The Neutron - Anti-Neutron Oscillation (NNBAR) Experiment at the ESS

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on behalf of the NNBAR collaboration

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Outline

- ESS/HighNESS
- NNBAR – Motivation
- Optics
- Detector
- Conclusion

The ESS and the HighNESS Project

- The European Spallation Source (ESS):
  - neutron research facility currently under construction in Lund, Sweden
  - designed to be the most powerful neutron source in the world
  - An international laboratory with Sweden and Denmark as host countries and 11 European partner countries
- The HighNESS project *https://highnessproject.eu/*
  - Initiated for the design of a second moderator system of the ESS
  - Funded by the EU and consisting of an international consortium of 8 Institutes in 7 countries.

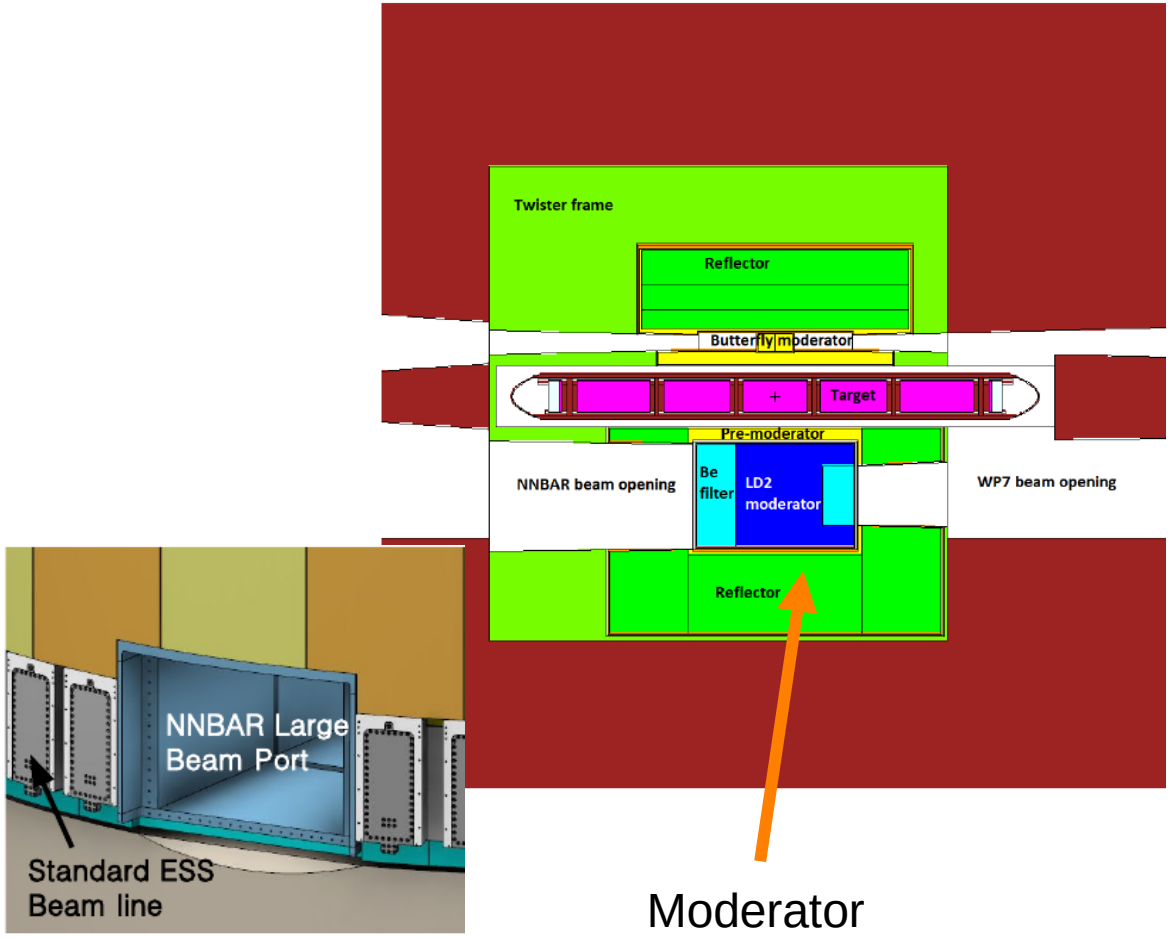
Aerial view of the ESS site January 2021 (Image from Perry Nordeng)

