The status of the search for a nEDM and the new UCN sources

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Outline

Neutron Electric Dipole Moment

New UCN Sources

nEDM Experiments:

CryoEDM Experiment @ ILL

nEDM Experiment @ SNS

nEDM Experiment @ PSI

The Baryon Asymmetry of the Universe

Observed:*
$n_B/n_\gamma = 6 \times 10^{-10}$

SM expectation:**
$n_B/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C, CP-violation
thermal non-equilibrium
JETP Lett. **5**, 24 (1967)

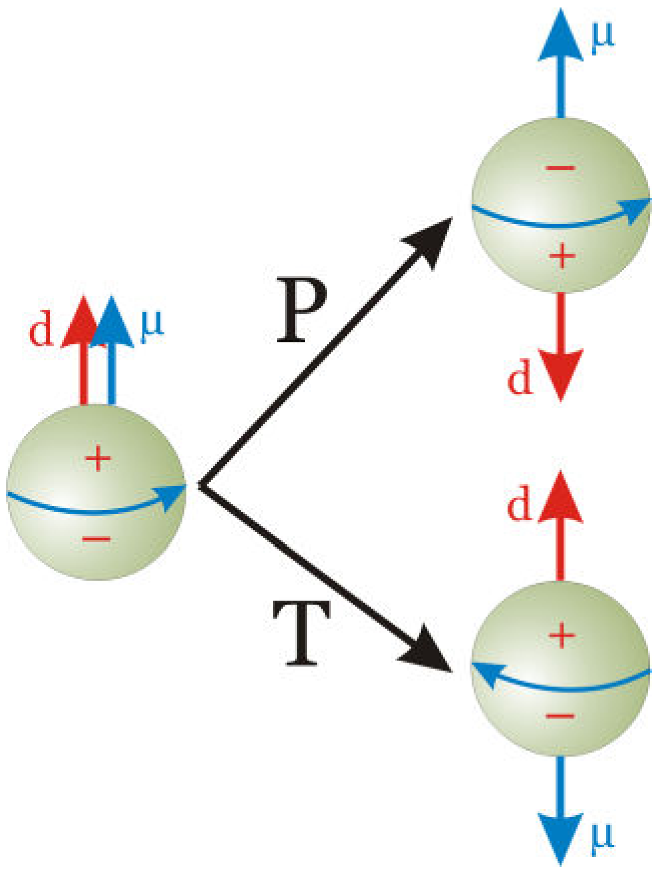
* WMAP data:
Astrophys. J. Supp. **170**, 377 (2007)
** Riotto and Trodden:
Ann. Rev. Nucl. Part. Sc. **49**, 35 (1999)

