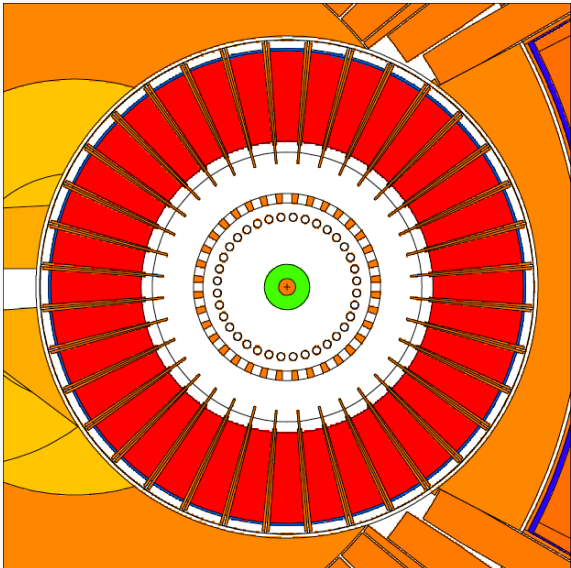
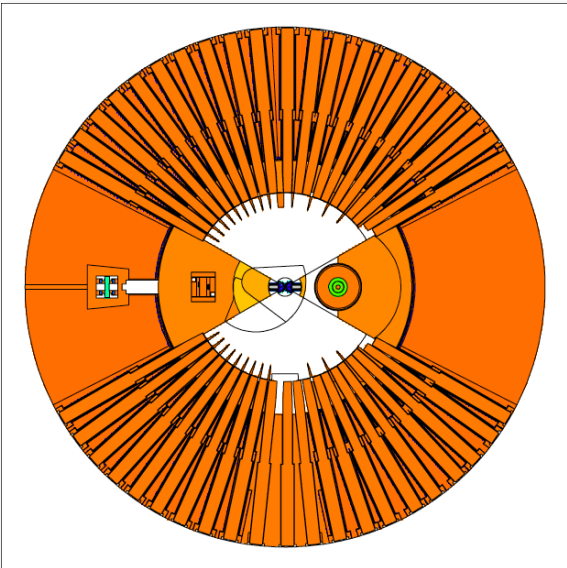
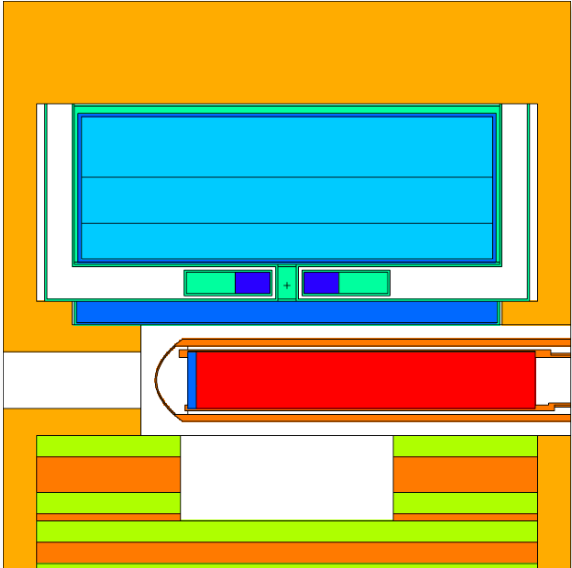
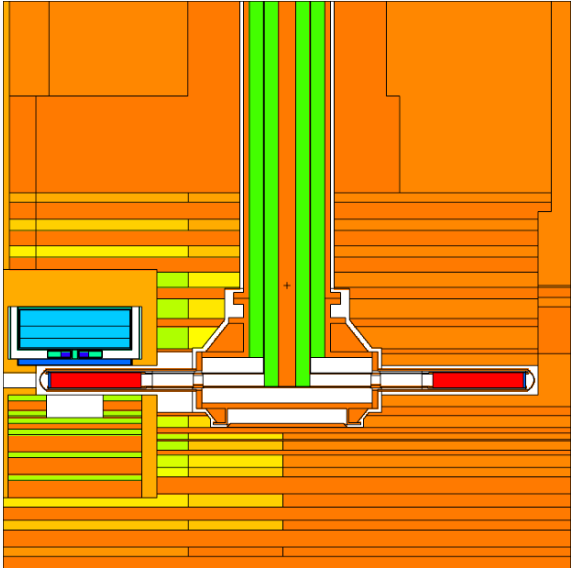
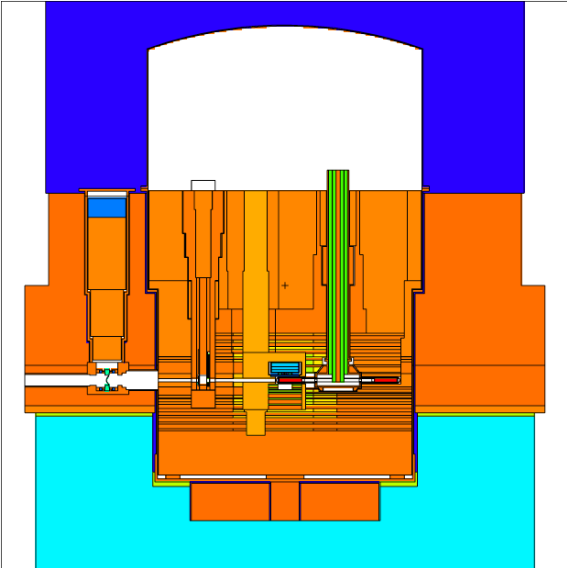
The heavy Target building and experimental halls are resting on a total of 6,400 piles of different types, in order to avoid unwanted movements in the structure.

### UNIQUE CAPABILITIES OF ESS

ESS will have 22 tailor-made instruments located in three experimental halls. Neutrons are excellent for probing materials on an atomic and molecular level – everything from motors and medicine, to plastics and proteins. The neutrons hit the sample and detectors register the neutron scattering, giving precise information about the material's structure and dynamics.



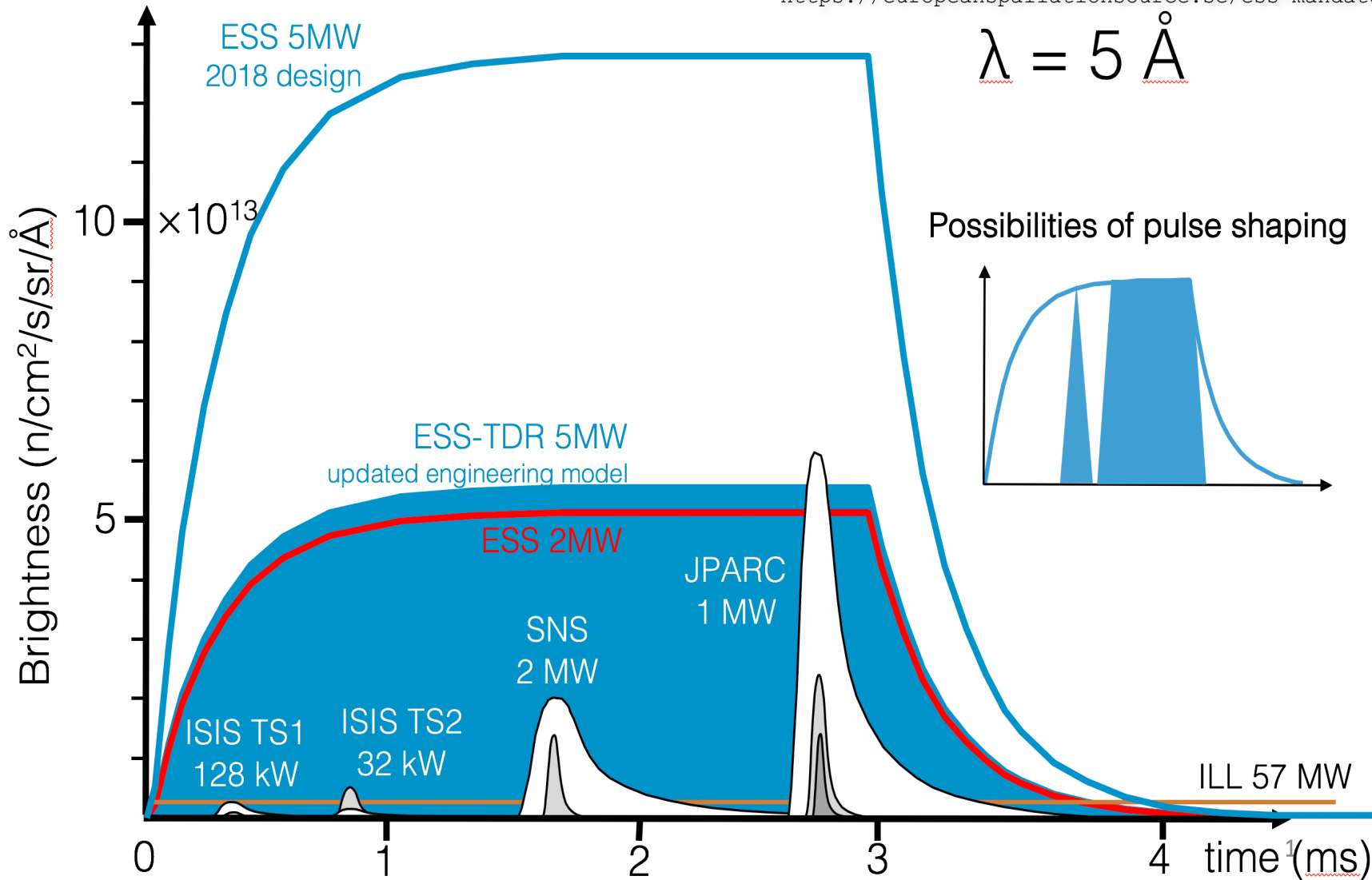
# ESS TARGET STATION MONOLITH



20 K Liquid Para-H<sub>2</sub>  
Moderator

# ESS PERFORMANCE

<https://europeanspallationsource.se/ess-mandate>



The European Spallation Source (ESS), under construction in Lund, Sweden, will be the most powerful neutron source in the world for neutron scattering experiments. The design of the ESS moderator system to produce both cold and thermal neutrons is based on the novel concept of a high-brightness bi-spectral moderator developed at ESS – the so-called quasi-low-dimensional moderators.

