

Conseil scientifique - in2p3

(24.10.2013)

The measurement of the neutron electric dipole moment
The n2EDM project

CSNSM, CNRS, IN2P3, Université Paris sud
LPC Caen, CNRS, IN2P3, ENSICAEN, Université de Caen
LPSC, Grenoble, CNRS, IN2P3, Université Joseph Fourier, INPG

G. Ban, B. Clément, T. Lefort, Y. Lemière, G. Pignol, G. Quéméner,
D. Rebreyend, S. Roccia

PhD students: V. Hélaine, Y. Kermaïdic

Technical departments
(Mechanics, Electronics, Detection, Instrumentation, Computing)

The n2EDM collaboration

M. Burghoff, S. Knappe-Grüneberg, A. Schnabel, J. Vogt	*Physikalisch Technische Bundesanstalt, Berlin*
G. Ban, V. Hélaine[1], T. Lefort, Y. Lemiere, G. Quéméner	*Laboratoire de Physique Corpusculaire, Caen*
K. Bodek, M. Rawlik, G. Wyszynski[3], J. Zejma	*Institute of Physics, Jagiellonian University, Cracow*
A. Kozela	*Henryk Niedwodniczanski Inst. Of Nucl. Physics,* Cracow
N. Khomutov	*Joint Institute of Nuclear Reasearch, Dubna*
M. Kasprzak, H.C Koch, A. Weis, Z. Grujic	*Département de physique, Université de Fribourg, Fribourg*
Y. Kermaîdic , G. Pignol, D. Rebreyend, B. Clément,	*Lab. de Physique Subatomique et de Cosmologie, Grenoble*
N. Severijns, P. Pataguppi	*Katholieke Universiteit, Leuven*
W. Heil	*Inst. für Kernchemie, Johannes-Gutenberg-Universität, Mainz*
S. Roccia,	*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Paris*
S. Afach, G. Bison , Z. Chowdhuri, M. Fertl[3], B. Lauss, S. komposch D. Ries, P. Schmidt-Wellenburg, G. Zsigmond	*Paul Scherrer Institut, Villigen*
B. Franke, K. Kirch[1], J. Krempel, F. Piegsa, D. Zhu	*Eidgenössische Technische Hochschule,* Zürich

also at: [1]*Paul Scherrer Institut,* [2]*PNPI Gatchina,* [3]*Eidgenössische Technische Hochschule*

Outline

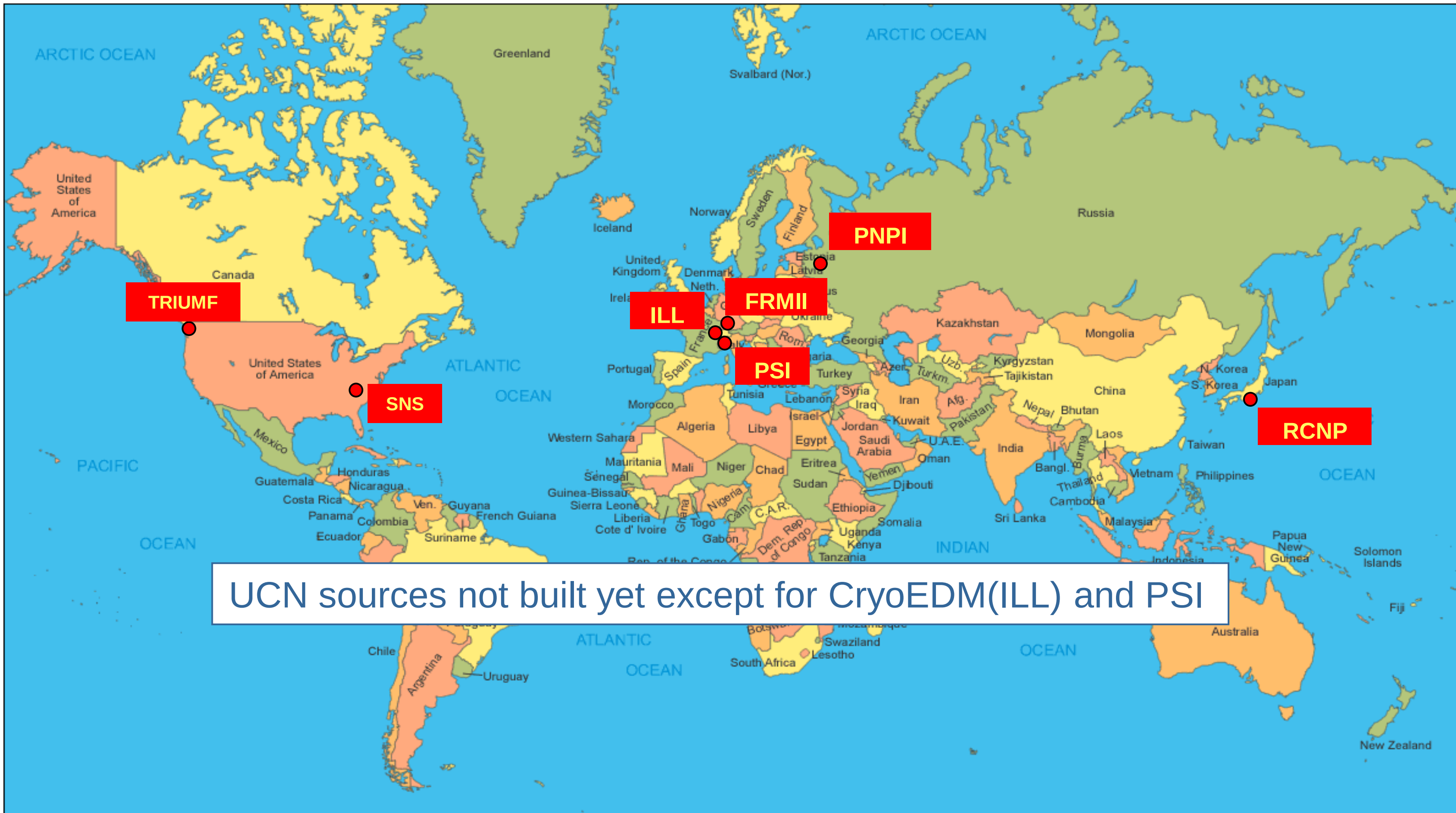
- International context
- General concept
- n2EDM spectrometer
- Systematic effect
- Statistical sensitivity
- French laboratories involvement
- Planning, Man power, Budget

International context

Six nEDM projects worldwide:

- Three running experiments: PSI, ILL (2)
- Three planned experiments: FRMII, SNS, RCNP/TRIUMPF

