High-sensitivity search for free neutron oscillations at the European Spallation Source

Blahoslav Rataj (blahoslav.rataj@fysik.lu.se, blahoslav.rataj@ess.eu)

On behalf of the HIBEAM/NNBAR collaboration

17 of June 2024

Outline of the presentation

(i) Motivation for search for neutron oscillations at the intensity frontier

(ii) Search for the free neutron oscillations at ESS: HIBEAM and NNBAR at ESS

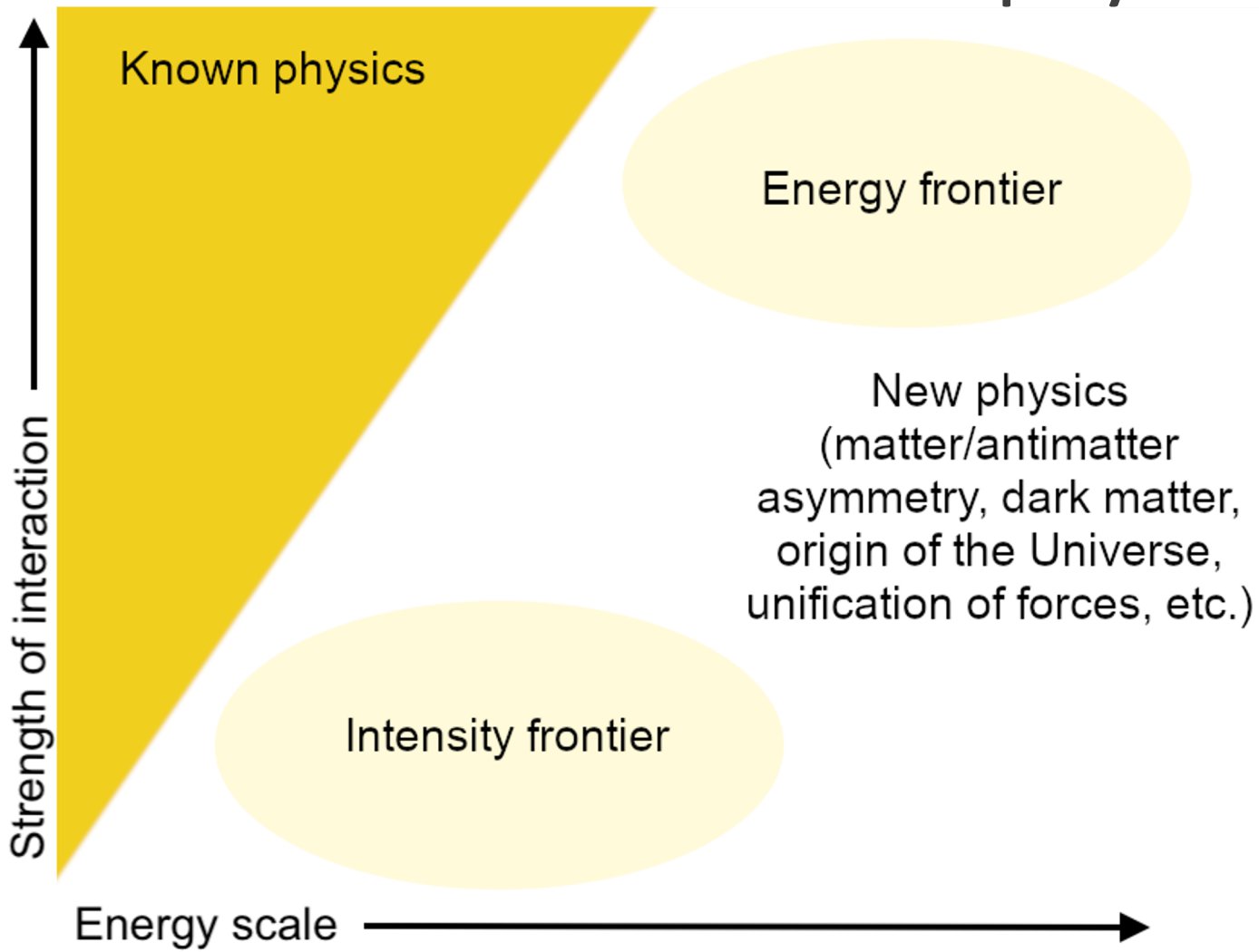
(iii) Development of HIBEAM

(iv) Development of NNBAR

(v) Development of annihalation detectors for HIBEAM/NNBAR

(vi) HIBEAM/NNBAR collaboration

Experiments at the energy and intensity frontier to discover new physics

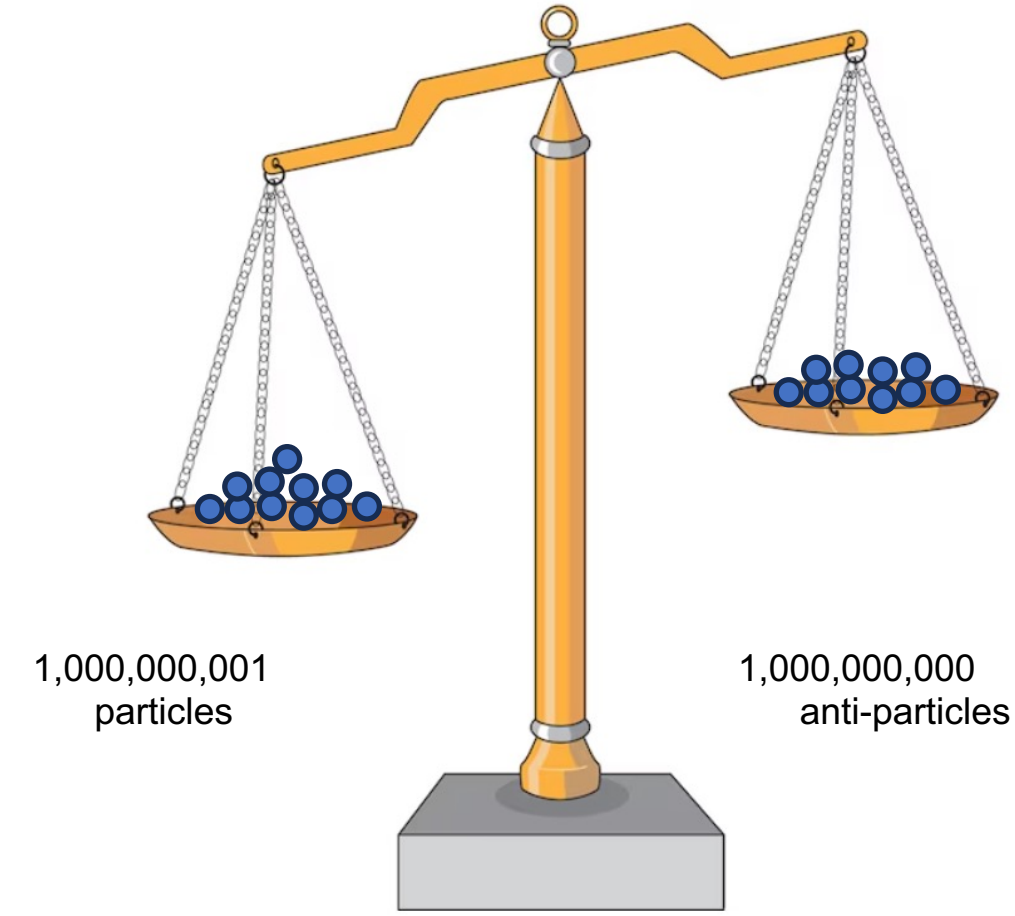


The motivation for pursuing experiments at the intensity frontier

- Highly sensitive experiments at the intensity frontier can provide an insight into phenomena of new physics
  - It can even probe phenomena at mass scales higher than the current circular particle colliders
- Examples of experiments at the intensity frontier:
  - Proton decay, neutrinoless double beta decay, electric dipole moments
  - Free neutron oscillations ← **Our goal at ESS**
    - The cleanest approach to search for a process that violates Baryon number (*B*) only

What is the origin of matter/antimatter asymmetry in our Universe

- Fundamental question to understand the nature of our Universe
- How a tiny excess of matter over antimatter formed in the early Universe?



What is the origin of matter/antimatter asymmetry in our Universe

- The scale of this tiny excess of matter of antimatter is challenging to visualize
- Picture with about 100,000,000 particles fill up the whole Los Angeles Reservoir:

Pictures from https://www.nationalgeographic.com/science/article/150812-shade-balls-los-angeles-California-drought-water-environment

What is the origin of matter/antimatter asymmetry in our Universe

- We search for processes that would satisfy Sakharov conditions to answer how the tiny excess of matter over antimatter formed:
  - **Baryon number *B* violation**
  - C-symmetry and CP-symmetry violation
  - Interactions out of equilibrium

Would be violated by neutron oscillations

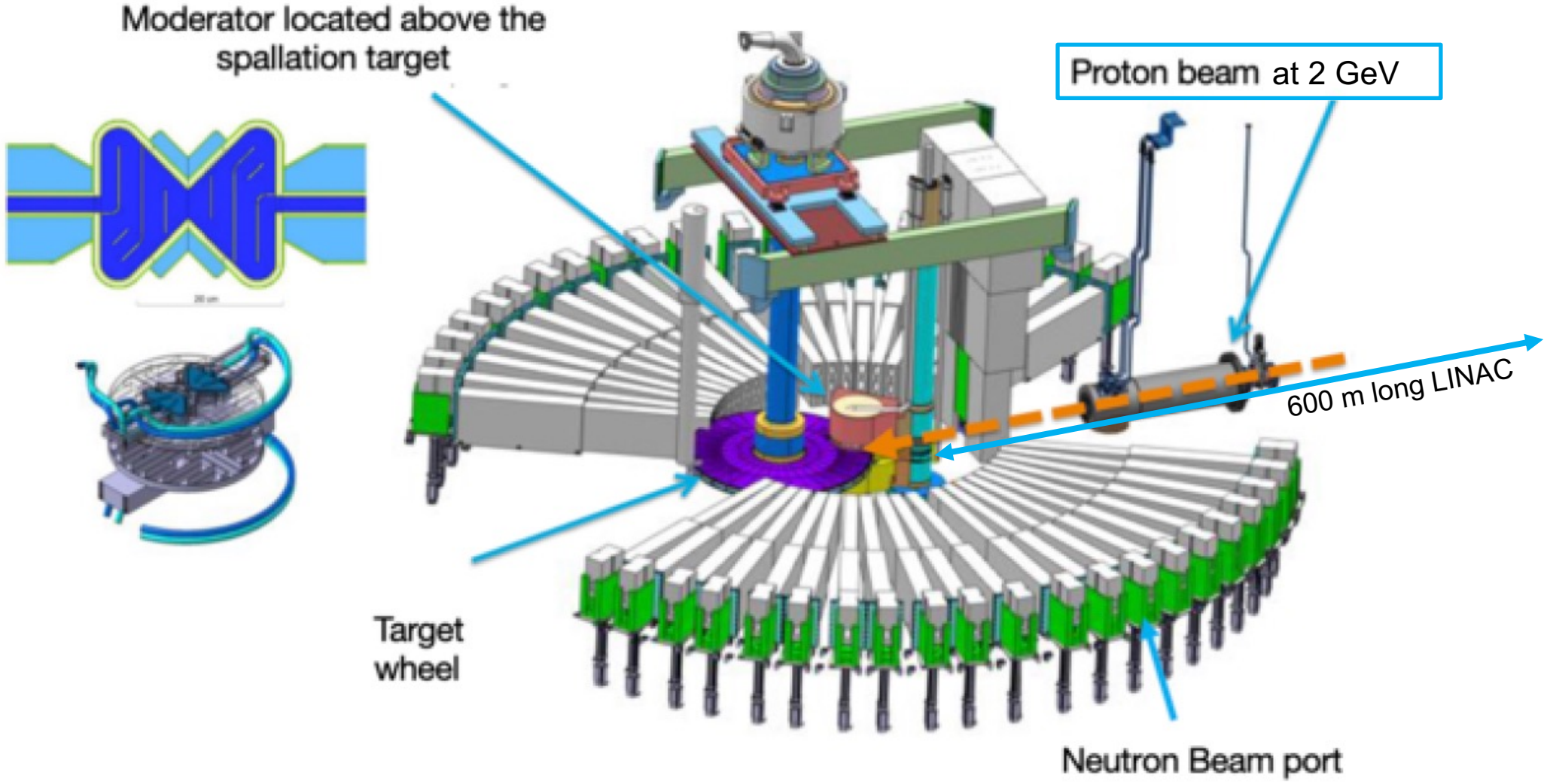
The European Spallation Source (ESS)

