PAUL SCHERRER INSTITUT

PSI

Georg Bison :: Paul Scherrer Institute :: for the neutron EDM collaboration

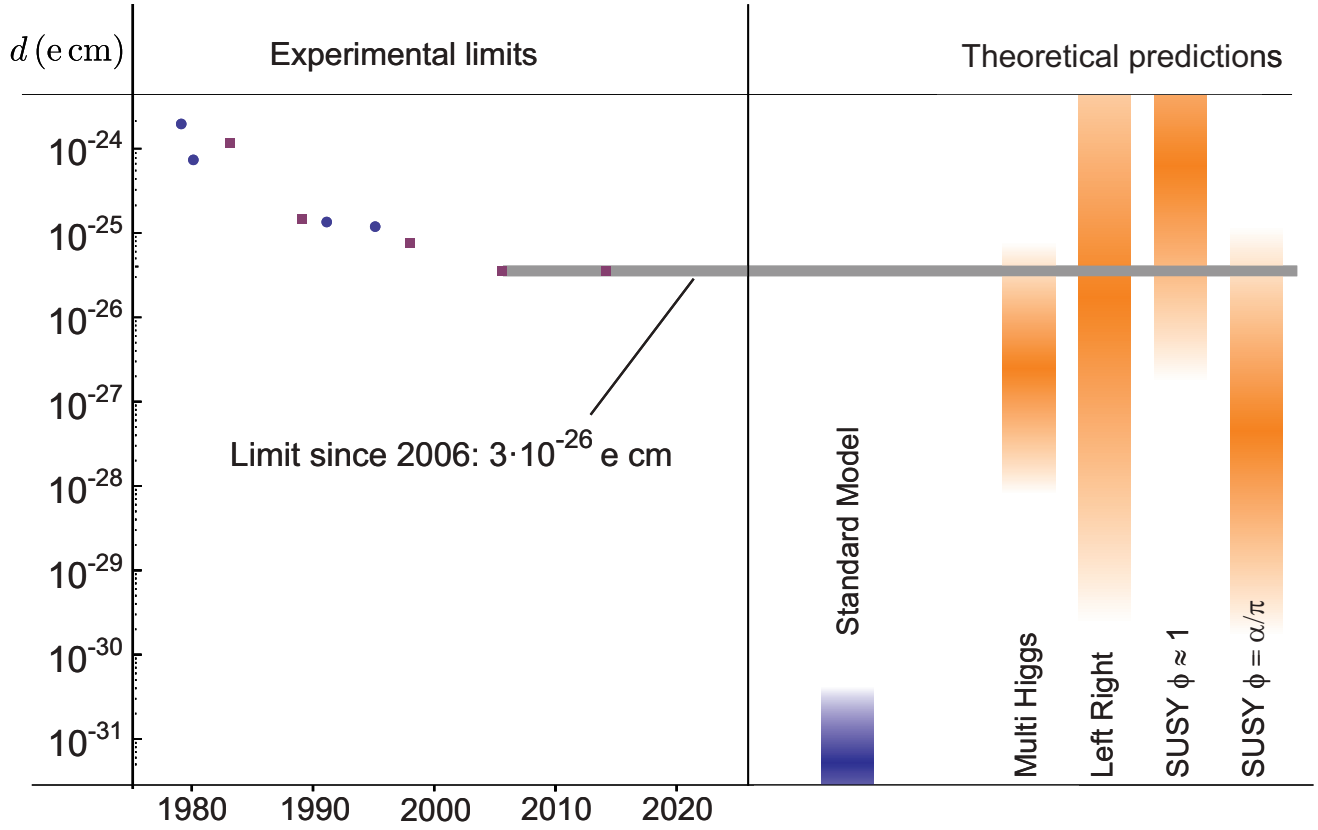
Neutron EDM search at PSI: results and future prospects

KMI Workshop, Nagoya, March 2023

n2EDM

- **Introduction & neutron EDM experiment @ PSI**
- Results
- New experiment n2EDM

Neutron EDM history (UCN era)



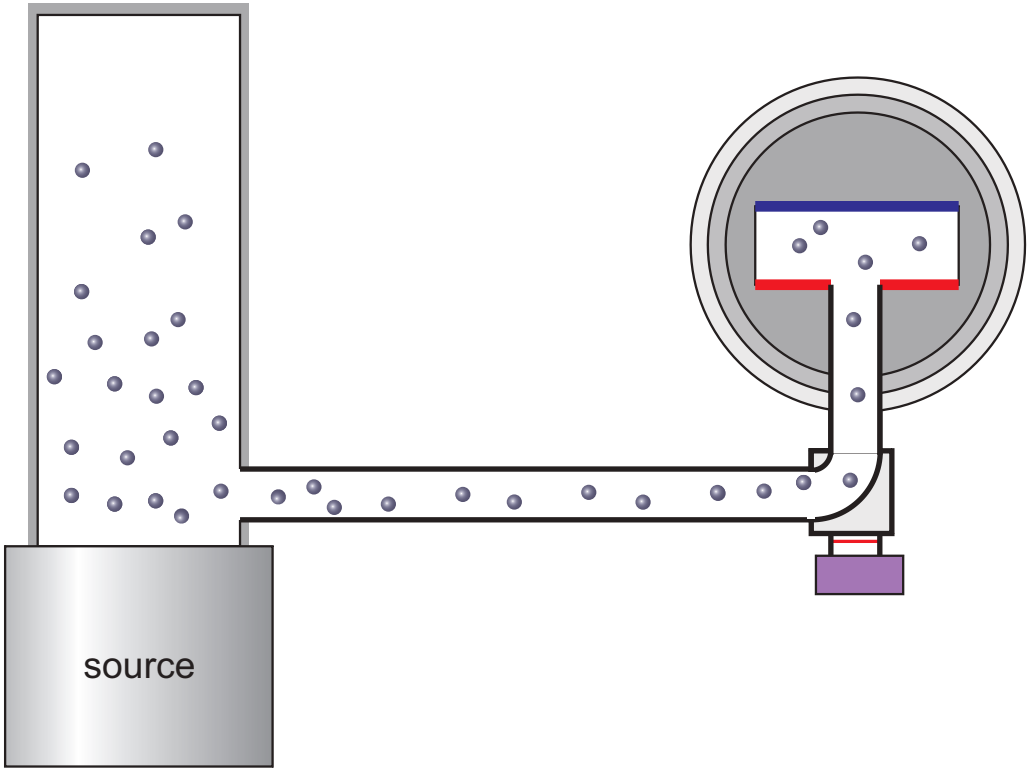
- Sussex RAL ILL
- LNPI/PNPI

Theoretical data: «Particle electric dipole moments» J.M. Pendlebury & E.A. Hinds, NIM A 440 (2000) 471

Ultra-cold neutrons (UCN)

Make Ultra Cold Neutrons (UCN)

Measure Electric Dipole Moment (EDM)

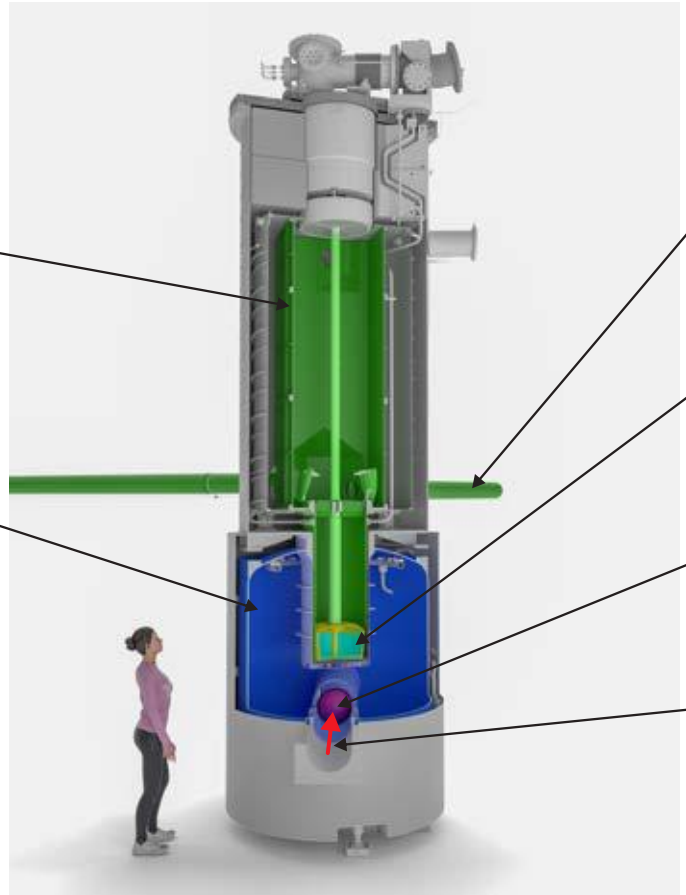


ultra cold neutrons

$v < 7$ m/s

$E_{kin} < 300$ neV

The ultra-cold neutron source @ PSI



DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3

heavy water moderator
3.6m^3 D_2O

UCN guide towards
experimental areas

cold UCN-converter
~30l solid D_2 at 5 K

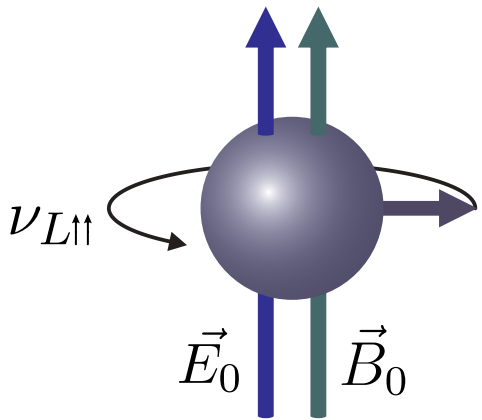
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

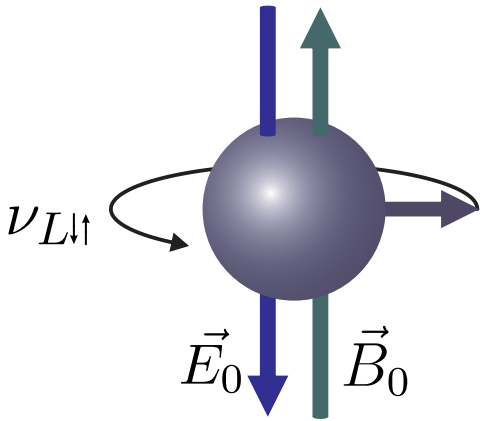
pulsed 1.3 MW p-beam
600 MeV, up to 2.4 mA,
up to 60 μA average
current on target

