HighNess

The HighNESS Project and Future Free Neutron Oscillations Searches at the ESS

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On Behalf of the NNBAR/HIBEAM Collaboration

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

The European Spallation Source

- The European Spallation Source is a neutron scattering facility under construction in Lund, in southern Sweden
- It is an international laboratory with host countries Sweden & Denmark and 11 partner countries with a total construction budget: 1843 M€$_{2013}$
- The facility's unique capabilities will both greatly exceed and complement those of today's leading neutron sources

CONSTRUCTION START	COMPLETION STATUS	PERSONNEL	NATIONALITIES	IN-KIND PARTNERS	USER PROGRAMME BEGINS
2014	79%	516	57	40	2023

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HighNess

Fundamental & Particle Physics @ ESS

ess

- In addition to neutron scattering the higher intensity and the pulse structure of ESS provide new possibilities for fundamental physics research with neutrons
- The ESS mandate includes a fundamental physics program, and the current lack of an appropriate beamline for fundamental physics has been identified as one of the most important missing capabilities

Precision experiments
Beyond SM
New interactions

High Intensity Baryon Extraction and Measurement (HIBEAM)

Neutron antineutron oscillation beamline (NNBAR)

Search for Dark Matter
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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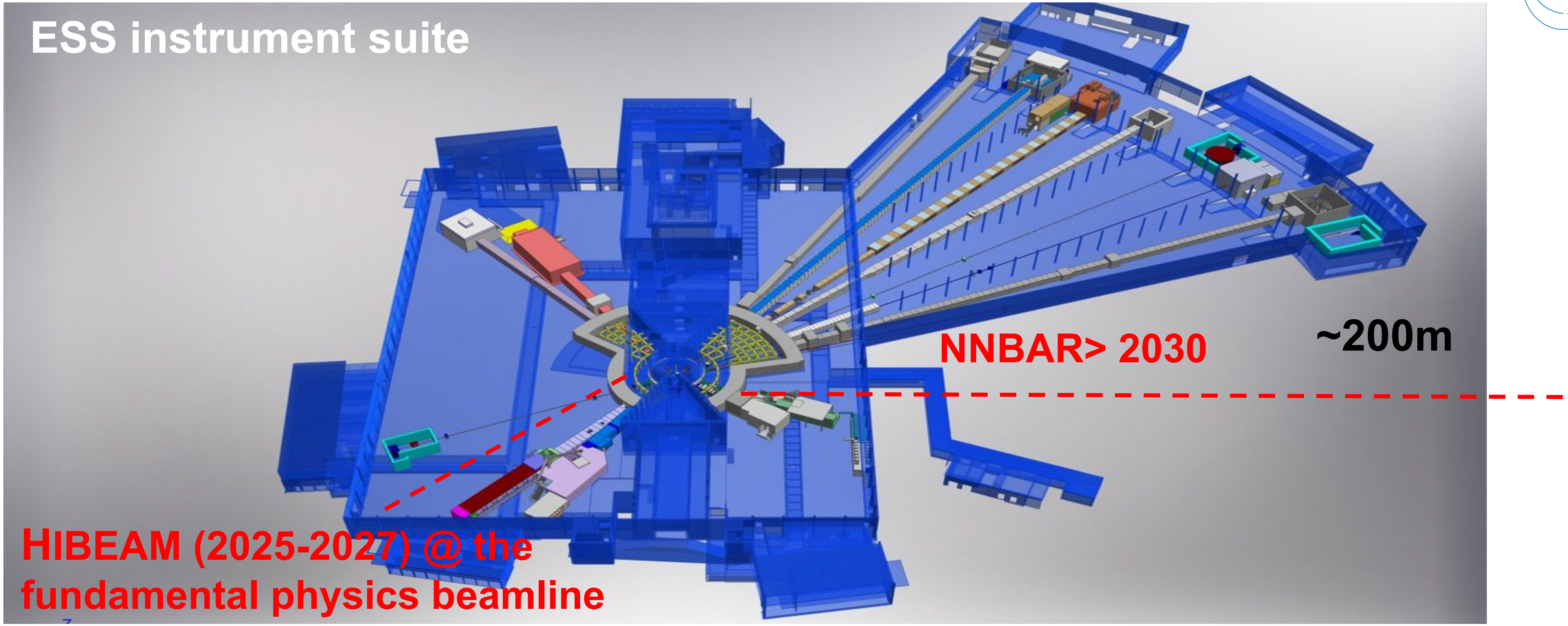
Future Free Neutron Oscillations Searches at the ESS



Two stage program:

- HIBEAM (≳2025): smaller program of complementary experiments (with focus on sterile neutron searches)
- NNBAR (>2030): search for $n \rightarrow \bar{n}$ oscillations (sensitivity increase of 10^3 compared to previous experiments)

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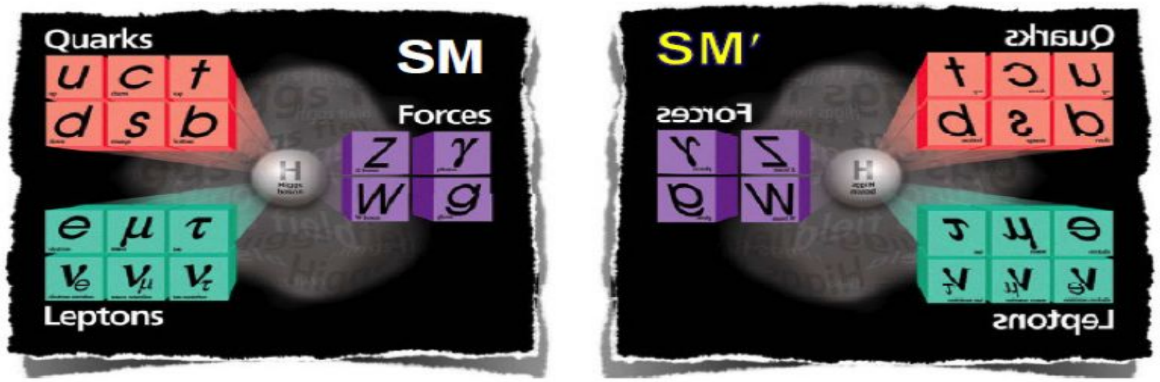
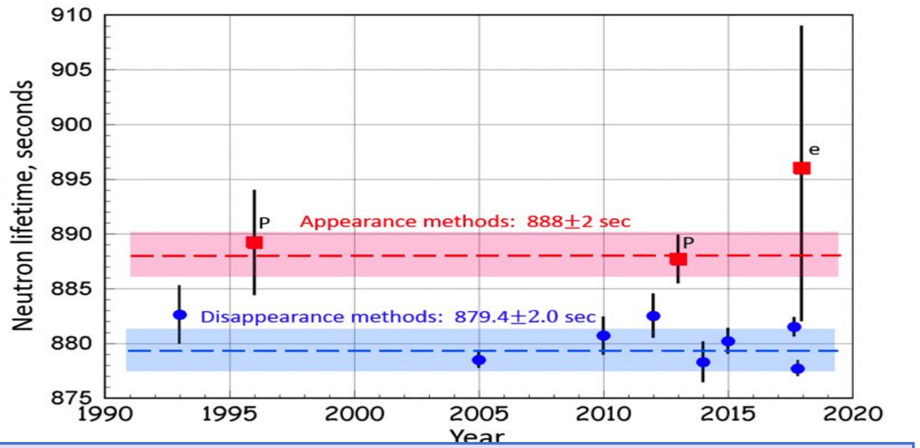
The HIBEAM program: search for neutron to sterile neutron conversion (I)

- 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”



- 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



An improved neutron lifetime measurement with UCNt arXiv:2106.10375

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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 feature of SM extensions (eg SUSY, extra dimensions..)

