Searching for a neutron electric dipole moment

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September, 2025

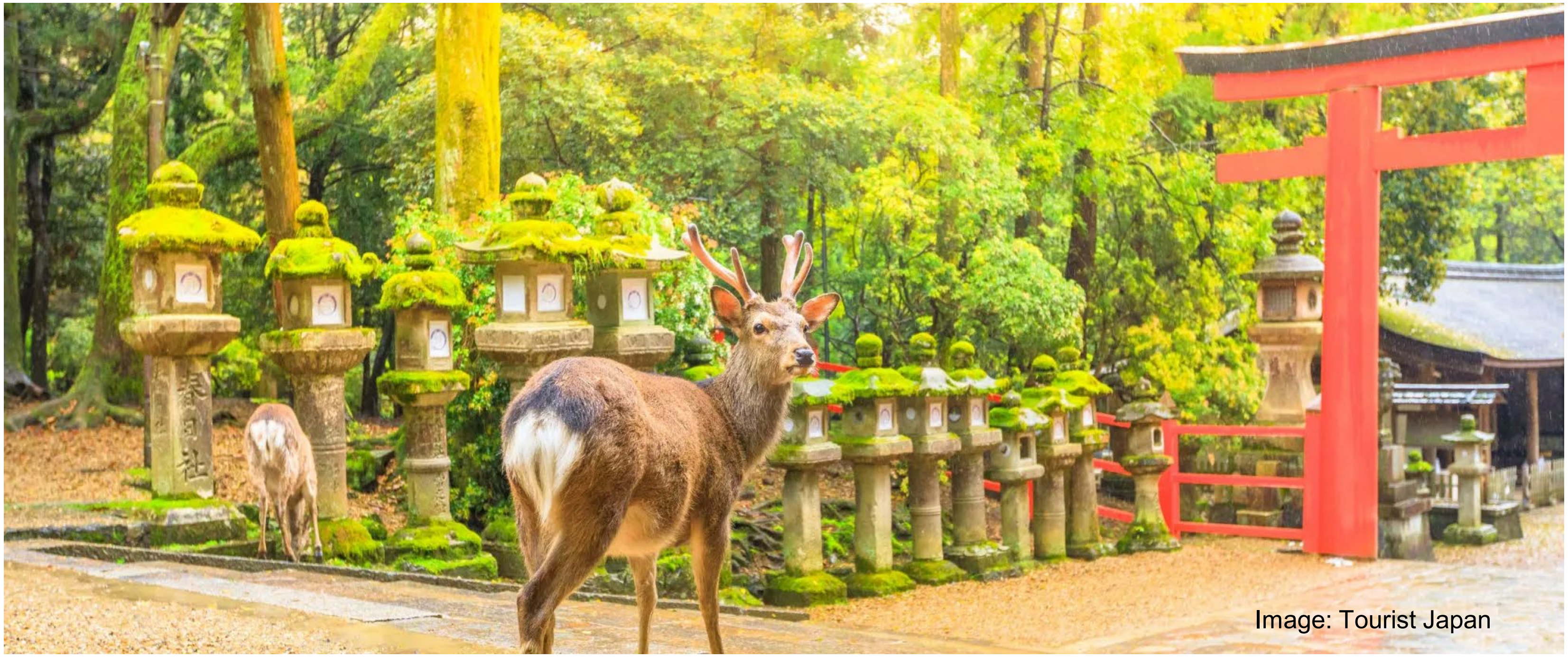
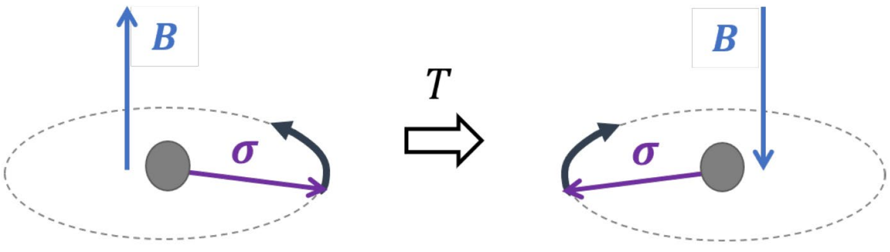
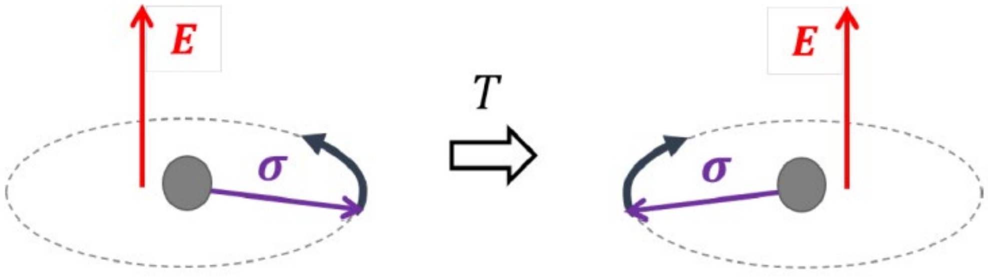


Image: Tourist Japan

An electric dipole moment violates charge-parity CP symmetry?



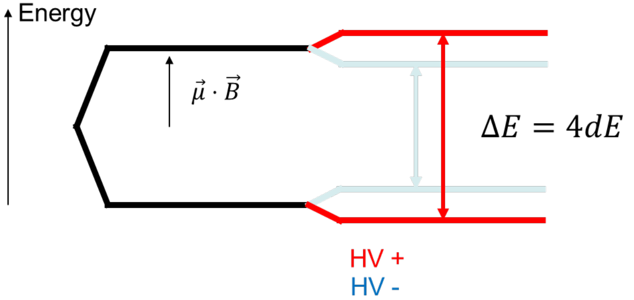


$\mu > 0$ $\mu > 0$ $d_n > 0$ $d_n < 0$

Observable = magnetic moment μ electric dipole moment d_n

$$H = -2(\mu \boxed{\vec{\sigma} \cdot \vec{B}} + d \boxed{\vec{\sigma} \cdot \vec{E}})$$

P,T conserving P,T violating



nEDM in the Standard Model

weak interaction → $d_n \sim 10^{-32}$ *e cm*

A. Czarnecki PRL 78 (1997) 4339
C.Y. Seng PRC 91 (2015) 025502

Naive picture of nEDM from quark EDMs, no contribution on the one loop level

$$L_{\text{eff}} = L_{\text{QCD}} + \theta \frac{\alpha_s}{8\pi} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$$d_{\text{n}} \approx \theta \cdot 10^{-16} \mathrm{e} \cdot \mathrm{cm}$$

$d_n < 1.8 \times 10^{-26}$ *e* cm → $\Theta \leq 10^{-10}$ "unnaturally small"

→ *Axion hypothesis*

R. Peccei, H.Quinn PRL 38 (1977) 1440

The big question ?

Why is there no anti-matter in our Universe ?

Sakharov Criteria

JETP Lett.5(1967)24

B-violation

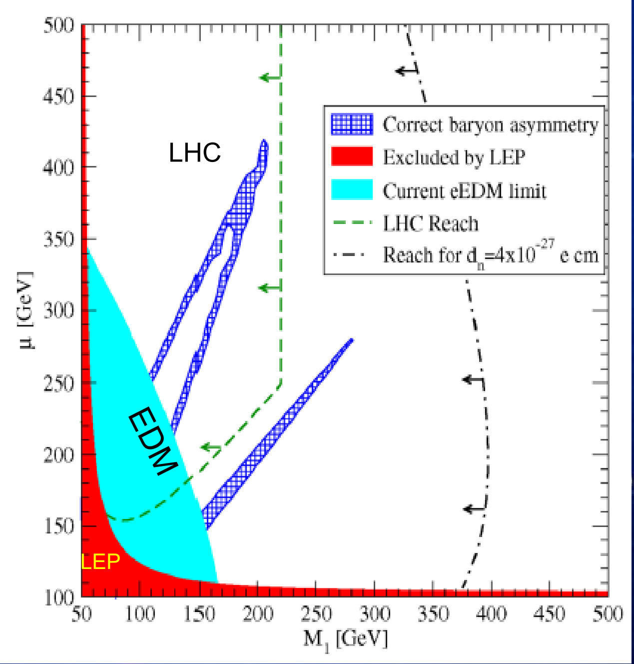
C & CP-violation

non-equilibrium

Additional source of violation of CP (charge-parity) symmetry necessary.

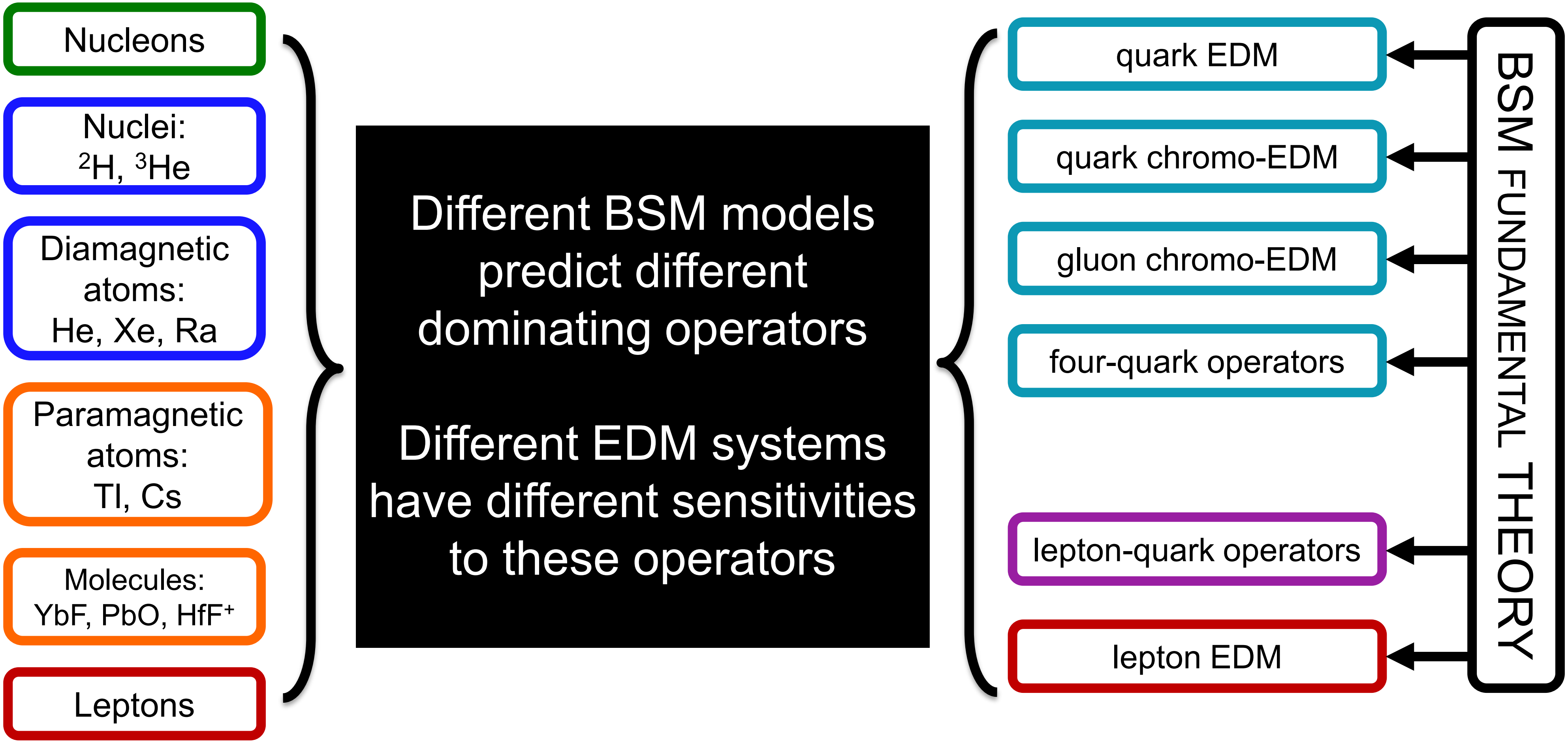
BSM Models predict nEDM far above SM value

M.J. Ramsey-Musolf / Nuclear Physics A 805 (2008) 137c–144c



EDM and LHC sensitivity to supersymmetric baryogenesis in the minimal supersymmetric standard model (MSSM). Dark blue hatched bands give regions of the supersymmetric mass μ and gaugino mass M1 parameter space leading to observed value of the baryon asymmetry.

Many systems where we can look for EDMs
Theoretical challenge what “BSM” gives an EDM



Nucleons

Nuclei:
^{2}H, ^{3}He

Diamagnetic atoms:
He, Xe, Ra

Paramagnetic atoms:
Tl, Cs

Molecules:
YbF, PbO, HfF$^+$

Leptons

Different BSM models predict different dominating operators

Different EDM systems have different sensitivities to these operators

quark EDM

quark chromo-EDM

gluon chromo-EDM

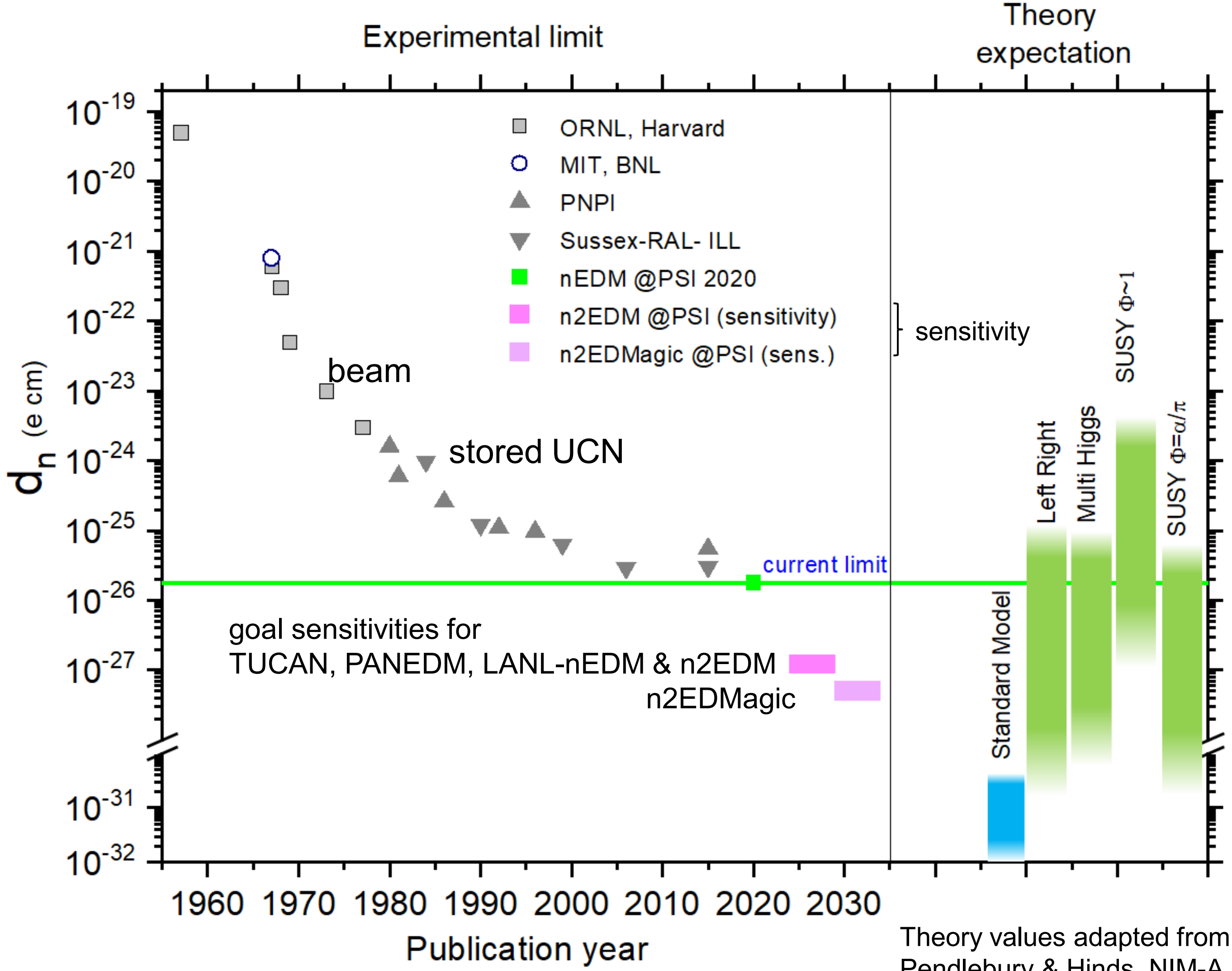
four-quark operators

lepton-quark operators

lepton EDM

BSM FUNDAMENTAL THEORY

History of neutron EDM searches and current goals



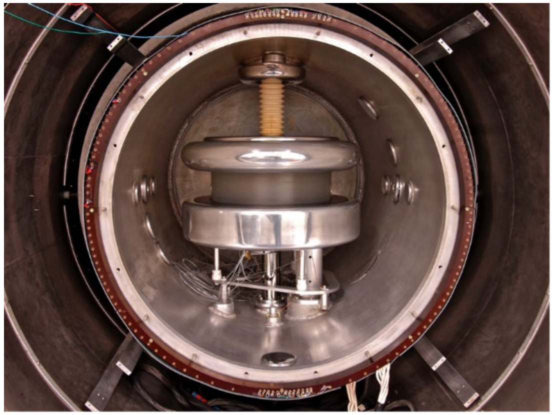
Theory values adapted from
Pendlebury & Hinds, NIM-A 440 (2000) 471