Neutron spin precession

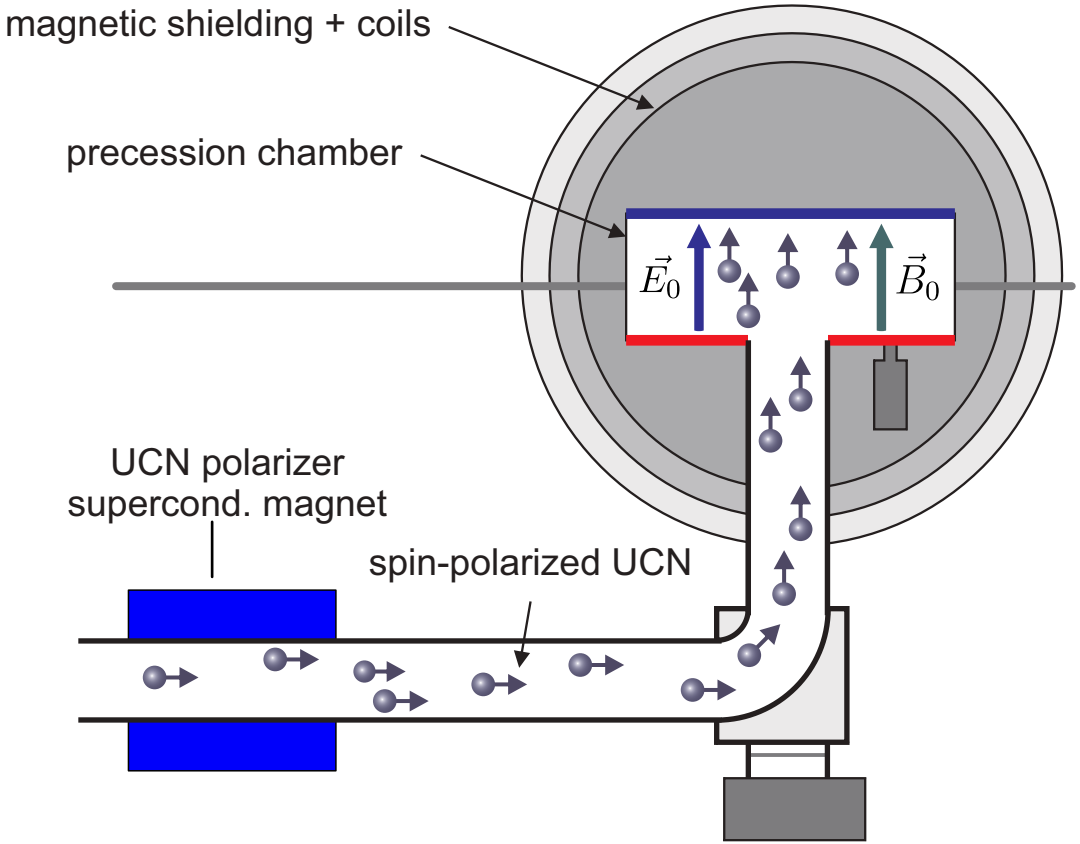
External Interaction Hamiltonian

$$H_{\text{ext}} = -2\,\mu_z\,B_0 \pm 2\,d_z\,E_0 = h\nu_L$$

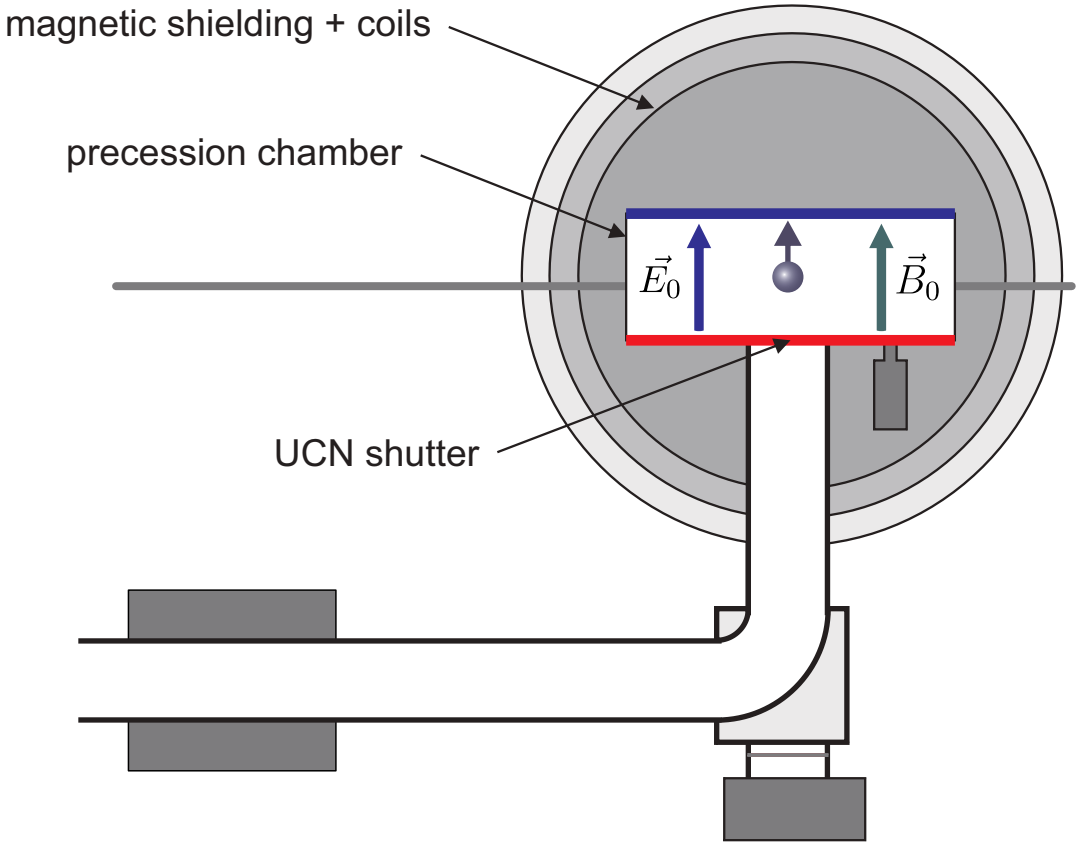




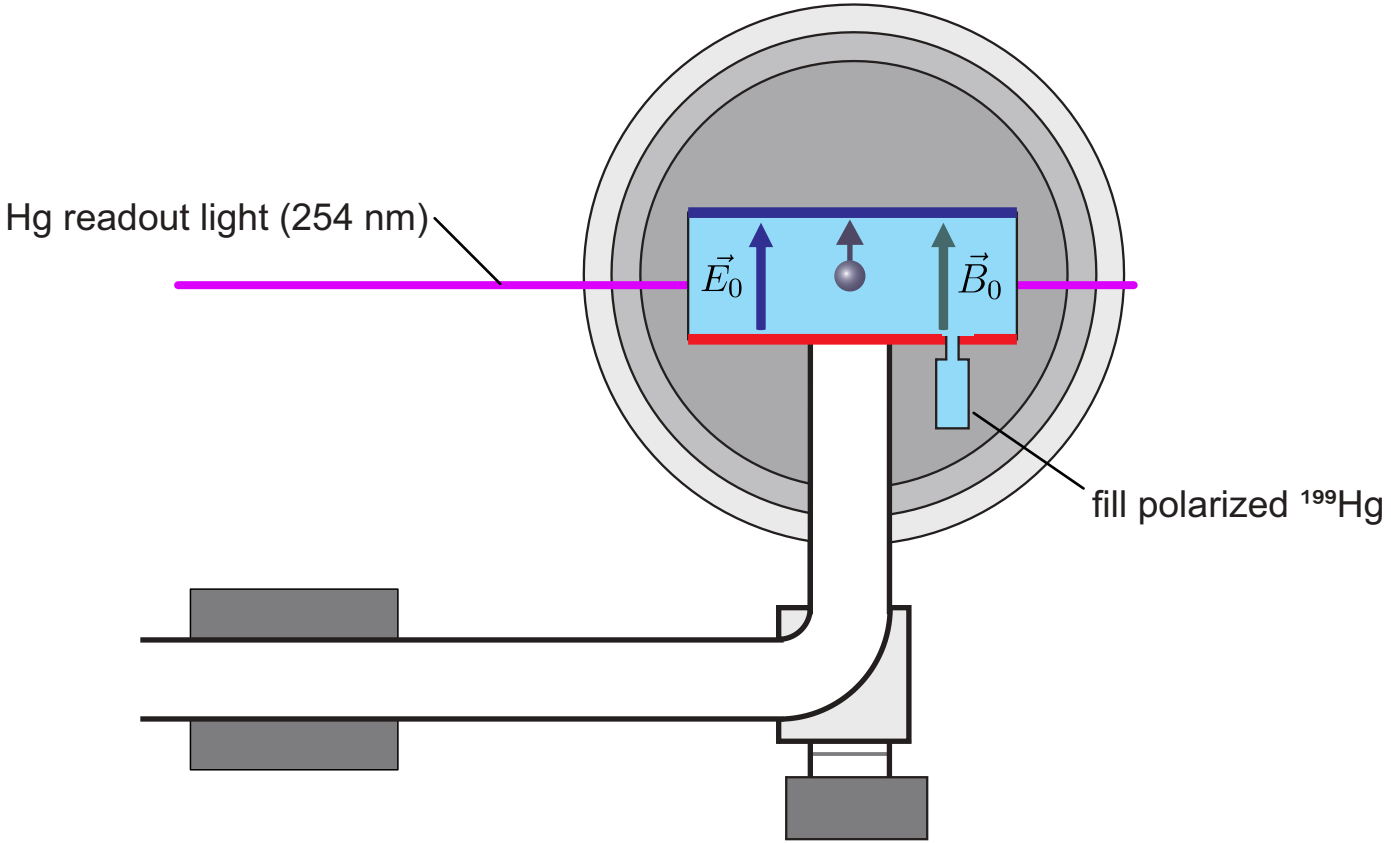
Filling the precession chamber



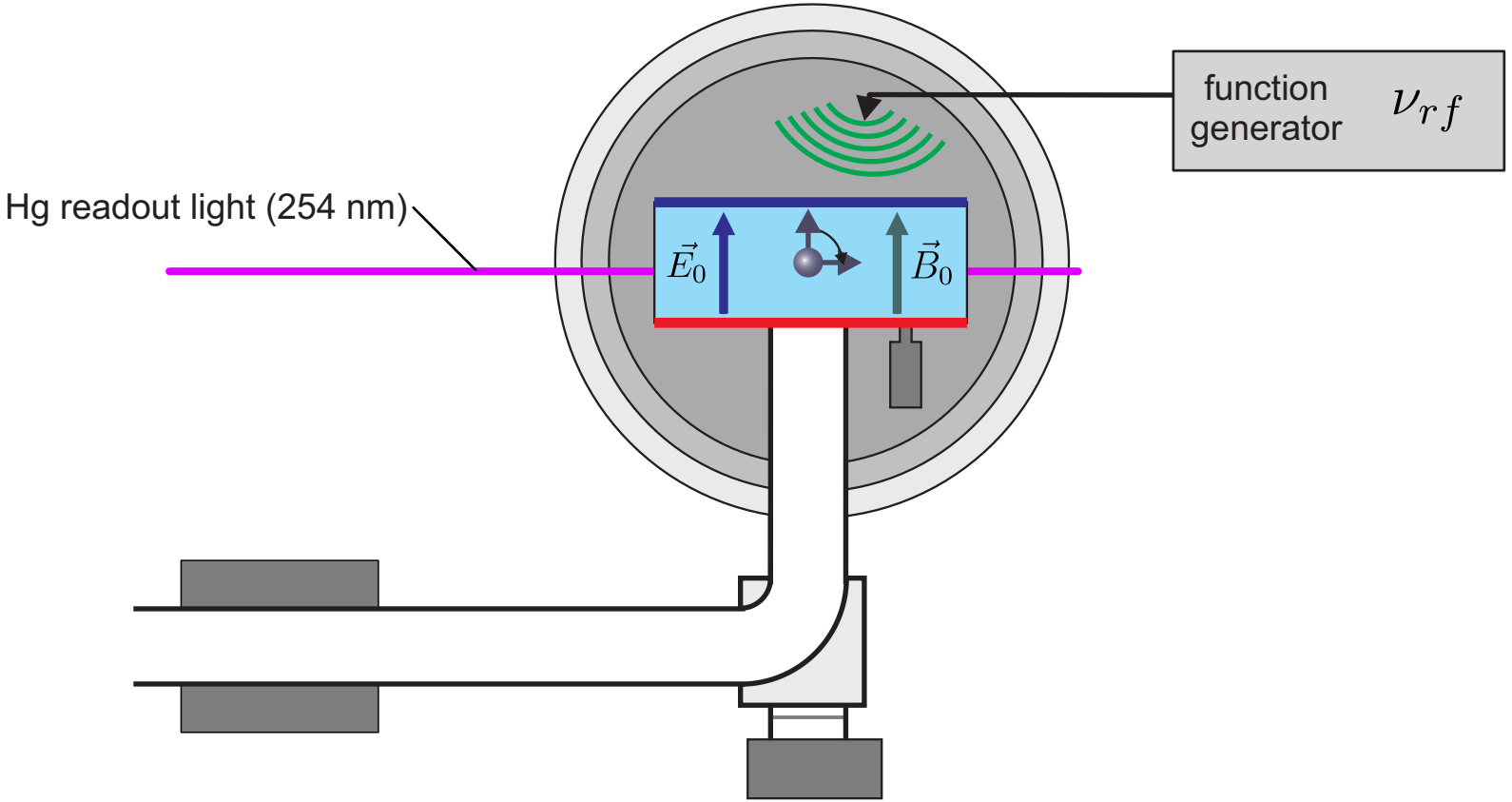
Filling the precession chamber



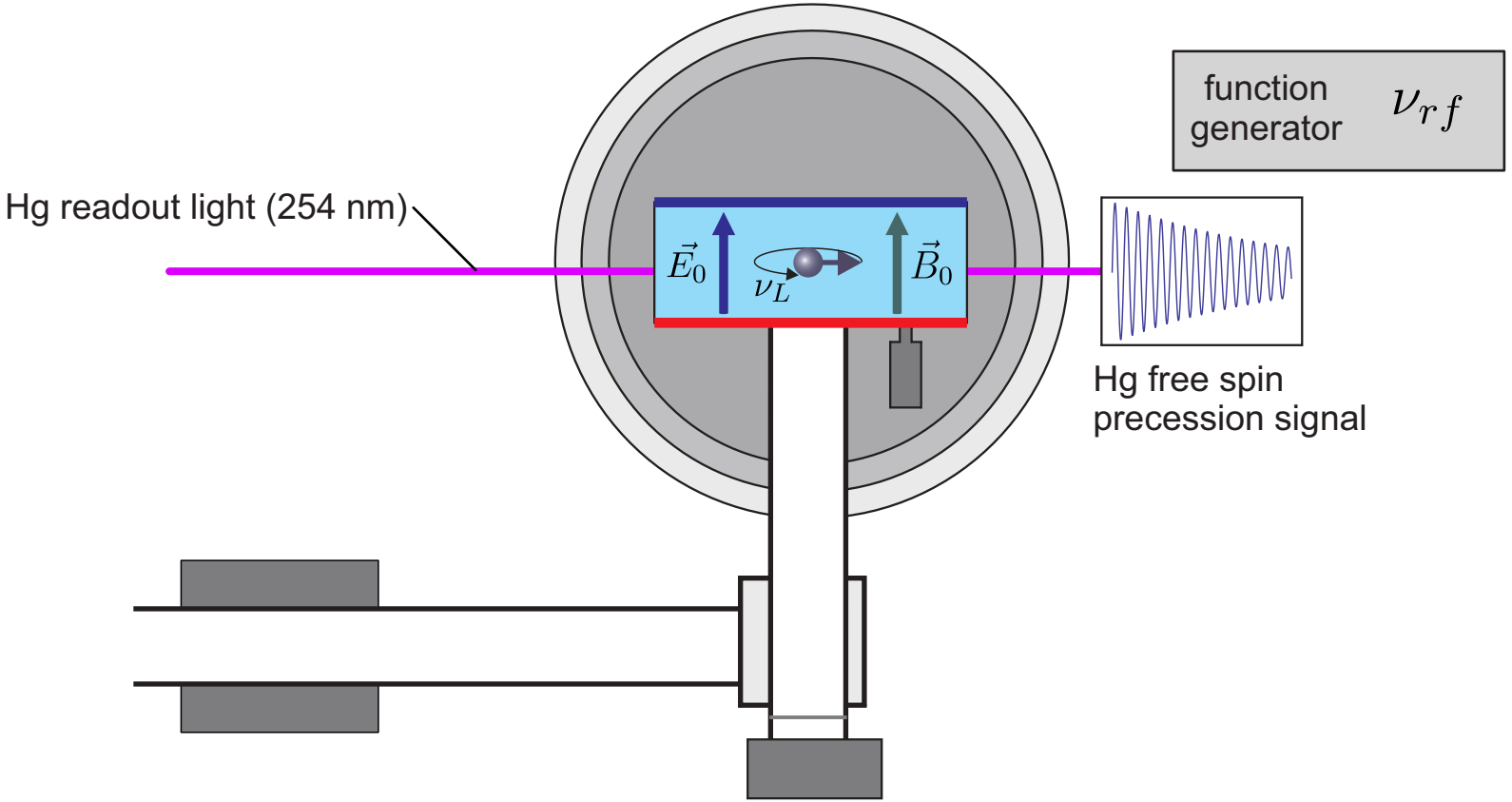
Filling the precession chamber



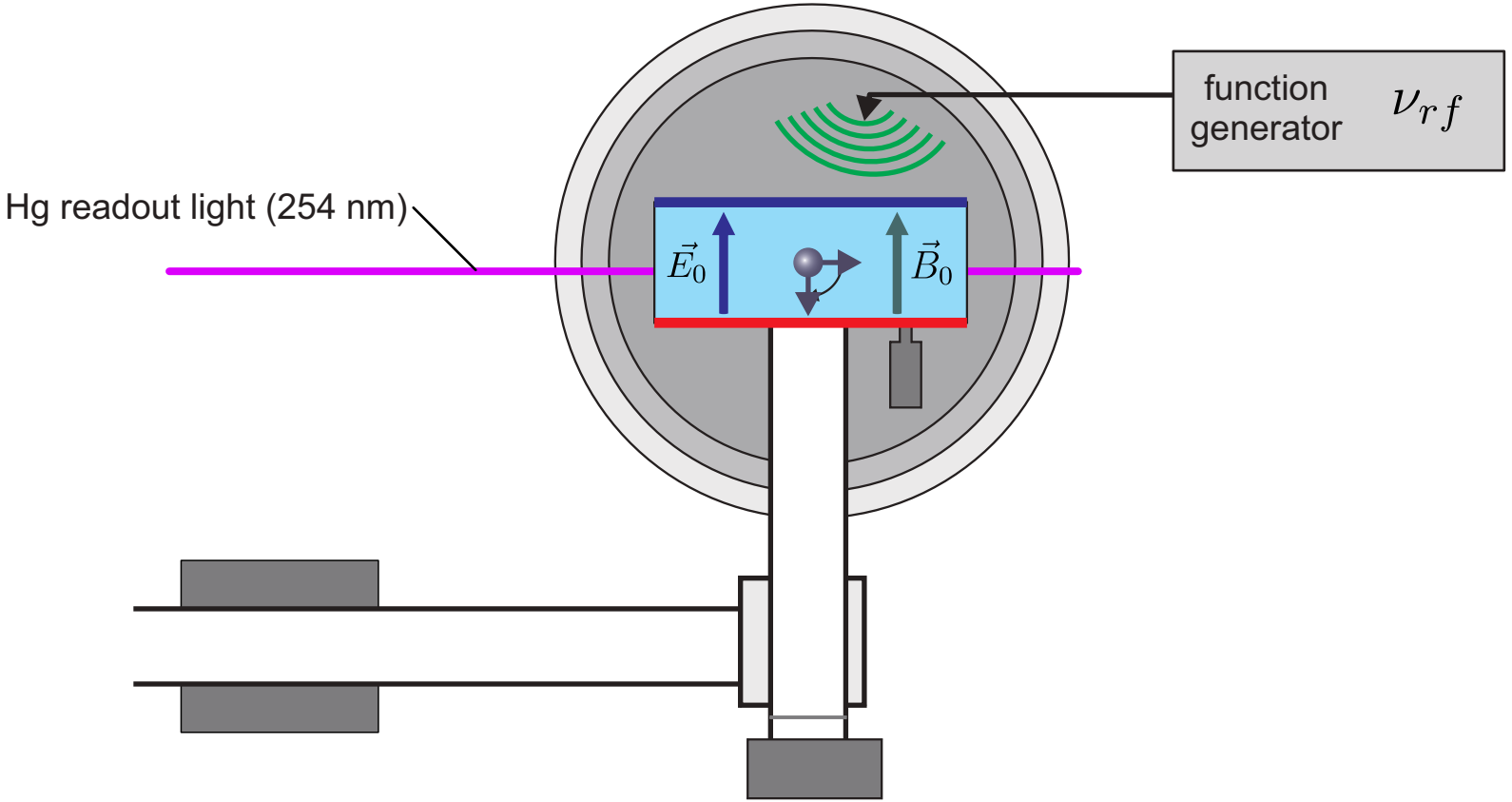
Ramsey cycle



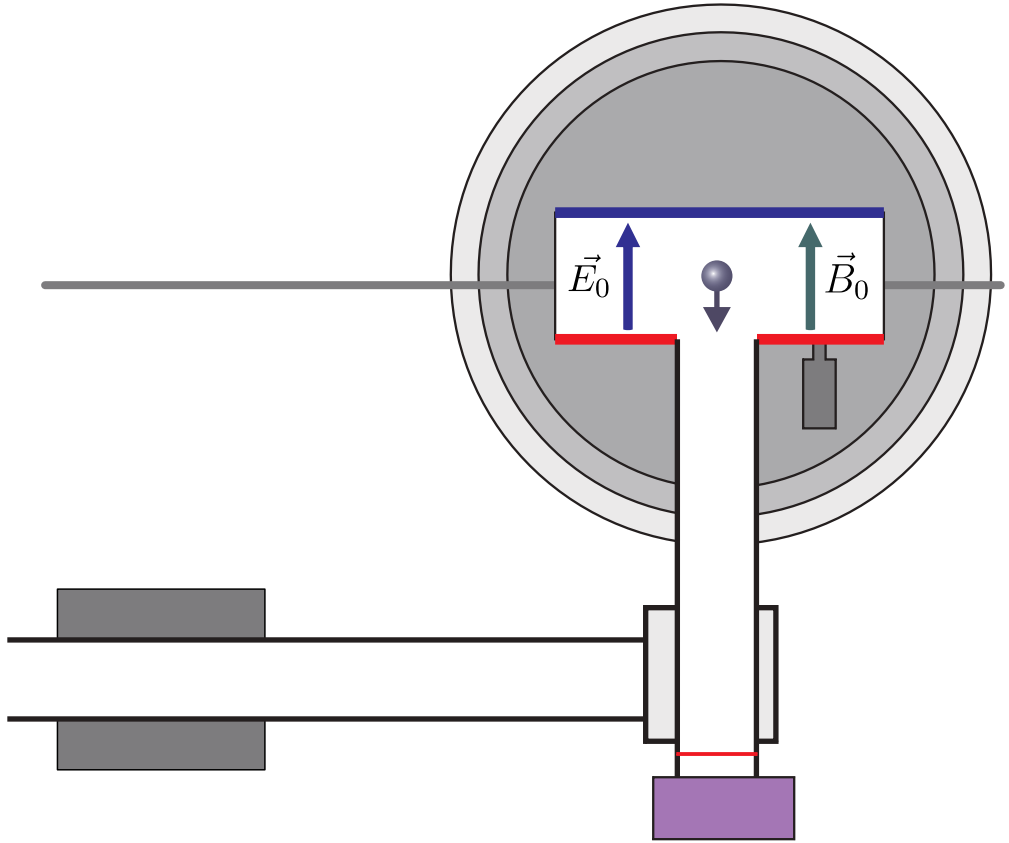
Ramsey cycle



Ramsey cycle

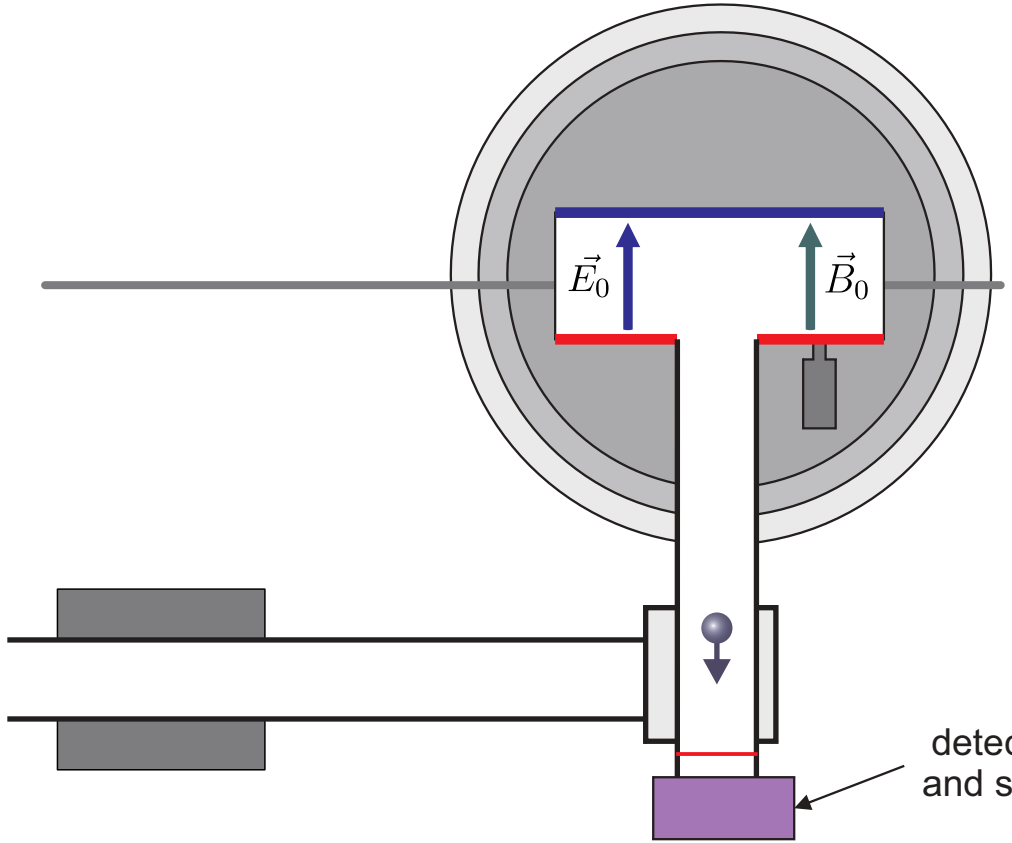


Emptying the precession chamber



function generator ν_{rf}

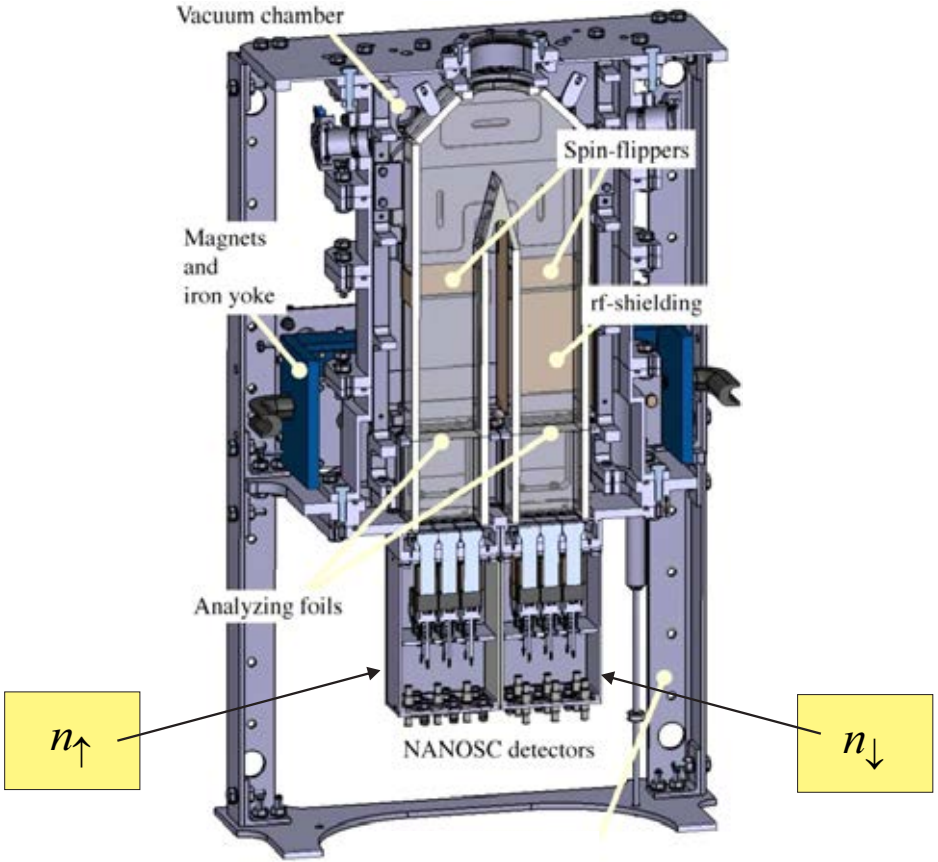
Emptying the precession chamber



function generator ν_{rf}

detector: count spin up and spin down neutrons

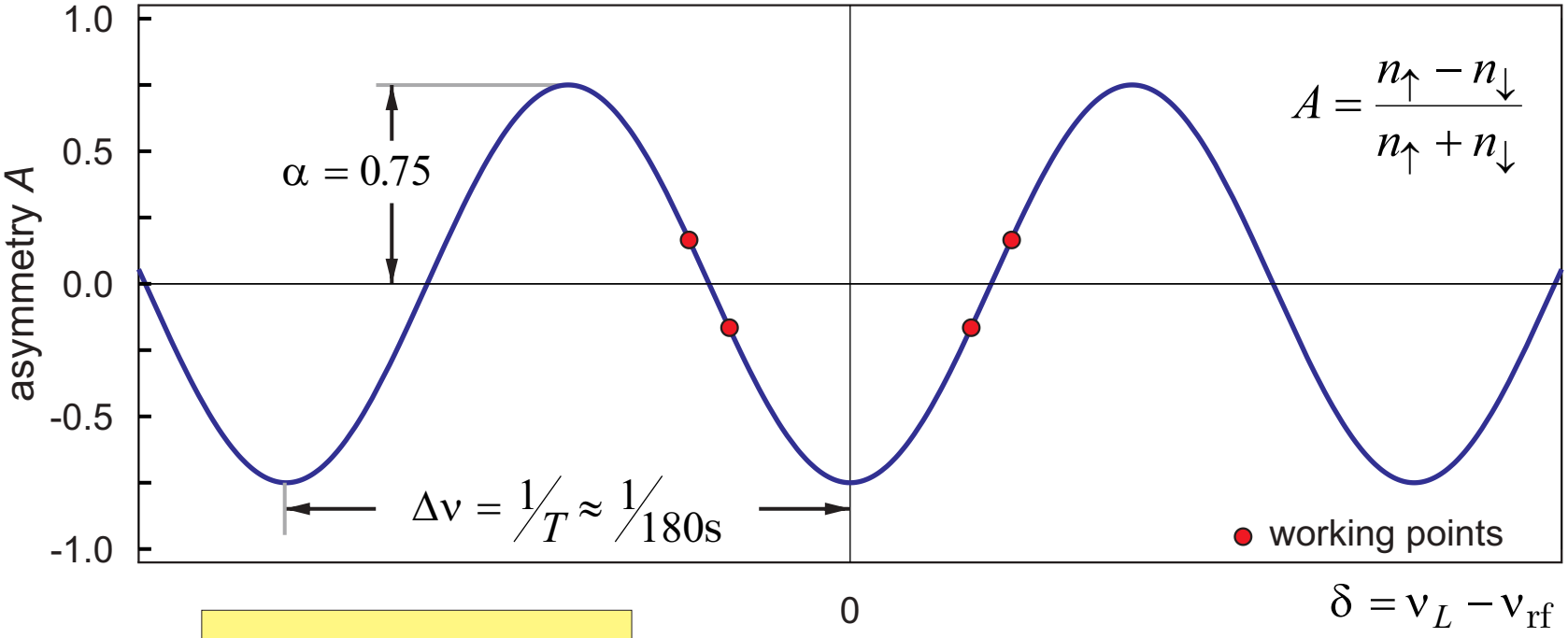
Neutron detection



A device for simultaneous spin analysis of ultracold neutrons. Afach, et al., Eur. Phys. J. A 51, 143 (2015).

