PSI Center for Neutron and Muon Sciences

n2EDM

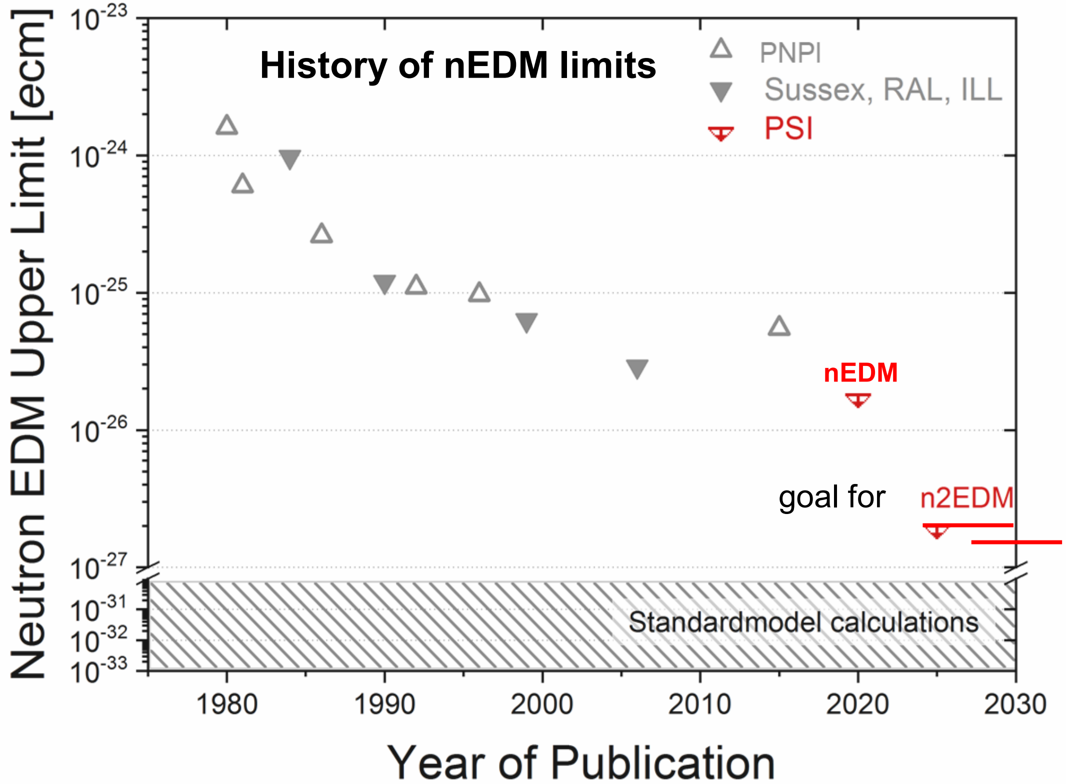
Searching a neutron electric dipole moment n2EDM at PSI

Bernhard Lauss

Center for Neutron und Muon Sciences
Paul Scherrer Institute

May 13, 2025

n2EDM - High sensitivity search for a permanent electric dipole moment d_n of the neutron



current best limit

$|d_n| < 1.8\times10^{-26}$ *e·cm*

by the nEDM collaboration at PSI

C.Abel et al. Phys.Rev.Lett. 124 (2020) 081803

new apparatus n2EDM: factor 10 sensitivity improvement in the baseline setup

The design of the n2EDM experiment, N.J. Ayres et al., Euro.Phys.J. C 81 (2021) 512

- future n2EDMagic phase ~5×10^{-28} *e·cm* sensitivity goal, at 10 μT field. 2028++

n2EDM needs 3 absolutely essential machines to operate at the same time

- the PSI proton accelerator - HIPA

- the ultracold neutron source - UCN

- the experiment apparatus - n2EDM

Time-scale of efforts at PSI

UCN source Letter of intent
UCN source proposal
nEDM proposal

Start UCN source operation

nEDM data taking

First nEDM result published

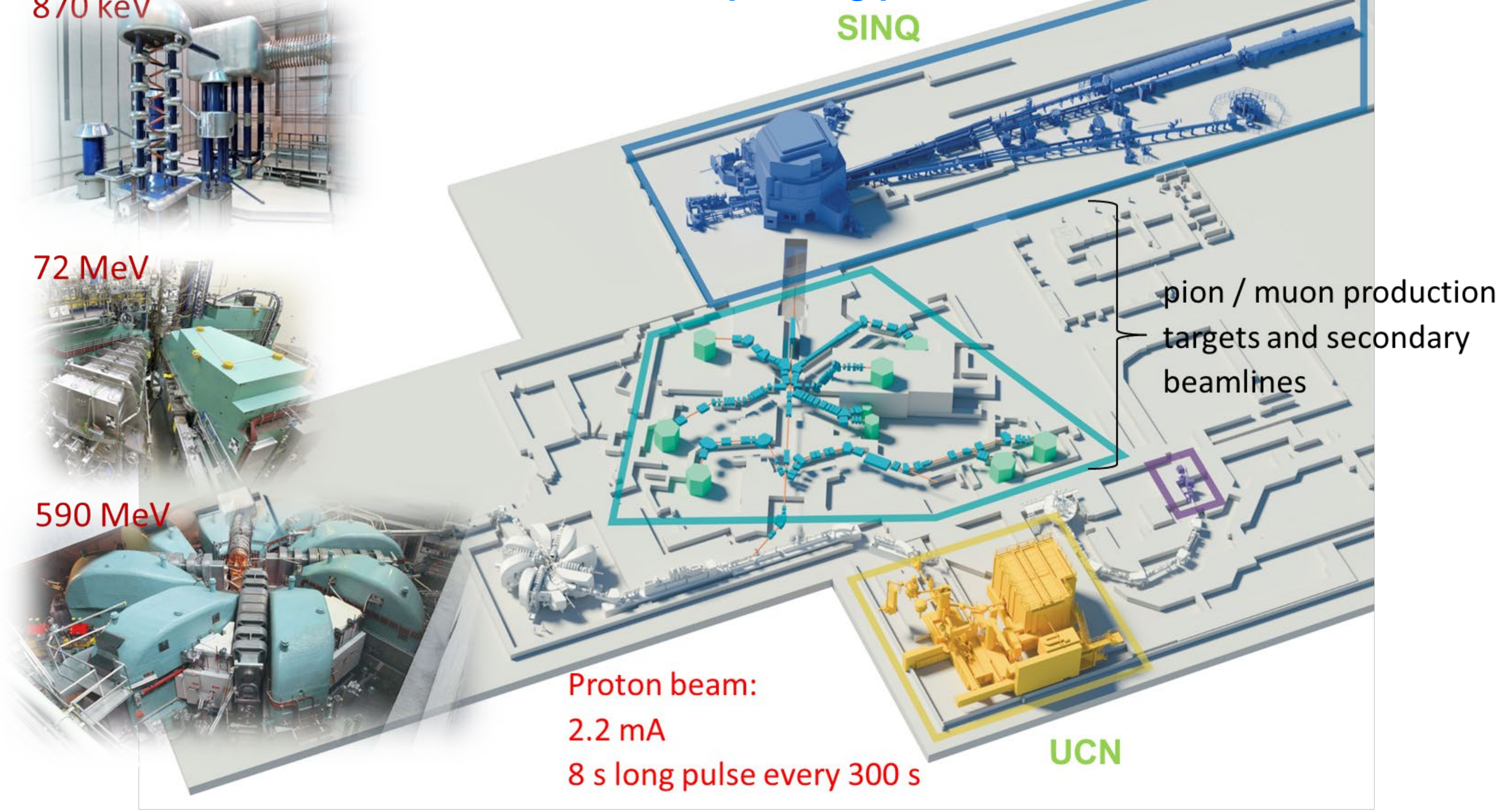
1998 2000 2011 2015/16/17 2018 2020 2025

n2EDM start construction

start data taking

High intensity proton accelerator HIPA

typically around 90% availability
June to December operating period



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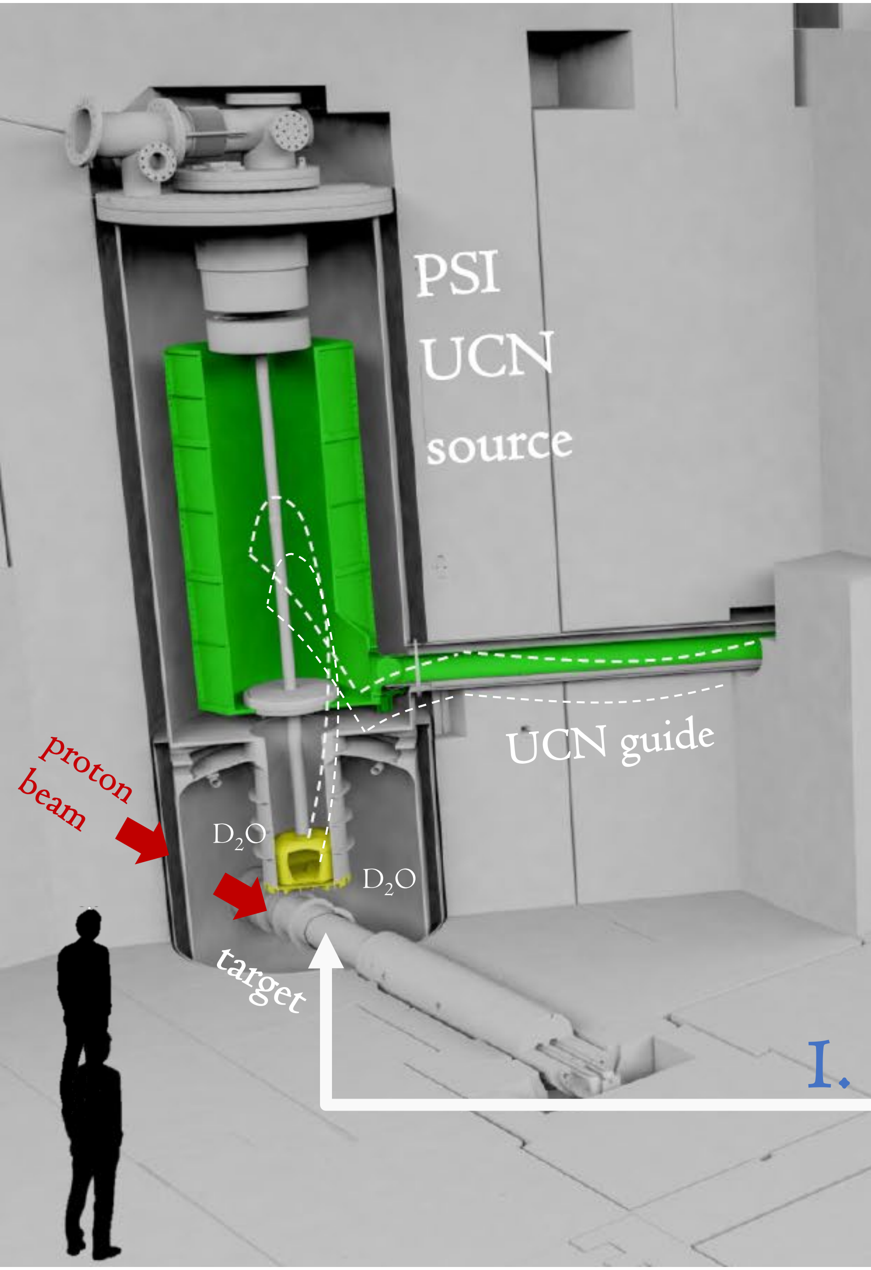
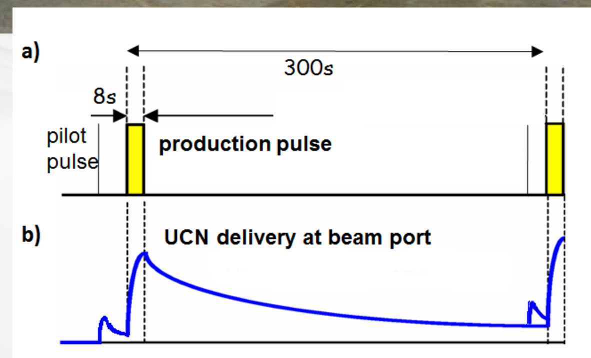
Ultracold Neutron Source - UCN



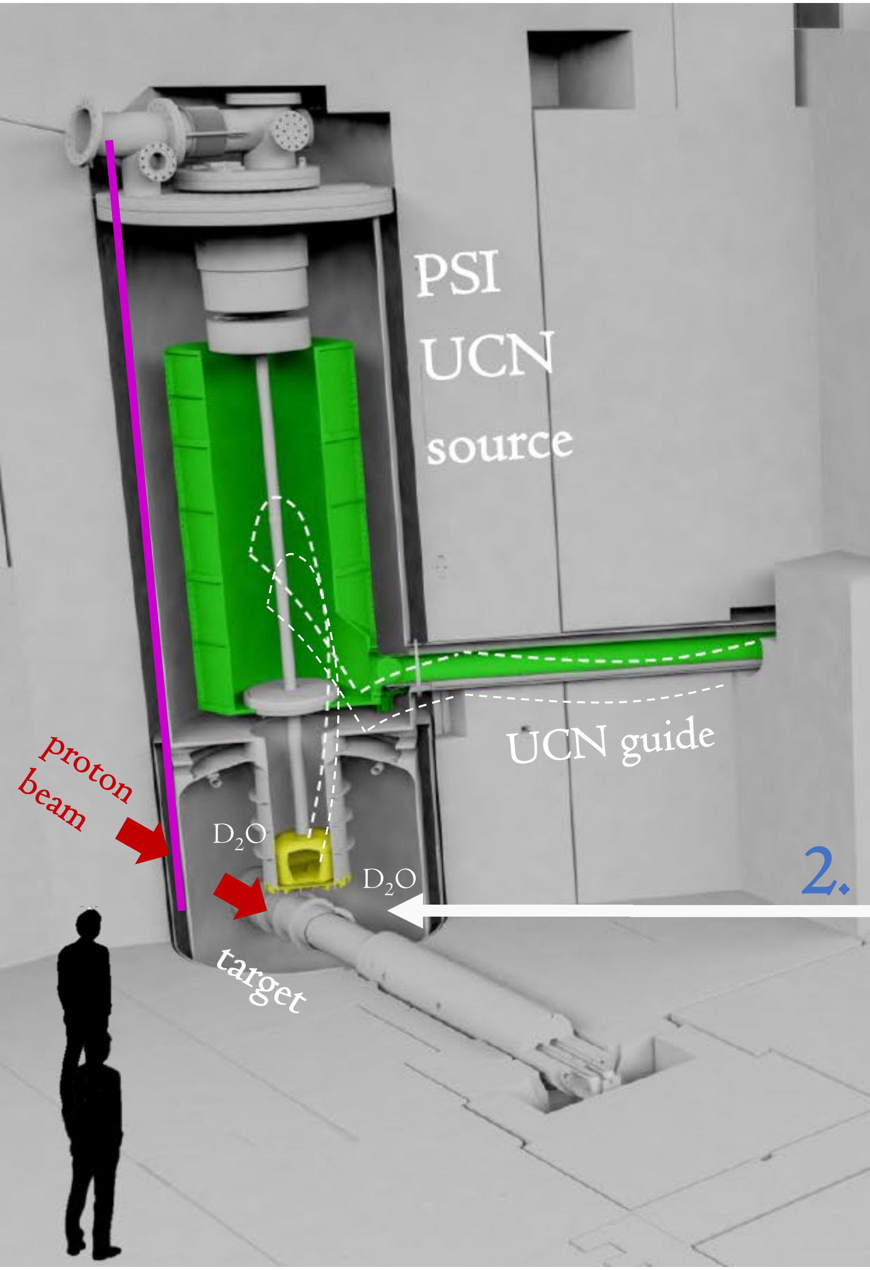
756 Zr/Pb Canneloni

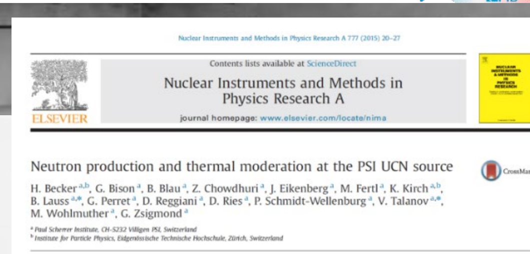
300s period



I. HIPA beam on Pb spallation target (up to 8s) produces ~8 free neutrons per proton

Ultracold Neutron Source - UCN



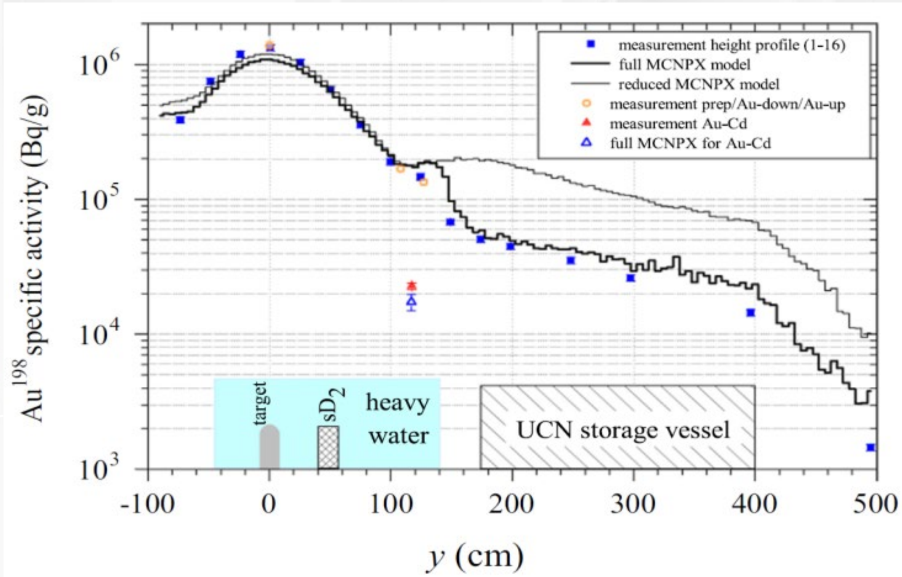


Nuclear Instruments and Methods in Physics Research A 777 (2015) 20–27
Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

Neutron production and thermal moderation at the PSI UCN source

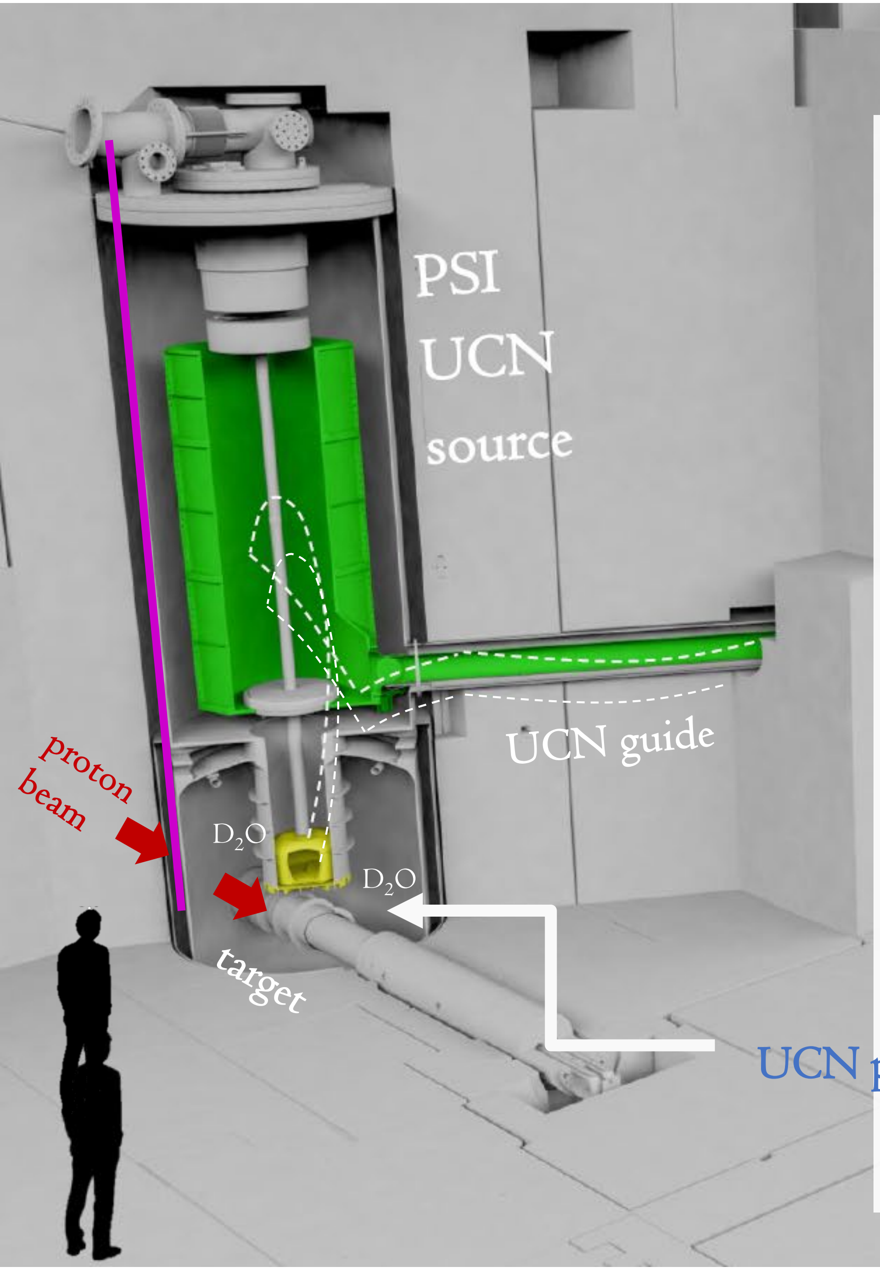
H. Becker[a,b], G. Bison[a], B. Blau[a], Z. Chowdhuri[a], J. Eikenberg[a], M. Fertl[a], K. Kirch[a,b], B. Lauss[a,*], G. Perret[a], D. Reggiani[a], D. Ries[a], P. Schmidt-Wellenburg[a], V. Talanov[a,*], M. Wohlmuther[a], G. Zsigmond[a]
[a] Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[b] Institute for Particle Physics, Eidgenössische Technische Hochschule, Zürich, Switzerland

