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The neutron Electric Dipole Moment

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Plan

- low energy precision measurements and EDMs
- measurement principle and experimental sensitivity
- UCNs and their sources
- present limit on the neutron EDM
- new in vacuum nEDM experiment at PSI
- new UCN source at PSI
- R&D activities (materials, magnetometry, detectors)
- cryoEDM experiments EU and US

Context

- Assuming CPT: CP-violation = T-violation

- In systems or processes without strangeness, the effects due to the CKM CP-violation are strongly suppressed
  (nEDM < $10^{-(31-33)}$ *e*cm; correlations in beta decay <10^{-10})

- Huge window to search for new physics!
  (without being affected by SM backgrounds)

- EDMs of quantum systems are very sensitive probes

Permanent EDMs

- observables
  - spin $\boldsymbol{S}$, unit vector $\hat{\boldsymbol{s}}$
  - magnetic dipole moment: $\boldsymbol{\mu} = \mu\, \hat{\boldsymbol{s}}$
  - for an elementary QM system: $\boldsymbol{d} = d\, \hat{\boldsymbol{s}}$

- classical dipole interaction

$$H = -\,(\boldsymbol{d} \cdot \boldsymbol{E} + \boldsymbol{\mu} \cdot \boldsymbol{B}) = -\,(d\, \boldsymbol{E} + \mu\, \boldsymbol{B}) \cdot \hat{\boldsymbol{s}}$$

- transformations under T and P

$\boldsymbol{B}$ and $\hat{\boldsymbol{s}}$ behave identically but not $\boldsymbol{E}$ and $\hat{\boldsymbol{s}}$

if $d \neq 0$: T and P are violated

EDM measurements

- upper limits have been obtained for:

  e, μ, τ, p, n, Λ, atoms, molecules

- new projects and approaches are being considered for:

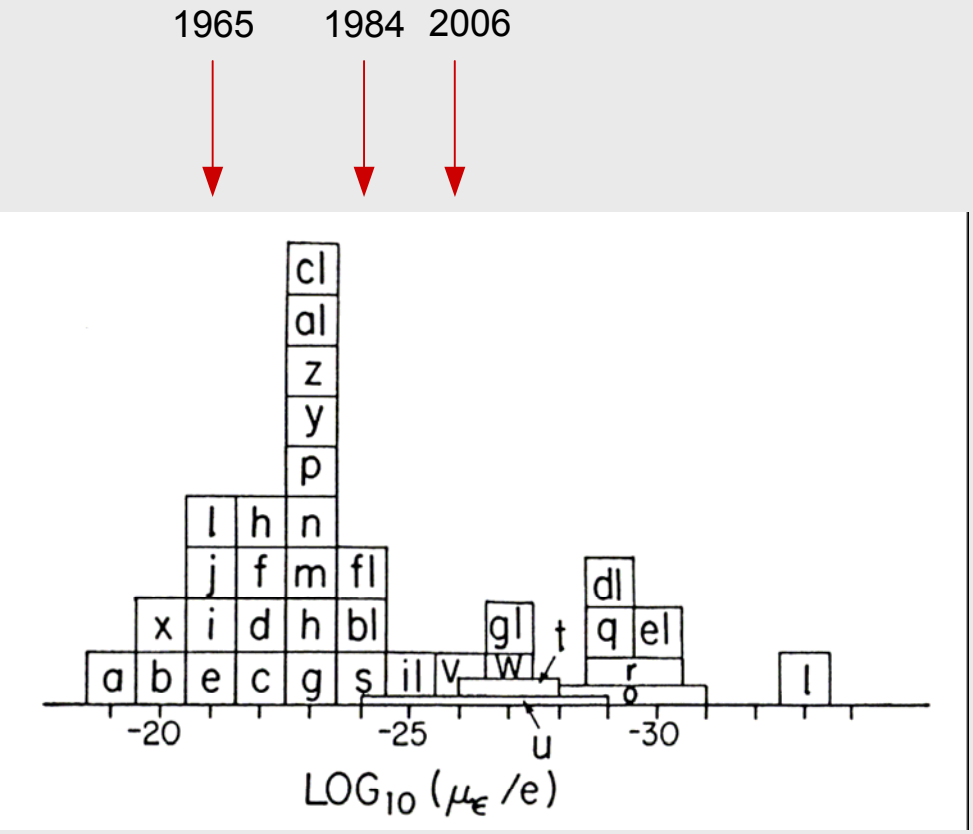
  e, μ, n, d, radioactive nuclei, atoms, molecules

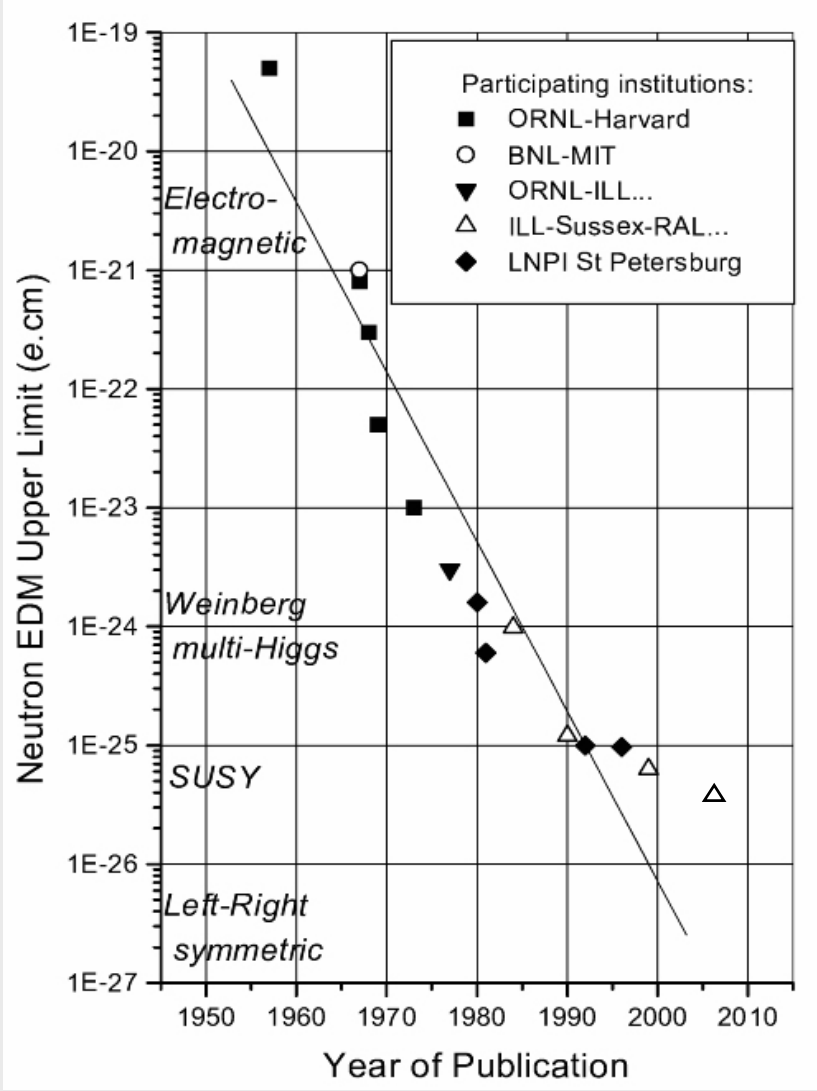
  - very active field !
  - complementary constraints (ex. SUSY phases)