Ultracold neutron detection with ^{6}Li-doped glass scintillators. Ban et al., Eur. Phys. J. A 52, 326 (2016).

Ramsey technique

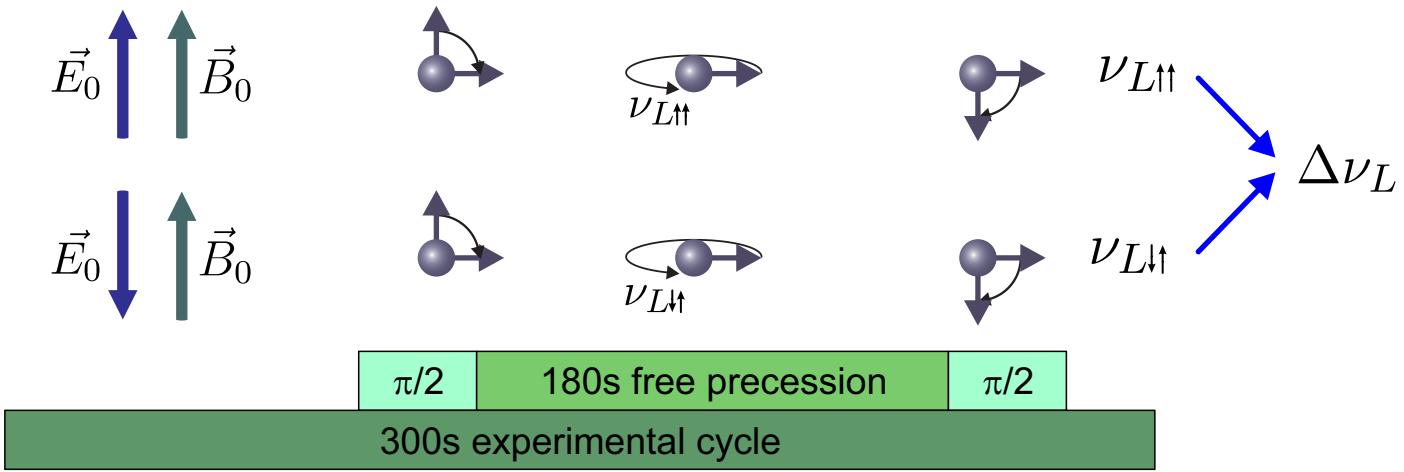


$$\sigma(d_n) = \frac{\hbar}{2E\alpha\, T\sqrt{N}}$$

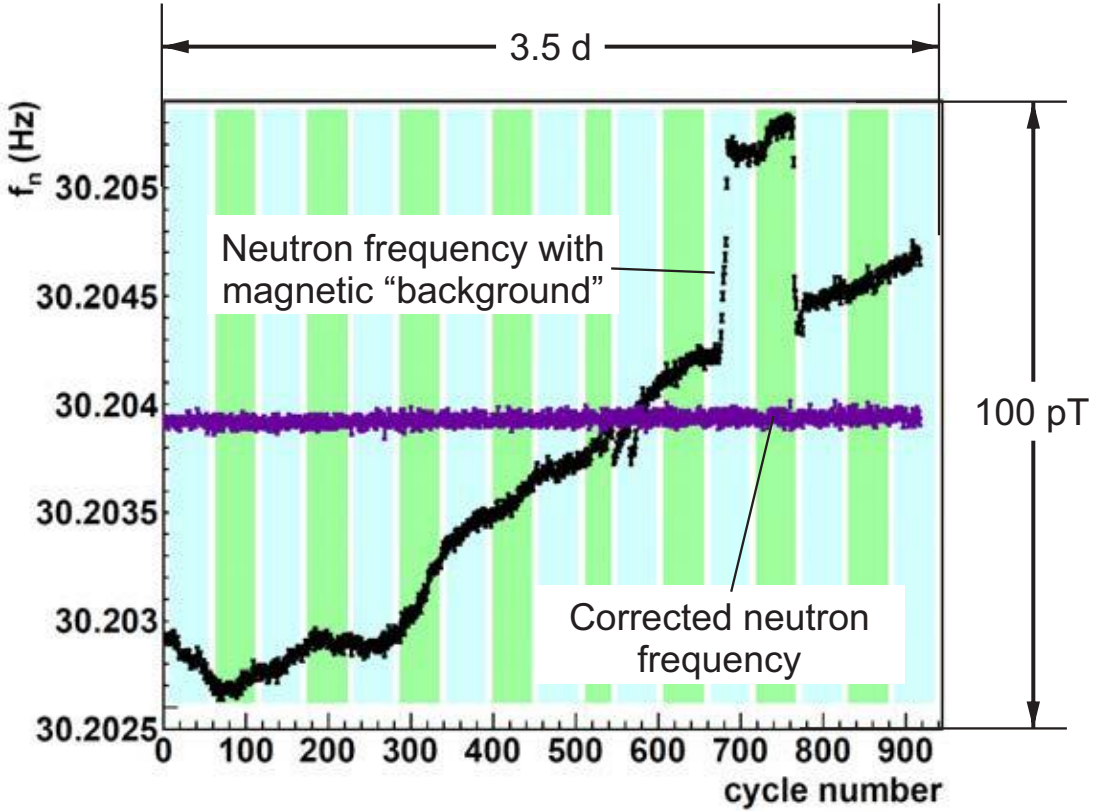
Ramsey technique

Neutron Larmor precession frequency

$$h\nu_L = -2\,\mu\,B_0 \pm 2\,d\,E_0$$



Magnetic field correction



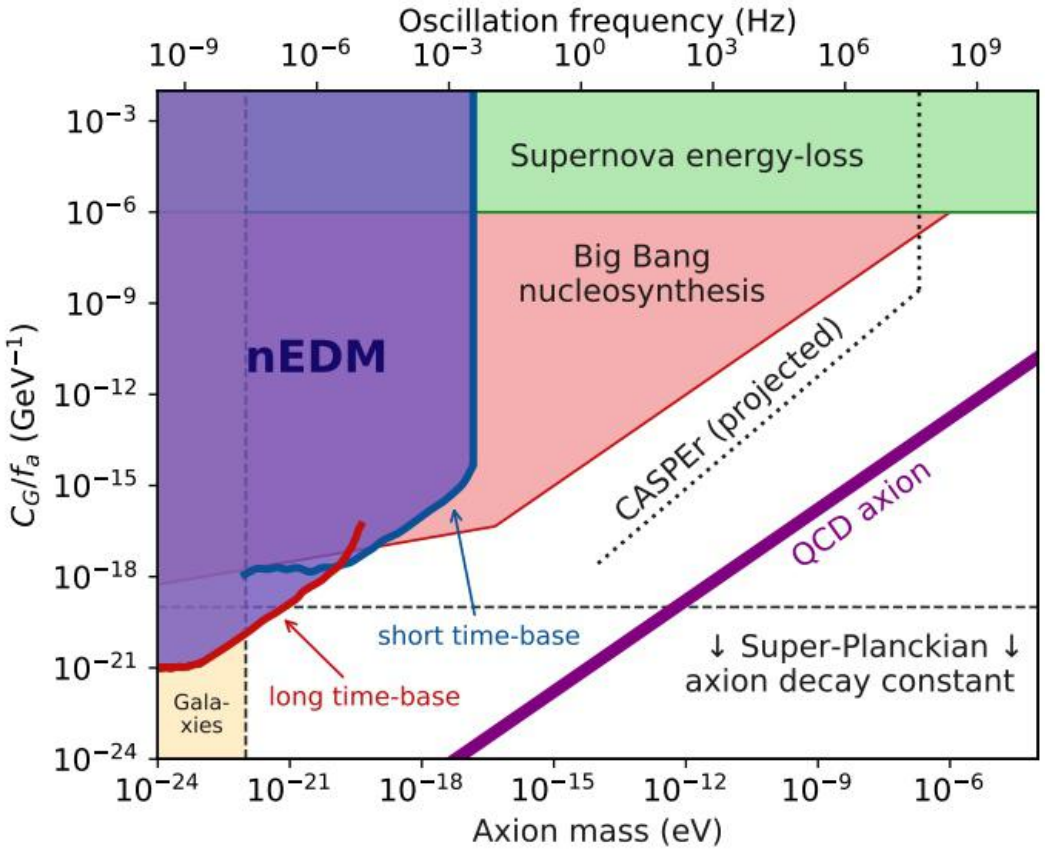
$$\Delta\nu_L = \frac{4\,d\,E_0}{h} + \frac{2\,\mu\,\Delta B}{h}$$

We use sensitive magnetometers to correct for this B-field dependence.

In total we recorded >50000 cycles in two years

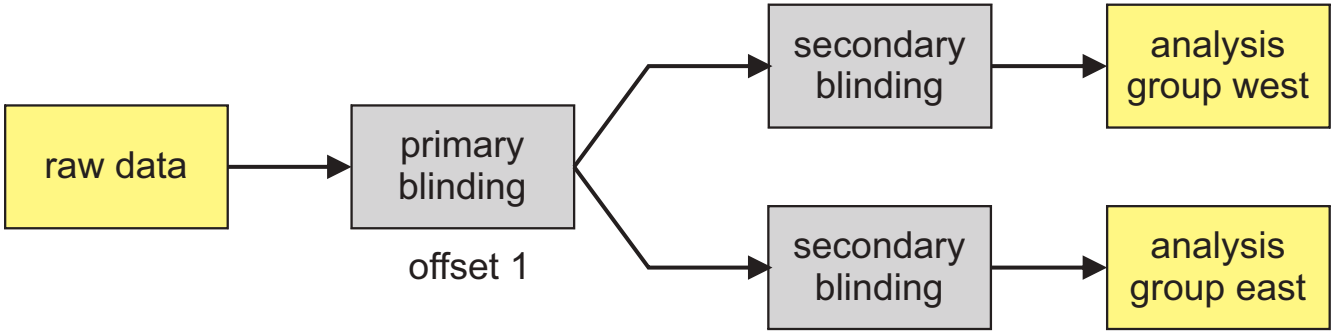
- Introduction & old neutron EDM experiment @ PSI
- **Results**
- New experiment n2EDM

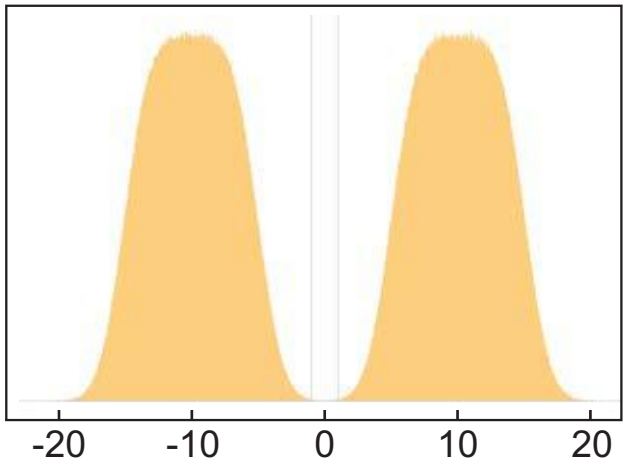
Our limit on the axion-gluon coupling



Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields, Abel et al. Phys Rev X **7**, 041034 (2017).

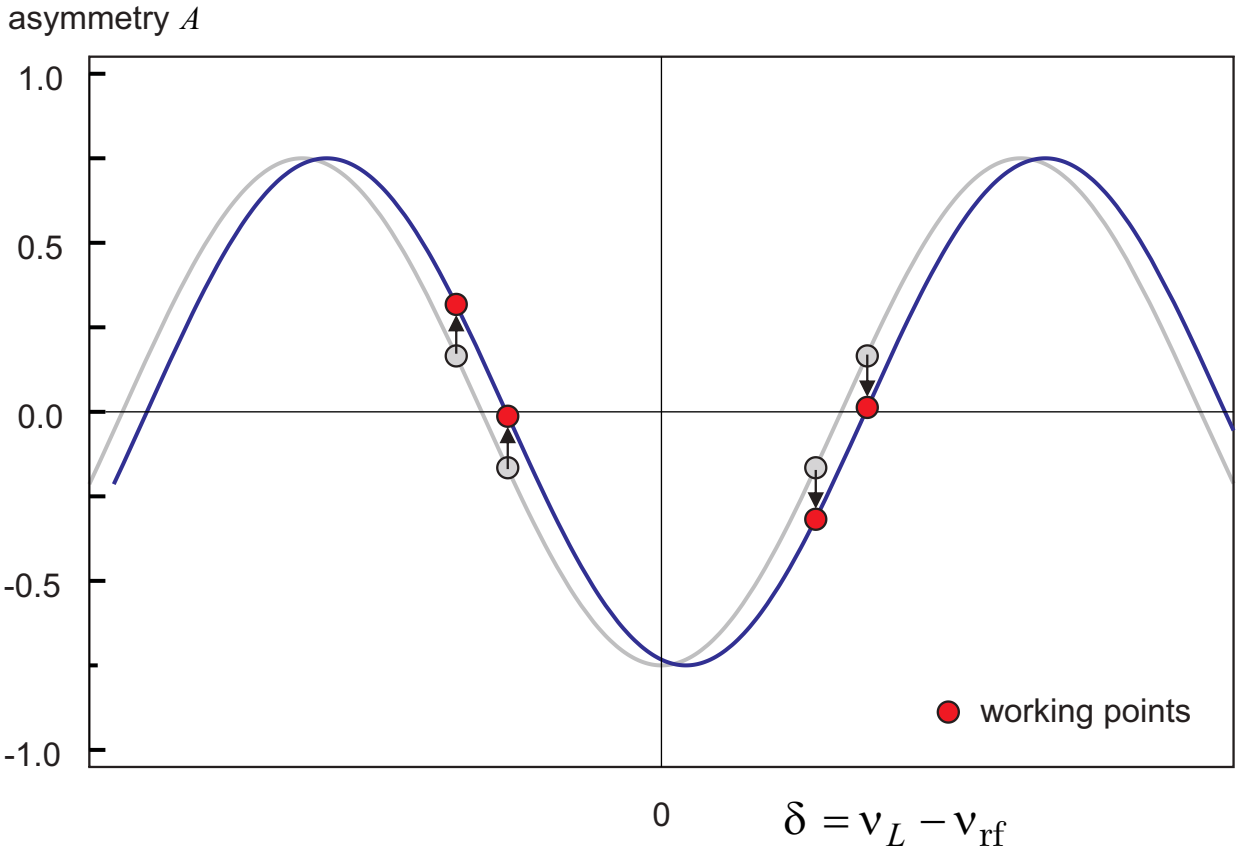
Blinding





Data blinding for the nEDM experiment at PSI. Ayres et al., Eur. Phys. J. A 57, 152 (2021).