- Currently constructed in Lund, Sweden with construction budget of 1 843 M€
- Will become the brightest source of neutrons that will be transported to 15 experiments initially

Reproduced from Nordeng, Perry. europeanspallationsource.se/media-bank. "Aerial View over ESS Site." *European Spallation Source*, April. 2022.

The European Spallation Source (ESS)

- Drawing of the target area

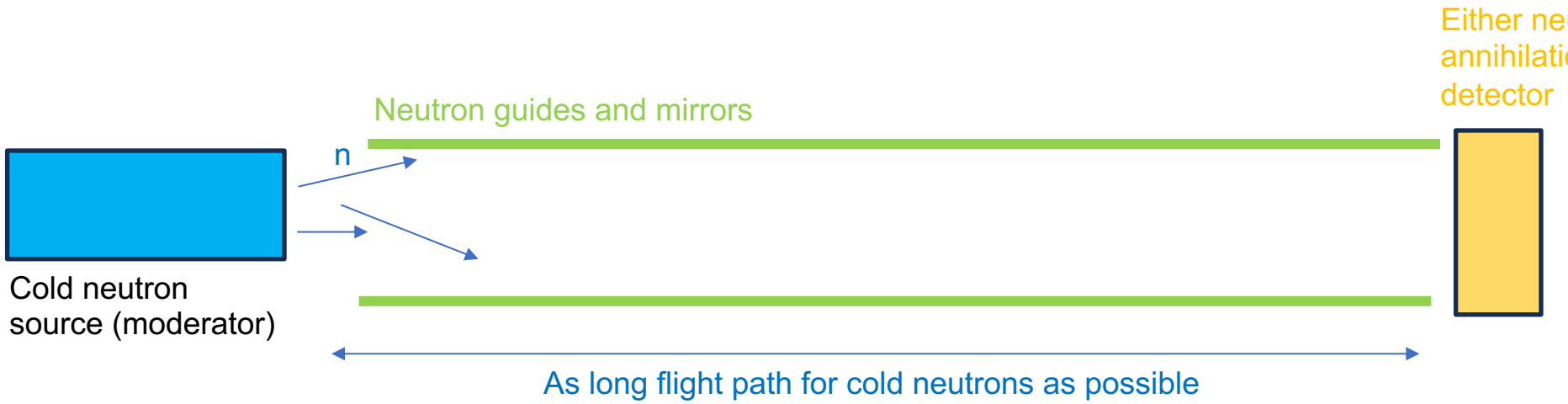


From recent visit of the construction site at ESS

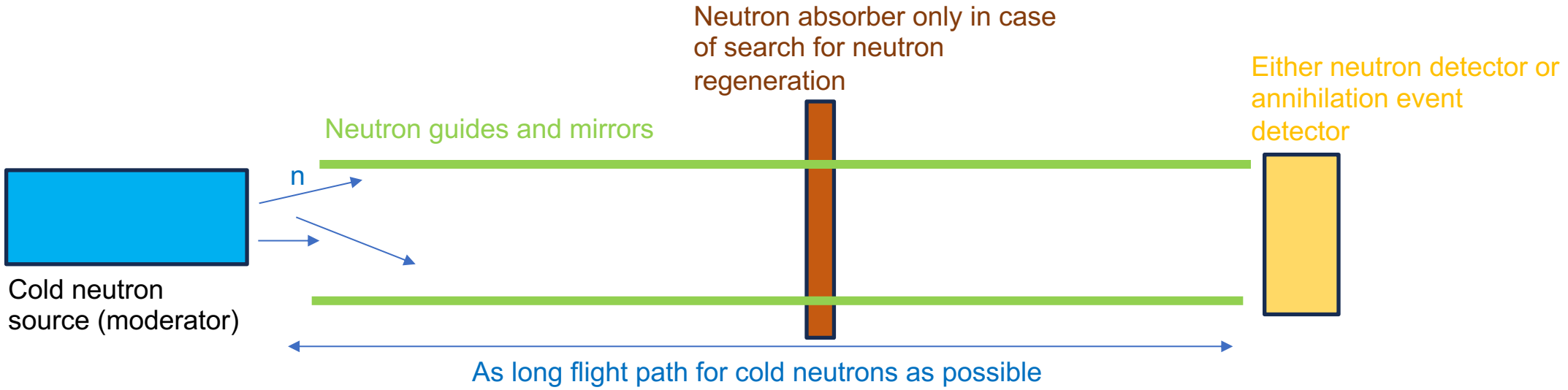
From recent visit of the construction site at ESS