# ESS PATH TO LOW-DIMENSIONAL MODERATORS

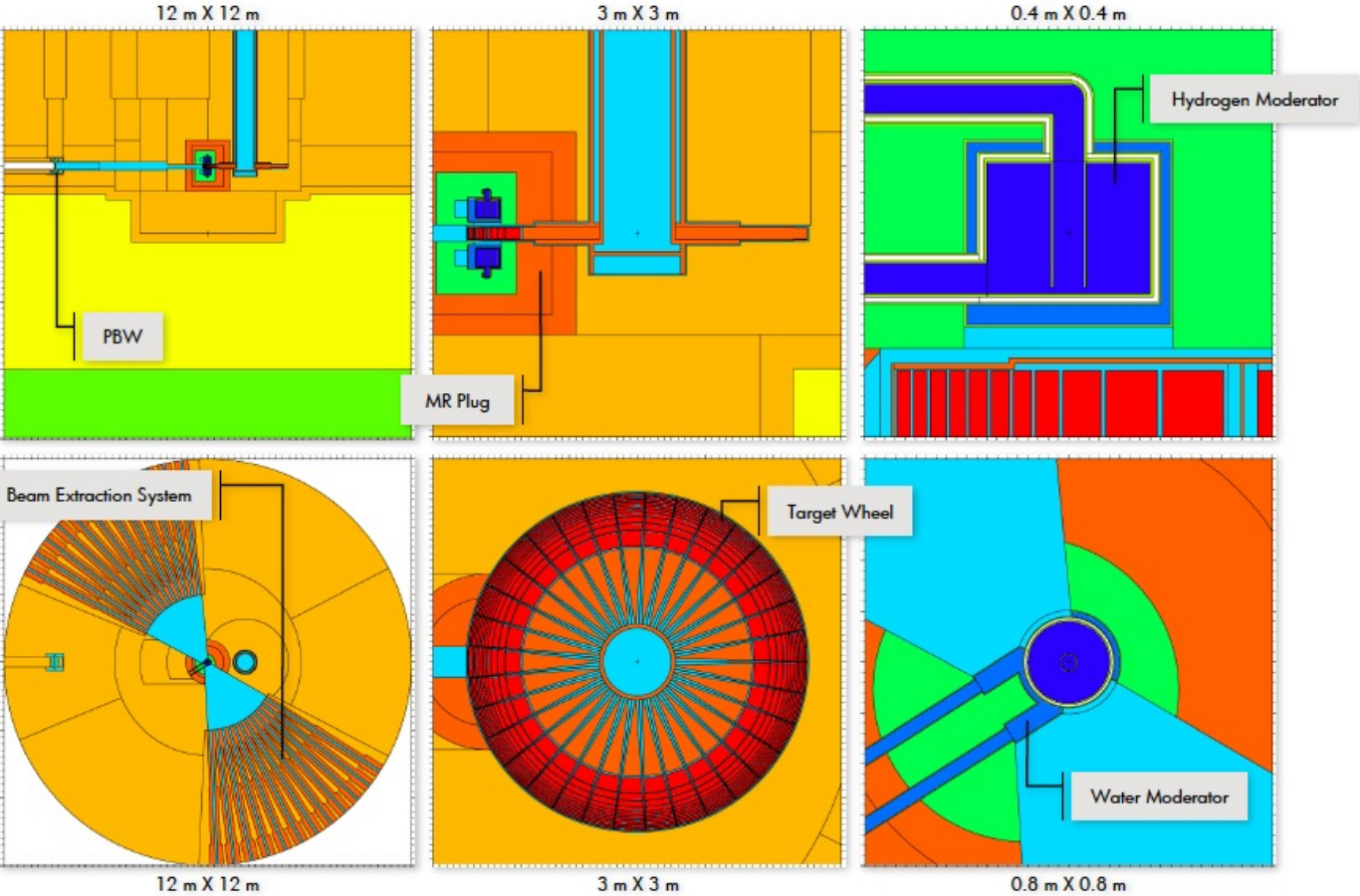


# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## ESS-2013

MCNP/PHITS neutronic model



# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## GENERIC VOLUME MODERATOR

Hydrogen moderator of 13 cm height X 16 cm diameter



0-5 meV Brightness:

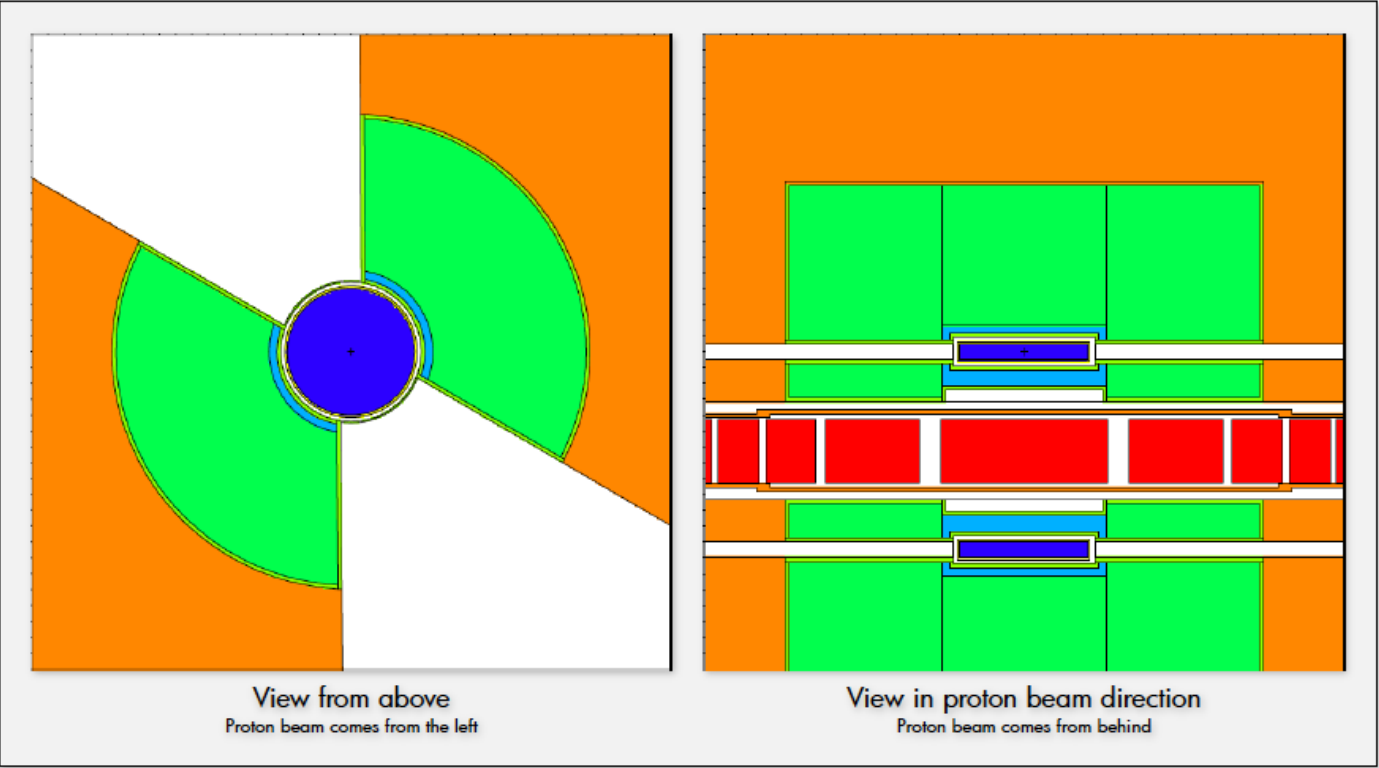
1.0

# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## CONTRACTING MODERATOR HEIGHT

Hydrogen moderator of 2 cm height X 16 cm diameter



0-5 meV Brightness:

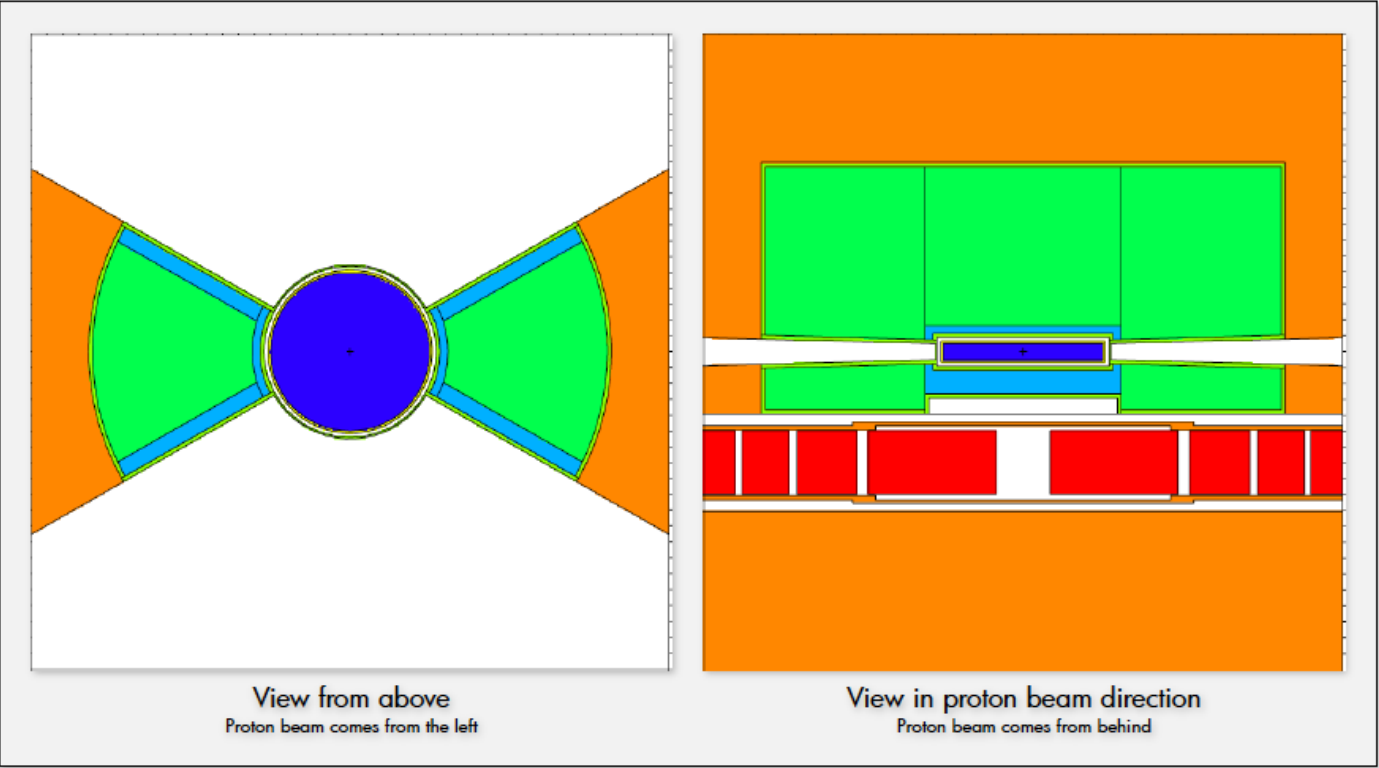
3.0

# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## FLAT MODERATOR CONCEPTUAL MODEL

Hydrogen moderator of 2 cm height X 20 cm diameter



0-5 meV Brightness:

3.3

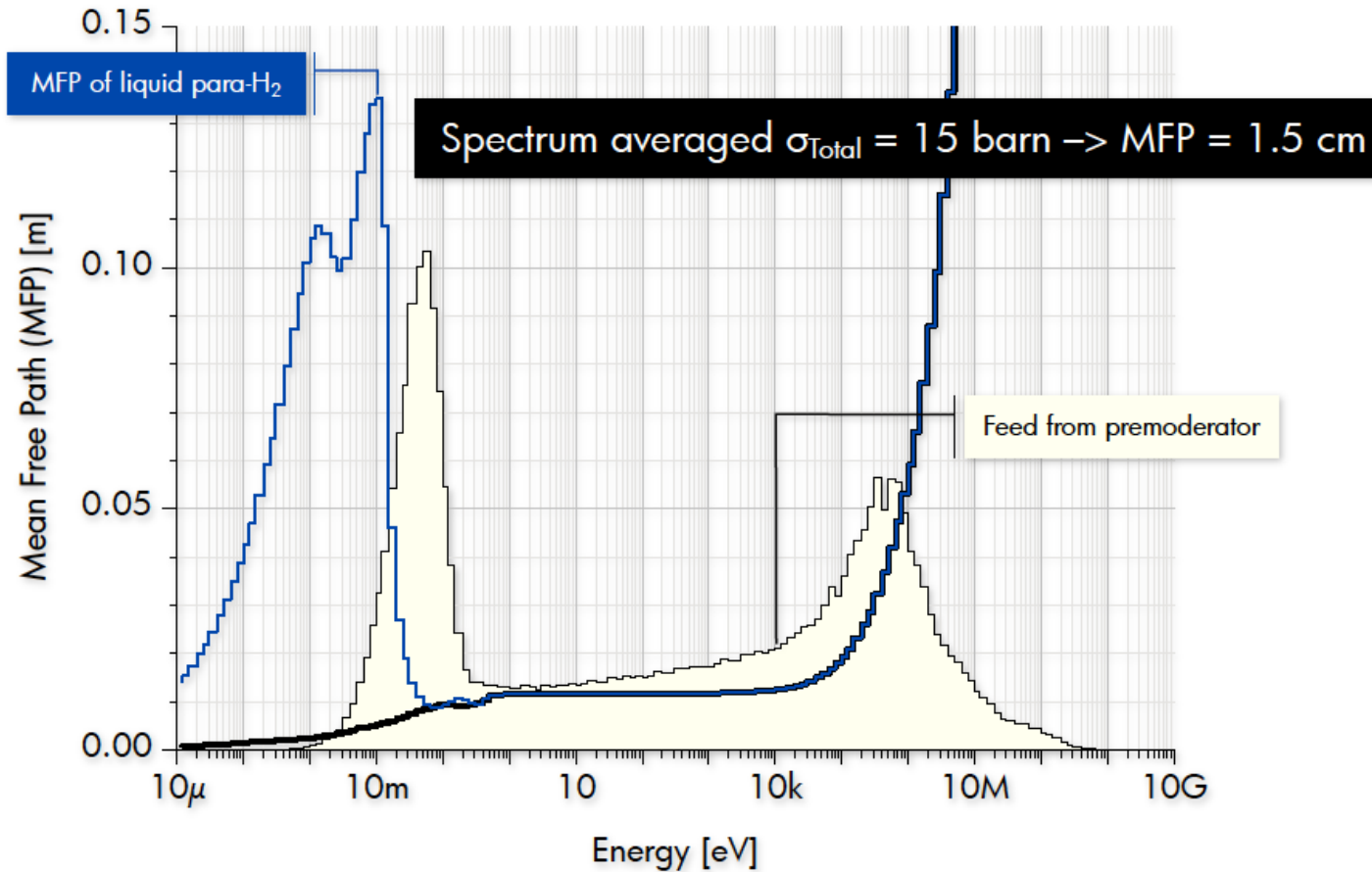


# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## WHY FLAT MODERATOR WORKS

A few cm of liquid hydrogen is enough to moderate neutrons





## PHYSICS SUMMARY

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Neutrons are effectively moderated in a few cm of liquid hydrogen

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Less parasitic absorption due to less amount of hydrogen

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Less perturbation due to less amount of reflector removed

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It works with any hydrogen-rich materials

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Para-H<sub>2</sub> transparency window allows to collect neutrons from depth

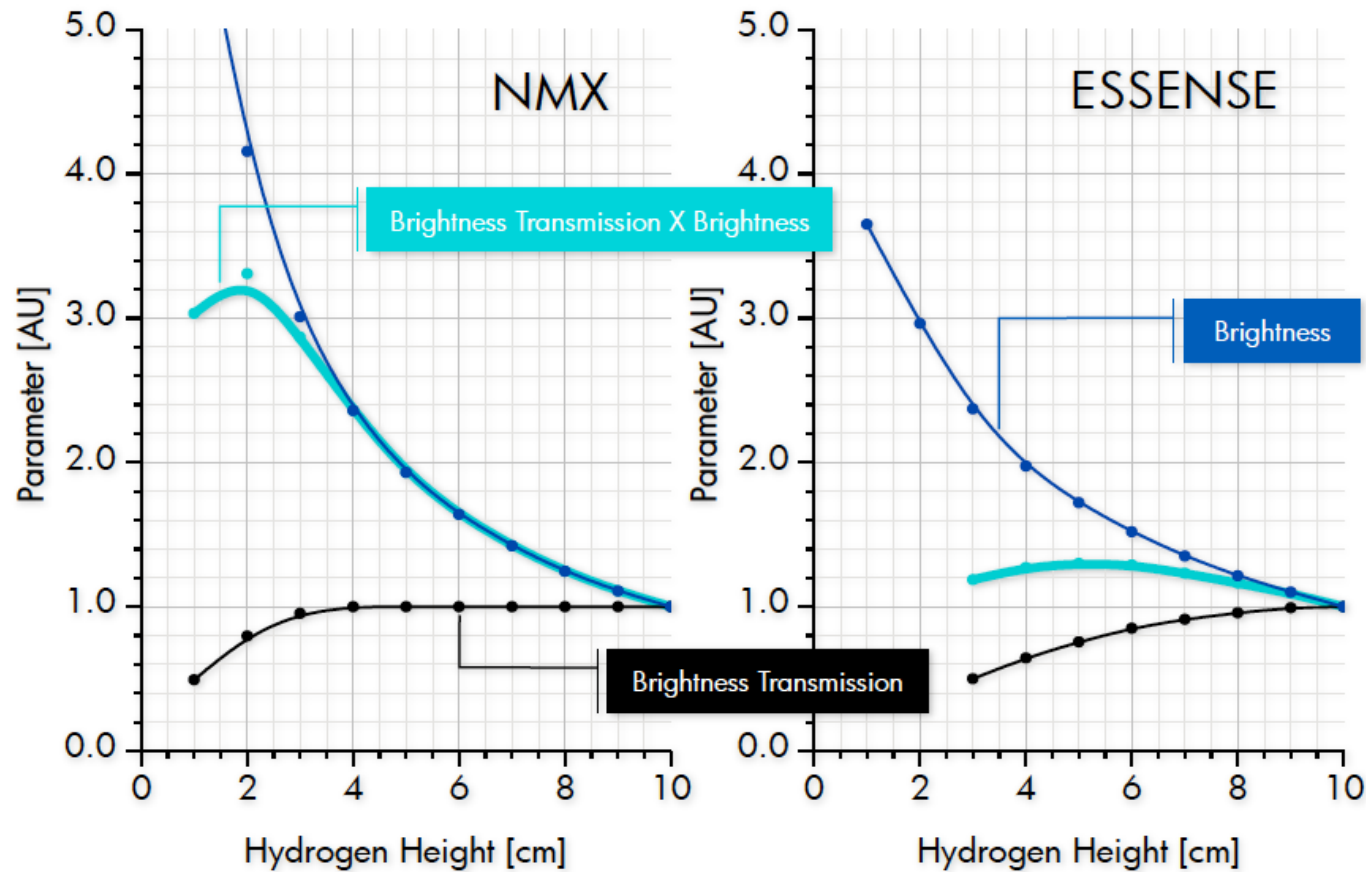
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# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## OPTIMIZATION OF INSTRUMENT SUITE