Electric Dipole Moment

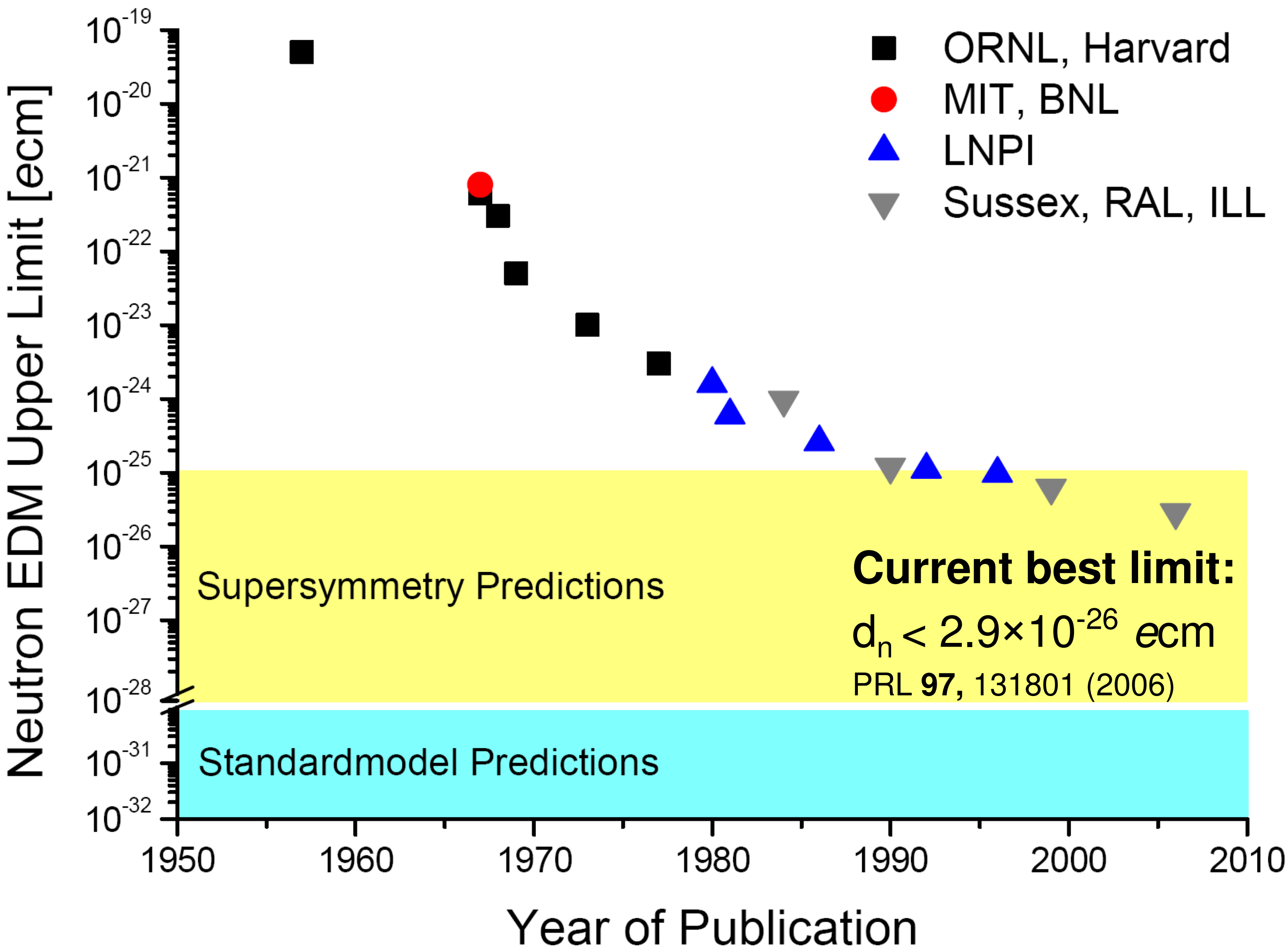
Non-zero, permanent EDM violates both parity P and time reversal T

→ Violates CP

→ Understand mechanism of CP violation



nEDM History



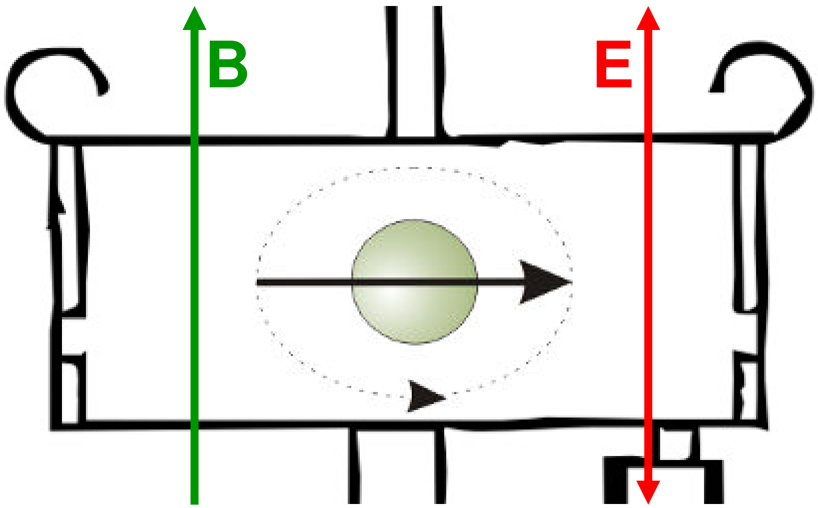
Measurement Principle

- An EDM couples to an electric field as a MDM couples to a magnetic field:

$$h\nu = 2\mu_n B \pm 2d_n E$$

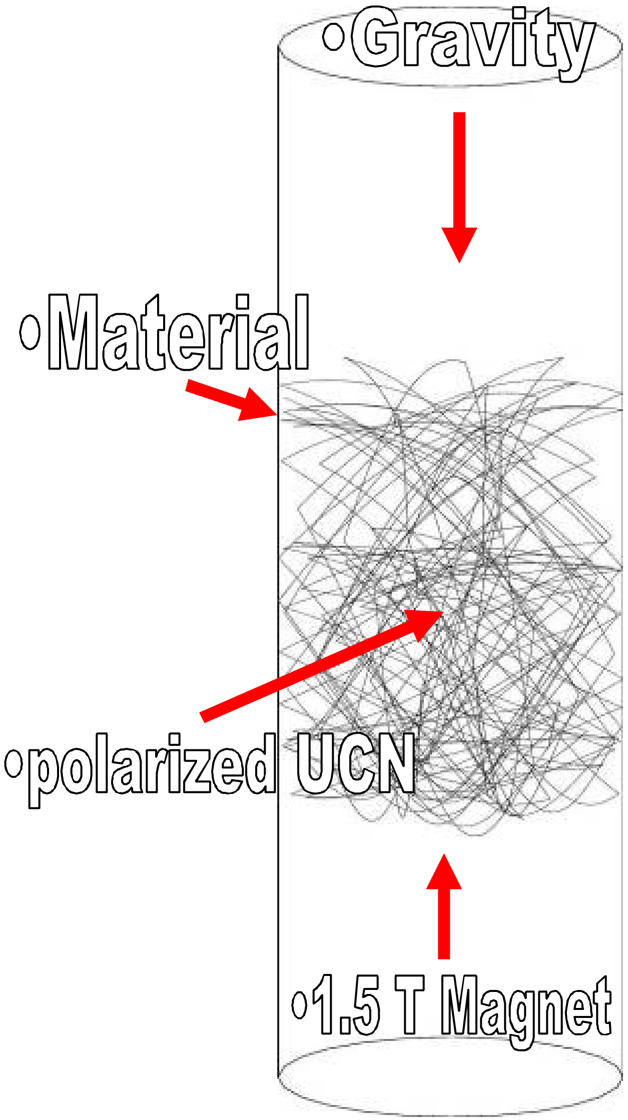
- Measure EDM from the difference of precession frequencies for parallel/anti-parallel fields:

$$d_n = \frac{h\Delta\nu}{4E}$$

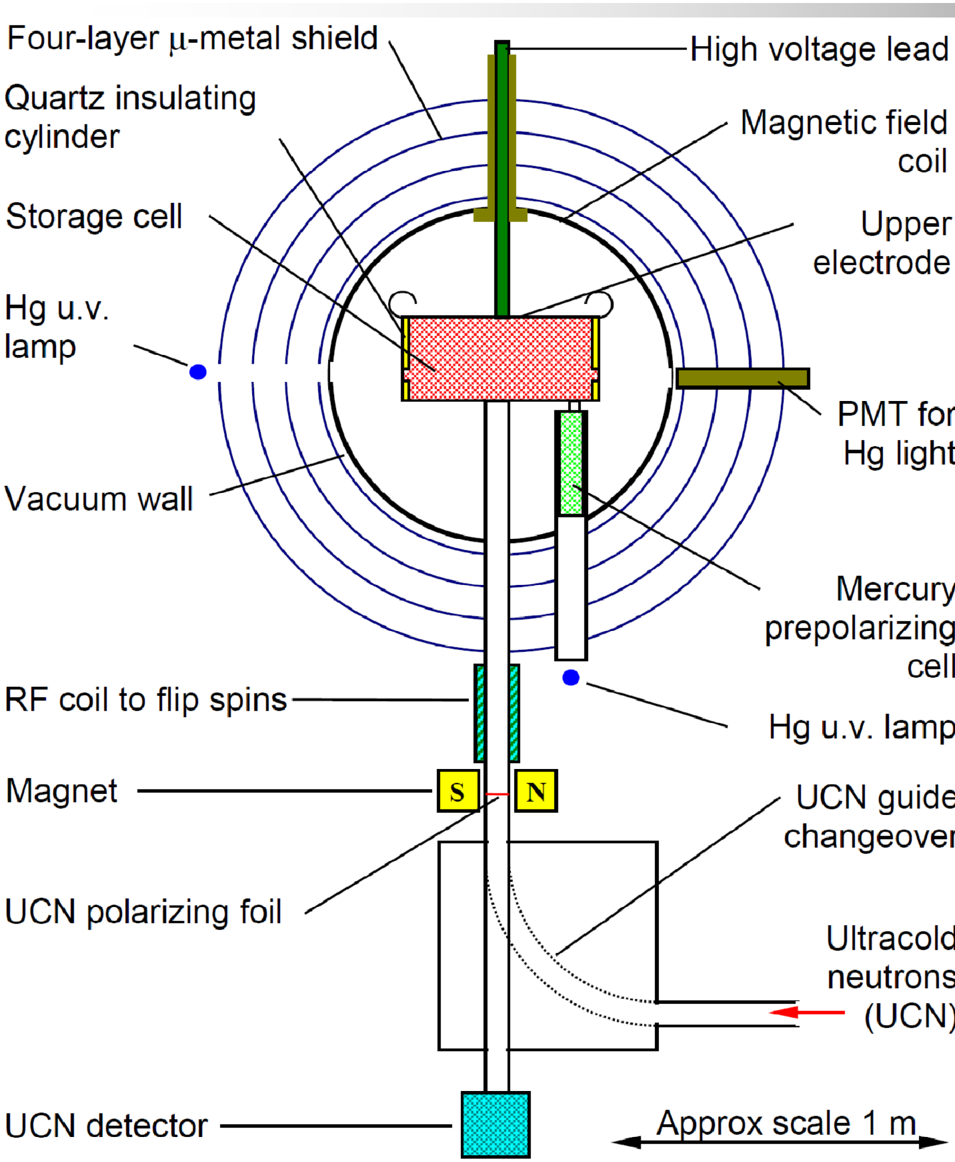


Ultracold Neutrons

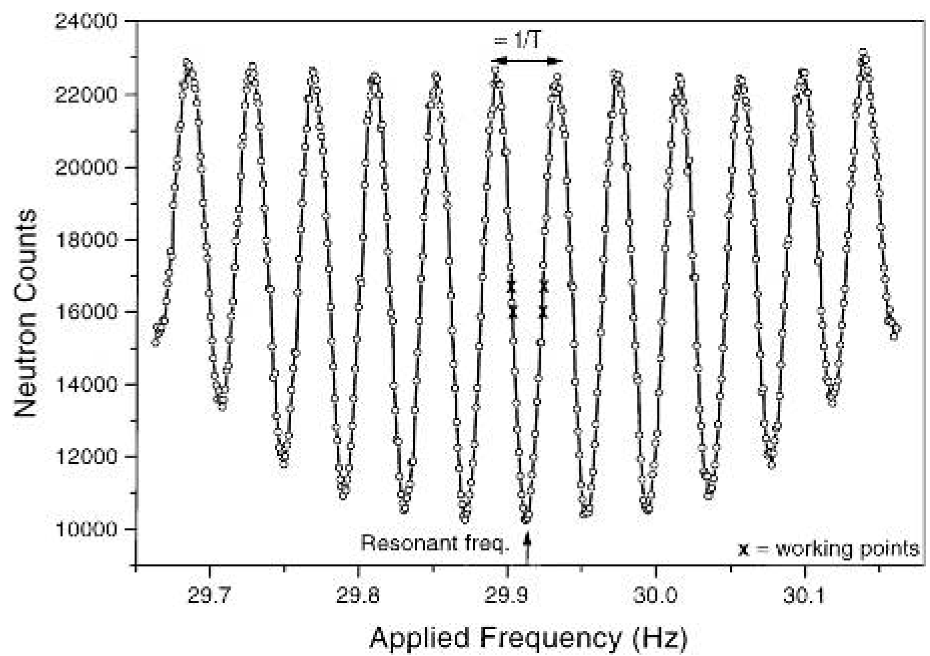
- Neutrons with kinetic energies of ~ 100 neV (~ 5 m/s)
- Interactions:
  - Gravitational: V_g = 100 neV/m
  - Magnetic: V_m = 60 neV/T
  - Strong: V_F up to 350 neV
  - Weak: n → p + e + ν



nEDM Apparatus



- Room temperature experiment
- Ramsey technique of separated oscillatory fields
- Mercury co-magnetometer to monitor magnetic field



