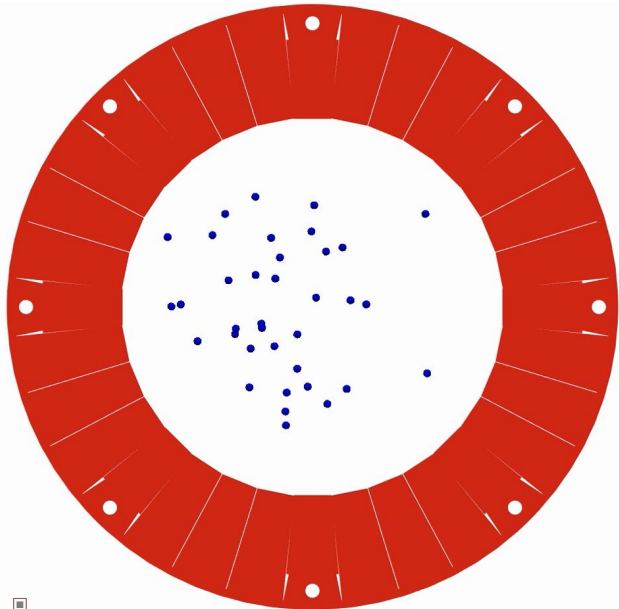


Trapping ultra-cold neutrons in a fully magnetic trap : the quest for the free neutron lifetime

Sylvain Vanneste

LPSC postdoc seminar

September 2026



Funded by
the European Union



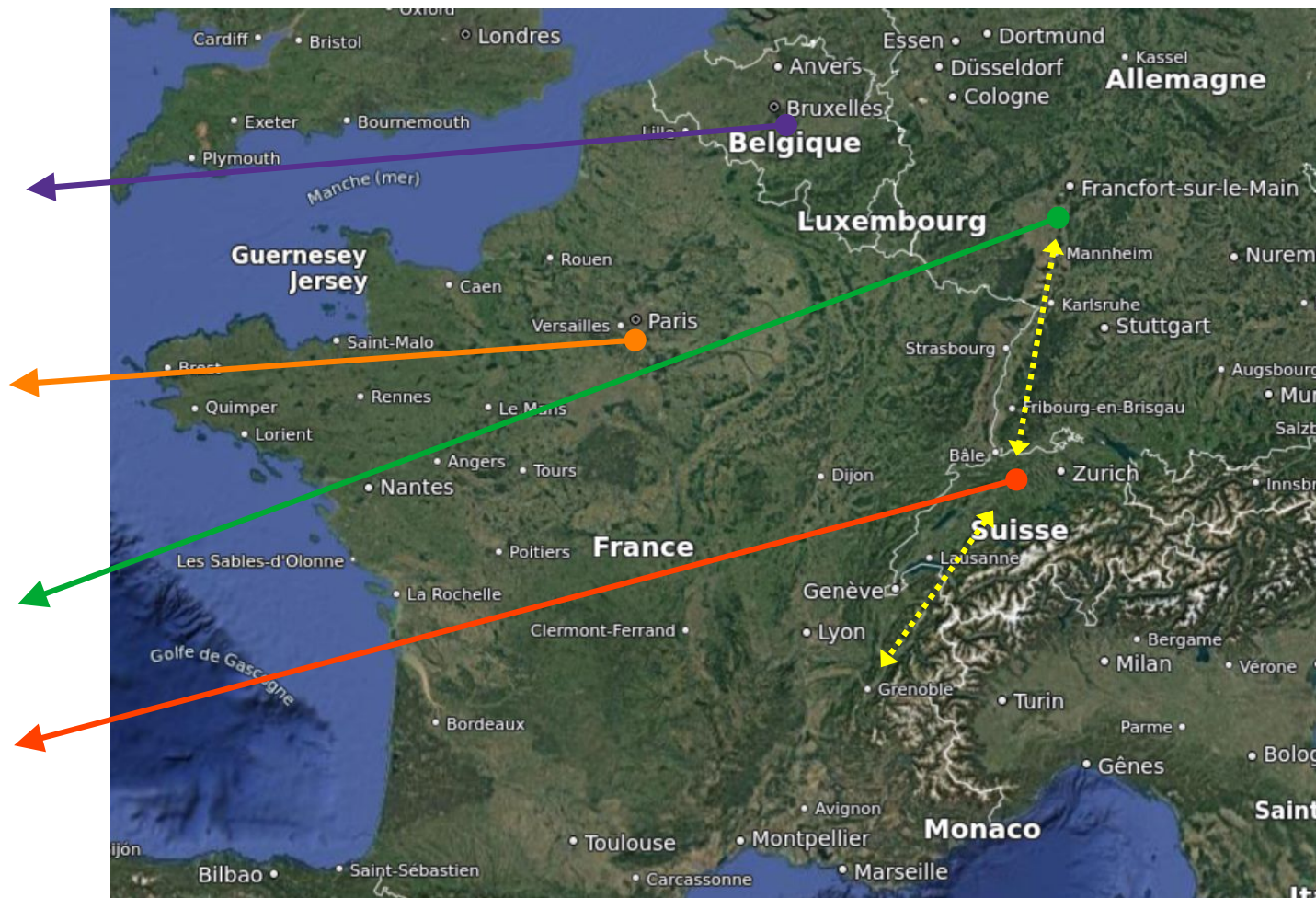
PRISMA+

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

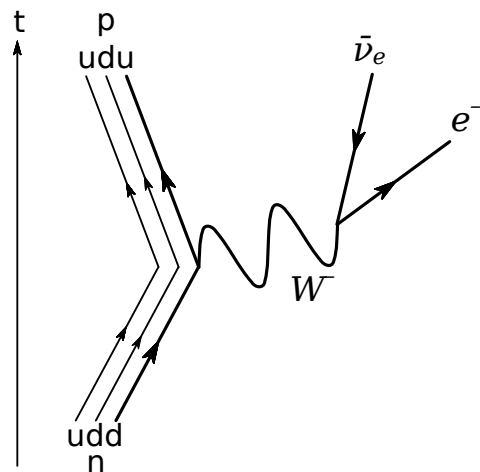


Career path

- **UCL, Belgium** :
 - Bachelor civil engineer,
 - Master physics, particle and cosmology.
- PhD Cosmology (CMB physics) at **IJClab, France**.
- Teaching activities
- Postdoc in **Mainz, Germany** :
Neutron lifetime study.
- tauSPECT experiment at **PSI, Switzerland**
- Postdoc LPSC, n2EDM at **PSI**



Free neutron lifetime and CKM constrains



Standard model "master formula"

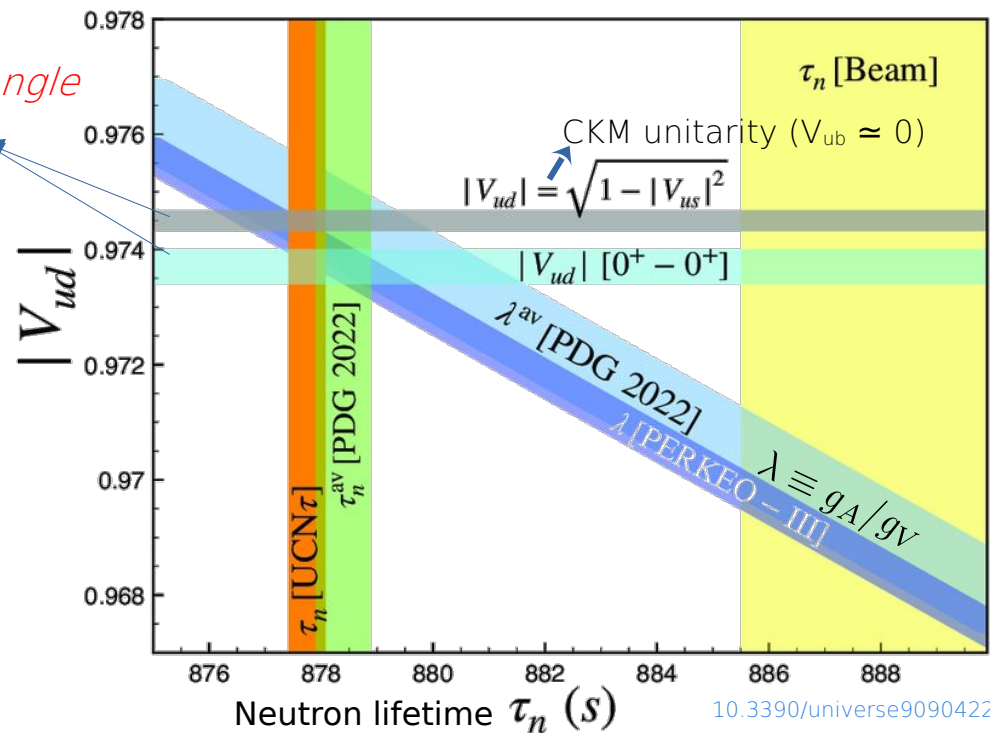
$$|V_{ud}|_n^2 \propto \frac{G_F^{-2}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

Neutron lifetime

$$\lambda \equiv g_A/g_V$$

Ratio axial-vector to vector couplings

Radiative corrections
 $\approx 40 \times 10^{-3}$



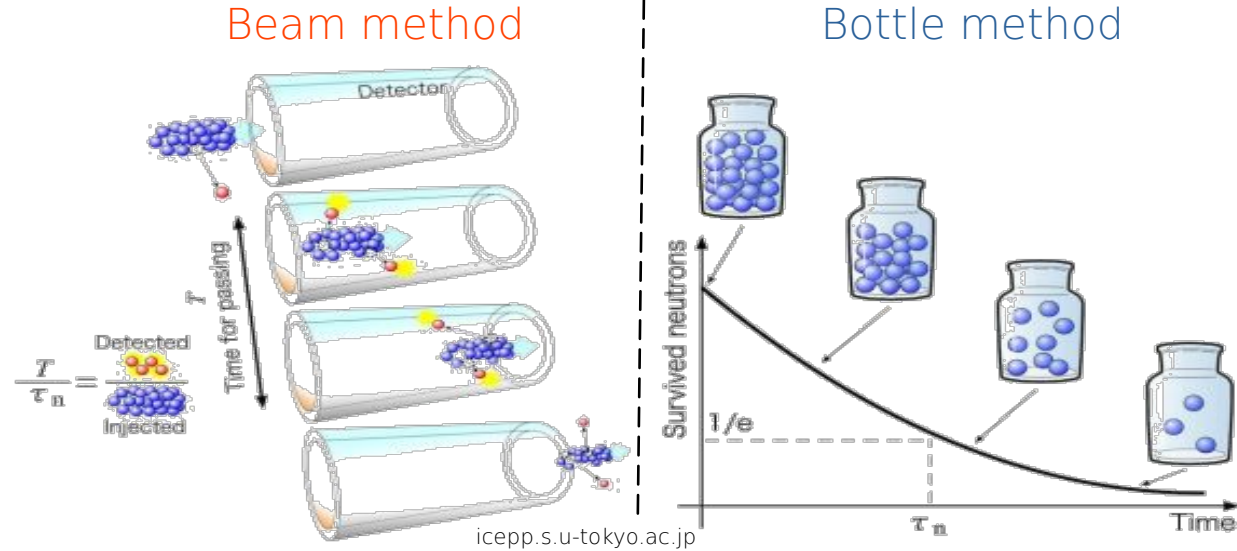
For CKM unitarity test at 10^{-4} level precision :

$$\rightarrow \sigma(\tau_n) < 0.3 \text{ s}$$
$$\rightarrow \sigma(\lambda) < 0.03 \%$$

Neutron lifetime puzzle

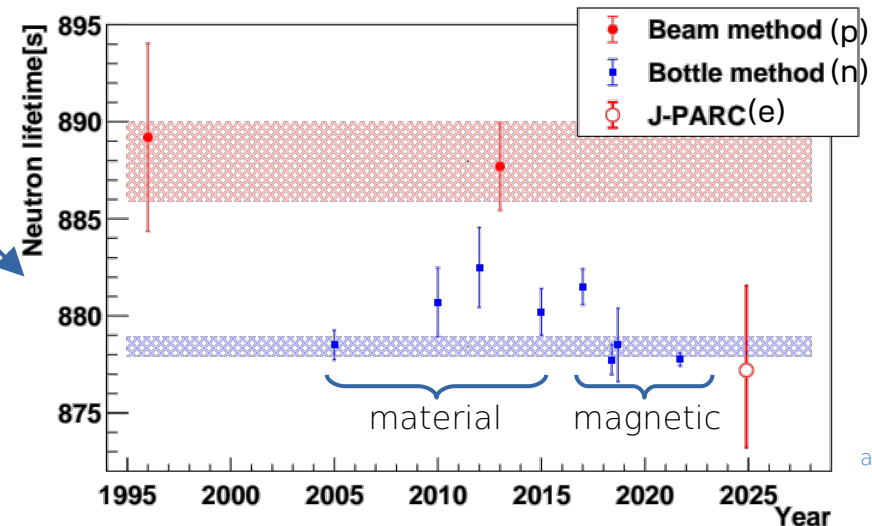
Two main experimental methods :

- **Beam** : counting the dead
($n \rightarrow p + e + \nu_e$)
- **Bottle** : counting the survivors



Beam & bottle methods disagree $> 4\sigma$!
 $\rightarrow$ *neutron lifetime puzzle*

- Unknown systematic error(s) in methods ?
- Exotic/dark neutron decays ?
- Neutron excited state ?
- Trapped neutrons kicked out by ambient DM



[arXiv:2412.19519](https://arxiv.org/abs/2412.19519)

Ultra-cold neutron

Ultra Cold Neutron (UCN) : speed $v \lesssim 8 \text{ m/s}$ $\rightarrow$ Kinetic Energy $E_k \lesssim 350 \text{ neV}$

- Strong interaction :

Coherent interaction with nuclei

$\rightarrow$ effective optical "Fermi" potential V_F

Material	V_F (neV)
Al	54
Steel	183
NiMo	300

- Gravitational interaction :

$$F_g = g \cdot m_n$$

$$\rightarrow \Delta E \approx \Delta z \cdot 102 \text{ neV/m}$$

- Weak interaction :

$$\text{Lifetime : } \tau_n \approx 880 \text{ s}$$

- Electromagnetism interaction :

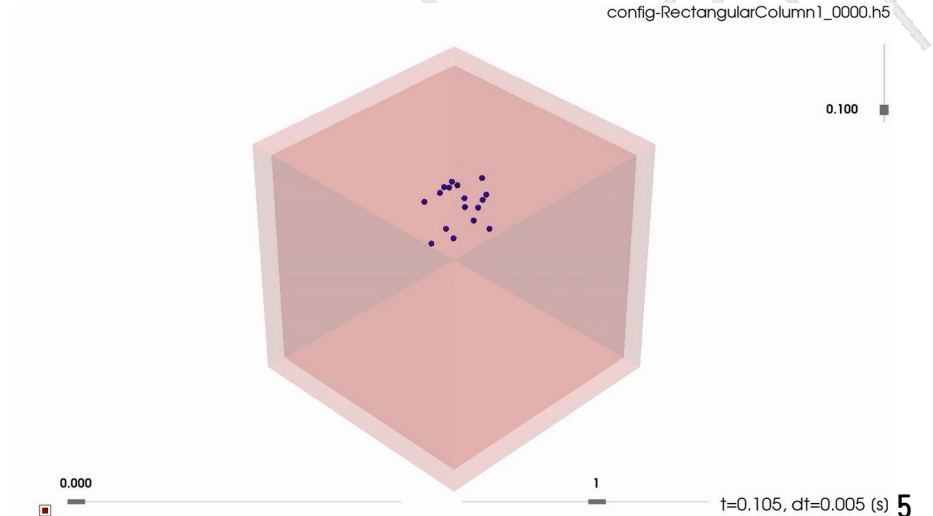
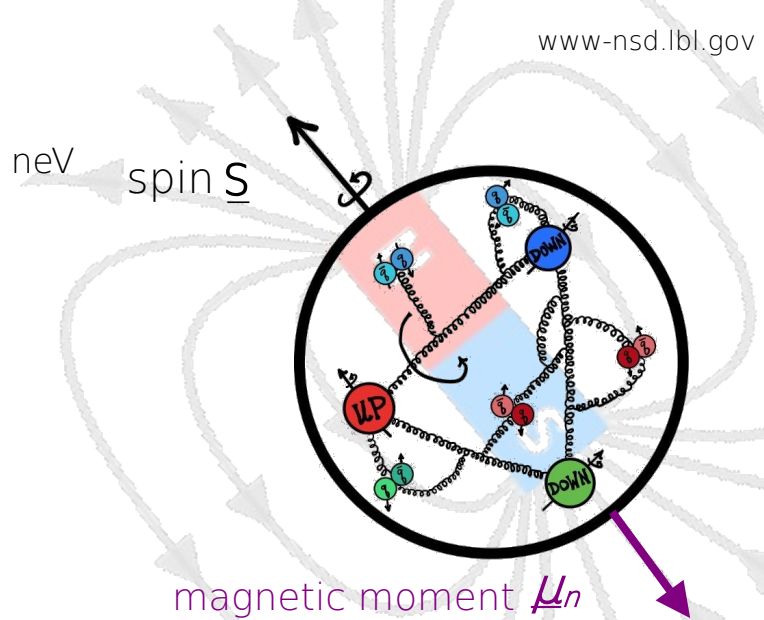
$$F_m = -\rho \cdot |\mu_n| \cdot \nabla |B|$$