Blinding


asymmetry A
1.0
0.5
0.0
-0.5
-1.0
0
working points
$\delta = \nu_L - \nu_{\mathrm{rf}}$

nEDM error budget

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

10^{-28} $e$cm

Systematic uncertainty five times smaller than before.

Measurement of the Permanent Electric Dipole Moment of the Neutron. Abel et al., Phys. Rev. Lett. 124, 081803

nEDM result

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}\, e\cdot cm$$

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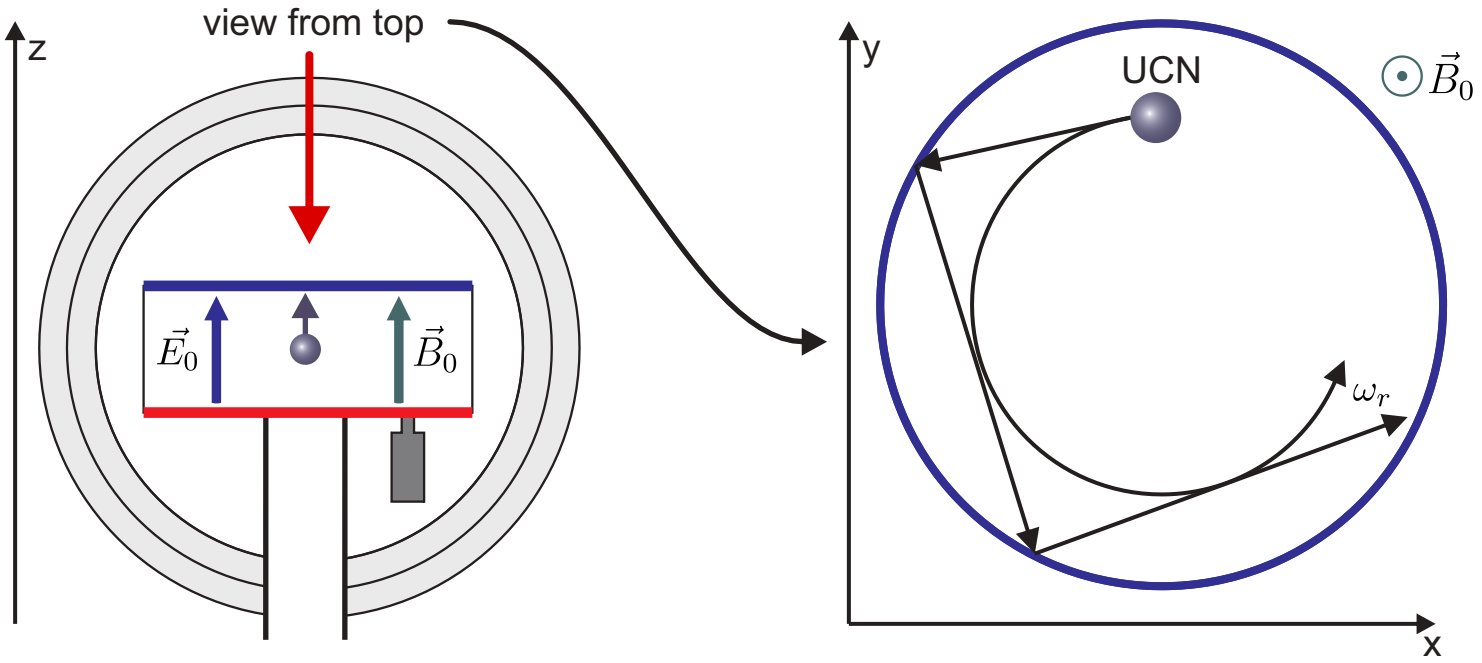
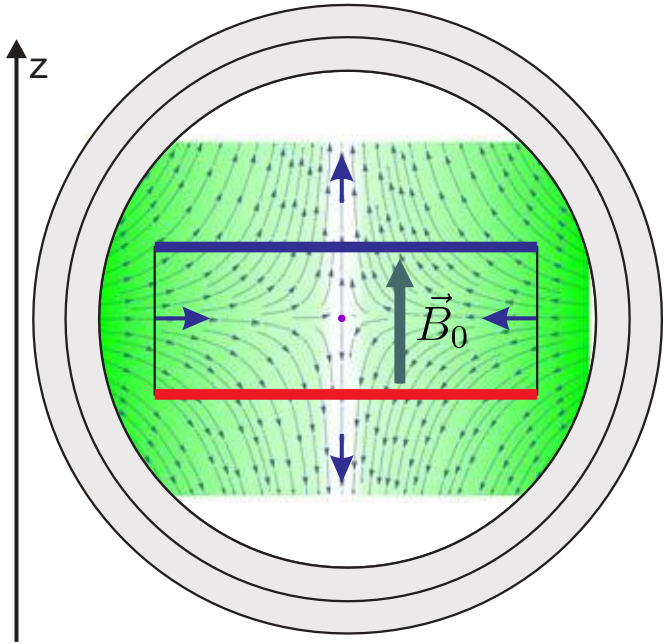
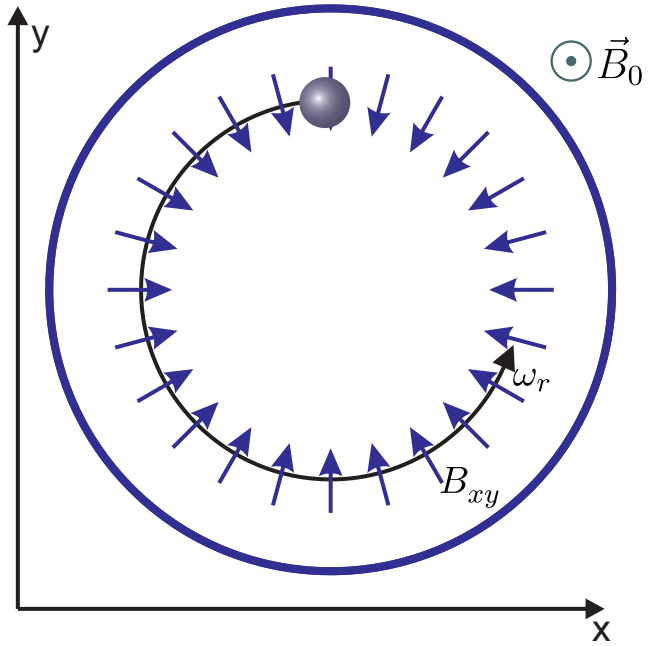
Ramsey-Bloch-Siegert shift



RBS shift due to magnetic gradients

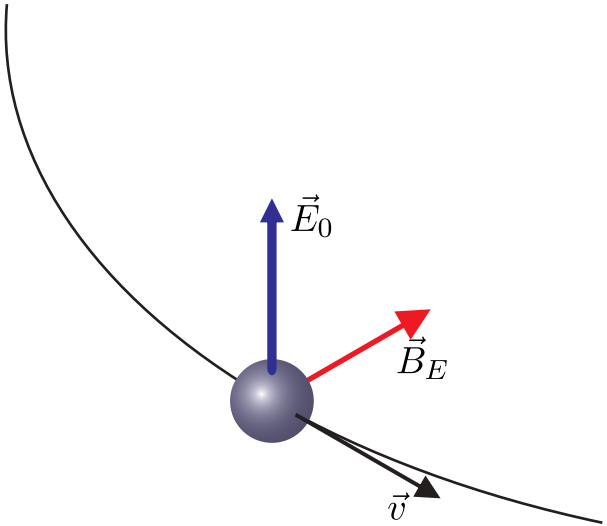


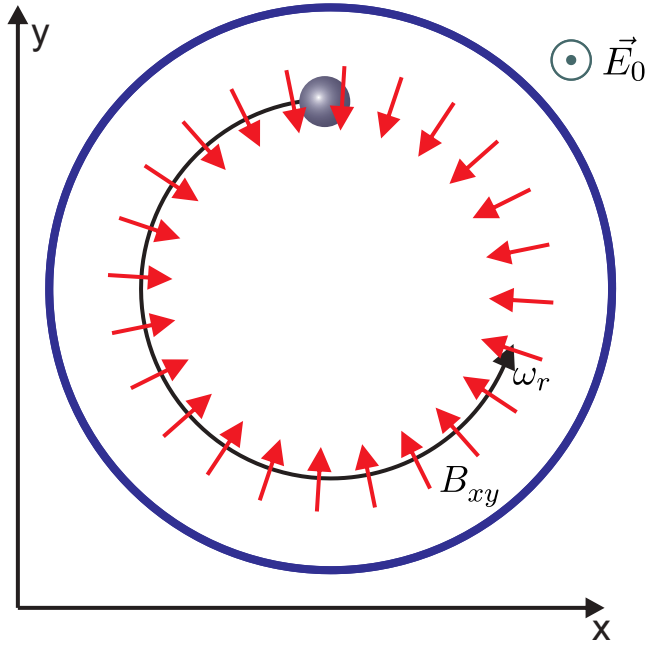


$$\vec{B}_G = \frac{\partial B_z}{\partial z}\frac{\vec{r}}{2}$$

$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

RBS shift due to motional magnetic fields

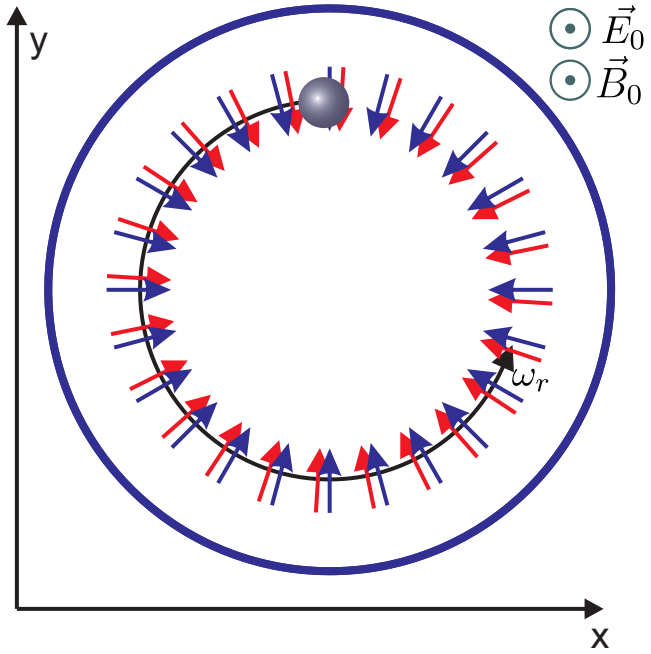




$$\vec{B}_E = \frac{\vec{E}_0 \times \vec{v}}{c^2}$$

$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

False EDM effect



$$\vec{B}_G + \vec{B}_E$$

$$\Delta\omega = \frac{\gamma^2 B_{xy}^2}{2(\omega_L \pm \omega_r)}$$

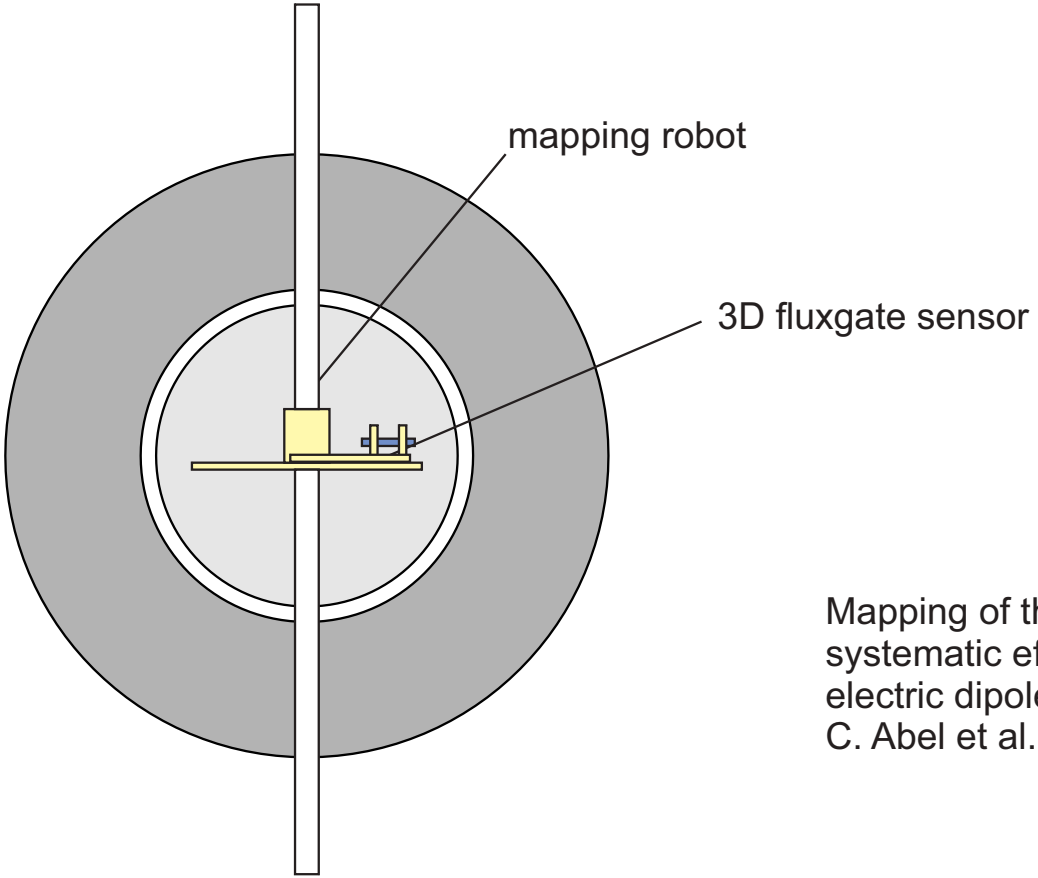
$$= \Delta\omega_{EE} + \Delta\omega_{GG} + \Delta\omega_{EG}$$

EDM-like signal: proportional to the E-field and the B-field gradient

$$d_{\text{false}} = \frac{\hbar\,\gamma_{Hg}\,\gamma_n}{2c^2}\,\langle xB_x + yB_y\rangle$$

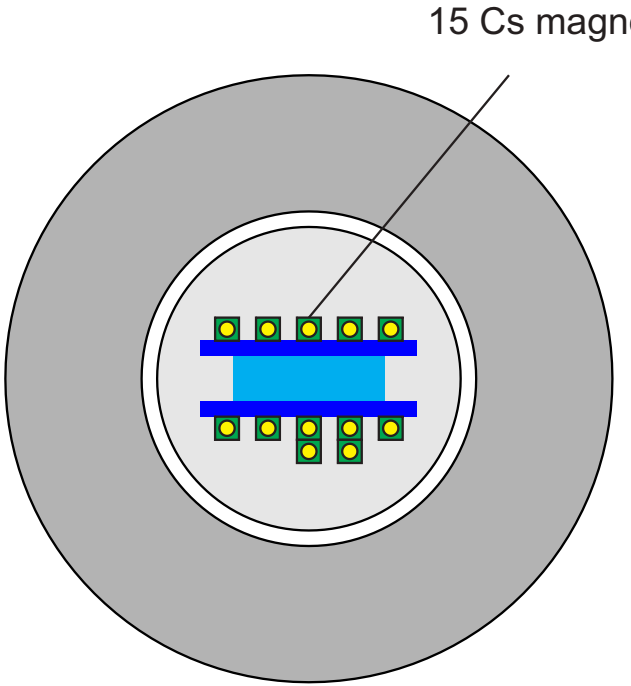
Pignol & Roccia, Phys. Rev. A 85, 042105 (2012)

Offline field mapping



Mapping of the magnetic field to correct systematic effects in a neutron electric dipole moment experiment.
C. Abel et al., PRA **106** 032808 (2022).

Online gradient measurements



Optically pumped Cs magnetometers enabling a high-sensitivity search for the neutron electric dipole moment, C. Abel et al. PRA 101, 053419 (2020)

- Introduction & old neutron EDM experiment @ PSI
- Results
- **New experiment n2EDM**

