Towards a new measurement of the neutron electric dipole moment

The n2EDM experiment

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n2EDM

Special Article - Tools for Experiment and Theory

The design of the n2EDM experiment

Sensitivity goal: 10^{-27} *e* cm

nEDM Collaboration

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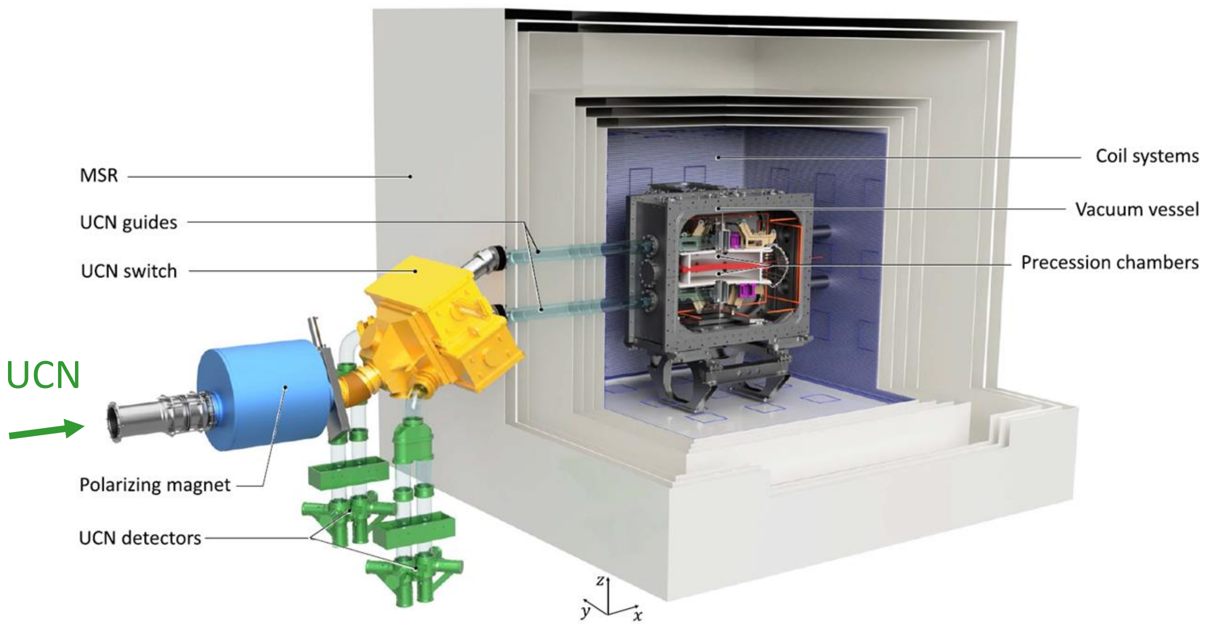
Collaboration of 12 institutes (mainly European)
(25 permanents, 15 doc + post-doc)

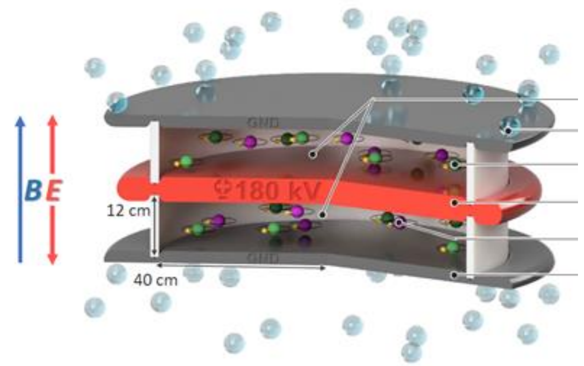
The design of the n2EDM experiment

From the measurement of two frequencies (parallel and antiparallel fields configurations)

$$d_n = \frac{\pi\hbar}{2|E|}(f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow})$$

