

Neutron-based particle physics at the European Spallation Source

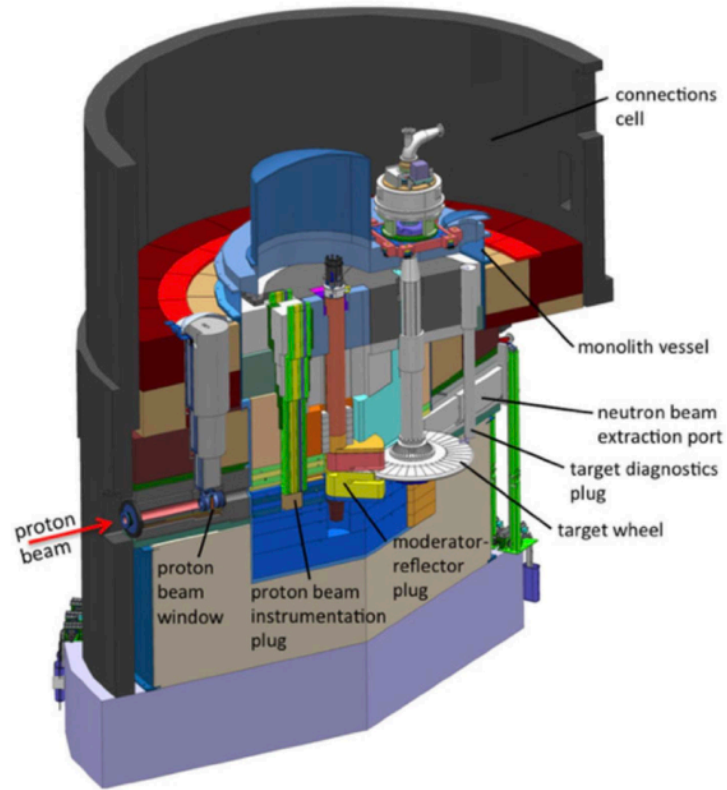
Linus Persson, linus.persson@fysik.lu.se



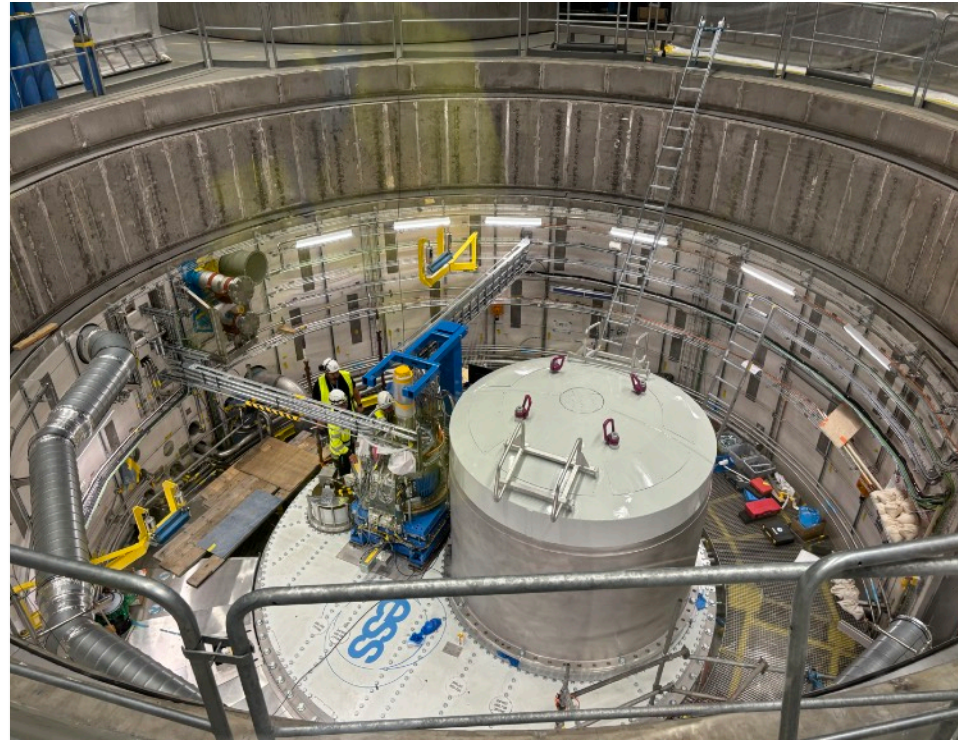
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Some construction updates...



Monolith cross-section

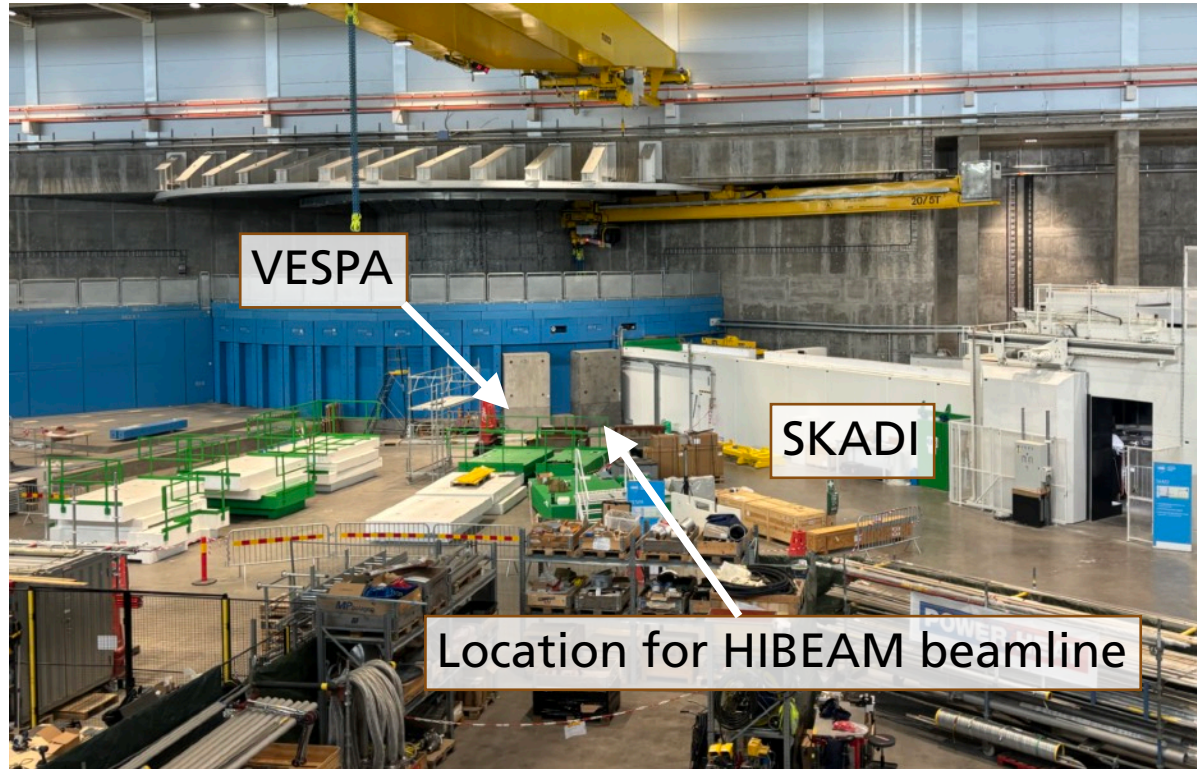


View from above,
~ 4 weeks ago



E5 beam port
now installed!

ESS bunker



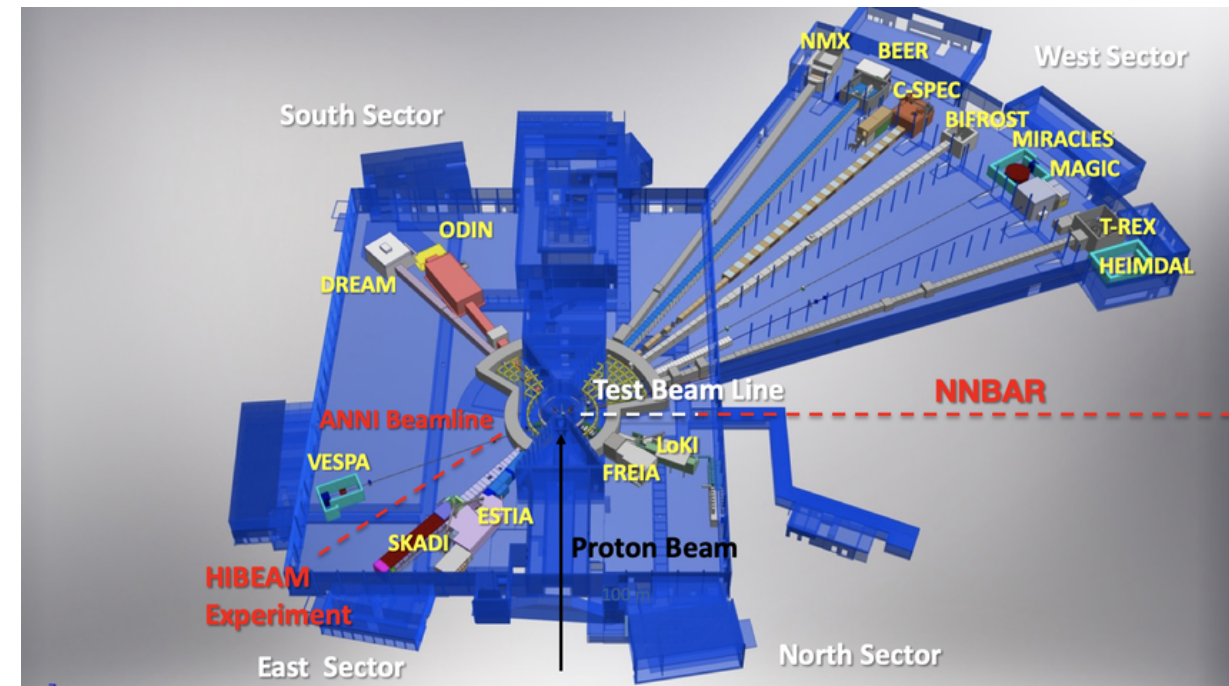
“Short sector” with the bunker, planned location for HIBEAM beamline