Thermal flux
MCNP-X + gold foil



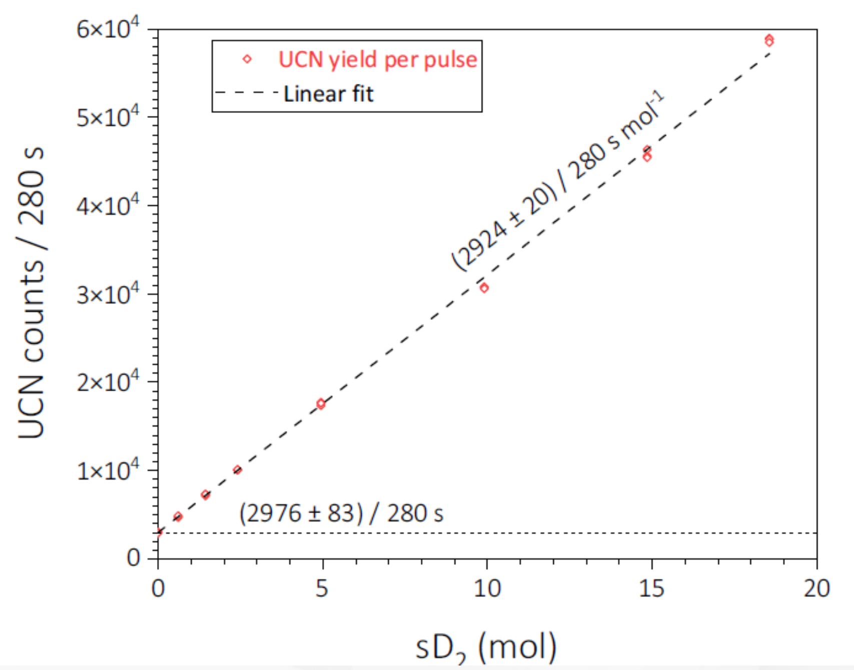
2. Moderation in heavy water thermalizes neutrons at room temperature

Ultracold Neutron Source - UCN



UCN intensity vs. deuterium mass

G.Bison et al., PHYSICAL REVIEW C **107**, 035501 (2023)



UCN production in solid deuterium at 5K

PhD thesis: I. Rienaecker

Solid deuterium surface degradation

EPJ A Highlight - Solid deuterium surface degradation at ultracold neutron sources

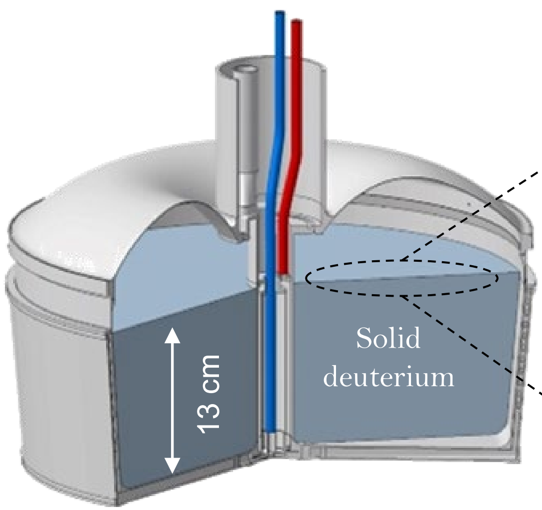
Published on 11 September 2018

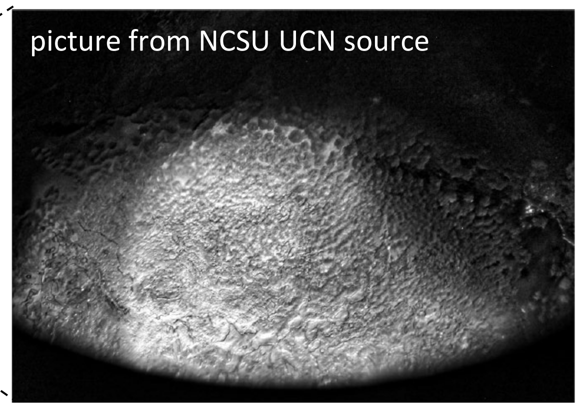
Sublimation:
Heat deposition during proton beam pulse causes sublimation of D2 vapor

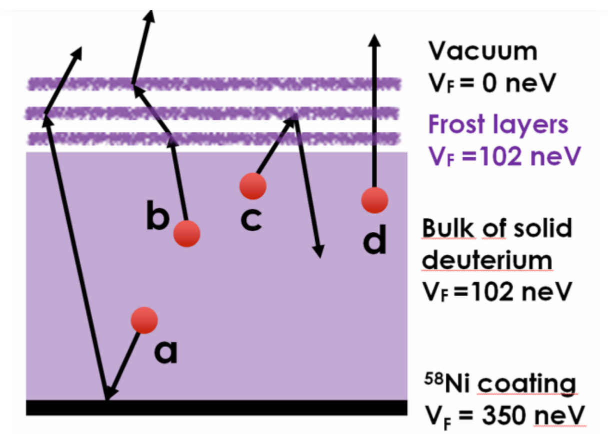
Frost deposition:
After the proton beam pulse the D2 vapor is deposited on the cold sD2 surface and forms an opaque frost layer

Albedo reflection:
Frost layer causes Albedo reflection of UCN back into the sD2 bulk where they are lost due to upscattering and absorption

Eur. Phys. J. A (2018) 54: 148







conditioning procedure - 'surface heating' - regains full UCN output

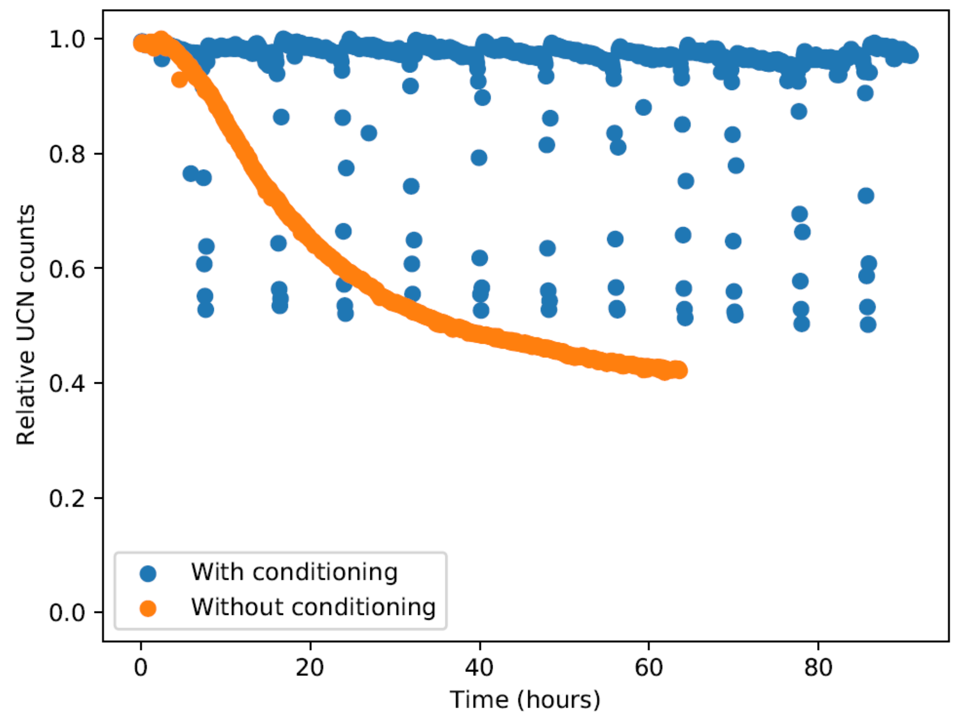
PhD theses: N. Hild

Regain intensity via automated daily conditioning procedure

The new conditioning procedure recovers the UCN output just as the standard conditioning for all cases investigated until now

Estimated gain on average UCN output: ≈ 20%

automated conditioning



PhD thesis: C.B. Doorenbos

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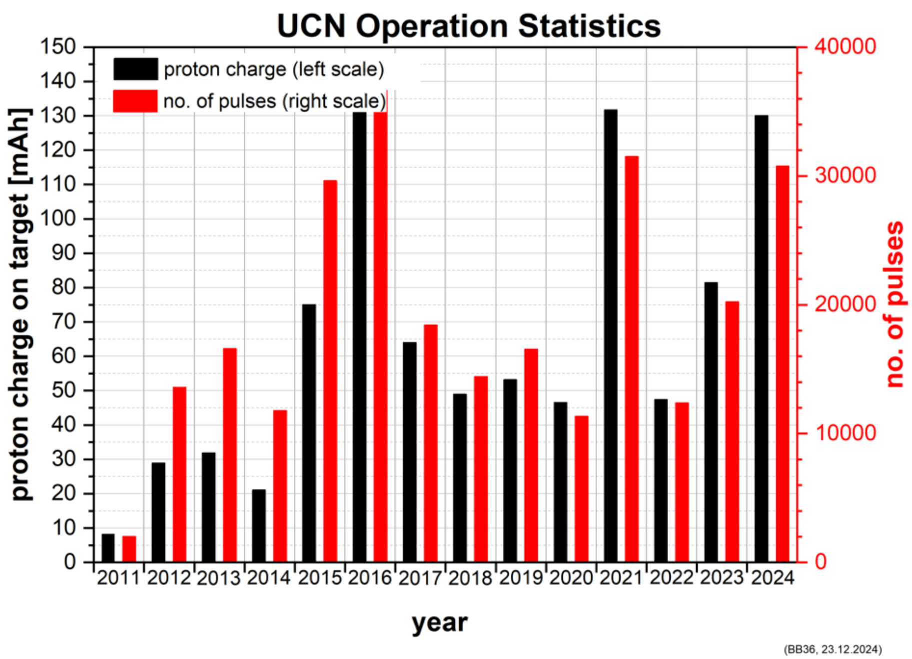
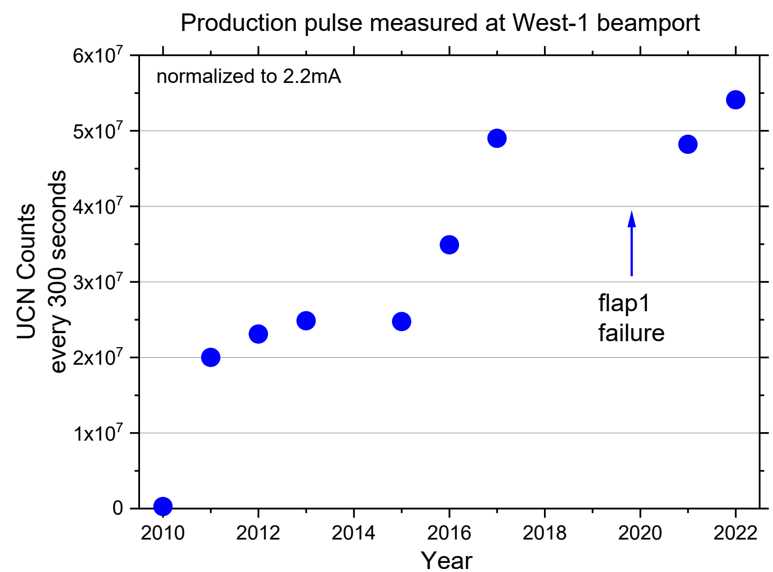
UCN operation

UCN intensity improvement

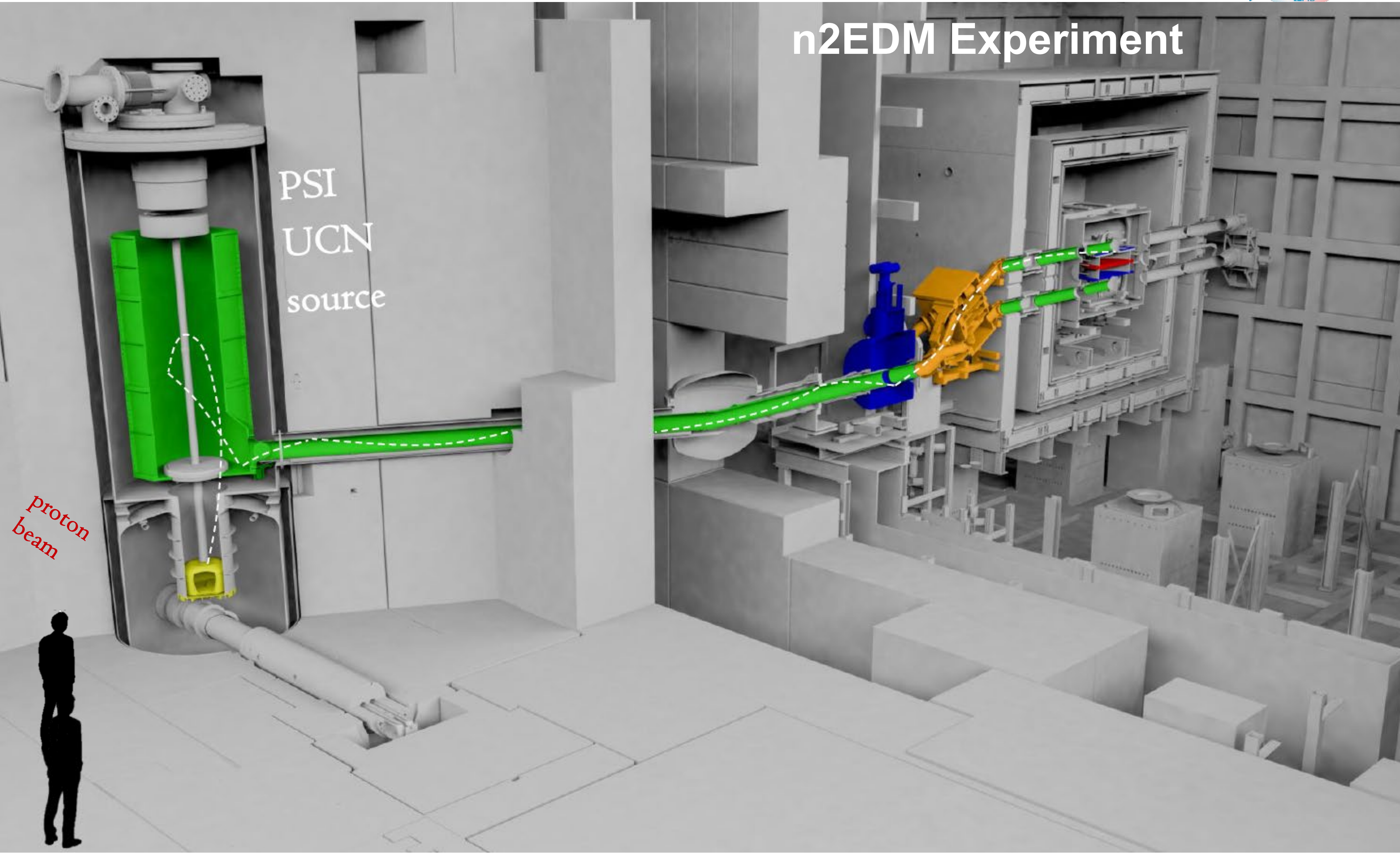


max. 280 pulses/day

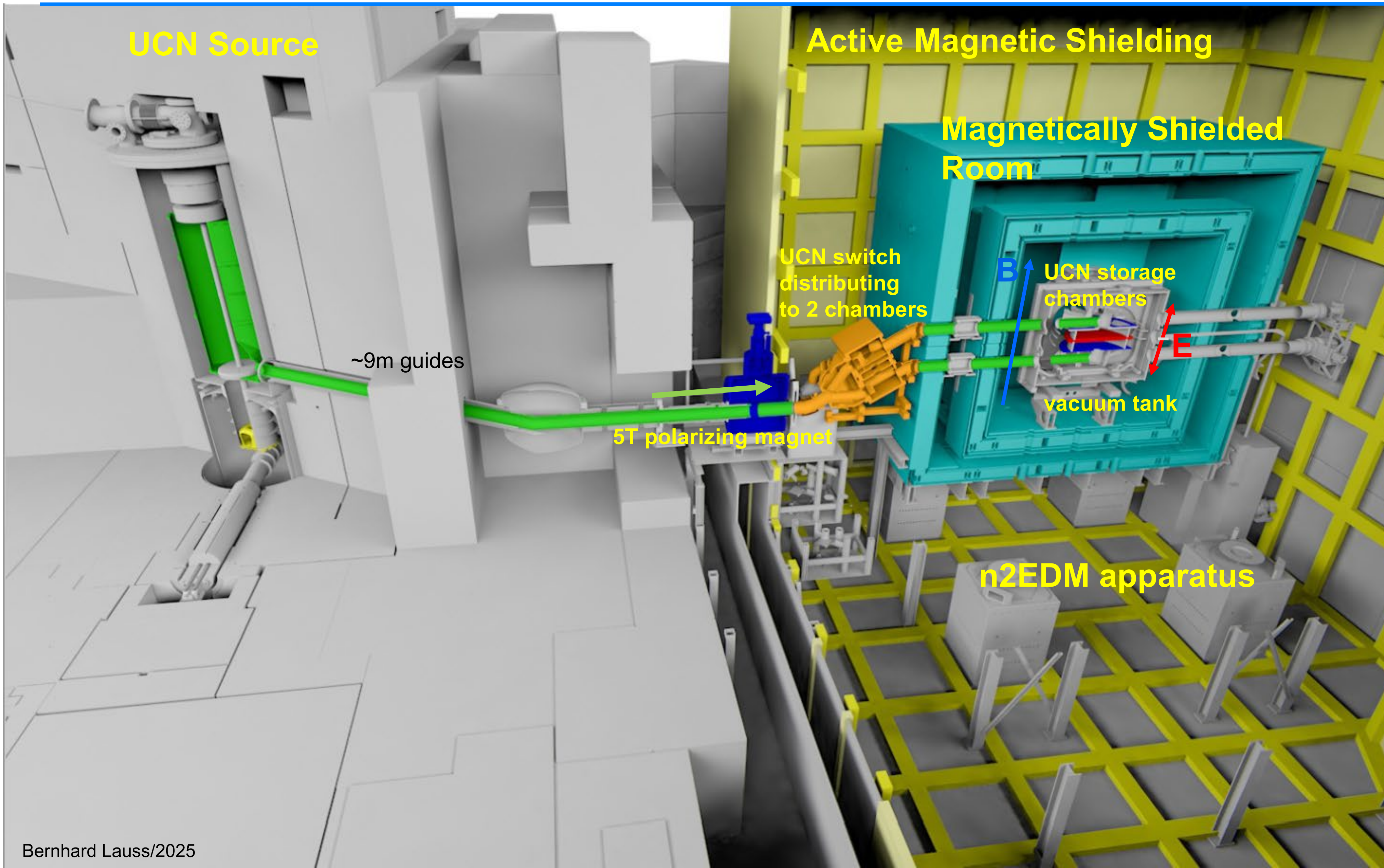
Operation in 2022 with largest D2 mass = 5.677 kg



