The NNBAR Experiment: A Search for Free Neutron–Antineutron Oscillations

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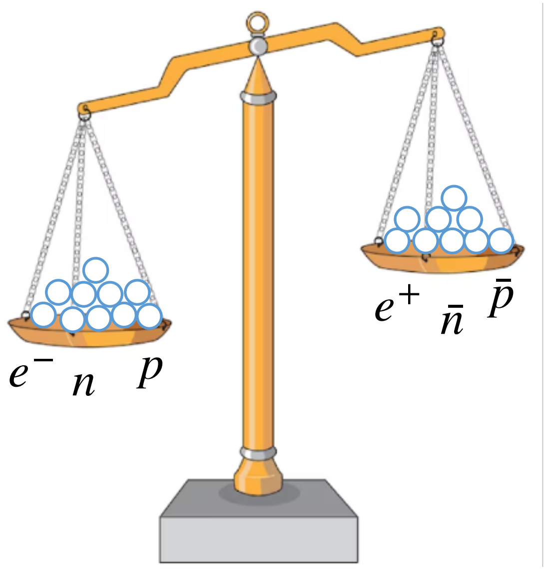
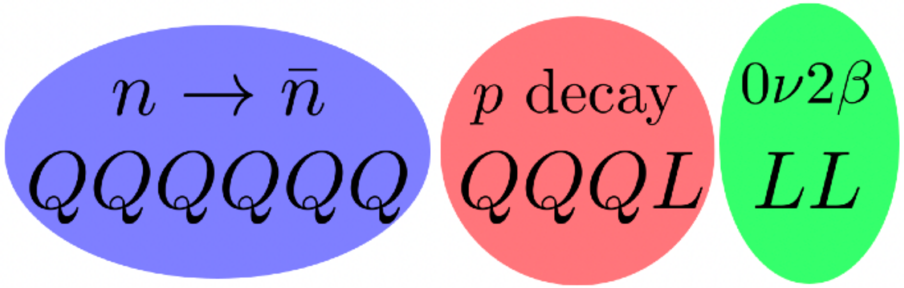
Why baryon number violation?

- Baryon number is an accidental symmetry of the SM, not protected by a gauge force.



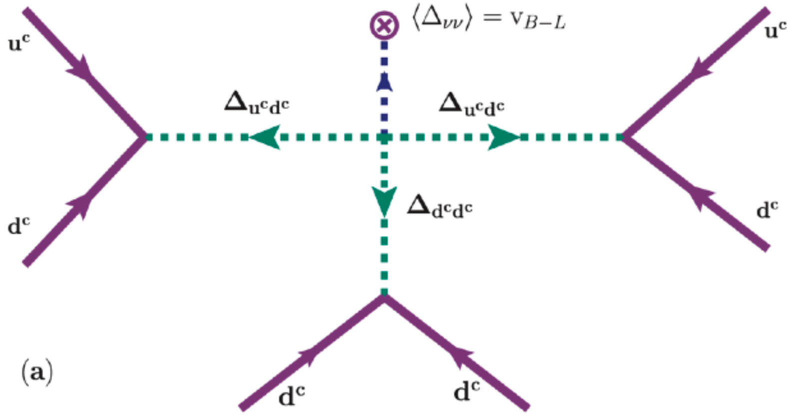
- One of the Sakharov conditions necessary for generation of matter-antimatter asymmetry.

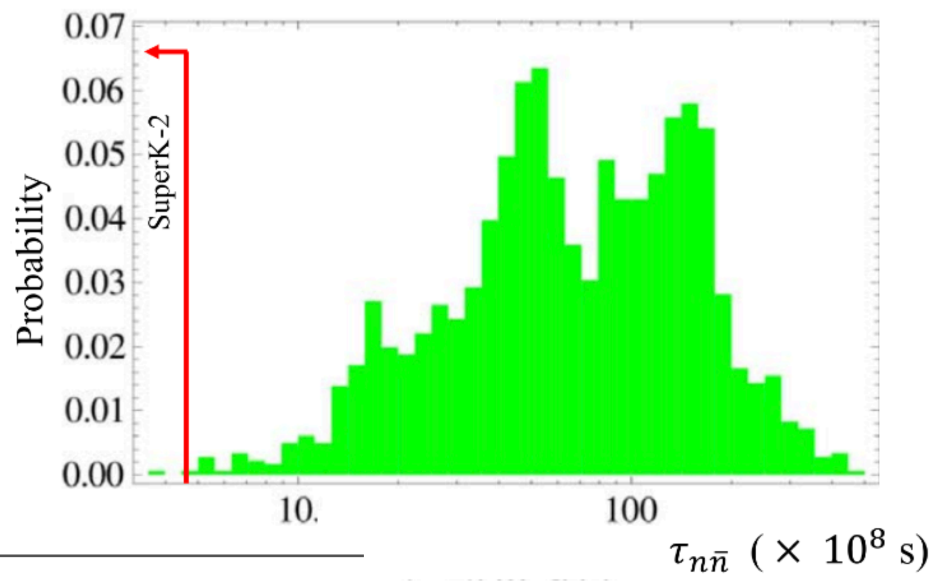
- SM already predicts (tiny) BNV via electroweak sphalerons, conserving $\mathscr{B} - \mathscr{L}$ but violating $\mathscr{B} + \mathscr{L}$.



Why free neutron-antineutron oscillations?

- Clean $\Delta B = 2$ channel, free from nuclear model uncertainties.
- Can be described by dimension-9 operator $\mathcal{O}_{n\to\bar{n}} \propto (udd)^2/\Lambda^5$ where $\Lambda \sim$ PeV scale. Beyond the sensitivity reach of current or planned colliders.
- Feature in models of post-sphaleron baryogenesis, R-parity violating supersymmetry, extra-dimensional models, …





Further reading: D.G. Phillips II *et al*. *Phys. Rep*. **612**:1 (2016).
Figure (top): Patra & Primita. *EPJ C*. **74**:3078 (2014).
Figure (bottom): K. S. Babu *et al*. *Phys. Rev. D* **87**:115019 (2013).

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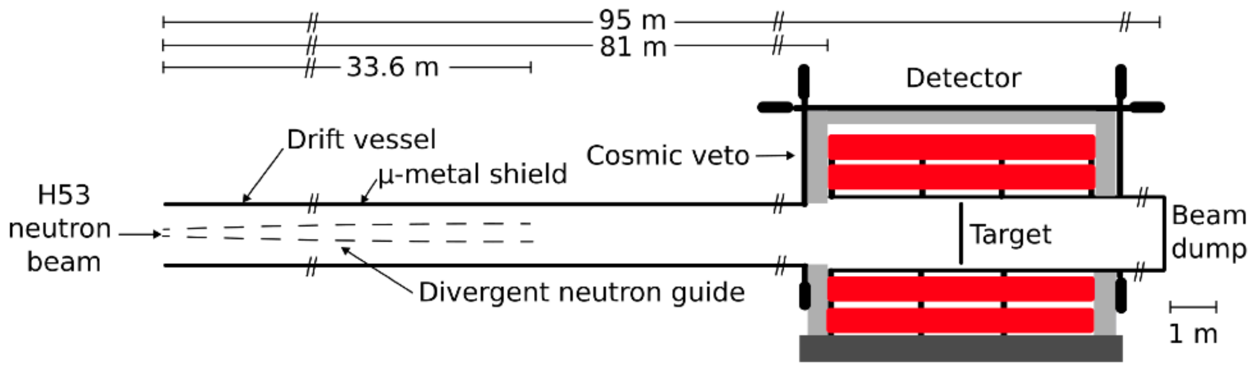
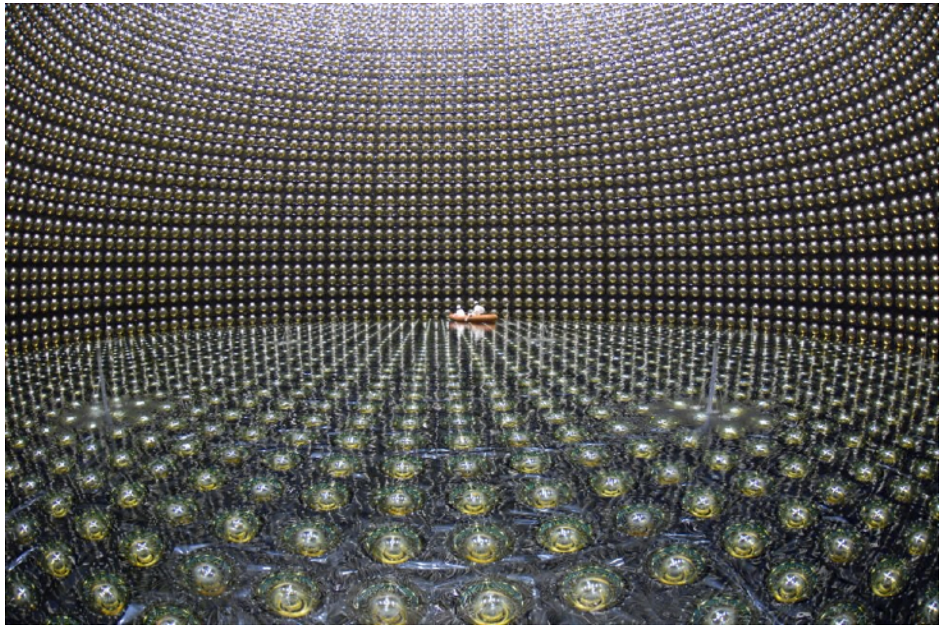
Status of previous searches

- ILL experiment (1990)[1]: Last free neutron oscillation search, $\tau_{n\bar{n}} = 8.6 \times 10^7$ s at 90% CL.

- Searches with bound neutrons in large-mass detectors: $\tau_{\text{nucl}} = R\tau_{n\bar{n}}^2$ where R is a nucleus-dependent parameter.

- Most competitive limits from ^{16}O at Super-Kamiokande[2] with $\tau_{n\bar{n}} = 4.7 \times 10^8$ s.