Any new mechanism for CP violation in the quark sector has in particular to pass the neutron EDM test

…or invent a mechanism (cancellation) to avoid it

Ramsey's hunting table



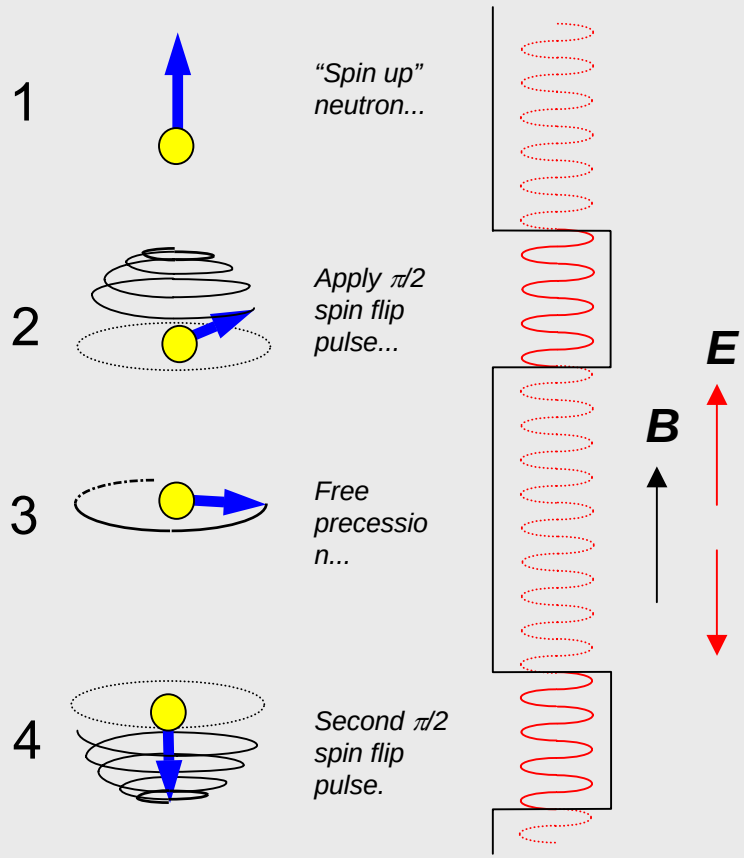


- electromagnetic
- weak
- milli-weak
- super-weak

- strong
- milli-strong
- multiple Higgs
- $N_q > 4$

Measurement principle

Ramsey method of
Separated Oscillating Fields



- prepare a sample of polarized neutrons
- make a $\pi/2$ spin flip ("start clock")
- allow free spin precession in parallel ***B*** and ***E*** static fields
- make a $\pi/2$ spin flip ("stop clock")
- analyze direction of neutron spin
- look at energy (frequency) shift under field inversion:

$$\Delta\varepsilon = h\,|\Delta\nu| = 4Ed_n$$

Sensitivity figure

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

- α : slope on resonance curve ("visibility")
- T : free precession time
- E : electric field strength
- N : total number of detected neutrons ($N \sim \rho\, V\, t_{mes}$)

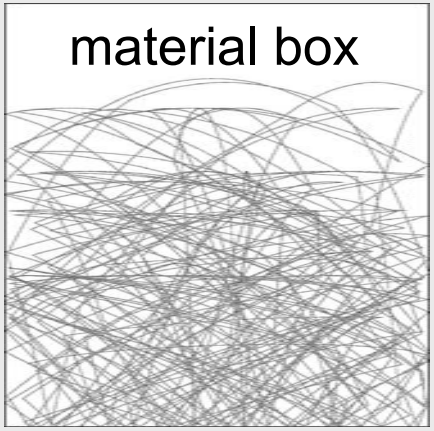
- high sensitivity requires
  - long precession times
  - large neutron densities

What are Ultra-Cold Neutrons ?

- definition

neutrons which are reflected at any angle of incidence

(the neutron kinetic energy is smaller than the “Fermi potential” of the surface)



$\lambda_n \approx 800$ Å;