⟶ Ramsey's method: required polarized neutrons





Storage chambers where neutron frequency measurement is performed

Two main challenges

neutron statistic & magnetic field uniformity and stability

Control of the magnetic field

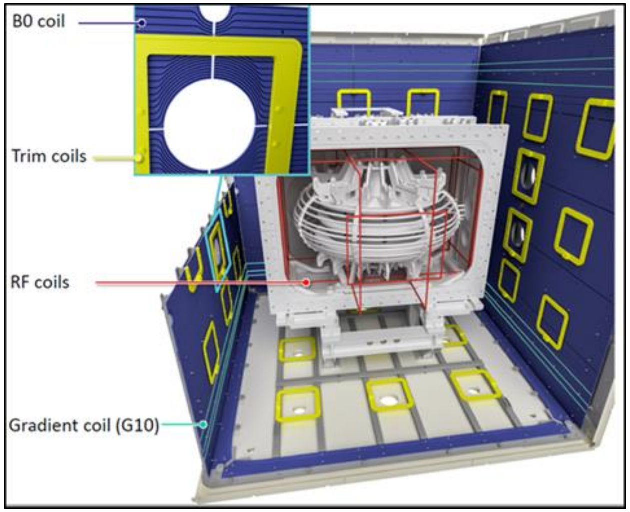
Magnetically shielded Room (MSR): 6-layers mu-metal shield (suppression factor of 10^5 for quasistatic field)

MSR in the thermo-house

Storage chambers in the VT

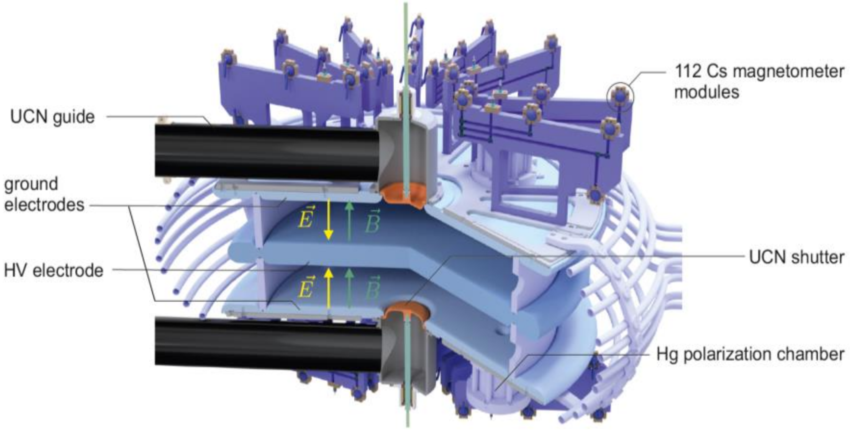
Magnetic field generation: internal coils system (64)

- 1 main B_0 coil + 63 correcting coils



Online measurements of the magnetic field:

- Hg comagnetometer (in situ): mag. field drift
- 112 Cs magnetometers : field non uniformities



Expected sensitivity

Gain with respect to the nEDM experiment:

	nEDM (2016)	n2EDM
Chamber diameter	47 cm	80 cm
N(per cycle)	15,000	120,000
T	180 s	180 s
E	11 kV/cm	15 kV/cm
α	0.75	0.8
$\sigma(d_n)$ per day	11×10^{-26} e cm	2.6×10^{-26} e cm

Based on 2016 UCN source performances

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

T: storage time
E: electric field intensity
α: UCN polarization
N: number of UCN

Sensitivity improvements: Number of UCN (x8): storage volume (x3) + optimized* connection source - apparatus
Electric field intensity (+35 %): HV electrode better insulated /nEDM

Final sensitivity of 10^{-27} *e* cm → 500 days of data taking (4 years)

Systematics: mostly induced by the magnetic field non uniformities

Highly uniform and stable magnetic field (1 µT) required

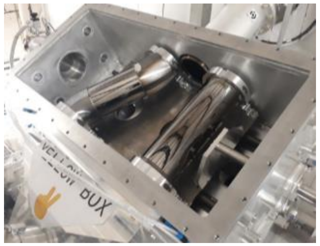
Field uniformity: $\sigma(B_z) < 170$ pT in the chambers
Field stability : *30* fT/min

Systematic effect	(10^{-28} e cm)
Uncompensated gradient drift	1
Quadratic $v \times E$	1
Co-magnetometer accuracy	1
Phantom mode of order 3	3
Phantom mode of order 5	3
Dipoles contamination	3
Total	6

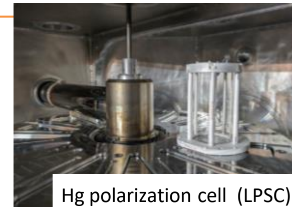
**G. Zsigmond et al, Eur. Phys. J.A 56, 33 (2020).*

