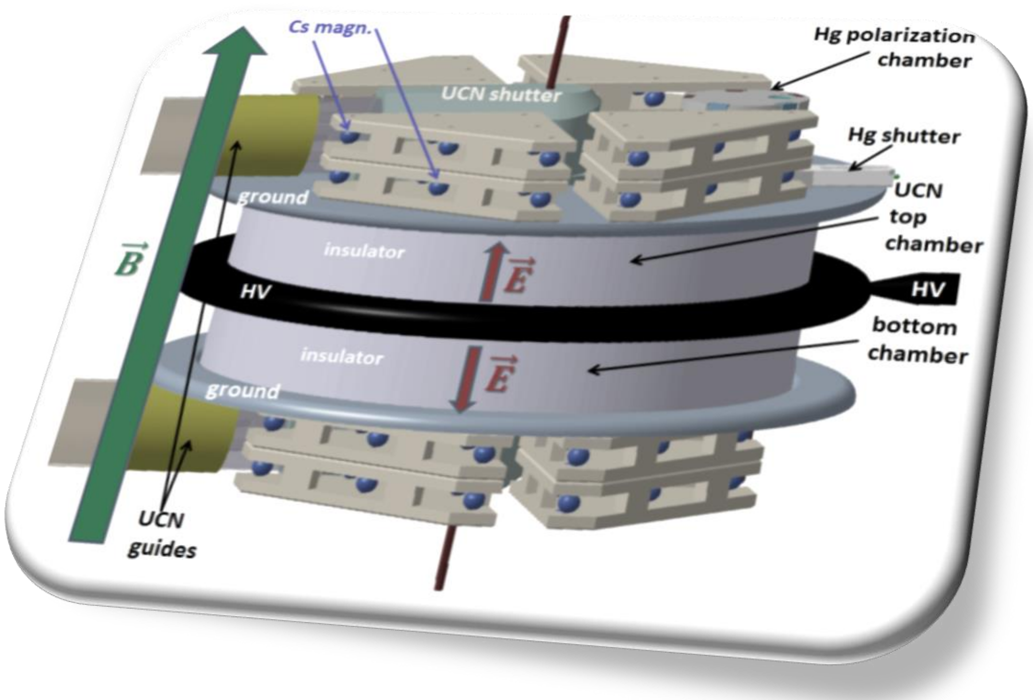
Pushing the limits of room temperature neutron electric dipole moment measurements with n2EDM

Romain VIROT



Introduction

- Baryonic asymmetry of the Universe (BAU): $\eta = \dfrac{n_b - n_{\bar{b}}}{n_\gamma}$

Theory
(w/ SM already known symmetry violations)

$\eta \leq 10^{-18}$

Many orders of magnitude!

Measurements

$\eta = 6.1^{+0.3}_{-0.2} \times 10^{-10}$ CMB

$5{,}1 \times 10^{-10} < \eta < 6.7 \times 10^{-10}$ Abundance of light elements produced in primordial nucleosynthesis

Sakharov conditions:

1. B violation
2. C and CP violation
3. Departure from thermal eq.

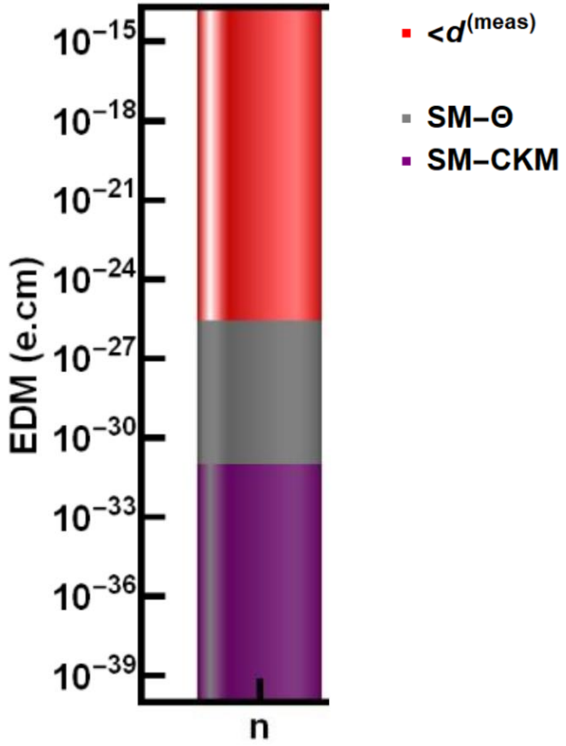
Particle with non-zero permanent Electric Dipole Moment (EDM):

- P and T violation
- CP violation (assuming CPT conservation)

Introduction

Beyond the Standard Model (BSM) physics are required to explain observed BAU

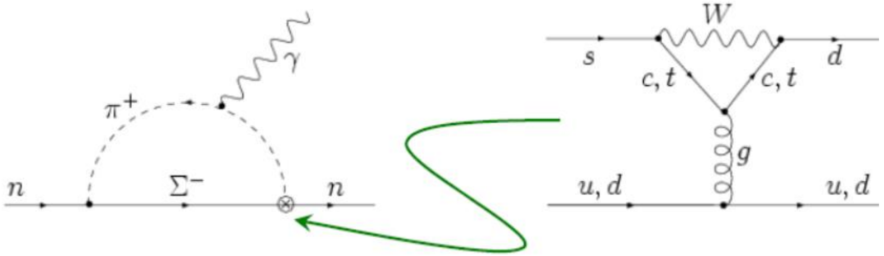
More CP-violation ⟺ larger EDM



Neutron EDM best limits:

- Direct: $\mathbf{3.0 \times 10^{-26}}$ **e.cm** — Baker et al, Phys Rev Lett 97, 131801 (2006); Pendlebury et al, Phys Rev D 92, 092003 (2015)
- Derived from ^{199}Hg (sole source assumption): $\mathbf{1.6 \times 10^{-26}}$ **e.cm**

arXiv:1601.04339v4 [physics.atom-ph] 17 Aug 2017



Strong discovery potential!

SM background (CKM) $\sim 10^{-32}$ e.cm

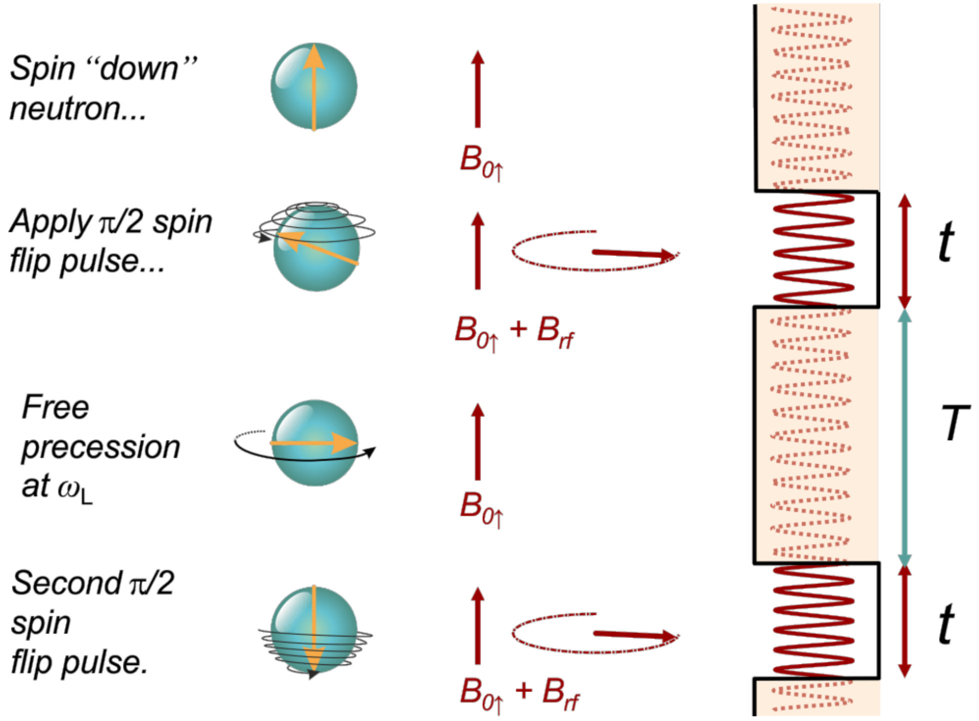
Ramsey method of time separated oscillating fields