- Important to probe possible BNV channels

- HIBEAM will search for $n \rightarrow n'$ ($|\Delta B|=1$) and
- NNBAR will search for $n \rightarrow \bar{n}$ ($|\Delta B|=2$)
  Sensitivity increase of 10^3 compared to previous experiments

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source **A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501**

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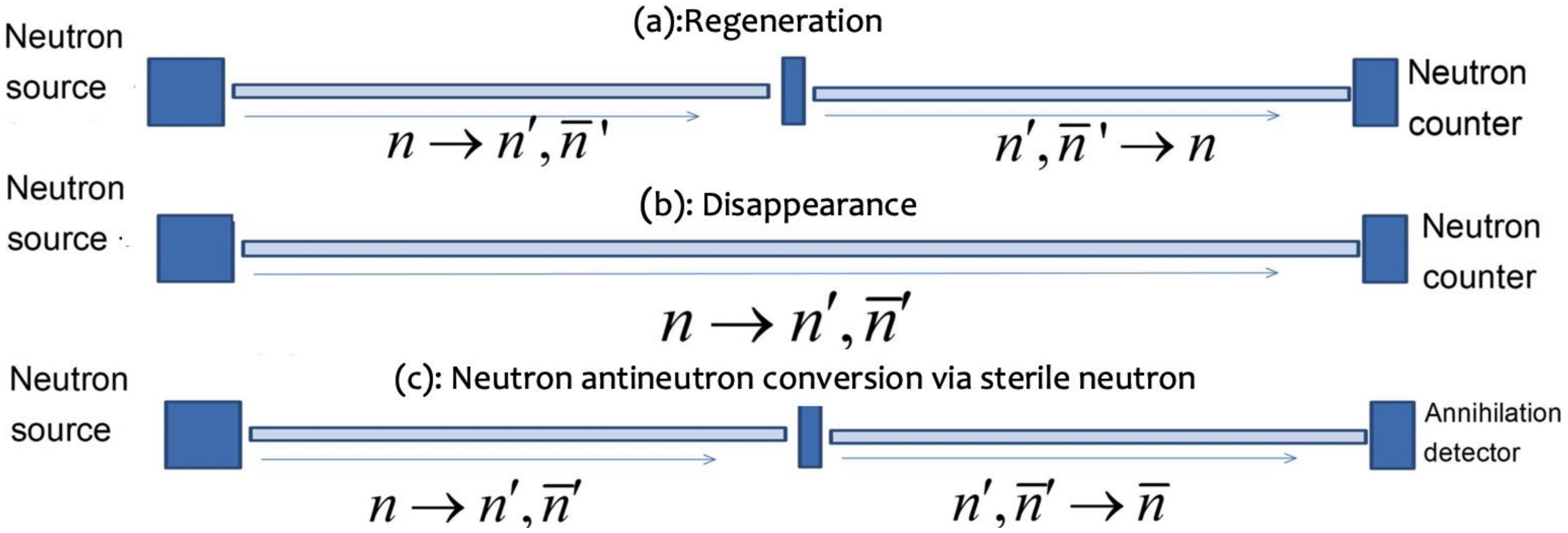
The HIBEAM program: search for neutron to sterile neutron conversion (II)

- HIBEAM will look for ***n*** regeneration, ***n*** disappearence and ***n*** to antineutron conversion via sterile neutron
- All experiments shown are dependent on the magnetic field. Experiments (a), (b), and (c) should scan through the magnetic field range ~ +/- 1 G to coincide in resonance with the unknown value of the “mirror magnetic field” in magnitude and in direction. For the flight path of these experiments, full 3D control of the magnetic field will be needed.



New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501

The NNBAR experiment @ ESS

NNBar

Abstract

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. Observing the n–$\bar{n}$ transition would show that baryon number (B) is violated by two units and that matter containing neutrons is unstable. It would provide a clue to how the matter in our universe might have evolved from the $B=0$ early universe. If seen at rates observable in foreseeable next-generation experiments, it might well help us understand the observed baryon asymmetry of the universe. A demonstration of the violation of $B-L$ by 2 units would have a profound impact on our understanding of phenomena beyond the Standard Model of particle physics.

