The UCN system for the n2EDM experiment

LTPhD talk May 2024

Cornelis B. Doorenbos

The n2EDM experiment

- Search for the neutron electric dipole moment (nEDM)
- Statistical sensitivity: $$\sigma(d_{\mathrm{n}}) = \frac{\hbar}{2\alpha|E|T\sqrt{N}}$$
- For long T: ultracold neutrons
- For a large N: we need a good UCN transport system!

Ultra cold neutron storage

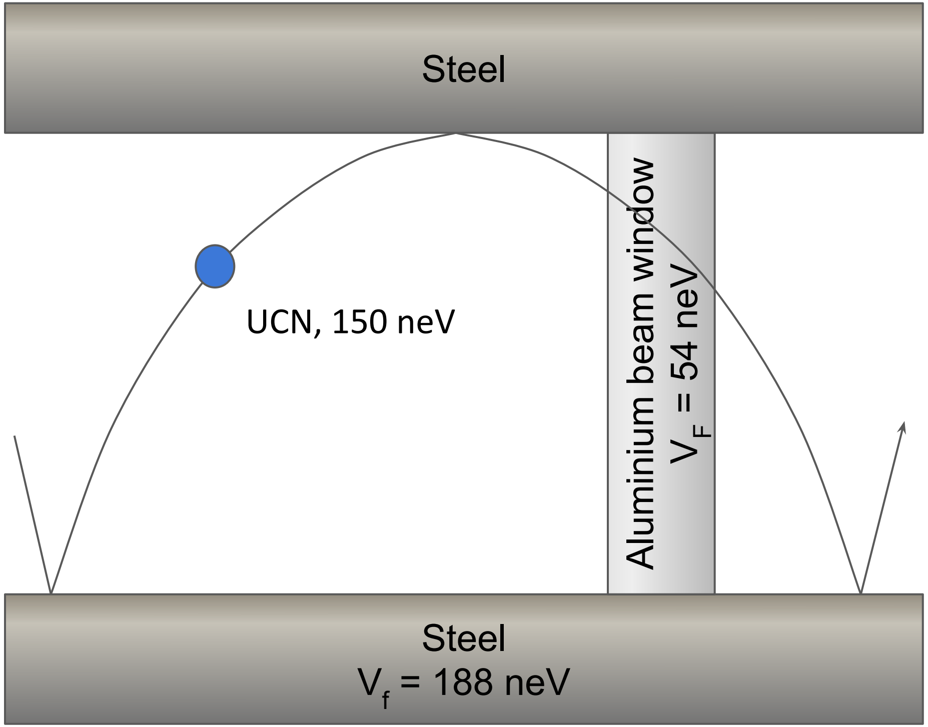
- $E_{kin} < 300$ neV $T \sim 2$ mK $v \sim 5$ m/s
- Weak: $n \longrightarrow p^+ + e^- + \bar{\nu}_e$ ($\tau \sim 880$ s)
- Electromagnetic
  - Magnetic dipole moment   ($dV/dB = -60.3$ neV/T)
  - Electric dipole moment   ($d < 10^{-26}$ e cm)
- Gravity   ($dV/dh = 102$ neV/m, at Earth surface)

- Gravitational-magnetic confinement, (e.g. in τSPECT, neutron lifetime exp.)

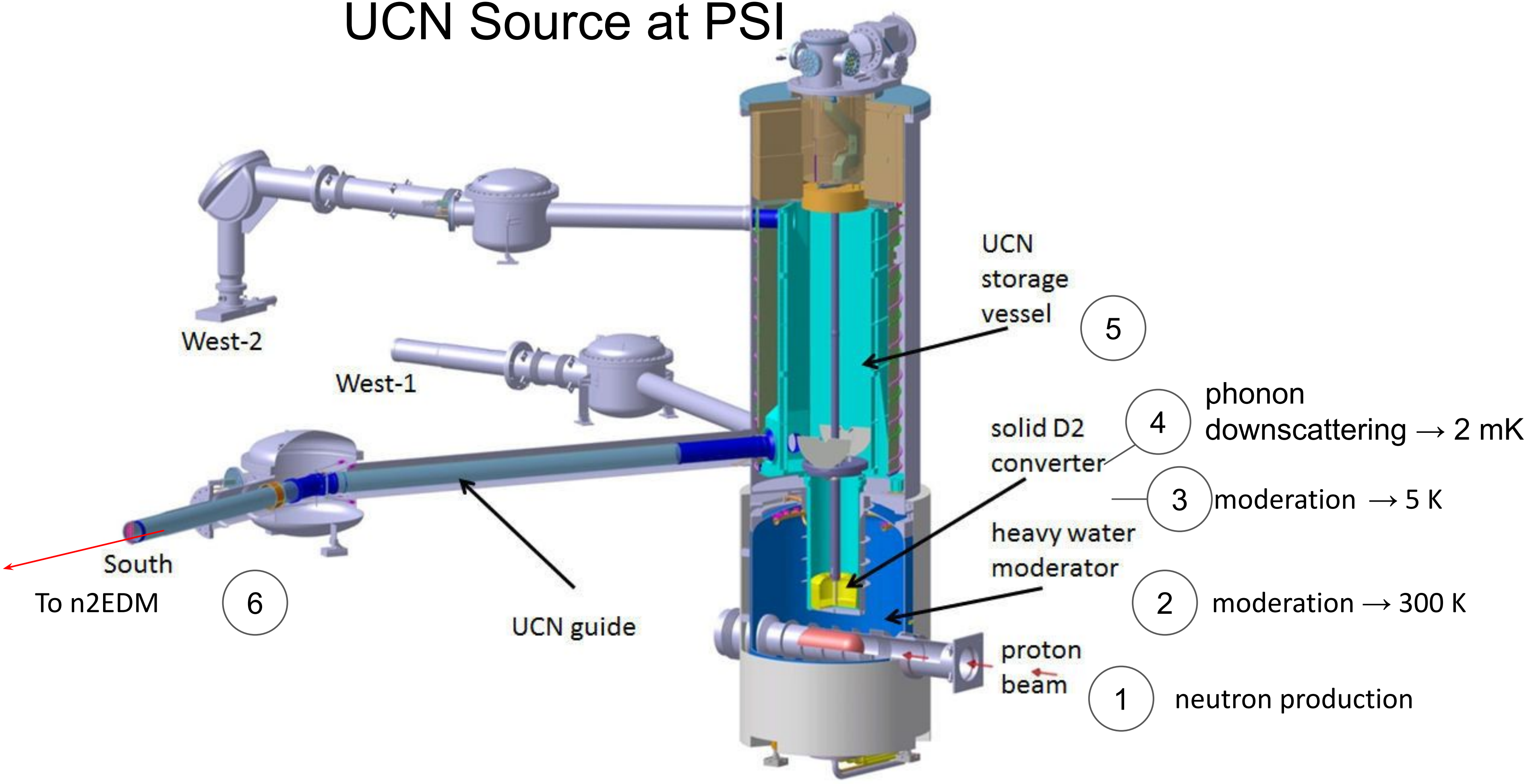
Ultra cold neutron storage

- E_{kin} < 300 neV, λ ~ 800 Å
- Strong force
  - Fermi pseudopotential (V_F) averages scattering lengths
  - $E_{kin} < V_f$: reflection under all angles