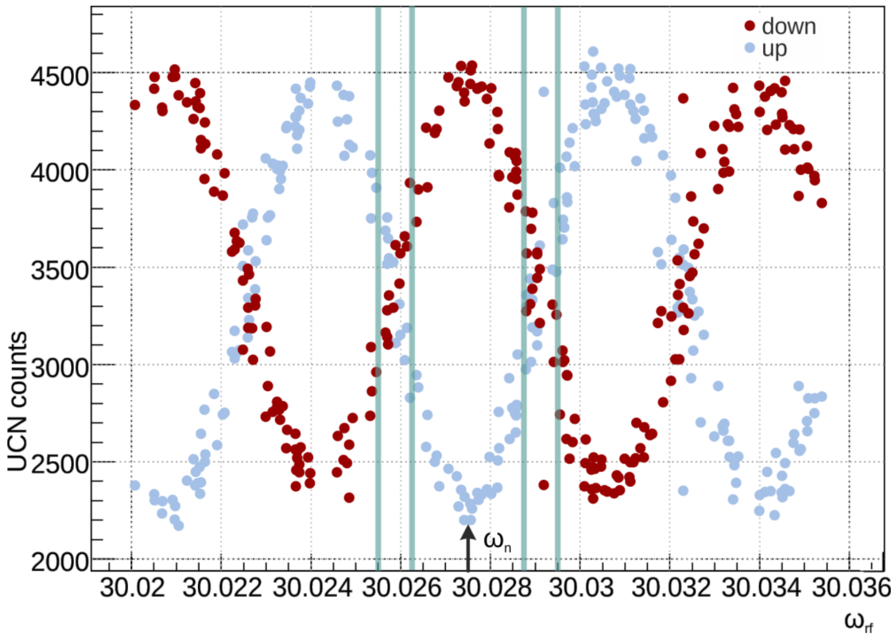
- Larmor frequency of a neutron in a parallel (↑↑) / anti-parallel (↑↓) B and E field configuration:

$$h\nu_{\uparrow\uparrow} = -2(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow})$$
$$h\nu_{\uparrow\downarrow} = -2(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow})$$

- Neutron EDM is extracted from the differential measurement between the two frequencies $\nu_{\uparrow\uparrow}$ and $\nu_{\uparrow\downarrow}$:

$$d_n = \frac{h(\nu_{\uparrow\downarrow} - \nu_{\uparrow\uparrow}) - 2\mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})}$$





Ultracold neutrons

Statistical sensitivity:

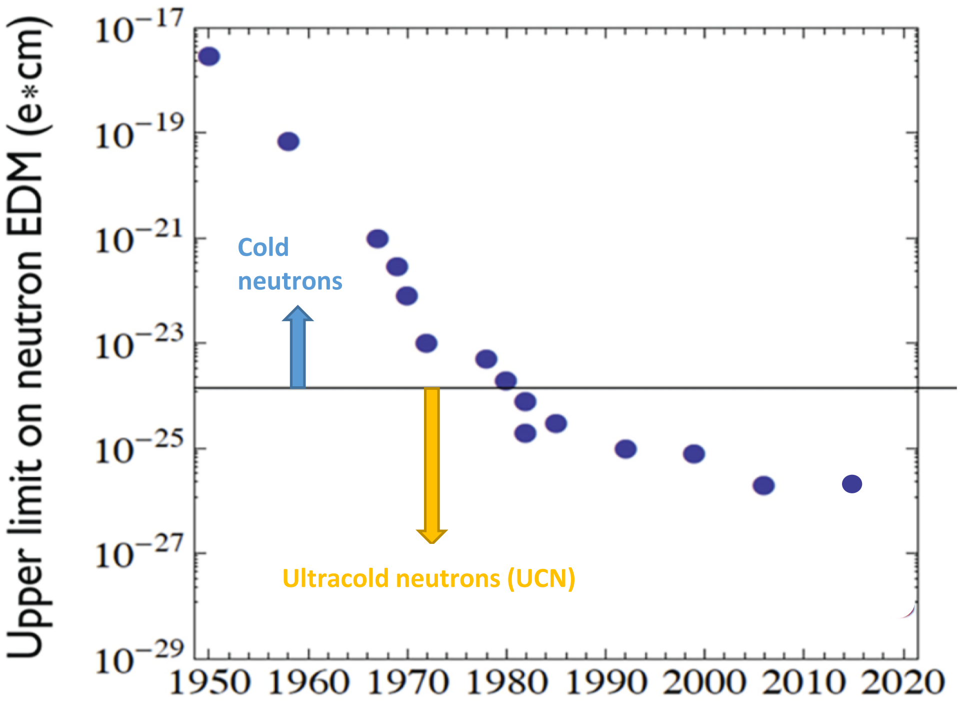
$$\sigma(d_n) = \frac{\hbar}{2\alpha|E|T\sqrt{N}}$$

Visibility = (final polarization) x (analyzing power)

Electric field

Free precession time

Number of counted neutrons



Hardest challenges: Number of neutrons and control of the B field!

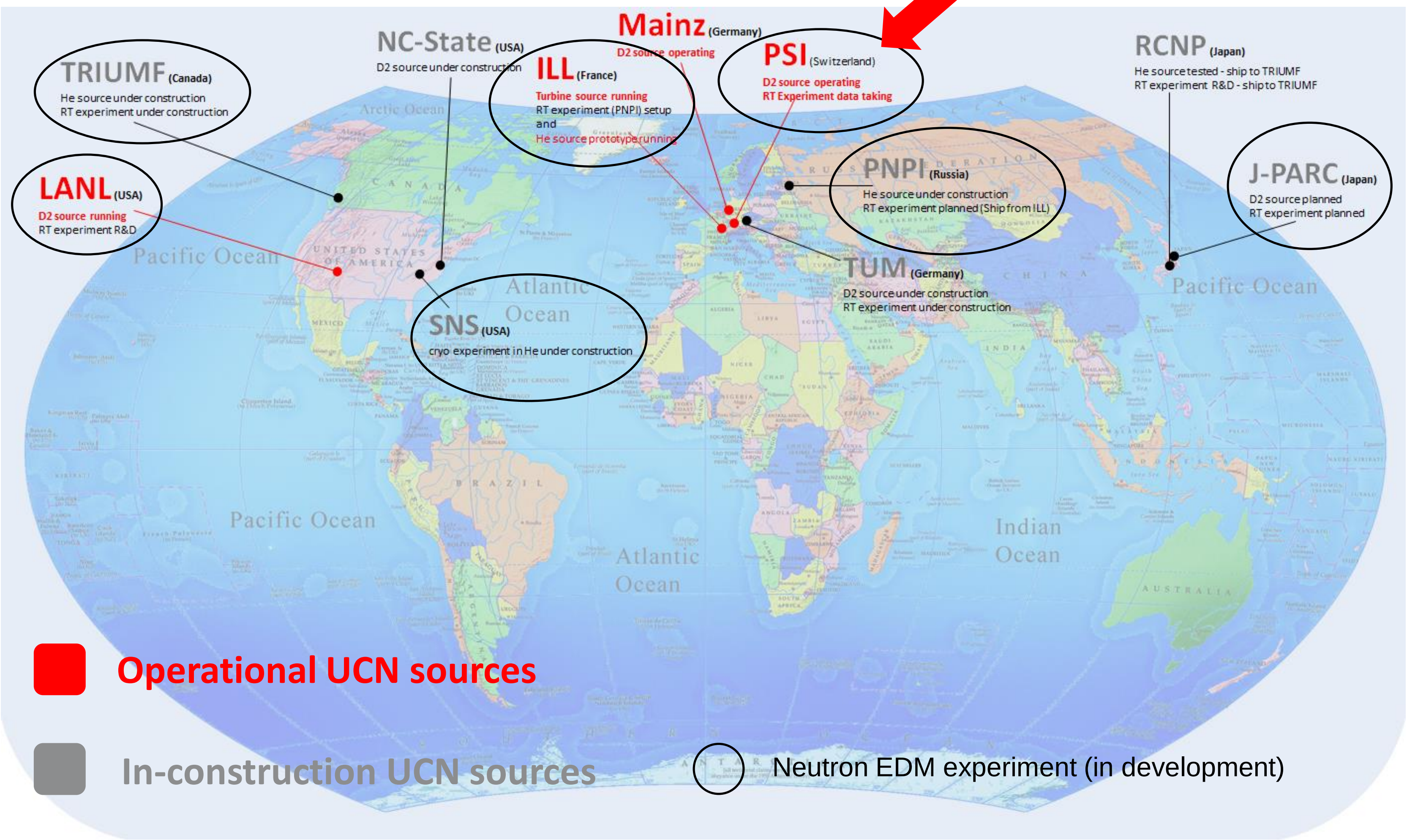
Ultracold neutron (UCN)

- <300 neV (~3.5 mK)
- Total reflection from surfaces of different materials
- Can be trapped in appropriate material volume for very long time (100+ sec.)
- ~1 neV/cm
- 60 neV/T

- Difficult to produce in large quantity still
- Produced from cold neutrons (Mechanical turbine, Superfluid He, Solid D2)
- Source extraction is difficult

Worldwide competition!

