The n2EDM project: a new measurement of the neutron EDM at the PSI

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GDR-InF annual workshop

UNIVERSITÉ CAEN NORMANDIE

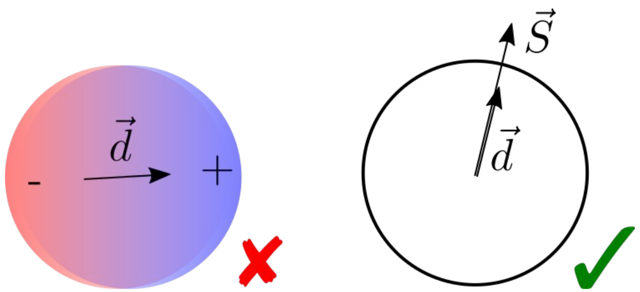
Outlook

- Motivation
- Neutron EDM
- Measurement principle
- n2EDM project
- A novel UCN gaseous detector
- Final remarks and perspectives

Motivation

Permanent electric dipole moments (EDM)
violate P, T and CP symmetries!

Not the classical interpretation



$$\hat{\mathcal{H}} = \vec{d} \cdot \vec{E} = d\vec{S} \cdot \vec{E}$$

$$\mathcal{P}\{\hat{\mathcal{H}}\} = d\vec{S} \cdot (-\vec{E}) = -\hat{\mathcal{H}}$$

$$\mathcal{T}\{\hat{\mathcal{H}}\} = d(-\vec{S}) \cdot \vec{E} = -\hat{\mathcal{H}}$$

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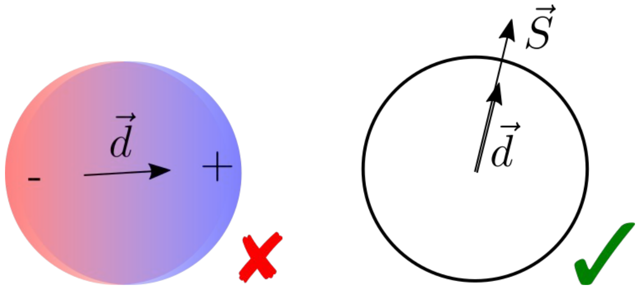


$$\mathcal{P}\{\hat{\mathcal{H}}\} = d\vec{S}\cdot(-\vec{E}) = -\hat{\mathcal{H}}$$

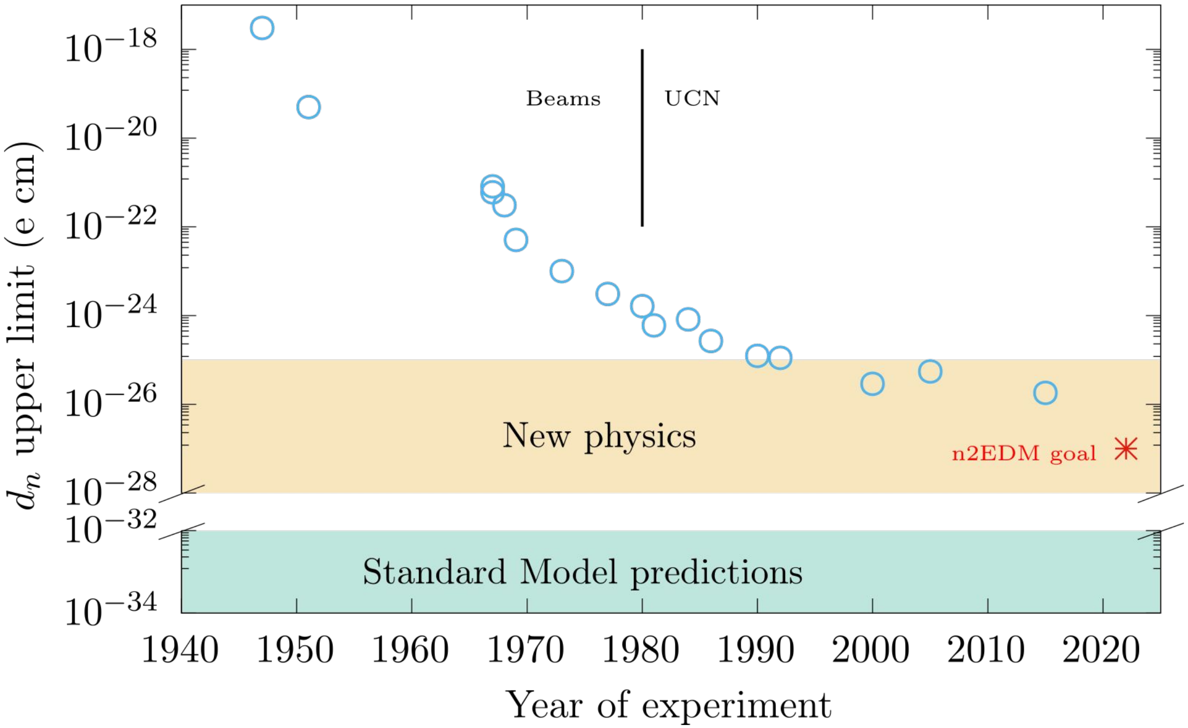
$$\boxed{\mathcal{T}\{\hat{\mathcal{H}}\} = d(-\vec{S})\cdot\vec{E} = -\hat{\mathcal{H}}}$$

CP violation assuming
CPT conserved

EDMs would be new source of CP violation explaining baryogenesis imbalance
(Sakharov conditions)

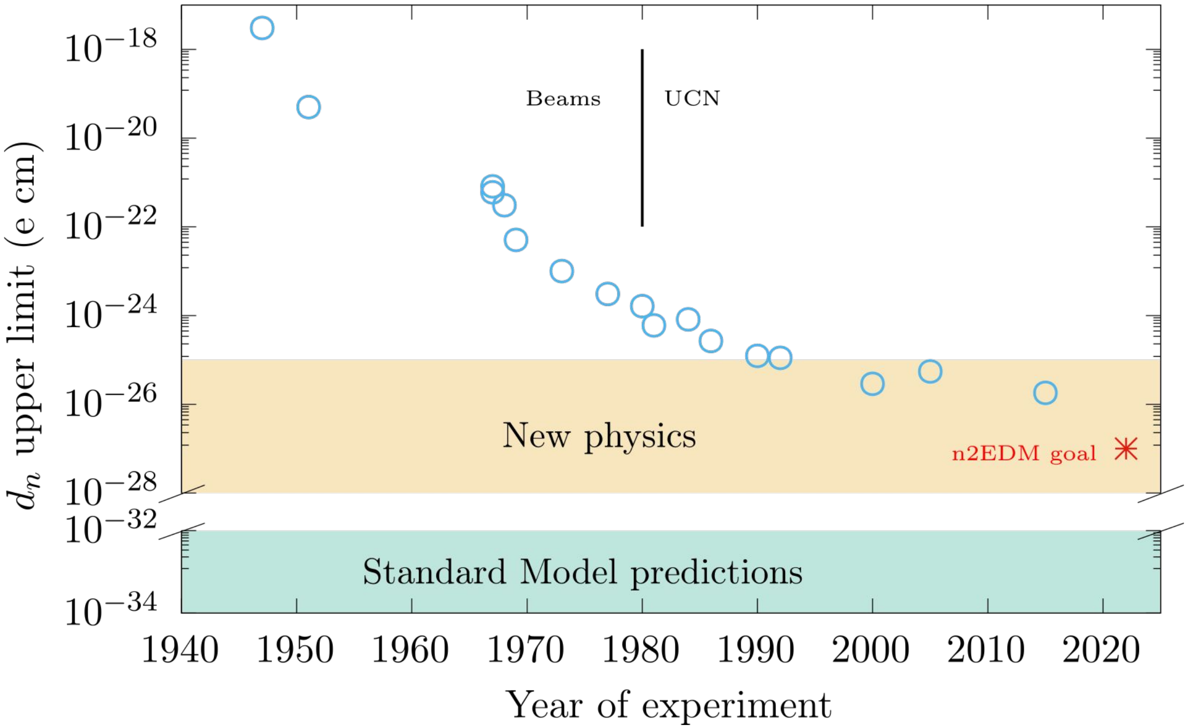
[A. D. Sakharov. JETP Letters, 5:24–27, 1967.]

Neutron EDM



- SM predictions in electroweak sector out of reach
- neutron EDM as a probe of SM extensions

Neutron EDM



- SM predictions in electroweak sector out of reach
- neutron EDM as a probe of SM extensions

n2EDM collaboration
- 14 laboratories
- 48 physicists

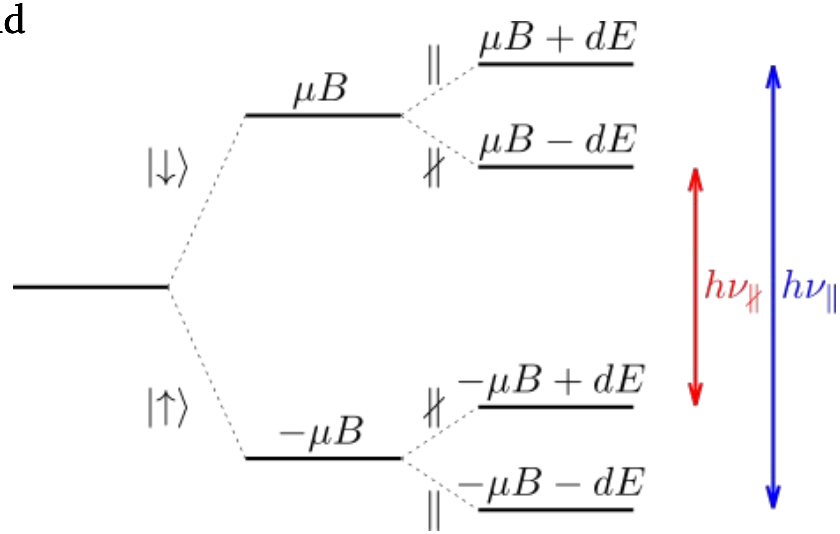
Most precise neutron EDM measurement
[Abel *et al*. Phys. Rev. Lett. 124, 081803 (2020)]:
$$d_n < 1.8 \times 10^{-26} \text{ e cm (90\% C.L.)}$$

n2EDM aims to improve the sensibility by one order of magnitude
[Abel *et al*. EPJ Web of Conf, 219, 02002 (2019)]