French contributions to the n2EDM experiment

In2p3 hardware contributions

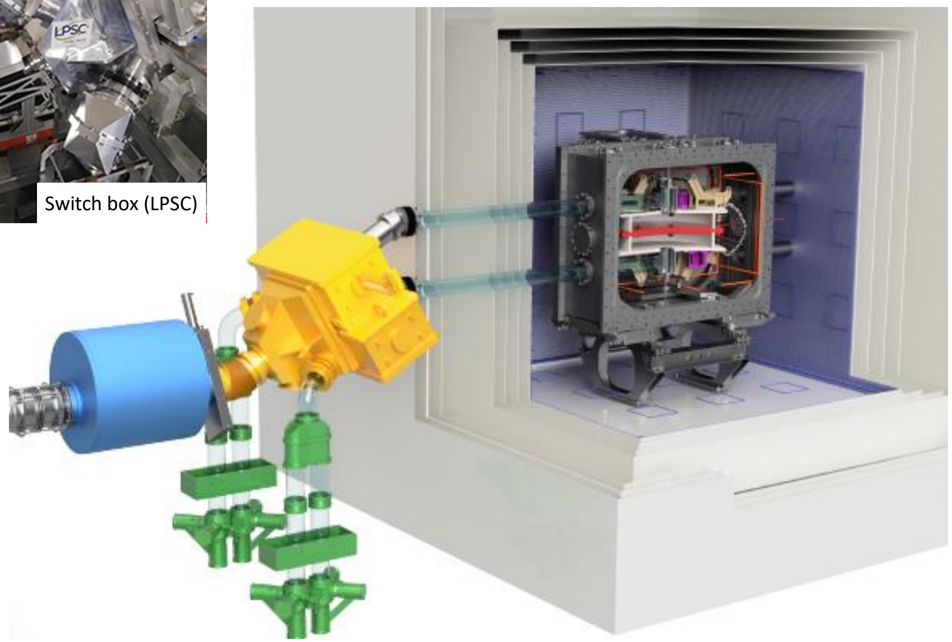


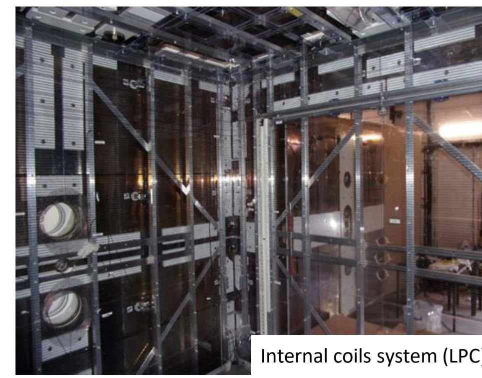
Switch box (LPSC)



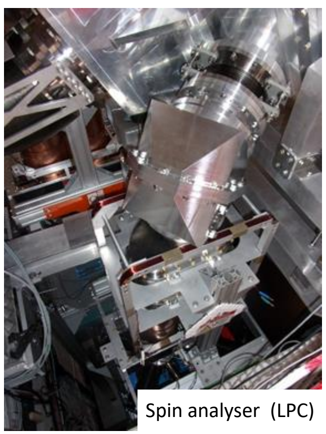
Hg polarization cell (LPSC)

Vacuum vessel (LPC)

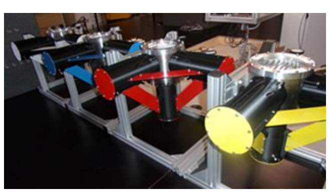


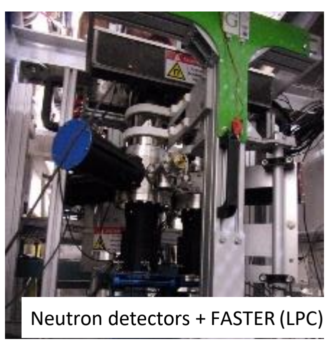


Internal coils system (LPC)



Spin analyser (LPC)





Neutron detectors + FASTER (LPC)

Data monitoring interface (LPSC)

Mapping robot (LPSC)

In2p3 hardware contributions

ANR (570 k€, 2014-2019) + ERC (200 k€, 2016-2021):

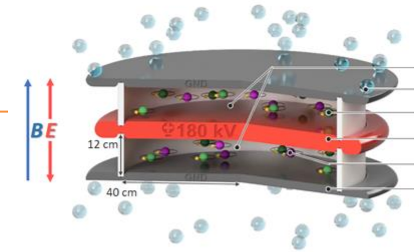
- strong implication of the technical services (4 FTE / year between 2015 and 2022)

Components	Laboratory	Cost (k€)	Construction period	status
Vacuum vessel	LPC	130	2017 - 2021	operational
Switch (× 2)	LPSC	110	2016 - 2023	operational
Internal coils system	LPC	80	2014 - 2022	operational
Mapping robot	LPSC	50	2017 - 2021	operational
UCN detectors (× 5)	LPC	140	2013 - 2020	operational
Spin analyzers (× 2)	LPC	90	2018 - 2021	operational
Hg polarizer	LPSC	100	2017 - 2024	installation ongoing
Data Monitoring	LPSC	2	2021 -	under development

+ data management (CCin2p3), data analysis, data blinding, systematic effects, strategy board ….