For detailed overview see

Development of high intensity neutron source at the European Spallation Source
V Santoro et al 2020,Journal of Neutron Research, 22(2-3)

Moderator and Large Beam Port (LBP)

- Designed in course of the HighNESS-Project
- Optimization criteria:
  Intensity of cold neutrons
  → wavelength range 2-20Å
- Liquid deuterium moderator with Beryllium filter
- Extraction through specially build port that's three times the size of a standard ESS beam line for a beam of highest intensity beam

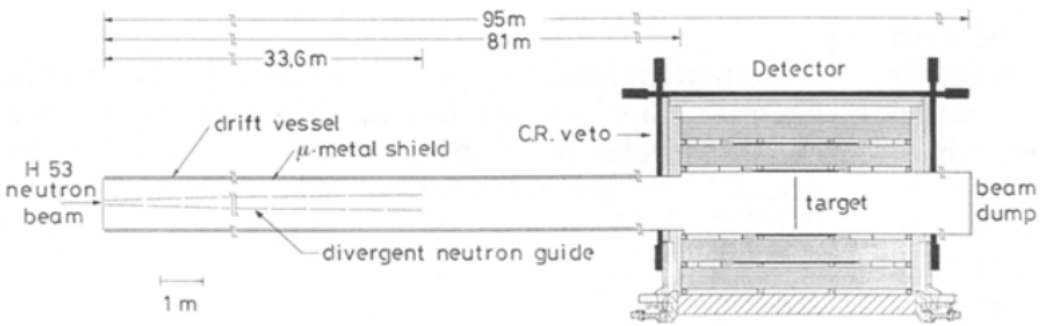


· Motivation for NNBAR Experiment

- Baryon Number Violation (BNV) may be the key to the observed matter and antimatter asymmetry of baryogenesis
- Search for BNV via neutron (n) – antineutron ($\bar{n}$) transformations, that may occur as free neutrons propagate to a detector, where the anti-neutron annihilates and creates a characteristic signal
- The processes with $|\Delta B| = 2$ is one of the cleanest channels to observe BNV

- NNBAR experiment is use case for fundamental physics at the second moderator beam lines at the ESS
- Fully utilize the high cold neutron intensities of the new LD_2 moderator

- Reference Experiment: 1991 at the ILL
- Holding the current Limit for free neutron-anti neutron oscillation time: $\tau > 0.86 \times 108$ s.
- Unit for figure of merit (FOM): FOM = 1



