



# Very High Brightness Source

## **Proposal for an instrument suite using a very high brightness cold moderator placed below the ESS spallation target**

**Proposal for the ESS Instrument Call**

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Radioecology, nuclear waste management



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part-time

2011-2019 Group Leader for Neutronics

main task: design of the upper moderator

2020-2023 WP leader HighNESS

main task: design of lower CN, VCN and UCN sources



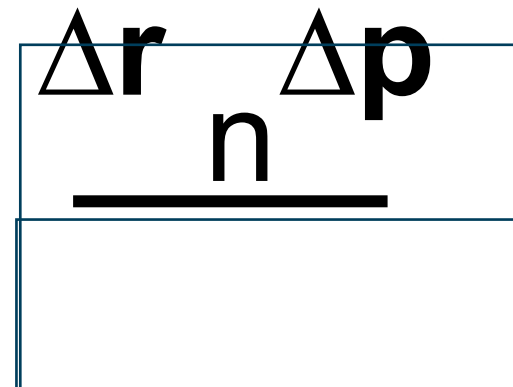
**Table 1**

List of instruments used for the optimization study described here.

In most cases, the instrument description in the first column matches the instrument name in the TDR reference suite (Peggs, 2013). Instruments marked with an asterisk (\*) in the first column are those which are substantially different from the TDR instruments. SLEIPNIR and HERITAGE are very similar to the TDR broad-band high-flux SANS and surface scattering instruments, respectively, in terms of phase-space requirements. HEIMDAL is similar to the TDR thermal powder diffractometer, with a SANS add-on to access multiple length scales. T-REX is similar to the TDR thermal chopper spectrometer, but employs a bispectral switch to extend its capabilities to the cold range. The n-nbar beamline has no equivalent in the TDR.

Instrument	$L_{m-s}$	Beam area at sample (H × V)	Beam divergence at sample (H × V)	Wavelength range
Multi-purpose imaging ODIN	50 m	3 × 3 cm pinhole	At pinhole: $\pm 0.7 \times 0.7^\circ$	Bispectral, 1–7 Å
General-purpose polarized SANS SKADI	30 m	3 × 3 cm	$\pm 0.29 \times 0.29^\circ$	Cold, 2–10 Å
Broad-band high-flux SANS LOKI	20 m	3 × 3 cm	$\pm 0.57 \times 0.57^\circ$	Cold, 2–12 Å
Compact SANS SLEIPNIR*	16 m	2 × 2 cm	$\pm 0.86 \times 0.86^\circ$	Cold, 3–19 Å
Horizontal reflectometer FREIA	27 m	0.4 × 4 cm	$1.5 \times 4^\circ$	Cold, 2–9.5 Å
Alternative horizontal reflectometer HERITAGE*	36 m	1 × 1 cm	$\pm 2 \times 0.75^\circ$	Cold, 2–10 Å
Vertical reflectometer ESTIA	52 m	1 × 10 mm	$\pm 0.75 \times 0.75^\circ$	Cold, 5–9 Å
Pulsed monochromatic powder diffractometer HOD	$L_{m-m}$ 45 m	6 × 30 cm mono	At mono: $\pm 0.5 \times 0.5^\circ$	Thermal, 1.89 Å
Bispectral powder diffractometer DREAM	75 m	1 × 1 cm	$\pm 0.25 \times 0.25^\circ$	Bispectral, 0.8–4.6 Å
Hybrid diffractometer HEIMDAL*	167 m	5 × 15 mm	$\pm 0.24 \times 1.0^\circ$ $\pm 0.5 \times 0.5^\circ$	0.6–2.3 Å 4–10 Å
Materials science and engineering diffractometer BEER	157 m	5 × 10 mm	$\pm 0.14 \times 0.86^\circ$	Bispectral, 0.5–3.8 Å
Single-crystal magnetism diffractometer MAGIC	150 m	1 × 1 cm	$\pm 0.2 \times 0.2^\circ$ $\pm 0.5 \times 0.5^\circ$	0.7–2.4 Å 2.4–8 Å
Macromolecular diffractometer NMX	150 m	5 × 5 mm	$\pm 0.2 \times 0.2^\circ$	Cold, 1.5–3.3 Å
Cold chopper spectrometer CSPEC	151 m	1.9 × 4 cm	$\pm 1 \times 1^\circ$	Cold, 2–6 Å
Bispectral chopper spectrometer VOR	31 m	1 × 1 cm	$\pm 1 \times 1^\circ$	Cold, 1–9 Å
Alternative bispectral chopper spectrometer T-REX*	150 m	1 × 3 cm	$\pm 1 \times 1^\circ$	Bispectral, 0.8–7.2 Å
Thermal chopper spectrometer	160 m	3 × 3 cm	$\pm 1 \times 1^\circ$	Thermal, 0.6–3 Å
Cold crystal-analyser spectrometer BIFROST	170 m	15 × 15 mm	$\pm 0.75 \times 1^\circ$	Cold, 1.65–6.4 Å
Backscattering spectrometer MIRACLES	163 m	3 × 3 cm	$\pm 2.5 \times 2.5^\circ$	Cold, 2–8 Å
High-resolution spin echo ESSENSE	27 m + 4 m	3 × 3 cm	$\pm 0.57 \times 0.57^\circ$	Cold, 4–25 Å
Wide-angle spin echo WA-NSE	47 m + 4 m	1.5 × 6 cm	$\pm 0.5 \times 1^\circ$	Cold, 2–10 Å
Fundamental and particle physics ANNI	30 m	6 × 6 cm	$\pm 0.57 \times 0.57^\circ$	Cold, 3–8 Å
n-nbar beamline*	300 m	Moderator surface	Brightness $\times \lambda^2$	Cold, 0–20 Å

*J. Appl. Cryst.* (2018). **51**, 264–281



**Phase space density**

**Phase space**



The brightness  $B$  is the product of the speed  $v$ , times the neutron angular density.

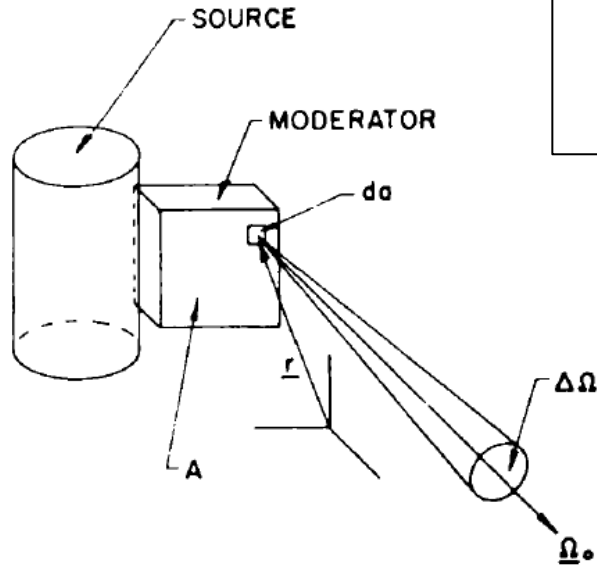
$$B(\mathbf{r}, \Omega, E, t) = vN(\mathbf{r}, \Omega, E, t) = v \frac{n(\mathbf{r}, \Omega, E, t)}{dV d\Omega dE} \quad (\text{A.2})$$

The unit of the brightness is  $\text{n/cm}^2/\text{s}/\text{sr}/\text{eV}$ .

On the other hand, the phase space density  $\rho(\mathbf{r}, \mathbf{p}, t)$  is the number of particles in the phase space volume  $d\mathbf{r}d\mathbf{p} = dV p^2 dp d\Omega$  at time  $t$ :

$$\rho(\mathbf{r}, \mathbf{p}, t) = \frac{n(\mathbf{r}, \Omega, E, t)}{dV p^2 dp d\Omega} = \frac{v}{p^2} \frac{n(\mathbf{r}, \Omega, E, t)}{dV d\Omega dE} \quad (\text{A.3})$$

where we used the relationship between kinetic energy and momentum  $E = \frac{p^2}{2m}$ .



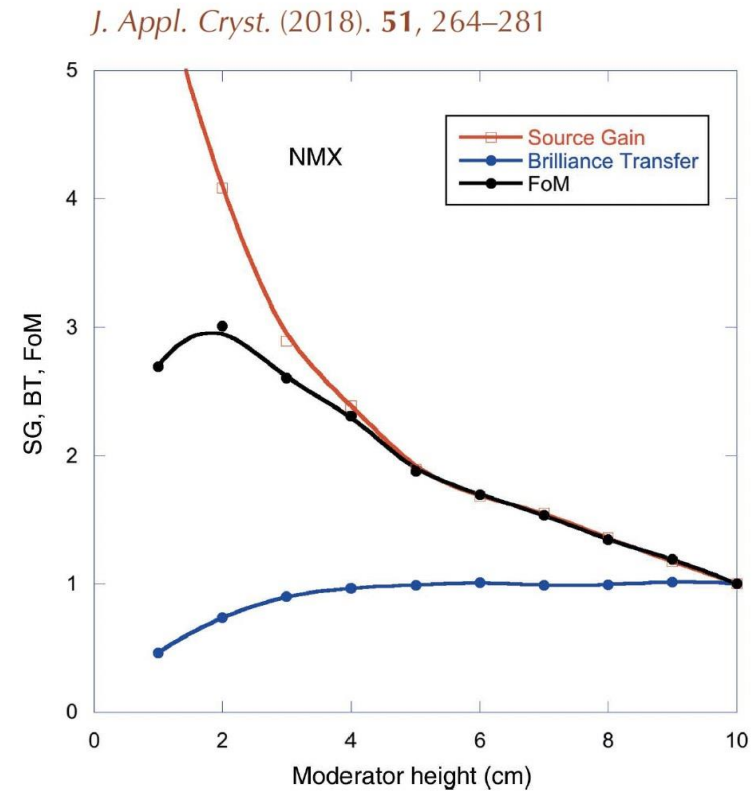
**At the sample: maximum phase space density**

