HighNESS and Future Free Neutron Oscillation Searches @ ESS

Valentina Santoro
ESS
on behalf of the NNBAR Collaboration

Outline

- The European Spallation Source
- The HIBEAM experiment (focus on mirror neutron searches) (2023-2027)
- The neutron antineutron oscillation experiment NNBAR (search for $n \to \bar{n}$) > 2030
- The HighNESS Project

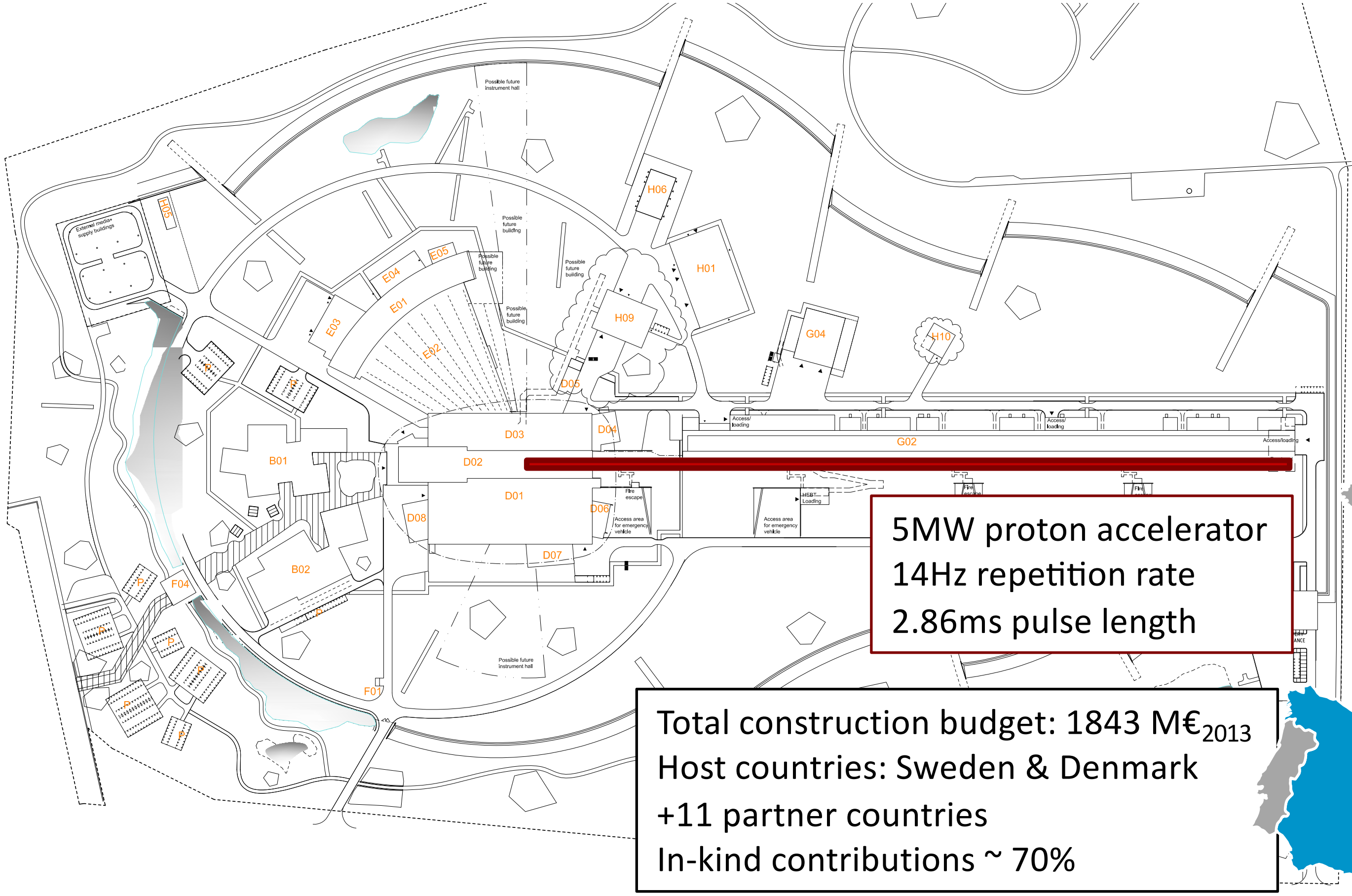
The European Spallation Source

- The European Spallation Source is under construction in Lund
- The facility's unique capabilities will both greatly exceed and complement those of today's leading neutron sources, enabling new opportunities for researchers across the spectrum of scientific discovery, including materials and life sciences, energy, environmental technology, cultural heritage and fundamental physics.

ESS Timeline	GROUNDBREAKING	INITIAL OPERATIONS	INSTRUMENT COMMISSIONING BEGINS	USER PROGRAMME BEGINS	PROJECT COMPLETION STATUS
	2014	2019	2022	2023	70%

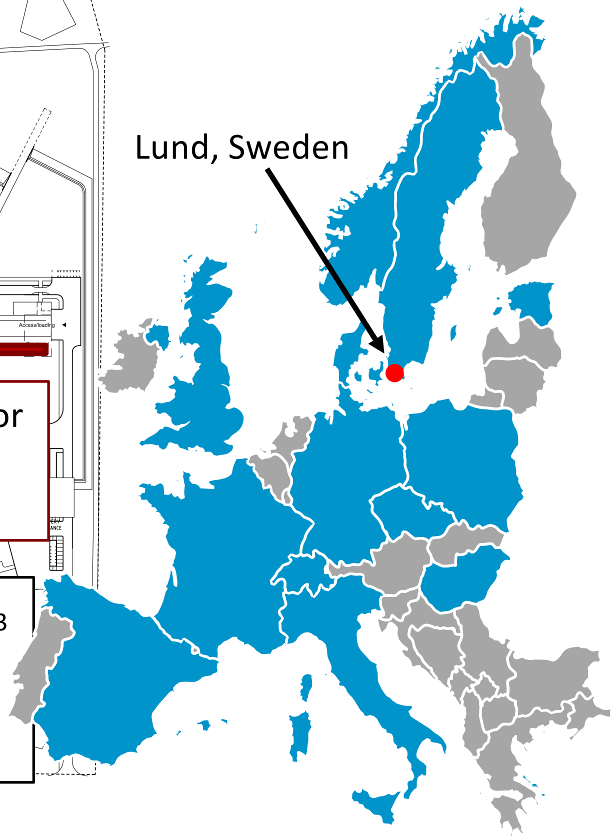
The European Spallation Source

ESS: The Next-Generation Neutron Source



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

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



Courtesy of Andreas Schreyer

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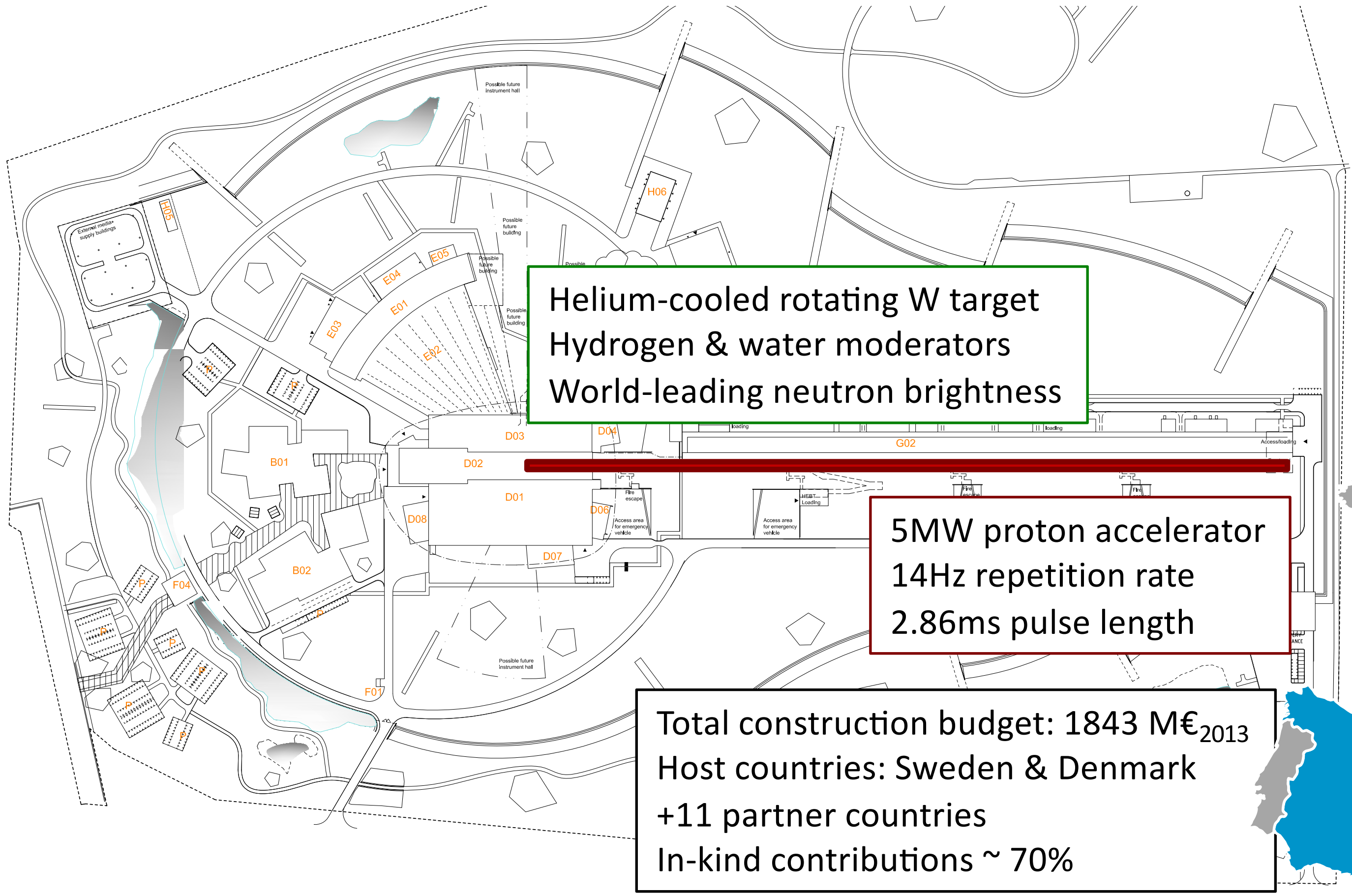