From Baldo-Ceolin (1994)
DOI:10.1007/BF01580321

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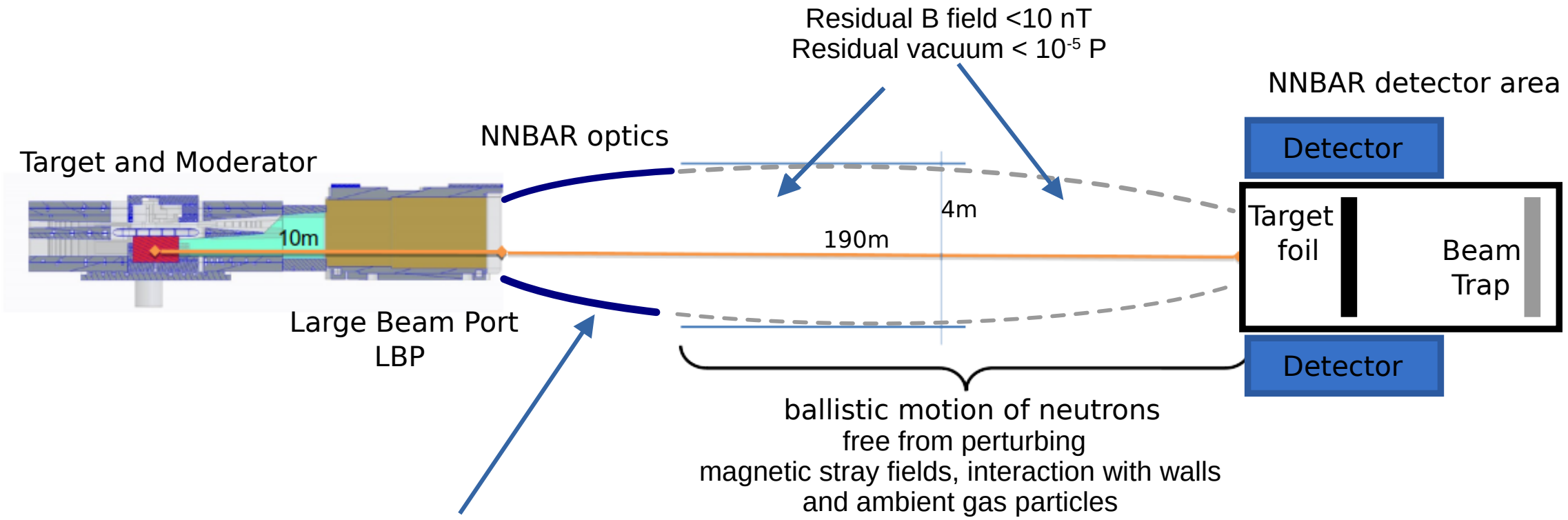
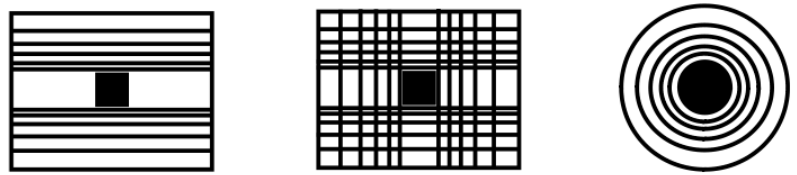
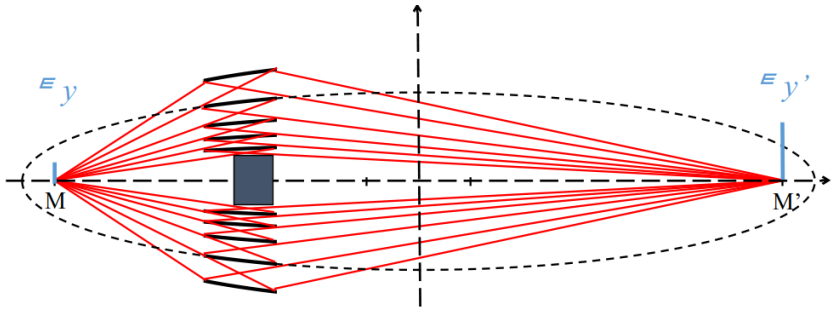
Schematics of ESS Experiment (not in scale)



Optics I

- Design of a nested system of neutron mirrors
- Elliptical mirrors (foci located in moderator and detector) in planar or cylindrical arrangement
- Alternative Wolter-optics studied, too
- McStas Simulations of performance of a given optical system
- Optical components for simulation are automatically generated





arXiv:1611.07353
Journal of Neutron Research 20 (2018) 91-98

Different optics are compared using the quantity: $FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}}$