1. M. Baldo-Ceolin *et al. Z. Phys. C* **63**:409 (1994).
2. K. Abe *et al. Phys. Rev. D* **103**:012008 (2021).

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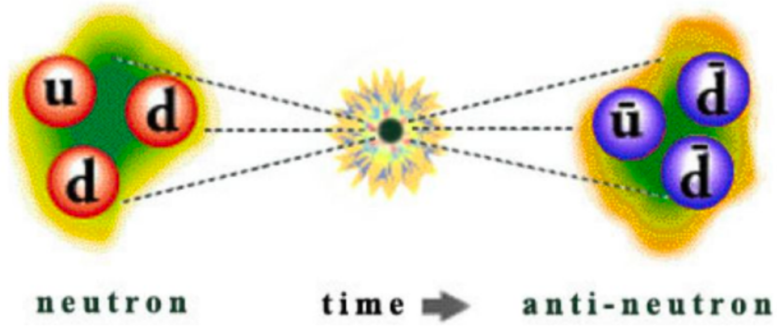
Quantum mechanical formalism

- Consider a Hamiltonian in the $\{|n\rangle, |\bar{n}\rangle\}$ basis:

$$\hat{H} \leftrightarrow \begin{pmatrix} E_n & \alpha \\ \alpha & E_{\bar{n}} \end{pmatrix}.$$



- Diagonalising gives:

$$P(n \to \bar{n}) = \frac{\alpha^2}{(\Delta E/2)^2 + \alpha^2} \sin^2\left(\sqrt{(\Delta E/2)^2 + \alpha^2}\, t/\hbar\right).$$

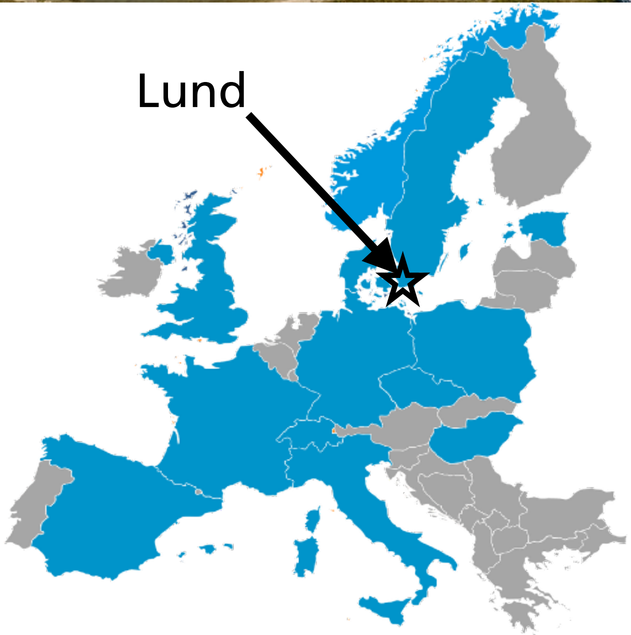
- Assume $\Delta E \cdot t$ small (quasi-free regime). Then:

$$P(n \to \bar{n}) \approx \left(\frac{\alpha \cdot t}{\hbar}\right)^2.$$

- Conclusion: $\mathrm{FOM} = Nt^2$. We need a high flux of low-energy neutrons in a long, magnetically shielded beamline.

European Spallation Source

- The world's brightest spallation neutron source under construction in Lund, Sweden.
- 13 European member states, construction cost of about ~$3B.
- Beam on target in March 2026, full user program in 2027.
- Currently 15 neutron beamlines approved for construction, no particle physics yet approved!



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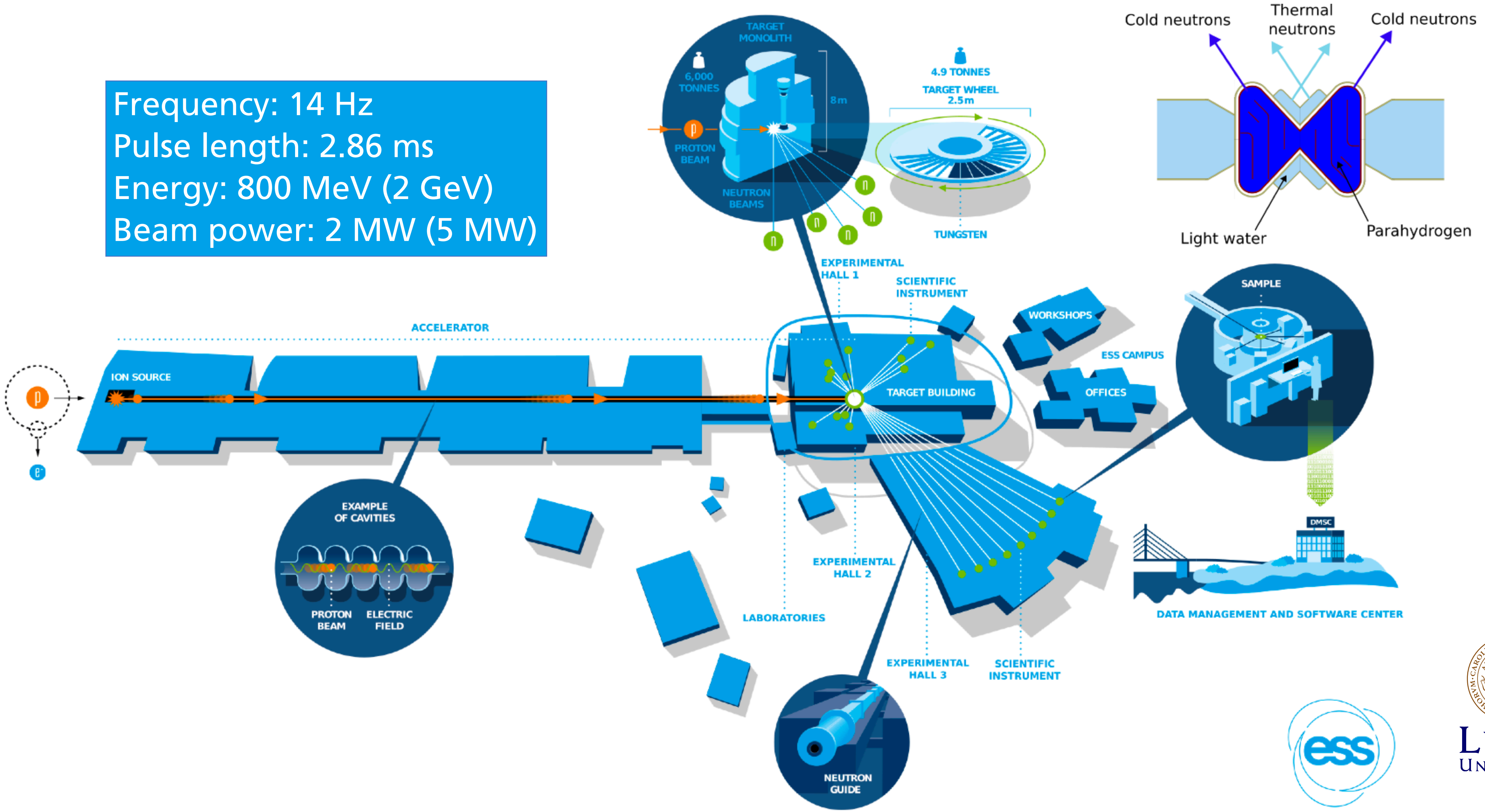
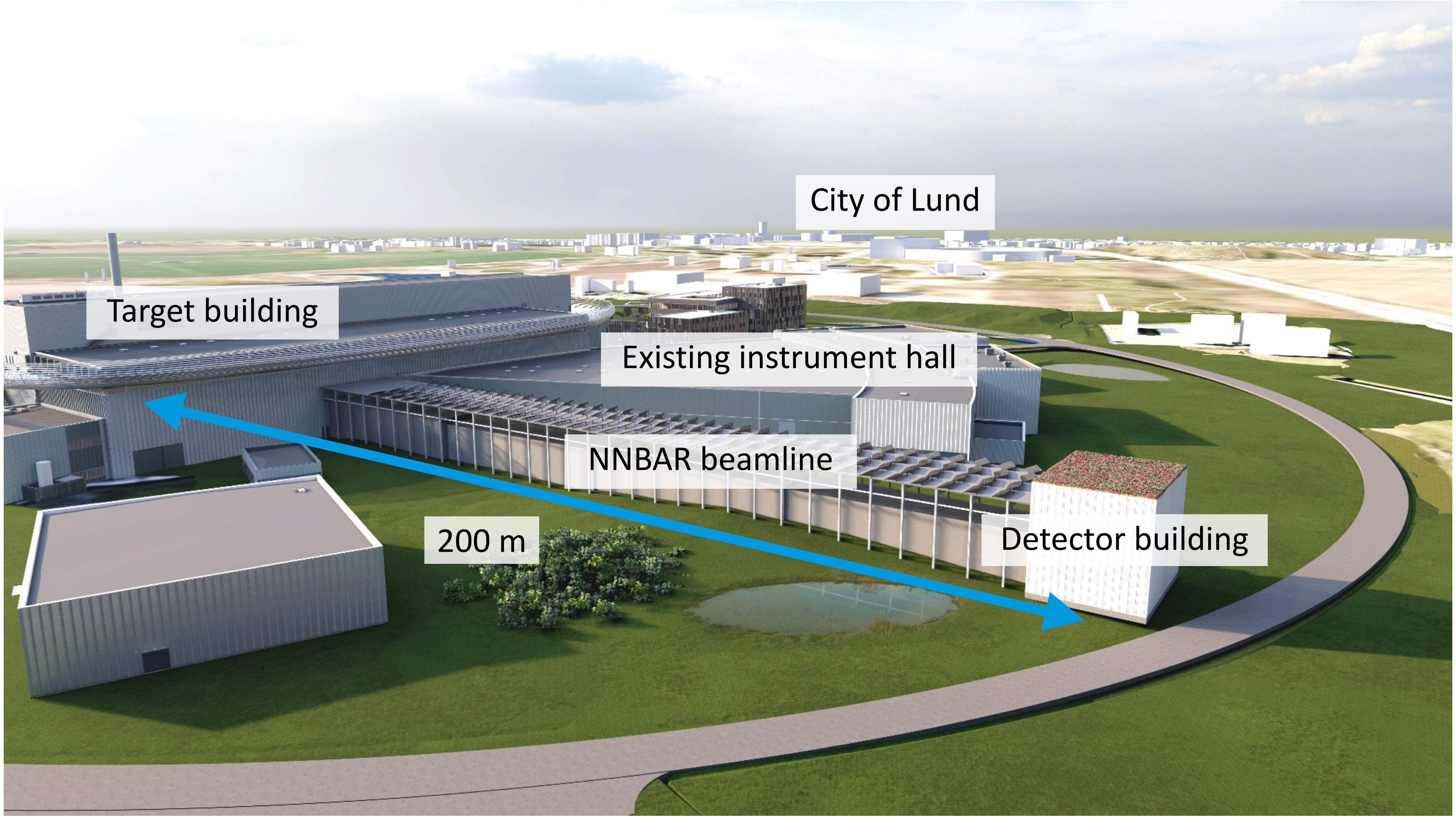
European Spallation Source overview