Helium-cooled rotating W target
Hydrogen & water moderators
World-leading neutron brightness

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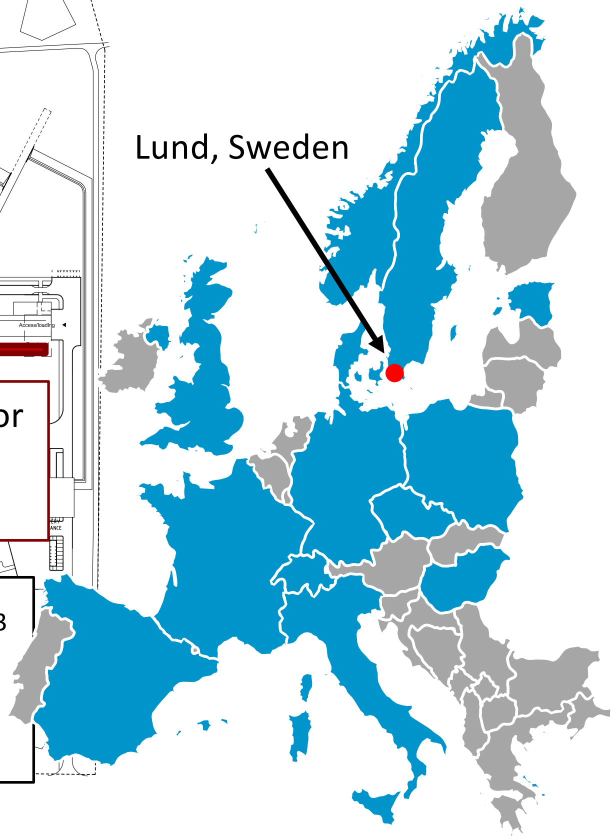

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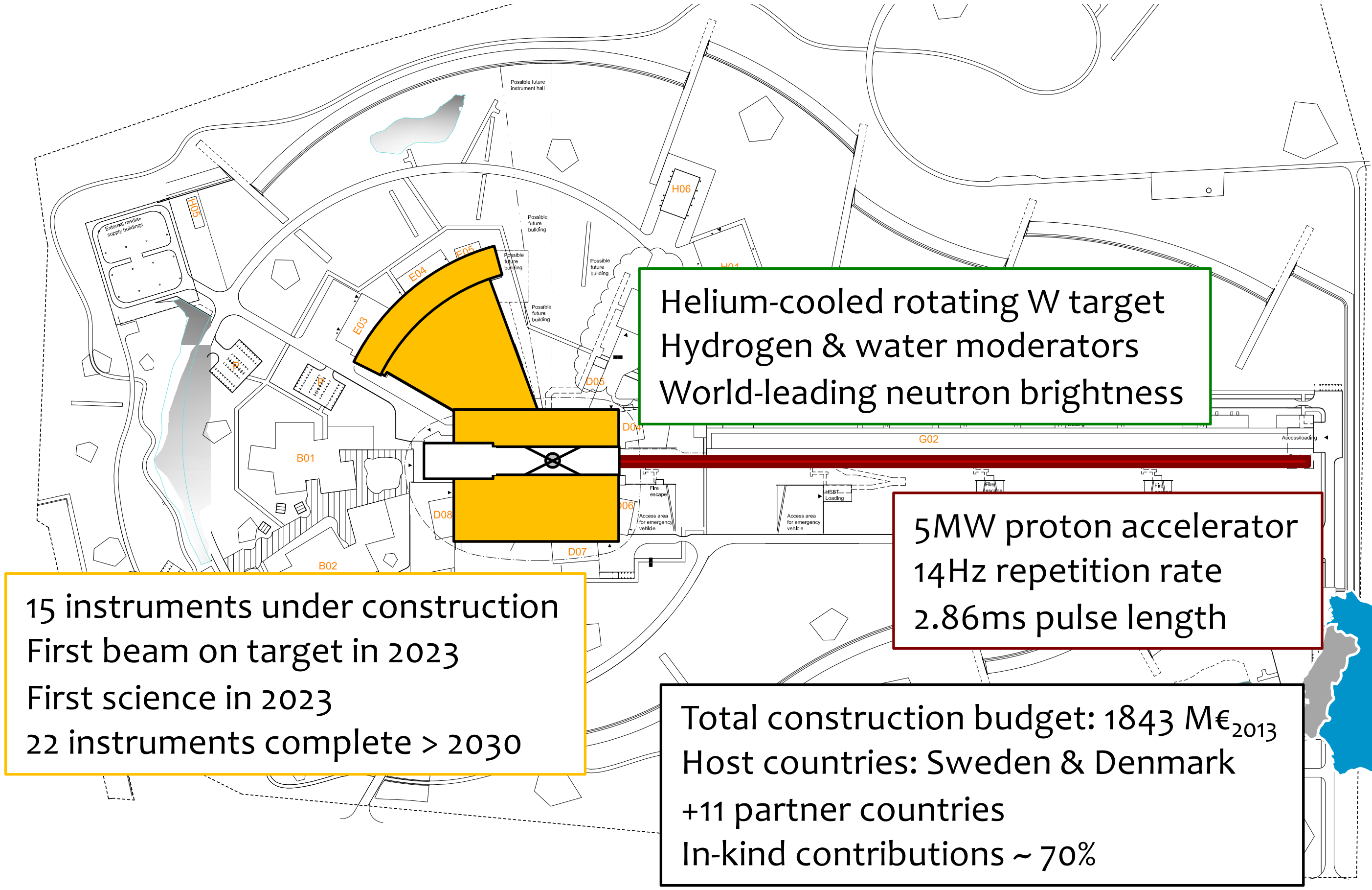

Helium-cooled rotating W target
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World-leading neutron brightness

5MW proton accelerator
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15 instruments under construction
First beam on target in 2023
First science in 2023
22 instruments complete > 2030

Total construction budget: 1843 M€$_{2013}$
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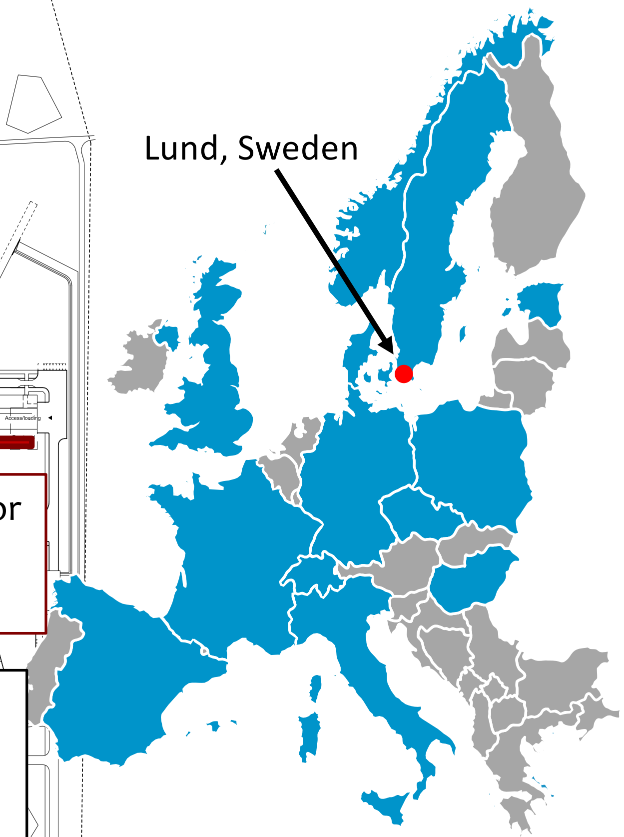

Courtesy of Andreas Schreyer

The Capability Gap Analysis

- The scope of ESS, as defined in the ESS statutes, is to build and operate 22 world-leading instruments in an open user program. Of these, the first 15 will be brought on-line by the end of 2025.

- Regarding instruments 16-22 a document from ESS (The ESS Instrument Suite – A Capability Gap Analysis (https://europeanspallationsource.se/instruments/capability-gap-analysis) has analysed the capability gaps

- Result of this analysis has shown that one of the community that is not catered is the particle physics community. <u>**Therefore filling this capability gap is given the highest priority.**</u>

Fundamental & Particle Physics @ ESS

ESS intended for n-scattering experiments, but significant component could be dedicated to fundamental physics research including **n-nbar search**

Precision experiments

Beyond SM
New interactions

High Intensity Baryon Extraction and Measurement (HIBEAM)
Neutron antineutron oscillation beamline (NNbar)

Baryon asymmetry of the Universe

Cold neutron beamline (ANNI)

Neutron beta decay
Hadronic parity violation
Electromagnetic properties of the neutron

