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The Search for Neutron – Antineutron Oscillations at the European Spallation Source

Richard Wagner, ILL - 21.10.2022
on behalf of the NNBAR collaboration

PSI2022, Villigen

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

Outline

- ESS/HighNESS
- NNBAR – Motivation
- Moderator
- Optics
- Magnetic Shielding
- Detector
- Conclusion

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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 a High Intensity Neutron Source at the European Spallation Source: The HighNESS project
V Santoro et al, 2022, https://doi.org/10.48550/arXiv.2204.04051

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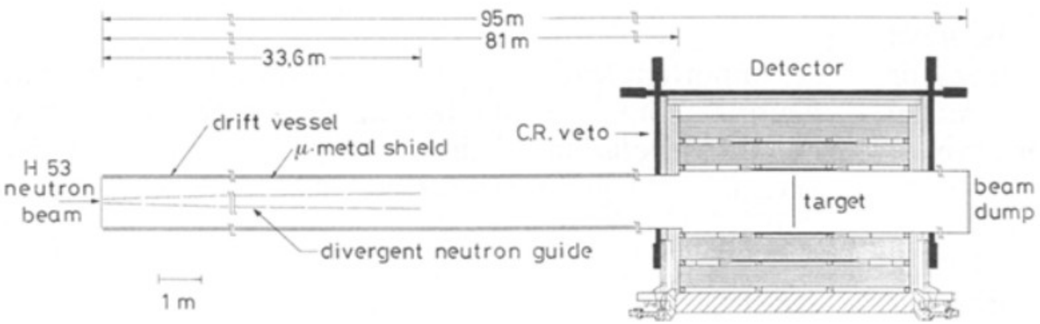
Motivation for NNBAR Experiment

- Baryon Number Violation (BNV) may be the key to the observed matter and antimatter asymmetry of baryogenesis
- BNV is a Sakharov condition and needed for theories of baryogenesis
- The process $n \rightarrow \bar{n}$ 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 to
- Fully utilize the high cold neutron intensities of the new LD_2 moderator
- Aim to improve 3 orders of magnitude compared to previous attempts

- Reference Experiment: 1991 at the ILL
- Holding the current Limit for free neutron-anti neutron oscillation time: $\tau > 0.86 \times 10^8$ s



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

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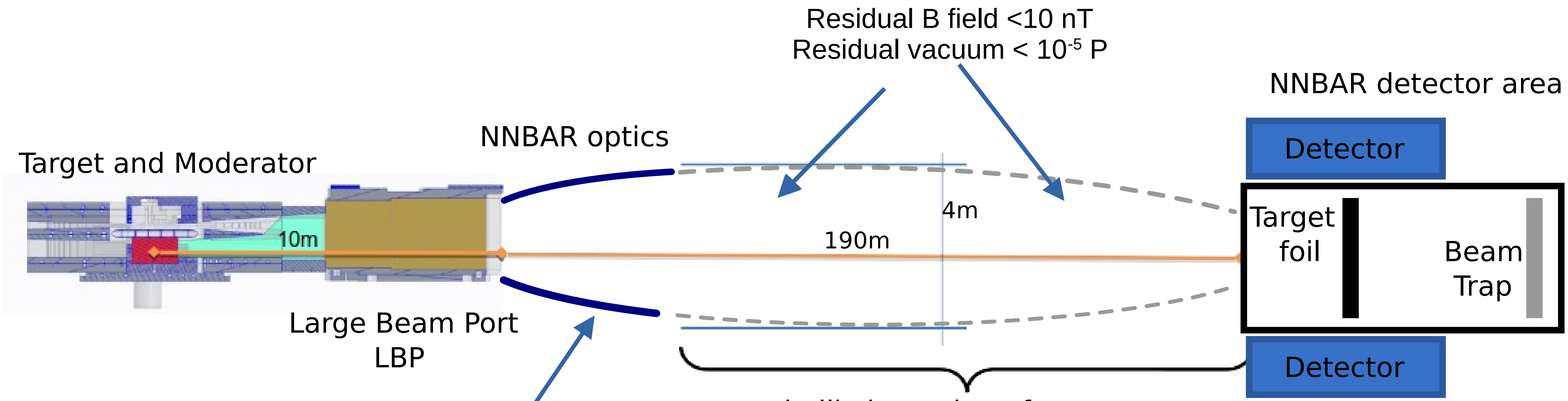
Schematics of ESS Experiment (not in scale)



ballistic motion of neutrons
free from perturbing
magnetic stray fields, interaction with walls
and ambient gas particles

Reflector Optics
collect large solid angle of emitted neutrons and re-focus to detector area

Transition probability
for quasi free condition

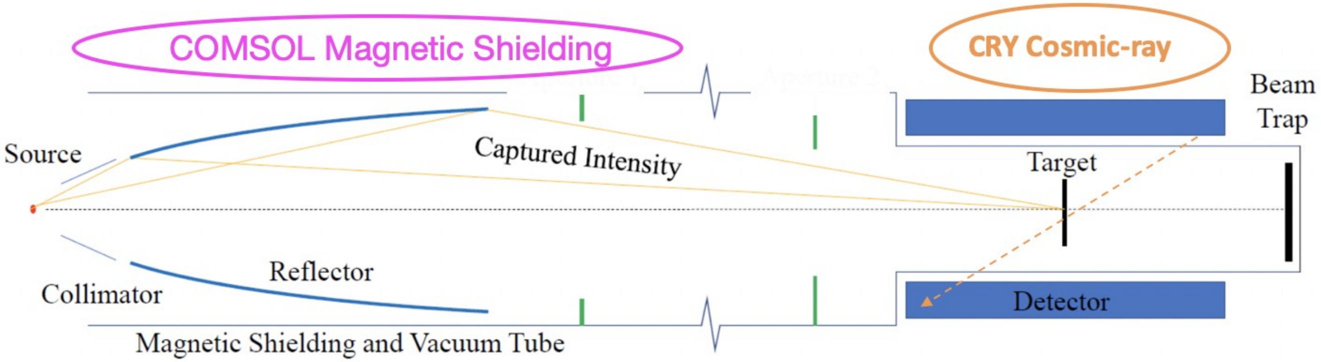
$$P_{n\bar{n}} = \left(\frac{t}{\tau}\right)^2$$

t … uninterrupted flight time
τ … free oscillation time

Monte Carlo Simulation Framework

Software environment set-up to predict neutron flux and backgrounds with

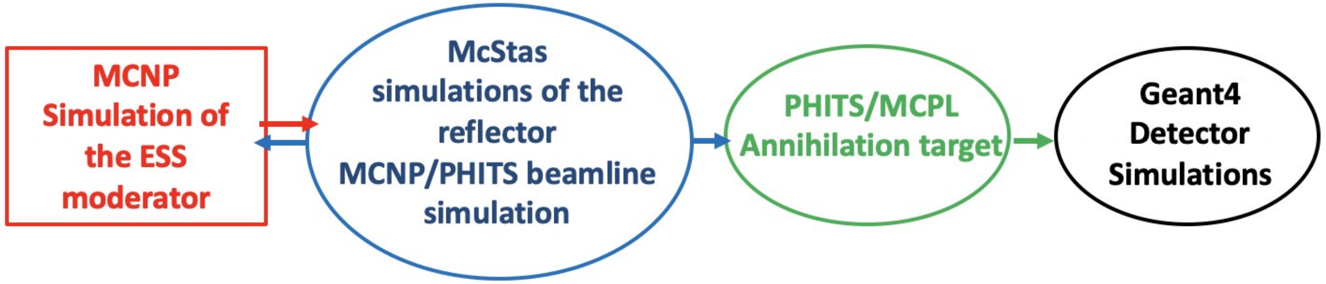
Interface between different tools:
MCPL File format (Monte Carlo Particle List)



A Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS

Joshua Barrow[10,11], *Gustaaf* Brooijmans[2], *José Ignacio Marquez* Damian[3], *Douglas* DiJulio[3], *Katherine* Dunne[4], *Elena* Golubeva[5], *Yuri* Kamyshkov[1], *Thomas* Kittelmann[3], *Esben* Klinkby[8], *Zsófi* Kókai[3], *Jan* Makkinje[2], *Bernhard* Meirose[4,6,*], *David* Milstead[4], *André* Nepomuceno[7], *Anders* Oskarsson[6], *Kemal* Ramic[3], *Nicola* Rizzi[8], *Valentina* Santoro[3], *Samuel* Silverstein[4], *Alan* Takibayev[3], *Richard* Wagner[9], *Sze-Chun* Yiu[4], *Luca* Zanini[3], and *Oliver* Zimmer[9]

EPJ Web of Conferences **251**, 02062 (2021)
CHEP 2021



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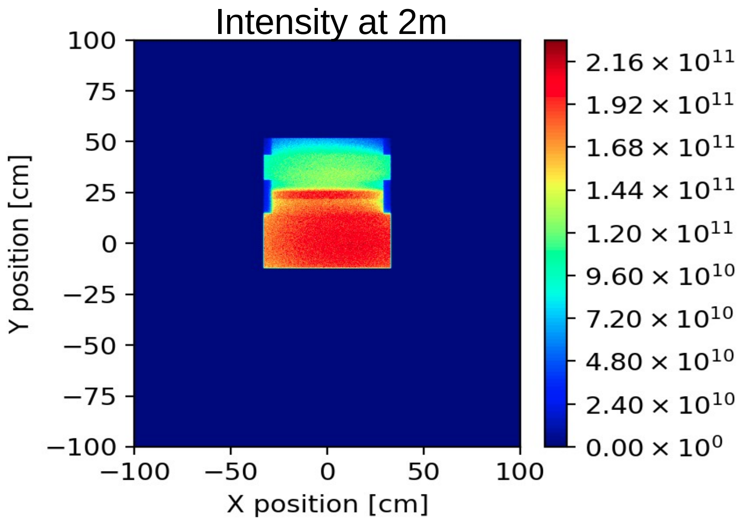
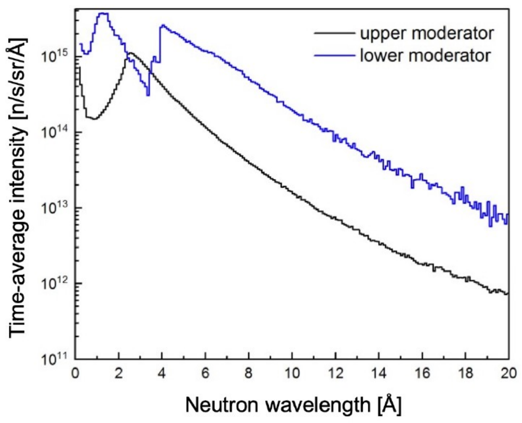
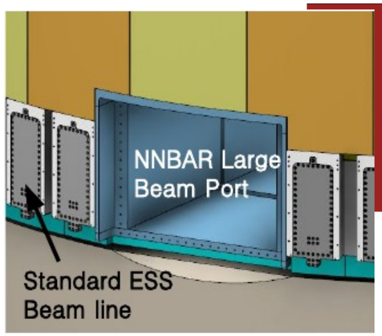
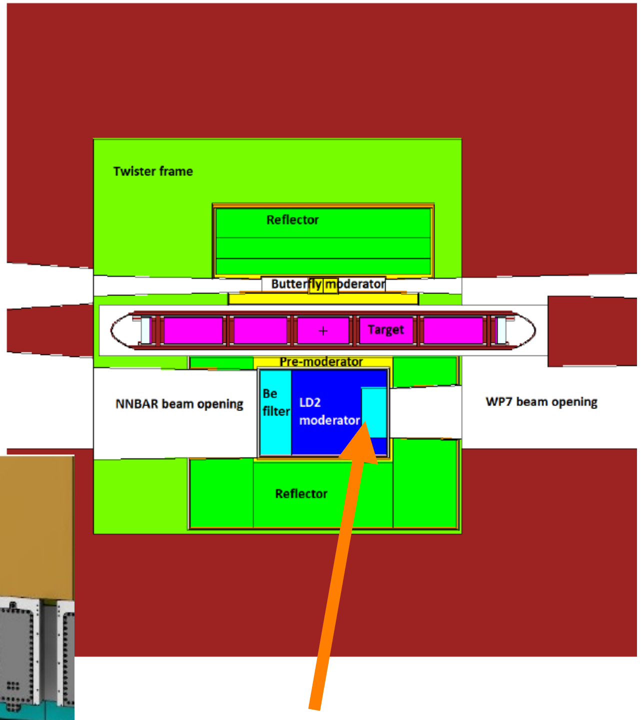
Moderator and Large Beam Port (LBP)

- 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









Moderator
24x45x47cm

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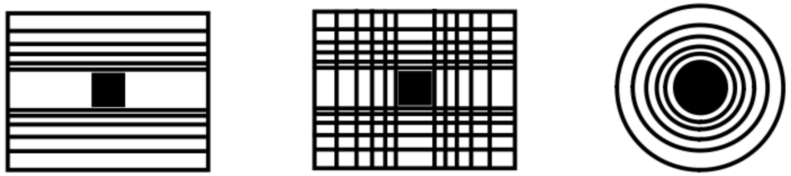
Optics I

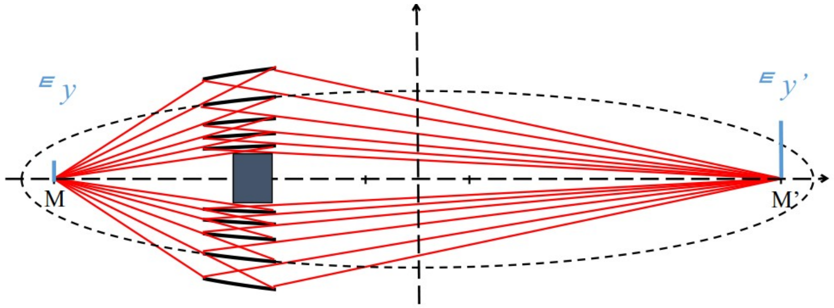
- Increasing length of experiment not sufficient
  (gain in flight time is compensated by loss in solid angle)