Material	V_F (neV)
Ni	252
Al	54
Steel	188
Glass	96

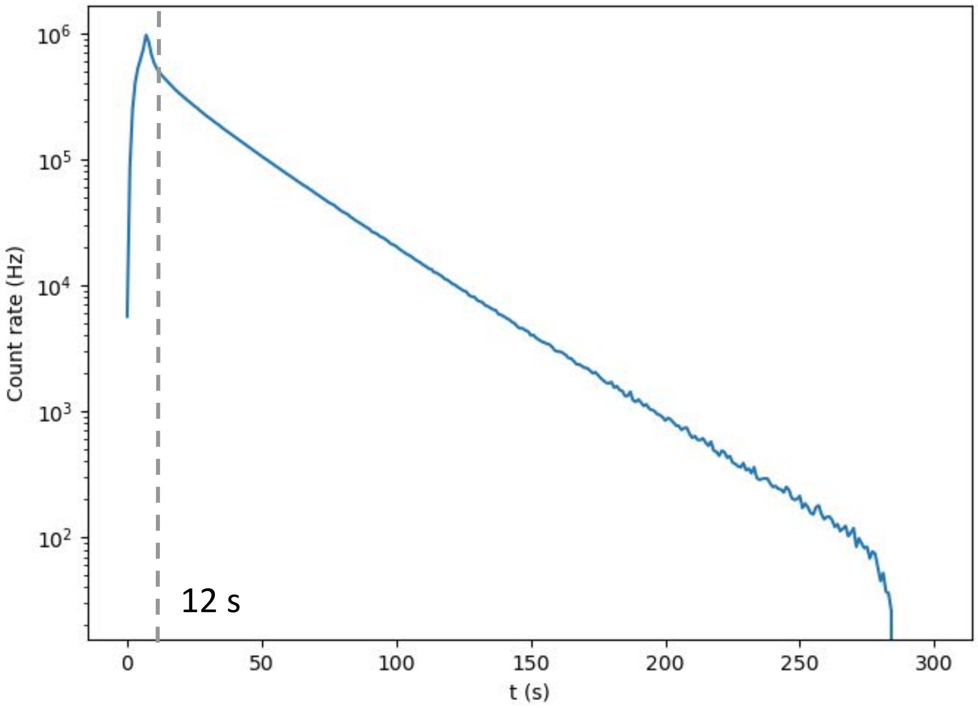


UCN Source at PSI

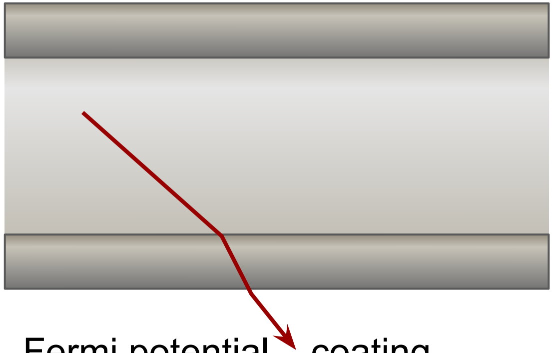


UCN source output

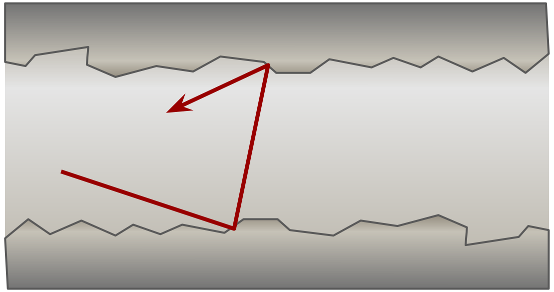
- Pulsed UCN source
- 8 s proton beam on spallation target
- UCN production
- Fill storage volume
- Drain into experiment



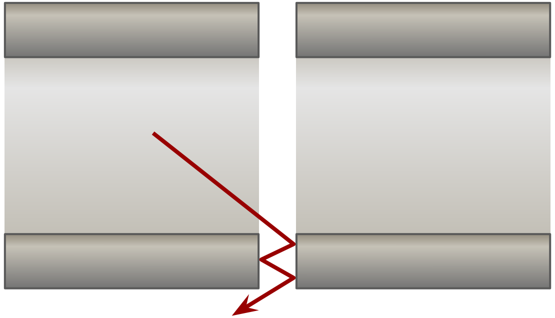
Requirements for UCN guides



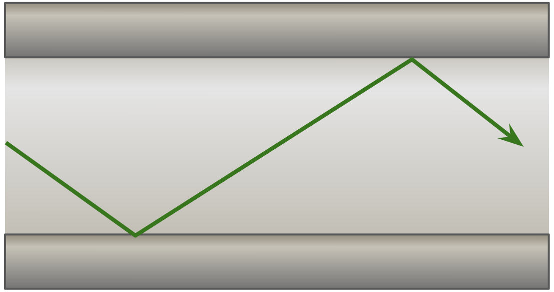
Fermi potential, coating



Smoothness

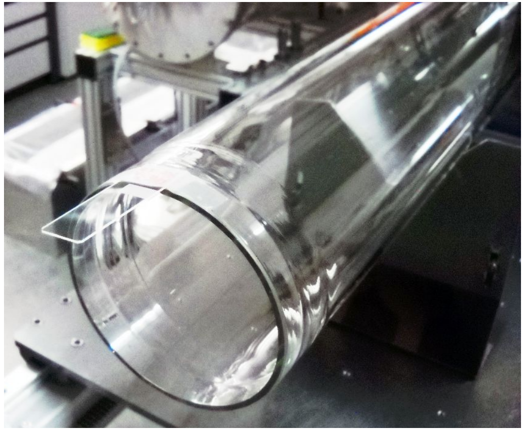


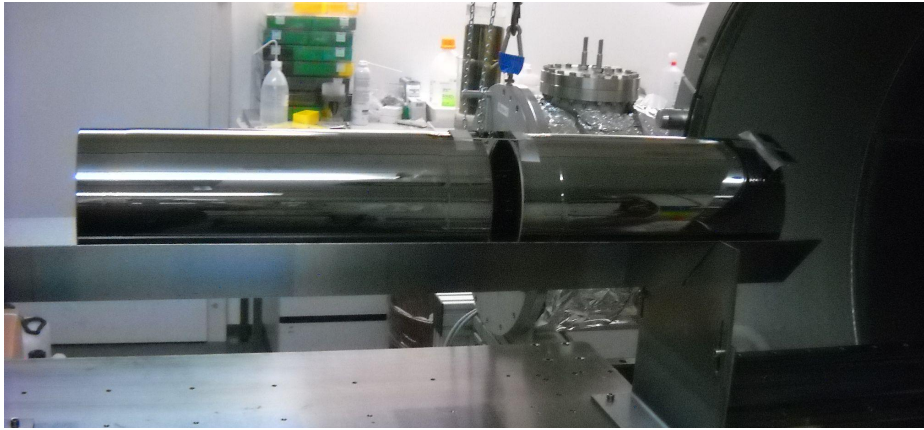
Gaps between guides



Required transmission:
90 % for 1m guide

UCN guides





Glass guides

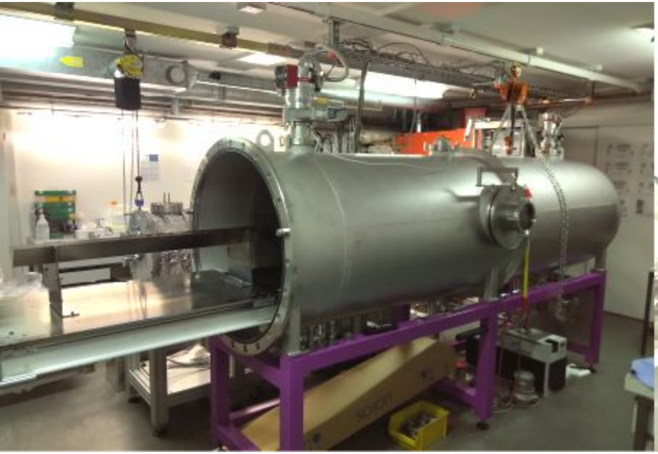
- smooth
- Inner diameter: 13 cm
- Length: varies, up to 125 cm