Two examples provided by K. Andersen

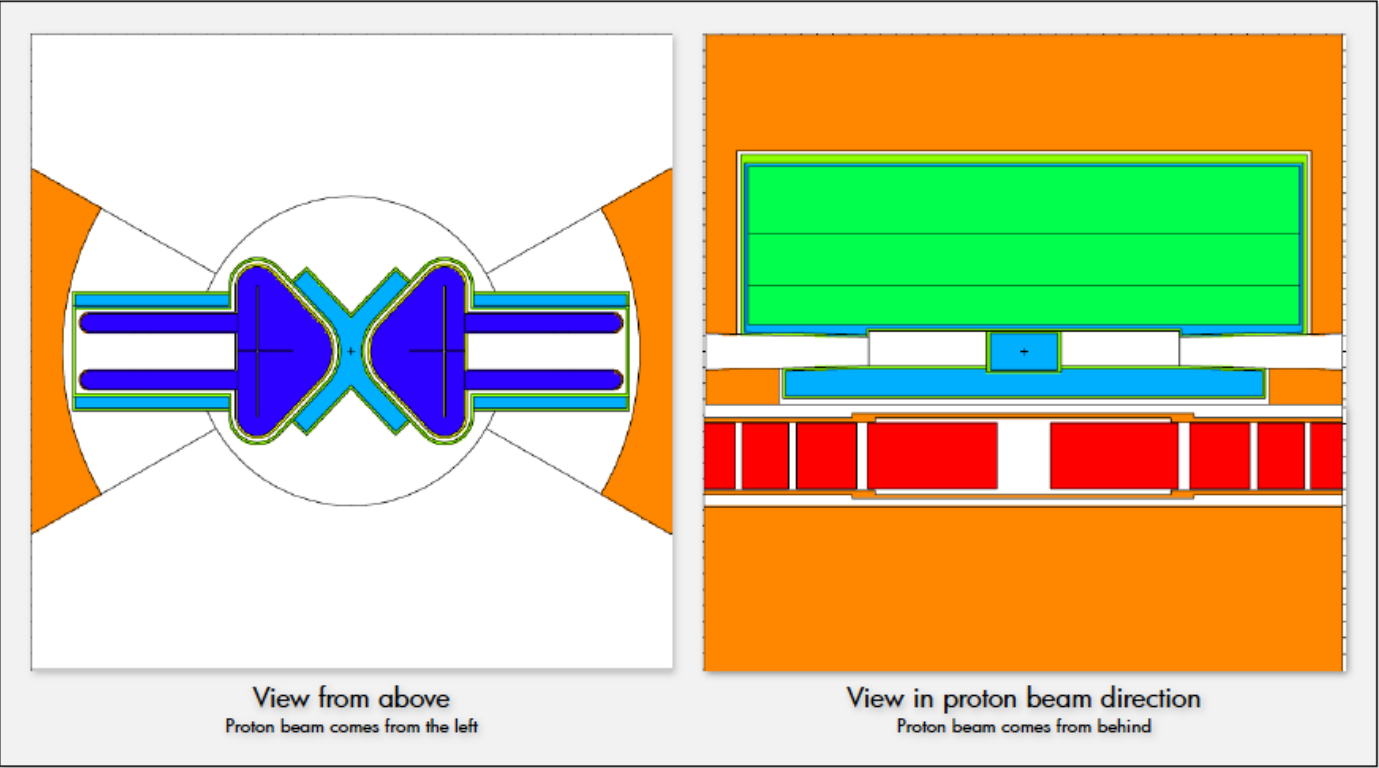


# ESS PATH TO LOW-DIMENSIONAL MODERATORS



## BUTTERFLY MODERATOR

Hydrogen moderators of 3 cm height above the target



0-5 meV Brightness:

2.5



Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Nuclear Inst. and Methods in Physics Research, A

journal homepage: [www.elsevier.com/locate/nima](http://www.elsevier.com/locate/nima)



## Design of the cold and thermal neutron moderators for the European Spallation Source



L. Zanini<sup>a,\*</sup>, K.H. Andersen<sup>a</sup>, K. Batkov<sup>a</sup>, E.B. Klinkby<sup>a,b</sup>, F. Mezei<sup>a</sup>, T. Schönfeldt<sup>a,b</sup>,  
A. Takibayev<sup>a</sup>

<sup>a</sup> European Spallation Source ESS ERIC, PO Box 176, 22100 Lund, Sweden

<sup>b</sup> DTU Nutech, Technical University of Denmark, DTU Risø Campus, Frederiksborgvej 399, DK-4000, Roskilde, Denmark

### ARTICLE INFO

#### Keywords:

Low-dimensional moderators  
Source brightness  
Parahydrogen  
Water  
Neutron beam extraction  
Long pulse sources

### ABSTRACT

At the European Spallation Source (ESS), neutrons will be generated by spallation induced by a 2-GeV proton beam on a tungsten target. ESS will have a grid of 42 beamports available for a variety of neutron scattering experiments. Neutron moderators will provide thermal and cold neutrons to the instruments, allowing bispectral beam extraction wherever needed.

The moderators were designed by adopting a holistic design approach that has considered brightness, brightness transfer and beam extraction constraints, resulting in a system with the following main features: low-dimensional moderators for enhanced brightness and maximum flux to the sample; a single moderator system placed above the spallation target; lateral shape of the moderators optimized for bispectral extraction. A moderator with a vertical extraction surface of 3 cm was chosen as result of the optimization process.

With all initial instruments pointing to the top moderator, and a beamport system that allows the possibility to extract neutrons from above and below the target, the adopted configuration opens the possibility to have different types of moderators below the target, so that other neutron beams of different intensity, or spectral shape, with respect to the ones delivered by the top moderator, could be envisaged, adding additional scientific opportunities to the facility without having the need to build a second target station.