→ Focusing reflector in (compact) nested arrangement

- Elliptical mirrors (foci located in moderator and detector) in planar or cylindrical arrangement
- McStas Simulations to quantify of performance of the optical system
- Optical components for simulation are automatically generated from a developed Python Library



McStas



O.Zimmer, arXiv:1611.07353
Journal of Neutron Research 20 (2018) 91-98

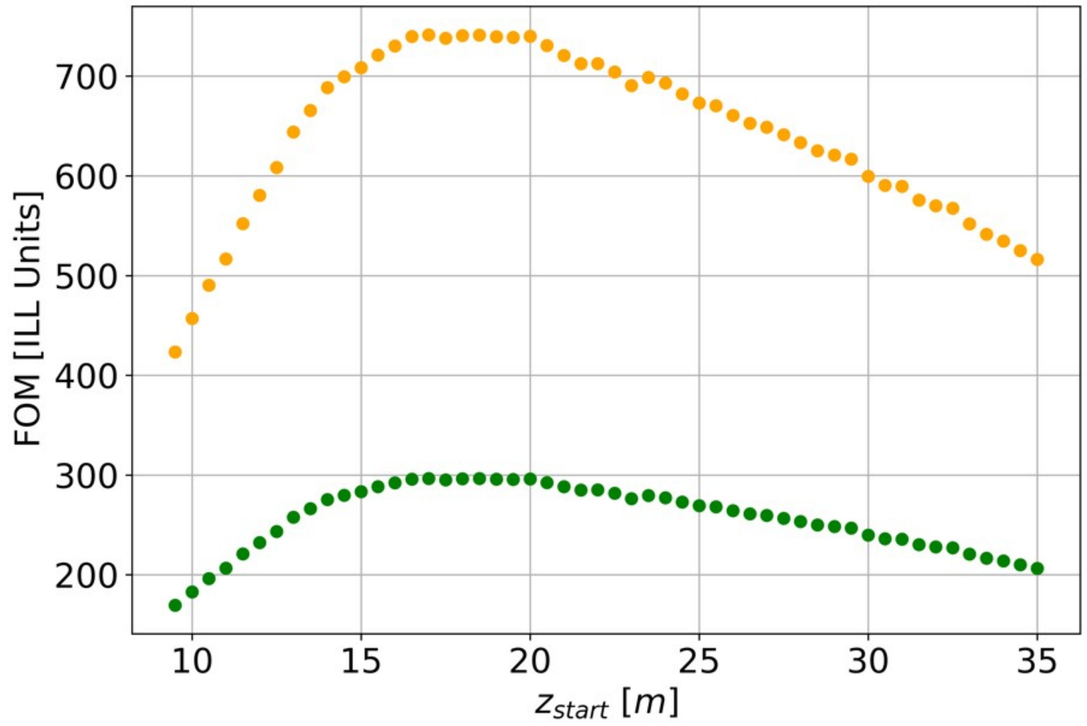
Figure of Merit (FOM)
Different optics are compared using the quantity:
Unit is 1991 experiment

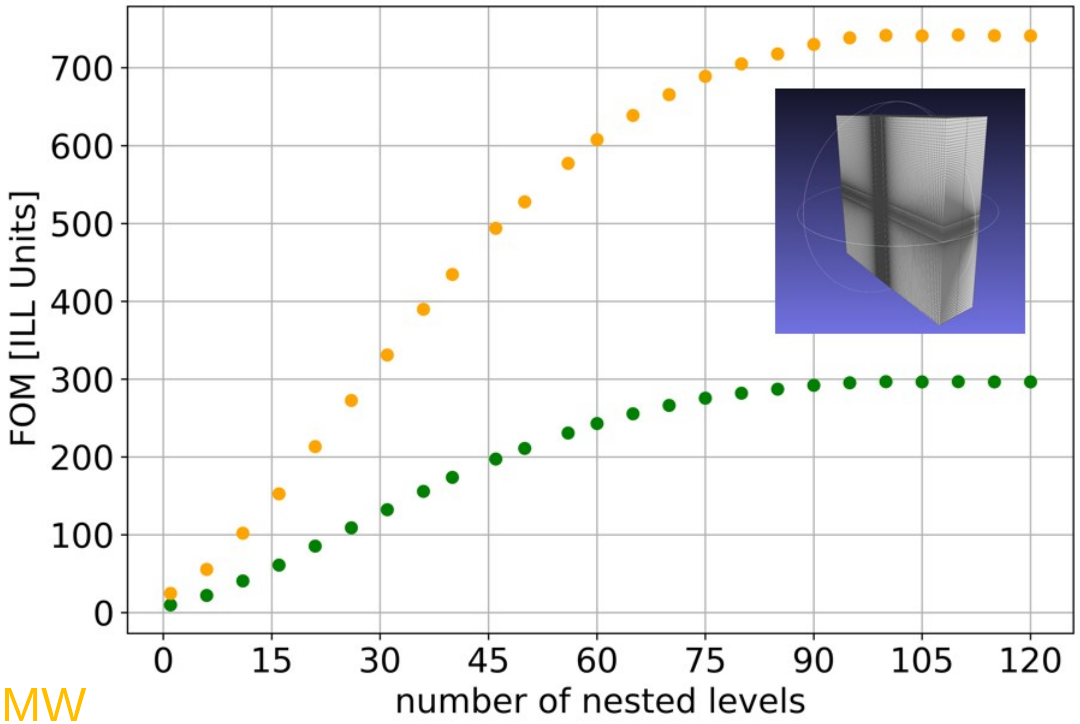
$$FOM = \sum_i \underbrace{N_i}_{\text{neutrons}} * \underbrace{t_i^2}_{\text{(uninterrupted) flight time}}$$