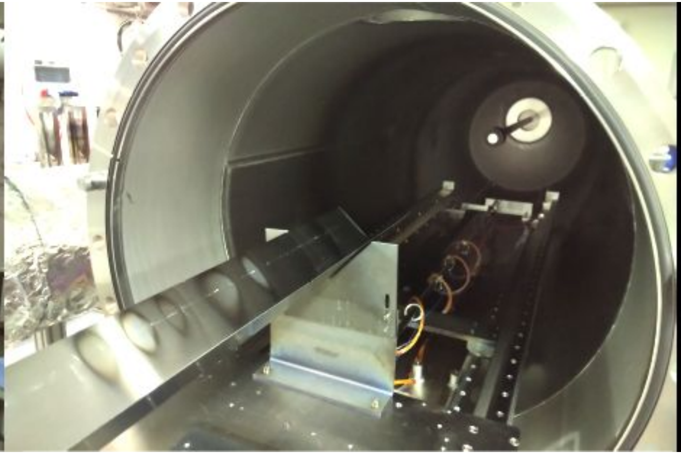
NiMo coating (85:15 mass ratio),

- V_f = 220 neV
- Ni: high fermi potential, but ferromagnetic
- Mo: reduces Curie temperature well below room temperature

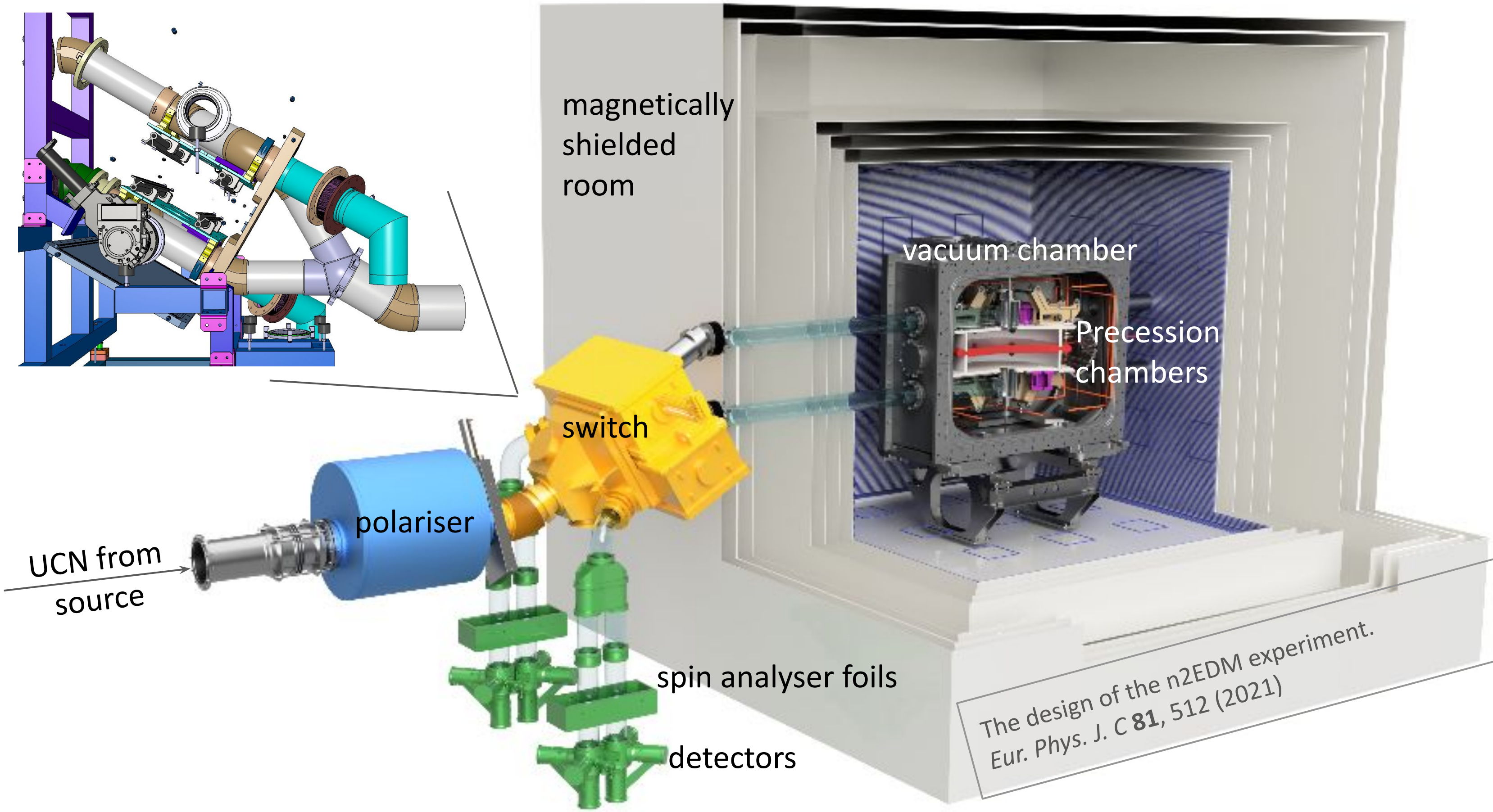
Coating

In house, DC magnetron sputter coating facility



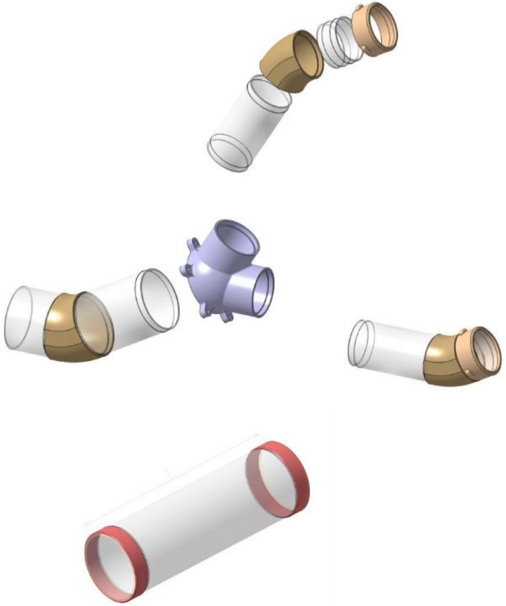


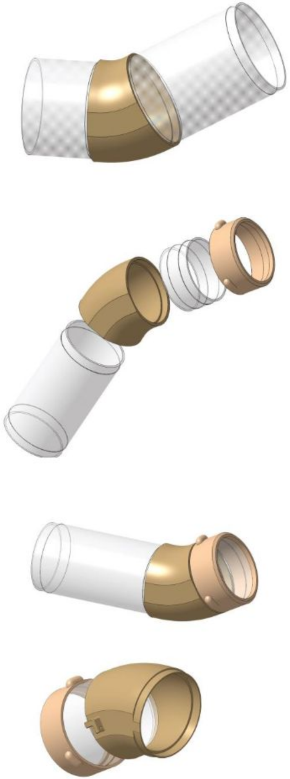
The n2EDM experiment

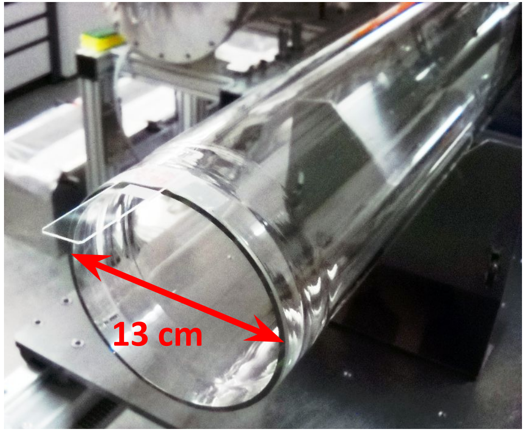


The design of the n2EDM experiment.
Eur. Phys. J. C **81**, 512 (2021)