# UPGRADEABILITY

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## EXPANDING THE SCOPE

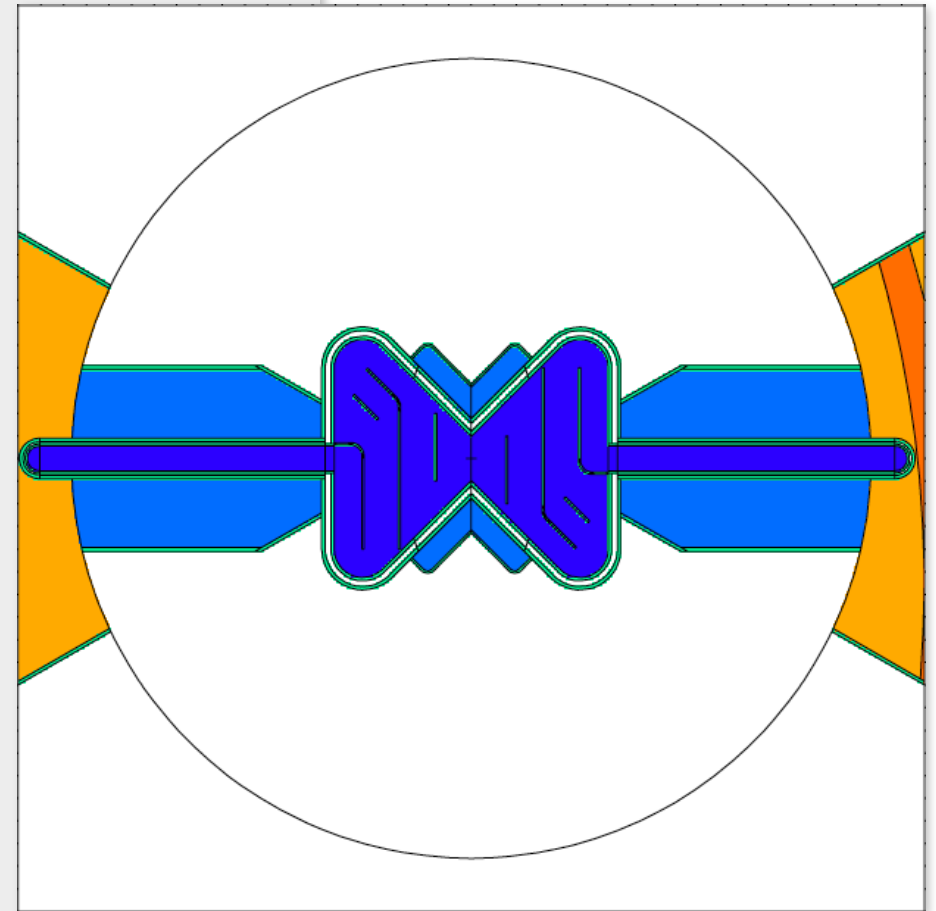
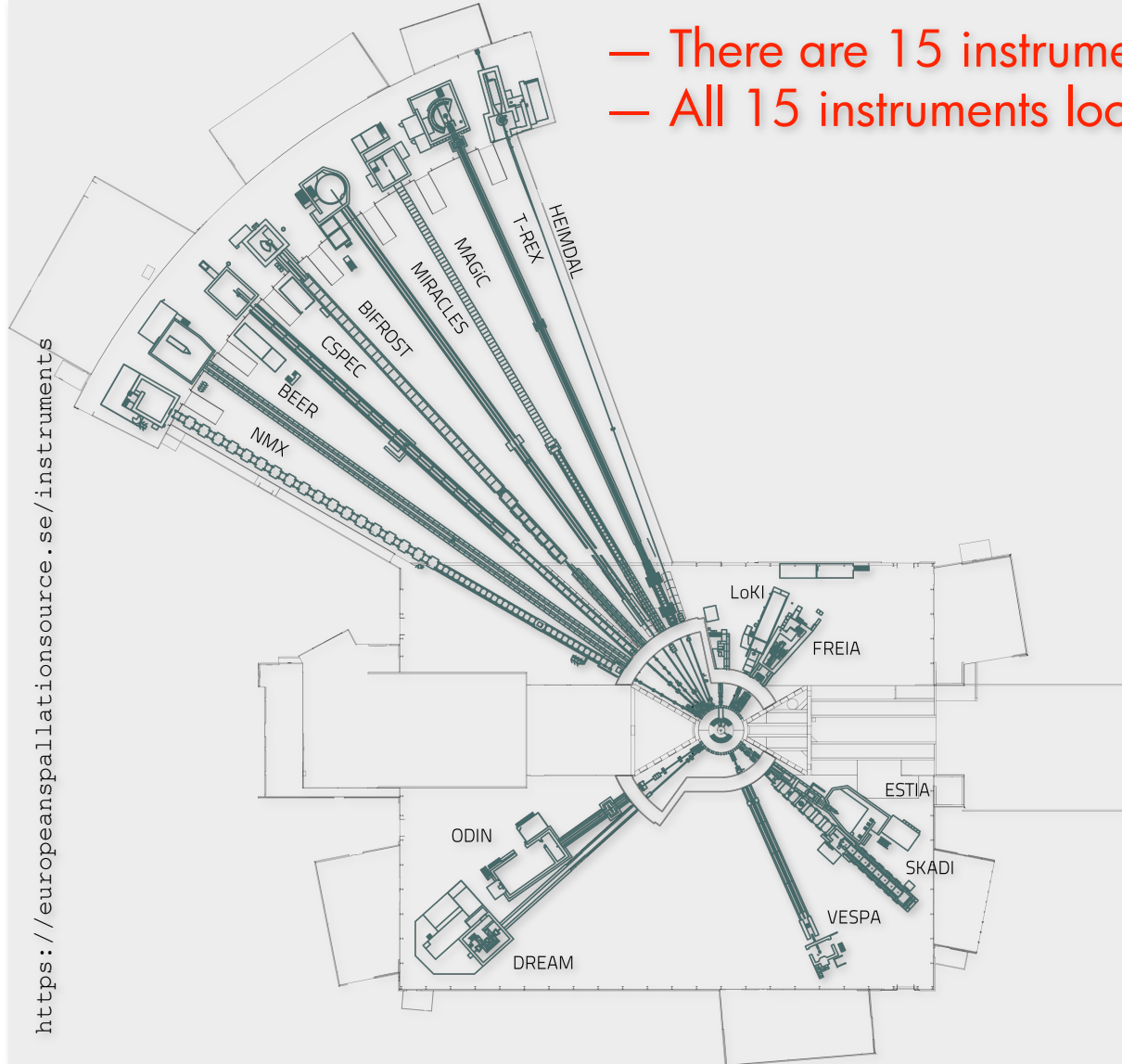
- Material irradiation station,
- Isotope production for medical use,
- Neutrino beams,
- Muon beams,
- Higgs factory?
- ...

## ESS IS A NEUTRON SCATTERING FACILITY FIRST AND FOREMOST!

- More neutrons,
- More experiments.

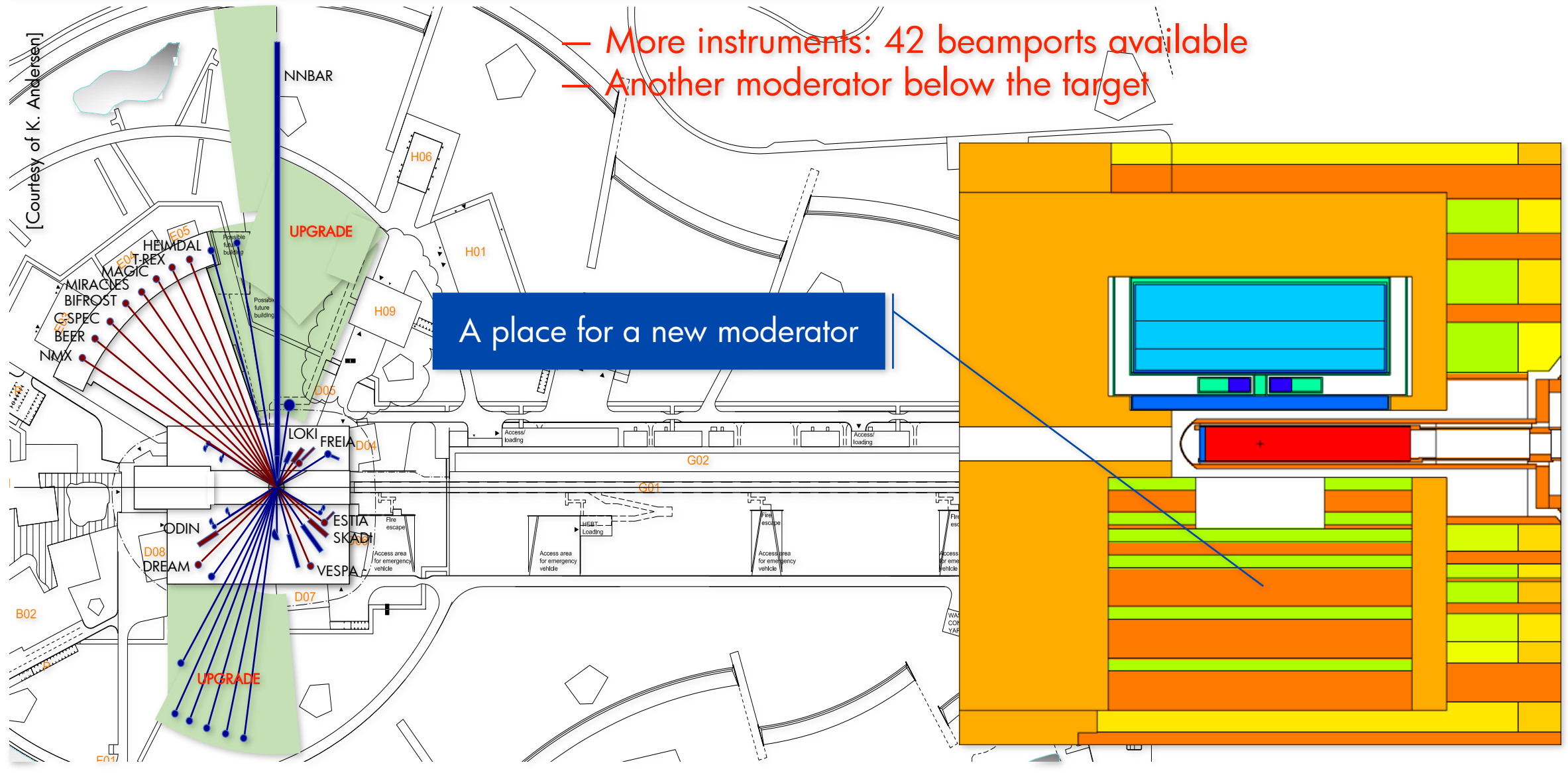
# UPGRADEABILITY

- There are 15 instruments (+ test beam line) currently under construction
- All 15 instruments look at the upper "flat" moderator





# UPGRADEABILITY



- More instruments: 42 beamports available
- Another moderator below the target

A place for a new moderator

# HIGNESS PROJECT

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## THE AIM OF HIGHNESS PROJECT

### High intensity

We aim at applications where the total number of neutrons is of higher value than the high brightness and low divergence achieved with a great performance by the upper quasi-low-dimensional moderator:

- NNBAR
- Condensed Matter (WP7)
- ...