**At the moderator:  
Maximum brightness**

$$\frac{n}{\Delta\Omega \Delta A s} = \frac{n}{\Delta r \Delta p}$$

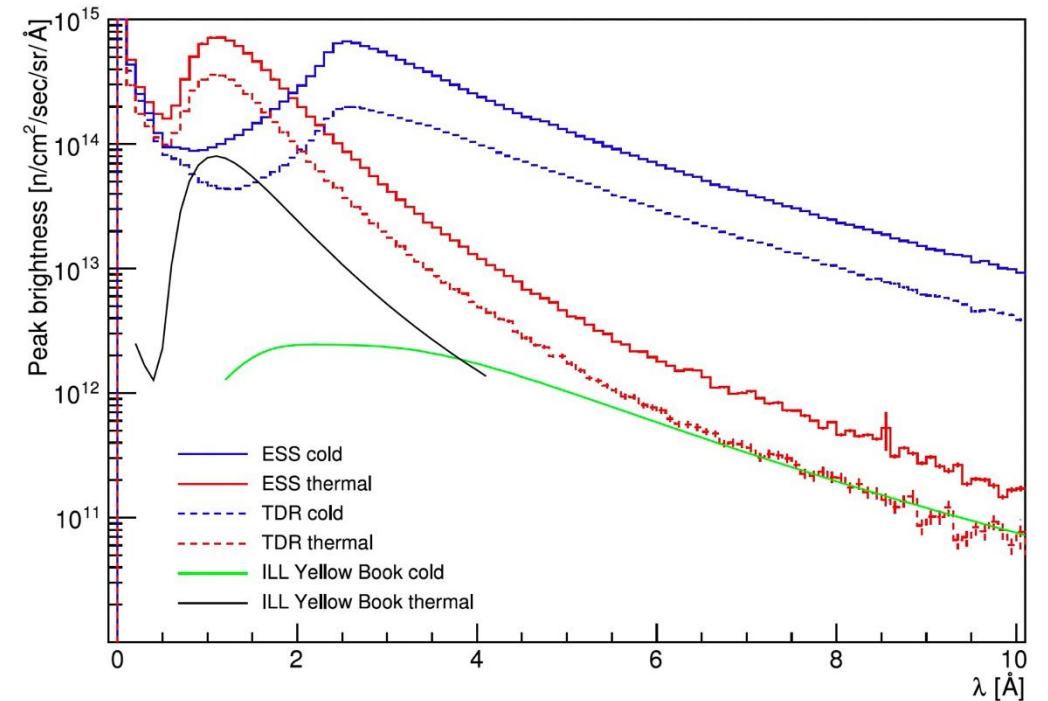
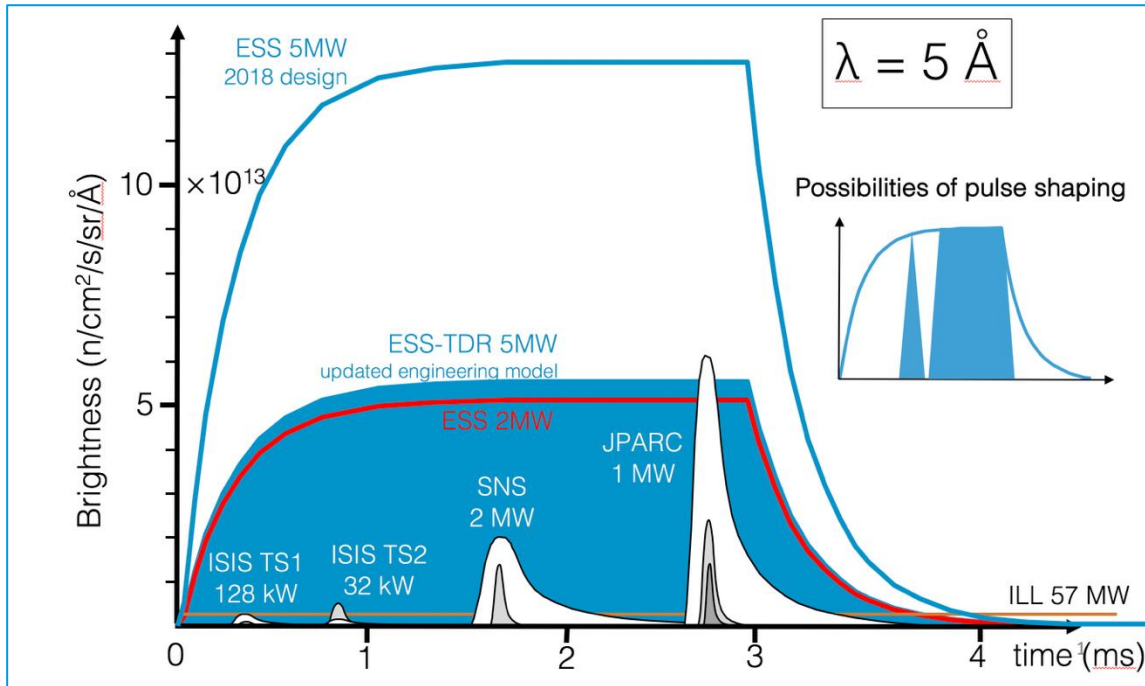
$(\text{n}/\text{cm}^2 \text{ s sr})$

The upper moderator has a thickness of 30 mm chosen as a compromise between brightness and brightness transfer



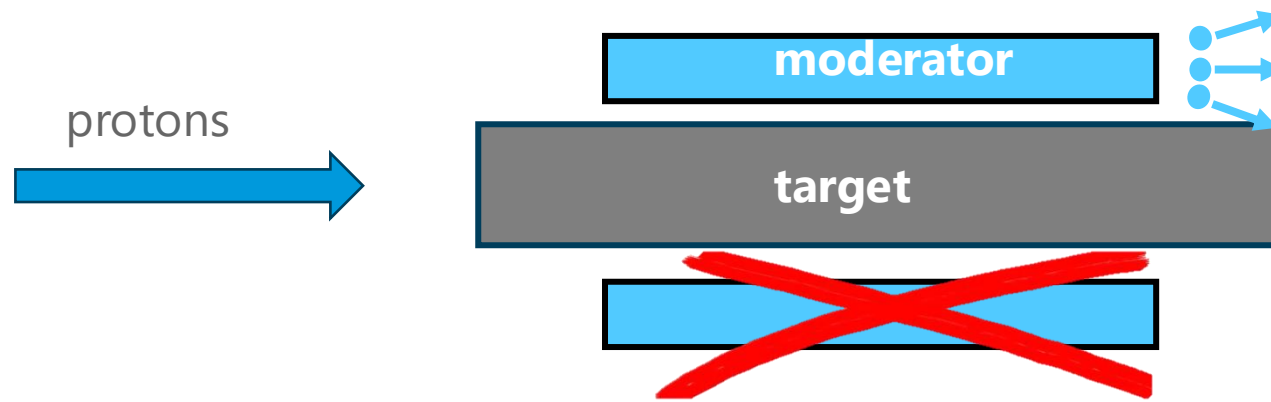
brightness transfer can be lower if the source is smaller than the guide, due to guide underillumination

With the upper butterfly moderator, the ESS performance at 2 MW is equivalent to the original (from Technical Design Report of 2014) expected performance at 5 MW



A very important by-product of using a low dimensional moderator, is that 1 moderator can serve all the instrument suite

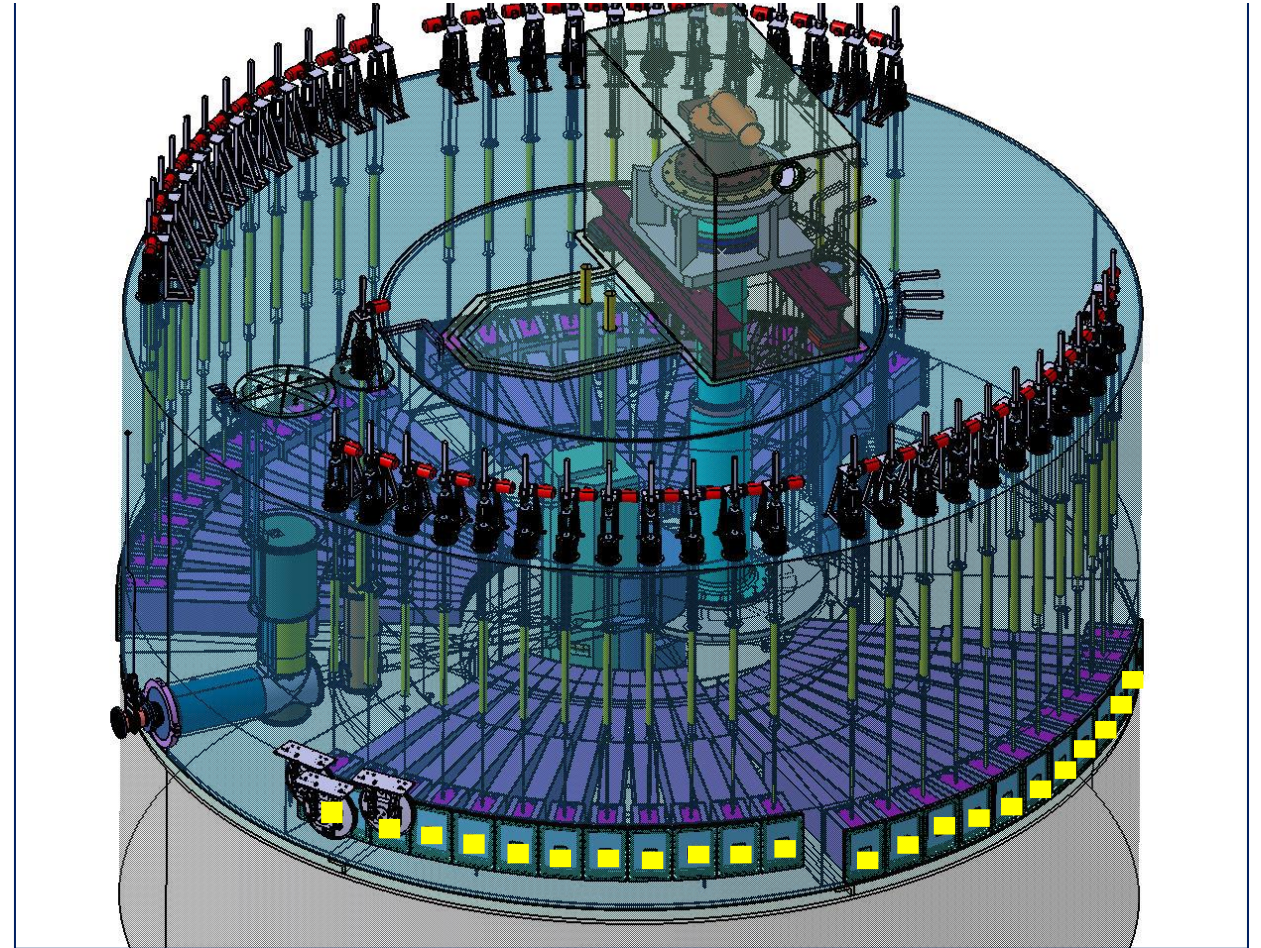
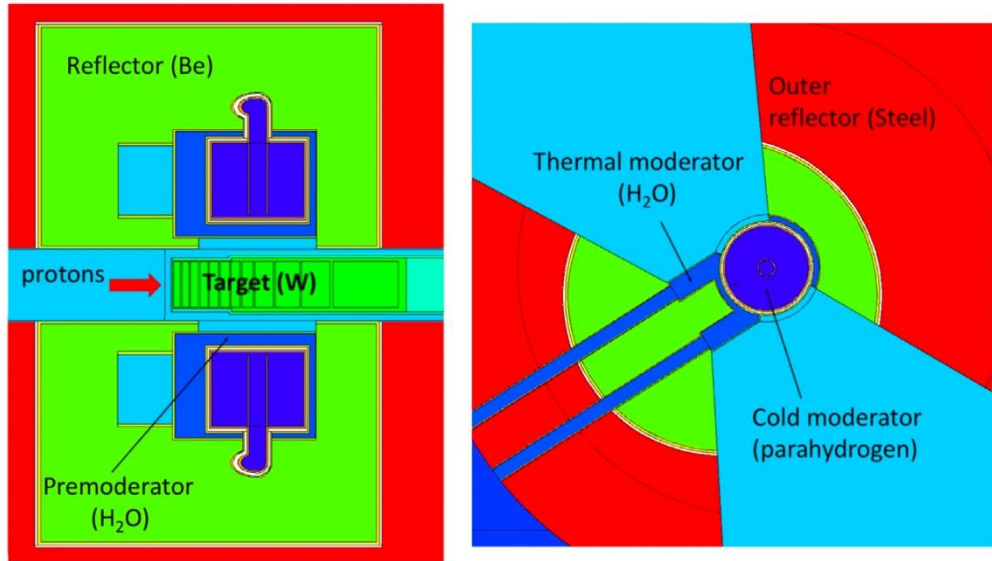
➔ Possibility to develop a second source