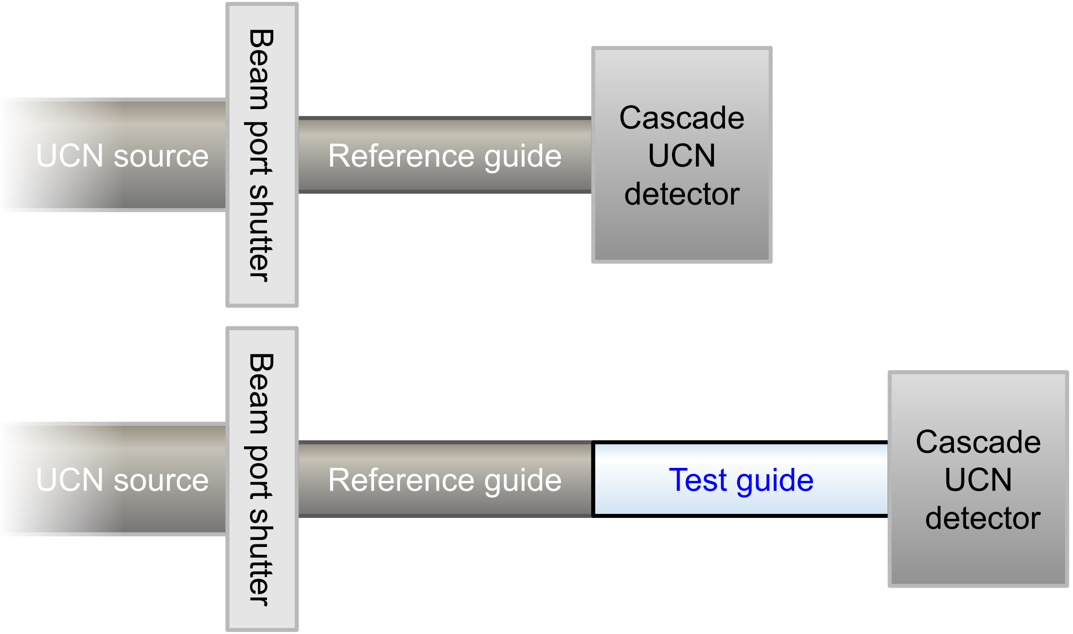
The guide system







UCN transmission measurements

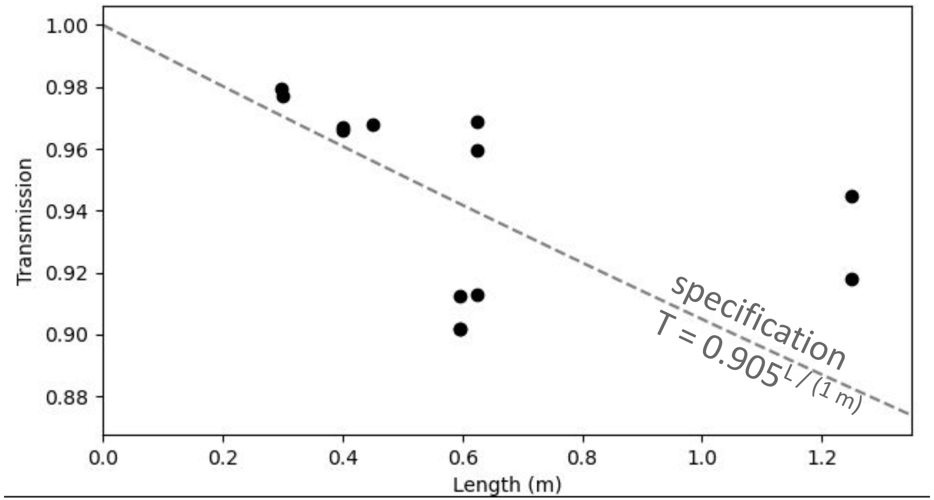


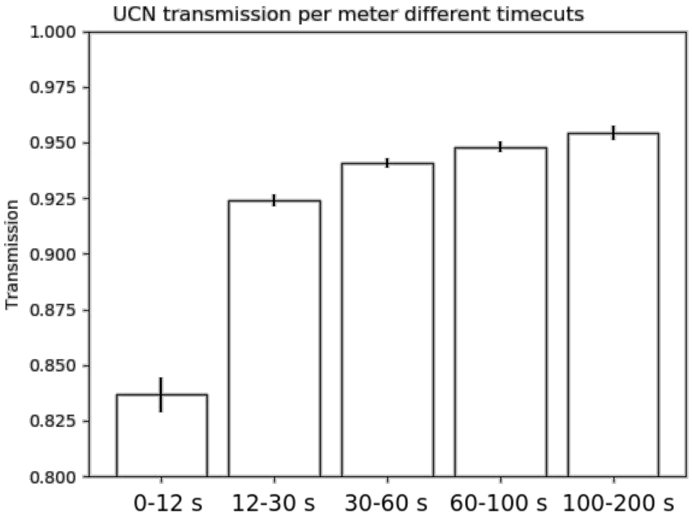
Reference setup

Test setup

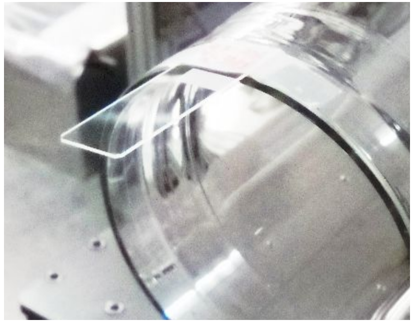
$$\text{Transmission} = \frac{\text{normalised UCN counts in test setup}}{\text{normalised UCN counts in reference setup}}$$