$$\rightarrow \Delta E \approx \Delta |B| \cdot 60 \text{ neV/T}$$

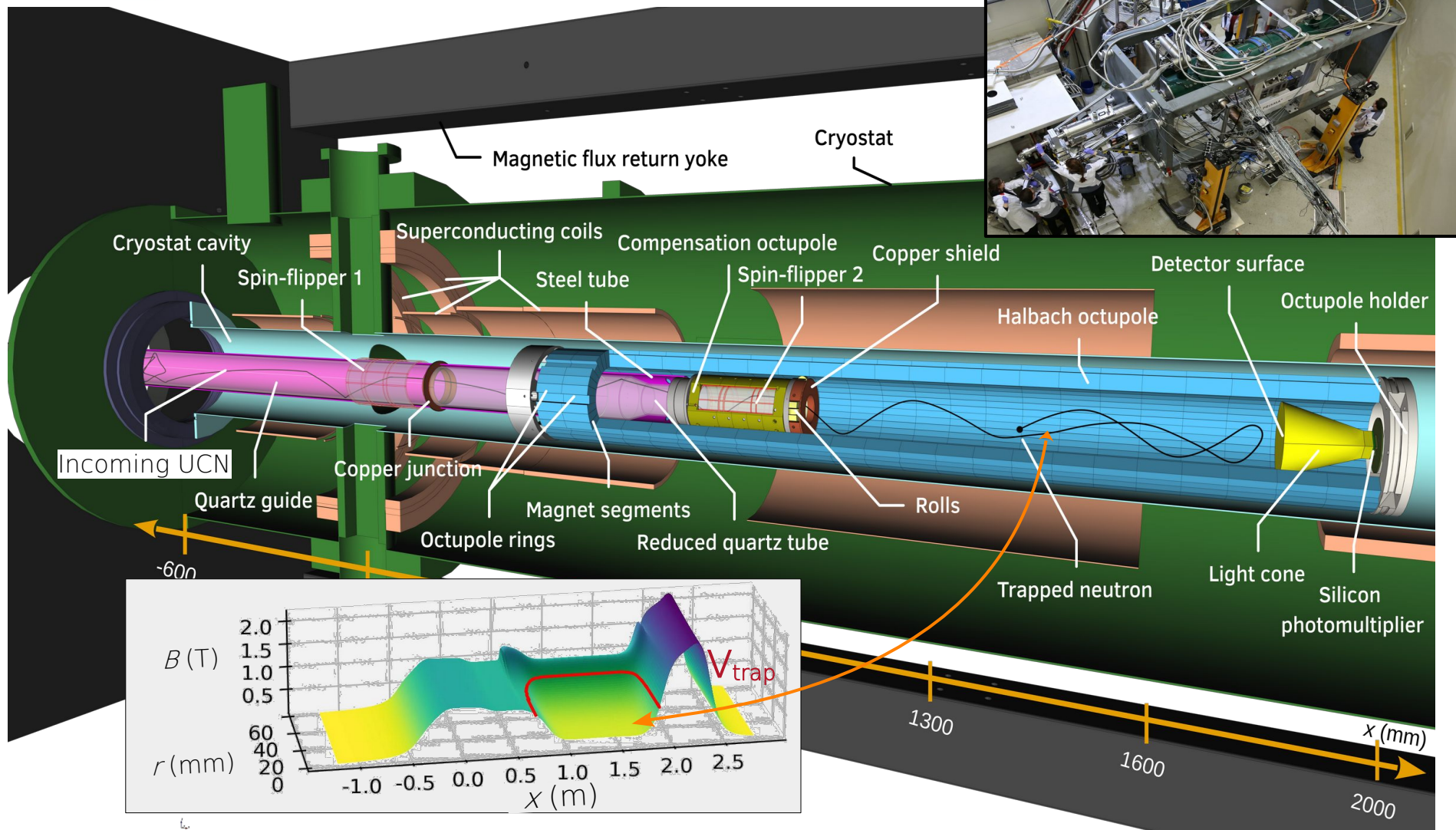
$\hookrightarrow$ polarization $\rho = \text{sign}(\underline{S} \cdot \underline{B})$

- High Field Seeker (HFS) : $\underline{S} \uparrow \downarrow \underline{B} \rightarrow \rho = -1$

- Low Field Seeker (LFS) : $\underline{S} \uparrow \uparrow \underline{B} \rightarrow \rho = +1$

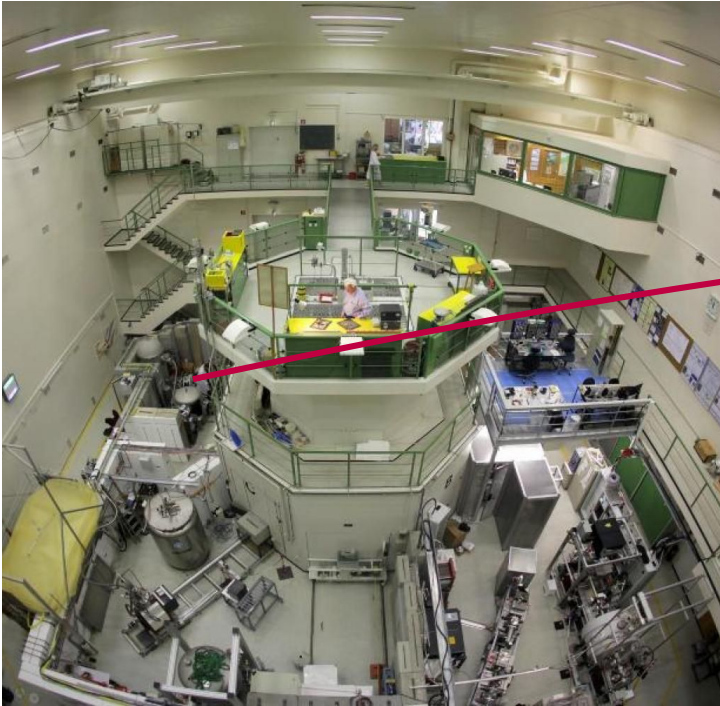


The τ SPECT experiment

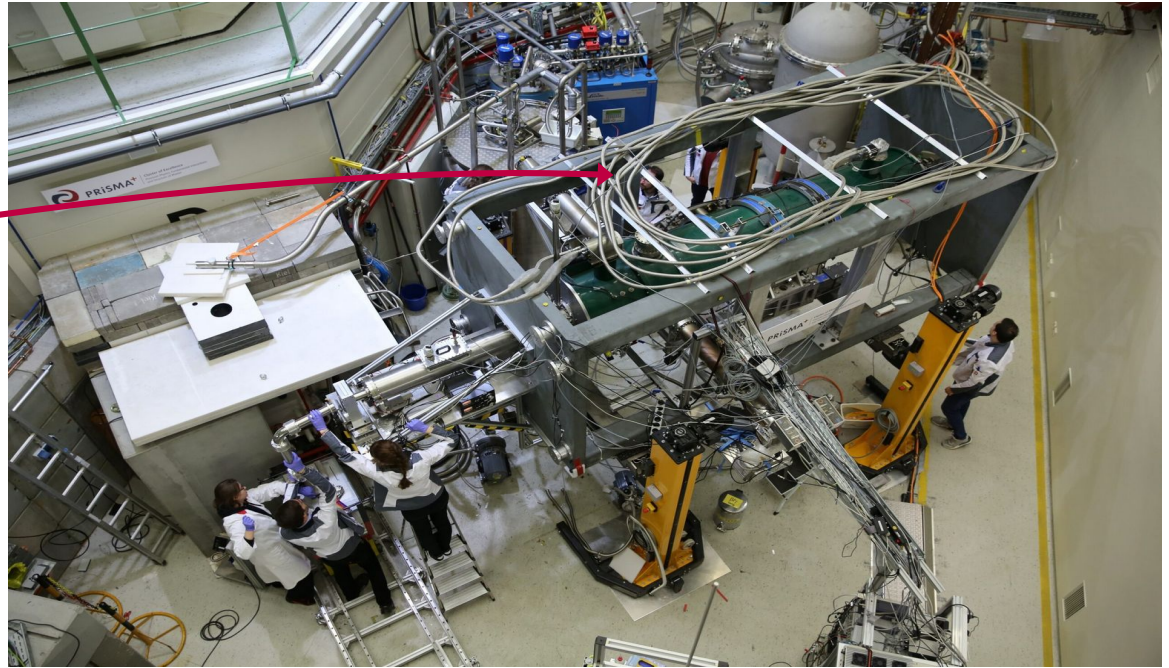


τ SPECT at Mainz, Germany

TRIGA nuclear reactor

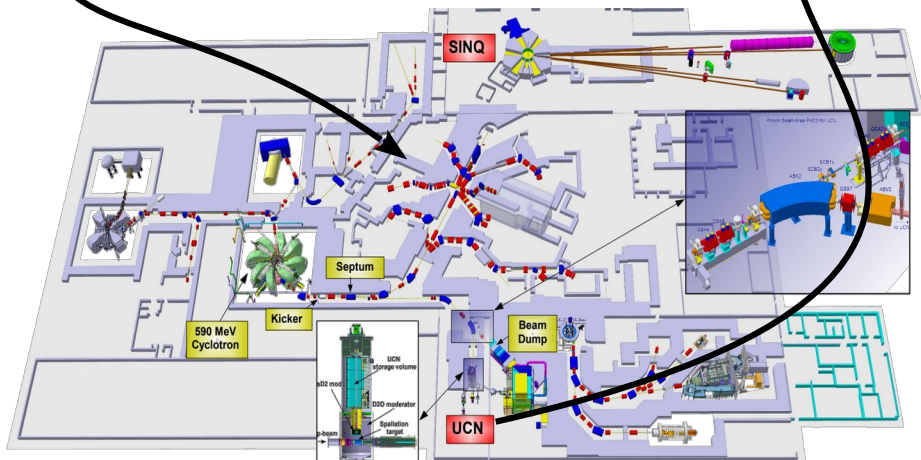


τ SPECT, 2015-2022



τ SPECT at PSI

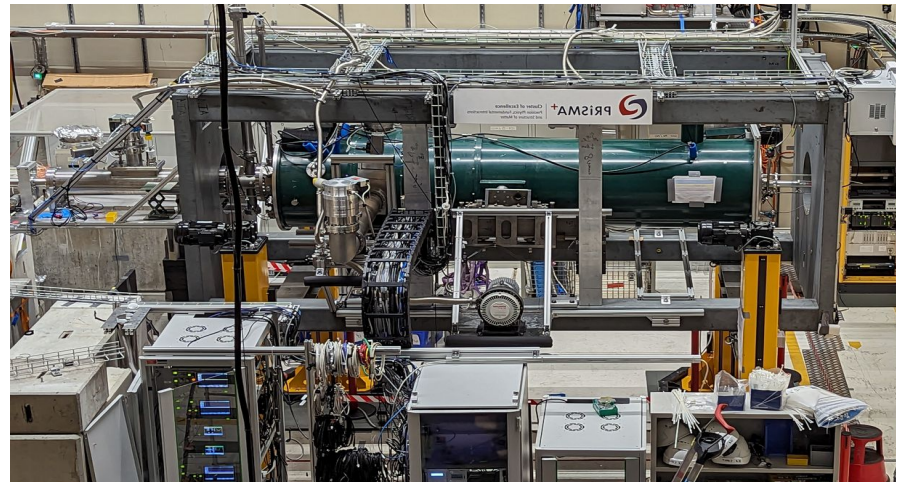
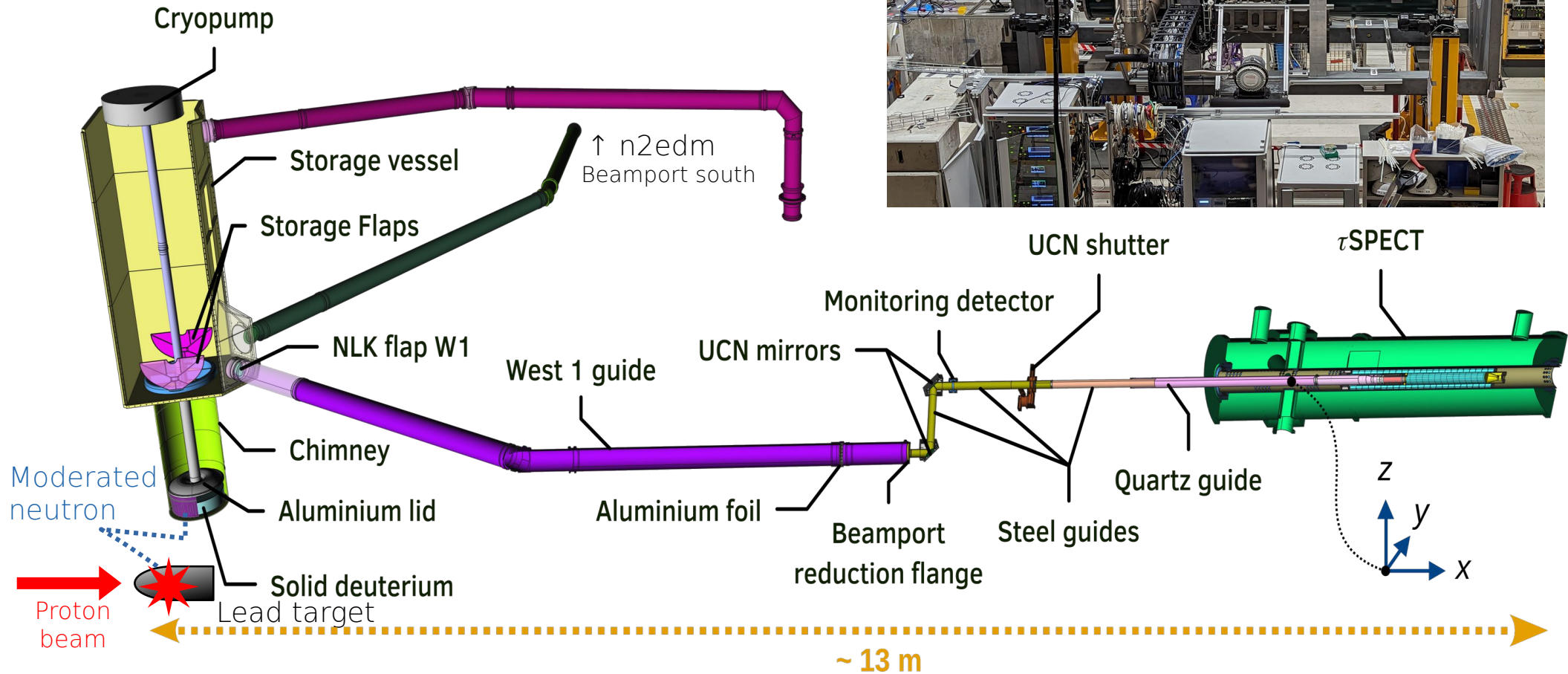
Paul Sherrer Institute (PSI), Switzerland