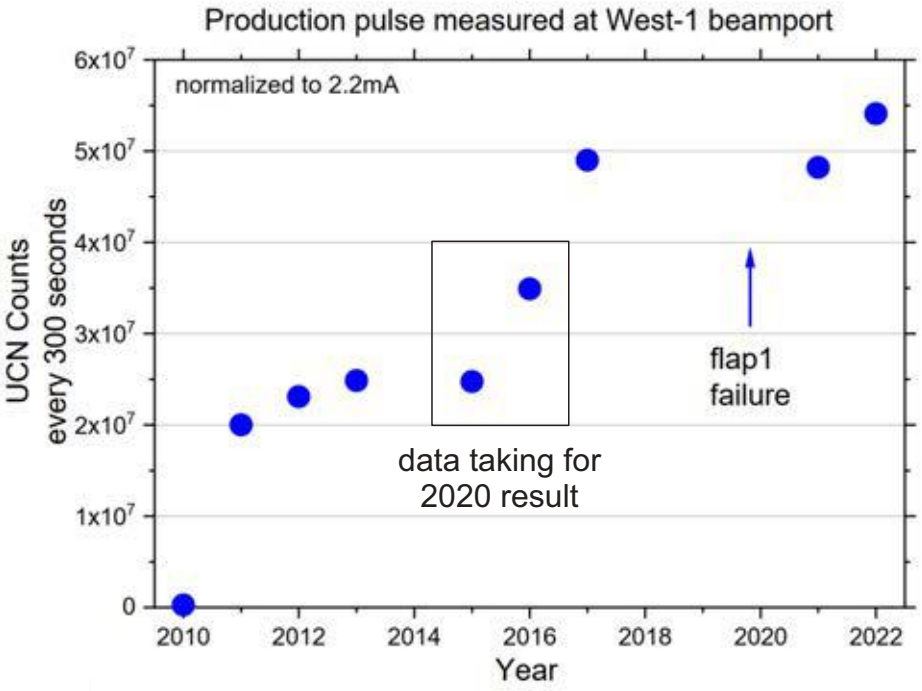
nEDM result

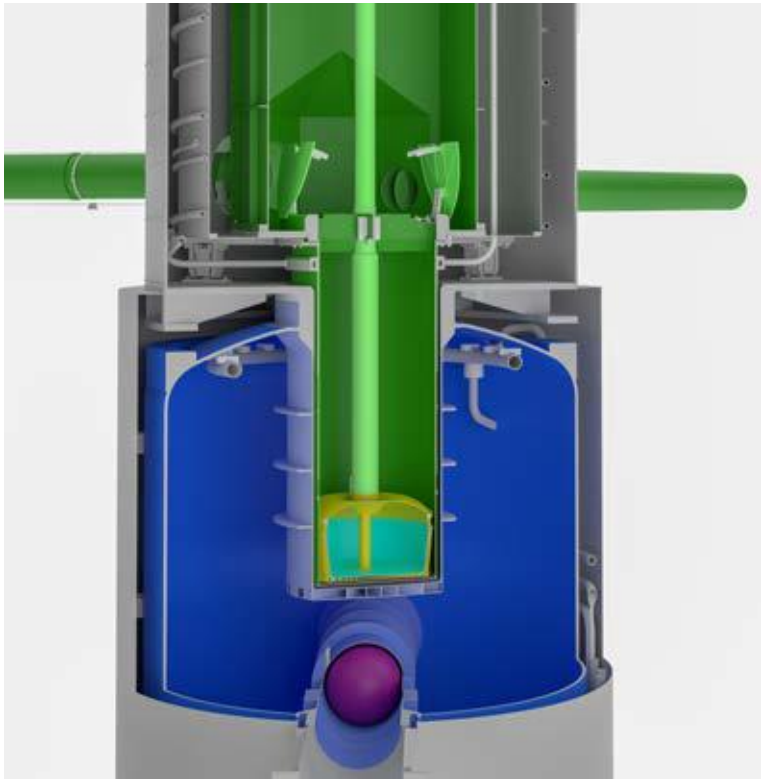
$$d_{\mathrm{n}} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\, e{\cdot}\mathrm{cm}$$

improve UCN statistics

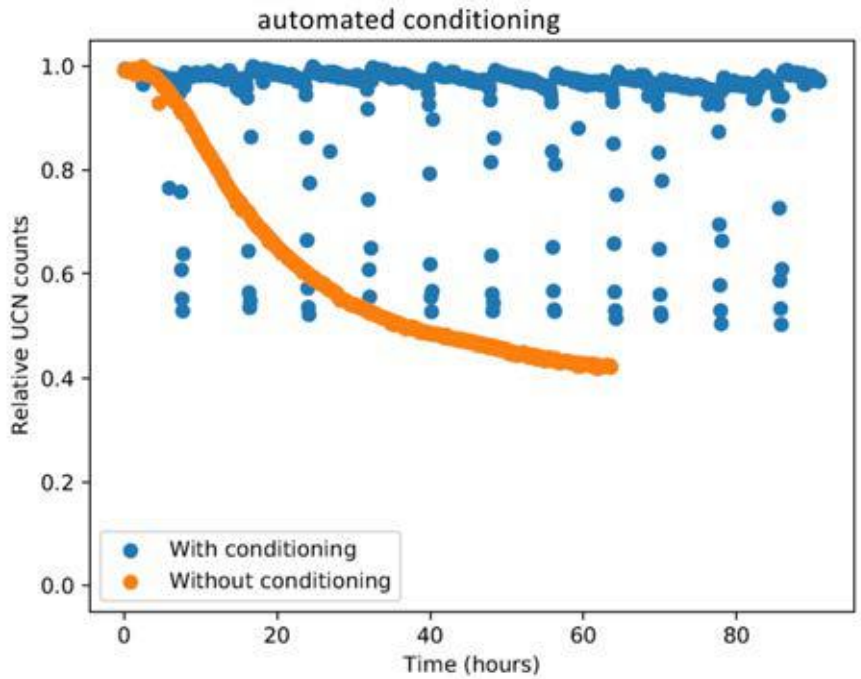
improve magnetic field

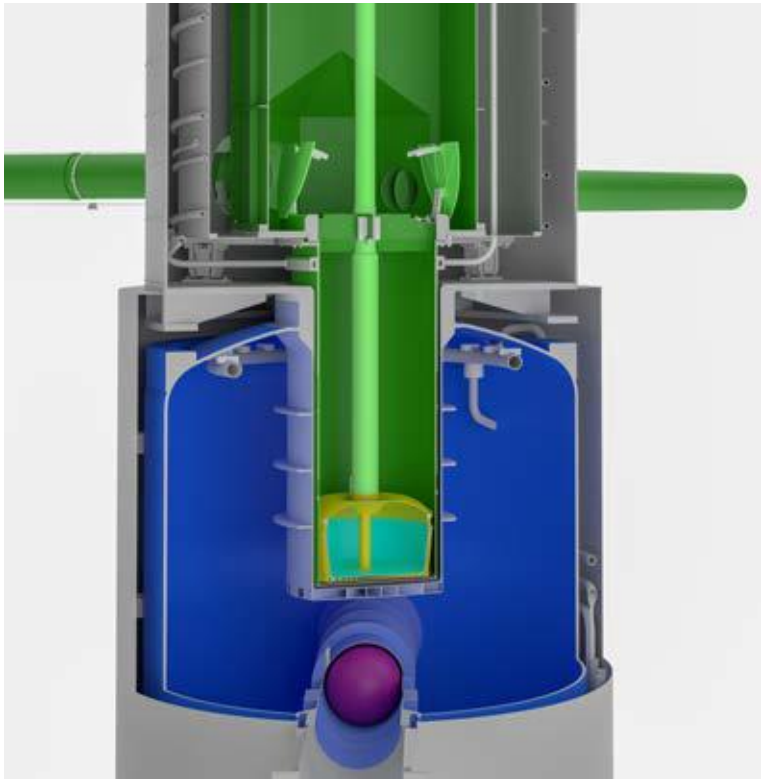
UCN source performance



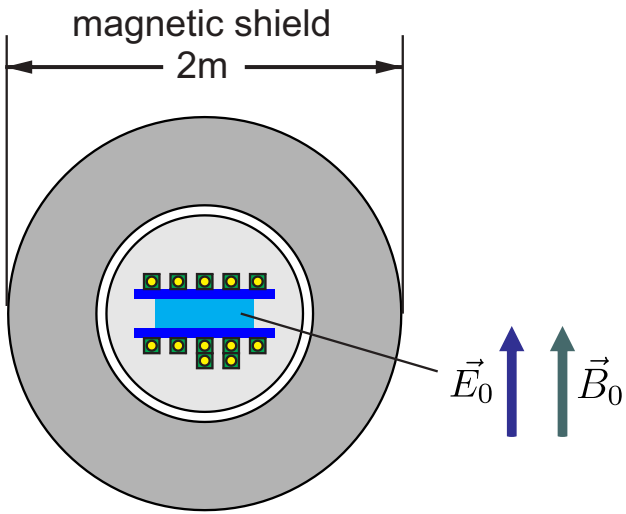


UCN source performance

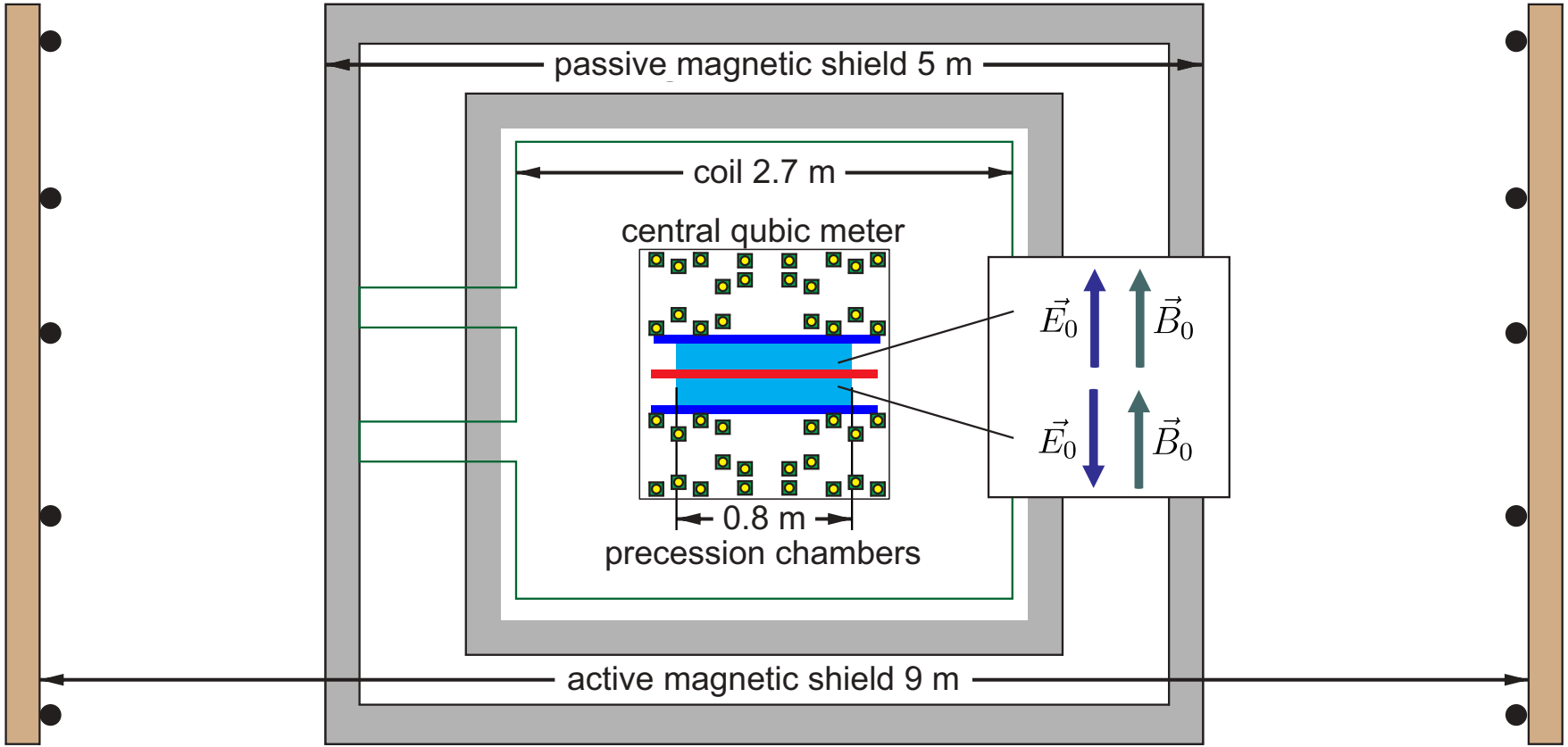




Former nEDM experiment



New n2EDM experiment



Magnetic setup

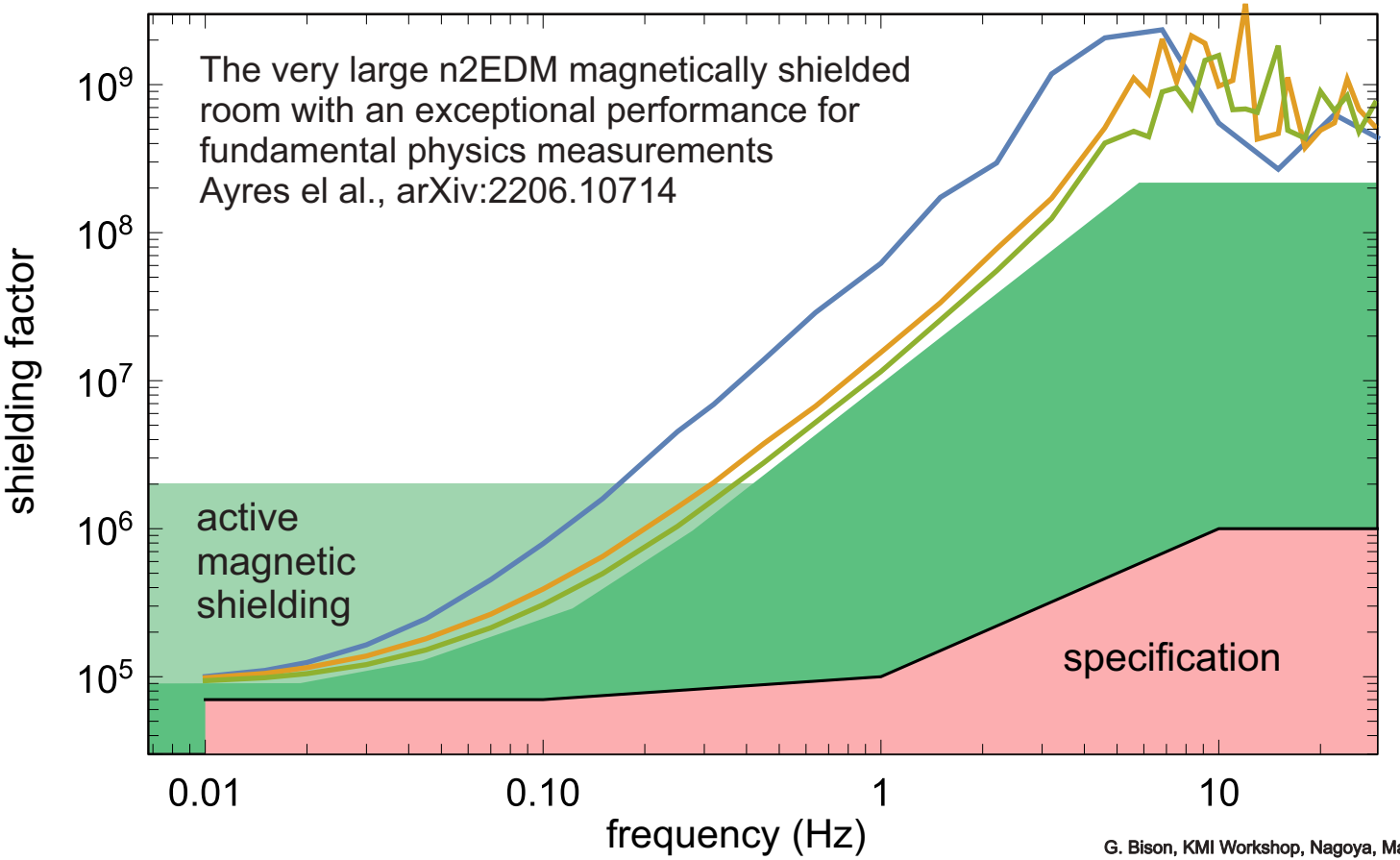
air-conditioned wooden house

active magnetic shield
55 km of cables
8 coils

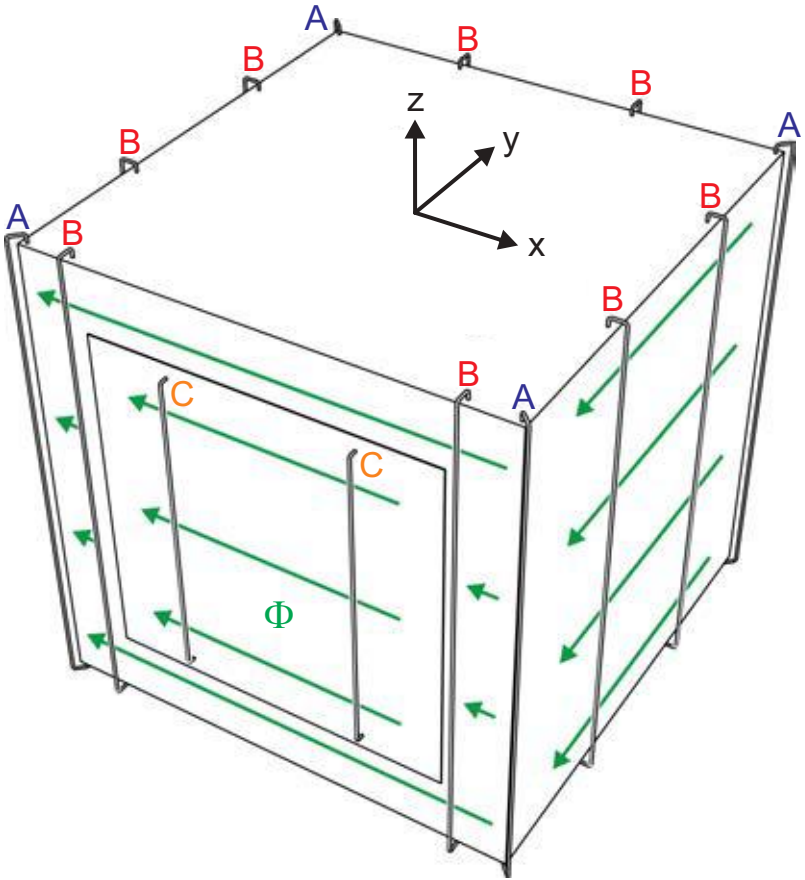
● eight 3-axis fluxgates provide the reference for the active field control

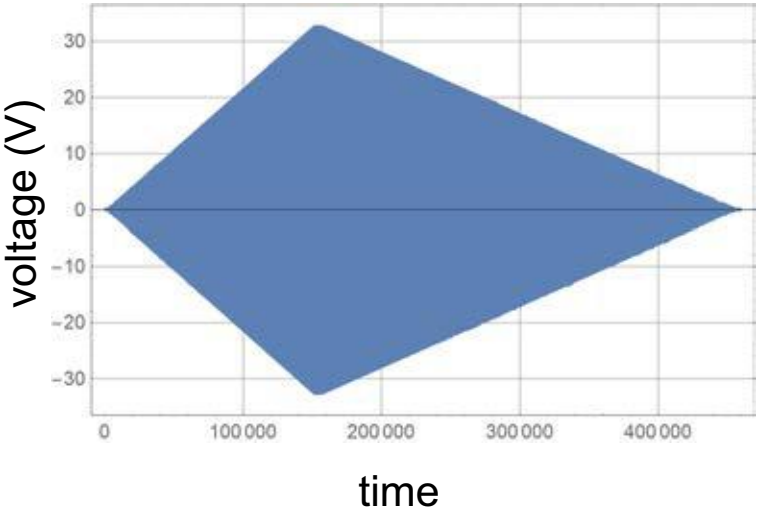
passive magnetic shield
six layers of Mumetal (25 tons)
one layer of Al (eddy-current shield)