Optics II

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

Example: Simulations for a 1m long nested Reflector

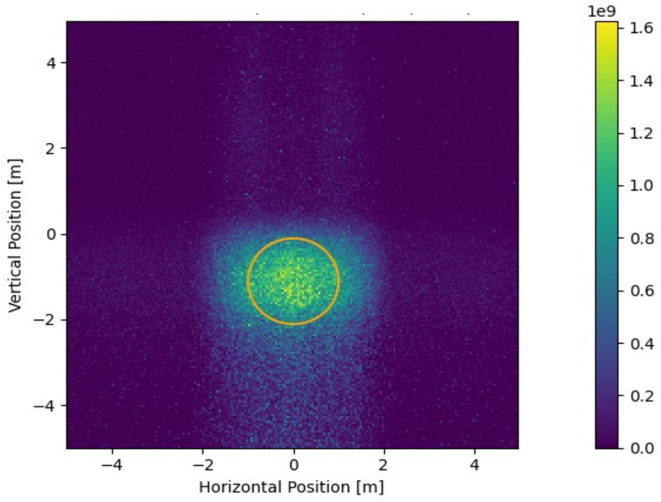




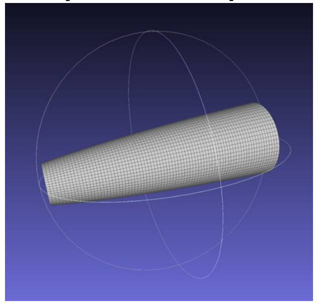
5 MW
2 MW

Optics III

Example: Simulations for a 10m Nested Reflector

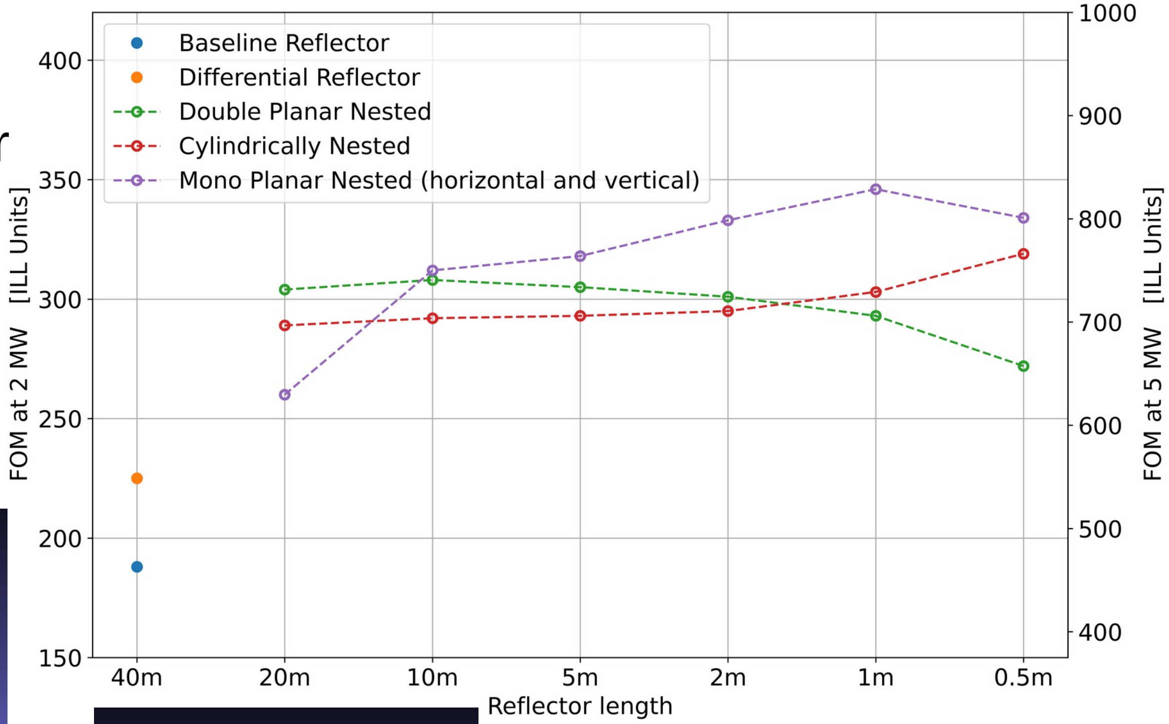


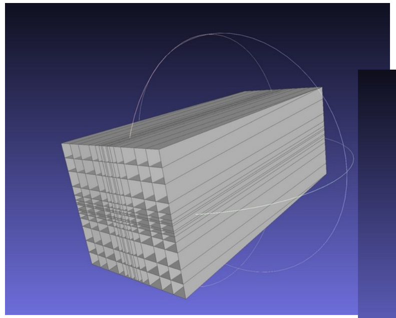
40m single layer (baseline)

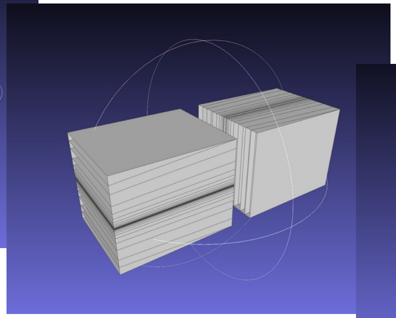


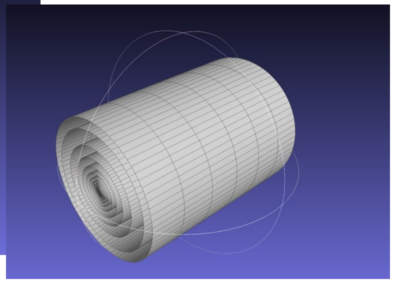
FOM: 308 (nested levels=13, 2 MW)

Collected results for different reflector systems









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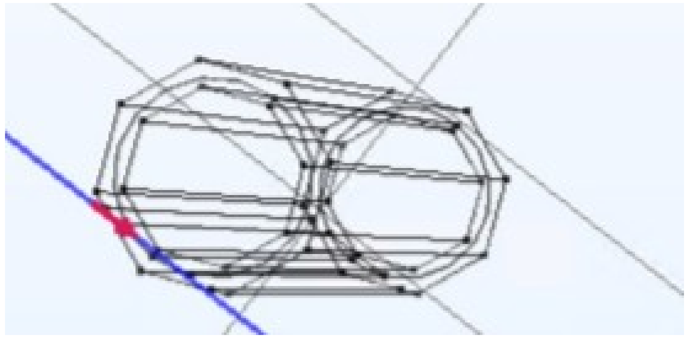
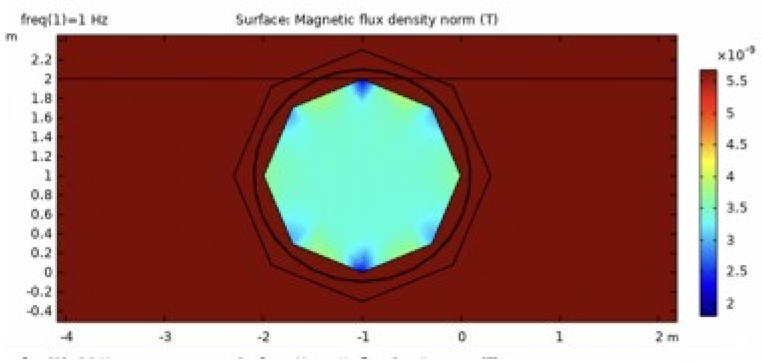
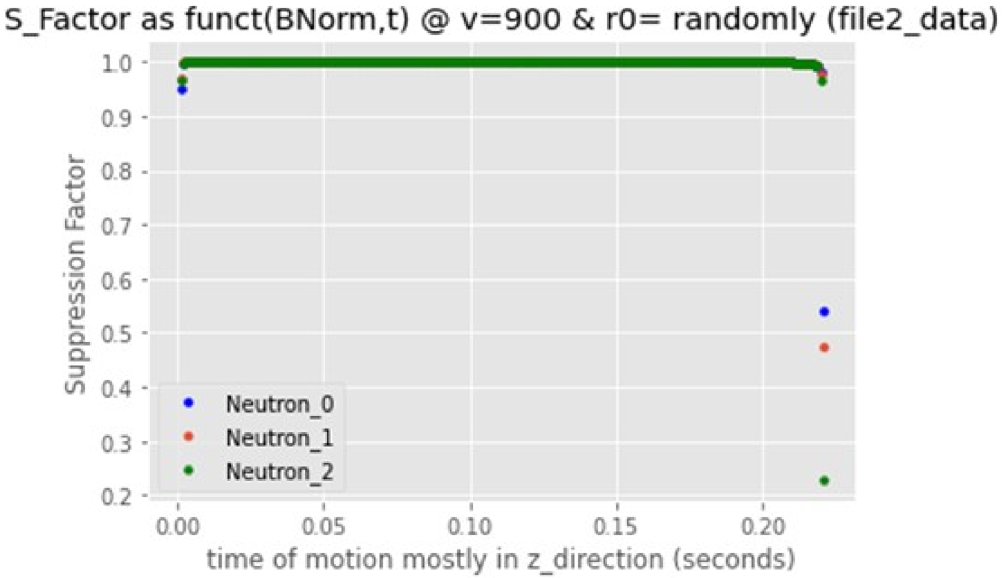
Magnetic shielding