UCN
Ultra Cold Neutron beamline

Gravity resonance spectroscopy

Neutron interferometry

Neutron beta decay

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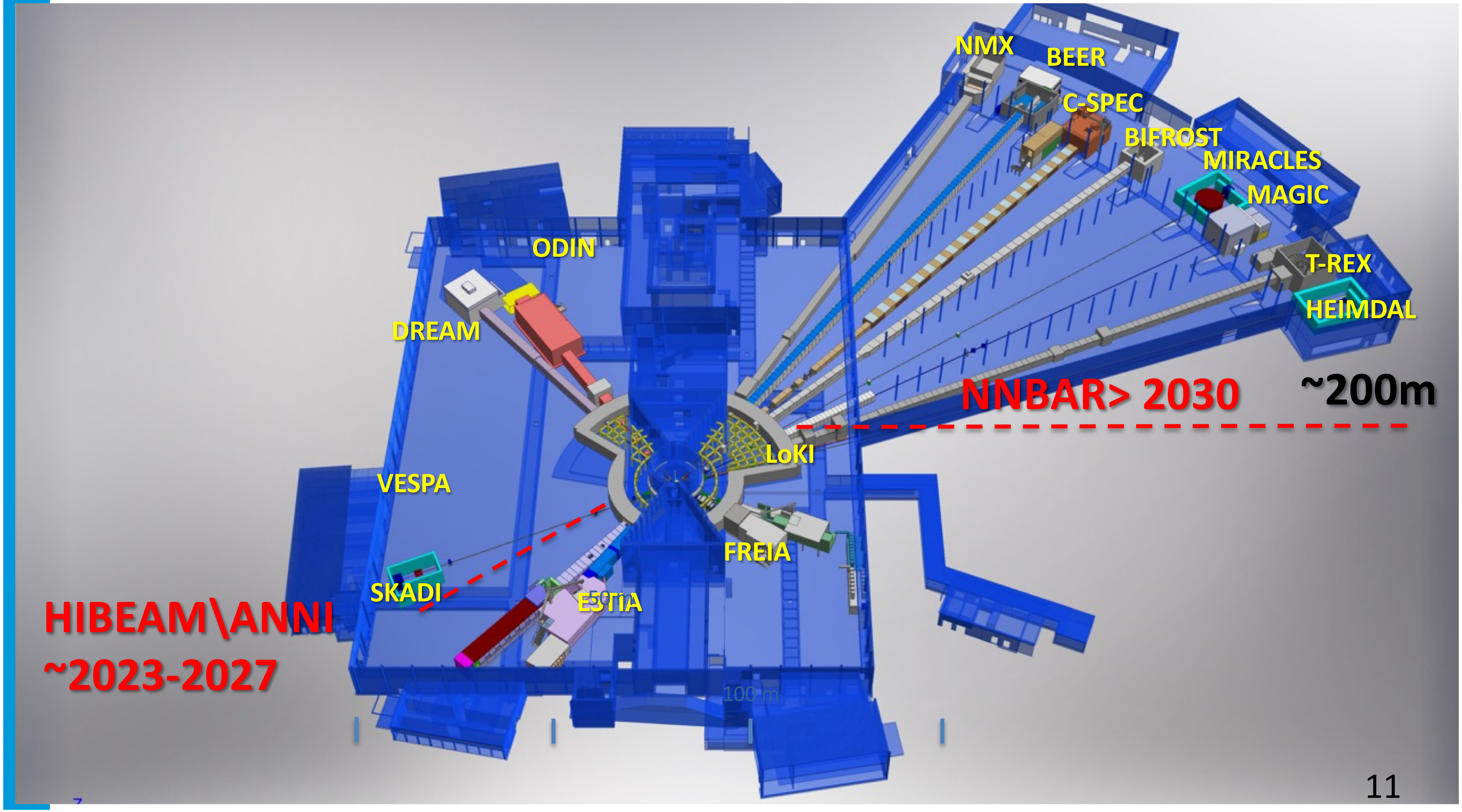
HIBEAM has its own physics program
but it will also provide R&D for the NNBAR experiment

ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations

- HIBEAM: smaller program of complementary experiments (with focus on mirror neutron searches) ≳2023
- NNBAR: Beamline earliest available ≥ 2030



Baryon Number Violation

- *BN* is an "accidental" global symmetry at perturbative level
  - *BNV* in SM non-perturbatively (eg instantons)
  - *B-L* is conserved, not *B, L* separately.

- *BNV* needed for baryogenesis

- *BNV* generic features of SM extensions (eg SUSY, extra dimensions …)

- Very good reason to believe that *BNV* is a part of Nature

- Important to probe possible *BNV* channels
- NNBAR will searche for $n \rightarrow \bar{n}$ $(|\Delta B| = 2)$ and
- HIBEAM will search for $n \rightarrow n'(|\Delta B| = 1)$.

- **Sensitivity increase of 10^3 compared with previous experiments.**

Phenomenology of neutron conversion processes

$$\mathbf{\Psi} = \begin{pmatrix} n \\ \bar{n}' \end{pmatrix}$$

Mixed $n, \bar{n}, n'$ QM state

$$H = \begin{pmatrix} E_n & \varepsilon \\ \varepsilon & E_{\bar{n}} \end{pmatrix}$$

ε is the mixing mass term that depends on the scale of the new physics
the mass mixing term ε is different for $n \to \bar{n}$ and $n \to n'$

$m_n = m_{\bar{n}}$ by CPT invariance, E_n and $E_{\bar{n}}$ are **not** generically equal due to enviromental effects (i.e. matter medium or magnetic fields)

Probability to find an antineutron at time t is given by

$$P_{n\bar{n}}(t) = \frac{\varepsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2} \sin^2\left[t\sqrt{(\Delta E/2)^2 + \varepsilon_{n\bar{n}}^2}\right] e^{-t/\tau_n},$$

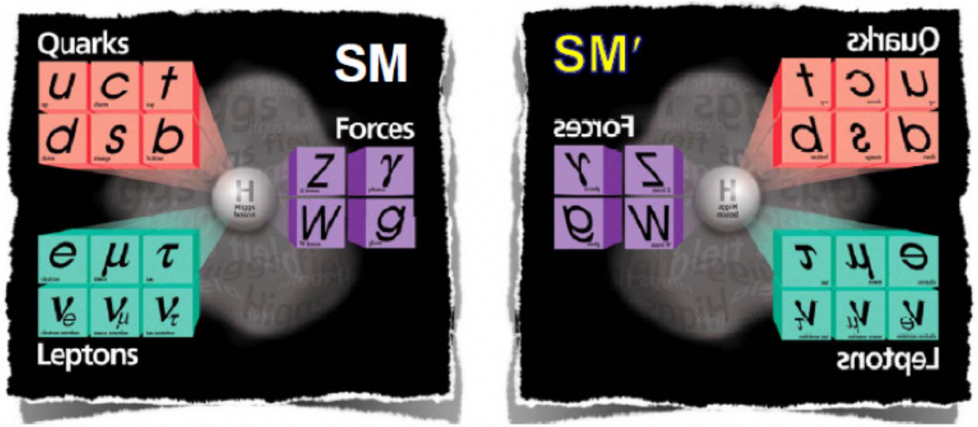
$\Delta E = E_n - E_{\bar{n}}$ and τ_n (mean life time of the free neutron)
-> the probability of conversion is suppressed when the energy degeneracy between neutron and antineutron is broken.
Quasi free regime $|\Delta E| t \ll 1$ can be realized in vacuum with very low magnetic shield. Under this condition

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

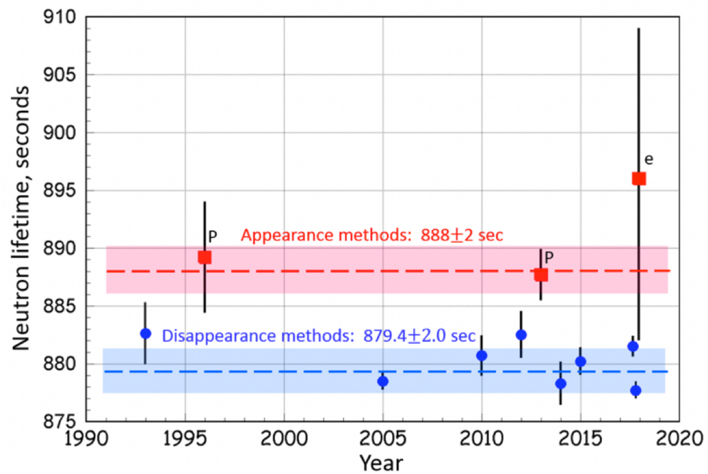
Figure of merit (background-free): $\mathbf{Nt^2}$

Mirror Neutrons

- As a meta-stable neutral particle, the neutron is one of the few possible portals to a hidden/dark sector. (e.g. mirror matter and generic dark sectors)
- These transitions can also shed light on the anomaly between neutron lifetime in ”beam” and ”bottle”
- These searches part of the experimental program of the HIBEAM beamline



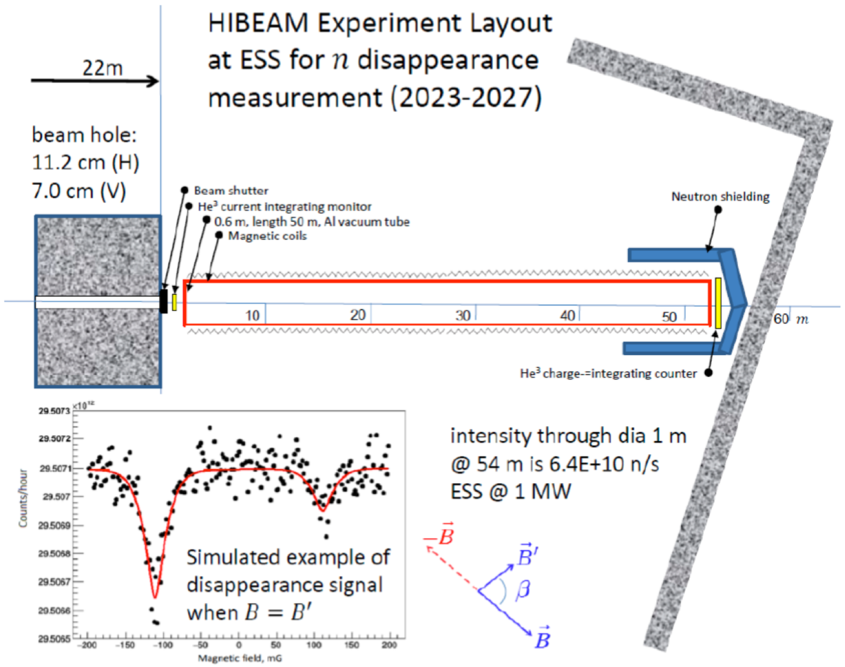
- Z. Berezhiani, Phys. Rev. Lett. 96 (2006) 081801
- Z. Berezhiani, arXiv:hep-ph/0508233 (2005)
- R. Foot, Int. J. Mod. Phys. A29 (2014) 1430013
- Z. Berezhiani, Int. J. Mod. Phys. A29 (2014) 3775-3806