### Shifting the spectrum of delivered neutrons to longer wavelengths

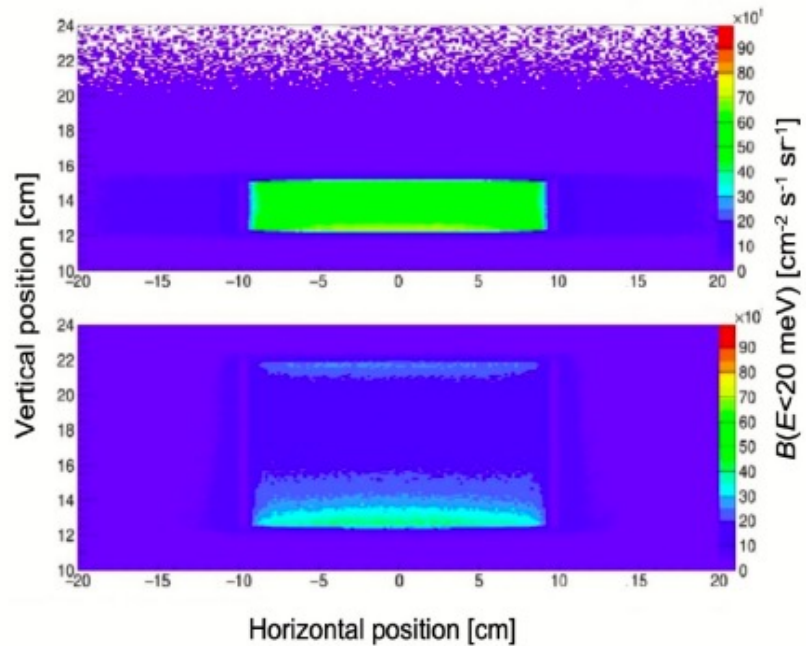
First of all, we are looking for cold neutrons (the upper moderator is a bi-spectral neutron source).

Besides cold neutrons, we are looking for Very Cold and Ultra Cold neutrons.

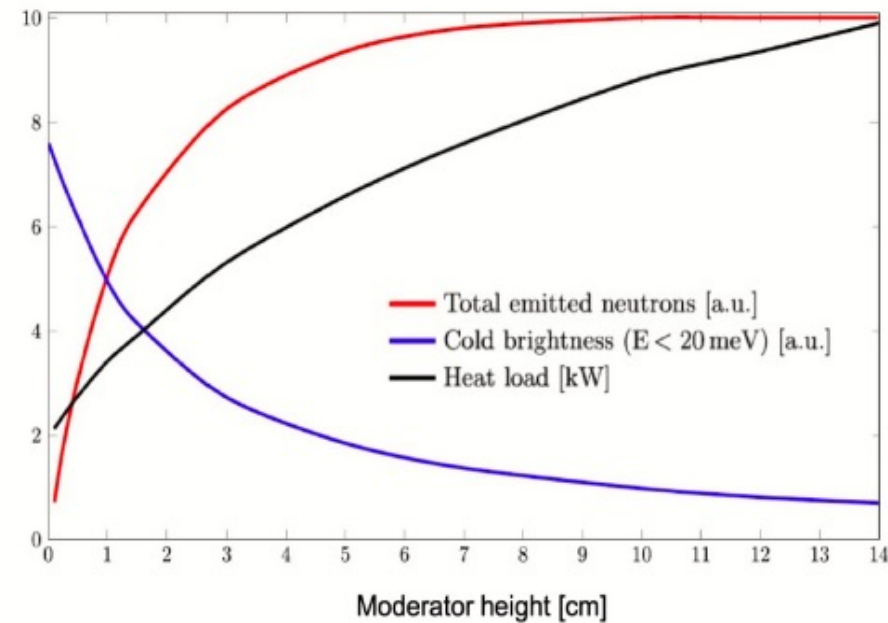
The primary cold source is intended to serve instruments and secondary VCN and UCN sources.



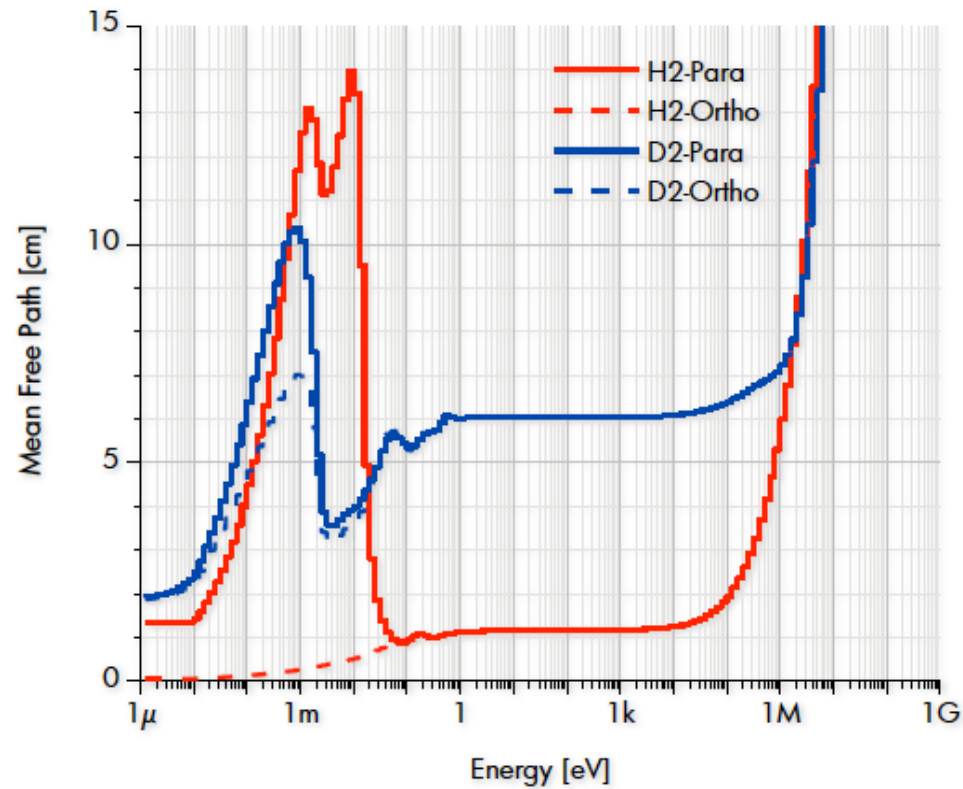
## LH2 MODERATOR?



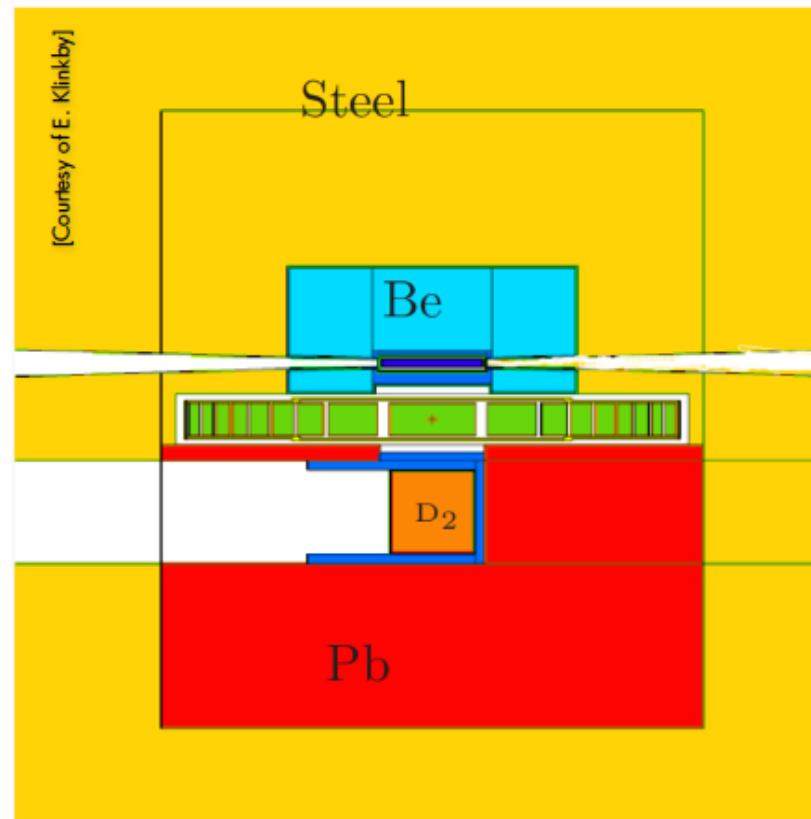
PARAHYDROGEN IS GOOD FOR BRIGHTNESS  
BUT NOT FOR INTENSITY!