- Shield geometry
  - Outer + inner octagon shield from mu-metal
  - Round steel vacuum chamber: between shields
  - COMSOL simulations
- <10 nT
- Monte Carlo study of inefficiency due to finite magnetic field with field map



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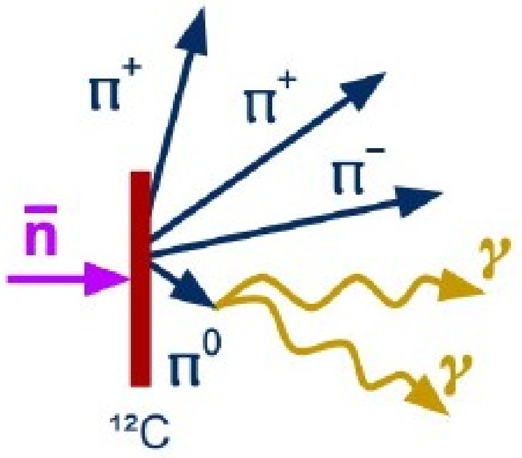
Detector Design

- 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
- Requirements for the Detector
  - Reconstruction of multi-pion final state
  - Invariant mass reconstruction
  - Particle identification
  - Timing sensitivity to reject cosmics and other out-of-time backgrounds



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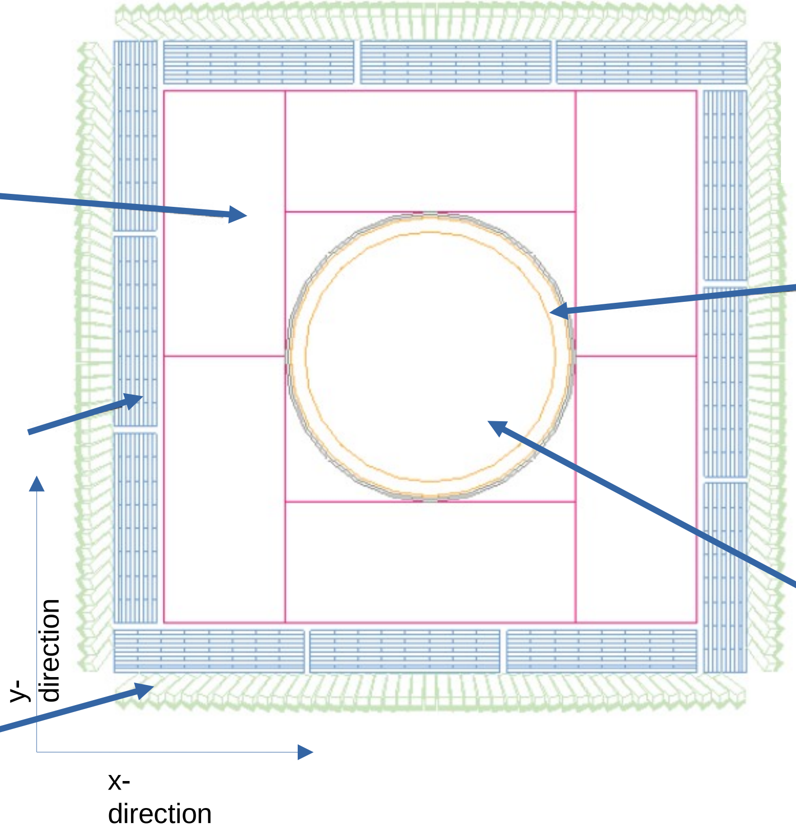
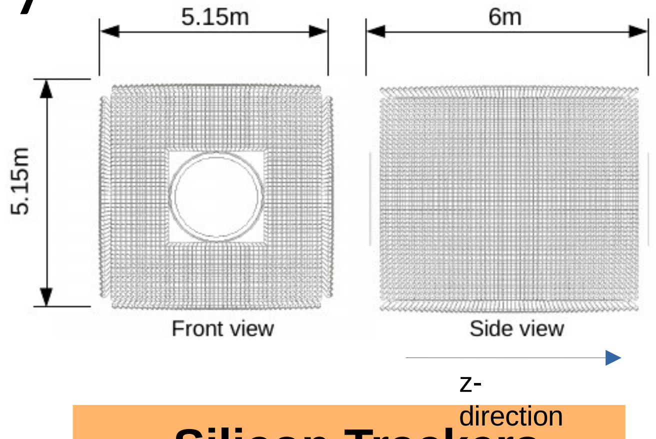
NNBAR Annihilation Detector – Box Geometry

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





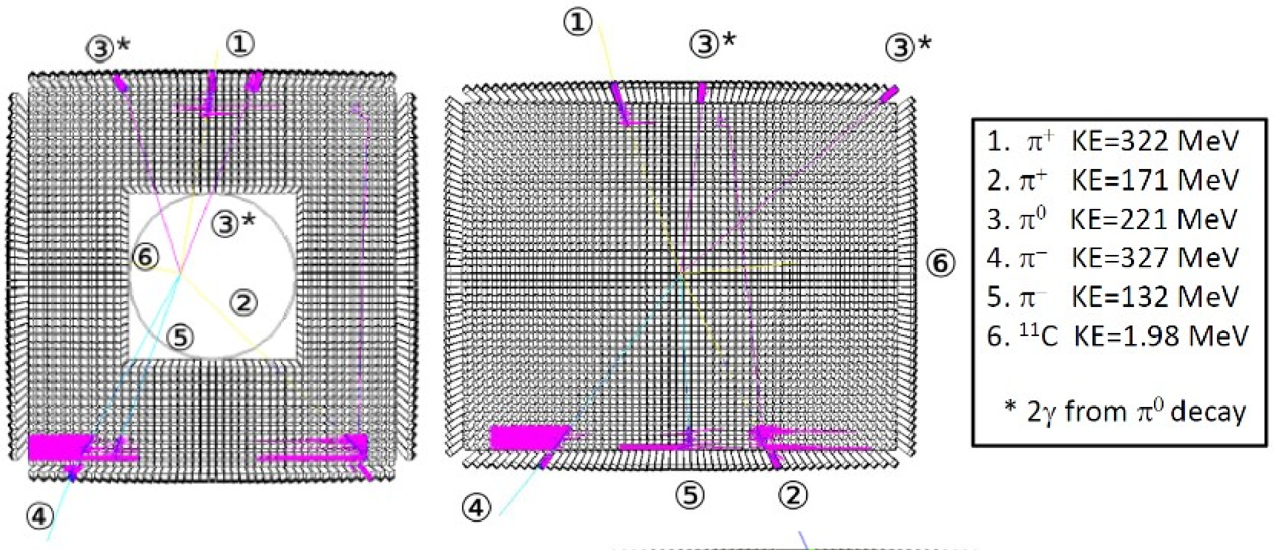
Silicon Trackers
2 layers
6m length
0.3 cm thickness