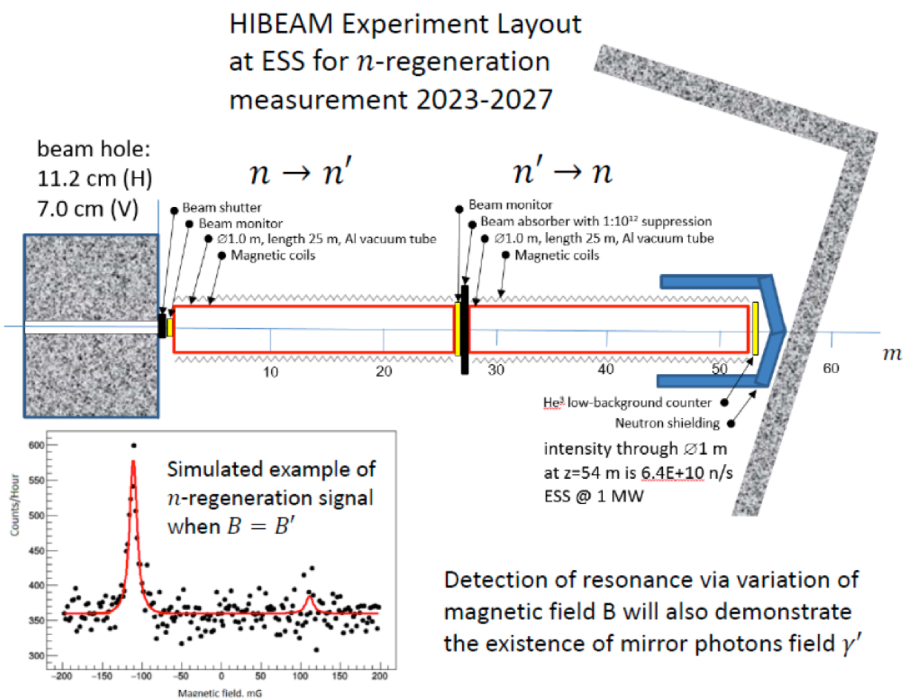


F. E. Wietfeldt, “Measurement of Neutron Lifetime,” Atoms 6(4) (2018)

THE HIBEAM program 2023~2027

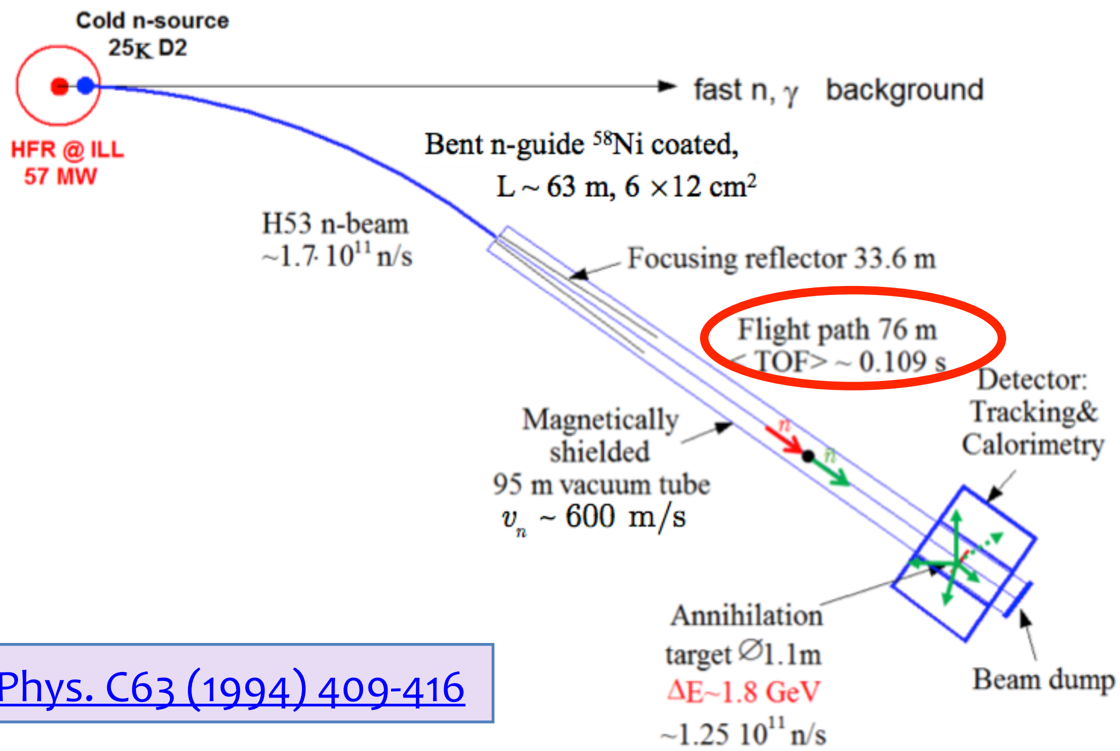
- A fundamental physics beamline is not a part of the first 15 instruments at ESS. ESS in his mandate has planned for 22 instruments.
- **High Priority for the next round of instrument will be given to the fundamental physics community**
- Two experimental collaborations: the ANNI beamline (A pulsed cold neutron beam facility for particle physics at the ESS) and the HIBEAM (High-Intensity Baryon Extraction and Measurement collaboration) have joined their effort for the fundamental physics beamline at ESS
- HIBEAM will look for n disappearance and n regeneration experiment





Detection of resonance via variation of magnetic field B will also demonstrate the existence of mirror photons field γ'

Search for neutron antineutron oscillation @ ILL



Baldo-Ceolin et al, [Z.Phys. C63 (1994) 409-416]

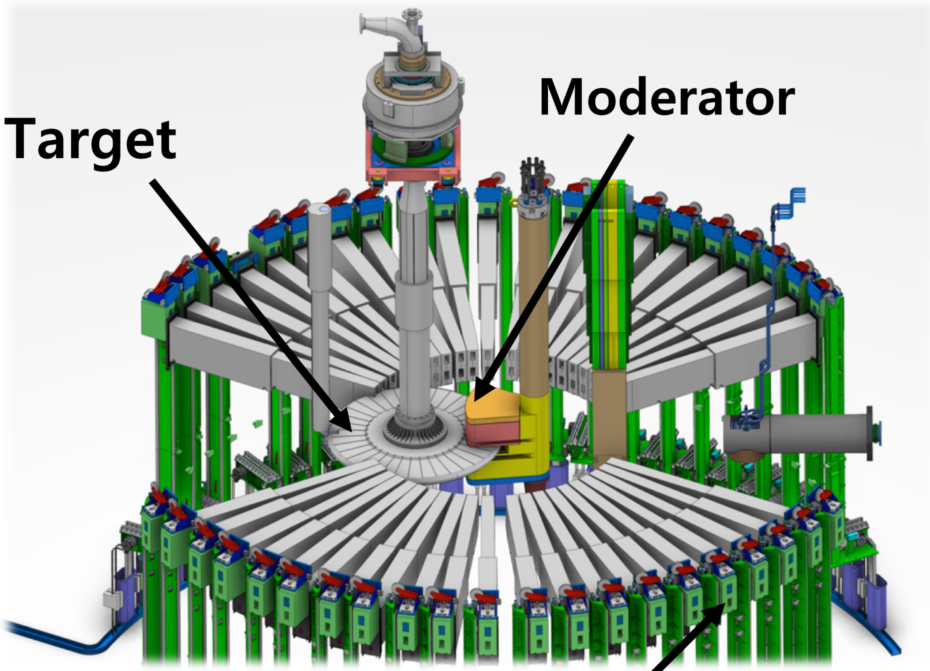
$Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau_{n \to \bar{n}} > 0.86\ 10^8$s

(***N*** is the free neutron flux reaching the annihilation target and ***t*** is the neutron observation time).