UCN delivery to Experiments

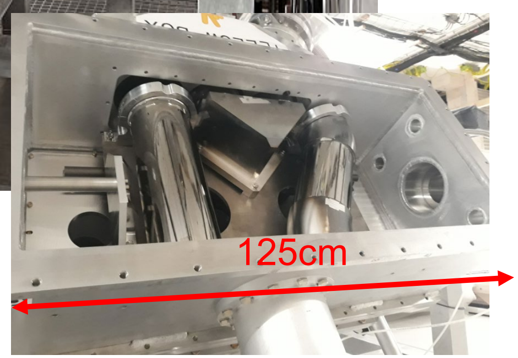


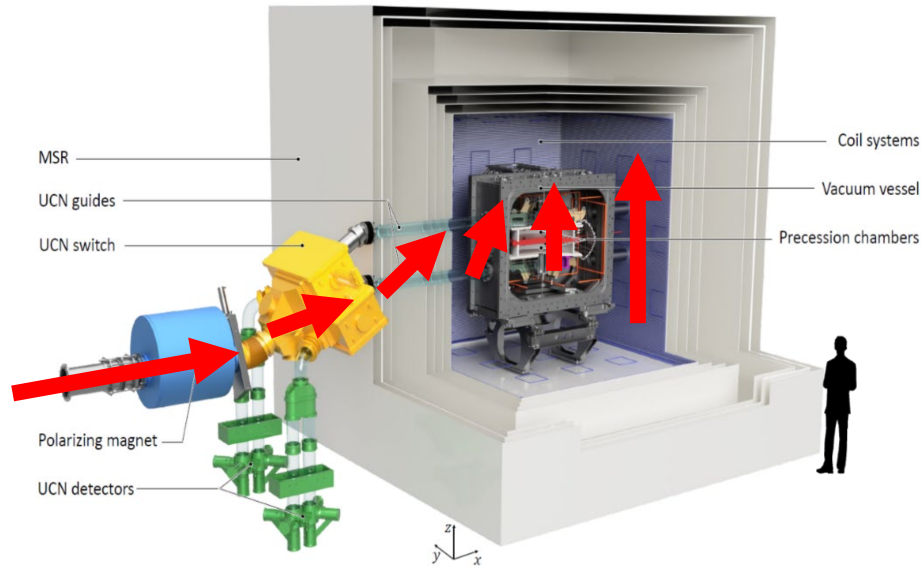
n2EDM - new apparatus



Bernhard Lauss/2025

Polarize UCNs & transport to storage

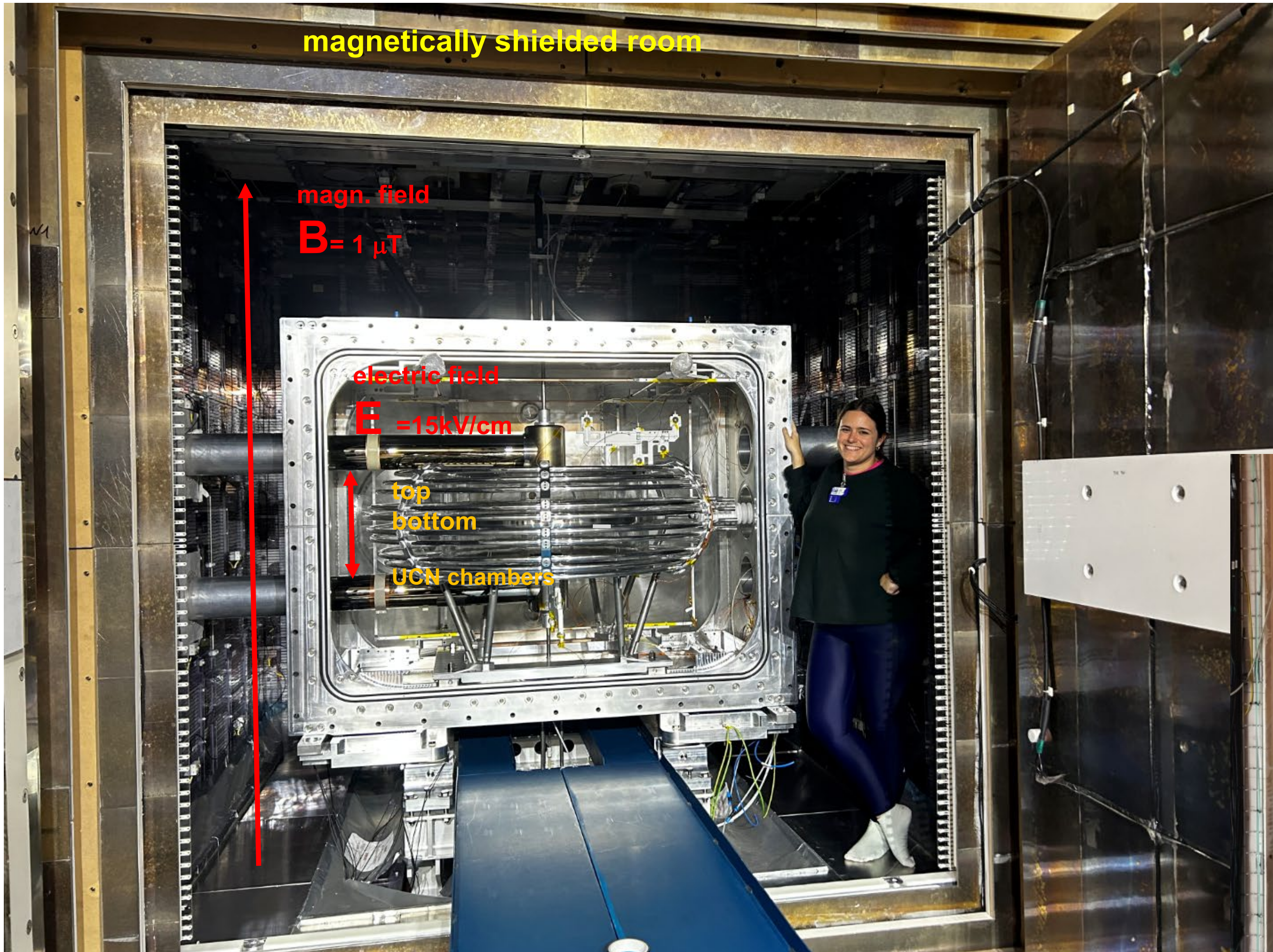



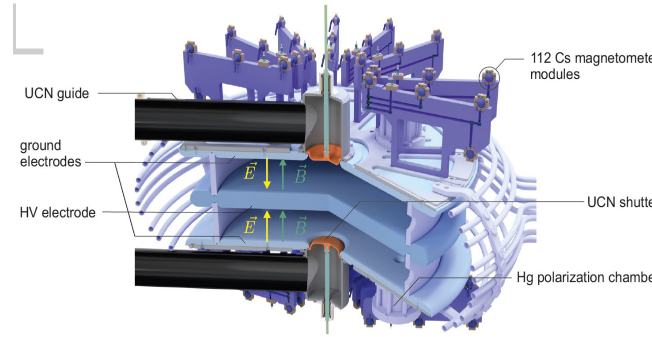


n2EDM

UCN chamber stack - 2x 60 liter volume

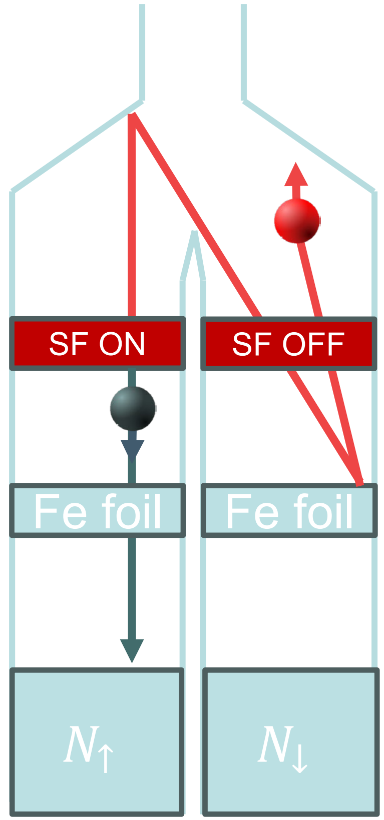
currently: DLC + Quartz

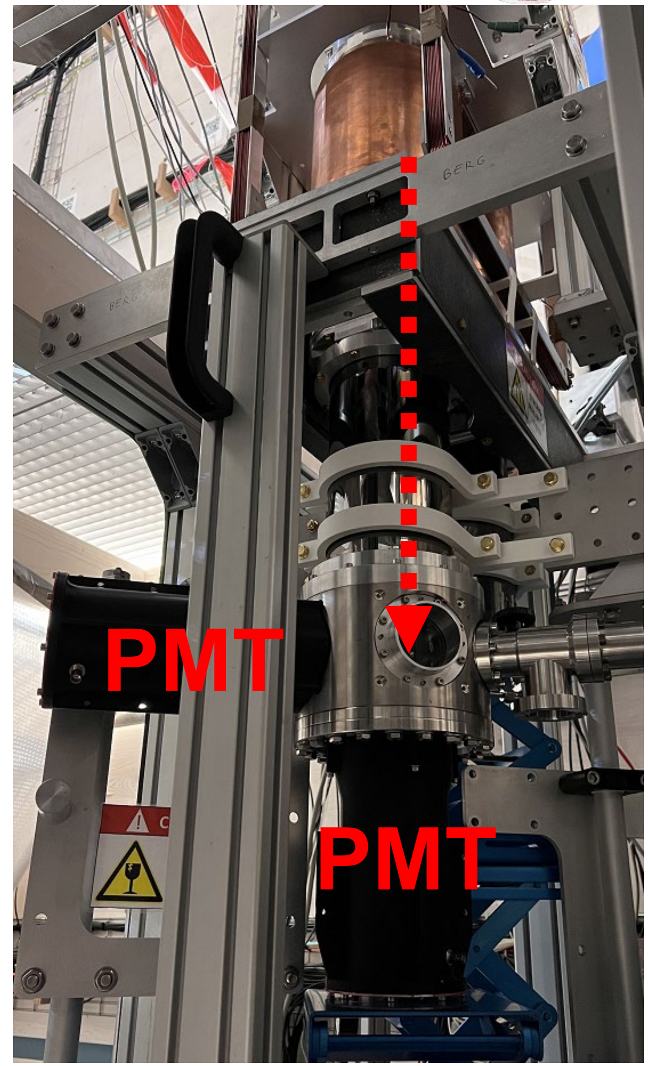




Measure spin state to extract frequency

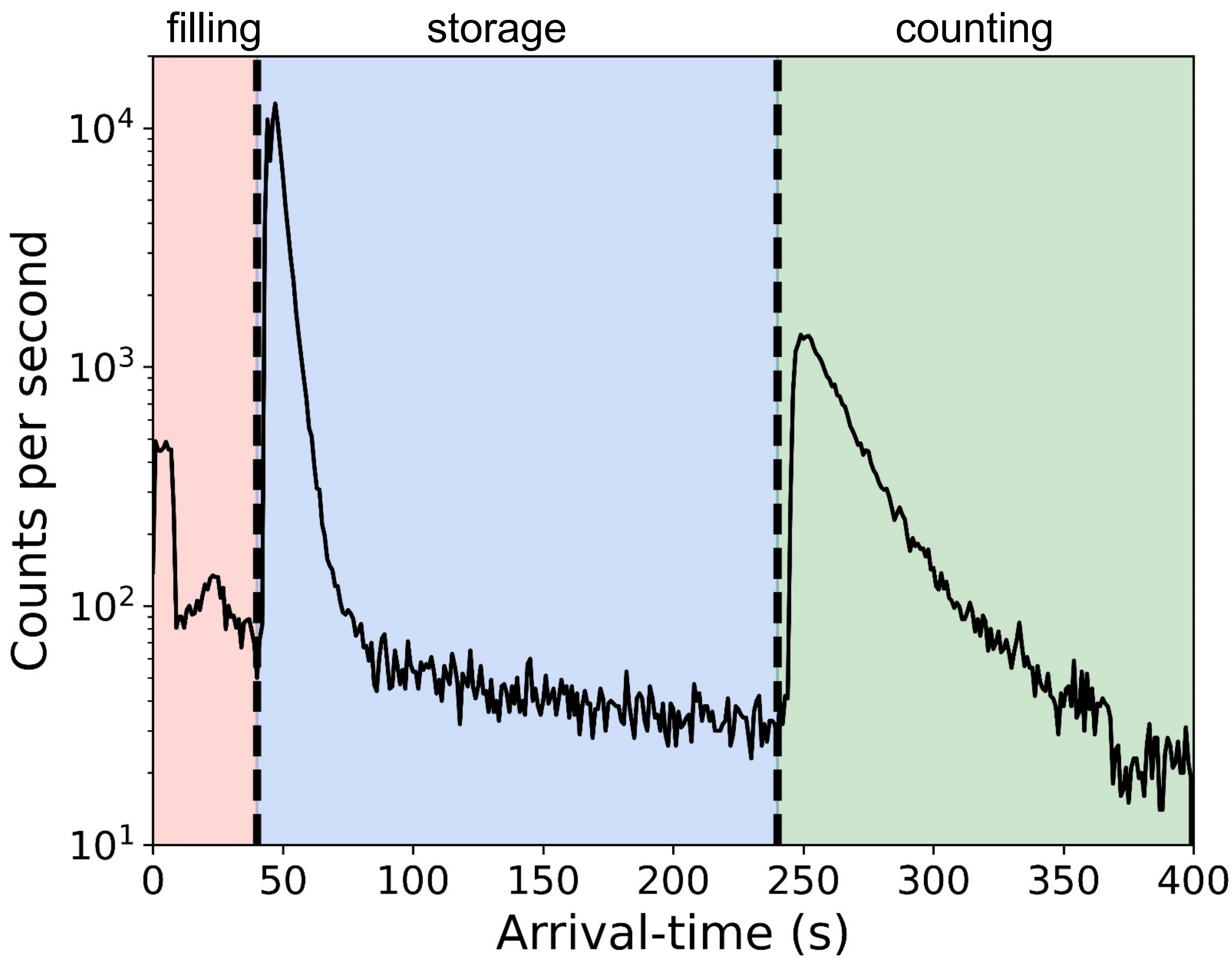
- He3 + CF4 gas detector
- $n + \mathrm{He3} \rightarrow p + t$
- 3-PMT coincidence readout
- Saturated (magnetized) Fe foil used for spin-discrimination





PhD theses W. Saenz-Arevalo, A. Lejuez

Counting UCNs in n2EDM

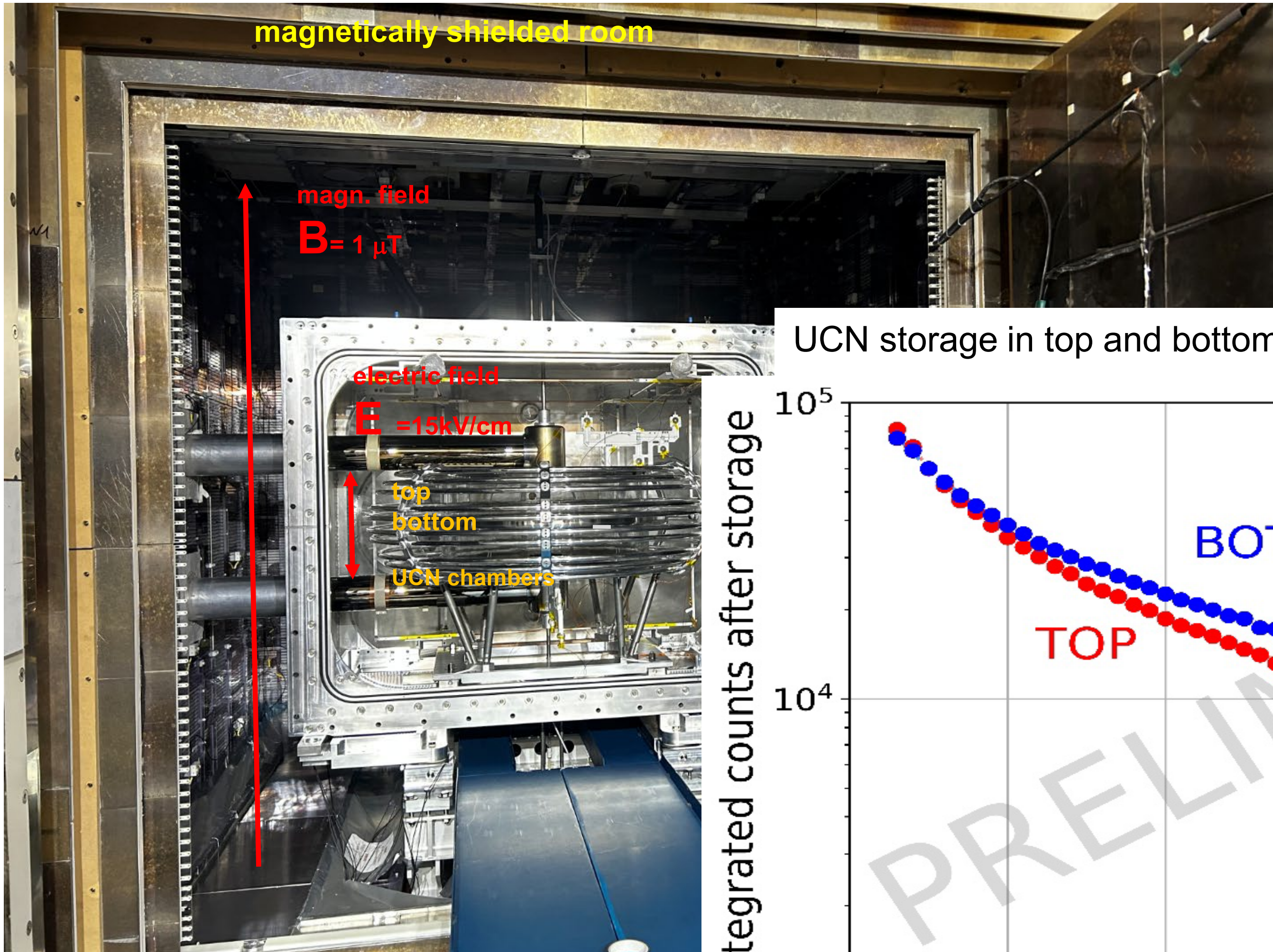


Sample time structure of one cycle as seen from UCN detectors (top + bottom).