Measurement principle

➢ Energy levels in E // B and E∦B configurations:

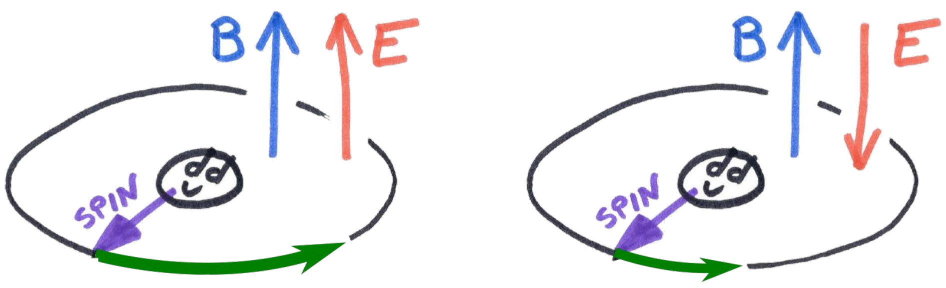
$$\hat{\mathcal{H}} = -(\mu\vec{B} + d\vec{E}) \cdot \vec{S}$$



$$\boxed{d_n = \frac{h(\nu_{\parallel} - \nu_{\nparallel})}{4E}.}$$

Measurement principle

➢ Energy levels in E // B and
E∦B configurations:



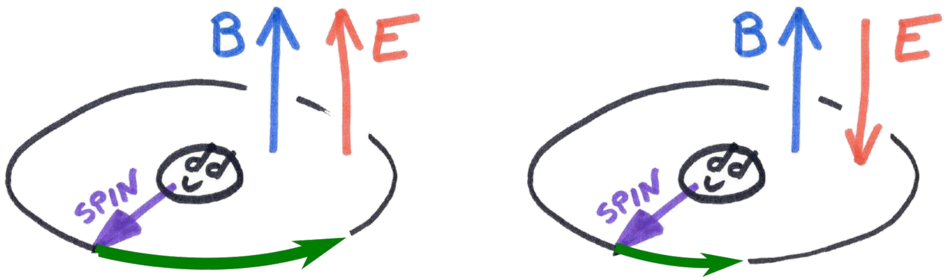
➢ Problem reduced to measuring the neutron
Larmor frequency

$$\nu_{\parallel,\nparallel} = \left|\frac{\gamma_n}{2\pi}B\right| \pm \frac{d_n}{\pi\hbar}\left|E\right|$$

(Ramsey interferometry)

Measurement principle

- Energy levels in E // B and
  E∦B configurations:



- Problem reduced to measuring the neutron **Larmor frequency**

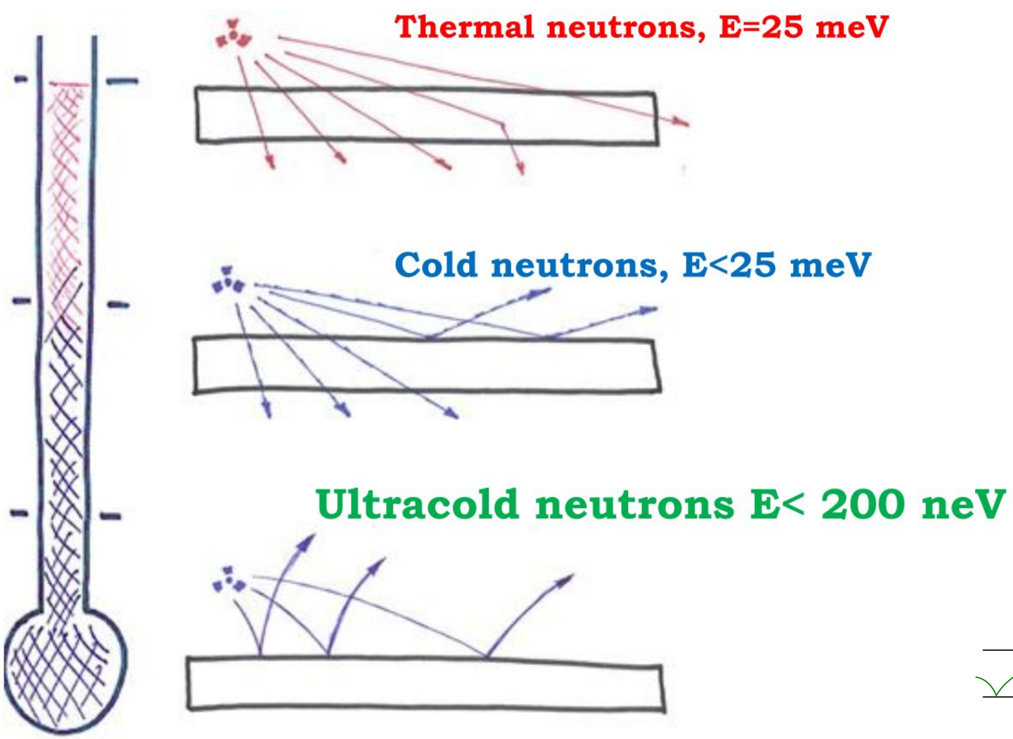
$$\nu_{\parallel,\nparallel} = \left|\frac{\gamma_n}{2\pi} B\right| \pm \frac{d_n}{\pi\hbar}\,|E|$$

- If $d_n = 10^{-26}$ e cm, E = 15 kV/cm and B = 1 μT

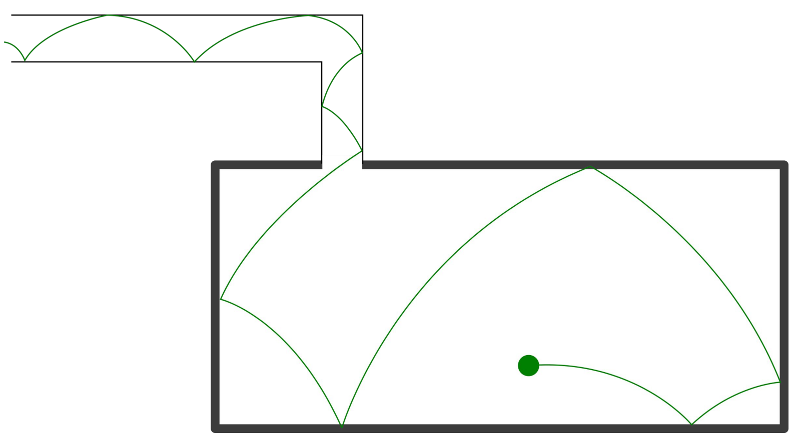
$$\frac{\frac{d_n}{\pi\hbar}|E|}{\left|\frac{\gamma_n}{2\pi}B\right|} \approx 2\times 10^{-9}$$

- Control of B-field is crucial!!!

Ultra-cold neutrons (UCN)



- $K_{ucn} < V_F \sim 200$ neV $\rightarrow$ Total reflection
- UCN storage = longer measurements

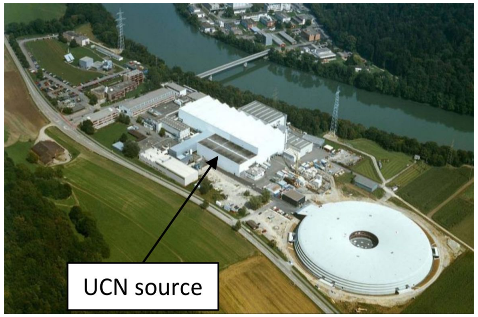


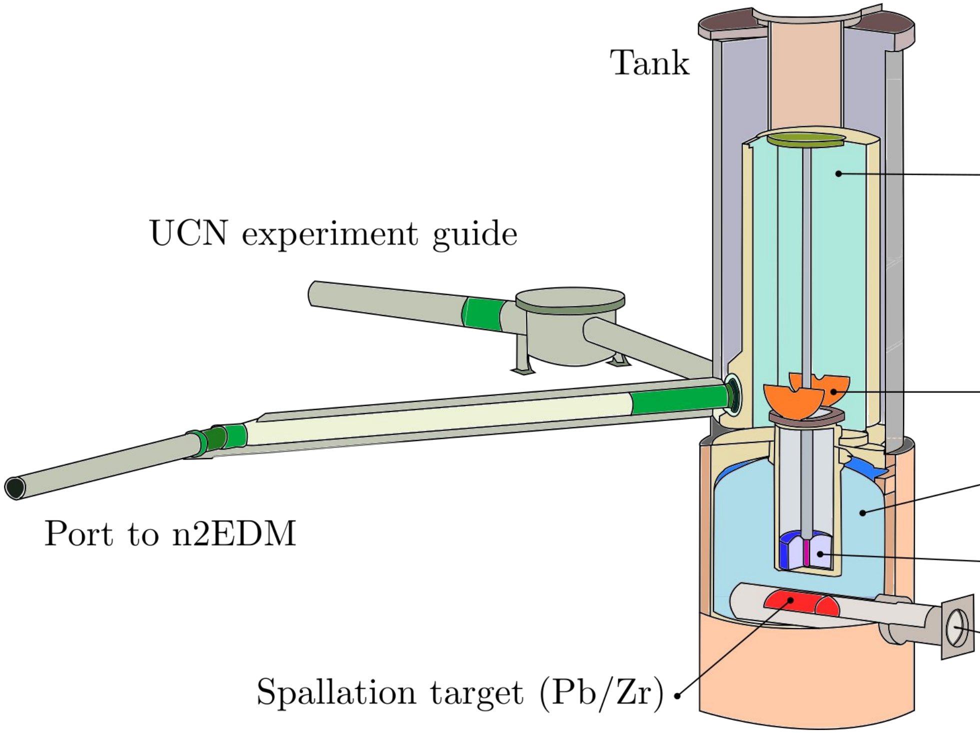
n2EDM experimental setup

PSI UCN source:

- Neutrons from proton (600 MeV, 2.2 mA) spallation of lead
- Cooling down using D_2O and sD_2

Paul Scherrer Institute





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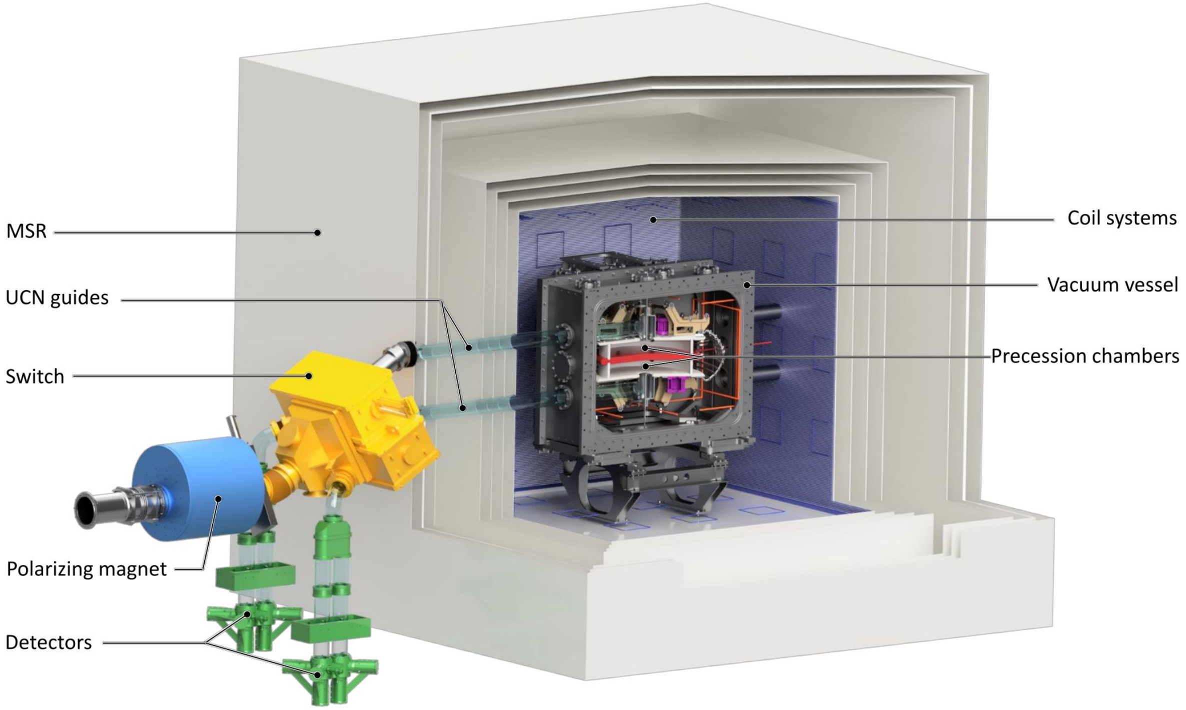
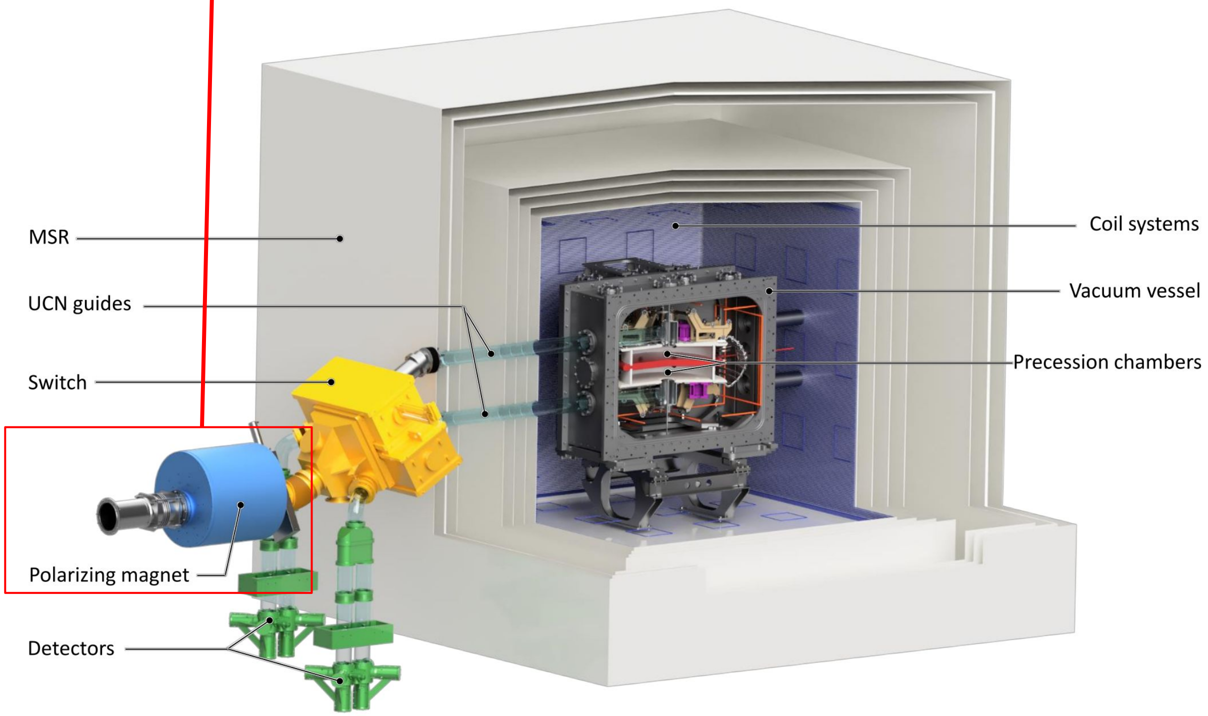


n2EDM experimental setup

5 T SC magnet (for Ramsey interferometry)



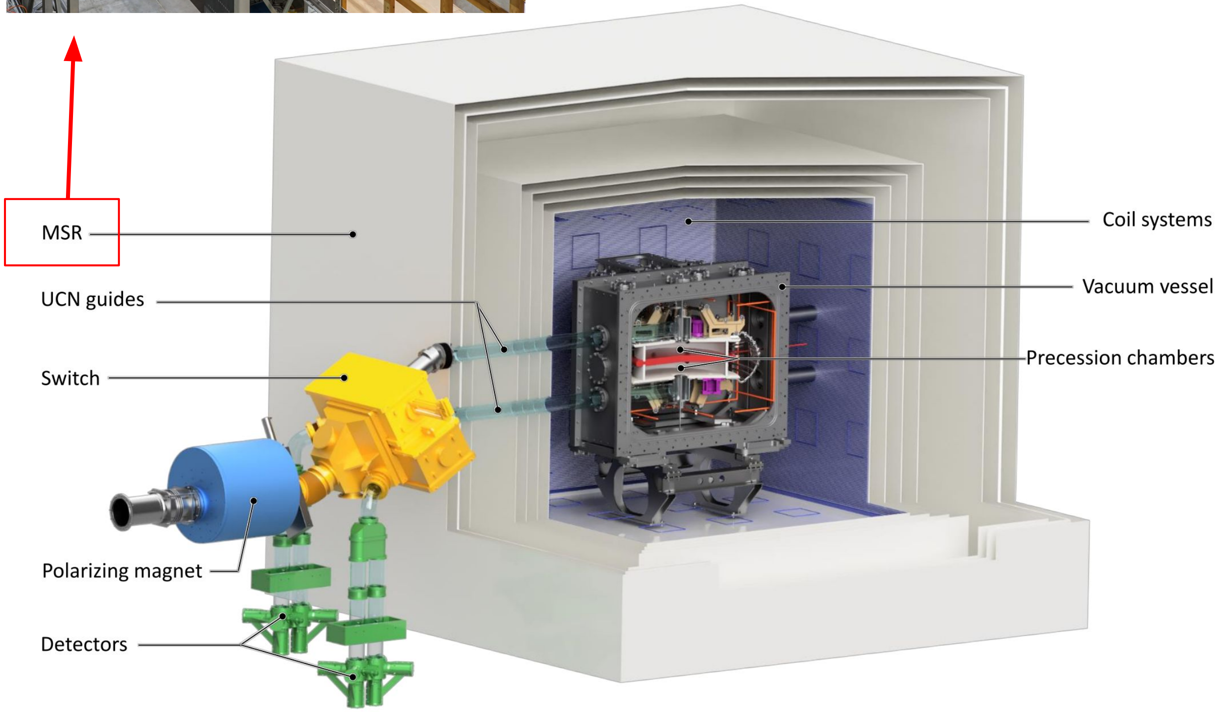
n2EDM experimental setup

Best MSR in the world:

→ residual field < 500 pT

→ shielding factor: 10^5

→ controlled volume: 1 m^3



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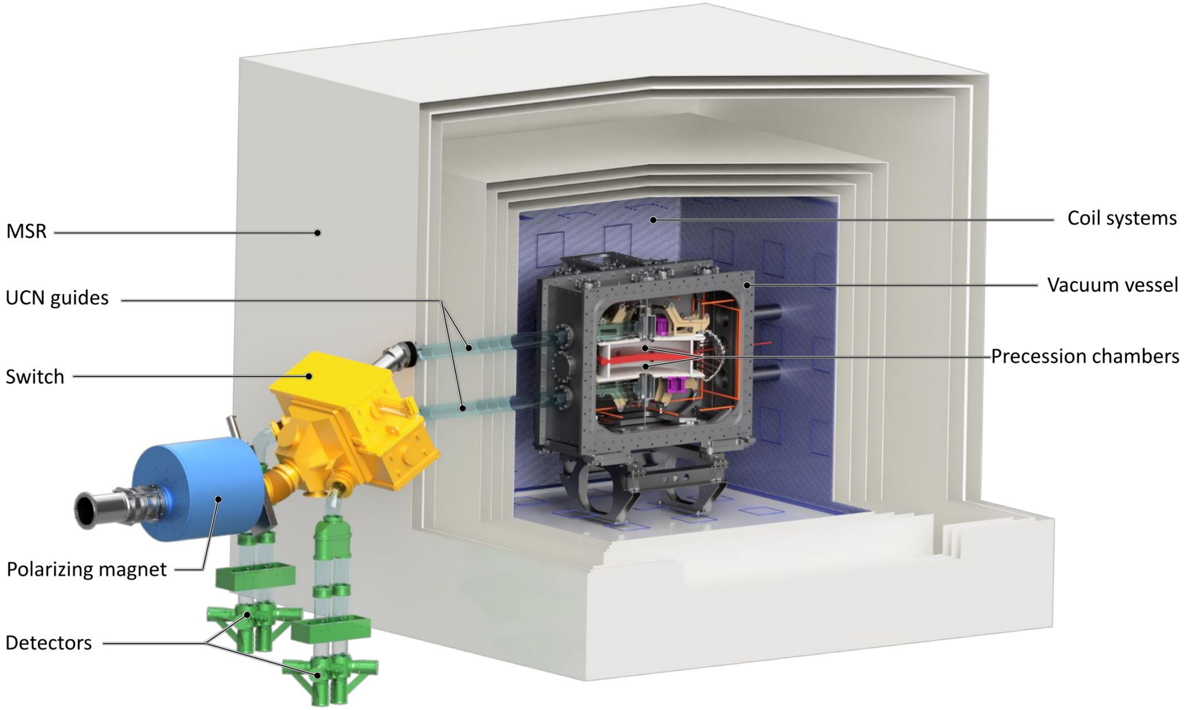

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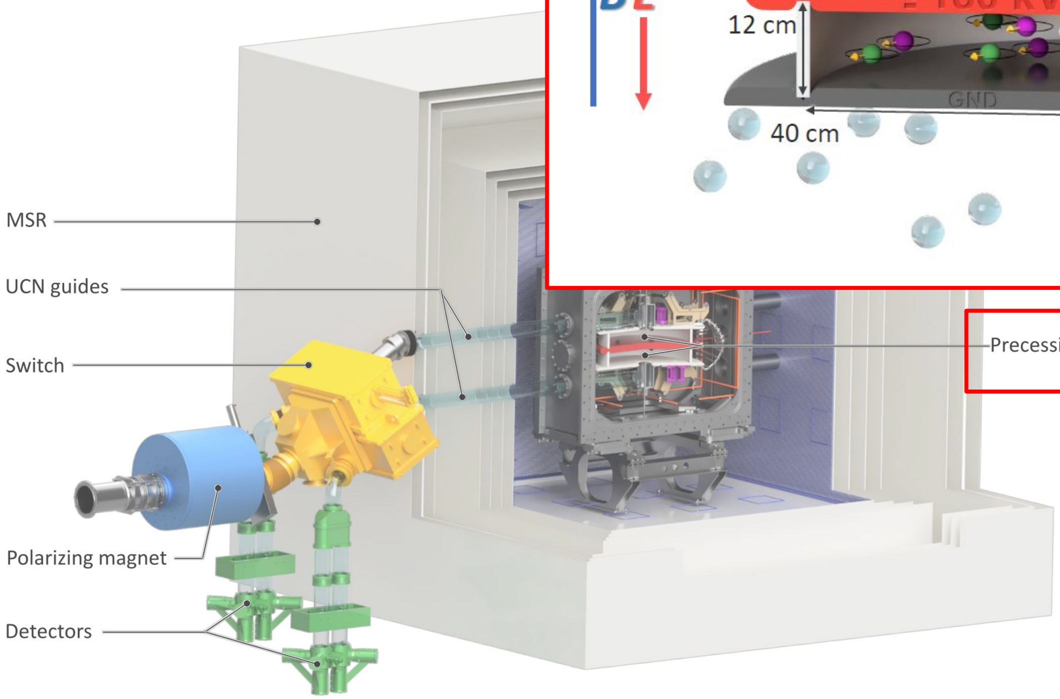
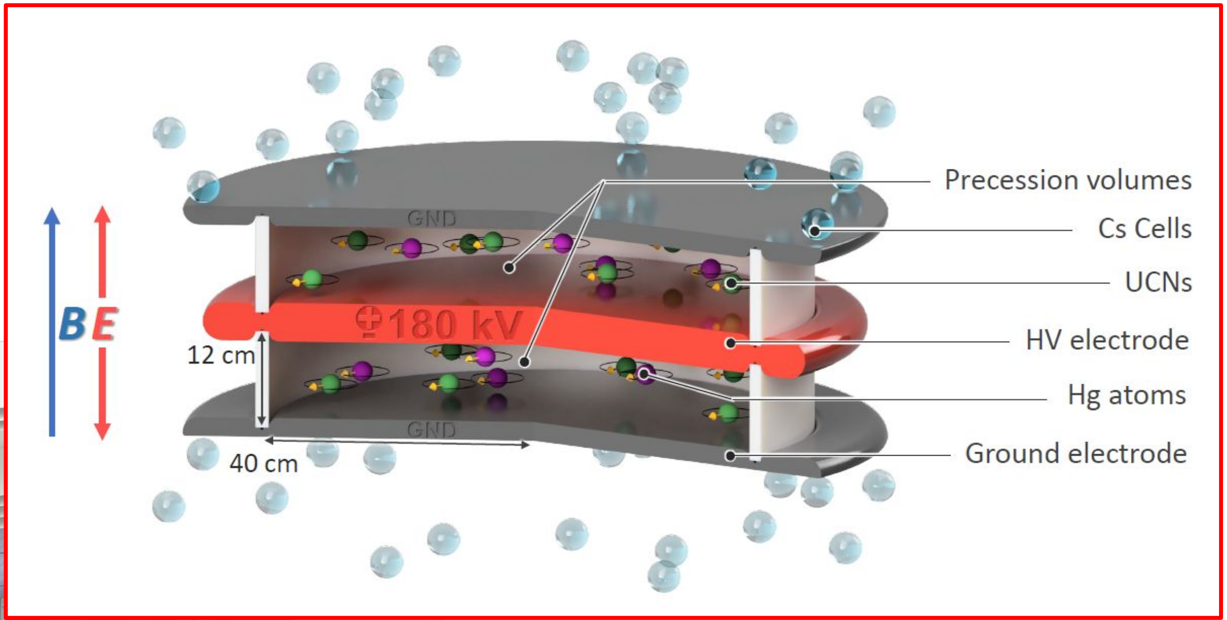




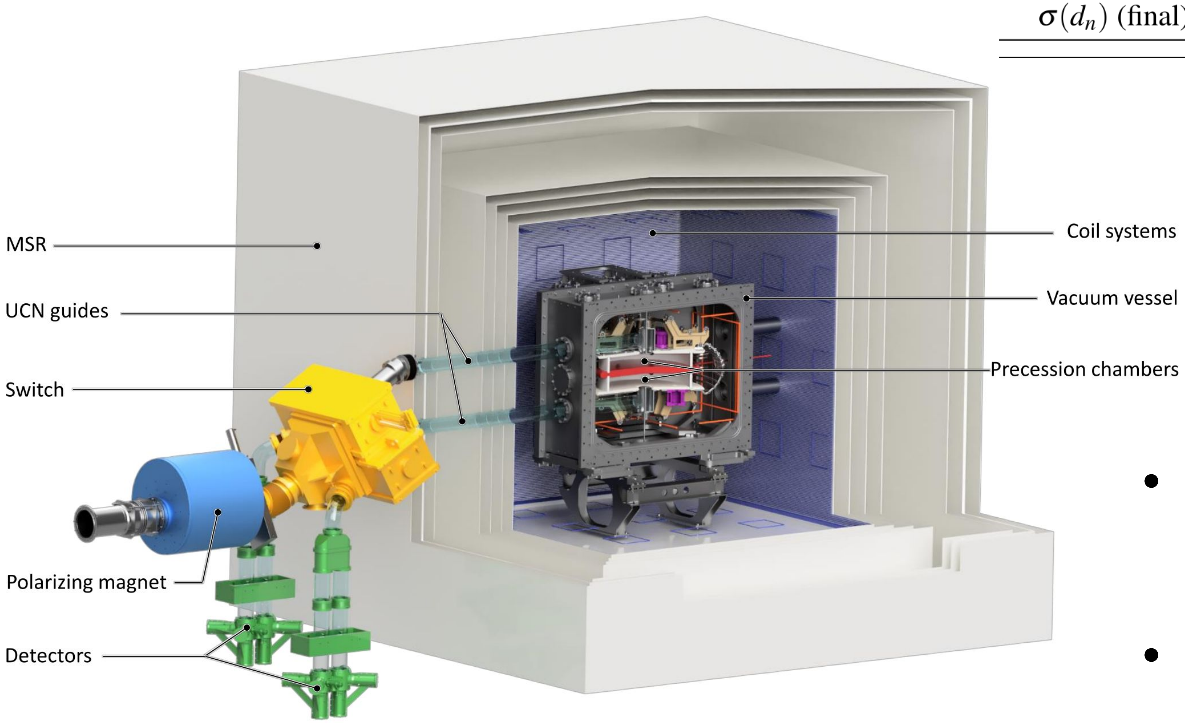
- Double-chamber arrangement ($E \parallel B$ and $E \nparallel B$ measured simultaneously)
- Larger UCN storage volume