**1 moderator is enough!**

# The original TDR (2014) moderators allowed for 42 beam openings (1 per beamport)

A given beamport would point to the upper OR to the lower moderator

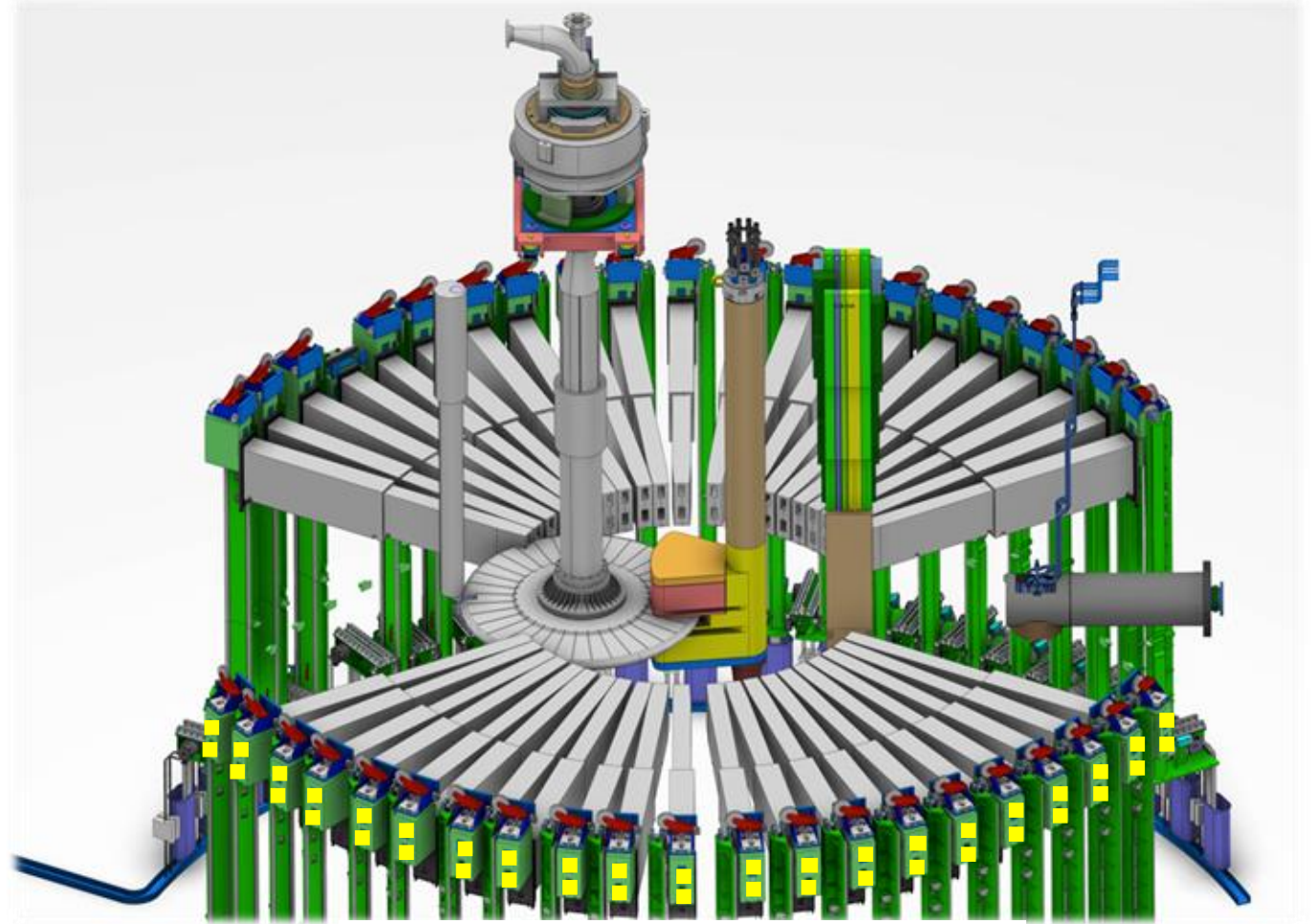
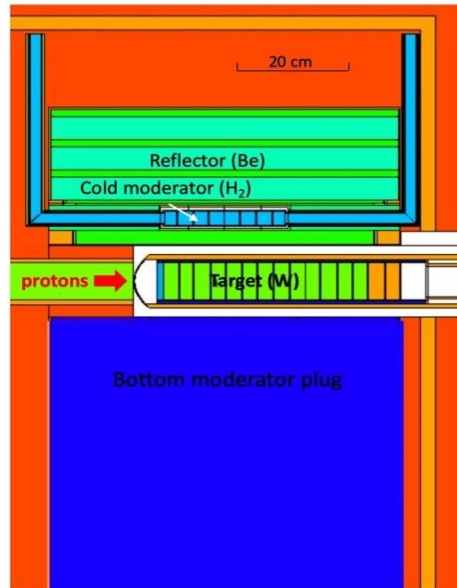


**TDR = 42 openings**

# The butterfly moderator allows for 84 beam openings (2 per beamport)



A given beamport can point to the upper AND to the lower moderator



**Present = 84 openings**

# First generation of parahydrogen moderators (BF2) –Twister



(in-kind FZJ Jülich)

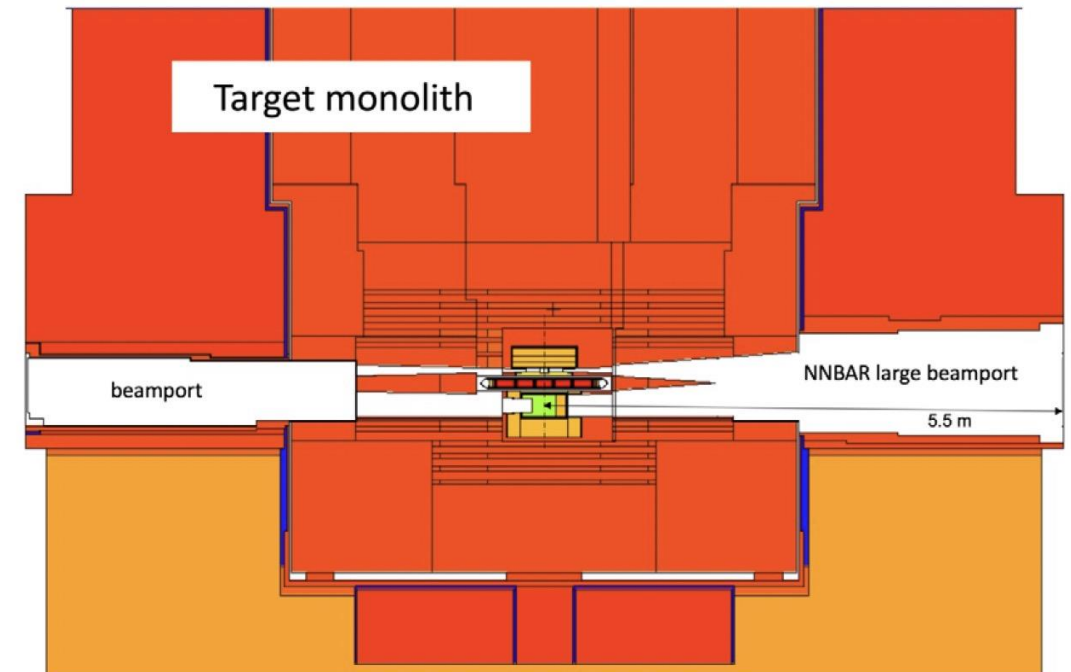
# Presently only 20% of the beam openings are used



*L. Zanini et al. / Very cold and ultra cold neutron sources for ESS*

	Openings from upper moderator	Openings from future lower moderator	TOTAL
available	42	42	84
used	16	0	16

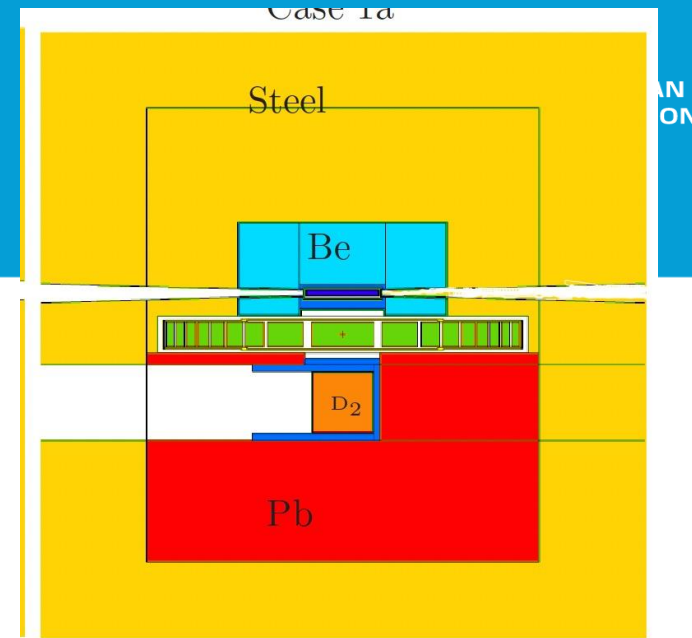
20%



## Voluminous D<sub>2</sub> source for intense cold neutron beam production at the ESS.

E. Klinkby<sup>1,2\*</sup>, K. Batkov<sup>1</sup>, F. Mezei<sup>1</sup>, T. Schönfeldt<sup>1,2</sup>, A. Takibayev<sup>1</sup>, L. Zanini<sup>1</sup>