Goal : $\leq 10^{-27}$ e.cm

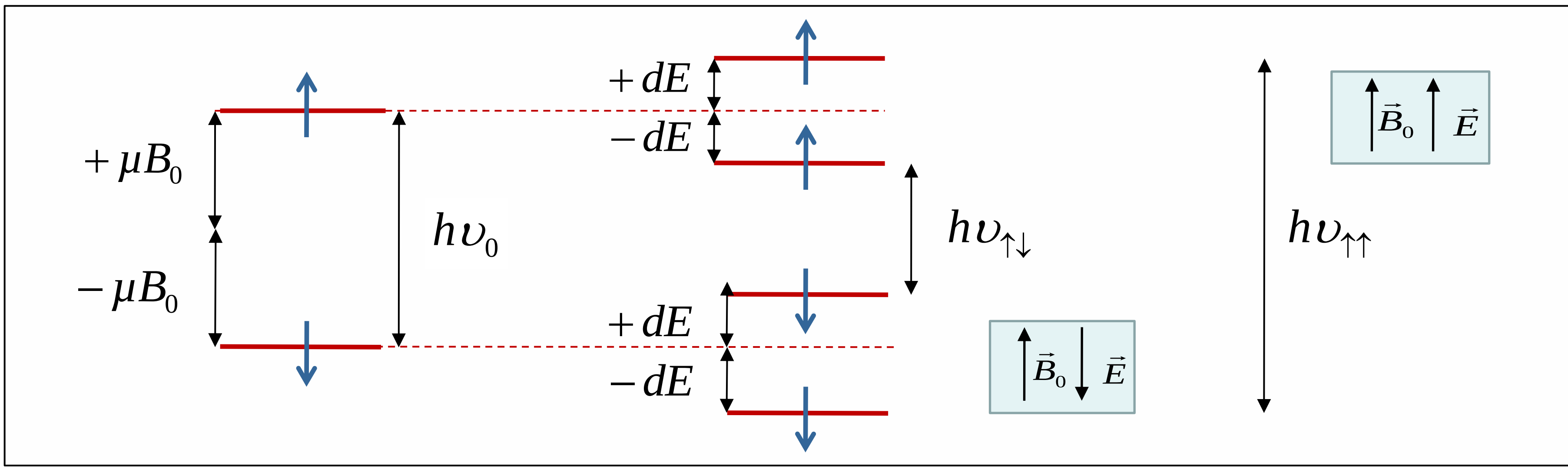


UCN sources not built yet except for CryoEDM(ILL) and PSI

The measurement principle

Neutron Larmor frequency shift induced by electric field

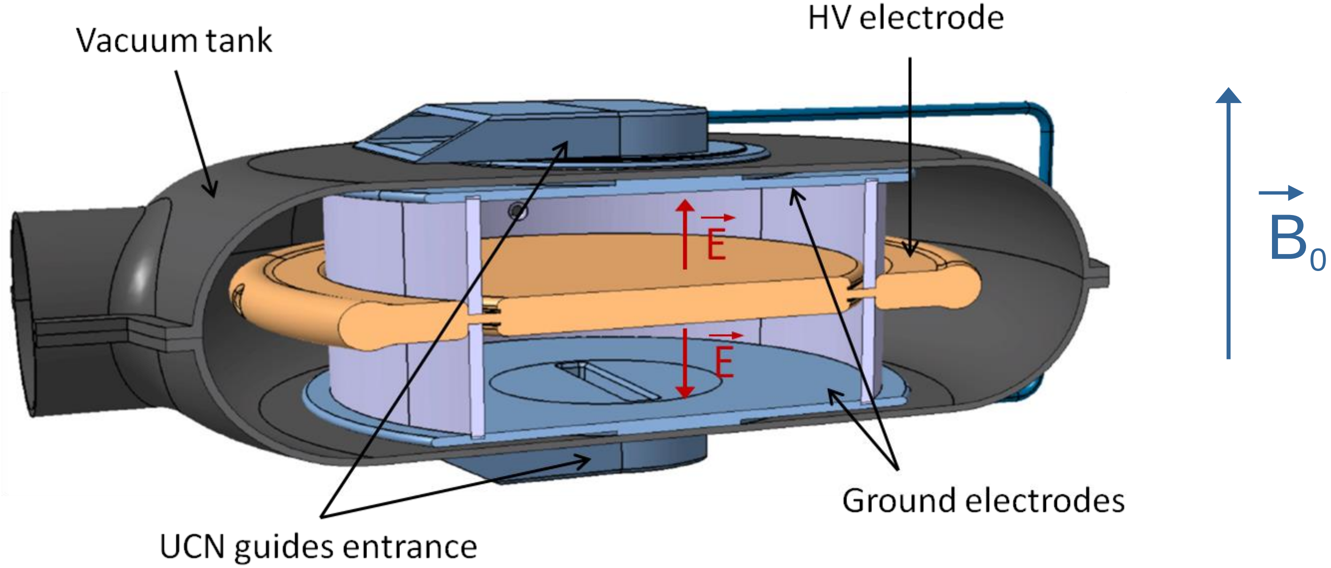
$$h\upsilon_{\uparrow\uparrow} - h\upsilon_{\uparrow\downarrow} = 4d_n E$$



n2EDM: general concept

Simultaneous measurement of the neutron frequency for both field configurations

→ means: two chambers with opposite electric field direction



→ independent of B field drift for parallel and anti-parallel (E,B)

Magnetic field control

Magnetic field stability and homogeneity (B_0 = 1 µT)

- New passive cubic multilayer shield (PSI)

  5 layers, shielding factor ≈ 10^5, shield delivered in 2015

- Coils system (LPC/Kentucky)

  new technique, field homogeneity 10^{-5}, no external field

- Stabilized B_0 current source (LPSC)

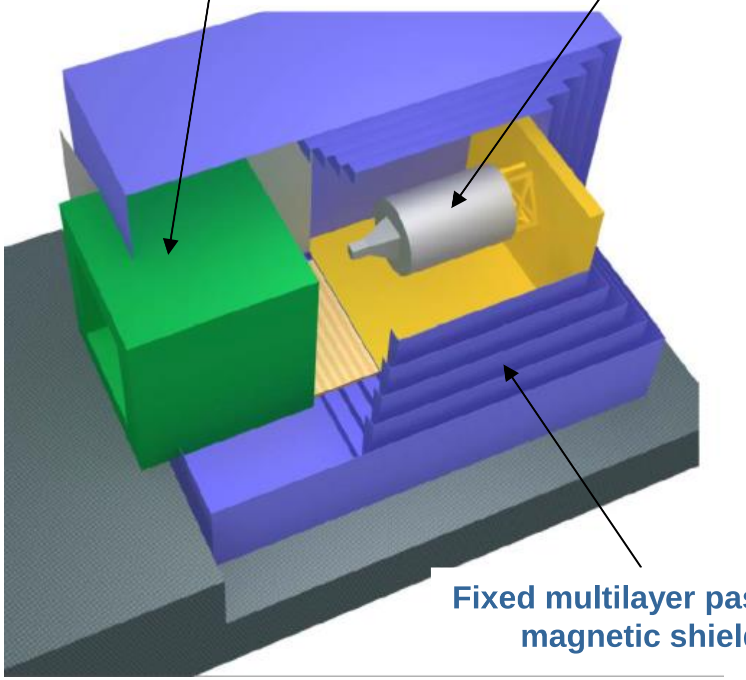
  B_0 drift during precession < 10^{-7} (100 fT)

- Active surrounding field compensation (ETH/Cr)

  reduce external field fluctuations and inhomogeneties

- Shield degaussing (PTB/PSI)

  residual field < 100 pT



+ electrodes degaussing @ PTB, active 3D field stabilization, thermohouse (built)

Magnetic field control

Magnetic field stability and homogeneity (B_0 = 1 µT)

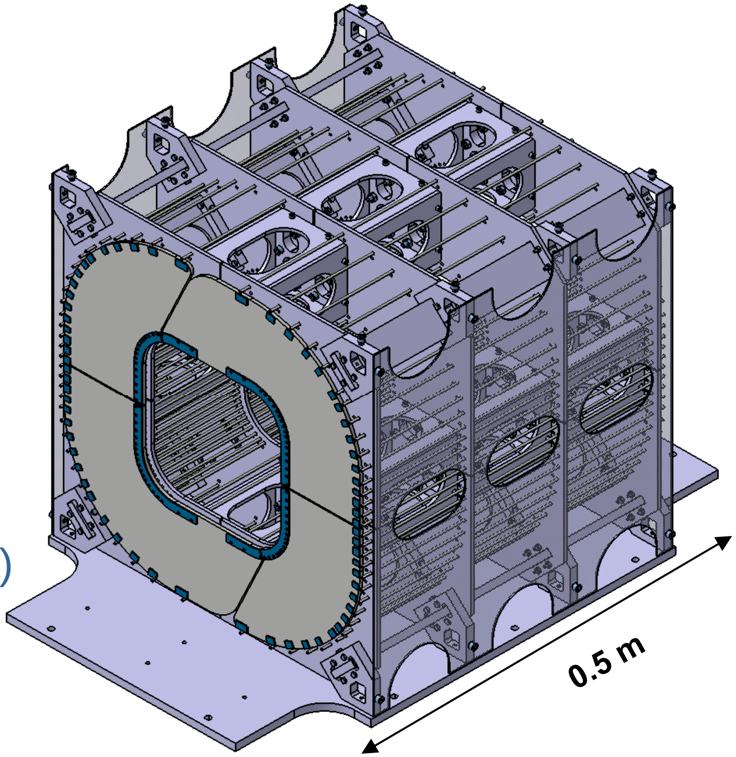
- New passive cubic multilayer shield (PSI)
  5 layers, shielding factor ≈ 10^5, shield delivered in 2015

- Coils system (LPC/Kentucky)
  new technique, field homogeneity 10^{-5}, no external field

- Stabilized B_0 current source (LPSC)
  B_0 drift during precession < 10^{-7} (100 fT)

- Active surrounding field compensation (ETH/Crakow)
  reduce external field fluctuations and inhomogeneties

- Shield degaussing (PTB,PSI)
  residual field < 100 pT



+ electrodes degaussing @ PTB, active 3D field stabilization, thermohouse (built)

Homogeneity < 10^{-5} (10 pT)