From recent visit of the construction site at ESS

Basic outline of an experiment to search for free neutron oscillations

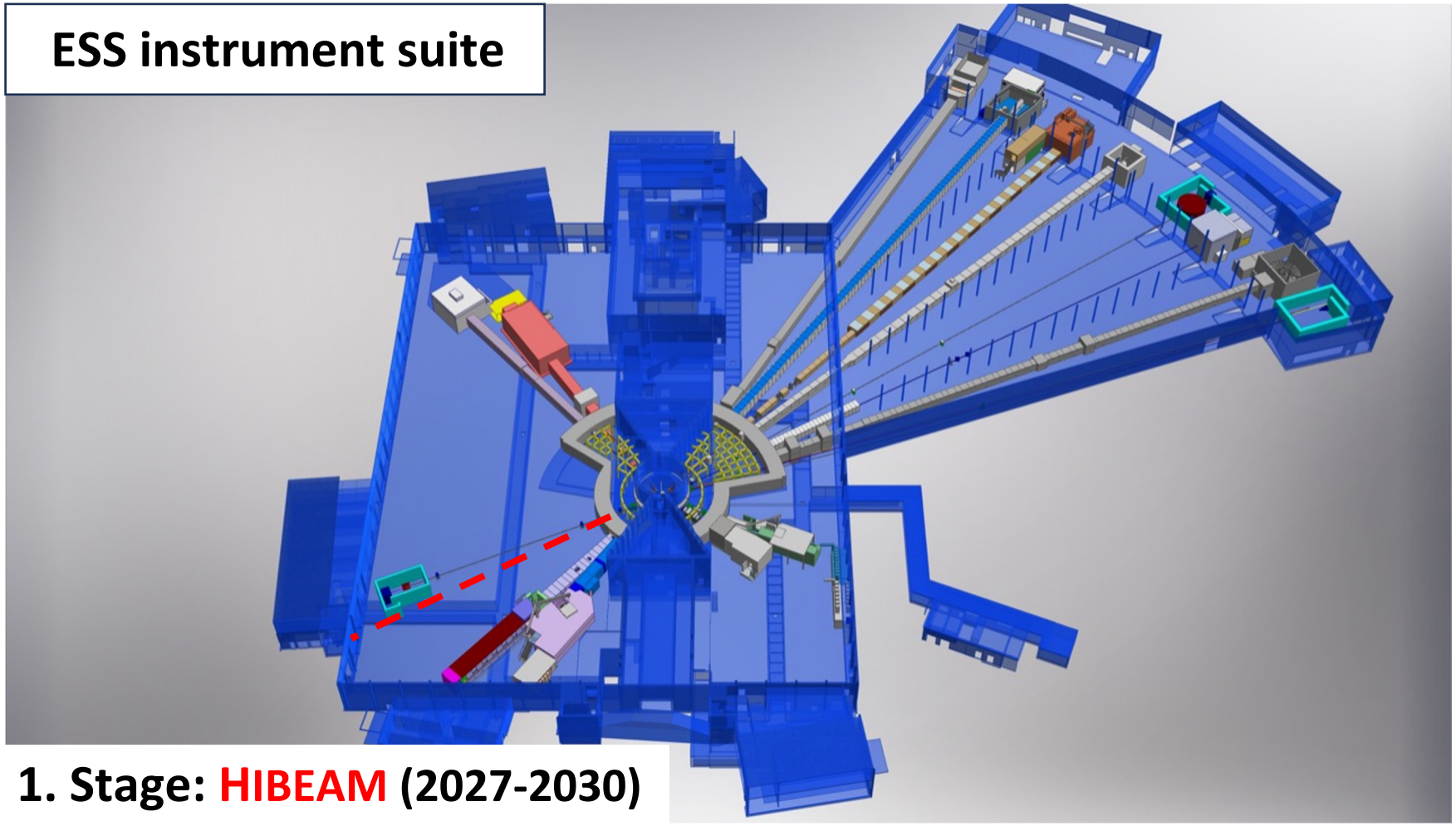


Basic outline of an experiment to search for free neutron oscillations



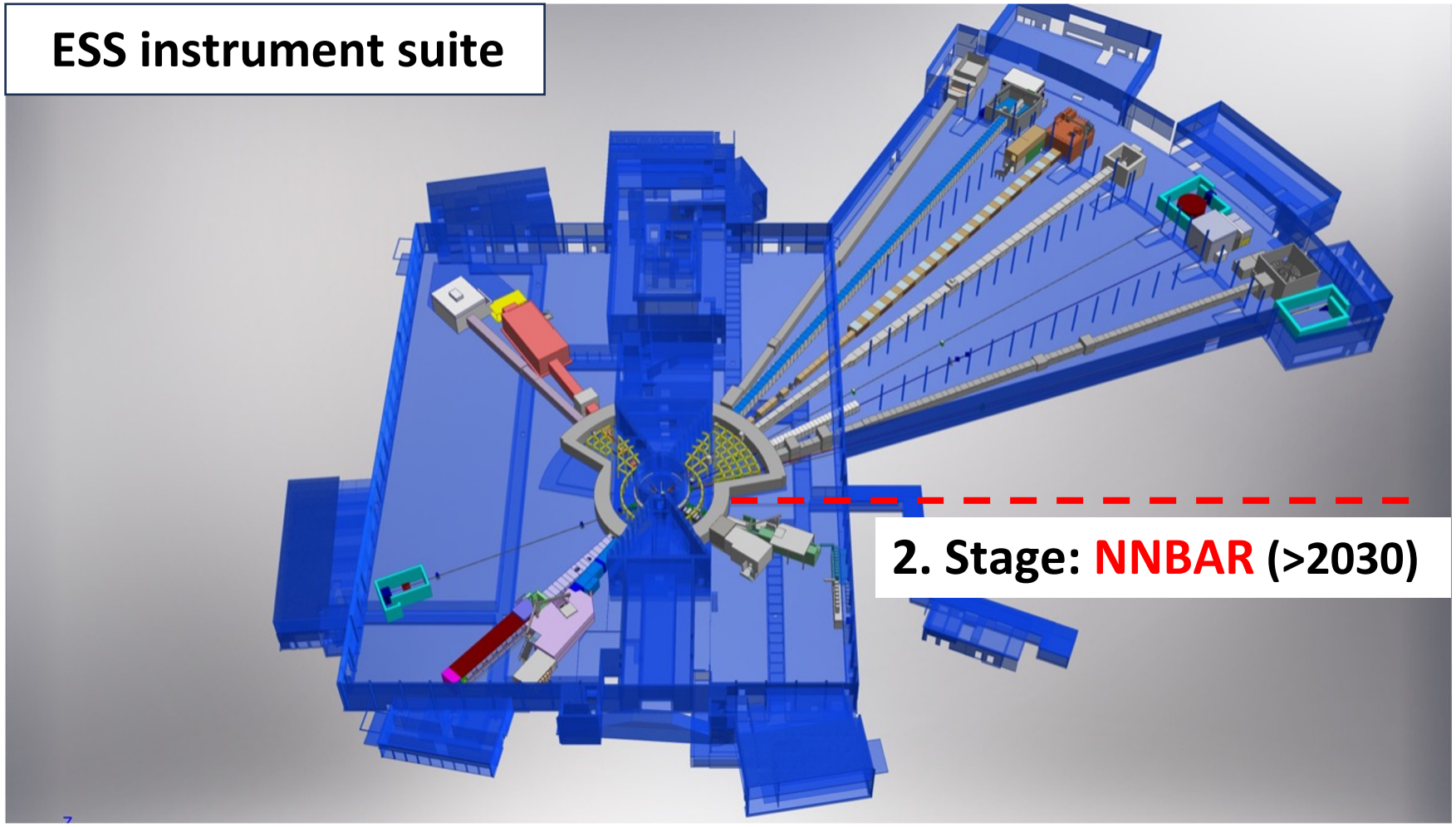
The search for free neutron oscillation at ESS

ESS instrument suite



1. Stage: HIBEAM (2027-2030)

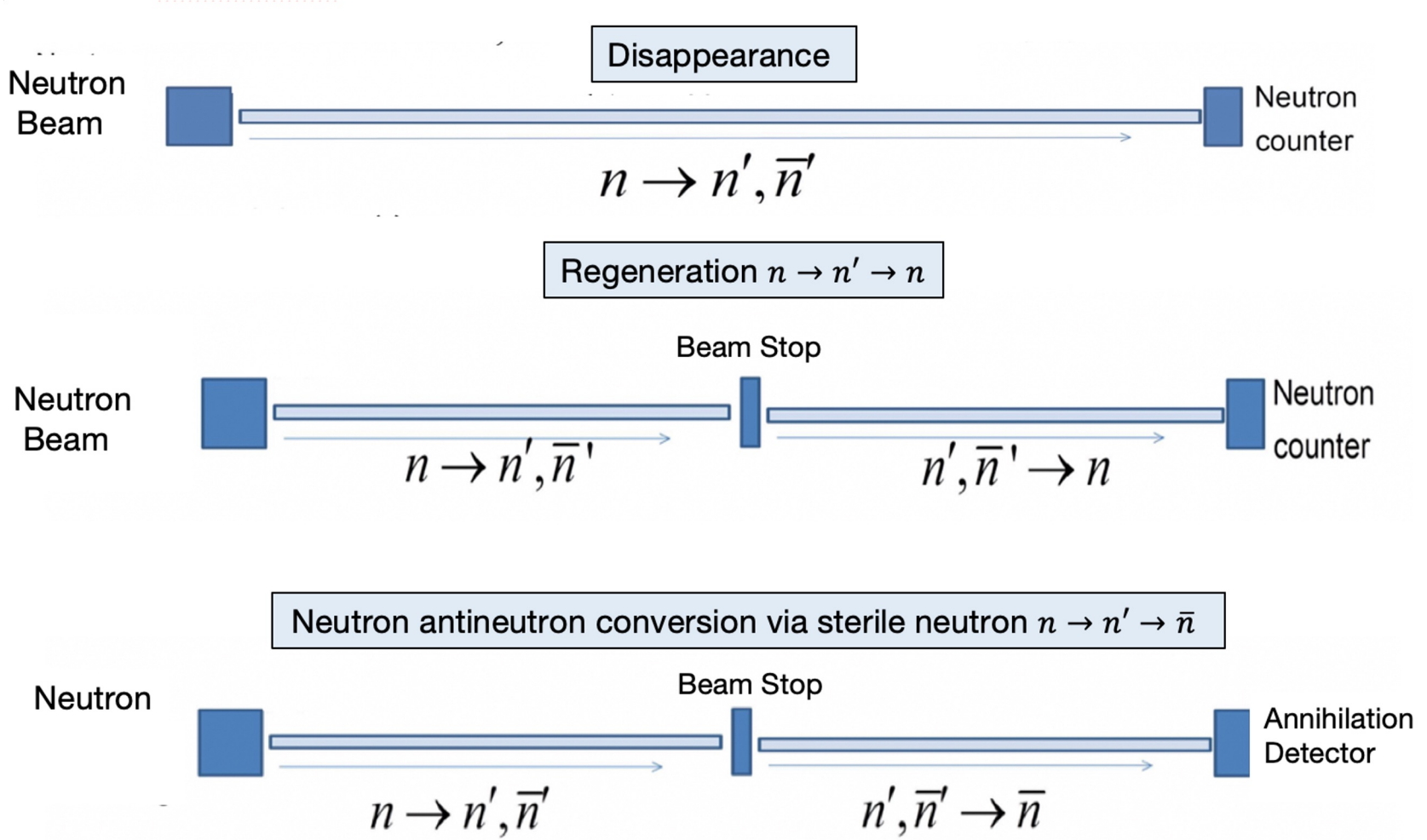
The search for free neutron oscillation at ESS



Search for free neutron oscillations at ESS: the **HIBEAM experiment**

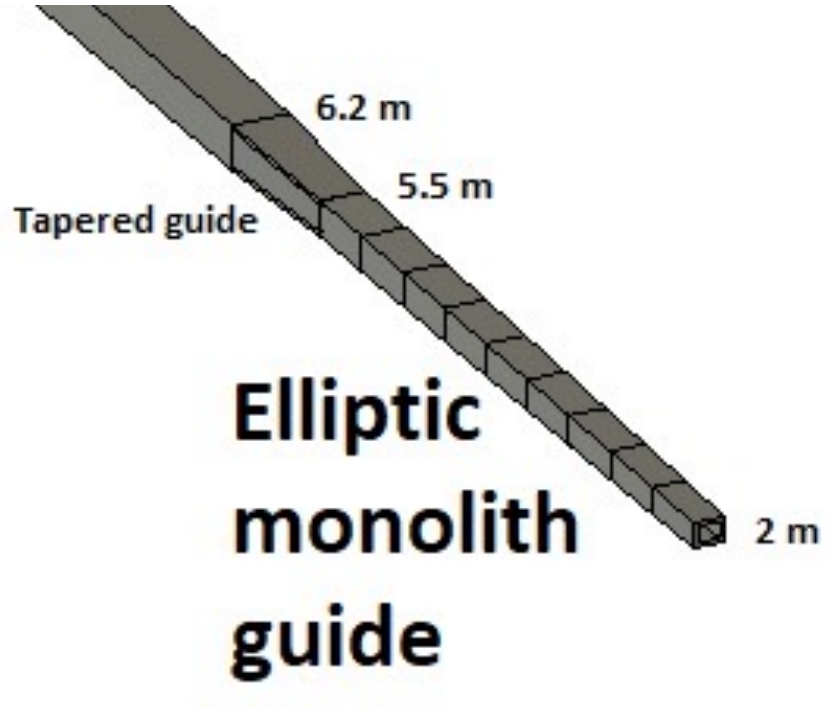
- **HIBEAM** is the first stage of the HIBEAM/NNBAR program
- Primary focus of **HIBEAM**:
  - Search for neutron into antineutron oscillations ($n \rightarrow \bar{n}$)
    - World leading sensitivity for this process
    - Would violate *B* by two units
  - Search for neutron into sterile neutron oscillations ($n \rightarrow n'$)
    - World leading sensitivity in several search modes
    - Would violate *B* by one unit
    - May provide a probe into a dark sector
- The generic monolith insert that can be utilized by HIBEAM was approved in late 2023

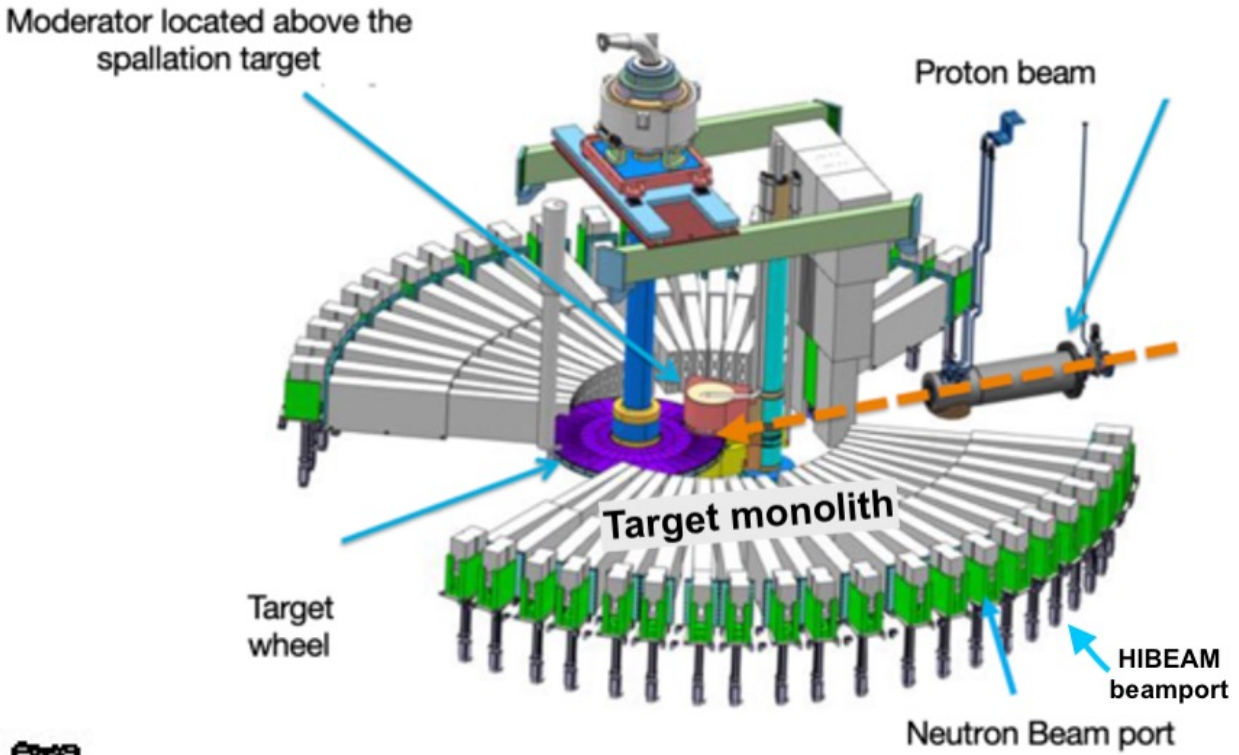
Modes of neutron oscillations searched at HIBEAM – sterile neutron search