current best limit

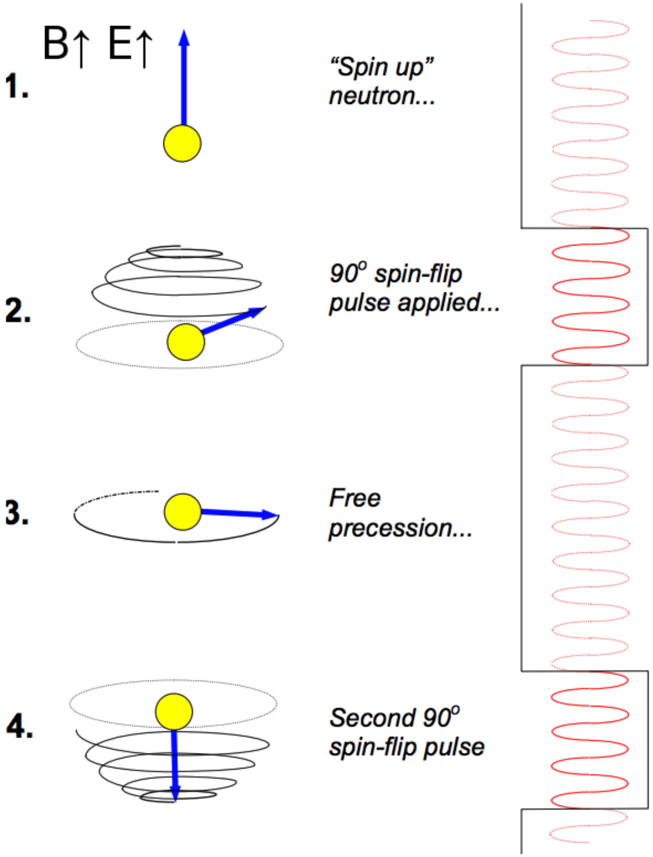
$|d_n| < 1.8\times10^{-26}$ *e·cm*

by the nEDM collaboration at PSI

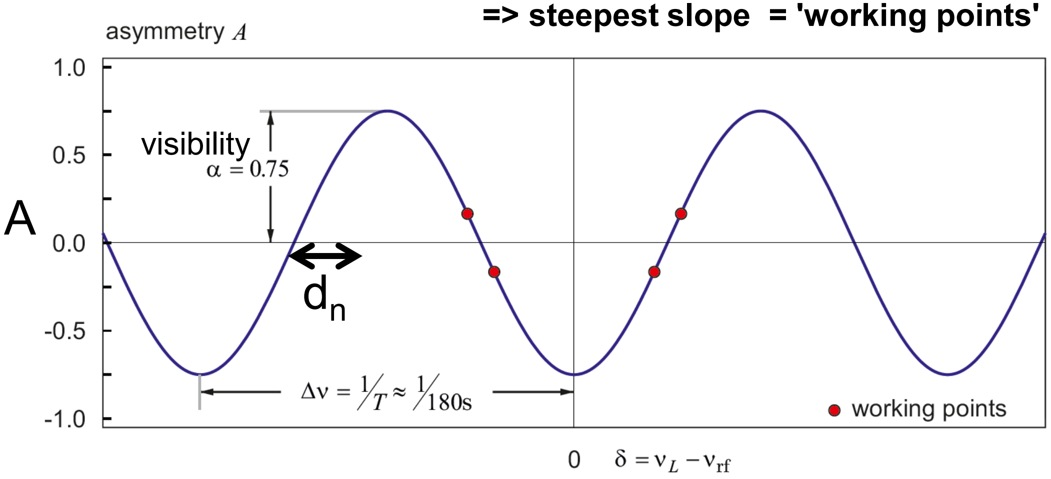
C.Abel et al. Phys.Rev.Lett. 124 (2020) 081803



Ramsey's Technique of oscillatory fields



Maximum sensitivity at A=0
=> steepest slope = 'working points'



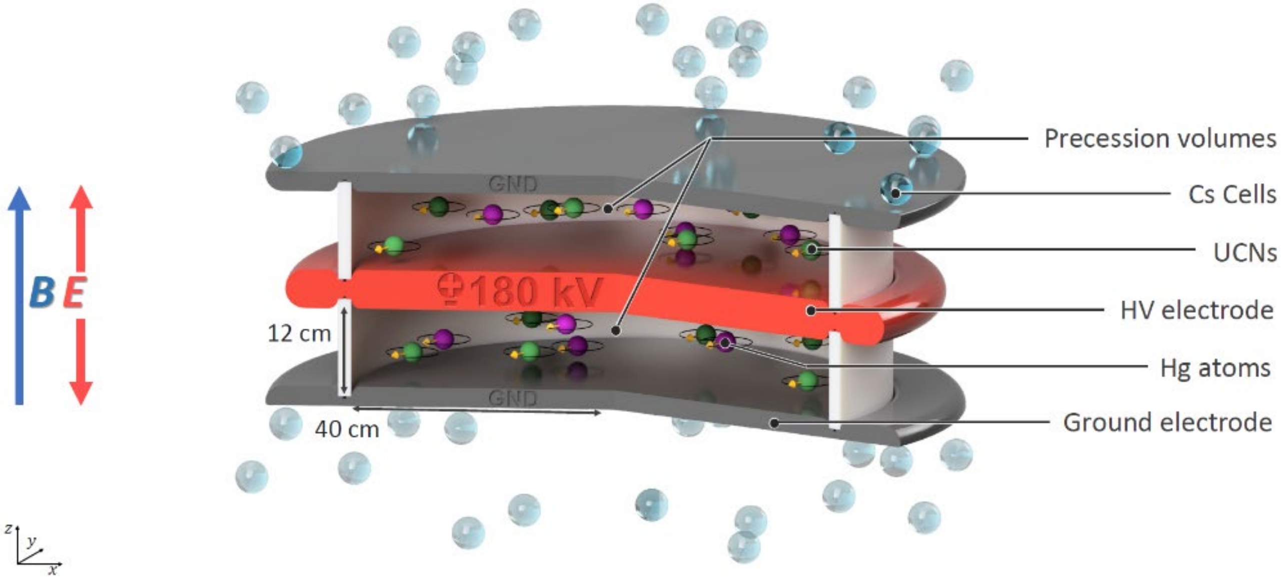
Asymmetry $$A \equiv \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

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

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

29 Hz @1µT 58 nHz @12 KV/cm

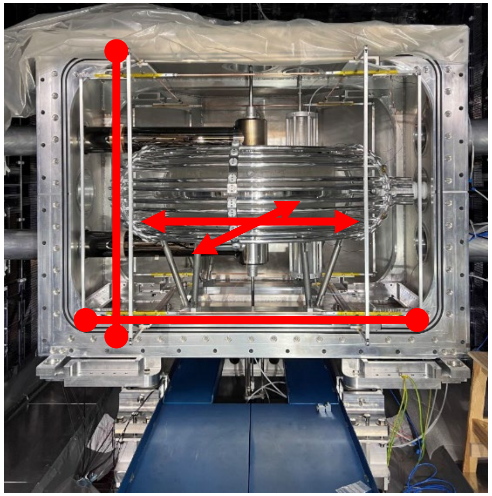
Ramsey's Method in double chamber n2EDM@PSI as example for room-temperature in vacuum double-chamber searches



simultaneous comparison of both E directions

- 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



Ramsey measurement with both spin-states of neutrons

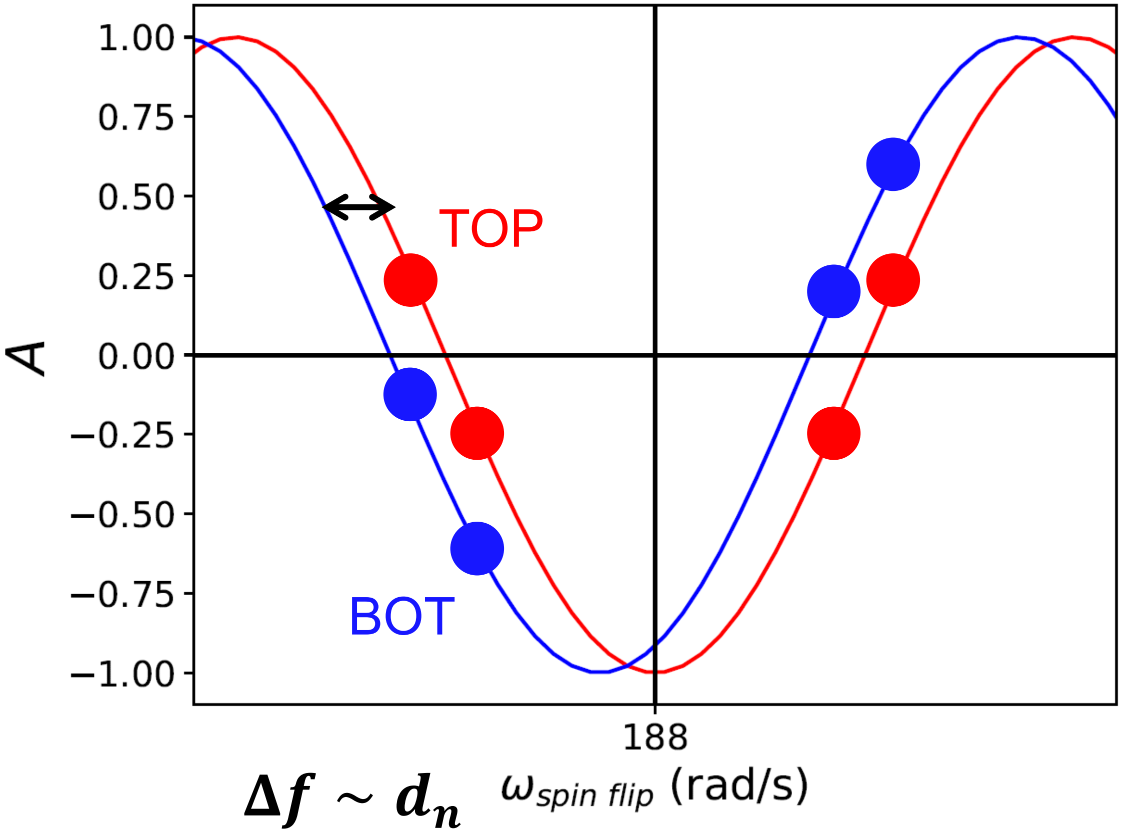
Strong constraint on “top-bottom” field matching

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

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

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

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



Sensitivity to nEDM

Maximum sensitivity at A=0
=> steepest slope = 'working points'

"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"

Neutron statistics

Interaction time
(precession time)

Electric-field
strength

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

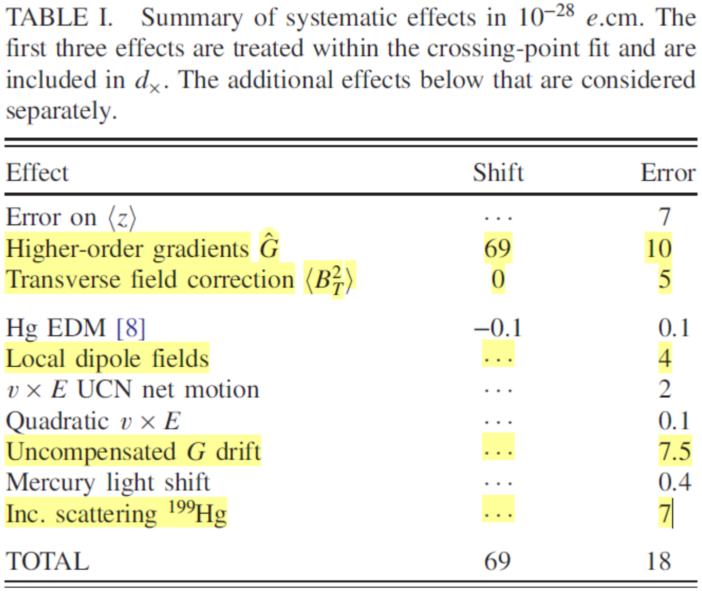


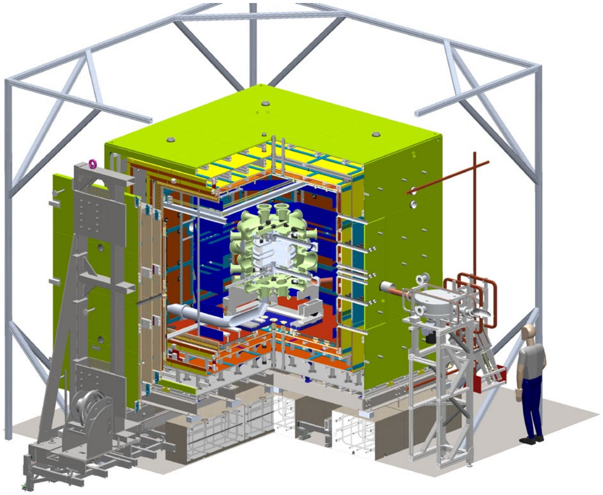
TABLE I. Summary of systematic effects in 10^{-28} e.cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below that are considered separately.

Effect	Shift	Error
Error on $\langle z \rangle$	···	7
Higher-order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_T^2 \rangle$	0	5
Hg EDM [8]	−0.1	0.1
Local dipole fields	···	4
$v \times E$ UCN net motion	···	2
Quadratic $v \times E$	···	0.1
Uncompensated G drift	···	7.5
Mercury light shift	···	0.4
Inc. scattering ^{199}Hg	···	7
TOTAL	69	18

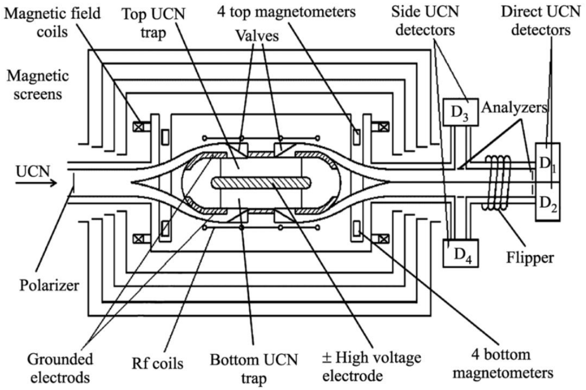
Goal for n2EDM low 10^{-27} ecm
Improve on every parameter
and in systematics

Worldwide efforts

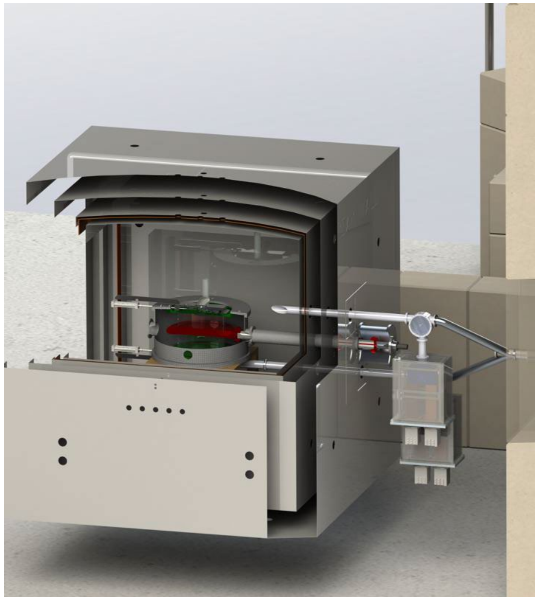
LANL-nEDM



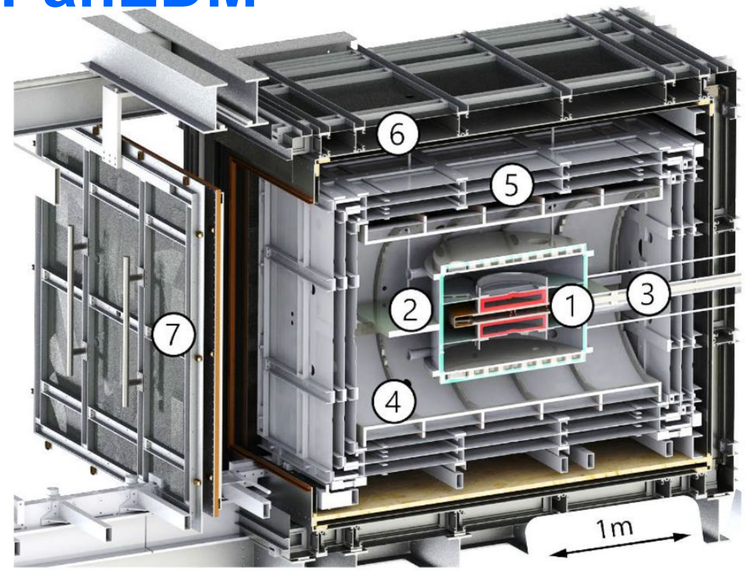
pioneering PNPI - 1980'ties



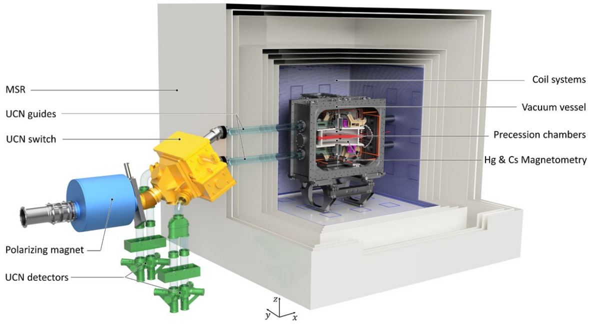
TRIUMF-TUCAN



ILL/TUM-PanEDM



PSI-n2EDM



nEDM measurement needs essential large machines to operate at the same time

- neutron production - the PSI proton accelerator
- 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