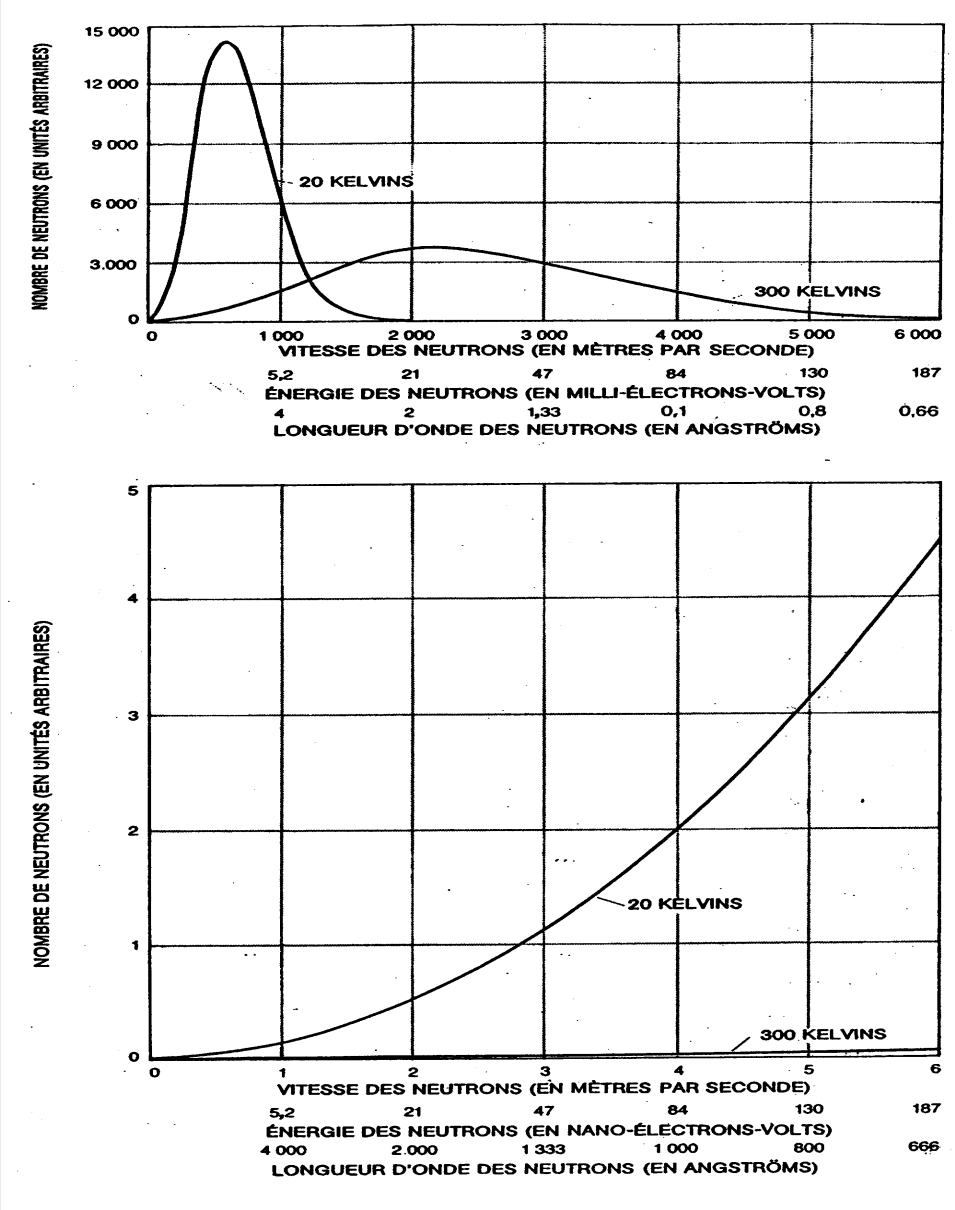
$v_n \approx 5$ m/s;

$T_n \approx 2$ mK ;

$E_n \approx 130$ neV

Potential energy:

- Gravitational (1m)
- Magnetic (1 T)
- Srong (several materials)

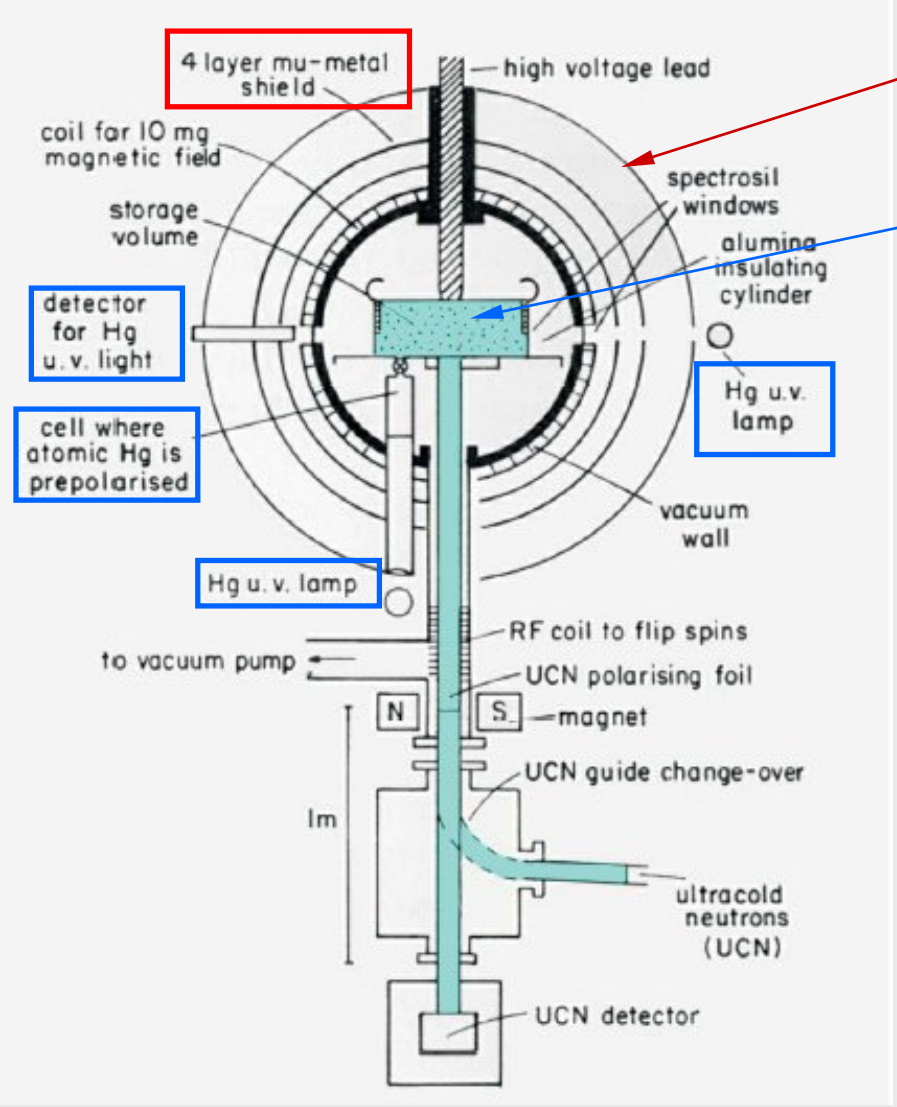


The UCN source at ILL

- the only multi-user UCN source in operation
- high flux reactor
  (thermal power: 58.3 MW)
- thermal n-flux: 1.5×10^{15} n/s/cm^2
- cold neutron source: 20 l of LD_2 at 25K
- vertical neutron guide 13m, 7×7 cm^2,
  (^{58}Ni coated)
- UCN source: rotating turbine
- UCN density at experiment: ρ = 20 /cm^3