2014

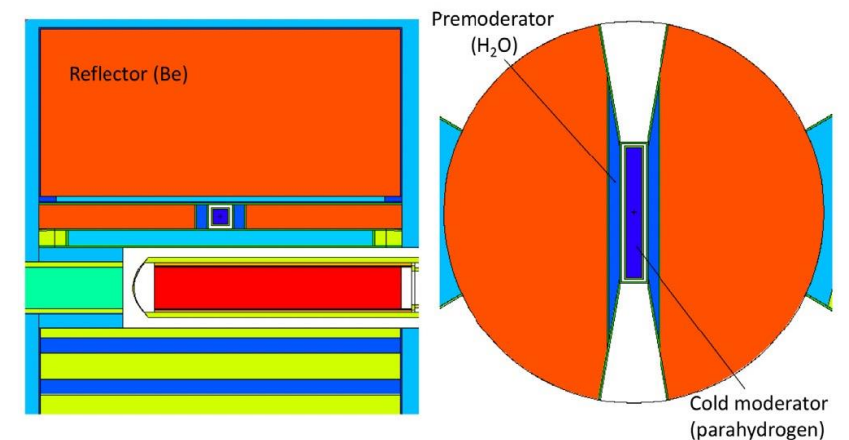


<https://arxiv.org/abs/1401.6003v1>.

Journal of Neutron Research 17 (2014) 101–105  
DOI 10.3233/JNR-140013  
IOS Press

## Low dimensional neutron moderators for enhanced source brightness

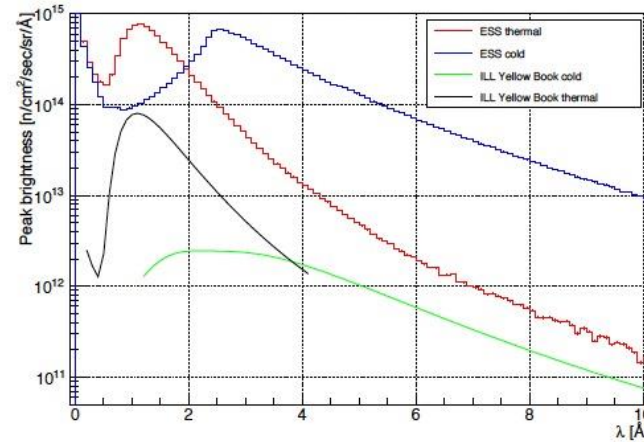
Ferenc Mezei<sup>a,b,\*</sup>, Luca Zanini<sup>a</sup>, Alan Takibayev<sup>a</sup>, Konstantin Batkov<sup>a</sup>, Esben Klinkby<sup>a,c</sup>,



L. Zanini et al. Nuclear Inst. and Methods in Physics Research, A 925 (2019) 33–52

# The neutron moderators for the European Spallation Source

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**Figure 4.** Brightness spectra averaged over 42 beam ports for 3 cm high moderator, compared with ILL official curves [8].

## 4. Future possibilities

The chosen configuration, where all initial instruments foreseen for ESS point to the top moderator, leaves open several attractive possibilities for future use at ESS. With a high-brightness moderator at the top, the bottom area could be reserved in future for a source of neutrons which should be complementary to the top one. Several possibilities could be explored, such as:

- Ultra Cold or Very Cold neutron source.
- High-intensity moderator, such as a large D<sub>2</sub> moderator, for specific experiments like the nnbar [10].
- A high-brightness moderator, even surpassing the brightness of the top moderator, which could be achieved either by using tube moderators (good for a few beam lines only, due to their strong directionality), or by further reducing the height with respect to the top moderator [3, 11].

# Highness

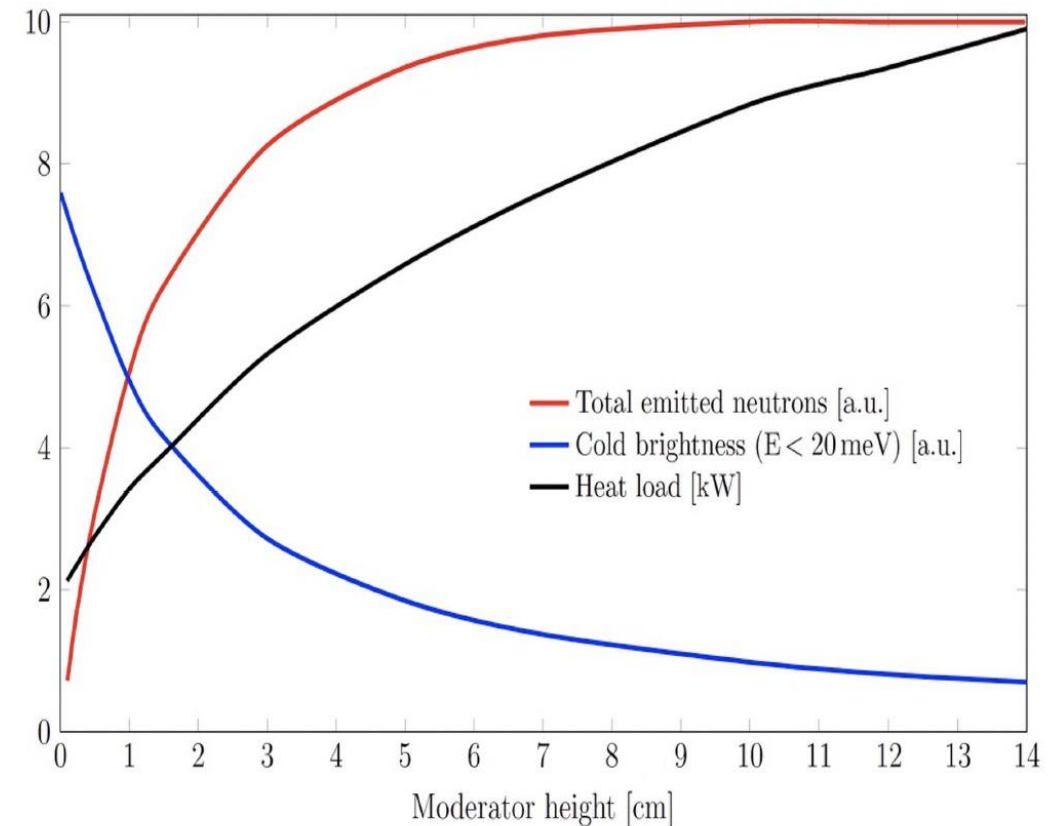
# This proposal

The lower moderator will have a higher brightness than the upper moderator for a combination of two effects



i) **Reduction in moderator dimensions.** Narrowing the height of the moderator from 30 mm to 10 mm or 5 mm alone increases brightness by approximately a factor of 1.8 or 2.2, respectively. In addition, narrowing the width of the moderator provides a further gain of at least  $\approx 10\%$ .

ii) **Simpler geometry.** Compared to the complex geometry of the upper moderator, which is designed to serve all 42 beamports at ESS and provide both thermal and cold neutrons (from water and parahydrogen moderators, respectively), a simpler, directional cold moderator can be placed in an optimal location.

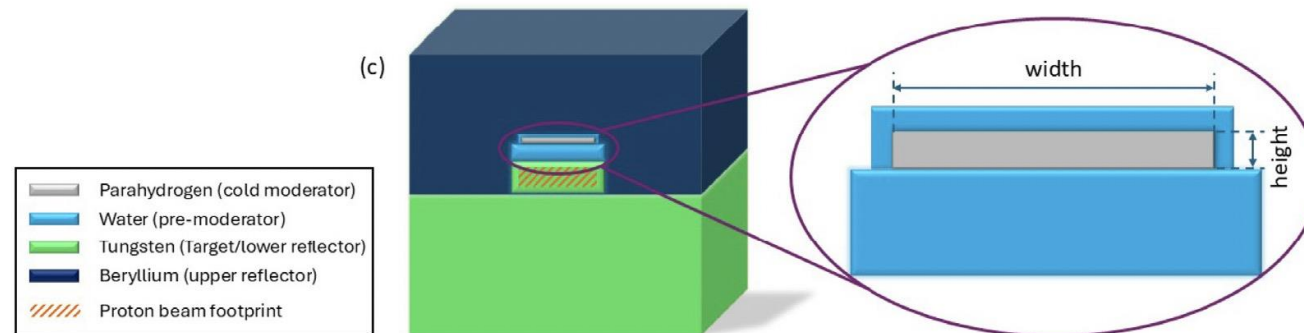


# Design concept of the moderator



M. Akhyani et al.

Nuclear Inst. and Methods in Physics Research, A 1086 (2026) 171379

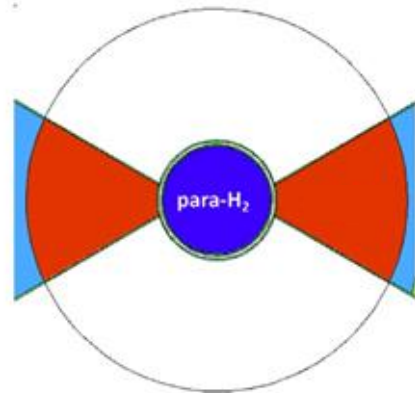


**Fig. 1.** Investigated TMR geometries for dedicated target station for neutron scattering under very high pulsed magnetic field experiments: (a) Flat geometry; (b) Inverted Tube geometry; and (c) Framed Flat geometry.