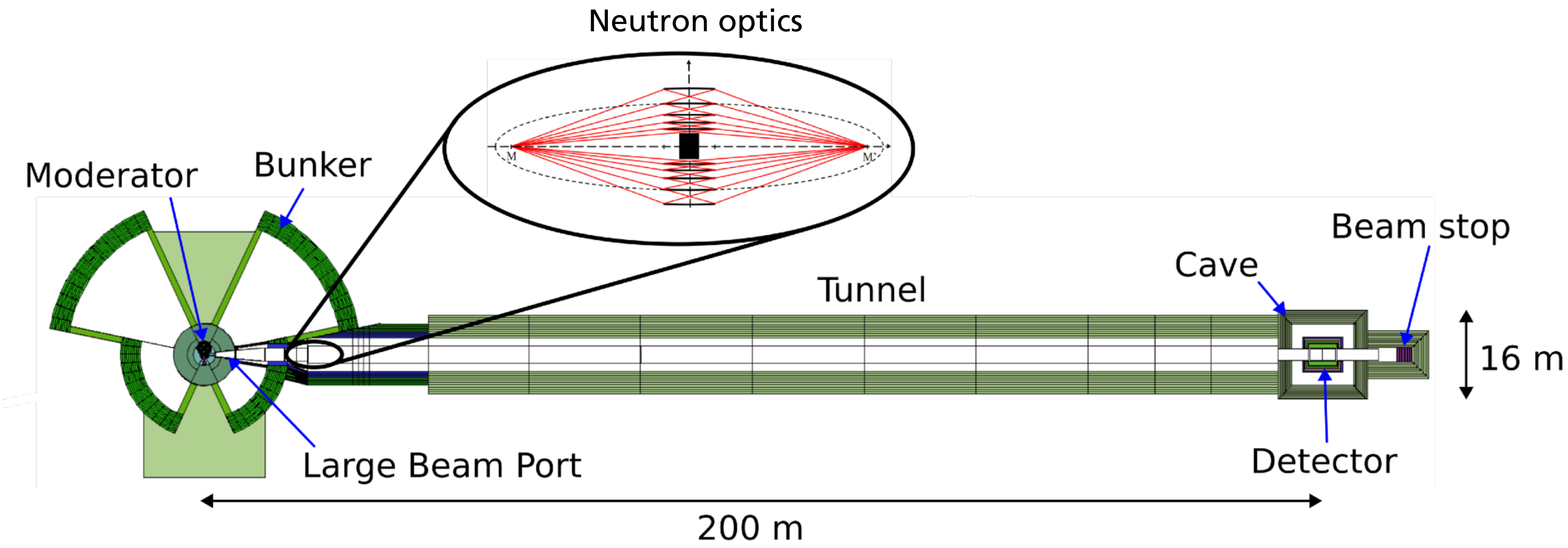
Frequency: 14 Hz
Pulse length: 2.86 ms
Energy: 800 MeV (2 GeV)
Beam power: 2 MW (5 MW)



Outside view of NNBAR



NNBAR beamline at a glance

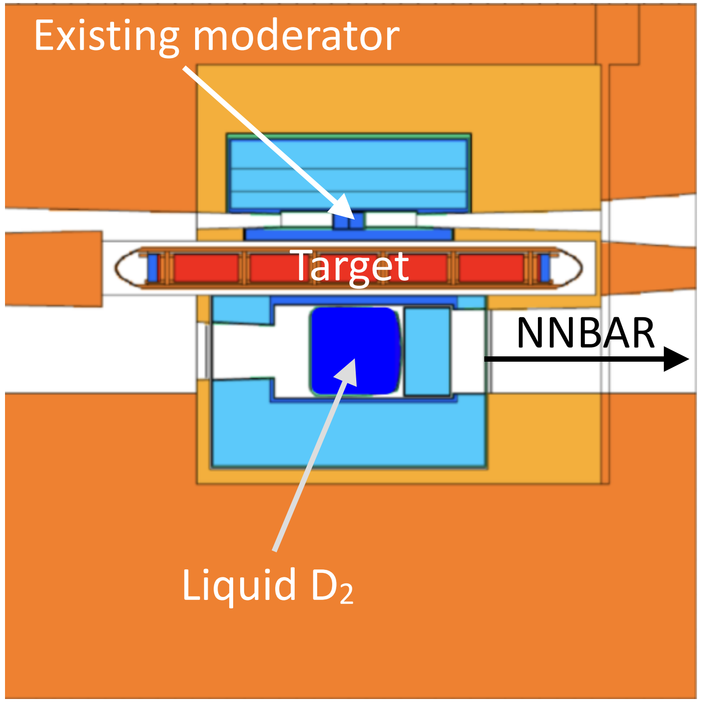


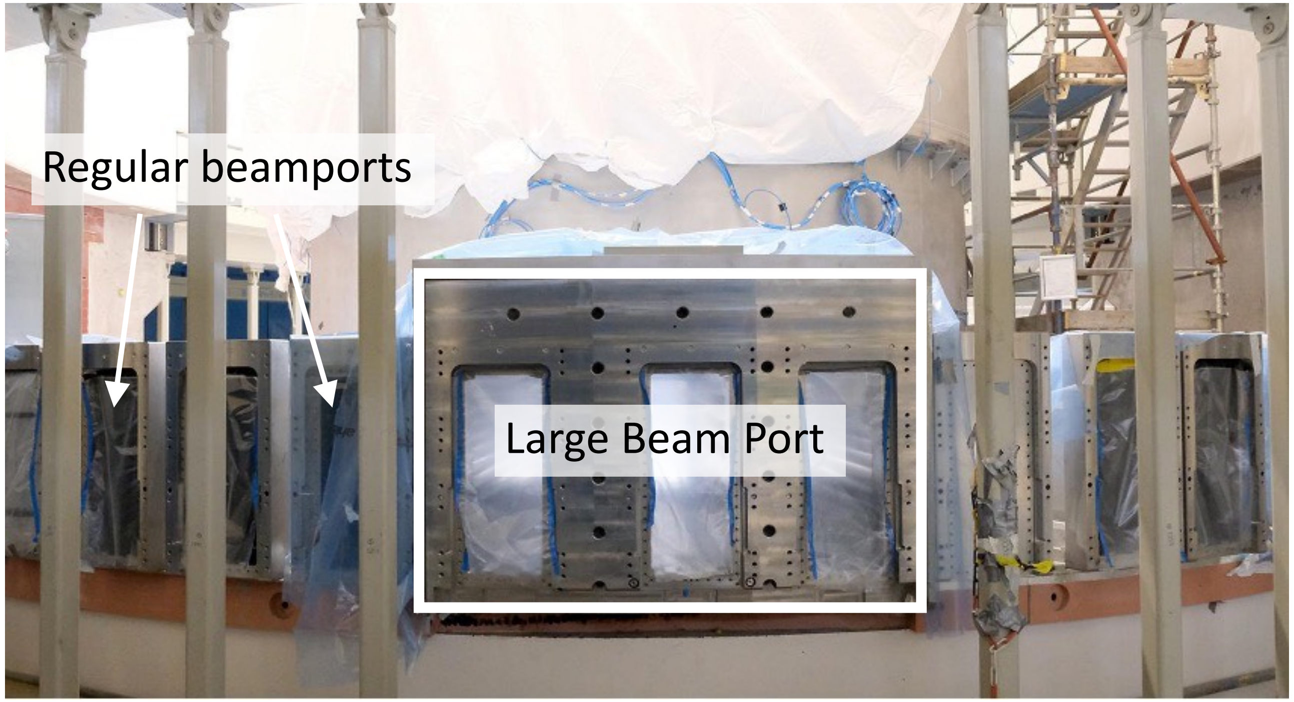
Further reading: V. Santoro *et al*. *JNR* **25**(3-4):315 (2024).

Preparing ESS for NNBAR

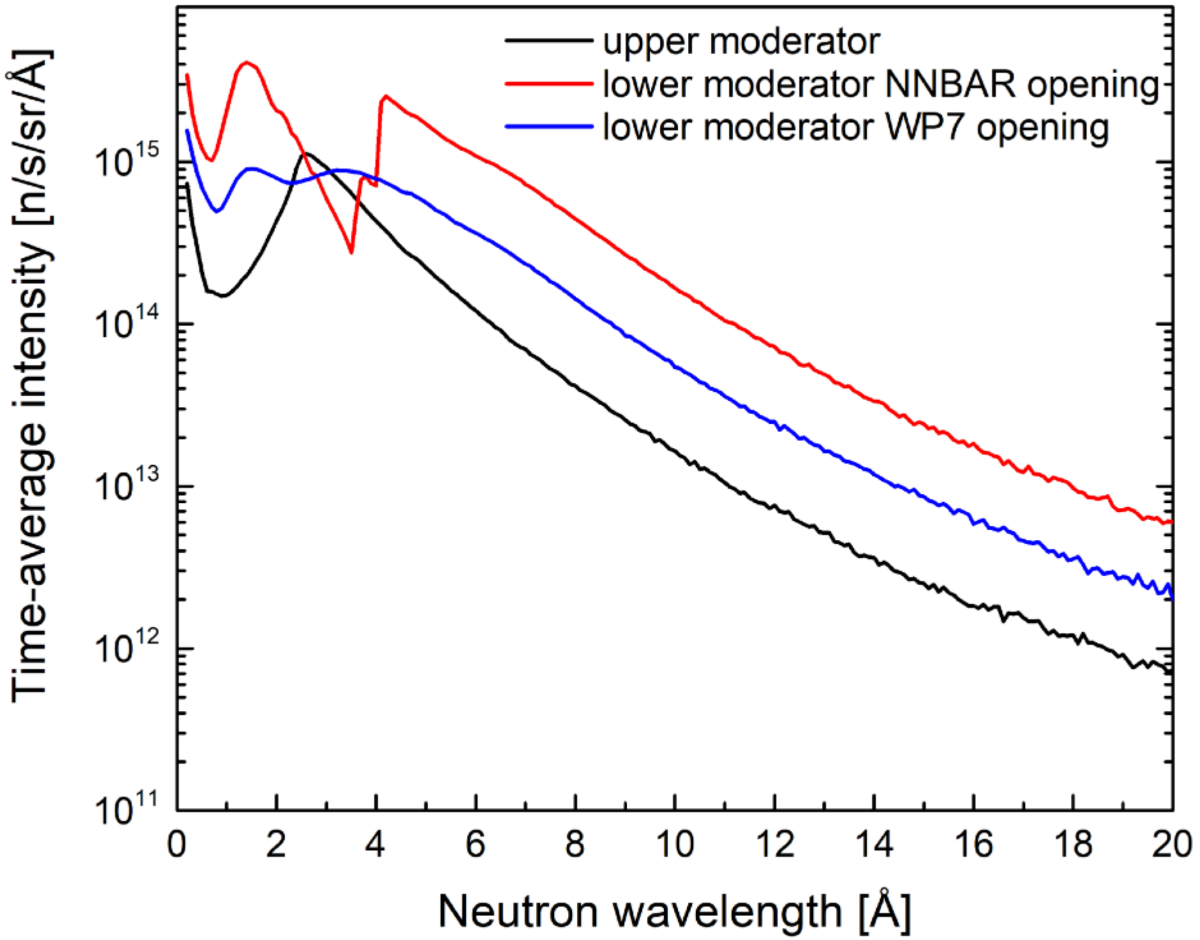
- Figure of merit scales as Nt^2, want high-intensity of cold neutrons with long flight path.