Unit is 1991 experiment

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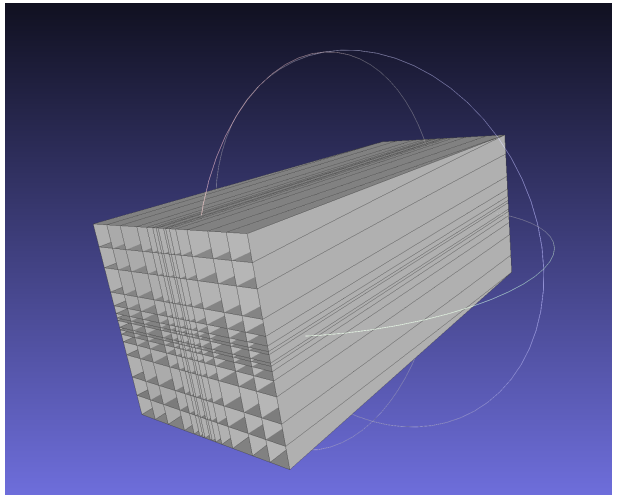
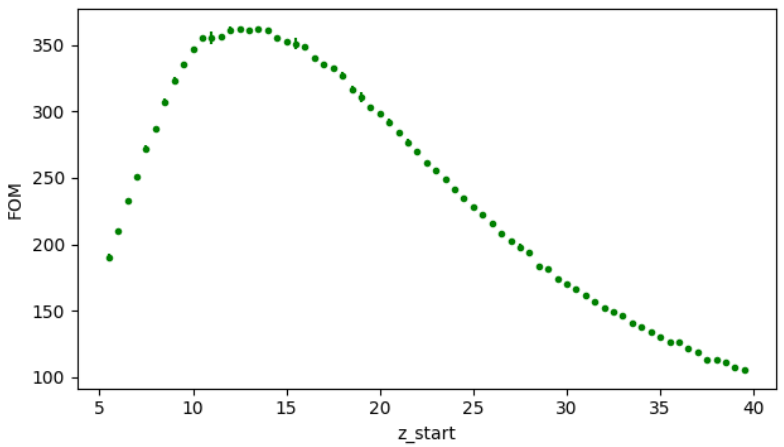
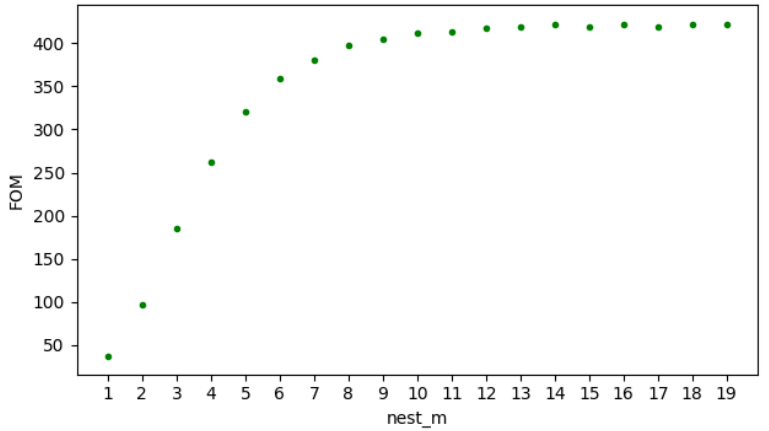
Optics II

Find the optimum optic by varying parameters (e.g. starting point, # of nested levels, ...)