n2EDM experimental setup

Statistical sensitivity

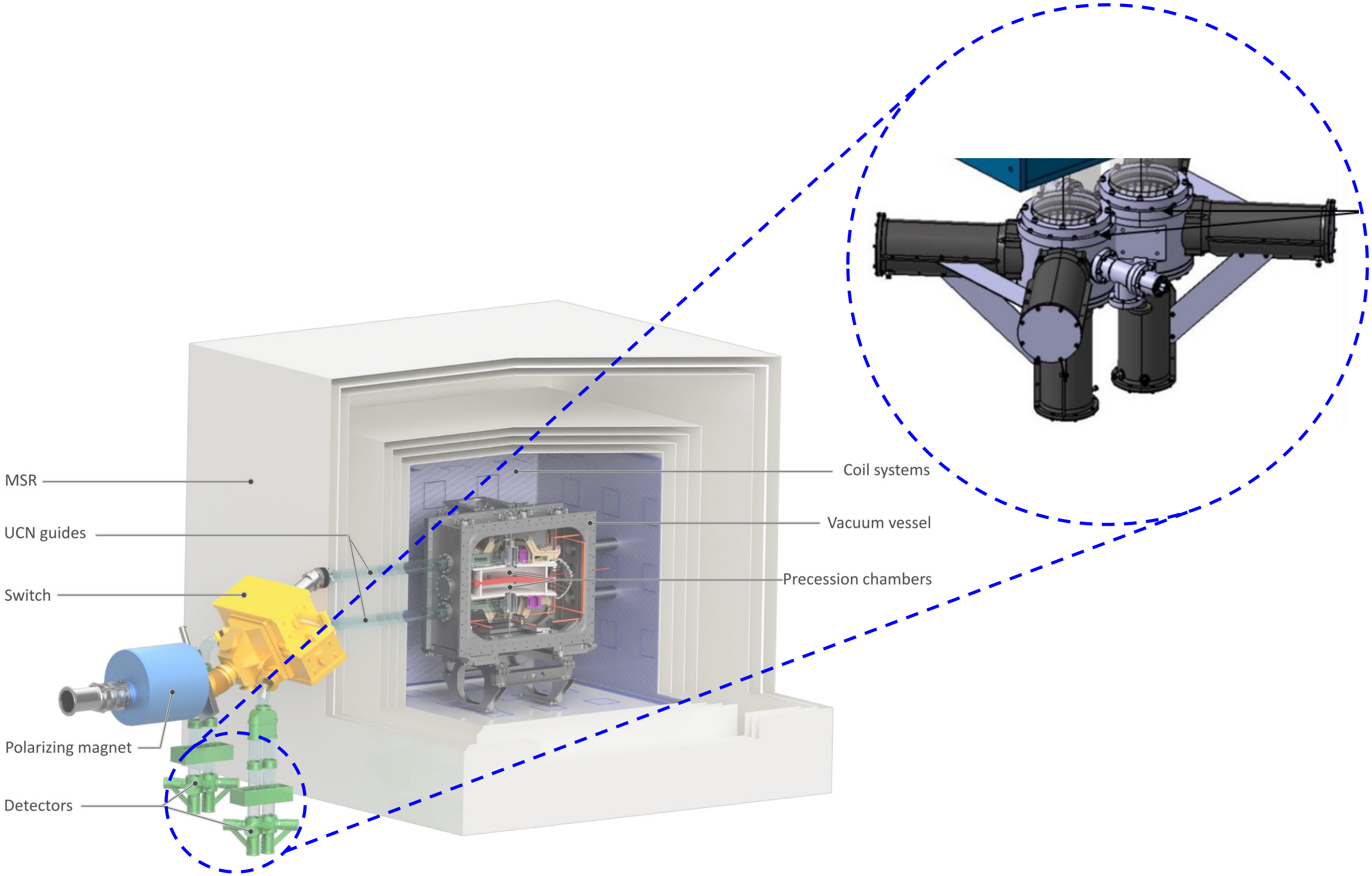
$$\boxed{\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}}$$

	nEDM 2016	n2EDM baseline
chamber diameter D	DLC & dPS 47 cm	DLC & dPS 80 cm
N (per cycle) T E α	15'000 180 s 11 kV/cm 0.75	121'000 180 s 15 kV/cm 0.8
$\sigma(f_n)$ per cycle	9.6 μHz	3.2 μHz
$\sigma(d_n)$ per day	11×10^{-26} $e \cdot$cm	2.6×10^{-26} $e \cdot$cm
$\sigma(d_n)$ (final)	9.5×10^{-27} $e \cdot$cm	1.1×10^{-27} $e \cdot$cm



- **Double-chamber arrangement ($E \parallel B$ and $E \nparallel B$ measured simultaneously)**
- **Larger UCN storage volume**

n2EDM experimental setup



A novel UCN gaseous detector

Requirements:

- High efficiency $\sigma_{d_n} \propto \dfrac{1}{\sqrt{N_0}}$
- High counting rate capability (10^5 Hz)
- Low sensitivity to gamma-rays
- Background identification

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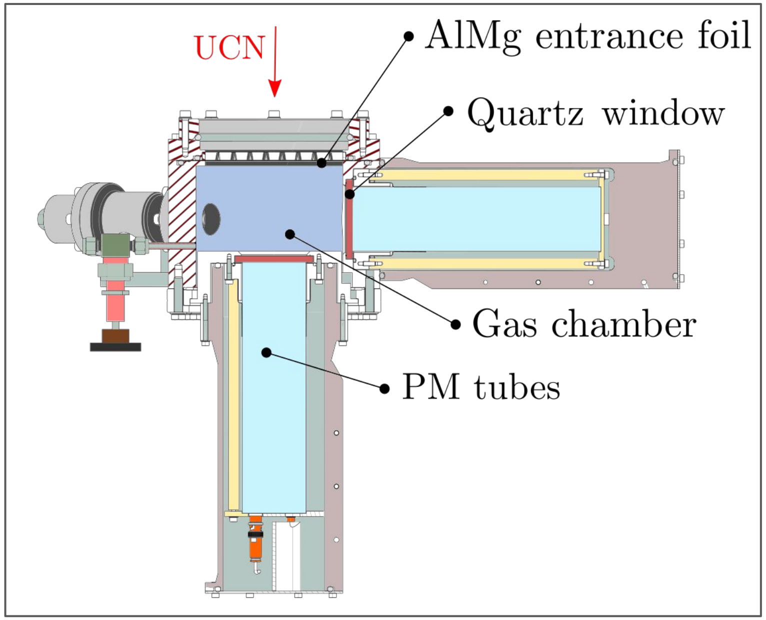


GADGET detector developed by LPC (^{3}He and CF_4 gas mixture):

1. UCN absorption

   $n + {}^3He \rightarrow p$ (0.57 MeV) + t (0.19 MeV)

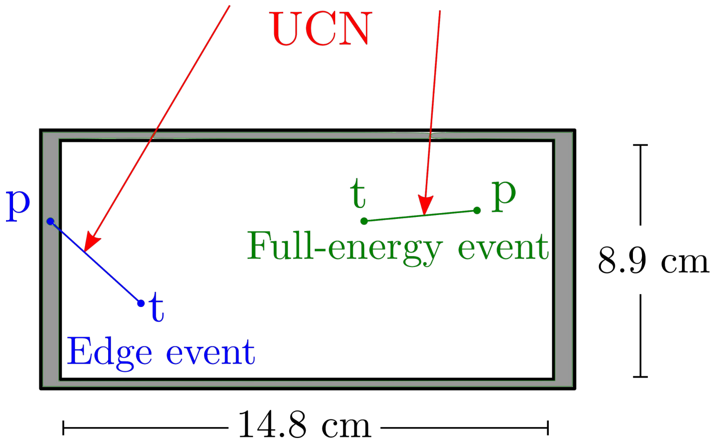
2. **CF_4** scintillation due to **p** and **t** ionization/excitation.

3. Light collection by 3 PM tubes

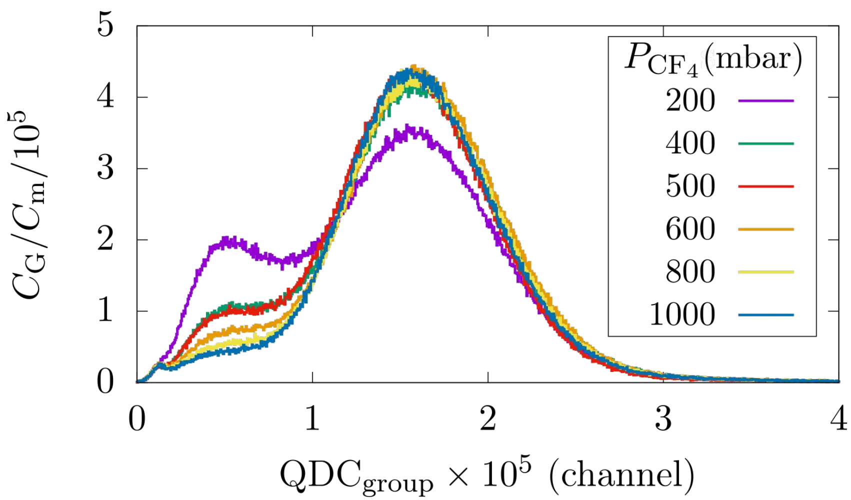
Gasses pressure dependency

CF_4 dependency

Edge events prevail @ low pressure!



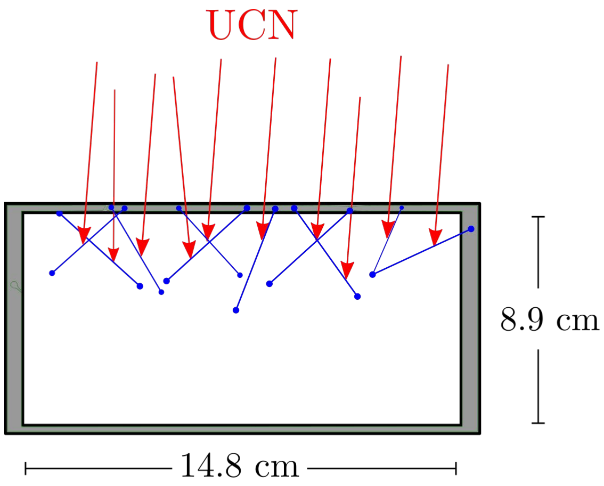
charge spectrum



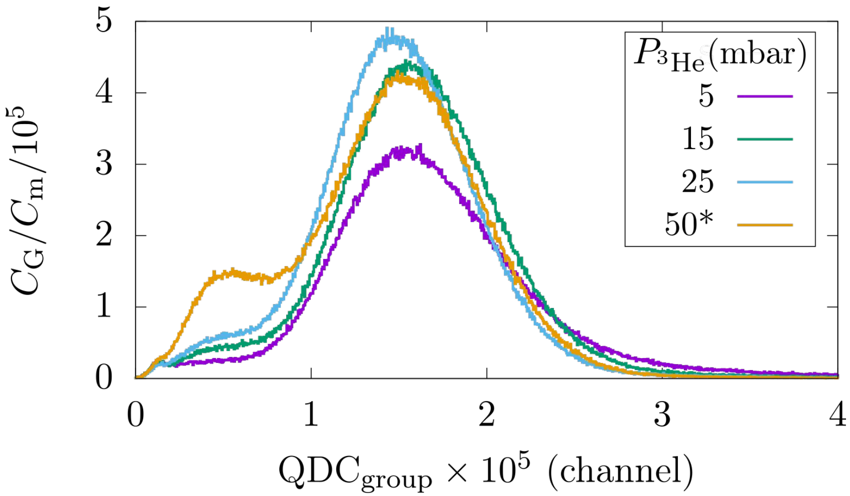
Gasses pressure dependency

^{3}He dependency

Edge events prevail @ high pressure!