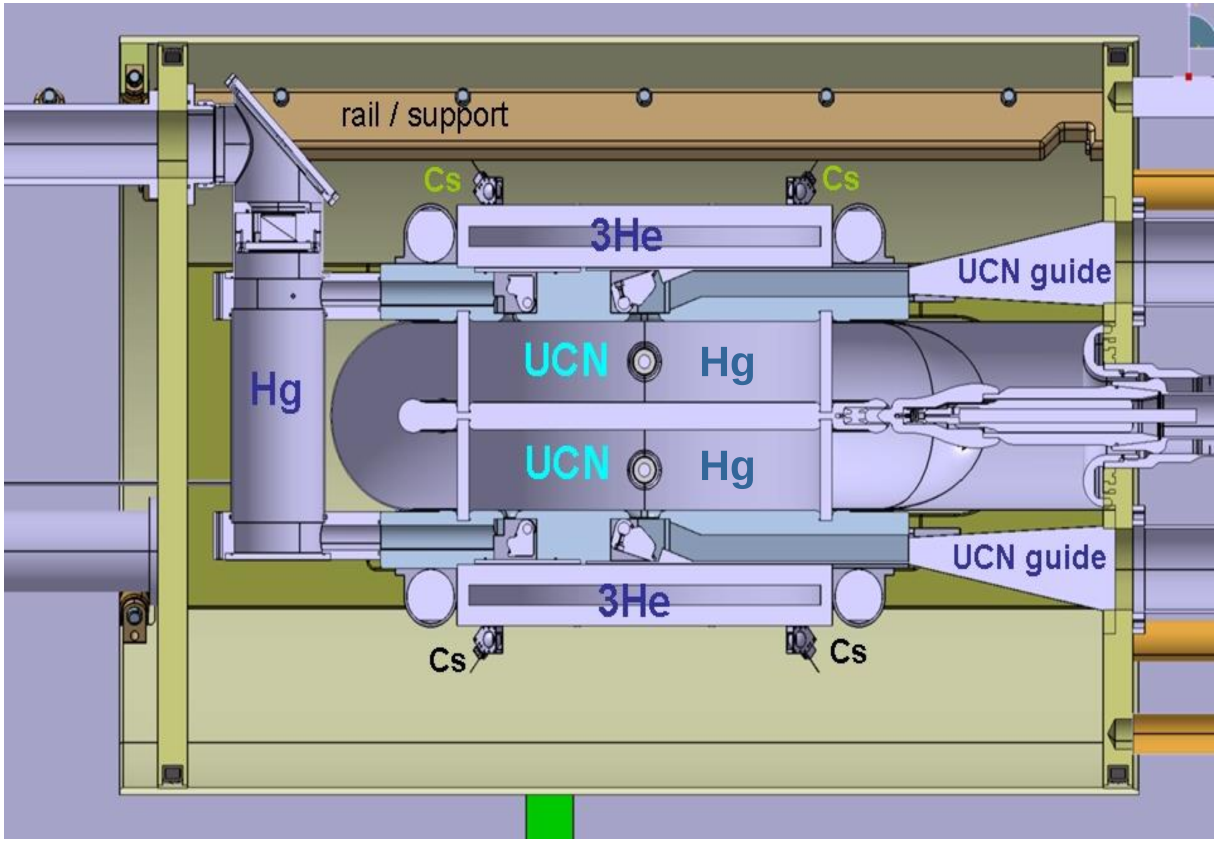
Gradient < 1 pT/cm

Stability during precession < 10^{-7} (100 fT)

Magnetic field monitoring

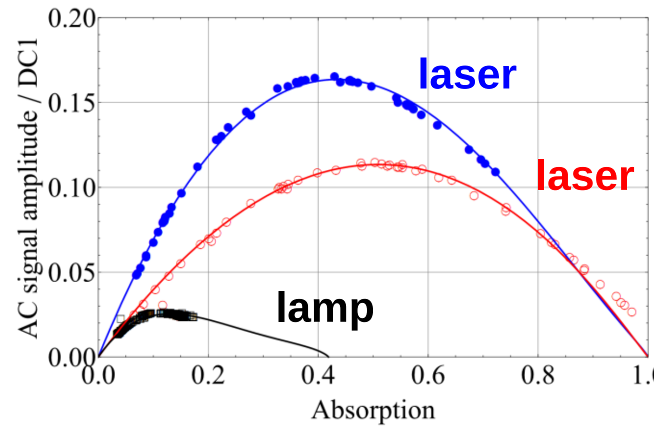
Three magnetometers are going to be used:

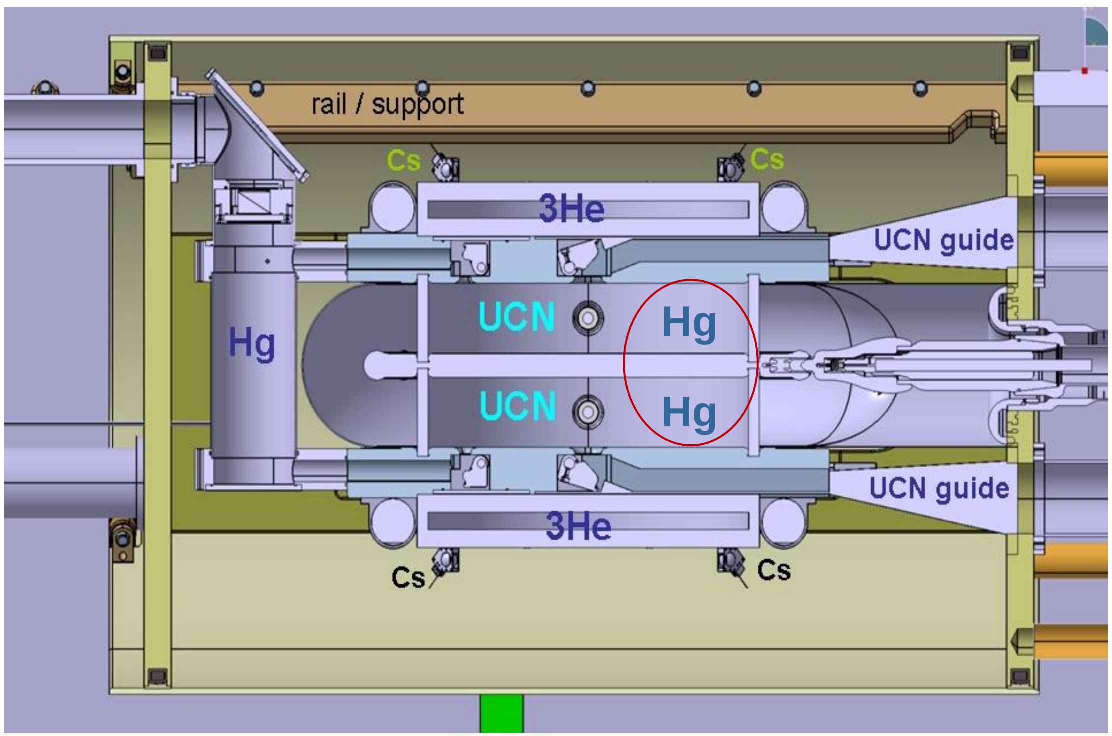
- scalar Hg comagnetometer: field within the precession chambers
- scalar ^{3}He magnetometer: field gradient
- vector Cs magnetometers: field components (transverse)

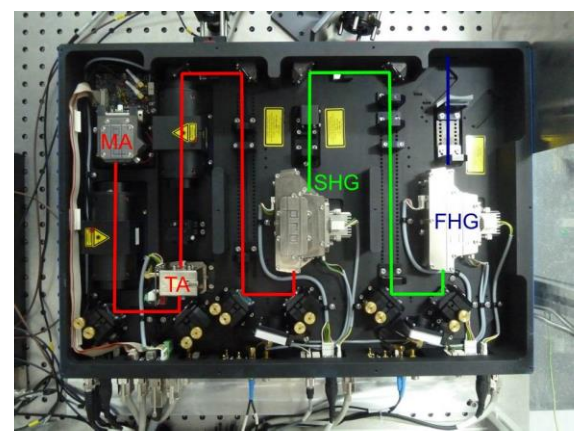


Hg comagnetometer with laser readout (instead of lamp readout)

- field measurement at UCN location (foreseen sensitivity < 50 fT)
- gradient measurement (foreseen sensitivity < fT/cm)
- but sensitive to Geometrical Phase Effect (GPE)