Measurement of the shielding factor

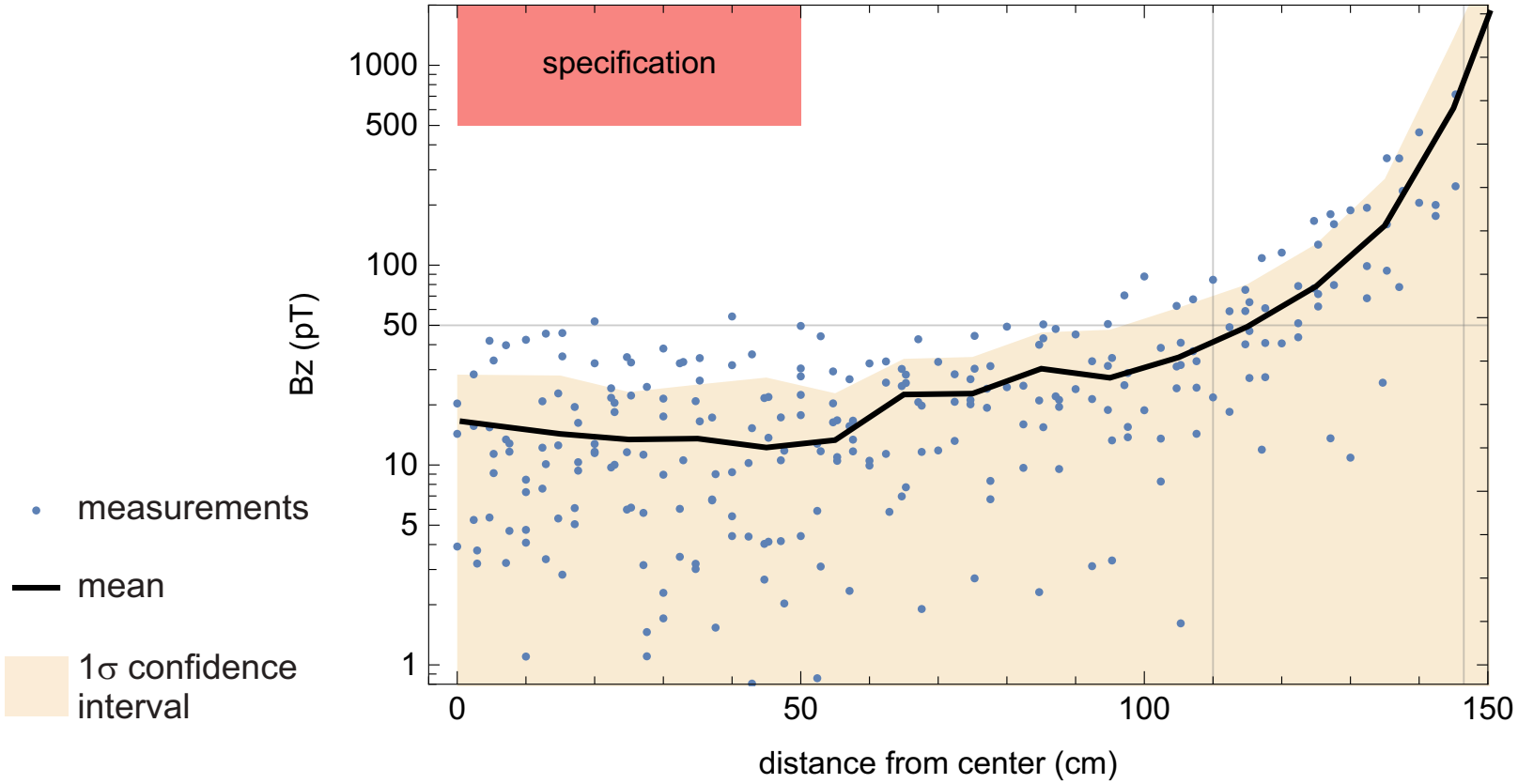


Degaussing


A
B
B
B
B
A
A
B
B
B
B
A
B
z
y
x
C
C
Φ


voltage (V)
30
20
10
0
−10
−20
−30
0
100 000
200 000
300 000
400 000
time

All Bz measurements combined



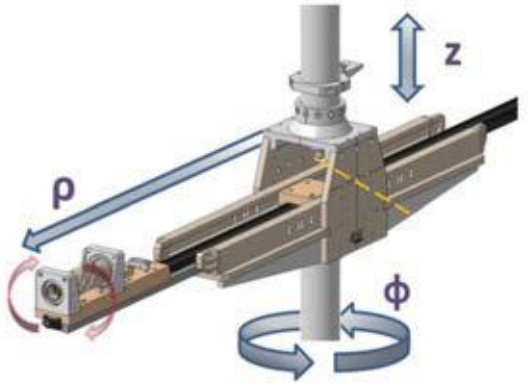
Magnetic field mapper inside the MSR

Windings of the main coil (produces the 1μT B0 field)

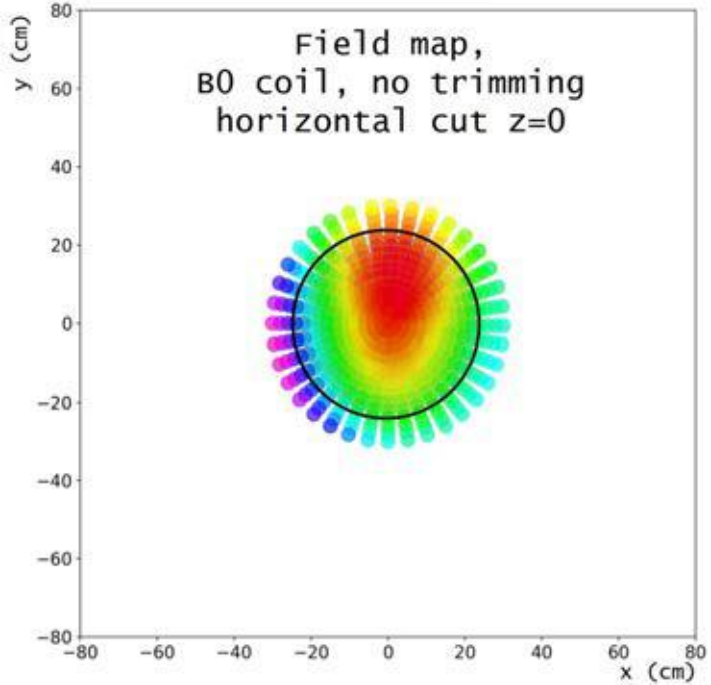
Vacuum tank (VT)