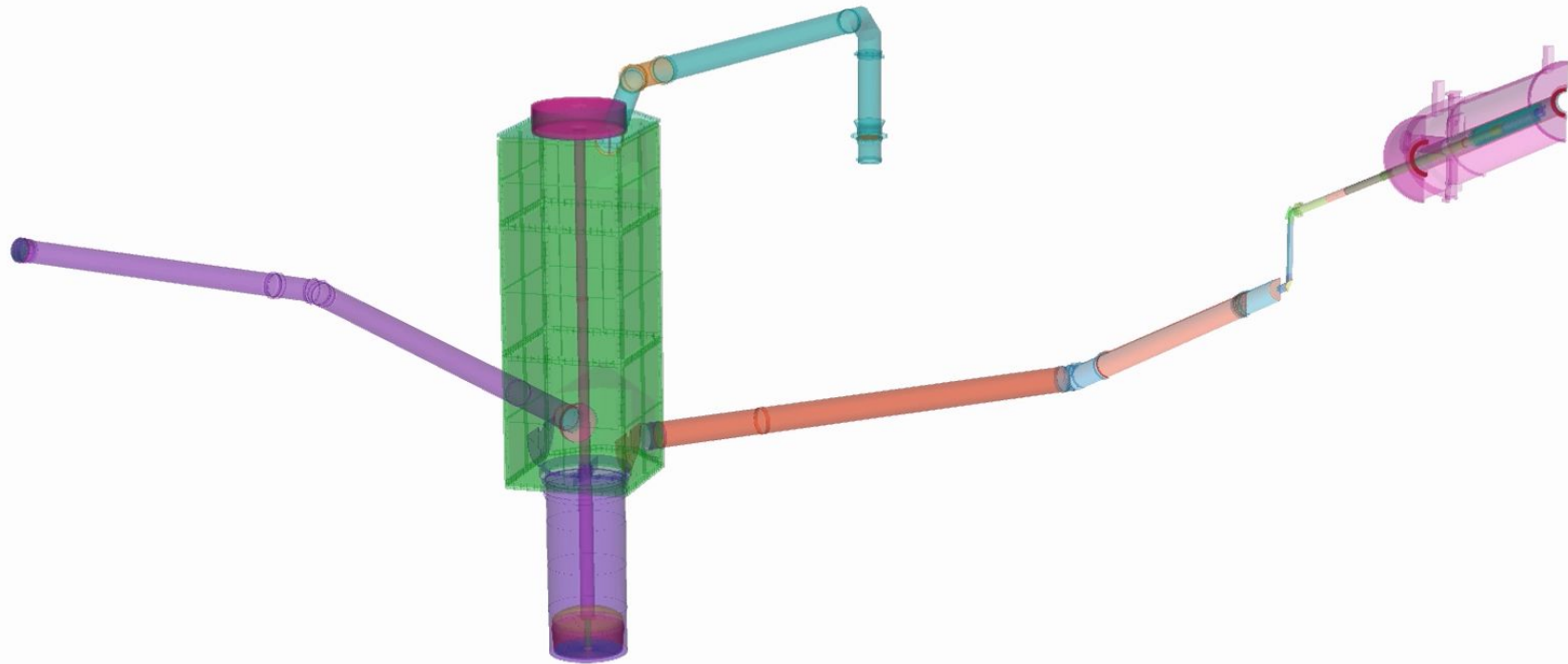
τ SPECT, 2023



τ SPECT & UCN source at PSI

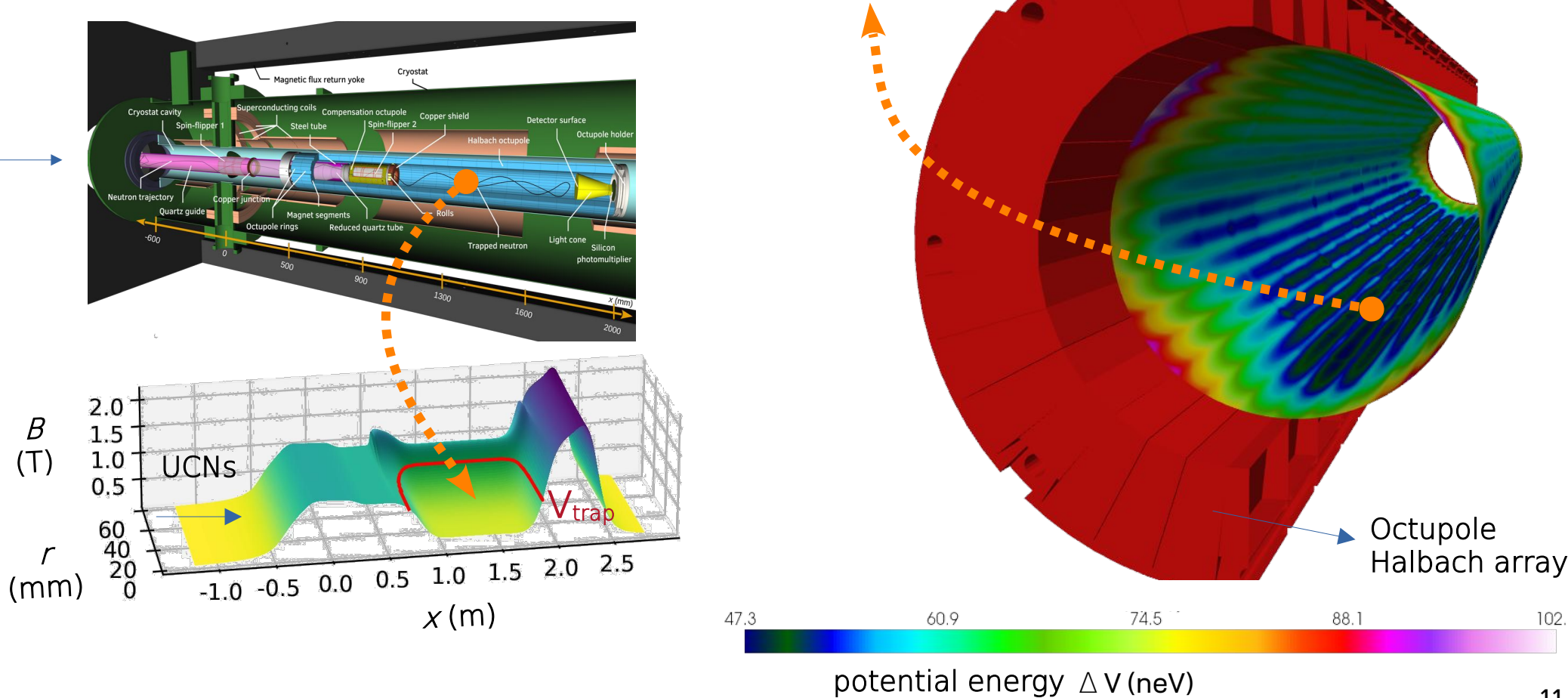


Complete simulation framework



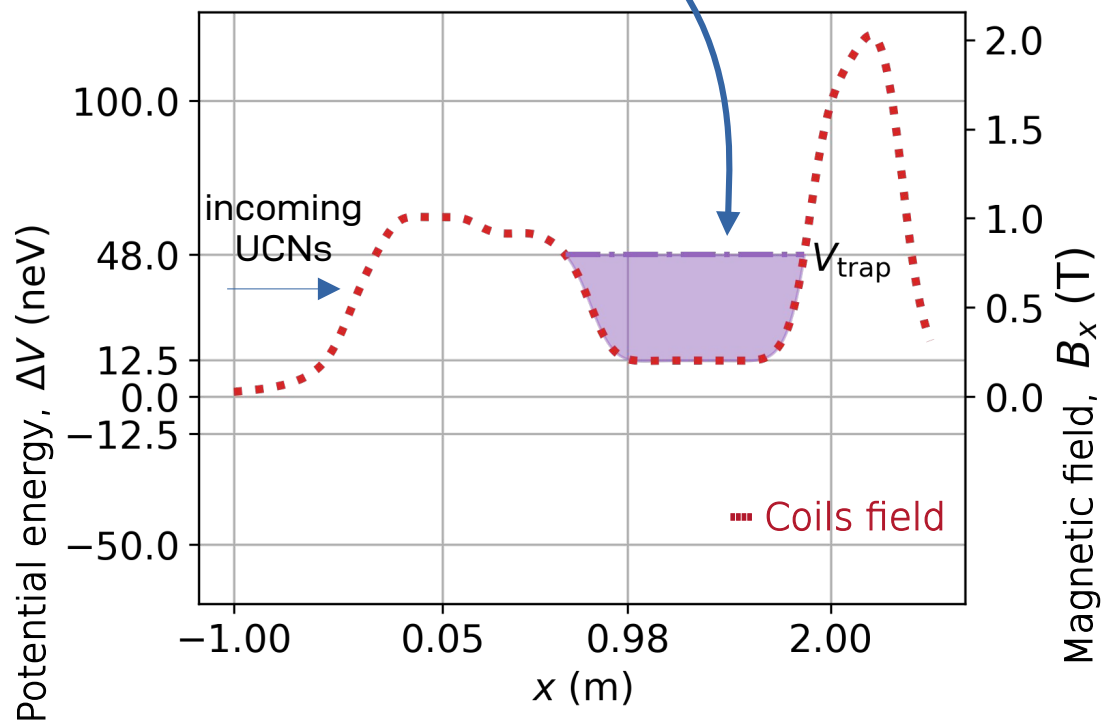
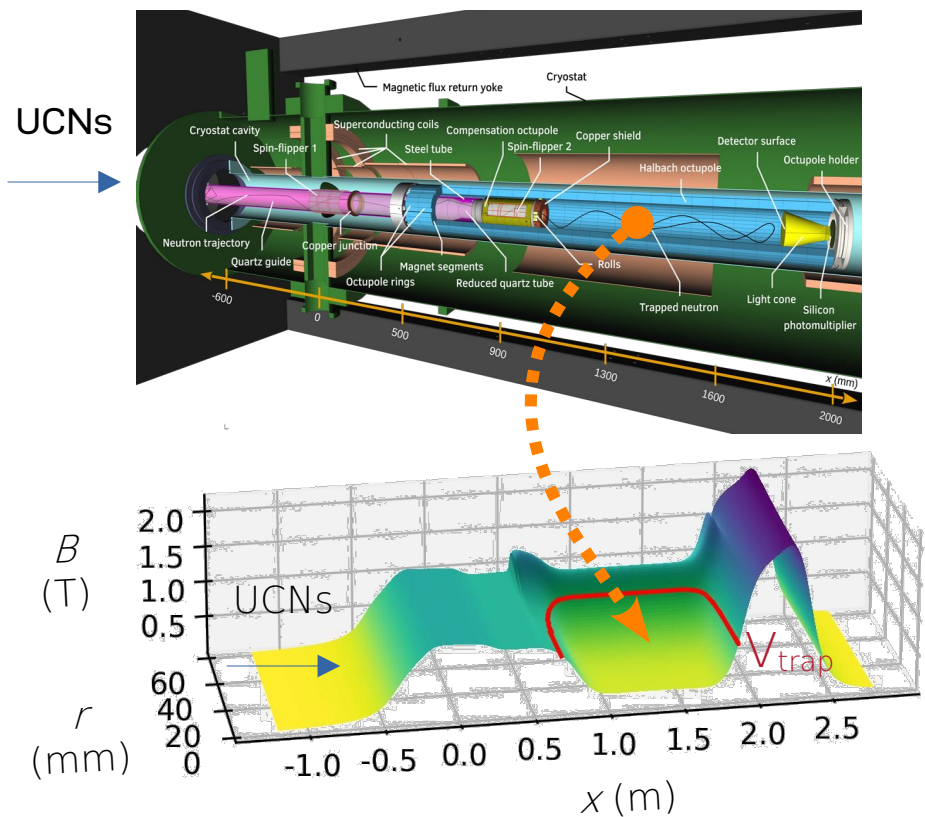
Trap magnetic potential

- Trap potential : $V_{\text{trap}} = \min(V_{\text{magnetic}} + V_{\text{gravity}})|_{r=R_i} \simeq 48 \text{ neV},$



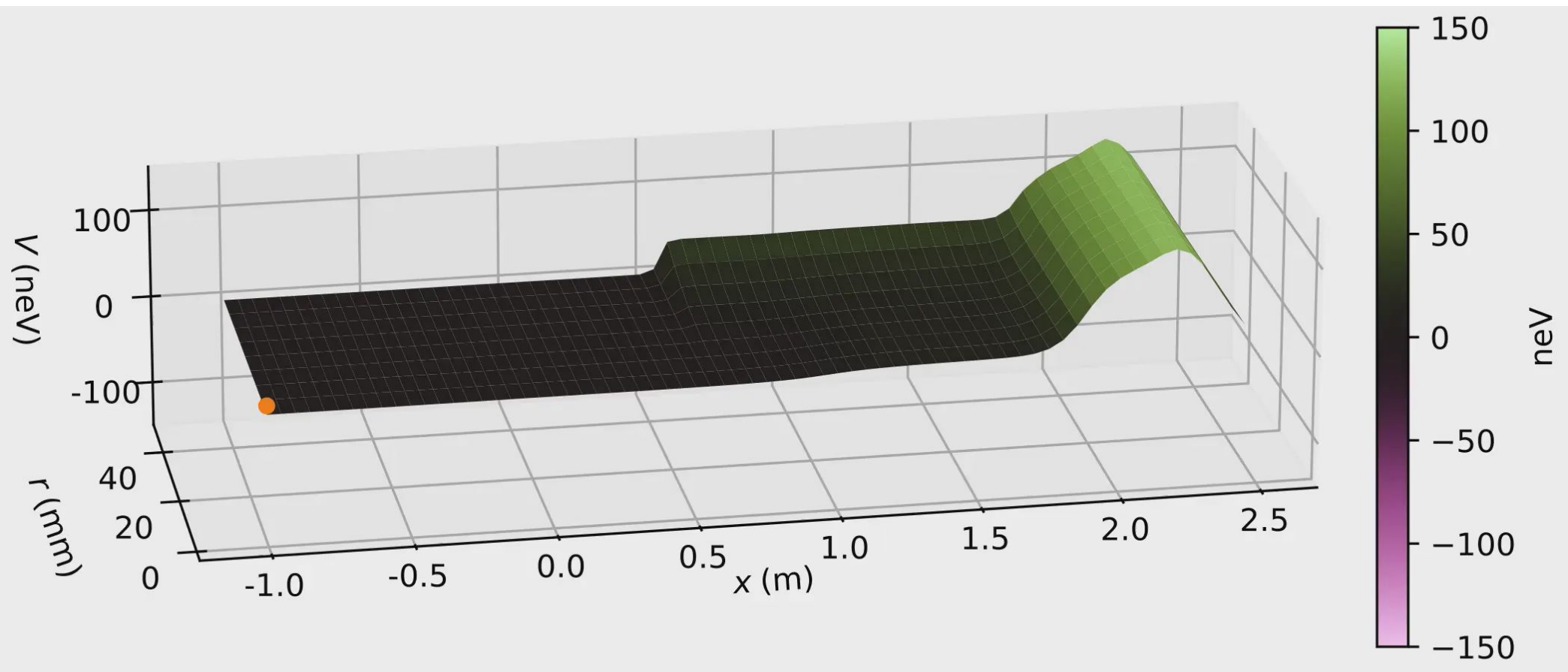
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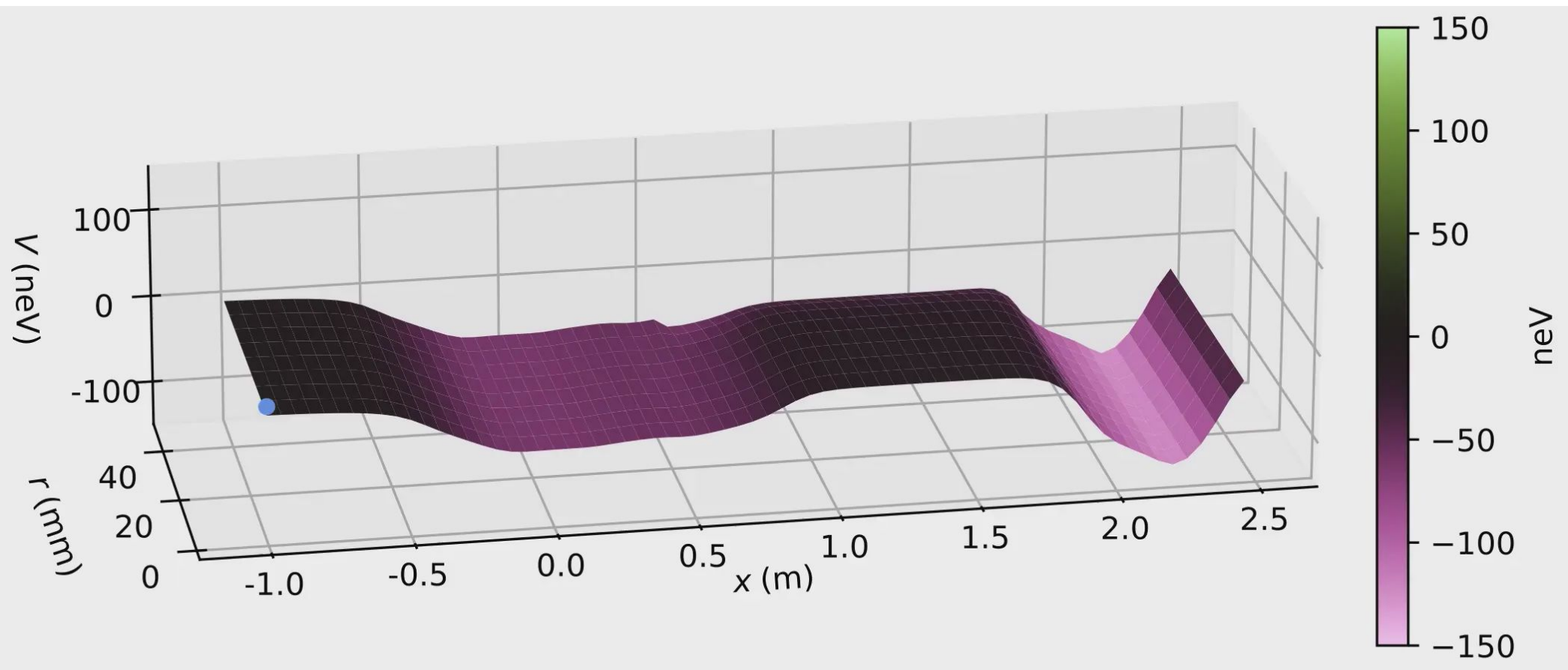
Filling a magnetic trap : field ramping

- 1) Wait for UCNs to come in the trap,
- 2) then close the door.



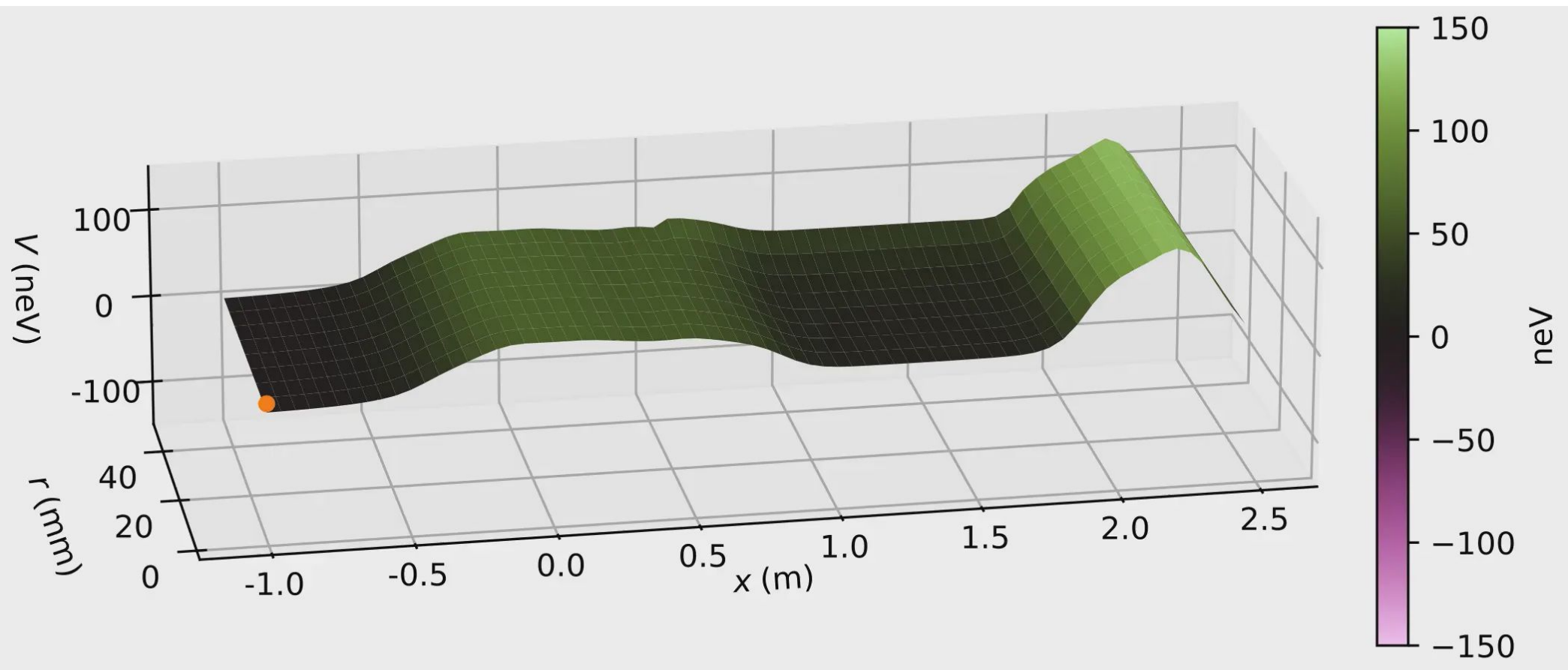
Filling a magnetic trap : neutron spin-flip

- 1) Let HFS pass the first magnetic bump
- 2) Then spin-flip them into LFS once in the trap.