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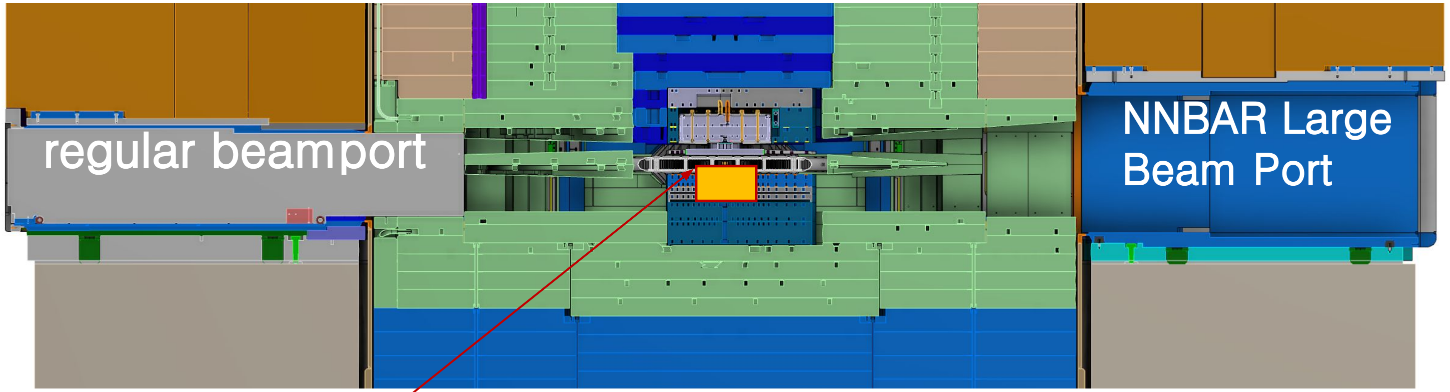
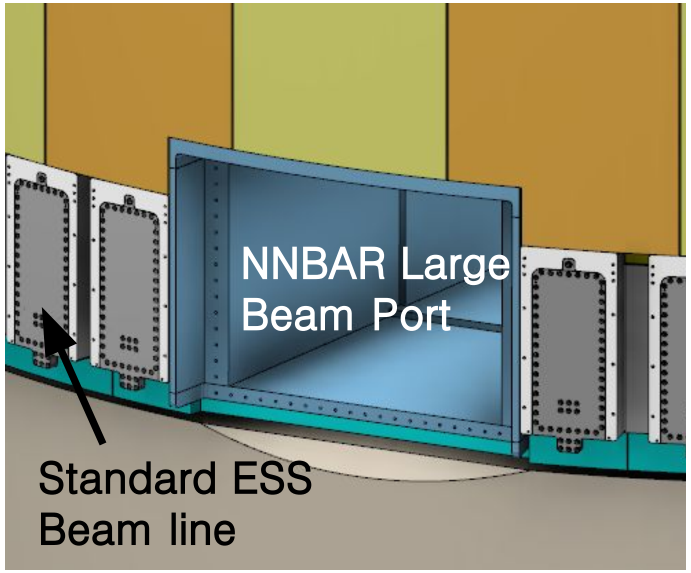
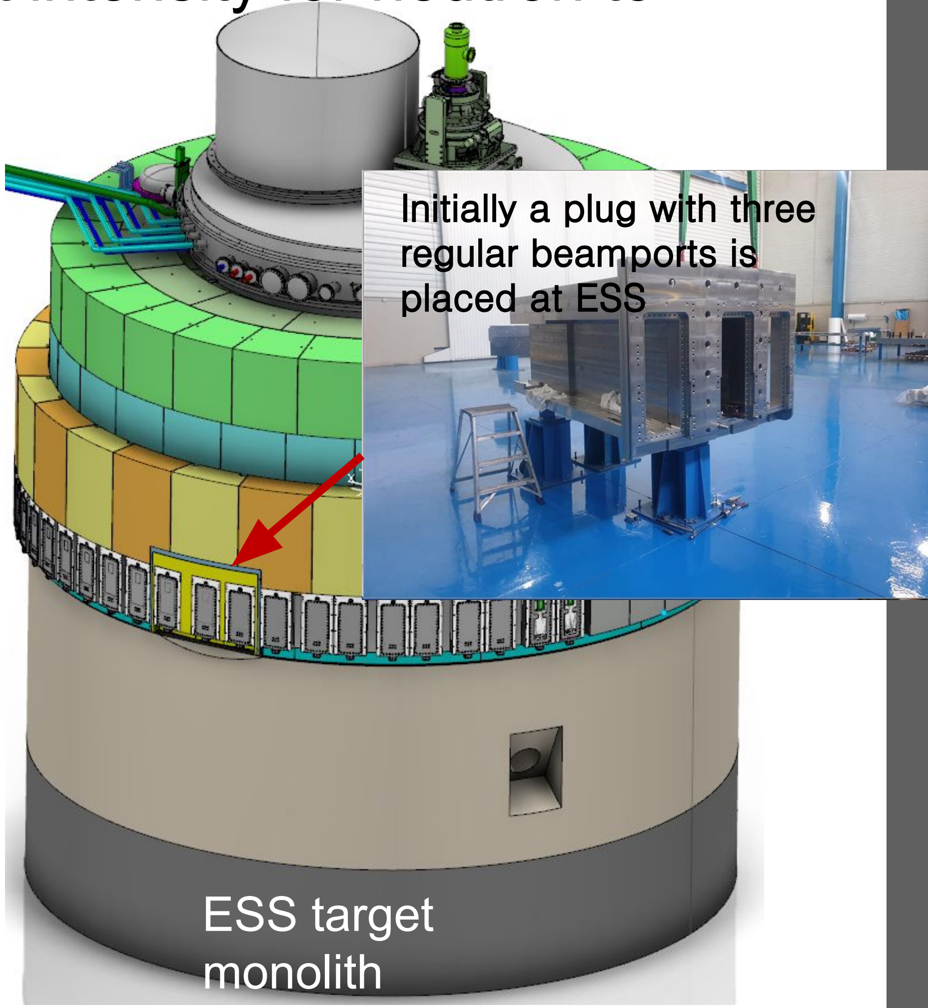
Why NNBAR at ESS?

A large beam port has been built at ESS specifically for NNBAR to allow for extraction of a high intensity beam to provide sufficient intensity for neutron to antineutron search



Location of lower moderator





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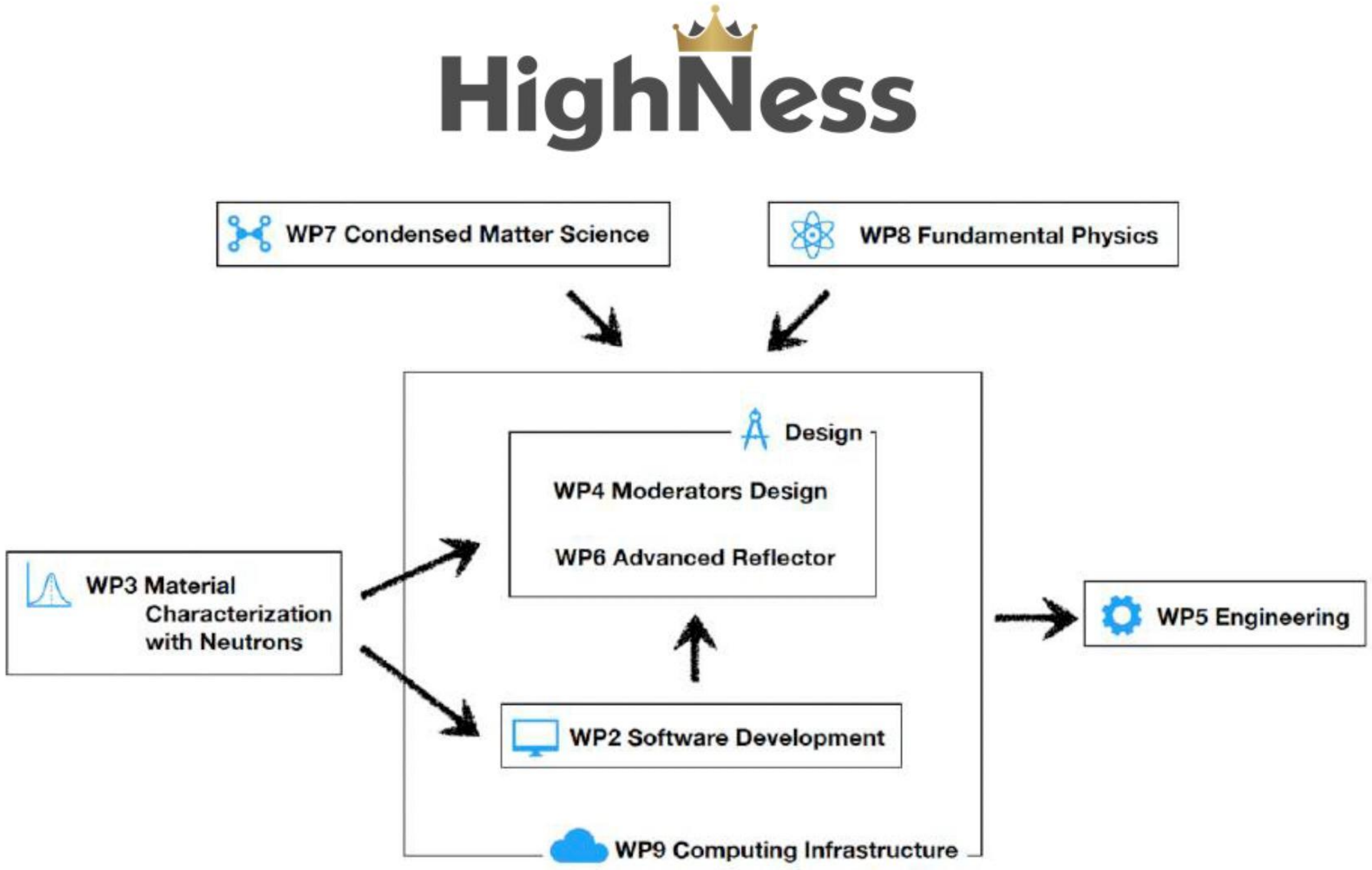
The HighNESS project at ESS, started october 2020