UltraCold Neutron sources and neutron EDM experiments around the world



Current limit:

Sussex-RAL-ILL collaboration

$d_n < 3 \times 10^{-26}$ **e cm** (90% C.L.)

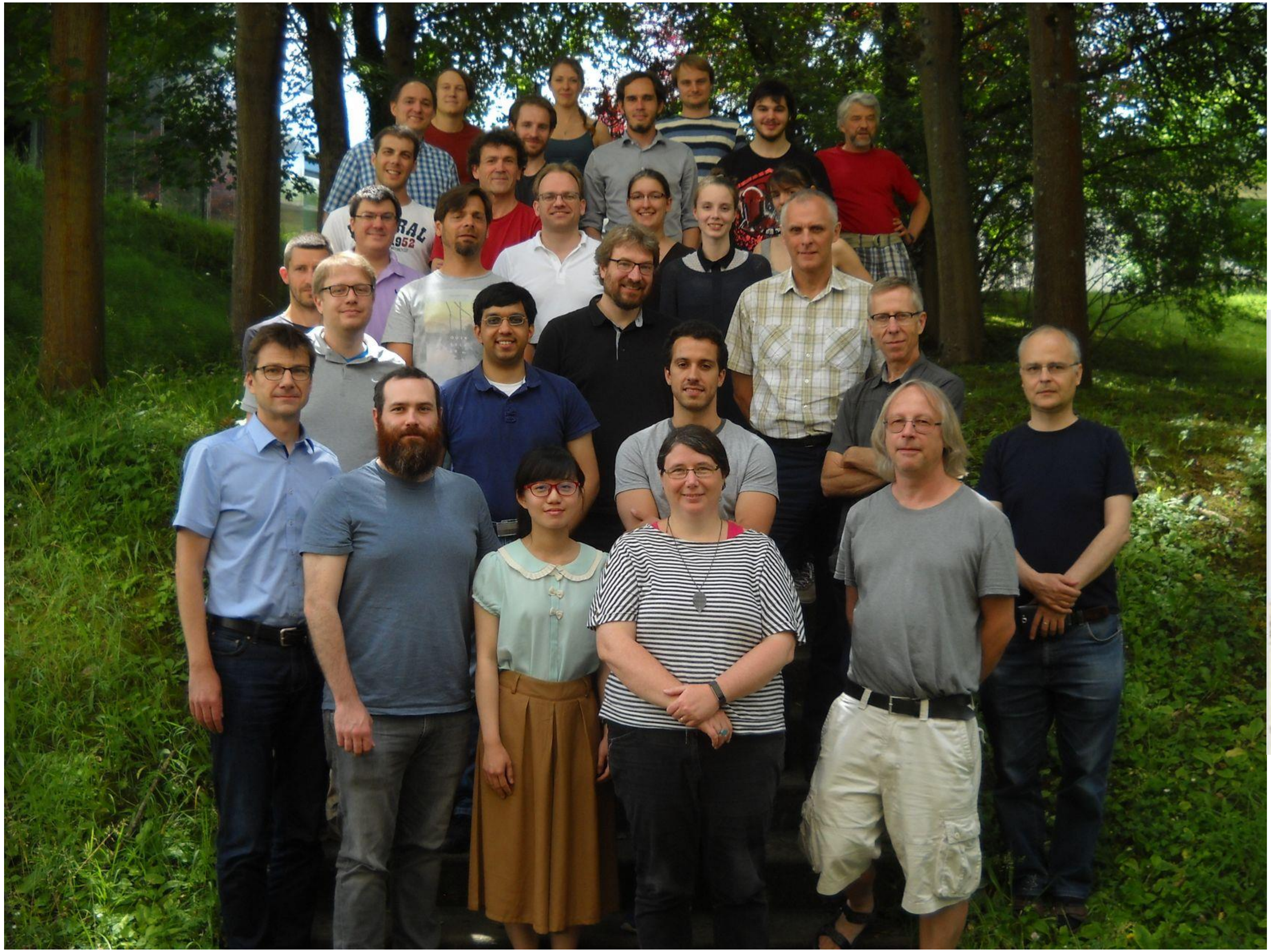
Baker et al, Phys Rev Lett 97, 131801 (2006)
Pendlebury et al, Phys Rev D 92, 092003 (2015)

Trapped UCN with N_{UCN} = 0.5 UCN/cm3

|E| = 5 - 10 kV/cm

100 sec storage time

The n(2)EDM collaboration



Around 50 people, 15 institutions, 7 countries.

Experiment(s) located at the Paul Scherrer Institute (PSI), Switzerland

From nEDM to n2EDM @ PSI…

nEDM

2009
- Spectrometer from the Sussex-RAL-ILL collaboration moved to PSI

Upgrading the system
Studying the systematics
Taking data
Preparing the next step, n2EDM

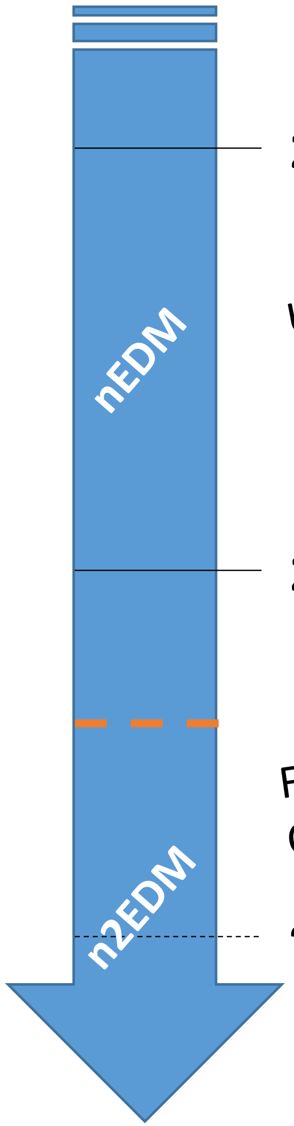
2017
- Dismounting the nEDM experiment

n2EDM

Finishing the nEDM data analysis
Construction of n2EDM @ PSI

~2021
- First data taking with n2EDM

From nEDM to n2EDM @ PSI…



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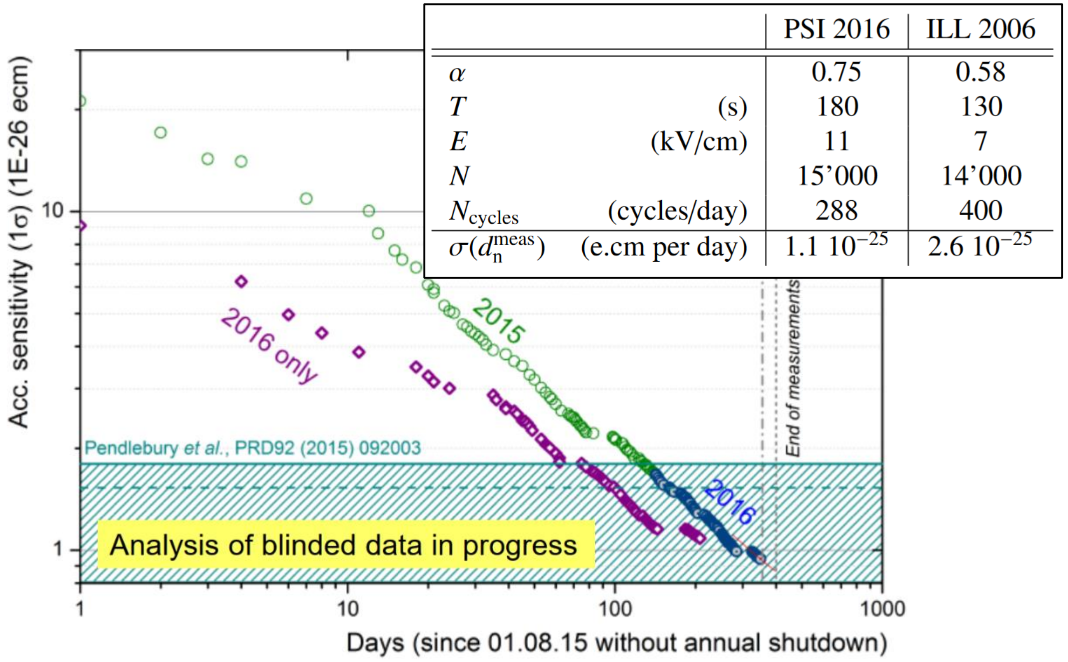