n2EDM

UCN chamber stack - 2x 60 liter volume

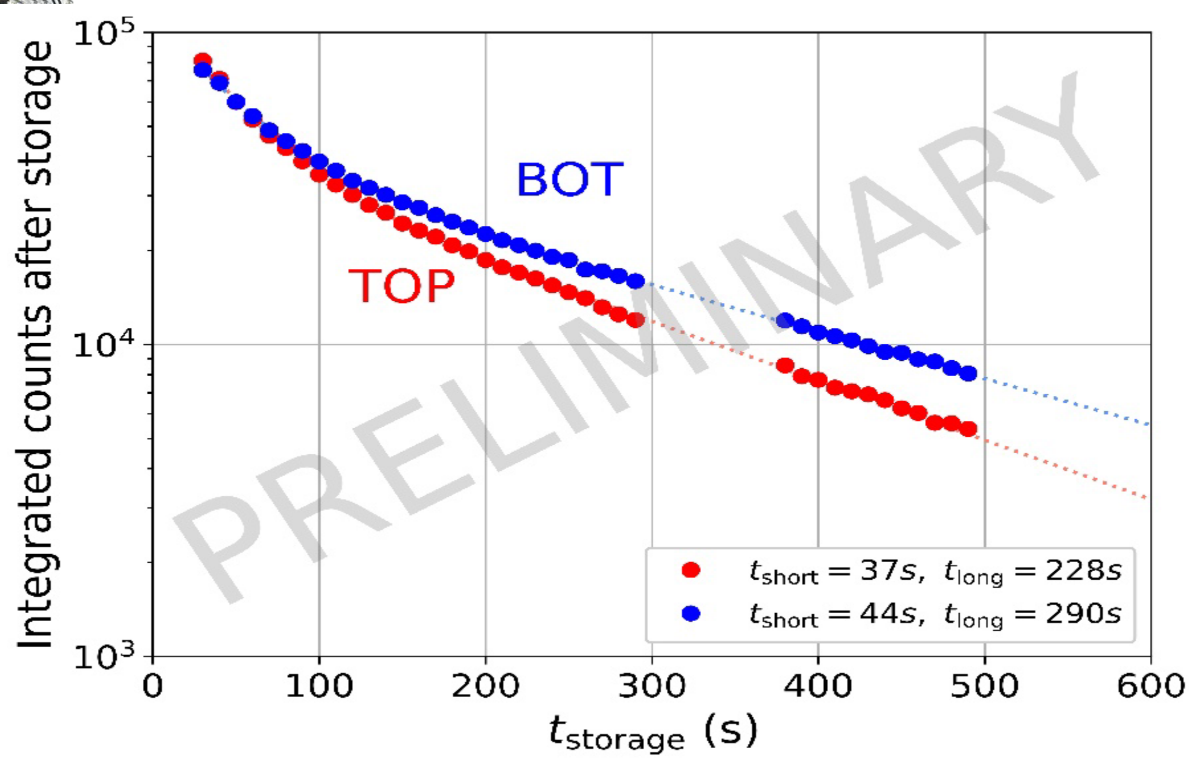
currently: DLC + Quartz



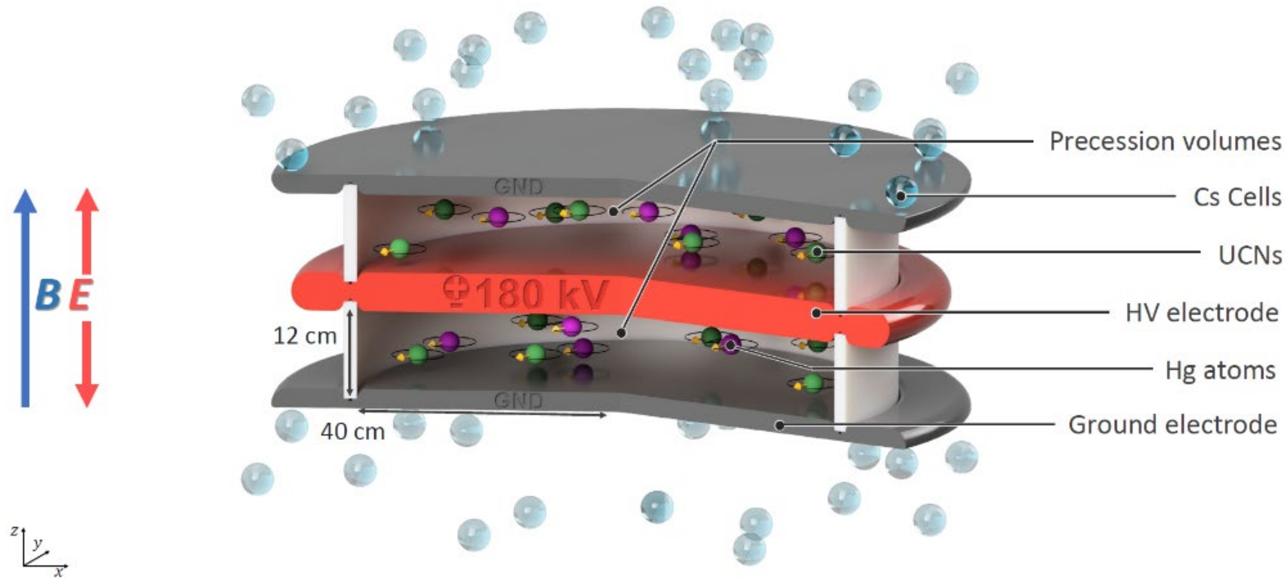
- regular nEDM measurements with full UCN system and Hg and Cs magnetometer in Dec. 2024

- **operated at a statistics of *25'000 UCN per chamber at t_{store}=180s in Dec.2024***

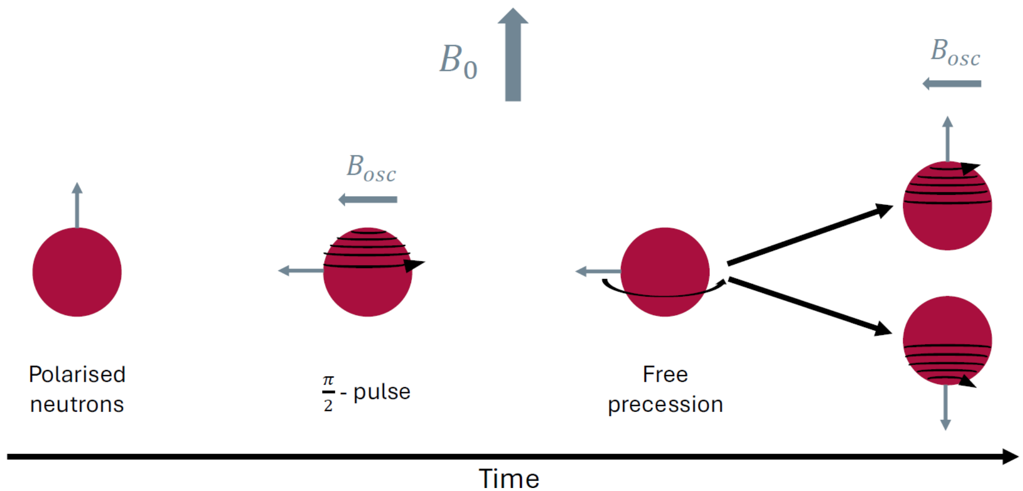
UCN storage in top and bottom chamber



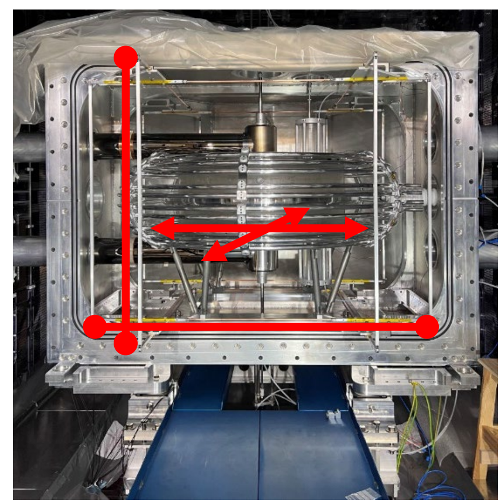
Ramsey's Method of Oscillating Fields
Simultaneous measurement of $f_n^{\uparrow\uparrow}, f_n^{\uparrow\downarrow}$



- 2 independent coils in to produce $B_\perp$ in x, y
- Induces current in Al vacuum vessel
- **Same** spin-flip pulse for TOP and BOT chambers



RF coils



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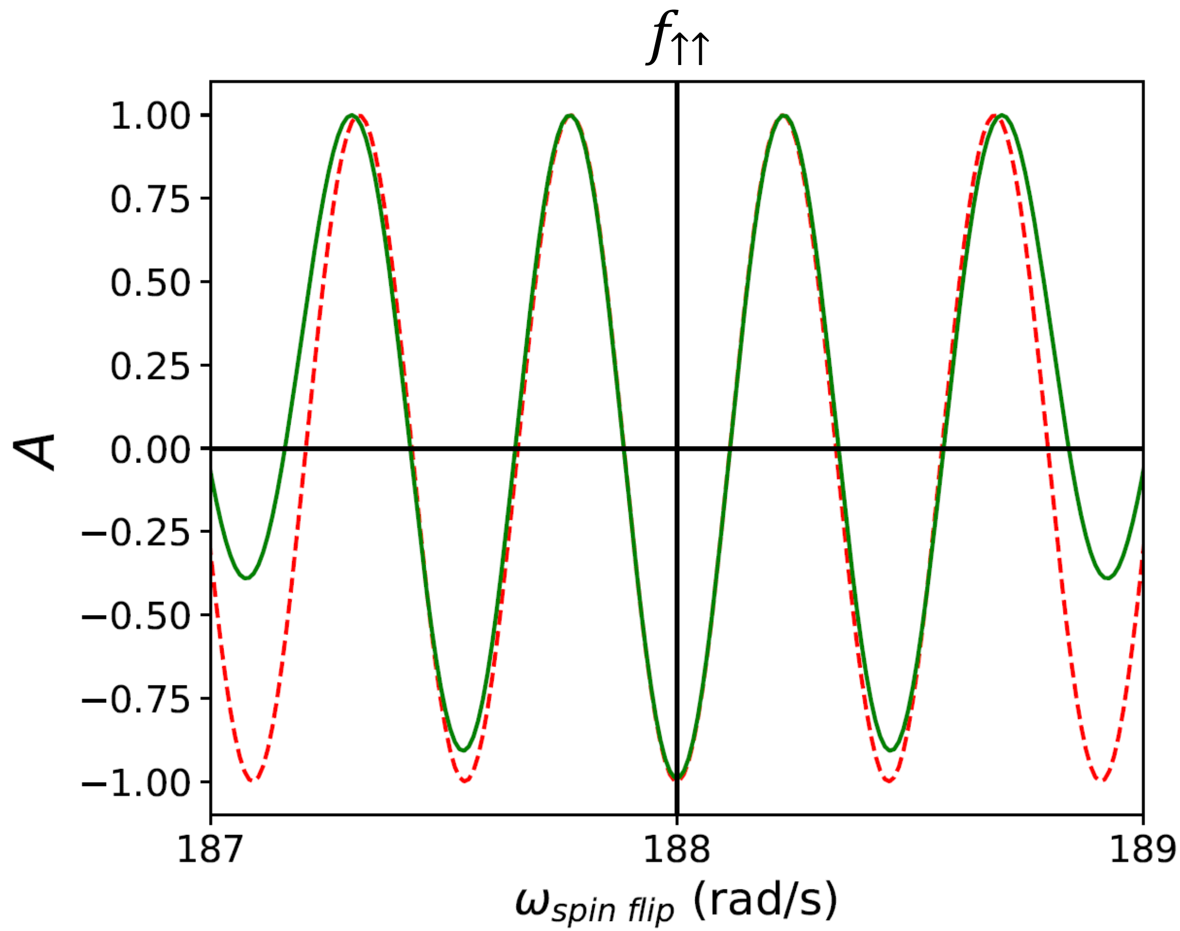
Ramsey measurement with both spin-states of neutrons

n2EDM

$$A \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$\approx -\alpha \cos\left(\pi \frac{f_{\text{spin flip}} - f_{\uparrow\uparrow}}{\Delta\nu}\right)$$

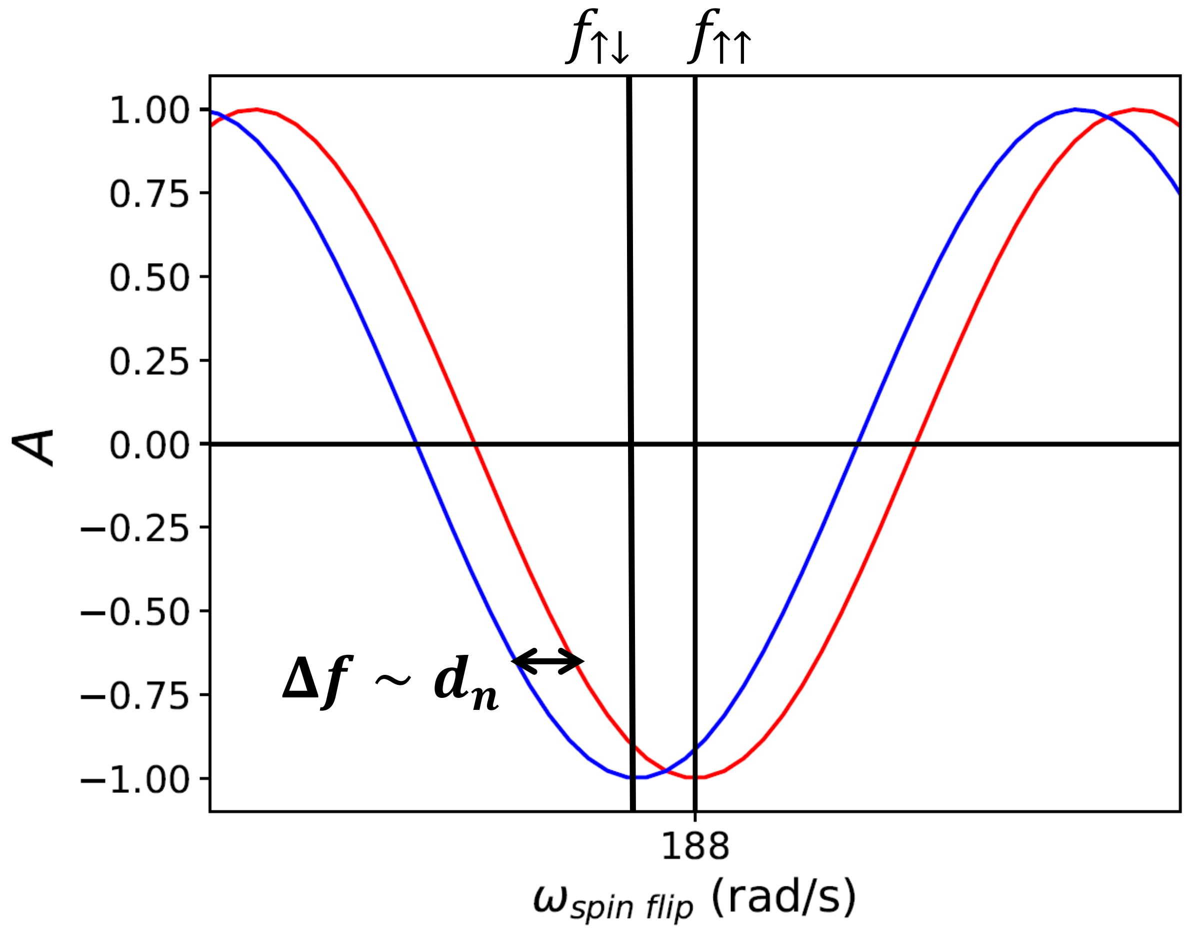


$$\Delta\nu = \frac{1}{2T + 4\, t_{\text{spin flip}}/\pi}$$

Ramsey measurement with both spin-states of neutrons

$$hf_{\uparrow\uparrow} = 2(\mu_n B + d_n E)$$

$$hf_{\uparrow\downarrow} = 2(\mu_n B - d_n E)$$

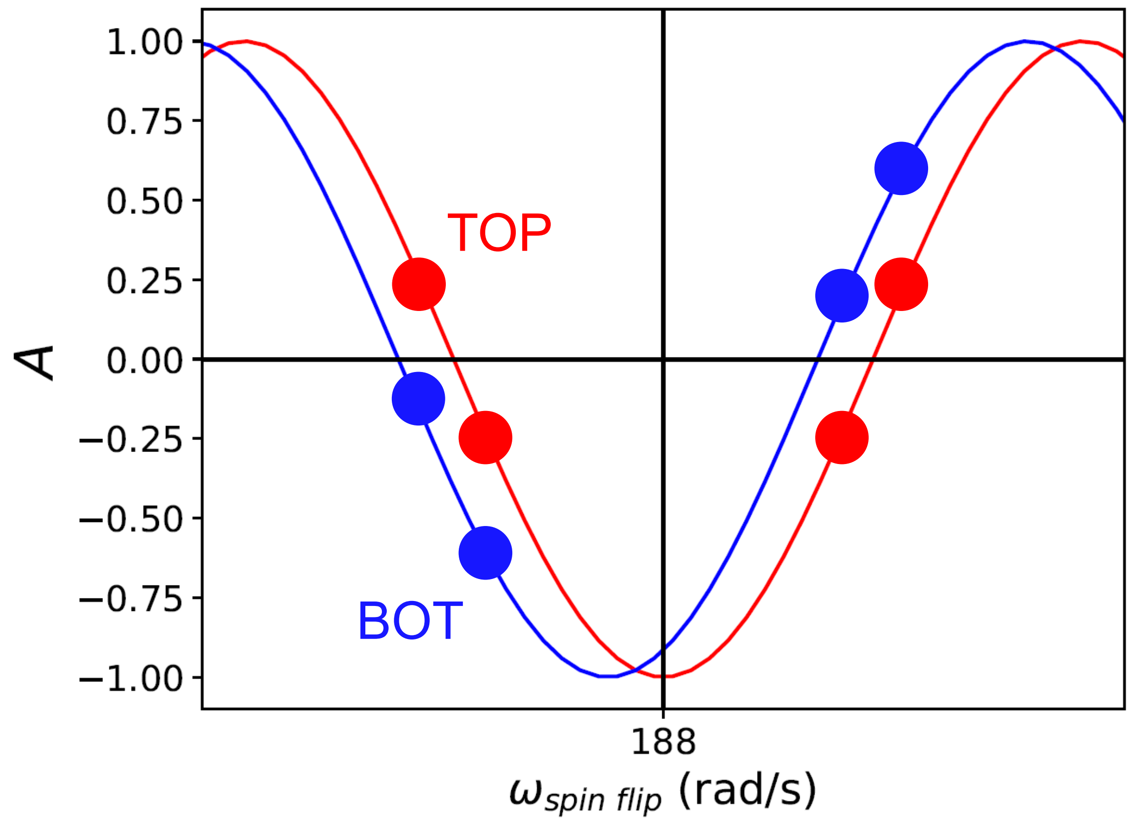


Strong constraint on "top-bottom" field matching

$$f^i = \frac{2\mu_n}{h} B^i \pm \frac{2d_n}{h} E^i$$

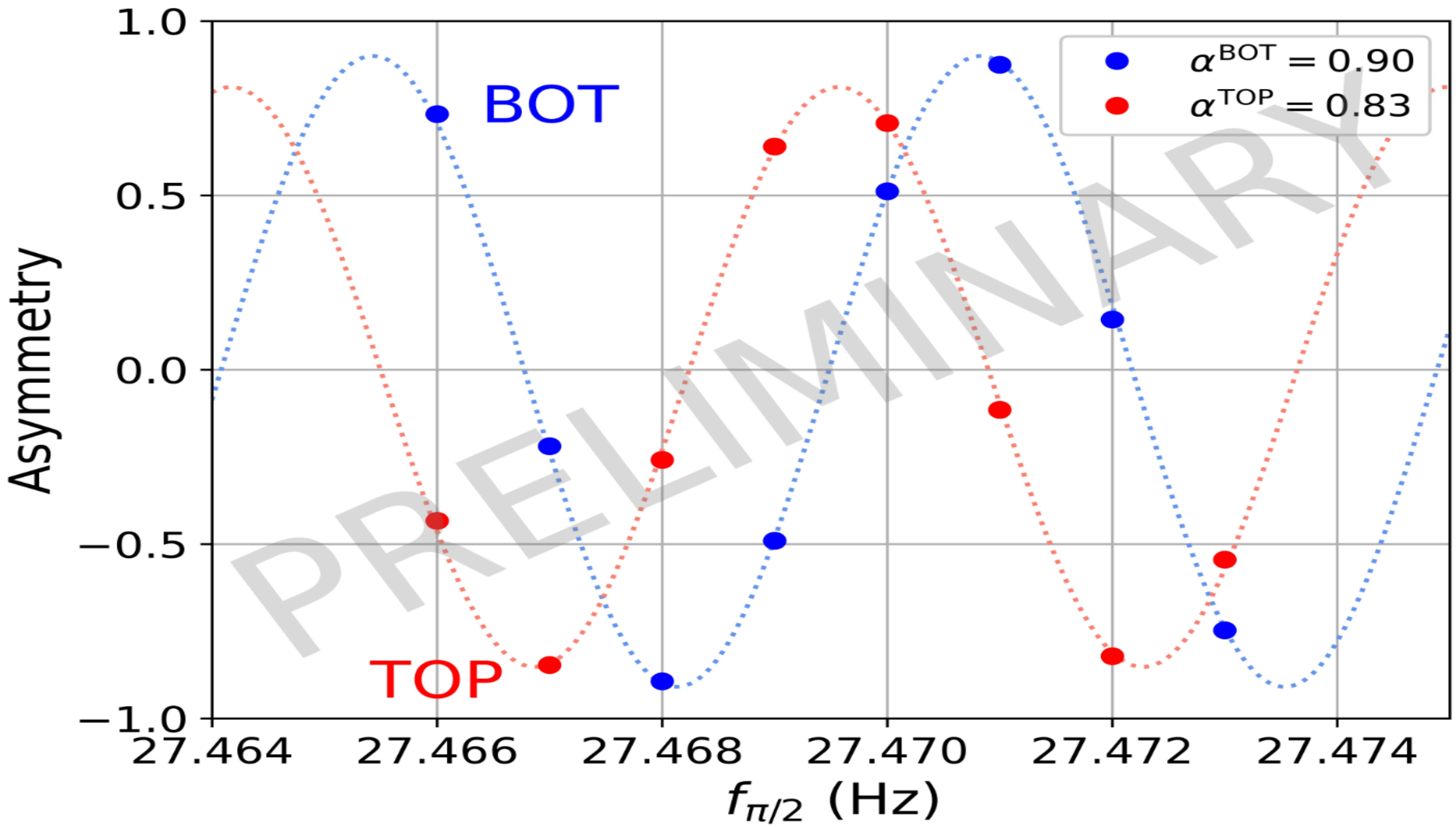
$$B_z^{\text{TOP}} = B_z^{\text{BOT}}$$

$$\frac{\Delta B_z}{\Delta z} < 0.6\text{pT/cm}$$



n2EDM Commissioning

Coincident Ramsey measurement in top and bottom UCN chambers already without B-field correction and highest asymmetry.