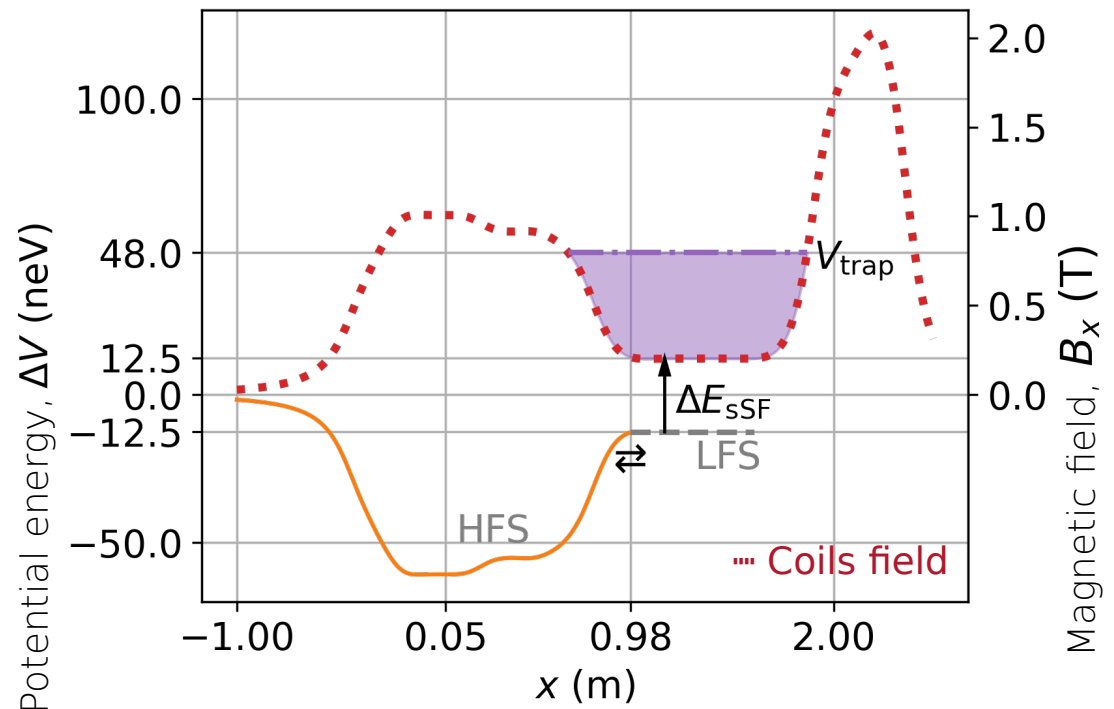
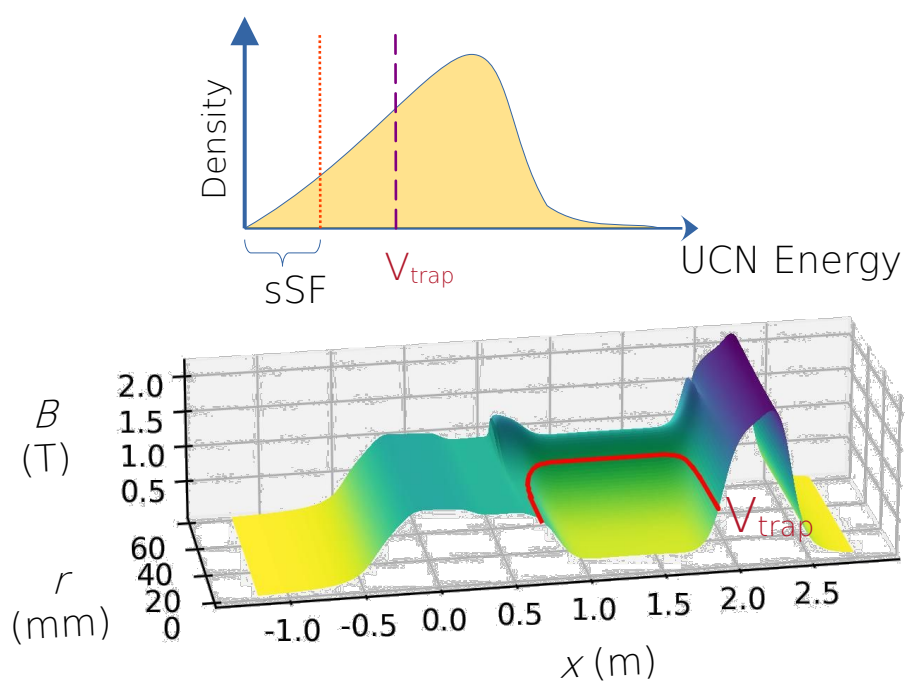
Filling a magnetic trap : double spin-flip

- 1) Slow down LFS that climb the first magnetic bump, then spin-flip them into HFS.
- 2) Slow down those HFS as they exit the first magnetic bump, then spin-flip them into LFS once in the trap.



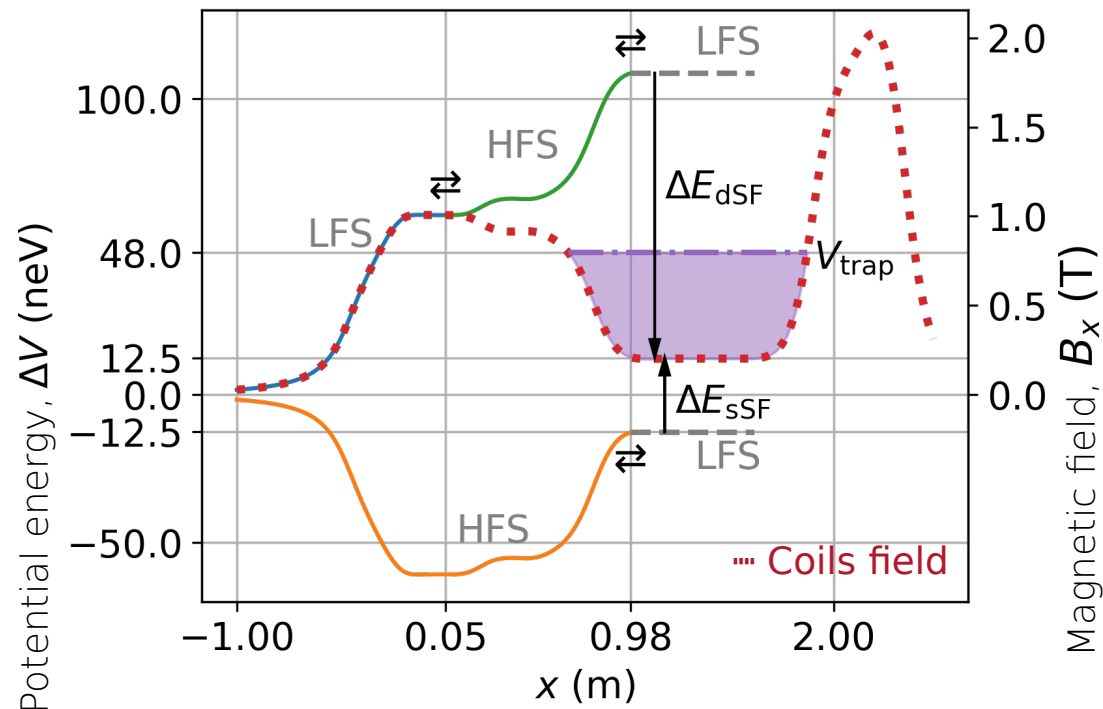
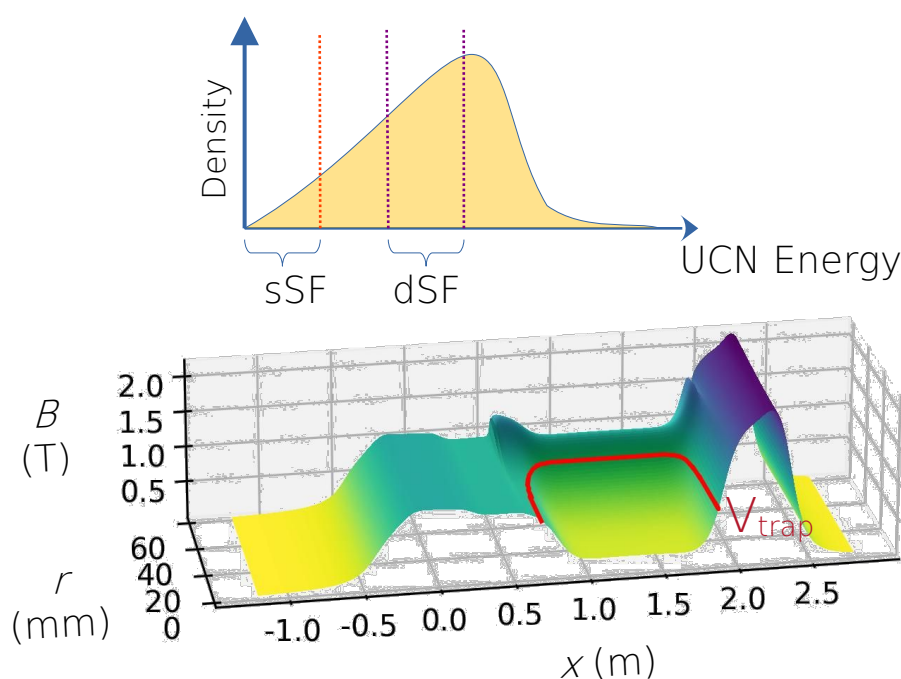
Spin-flip & energy acceptance

- Trap potential : $V_{\text{trap}} = \min(V_{\text{magnetic}} + V_{\text{gravity}})|_{r=R_i} \simeq 48 \text{ neV}$,
- Storable neutrons with single spin-flip (sSF), total energy acceptance : $E_{\text{sSF}} \in [0, V_{\text{trap}} - \Delta E_{\text{sSF}}] \simeq [0, 23] \text{ neV}$.



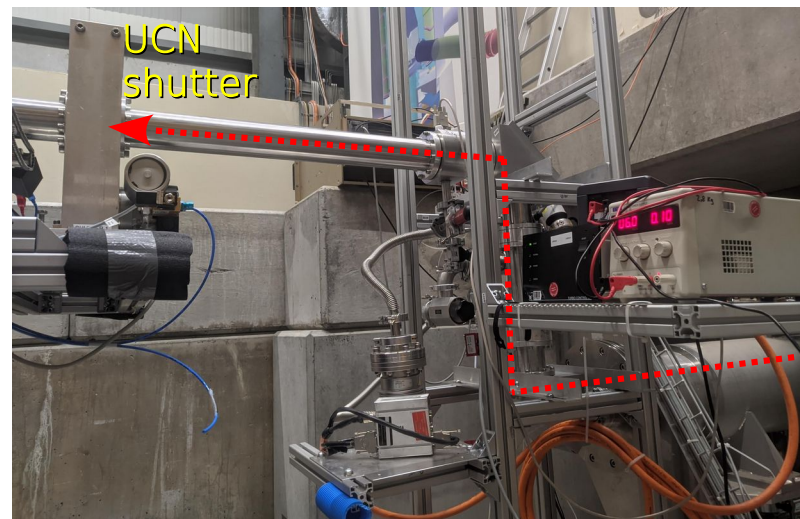
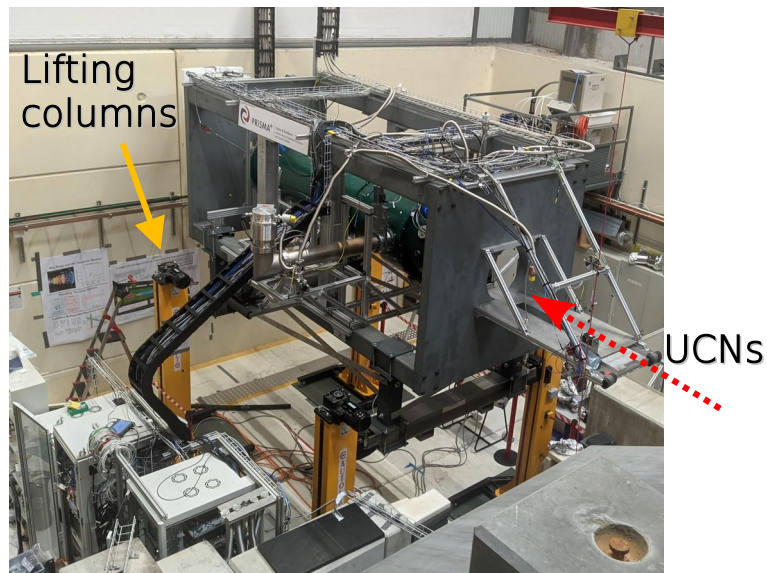
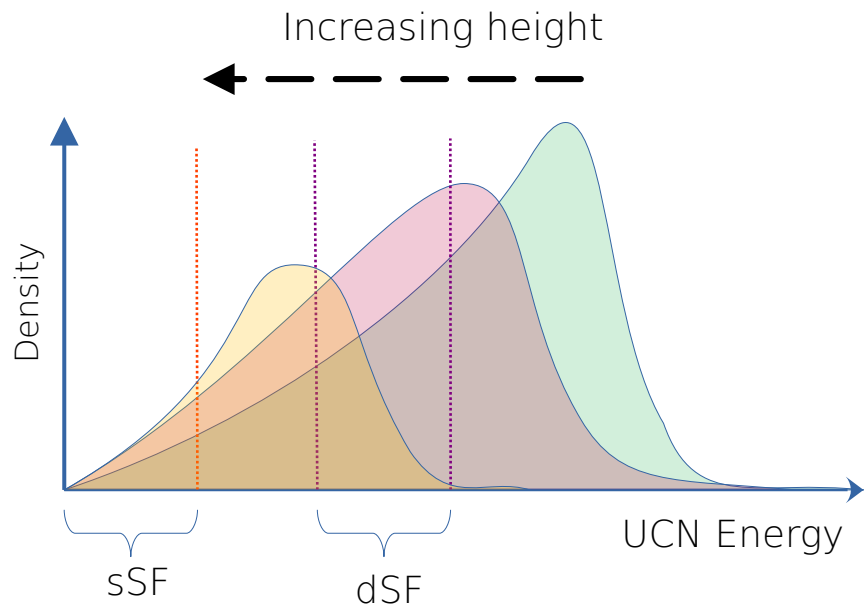
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- For double spin-flip (dSF) : $E_{\text{dSF}} \in [\Delta E_{\text{dSF}} - V_{\text{min}}, V_{\text{trap}} - \Delta E_{\text{dSF}}] \simeq [108, 134] \text{ neV}$.