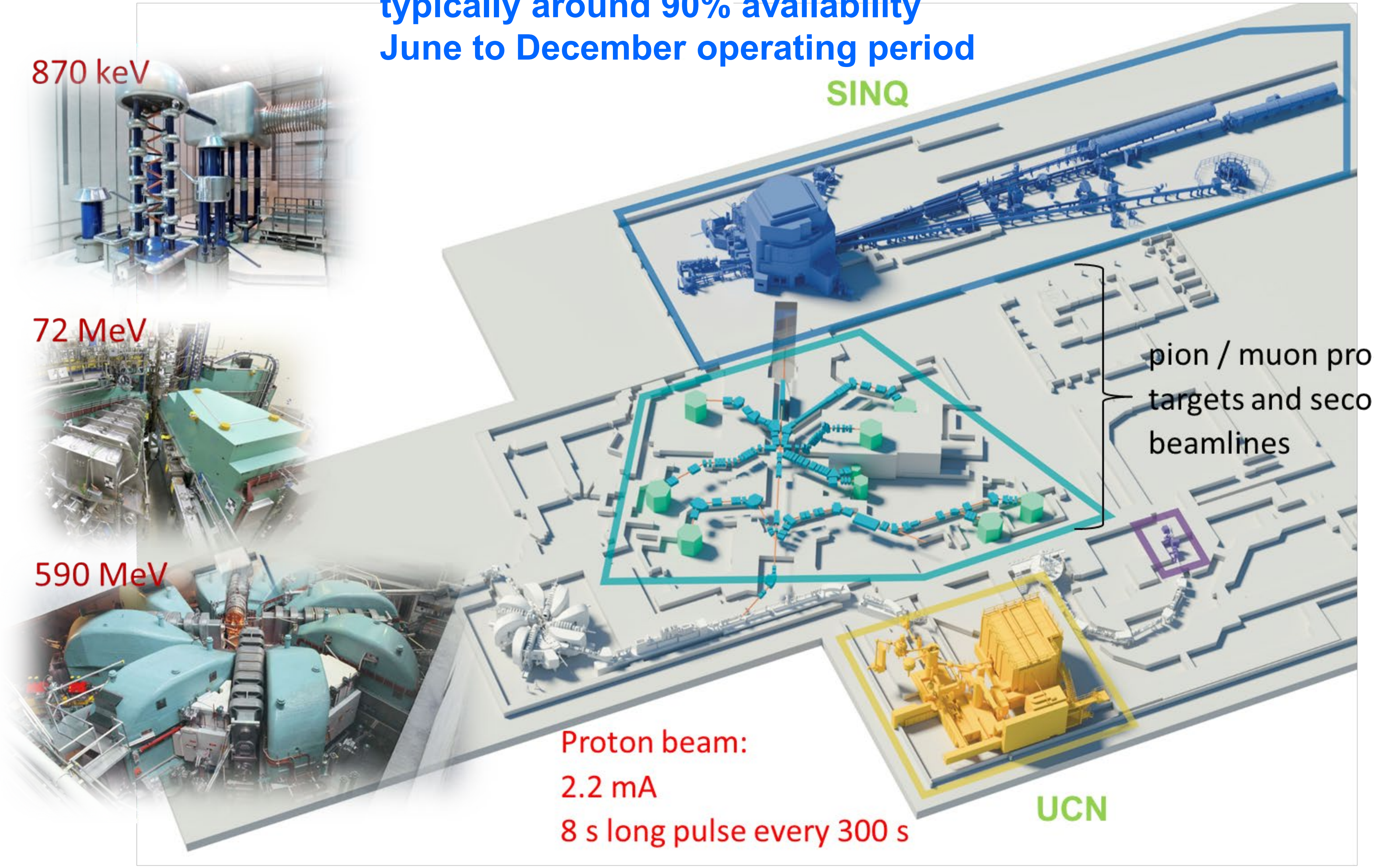
1998 2000 2011 2015/16/17 2018 2020 2025

n2EDM start construction

m2EDM start data taking

High intensity proton accelerator HIPA

typically around 90% availability
June to December operating period

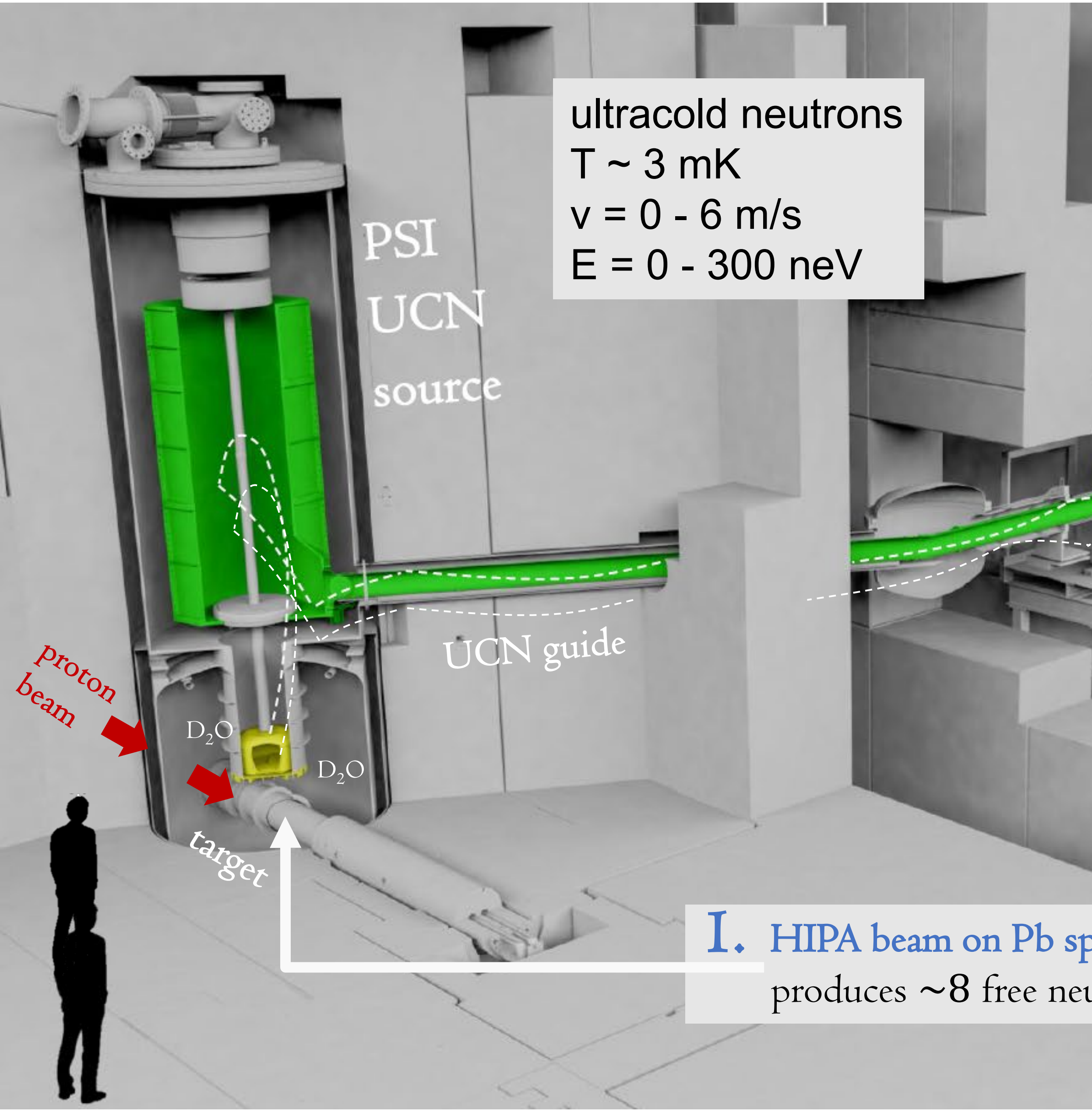


pion / muon production targets and secondary beamlines

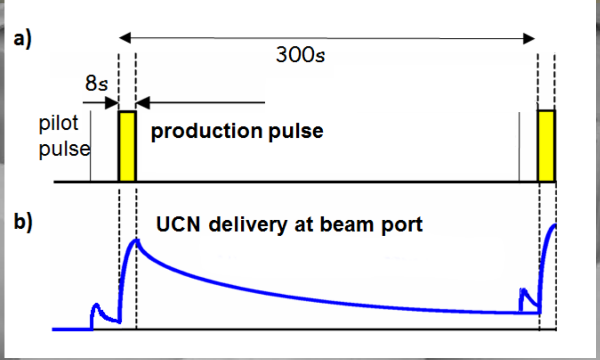
Proton beam:
2.2 mA
8 s long pulse every 300 s

PSI Center for Neutron and Muon Sciences

Ultracold Neutron Source - UCN



ultracold neutrons
T ~ 3 mK
v = 0 - 6 m/s
E = 0 - 300 neV



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

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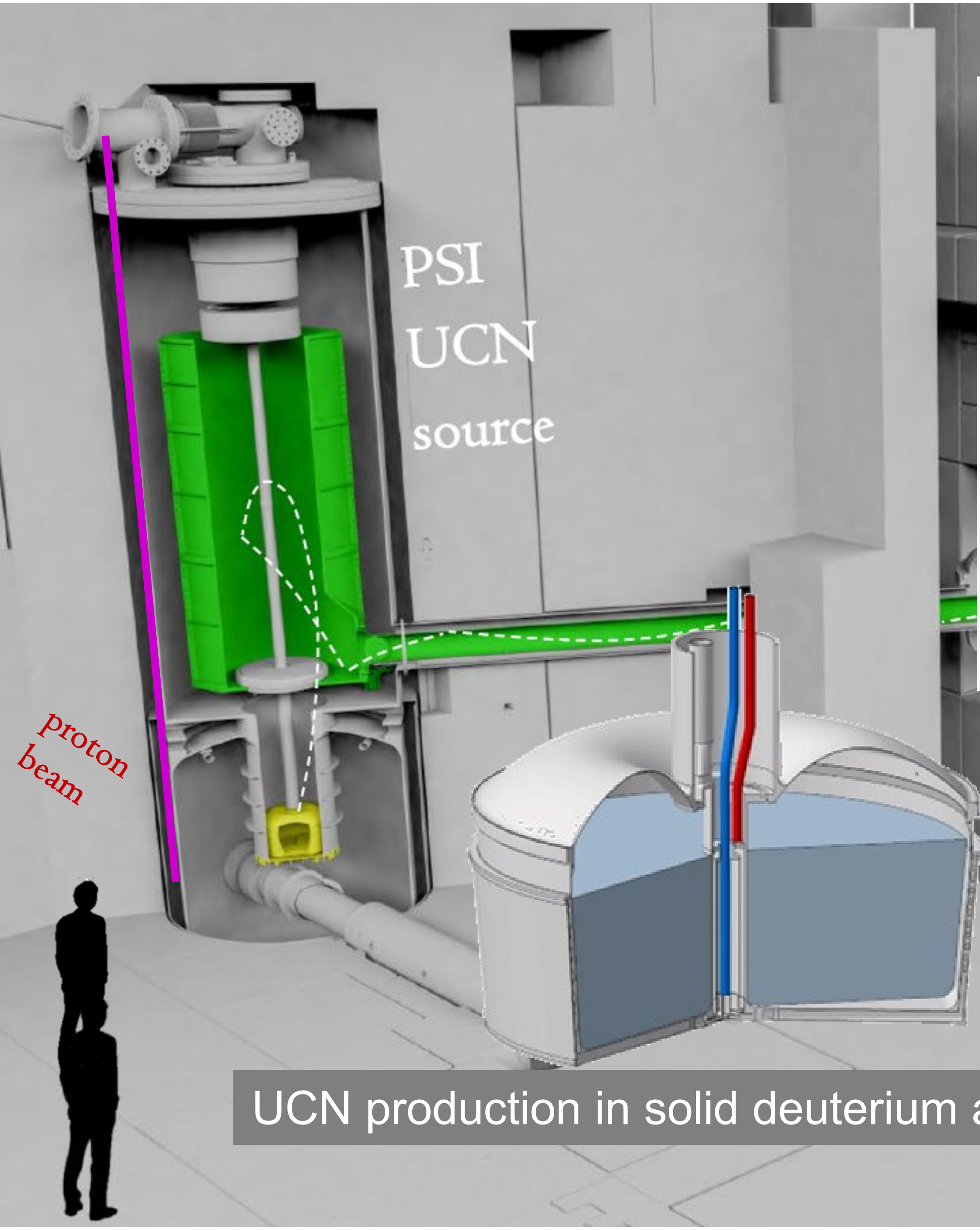
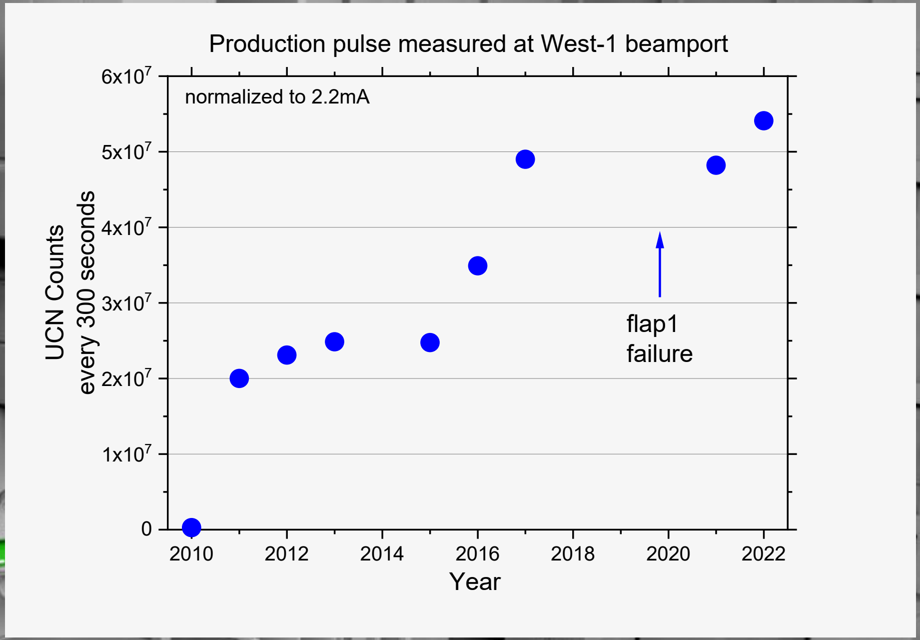
Ultracold Neutron Source - UCN