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Sensitivity to nEDM

n2EDM

“Analyzing power”

$$\sigma(d_n) = \frac{\hbar}{2\,\alpha\,E\,T\,\sqrt{N_\uparrow + N_\downarrow}}\left(1 - \frac{A^2}{\alpha^2}\right)^{-1/2}$$

“Visibility”

Electric-field strength

Interaction time (precession time)

Neutron statistics

Maximum sensitivity at A=0

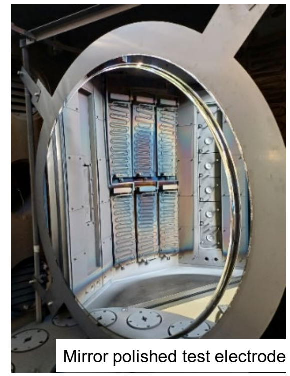
=> steepest slope = 'working points'

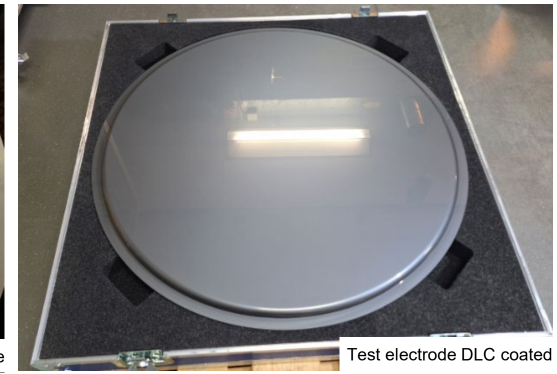
Recent advances

UCN statistic (2024)

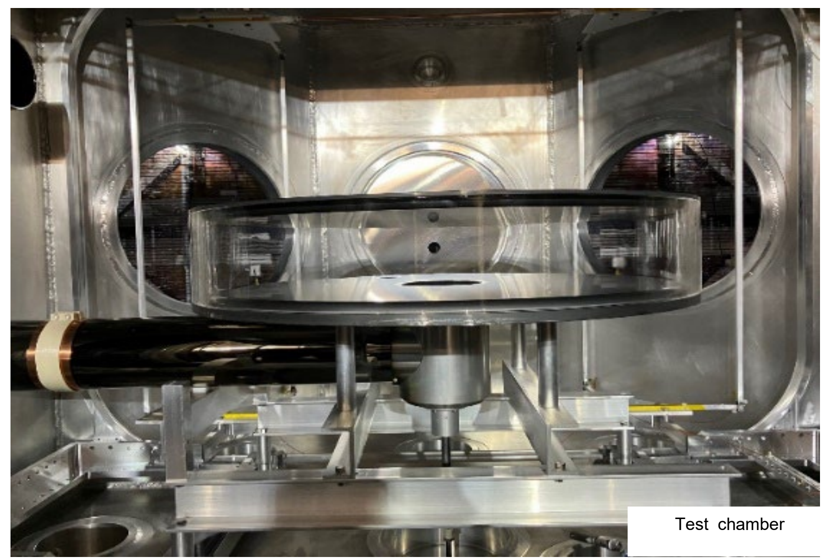
Lot of efforts to improve UCN storage capability:
- problems with coatings of electrodes (DLC) & insulator ring (DPS)


New insulator ring (quartz)


Mirror polished test electrode


Test electrode DLC coated

Test of a new UCN storage chamber:
- new insulator rings (quartz instead of Rexolite)
- test electrodes: higher surface quality (polishing) + DLC


Test chamber

Uncoated quartz ring + DLC electrodes
Nov. 2024: 42,000 UCN in one chamber at every filliing - 400s pulse period

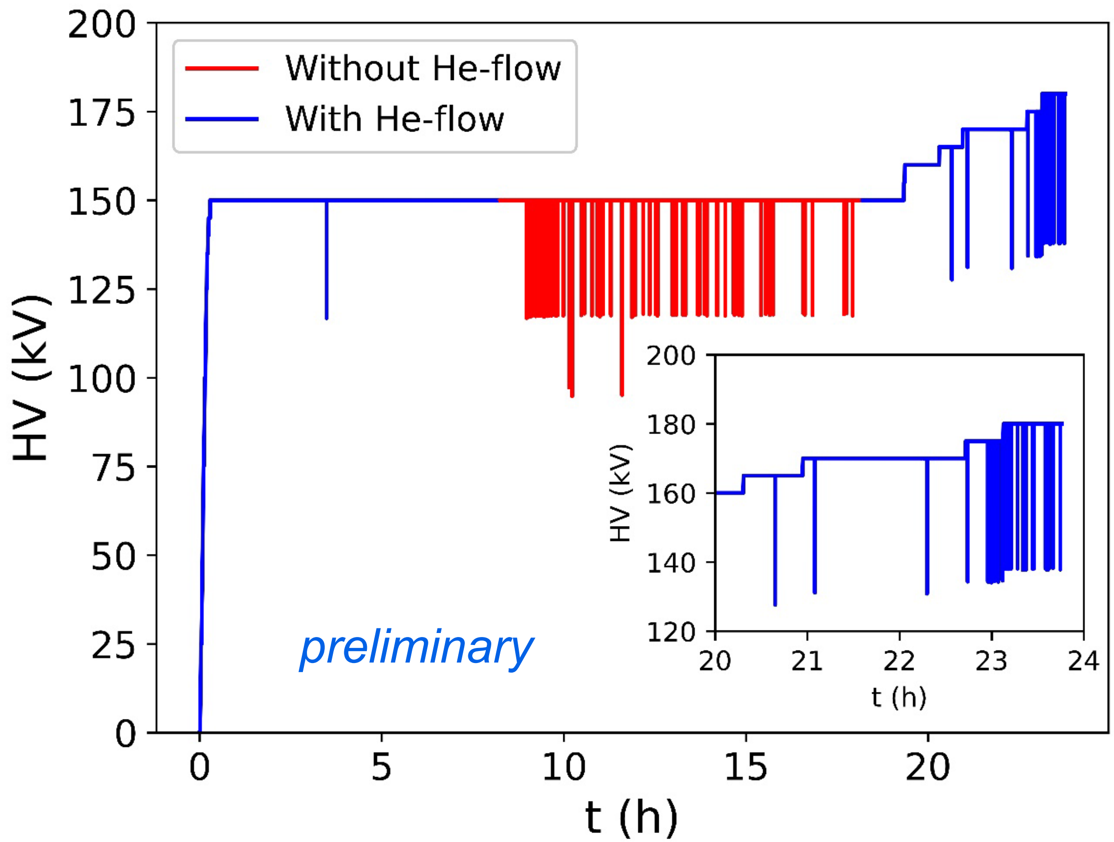
~70% of design statistics

High Voltage

Bipolar power supply replaced by two unipolar supplies (300 kV)
Full setup tested for the first time in 2024

Performance:
Stable (sparkless) operation at 150 kV (E= 12.5 kV/cm) : ready for data taking !
Up to 180 kV (design goal) but sparkling (conditioning procedure to improve)

Design and construction of a HV selector device



Master thesis R. Koch

Magnetic Environment

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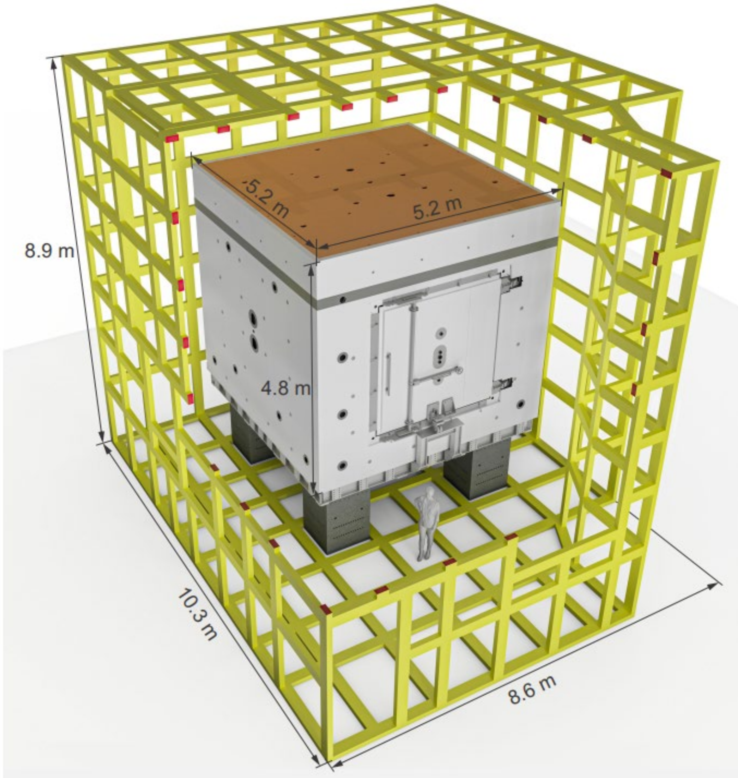
Active magnetic shield (AMS)

n2EDM



- 8 independent coils
- 55 km of wires
- kW heat dissipated

Eur. Phys. J. C **83**, 1061 (2023). https://doi.org/10.1140/epjc/s10052-023-12225-z

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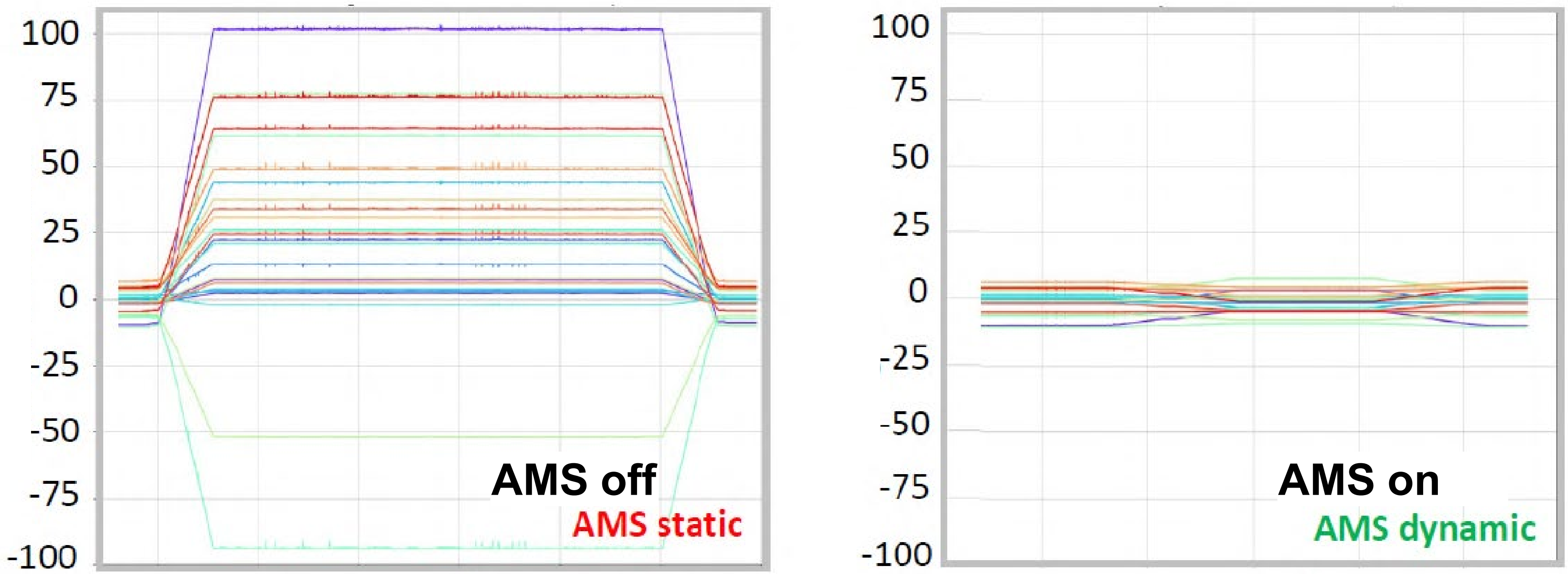
Active magnetic shield (AMS)

$B_{\text{outside MSR}}$ (μT)



Eur. Phys. J. C **83**, 1061 (2023). https://doi.org/10.1140/epjc/s10052-023-12225-z

PhD theses M. Rawlik, S.Emenegger, N. Ziehl

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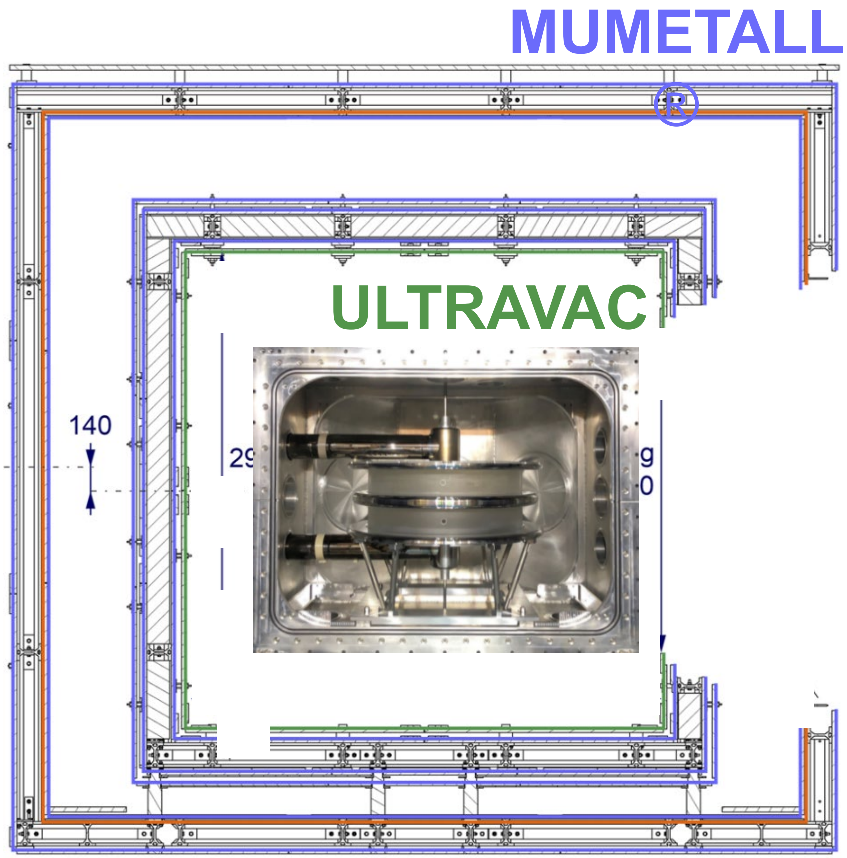
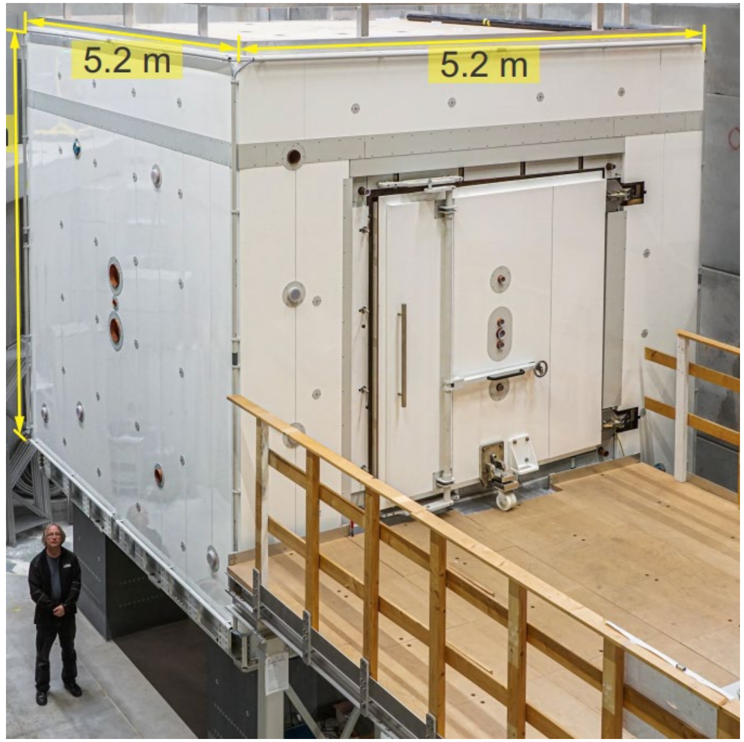
The Magnetically Shielded Room (MSR)

n2EDM





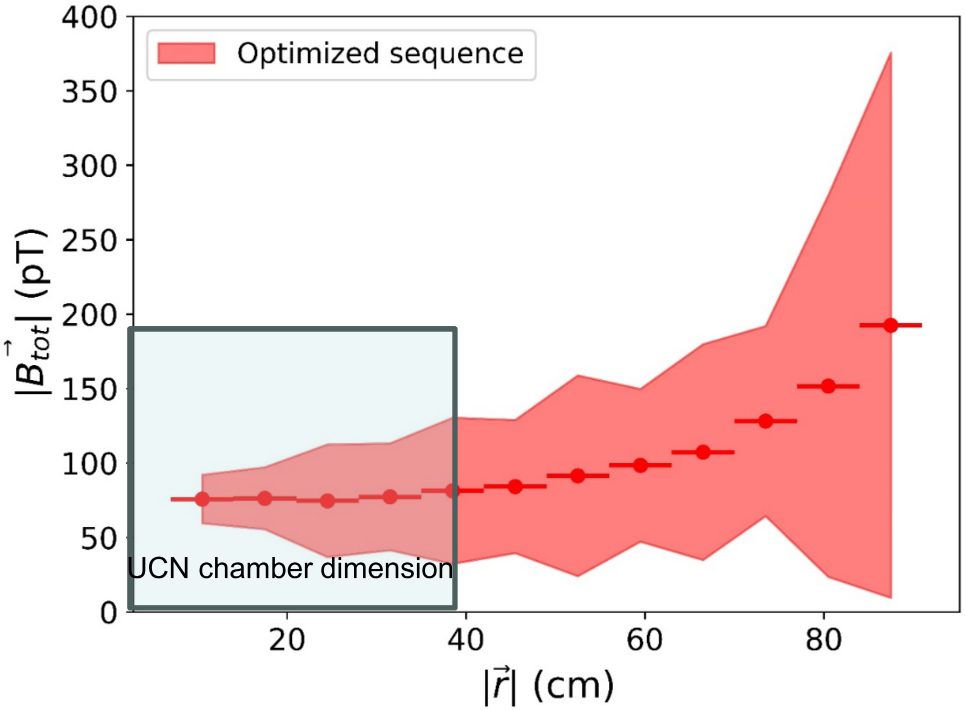
- 6 permeable layers
- Shielding factor 10^5 at 0.01 Hz ($1\mu\text{T} \rightarrow 10\text{pT}$)
- Excitation coils to degauss permeable layers