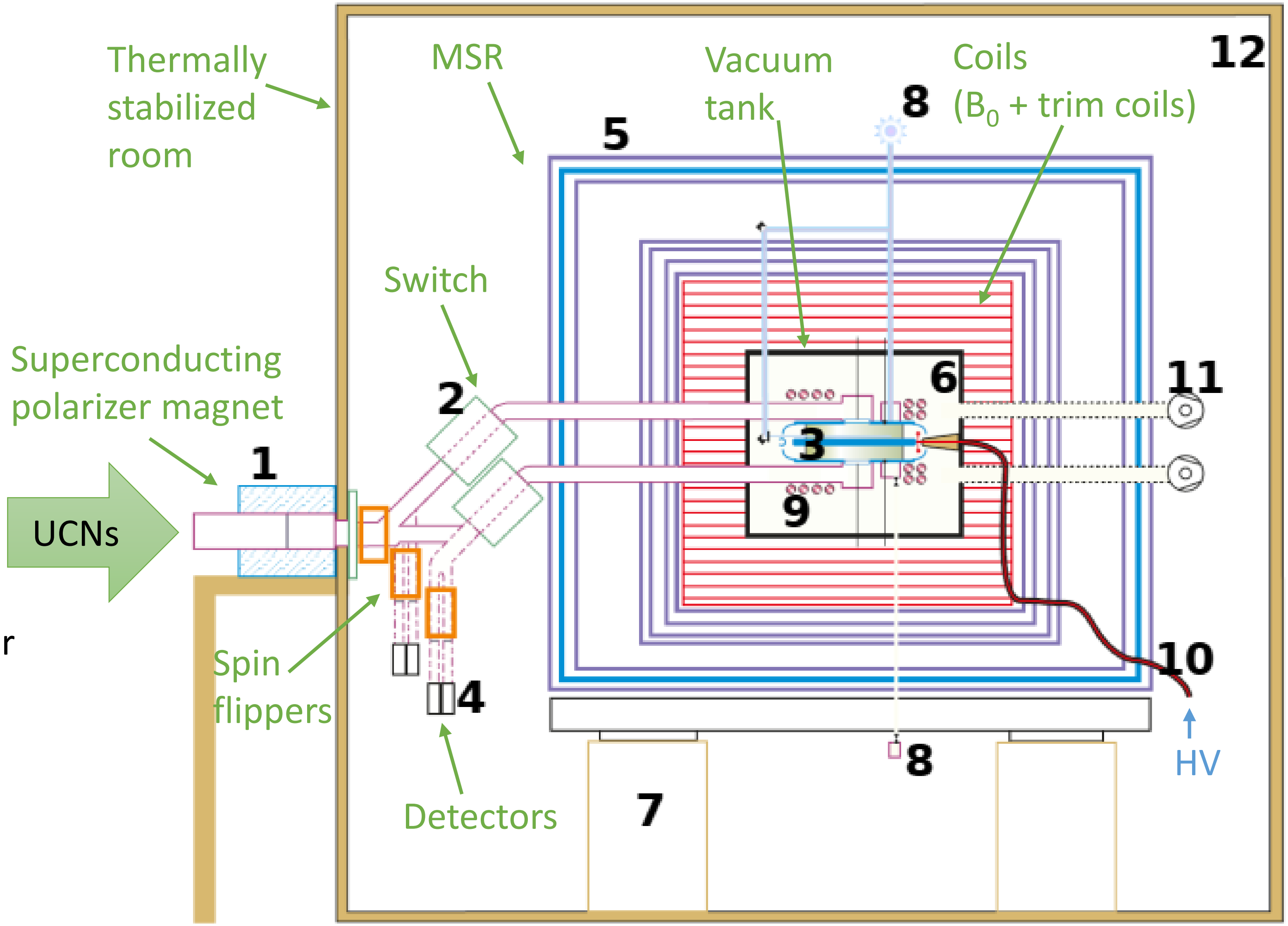
		PSI 2016	ILL 2006
α		0.75	0.58
T	(s)	180	130
E	(kV/cm)	11	7
N		15'000	14'000
N_{cycles}	(cycles/day)	288	400
$\sigma(d_n^{\mathrm{meas}})$	(e.cm per day)	$1.1\ 10^{-25}$	$2.6\ 10^{-25}$

- 2-levels data blinding
- 2 data analysis groups
- Final result should be ready in a few months

And now n2EDM @ PSI!

Dual big precession chambers setup!

Strong magnetic field requirements:
- B stability on minutes timescale: 0.03 pT
- Vertical uniformity $\partial B_z/\partial z$: 0.7 pT/cm
- Horizontal uniformity $\partial B_z/\partial x, y$: 8 pT/cm