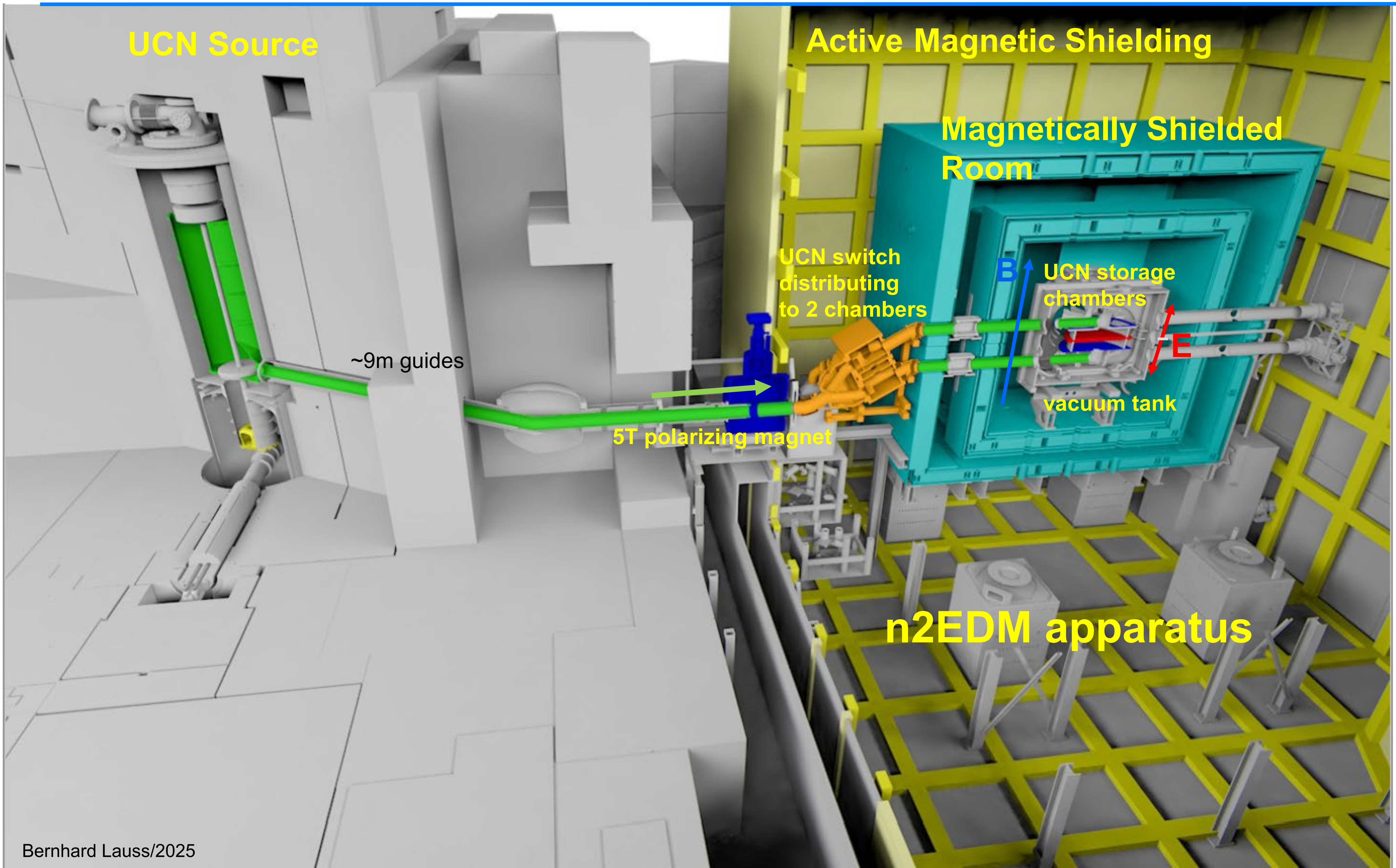
n2EDM





UCN production in solid deuterium at 5K

UCN delivery to Experiments

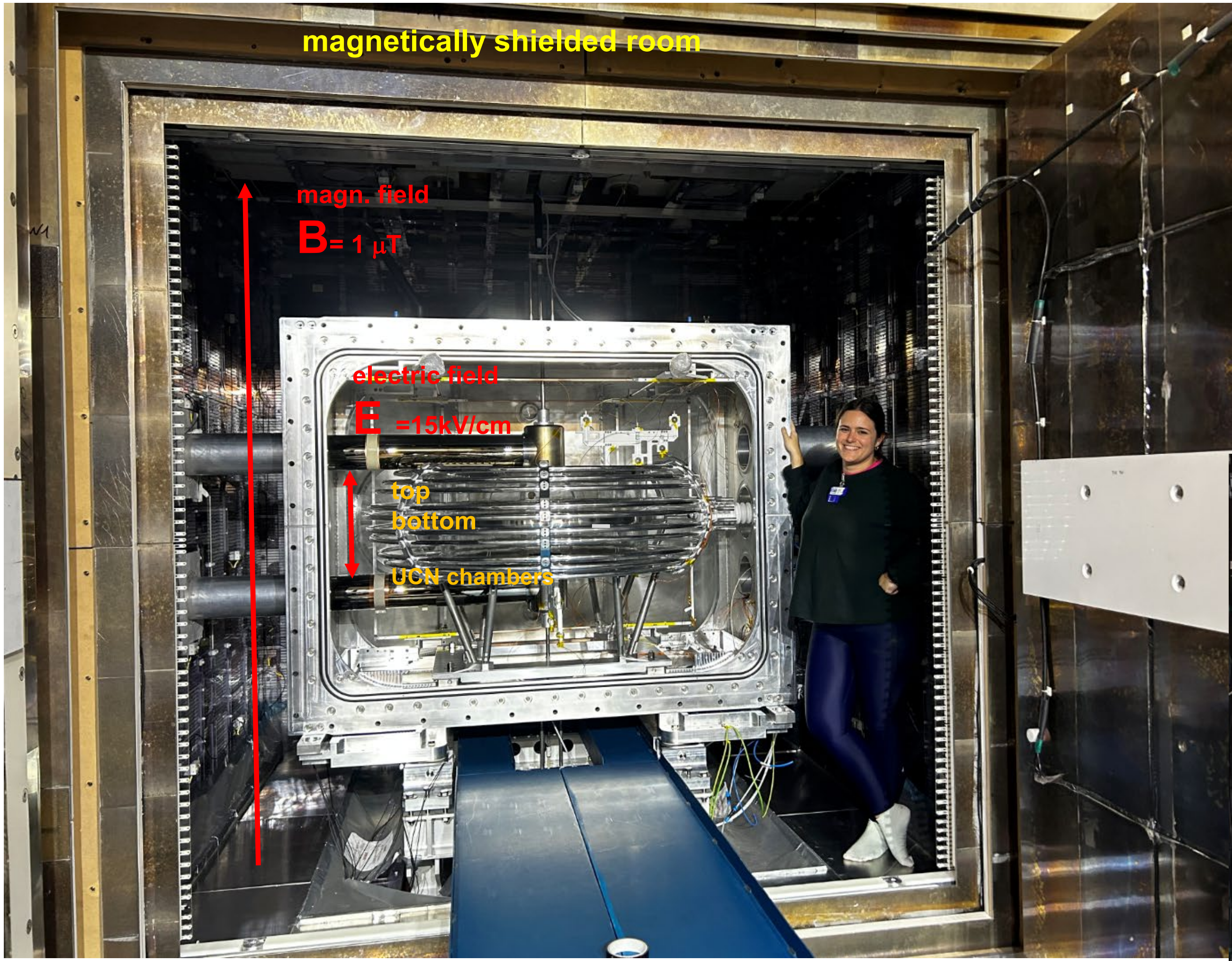


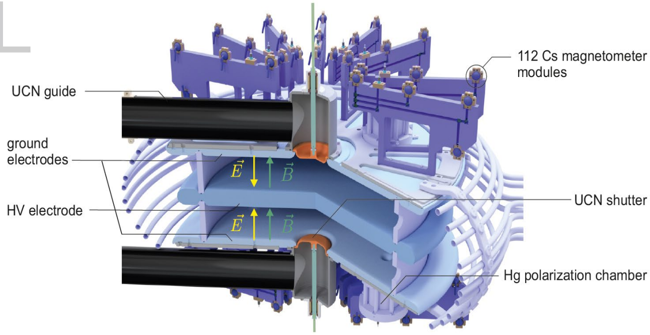
Bernhard Lauss/2025

n2EDM

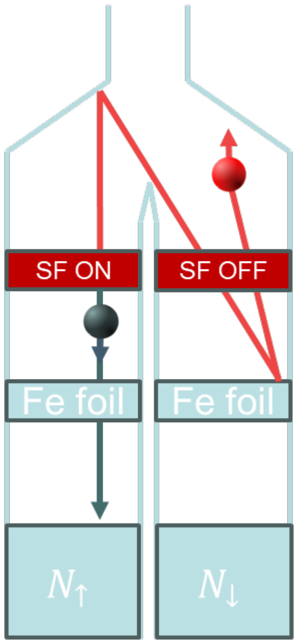
UCN chamber stack - 2x 60 liter volume

currently: DLC + deuterated paraffin

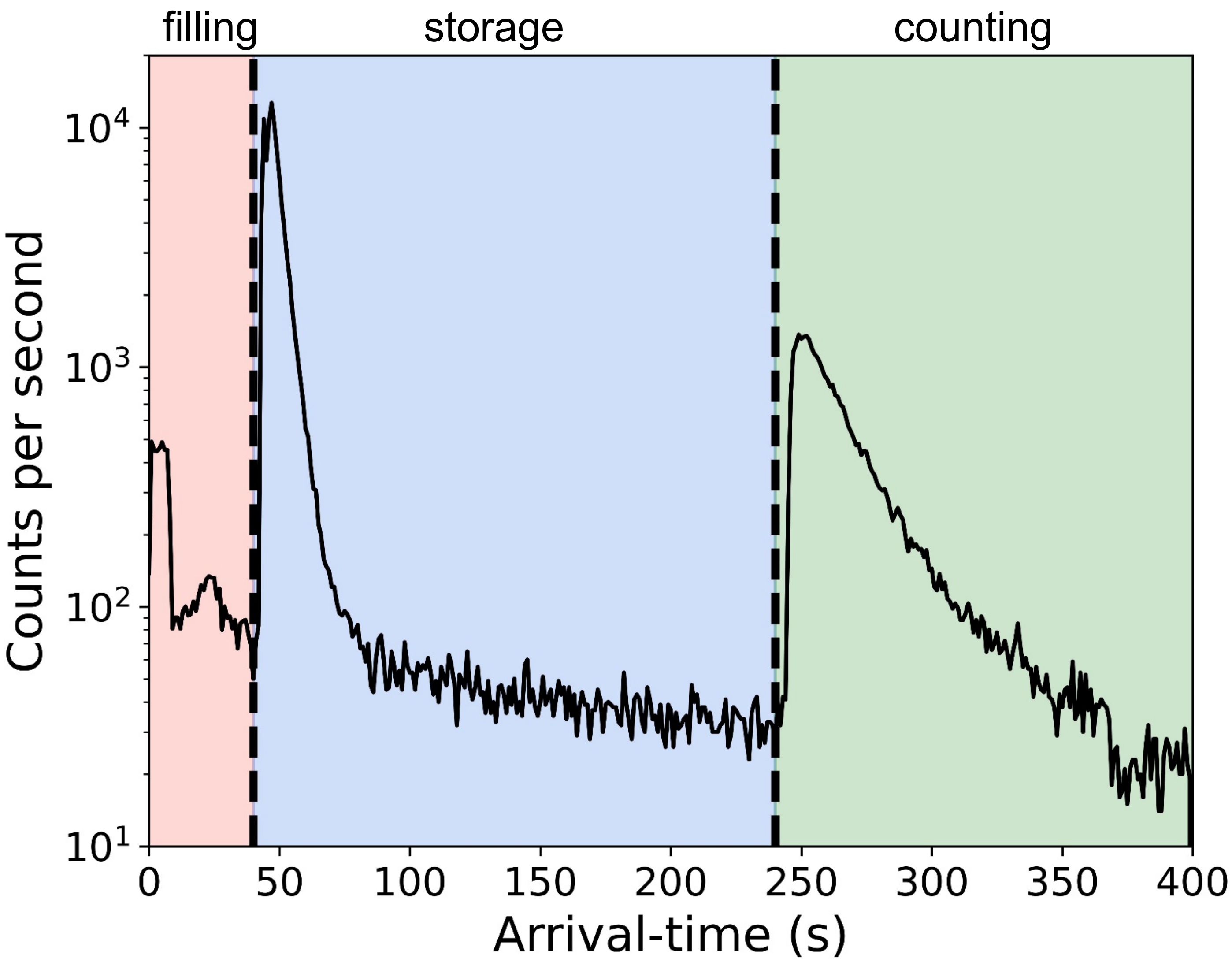




Counting UCNs in n2EDM



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



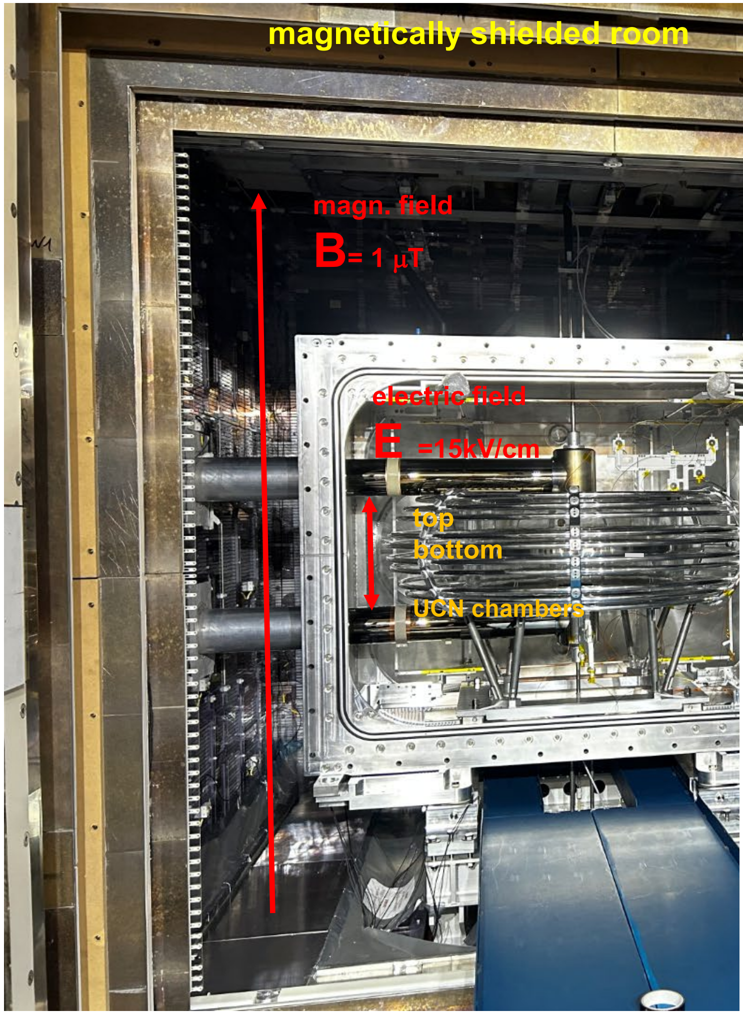
Sample time structure of one cycle as seen from UCN detectors (top + bottom).