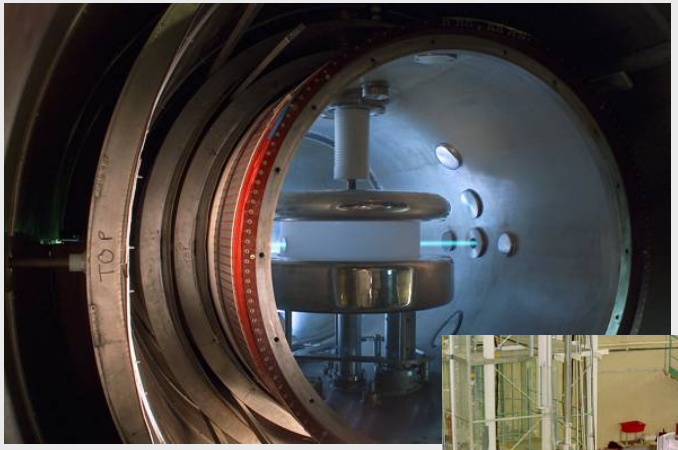
The most sensitive spectrometer

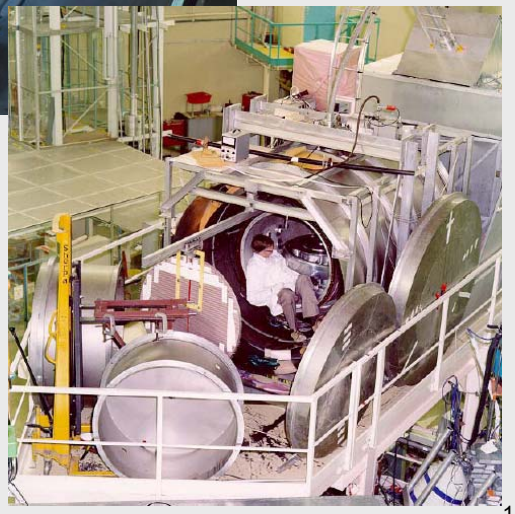
Sussex-RAL-ILL at the PF2 UCN source at ILL-Grenoble



4 layers of passive (μ-metal) shield

Co-habiting ^{199}Hg magnetometer

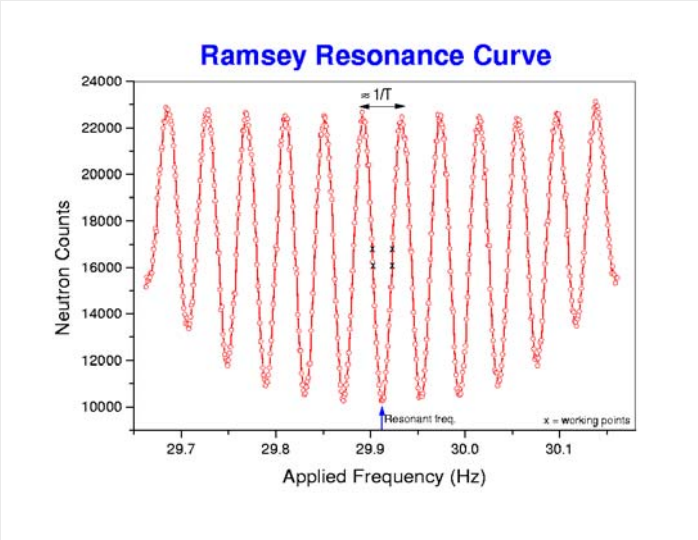




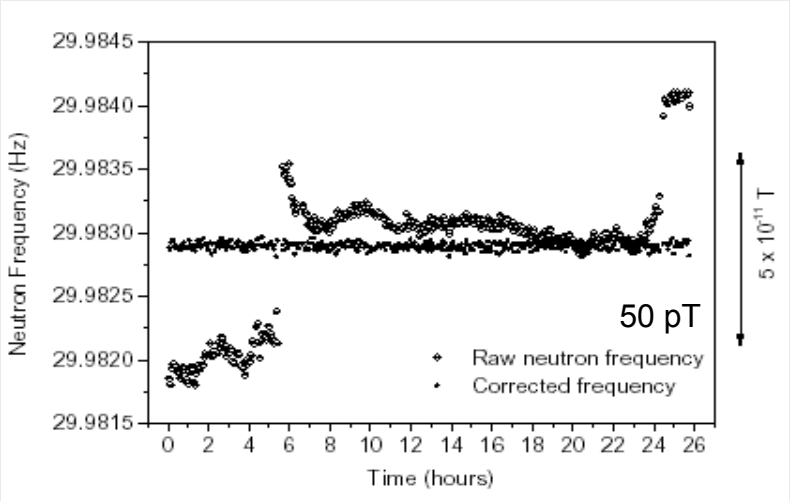
- V = 20 l
- B = 10 mG, ν_L = 30 Hz
- E = 4.5 - 11.0 kV/cm
- T = 120 - 140 s

Present nEDM limit

Ramsey resonance technique

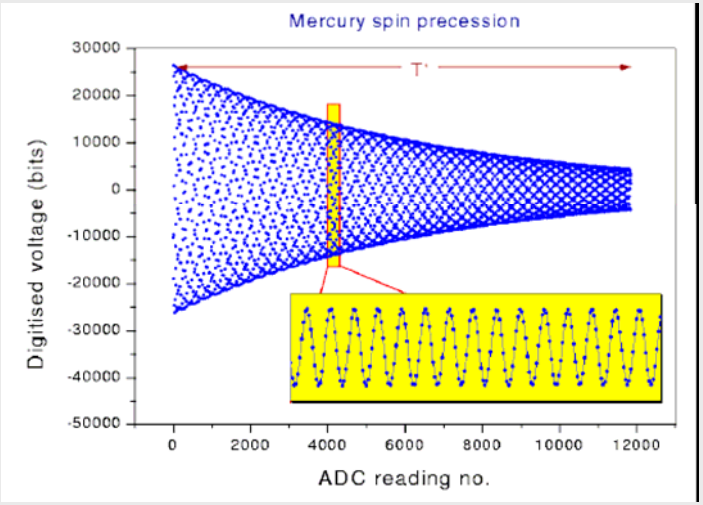


Correction to the neutron precession



50 pT = 500 nG ≈ 10^{-6} x Earth Field

^{199}Hg co-magnetometer $d(^{199}\mathrm{Hg}) < 8.7 \times 10^{-28}$ *ecm*



P.G. Harris *et al.*, PRL **82**(1999)904

C.A. Baker *et al.*, PRL **97**(2006) 131801

$$|\, d_n \,| < 2.9 \times 10^{-26} \text{ ecm (90\% CL)}$$

Final Sussex-RAL-ILL result

(limited by statistics but new systematics effects are not far)