Example: Simulations for a 10m Nested Reflector

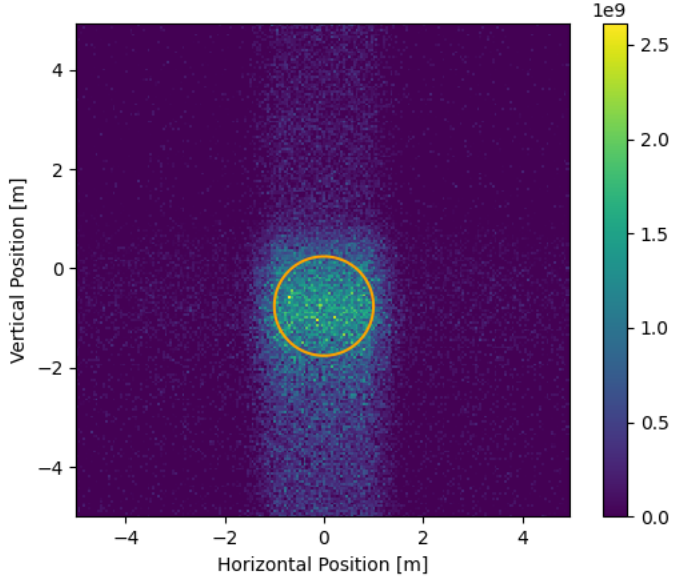






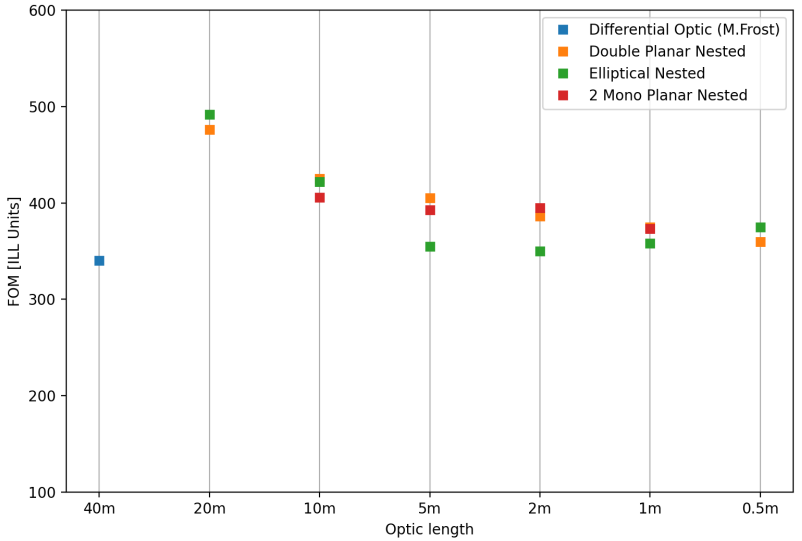
Optics III

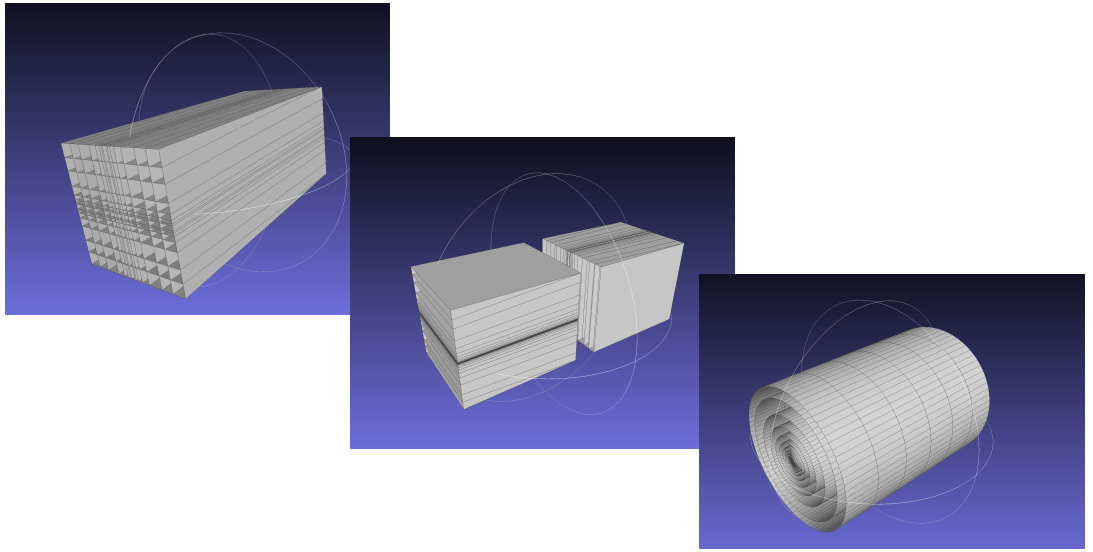
Example: Simulations for a 10m Nested Reflector



FOM: 362 (nested levels=7)

Collected results for different reflector systems





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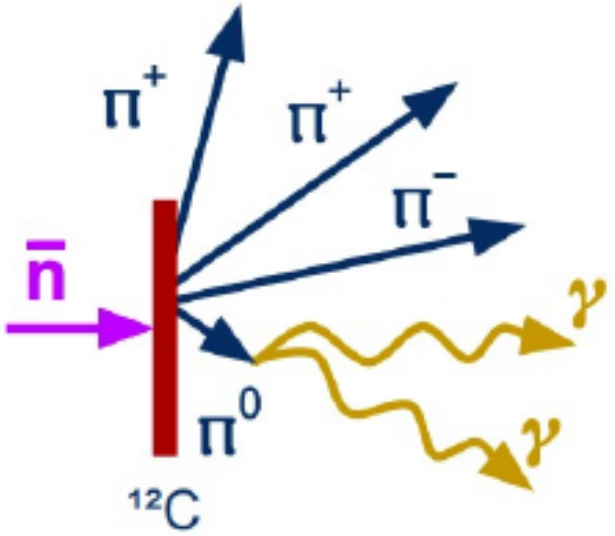
Detector

- Designed to detect a multi-pion final state
- Created due to the annihilation of the anti-neutron in the carbon target foil
- An annihilation generates (on average) 4-5 pions, including a π^0 which decays immediately to 2 γ - rays
- The invariant mass of the final state matches 2 neutron masses: ~1.88 GeV
  - ➔ characteristic signature for a discovery