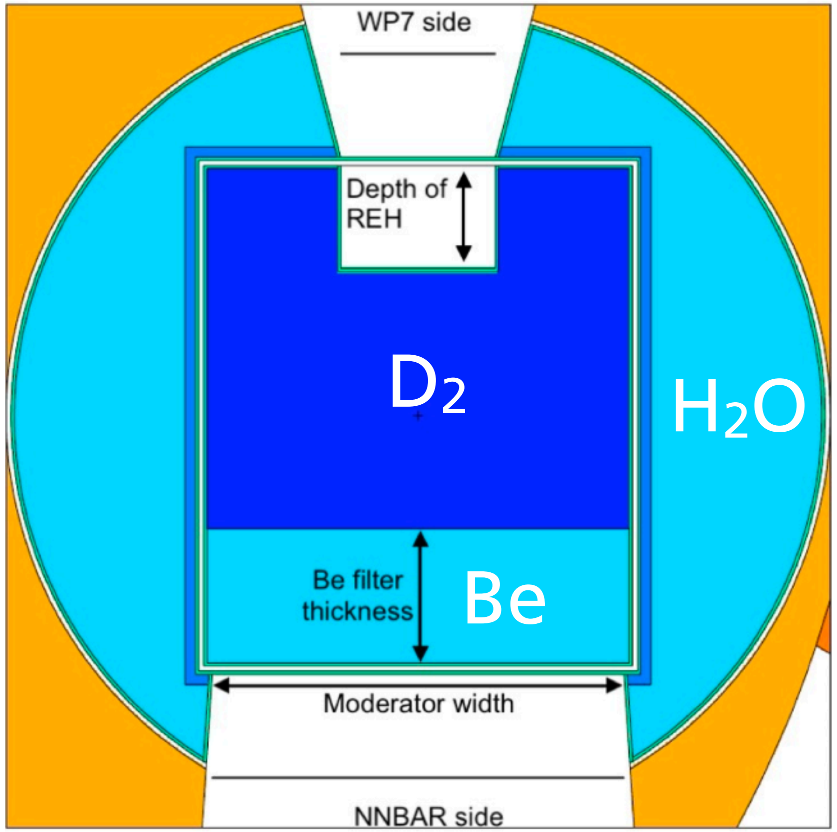
- Use new LD_2 moderator below the ESS target and the Large Beam Port.





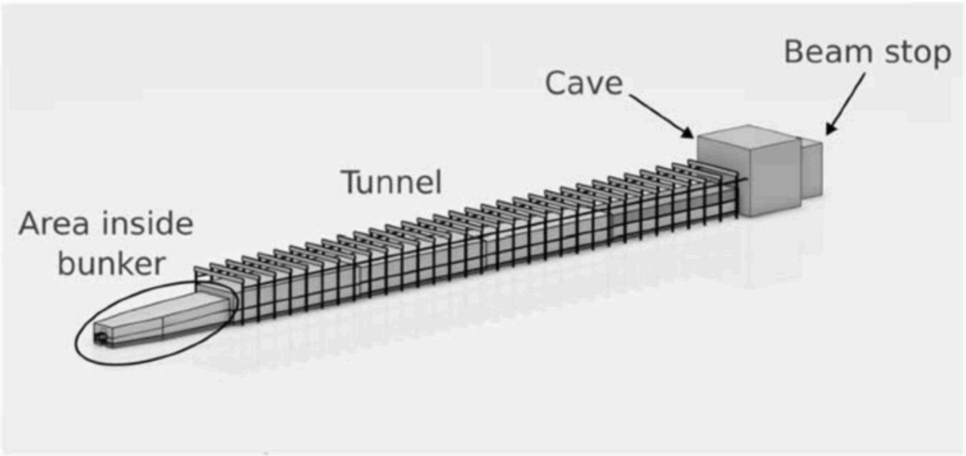
Liquid deuterium moderator spectrum

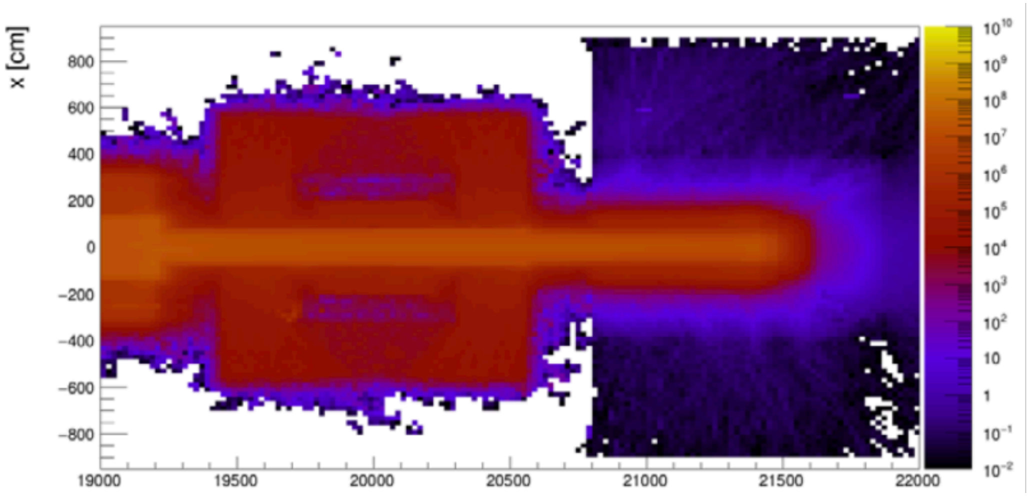


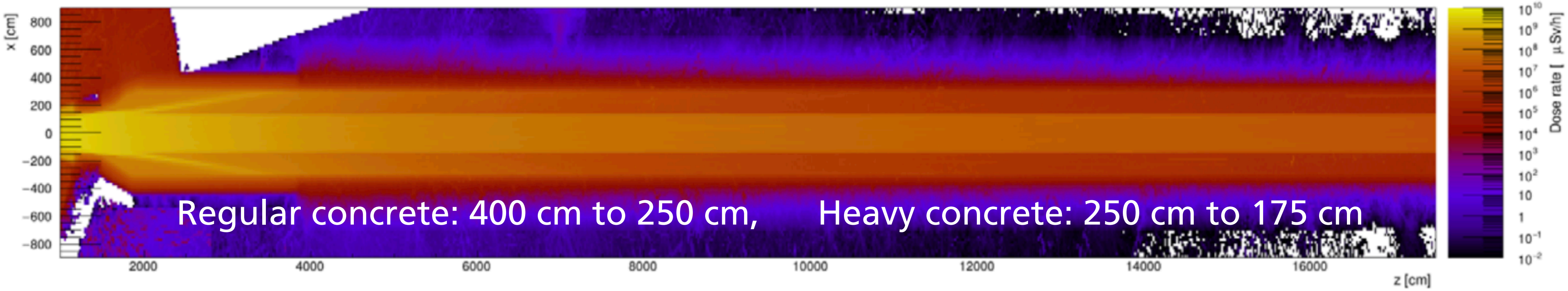


Beamline shielding

- MCNP simulations of full beamline using duct source. Shielding solutions presented for full beamline including bunker, tunnel and cave.