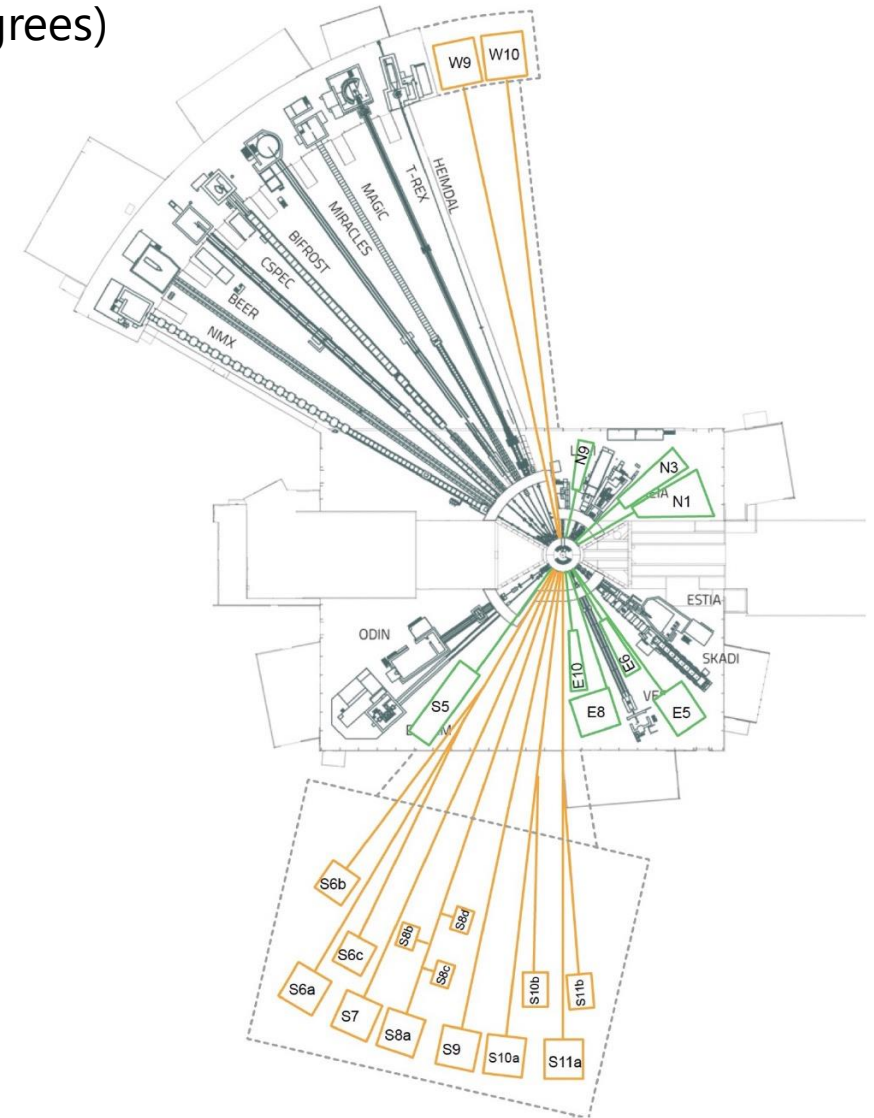
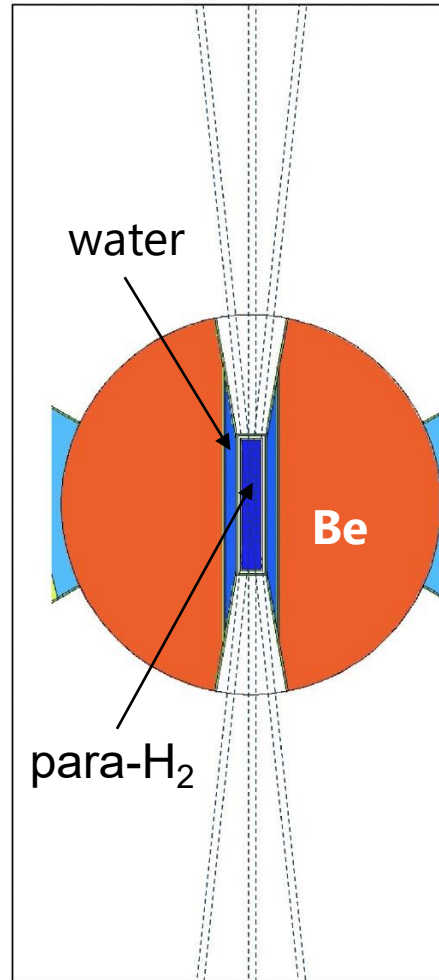
# The geometry of the lower moderator can be adapted to the number of instruments



Tube geometry (approx 200 X 40 X 5 mm<sup>3</sup>)  
For six instruments spacing of 6 degrees)



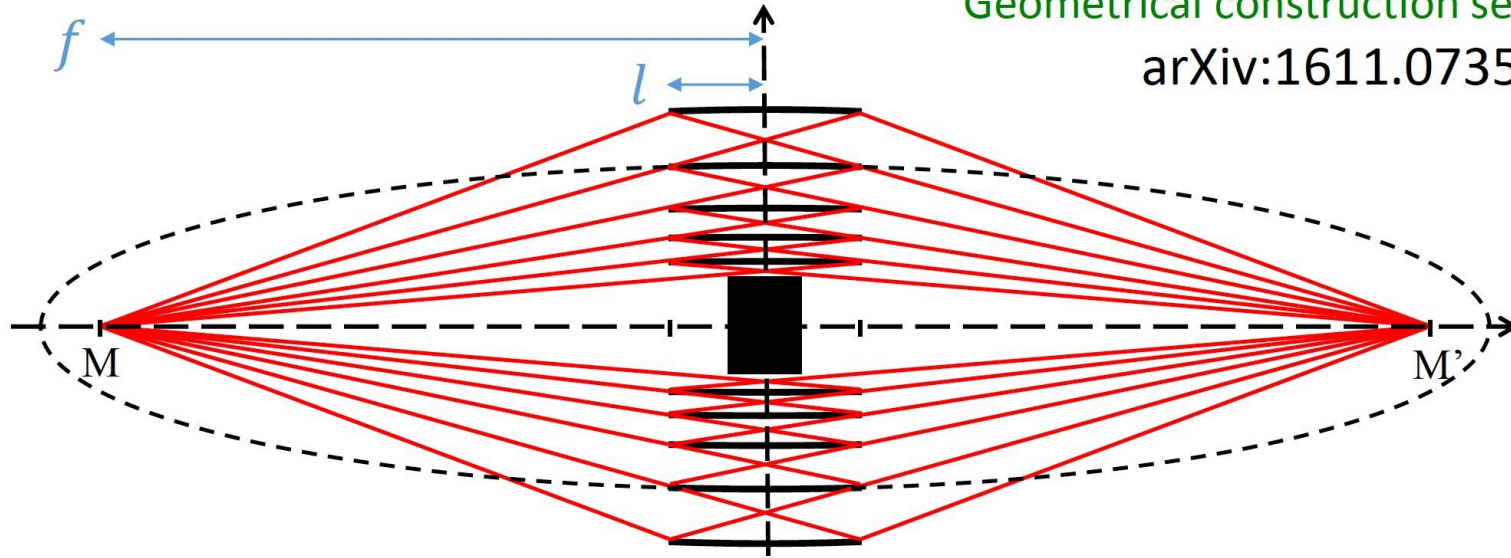
Pancake geometry (approx. 200 mm diameter X 5 mm height) for all 42 beamports.



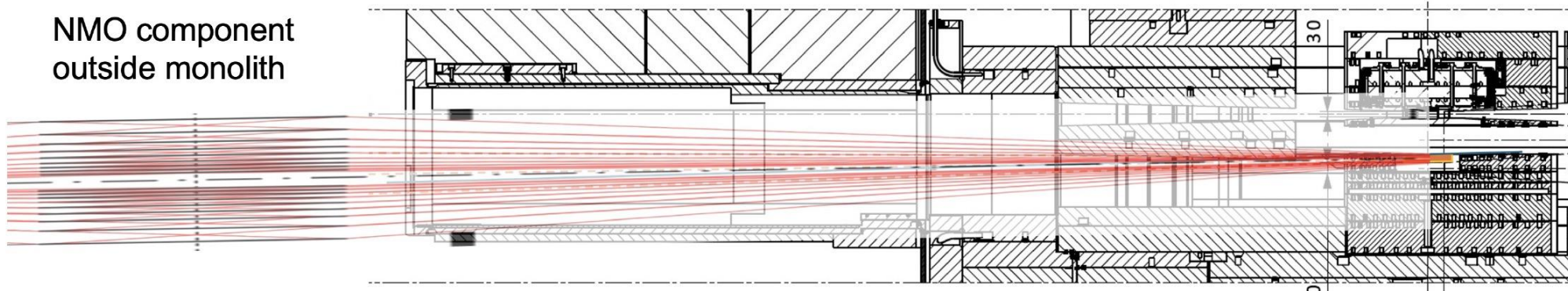
# NMO placed outside monolith, no heating or radiation damage



Geometrical construction see:  
arXiv:1611.07353



NMO component  
outside monolith



5.5 m

C. Herb, O. Zimmer, R. Georgii et al.

*Nuclear Inst. and Methods in Physics Research, A 1040 (2022) 167154*

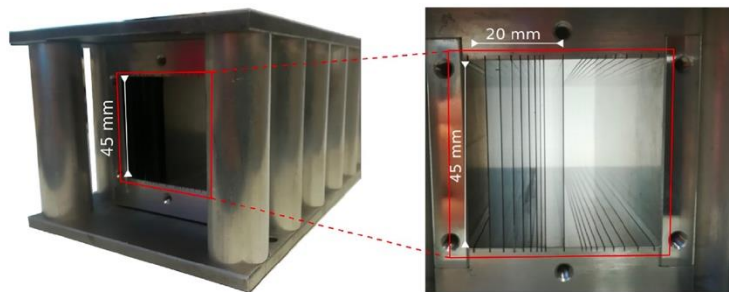


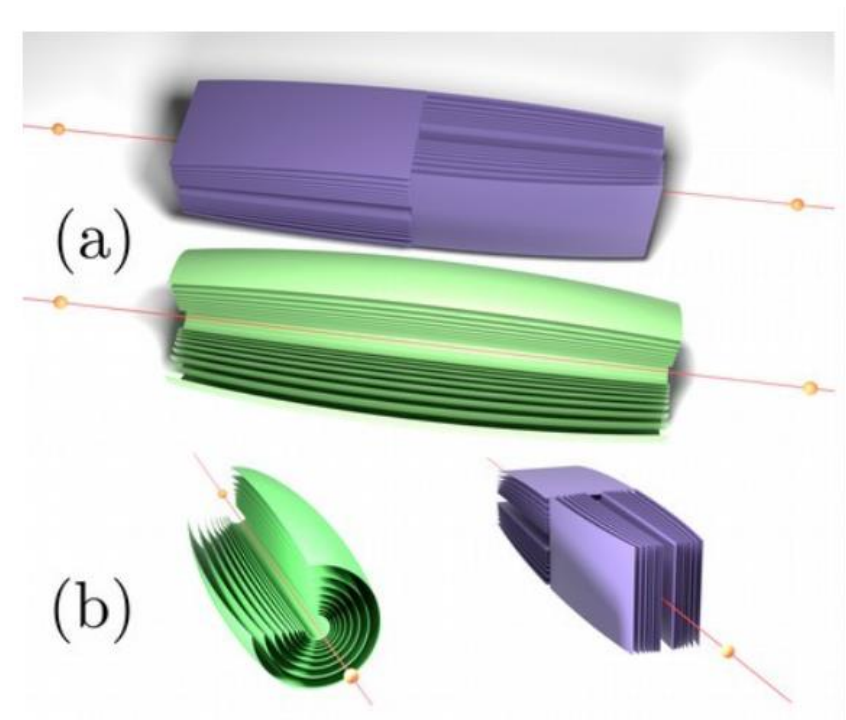
Fig. 4. Pictures of the NMO prototype with its eight elliptic mirror plates. A ninth, central and straight mirror solely facilitates the alignment of the optic. The grooves visible on the right hand side were left empty. The rods on the sides of the device contain the permanent magnets for magnetization of the supermirrors. (See text for a description of the geometry and more details of the mirror setup).