Towards a new EDM measurement

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Our “phase 2” goal

- Install and use the most sensitive EDM spectrometer operated so far (in vacuum-room-temperature)…

-…at the most intense UCN source in the world (under construction)

  - Move spectrometer from ILL to PSI by end 2008
  - Operate and measure at PSI : 2009-2011
  - Sensitivity goal: 5×10^{-27} *ecm*

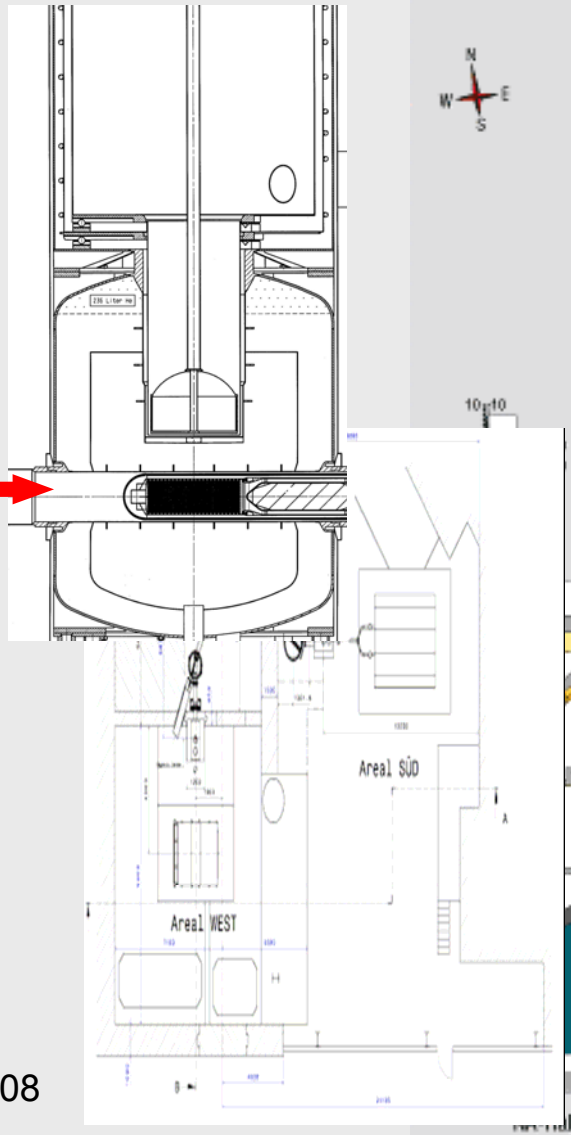
Spallation UCN source at PSI

Ultra Cold Neutron Source

- 590 MeV, 2 mA, proton beam
- pulsed (1% duty cycle)
- target: Pb

- moderators: D_2O (20-80 K)
- UCN source: SD_2 (30 l, 8K)
- storage volume: 2-3 m^3

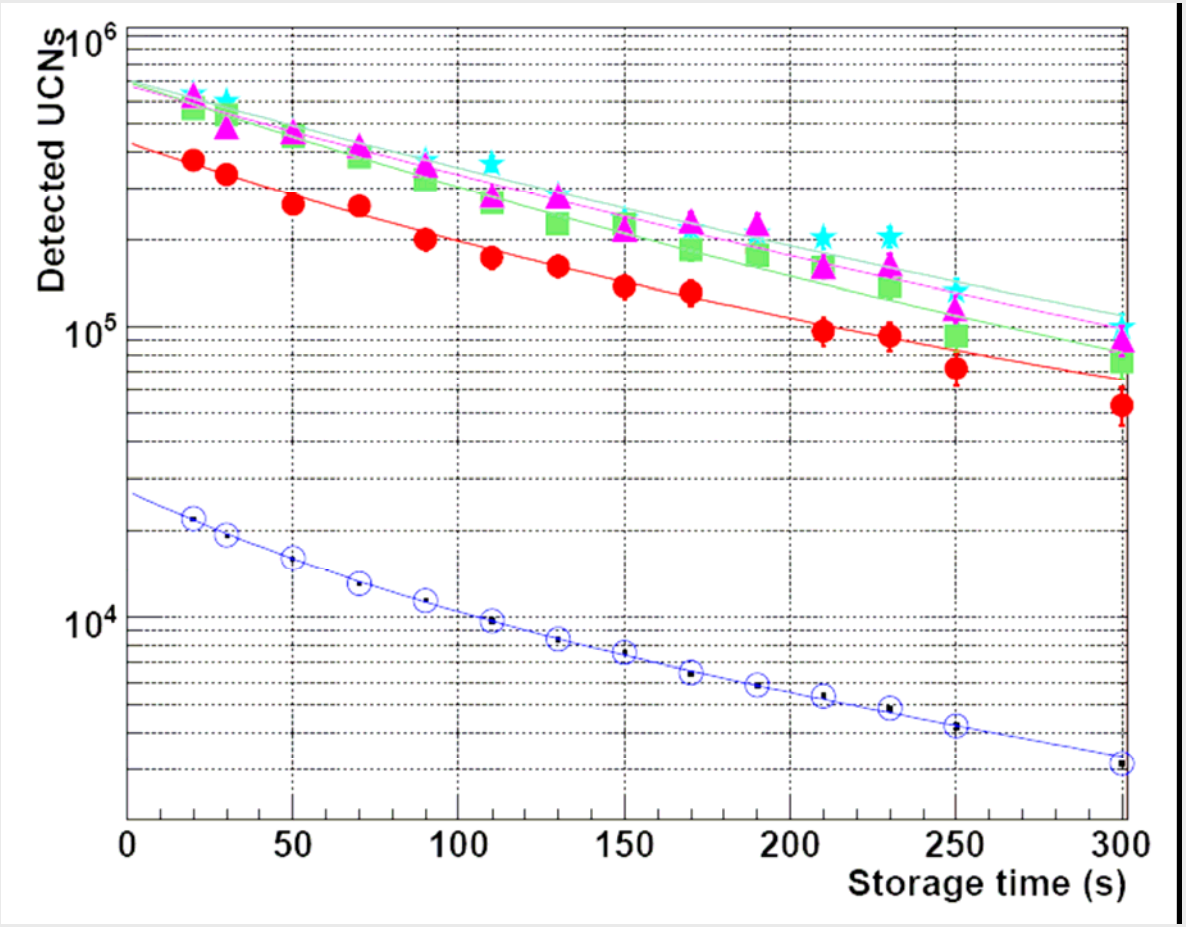
- expected density: $\rho > 1000$ /cm^3
- start operation: autumn-winter 2008