“Long sector”, 160 m long beamlines

More construction updates and pretty pictures: <https://www.youtube.com/watch?v=A-05cny4jXQ>

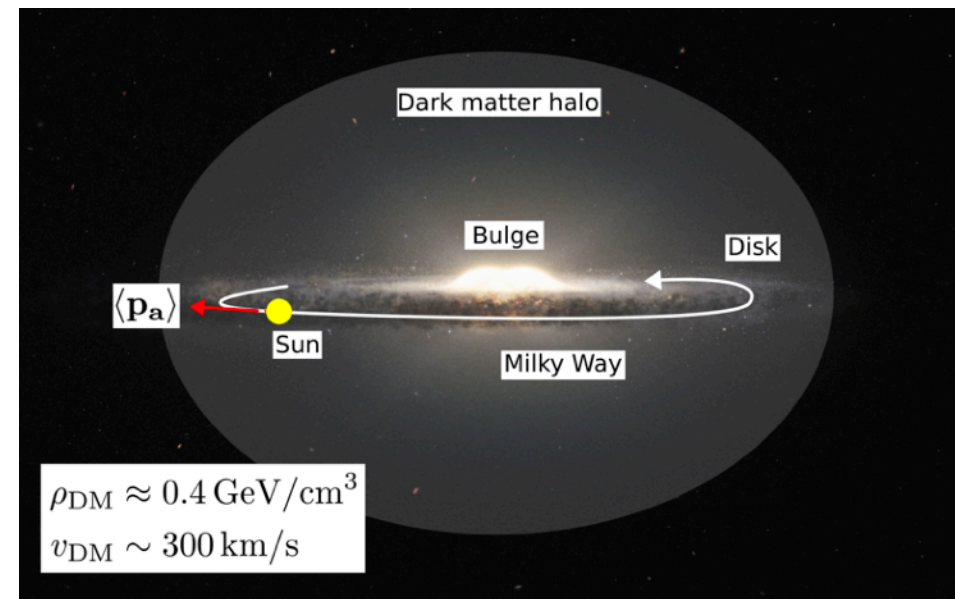
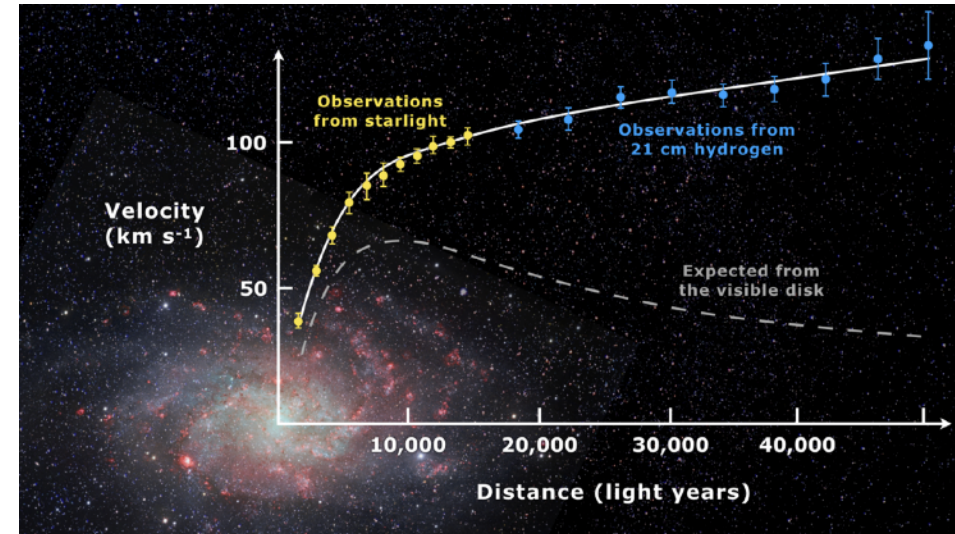
A multistage approach for particle physics

- **short-HIBEAM:** 25 m long beamline at E5 beamport to look for axion-like particles. Possible testing for oscillation experiments, non-zero charge, hadronic parity violation, ??.
- **HIBEAM beamline:** 65 meter long extension, initial focus on $n - \bar{n}$ and $n - n'$ searches.
- **NNBAR beamline:** Separate 200 meter long beamline for $n - \bar{n}$ oscillation, improve sensitivity to free oscillation by 3 orders of magnitude compared to ILL experiment (1990).



Dark matter and the axion

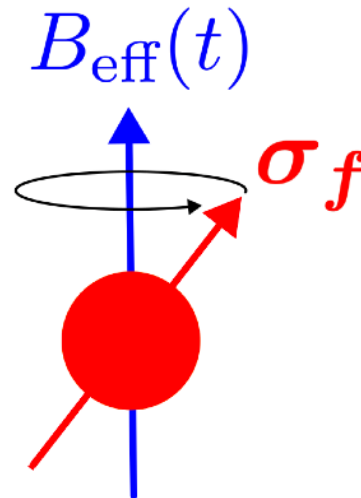
- Based on galactic rotation curves, gravitational lensing and large-scale cosmological structure, dark matter known to constitute $\sim 25\%$ of the energy density of the Universe.
- **Axion-like particles:** Light, weakly interacting pseudoscalar particles.
- Ultralight ALPs ($\ll eV$ mass) act as coherent fields on astrophysical scales.



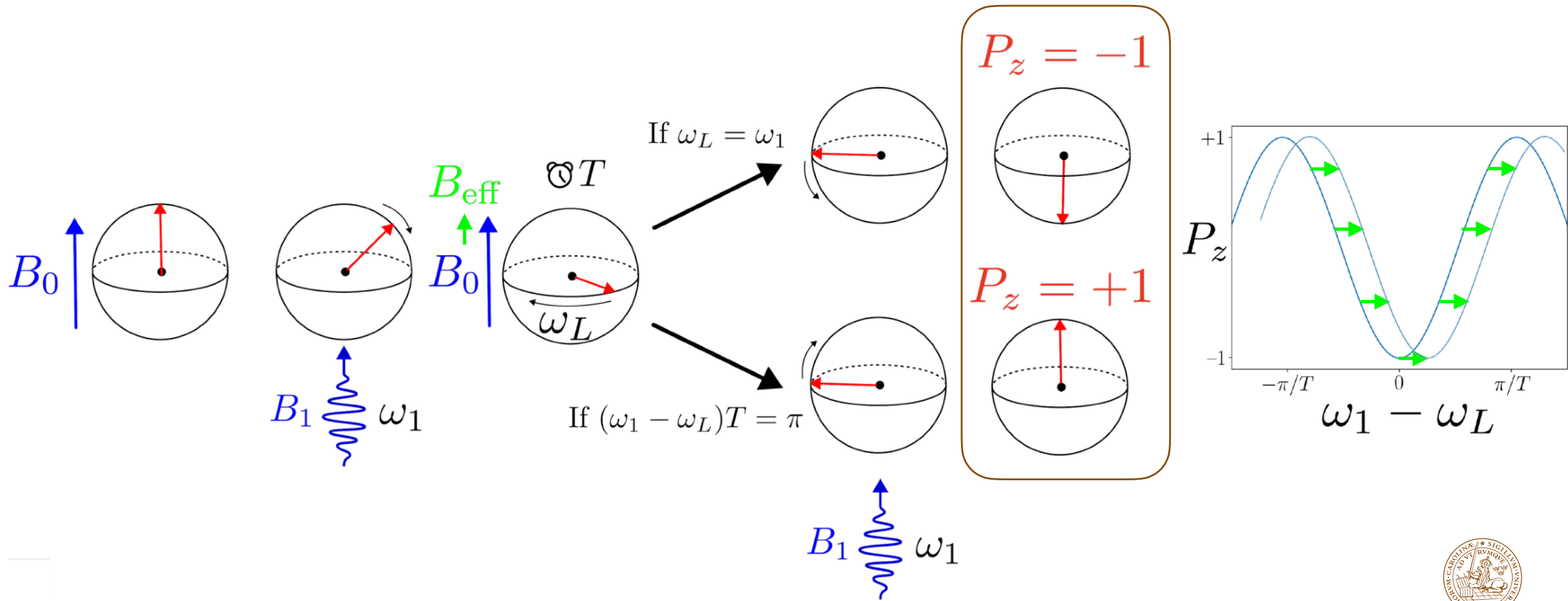
Axion interaction with fermion spin

$$\mathcal{L}_f = -\frac{C_f}{2f_a} \partial_i [a_0 \cos(m_a t - \mathbf{p}_a \cdot \mathbf{x})] \bar{f} \gamma^i \gamma^5 f$$
$$\implies H_{\text{eff}}(t) \propto \boldsymbol{\sigma}_f \cdot \mathbf{p}_a \sin(m_a t) \propto \boldsymbol{\sigma}_f \cdot \mathbf{B}_{\text{eff}}(t)$$