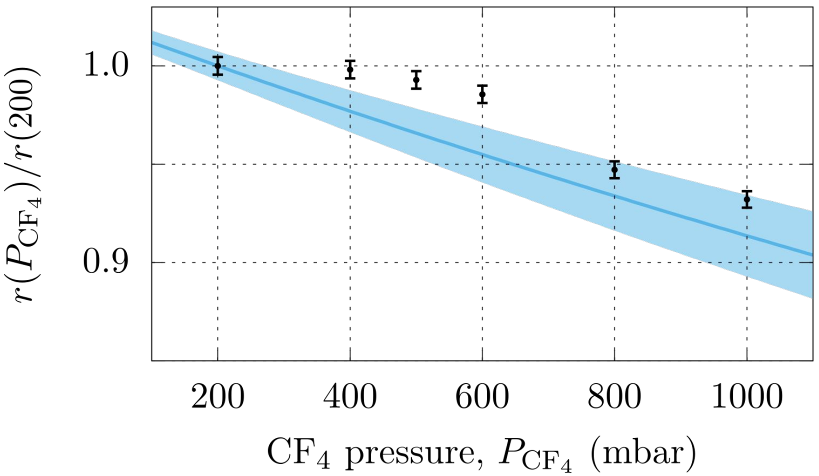


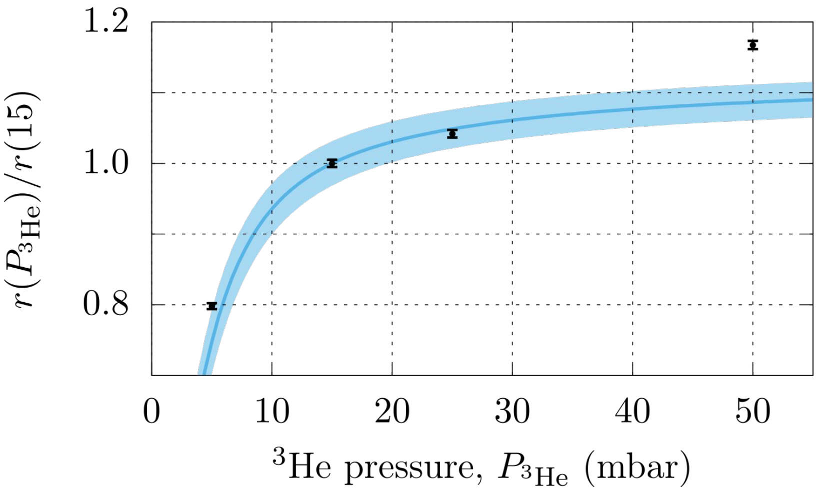
charge spectrum



Gasses pressure dependency

Total counting rates





Gasses pressure dependency

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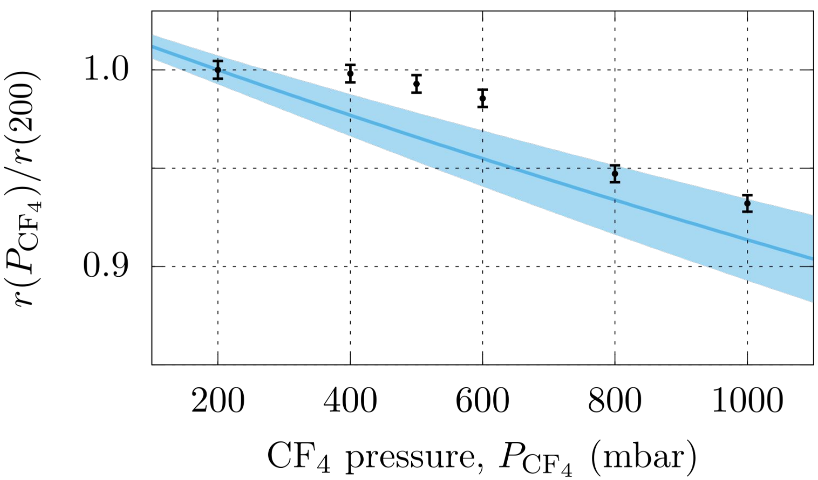
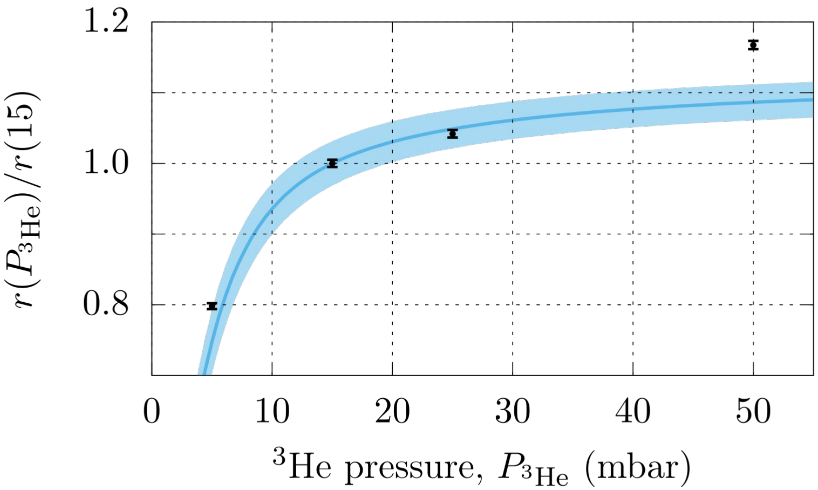


	σ_{ab} (barn)	σ_{up} (barn)
^{3}He	1 777 667(2333)	2 000(133)
CF_4	14	3 300(660)

^{3}He <u>absorption</u> and CF_4 <u>upscattering</u> determine the UCN absorption probability

$$\mathcal{P}_{ab}^{tot}(P_{^3He}, P_{CF_4}) = \frac{P_{^3He}\sigma_{ab}}{P_{CF_4}\sigma_{up} + P_{^3He}\sigma_{ab}}\left[1 - \exp\left(-L/\lambda\right)\right]$$



Optimal operation condition:

- CF_4 @ 400 mbar → Low upscattering
- ^{3}He @ 25 mbar → High absorption

Final remarks and perspectives

- Baseline n2EDM setup under construction at PSI
- The design of the core components will be completed on 2021
- Largest components, the thermal enclosure and the magnetically shielded room already installed
- n2EDM experiment commissioning scheduled to 2022

Thank you

Sakharov conditions

Elementary processes should not conserve baryon number *B:*
B = # Baryon - # Anti-Baryon

Initially B=0; current universe B>0

C and *CP* violation

CP violation = *T* violation (from *CPT* theorem)

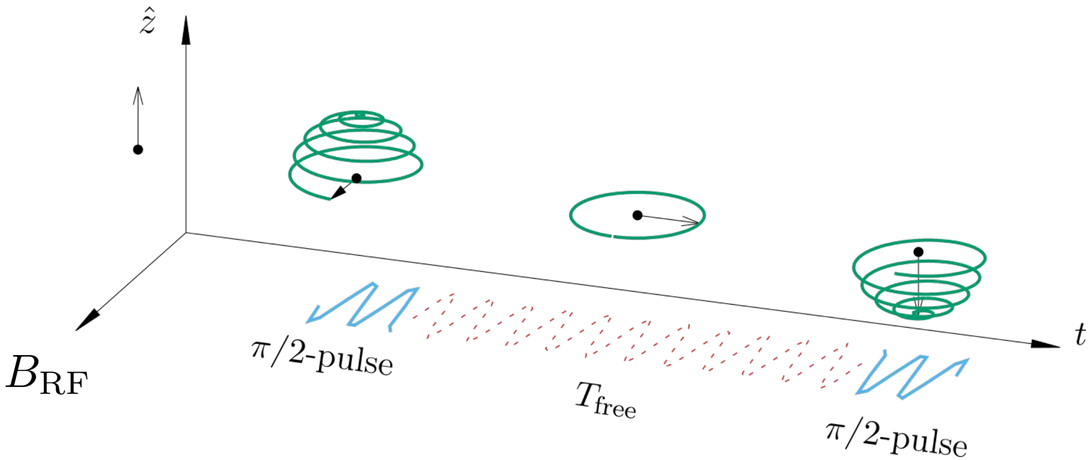
Large evidence of *C* but not of *CP* violation

Baryogenesis

Out of thermal equilibrium so that *CPT* symmetry does not recover *B*, *C* and *CP* breakings

Separated oscillatory fields method

- $\nu_{\nparallel}$ and $\nu_{\parallel}$ measured through **Ramsey interferometry**



Ramsey cycle:

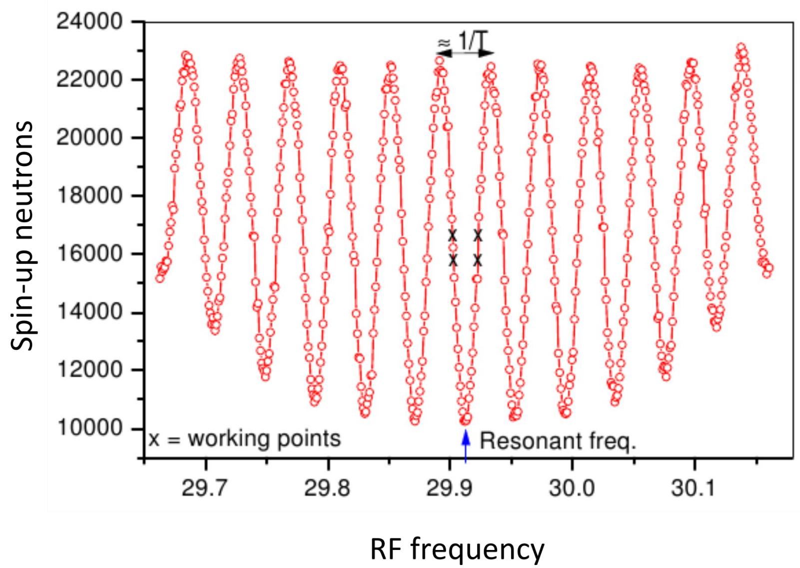
1. Initial state: spin-up
2. pi/2 RF-pulse (~ 2 s)
3. Free precession (~ 100 s)
4. pi/2 coherent RF-pulse (~ 2 s)

- When resonance is fulfilled ($\nu_{\mathrm{RF}} = \nu_{\mathrm{Larmor}}$) all spin-up states are inverted.