Eur. Phys. J. C **84**, 18 (2024). https://doi.org/10.1140/epjc/s10052-023-12351-8

Rev. Sci. Instrum. 1 September 2022; 93 (9): 095105. https://doi.org/10.1063/5.0101391

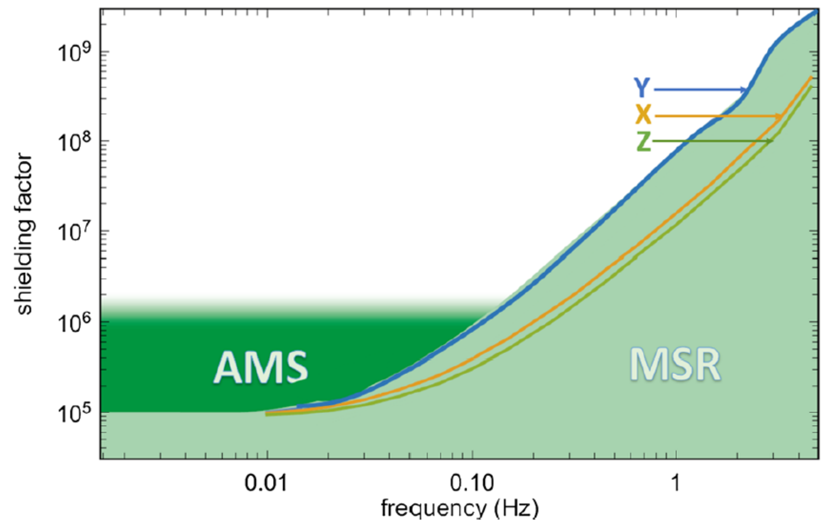
n2EDM
active and passive magnetic shielding

Residual field inside MSR after degaussing



AMS + MSR

shielding factor versus frequency



Magnetic environment at or better than design values:

Design of the n2EDM experiment:	EPJC 81 (2021) 512
Magnetically shielded room:	Rev.Sci.Instr. 93 (2022) 095105
Active magnetic shielding:	EPJC 83 (2023) 1061
Ultralow magnetic fields:	EPJC 84 (2024) 18

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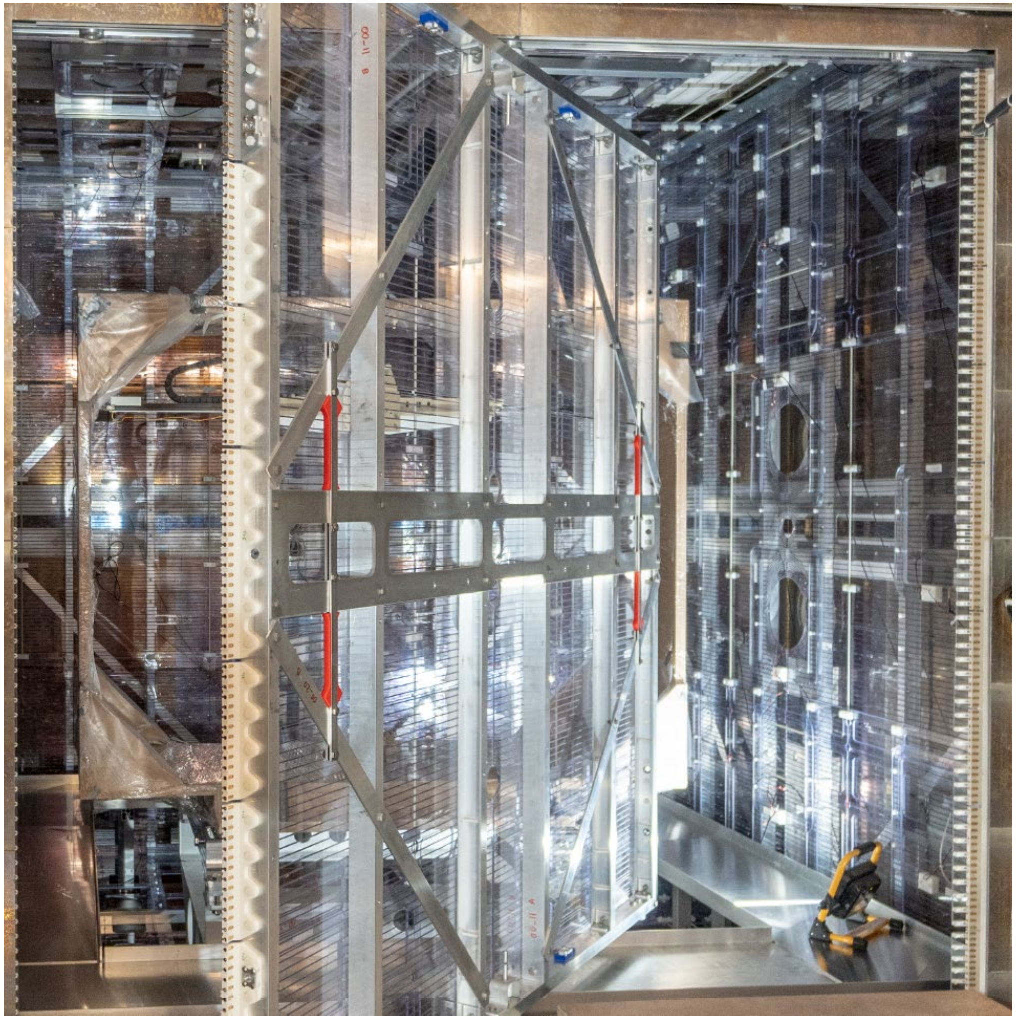
n2EDM

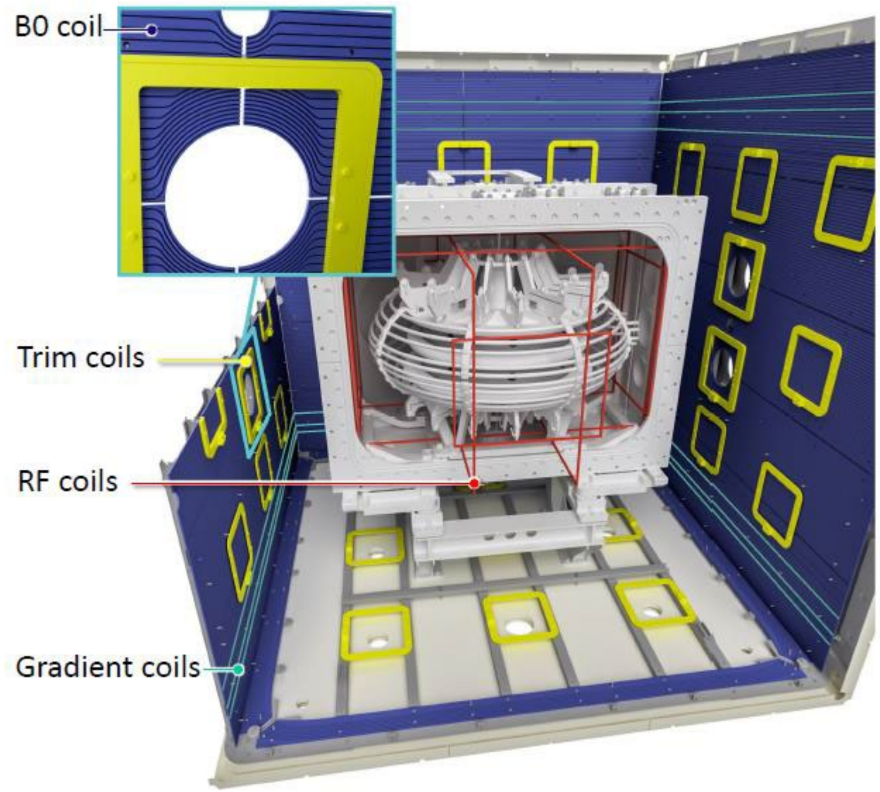
Coil system for homogeneous 1μT vertical field

$\vec{B}$ field



PhD thesis P.Flaux

1μT



Field description in spherical polynomic expansion

Method developed in nEDM: C.Abel et al, Phys.Rev.A 99 (2019) 042112

$$\langle B_z(\vec{r})\rangle = \frac{1}{V}\sum_{l,m} G_{l,m}\int dV\,\Pi_{z,l,m}(\vec{r})$$

$$B_z = B_0 + yG_{1,-1} + zG_{1,0} + xG_{1,1} + 2xyG_{2,-2} + 2yzG_{2,-1}$$
$$+\left(z^2 - \frac{1}{2}(x^2+y^2)\right)G_{2,0} + 2xzG_{2,1} + (x^2-y^2)G_{2,2} + \cdots$$

Chambers are offset (in z) with respect to the magnetic center ($z\in[\pm 1/2\, d, \pm(H+1/2\, d)]$, where d is thickness of HV electrode, H is height of chamber)

Eur. Phys. J. C (2025) 85:202 Page 15 of 19 202

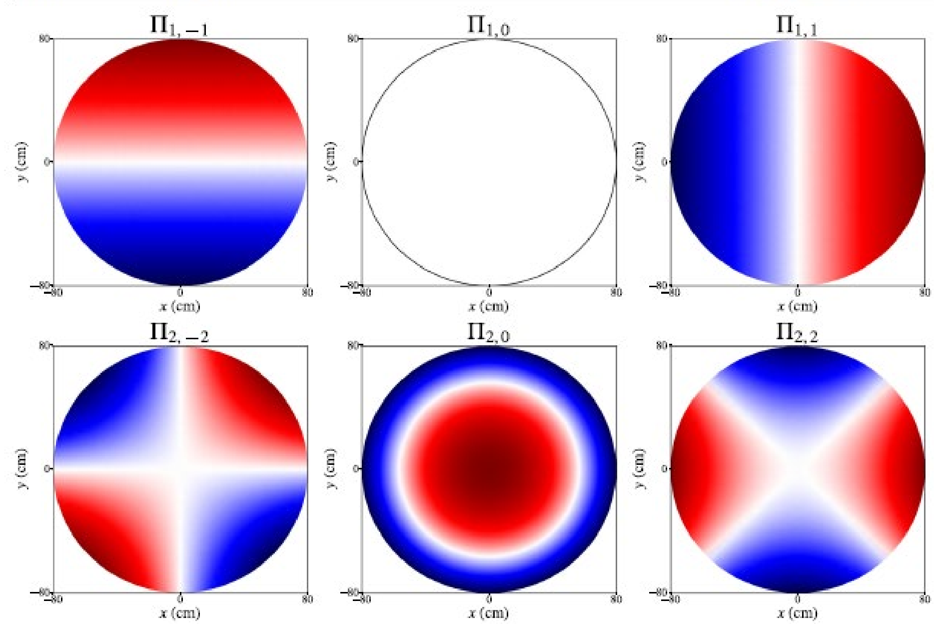
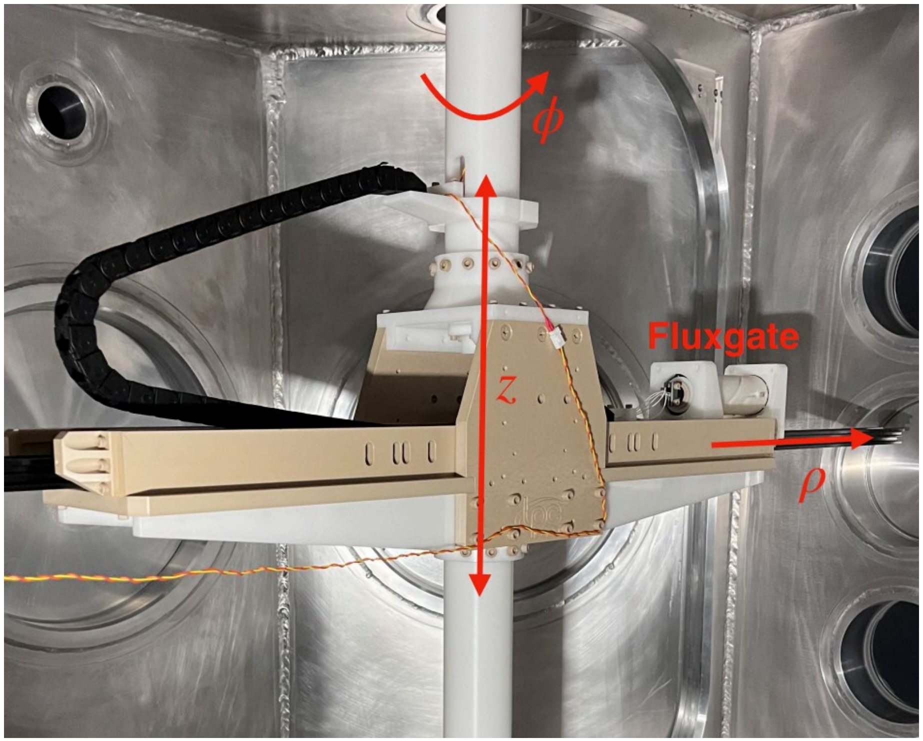


Fig. 10 Vertical field component of single harmonic modes in the $z = 0$ plane. The field ranges in magnitude from blue to red

n2EDM field evaluation:

C.Abel et al., Eur. Phys. J. C (2025) 85:202
https://doi.org/10.1140/epjc/s10052-025-13902-x

Mapping the magnetic environment



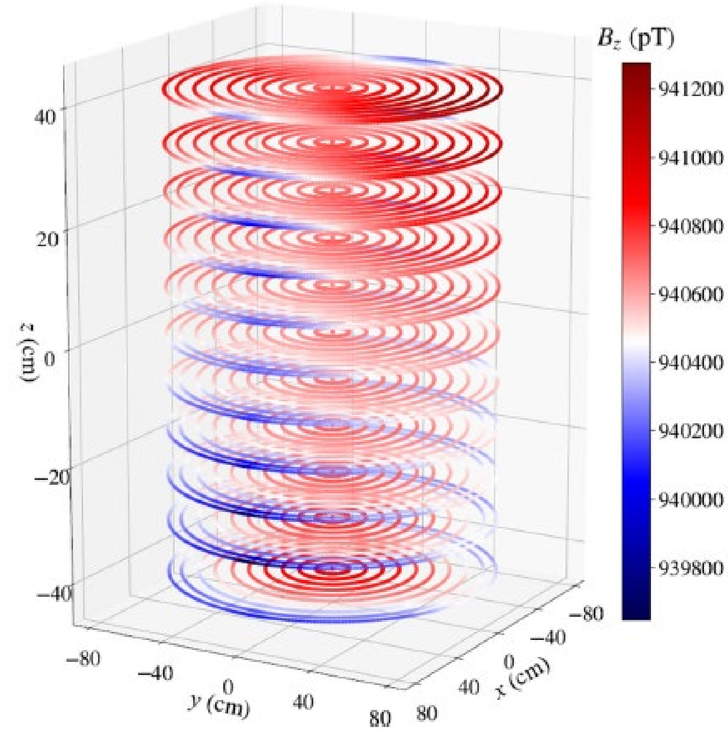
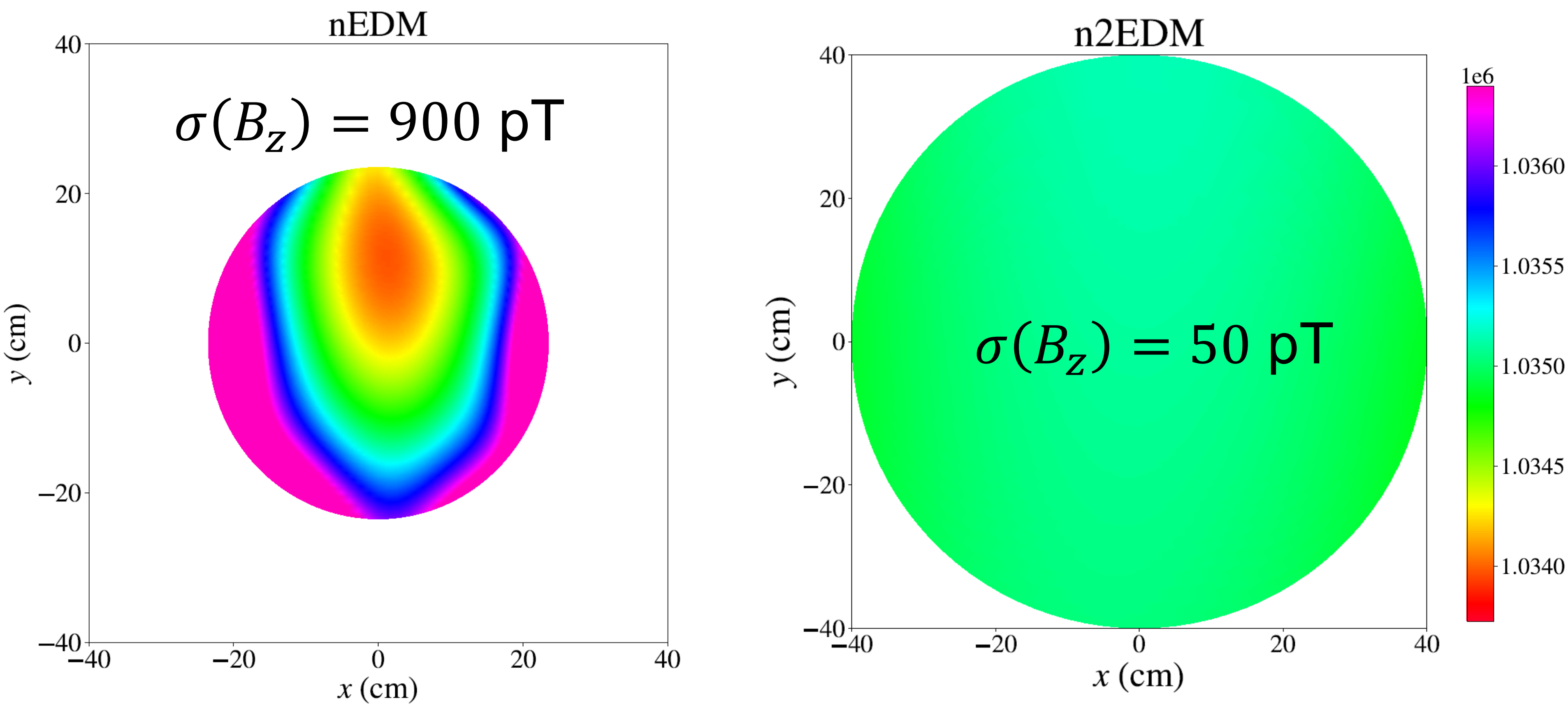


Fig. 5 An example of a magnetic field map of the field generated by the n2EDM coil system and recorded by the mapper. Each point corresponds to the vertical projection of the magnetic field inside a cylindrical volume of radius 78 cm and height 82 cm

PhD theses T. Bouillaud

Remarkable field uniformity

@z=0



PhD theses T. Bouillaud

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n2EDM

Non-uniformities introduces complex systematic effects that yield **demanding magnetic field constraints**

$$R \equiv \frac{f}{f_{\mathrm{Hg}}} = \frac{\mu_n}{\mu_{\mathrm{Hg}}} \pm \frac{2E}{hf_{\mathrm{Hg}}} d_n$$

$$d_{n\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \mathrm{Const} \cdot \langle \rho B_\rho \rangle$$

$$\vec{B}(\vec{r}) = \sum_{l\geq 0} \sum_{m=-l}^{l} G_{l,m} \Pi_{l,m}(\vec{r})$$

$$d_{n\leftarrow\mathrm{Hg}}^{\mathrm{false}} \propto G'_{10} + G'_{30} + G'_{50} + \cdots < 3 \cdot 10^{-28}\ e\ \mathrm{cm}$$

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Mapping the magnetic environment

n2EDM nEDM

Statistical & systematic requirements on field uniformity

- Top-bottom matching: $|G_{10}| < 0.6\mathrm{pT/cm}$
- Depolarization: $\sigma(B_z) < 170\mathrm{pT}$ ($\mathrm{T_2}$ time $\rightarrow \alpha$)
- Mercury-induced false EDM: $< 3 \cdot 10^{-28}\, e\,\mathrm{cm}$