The HighNESS project (3 MEURO 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 source using advanced reflectors. **The new source will be designed to be optimal for NNBAR**
In the project will be also developed the associated experiments including NNBAR **-> Conceptual Design Report expected by the end of 2023**

8 EU Institutes,
7 countries,
34 people presently involved



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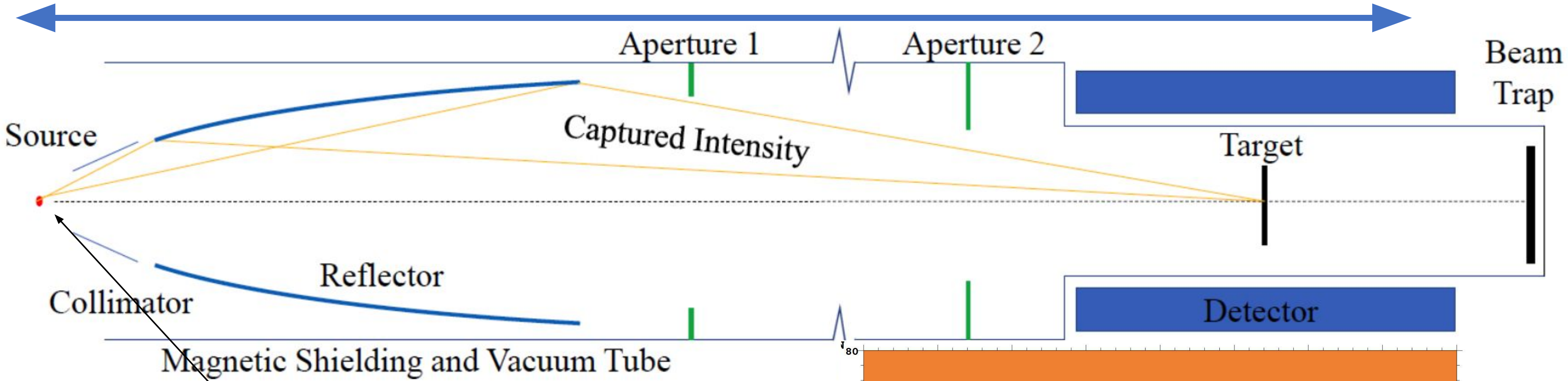
Research and Innovation Horizon 2020, u

Schematic of the NNBAR experiment

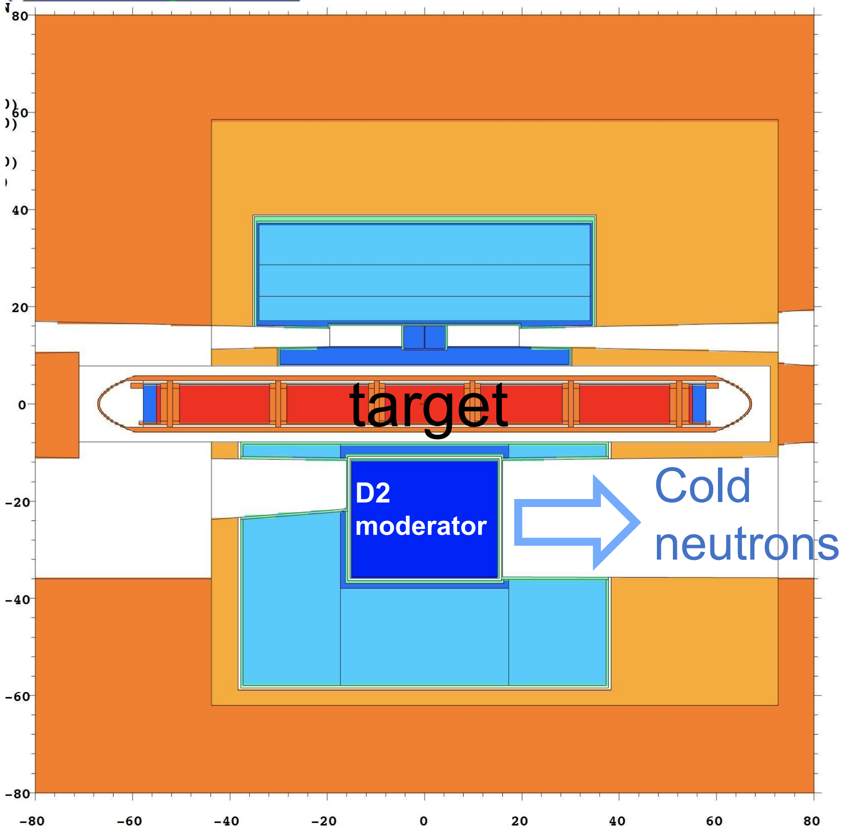


To design the optimal experiment you need to take into account several different aspects:

Source (Moderator):

It determines the number of cold neutrons emitted by the source

Work-on going at ESS+ collaborators to design the ideal source for NNBAR



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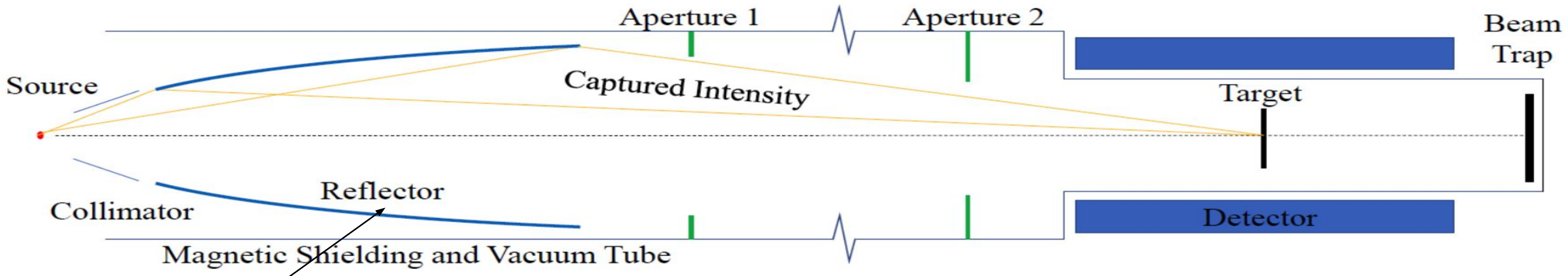
The NNBAR experiment (schematic)