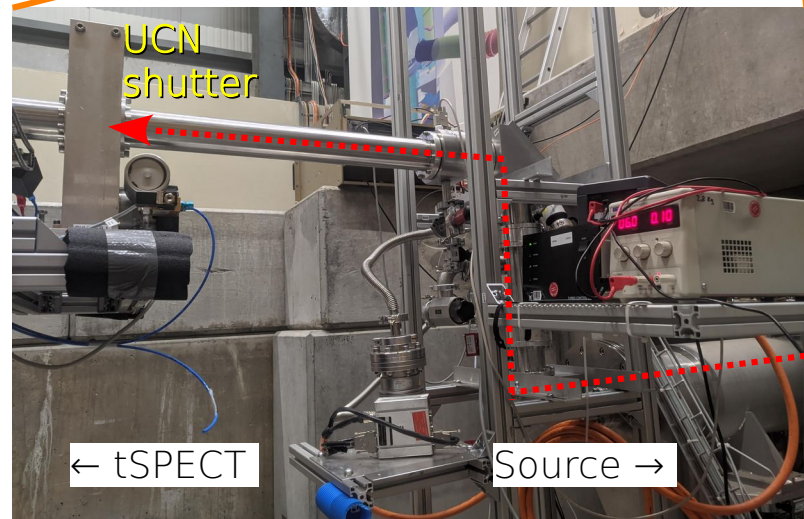
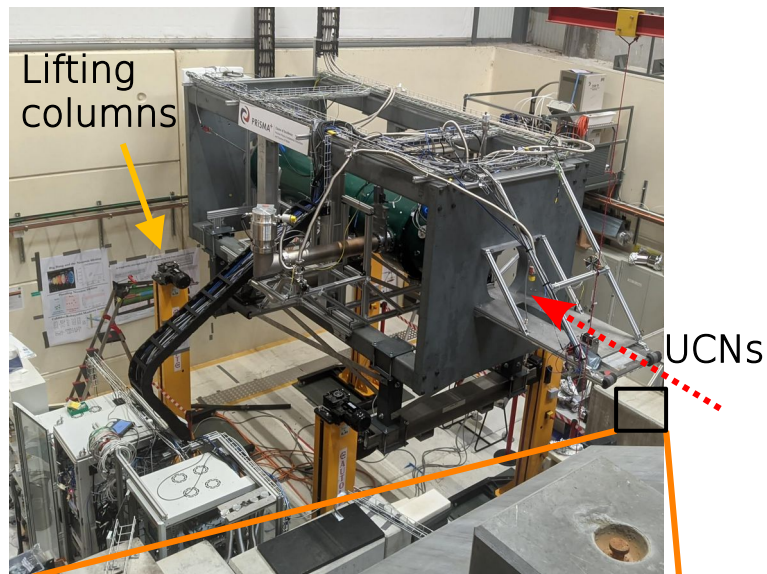
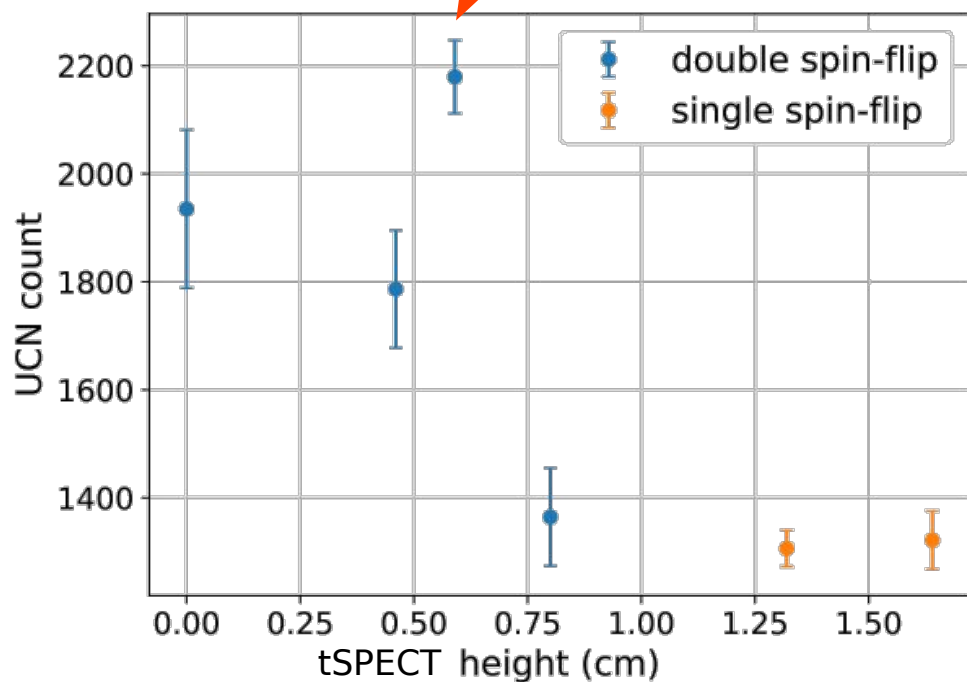
Height scan

- tSPECT height relative to the beamport can be changed
- → modifies the kinetic energy spectrum of loaded UCNs.



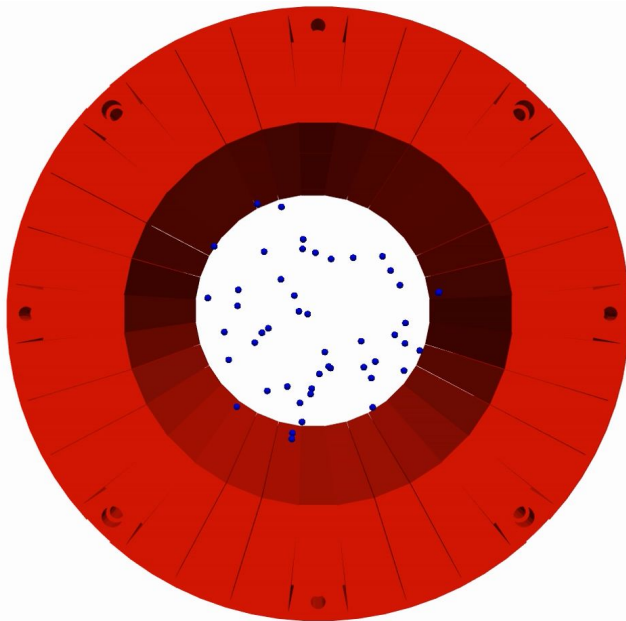
Height scan

- tSPECT height relative to the beamport can be changed
- → modifies the kinetic energy spectrum of loaded UCNs.
- Optimised height for double spin-flip found around 60 cm height.

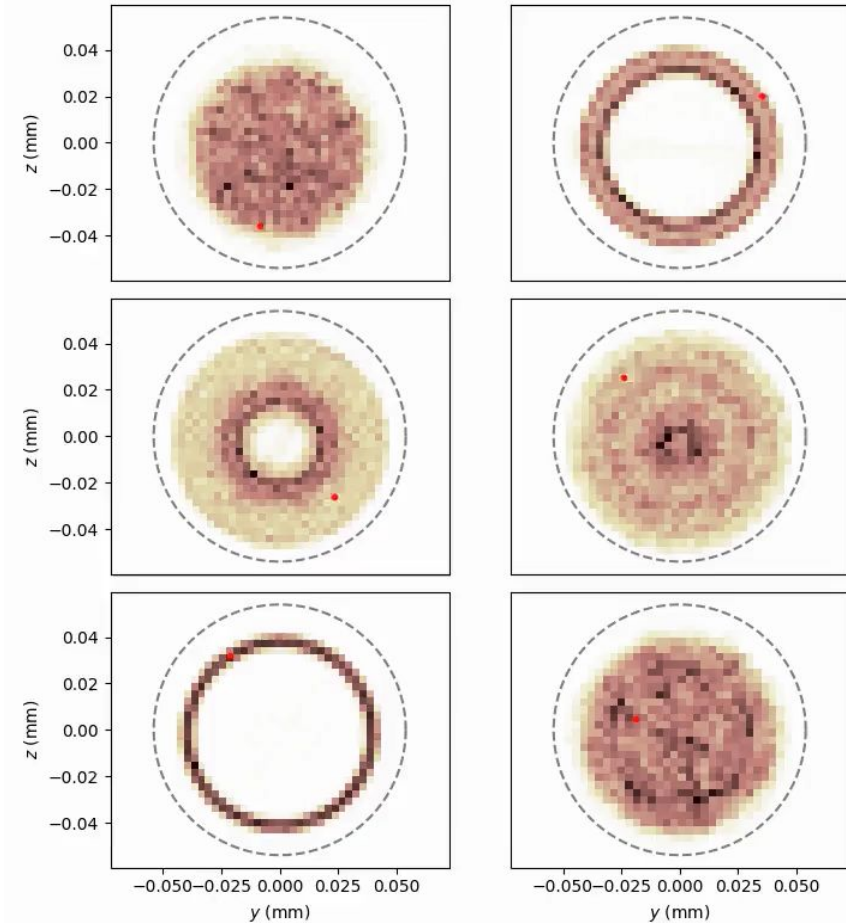


Marginally trapped UCNs

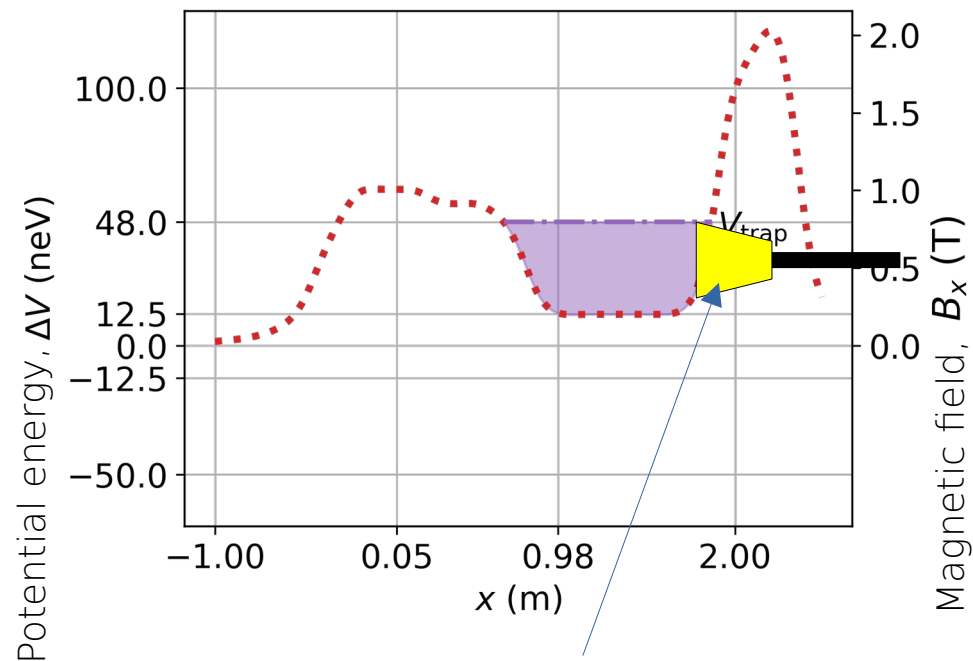
- Energy above trapping potential, $E > V_{\text{trap}}$.
- Escape trap on times scale of order of neutron lifetime.
- Main source of systematic uncertainty for neutron lifetime measurement



$t=29.3$, $dt=0.000136$ (s)



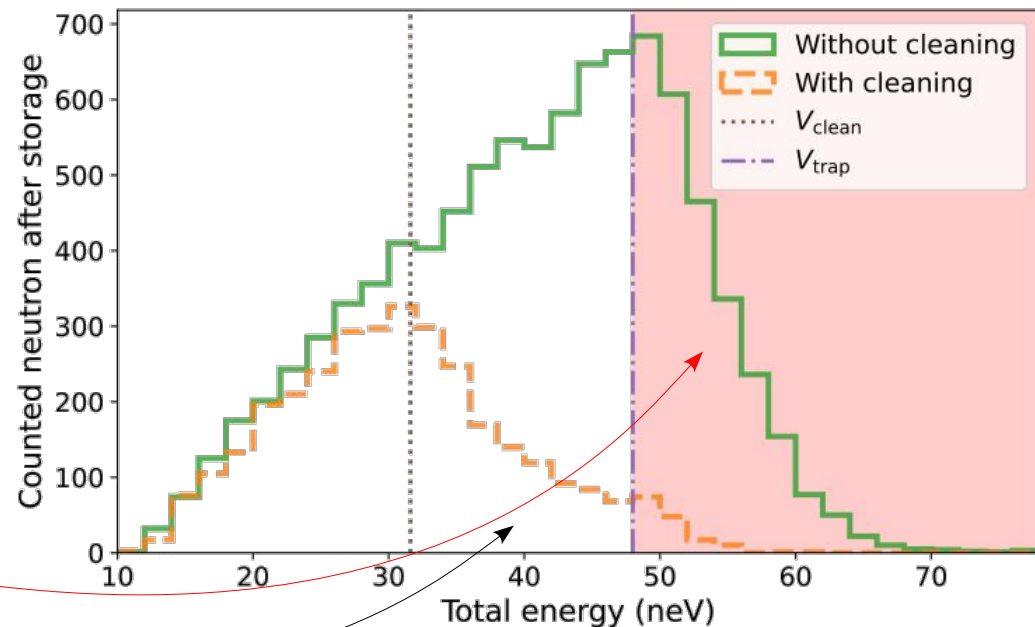
Spectral cleaning



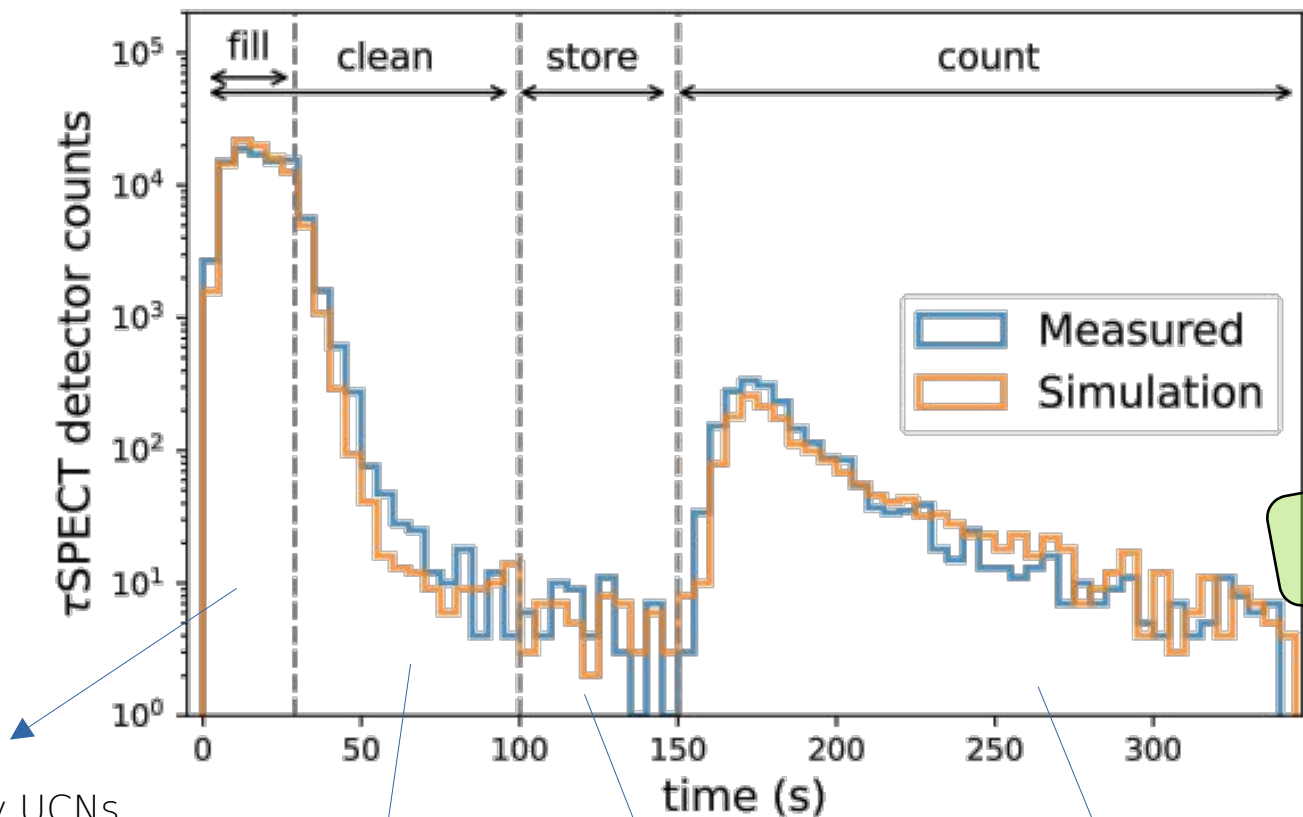
Partially insert the detector in the trap

→ removes high energetic UCNs.

→ cannot remove all marginally trapped UCNs without removing part of storable UCNs.



Measurement cycle : UCN count arrival time

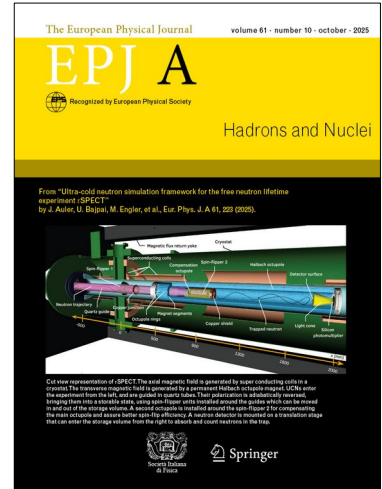


High-velocity UCNs flying through the trap during filling

Residual high-velocity UCNs

Background events

Long counting tail from slowest UCNs reflecting off the detector surface !