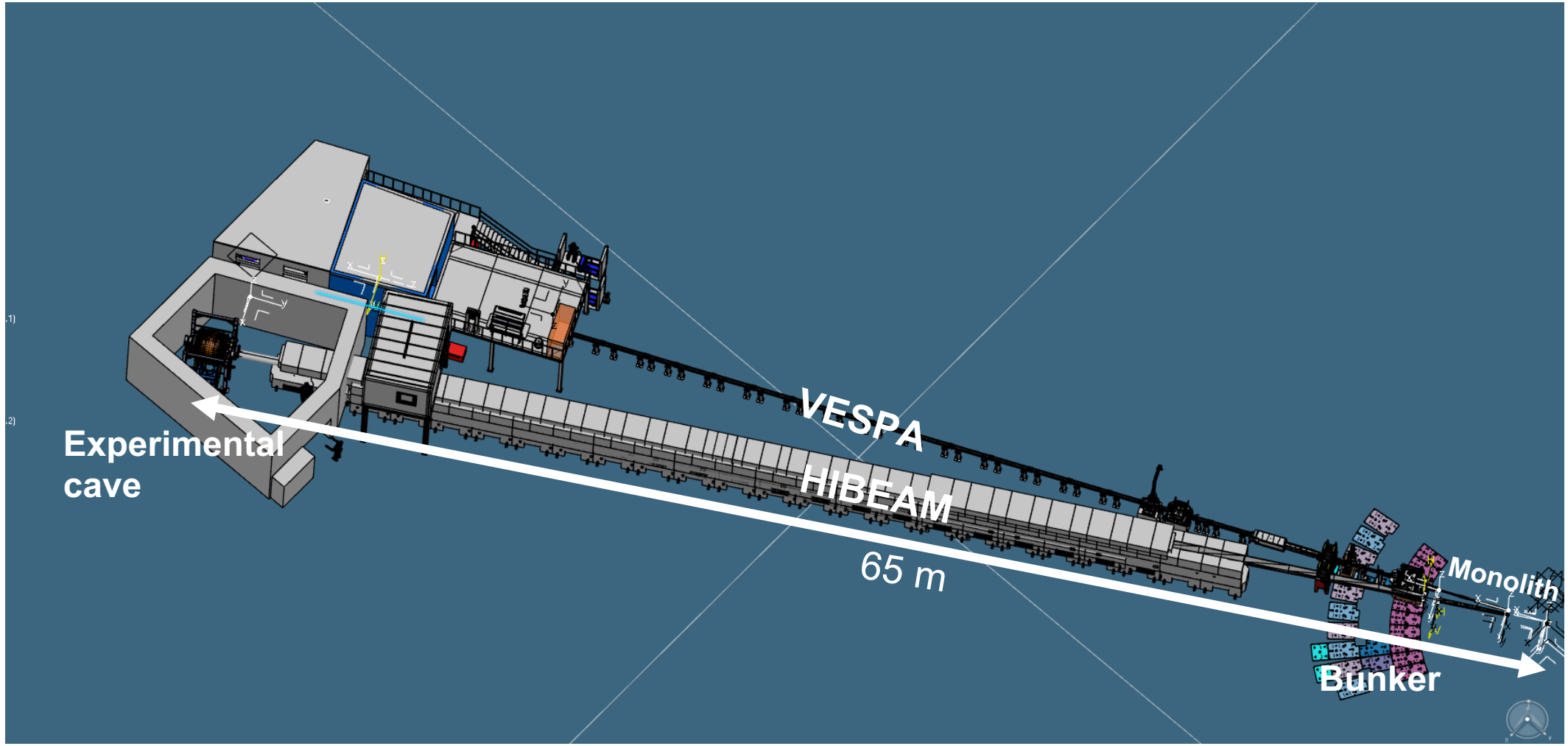
Location of HIBEAM in the east sector of ESS instrument hall

First part of HIBEAM beamline: neutron extraction system





Ongoing work on the engineering model of HIBEAM – need new images

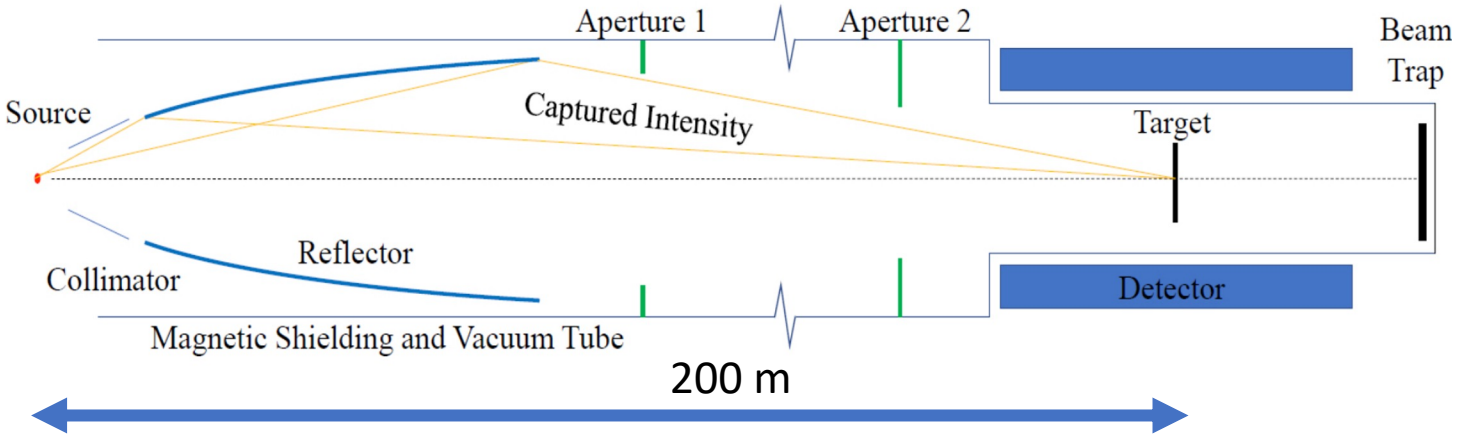


The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

- **NNBAR** experiment is designed to provide world leading sensitivity for $n \rightarrow \bar{n}$ search
  - Sheds lights on baryogenesis that occurred in the early Universe
  - The goal is to exceed the sensitivity set by previous $n \rightarrow \bar{n}$ experiment at ILL by the factor of 1000
  - The current lower limit for $n \rightarrow \bar{n}$ set by ILL: 0.86 x 10^8 s [1]
  - Increasing the sensitivity requires a higher flux of cold neutrons
  - A need for development of new intense cold neutron source for the ESS, highly-efficient neutron reflectors, state-of-art annihilation detector and magnetic shielding and many other key components
    - A design study of these components was conducted within the **HighNESS** project

[1] Baldo-Ceolin, Massimilla, et al. "A new experimental limit on neutron-antineutron oscillations." *Zeitschrift für Physik C Particles and Fields 63* (1994): 409-416.