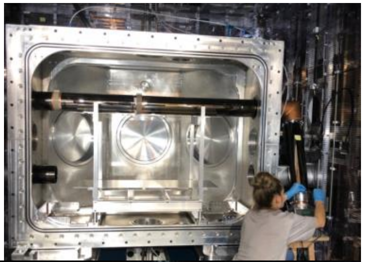
Commissioning results

UCN commissioning (2023)



First UCN in the apparatus in July 2023: number of neutrons too low by a factor 20 !!

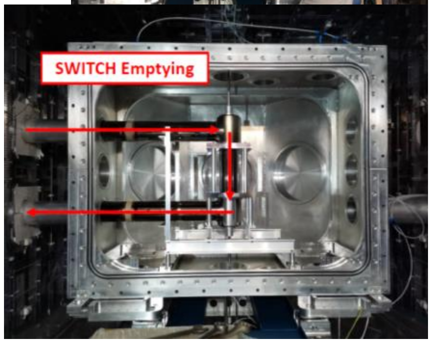
Number of stored UCN end of 2023 (180 s): 24,000
(still a factor 5 missing / design goal)



Many tests performed during Fall 2023:

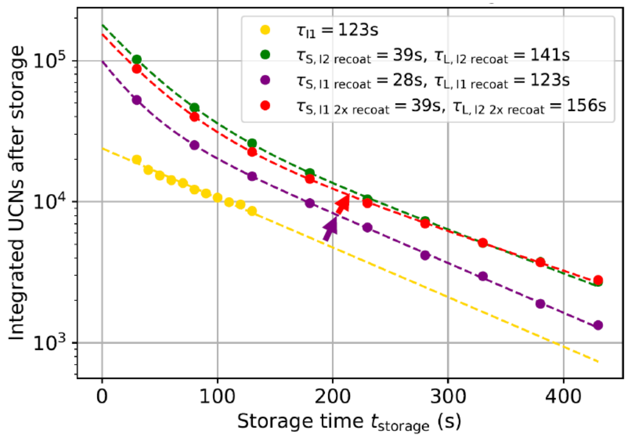
UCN transport: up to the chambers: OK !
during emptying phase: factor 2 too low / simulations

Storage capacity of the chambers:
- Insulator rings: redo the DPS coating → increase of UCN statistic
  nEDM insulator ring → increase of UCN statistic
- Electrodes : dummy copper electrodes → increase of UCN statistic
  visual inspection : small spots peeled off

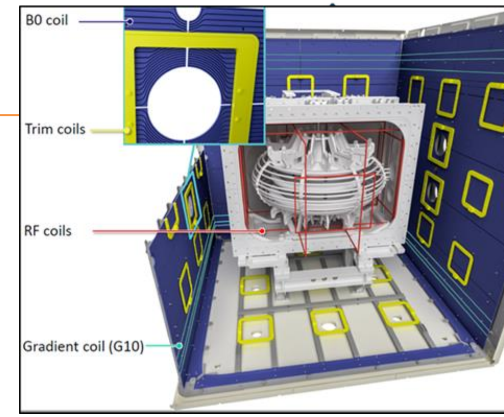


Electrode coating (DLC) and insulator coating (DPS): underperforming
Two culprits: coating technique and surface roughness

Test chambers under construction (coating investigation during Fall 2024)
- new insulator ring (quartz instead of PS)
- new electrodes with exchangeable parts (test of coating procedures)