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

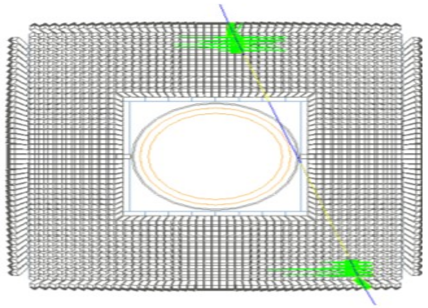
GEANT4 Simulations

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

$n\bar{n} \rightarrow 5\pi$



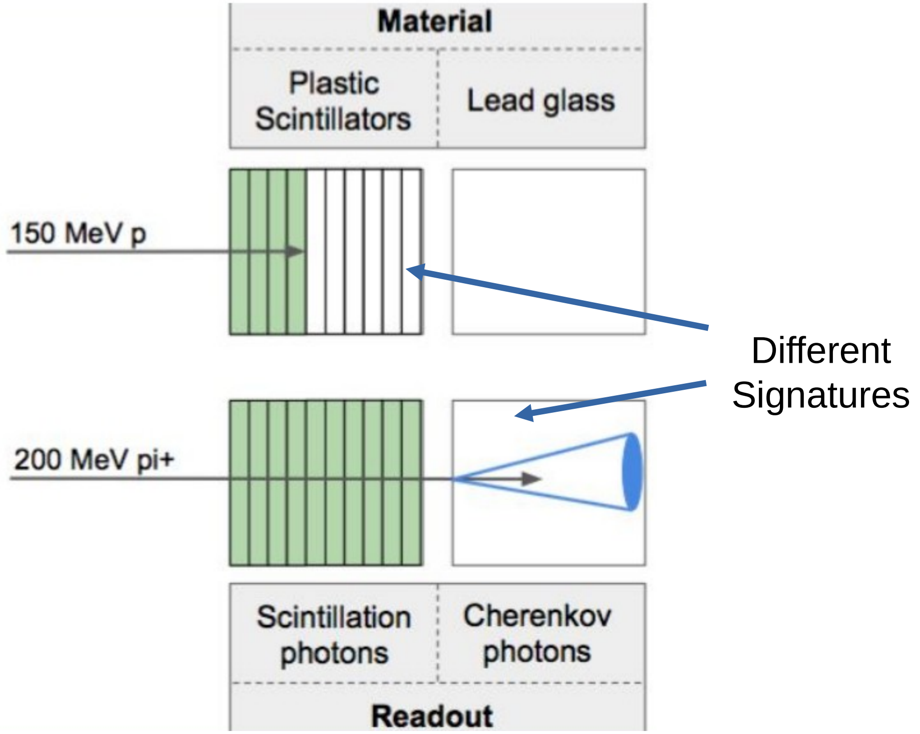
Cosmic muon background

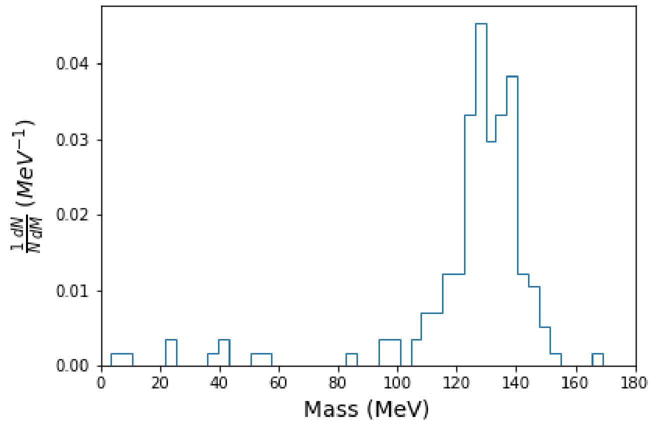


From
Computing and Detector Simulation Framework for the HIBEAM/NNBAR Experimental Program at the ESS
J. Barrow et al, EPJ Web Conf., vol. 251, p. 02062, 2021