small prototype elliptic NMO equipped with non-polarising supermirrors, demonstrated a brilliance transfer for small samples of 72%

# NMO in McStas

## Ready made components

- Conic component
  - Base by Giacomo Resta (MIT)
  - Supports wolter optics
    - Elliptic – Hyperbolic (point to point with magnification)
    - Parabolic - Elliptic (parallel beam to point)
- Derived flat version called NMO
  - Christoph Herb (TUM)
  - Elliptic shape (point to point)
- Neither support gravity or waviness



# Alternatives to NMO

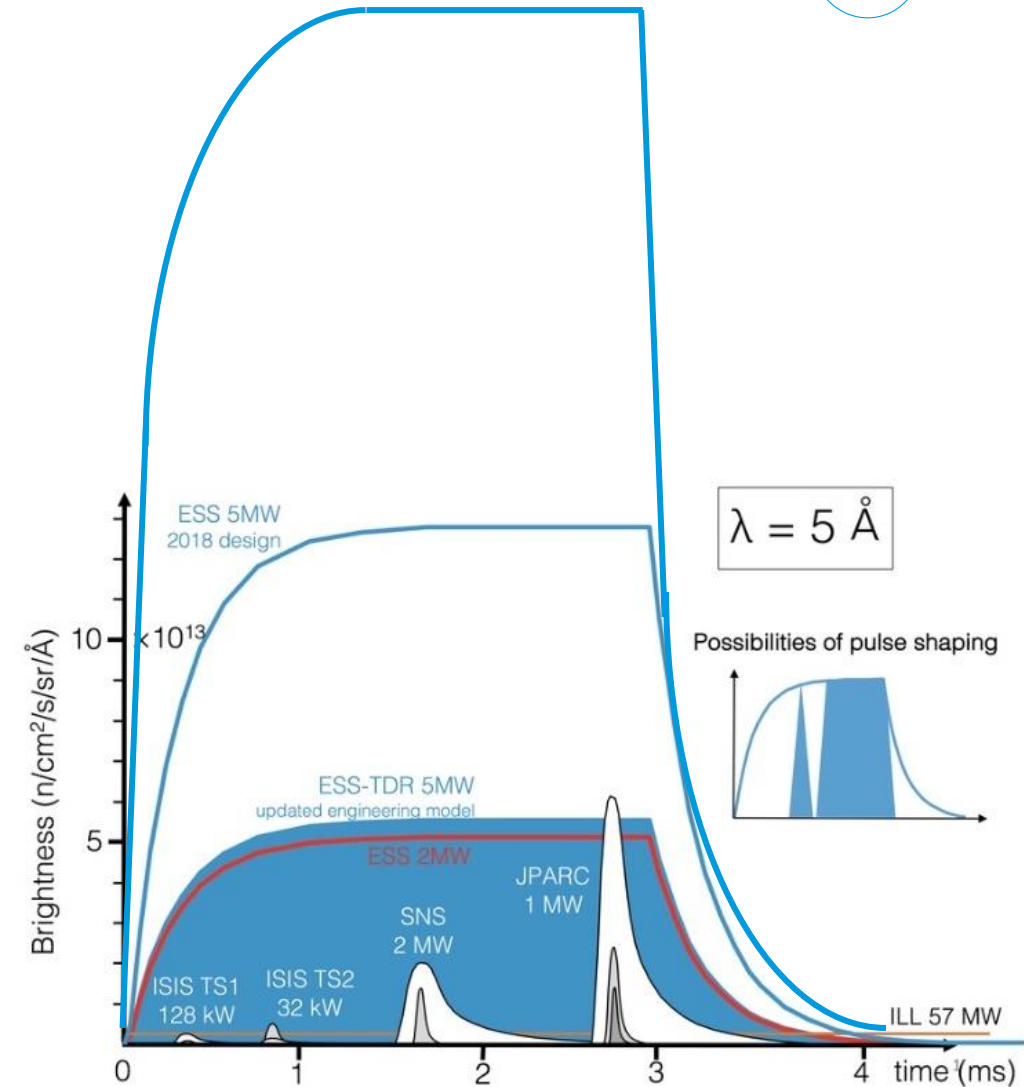
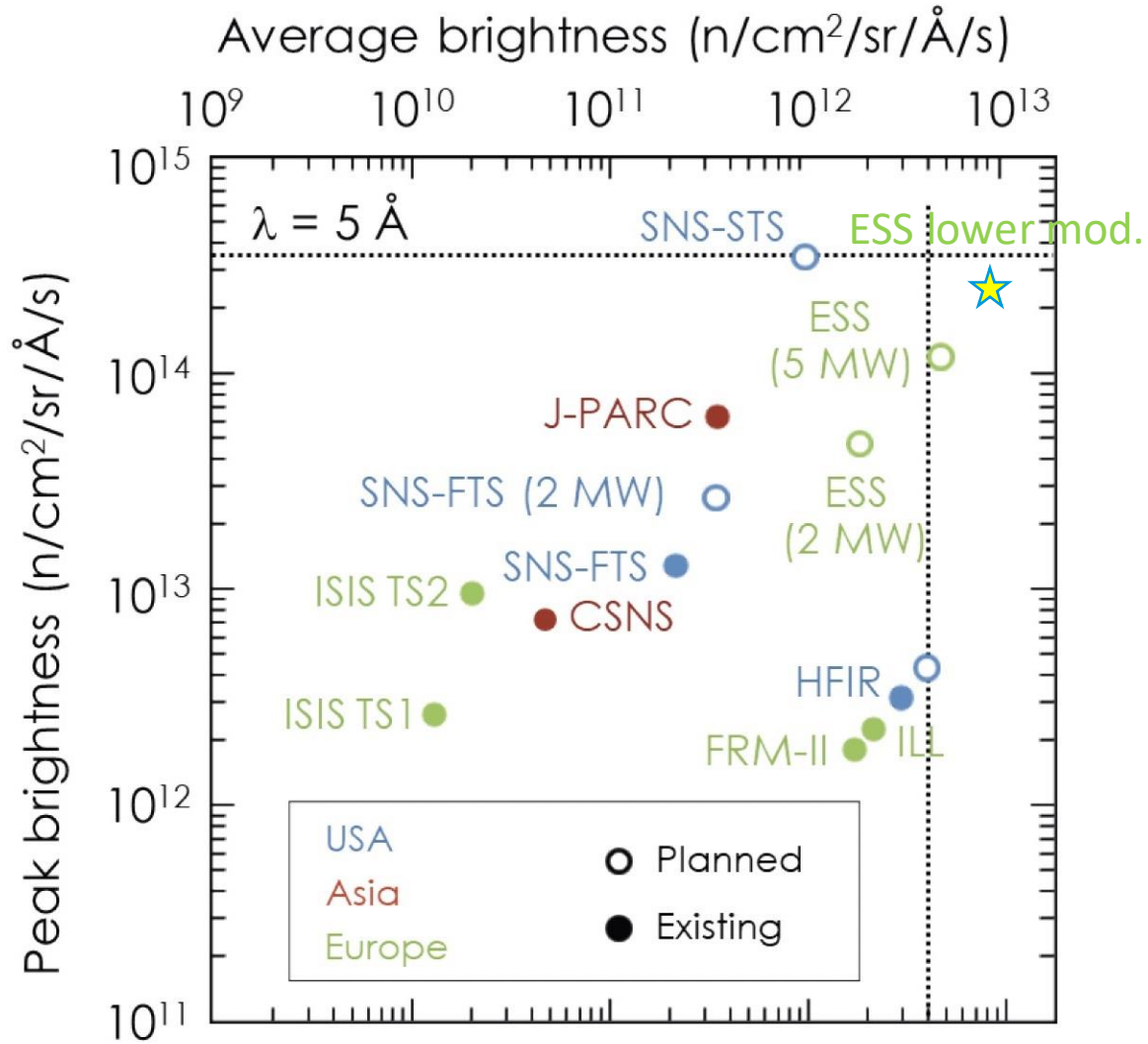


- For very small sample sizes (mm) and very low divergence, NMO might not be needed and conventional optics used instead
- See NEUSTRUCT proposal (slide 28)