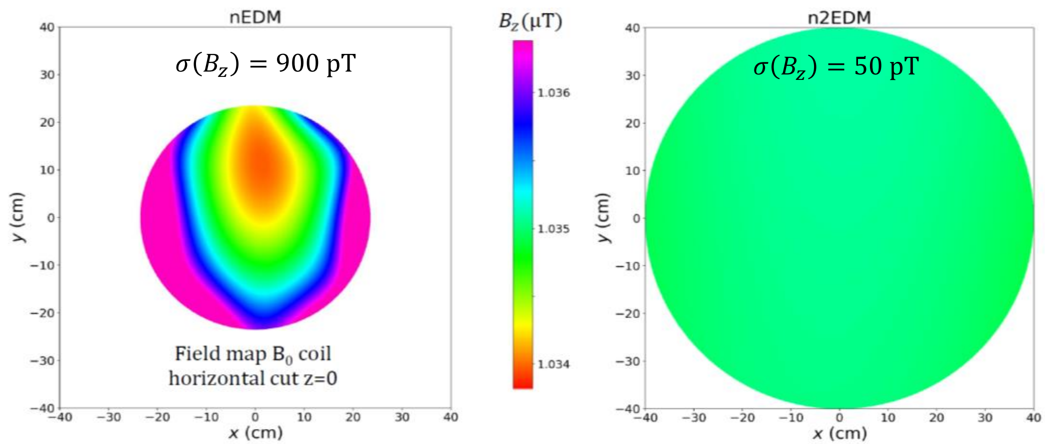


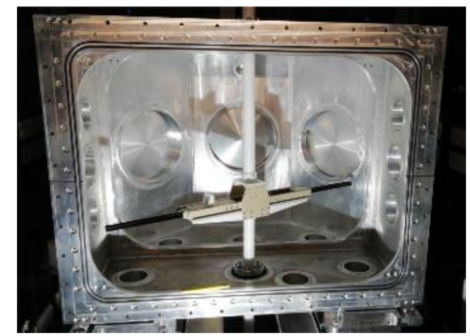
Magnetic field commissioning



Magnetic field characterization (2021-2022): close collaboration between LPC and LPSC

- internal coils system simulated, built and installed by LPC
- field characterization performed by LPSC





	Required	w/o optim.	w/ optim.
Statistical requirements			
Vertical uniformity $\sigma(B_z)$ (pT)	< 170	49.1 ± 1.5	34.7 ± 1.5
Systematical requirements			
$d^{\text{false}}_{n \leftarrow Hg}(\acute{G}_{30}\acute{\Pi}_{30})$ $(10^{-28}\, e\,\text{cm})$	< 3	81.7 ± 2.9	2.3 ± 2.9
$d^{\text{false}}_{n \leftarrow Hg}(\acute{G}_{50}\acute{\Pi}_{50})$ $(10^{-28}\, e\,\text{cm})$	< 3	9.2 ± 0.7	0.7 ± 0.7
$d^{\text{false}}_{n \leftarrow Hg}(\acute{G}_{70}\acute{\Pi}_{70})$ $(10^{-28}\, e\,\text{cm})$	< 3	0.3 ± 0.1	0.2 ± 0.1

Performances are excellent

Part of the systematics already below requirements

T. Bouillaud, P. Flaux, "An exceptionally uniform magnetic field for the n2EDM experiment" (LPC-LPSC); internal review.

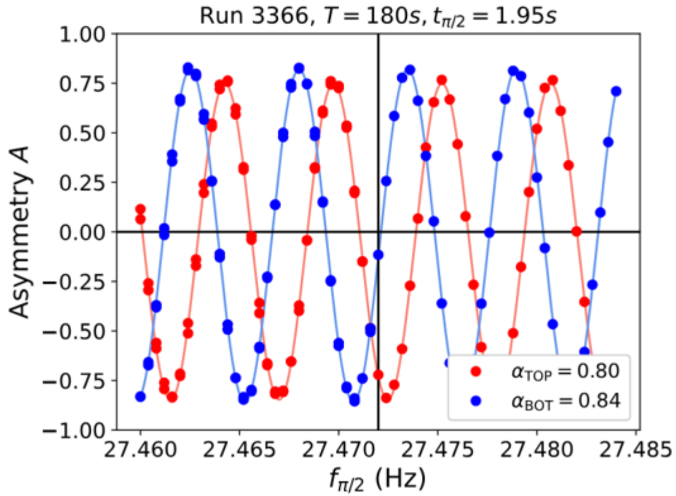
Apparatus commissioning

Neutron frequency measurement:

Ramsey oscillating field method: operational !

neutron polarization, transport, storage and detection: OK !

Final polarization larger than in design goal (> 0.8) !!