UCN transmission measurements, results





Measurement of V_F

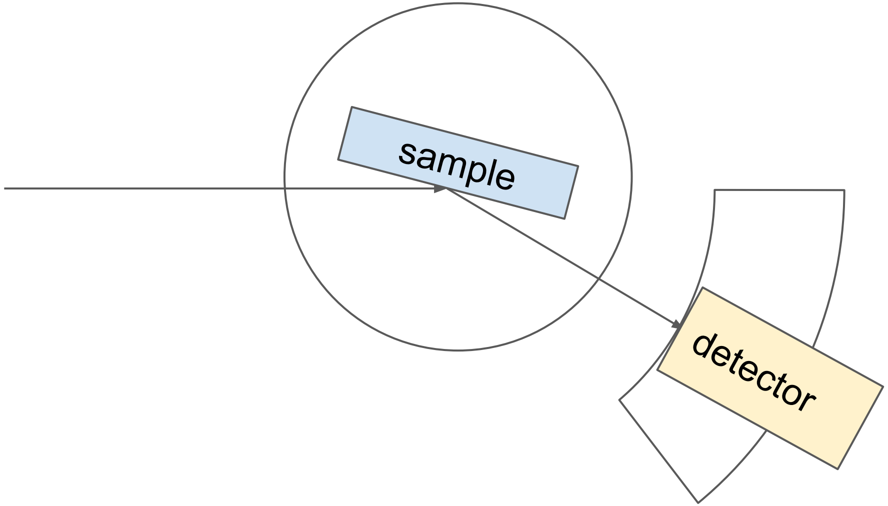


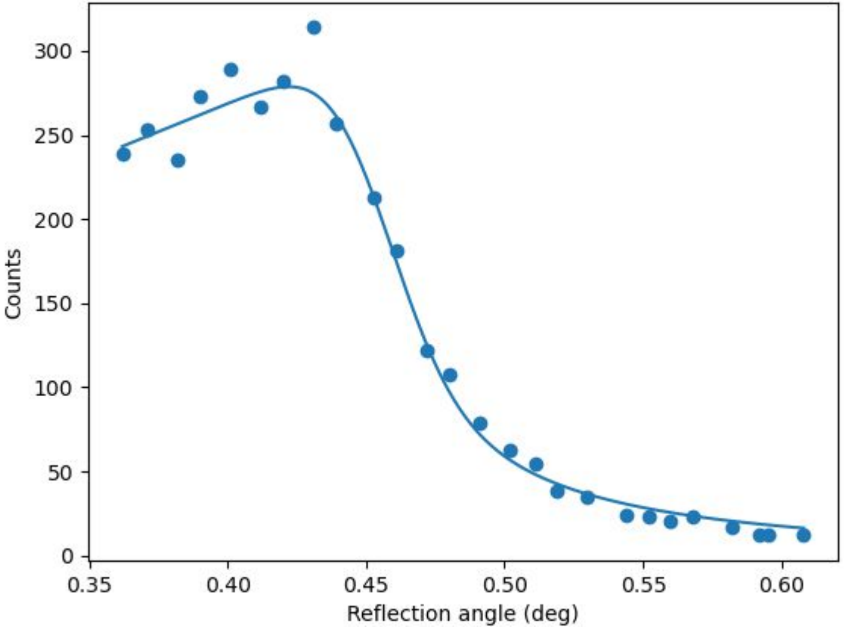
Reflectometry

3.3 meV cold neutrons

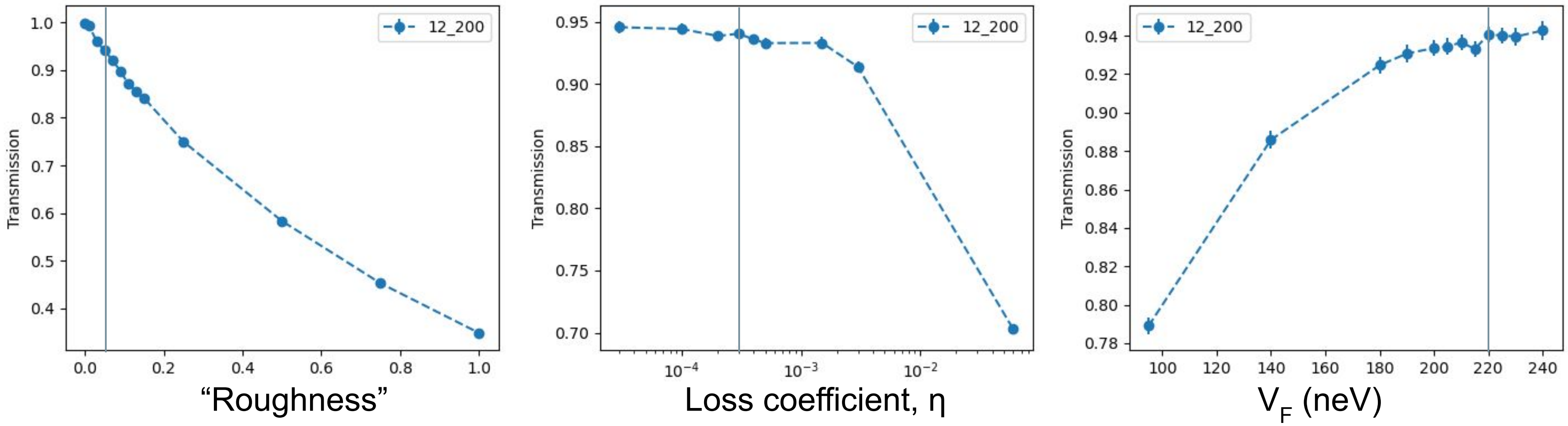
Confirmed that for our NiMo coating

V_F = 216 +- 9 neV





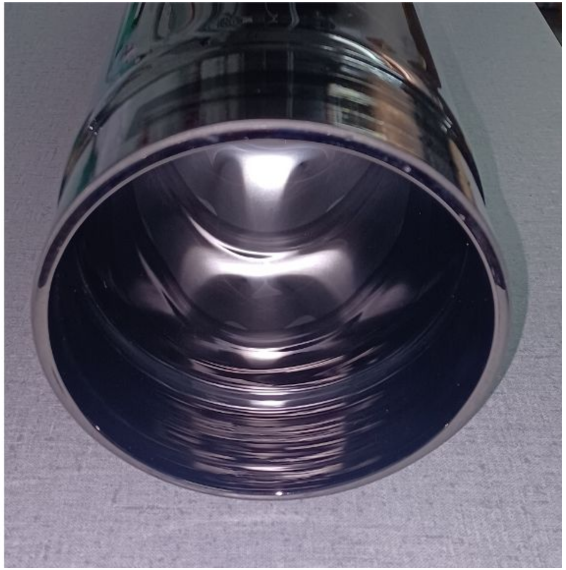
UCN transport simulations



- Simulation of the transmission measurements, from source to detector
- Diffuse scattering fraction (“roughness”) explain differences (Lambert model)
- Not caused by coating, intrinsic to guides
- Not sensitive to the other parameters

The MCUCN simulation code for ultracold neutron physics
Nucl. Inst. and Meth. A, Vol. 881, p. 16-26.
https://doi.org/10.1016/j.nima.2017.10.065

Roughness in UCN guides



Simulation: wrinkles in ends of guides can explain observations with diffusive scattering fraction up to 0.33.

Roughness in UCN guides

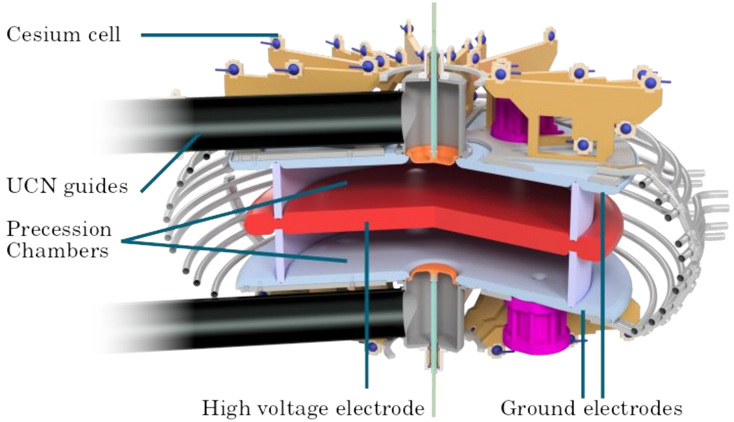
- We ordered 2 new UCN guides
  - One with the wrinkles
  - One from a new company, without wrinkles
- Coated simultaneously (equal coating process)
- Transmission, normalised to 1 m:
  - With wrinkles: 0.89
  - Without wrinkles: 0.94

Summary

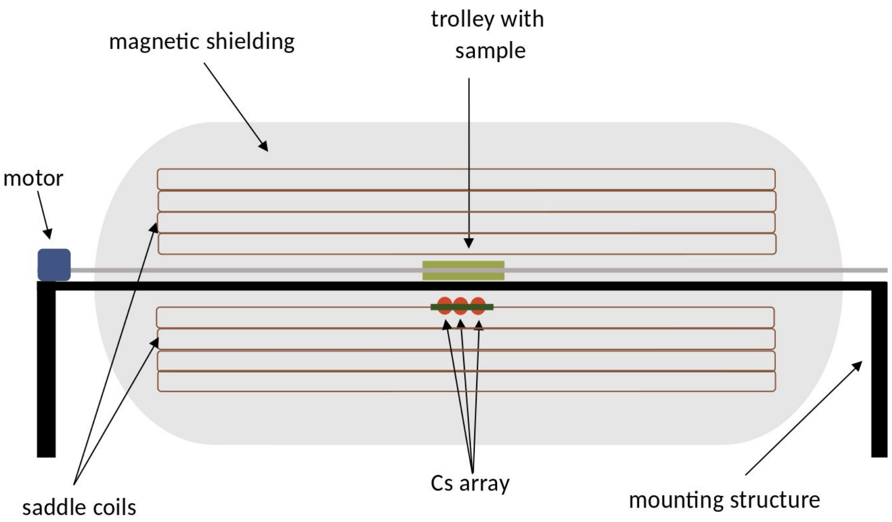
- Our goal: to search for nEDM with 10^{-27} e cm sensitivity
- Our requirements
  - Transmission per meter > 90 %
- We produce guides that satisfy these requirements
- We found out how to produce better guides, improving our statistics