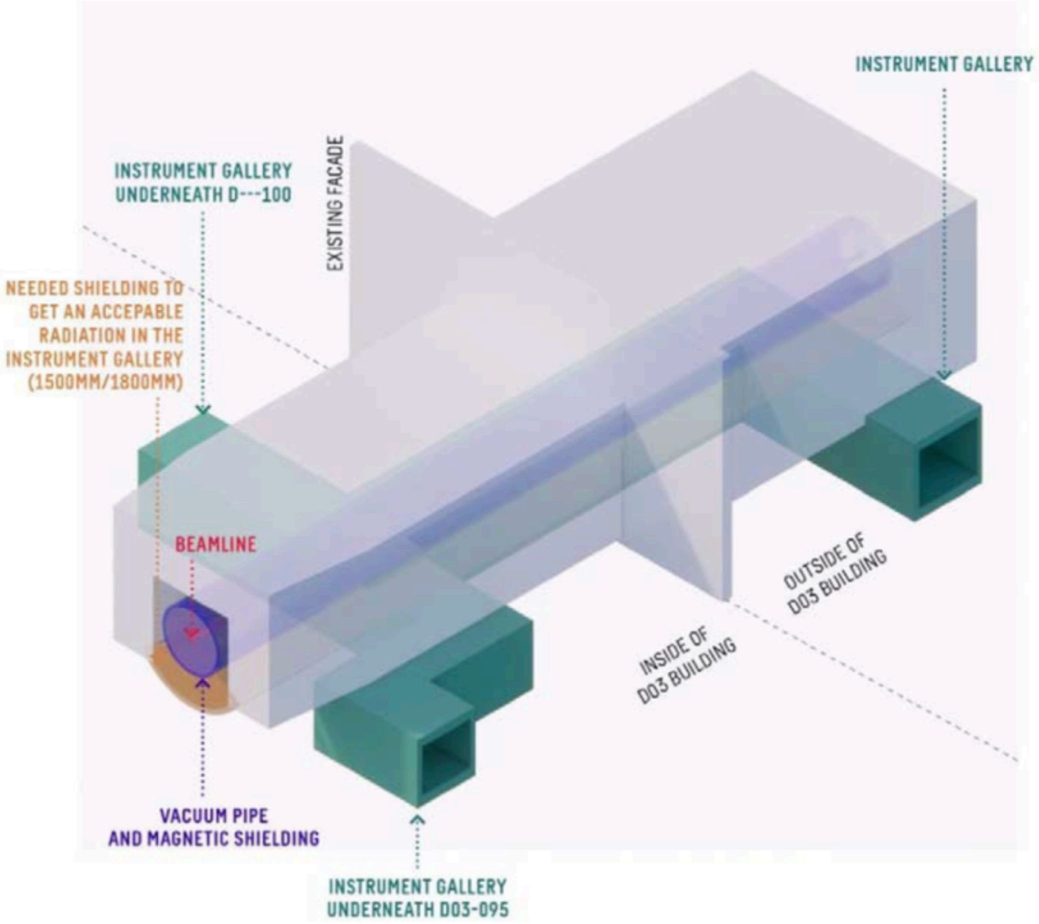


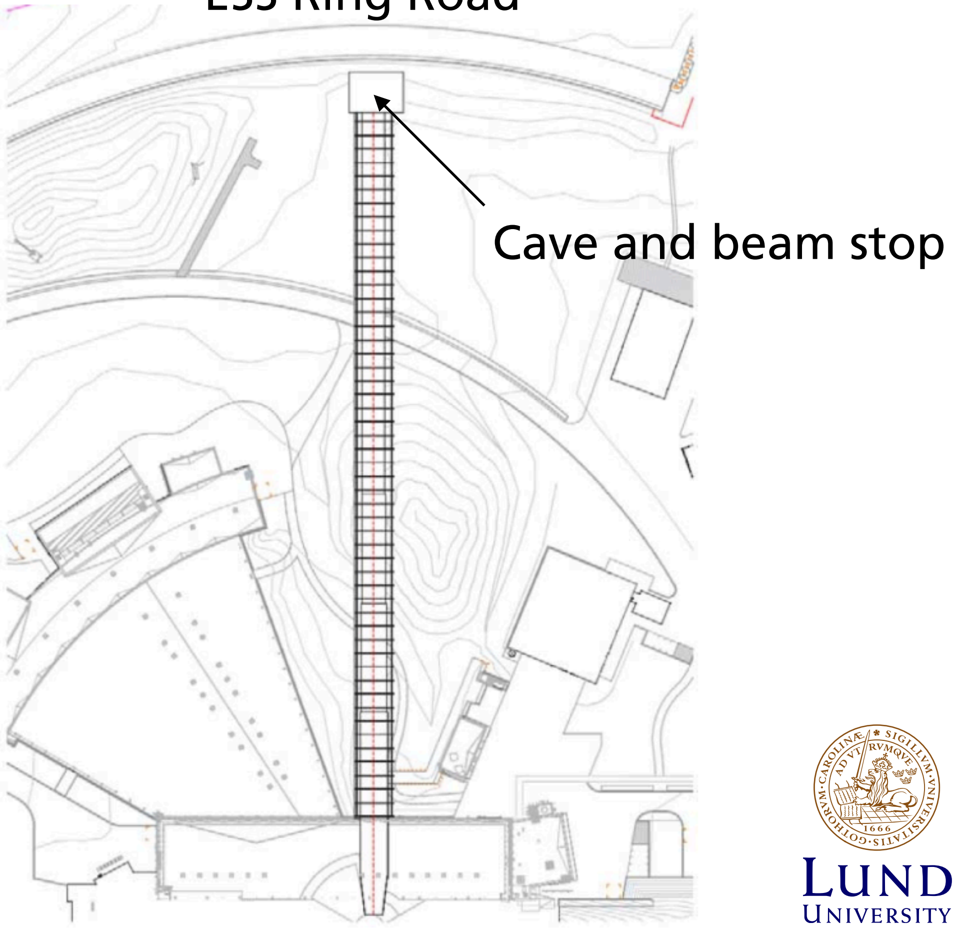




Civil engineering studies

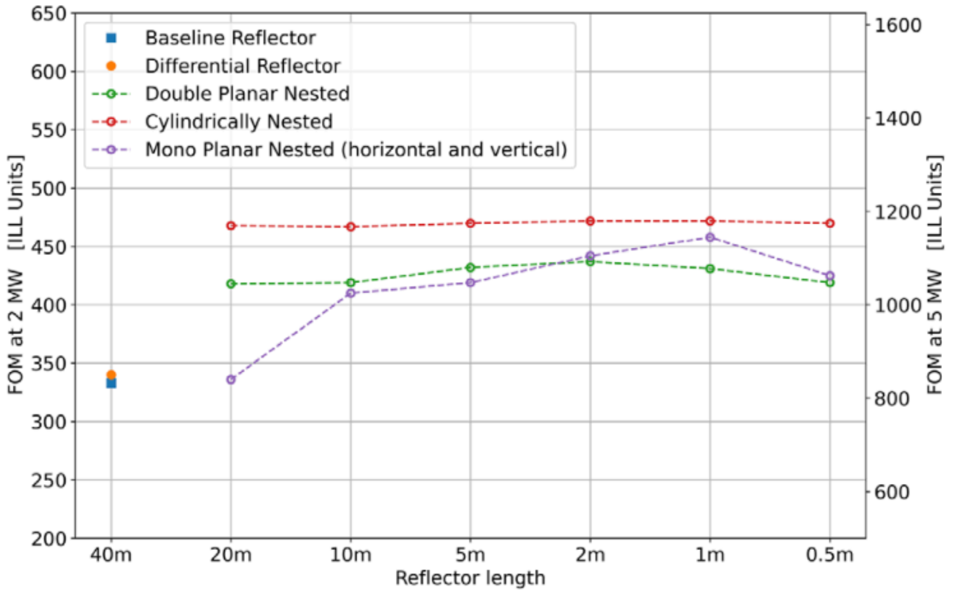
- Performed in collaboration with ESS Facility Management and building company SWECO.





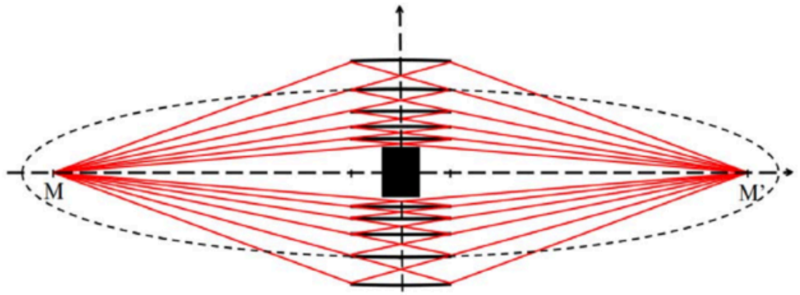
Neutron optics

- Various optics solutions including elliptical guides, differential reflectors and nested mirrors.
- Simulated in McStas using particle trajectories from MCNP model of moderator.
- Nested mirrors shows highest performance of the investigated options with m=6 considered as the baseline. Further options under consideration.



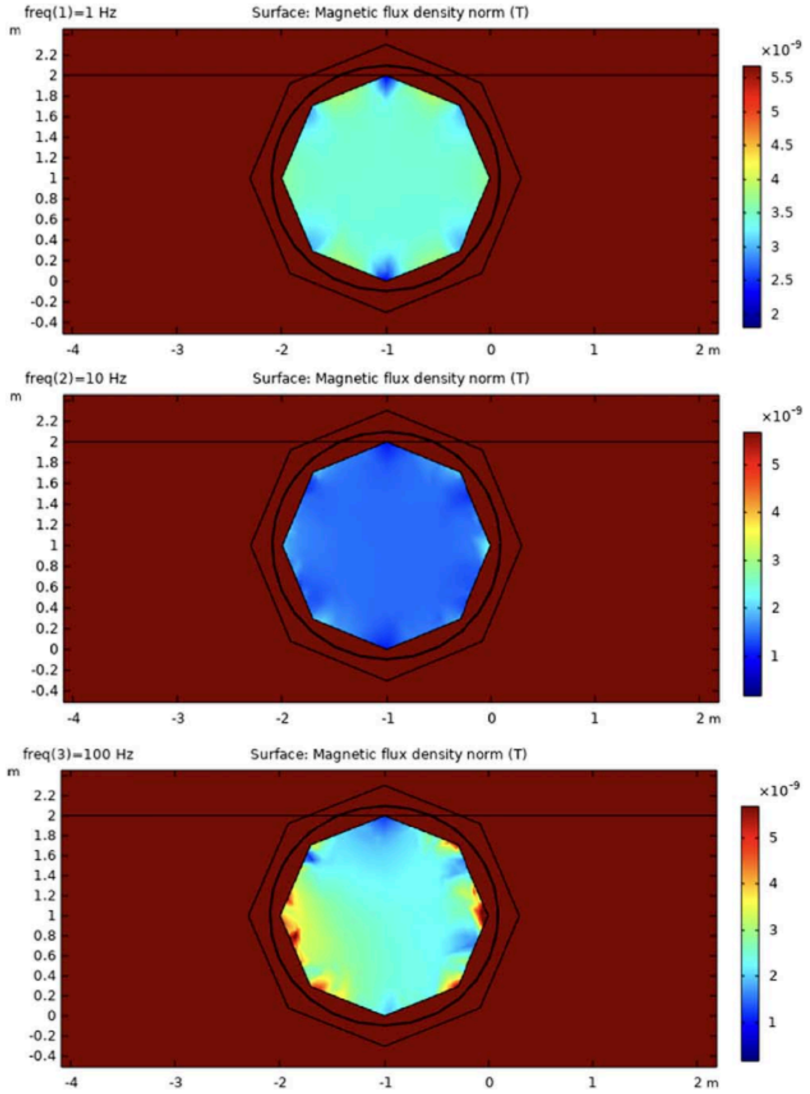
Gains in FOM that can be achieved by increasing the m-value of a nested mirror reflector that covers an opening of $\pm 4°$

m-value	1	1.5	2	3	4	5	6	7	8
Relative gain	-	1.11	0.55	0.51	0.16	0.06	0.01	0.00	0.00
Absolute gain	-	1.11	2.29	3.97	4.74	5.09	5.17	5.23	5.23



Magnetic shielding and vacuum

- Requirement: B < 5–10 nT over 200 m.
- Two-layer octagonal mu-metal magnetic shielding.
- Vacuum requirement of ~10^{-3} Pa to preserve quasi-free propagation. Steel vacuum tube provides AC shielding.
- Performance simulations in COMSOL.



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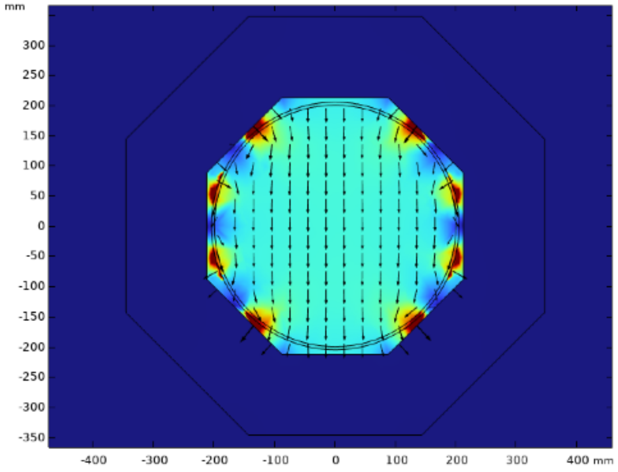
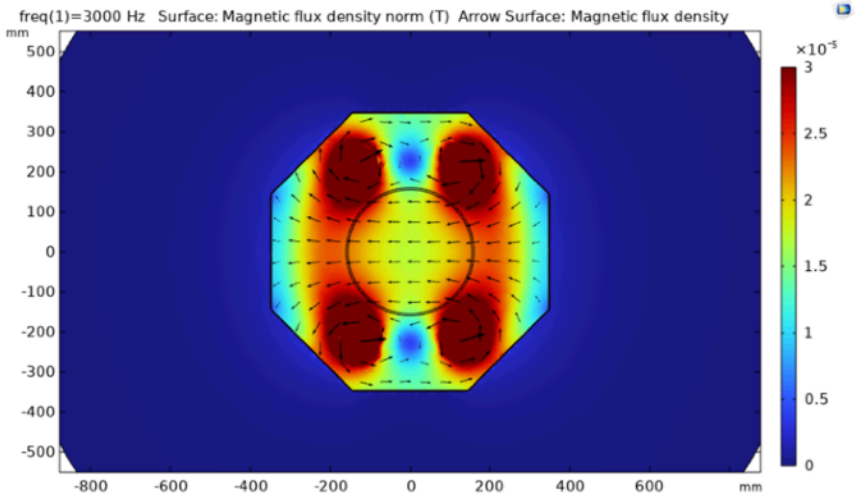
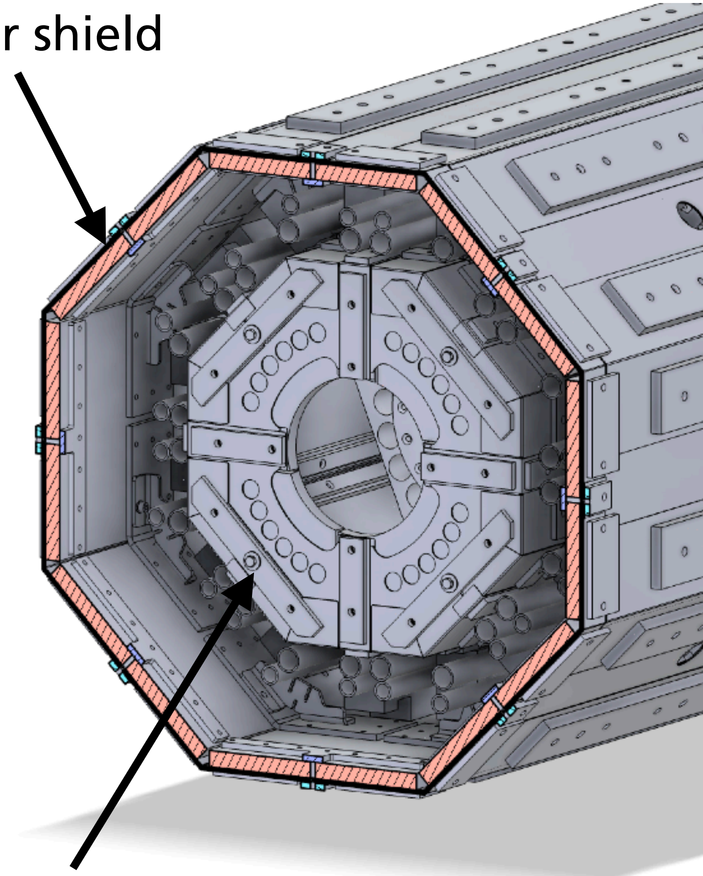
Magnetic shield prototype

- Ongoing procurement of 10 m long dual-layer magnetic shield prototype, funded by SSF.
- Planned to be used in the progenitor HIBEAM beamline for searches for axion-like particles with Ramsey interferometry[1], sterile neutrons via regeneration, and other experiments.