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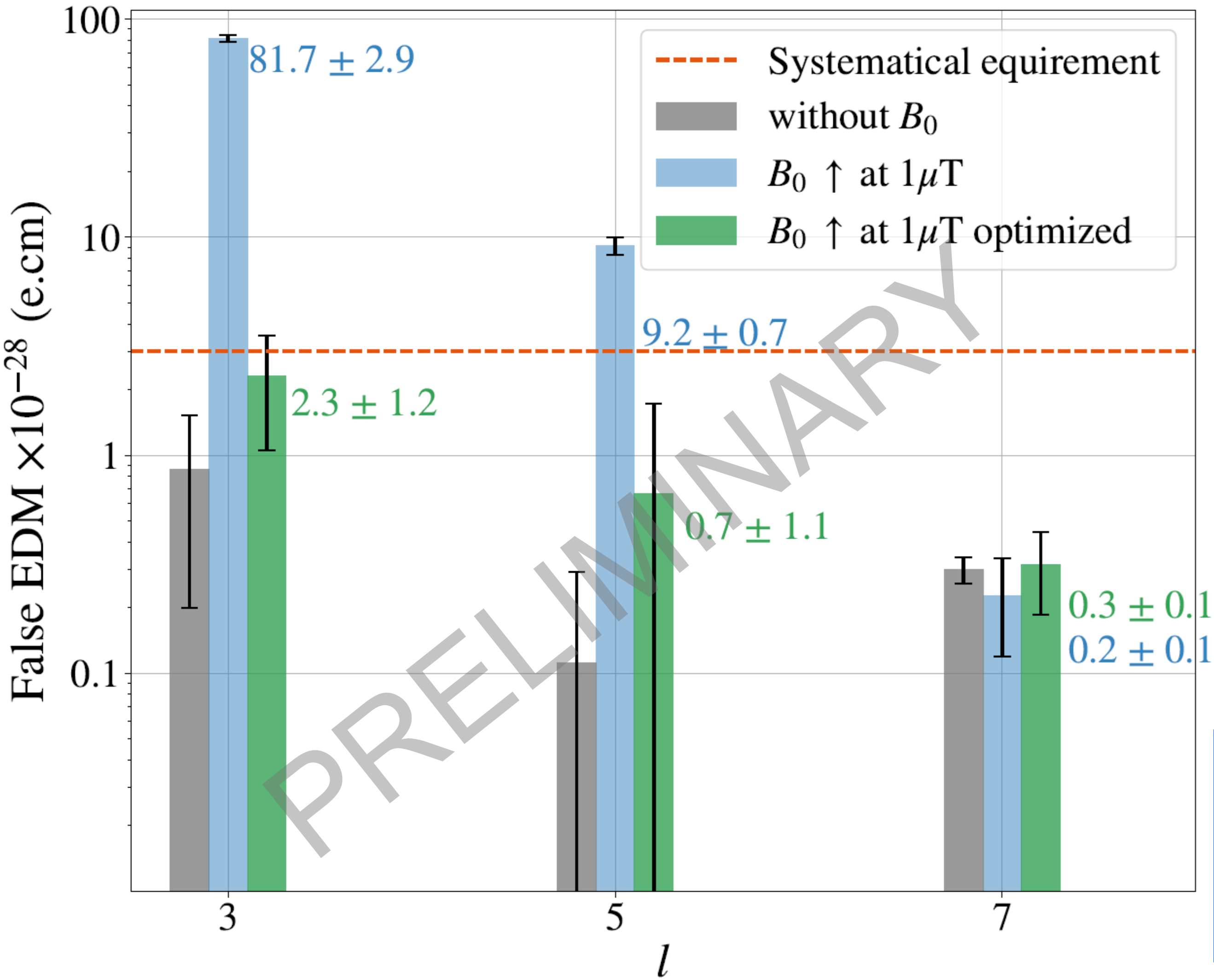
Phantom modes (accessible via mapping)
top-bottom gradient l=1 (online monitored)



$3 \times 10^{-28}\ e$ cm

$$\vec{B}(\vec{r}) = \sum_{l \geq 0} \sum_{m=-l}^{l} G_{l,m} \Pi_{l,m}(\vec{r})$$

Normalized gradients responsible for the false EDM extracted from the magnetic field maps. The 23 fT/cm limit (dotted line) imposed on the gradients corresponds to a false EDM of 3×10^{-28} ecm. The G_{TB} gradient can be corrected with special coils.

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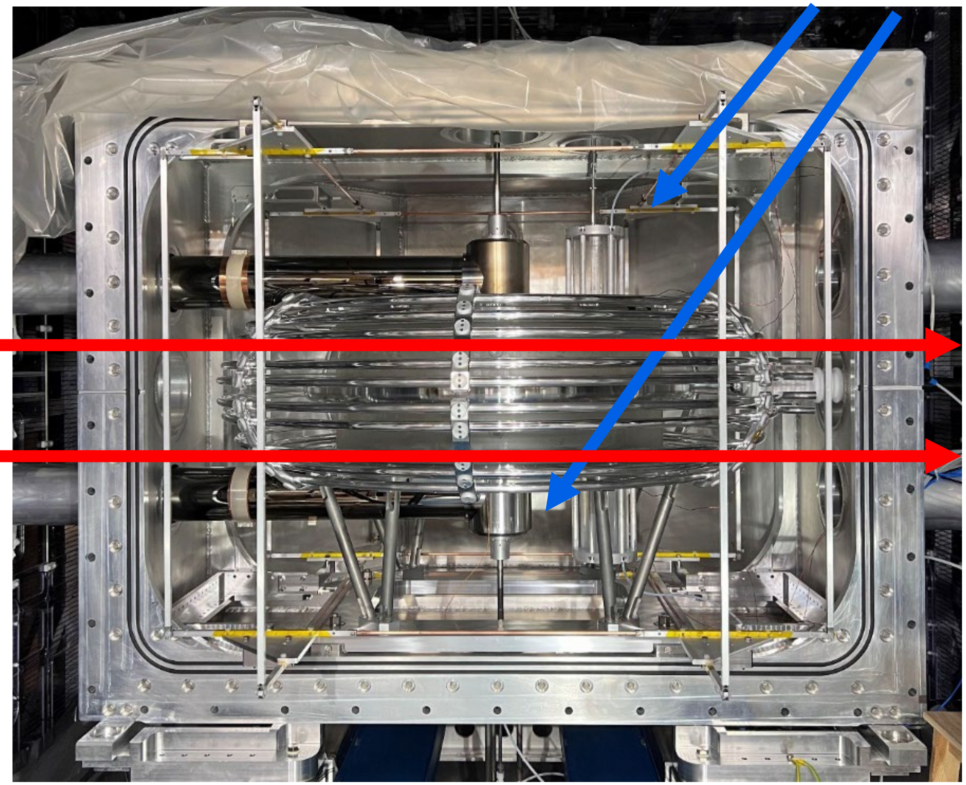
Mercury Co-magnetometer

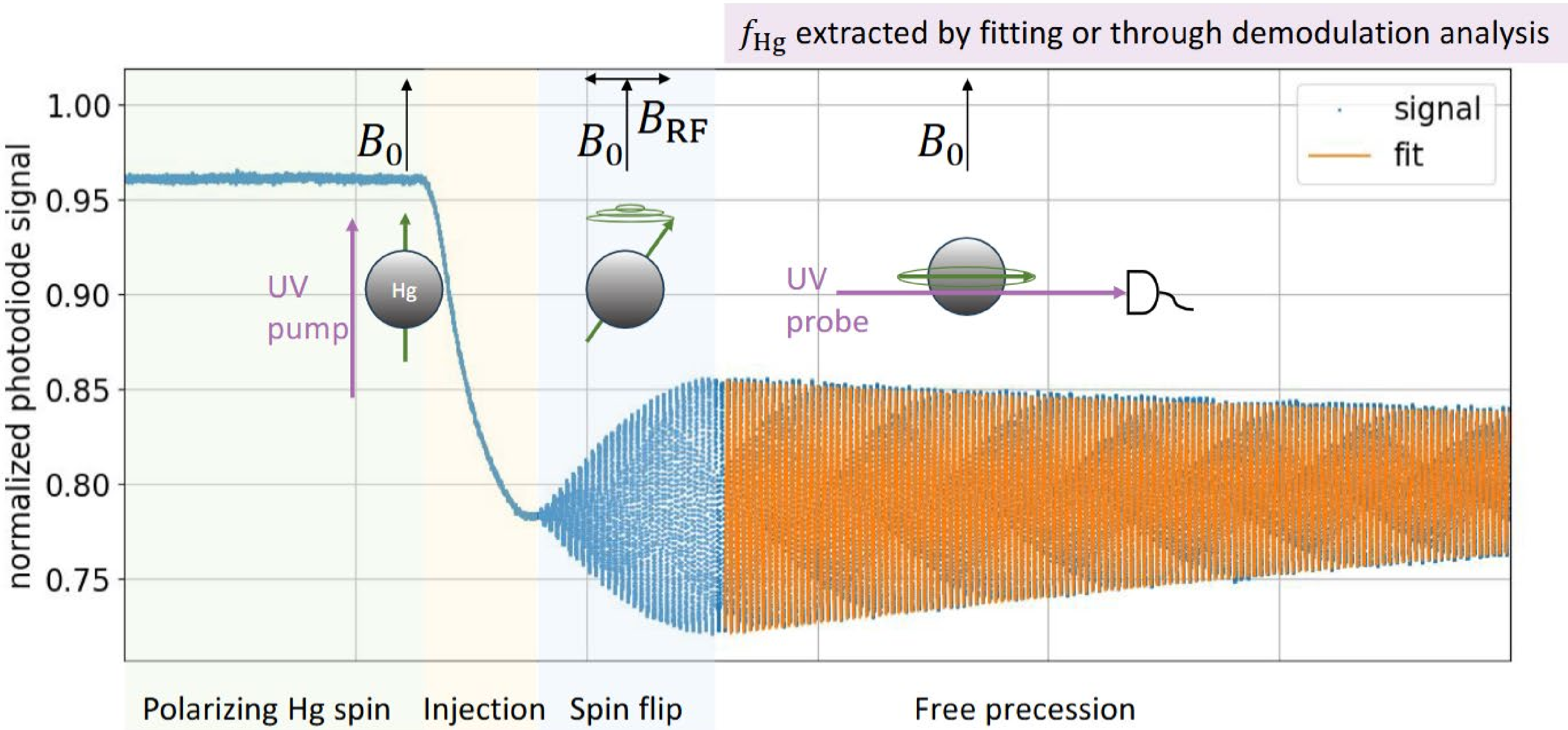
- Hg spin polarized outside chamber with circularly polarized 254nm light
- Inject Hg into chamber and perform $\pi/2$ spin-flip
- Probe free precession optically to extract $f_{\mathrm{Hg}}(B)$
- online monitoring of top-bottom gradient

Hg polarization chamber with paraffine coating



PhD Theses:
W.Chen, K. Michielsen, N.v.Schick

Mercury Co-magnetometer



Hg co-magnetomer operational over weeks in 2024

T_2 (TOP) = 50 s ; T_2 (BOT) = 80 s

Performance still be improved but nearly at the design goal sensitivity (factor ~ 4 missing)

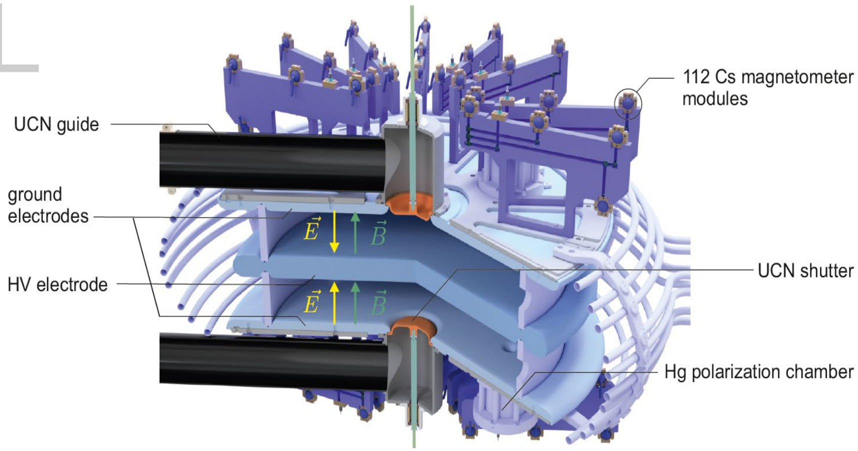
-> Operational for nEDM measurement (but sensitivity to improve)

PhD Theses:
W.Chen, K. Michielsen, N.v.Schick

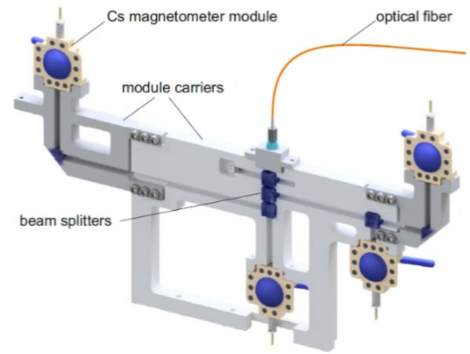
Cesium Magnetometer

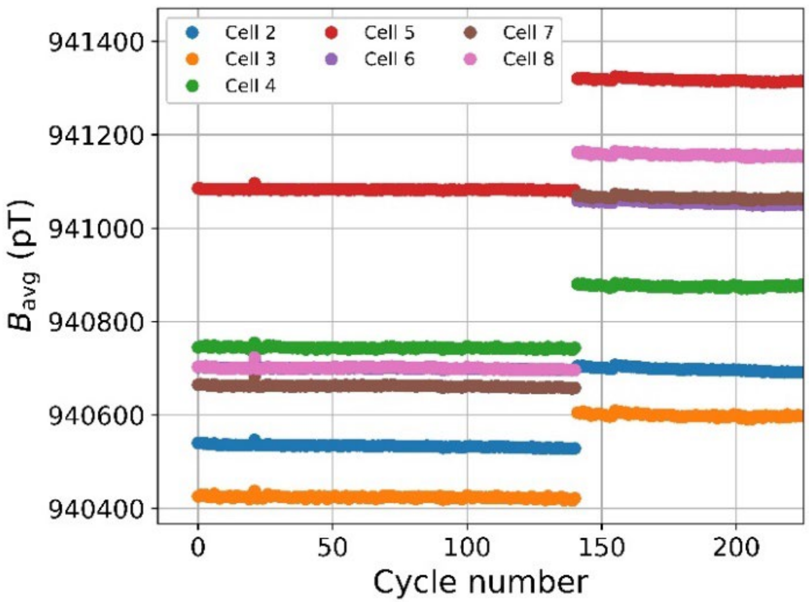
Online monitoring of field non uniformities - G_{30}: systematic assessment

Two Cs units installed in 2024: steady operation over weeks



One Cs unit (4 cells)





Cs magnetometry planning:

2025: half of Cs setup installed (56 cells) before data taking
2026: full Cs setup installed (112 cells)

PhD theses D.Pais, V. Kletzl, L.Segner, L. Sanchez-Real Zielniewicz

Biggest challenge right now: magnetic contamination

It is crucial to check all parts which are in the central region of the apparatus = the innermost chamber of the MSR
for magnetic contaminants - searching vor magnetic dipoles
--- there is no apriori non-magnetic material

e.g. same batch of screws can be good or bad

we check small parts in **new gradiometer at PSI to ~ 3pT noise level** in 25mm distance (PhD V. Kletzl)
and large parts (electrodes, insulator rings, vacuum tank sides)
at BMSR2- PTB Berlin

magnetic dipoles cause frequency shift

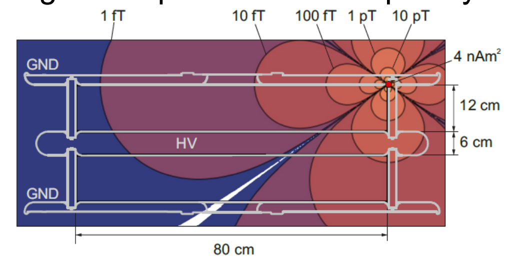
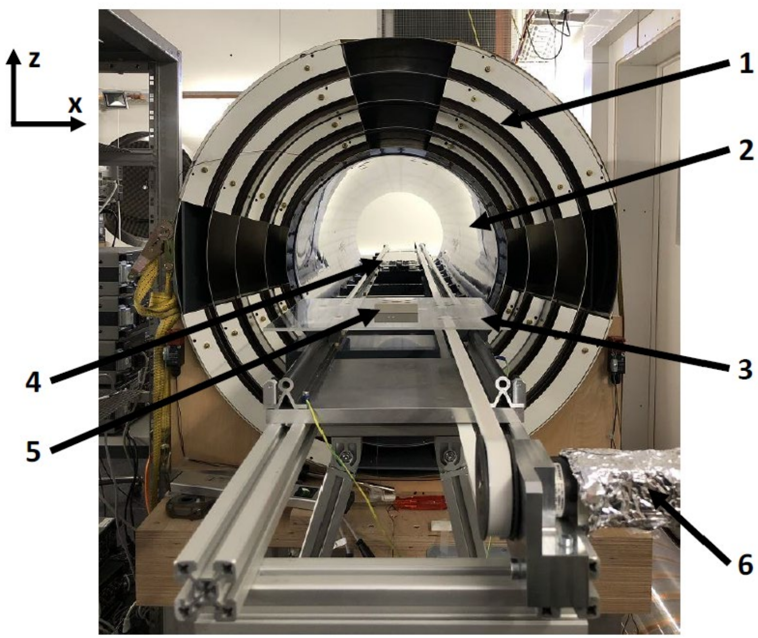
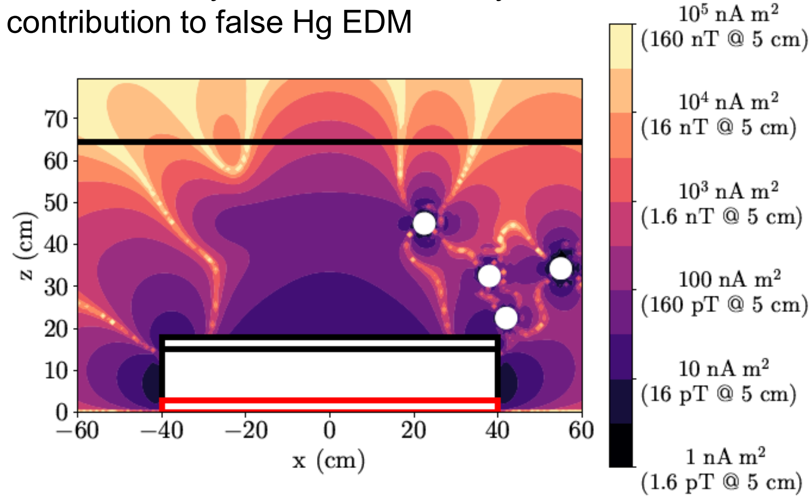


Fig. 1: Sketch of the central storage chambers of the n2EDM apparatus. The contours of the field modulus generated by a magnetic dipole located close to the upper ground electrode with a strength of 4 nAm^2 are shown. The dipole is located at one of the positions where it causes the largest shift in the nEDM result. HV: high voltage electrode, GND: ground electrodes.