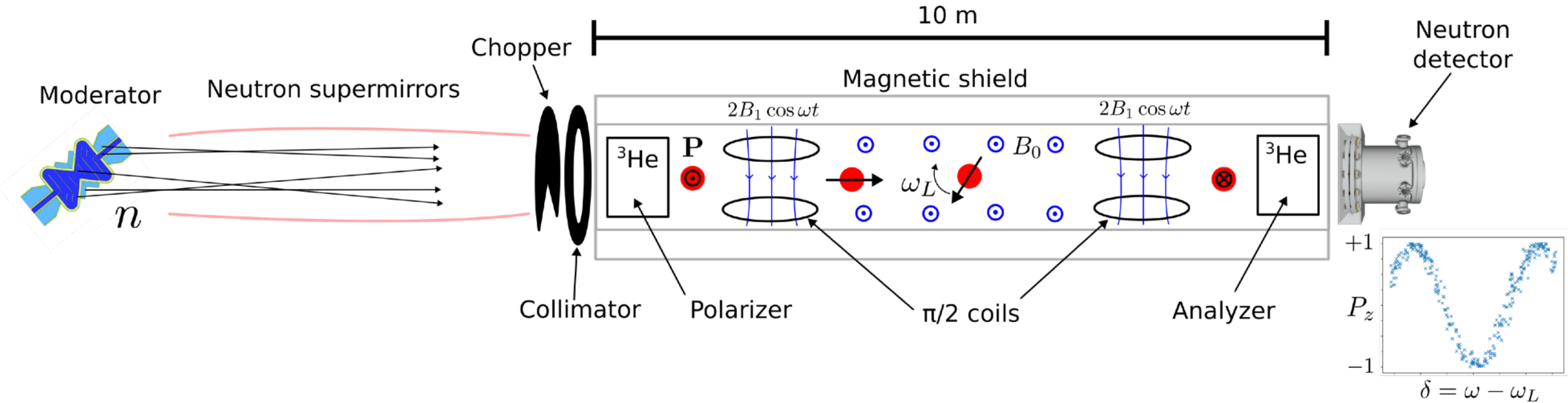
Axion interaction
leads to spin
precession!



Ramsey interferometry



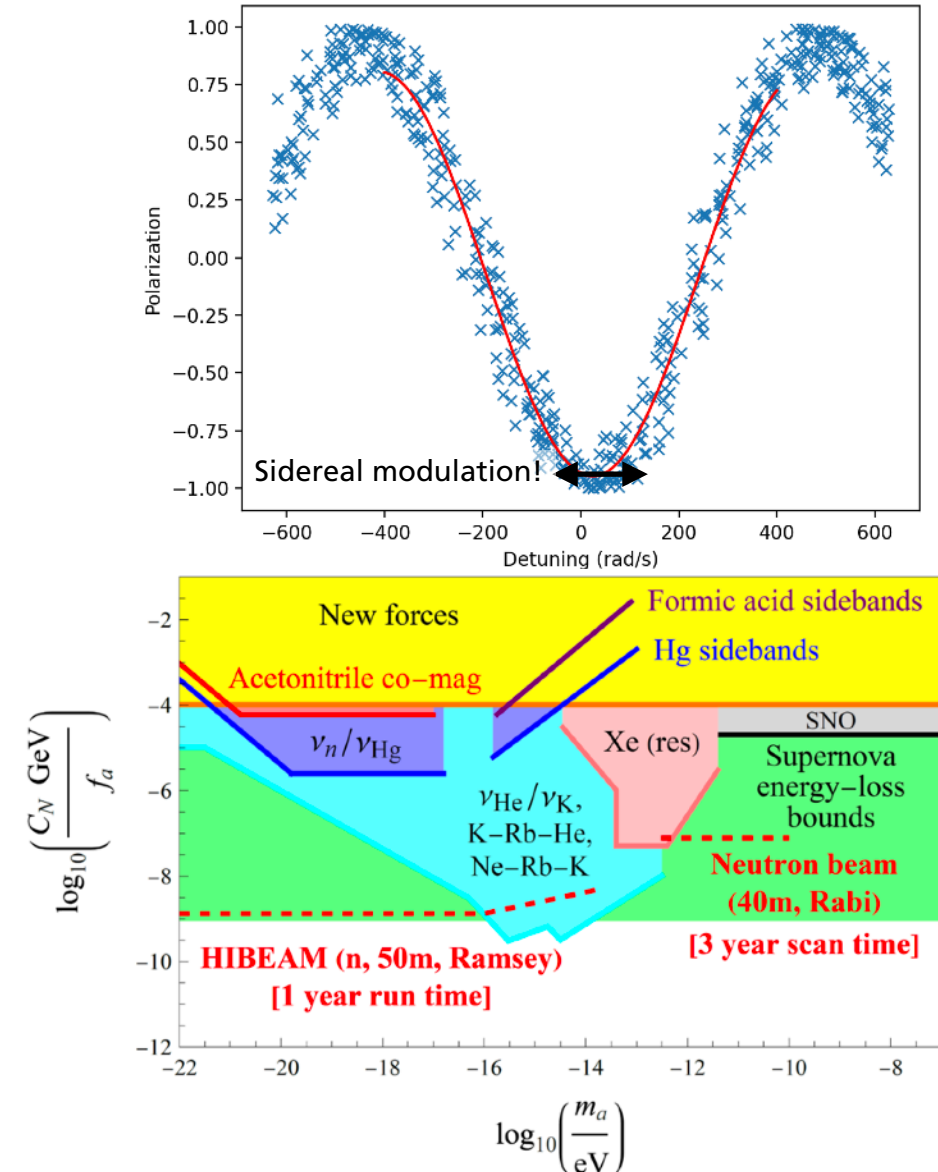
A neutron beamline for Ramsey interferometry



Further reading: P. Fierlinger *et al.* *Phys. Rev. Lett.* **133**, 181001 (2024).

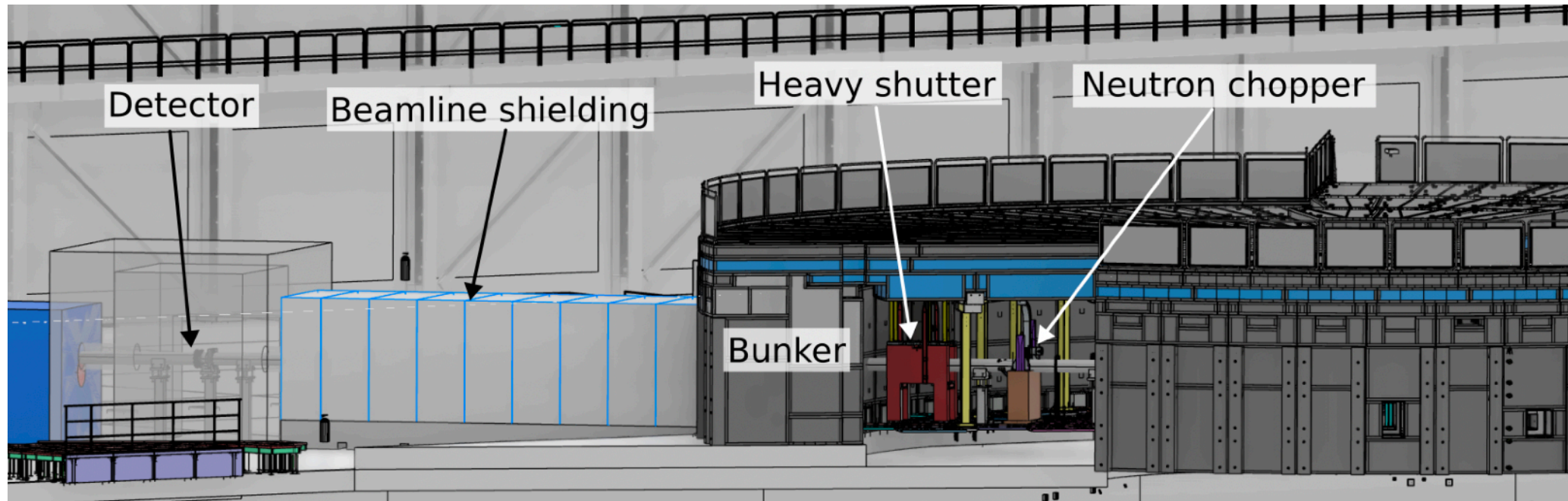
Simulation work

- My task: Simulate neutron trajectories (McStas) and magnetic fields (COMSOL), evolve the neutron spins and study the Ramsey fringe resolution.
- Beamline simulation, detector simulation and optics simulation in collaboration with undergraduates.
- Full-scale experiment improves the laboratory sensitivity to axion-neutron coupling by orders of magnitude.