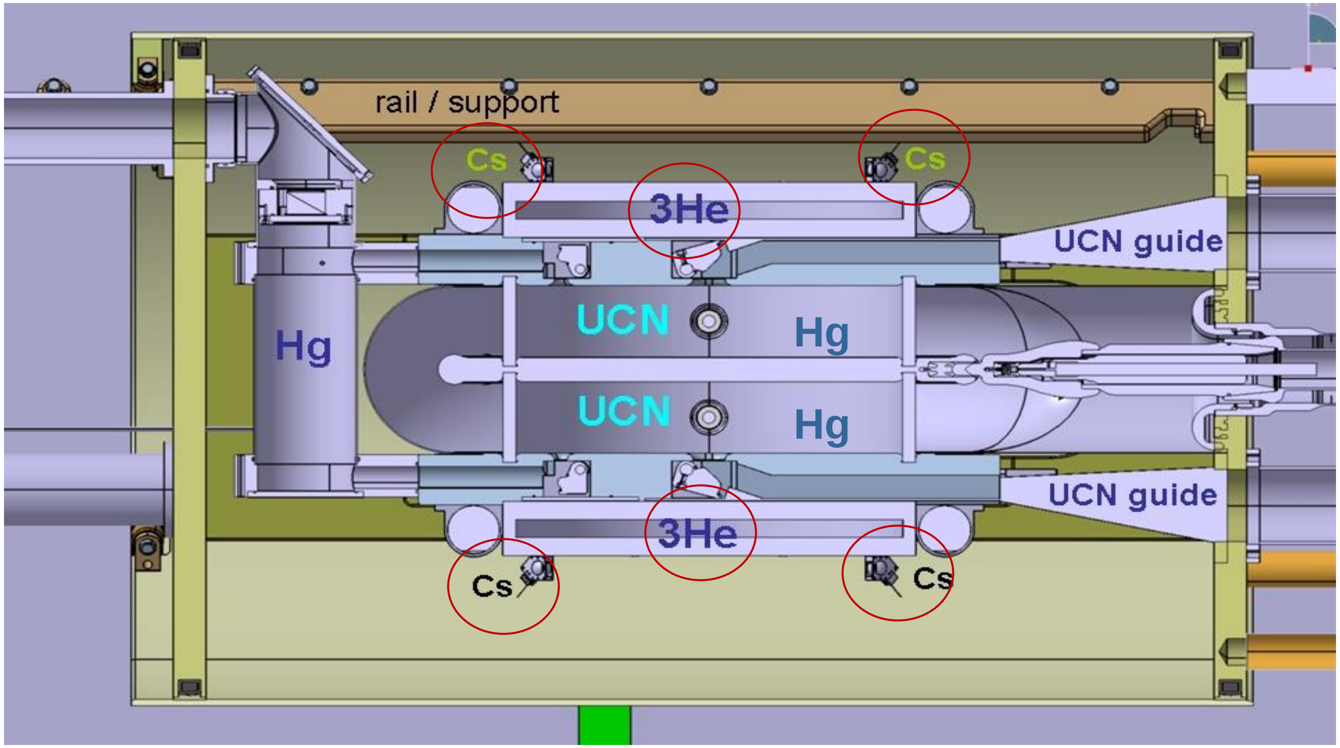




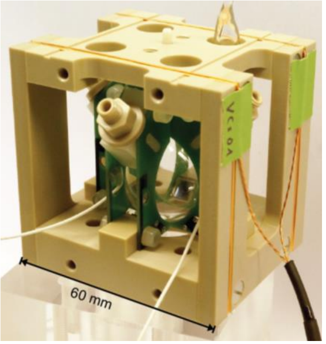
Magnetic field monitoring

External magnetometers: Cs + ^{3}He (free from GPE but further away from UCN location)

- ^{3}He magnetometers (Cs readout): gradient measurement (foreseen sensitivity : < 10 fT/cm)
- vector Cs magnetometers: field components (transverse !)

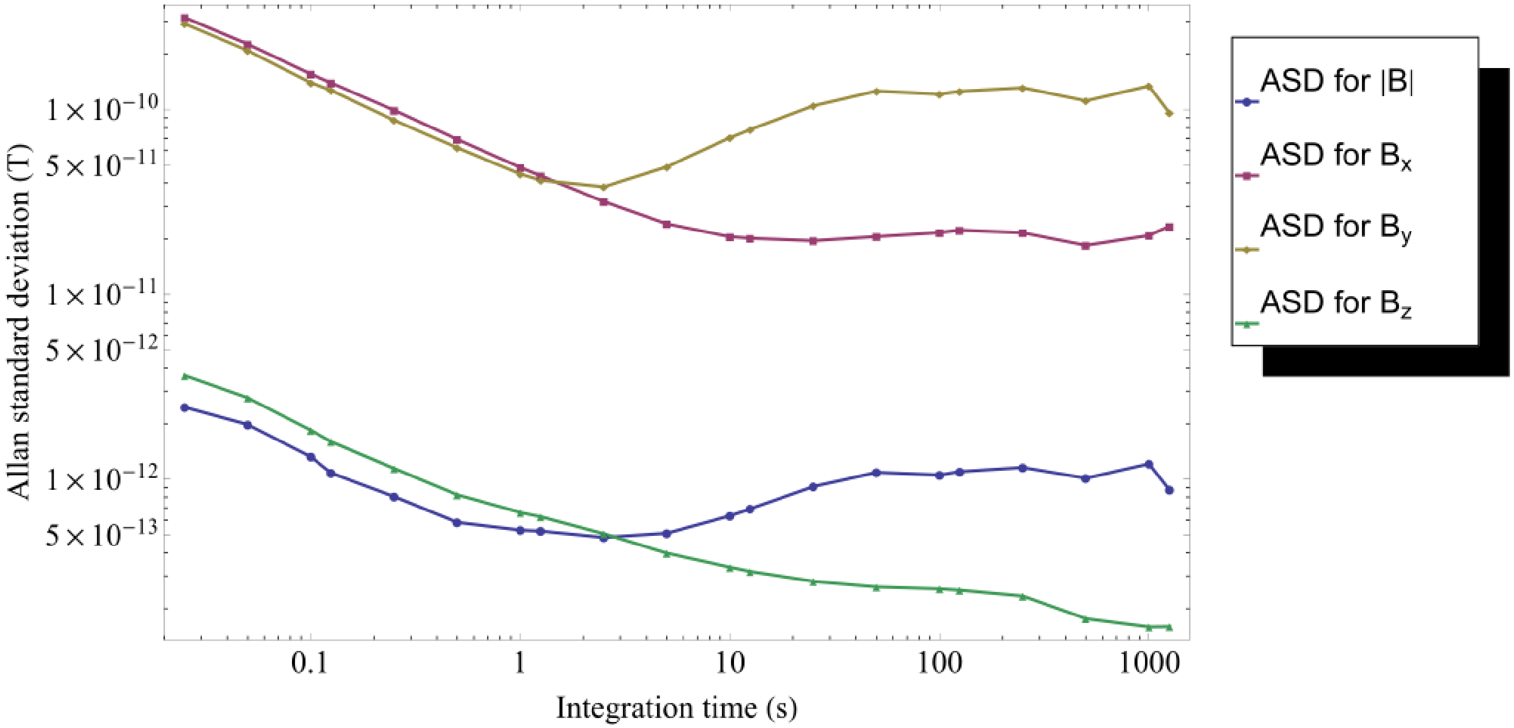


Magnetic field monitoring



External magnetometers: Cs

- Vertical component and field modulus @ 100 s: few 100 fT
- Transverse component @ 100 s: few 10 pT



Mechanical stability has to be improved: 400 pT for transverse components

Systematic effects control

Effects	Status
Direct Effects	
Uncompensated B-Drifts	0.5 ± 1.2
Leakage Current	0.00 ± 0.05
$V \times E$ UCN	0 ± 0.1
Electric Forces	0 ± 0.4
Hg EDM	0.02 ± 0.06
Hg Direct Light Shift	0 ± 0.008
Indirect Effects	
Hg Light Shift	0 ± 0.05
Quadrupole Difference	1.3 ± 2.4
Dipoles	
At the surface	0 ± 0.4
Other Dipoles	0 ± 3
Total	1.8 ± 4.1

Homogeneity and stability
Field homogeneity: < 10^{-5}
Field stability : 10^{-7}

Online field monitoring
Comagnetometer (Hg)
External magnetometers (Cs + ^{3}He)

↓

Vertical gradient
Field components (transverse)

+ offline 3D field maps

Global systematic error < 10^{-27} e.cm

Expected statistical sensitivity

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

→ work on improving (α, E,T,N) parameters

Parameter	Improvement factor	Comment
Neutrons number $\sqrt{N}$	5	Spectrometer – source height (x 3) Double precession chambers (x 1.5)
Electric field E	1.3	New electrodes geometry
Visibility α	1.25	Larger T2 (field homogeneity)
Precession time T	?	Coating investigation (Diamond)
Statistical sensitivity	8	Based on the current source performances