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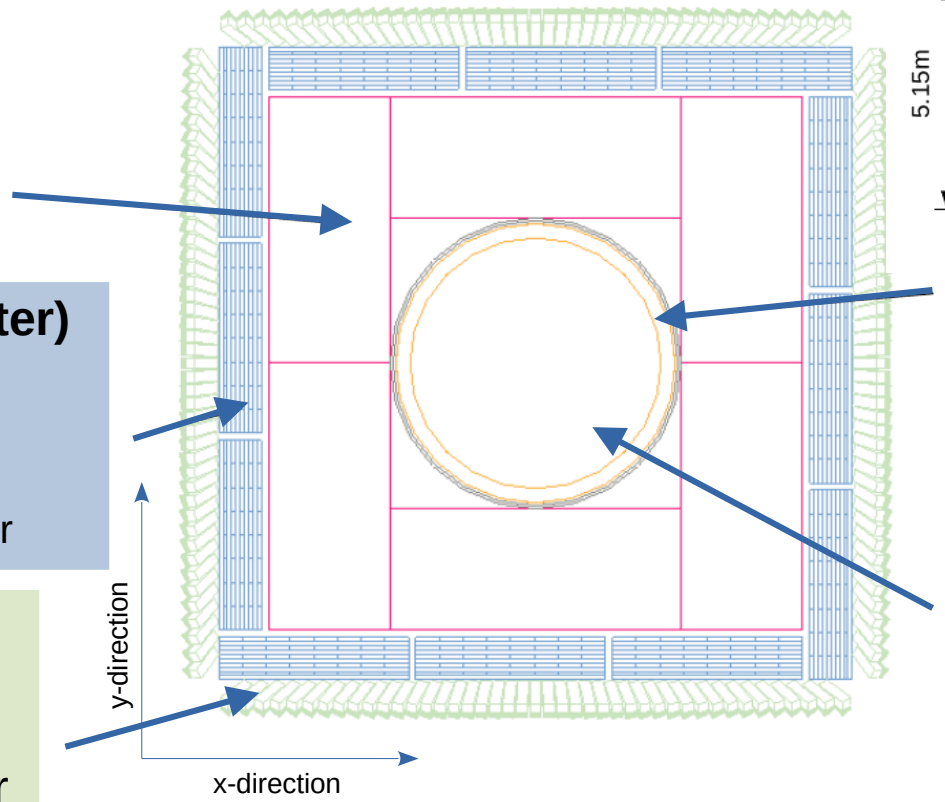
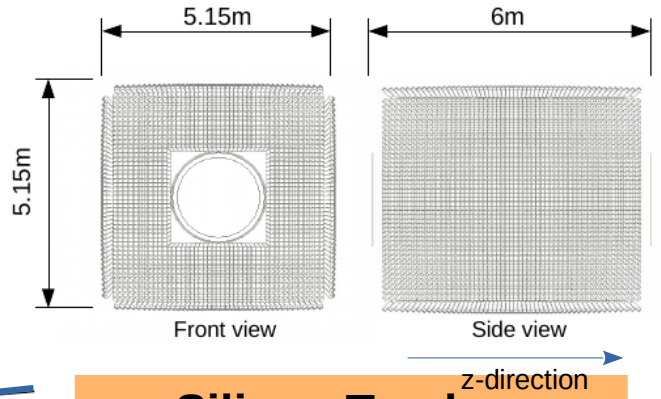
NNBAR Annihilation Detector – Box Geometry

Time Projection Chamber
Filling gas: 80% Ar, 20%CO_2
2 different dimensions (x-y):
0.85 m x 1.87 m
2.04 m x 0.85 m
Both:
2 m length in z-direction

Scintillator Modules (Calorimeter)
10 layers
3 cm thickness per layer
8 staves per layer
consecutive layers are perpendicular

Lead Glass Blocks
8 x 8 cm base area
25 cm height
Oriented towards center of detector