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

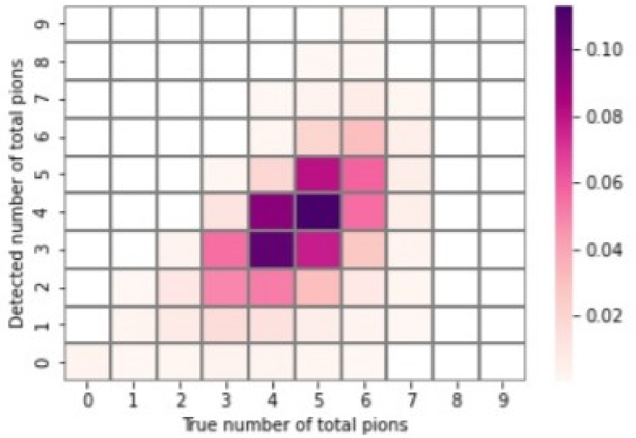


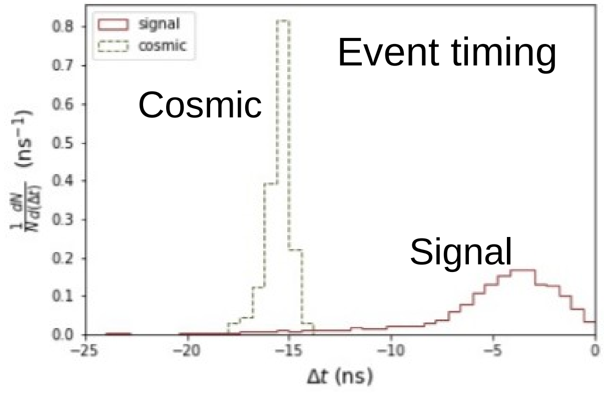


Example: Simulated π^0 mass reconstruction in the calorimeter

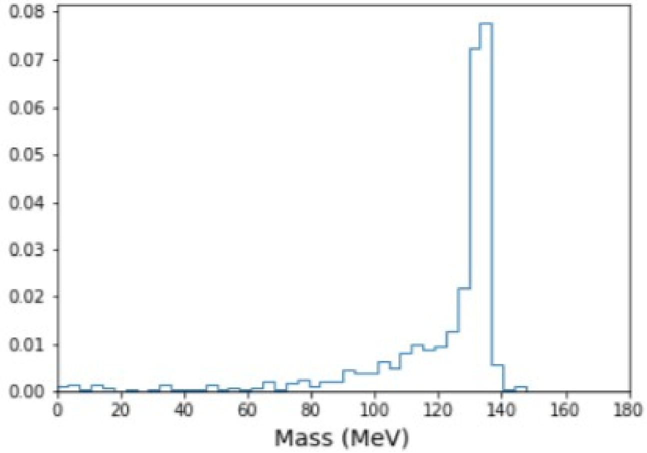
Detector simulation

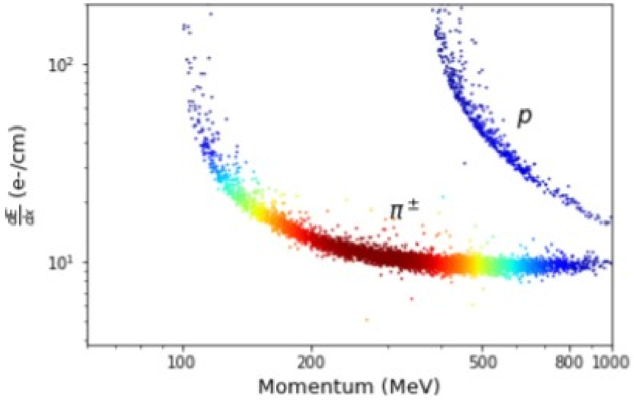
Pion multiplicity

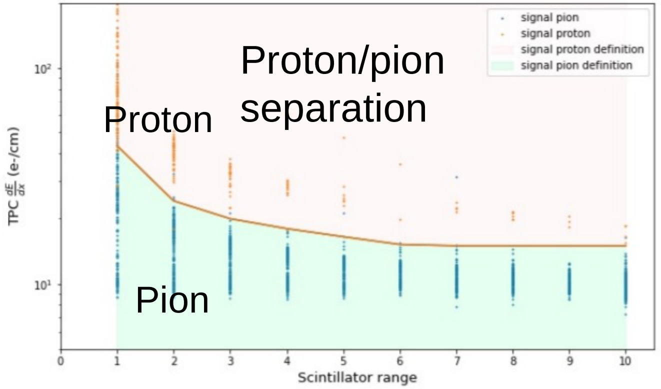


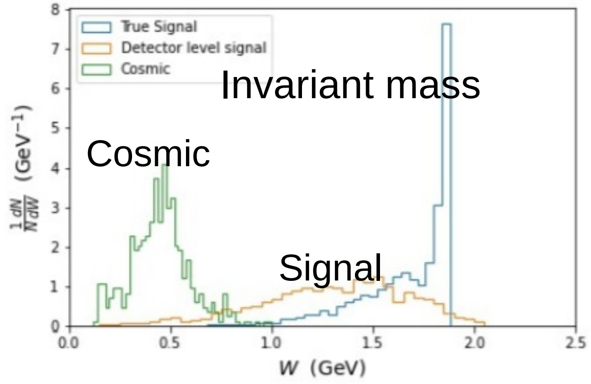


π^0 mass reconstruction



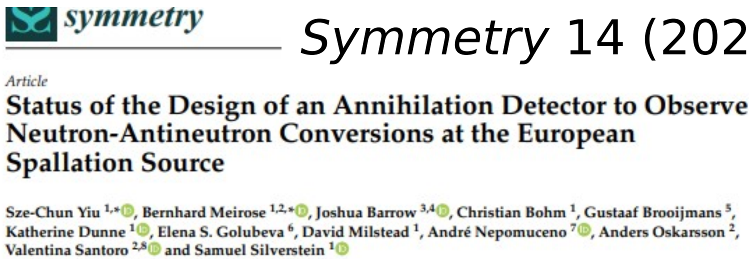






Geant 4 model designed and reproducing well expected distributions

Symmetry 14 (2022) 1, 76


symmetry

Article

Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source

Sze-Chun Yiu [1,*], Bernhard Meirose [1,2,*], Joshua Barrow [3,4], Christian Bohm [1], Gustaaf Brooijmans [5], Katherine Dunne [1], Elena S. Golubeva [6], David Milstead [1], André Nepomuceno [7], Anders Oskarsson [2], Valentina Santoro [2,8] and Samuel Silverstein [1]

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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 !!

NNBAR

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

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arXiv > physics > arXiv:2209.09011

Physics > Instrumentation and Detectors

[Submitted on 19 Sep 2022]

The Development of the NNBAR Experiment

F. Backman, J. Barrow, Y. Beßler, A. Bianchi, C. Bohm, G. Brooijmans, L. J. Broussard, H. Calen, J. Cederkäll, J. I. M. Damian, E. Dian, D. D. Di Julio, K. Dunne, L. Eklund, M. J. Ferreir
M. Holl, T. Johansson, Y. Kamyshkov, E. Klinkby, R. Kolevatov, A. Kupsc, B. Meirose, D. Milstead, A. Nepomuceno, T. Nilsson, A. Oskarsson, H. Perrey, K. Ramic, B. Rataj, N. Rizzi, V. S
Takibayev, R. Wagner, M. Wolke, S.C. Yiu, A. R. Young, L. Zanini, O. Zimmer

The NNBAR experiment for the European Spallation Source will search for free neutrons converting to antineutrons with a sensitivity improvement of three orders of magnitude compared to the last such search. Thi
conceptual design report for NNBAR. The design of a moderator, neutron reflector, beamline, shielding and annihilation detector is reported. The simulations used form part of a model which will be used for optimisa
quantification of its sensitivity.

Comments: 30 pages, 26 figures, accepted for publication in Journal of Instrumentation (JINST)

Thank you for your attention!

Credits: Sze Chun Yiu, Kathie Dunne, Jonathan Collin, Gautier Daviau, Matthias Holl, Bernhard Meirose, Valentina Santoro, David Milstead, Peter Fierlinger, Nicola Rizzi, Luca Zanini, Oliver Zimmer