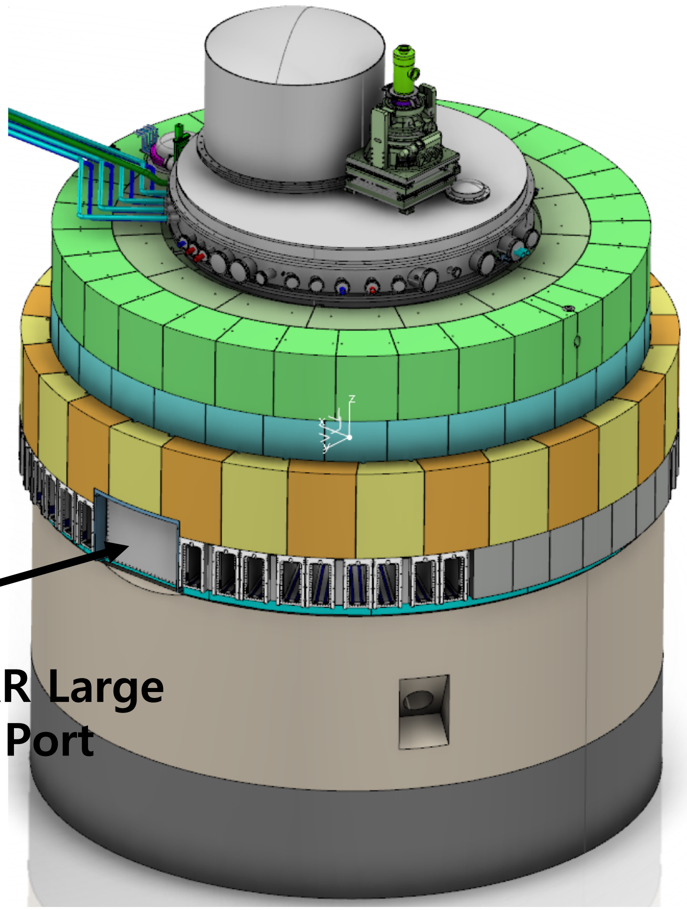
Many subtle optimizations to minimize losses and backgrounds

Experiment was background-free

ESS Target

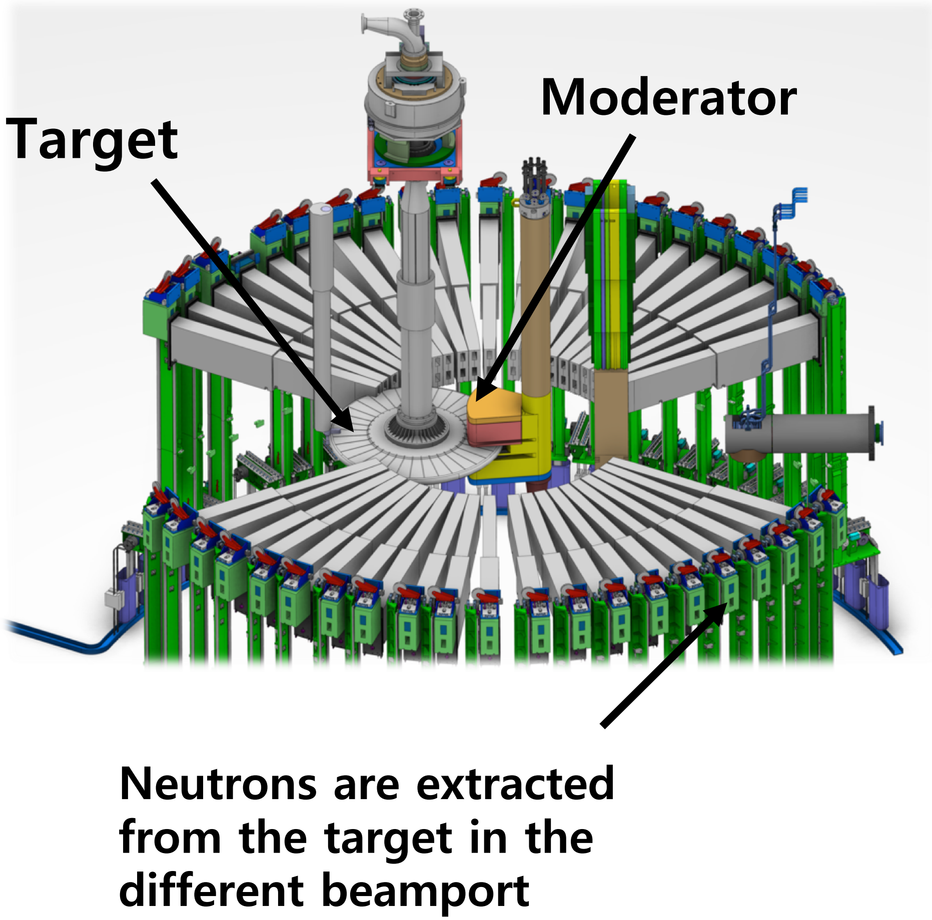


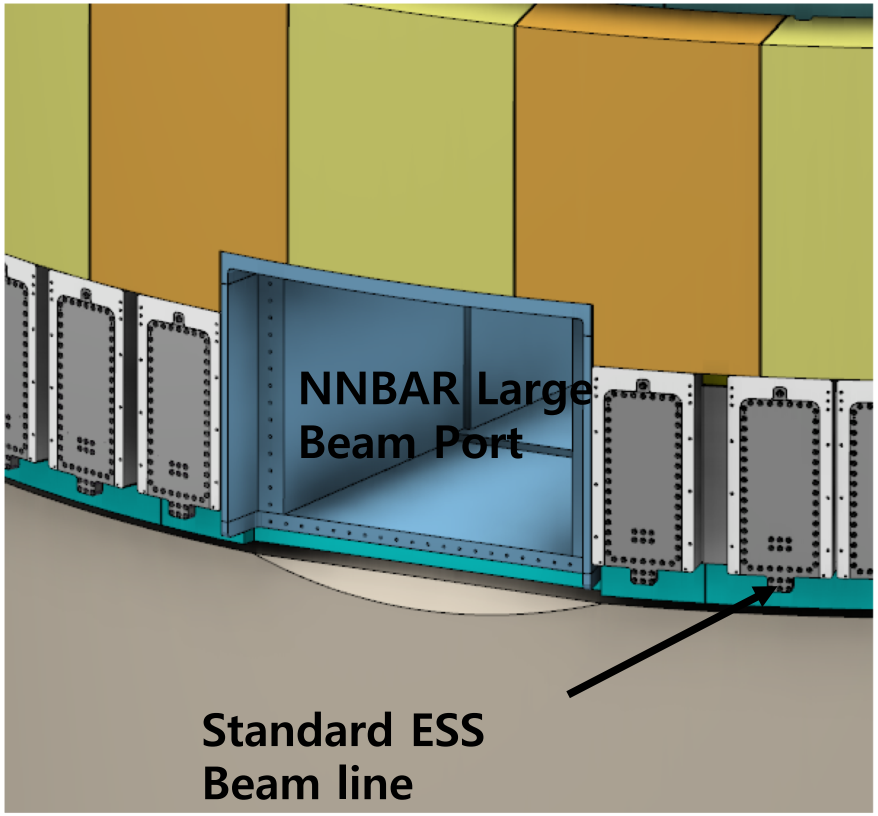
Neutrons are extracted from the target in the different beamport



- LBP has been constructed and will provide sufficient intensity for $n \rightarrow \bar{n}$ search
- Room for 200m of large diameter neutron beamguide

ESS Target





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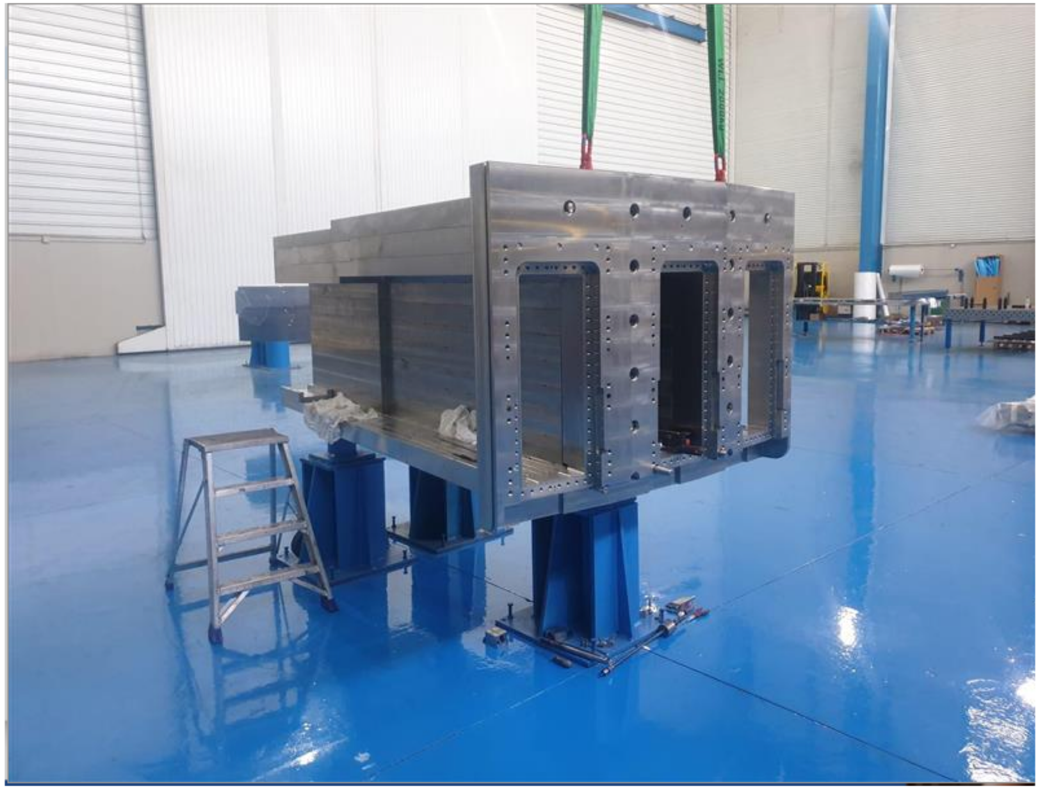
- Room for 200m of large diameter neutron beamguide

The Large Beam Port

- LBP has been constructed and will provide sufficient intensity for $n \to \bar{n}$ search
- Room for 200m of large diameter neutron beamguide

Currently under manufacture will be installed next year



"The Large Beam Port is an opportunity to broaden the ESS mission"
Rikard Linander Head of the ESS Target Division

The HighNESS project at ESS

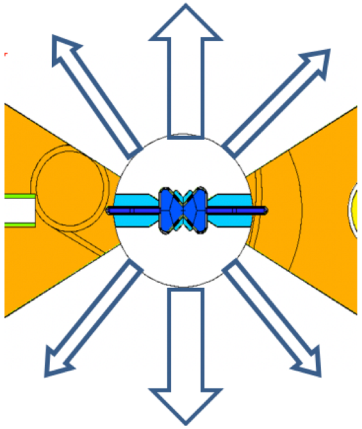
The HighNESS project ($3MEURO funded by the European Commission) has as purpose the development of the new source that will be installed at ESS >2030

The new source will be composed by Liquid deuterium moderator that will serve a UCN moderator and a VCN moderator.