Components	Operational	Performances
Neutrons statistic	√	24,000
Magnetic field	√	$\sigma(B_z) = 35$ pT ; systematics
High Voltage	√	+15 KV/cm
Ramsey meas.	√	$\alpha > 0.8$
Hg Comagnetometer	√	T_2 = 35 s → 100 s
Cs magnetometers		

2024 goal: first nEDM data

Current performances:

	N (per cycle)	T	E	α
06/2024	24,000	180 s	10 - 12.5 kV/cm	0.80 - 0.84

↑ 15 kV/cm last Wednesday !

Sensitivity already better than in nEDM (1.9)

Perspectives and conclusions

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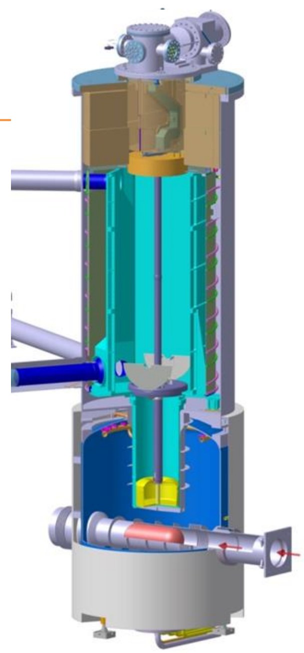
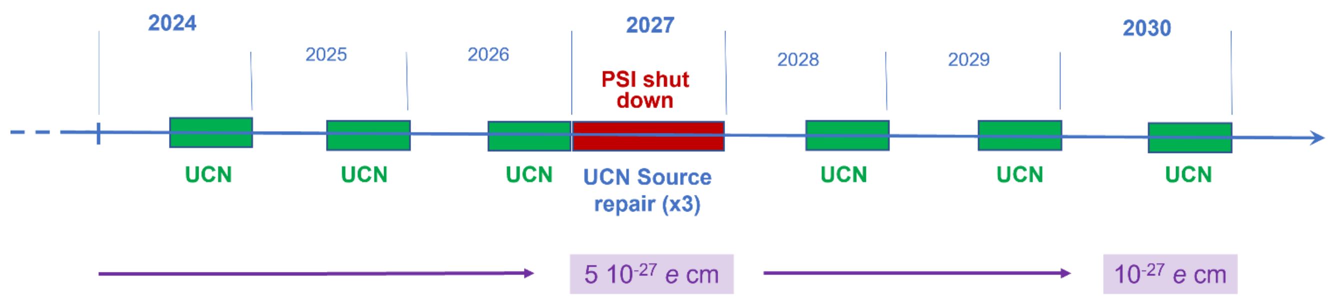


UCN source (PSI)

Towards a final sensitivity of 10^{-27} *e* cm: two steps approach



First phase (2024-2026):
Sensitivity already improved / nEDM (x1.9): new result is guaranteed
final sensitivity will depend on new chambers storage properties
Systematics : part of the systematics already under control (magnetic commissioning)

Second phase (2028-2030):
UCN source repair/upgrade (x3): D_2 container and UCN shutter exchanged, proton beam intensity, D_2 solid prod.
final sensitivity will depend on UCN source performances (missing 2.2)

New operation mode: suppress the main systematic effect (false motional EDM) with magic B0 field (10 µT)

Beyond 2030: nEDM measurement in superfluid Helium (SNS prototype move to Europe) ?

*G. Pignol, A magic magnetic field to measure the neutron electric dipole moment, Phys. Lett. B, **793**, 440 (2019)*

Summary and requests

Summary of our involvement since 2004:

There was always a French co-spoke (LPC or LPSC) person since 2004 (beside 2008-2012)

Project	Funding	FTE (Tech. + Eng.)	FTE (Phys)	PhD + Post.Doc
nEDM (2005-2020)	ANR (290 k€) in2p3 (250 k€)	1/year	2/year	7 PhD 1 Post-Doc
n2EDM (2015-2030)	ANR (570 k€) ERC (200 k€) in2p3 (430 k€)	4/year (2015-2022) 3/year (2022-2024)	2,5/year	6 PhD 6 Post-Doc

French involvement in the n2EDM experiment:
Budget : ≈ 20 %
Staff : ≈ 20 - 25 %

n2EDM experiment is the worldwide leader: UCN source operational + preliminary measurements ongoing
- sensitivity already better than for nEDM: any improvements bring us towards 10^{-27} *e* cm