The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**



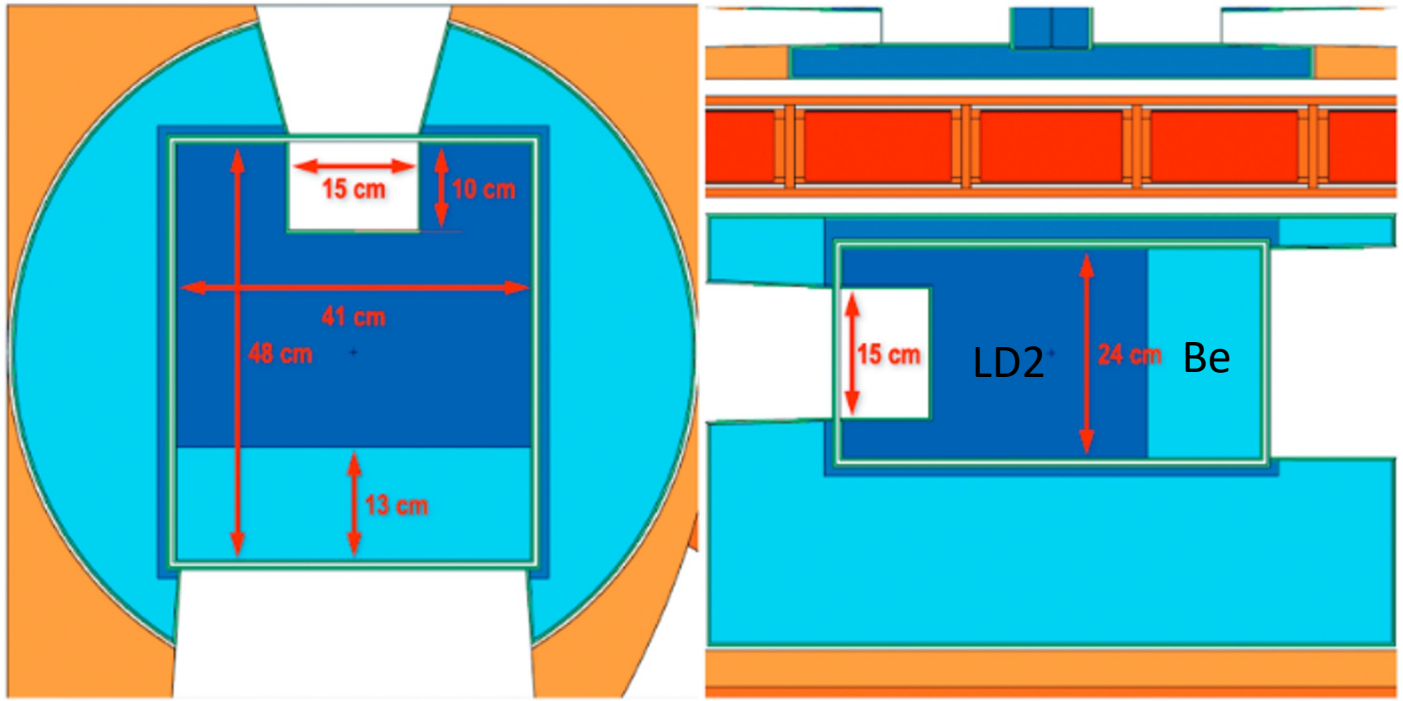
- Drawing of NNBAR experiment

- Civil engineering for NNBAR experiment

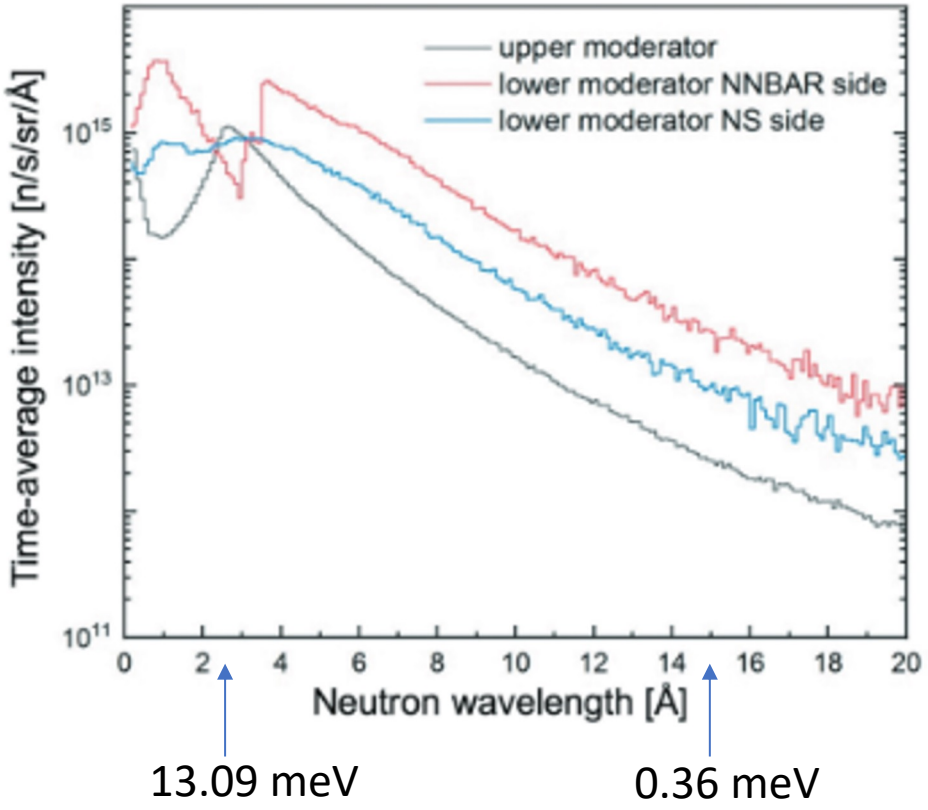
The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

- A new source of neutrons designed for ESS optimised to deliver intense beam of cold neutrons to NNBAR

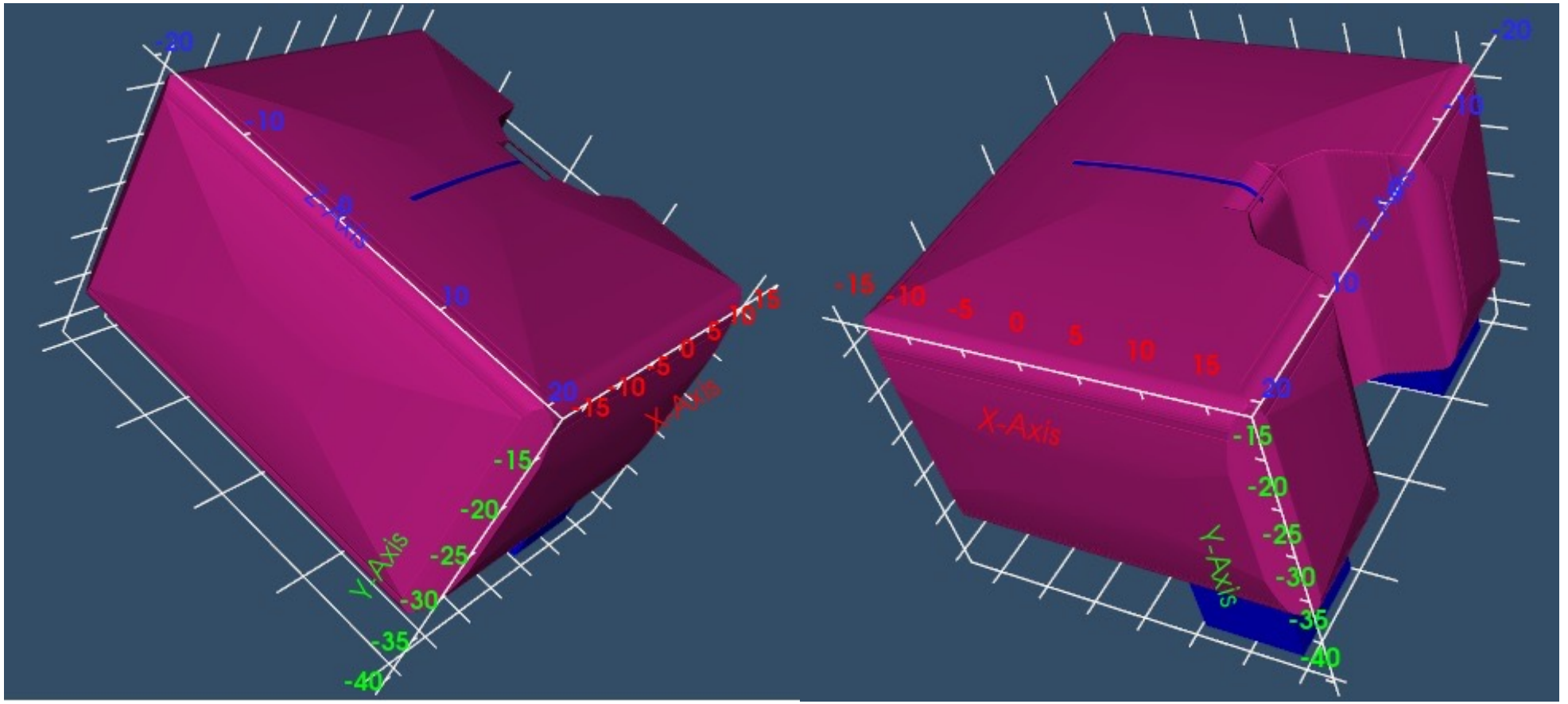


Neutron spectra from MCNP simulation:



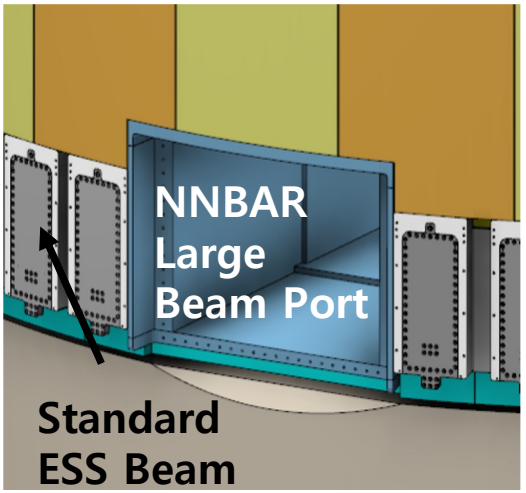
The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

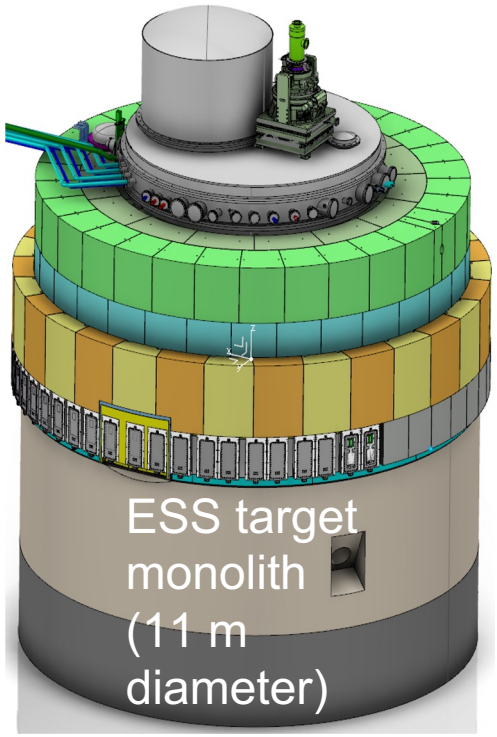
- A recent model of cold neutron source with engineering detail



The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

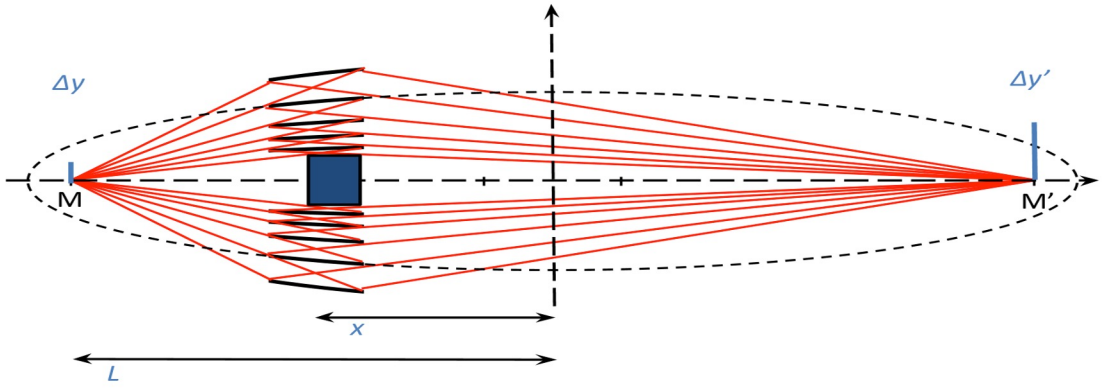
- A large beam port has been built at the ESS to deliver unprecedented intense beam of cold neutrons (0.36 meV – 13.09 meV) to NNBAR to reach the world leading sensitivity



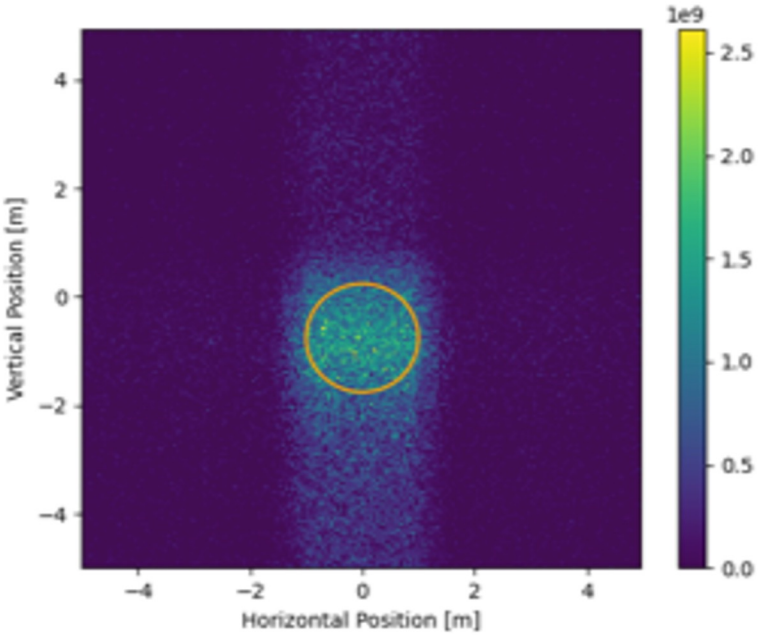


The search for neutron into antineutron oscillations at ESS: the **NNBAR experiment**