PhD Thesis V.Kletzl 2025

'allowed' magnetic dipoles to reach a 3x 10^{-28} ecm systematic uncertainty contribution to false Hg EDM



Design of the n2EDM experiment: EPJC 81 (2021) 512

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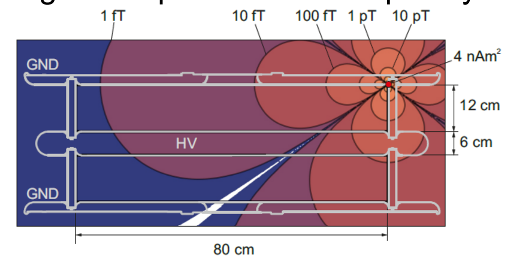

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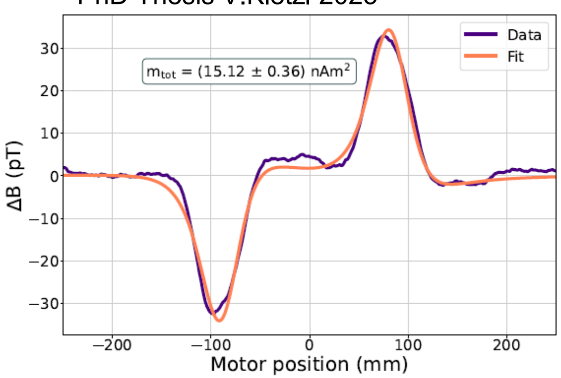
e.g. PEEK part

PhD Thesis V.Kletzl 2025



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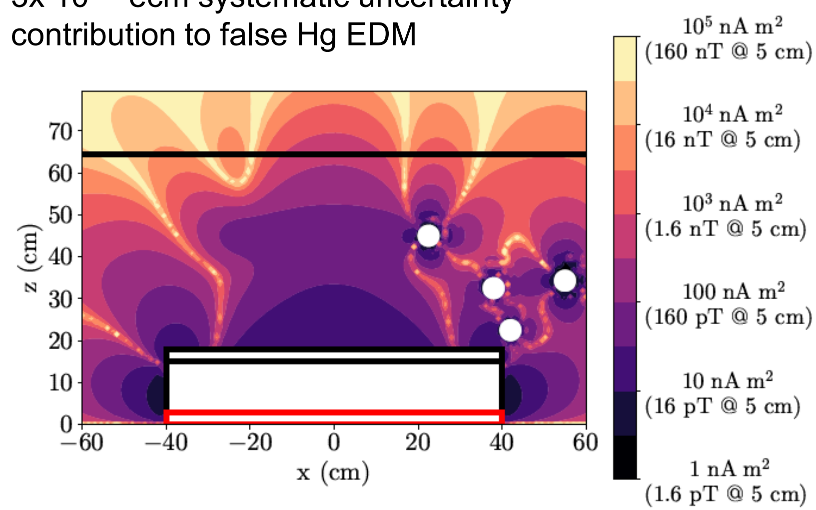

Design of the n2EDM experiment: EPJC 81 (2021) 512

=> immense work and time spent with scanning parts!

Recent results from commissioning

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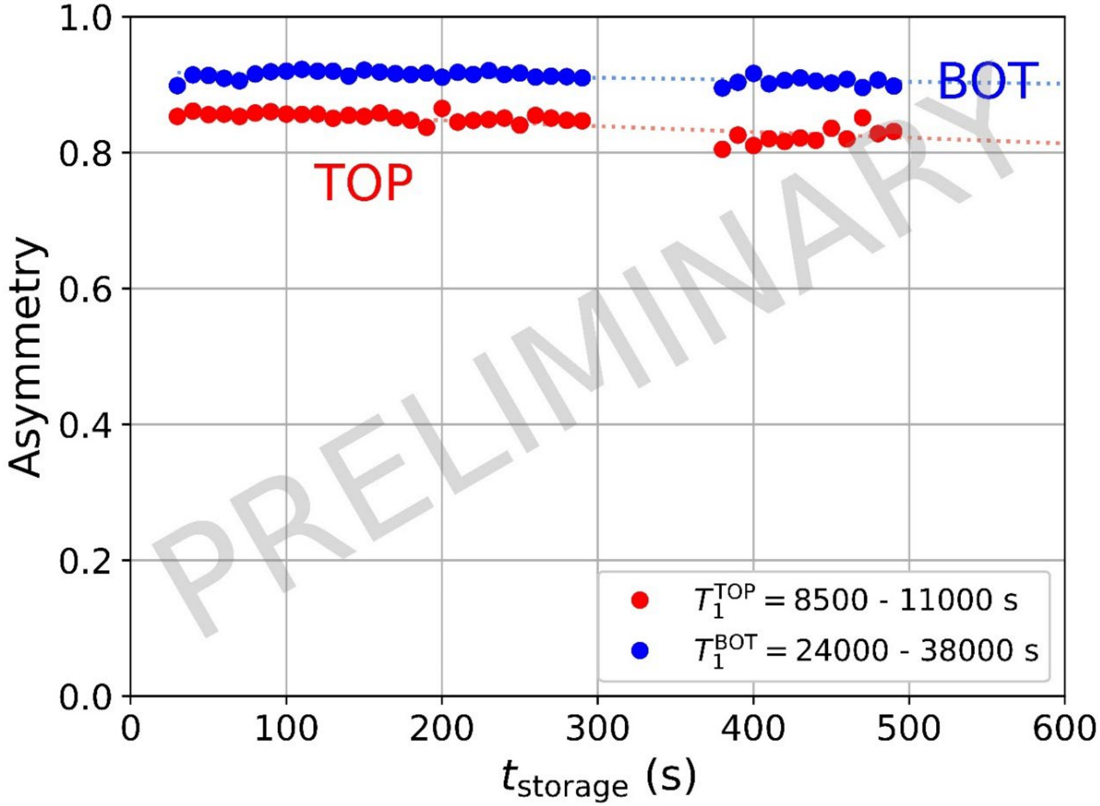
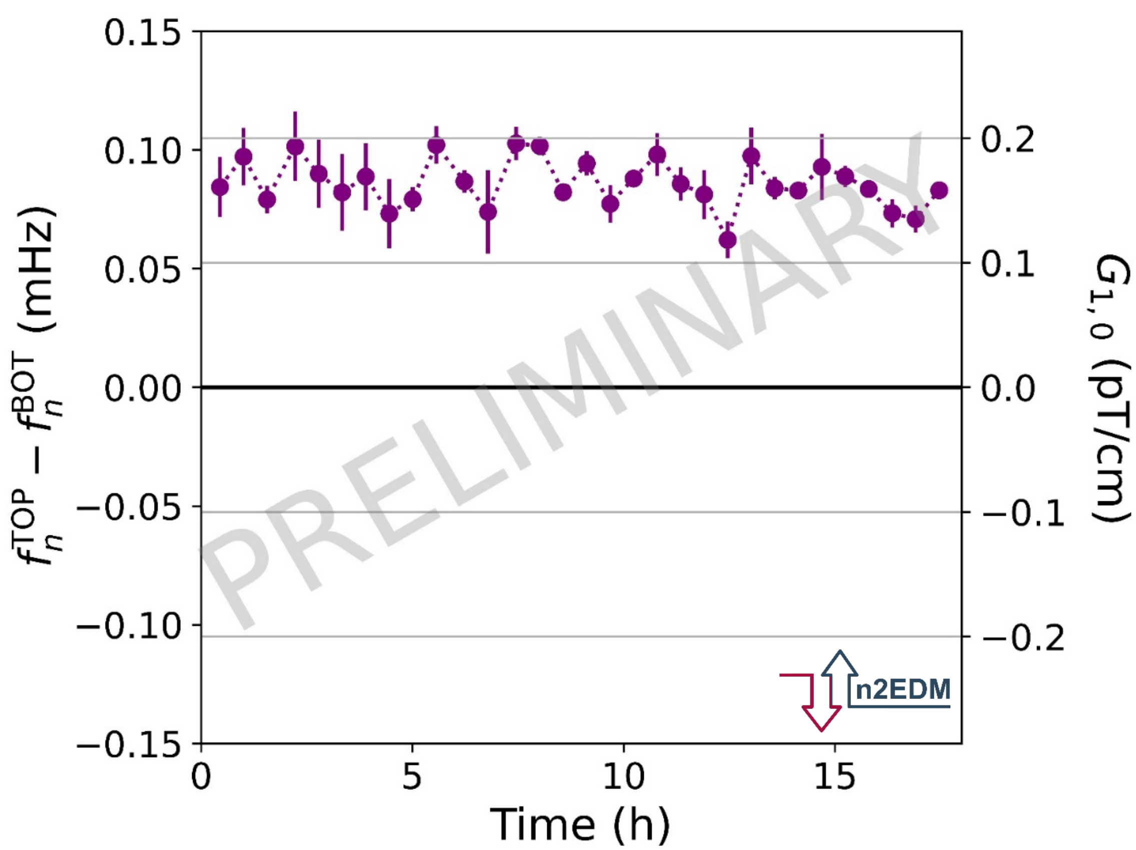
n2EDM nEDM

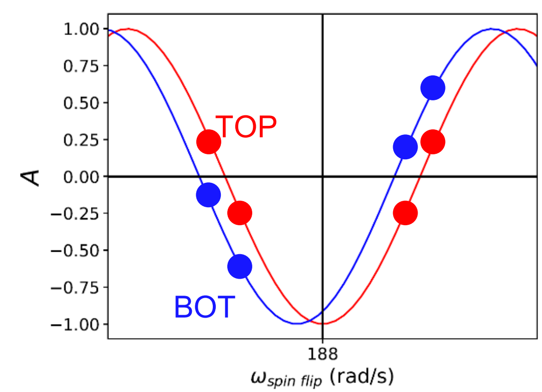
Storage chamber & field uniformity maintains longitudinal polarization



$$\sigma(d_n) = \frac{\hbar}{2\,\alpha\,E\,T\sqrt{N_\uparrow + N_\downarrow}}\left(1 - \frac{A^2}{\alpha^2}\right)^{-1/2}$$

Magnetic-field gradient stable enough for data-taking even without online adjustment





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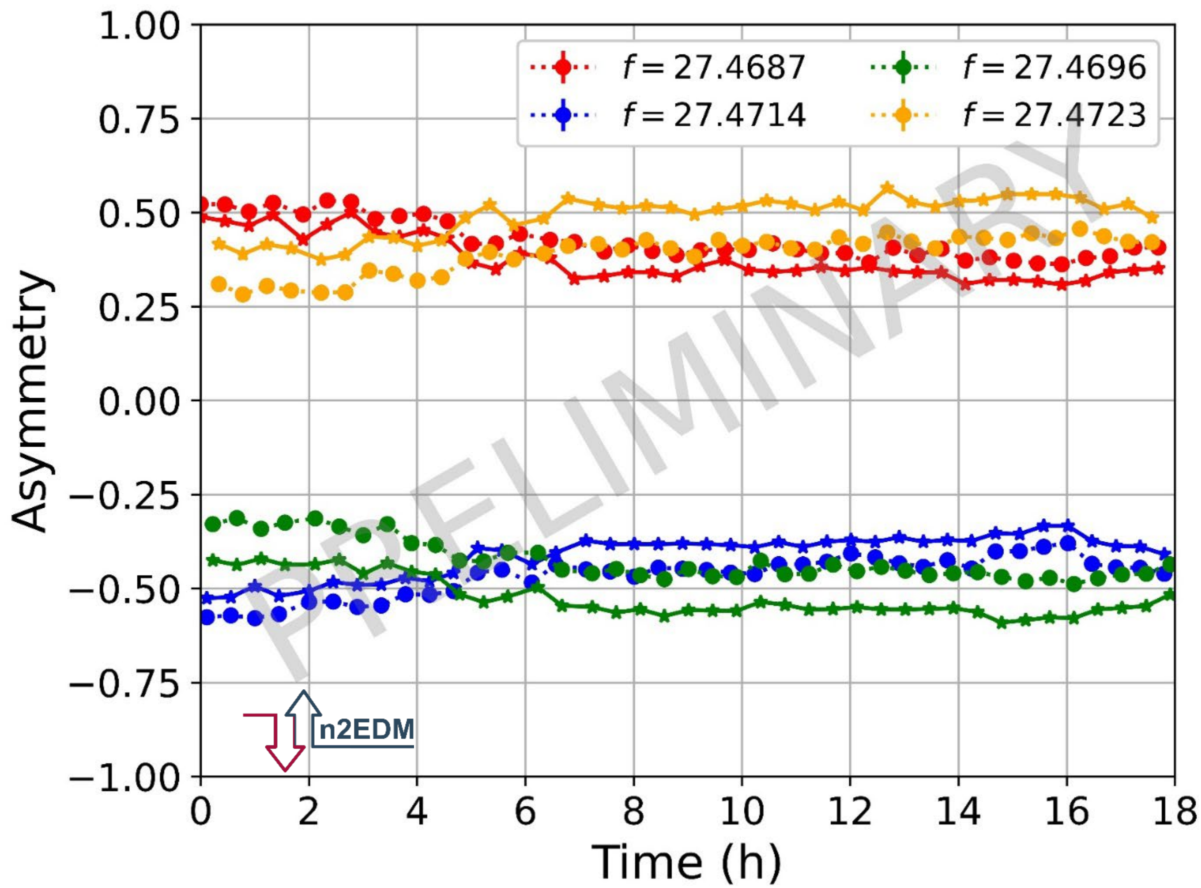
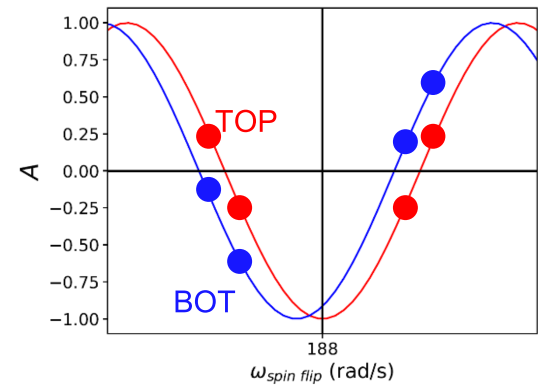
n2EDM

"Dry" EDM run in n2EDM $@E = 130\mathrm{kV}$ working point stability



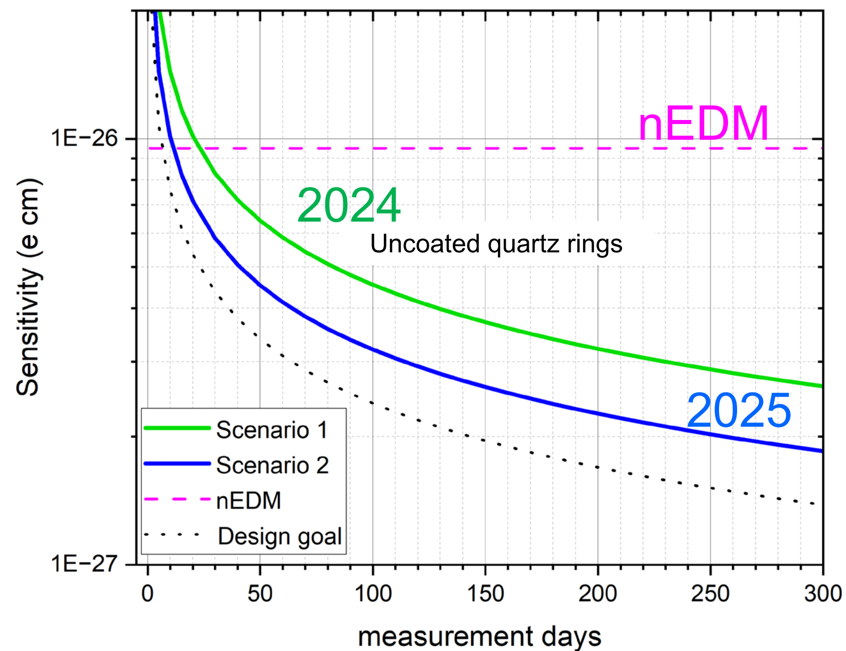


Current n2EDM sensitivity

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Components	nEDM (2016)	n2EDM (2024)	Design goal
Precession time (T)	180 s	180 s	180 s
Neutrons statistic (N)	15,000	64,000 * * Former electrodes	120,000
High Voltage (E)	± 11 KV/cm	± 12.5 KV/cm	± 15 KV/cm
Polarisation (α)	0.75	0.82 - 0.85	0.80
Daily sensitivity (σ)	11. 10^{-26} ecm	4.5 10^{-26} ecm	2.6 10^{-26} ecm

< 30 days required to reach previous experiment sensitivity



Room for improvement: UCN statistic (ring coating) + High Voltage (conditioning)

→ towards the design goal sensitivity

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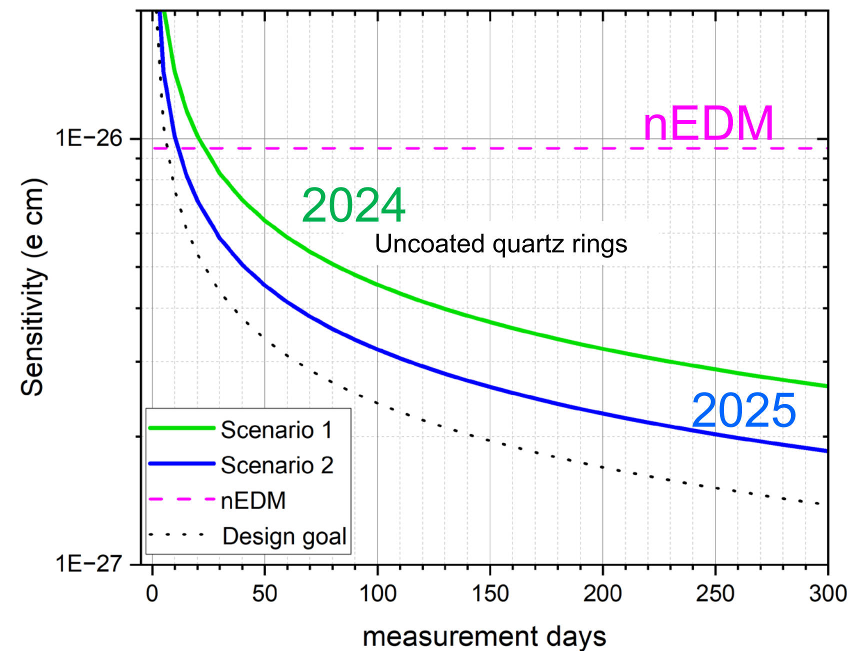

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→ towards the design goal sensitivity

2025: first measurement in the 10^{-27} e cm range ?

	2025	2026	2027	2028	2029	2030	2031	2032	2033
HIPA & UCN Source - *running*			*IMPACT Shutdown*						
UCN source - *renovation project*									
n2EDM data taking		*x 10^{-27} ecm*							
n2EDMagic - *commissioning*									
n2EDMagic - *running*									*x 10^{-28} ecm*

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n2EDM
Status spring 2025

- magnetically shielded room (MSR) - ultralow remanent field in 25m^3 - **operating**
- active magnetic shield (AMS) - **operating**
- internal magnetic field system at 1 μT and high homogeneity - **operating**
- UCN chambers and beamline - **operating**
- high voltage system operated at up to 180 kV - commissioning ongoing
- Hg comagnetometry - commissioning ongoing
- Cs magnetometers - commissioning ongoing, full array in production
- test nEDM measurement with all subsystems together done in Dec. 2024
- daily sensitivity of 4.45 x 10^{-26} *ecm (~54% of design sensitivity reached in continuous operation)*
- *new UCN chambers for summer 2025 to reach 100% design sensitivity in production*
- **first double chamber Ramsey curve measured**
- **many auxilliary measurements (gradient scans with UCN,Hg,Cs , R-curves etc done)**
- *full data blinding in preparation to be implemented soon*
- *magnetic scanning and cleaning of many parts ongoing*
- **plan to start nEDM measurements after PSI accelerator shutdown in summer 2025**

the nEDM Collaboration

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A. Weis
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PSI: *Paul Scherrer Institut, Villigen, Switzerland*

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ETHZ: *ETH Zürich, Zürich, Switzerland*

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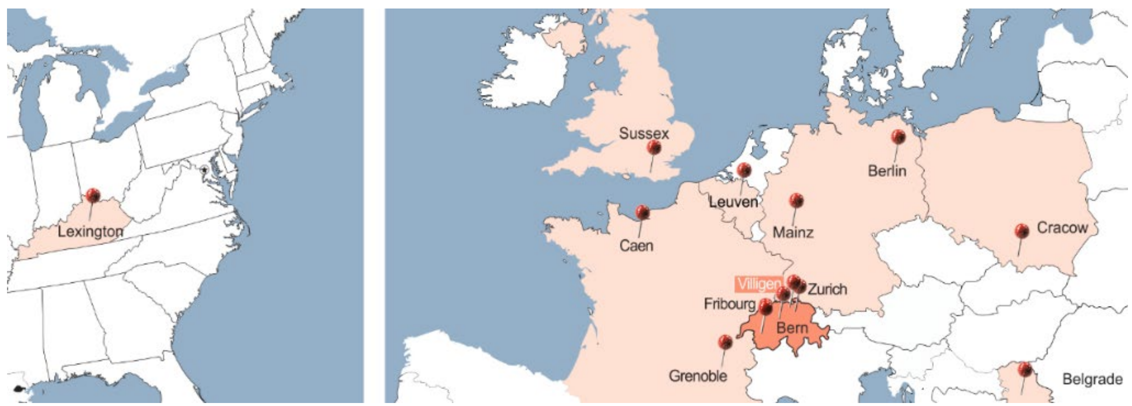
Thanks for your attention !



thanks for many plots and slides to all my colleagues of the nEDM collaboration, especially E.Segarra