Strong involvement of the French teams in n2EDM ?
- The only CNRS staff is going to retire (LPSC) → CR recruitment (LPC or LPSC)
- Keep on implying PhD & post-doc in the project
- Collaboration agreement (common funds) up to 2026: to be secured till 2030
- Support the mission to PSI for shift duty (3.5 weeks /year/person)
- L4M @ LPSC: magnetometry developments → in2p3 support
- Maintenance of all French components (technical services: 1-2 FTE/year)

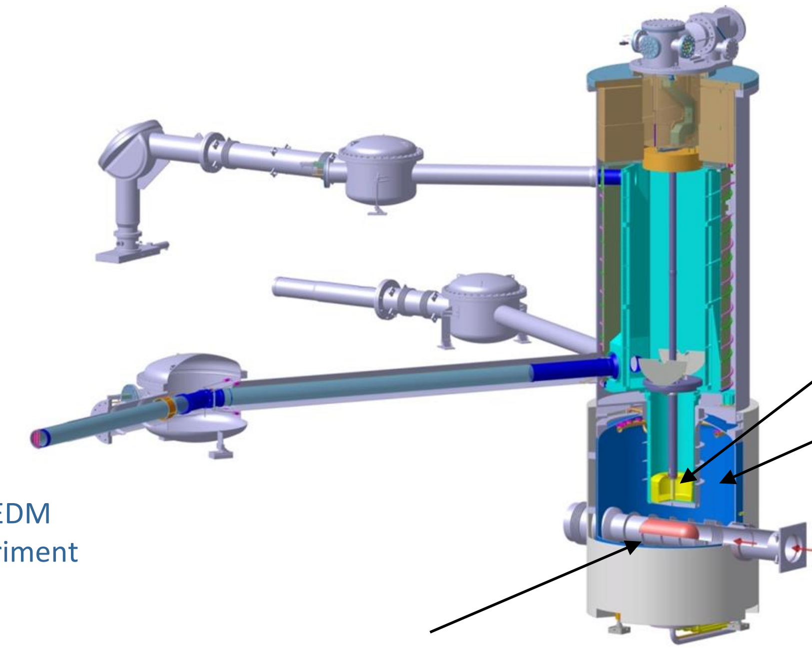
Merci

Design of the n2EDM experiment

PSI UCN source: pulsed proton beam on a Deuterium crystal (5 K)

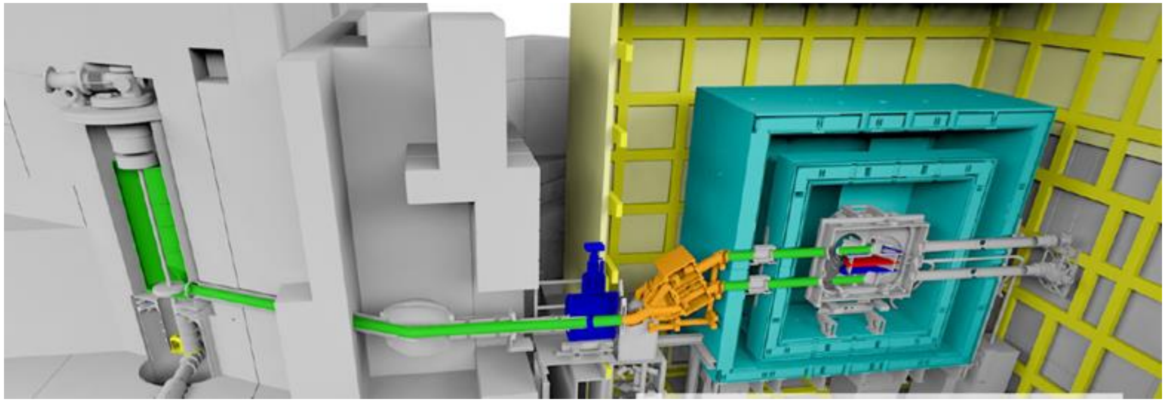
Production of ultracold neutrons (T < 300 neV)
Can be stored in chambers for a few minutes

Pulsed UCN source
measurement performed every cycle (7 min)



UCN source improvements since 2016:
Solid D2 improvements: x1.5
UCN source improvements in 2027:
Flap repair: x1.3
D2 container lid: x1.8
Proton beam current intensity: x1.2
Source conditioning: x1.2

Built at PSI for the nEDM project
(start in 2011)