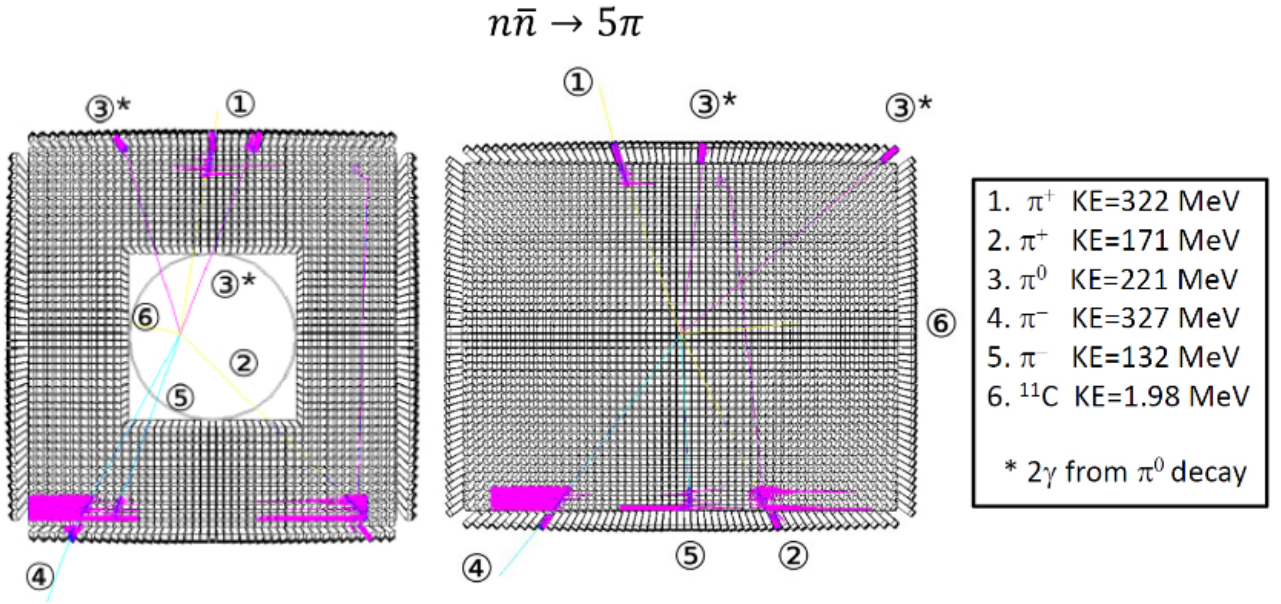


Silicon Trackers
2 layers
6 m length 6 m,
0.3 cm thickness

Vacuum tube
1 m inner radius
2 cm wall thickness
6 m tube length

GEANT4 Simulations

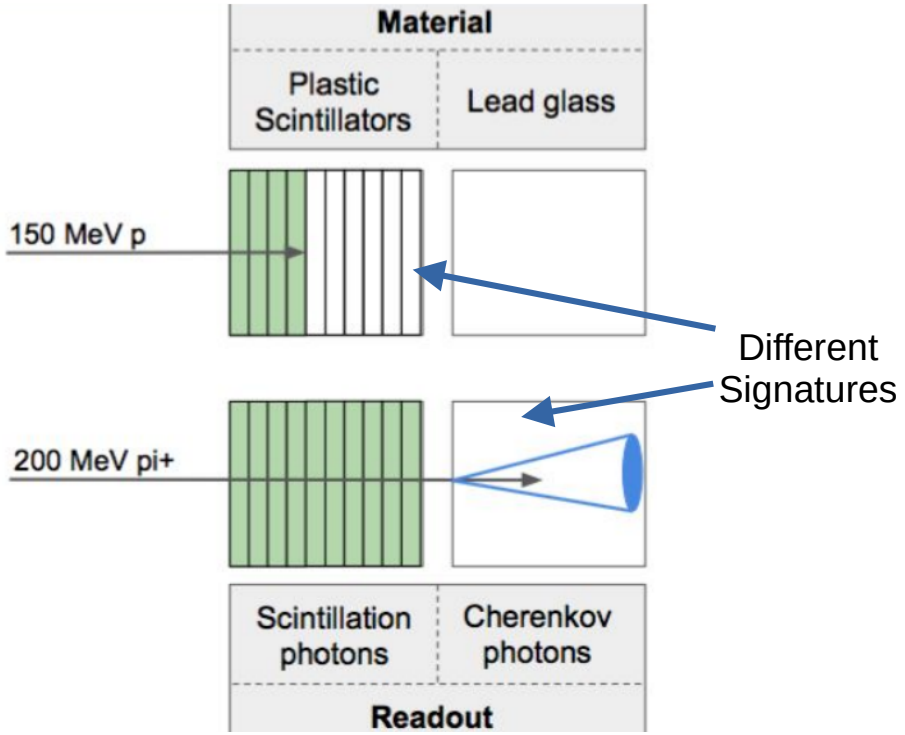
- Exhaustive simulations for the development of the detector (design, material geometry, optimization, cosmic background)
- Left:
  example for the annihilation process of an antineutron with ^{12}C in the target foil