- Advanced neutron optics to focus cold neutrons on the NNBAR annihilation detector:

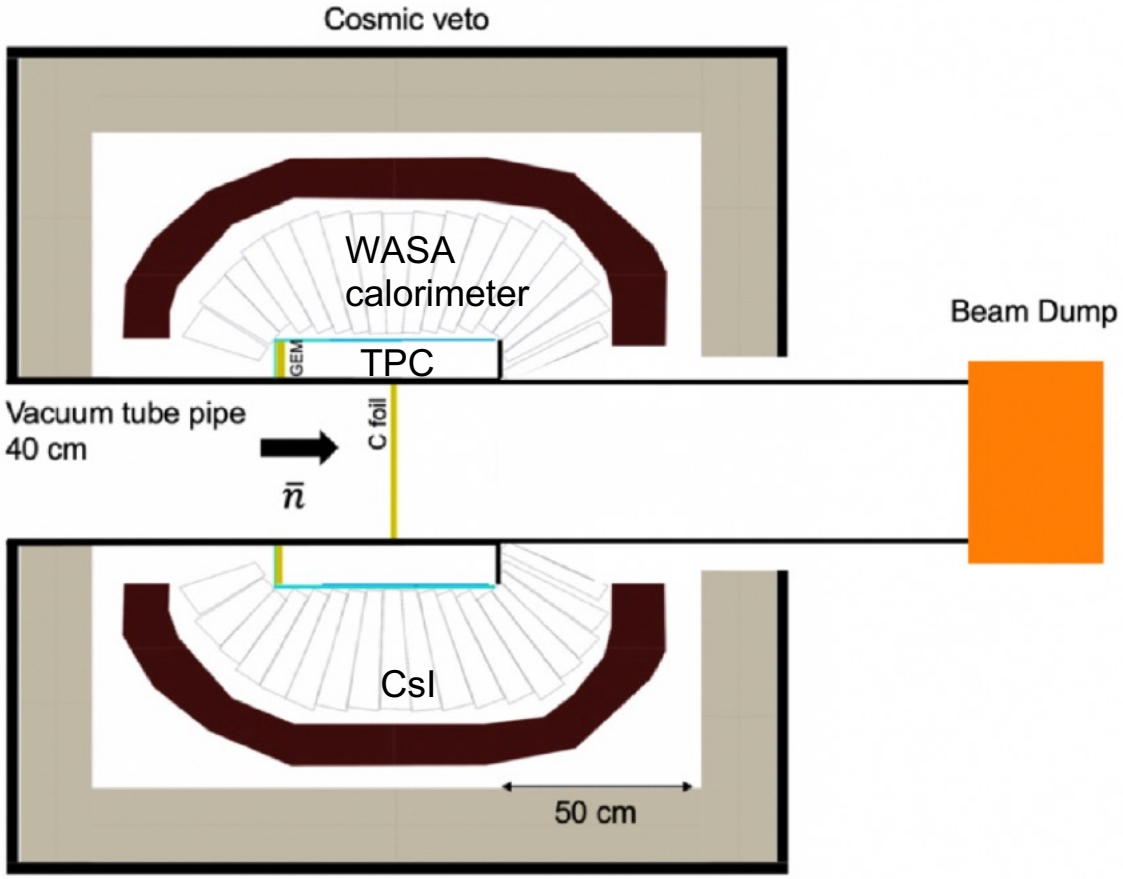


Distribution of cold neutrons at the NNBAR detector simulated with McStas:

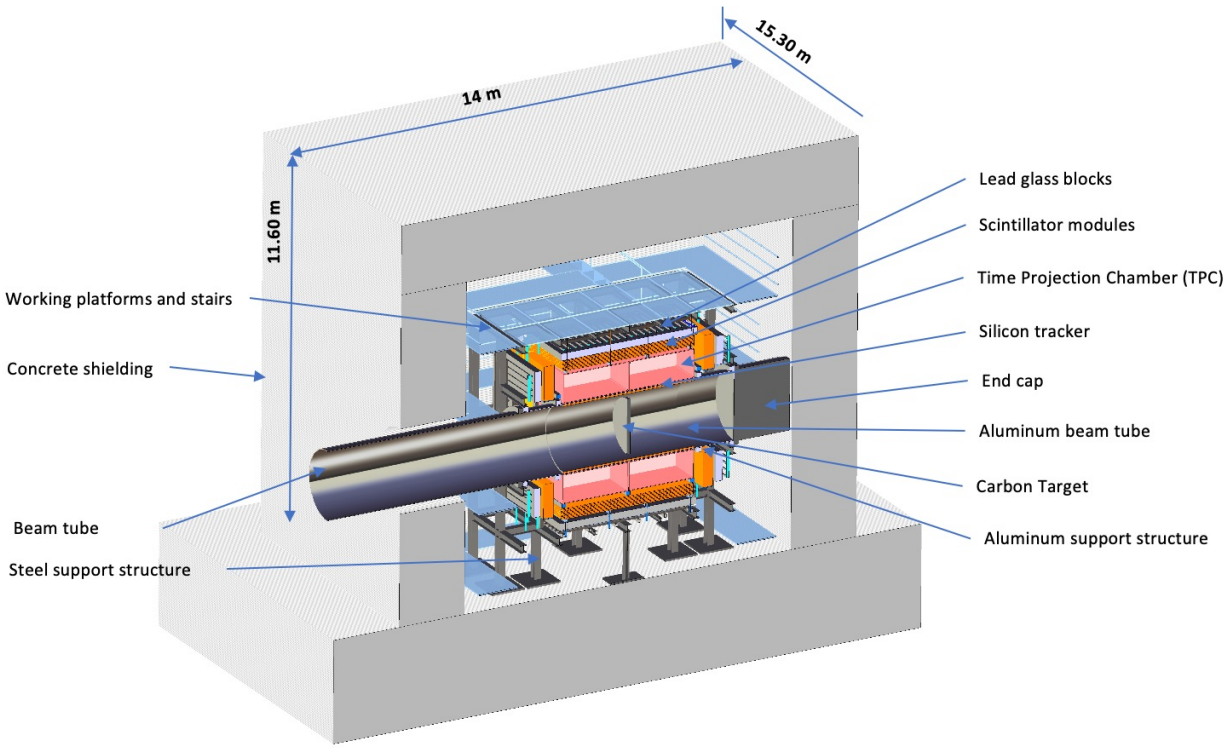


Development of annihilation detectors for HIBEAM/NNBAR

- Development of the zero-background annihilation detector for the n -> $\bar{n}$ search
- $\bar{n}N \rightarrow \sim 5\pi$, $\sqrt{s} \sim 1.9$ GeV