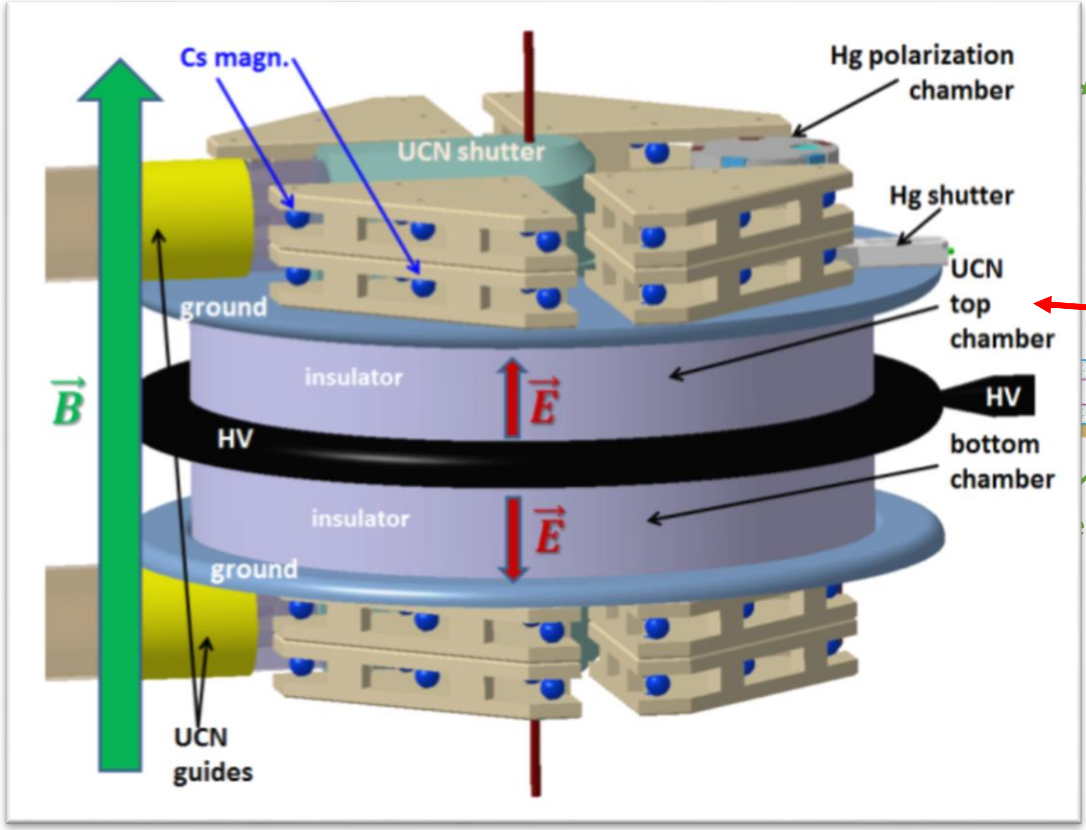


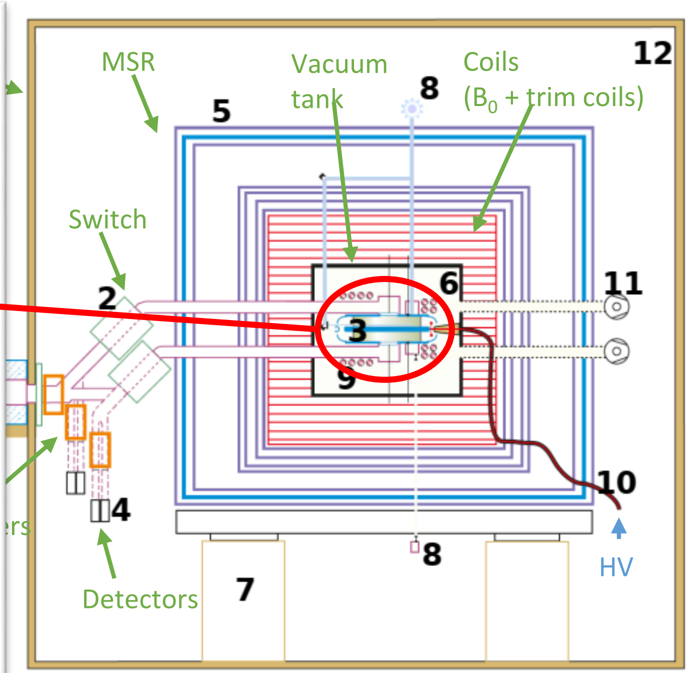
Huge Magnetically Shielded Room (MSR) **#5**:
- 6 x μ-metal layers + 1 x 8mm Al RF shield layer
- Innermost room : 1.9 x 1.9 x 1.5 m
- Expected shielding factor
  - @ 0.01 Hz > 80 000
  - @ 75 Hz > 1 000 000

Double precession chambers and their magnetometers

Dual precession chambers **#3**:
- 12 cm height
- Baseline diameter: 80 cm
- Final diameter: 100 cm

X8 times more neutron (/nEDM)
~ 120 000 UCN/cycle (300 sec)





Magnetometry **#8 & 9**:

1. Hg co-magnetometer:
   - ^{199}Hg atoms explore the same volume as the UCN
   - Very efficient correction of the neutron frequency due to magnetic field drifts
   - But adds some effects to correct for

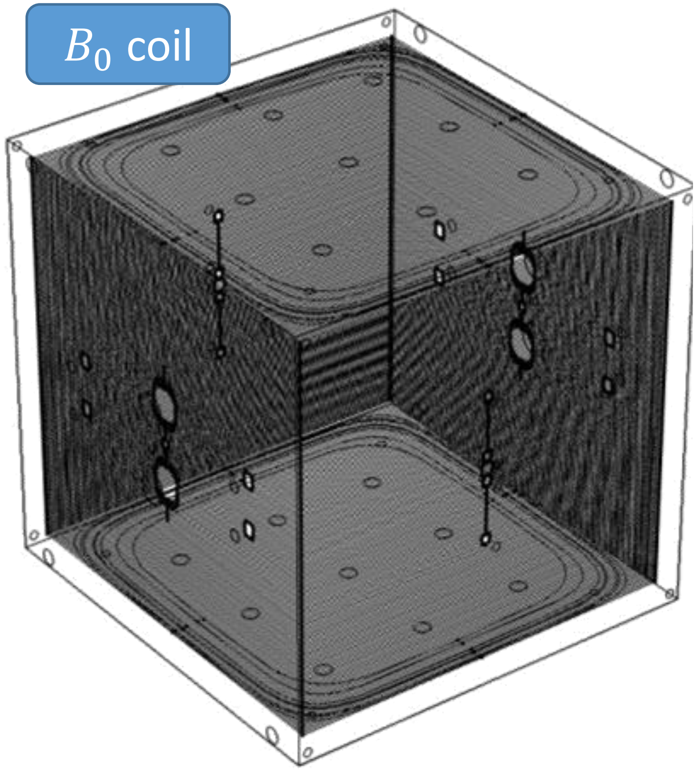
2. Array of Cs magnetometer:
   - ~100 Cs magnetometers above and below the electrode stack
   - Magnetically silent (all optical)
   - Used to minimize the magnetic field gradients (with Trim coils)

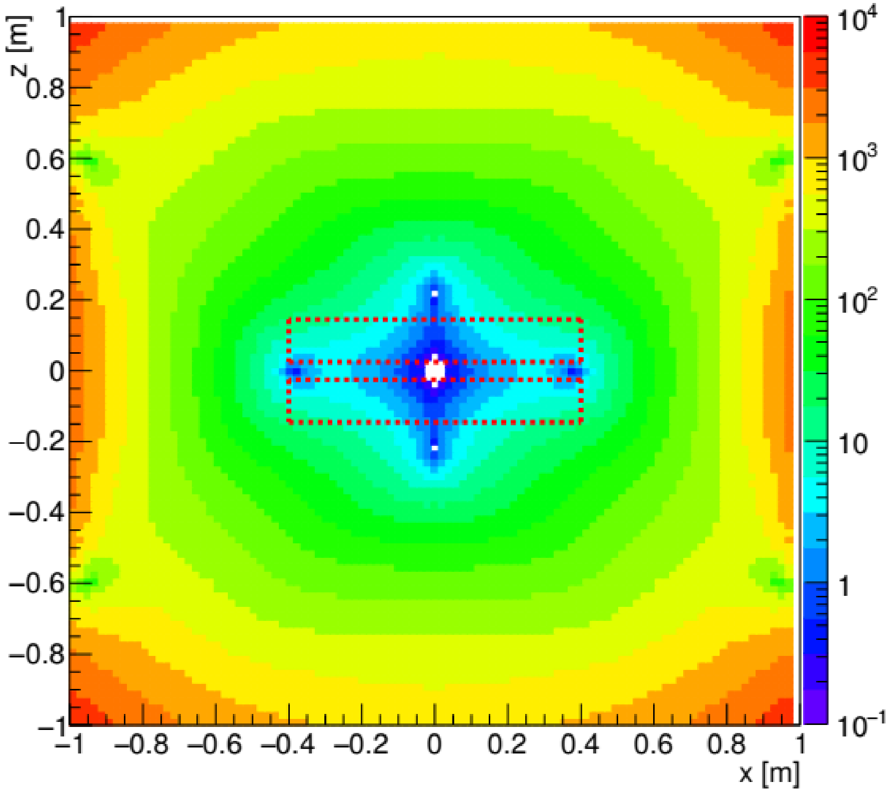
The challenge of the magnetic field generation…

Magnetic field generation:

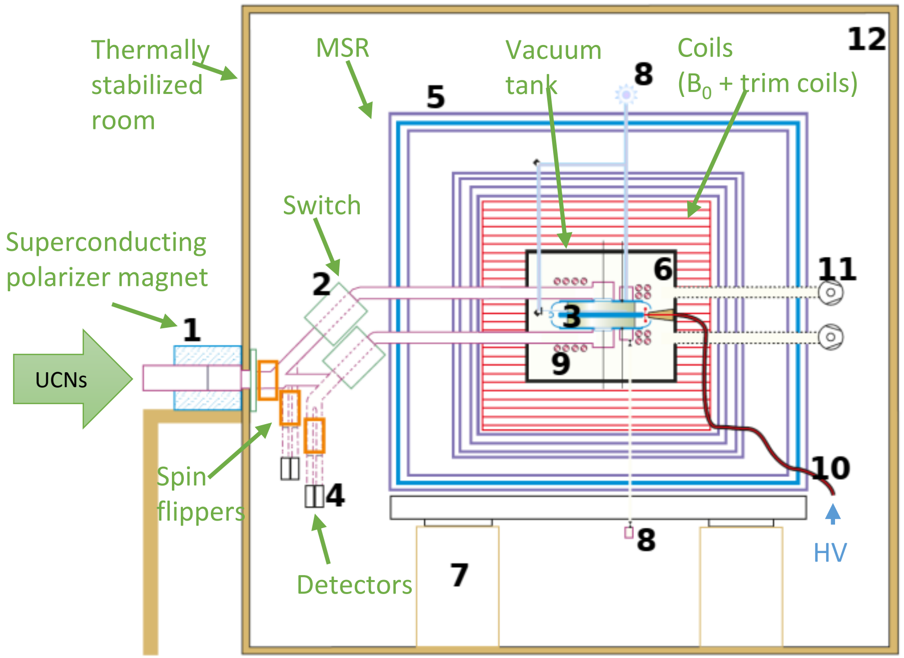
- $\overrightarrow{B_0}$ field of $\sim 1\ \mu\mathrm{T}$, uniformity better than 10^{-4} in the chambers
- Many trim coils:
  - ➢ correct small imperfections of the field
  - ➢ test different magnetic field gradients