Auler et al. 2025, Eur. Phys. J. A (2025) 61: 223

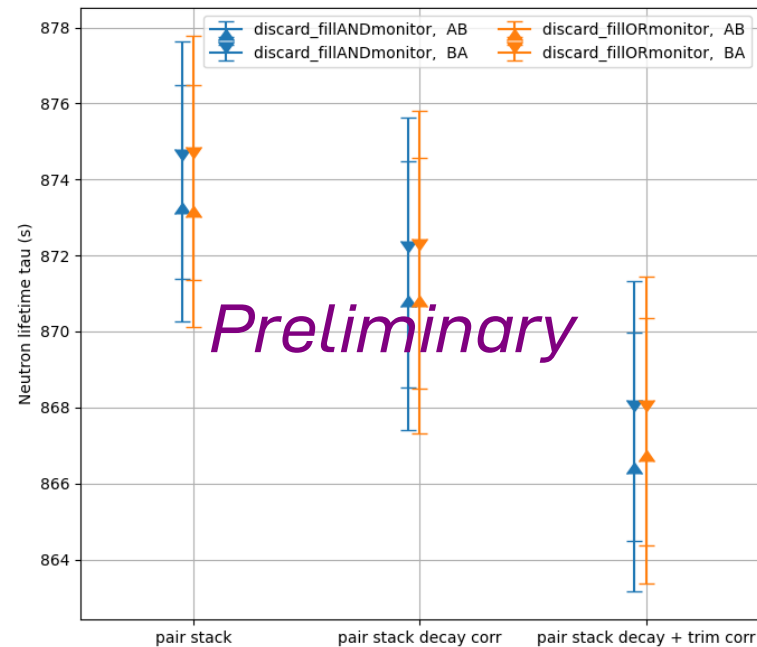
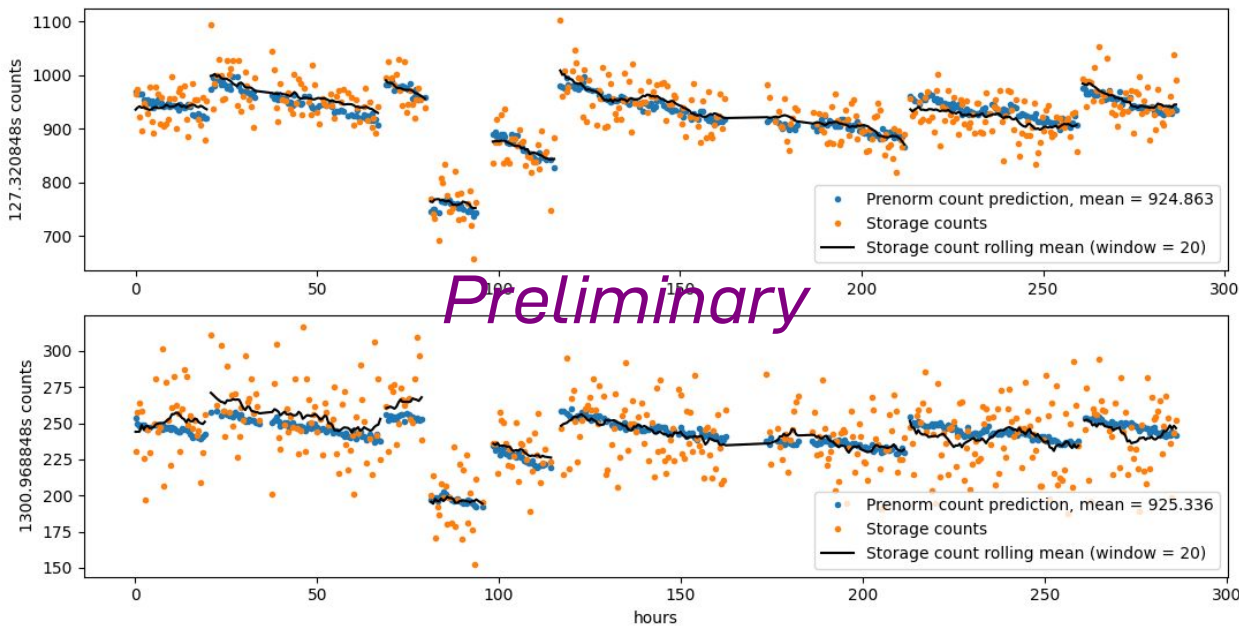
Analysis pipeline

Complete neutron lifetime analysis on tauSPECT data.

- Analysis material : python classes and scripts, routines, internal notes, analysis roadmap.
- Peak-finder algorithm, UCN detection event, data blinding.
- Mock dataset Monte-Carlo simulations.
- Measurement filtering, normalisation.
- Neutron lifetime estimators, likelihood derivation, data models, systematic correction, error propagation, etc.

Publication in preparation

Prenormalisation model: $a \cdot M + b \cdot F + c \cdot C + d$



Summary & outlook

Status :

- ✓ Extensive and successful commissioning during 2024.
- ✓ Double-spin flip is a validated UCN loading approach, **scalable**.
- ✓ First science data run with **1-3s precision** on the free neutron lifetime in 2025

Short term :

- Analyse 2025 dataset : 4 months, ~ 4000 storage measurements.
- Improves statistics, UCN loading, experimental settings, automation controls, characterization, ...
- Accumulate similar statistics 2026 & 2027, before PSI long shutdown.

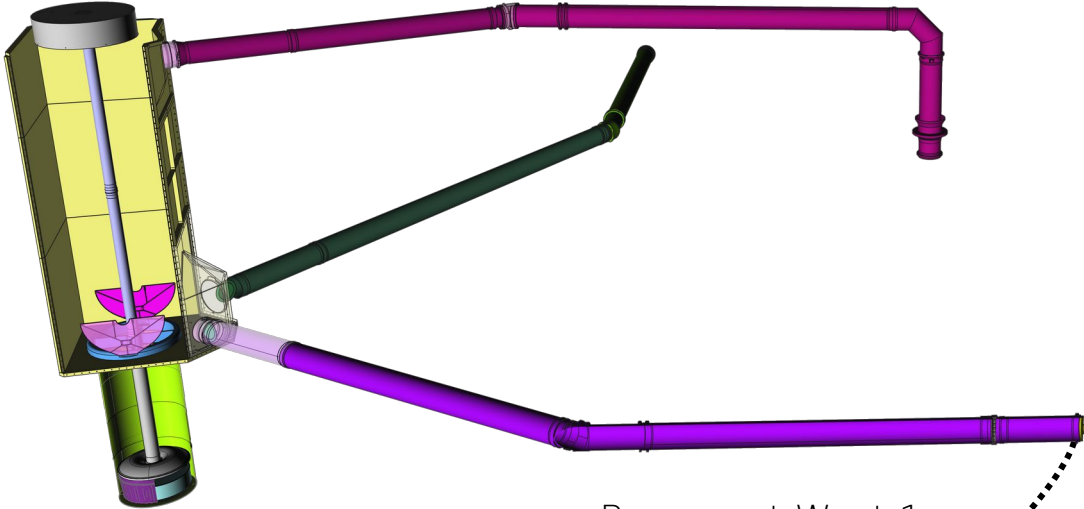
Long term :

- Design next-generation of fully magnetic neutron trap experiment.
 - Larger diameters and volume
 - Stronger magnetic field
 - More efficient spin-flippers and UCN detector

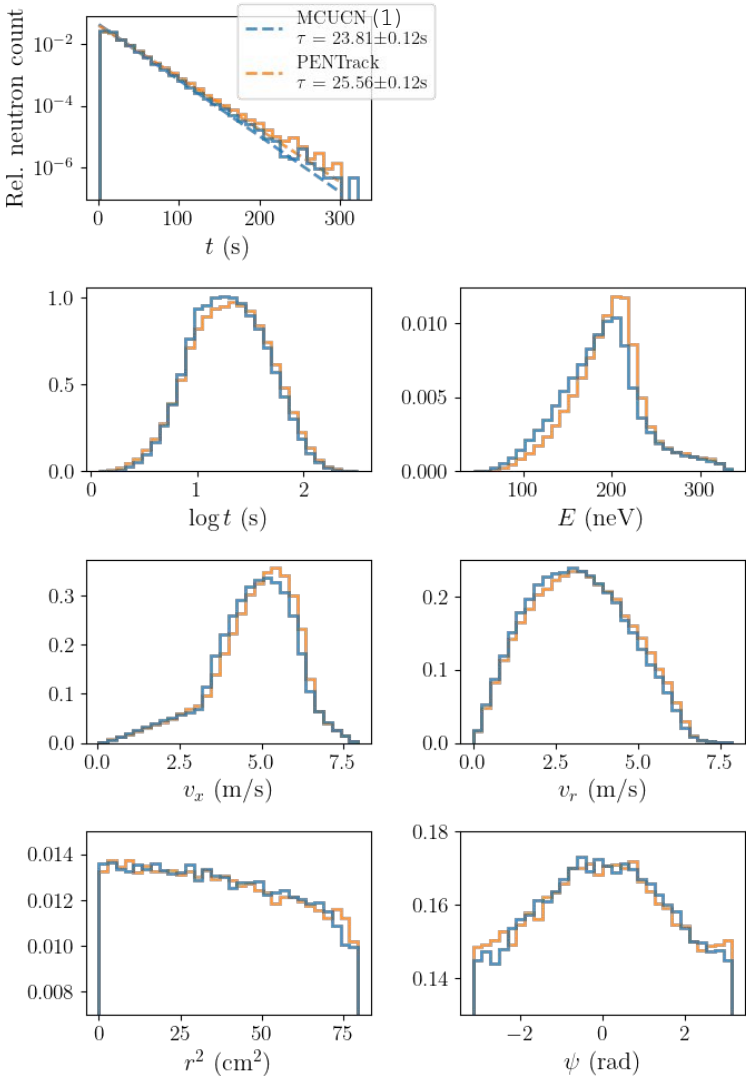
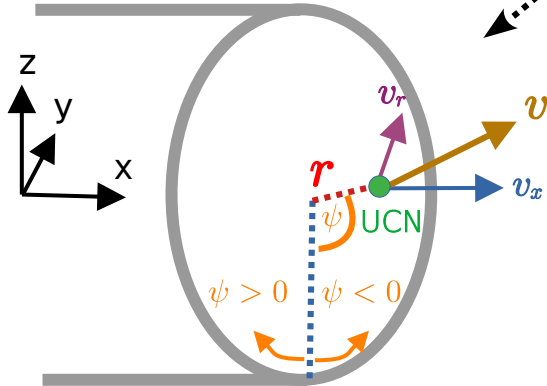


Backups

UCN distribution at PSI beamport W1



Beamport West 1

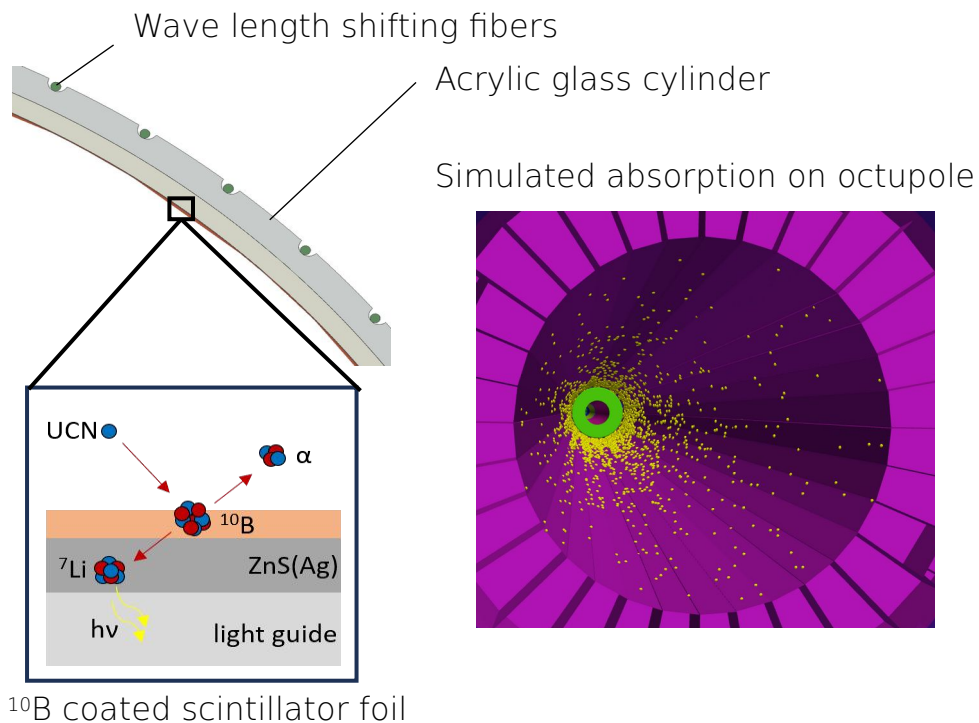


(1) <https://doi.org/10.1016/j.nima.2017.10.065>

UCN detector upgrades

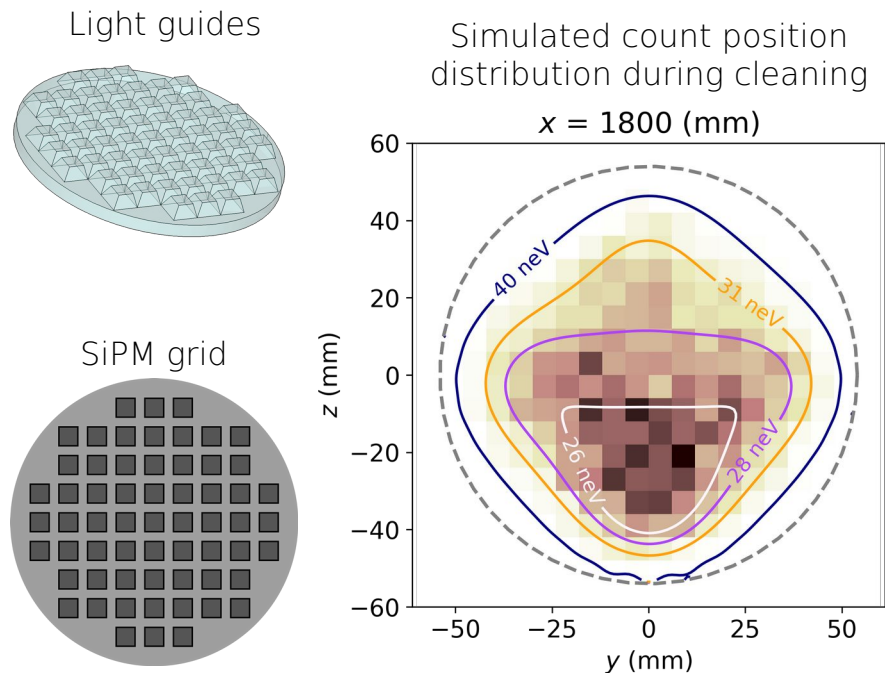
Radial detector

- Counts radially escaping UCNs
- Upgrade : counts electron/protons

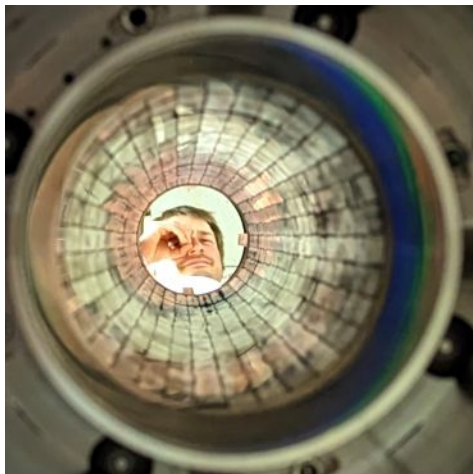


Segmented UCN detector :

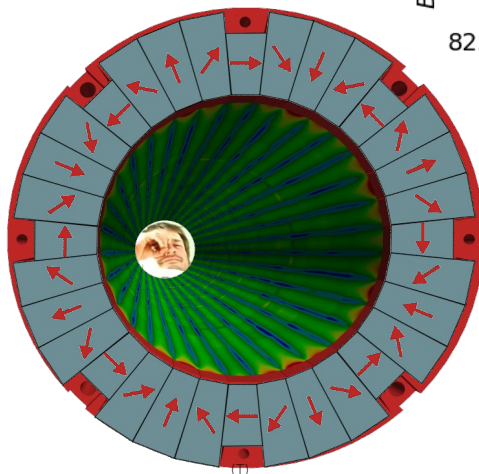
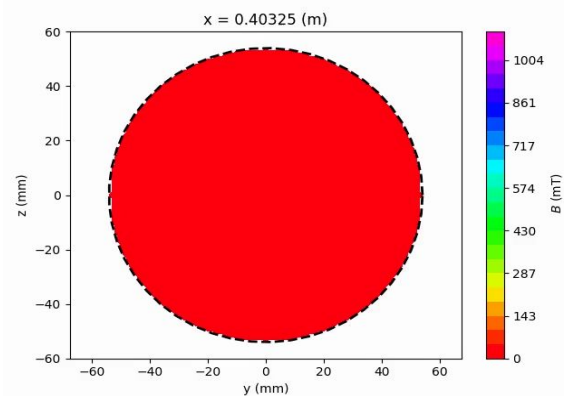
- Spatially resolves UCN counts
- Better background signal control



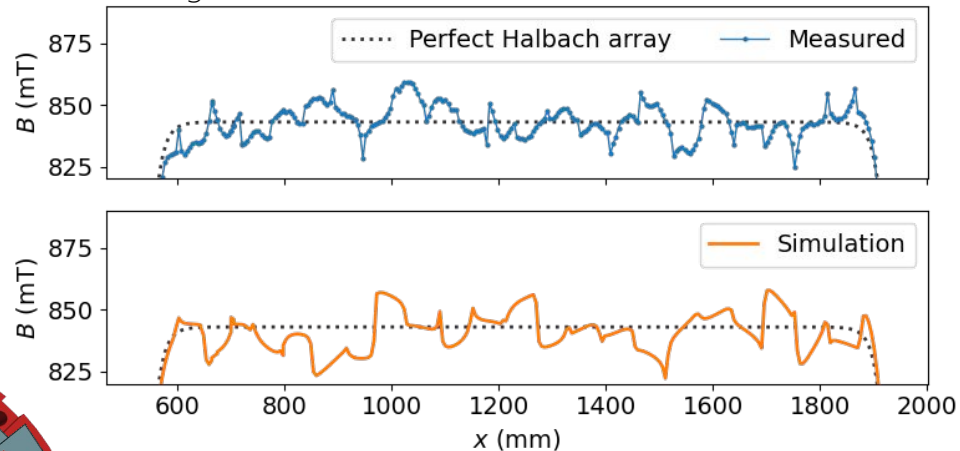
Halbach octupole



- 32 permanent magnet segments in a ring ($\text{Sm}_2\text{Co}_{17}$),
- 24 rings,
- 54 mm inner radius
- 1380 mm long