## HighNESS

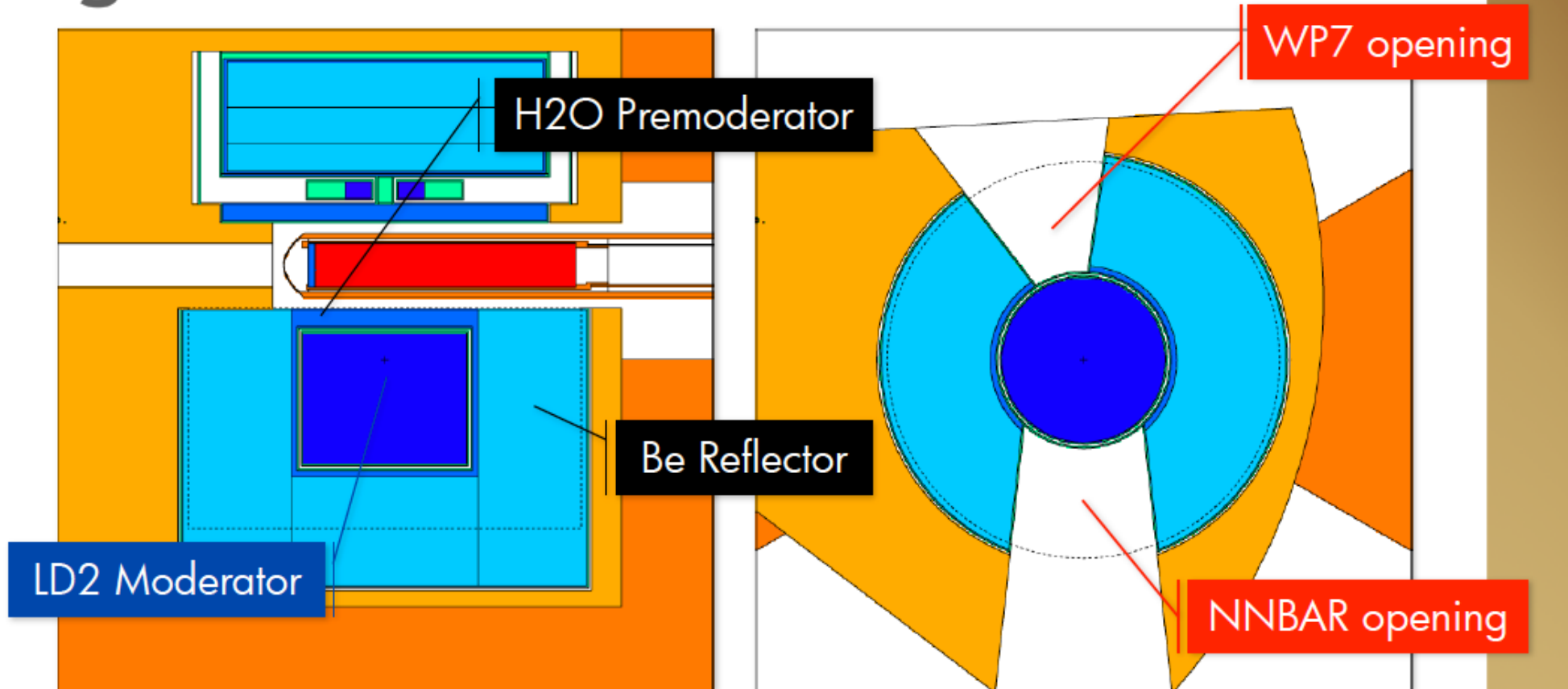


## LD2 MODERATOR?



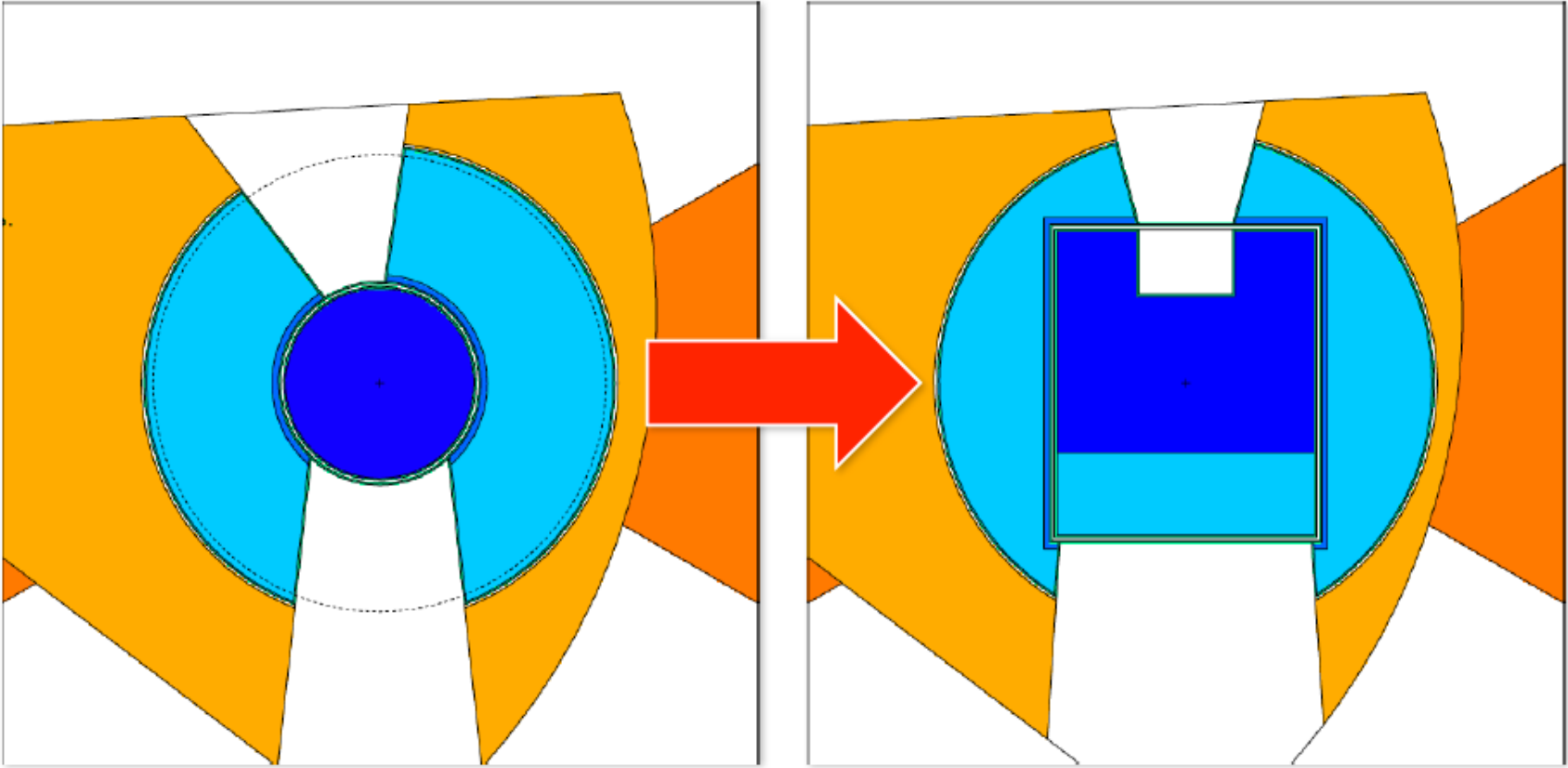
**HighNess**

## GENERIC LD2 MODERATOR



HighNess

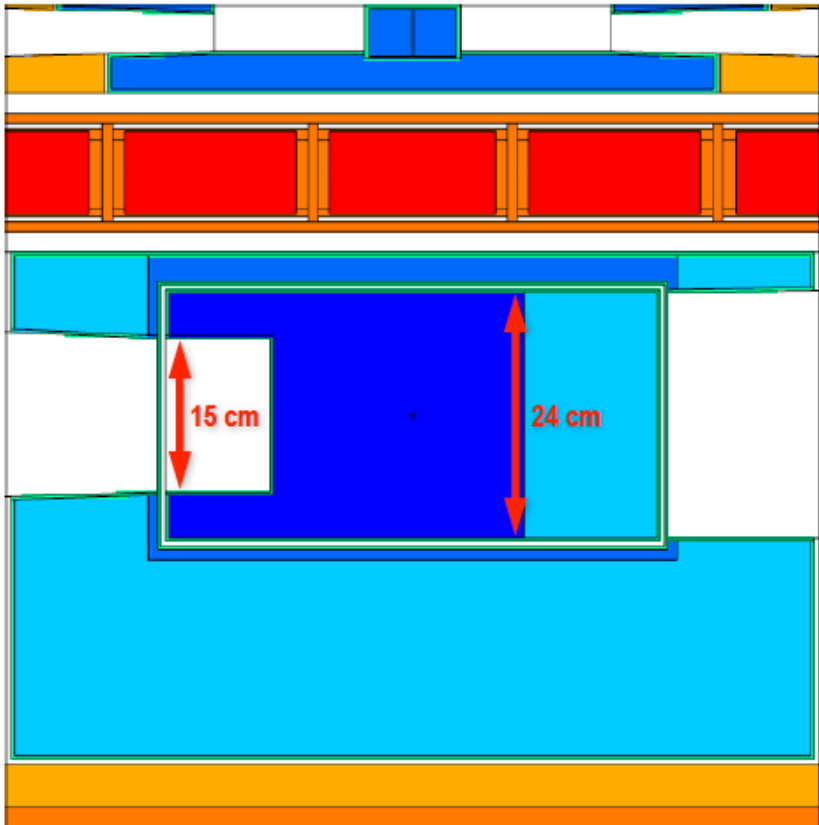
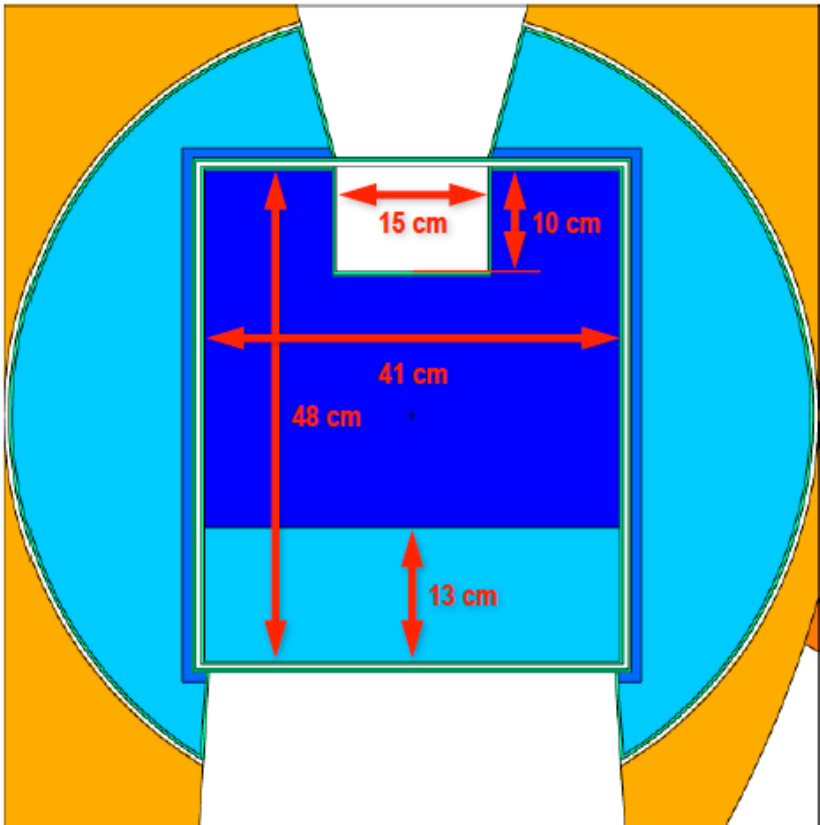
## DESIGN AND OPTIMIZATION RESULTS