Foreseen sensitivity

4.10^{-26} e.cm / day → 2.10^{-27} e.cm / 4 years

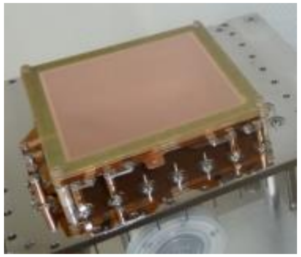
Tasks distribution

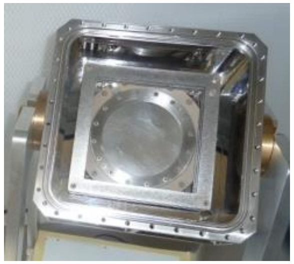
ITEM	TASK RESPONSIBLE
UCN Source	PSI
New thermohouse (completed)	PSI
Passive magnetic shield	ETH/ PSI
B0, correcting, RF coils system	Caen (Design, prototype) / Kentucky/ ETH/ PSI/ Grenoble (Source)
UCN precession chamber + guides	Mainz/ PSI
Surrounding field compensation	ETH/ Cracow
Degaussing	PTB/ PSI
Vacuum tank + vacuum system	Leuven+ Caen (Design, construction)
High voltage	PSI
Magnetometry (Hg, Cs, ^{3}He)	Fribourg/ Mainz/ Jena/ Grenoble (Hg)/ PTB/ PSI
Setup / experiment support	PSI+ Caen (Design, construction)
Detector+ Spin Analysis	Caen
DAQ	Cracov/ Caen (Front End-Faster)

+ French group: data analysis + systematic effects studies
+ n2EDM design (simulation, modeling)

French laboratories involvement

$n + {}^{3}He \rightarrow {}^{1}H + {}^{3}H$ (+ 0.77 MeV)

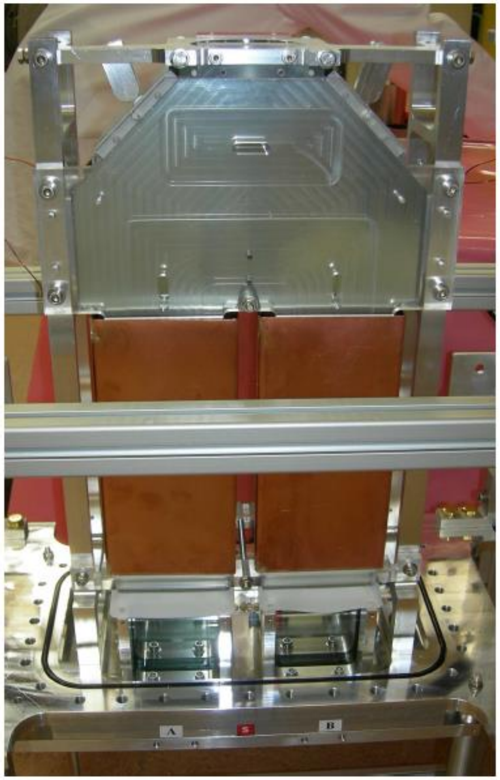




Detection: development of a new fast ^{3}He gas detector
- lower gamma sensitivity, larger detection efficiency
- ability to handle large rate: up to few 10^5 UCN/s

Two sealed versions are considered : HeGEM vs HeScint

Combined with FASTER acquisition system



Spin analysis and guiding fields:
- holding fields along UCN path (E. Pierre thesis, 2012)
- simultaneous measurement of UCN polarization (V. Hélaine,)

Prospective: diamond coating for the apparatus inner walls
major improvement if successful (test in 2014)

n2EDM requirements:

- 2 simultaneous spin analysers + 4 detectors

French laboratories involvement

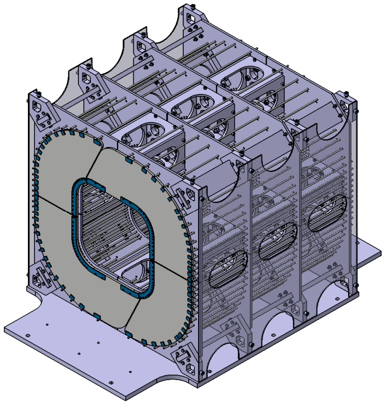
Coil design: new technique + double layers
→ field uniformity < 10^{-5} (LPC/Kentucky)

Magnetic field mapping:
→ 3D field map within vacuum chamber

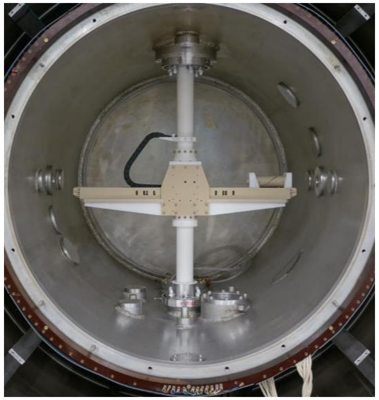
Stable B_0 current source (Y. Kermaïdic thesis):
→ stability during precession < 10^{-7} (100 fT)

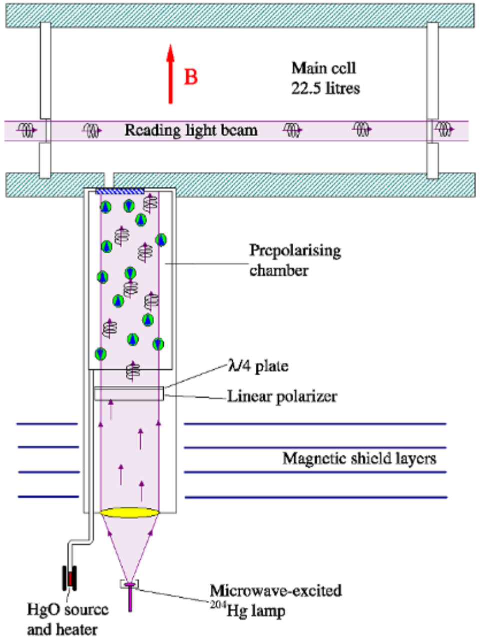
Hg comagnetometer (Y. Kermaïdic thesis):
→ Hg depolarisation vs electric field reversal
→ Buffer gas: GPE suppression

DISCO prototype



Mapper – winter 2013





B0 current source

Planning

Global planning
2014-2017 : construction
2018 : commissioning
2018-2022 : data taking

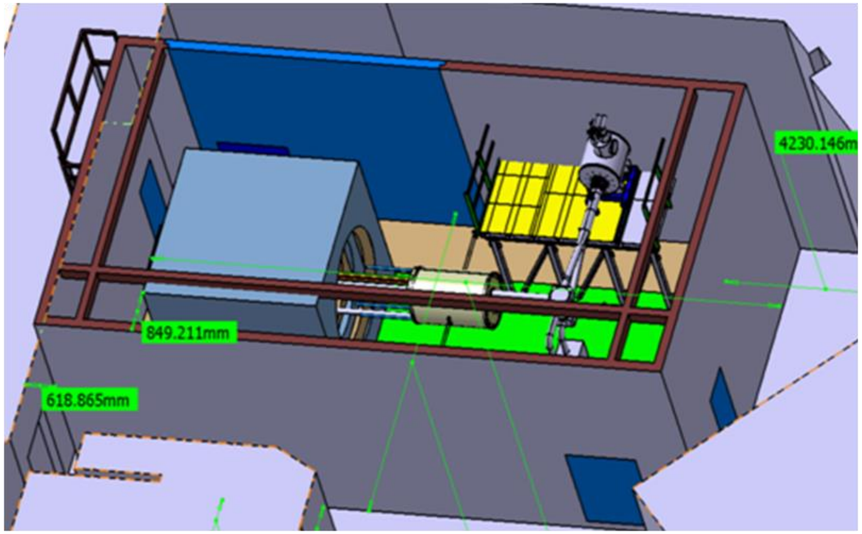
2013: thermohouse built + shield WTO call

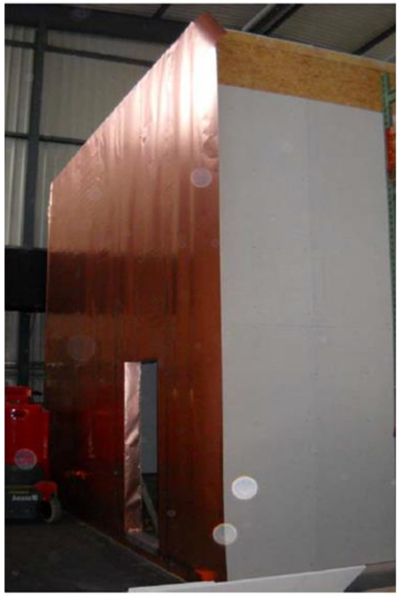
2015: magnetic shield delivered to PSI

2014-15:
- overall mechanical design
- detectors prototype, diamond coating
- Hg test bench

2015-17:
- mechanical support, vacuum chamber, coils
- UCN guides and switch, HV feed-through
- storage chamber, corona ring