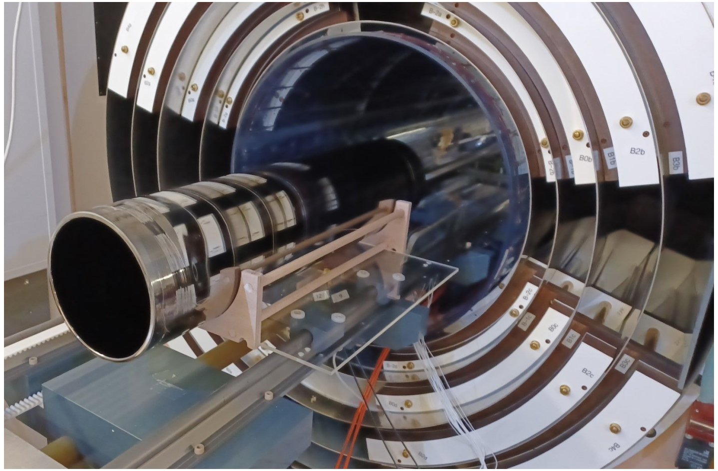
Checking for magnetic dipoles

- Guides closest to precession chamber
- Limit for magnetic contamination:
  - 16 nA m2
  - 25 pT at 5 cm distance
  - 2 million times lower than geomagnetic field
- The guides fulfil the specifications



Checking for magnetic dipoles

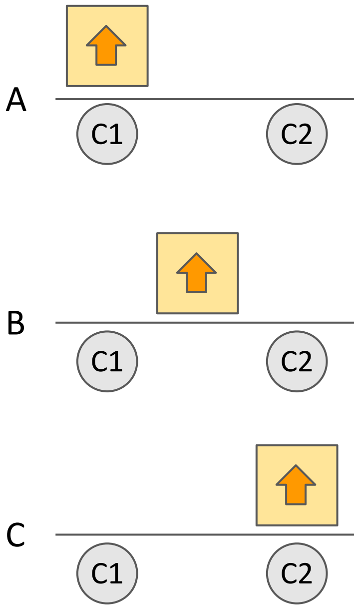


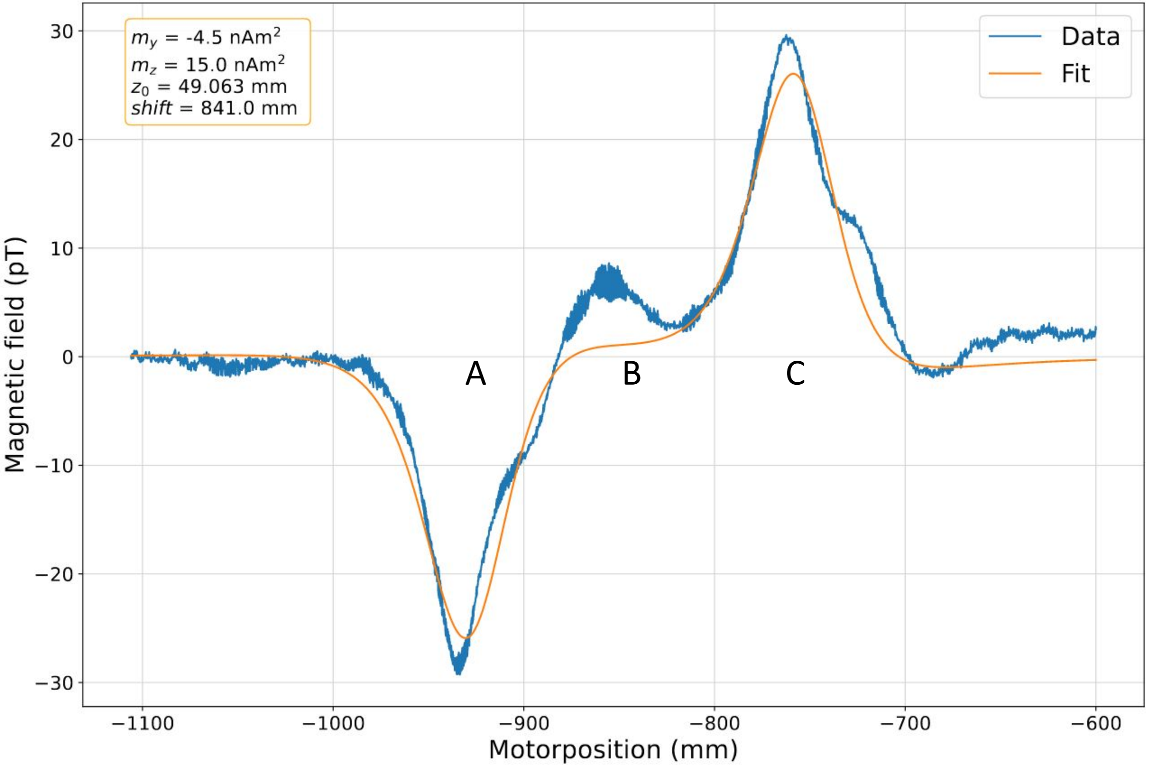


- Vertical B_0 field: 2.6 uT
- Sample driven past Caesium magnetometers
- Quantity of interest: ΔB between Cs magnetometers
- Sensitive to dipoles of 1 nA m^2 (1 pT level)