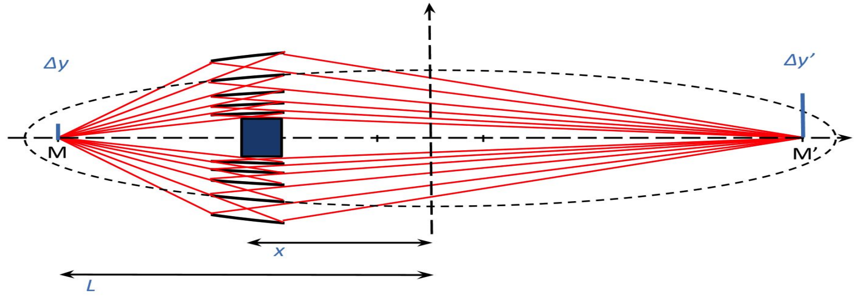


Reflector :

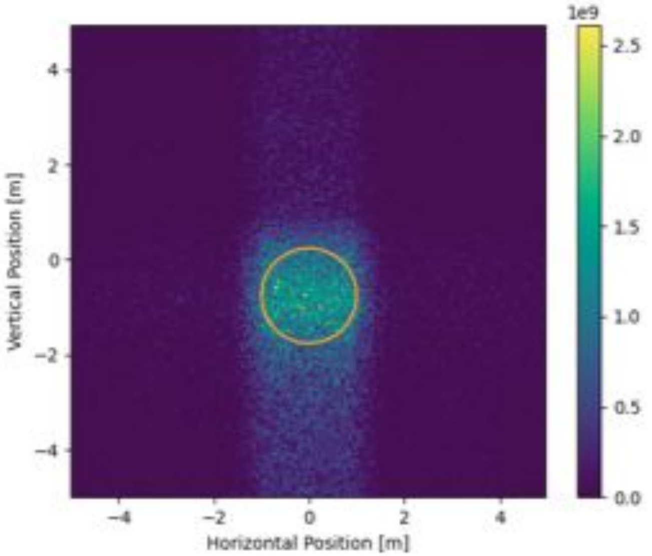
How many neutrons you collect, transport and focus in the experiment

Courtesy of Oliver Zimmer
and Richard Wagner (ILL)

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



Optimization studies
on-going at ILL
+collaborators
Circle of radius 1m at
maximum (⇒ detector
placed at optimal position)



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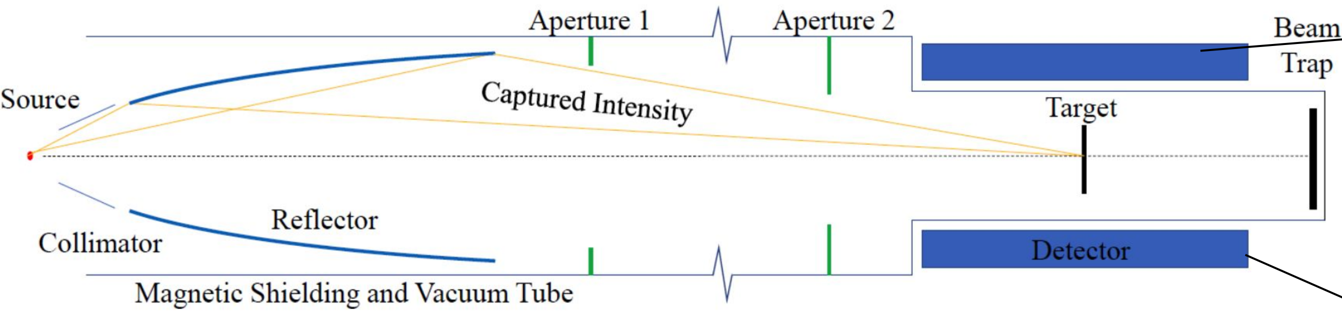
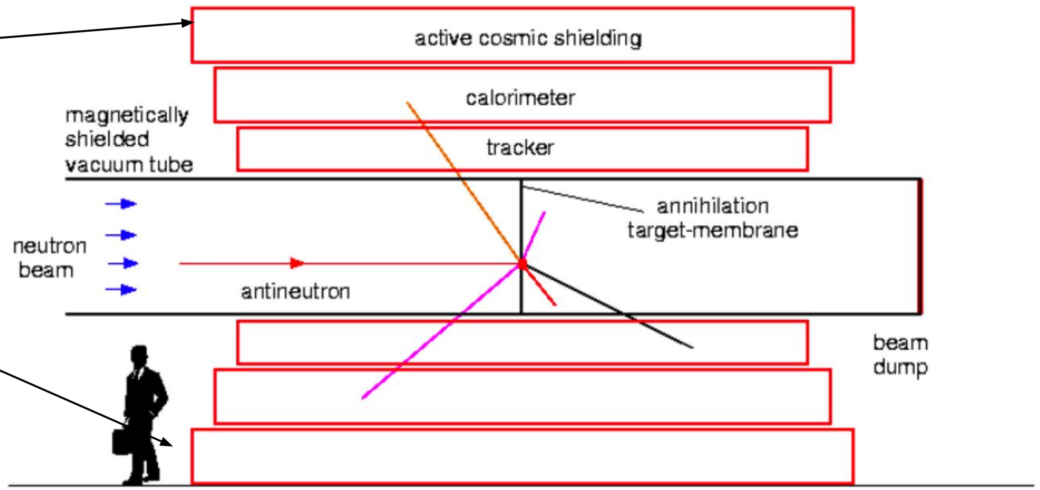
Propagation and annihilation detector





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

Work on–going to design the magnetic shielding system and the vacuum pipe

Detector :

- At the end of the beamline the neutron beam will hit a thin carbon foil target
- If the neutron has converted to antineutron it will annihilate in the carbon foil
- The carbon has large $\overline{n}$ annihilation cross section
  ~5 pions produced in annihilation
- Detector design on-going (TPC for tracker, scintillator+lead-glass for calorimeter +cosmic shield)