2017-2018 :
- test, optimization, assembling





Manpower involvement

LPC, Caen
Gilles Ban (Prof. ENSI - 50%)
Victor Hélaine (PhD, 2011-14)
Thomas Lefort (MdC UCBN - 100%)
Yves Lemière (MdC UCBN - 50%)
Gilles Quéméner (CR - 35%)

CSNSM, Paris
Stéphanie Roccia (MdC - 50%)

LPSC, Grenoble
Benoit Clément (MdC – 50%)
Y. Kermaïdic (PhD, 2013 -16)
Guillaume Pignol (MdC - 40%)
Dominique Rebreyend (DR - 75 %)

LPSC + CSNSM + LPC
Physicist: 2.8 ETP

Department	Man year
Mechanical design and manufacturing	6
Front end electronics and data acquisition	2.5
Instrumentation and detectors	4

for 2014 - 2018

PhD students: keep on co-advised PhD students with share funding (3 with nEDM)
Current request : post docs @ LPC

Overall budget

ITEM	COST (k€)	TASK RESPONSIBLE	FUNDED
UCN Source	A lot…	PSI	X
New thermohouse (completed)	260	PSI	X
Passive magnetic shield	2'000	ETH/ PSI	X
B0, correcting, RF coils system	400	Caen (Design, prototype) / Kentucky/ ETH/ PSI/Grenoble (Source)	
UCN precession chamber + guides	600	Mainz/ PSI	
Surrounding field compensation	200	ETH/ Cracow	
De-Gaussing	100	PTB/ PSI	
Vacuum tank + vacuum system	250	Leuven+ Caen (Design, construction)	
High voltage	100	PSI	
Magnetometry (Hg, Cs, ^{3}He)	700	Fribourg/ Mainz/ Jena/Grenoble (Hg)/ PTB/ PSI	
Setup / experiment support	150	PSI+ Caen (Design, construction)	
Detector+ Spin Analysis	200	Caen	
DAQ	200	Cracov/ Caen (Front End-Faster)	
Total	***5'160***		

Funding

← ANR application (535 k€) →

	2014	2015	2016	2017	2018	2019
Equipment	135	110	220	70	20	20
Travels + meeting + conf	35	35	35	35	35	35
nEDM maintenance	15	15	15	15	15	15

ANR grant application :

- pre-proposal submitted → 2014-2018
- budget: 535 k€ → exp. development

- in2p3 involvement:
  travels + minimal technical developments

- in2p3 support

Task	Item	Cost (k€)
Detection	Scintillating ^{3}He detectors GEM ^{3}He detectors	55 125
Spin analysis and guiding coils	Diamond coating Simultaneous spin system	40 40
Hg magnetometer	Test bench n2EDM Hg co-magnetometer design and construction	70 50
Current source	Design and construction	30
B field mapping and reconstruction	Computer and software	15
Coil design and construction	Self compensated coil	100
General design	Vacuum tank (if granted to the French groups by the collaboration)	100

Conclusion

International context:

- CryoEDM @ILL → 10^{-27} e.cm level: but not running yet
- other experiments are waiting for their UCN source

PSI n2EDM project:

UCN source already started, improvements are actively pursued, strong PSI support

Any new technique or device can be tested within OILL spectrometer

→ allow producing real improvements for n2EDM spectrometer

Foreseen sensitivity: 2.10^{-27} e.cm in 2022
(with current source performances)

→ Test of the generic electroweak baryogenesis

Potentially achievable: 10^{-28} ecm range
with UCN source improvement (factor 10 not understood yet)

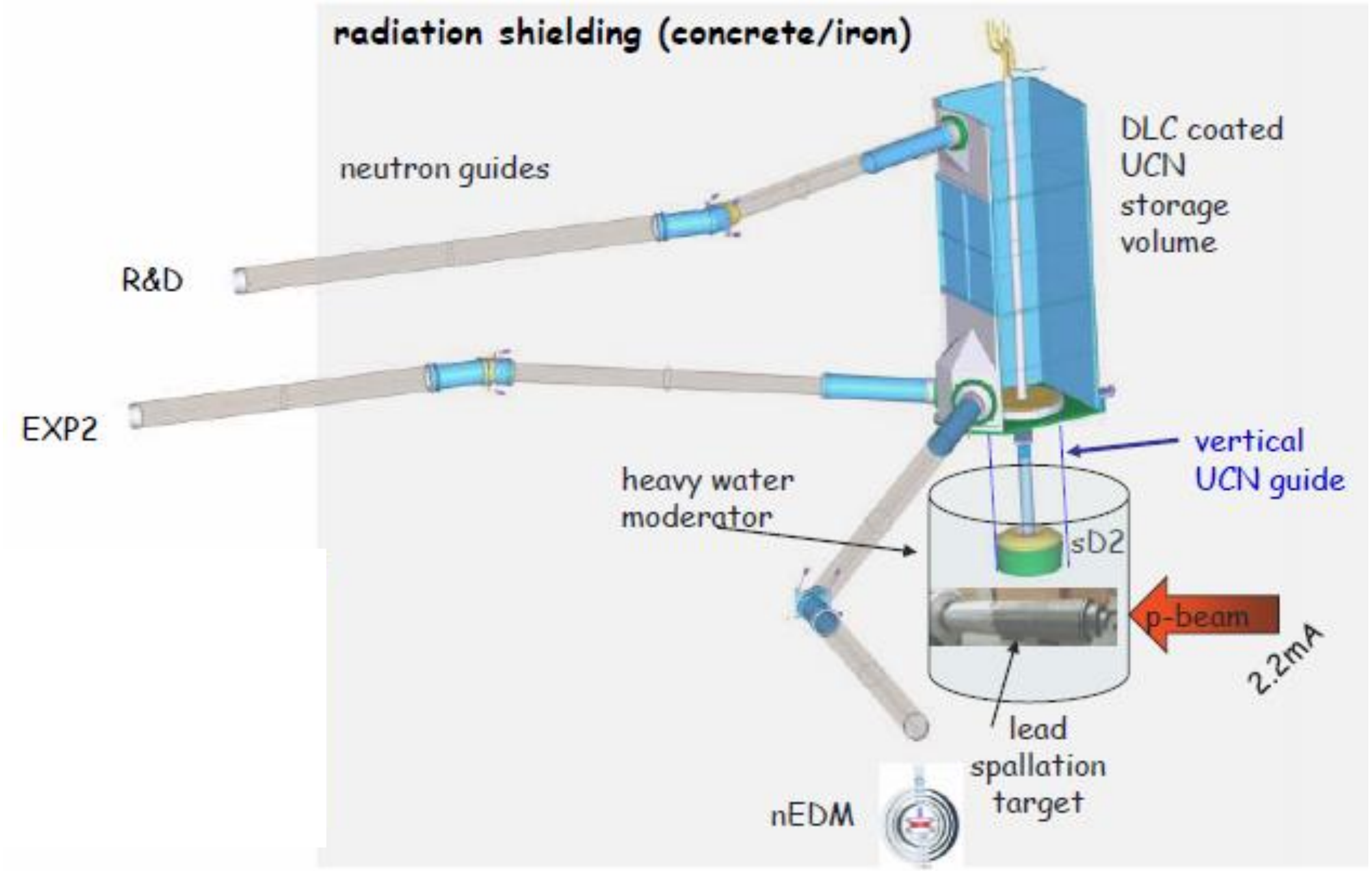
→ Further constraints on SM extensions

Magnetic field control

	nEDM	n2EDM
Passive magnetic Shield: shielding factor	1500 – 10000 (< 1 Hz)	10^5 (< 1 Hz)
Active surrounding field compensation (SFC): attenuating factor	DC field: 20 AC field: 5 – 50 @ 10^{-4} – 1 Hz	Uniform field (> 12 coils)
Correcting coils: internal field homogeneity	~ 10^{-4}	< 10^{-5} (<10 pT)
Correcting coils: external field	Shield is magnetized	No ext. field
Active 3D field stabilization	-	Vector Cs
Current source: B0 drift during precession	~ 200 fT	100 fT
Field gradient	~ 10 pT/cm	< 1 pT/cm
Residual field after degaussing *(in situ)*	< 2 nT	< 100 pT
Hg cohabiting magnetometer: sensitivity	200 fT (lamp)	< 50 fT (laser)
External ^{3}He magnetometer with Cs readout: sensitivity	-	Calcul: ~1 fT Exp: ~ 50 fT over 100 s
External vector Cs mag.: sensitivity	Scalar Cs: 50 pT	1 pT

Thermo house (ΔT=0.2 K) knowing that ΔB = 2 pT/K due to shield dilatation
Electrodes degaussing @ PTB: < 50 pT @ 3 cm