- If $\delta\nu = \nu_{\mathrm{Larmor}} - \nu_{\mathrm{RF}} \neq 0$, a phase $\delta\nu T_{\mathrm{free}}$ is accumulated in stage 3 and the spin inversion is hindered → fringes pattern

Separated oscillatory fields method

➢ $\nu_{\nparallel}$ and $\nu_{\parallel}$ measured through **Ramsey interferometry**



$$N_{\uparrow\downarrow}(\Delta\nu) = \frac{N_0}{2}\left(1 \mp \alpha\cos(2\pi[\nu_{\mathrm{osc}} - \nu_{\nparallel,\parallel}]T_{\mathrm{free}})\right)$$

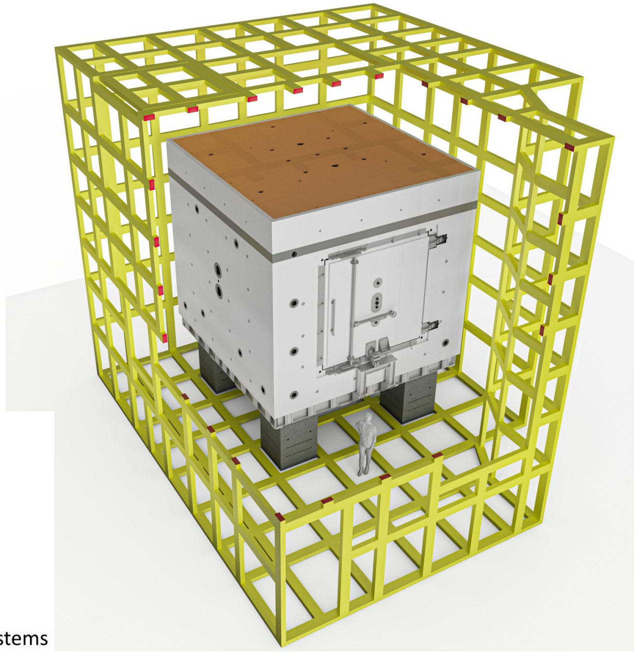
Total UCN   polarization level   RF frequency

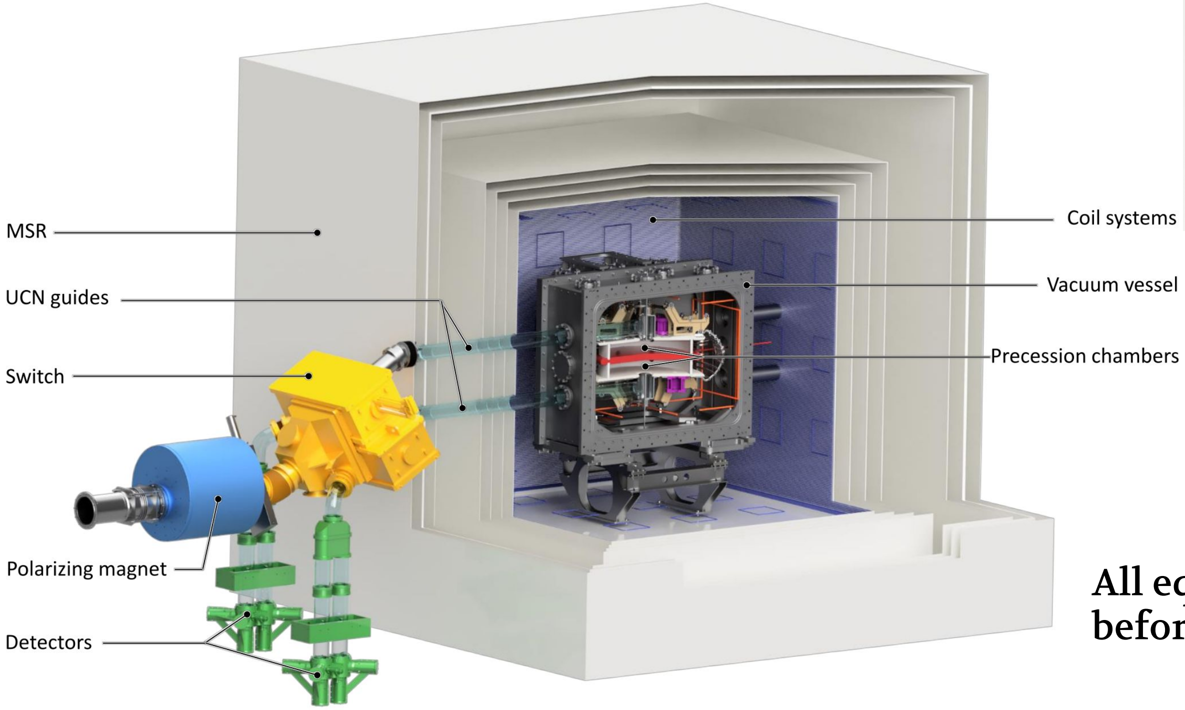
➢ When resonance is fulfilled ($\nu_{\mathrm{RF}} = \nu_{\mathrm{Larmor}}$) all spin-up states are inverted.

➢ If $\delta\nu = \nu_{\mathrm{Larmor}} - \nu_{\mathrm{RF}} \neq 0$, a phase $\delta\nu T_{\mathrm{free}}$ is accumulated in stage 3 and the spin inversion is hindered → fringes pattern

B-field control

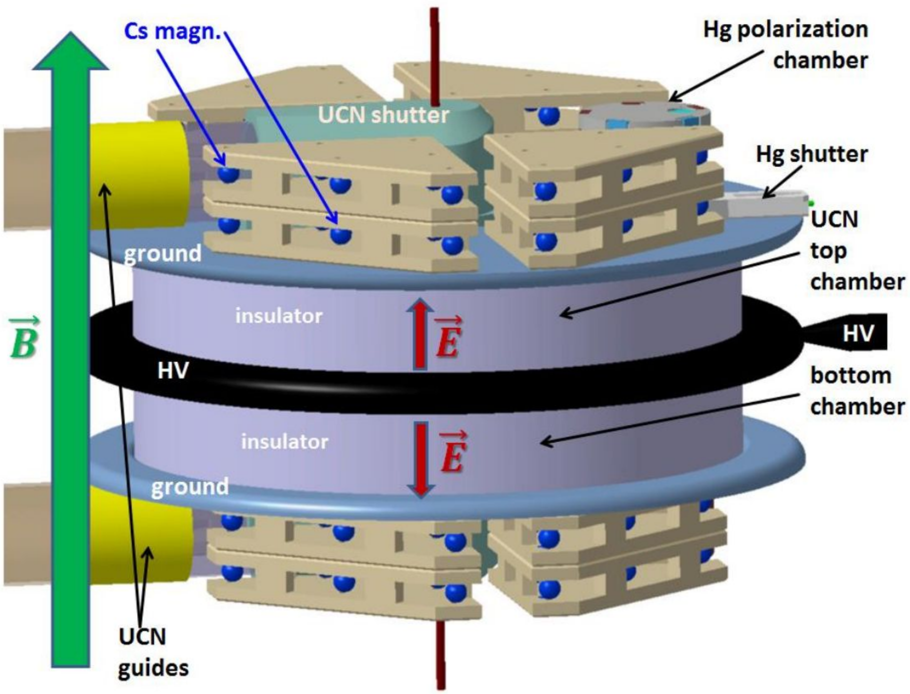
The active magnetic shield (AMS)

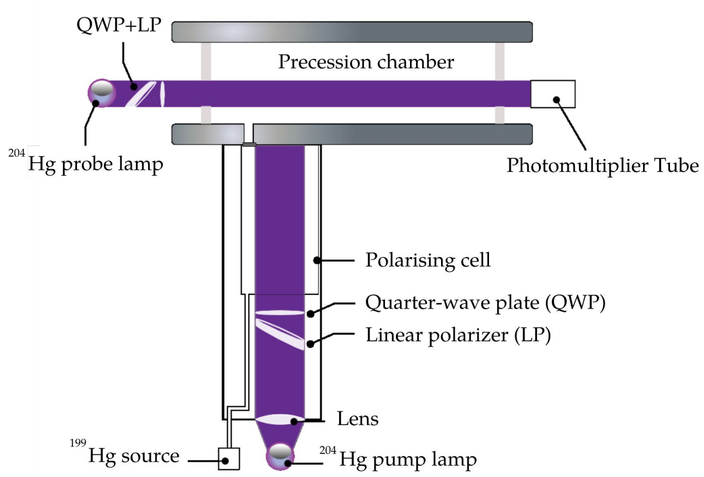




All equipment magnetically tested before installed in the experiment

Magnetometry





- Hg co-magnetometers , to correct for B linear drifts: $\sigma(B)$ ~ 30 fT over 180 s
- Cs magnetometer array, to fine-tune B-field homogeneity