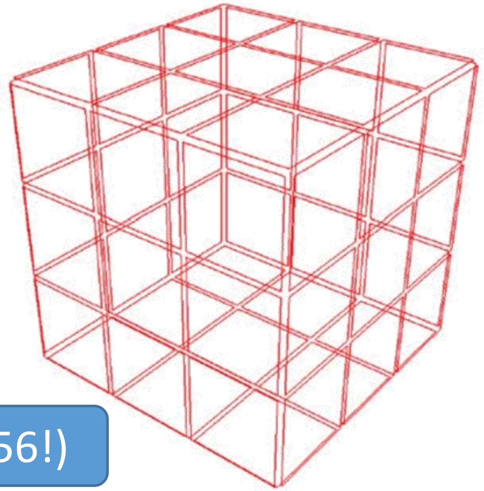
B_0 coil





(b) B_0 uniformity in the XZ plane in pT.



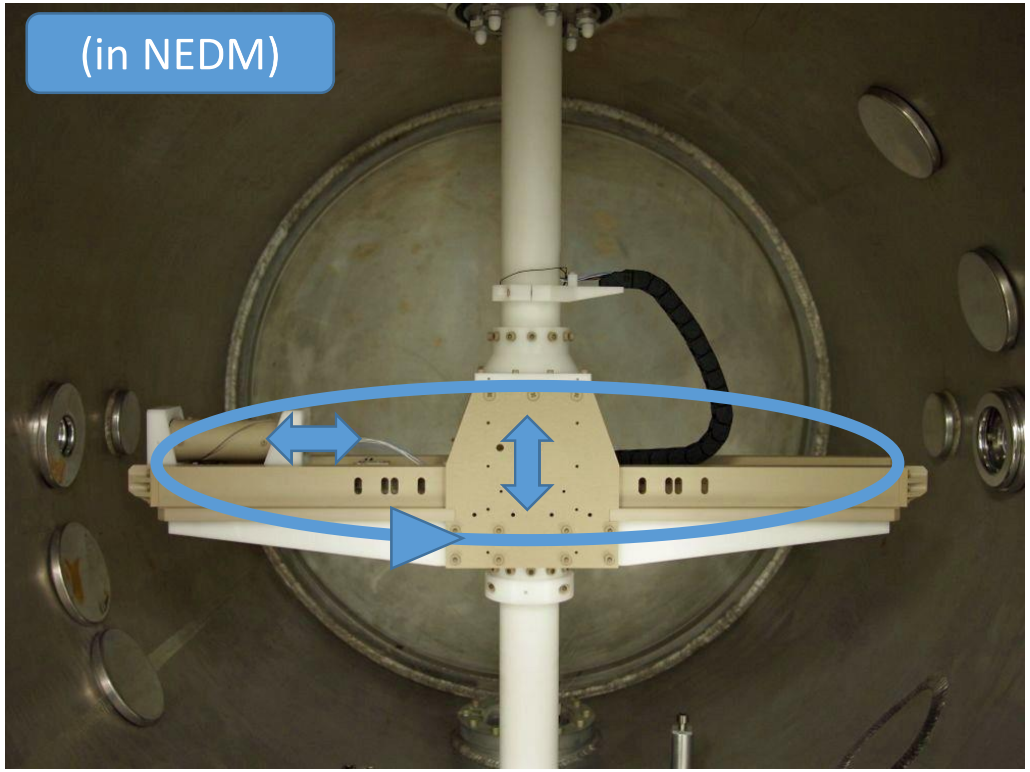


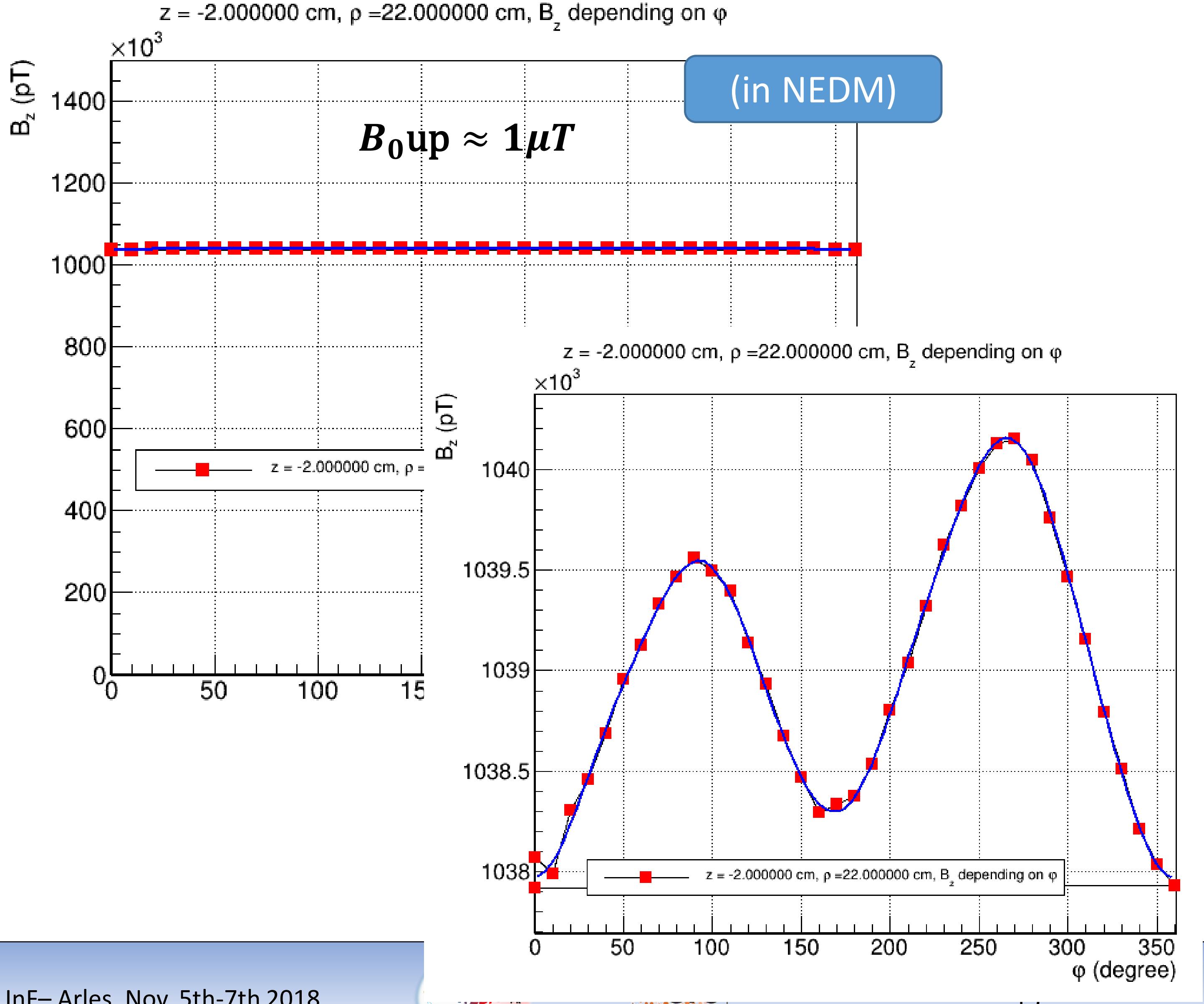
Trim Coils (56!)

… and its measurement!