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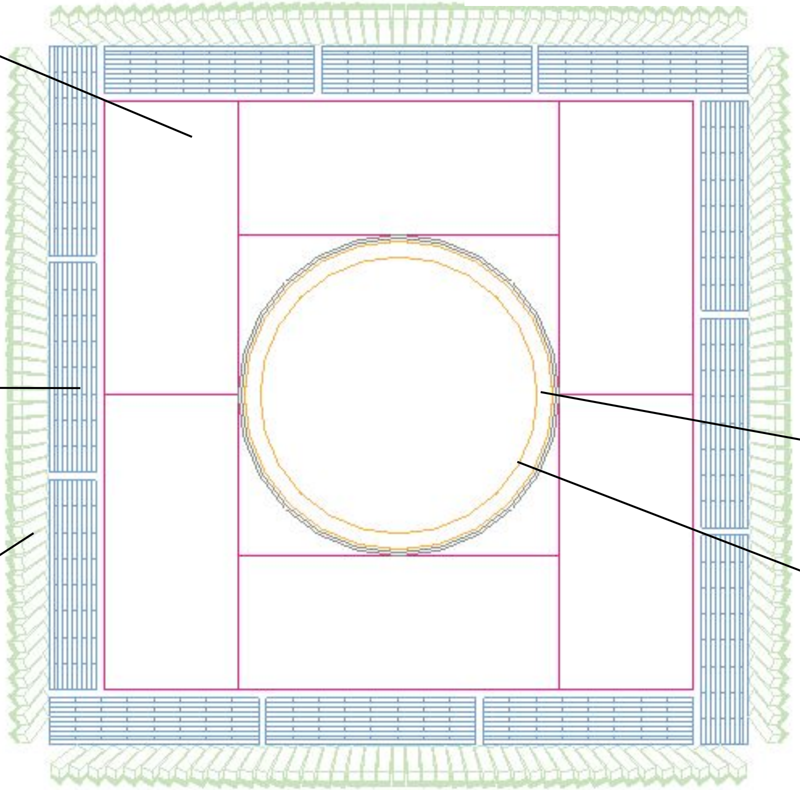
NNBAR Annihilation detector

Design and optimization of the NNBAR detector on going

y direction



Time Projection Chamber

80% Ar + 20% CO_2
Two different dimensions (x-y)
- 0.85 m x 1.87 m
- 2.04 m x 0.85 m

2m long (z direction)

Scintillator Modules

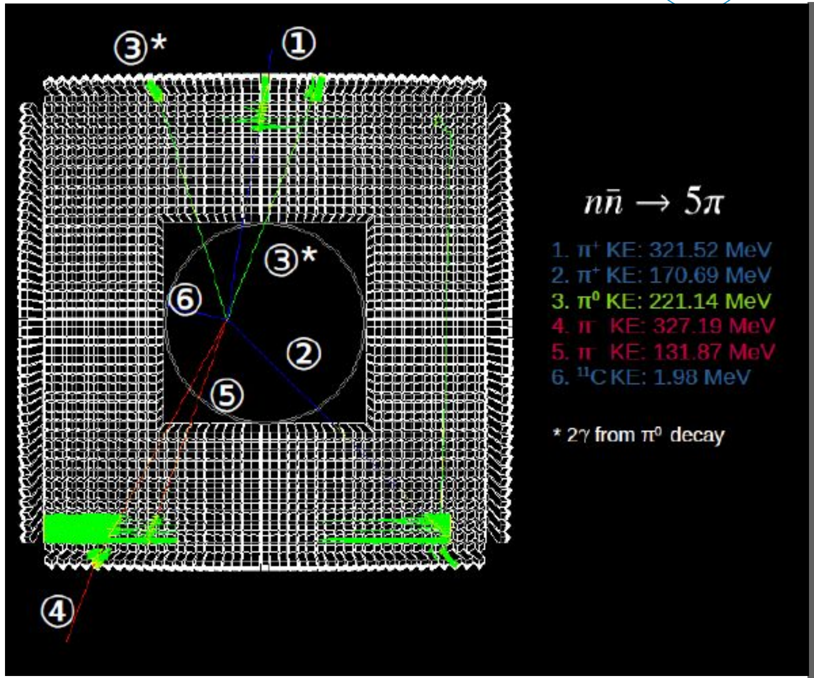
10 layers of plastic scintillator
3 cm thick for each layer

Each layer is divided into 8 staves

Consecutive layers are perpendicular

Lead Glass Blocks

Base: 8 cm x 8 cm
Height: 25 cm
Pointing towards the **center of the detector**



Silicon Trackers

Layer 1:	Layer 2:
Inner radius = 87.97 cm	Inner radius = 97.97 cm
Thickness = 0.03 cm	Thickness = 0.03 cm
Length = 6 m	Length = 6 m

Vacuum tube

1 m inner radius
2 cm thick
6 m long (z direction)

A computing and Detector Simulations framework for the HIBEAM/NNBAR Experimental program at the ESS arxiv 2106.15898

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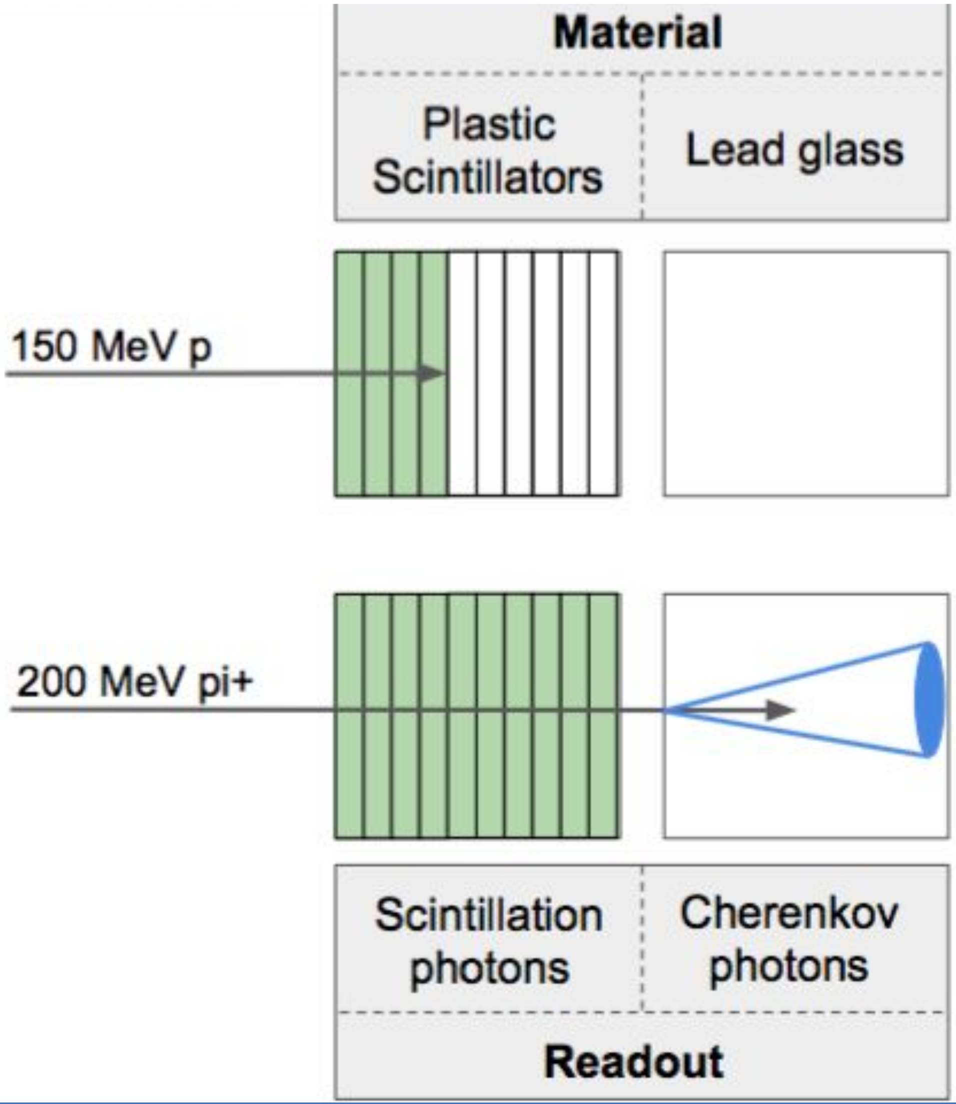
NNBAR prototype Calorimeter