PhD thesis A. Lejuez

n2EDM

UCN chamber stack - 2x 60 liter volume

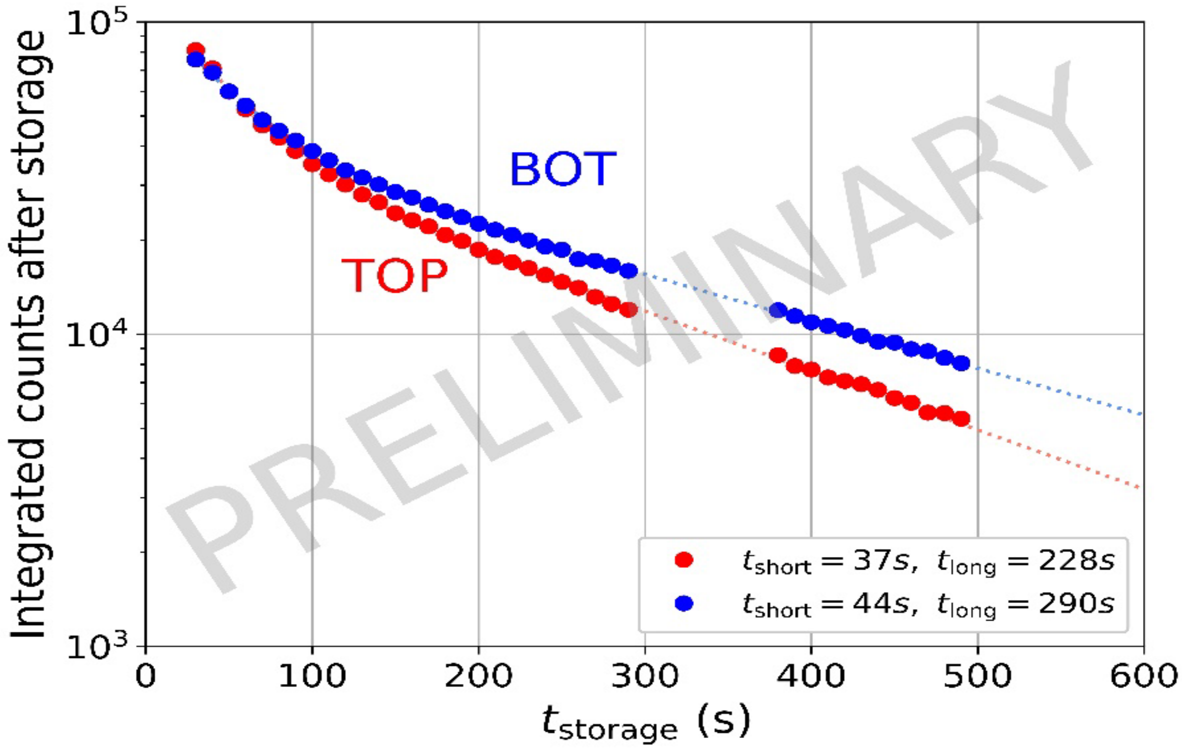
currently: DLC + Quartz



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

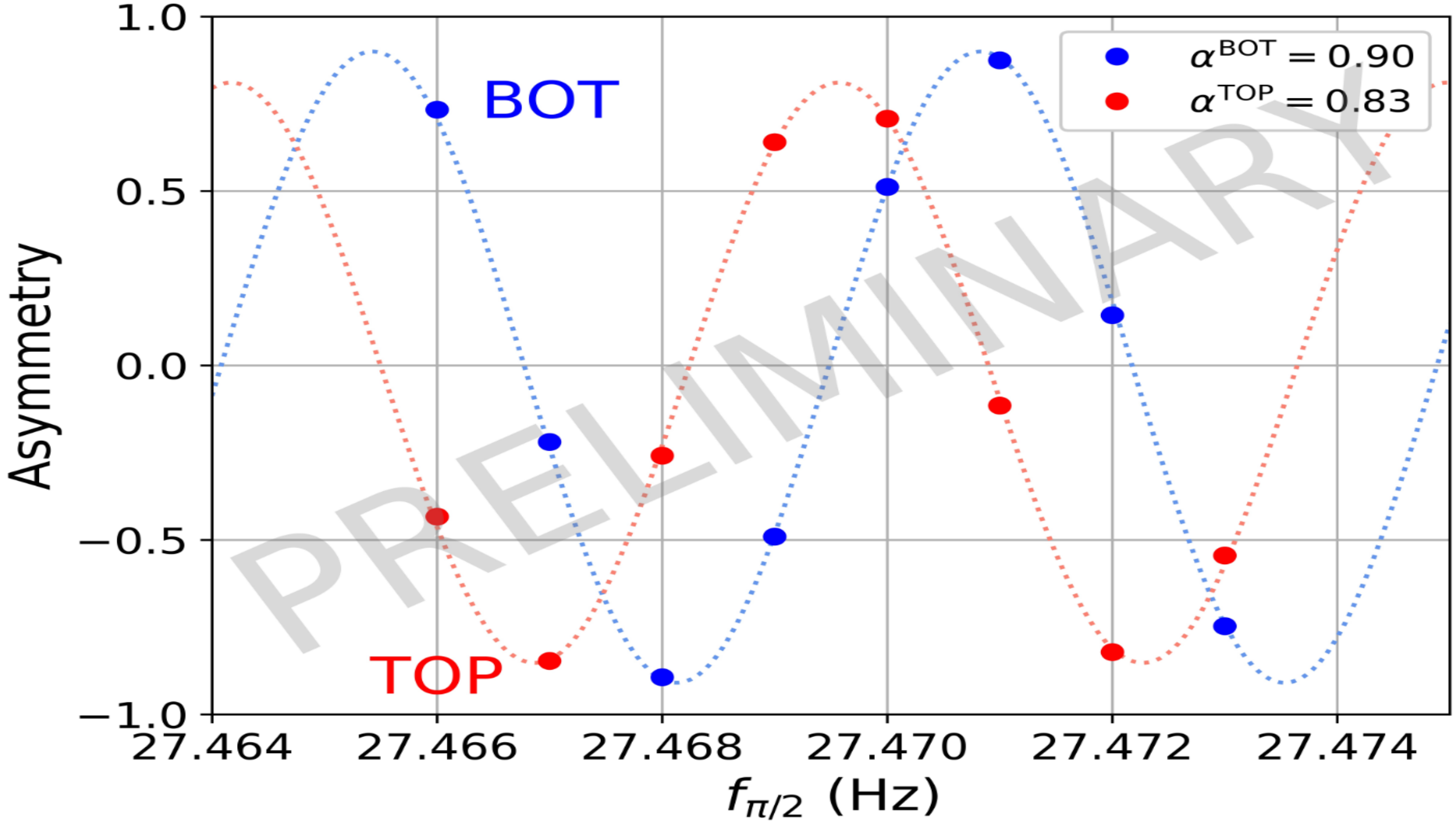
- operated at a statistics of ***25'000 UCN per chamber at t_{store}=180s in Dec.2024 already improved in 2025***

UCN storage in top and bottom chamber 12/2024



n2EDM Commissioning

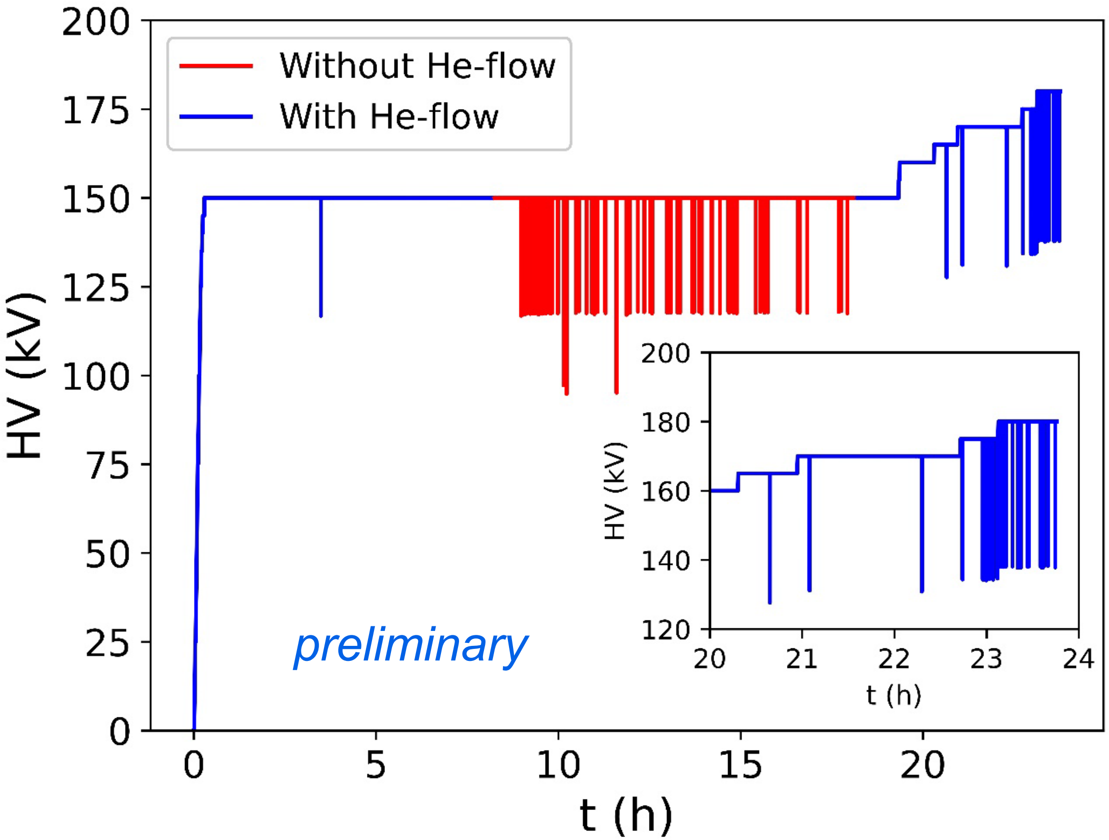
Coincident Ramsey measurement in top and bottom UCN chambers already without B-field correction and highest asymmetry.



High Voltage

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) tested but needs longer conditioning procedure.

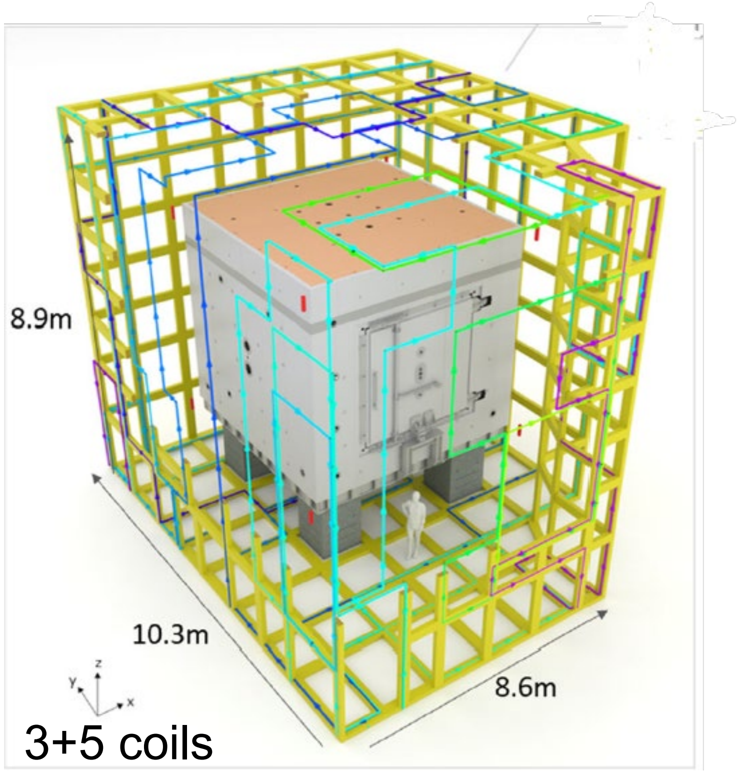


Master thesis R. Koch

Magnetic Environment

Active magnetic shield (AMS)

magnetically shielded room (MSR)



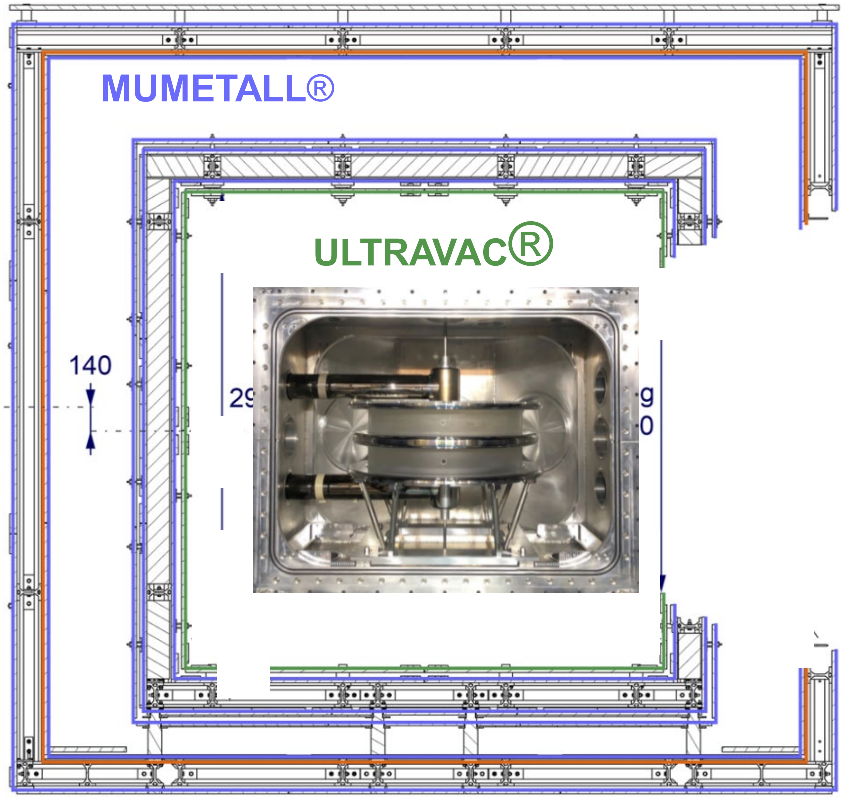
3+5 coils

- 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

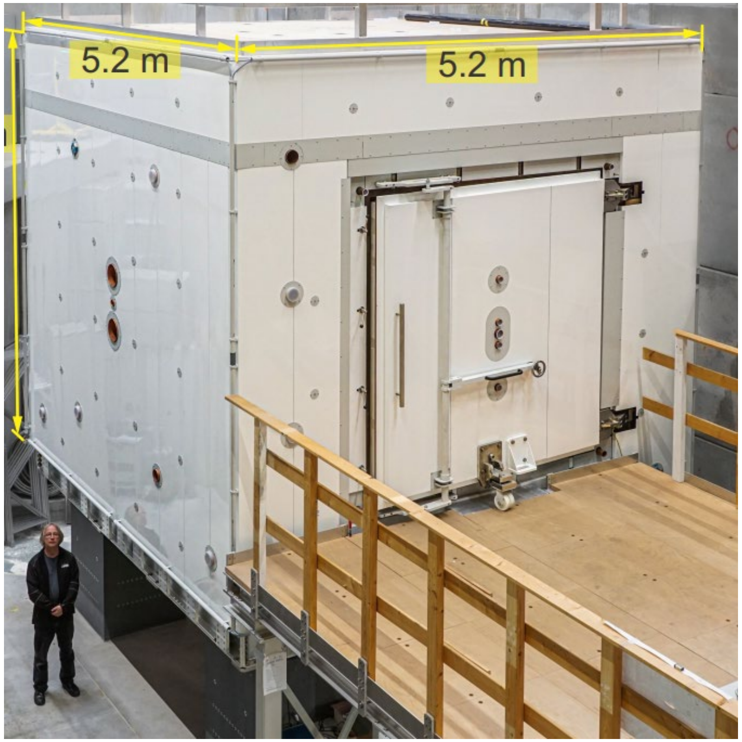
PhD thesis: M.Rawlik, S. Emenegger

The Magnetically Shielded Room (MSR)



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

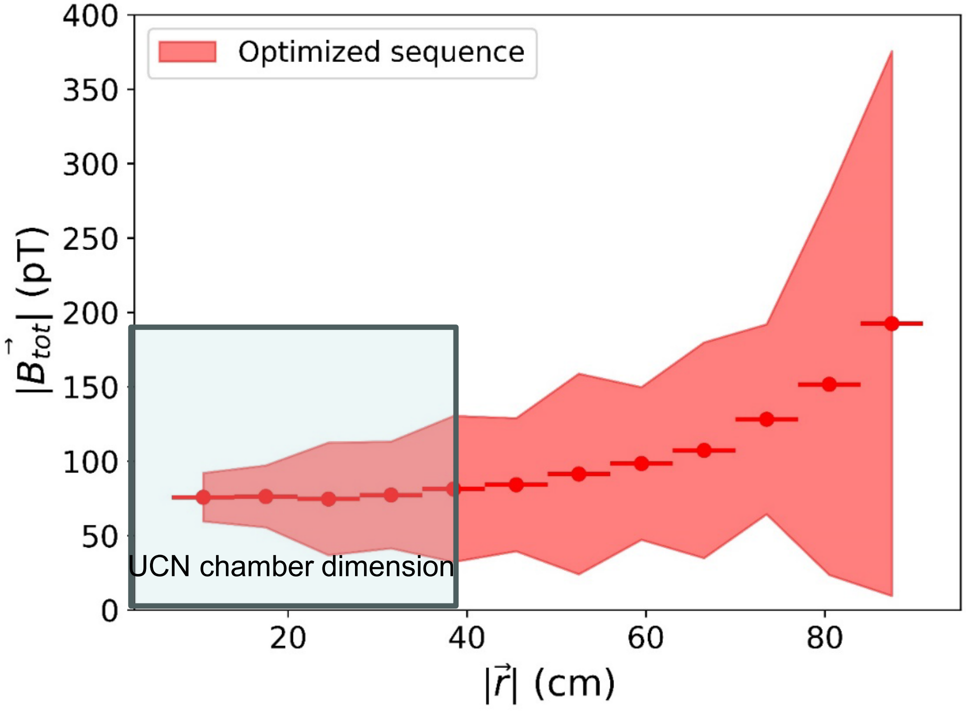
Rev. Sci. Instrum. 1 September 2022; 93 (9): 095105. https://doi.org/10.1063/5.0101391



- 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

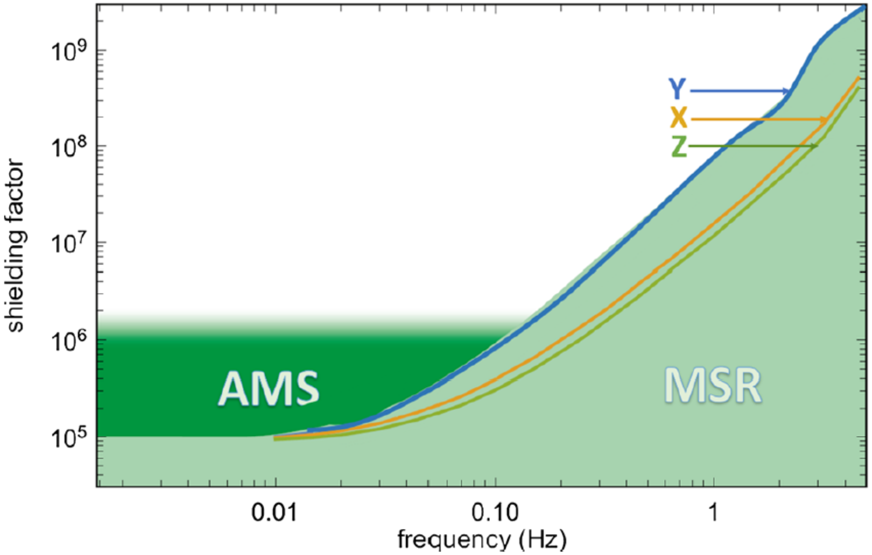
Performance of active and passive magnetic shielding