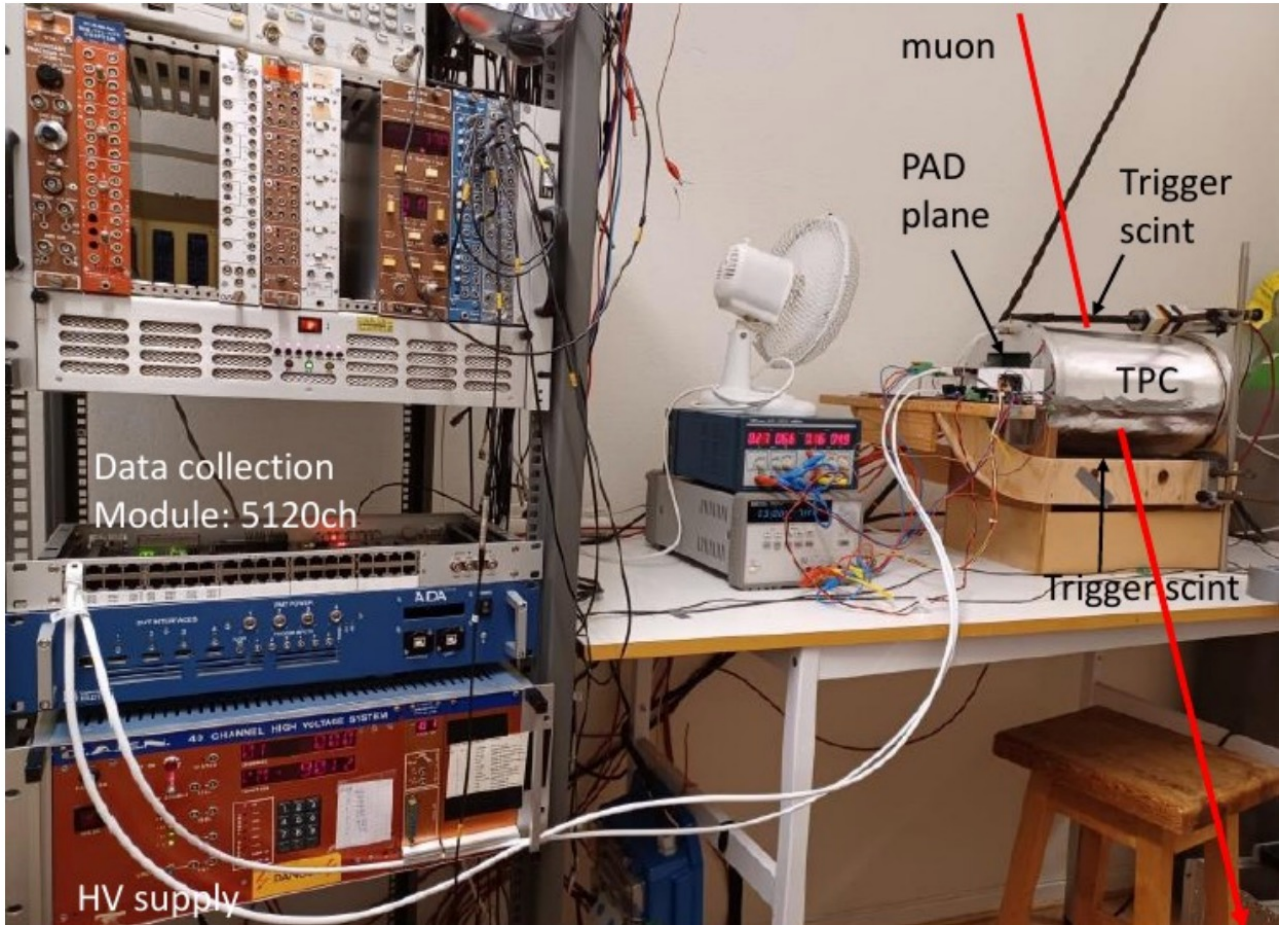
(i) HIBEAM



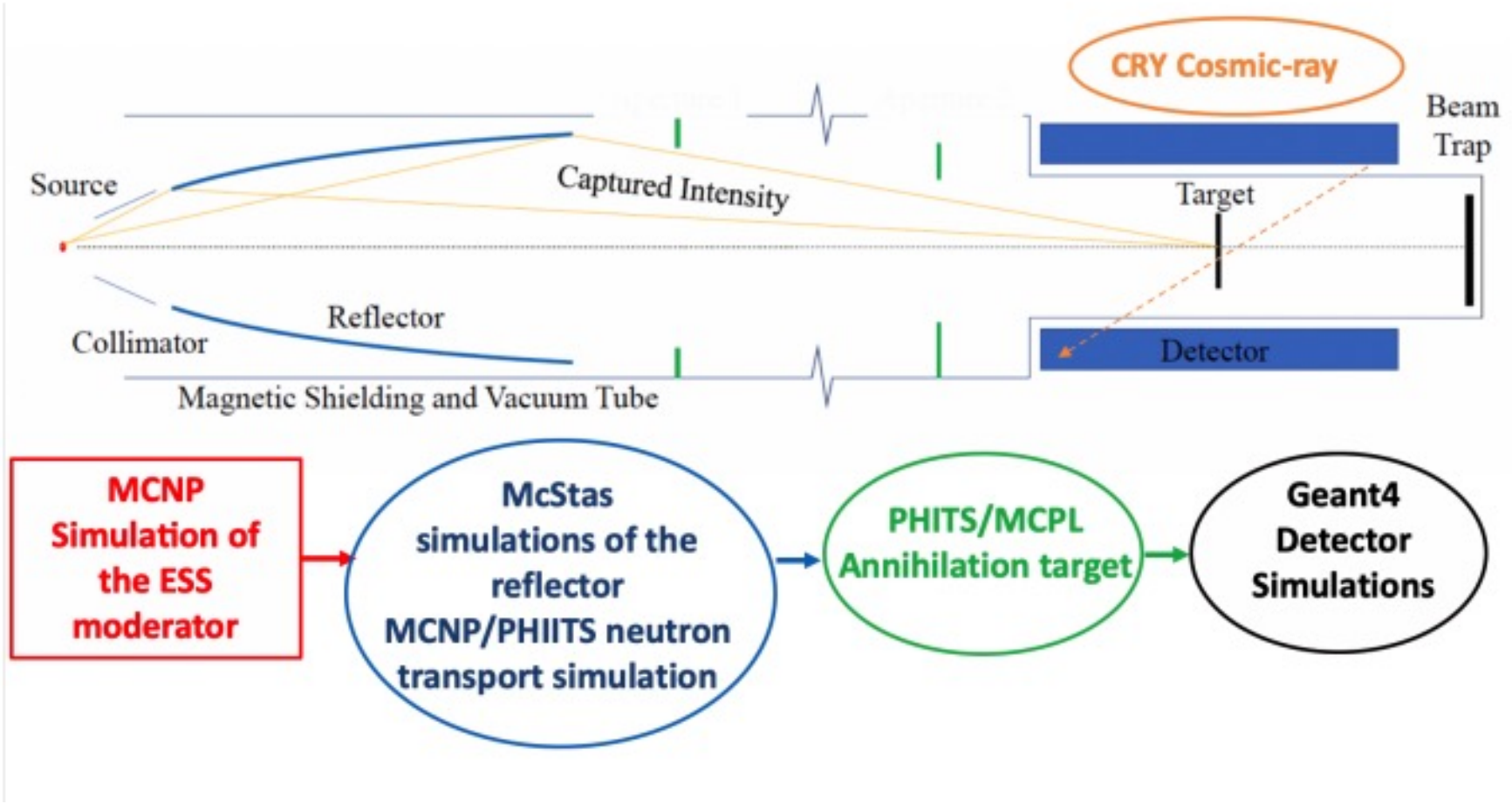
(ii) NNBAR

Development of annihilation detectors for HIBEAM/NNBAR

- Prototype of TPC for HIBEAM at Lund University
- Now just detecting cosmic radiation



Development of components for HIBEAM/NNBAR requires a broad expertise in simulation codes



HIBEAM/NNBAR collaboration

- Wide international base of supporters
  - ~ white paper: 100 authors from 50 institutes in 8 countries
- Combines experts in neutronics, magnetics, nuclear and particle physics.
- Developed into the multi-stage HIBEAM/NNBAR program
- Development of HIBEAM supported by the Swedish Research Council (1.4M €)
  - Preparing grant application to cover actual construction and operating costs of HIBEAM
- Development of NNBAR within HighNESS supported by 3M € H2020 program (financed by the European Union) – finished in September 2023
  - March 2024 - Submitted grant application for continuation of HighNESS
- Co-ordinated by Valentina Santoro

Summary

- We are developing highly sensitive experiments to search for free neutron oscillations at ESS
  - $n \rightarrow \bar{n}$ and $n \rightarrow n'$ are the cleanest and most sensitive ways to observe *B* violation
- Our goals:
  - World leading search for $n \rightarrow \bar{n}$ and $n \rightarrow n'$ at **HIBEAM** – Recent approval of first part of the beamline at ESS
  - World leading search for $n \rightarrow \bar{n}$ at **NNBAR** (increase in sensitivity by factor 1000)
- An ongoing development of key components and engineering models:
  - Development of HIBEAM/NNBAR detector prototypes
  - HIBEAM: Technical design report to be delivered in 2024
  - NNBAR: Recent delivery of the conceptual design report (available at https://github.com/highness-eu/CDR)
- We benefit from a wide international collaboration of scientists and engineers

HIBEAM/NNBAR collaboration - backup

The HighNESS Project at the European Spallation Source: Current Status and Future Perspectives

V. Santoro,[a]* K. H. Andersen,[b] P. Bentley,[a] M. Bernasconi,[c] M. Bertelsen,[a] Y. Beßler,[d] A. Bianchi,[a] T. Brys,[a] D. Campi,[c] A. Chambon,[e] V. Czamler,[f] D. D. Di Julio,[a] E. Dian,[g,h] K. Dunne,[i] M. J. Ferreira,[a] P. Fierlinger,[j] U. Friman-Gayer,[a] B. T. Folsom,[a,c] A. Gaye,[a] G. Gorini,[c] C. Happe,[d] M. Holl,[a] Y. Kamyshkov,[k] T. Kittelmann,[a] E. B. Klinkby,[e] R. Kolevatov,[l] S. I. Laporte,[c] B. Lauritzen,[e] J. I. Marquez Damian,[a] B. Meirose,[i,m] F. Mezei,[g] D. Milstead,[i] G. Muhrer,[a] V. Neshvizhevsky,[f] B. Rataj,[a,m] N. Rizzi,[e] L. Rosta,[h] S. Samothrakitis,[n] H. Schober,[a] J. R. Selknaes,[a] S. Silverstein,[i] M. Strobl,[m] M. Strothmann,[d] A. Takibayev,[a] R. Wagner,[f] P. Willendrup,[a,e] S. Xu,[a] S. C. Yiu,[h] L. Zanini,[a] and O. Zimmer[f]

[a]*European Spallation Source ERIC, Lund, Sweden*
[b]*Oak Ridge National Laboratory, Oak Ridge, Tennessee*
[c]*University of Milano-Bicocca, Milano, Italy*
[d]*Forschungszentrum Jülich, Germany*
[e]*DTU Physics, Technical University of Denmark*
[f]*Institut Laue-Langevin, Grenoble, France*
[g]*Mirrotron Ltd, Budapest, Hungary*
[h]*Centre for Energy Research, Budapest, Hungary*
[i]*Stockholm University, Stockholm, Sweden*
[j]*Technical University Munich, Garching, Germany*
[k]*The University of Tennessee, Department of Physics and Astronomy, Knoxville, Tennessee*
[l]*ESS consultant, Norway*
[m]*Lund University, Lund, Sweden*
[n]*Paul Scherrer Institut, PSI Villigen, Switzerland*

Status and Future Perspectives." *Nuclear Science and Engineering* (2023): 1-33.

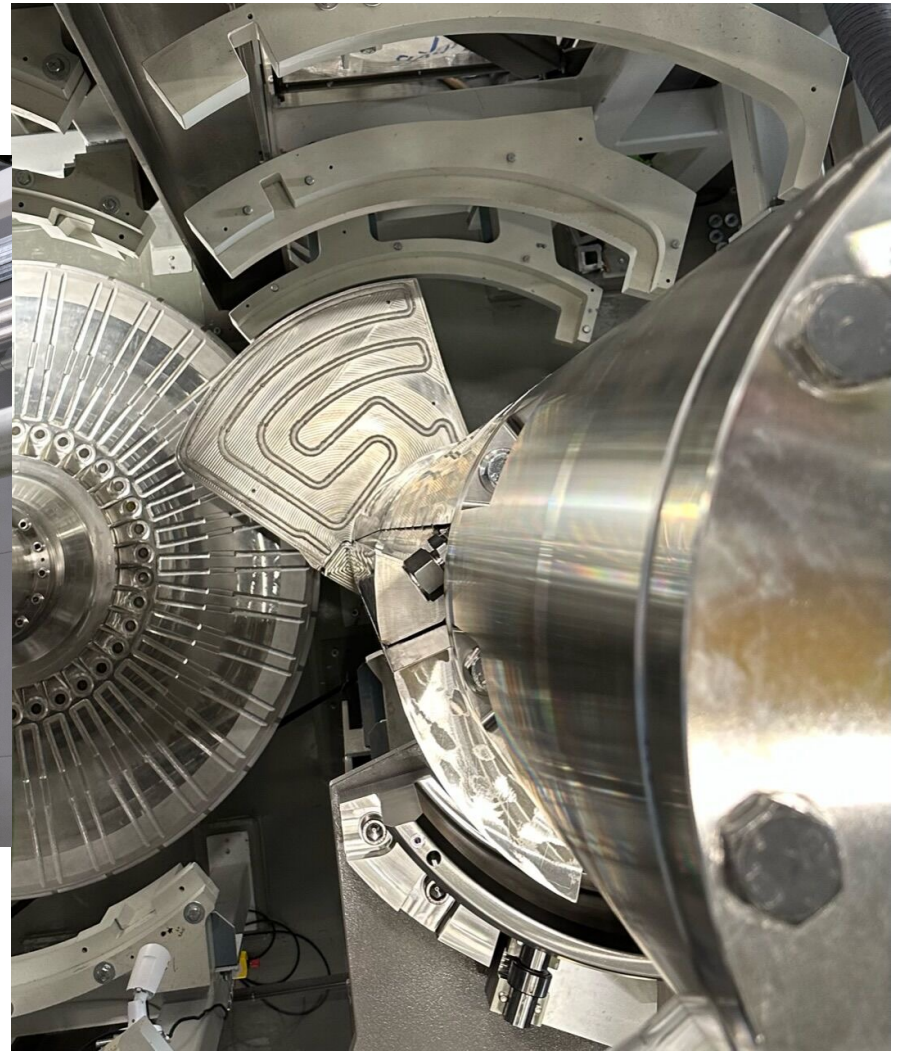
New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