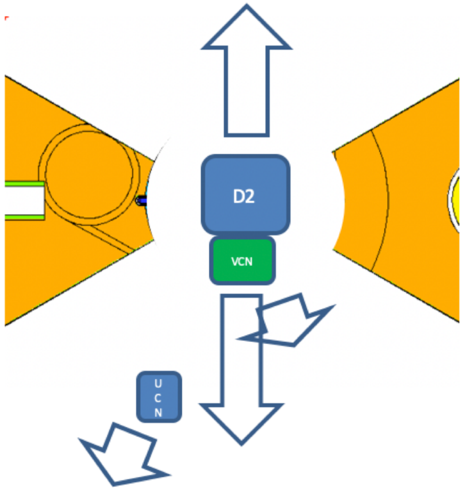
In the project will be also developed the NNBAR experiment **-> Conceptual Design Report expected by the end of 2023**

Development of high intensity neutron source at the European Spallation Source Journal of Neutron Research, vol. Pre-press, no. Pre-press, pp. 1-11, 2020

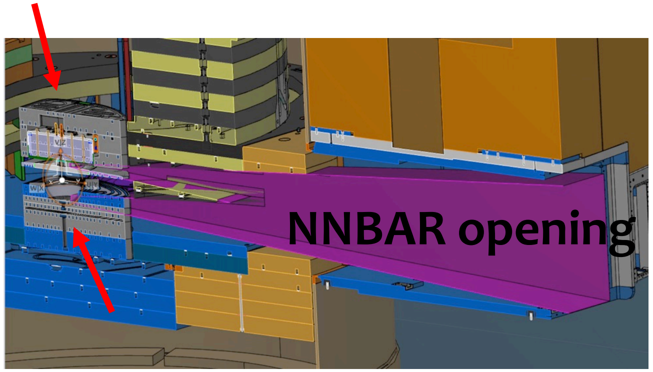
ESS current moderator. Located above the target already in place



ESS Liquid Deuterium moderator. Located below the target (future)



ESS current moderator

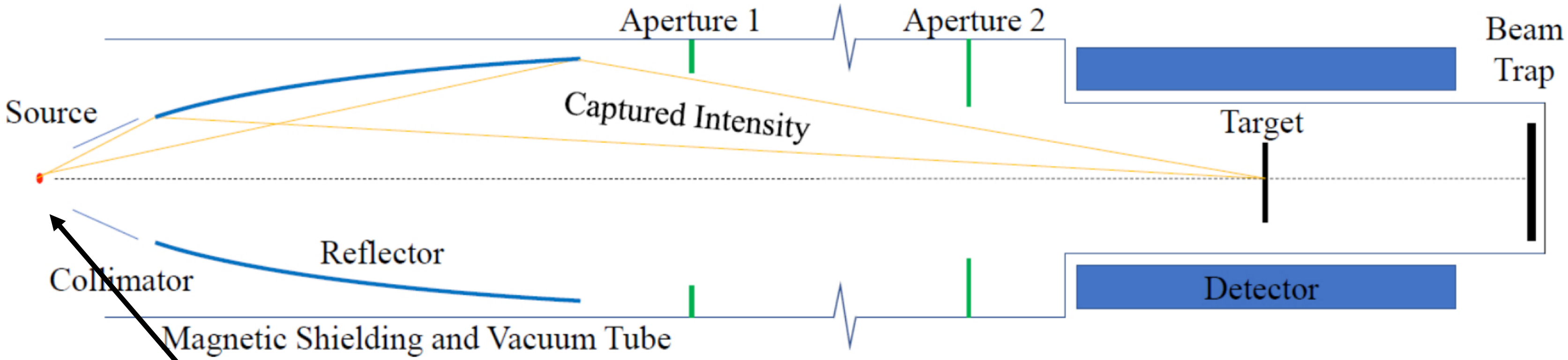


ESS Liquid Deuterium moderator

The liquid deuterium moderator will be designed in order to be optimal for NNBAR

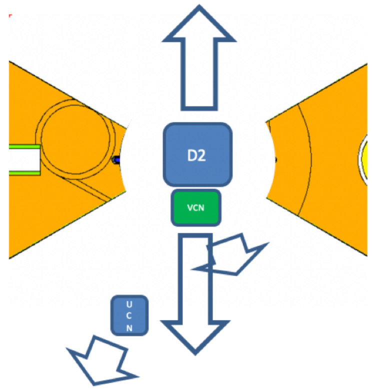
European Commission
HighNESS is funded by the European Union Framework Program for Research and Innovation Horizon 2020, under grant agreement 951782

The NNBAR experiment (schematic)



To design the optimal experiment you need to take into account several different aspects:

Moderator:
It determines the number of cold neutrons emitted by the source



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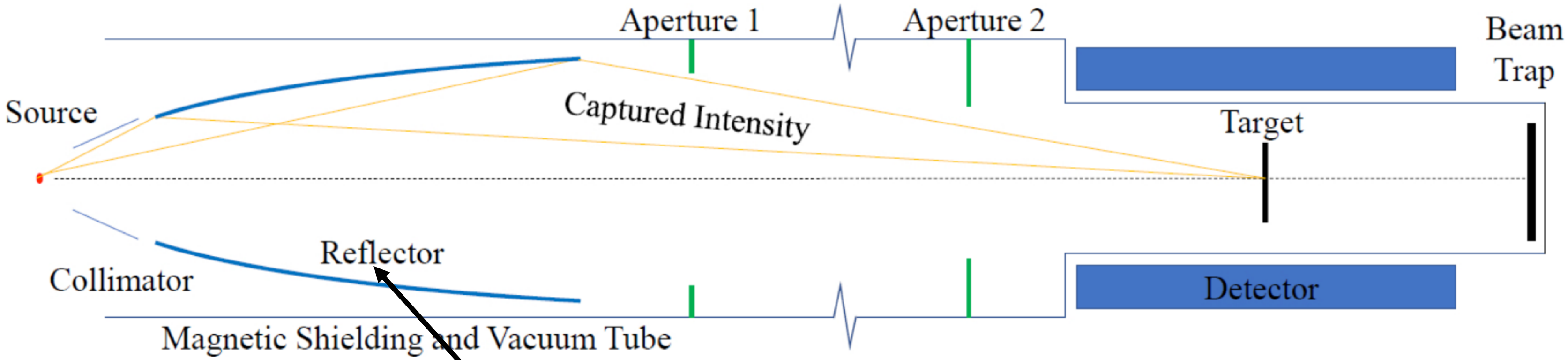
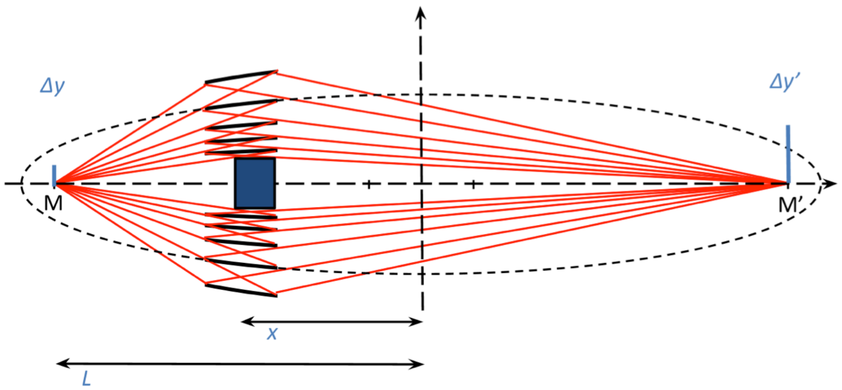


Reflector :
How many neutrons you collect, transport and focus in the experiment

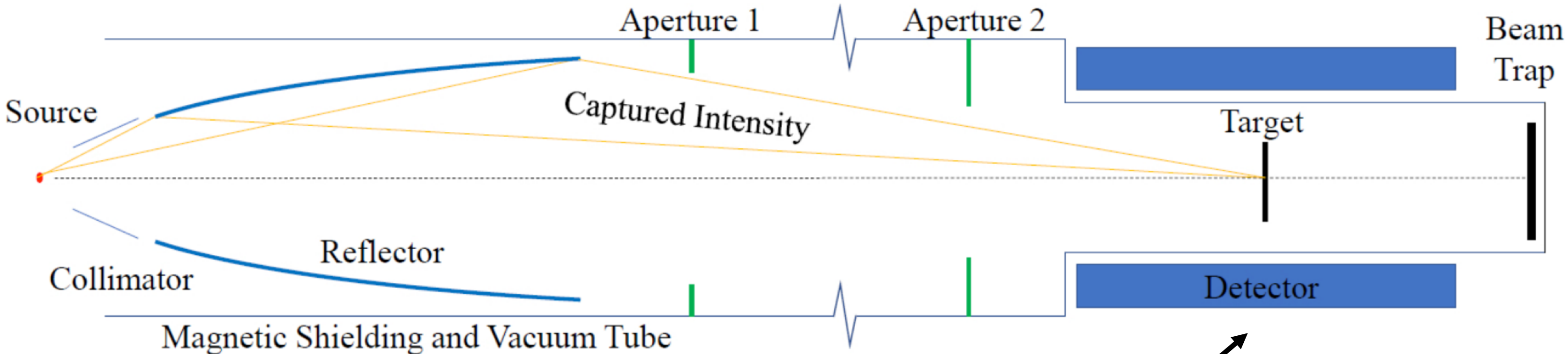


Much larger viewable area of the lower moderator -> optimised imaging instrument to extract a large divergence neutron flow and focus over long distance (~200m).

Design nested mirror systems of a single set of elliptic/short mirrors and of Wolter-optic types.