MC simulations and coatings

- required the inclusion of UCN physics into GEANT4 – P. Fierlinger and others, NIMA **552** (2005) 513
- MC simulation tested with UCN data from the Sussex-RAL-ILL spectrometer

Storage time with chamber 1m above beam line



Chamber/Electrode

Spectrometer @ PSI

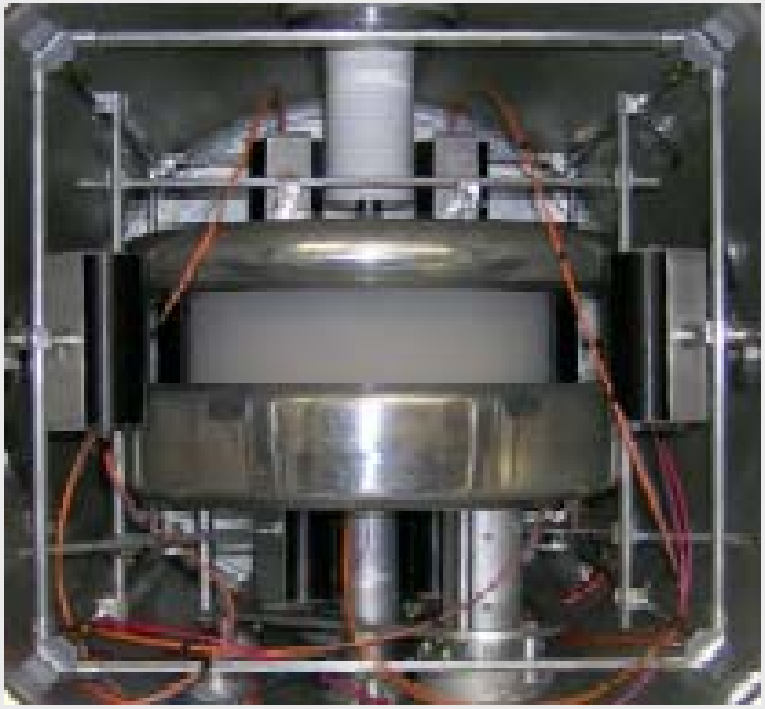
Diam/Diam:	35
Diam/DLC:	33
Si3N4/DLC:	29
Quartz/DLC:	19

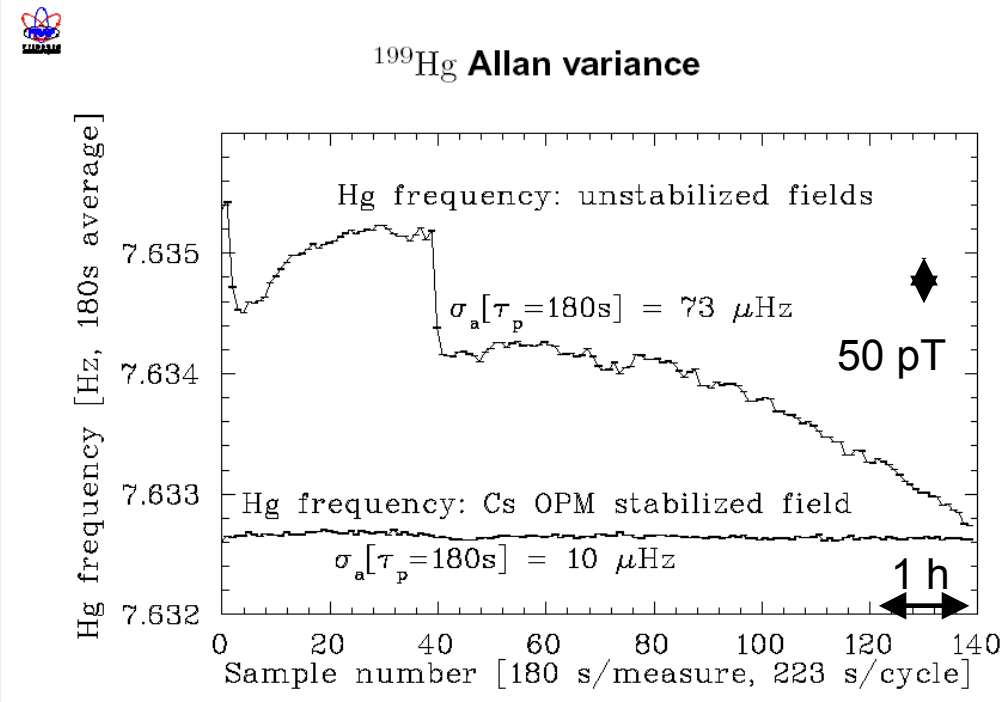
Present system @ ILL

Quartz/DLC:	1

Magnetometry

- operate Cs and Hg magnetometers simultaneously
- use Cs-OPM to stabilize magnetic field
- control with ^{199}Hg precession