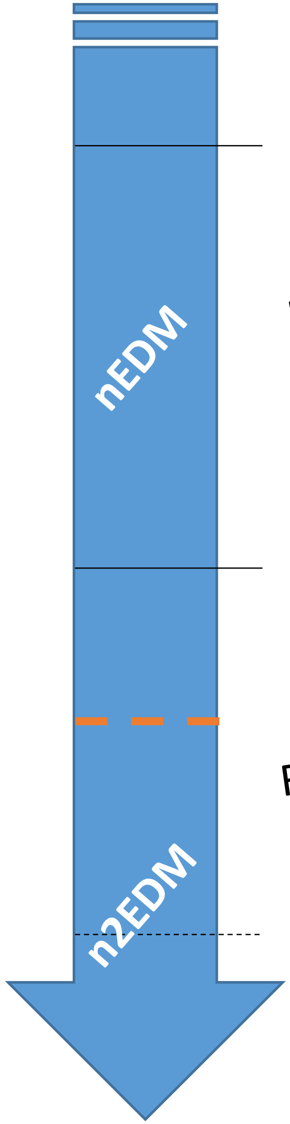
Field mapper robot:

- Completely non-magnetic
- Moving low-noise 3-axis fluxgate
- Mapping campaign each year:
  - ➢ Characterization of the mag. configurations
  - ➢ Remnant field measurement





From nEDM to n2EDM @ PSI…



2009
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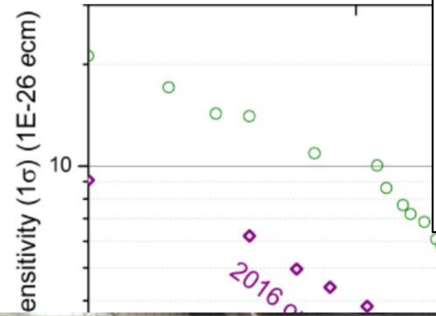
Finishing the nEDM data analysis
Construction of n2EDM @ PSI

~2021
- First data taking with n2EDM



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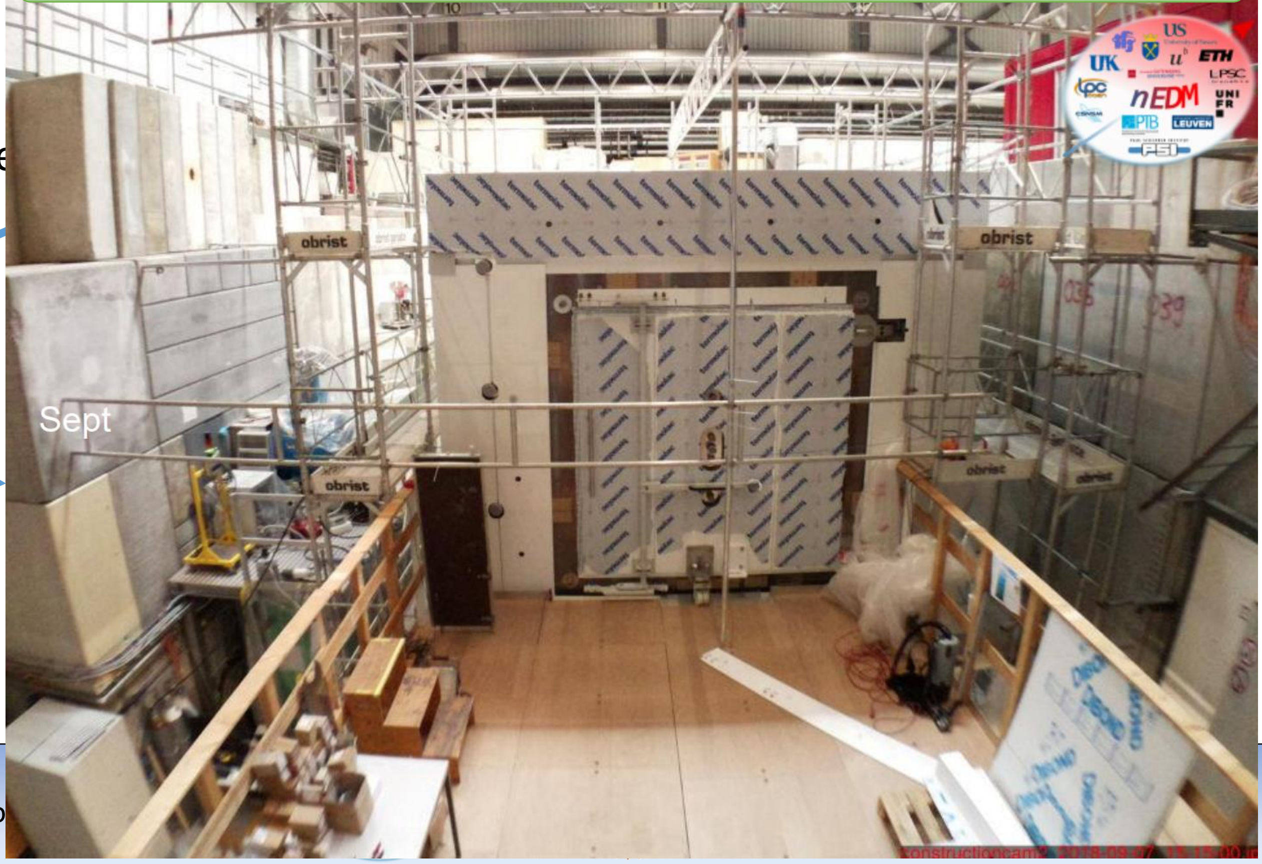
T	(s)	180	130
E	(kV/cm)	11	7
N		15'000	14'000
N_{cycles}	(cycles/day)	288	400
$\sigma(d_n^{\mathrm{meas}})$	(e.cm per day)	$1.1\ 10^{-25}$	$2.6\ 10^{-25}$

Installation of the n2EDM MSR



Conclusion

n2EDM schedule:

Spring/summer 2019:
- Installation of the inner part of the MSR
- Coils assembly and commissioning (with the upgraded field mapper)
- Vacuum tank installation

End of 2019:
- Installation of the detectors
- Installation of the magnetometers

2020:
- Precession chambers and High Voltage

~2021: First data taking!

	nEDM 2016	n2EDM baseline
diameter (cm)	47	80
α	0.75	0.8
E (kV/cm)	11	15
T (s)	180	180
N (per cycle)	15'000	121'000
$\sigma(d_n)$ (per day)	11×10^{-26} e cm	2.6×10^{-26} e cm
$\sigma(d_n)$ (total)	9.8×10^{-27} e cm	1.1×10^{-27} e cm

500 data days

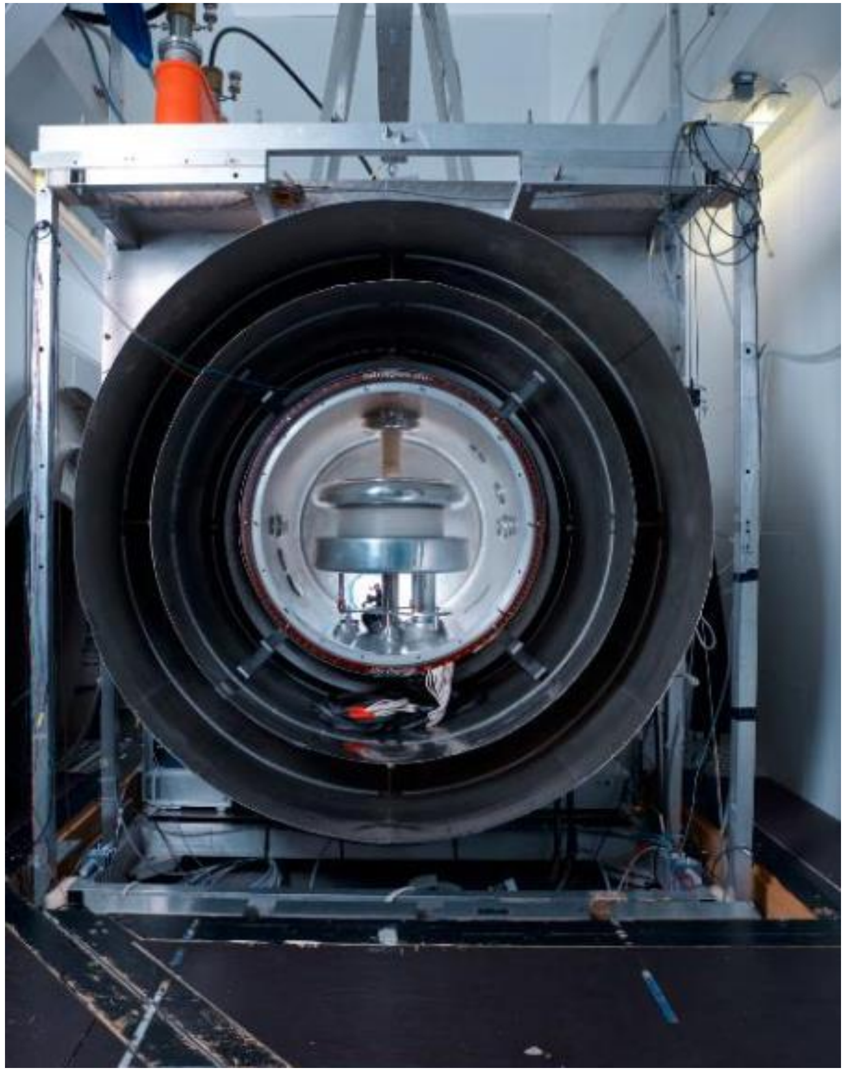
The end!