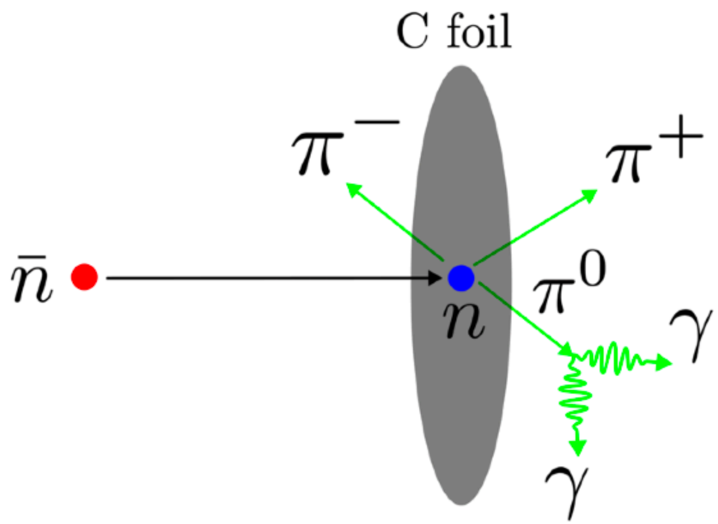


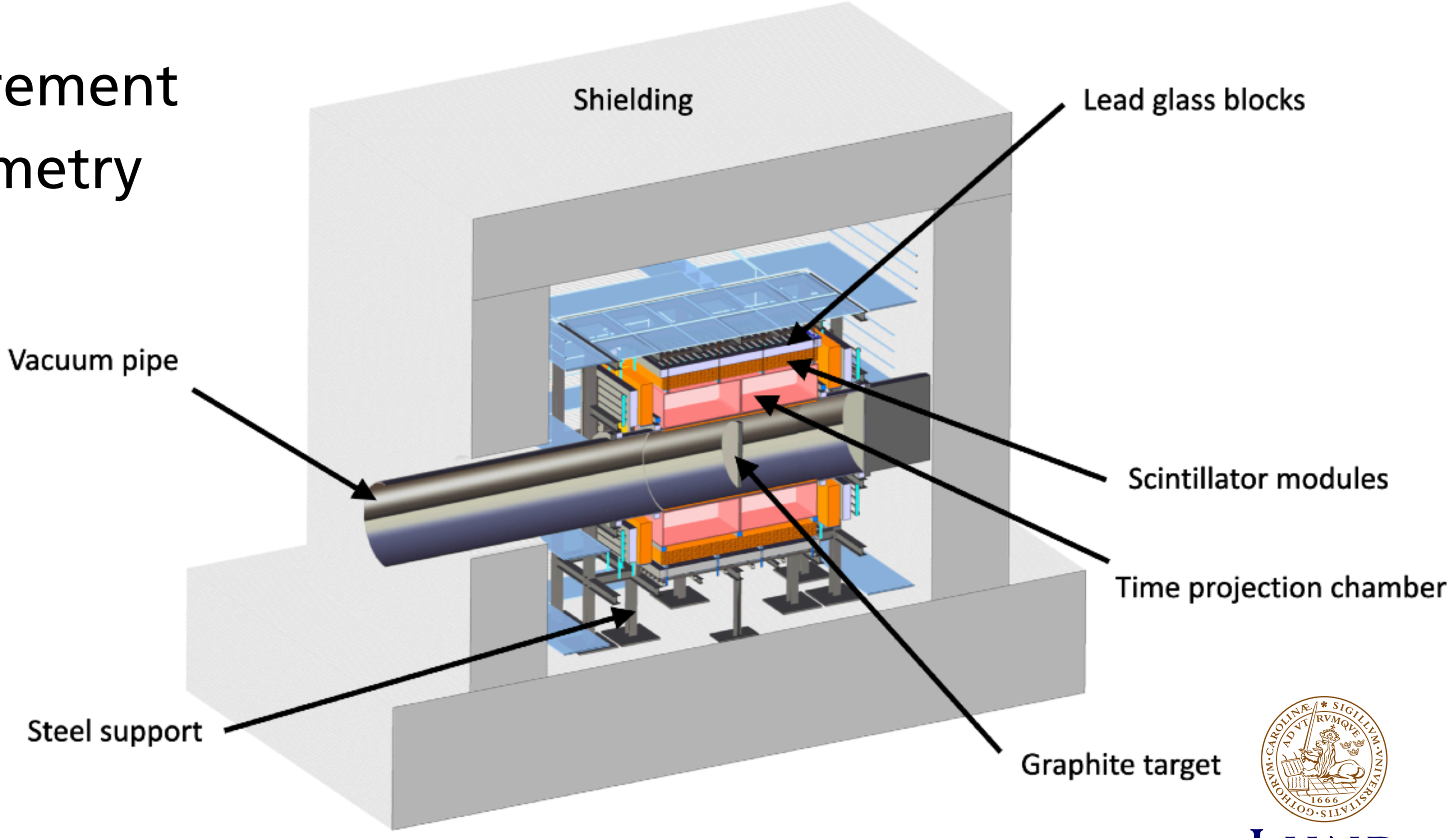
1. P. Fierlinger *et al*. *PRL* **133**:181001 (2024).

Detector design

- Goal: Identify multipion annihilation signature with full background rejection.

- Subsystems:
  - TPC: 3D vertexing, $\mathrm{d}E/\mathrm{d}x$ measurement
  - Scintillator and lead glass: Calorimetry
  - Cosmic veto: Cosmic ray rejection





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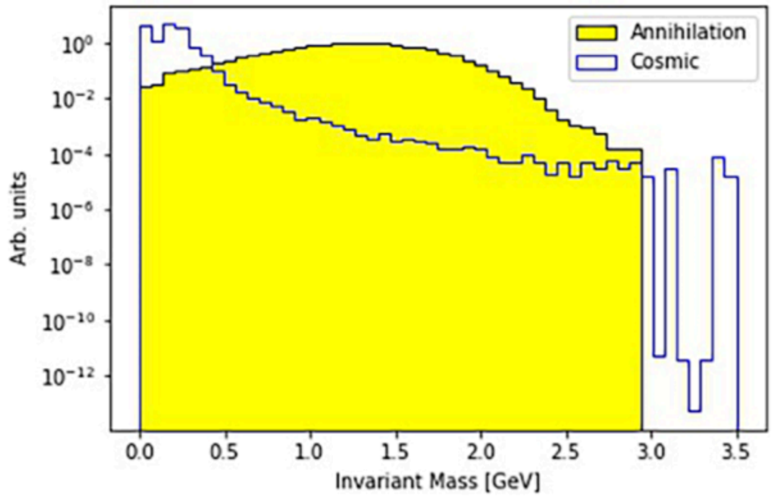
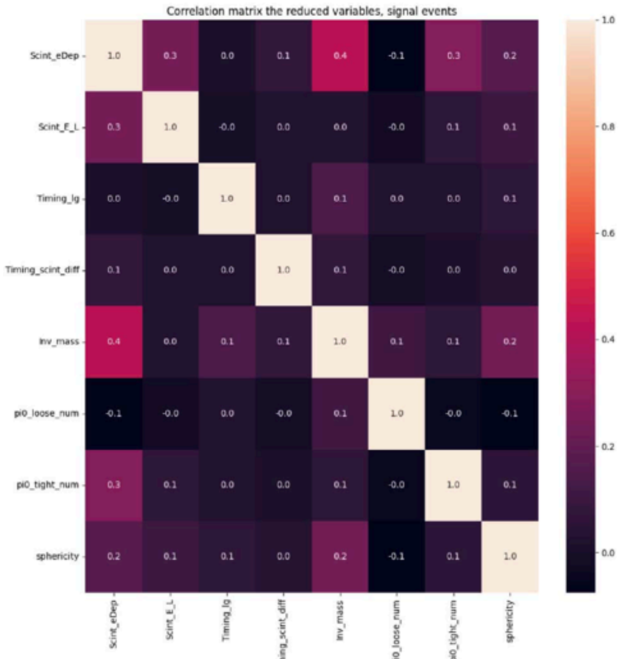
Detector and background simulations

- Background sources:
  - Cosmic rays, simulated via CRY library.
  - Fast neutrons and skyshine from ESS target. Can be removed through timing cuts relative to ESS beam pulse.
  - Low-energy background inhibiting detector function through pile-up.

- TPC tracking, calorimetry and veto together give powerful discrimination.