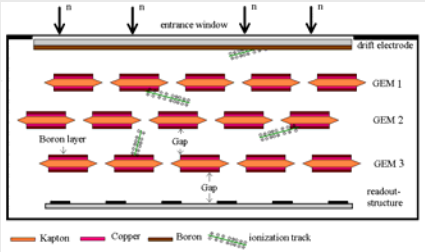


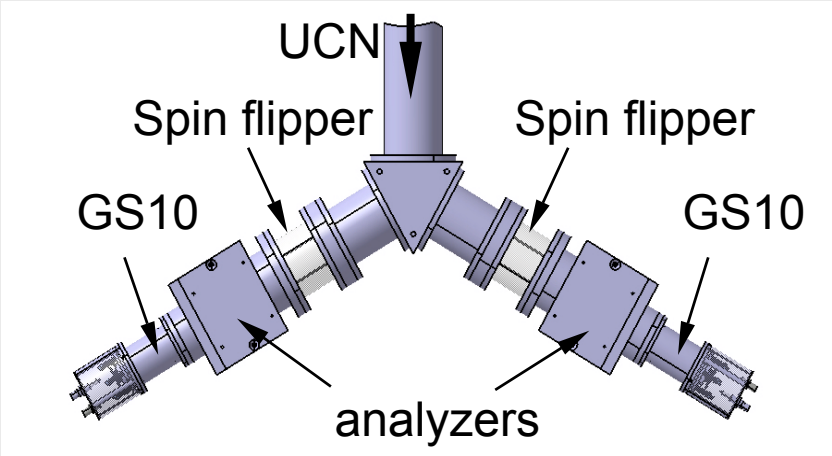


Detector tests and spin analysis

Doped glass scintillator

GEM

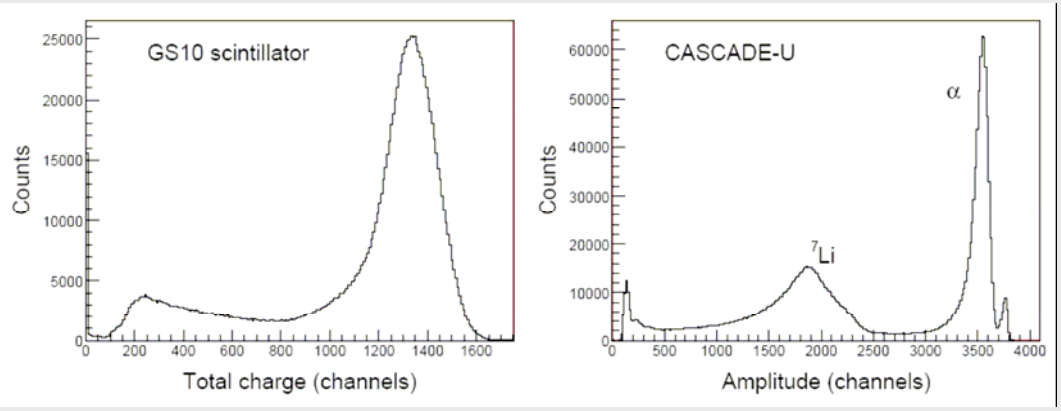


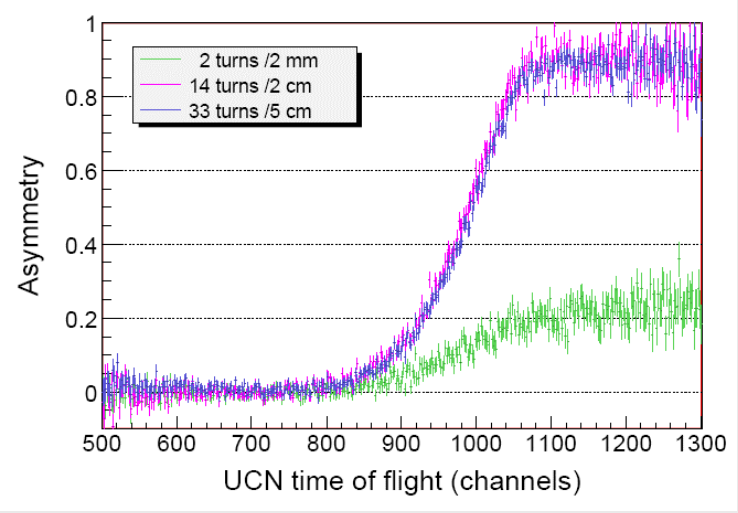


$$n + {}^{6}Li \rightarrow \alpha + t$$

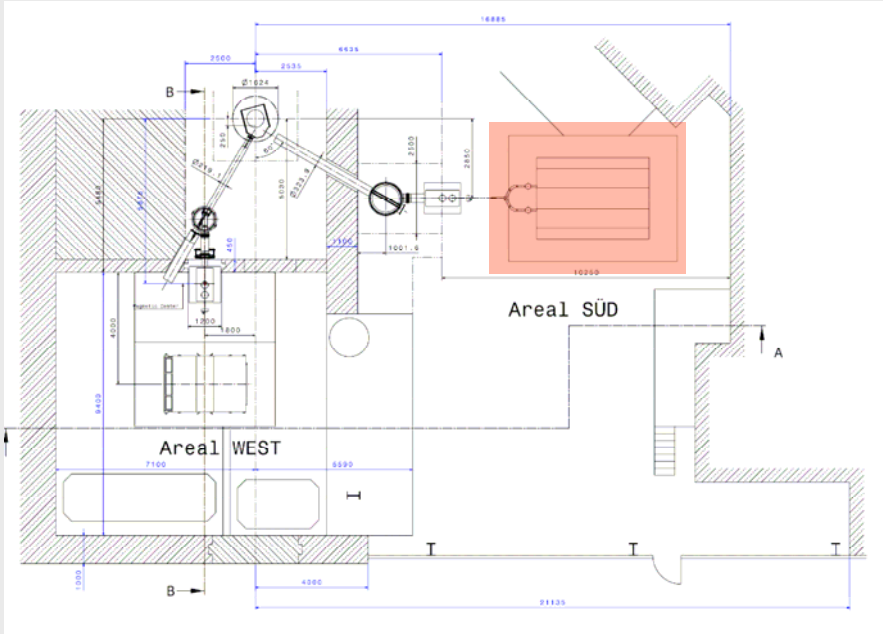
$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li$$