Residual field inside MSR after degaussing



AMS + MSR

shielding factor versus frequency

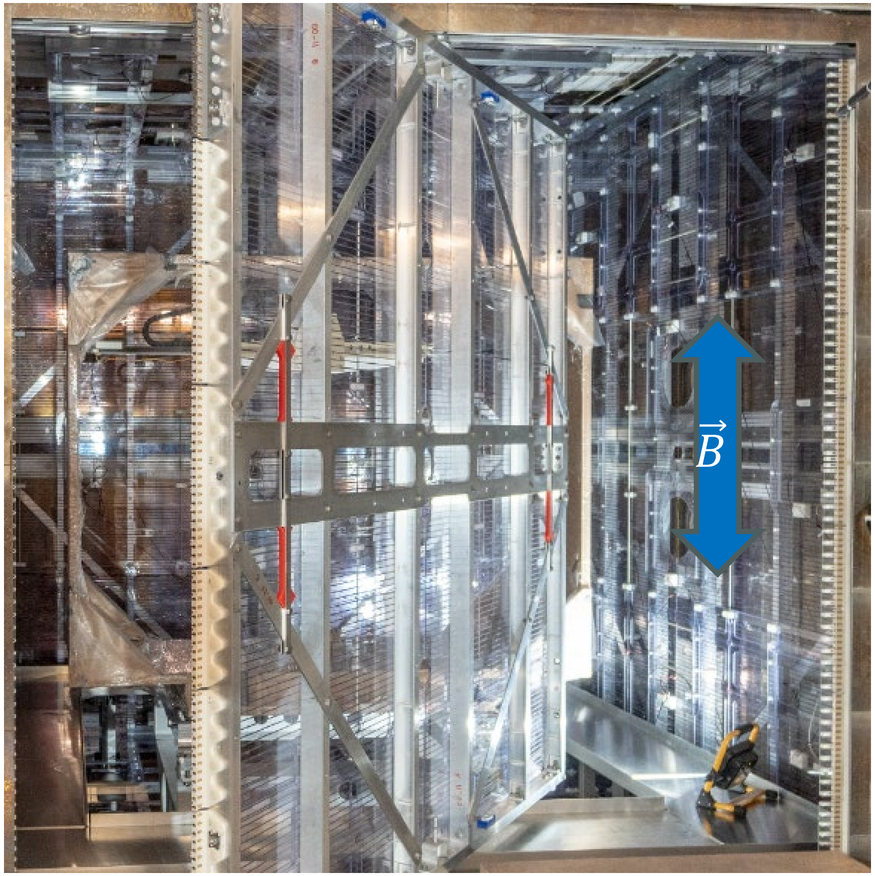


Magnetic environment at or better than design values:

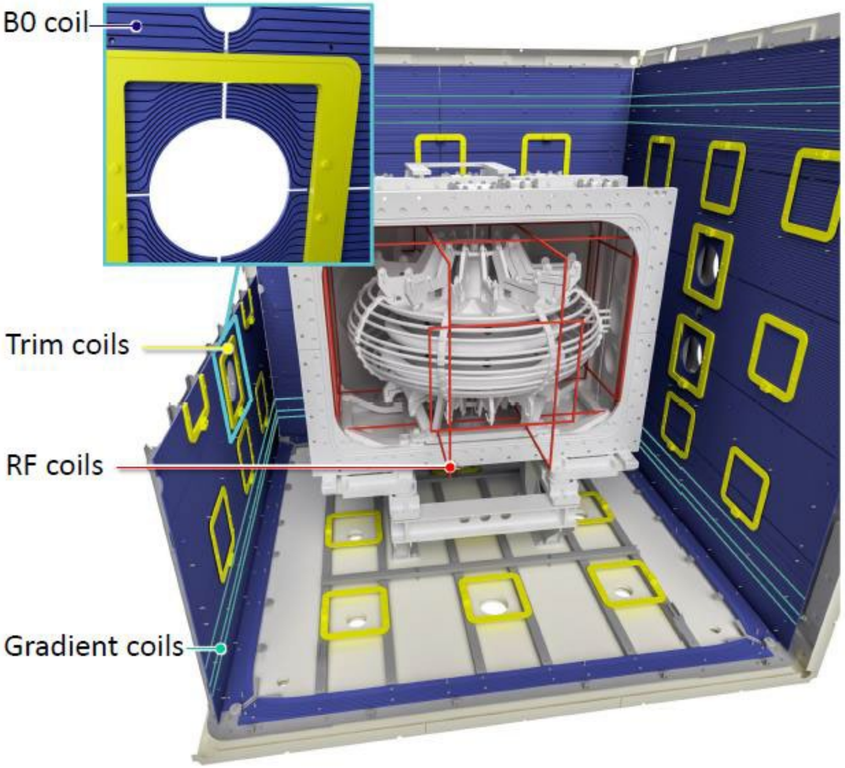
Design of the n2EDM experiment:	EPJC 81 (2021) 512
Magnetically shielded room:	Rev.Sci.Instr. 93 (2022) 095105
Active magnetic shielding:	EPJC 83 (2023) 1061
Ultralow magnetic fields:	EPJC 84 (2024) 18

Coil system for homogeneous 1μT vertical field

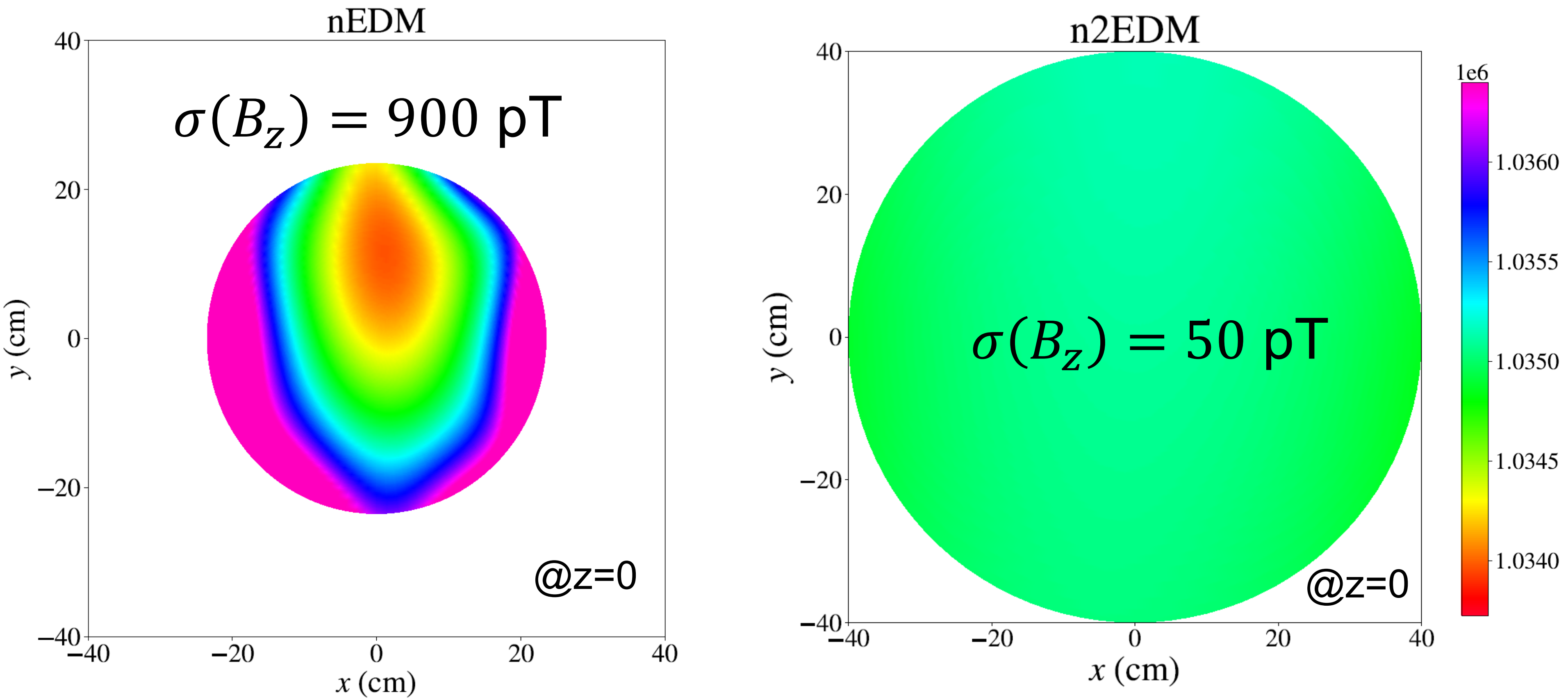
vertical $\vec{B}$ field



PhD thesis P.Flaux



Remarkable field uniformity



$\sigma(B_z) = 900$ pT

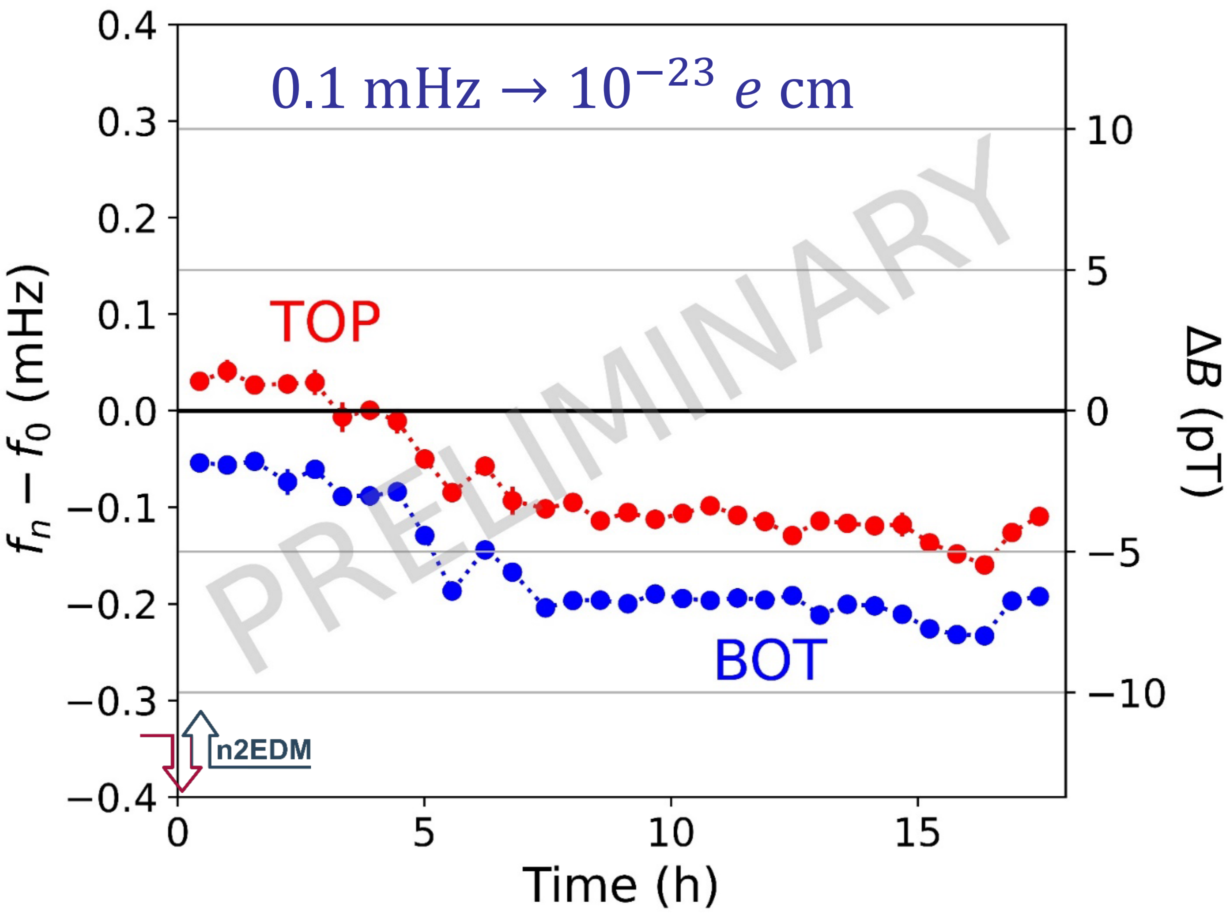
@z=0

$\sigma(B_z) = 50$ pT

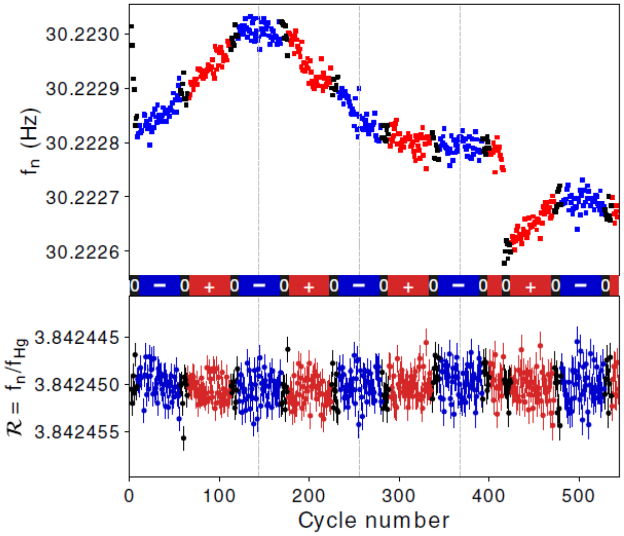
@z=0

PhD thesis T. Bouillaud

Despite best efforts, still see magnetic-field drifts when looking at neutron frequency