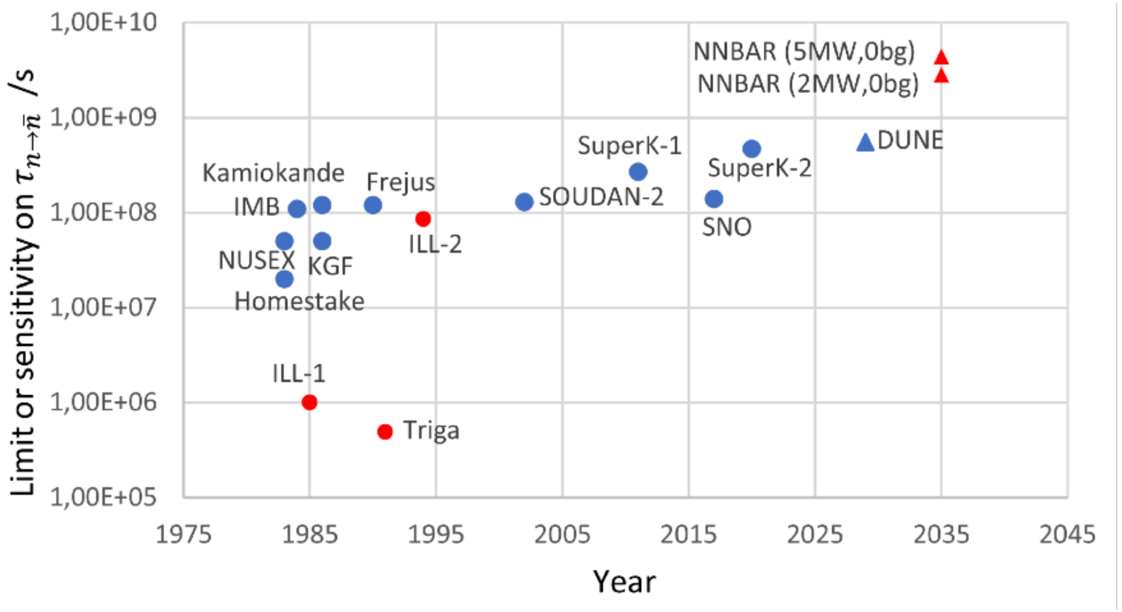
- Machine learning classifiers achieve ~68% signal efficiency with full background rejection in Geant4 simulations.

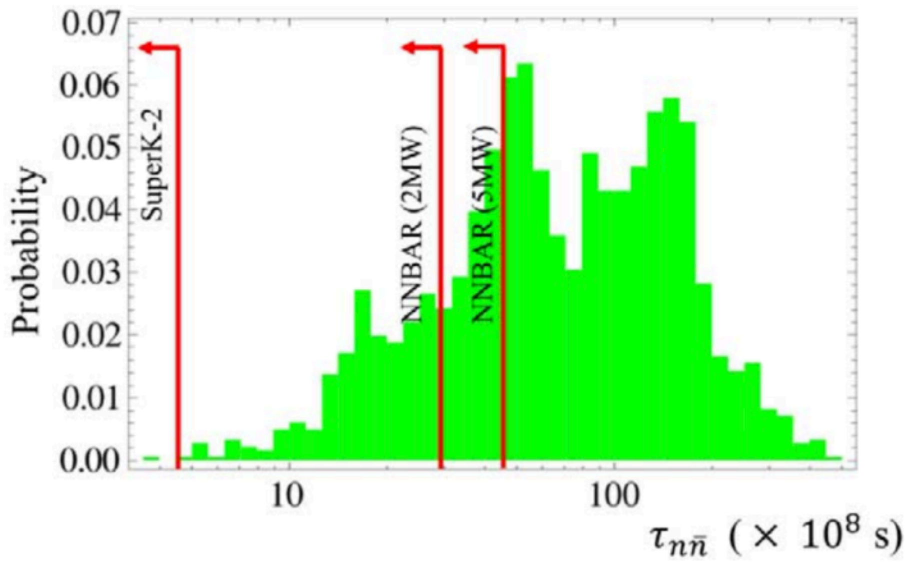




Expected sensitivity

- Assuming 2 MW beam power, 1 m radius carbon foil target, monoplanar nested mirrors, 3 years run-time.
- FOM is 1100 times that of the last ILL experiment.
- Limits on oscillation time goes with square root of FOM.





Cost estimates

- Parametric costing model of the whole experiment.
- Detector cost based on existing detectors used, e.g. at LHC and Fermilab.

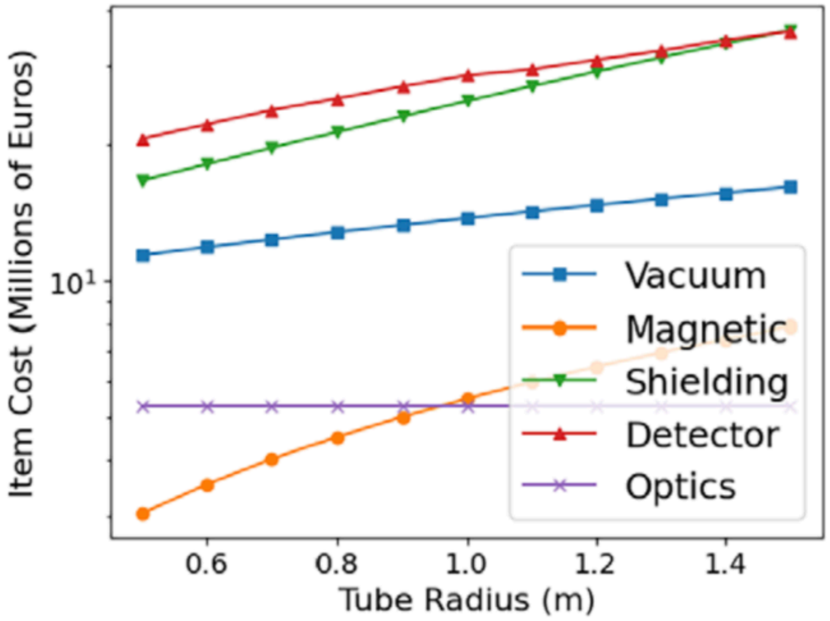


Table 13

Cost breakdown of an instrument with the baseline specifications, i.e. length = 200 m, $m = 6.0$, and radius = 1 m, rounded to nearest k€

Item	Cost (M €)
Carbon target	0.07
Vacuum tube	4.76
Vacuum system	9.0
Magnetic shielding	5.5
Steel shielding	3.05
Beam tube concrete shielding	11.07
Detector cave concrete shielding	1.42
Detector mechanical construction	0.75
Counting house	0.03
Beamstop	4.78
TPC and front-end electronics	3.53
TPC readout to DAQ	1.94
Lead glass	7.07
Lead glass SiPM and analog front-end	13.60
Stave scintillators	0.12
Stave SiPM and analog front-end	0.46
Stave WLS	0.36
Veto scintillators	0.07
Veto WLS	0.19
Veto SiPM and analog front-end	0.38
Calorimeter/Veto digitization and readout	2.11
Timing and slow control	0.19
DAQ system	2.11
Optical elements	5.10
Total	**77.66**

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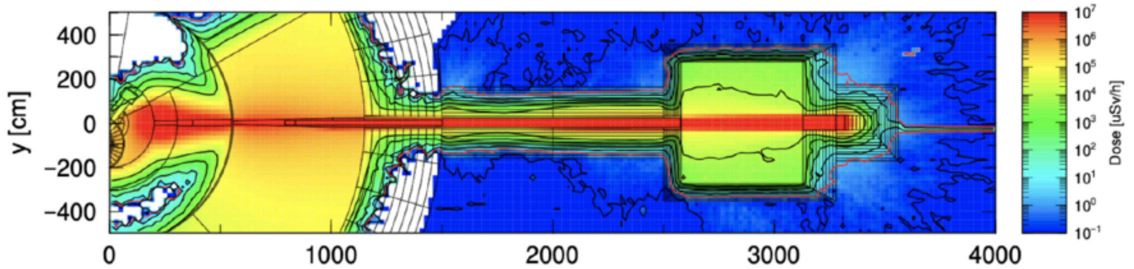
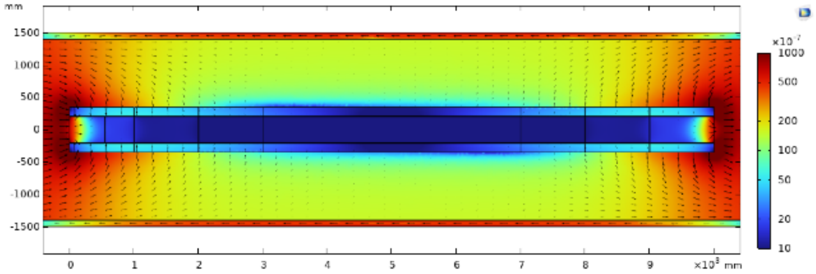
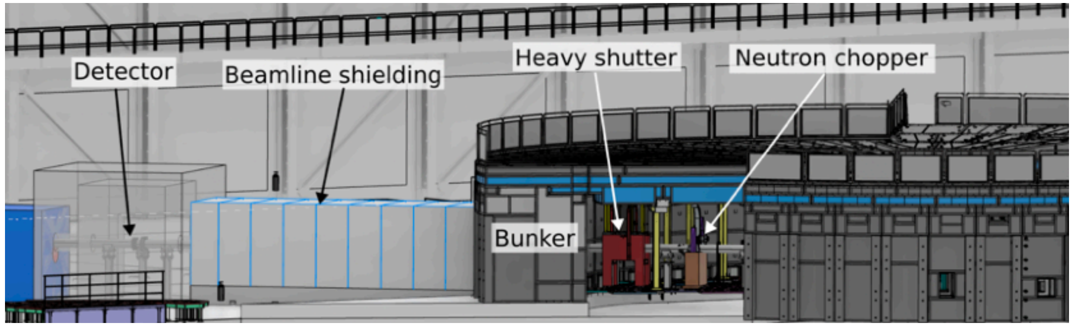
HIBEAM beamline at ESS

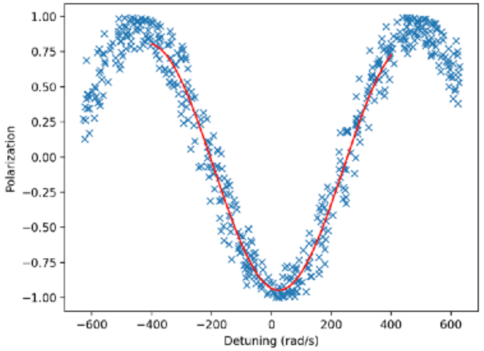
- Proposed beamline for axion-like particle searches, sterile neutron experiments, neutron charge, EDM and a smaller-scale NNBAR experiment.

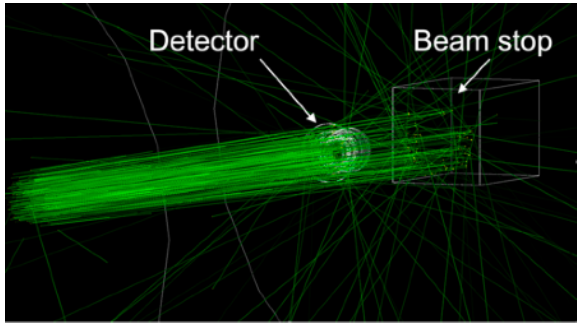
- Ongoing or completed work on neutron optics, biological shielding, magnetics and spin propagation, detector backgrounds and event reconstruction, vacuum, mechanical engineering and prototype testing.