The UCN source @ PSI



International context

Running experiments:

nEDM @ ILL (RAL Sussex): 10^{-27} ecm in …

- commissioning phase: first nEDM data in 2016 ?
- UCN production within superfluid He → cryogenic issue slow down progresses

nEDM @ ILL (PNPI): < 10^{-27} ecm level in …

- old PNPI spectrometer at PF2: 10^{-26} ecm level in 2016 with EDM beam line
- new storage chamber + new UCN source (reactor + SD_2) @ PNPI, not built yet

Planned experiments:

nEDM @ Munich: < 10^{-27} *ecm* in …

- UCN source @ FRMII reactor, building ongoing (SD_2), experiment in 2016 ?

nEDM @ Oak Ridge (SNS):

- spallation + superfluid He, building ongoing, exp. not before 2020

nEDM experiment at RCNP/TRIUMF:

- spallation + superfluid He, building ongoing, experiment not before 2020

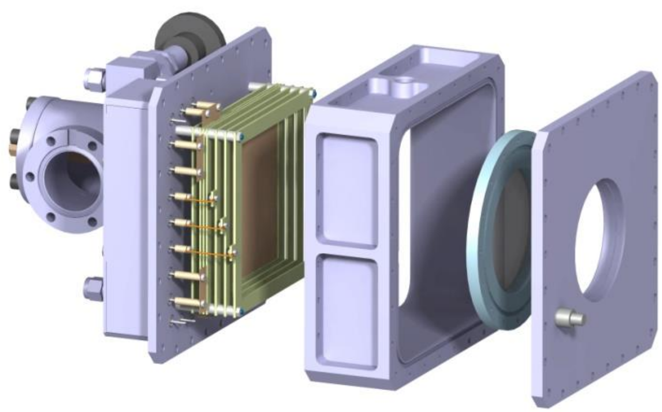
French laboratories involvement (LPC)

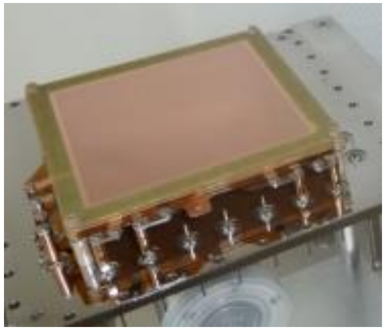
Detection: development of a new fast ^{3}He gas detector

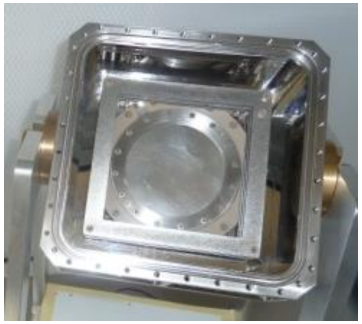
- lower gamma sensitivity and larger detection efficiency (~20 %)
- ability to handle large rate: up to few 10^5 UCN/s

Two sealed versions are considered :

- HeGEM: induced current, readout performed with GEM
- HeScint: scintillation in CF_4, readout performed with PMT no gas contaminant, more stable







Combined with FASTER acquisition system

$n + {}^3He \rightarrow {}^1H + {}^3H$ (+ 0.77 MeV)

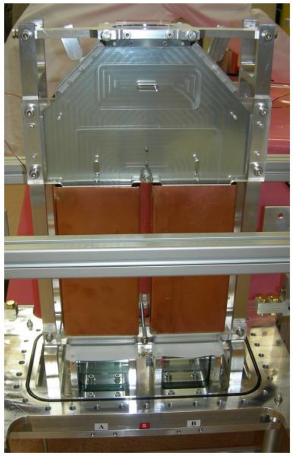
Status: HeGEM successfully tested with alpha source @ 1 MeV, 100 ns
HeScint OK with alpha @ 5 MeV, 20 ns

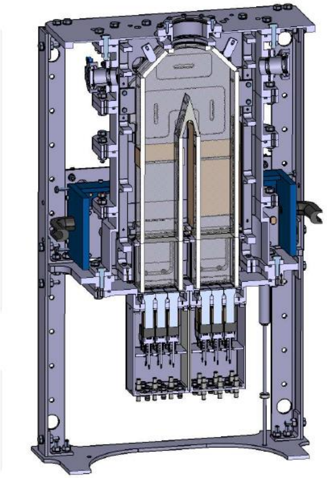
n2EDM: 4 detectors are required

French laboratories involvement (LPC)

Spin analysis and guiding fields:

- holding fields along UCN path (E. Pierre thesis, 2012)
- simultaneous measurement of UCN polarization (V. Hélaine, ongoing PhD)





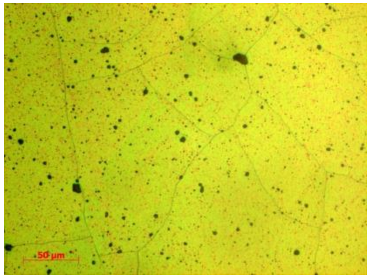
Status: prototype (USSA) has been built
→ final tests this week

Former tests have already shown that:

- spin analysis is under control
- UCN transmission can be improved

Prospectives: diamond coating for the inner walls of the apparatus

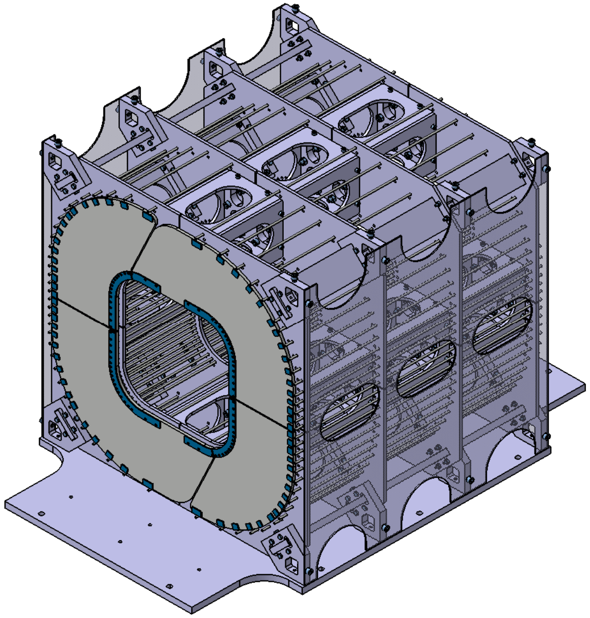
major improvement if successful !



Status:
Fermi potential ~ 300 neV → 25 % higher than current coating
Further tests in 2014 (LPC/PSI): storage chamber

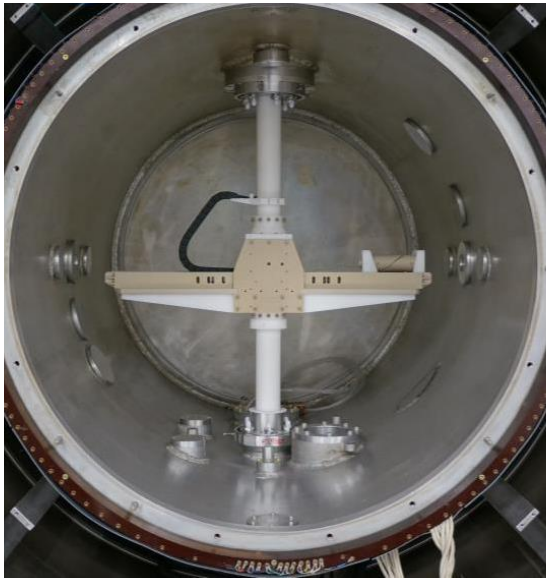
French laboratories involvement (LPC)

Coil design: new technique + double layers
→ field uniformity < 10^{-5}



Status: prototype is studied (LPC/Kentucky)
if funded, construction at LPC in 2014

Magnetic field mapping:
→ 3D field map within vacuum chamber

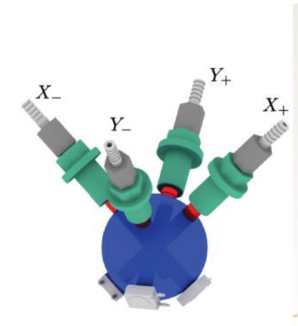


Status: keep on doing such activities

n2EDM: the new spectrometer

Vector Cs magnetometer (Georg)

Field modulus: the frequency of the recorded FID signals
Field direction : amplitudes and relative phases of the three FID signals