previous experiment

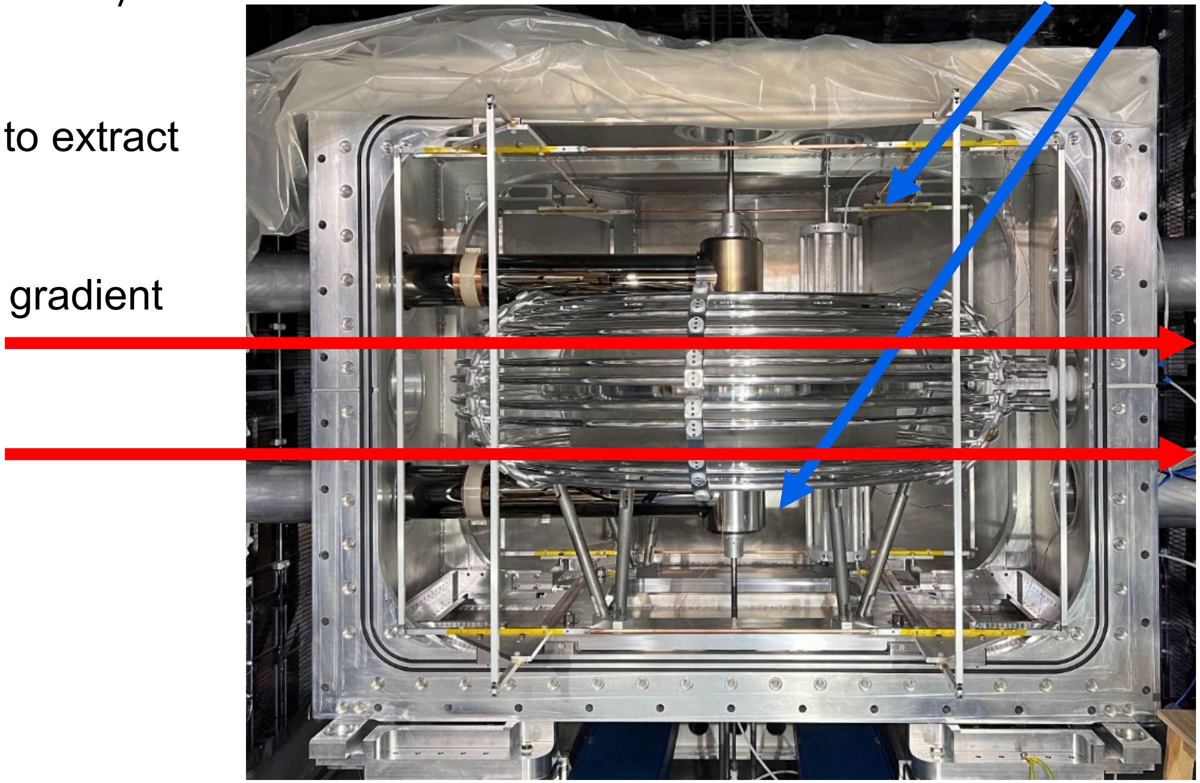


C.Abel et al. Phys.Rev.Lett. 124 (2020) 081803

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

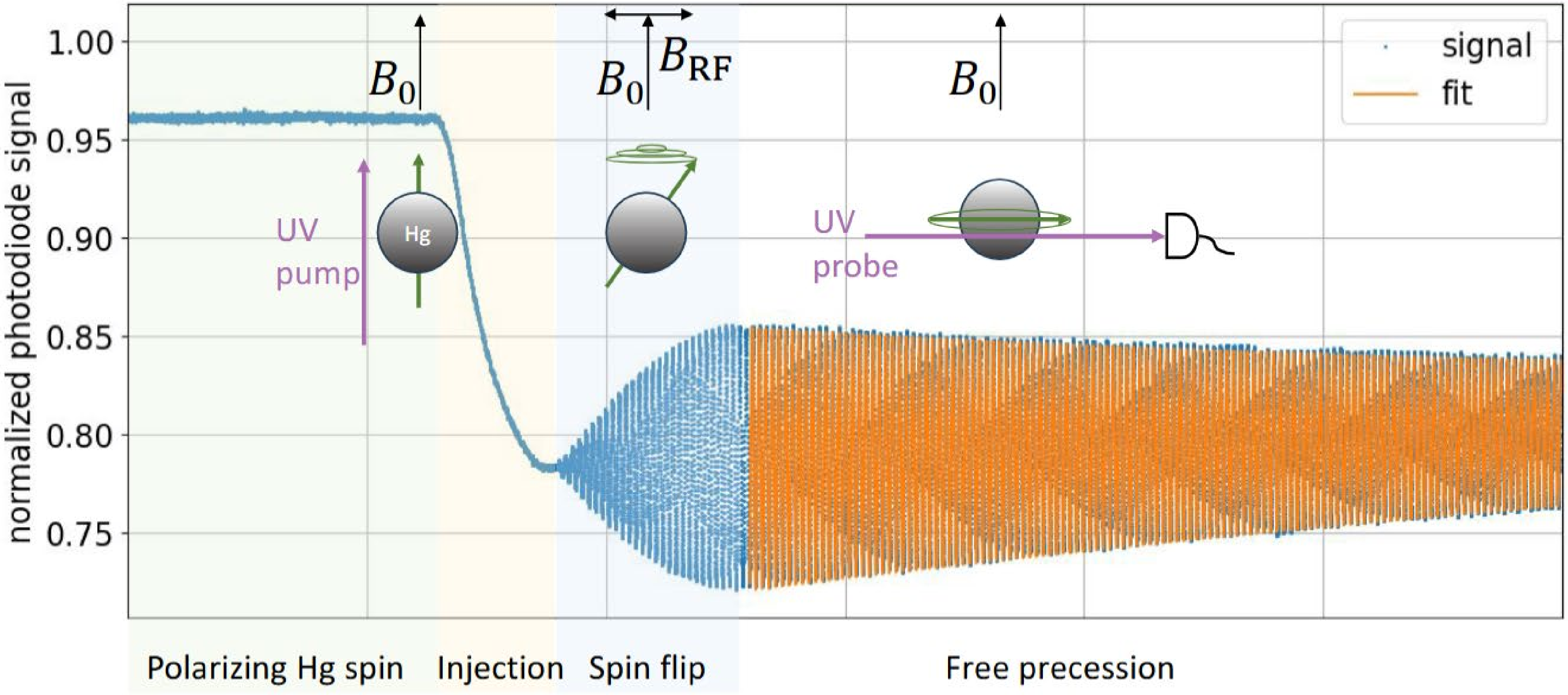
Hg polarization chamber with paraffine coating



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

Mercury Co-magnetometer in same storage volume as neutrons

f_{Hg} extracted by fitting or through demodulation analysis



Hg co-magnetomer operational over weeks in 2024

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

Performance still to be improved but nearly at the design goal sensitivity

-> Operational for nEDM measurement

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

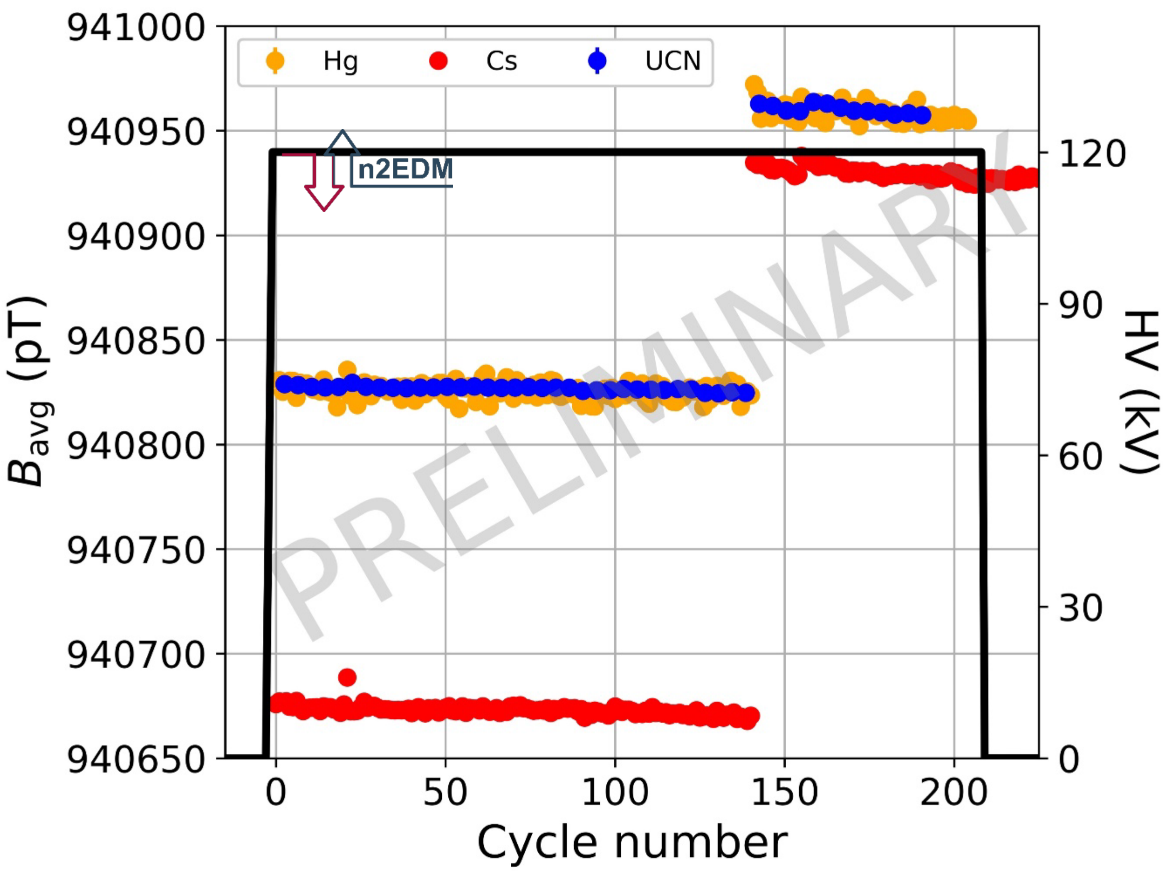
Instead of just using neutrons, we can sample the magnetic field with a ^{199}Hg **co-magnetometer** (fT)

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

Ratio R

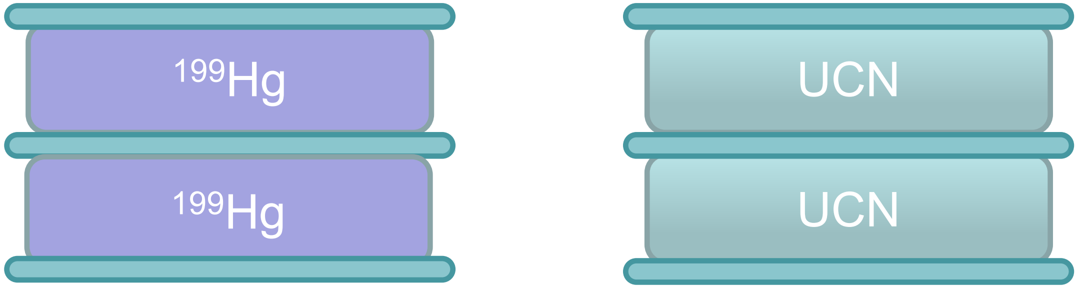
$$\frac{f_{\uparrow\downarrow}}{f_{\uparrow\downarrow}} = \frac{\mu_n}{\mu_{Hg}} \cancel{\frac{B_{\uparrow\downarrow}}{B_{\uparrow\downarrow}}} + \frac{d_n}{\pi\hbar} \frac{E_{\uparrow\downarrow}}{f_{\uparrow\downarrow}}$$

But neutrons and mercury do not see the same magnetic field…



Analysis: Frequency ratio R = f_n/f_{Hg}

Center of mass offset δh
Non-adiabaticity ->
new systematic effects
motional (false) EDM



$\overline{v_{\mathrm{Hg}}} \approx 160$ m/s vs. $\overline{v_{\mathrm{UCN}}} \approx 3$ m/s

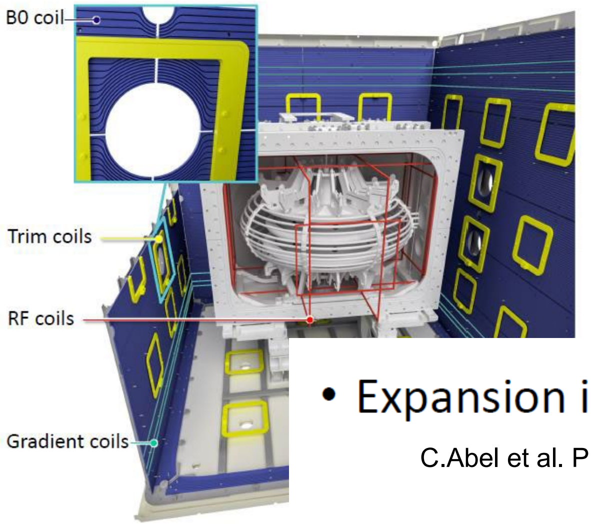
$$\boxed{R = \frac{\langle f_{\mathrm{UCN}}\rangle}{\langle f_{\mathrm{Hg}}\rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}}\left(1 \mp \frac{\partial B}{\partial z}\frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp}\rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}}\right)$$

$$d_{n\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar|\gamma_{\mathrm{n}}\gamma_{\mathrm{Hg}}|R^2}{8c^2}\left(G_{\mathrm{TB}} + \acute{G}_3 + \acute{G}_5 + \cdots\right).$$

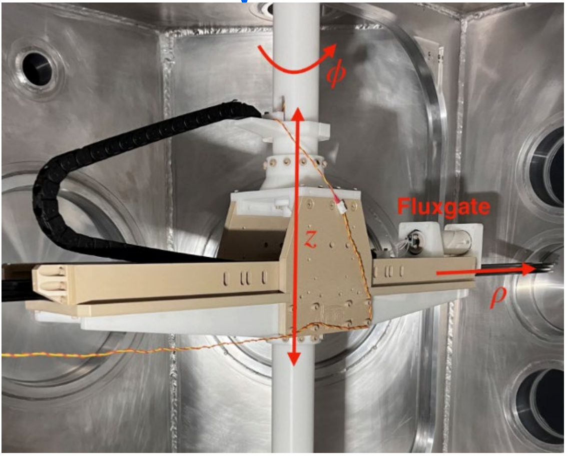
Measure R as function of dB/dz

Coil system for homogeneous 1μT vertical field

$\vec{B}$ field



PhD thesis P.Flaux



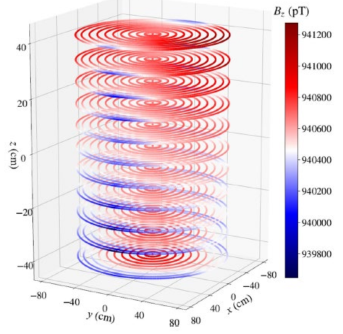


Fig. 5 An example of a magnetic field map of the field generated by the n2EDM coil system and recorded by the mapper. Each point corresponds to the vertical projection of the magnetic field inside a cylindrical volume of radius 78 cm and height 82 cm

- Expansion in harmonic modes :

  C.Abel et al. PRA99 (2019)042112

$$B(x,y,z) = \sum_{l,m} G_{lm} \Pi_{l,m}(x,y,z)$$

Gradient terms

Legendre polynomials

- G_{00} : Uniform vertical magnetic field
- G_{10} : vertical gradient
- G_{lm} $l \geq 2$: non uniformities

- Non uniformities (modes $l \geq 1$) affect the frequency ratio R.
- **Odd-modes** result in an EDM-like signal

Specifications	fT/cm	Measured by…
Mode 1 of the magnetic field	$\delta G_1 < 25$	Hg, online
Mode 3 of the magnetic field	$\delta G_3 < 20$	Cs, online
Mode 5 of the magnetic field	$\delta G_5 < 20$	Mapper, offline

✓

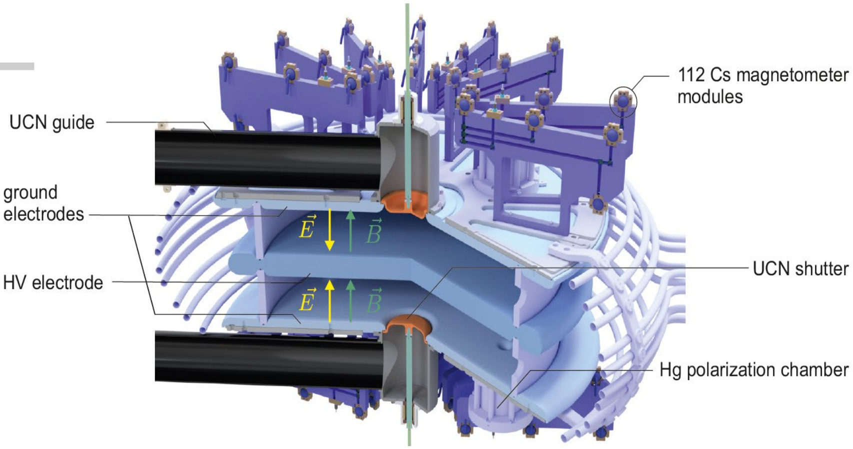
to do

✓

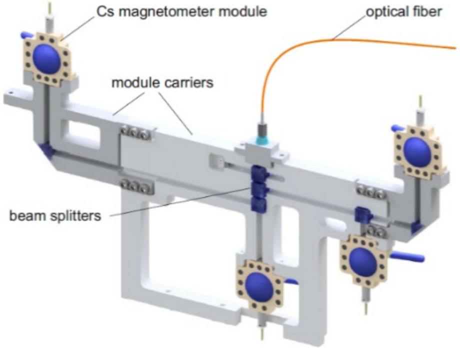
Cesium Magnetometer

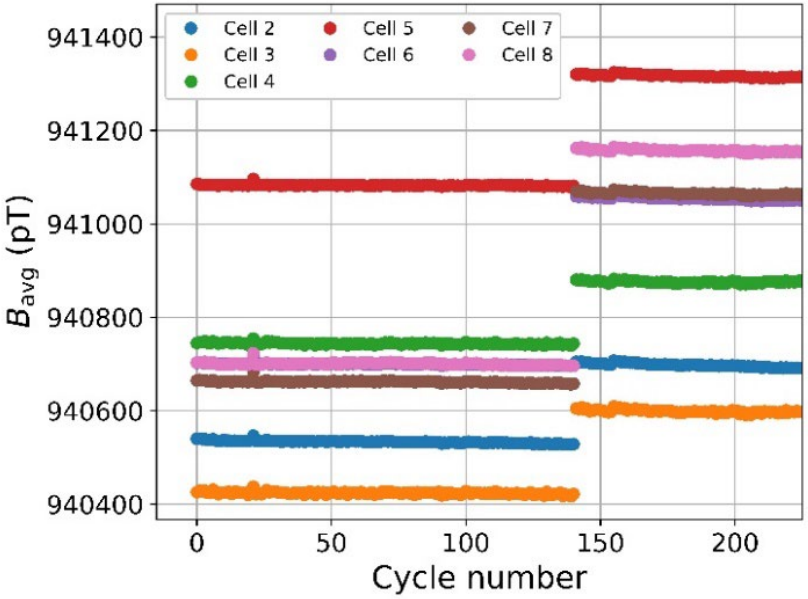
Online monitoring of field non uniformities - $G_{30,}$: systematic assessment

Two Cs units installed in 2024: steady operation over weeks



One Cs unit (4 cells)





Cs magnetometry plan:

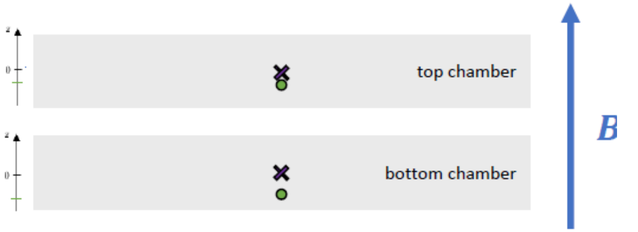
2025: half of Cs setup installed (56 cells)
2026: full Cs setup installed (112 cells)

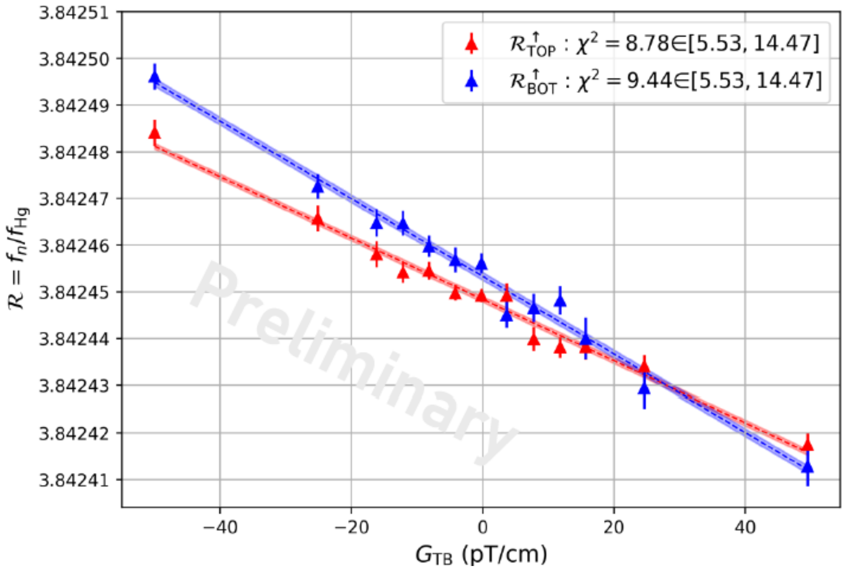
PhD theses D.Pais, V. Kletzl, L.Segner, L. Sanchez-Real Zielniewicz

Observation of gravitational shift on $R = \frac{f^{n}}{f^{Hg}}$

- Neutrons have a lower center of mass than Hg atoms because of gravity

→ R slightly depends on the vertical gradients G_{TB}





Susceptibility to vertical gradient

$$\frac{dR_{T,B}}{dG_{TB}} = R_0 \frac{< z_{T,B} >}{< B >}$$

Result:

$$< z_T > = -0.161(4)\ \text{cm}$$
$$< z_B > = -0.214(6)\ \text{cm}$$

Provides information of the energy spectrum of neutrons!