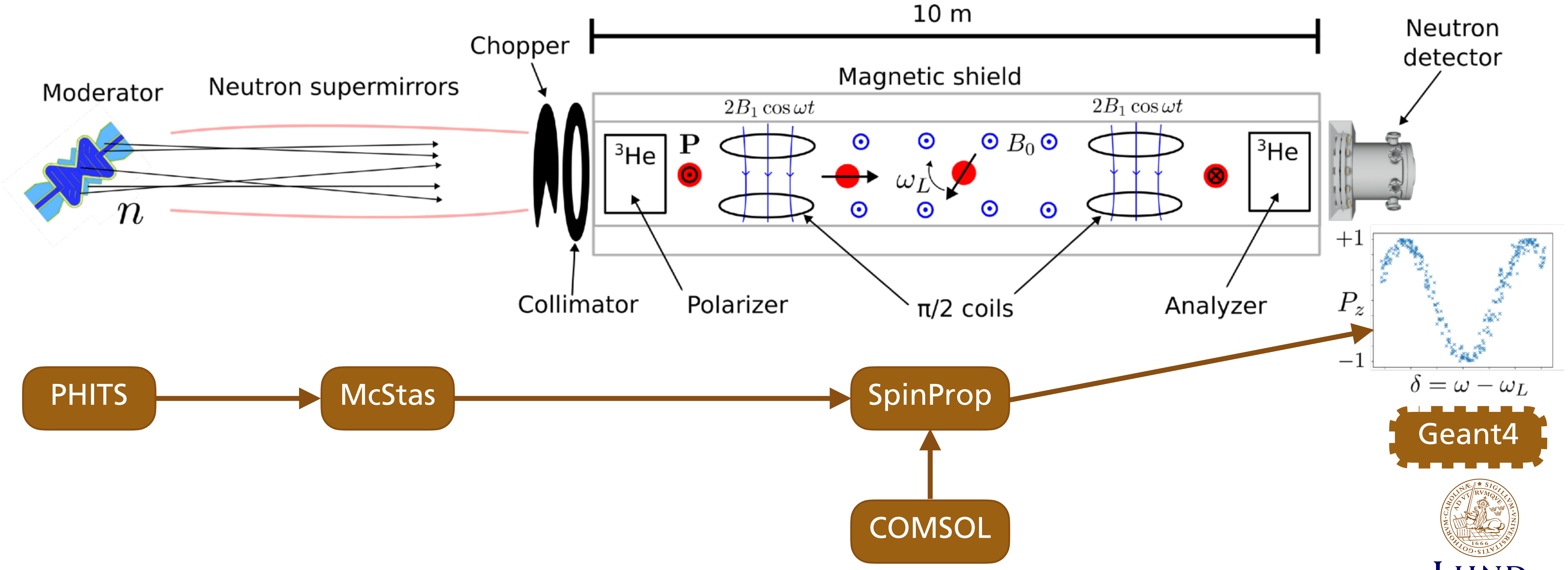






Further reading: V. Santoro *et al*. *J. Phys. G: Nucl. Part. Phys*. 52:040501 (2025).

A simulation framework for Ramsey interferometry



Further reading: P. Fierlinger *et al*. *PRL* **133**:181001 (2024).

Project status

- HighNESS (moderator development)[1] and NNBAR[2] CDR published in May 2024 with support from 3 M€ grant from the European Commission.

- NNBAR and the pre-stage HIBEAM project[3] will be presented as proposals to the ”Call for Input to the ESS Instrument Roadmap” in February 2026.

- Future possible developments being studied include using the ESS pulse shape for neutron focusing and a tracking system inside the vacuum.

1. V. Santoro *et al*. *JNR* **25**(3-4):85 (2024).
2. V. Santoro *et al*. *JNR* **25**(3-4):315 (2024).
3. V. Santoro et al. *J. Phys. G: Nucl. Part. Phys*. 52:040501 (2025).

The HIBEAM/NNBAR collaboration

+ many more…

- Interdisciplinary collaboration with experts in neutronics, optics, magnetics, particle and nuclear physics. ~100 members from 10 countries.

- New collaborators are welcome!

Conclusion

- NNBAR is a large-scale search for free neutron-antineutron oscillations at the European Spallation Source, providing the most stringent limits on the neutron-antineutron oscillation time.

- 200 meter long beamline with advanced neutron optics to focus cold neutrons from the deuterium moderator towards an annihilation target.

- Large backgrounds and strict event identifications require innovative detector designs, extensive simulations and cost feasibility analysis.

- An exciting opportunity to learn about the origin of matter!

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Thank you for listening!
ご清聴、ありがとうございました

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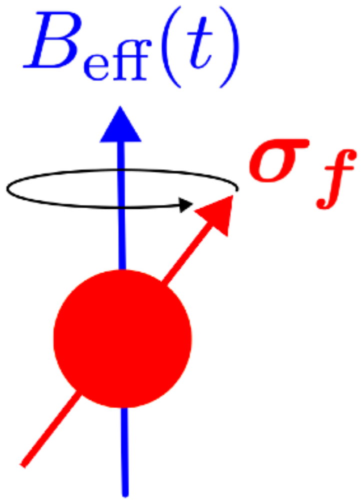
Axion interaction with fermion spin

$$\mathcal{L}_f = -\frac{C_f}{2f_a}\partial_i \left[a_0 \cos(m_a t - \boldsymbol{p_a} \cdot \boldsymbol{x})\right] \bar{f}\gamma^i\gamma^5 f$$

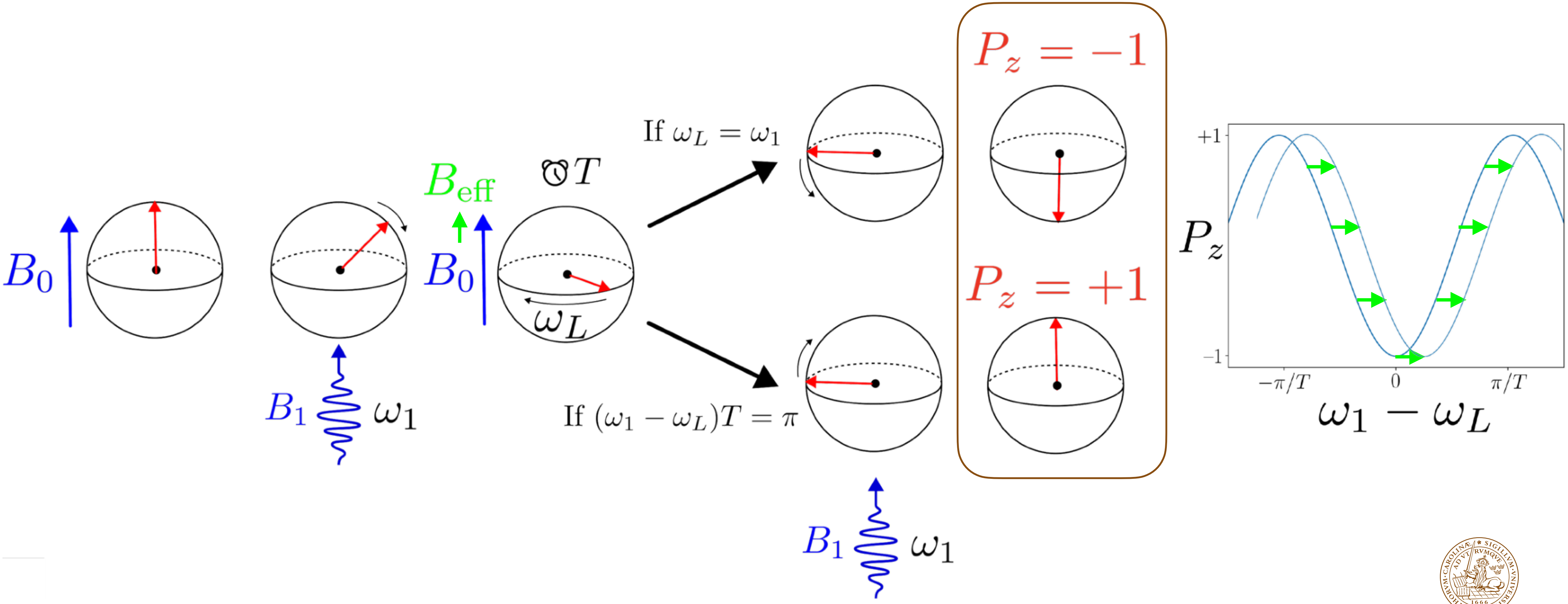
$$\Longrightarrow \quad H_{\text{eff}}(t) \propto \boldsymbol{\sigma_f} \cdot \boldsymbol{p_a} \sin(m_a t) \propto \boldsymbol{\sigma_f} \cdot \boldsymbol{B}_{\text{eff}}(t)$$

Axion interaction leads to spin precession!



Further reading: Y. V. Stadnik & V. V. Flambaum. *Phys. Rev. D.* **89**, 043522 (2014).

Ramsey interferometry



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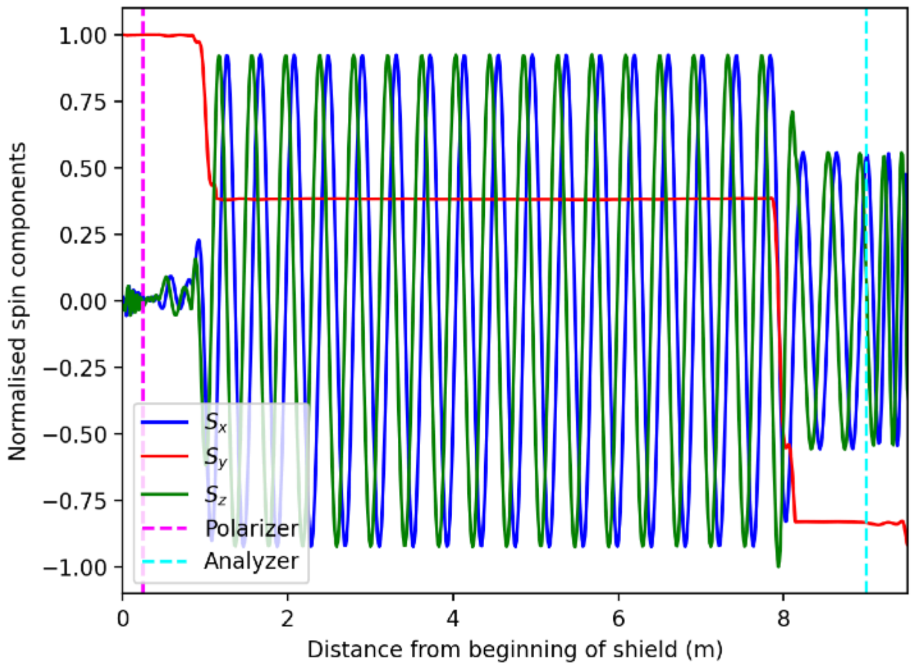
Spin dynamics simulation

- A new software package *SpinProp*[1] for spin evolution by solving the Bloch equation.
- Neutron tracks from optics simulation.
- Time-dependent magnetic field can be defined analytically or interpolated from COMSOL simulation.
- Outputs magnetic field, polarization vector and adiabaticity along the trajectory.

$$\frac{d\mathbf{S}(t)}{dt} = \gamma \mathbf{S}(t) \times \mathbf{B}(\mathbf{r}(t), t)$$



1. https://github.com/HIBEAM-NNBAR/SpinProp

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Simulating the Ramsey fringes

- Performs the calculation for different detuning, plots and fits the Ramsey fringes.
- Allows study of impact of neutron optics and magnetics design on experimental performance.
- Full-scale experiment improves the laboratory sensitivity to axion-neutron coupling by orders of magnitude.