Example dipole signal

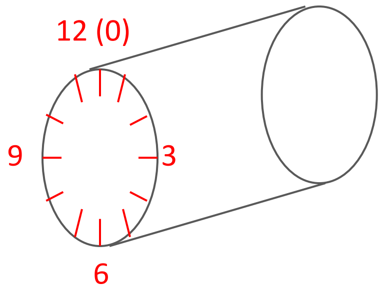
- PEEK (plastic)
- Signal: C2 - C1

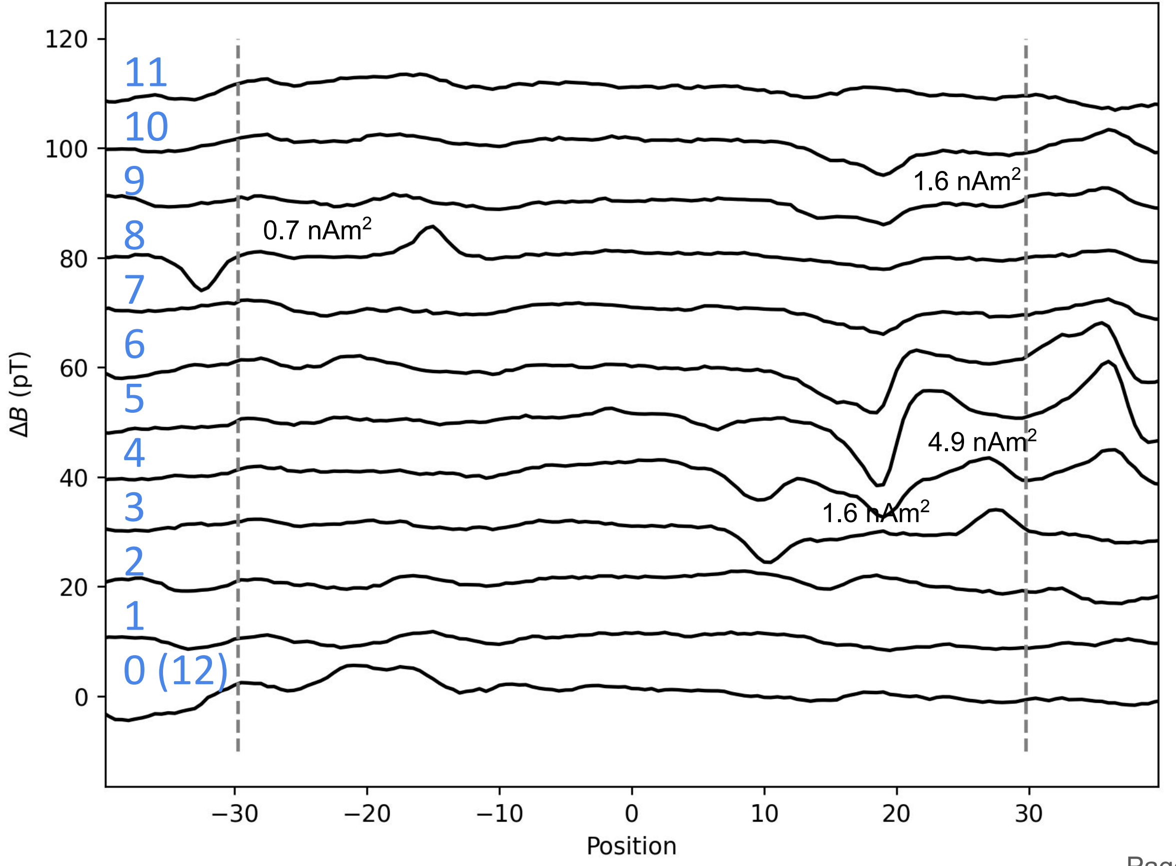




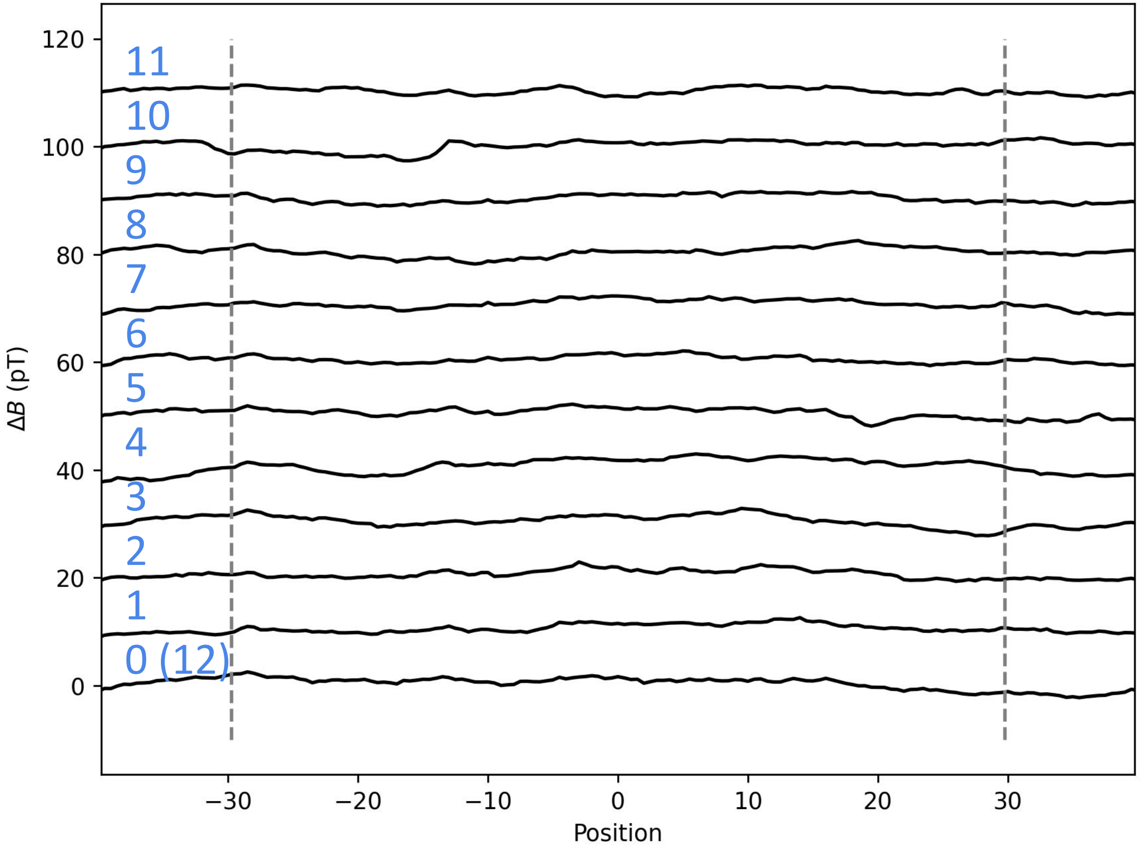
UCN guide dipole scan

Max allowed dipole strength:
10 nAm^2
16 pT

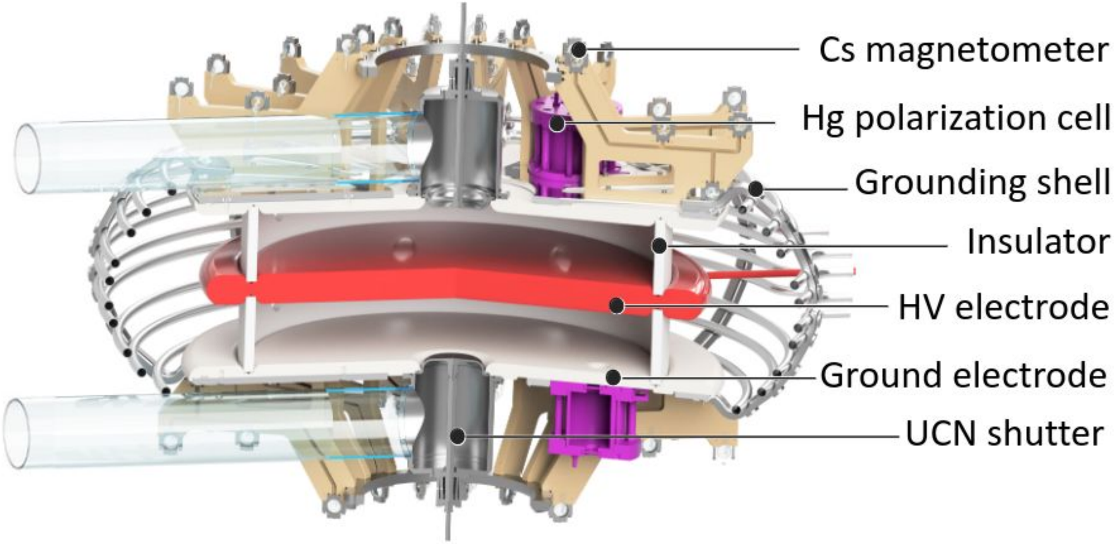




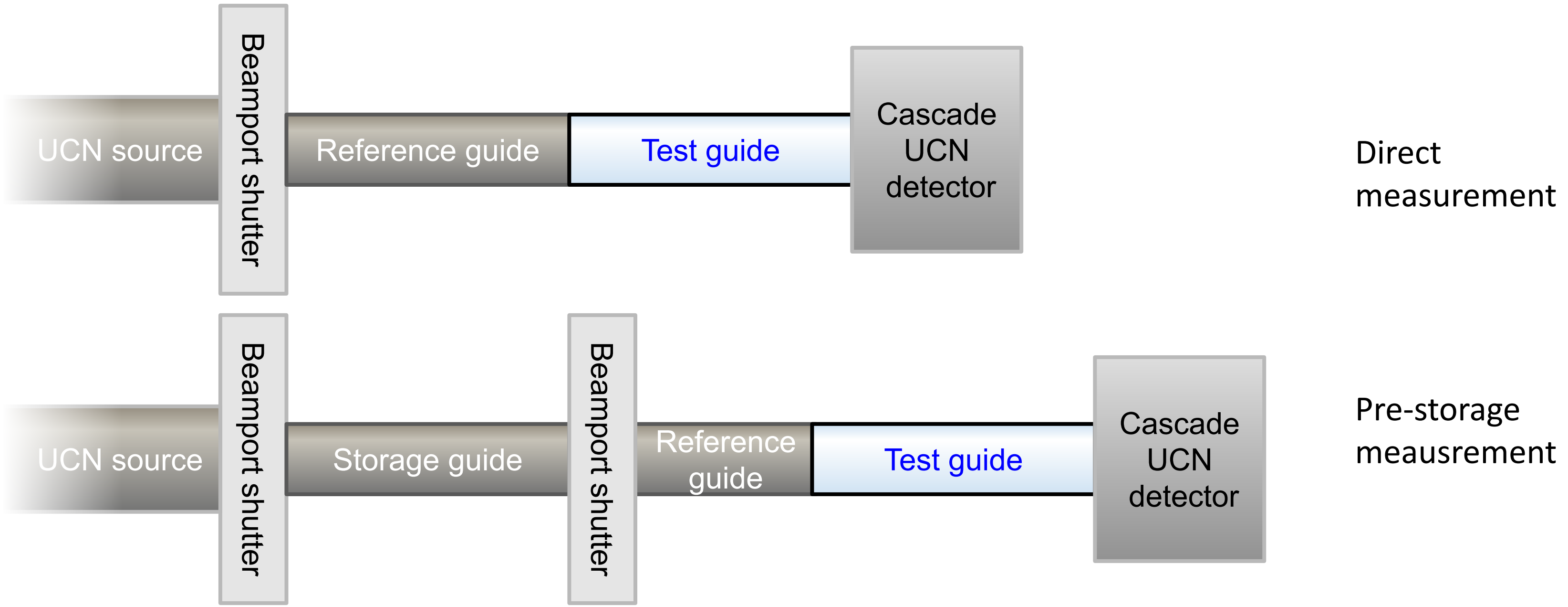
UCN guide dipole scan, degaussed



The precession chambers

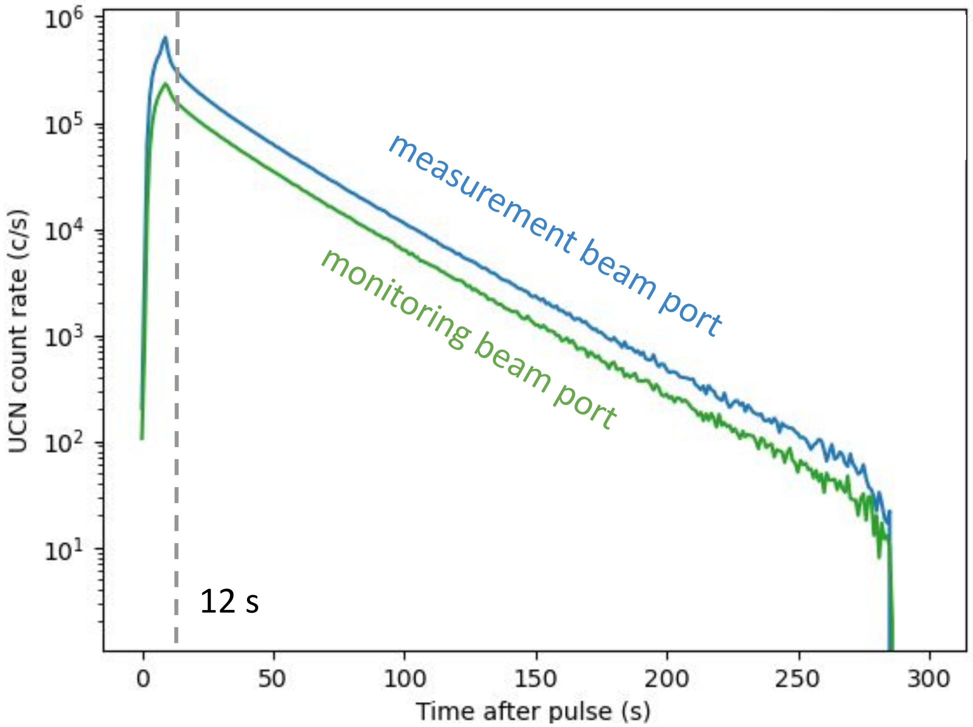


UCN transmission measurements



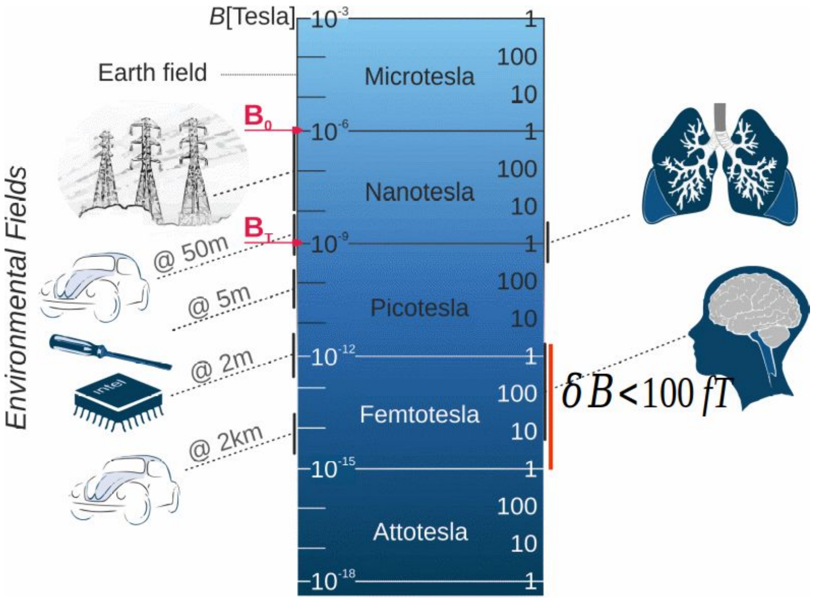
UCN transmission measurements

- Pulsed UCN source
  - 8 s proton beam on spallation target
  - UCN production
  - Fill storage volume
  - Drain into experiment
- Region of interest: 12-200s
  - not all neutrons before 12s are storable
- Normalisation using second beam port at same height



Requirements for UCN guides

- 90% transmission, normalised to 1 m
- Homogeneous magnetic field
  - Field stability (30 fT)
  - Accurate magnetometry (30 fT)