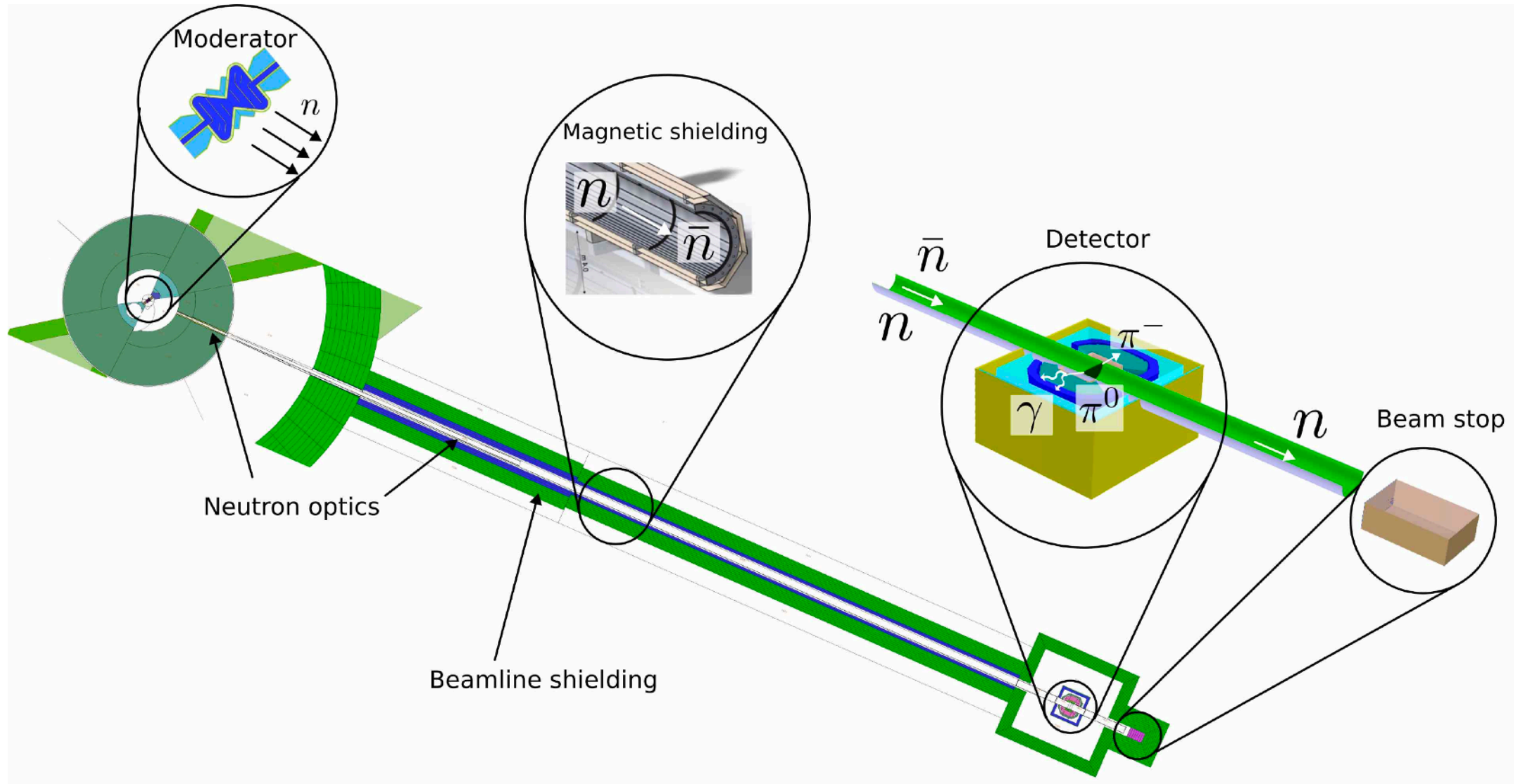


From simulation to reality

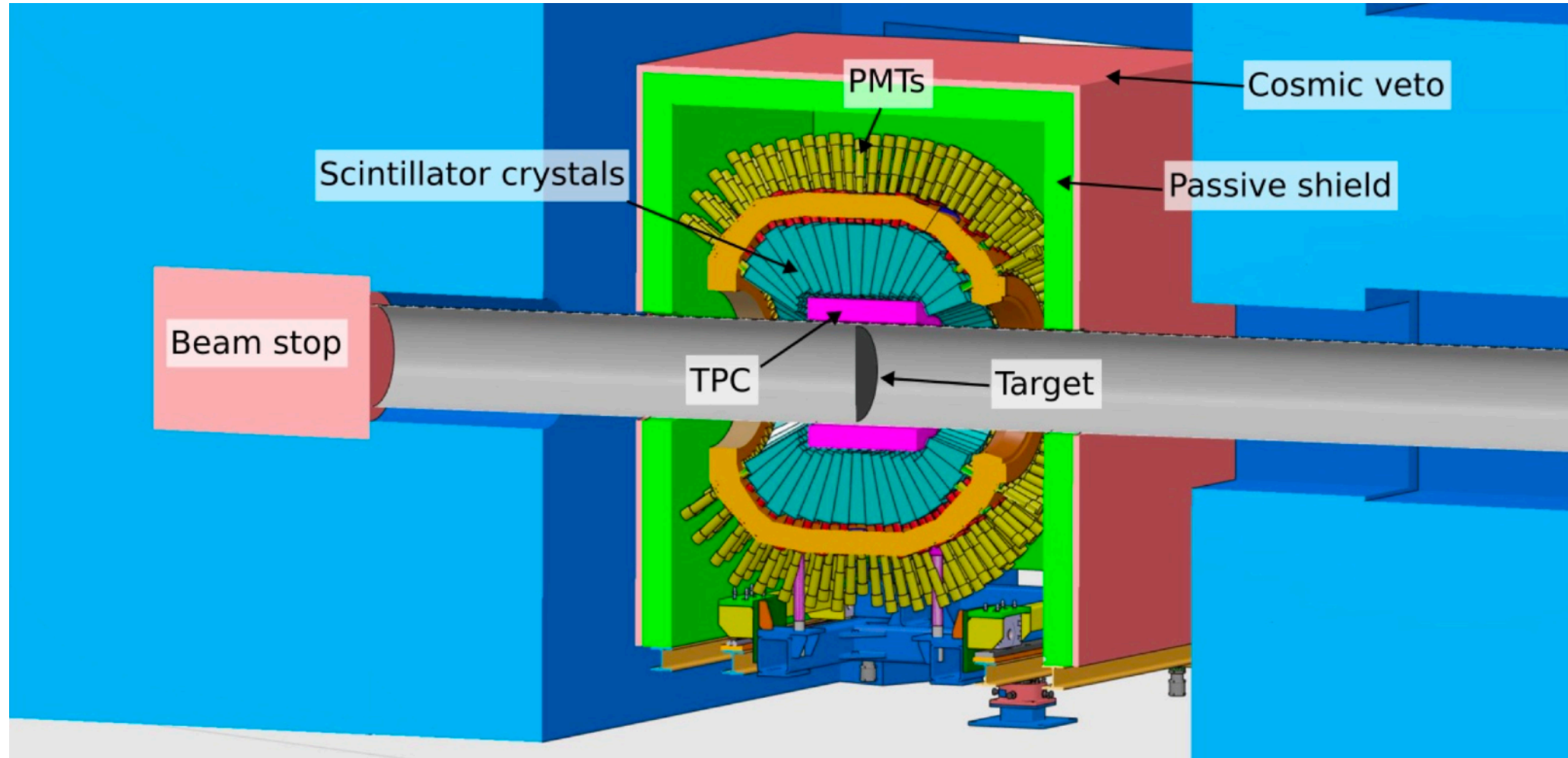
- “Call for Input to the ESS Instrument Roadmap” open until February 2026. By then we expect to have a TDR-level design of the whole Ramsey setup + Proposals for full HIBEAM and NNBAR.
- ESS invested ~\$1.3M into the E5 beam port. \$1.5M SSF grant for magnetic shield prototype and \$420K VR grant for Ramsey setup.