Courtesy of Oliver Zimmer

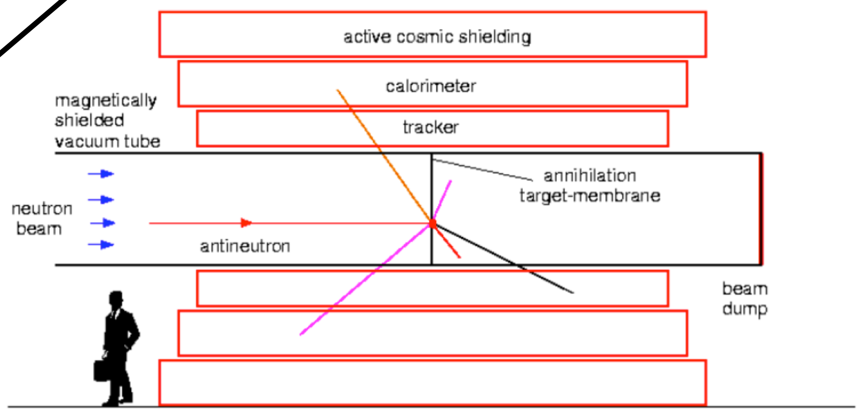
The NNBAR experiment (schematic)



Annihilation detector :

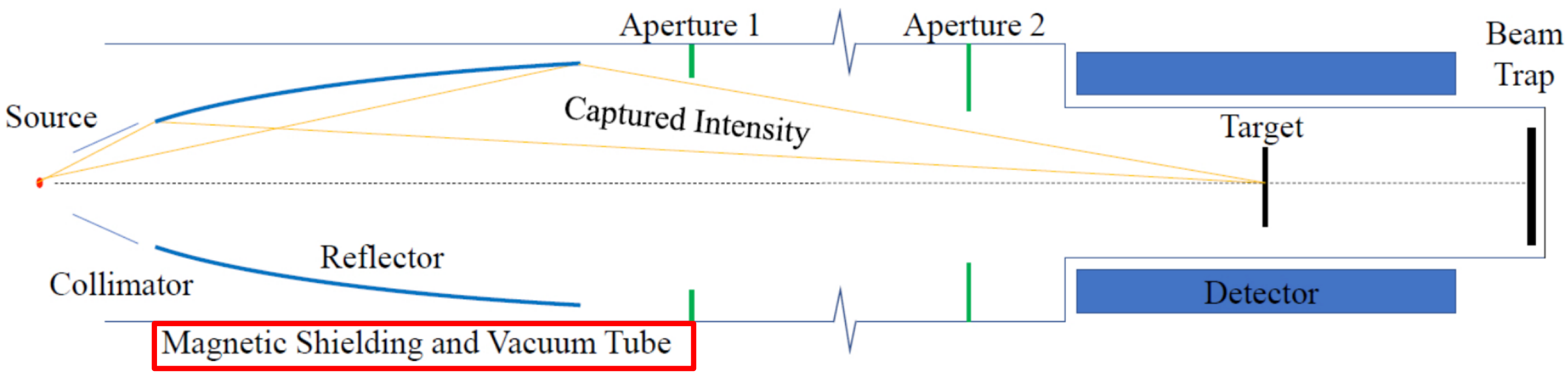
The neutron beam will hit a thin carbon foil target
The carbon has large $\bar{n}$ annihilation cross section , mostly transparent to neutrons
$\bar{n}N \rightarrow$ <5> pions (1.8 GeV)

Should be background free as in ILL experiment



See Katherine Dunne's talk

The NNBAR experiment (schematic)



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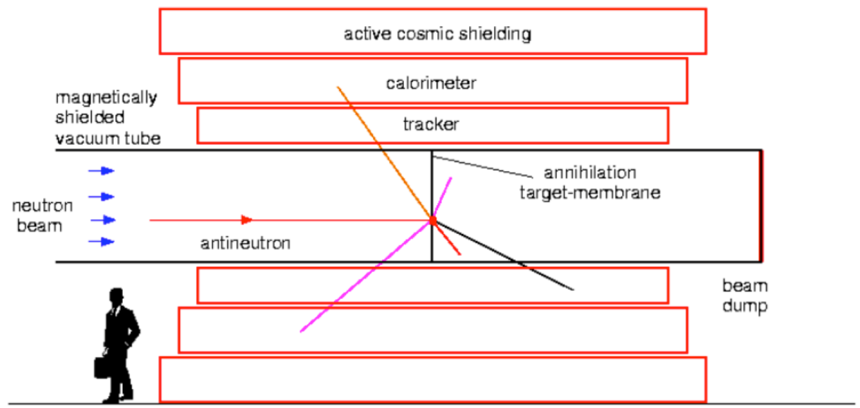


Residual B field <5 nT
Residual vacuum < 10^{-5} P

Sensitivity of the NNBAR experiment at ESS

- **Increase number of neutrons**
  - Flux
  - Moderator brightness and area
  - Angular acceptance
  - Longer run
- **Increase time-of-flight**
  - Longer beamline
- Keep (or even increase) detection efficiency (~50%), keep background at ~0
- **Better B_{Earth} suppression**

Factor	Gain wrt ILL
Source Intensity	≥ 2
Neutron Reflector	40
Length	5
Run time($\propto t^2$)	3
Total gain	≥ 1000

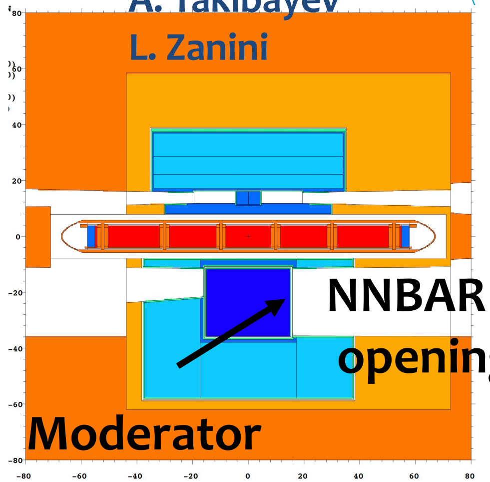
All these factors will be studied and optimized in the HighNESS Project

NNBAR final design aim
to improve by 10^3 the ILL limit

On-Going activity in the HighNESS Project

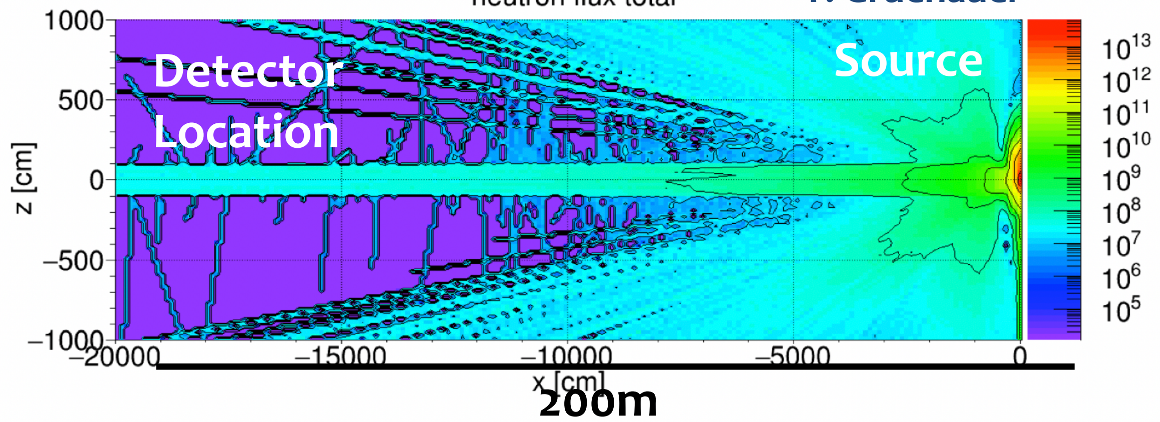
Moderator simulation

target+moderator: model fully parametrized to allow easy changes in the geometry for sensitivity studies and optimization.



NNBAR background simulation

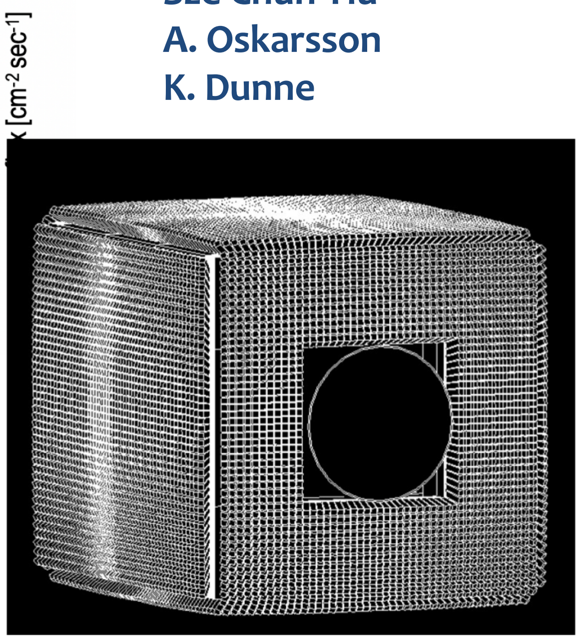
Particle must be transported form the source to the detector over long distances



D. Milstated
B. Mehroise
Sze Chun Yiu
A. Oskarsson
K. Dunne

Full detector implementation in Geant4

See Sze Chun Yiu talk's



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

Conclusions

Lot of activities are going on right now:

- HighNESS project started in October:
  - Design of the optimal moderator configuration for NNBAR.
  - CDR of the NNBAR experiment. Detector development and design optimization. Simulations of backgrounds and shielding. Address uncertainties in cost of experiment