B_0 coil design

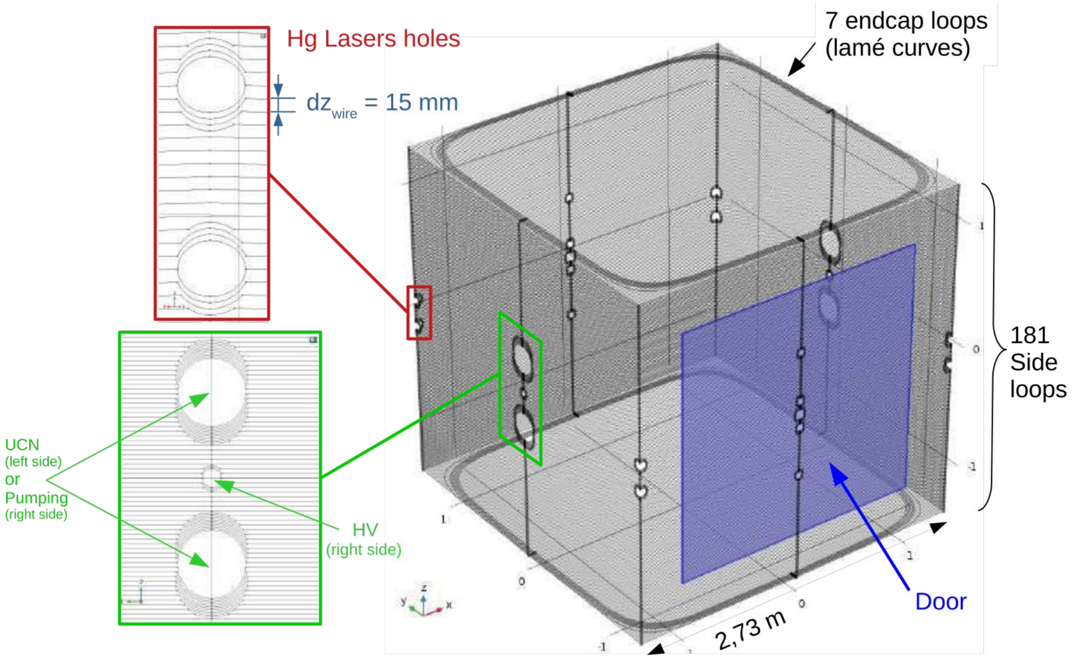
Field requirements over the precession chambers:

→ Magnitude and direction: $\mathbf{B}_0 = B_z\hat{\mathbf{z}}$, with $B_z = 1\ \mu$T

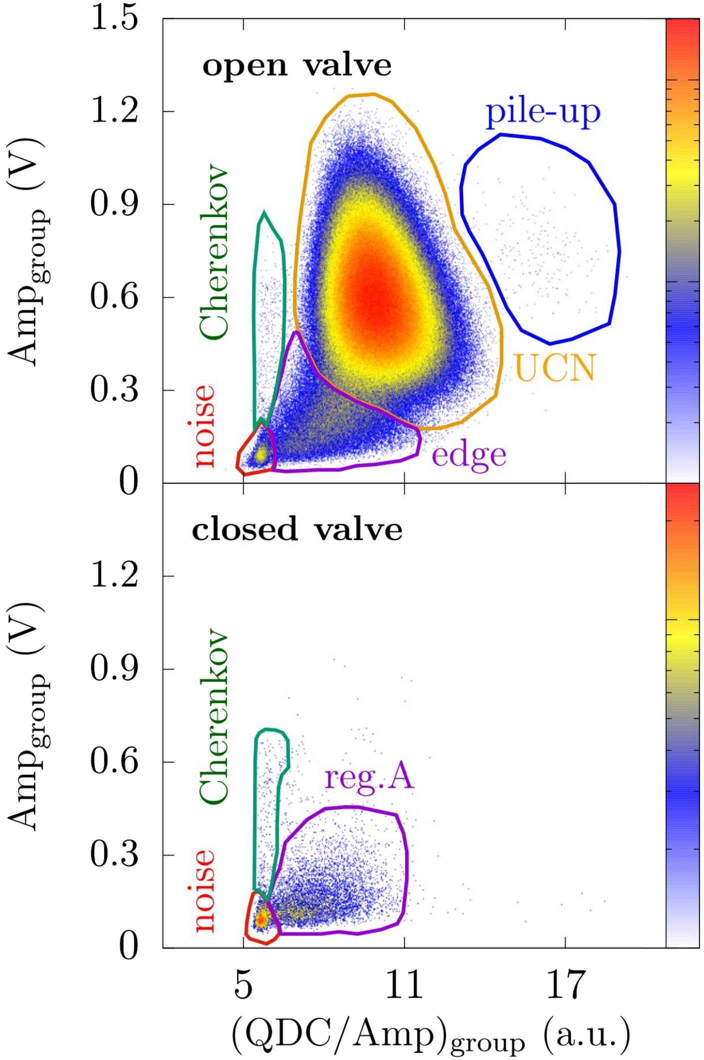
→ Uniformity: $\sigma(B_z) = \sqrt{\langle (B_z - \langle B_z\rangle)^2\rangle} < 170$ pT → To maintain UCN polarization

First <u>comsol</u> model of the B_0 coil and the MSR [P. Flaux PhD thesis]:

- Cubic solenoid (2121.6 m wire)
- Endcaps to improve field uniformity at the coil edges
- Strong coupling between the MSR and the coil



Pulse shape analysis (PSA)



PSA based on ***amplitude to charge/amplitude*** ratio

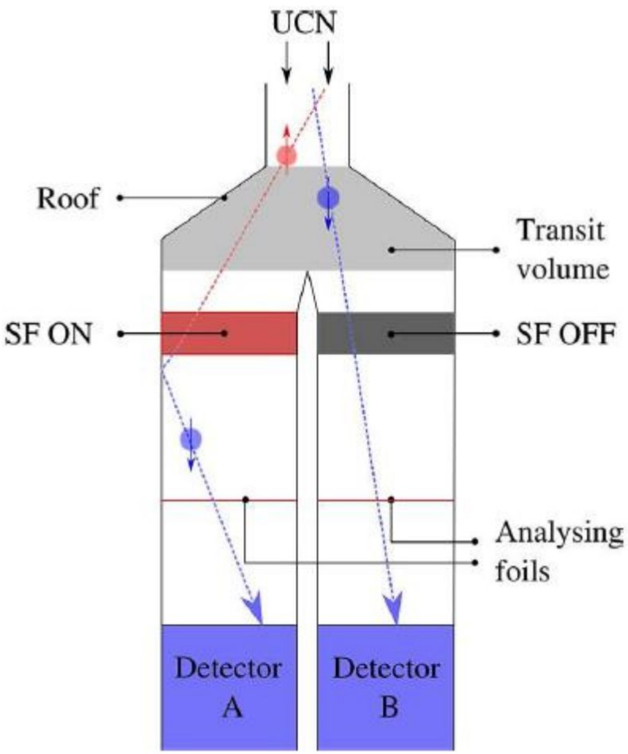
- (a) total $(\sim 10^6)$
- (b) UCN (94.0%)
- (c) noise (0.6%)
- (d) edge (5.0%)
- (e) pile-up (0.2%)
- (f) Cherenkov (0.2%)

- (a) total $(\sim 10^4)$
- (b) noise (13.9%)
- (c) reg.A (65.3%)
- (d) Cherenkov (6.3%)

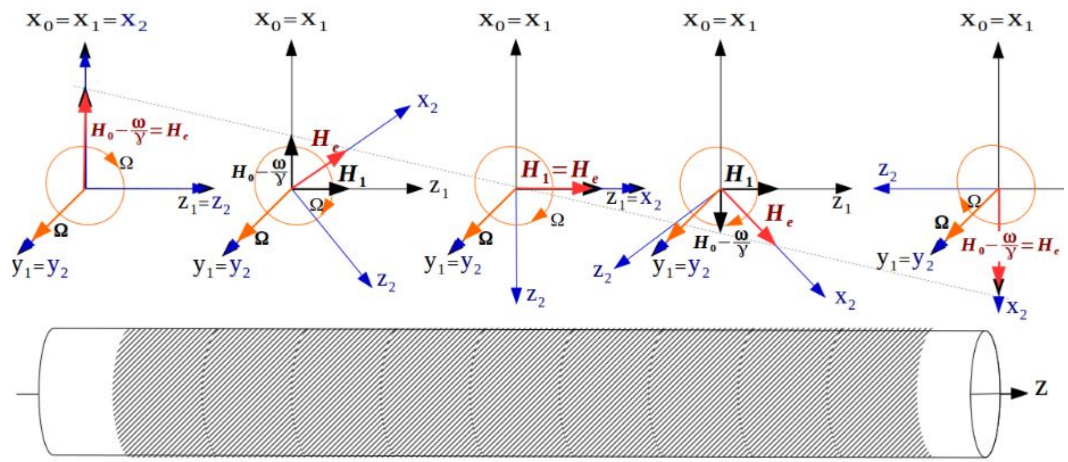
- Non UCN events account for **less than 1%**!
- 'edge' and 'reg.A' overlap -> need to discriminate gamma-rays from edge events OR use lead shielding

USSA: U-shape Simultaneous Spin Analyzer

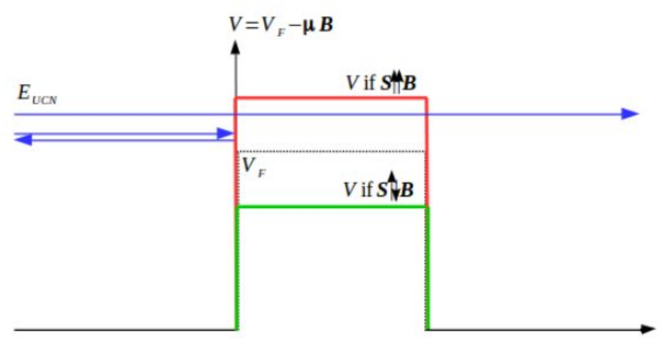
Double arm -> spin-up and spin-down simultaneous counting



Spin flipping process in rotating frame



Analyzing foil energy scheme



[nEDM spin analyzer model, V. Hélaine PhD thesis]