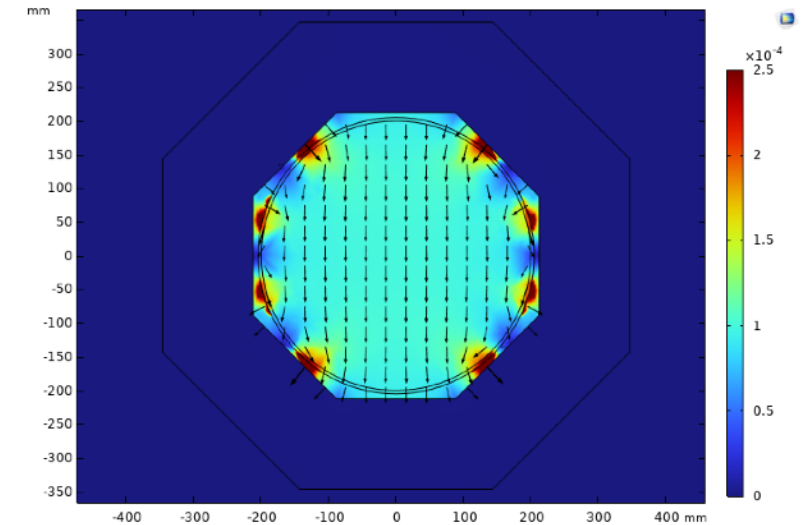
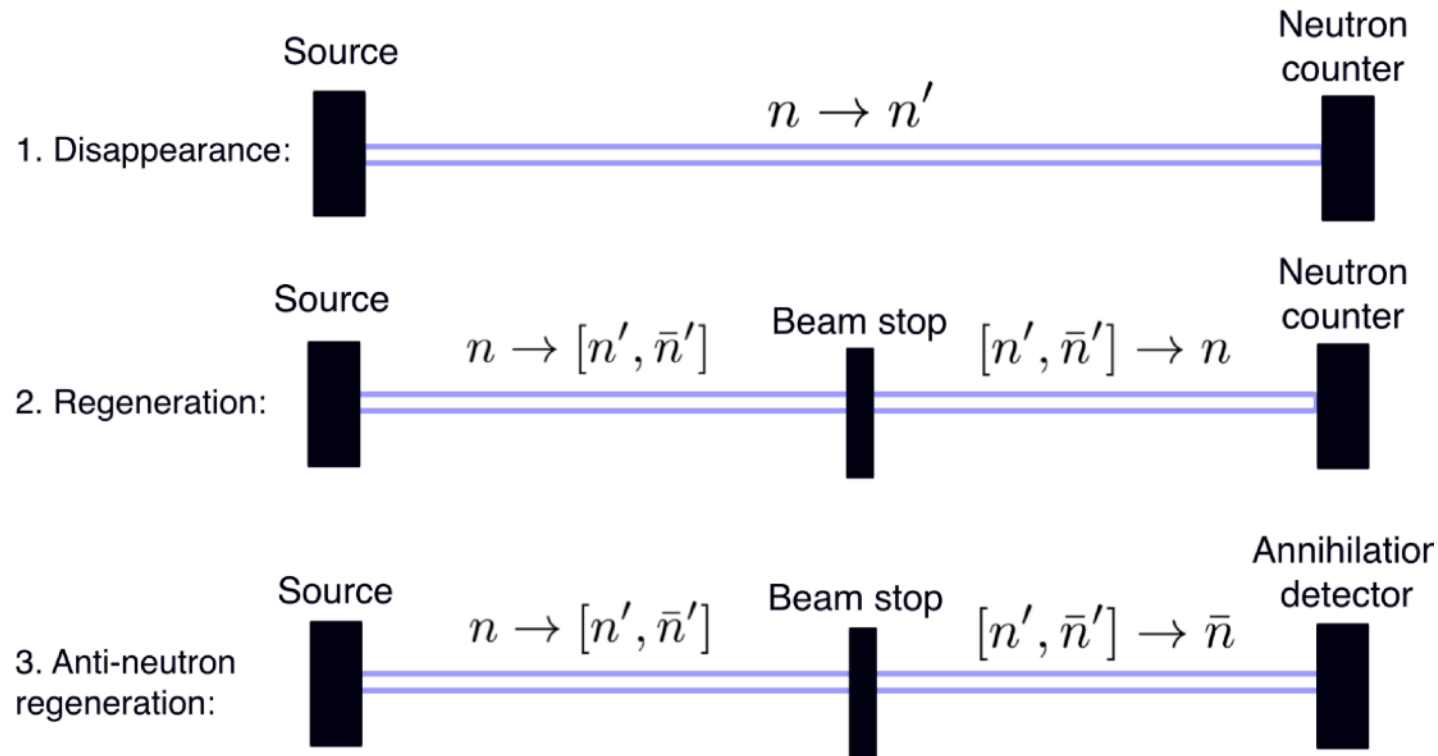
HIBEAM beamline for neutron-antineutron oscillation