HIBEAM@ANNI ~ 2025: searches for sterile neutrons

NNBAR> 2030: x1000 improvement $n \to \bar{n}$ @ILL

Improve by 10^3

- Baryon Number Violation at the core of our existence

Physics of Baryon Number Violation of utmost importance

- Standard Model tells us about interactions

But *nothing* about nature of quarks and leptons

Our existence, Grand Unification our best hints

- Baryon Number Violation excellent probe

We *know* it exists

- **Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare**

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

arXiv:2006.04907

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

A. Addazi, K. Anderson, S. Ansell, K. Babu, J. Barrow, D.V. Baxter, P.M. Bentley, Z. Berezhiani, R. Bevilacqua, C. Bohm, G. Brooijmans, J. Broussard, R. Biondi, B. Dev, C. Crawford, A. Dolgov, K. Dunne, P. Fierlinger, M.R. Fitzsimmons, A. Fomin, M. Frost, S. Gardner, A. Galindo-Uribarri, E. Golubeva, S. Girmohanta, G.L. Greene, T. Greenshaw, V. Gudkov, R. Hall-Wilton, L. Heilbronn, J. Herrero-Garcia, G. Ichikawa T.M. Ito, E. Iverson, T. Johansson, L. Joensson, Y-J. Jwa, Y. Kamyshkov, K. Kanaki, E. Kearns, M. Kitaguchi, T. Kittelmann, E. Klinkby, L.W. Koerner, B. Kopeliovich, A. Kozela, V. Kudryatsev, A. Kupsc, Y. Lee, M. Lindroos, J. Makkinje, J.I. Marquez, R. Mohapatra, B. Meirose, T.M. Miller, D. Milstead, T. Morishima, G. Muhrer, H.P. Mumm, K. Nagamoto, V.V. Nesvizhevsky, T. Nilsson, A. Oskarsson, E. Paryev, R.W. Pattie Jr, S. Penttil, Y. N. Pokotilovski, I. Potashnikova, C. Redding, J-M Richard, D. Ries, E. Rinaldi, A. Ruggles, B. Rybolt, V. Santoro, U. Sarkar, A. Saunders, G. Senjanovic, A.P. Serebrov, H.M. Shimizu, R. Shrock, S. Silverstein, D. Silvermyr, W.M. Snow, A. Takibayev, L. Townsend, I. Tkachev, L. Varriano, A. Vainshtein, J. de VRies, R. Woracek, Y. Yamagata, A.R. Young, L. Zanini, Z. Zhang, O. Zimmer

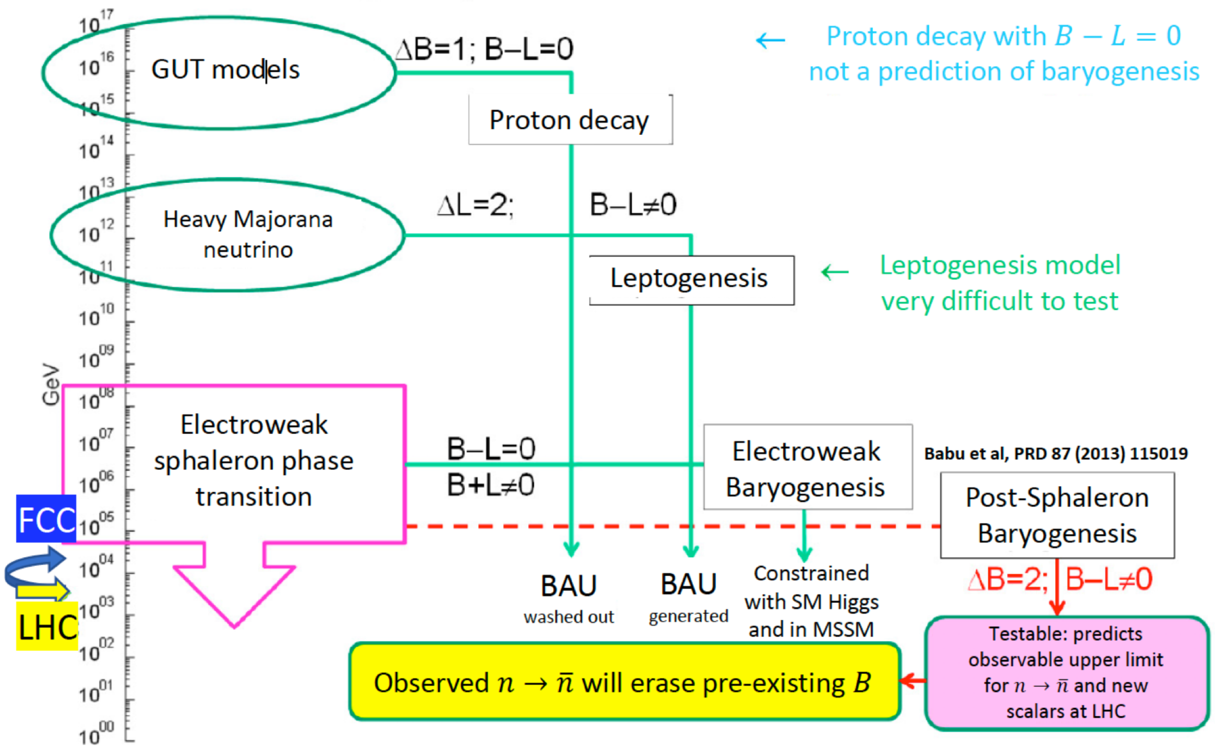
The violation of Baryon Number, $\mathcal{B}$, is an essential ingredient for the preferential creation of matter over antimatter needed to account for the observed baryon asymmetry in the universe. However, such a process has yet to be experimentally observed. The HIBEAM/NNBAR %experiment program is a proposed two-stage experiment at the European Spallation Source (ESS) to search for baryon number violation. The program will include high-sensitivity searches for processes that violate baryon number by one or two units: free neutron-antineutron oscillation ($n \to \bar{n}$) via mixing, neutron-antineutron oscillation via regeneration from a sterile neutron state ($n \to [n', \bar{n}'] \to \bar{n}$), and neutron disappearance ($n \to n'$); the effective $\Delta\mathcal{B} = 0$ process of neutron regeneration ($n \to [n', \bar{n}'] \to n$) is also possible. The program can be used to discover and characterise mixing in the neutron, antineutron, and sterile neutron sectors. The experiment addresses topical open questions such as the origins of baryogenesis, the nature of dark matter, and is sensitive to scales of new physics substantially in excess of those available at colliders. A goal of the program is to open a discovery window to neutron conversion probabilities (sensitivities) by up to three orders of magnitude compared with previous searches. The opportunity to make such a leap in sensitivity tests should not be squandered. The experiment pulls together a diverse international team of physicists from the particle (collider and low energy) and nuclear physics communities, while also including specialists in neutronics and magnetics.

BACK-UP SLIDES

Baryogenesis Models

Regimes for baryogenesis

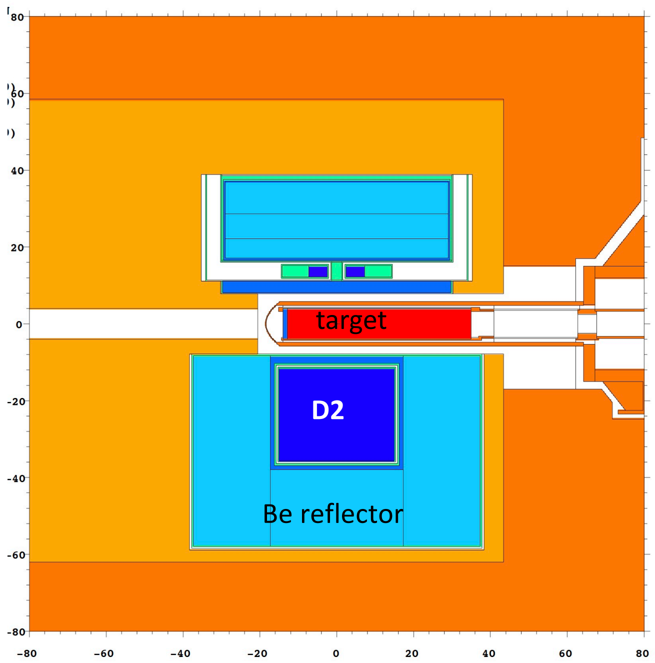
- Leptogenesis: Sphalerons convert L into B
- Electroweak baryogenesis: T violation near EW scale creates B without L
- Post-sphaleron baryogenesis: New BNV process below EW phase transition
- $n \rightarrow \bar{n}$ targets accessible energy scales . Null result will restrict phase space of PSB models

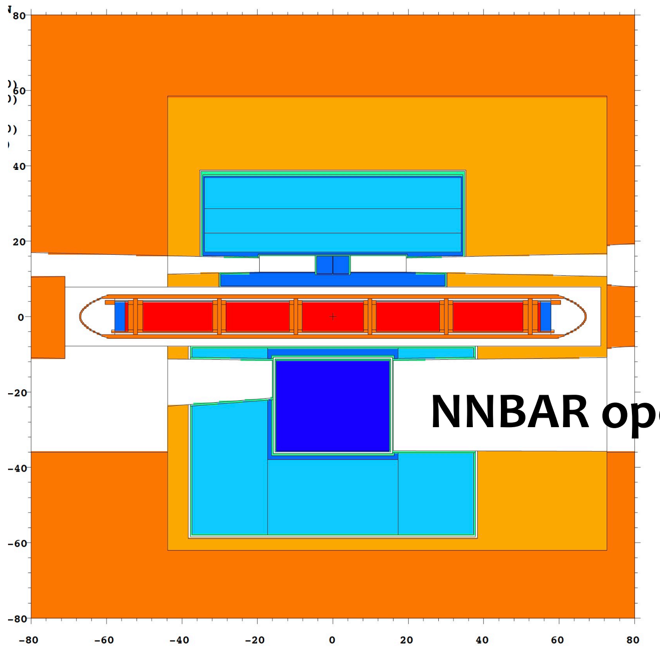


see talk Rabi Mohapatra

Recent progress in HighNESS

MCNP baseline model developed





- Monte Carlo Model of the ESS targer+moderator model fully parametrized to allow easy changes in the geometry for sensitivity studies and optimization.