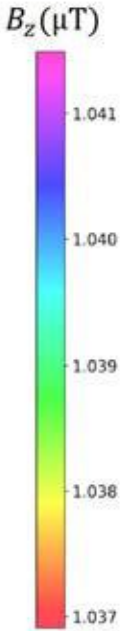
● temperature sensors on the VT

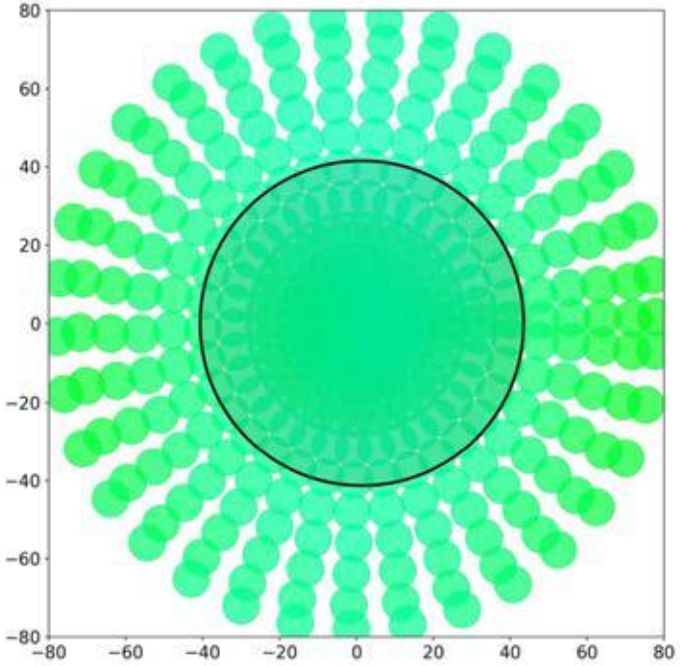
Magnetic field mapper



Mapper results without trim-coils



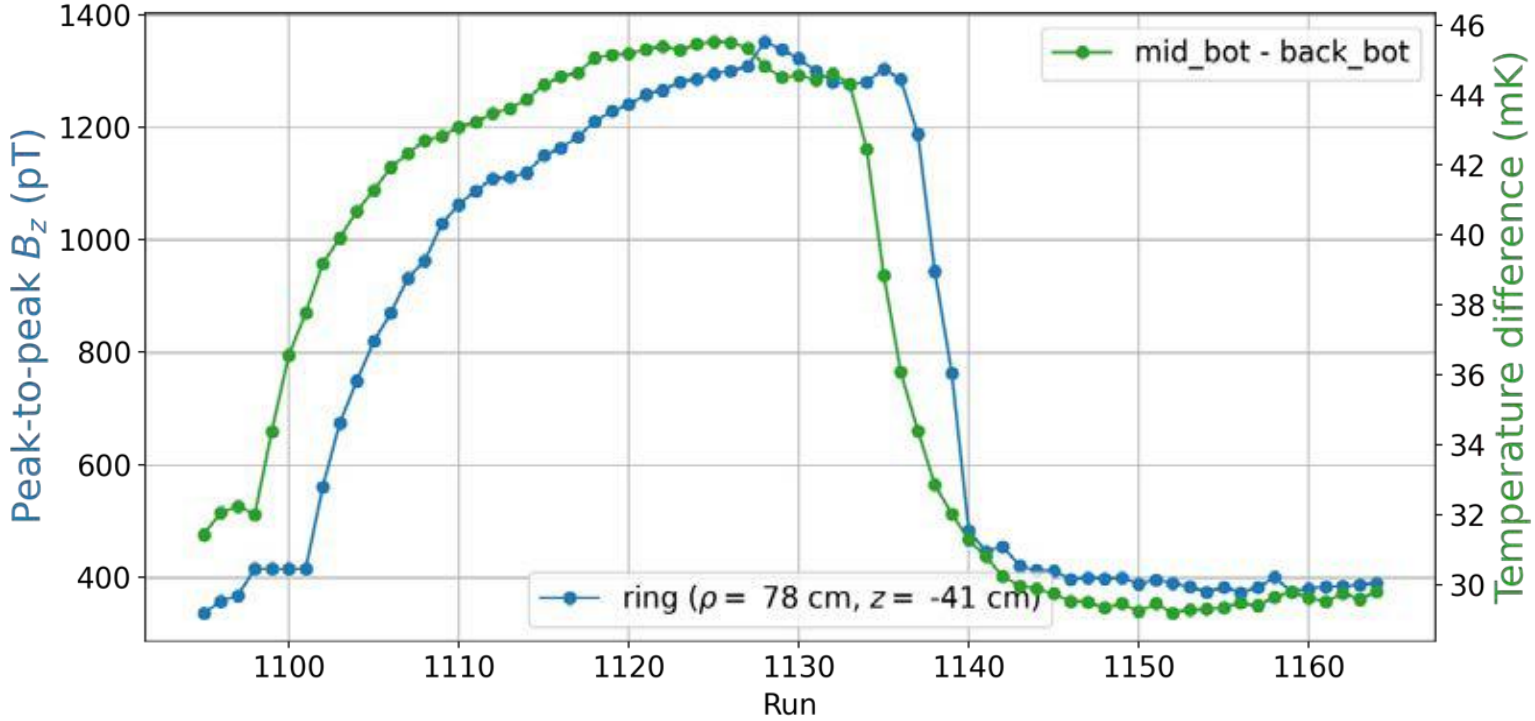




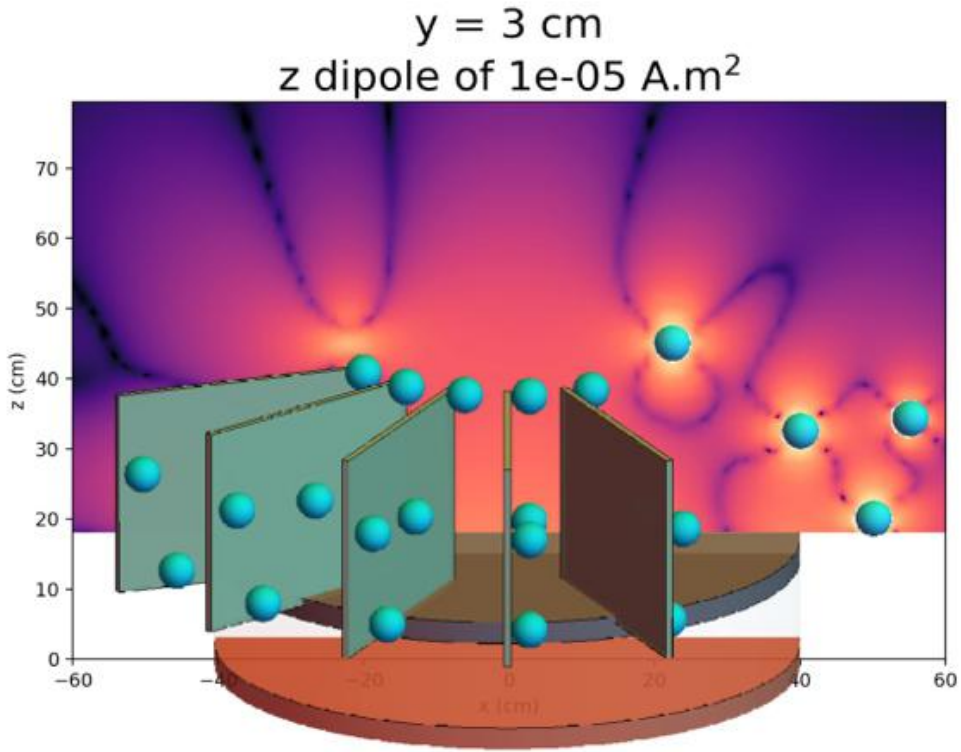
old experiment
ΔB = 860 ppm over 46 cm

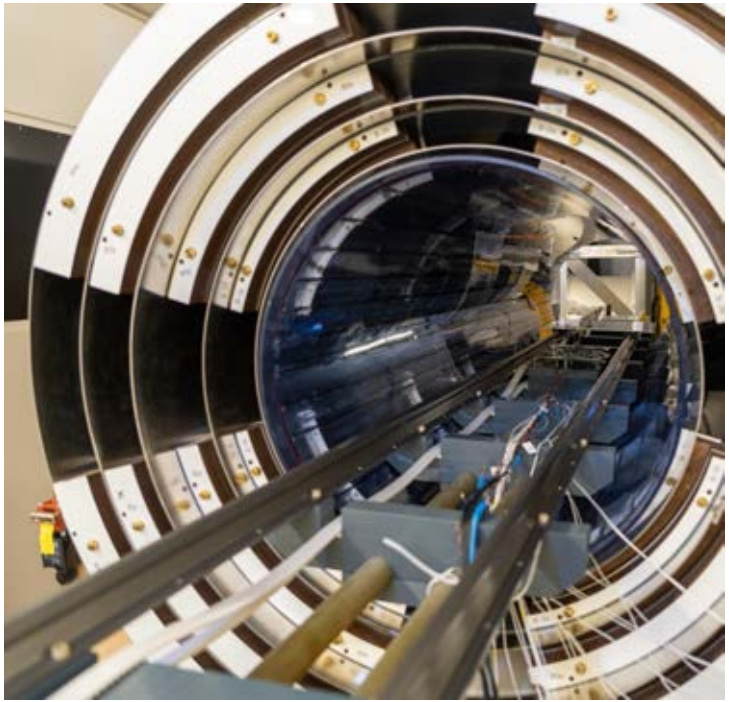
n2EDM
ΔB = 60 ppm over 80 cm

Thermo-magnetic effect

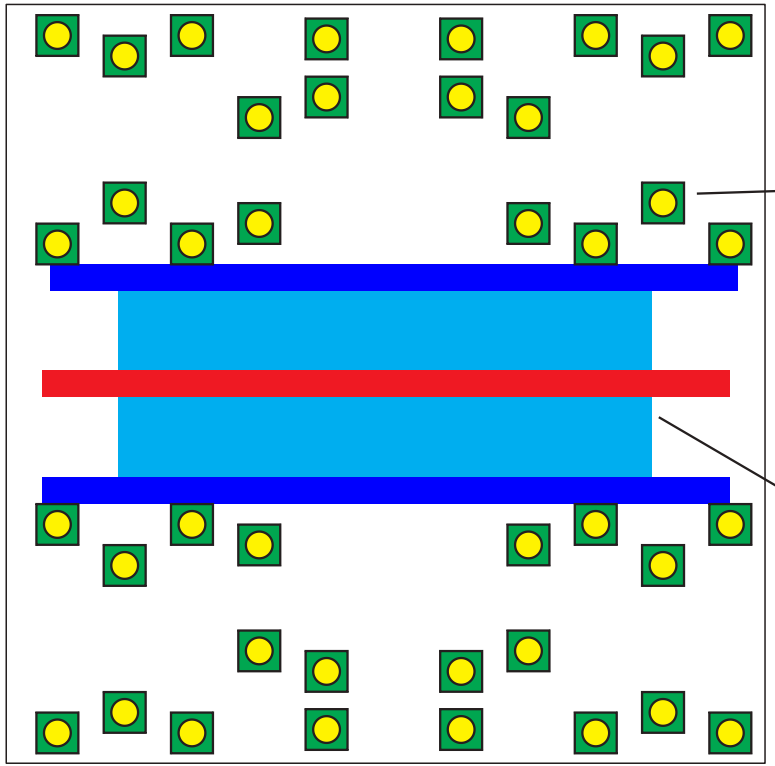


Magnetic dipole contamination





Magnetometry concept



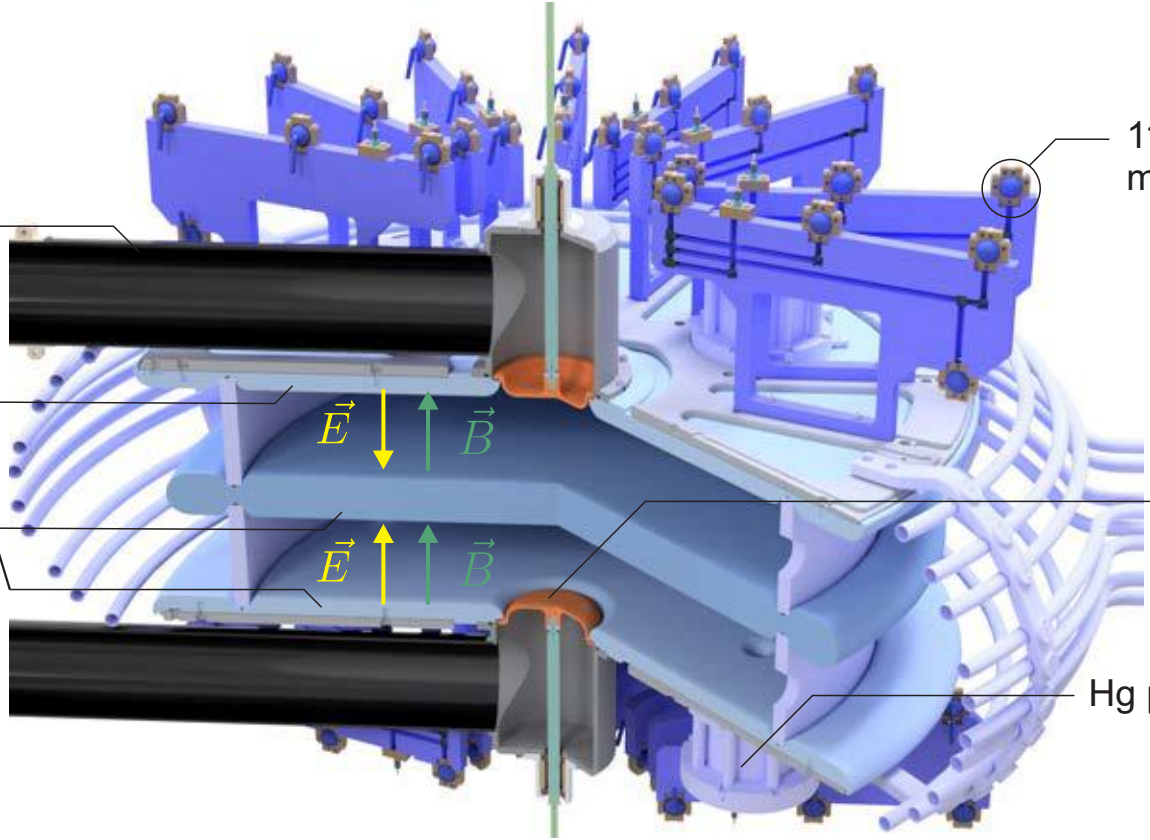
Cs magnetometer array

- field homogenization
- online gradient

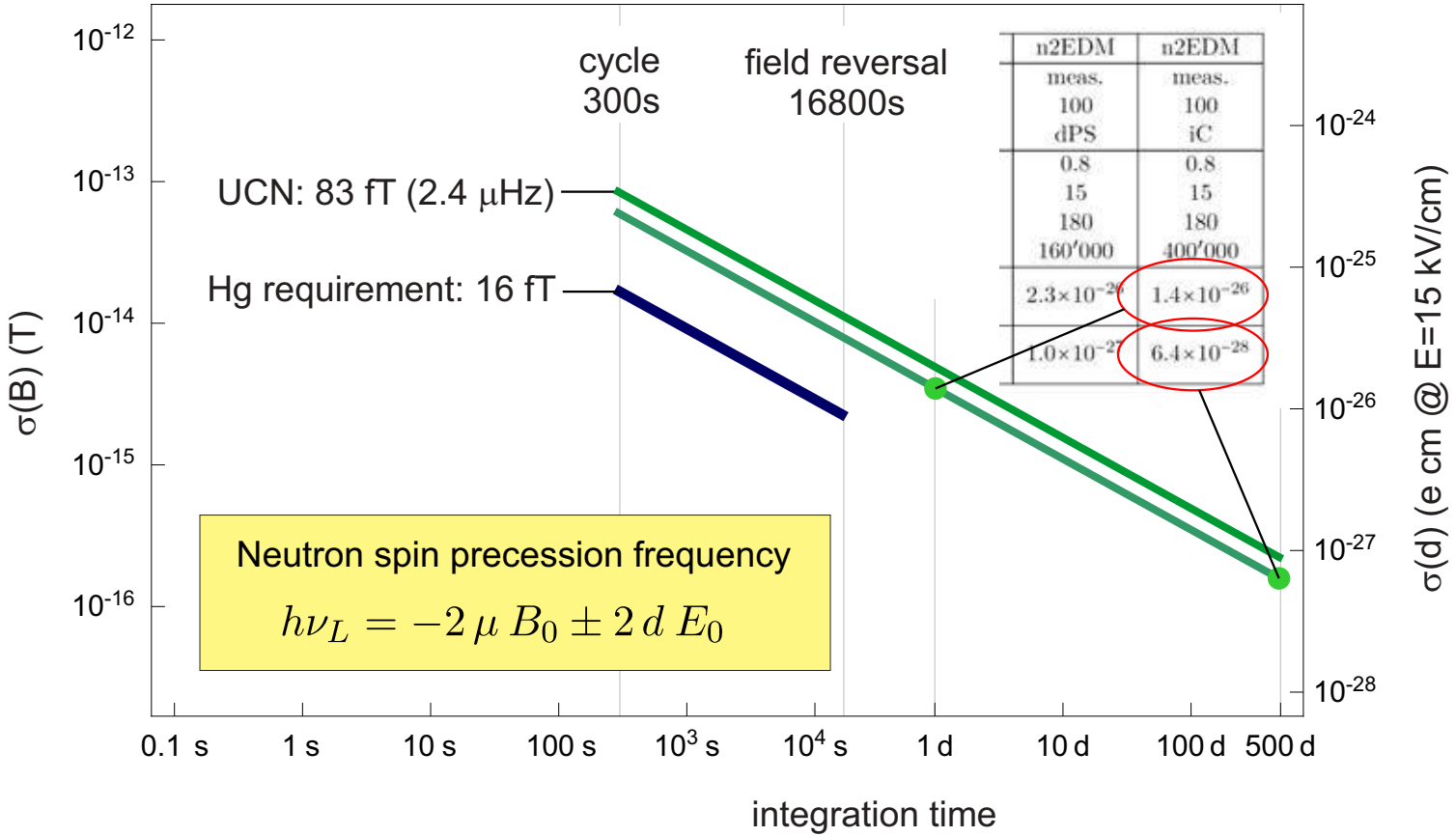
Hg co-magnetometers

- primary magnetic reference
- online gradient

Design of the electrode stack

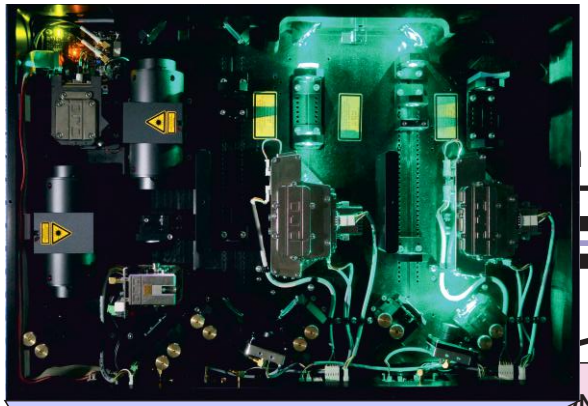


Projected statistical performance



n2EDM meas. 100 dPS	n2EDM meas. 100 iC
0.8	0.8
15	15
180	180
160′000	400′000
2.3×10^{-26}	1.4×10^{-26}
1.0×10^{-27}	6.4×10^{-28}

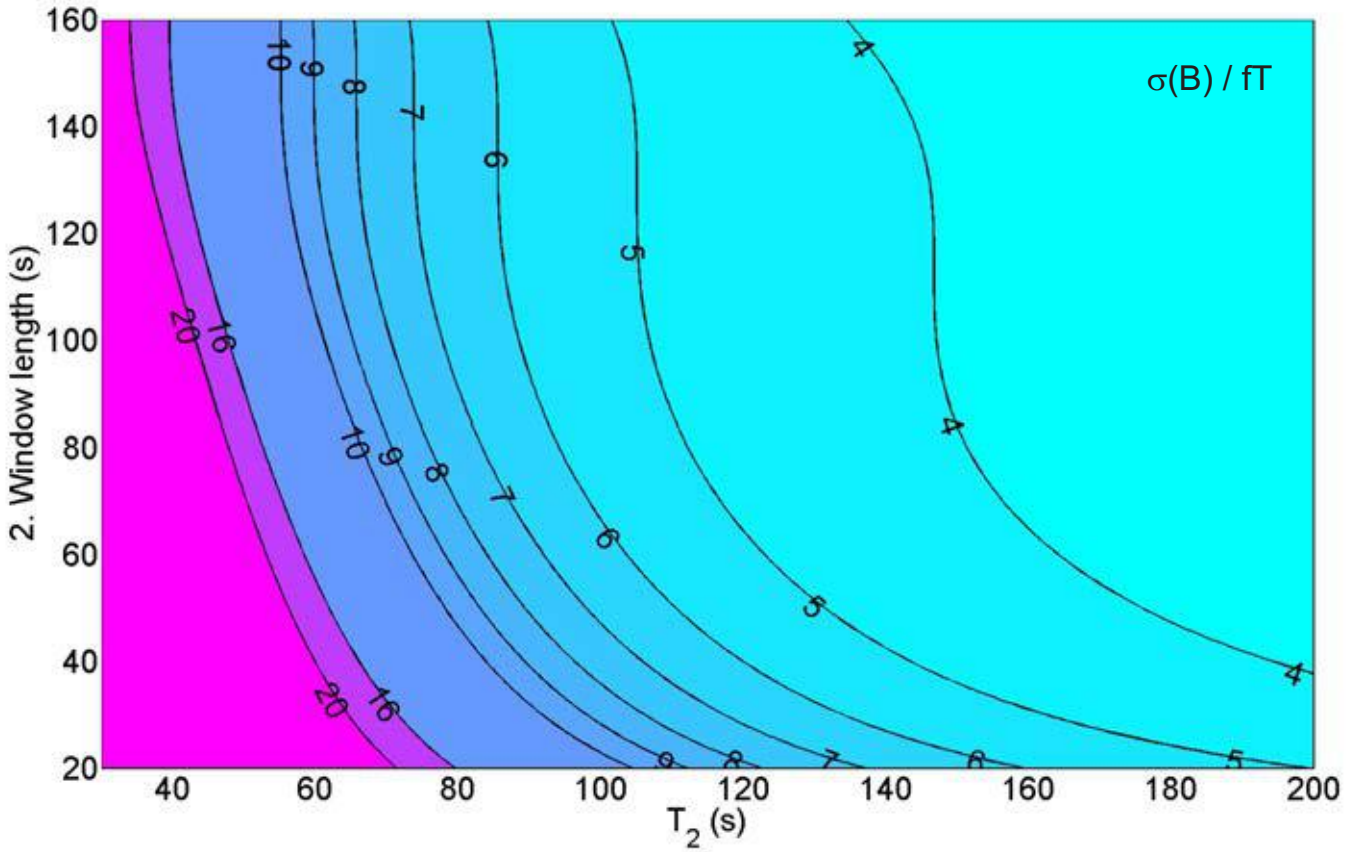
Hg magnetometer setup



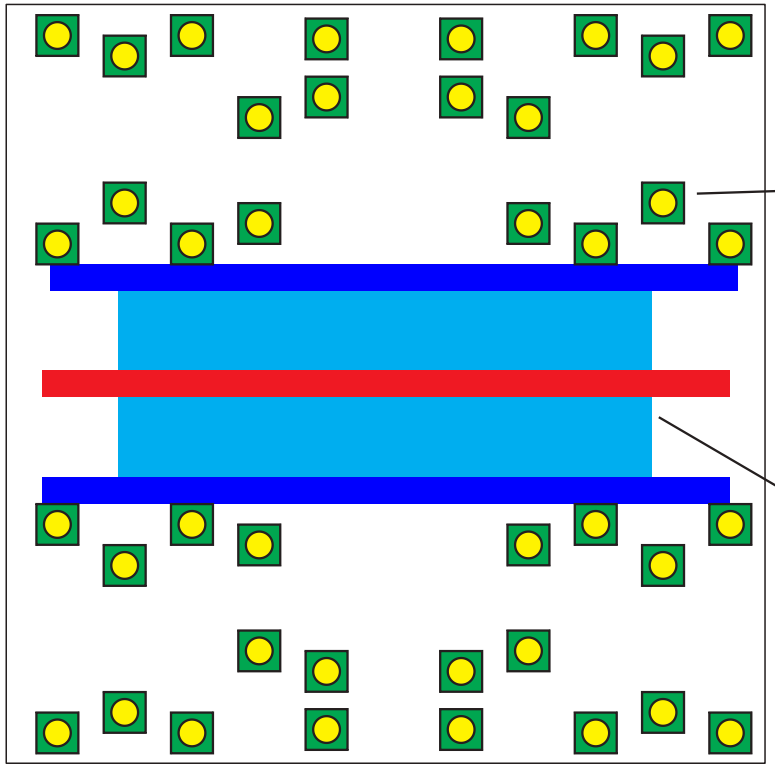
Toptica FHG, 254 nm

almost shot-noise limited performance @ 8 Hz

Hg magnetometer stat. performance



Magnetometry concept



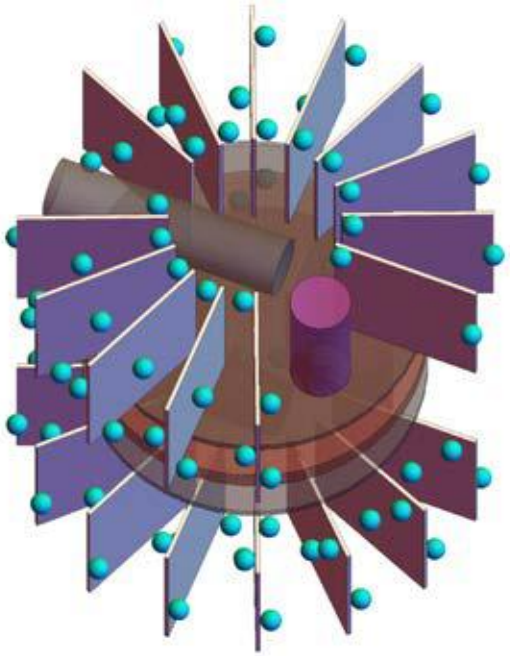
Cs magnetometer array

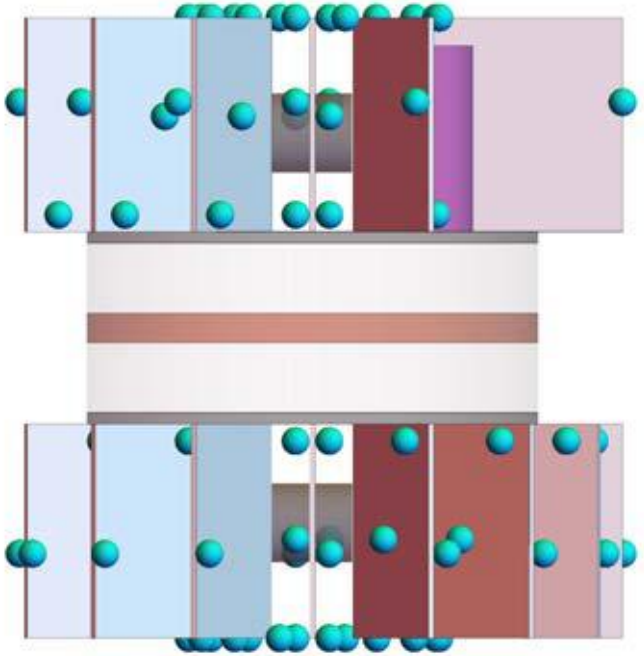
- field homogenization
- online gradient

Hg co-magnetometers

- primary magnetic reference
- online gradient

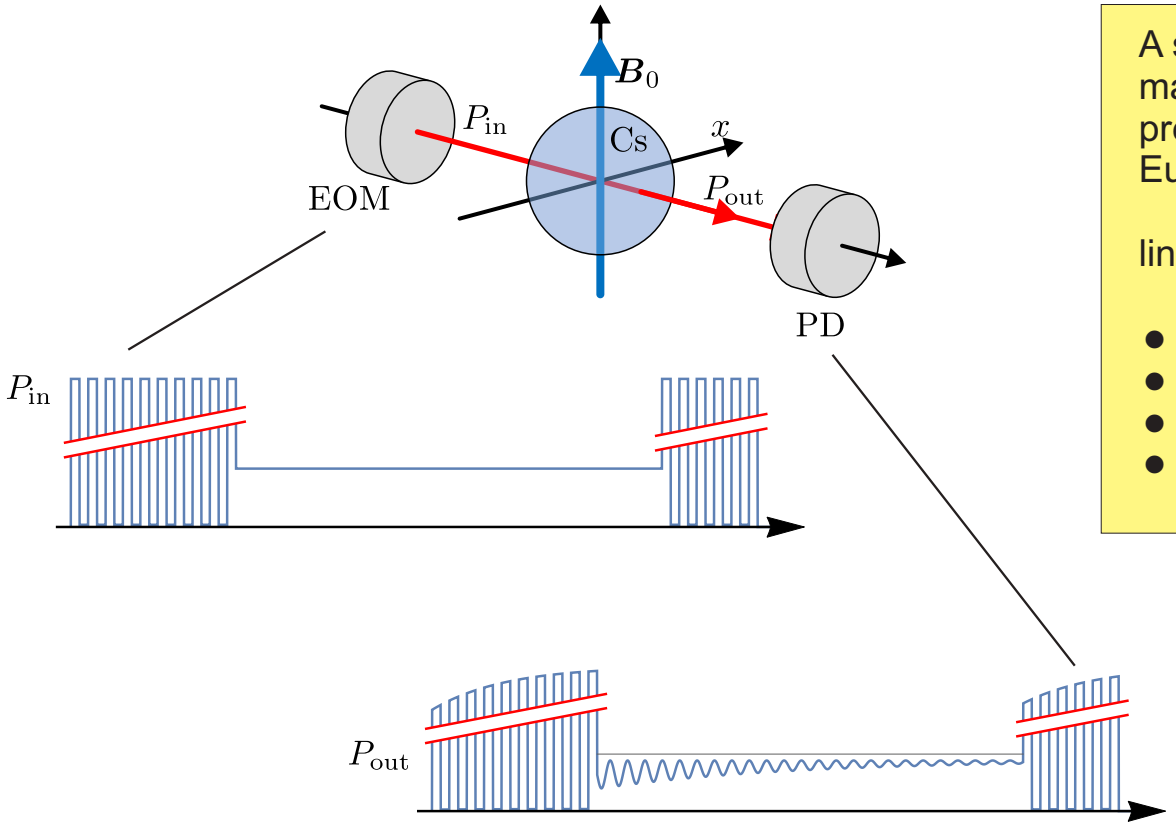
Cs magnetometer array optimization





26 segments, 4 Cs cells per segment, magnetic accuracy 5 pT, position accuracy 0.5 mm

Cs magnetometer concept

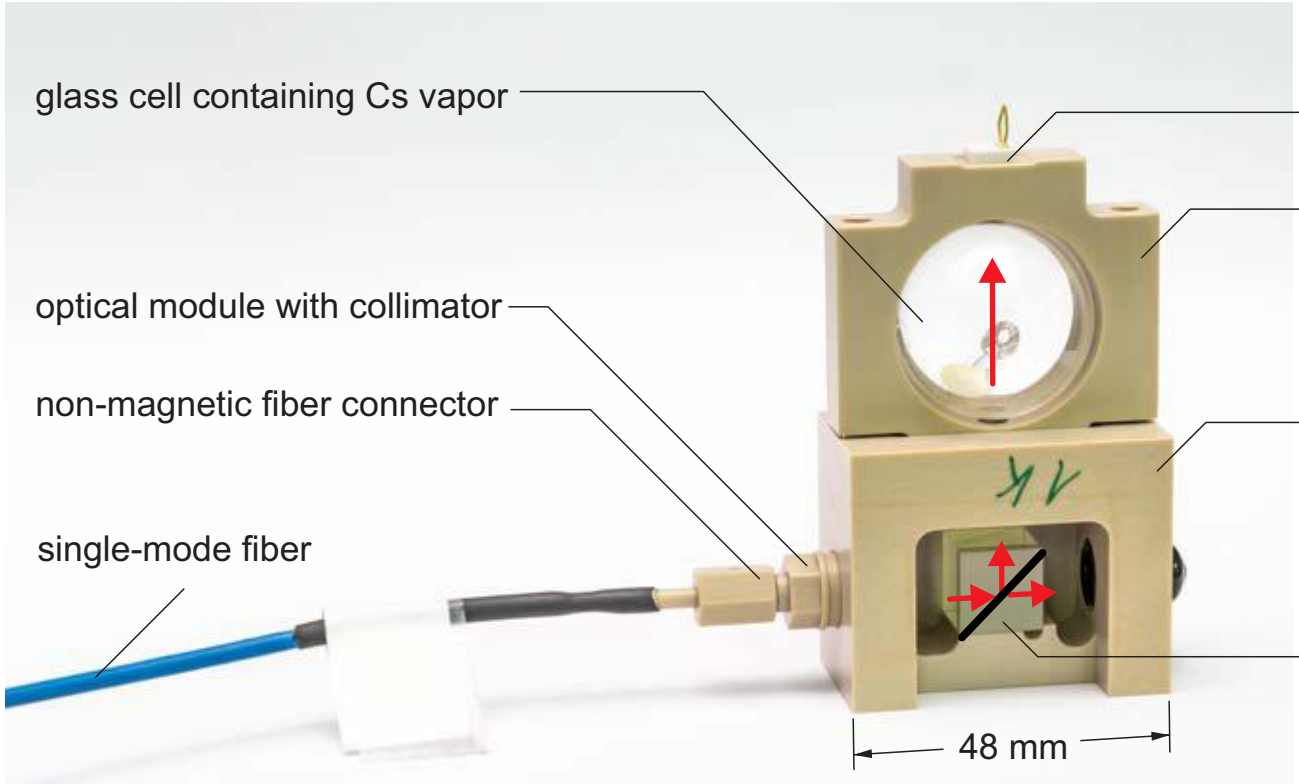


A sensitive and accurate atomic magnetometer based on free spin precession. Z. D. Grujic et al., Eur. Phys. J. D, 69(5), 2015.