HIBEAM annihilation detector

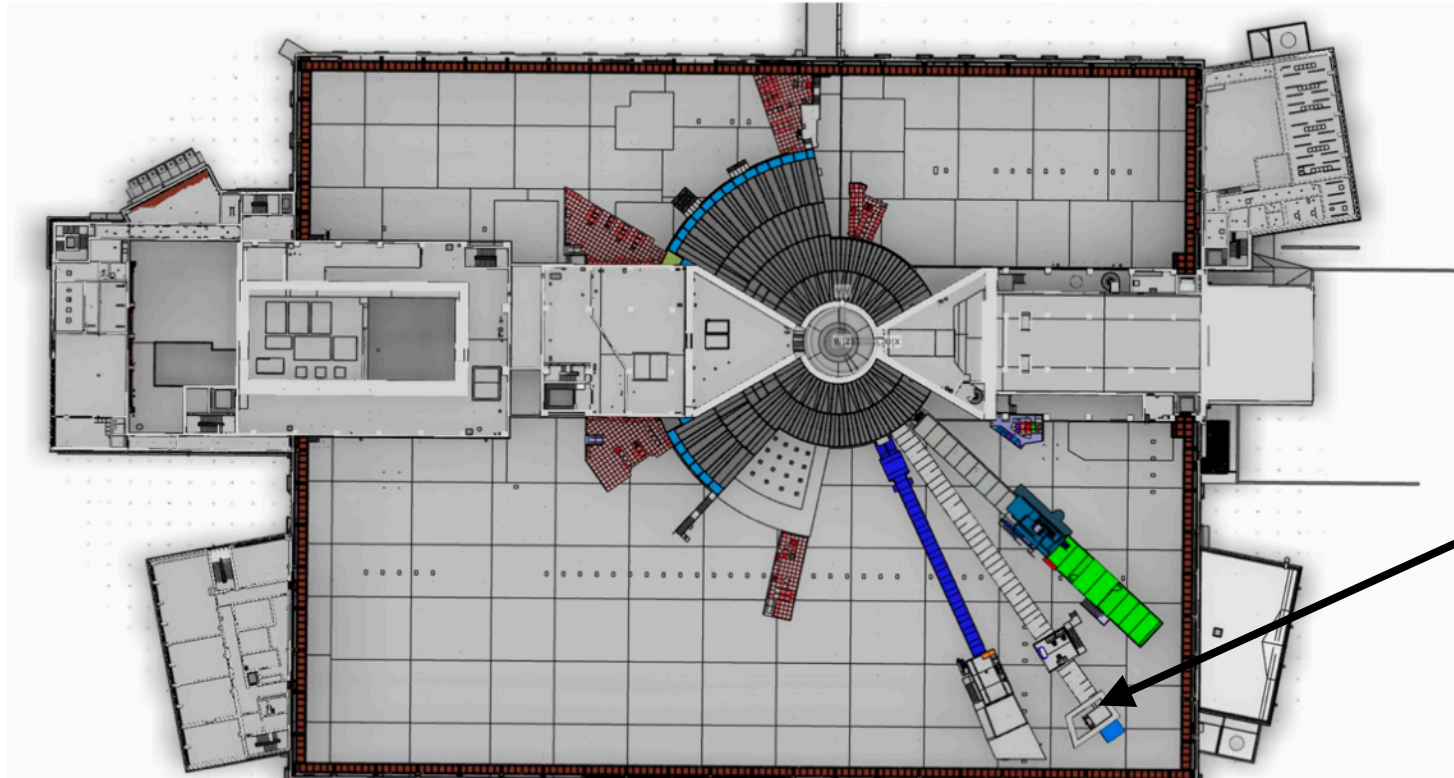


HIBEAM for sterile neutron searches

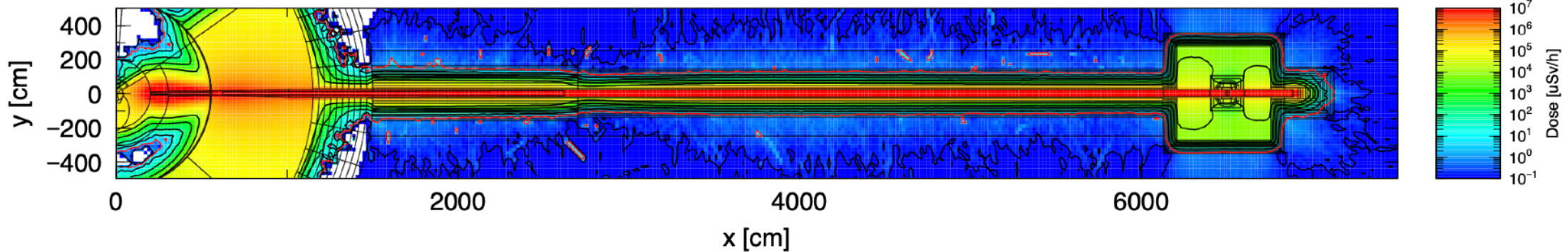


3D magnetic field control inside magnetic shield

HIBEAM in the ESS hall

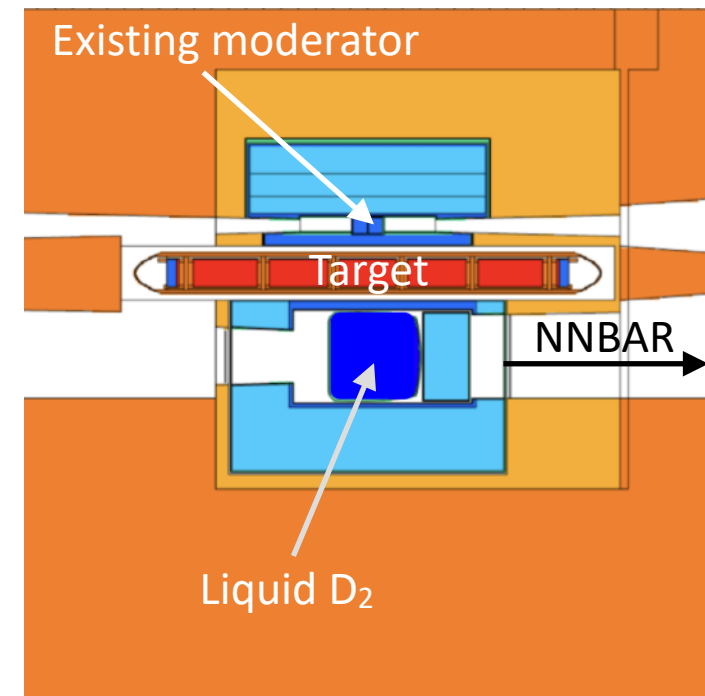
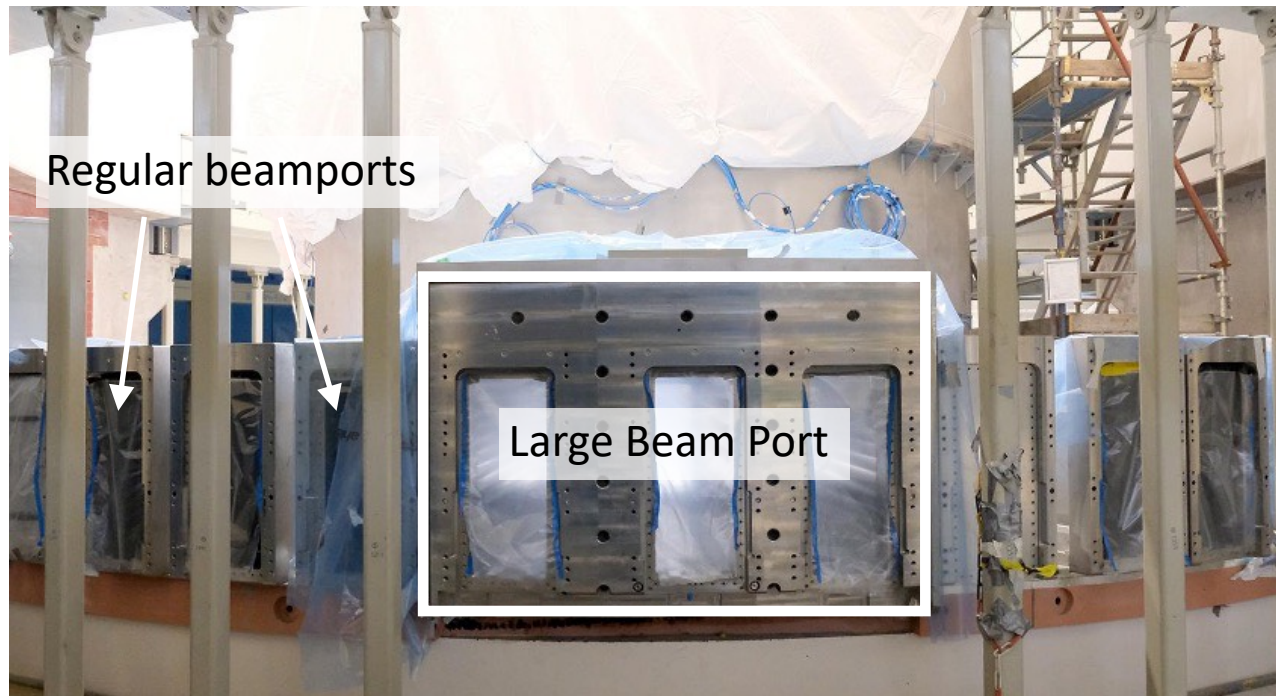


HIBEAM



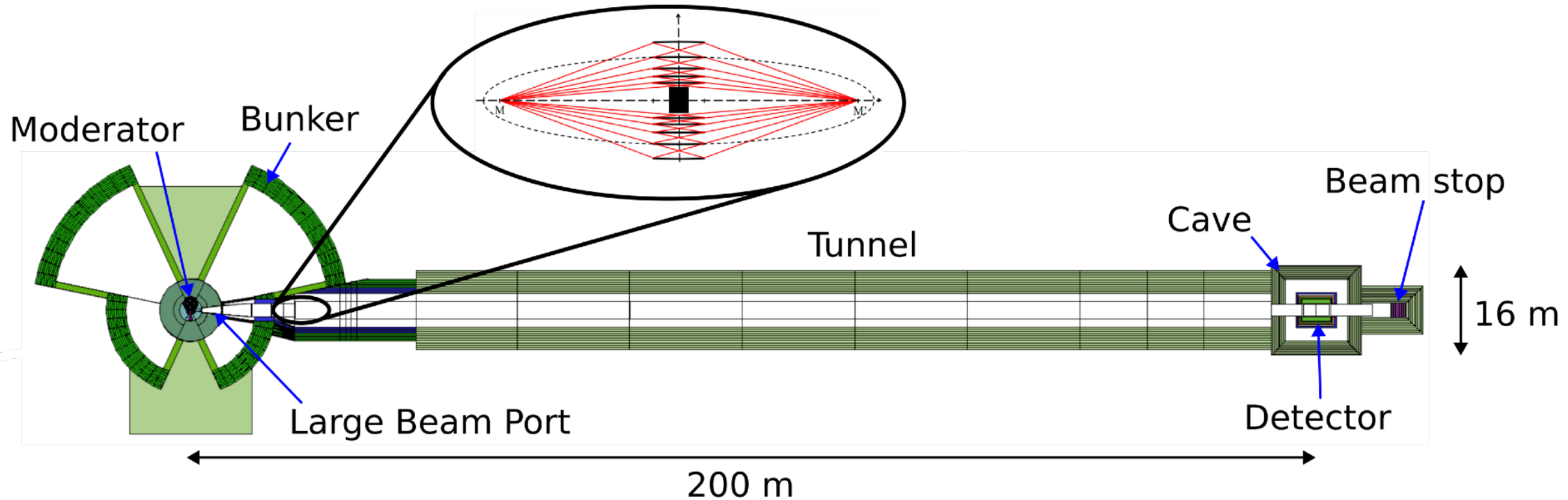
Preparing ESS for NNBAR

- Figure of merit scales as Nt^2 , want high-intensity of cold neutrons with long flight path.
- Use the Large Beam Port and a new LD₂ moderator below the ESS target.