  - Limit on local magnetic impurities
    - 10 nA m^2
    - 16 pT @ 5 cm



Related to statistical errors	
(B-gen) Top-Bottom resonance matching condition	$-0.6\,\mathrm{pT/cm} < G_{1,0} < 0.6\,\mathrm{pT/cm}$
(B-gen) Field uniformity in the chambers	$\sigma(B_z) < 170\,\mathrm{pT}$
(B-gen) Field stability on minutes timescale	< 30 fT
(B-meas) Precision Hg co-magnetometer, per cycle, per chamber	< 30 fT
Related to systematical errors	
(B-gen) Gradient stability on the timescale of minutes	$\sigma(G)[5\mathrm{min}] < 50$ fT/cm
(B-meas) Accuracy mercury co-magnetometer per chamber	< 100 fT
(B-meas) Accuracy on cubic mode (Cs magnetometers)	$\delta \acute{G}_3 < 20\,\mathrm{fT/cm}$
(B-gen) Reproducibility of the order 5 mode	$\sigma(\acute{G}_5) < 20\,\mathrm{fT/cm}$
(B-meas) Accuracy of the order 5 mode (field mapper)	$\delta \acute{G}_5 < 20\,\mathrm{fT/cm}$
(B-gen) Dipoles close to the electrode	< 20 pT at 5 cm
(E-gen) Relative accuracy on E field magnitude	$< 10^{-3}$