- Work on-going at Stockholm University + collaborators
- Hybrid hadronic range detector + EM calo
- Binary readout (hit/not hit) of staves+ Cherenkov light from lead glass
- Measurement inform simulations of full detector
- Next year Low energy hadrons/electrons
  - PSI : protons 74--230 MeV
  - INFN : electrons 25--500 MeV
- Ultimately to be deployed at ESS test beam to validate in situ background



The HIBEAM/NNBAR Calorimeter prototype arxiv 2107.02147

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Conclusions

- Lots of activities are going on right now in the HIBEAM/NNBAR collaboration

- HighNESS project started in October 2020:
  - **Design of the optimal moderator for NNBAR**
  - **CDR of the NNBAR experiment**
    - Beamline design (reflector, magnetic shielding and background simulations)
    - Detector development and design optimization

- Prototype development and construction on-going

  - **HIBEAM > 2025 search for sterile neutron transitions**
  - **NNBAR ~2030 search for neutron to antineutron oscillations x1000 improvement respect to the previous limit**

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HIBEAM/NNBAR collaboration

- Broad international base and supporters
  ~ 100 authors from 50 institutes in 8 countries
- Combines experts in neutronics, magnetics, nuclear and particle physics.
- Co-spokespersons: G. Brooijmans (Columbia), D. Milstead (Stockholm Uni.) Lead scientist: Y. Kamyshkov (Tennessee Uni.) Technical coordinator: V. Santoro (ESS)
- White paper: A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501
- CDR in 2023 as part of HighNESS program
- **Collaborators are welcome !!**

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the HIBEAM/NNBAR experiment at the European Spallation Source A Addazi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* 48 070501

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BACK-UP SLIDES

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HighNess

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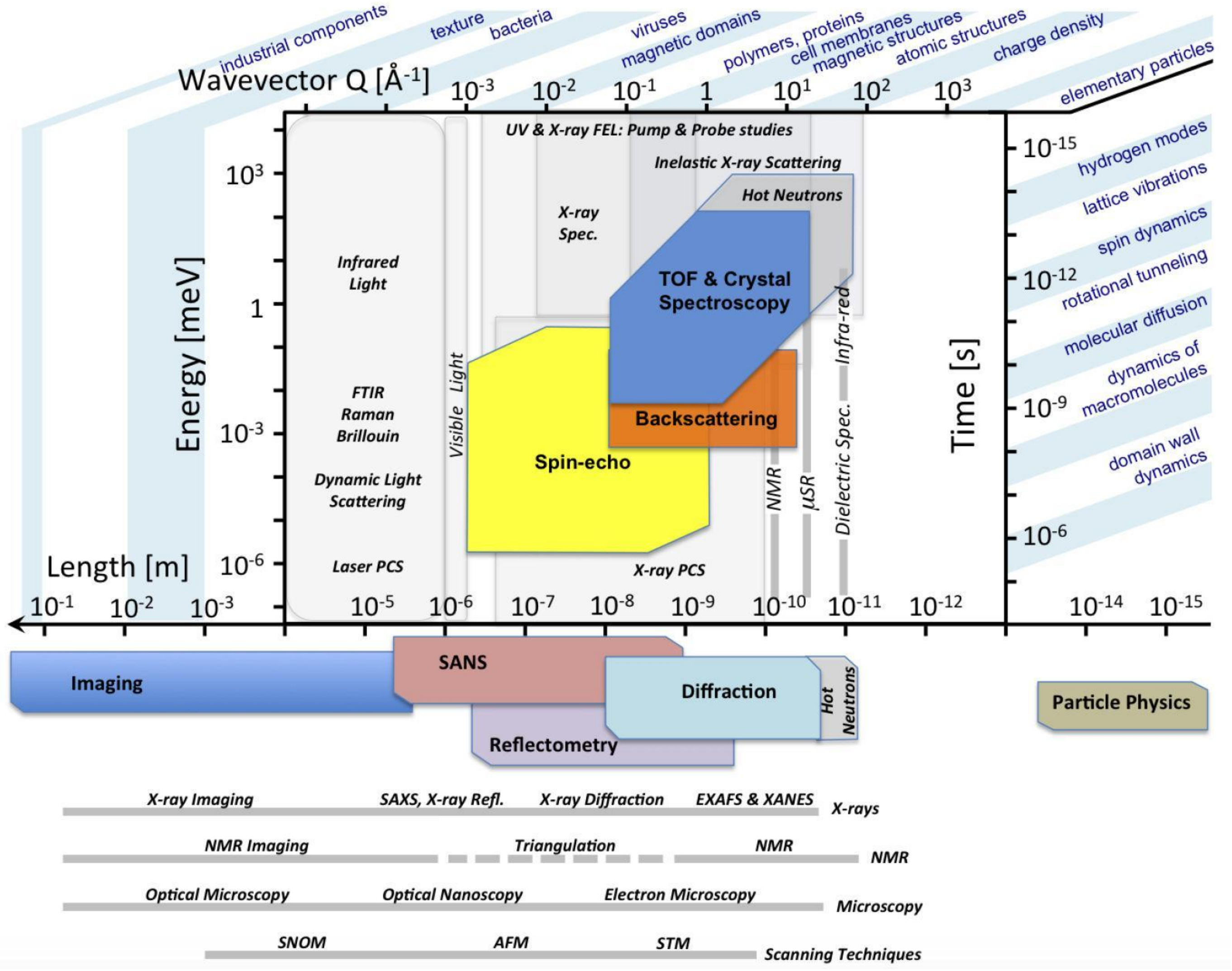
The European Spallation Source (II)



- Neutron scattering can be applied to a range of scientific questions, spanning the realms of physics, chemistry, geology, biology and medicine.
- In neutron scattering the neutron is used as a probe for revealing the structure and function of matter from the microscopic down to the atomic scale.