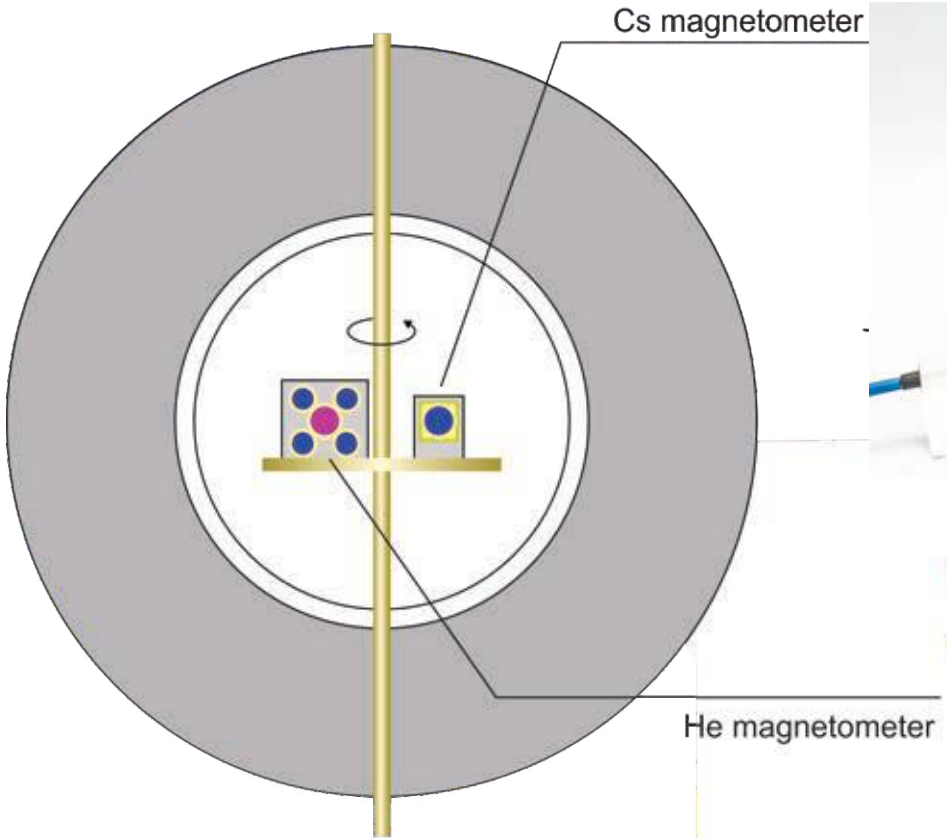
linear polarized light

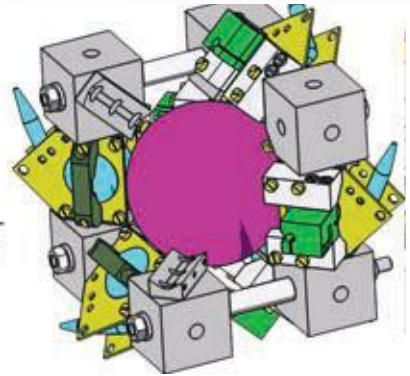
- no light shift
- no magnetic cross-talk
- less systematic shifts
- but: less sensitive

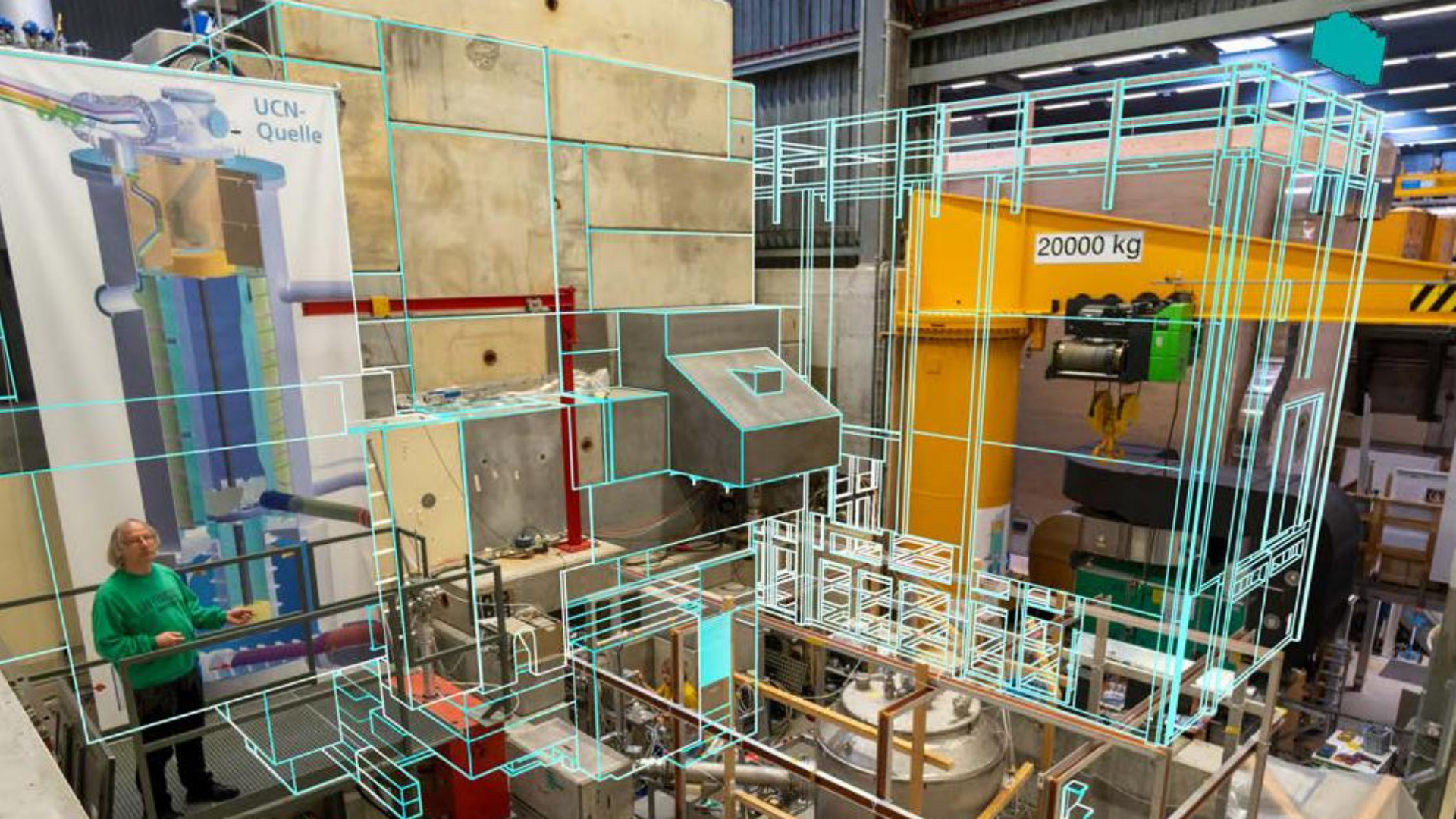
Cs magnetometer prototype

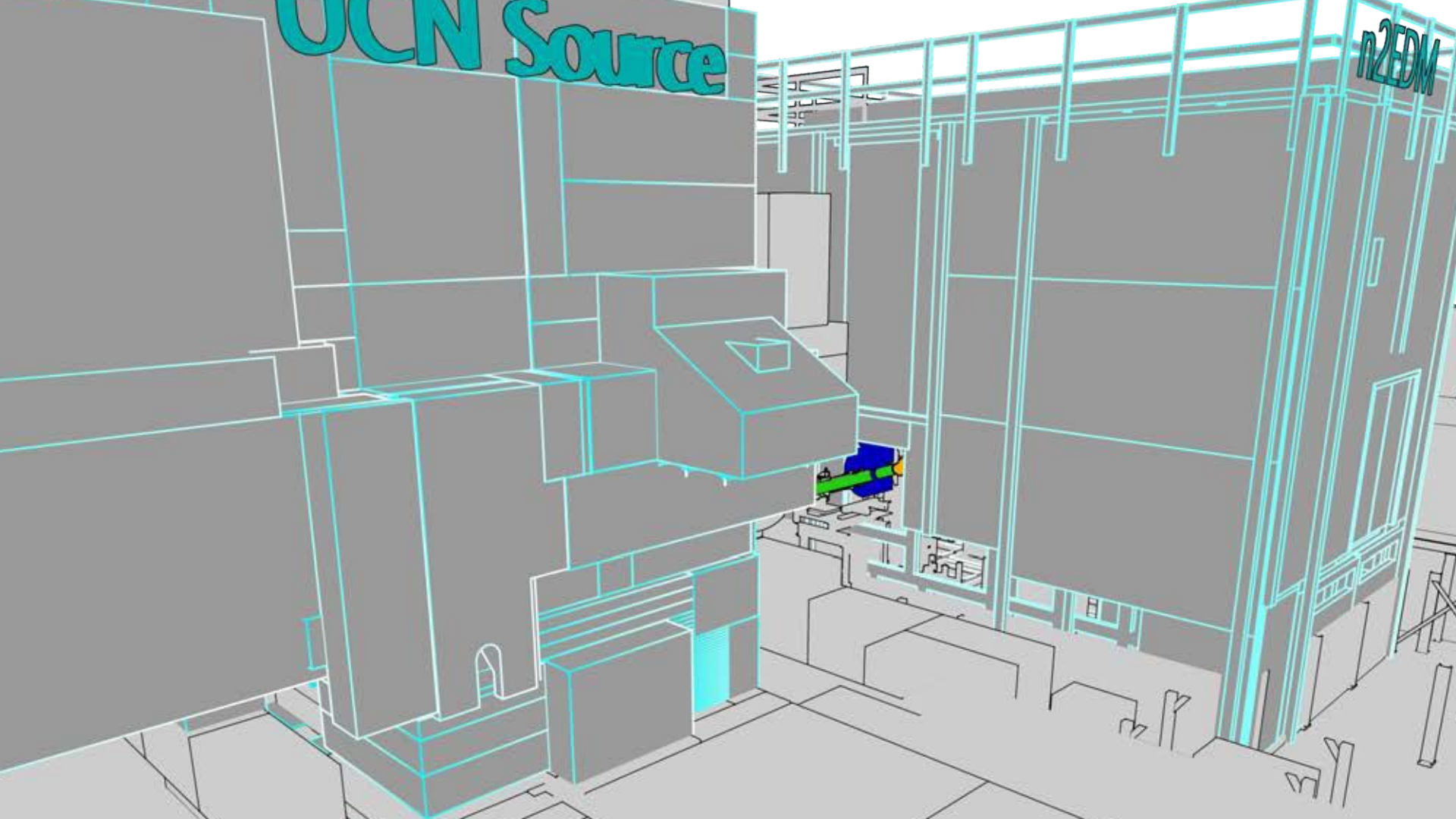


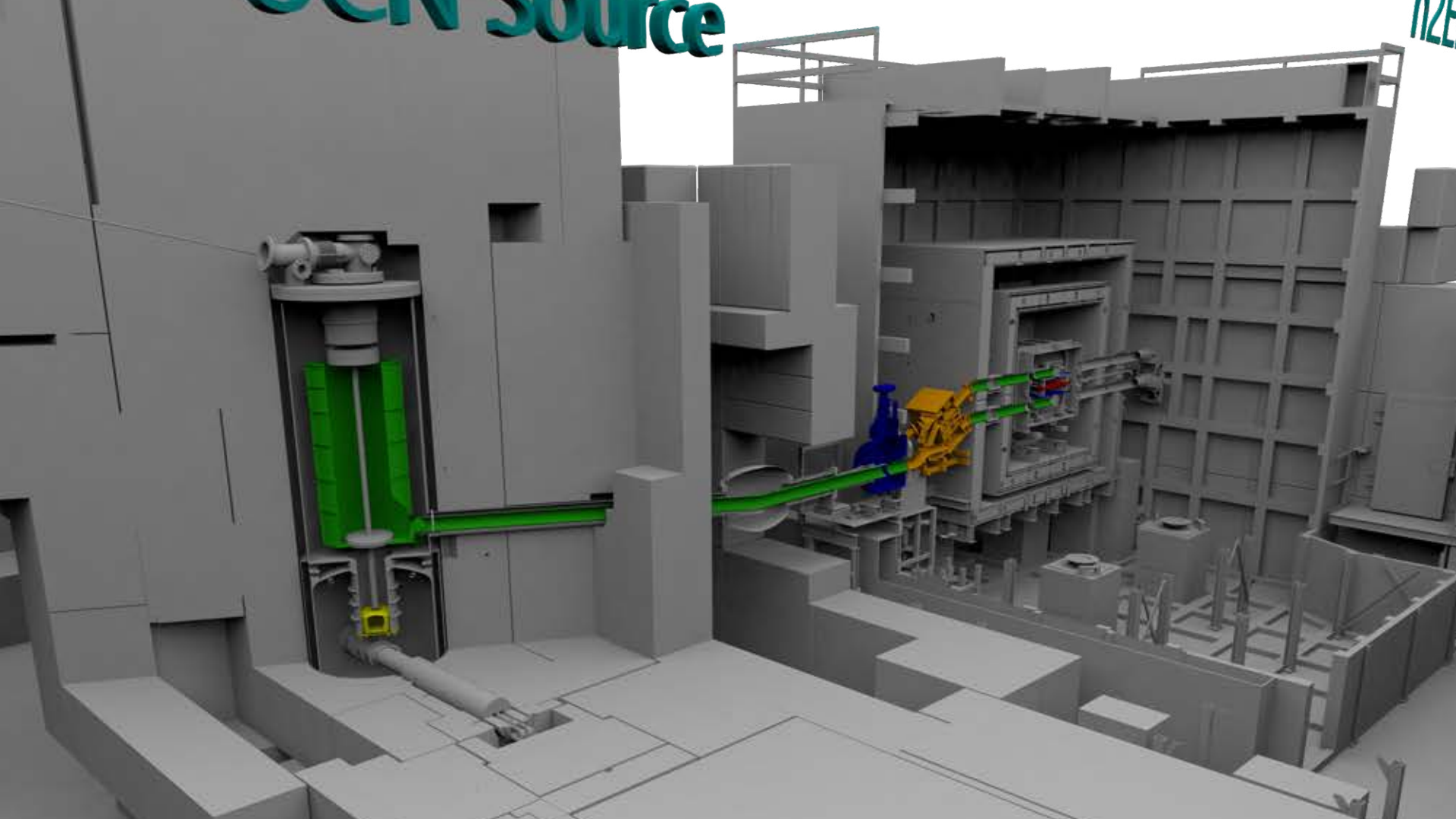
Cs magnetometer calibration



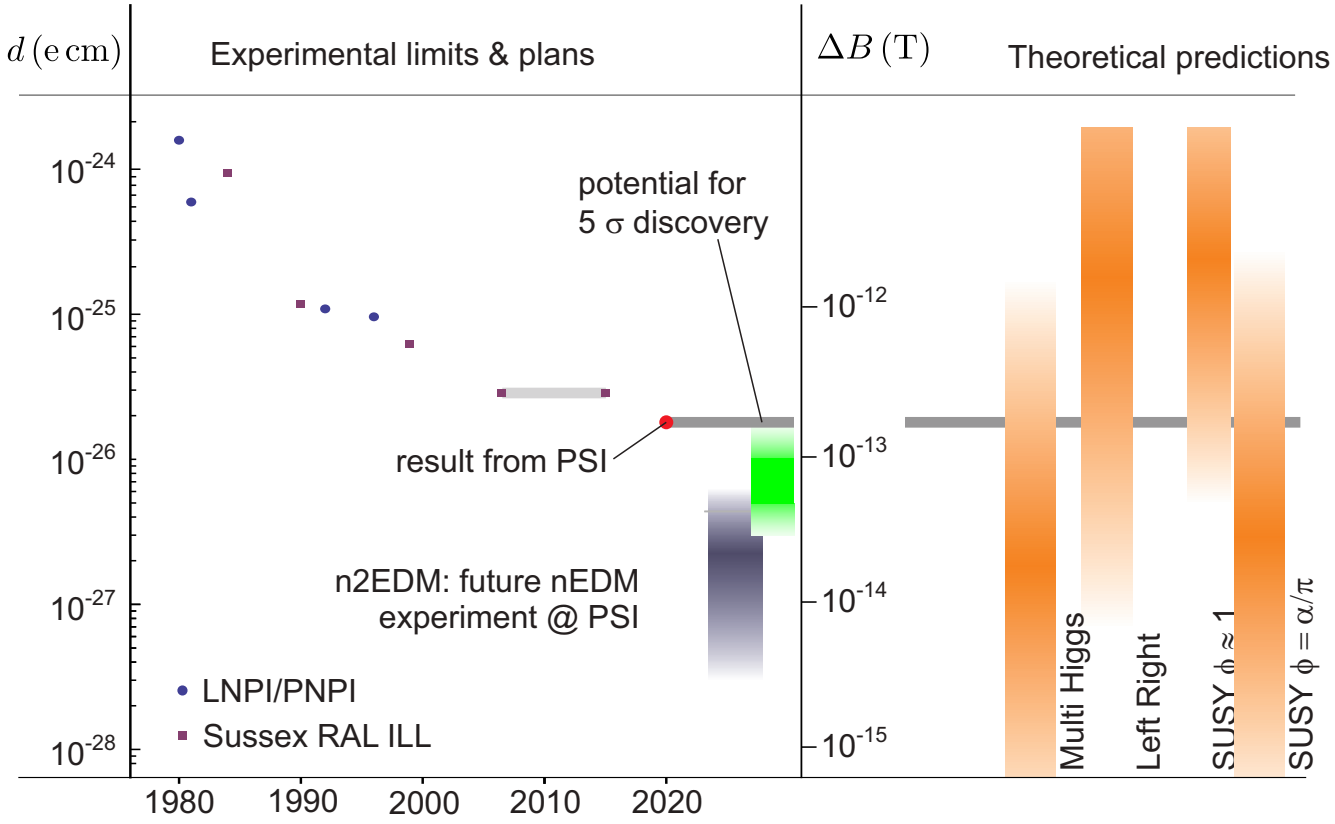



UCN-
Quelle
20000 kg


UCN Source
n2EDM


ESS Source

nEDM result & outlook for n2EDM



The nEDM collaboration