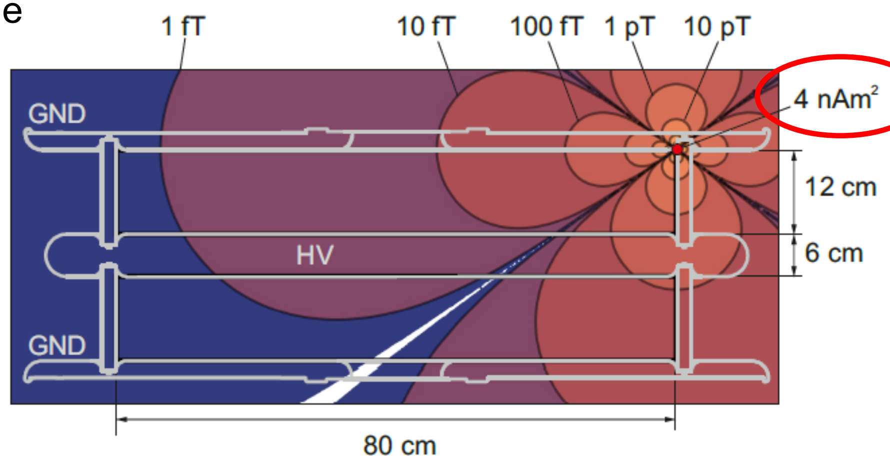
PhD K. Michielsen

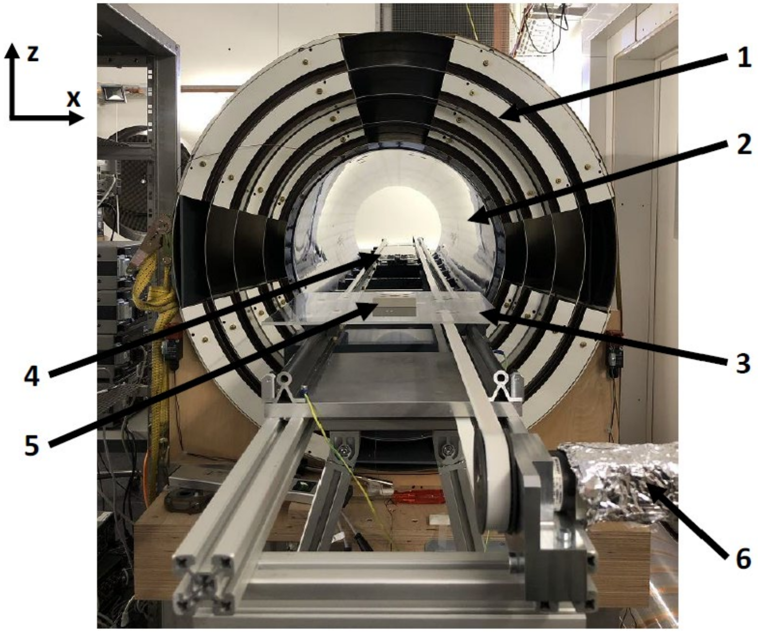
Challenge for all parts: magnetic contamination

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

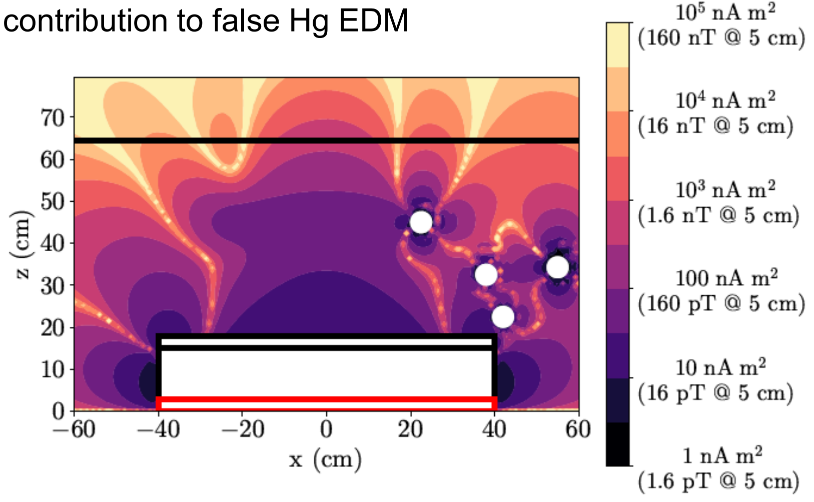
magnetic dipoles cause frequency shift





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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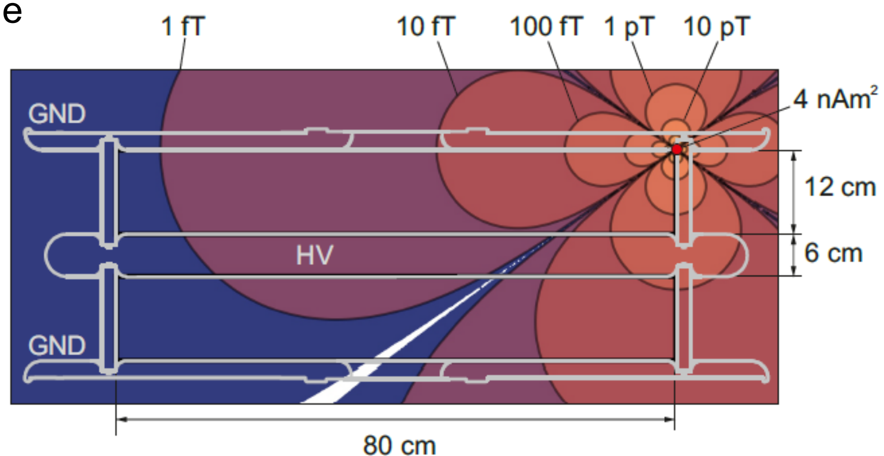
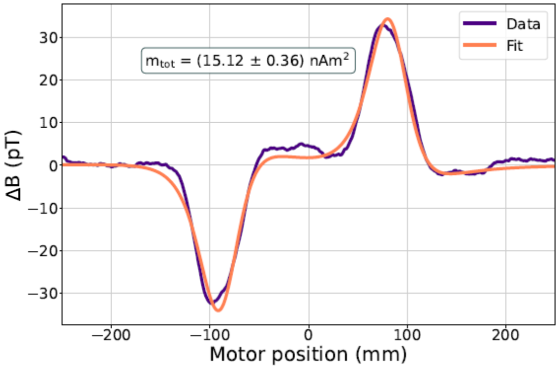


PhD Thesis V.Kletzl 2025



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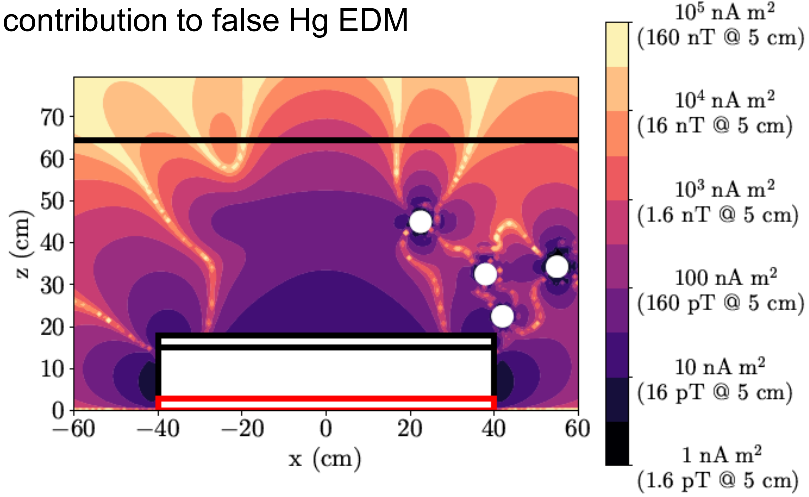
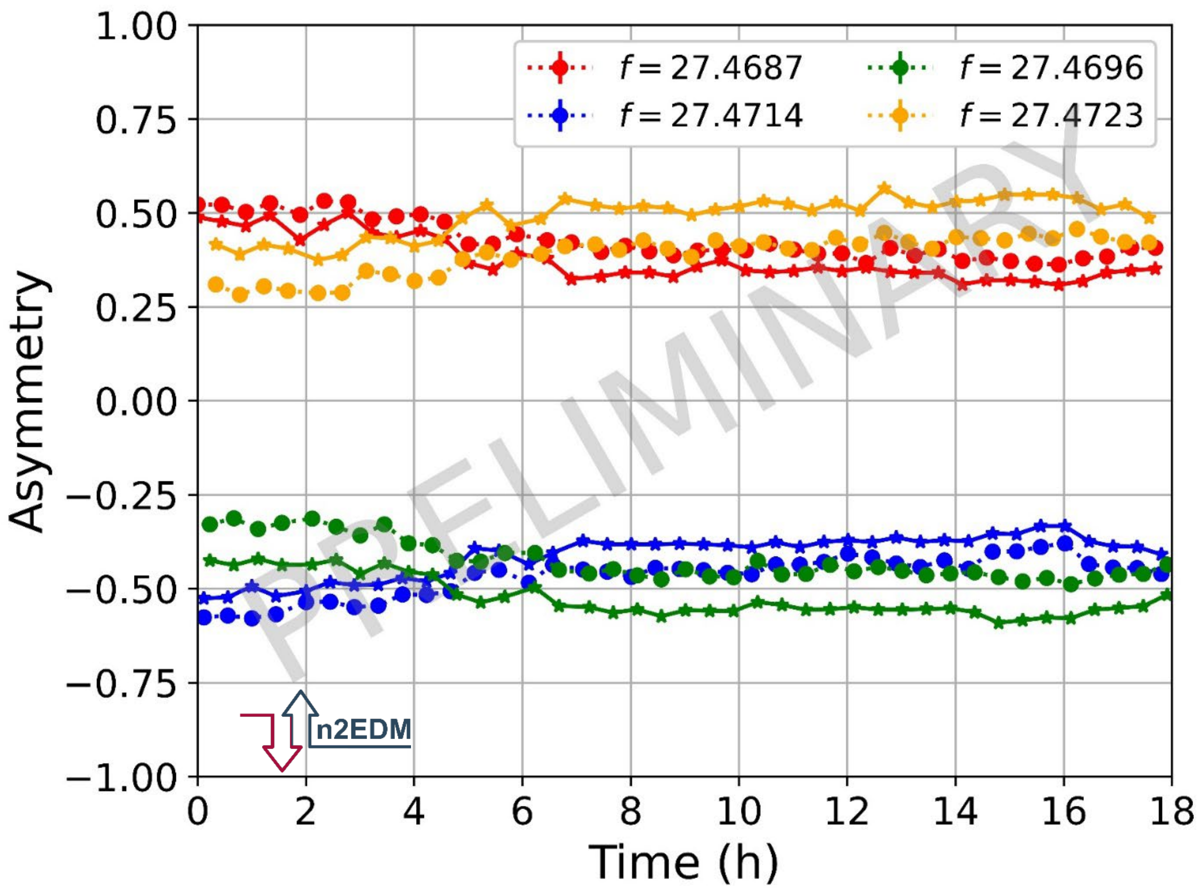
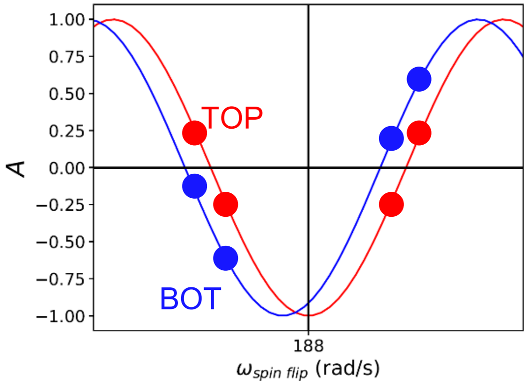


Design of the n2EDM experiment: EPJC 81 (2021) 512

PhD Thesis V.Kletzl 2025

“Dry” EDM run in n2EDM $@E = 130\text{kV}$ working point stability





Dec.2024

daily sensitivity ~ 4.5 10^{-26} ecm

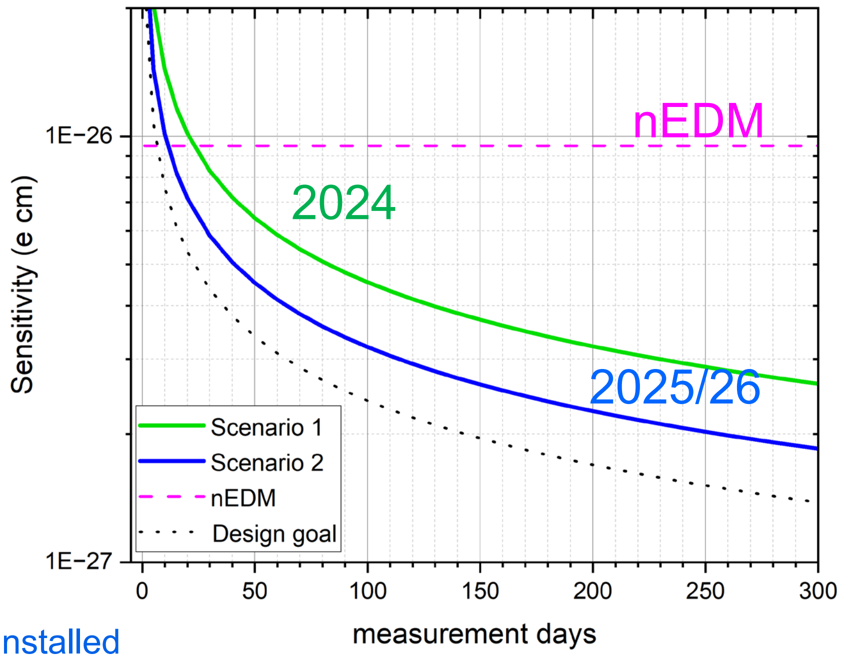
PSI Center for Neutron and Muon Sciences

n2EDM sensitivity status & outlook

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

Components	nEDM (2016)	n2EDM (2024)	Design goal
Precession time (T)	180 s	180 s	180 s
Neutrons statistic (N)	15,000	64,000 *	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



2025: improved electrodes and insulator rings currently being installed

first nEDM measurements soon to start

	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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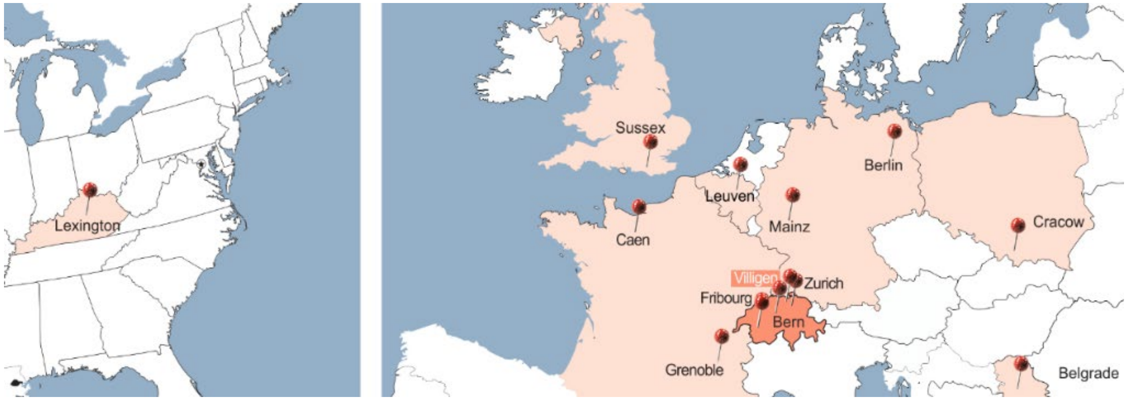
Thanks for your attention !

nEDM Collaboration
11/2024



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

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