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The Capability Gap Analysis

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- 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. **Therefore filling this capability gap is given the highest priority.**

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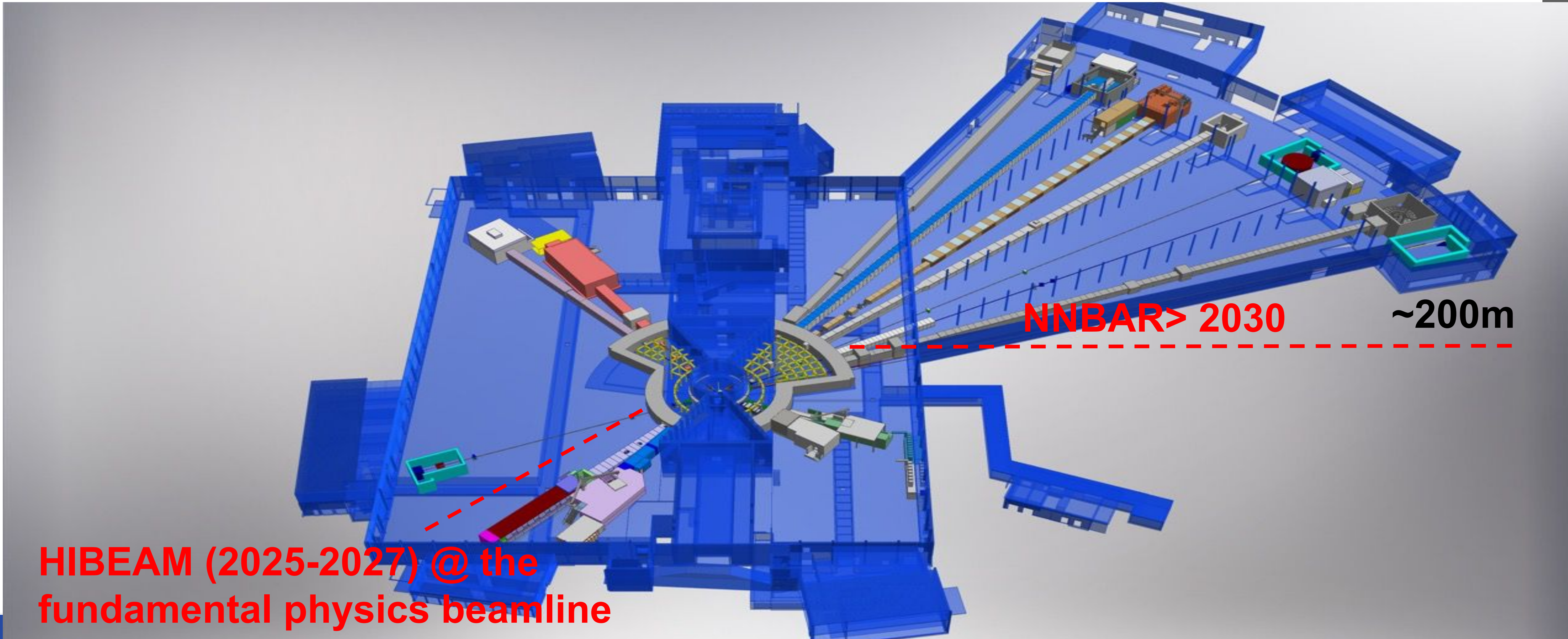
DARK Matter

- **What is the nature of dark matter?**
- **The fact that our astronomical observations are not sufficiently well described by the SM is unquestioned.**
- **The existence of a dark sector, interacting primarily gravitationally with our familiar visible sector, has long been postulated to explain astronomical data**
- **Such dark sector is assumed to have particles having interactions similar to our own SM interactions, sterile neutrinos and sterile baryons**
- **In principle, observable portals onto such a sector can occur ia mixing phenomena between any stable or meta-stable electrically neutral particles, allowing for conversion into a dark partner particle.**

ESS Neutron Instruments 1-15 and HIBEAM and NNBAR locations

- HIBEAM: smaller program of complementary experiments (with focus on sterile neutron searches) ≳2025
- NNBAR: Beamline earliest available ≥ 2030



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**

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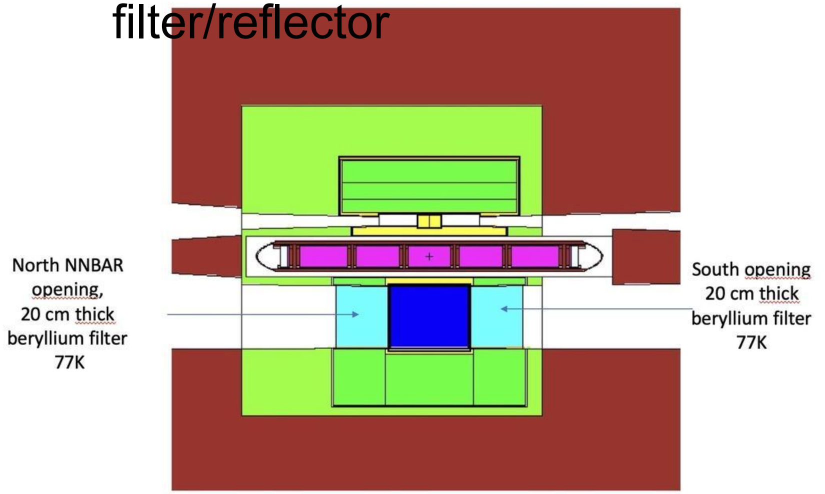
Liquid deuterium moderator design on-going

ess

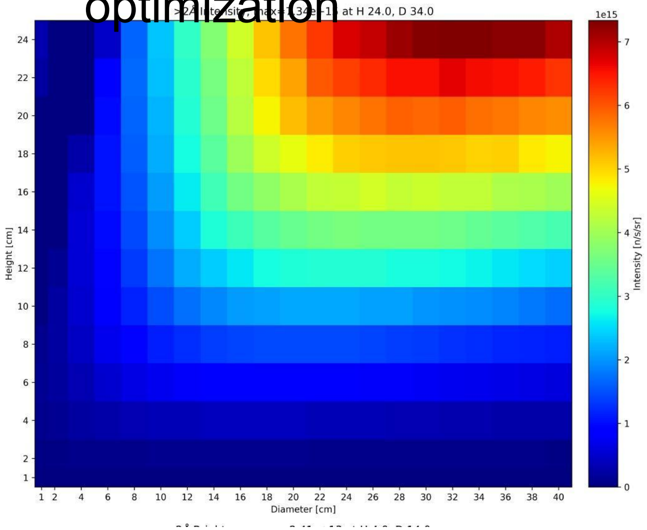
- Neutronic study of large D_2 moderator ongoing
  - Intensity variation with dimenstions, number of beamlines, use of Be filter /reflector
- Additional works:
  - Design of nanodiamond reflector for cold and very cold neutrons (advanced reflector)
  - Design of UCN source
  - Prototype experiment will be performed at Budapest reactor

opening optimization

Use of Be filter/reflector



size optimization



Luca Zanini
Alan Takibayev and many others

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- Two stage experiment
- HIBEAM (>2025)
  - High precision (x10 improvement): $n \rightarrow \bar{n}', n'$ (disappearence) ; $n \rightarrow [\bar{n}', n'] \rightarrow n$ (regeneration) ; $n \rightarrow [\bar{n}', n'] \rightarrow \bar{n}$ (nnbar via sterile neutrons)
  - Possibility to match earlier sensitivity from 1990's ILL experiment: $n \rightarrow \bar{n}$ and perform new search $n \rightarrow [\bar{n}', n'] \rightarrow \bar{n}$
  - ANNI cold neutron beamline
- NNBAR (>2030)
  - $\sim 10^3$ improvement in sensitivity: $n \rightarrow \bar{n}$
  - Large Beam Port

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