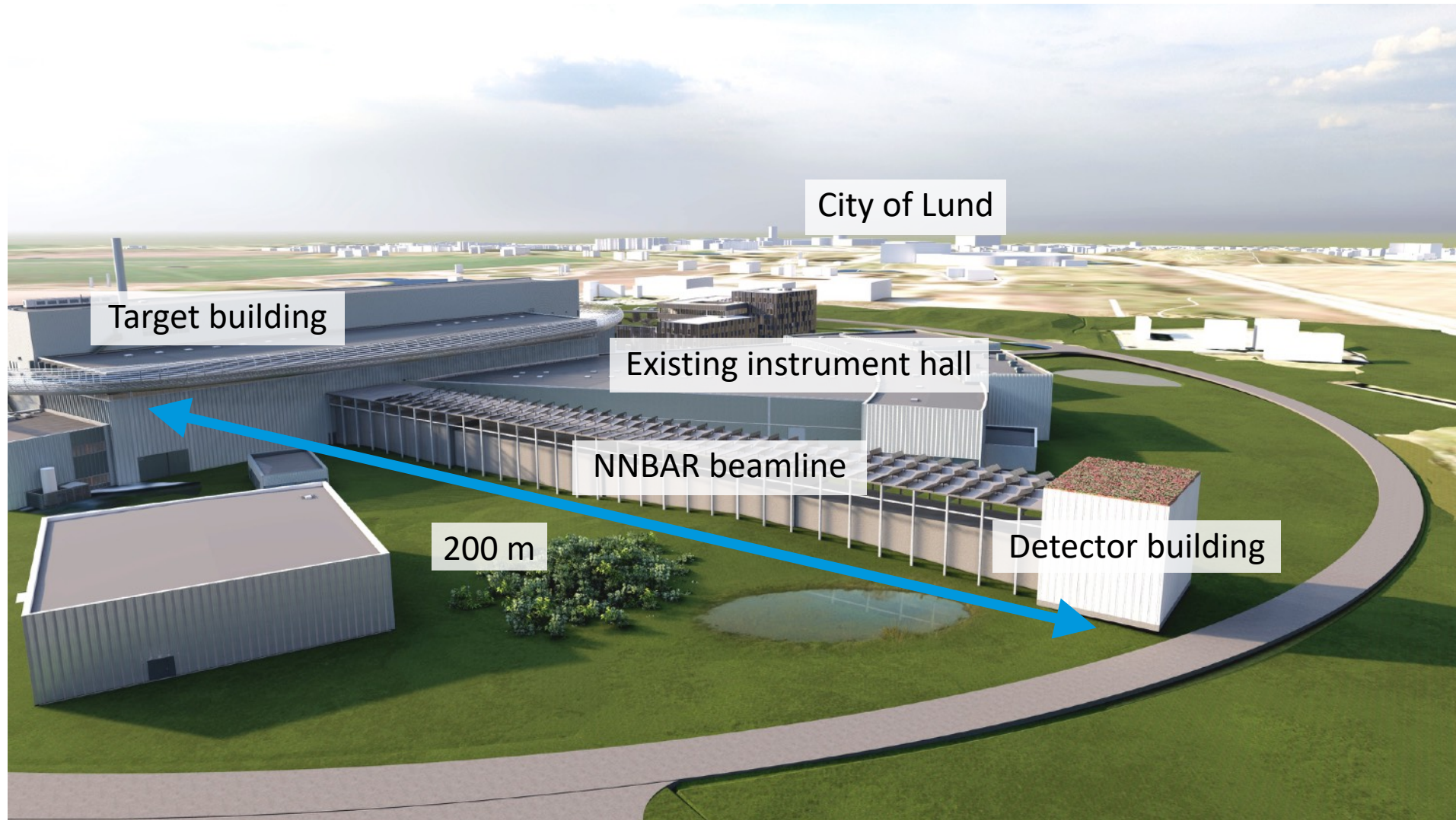


NNBAR beamline

Nested mirror optics



Outside view of NNBAR

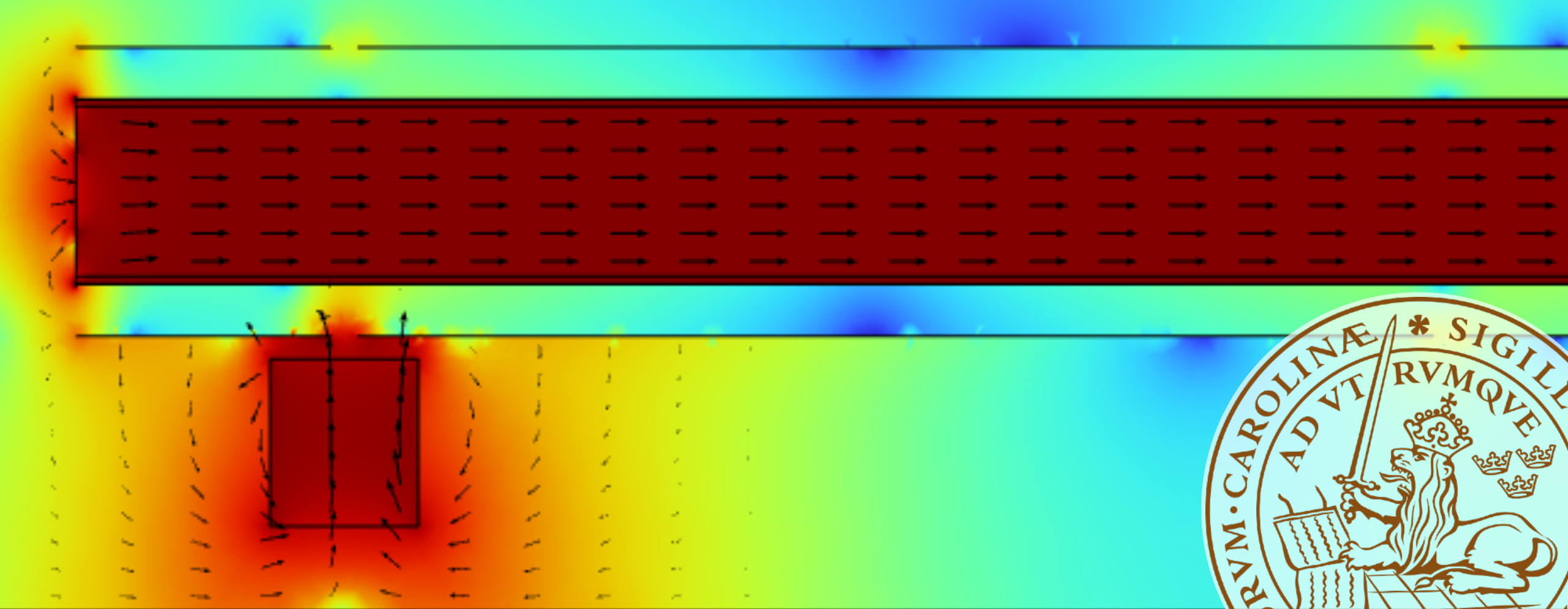


COMSOL simulation status for the nTMM experiment

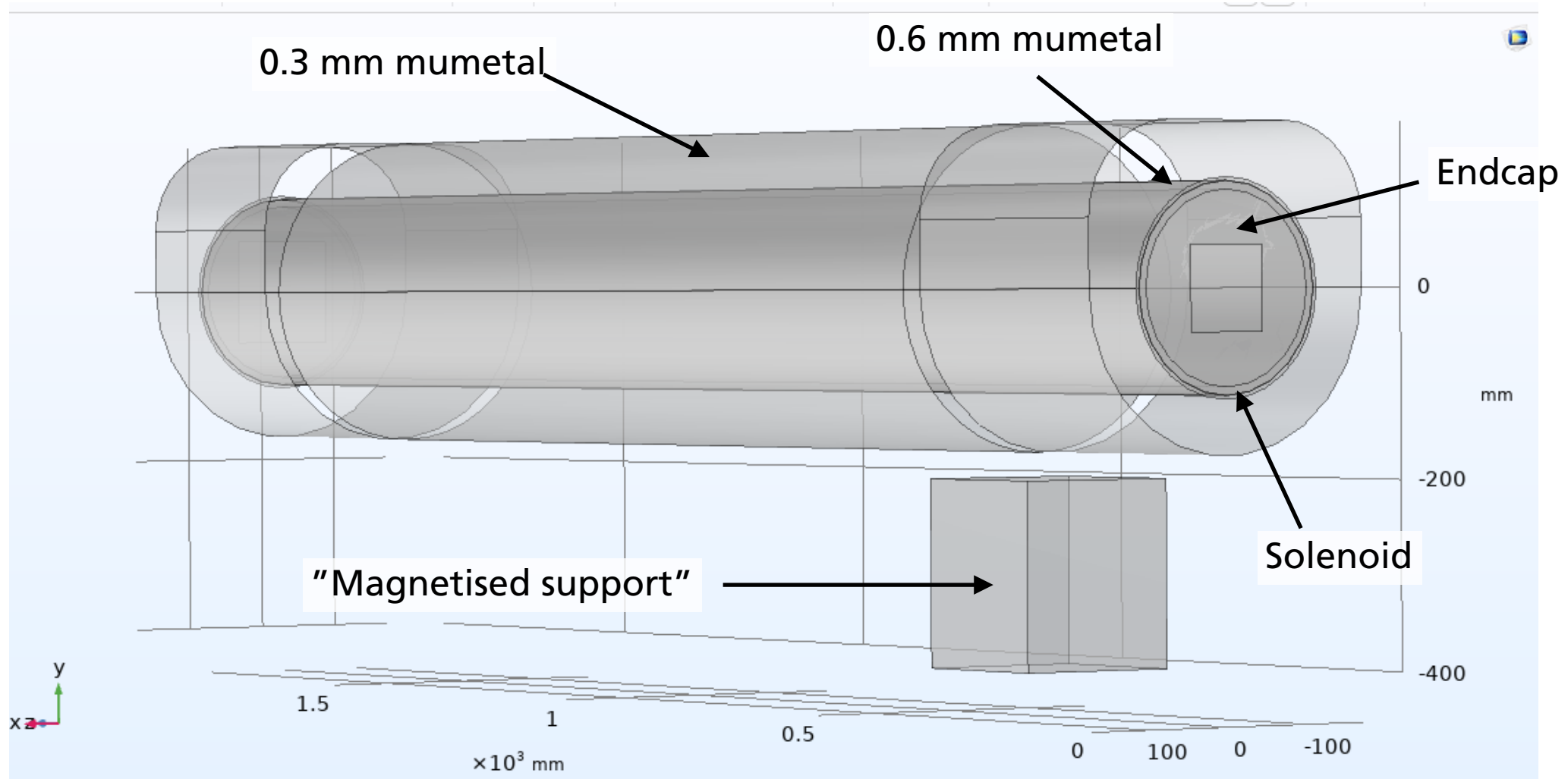
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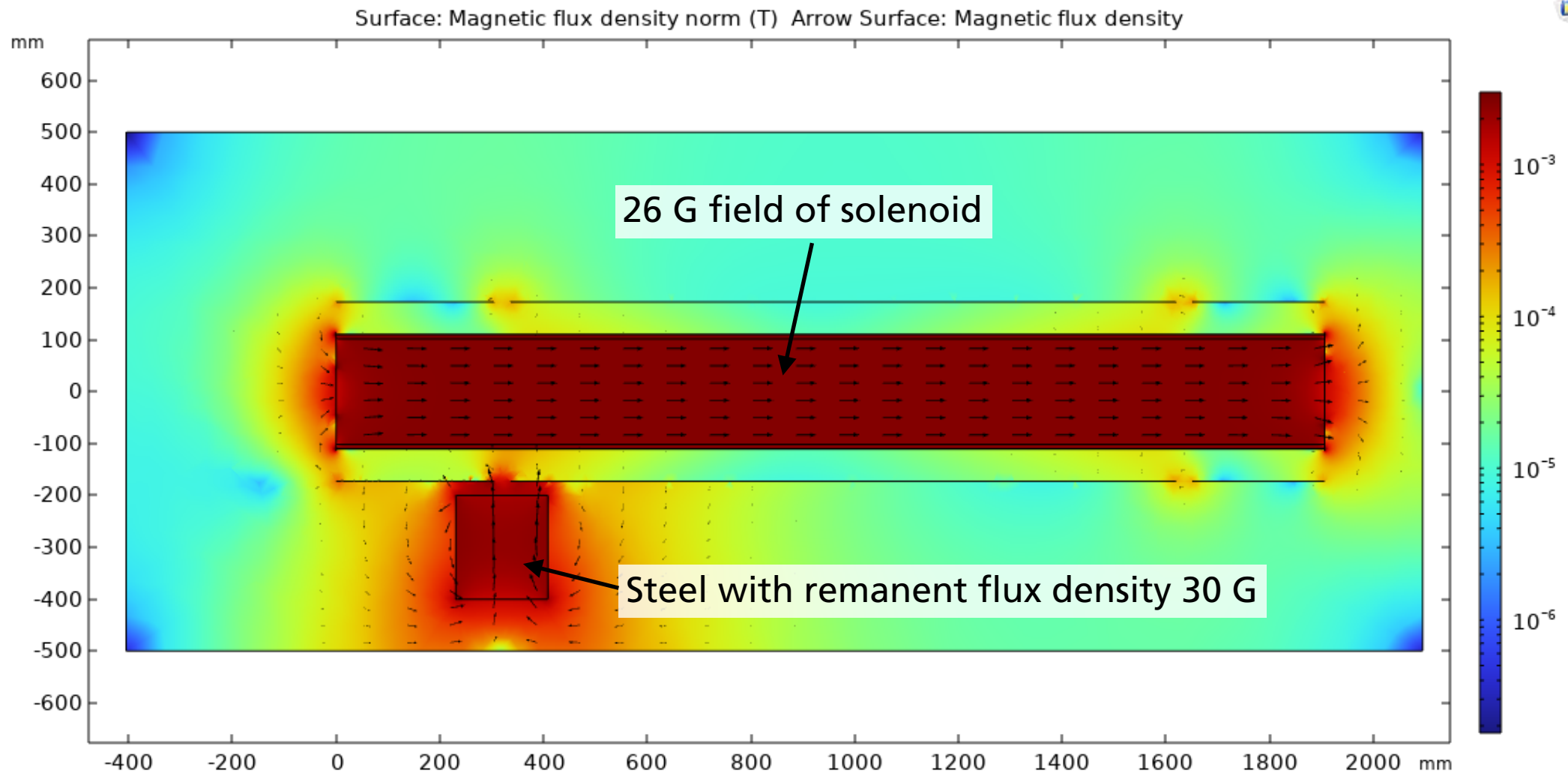
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COMSOL model of nTMM solenoid