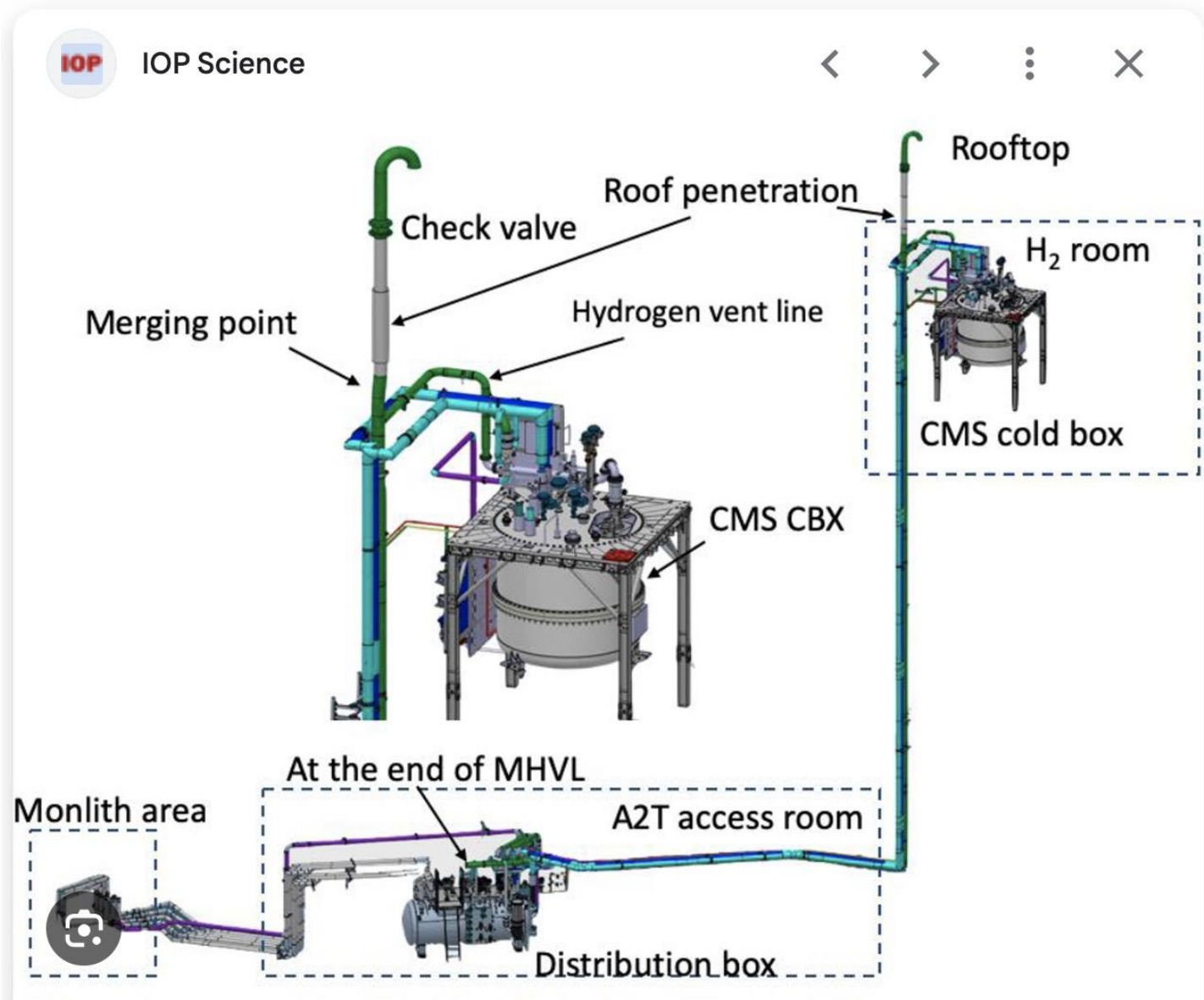
# The second source will bring ESS at the top for both peak and time-average brightness



ESS lower moderator,  
3X1 cm<sup>2</sup> emission surface



# The lower moderator will use the existing cryogenic infrastructure of the upper moderator

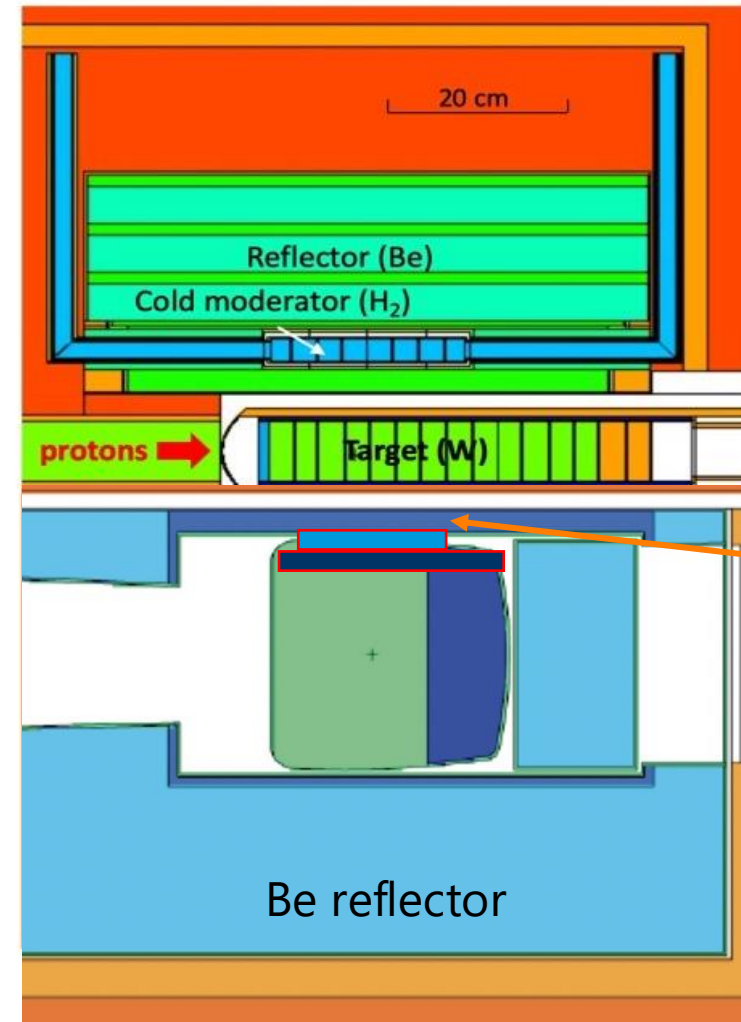
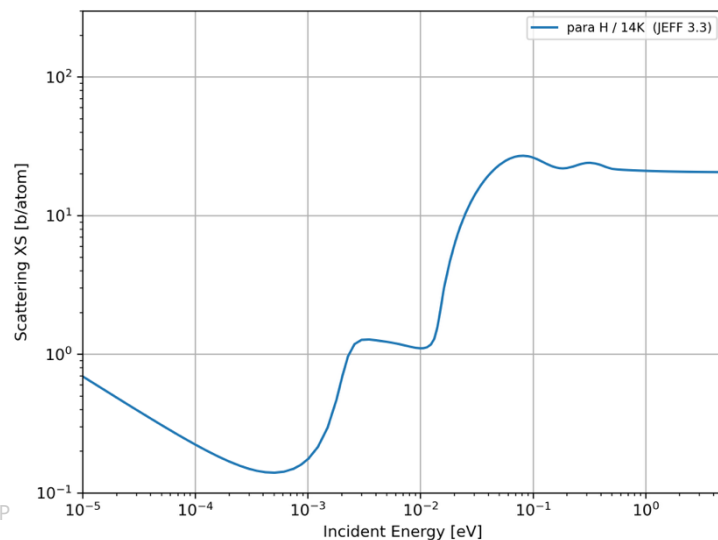


# Possible integration with a high intensity LD2 moderator



Impact of HB moderator on LD2: likely less than 10%  
Impact of LD2 moderator on HB mod: to be quantified but certainly larger

- LD2 replaces Be reflector
- will be transparent to cold neutrons from the LD2
- possible mitigation from additional premoderator?
- Needs a dedicated study



Water premoderator

# Gap analysis

The analysis of the remaining capability gaps in the instrument suite of the ESS, conducted after the instrument selection for phase one, results in the following highlight areas:

- High-Pressure Diffraction
- GISANS
- High Magnetic Fields
- Very Fast Spectroscopy
- Wide Bandwidth Spectroscopy

Three first instruments from these areas are specialised in topics not adequately covered by the current 15 instruments and will use samples with small transverse cross-section in the mm and sub-mm range. Though the ESS peak cold moderator intensity (at 5 Å) will be about two orders of magnitude higher compared to today's highest time-averaged flux from the ILL cold source, and that will reduce typical measurement times accordingly, nevertheless the measuring times for demanding tasks (e.g., study of very small samples and very thin, in Ångstrom range, interfaces) will still be many hours. Therefore, a further increase in flux by a factor of about two is very desirable.

# Proposed new instruments what would use the very high brightness moderator (1)



## SMÅ - SANS FOR MATERIALS ANALYSIS

The instrument will make maximum use of the cold spectrum from the existing top moderator. Various ideas exist for a second, bottom, moderator at ESS. As a low-divergence, small sample, instrument SMÅ would directly benefit if a higher brightness moderator is chosen and that would then be the preferable option for this instrument. In the case that a lower brightness, large, bucket-type moderator is chosen for the bottom position, SMÅ would make use of the existing cold moderator.



# Proposed new instruments what would use the very high brightness moderator (2)

## **KVASIR:**

**A backscattering instrument optimised for hard condensed matter.**

While KVASIR is designed to have a high performance at the baseline ESS moderator, the high-brightness cold moderator would significantly enhance its performance. In particular, the increased brightness would enable improved signal-to-noise ratios, reduced measurement times, and access to smaller sample volumes. This is especially critical for experiments involving extreme conditions, such as pressure cells, where sample sizes are intrinsically small.

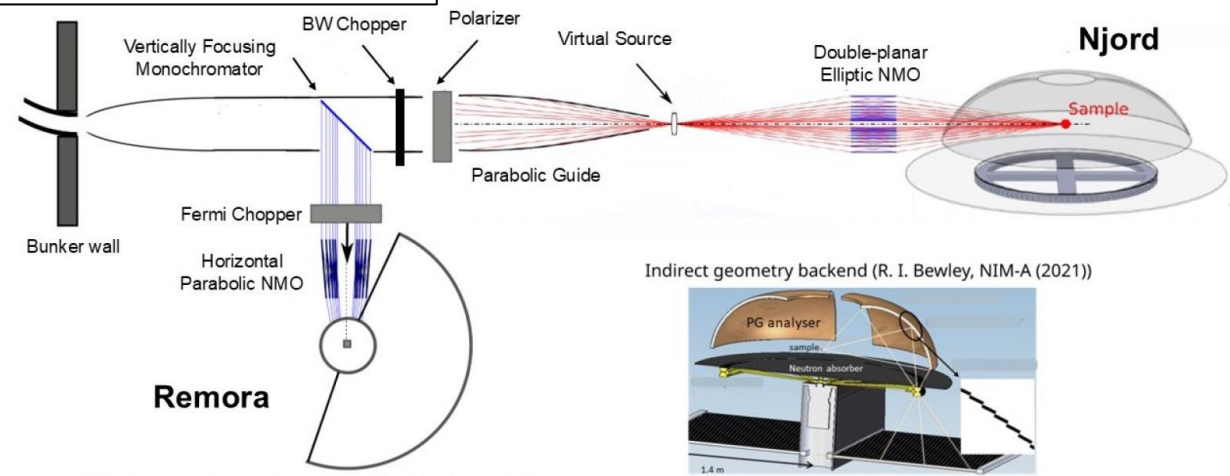


# Proposed new instruments what would use the very high brightness moderator (3)

## Njord and Remora Spectrometers in Symbiosis

While our instrument concept is designed to operate well with the current ESS moderator, the very high-brightness moderator proposed by L. Zanini and co-workers would significantly enhance the performance of Njord and enable inelastic neutron scattering studies of even tinier samples (< mm), under even more extreme pressures (> 100 GPa), and under very high pulsed magnetic fields (> 50 T).