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

## HighNESS

## BASELINE SOLUTION



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



## HighNess

## WHAT WE LEARNED

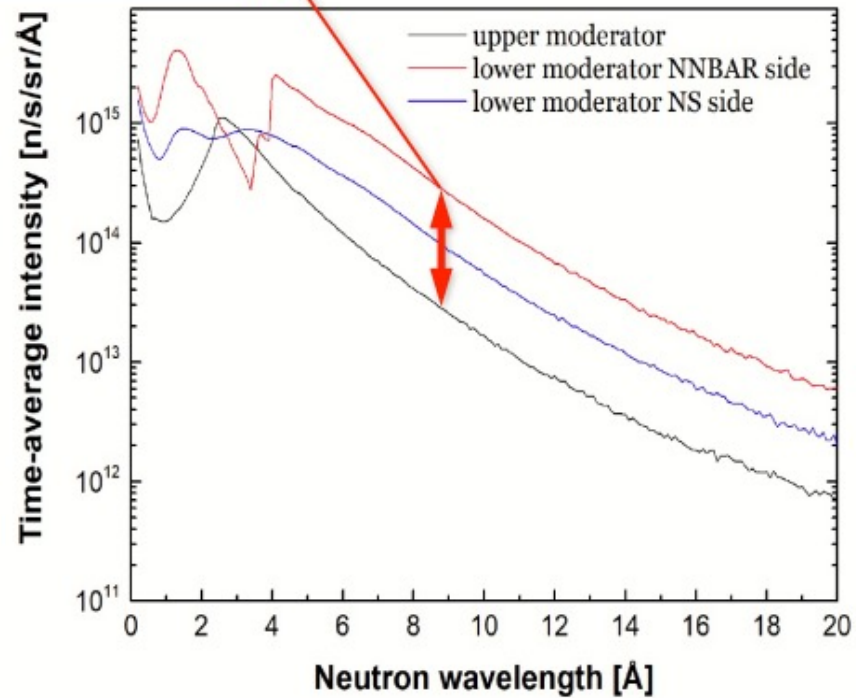
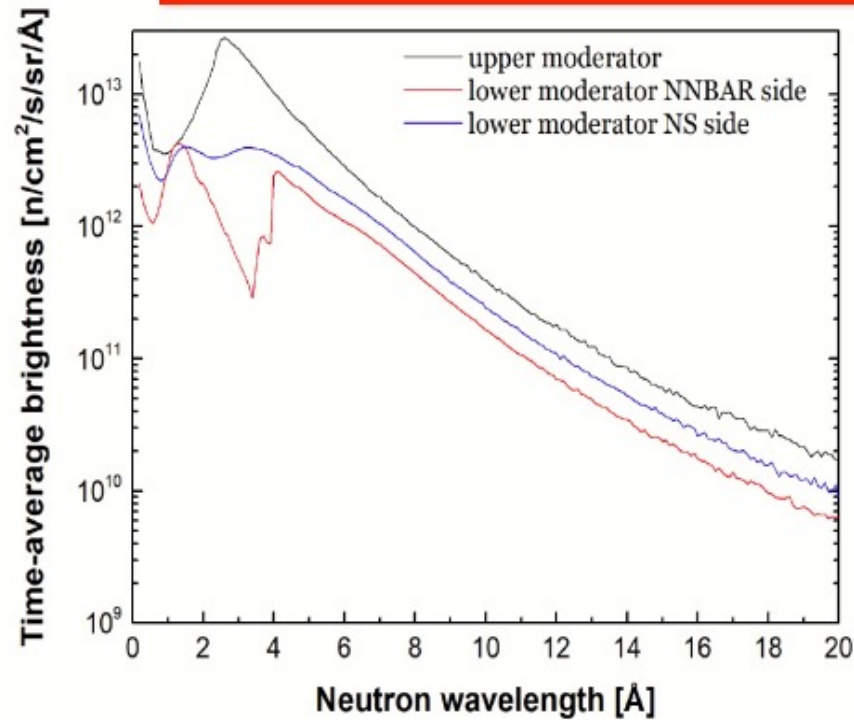
<b>Shape</b>	Rectangular is better than cylindrical
<b>Re-entrant hole (REH)</b>	WP7 FOM: about 30% gain
<b>Cold Be filter</b>	NNBAR FOM: about 30% gain
<b>Premoderator</b>	Unlike the upper moderator, water layer between cold moderator and reflector is essential
<b>Ortho/para ratio</b>	Unlike the upper moderator, the ratio is not crucial but 100% ortho-D2 gives about 5-10% gain comparing with normal (2:1 ortho/para ratio) D2
<b>Al content</b>	Unlike the upper moderator, Al content is important: around 4% loss in performance per 1%vol. of Al



## HighNess

## NEUTRON SPECTRA

ONE ORDER OF MAGNITUDE GAIN ABOVE 4 Å



**DTU HighNess** [Courtesy of N. Rizzi]

## Nanodiamonds in MCNP

**Total microscopic per-atom cross section**

$$\sigma_{SANS}(k_0) = \int I(q) d\Omega = \int_0^{2\pi} d\phi \int_0^{\pi} I(q) d\theta$$

$$\sigma_{SANS}(k_0) = \frac{2\pi}{k_0^2} \int_0^{2k_0} I(q) q dq$$

SANS experimental  $I(q)$  in absolute units =  $\frac{d\sigma}{d\Omega}(q)$  microscopic differential per-atom cross section with units barn sr<sup>-1</sup>

3 May 2023 DTU Physica SD2 converter 5

**HighNess**

## Conventional vs. SLS (3D printed) foams

- SLS has better heat extraction in some applications. May be prohibitively expensive with beryllium due to toxicity measures. Additionally, the outer surface is left porous after fabrication.
- With conventional foaming-agent production, density and porosity can be tuned homogeneously. This is a more mature technology and may be more feasible for beryllium.

[6]

[Courtesy of B. Folsom]

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[Courtesy of B. Rataj] **HighNess**

## Outline of the presentation

- (i) A location of moderator moderator cooling block in the ESS target model
- (ii) Calculating  $P_{UCN}$  using the UCN production cross-section in SD2
- (iii) Designing the UCN SD2 converter with a cylindrical channel
- (iv) Designing the UCN SD2 converter with a direct view on the NNBAR emission surface
- (v) Testing the water reflector around the converter
- (vi) Testing the gamma shielding made of Bismuth

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

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## Motivations

Clathrate hydrates are ice-like compounds having a cage structure. Small molecules such as methane can be enclathrated in the cage, stabilising the structure.

- Tetrahydrofuran (THF/TDF)-containing clathrate hydrates: low energy modes
- Oxygen-containing clathrate hydrates: neutron inelastic magnetic scattering

[Courtesy of S. Xu]

- large Bragg cutoff wavelength (2 nm)
- small absorption of deuterium

This work was funded by HighNess project at European Spallation Source ERIC under HORIZON 2020 grant agreement ID: 951782.

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## WHAT IS ESS?

- ESS will be the world's most powerful "neutron microscope".

## SELECTED DESIGN FEATURES

- A moderator system based on a novel quasi-low-dimensional moderator concept,
- Initial 15-instrument suite served by a single "flat" high-brightness bi-spectral moderator.

## UPGRADEABILITY

- Uniform grid of 42 beamports: more instruments,
- A place for a second neutron source: HIGHNESS Project.

## DEVELOPMENT OF A SECOND NEUTRON SOURCE

- A high-intensity LD2 moderator has been neutronically designed,
- LD2 moderator will serve both instruments and dedicated VCN and UCN sources,
- New materials under investigation: nanodiamonds, metal hydrides, deuterated clathrates, etc.