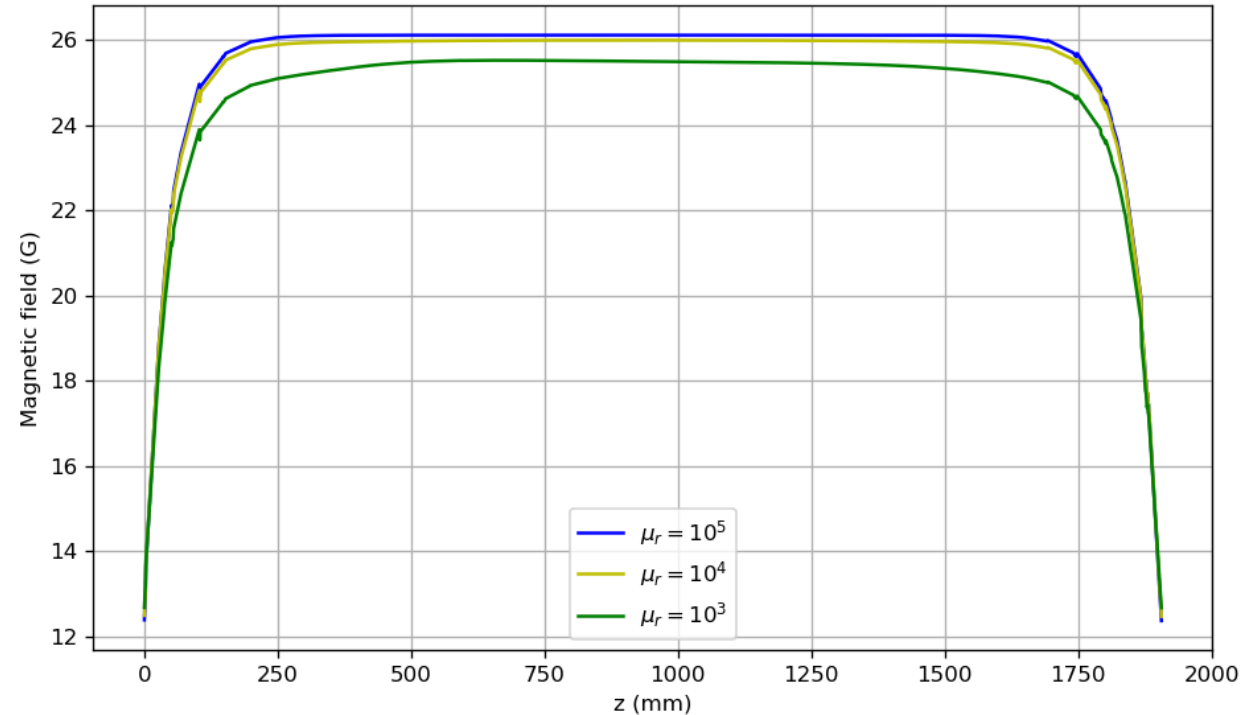


COMSOL simulation

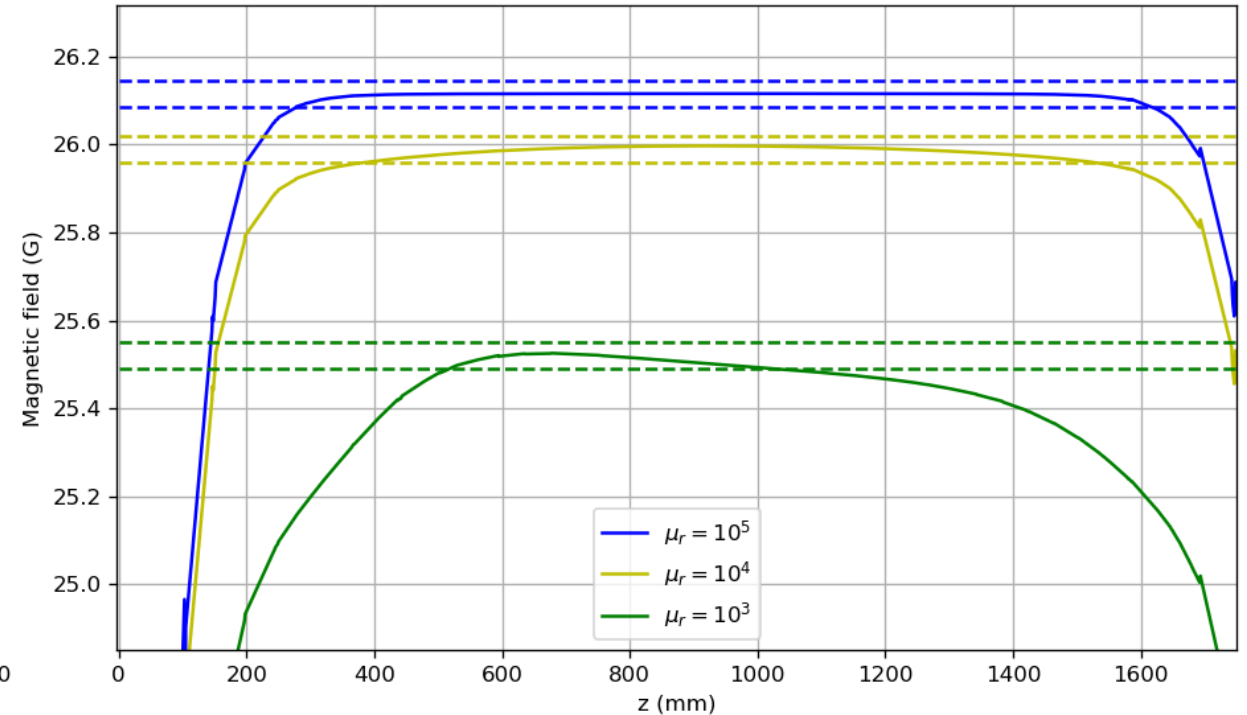


Total magnetic field along solenoid axis

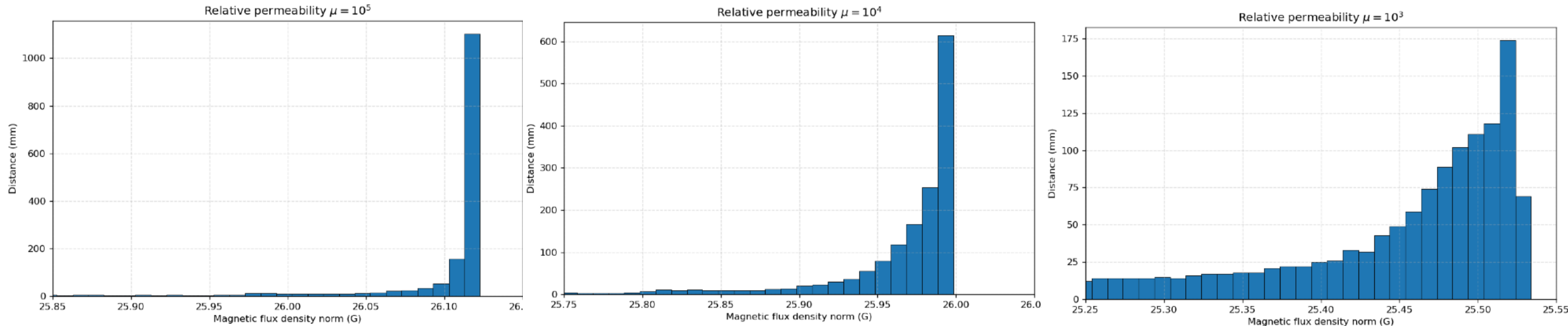
Comparison of Magnetic Flux Density Profiles



Comparison of Magnetic Flux Density Profiles



Total magnetic field along solenoid axis



What relative permeability should be used for the simulations?
This is what we need the prototype to determine!

Do we need to use the B-H curve magnetisation model in COMSOL?