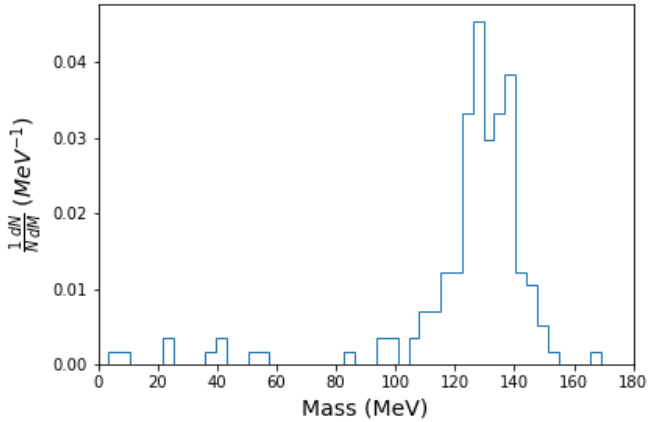


From
Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS
J. Barrow et al, EPJ Web Conf., vol. 251, p. 02062, 2021

Tracker and Calorimeter

- The time projection chambers (TPC) plays an important role in particle identification
- Discriminate pions from protons/muons
- Identification by measurement of the the continuous energy loss dE/dx .
- Components are concealed by an active cosmic muon shield made of scintillators and a passive enclosing overburden





Example: Simulated π^0 mass reconstruction in the calorimeter

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The NNBAR collaboration

- Broad international cooperation and support
- ~ 100 researcher from 50 institutes in 8 countries
- Interdisciplinary team that combine 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)

Collaborators are welcome !!

https://nnbar.eu

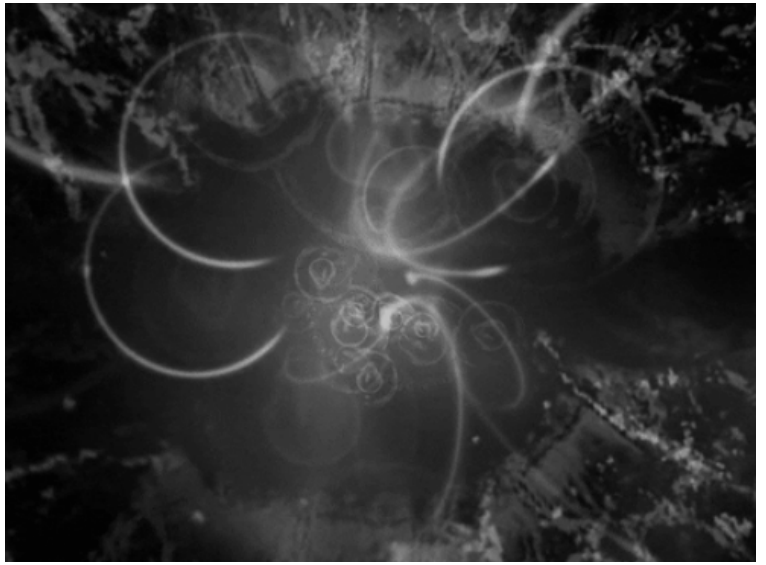
White Paper

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

Conclusion

- NNBAR experiment will tackle key open questions in modern physics:
  - the origin of matter-antimatter asymmetry and
  - the nature of the mysterious dark matter in the universe
- Contribution in course of the HighNESS project 2020-2023:
  - Design of the optimal moderator for NNBAR
  - Beam line layout
  - Reflector studies for neutron transport
  - Magnetic shielding and background simulations
  - Detector development and design optimization
  - Critical Design review for the full NNBAR experiment



- Prototype development and construction on-going
- Overall goal: Become the flagship experiment for fundamental physics at the ESS with 1000 times improved sensitivity on previous attempts