Longitudinal field scan, 2.5 mm from surface



Random perturbation of each segment's

- magnetisation orientation and amplitude,
- position,
- dimensions

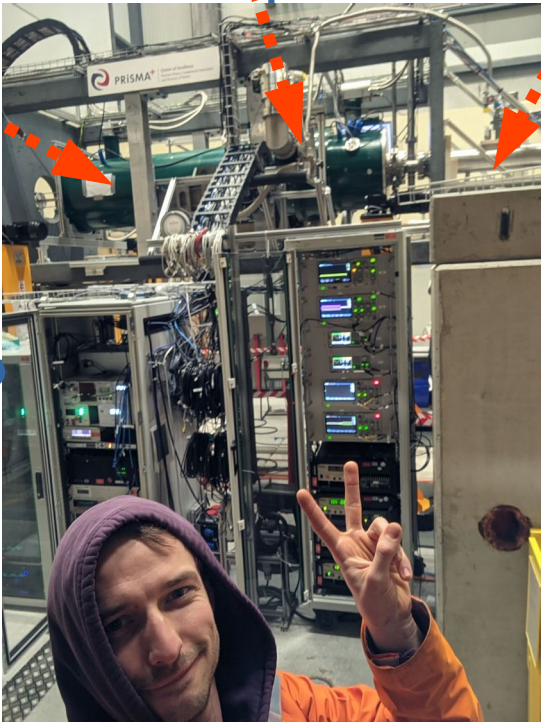
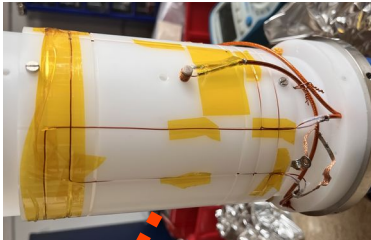
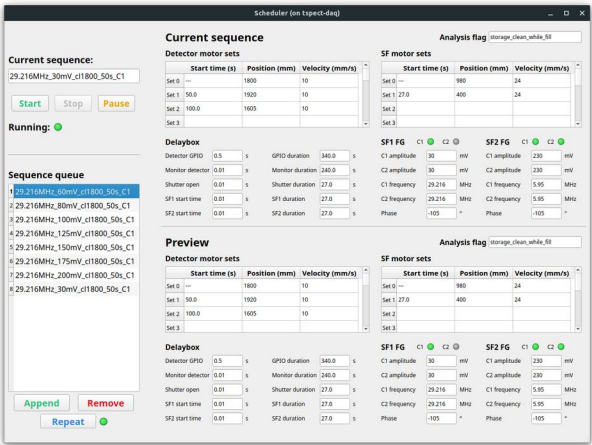
Experiment settings

Coils, magnetic field

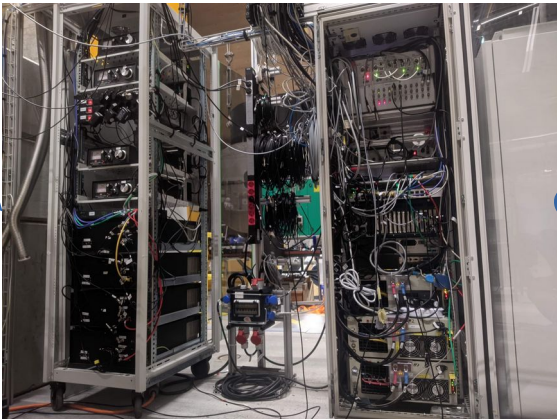
Spin-flippers + motors

Scheduler

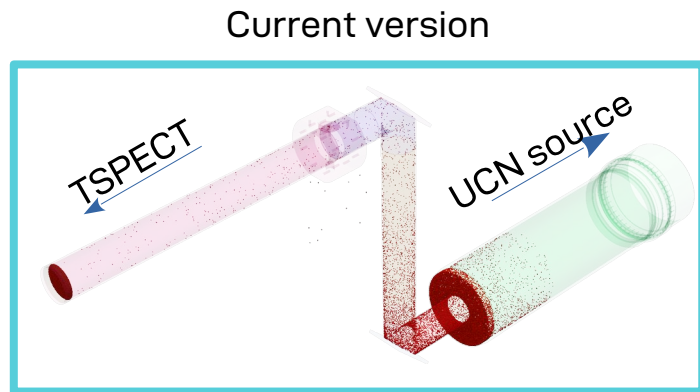
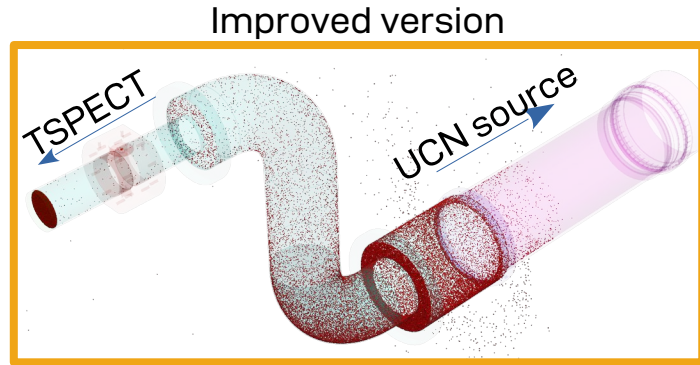
Detector + motors



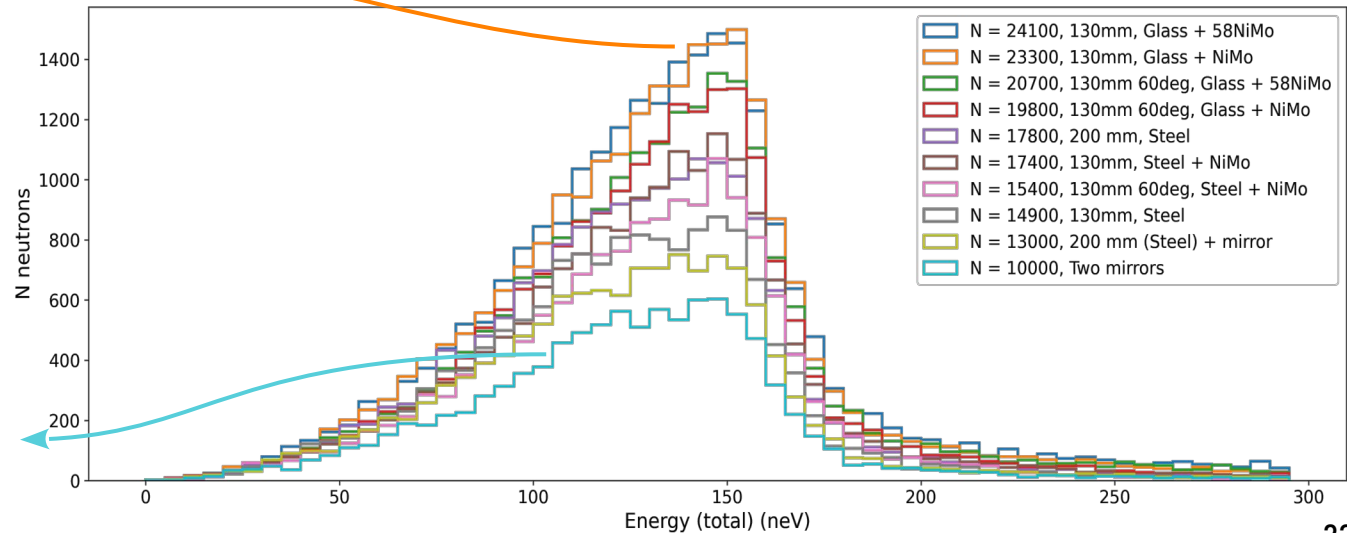
Racks (signals, readout, ...)



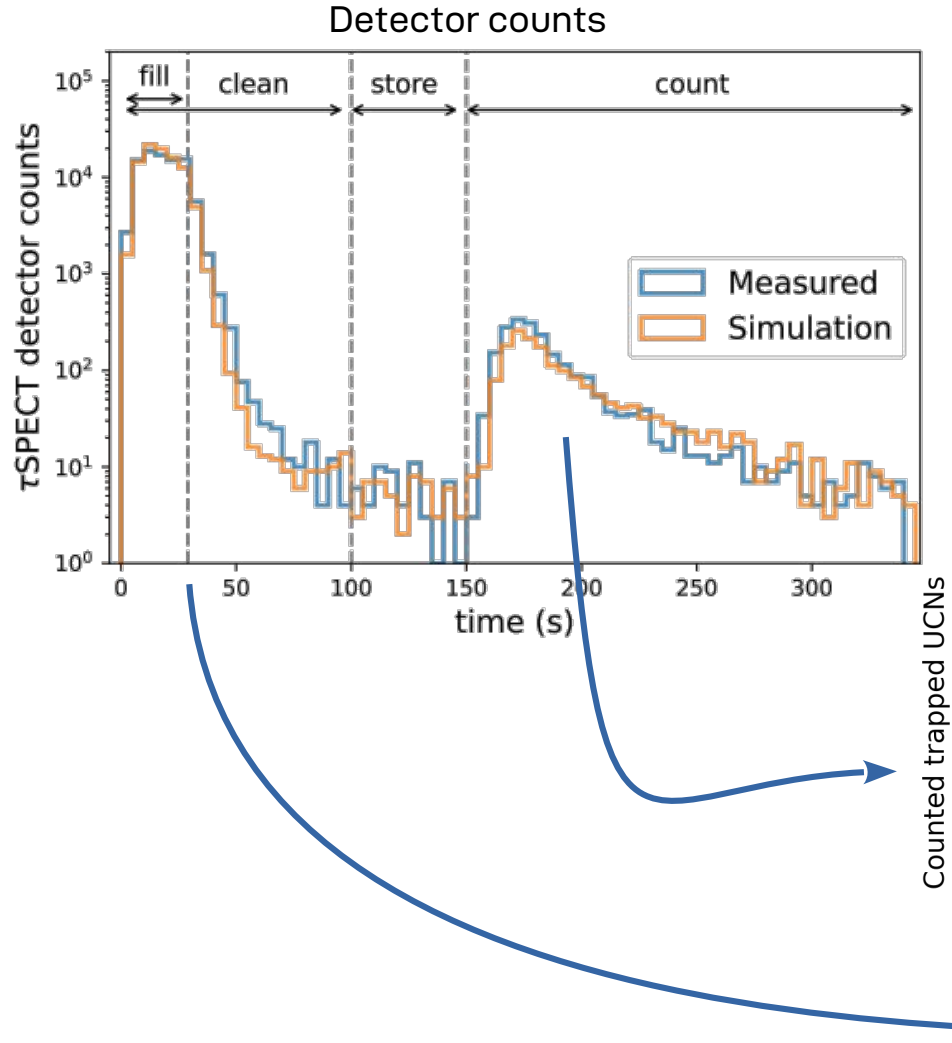
2025 upgrades



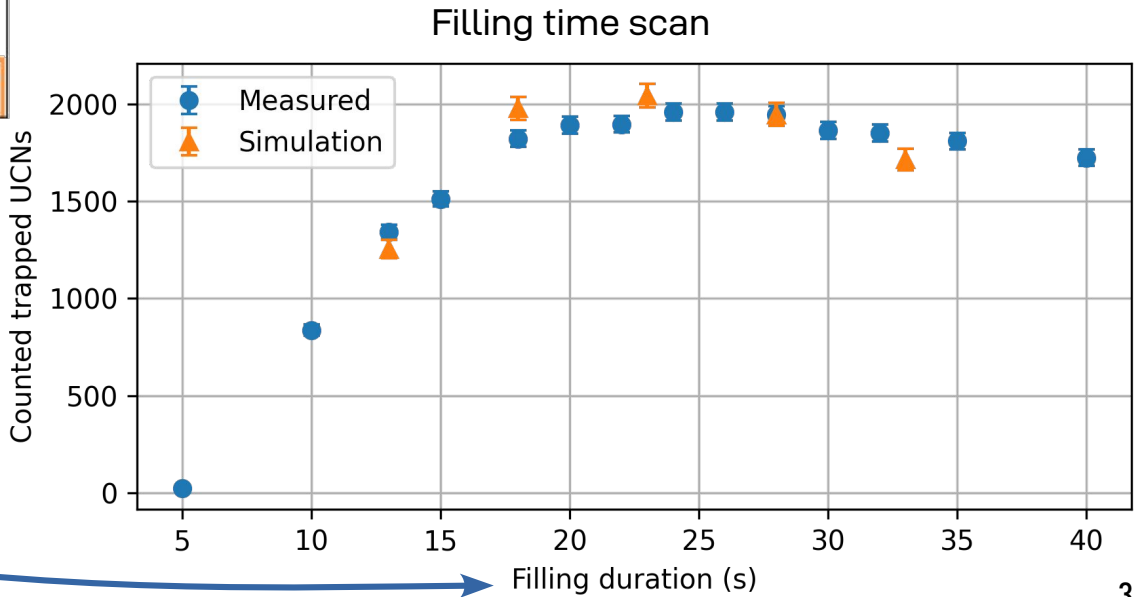
- Improved spin-flipper 1, accept more power (current).
- Monitoring and correction of super-conducting coil current drift.
- Improved UCN transmission : guides inside tSPECT, new coating, polish pieces, ...
- New beamline (+240% UCNs expected)



Filling time optimisation



- Optimal filling time around 25 s.
- Measurement data and simulations in agreement.

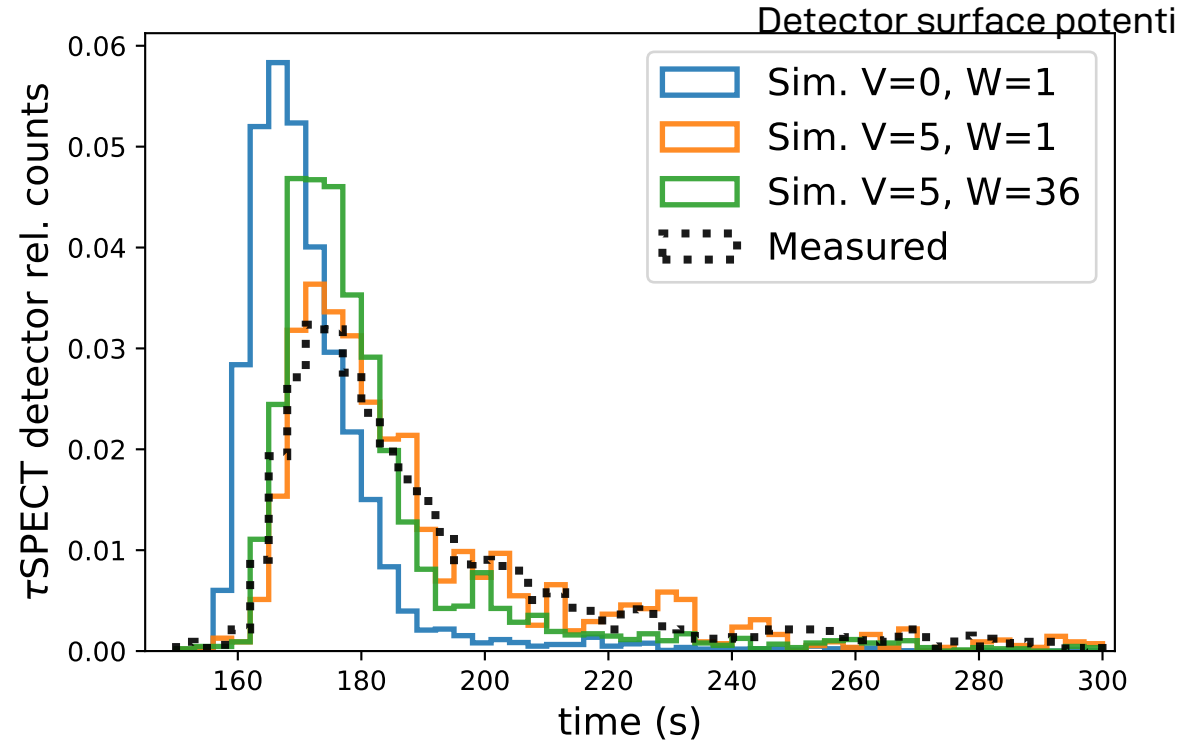


Upgrades and improvements

- Detector surface seems to have a non-zero Fermi potential ($V=5$ neV, $W=1$ neV)

→ (too) long counting tail.