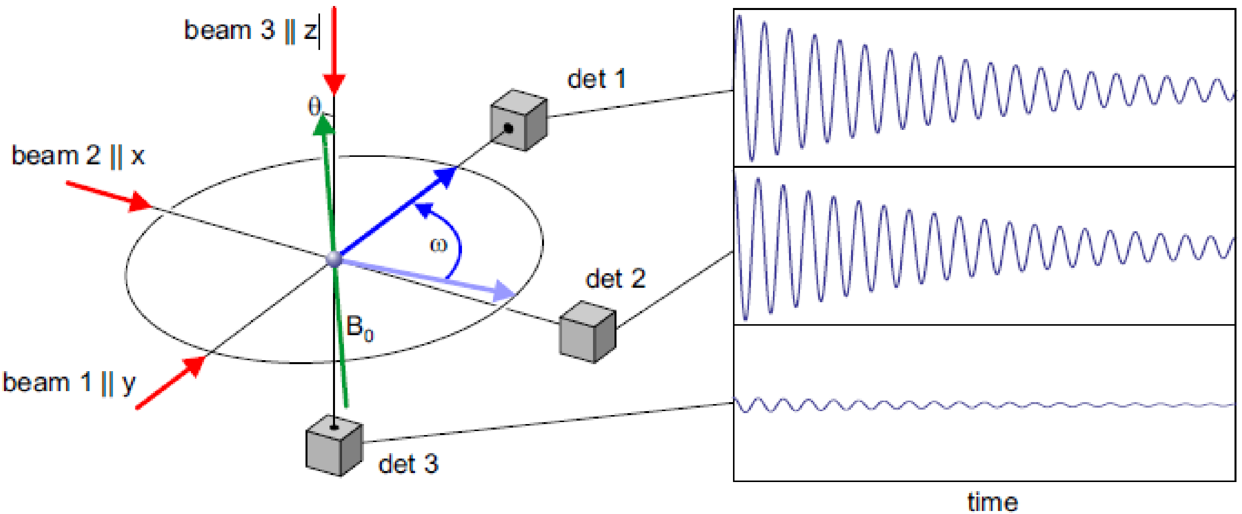
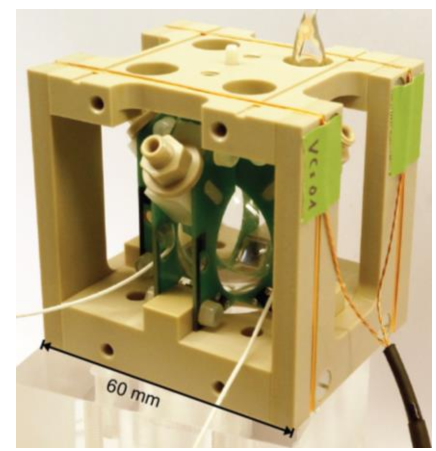


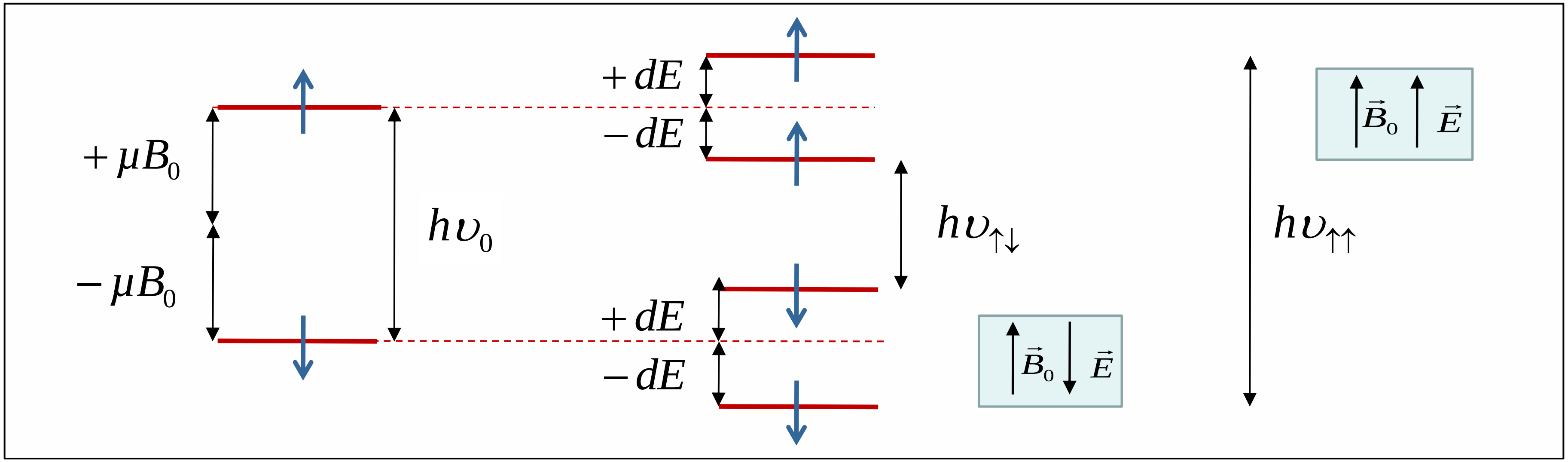
Figure 73: Schematic setup of a multi-beam vector magnetometer. The atomic spins (blue arrows) precess in a plane perpendicular to the static magnetic field B_0. Three laser-beams along the coordinate axes are used to detect the spin precession. Three detectors (det 1,2,3) detect the intensity changes in the leaser beams caused by —spin-direction dependant— absorption. The FID signals show a smaller amplitude in the z-direction since the polar angle θ of the magnetic field is small in this example.



The measurement principle

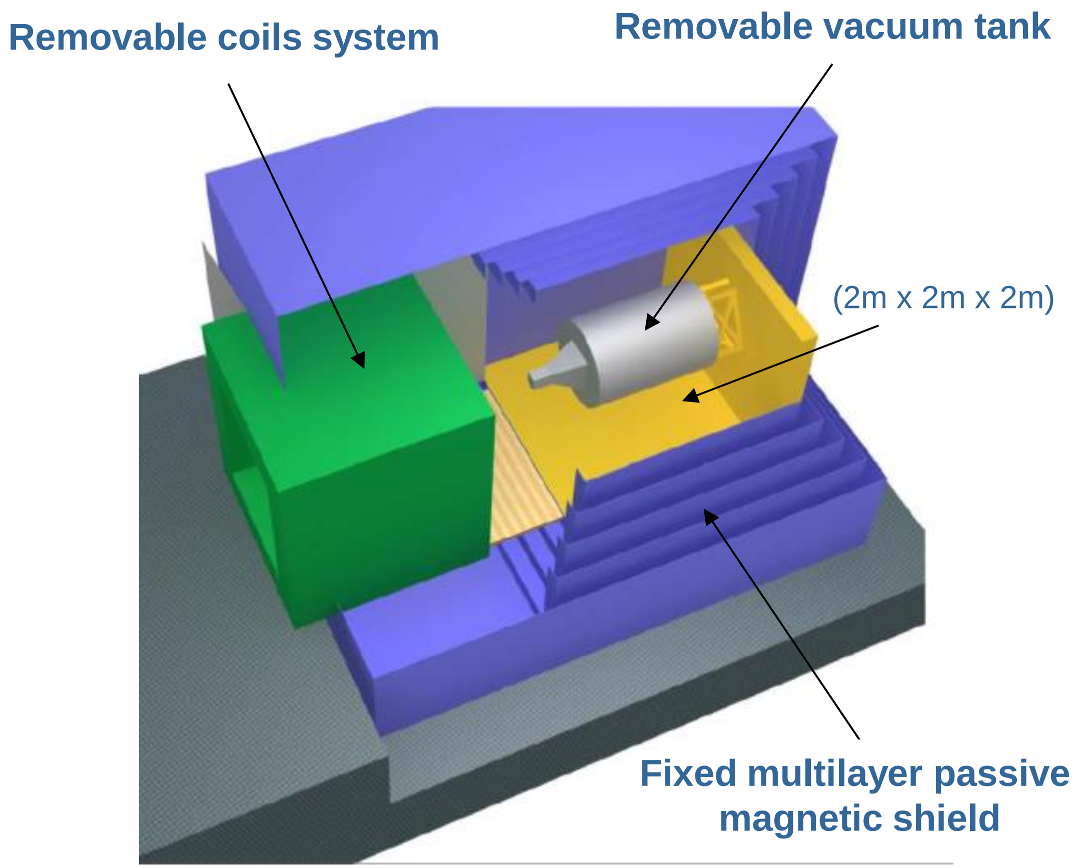
Neutron Larmor frequency shift induced by electric field

$$h\upsilon_{\uparrow\uparrow} - h\upsilon_{\uparrow\downarrow} = 2\mu(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}) + 4d_n E$$



n2EDM: general concept

Passive multilayer magnetic shield + correcting coils system + magnetometers + ...



General concept