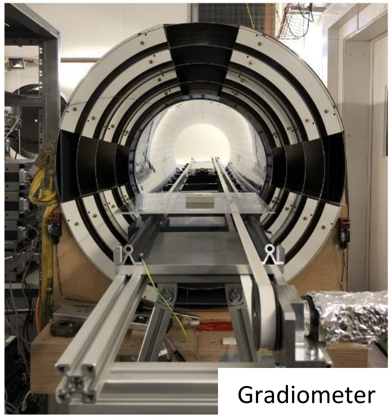


Control of the magnetic field

Magnetically shielded Room (MSR): 6-layers mu-metal shield (suppression factor of 10^5 for quasistatic field)
Active Magnetic Shield (AMS): suppress the ambient field variations around the MSR (a few µT)
Thermo-house: controlled environment (temperature, humidity)

MSR in the thermo-house

Storage chambers in the VT



Gradiometer

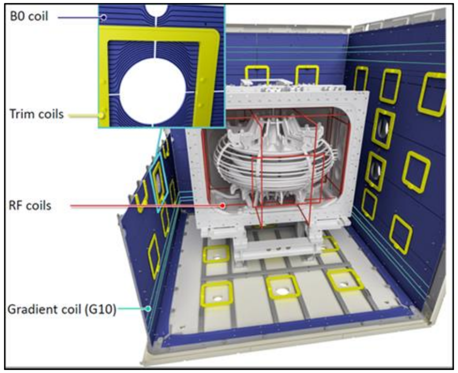
Stringent magnetic requirements in the MSR:
- at the vacuum tank level: < nT @ 5 cm
- close to the precession chambers: < 20 pT @ 5 cm

Magnetic properties of every pieces installed are checked:
- small components : specific device (gradiometer developed at PSI)
- large pieces: at PTB Berlin (electrodes, vacuum tank …)

Any magnetic dipole on the chambers walls must be removed (cleaning procedure)

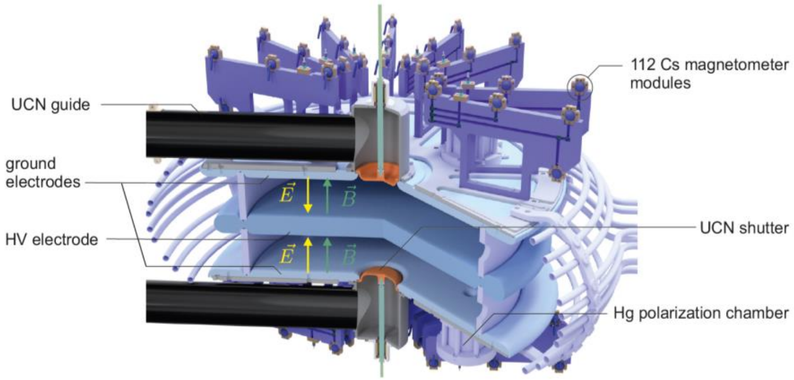
A very large magnetically shielded room with an exceptional performance for fundamental physics measurements
A large 'Active Magnetic Shield' for a high–precision experiment. *Eur.Phys.J.C*, 2023, 83 (11), pp.1061

Control of the magnetic field



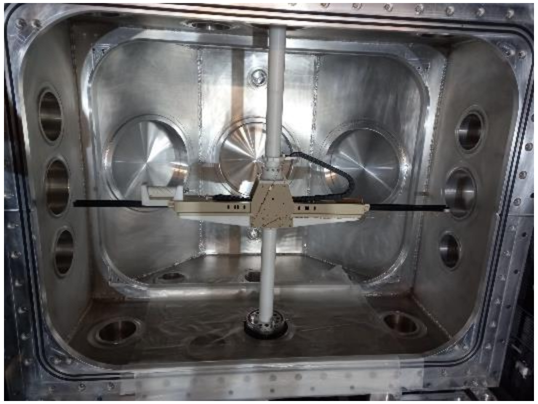
Magnetic field generation: internal coils system (64)

- 1 main B_0 coil (optimized vertical solenoid)
- 56 squared correcting coils
- 7 gradients coils (G_{10}, G_{20} , G_{30}, G_{11} , $G_{1\text{-}1}$ …)



Online measurements of the magnetic field:

- Hg comagnetometer (in situ)
  - ⟶ magnetic field drift + $\partial B_z/\partial z$ (G_{10})
- 112 Cs magnetometers surrounding the chambers
  - ⟶ field non uniformities (G_{30},G_{50})



Offline measurements:

- magnetic field mapping (field non uniformities: G_{30}, G_{50} , G_{70})
- field mapping before and after the data taking
- offline corrections of some systematic effects (reproducibility)