Simulated storage counting spectra VS measurements



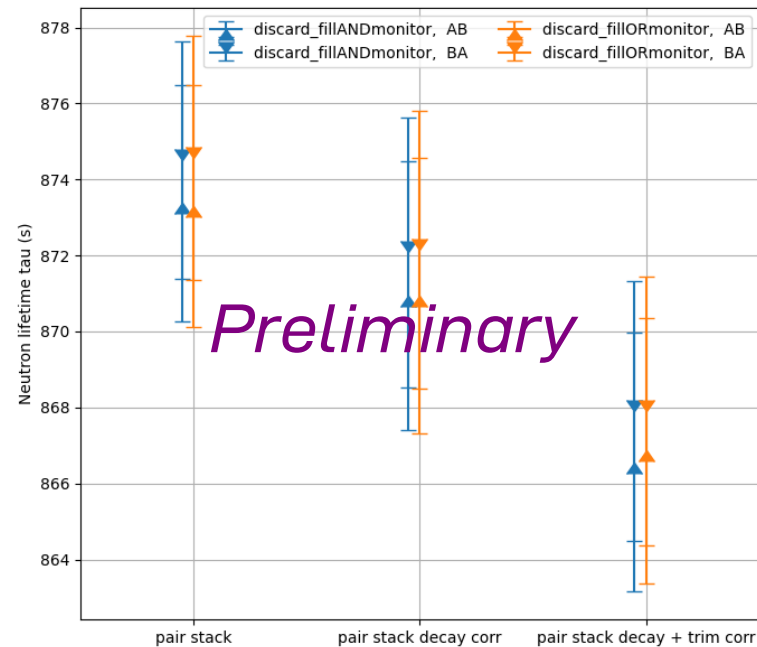
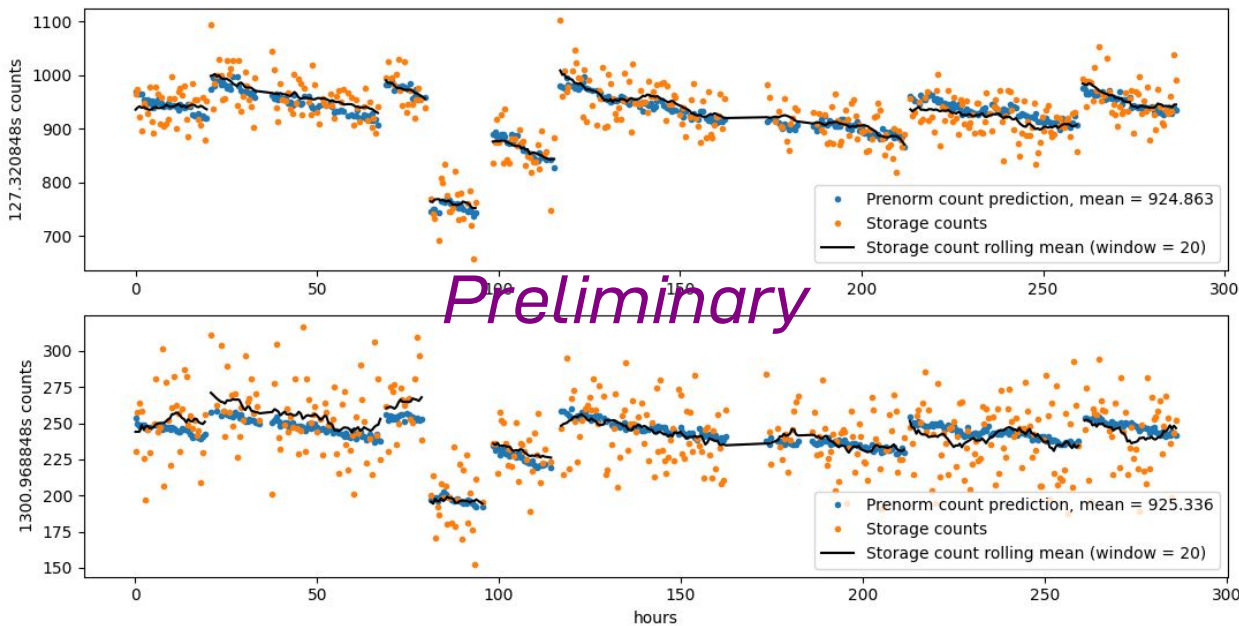
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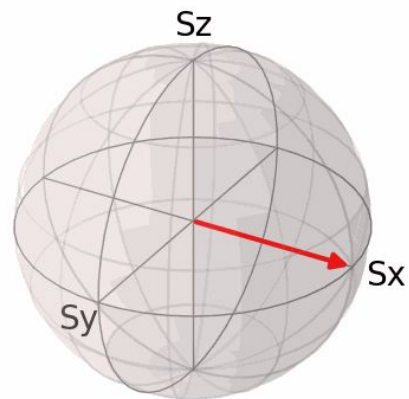
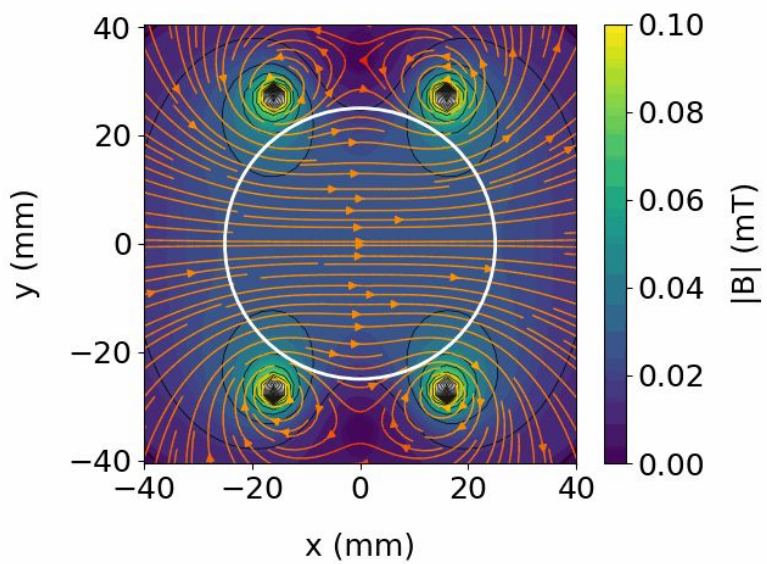
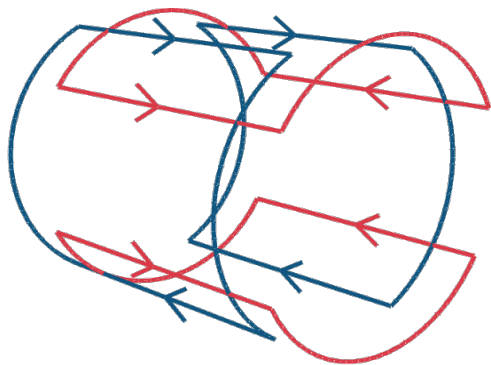
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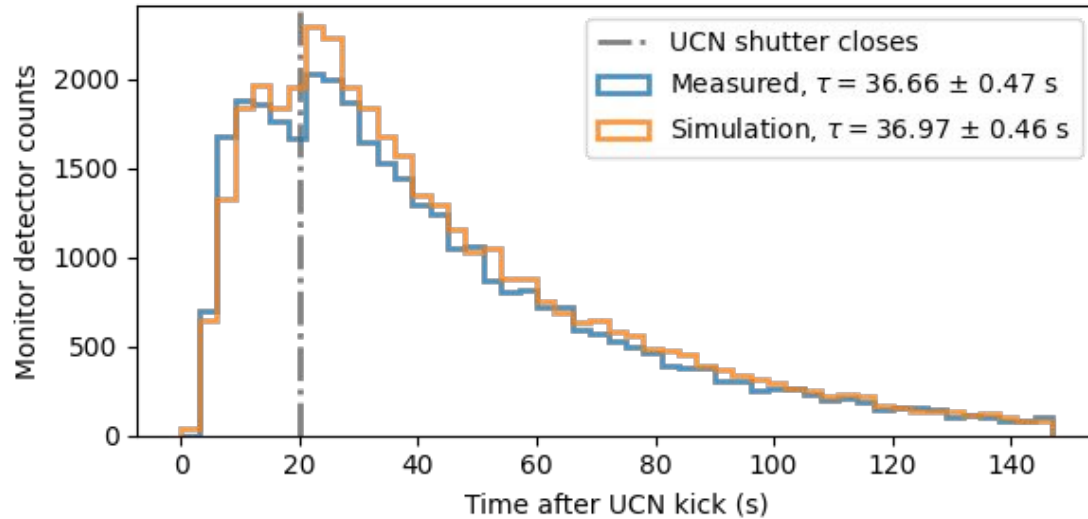
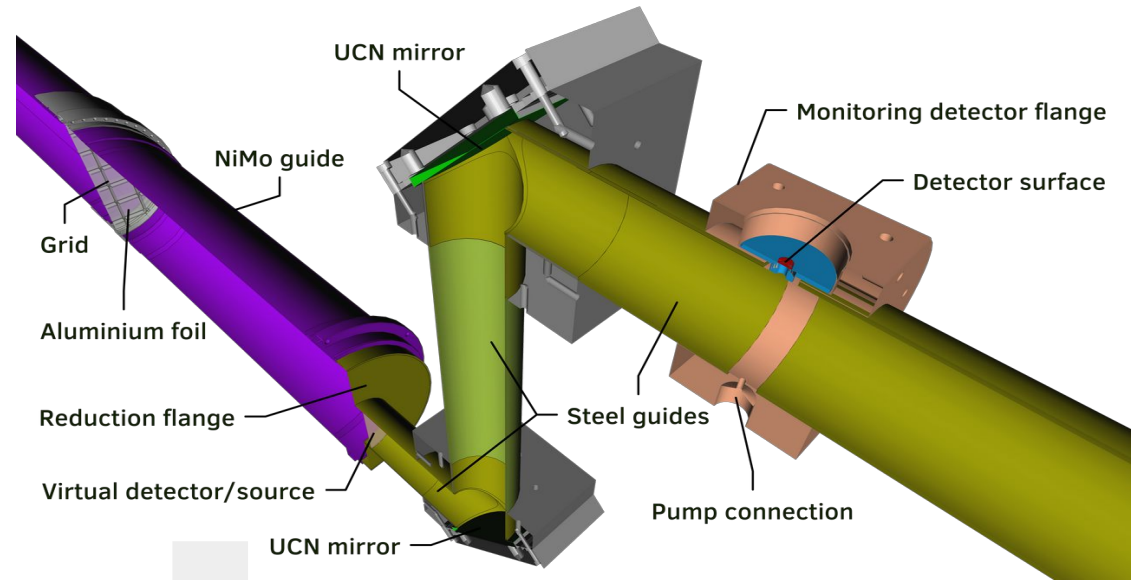


Spin-flipping units

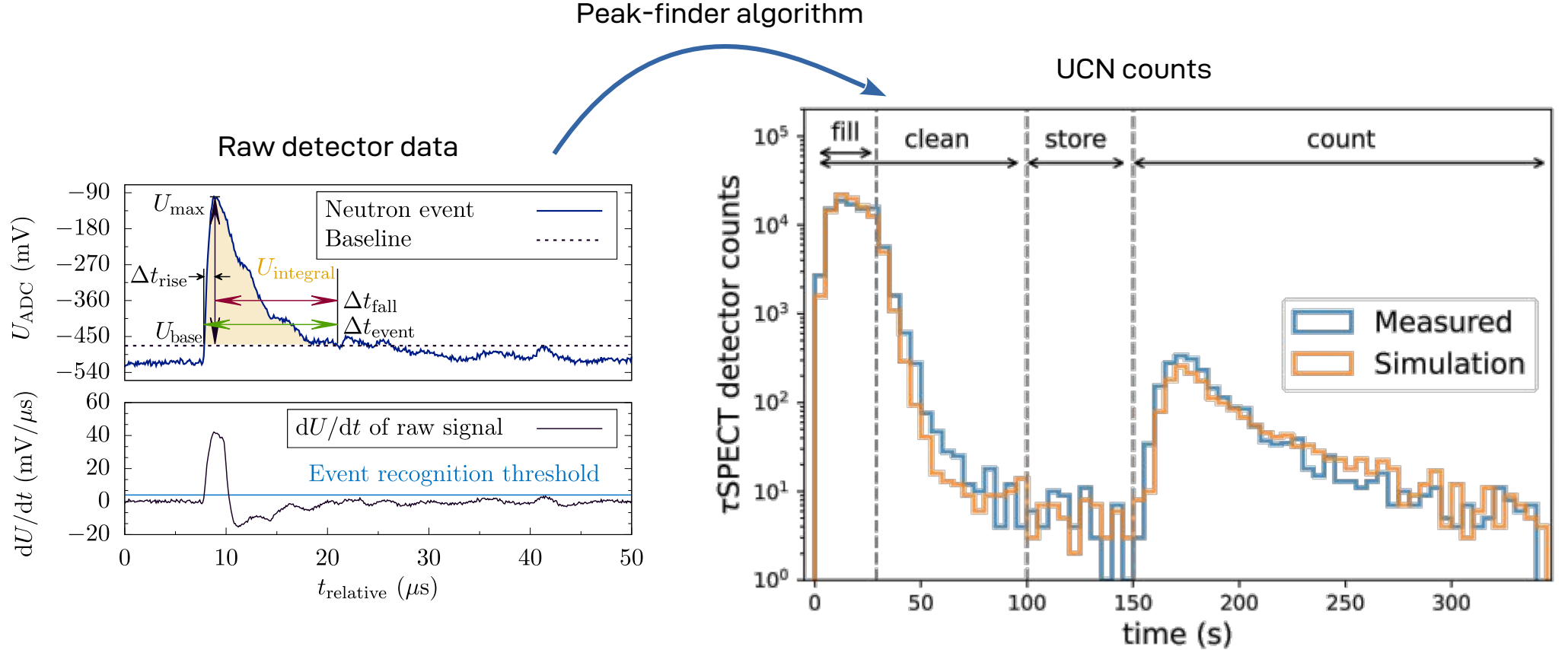


Monitoring detector

- Count relative number of UCN per kicks.
- Help tracking UCN source fluctuations.
- Used to normalise the filled UCN number.



Detector UCN counts



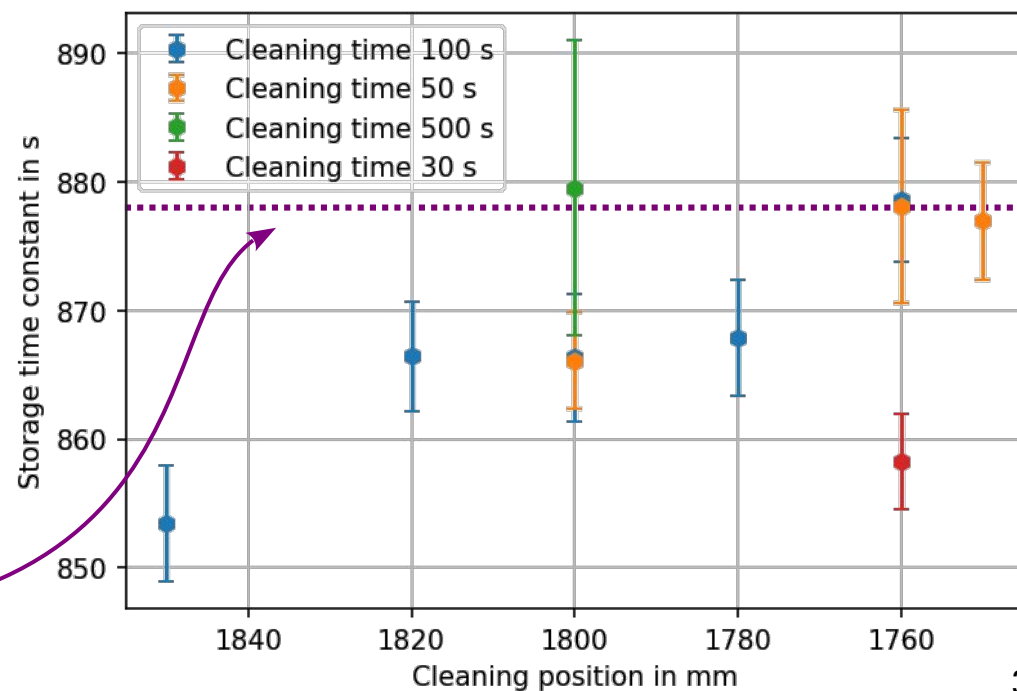
Neutron lifetime against cleaning settings

- Various cleaning (detector) positions and cleaning durations.
- Two storages durations :
 - Short, $t_1 = 50$ s, N_1 counts
 - Long, $t_2 = 1200$ s, N_2 counts

$$\text{UCN count number } N(t) = N_0 \cdot e^{(-t/\tau)}$$

$$\rightarrow \tau_n = (t_1 - t_2) / \ln(N_2/N_1)$$

- 3-4 days for 3s uncertainty on neutron lifetime.
- Deep (**1760 mm**) + long cleaning (**100 s**) compatible with world best measurement from UCN τ at LANL : **$877.82 \text{ s} \pm 0.22^{+0.20}_{-0.17} \text{ s}$**



Blinded data

Legend :
— Known
--- Hidden

Base timing parameters :

- Filling : 25 s
- Cleaning : 100 s
- Counting : 190 s
- Monitoring detector : 240 s

Actual timing parameters :

- 1) Bases parameters $\pm$ random value (2.5% range)
- 2) Storage durations:
 - 2 shorts : range [20 s, 30 s]
 - 1 medium : range [300 s, 1000 s]
 - 2 longs : range [1100, 1700s]

Blinded timing parameters :

- (**blinding factor**) $\times$ (actual parameters)

True neutron lifetime

- (blinded lifetime) / (**blinding factor**)

Simulation framework receipe

UCN MC simulation : **PENTrack** (C++):

(<http://dx.doi.org/10.1016/j.nima.2017.03.036> & <https://github.com/wschreyer/PENTrack>)

- Computes:
 - Trajectories of UCN + decay products.
 - Spins precession in EM fields.
 - Interaction with matter (Fermi potential) + diffuse scattering models.
- Input:
 - UCN initial distributions : energy, time, position ...
 - Geometries : **freeCAD** <https://www.freecad.org/>
 - Fields : open source python package **magpylib** <https://doi.org/10.1016/j.softx.2020.100466>
 - ➔ Meshes contains B value and relevant derivatives for tricubic interpolation

Companions modules (python):

- **penconf**: manage configuration files for pentrack. <https://gitlab.rlp.net/tauSPECT/penplot>
- **penplot**: data manipulation, 3d plots, and animations. <https://gitlab.rlp.net/tauSPECT/penconf>