$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li + \gamma(0.48MeV)$$



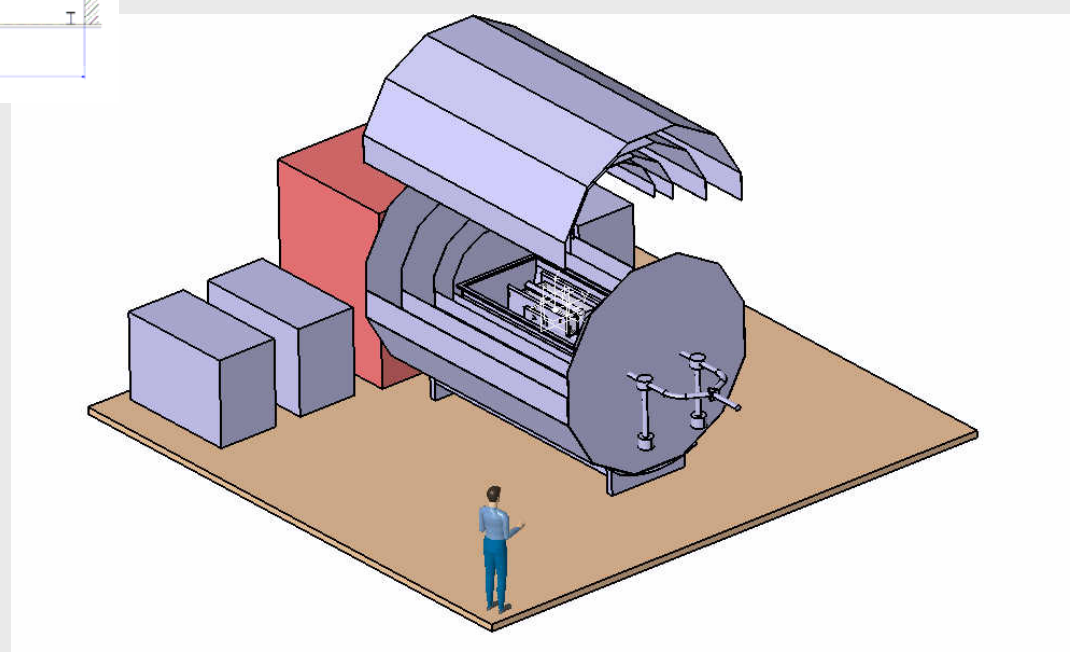


Design of a new spectrometer



- Larger double chamber volume
- Optimized for UCN source at PSI
- Improved monitoring and stabilization with Cs-OPM
- potential to incorporate co-co-magnetometers (^{3}He, ^{129}Xe)

- Sensitivity goal: $5x10^{-28}$ecm

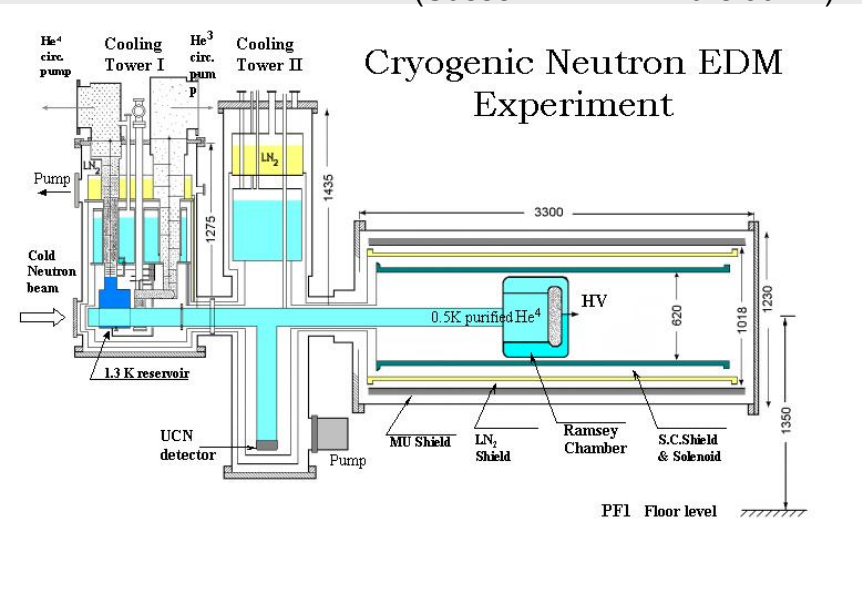


(2011-2015)

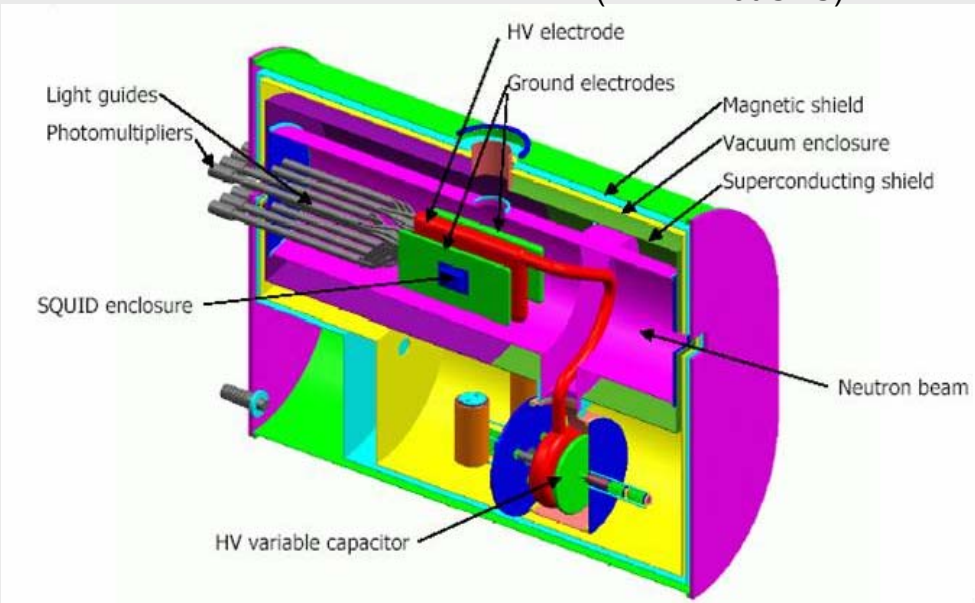
Cryo EDM experiments

- produce UCN in super-fluid He from thermal neutrons
- use superconducting shields
- SQUID magnetometry
- full in LHe experiments

(Sussex-RAL-ILL-Kure at ILL)



(LANL++ at SNS)



Summary

- The neutron EDM plays a crucial role to constraint new scenarios for CP violation (complementary to other systems)
- The most sensitive limit on the neutron EDM was obtained using a room temperature spectrometer with UCN in vacuum
- A new effort has been undertaken to push this technique to new sensitivity levels
- The level of 5×10^{-27} ecm appears reachable at the new UCN source at PSI, in about 4-5 years
- Efforts to measure the nEDM with the Ramsey technique are also under way using cryogenic sources/spectrometers