For these reasons, we strongly support the very high-brightness moderator as an important future upgrade at the ESS.



# Proposed new instruments that would likely use the very high brightness moderator (4)

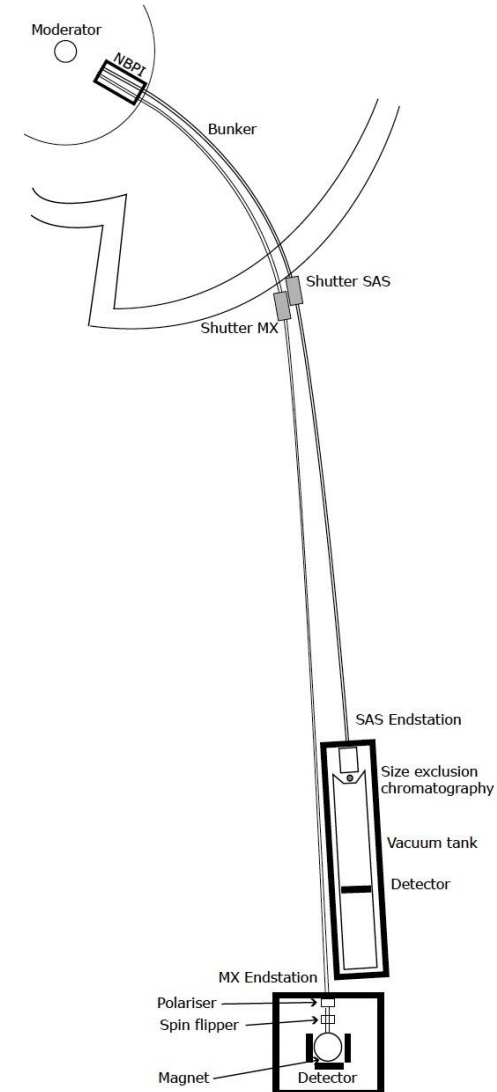


## NeuStruct – Neutron Structural Biology at Multiple Length Scales

Table 1 Summary of scientific requirements for the MX endstation

Parameter	Requirement
Maximum unit cell edge	200 Å
Beam divergence	$\pm 0.2^\circ$
Wavelength resolution	5% $\Delta\lambda/\lambda$
Wavelength range	1.8-4.5 Å

Due to the very small phase space, the NeuStruct team has indicated that conventional optics instead of NMOs might be used. Would likely take neutrons from upper moderator for SANS end station, and neutrons from lower moderator (from the same beamport) for the MX endstation.



# Proposed new instruments what would use the very high brightness moderator (5)



## **3.3.2 Polarised SANS-WANS**

The Yggdrasil instrument proposal aims to build a polarised SANS instrument with a wide angle bank to bridge the Q range gap between SANS and Diffraction with full polarisation analysis. The instrument will utilise a small sample size to enable the use of high magnetic fields. Such an instrument also requires very high fluxes to be able to efficiently operate whilst losing neutrons to the polarisation and polarisation-analysis processes. Furthermore the magnetic scattering signals are weak in comparison to the nuclear scattering and so any increase in flux leads directly to an increase in signal quality. This enables more complex modelling to be performed and opens up an array of measurements that are not currently possible in areas such as unconventional magnetism and magnetism of disordered materials.

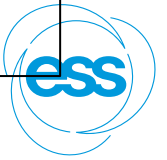


# Additional instruments that could use the very high brightness moderator (6,7)

## **3.2 Instrument concepts for Reflectometry and GISANS**

Both neutron reflectometry (NR) and grazing-incidence small-angle neutron scattering (GISANS) employ grazing-incidence neutron beams on the sample surface. In this geometry, the effective illuminated sample cross-section in the scattering plane is determined by the small angle of incidence  $\theta$  and therefore becomes very small. As a result, even for relatively large incidence angles, the effective illuminated area of the sample remains limited. The ASGARD reflectometer and SAGA GISANS/Reflectometry instrument are both instruments that could potentially benefit from this moderator concept and this should be considered during the technical development of those instruments.

This moderator achieves much of the gains previously proposed for a dedicated mHz source with obvious advantages of serving more instruments and of being able to deliver not just mHz but also 14Hz.



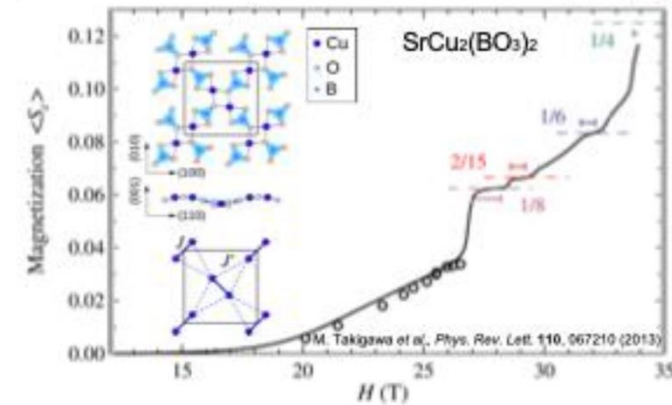
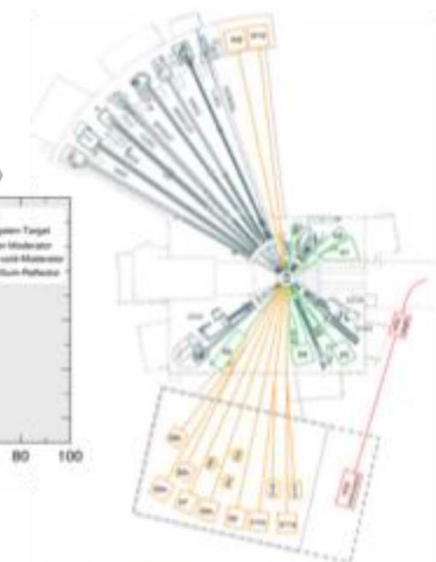
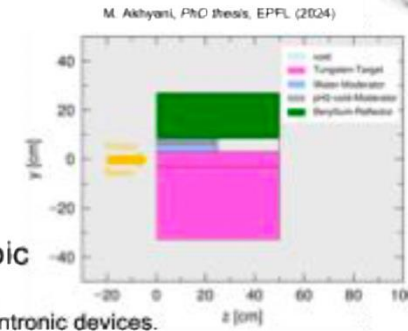
## Optimized mHz source-instrument assembly for very high pulsed magnetic field experiments

### Science case for very high magnetic fields:

- Novel phases and transitions in quantum matter
  - New proximate orders accessible above ~20–40 T
  - Fractionalized excitations & confinement by field in quantum spin liquids
- Superconductivity exposed to pair breaking fields
  - unmask competing orders CDW/SDW, FFLO states, amplitude "Higgs" modes
- Topological magnonics & spintronics, magneto-elastic, multiferroic
  - restructure electron and magnon bands (gaps, Dirac/Weyl points, Chern phases), enabling nontrivial electron and thermal Hall responses and tunable magnonic/spintronic devices.
  - Strong B reveals spin-phonon coupling, magnetostriction, and field-switchable ferroelectric states
- Technological magnets
  - Establish predictive models for mechanisms, time-scales and control of magnetization dynamics in technologically relevant magnets
- Out-of-equilibrium studies

### mHz dedicated source optimized for one instrument

- 50–60 T pulsed magnet with 10–30 minute duty cycle
- 5 proton pulses per duty cycle -> mHz source (1 signal / 4 bck)
- $10^4$  less heat and radiation -> perfect target-moderator-neutronics optimization for a single instrument
- Instrument optimized for pulsed magnet
- => **factor 20-100 better statistics than pulsed magnet on standard instrument**



Contact: Henrik M. Rønnow, EPFL



# Technical level of maturity: moderator

- ❑ Concept uses established decade-long best practice in parahydrogen moderators.
- ❑ Materials established (parahydrogen, beryllium, structural materials)
- ❑ Scaled-down complexity wrt to upper moderator, but similar in concept
  
- ❑ Should these instruments be accepted, such moderator could be immediately implemented
  - ❑ Uses the existing cryogenic infrastructure
  - ❑ Only cost is the additional Be material

# Technical level of maturity: optics



- ❑ **NMO** is a new concept, derived from Wolter Optics
- ❑ Not yet used at neutron sources
- ❑ Experimental validation of prototypes performed at FRM-II and PSI (Herb, Zimmer, Böni et al)
  - ❑ The reported experimental results, obtained with a small prototype elliptic NMO equipped with non-polarising supermirrors, have demonstrated a brilliance transfer for small samples of 72%.
- ❑ There are ongoing measurements and developments (P. Böni et al).
- ❑ Will require additional R&D to consolidate the technology, improve brilliance transfer, and study effects such as waviness
- ❑ Can profit from parallel developments from other teams (NNBAR, NJORD) that have NMOs in their proposals
  
- ❑ **Conventional optics** might be used for instruments using very small sample areas and divergences (NEUSTRUCT)



# Strength of the team

- ❑ The present consortium consists of specialists in source design, optics, and instrument scientists
- ❑ More resources would be needed for neutronic, optics design and prototyping
- ❑ Detailed neutronic design of moderator will need additional resources (1 PhD)
- ❑ It is expected that as the interest grows, there will be collaborations with the different instrument teams using the lower moderator
  - ❑ Optics design would be done in collaboration with instrument teams using lower moderator, as it was done for the upper moderator
  - ❑ Additional development of NMO would also be done in collaboration

# Conclusions



- ❑ The VHBS, consisting of a high brightness moderator combined with the beam extraction of NMOs, may provide a factor 2 in brightness for neutron scattering instruments with small phase space volume.
- ❑ Ideal for instruments with small samples and low-divergence beams
- ❑ Once ESS reaches 5 MW, it would make ESS simultaneously the source with highest peak and time average brightness in the world
- ❑ Four proposed instruments (NJORD, KVASIR, SMÅ, NEUSTRUCT) have expressed strong interest in this source, and the VHBS would likely become their source of choice instead of the upper moderator (NEUSTRUCT would use both)
- ❑ Other proposed instruments (YGGDRASIL, ASGARD, SAGA) would likely benefit from it.
- ❑ There might be more of the proposed instruments, we have not talked with all the teams
- ❑ Should these instruments be accepted, the moderator could be soon implemented thanks to:
  - ❑ Uses the existing cryogenic infrastructure
  - ❑ Low additional cost (Be reflector) for the planned twister plugs.

❑ Integration with a future LD2 moderator seems possible: needs detailed study