A. Addazi[h,at], K. Anderson[aq], S. Ansell[bm], K. S. Babu[az], J. Barrow[w], D. V. Baxter[d,e,f], P. M. Bentley[ac], Z. Berezhiani[b,l], R. Bevilacqua[ac], R. Biondi[b], C. Bohm[ba], G. Brooijmans[an], L. J. Broussard[aq], B. Dev[ay], C. Crawford[z], A. D. Dolgov[ai,ao], K. Dunne[ba], P Fierlinger[o], M. R. Fitzsimmons[w], A. Fomin[n], M. Frost[aq], S. Gardiner[c], S. Gardner[z], A. Galindo-Uribarri[aq], P. Geltenbort[p], S. Girmohanta[bb], E. Golubeva[ah], G. L. Greene[w], T. Greenshaw[aa], V. Gudkov[k], R. Hall-Wilton[ac], L. Heilbronn[x], J. Herrero-Garcia[bc], G. Ichikawa[bf], T. M. Ito[ah], E. Iverson[aq], T. Johansson[bg], L. Jönsson[ad], Y-J. Jwa[an], Y. Kamyshkov[w], K. Kanaki[ac], E. Kearns[g], B. Kerbikov[al,aj,ak], M. Kitaguchi[ap], T. Kittelmann[ac], E. Klinkby[ae], A. Kobakhidze[bl], L. W. Koerner[x], B. Kopeliovich[bi], A. Kozela[y], V. Kudryavtsev[ax], A. Kupsc[bg], Y. Lee[ac], M. Lindroos[ac], J. Makkinje[an], J. I. Marquez[ac], B. Meirose[ba,ad], T. M. Miller[ac], D. Milstead[ba,*], R. N. Mohapatra[j], T. Morishima[ap], G. Muhrer[ac], H. P. Mumm[m], K. Nagamoto[ap], F. Nesti[i], V. V. Nesvizhevsky[p], T. Nilsson[r], A. Oskarsson[ad], E. Paryev[ah], R. W. Pattie, Jr.[t], S. Penttilä[aq], Y. N. Pokotilovski[am], I. Potashnikova[bi], C. Redding[x], J-M. Richard[bj], D. Ries[af], E. Rinaldi[au,bc], N. Rossi[b], A. Ruggles[x], B. Rybolt[u], V. Santoro[ac], U. Sarkar[v], A. Saunders[ab], G. Senjanovic[bd,ba], A. P. Serebrov[n], H. M. Shimizu[ap], R. Shrock[bb], S. Silverstein[ba], D. Silvermyr[ad], W. M. Snow[d,e,f], A. Takibayev[ac], I. Tkachev[ah], L. Townsend[x], A. Tureanu[q], L. Varriano[i], A. Vainshtein[ag,av], J. de Vries[a,bh], R. Woracek[ac], Y. Yamagata[bk], A. R. Young[as], L. Zanini[ac], Z. Zhang[ar], O. Zimmer[p]

[a]*Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts, Amherst, MA, USA*
[b]*INFN, Laboratori Nazionali del Gran Sasso, 67010 Assergi AQ, Italy*
[c]*Fermi National Accelerator Laboratory, Batavia, IL 60510-5011, USA*
[d]*Department of Physics, Indiana University, 727 E. Third St., Bloomington, IN, USA, 47405*
[e]*Indiana University Center for Exploration of Energy & Matter, Bloomington, IN 47408, USA*
[f]*Indiana University Quantum Science and Engineering Center, Bloomington, IN 47408, USA*
[g]*Department of Physics, Boston University, Boston, MA 02215, USA*
[h]*Center for Theoretical Physics, College of Physics Science and Technology, Sichuan University, 610065 Chengdu, China*

Addazi, A., et al. "New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source." *Journal of Physics G: Nuclear and Particle Physics* 48.7 (2021): 070501.

How can be a new moderator for ESS installed - backupx



Reproduced from: ESS. “Progress reports from the ESS site." Available online: https://europeanspallationsource.se/construction-update/2023/04/05 and https://europeanspallationsource.se/construction-update/2023/03/20 (2023).

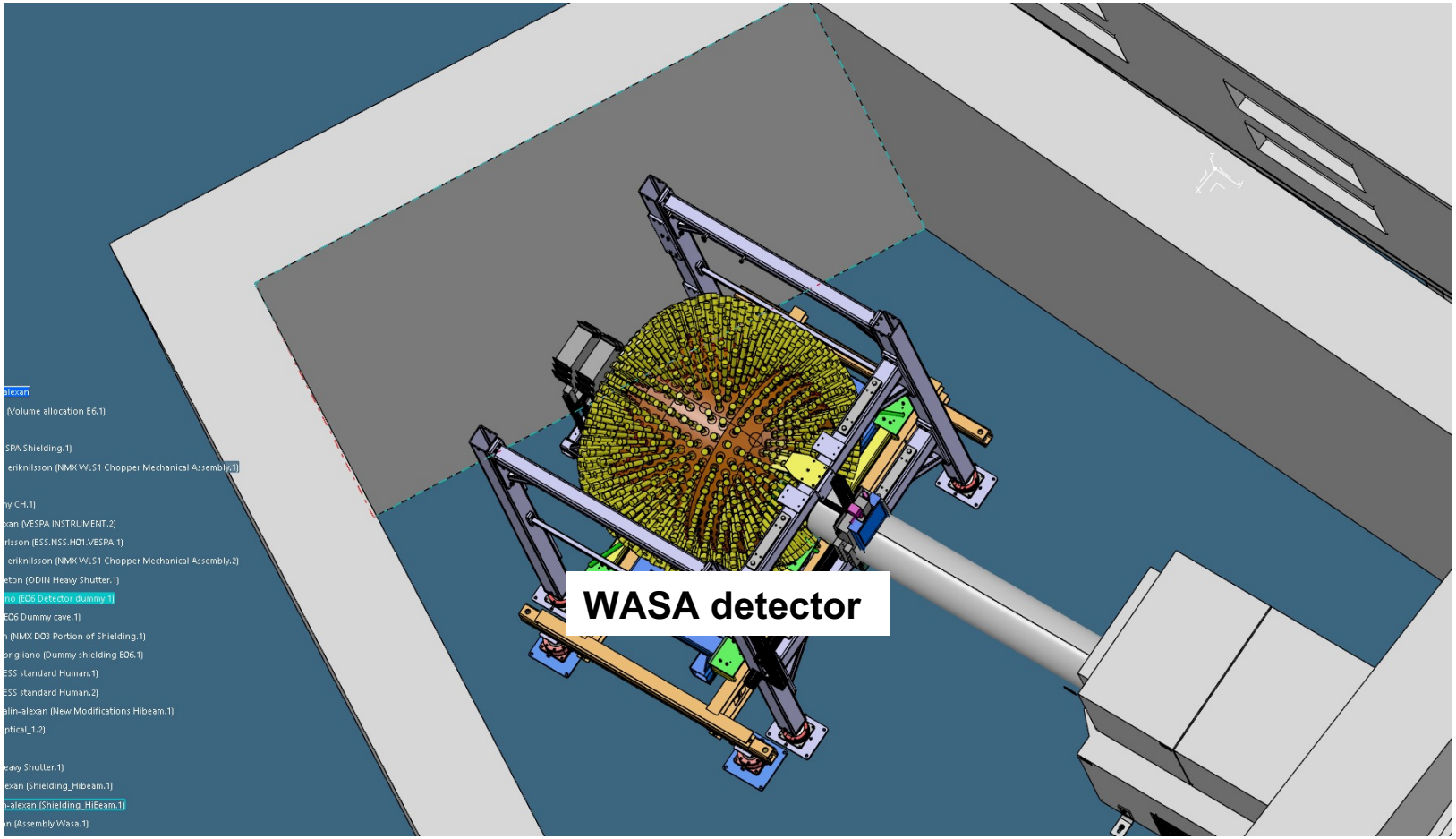
Installation of target monolith at ESS - The heart of ESS = backup

HIBEAM/NNBAR collaboration - backup

General HIBEAM/NNBAR meeting
January, 2023

Ongoing work on the engineering model of HIBEAM – backup

- GSI/FAIR will donate WASA detector for $n \rightarrow \bar{n}$ at HIBEAM
- HIBEAM will utilize the He-3 neutron detector for n -> n' at HIBEAM



Formalism for neutron – antineutron oscillations -backup

- $n \rightarrow \bar{n}$ formalism

Mixing mass term depends on scale of new physics

$$i\hbar \frac{\partial}{\partial t}\begin{pmatrix} n \\ \bar{n} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}\begin{pmatrix} n \\ \bar{n} \end{pmatrix}$$

$$\delta m = \langle \bar{n}|H_{eff}|n\rangle < 10^{-29}\ \text{MeV} = n\bar{n}\ \text{mixing physics}$$

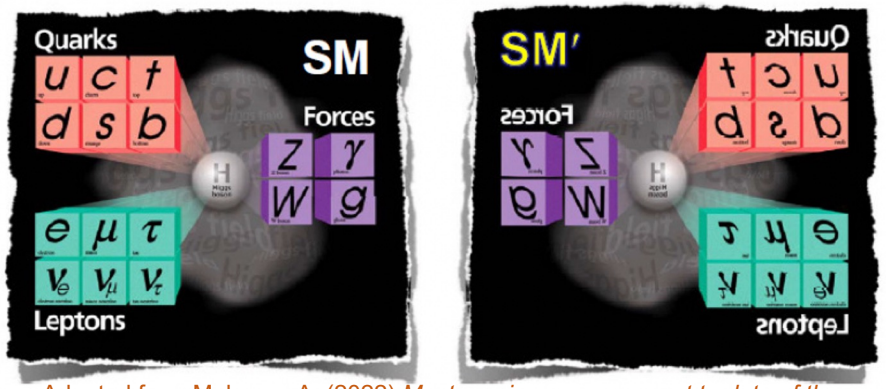
$$P_{n\rightarrow\bar{n}} = \left(\frac{\delta m}{\Delta E}\right)^2 \sin^2(\Delta E \times t)\ \ ; \Delta E = E_n - E_{\bar{n}}$$

- Free neutron oscillation: $\Delta E \times t \ll 1 \Rightarrow P \sim (\delta m \times t)^2$

$$P_{n\rightarrow\bar{n}}(t) = \left(\frac{t_{free}}{\tau_{n\rightarrow\bar{n}}}\right)^2$$

Sterile neutrons – backup slide

- Neutrons are electrically neutral quasi-stable particles that can be produced at high fluxes
- A portal into dark sector via mixing into sterile neutrons



Adapted from Malewar, A. (2022) *Most precise measurement to date of the mass of the W Boson*, *Tech Explorist*. Available at: https://www.techexplorist.com/precise-measurement-date-mass-w-boson/.

- Exploration with beam neutrons at HIBEAM to extend sensitivity