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Additional Slides

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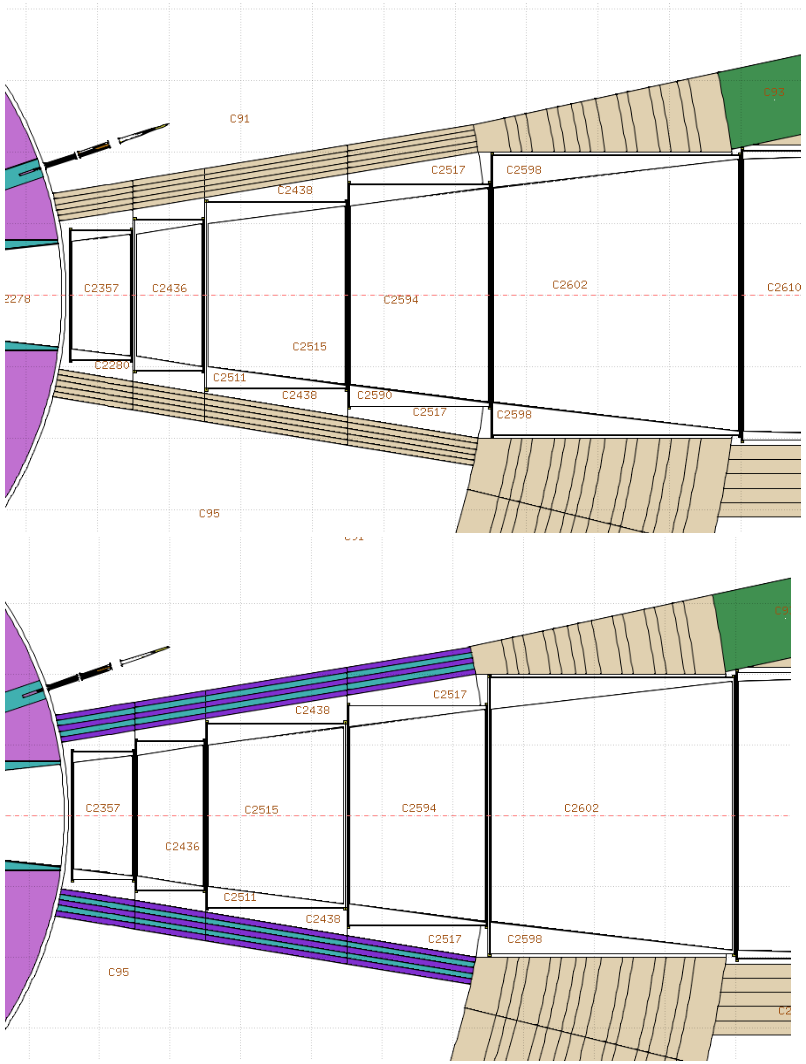
Radiation Shielding (in Bunker)

- Unshielded LBP would cause background dose of ≳100 Sv/h
- Needs to be reduced to ~1 Sv/h
- MCNP 6 calculations
- Beamline model created in CombLayer (https://github.com/SAnsell/CombLayer)
- Two materials investigated:
  - Heavy concrete
  - Layers of regular concrete/steel

Steel
Concrete
Heavy Concrete



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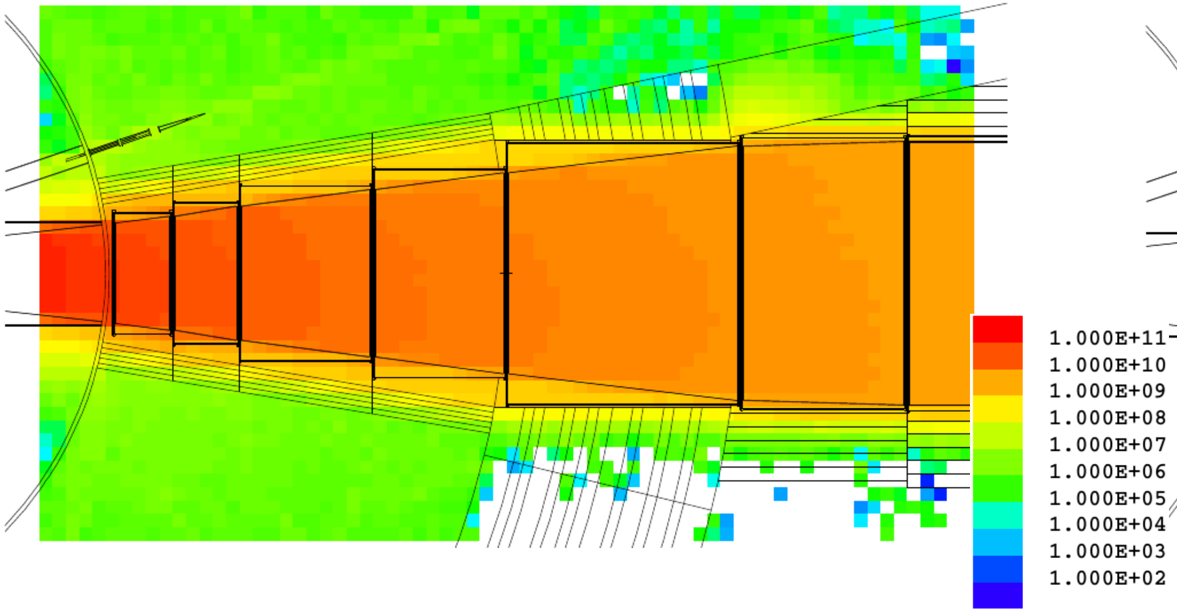
Radiation Shielding (in Bunker)

- First results look promising
- Work is ongoing

Heavy concrete



Concrete + Steel

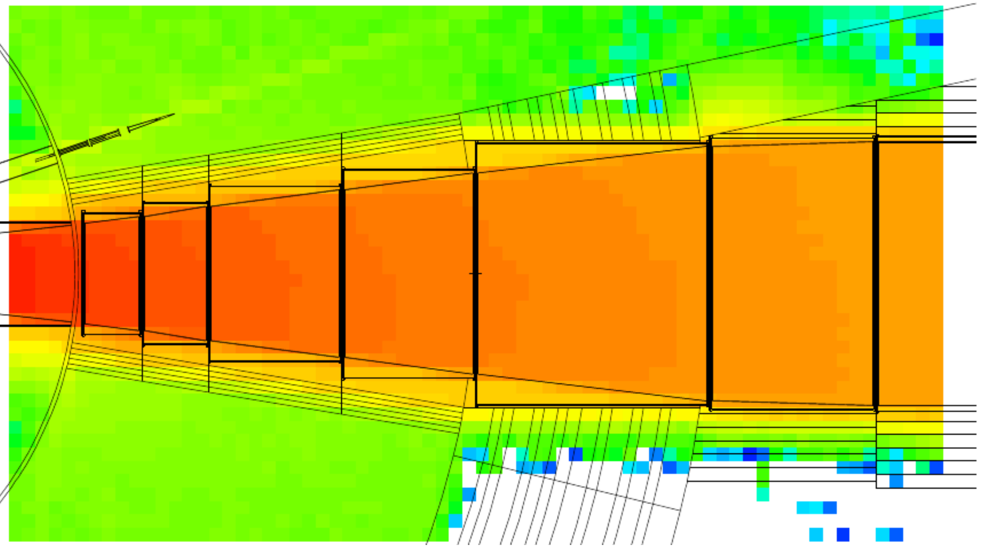


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Figure of Merit (FOM)

$$FOM = \sum_i \overbrace{N_i}^{\text{neutrons}} * \overbrace{t_i^2}^{\text{(uninterrupted) flight time}} / \underbrace{(4 \times 10^9)}$$

$$\underbrace{(1.5 \times 10^9)}_{\text{Intensity ILL experiment}} \times \underbrace{\frac{6600}{5000}}_{\text{Ratio operating hours per year ILL/ESS}} \times \overbrace{2}^{\text{Detector efficiency (50\%)}}$$

Different optics are compared using this quantity