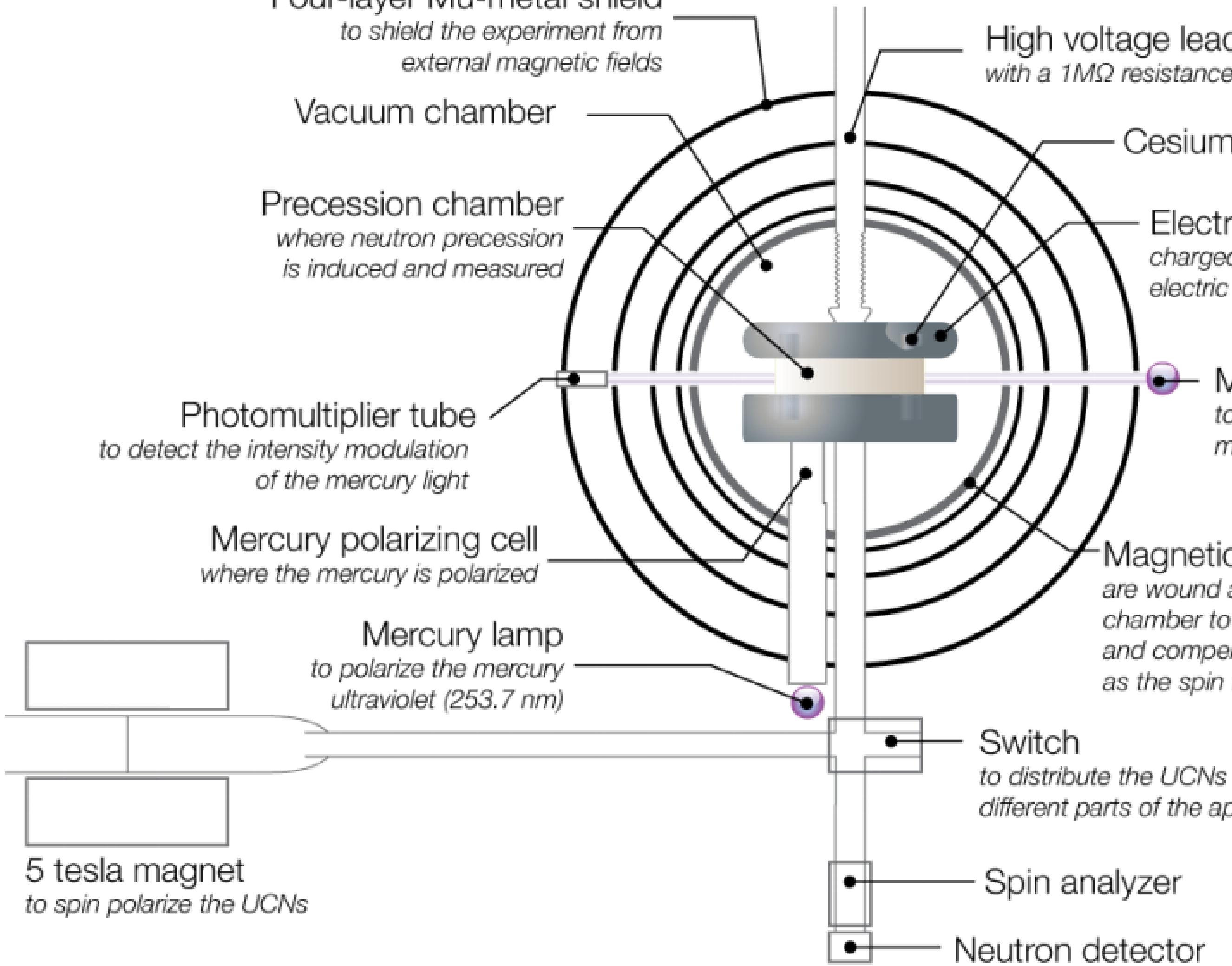
Thanks for your attention!

Backup

Backup Slides

nEDM at the Paul Scherrer Institute (PSI)

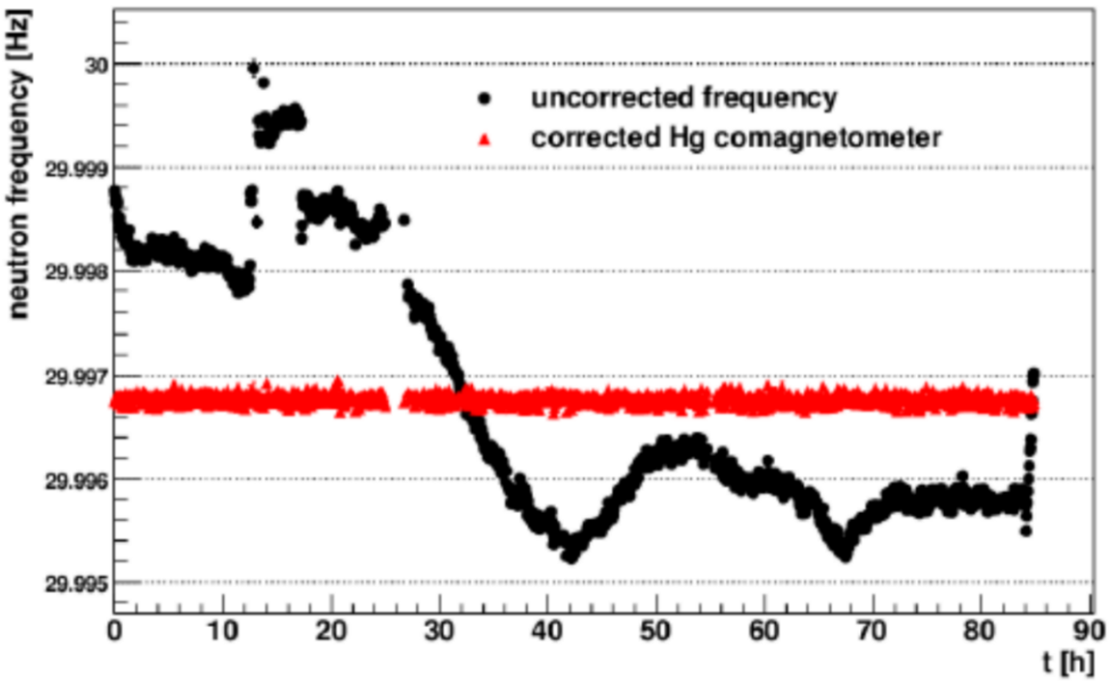




Magnetic field drifts corrections using $^{199}\mathrm{Hg}$

Hg co-magnetometer:

- $^{199}\mathrm{Hg}$ atoms explore the same volume as the UCN
- Very efficient correction of the neutron frequency due to magnetic field drifts
- But adds some effects to correct for (see next slides)



Use of the frequency ratio $\mathcal{R}$:

Single cell: $\mathcal{R} = \frac{\nu_n}{\nu_{Hg}} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right|\left(1 + \frac{\langle z\rangle G}{B_0}\right) + \frac{E}{\pi\hbar f_{Hg}} d_n$

Double cells: $\mathcal{R}^T - \mathcal{R}^B = \frac{2E}{\pi\hbar\nu_{Hg}} d_n + \left|\frac{\gamma_n}{\gamma_{Hg}}\right|\left(\langle z\rangle^T - \langle z\rangle^B\right)\frac{G}{B_0}$