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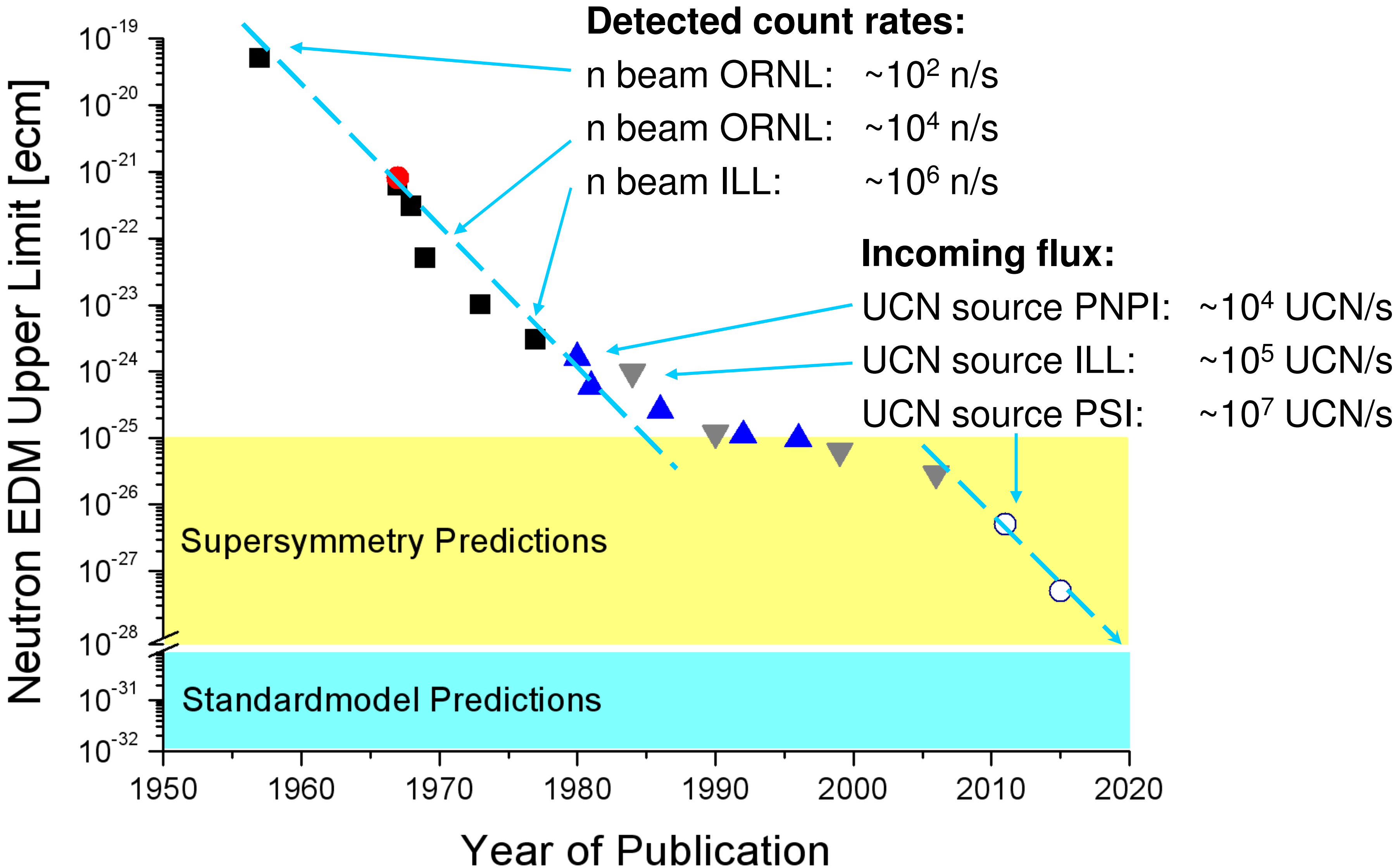
Need for Neutrons!

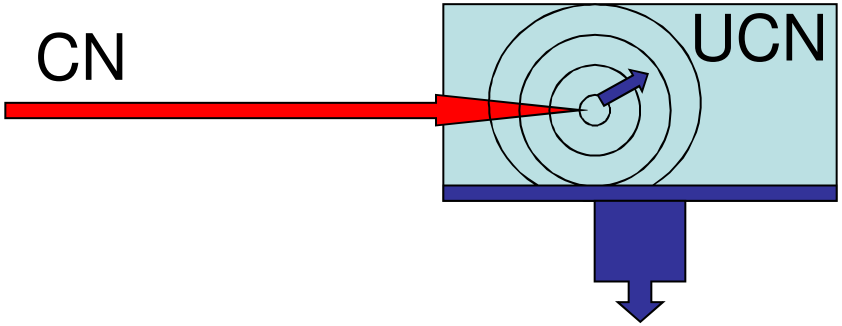


Superthermal UCN Production

- Golub and Pendlebury, PLA **62**, 337 (1977): superfluid ^4He
- Golub and Böning, ZPB **51**, 95 (1983): solid D_2

$$\rho_{UCN} = \Phi_{CN} \, R \, \tau_{UCN}$$

	R [cm^{-1}]	τ_{UCN} [s]
D_2	10^{-8}	0.03…0.1
^4He	1..3 x 10^{-9}	10…1000



Cooling machine = phonon pump

Detailed balance:
upscattering cross section = exp(-ΔE/kT) x downscattering

UCN sources

Existing:

ILL, France	liquid D_2, turbine	$\rho \sim 10$ UCN/cm^3
LANL, USA	solid D_2	$\rho \sim 10$ UCN/cm^3
Mainz, Germany	solid D_2	$\rho \sim 1$ UCN/cm^3
NCSU, USA	solid D_2	$\rho \sim 10$ UCN/cm^3

2010:

PSI, Switzerland	solid D_2	$\rho \sim 1000$ UCN/cm^3

≥2010:

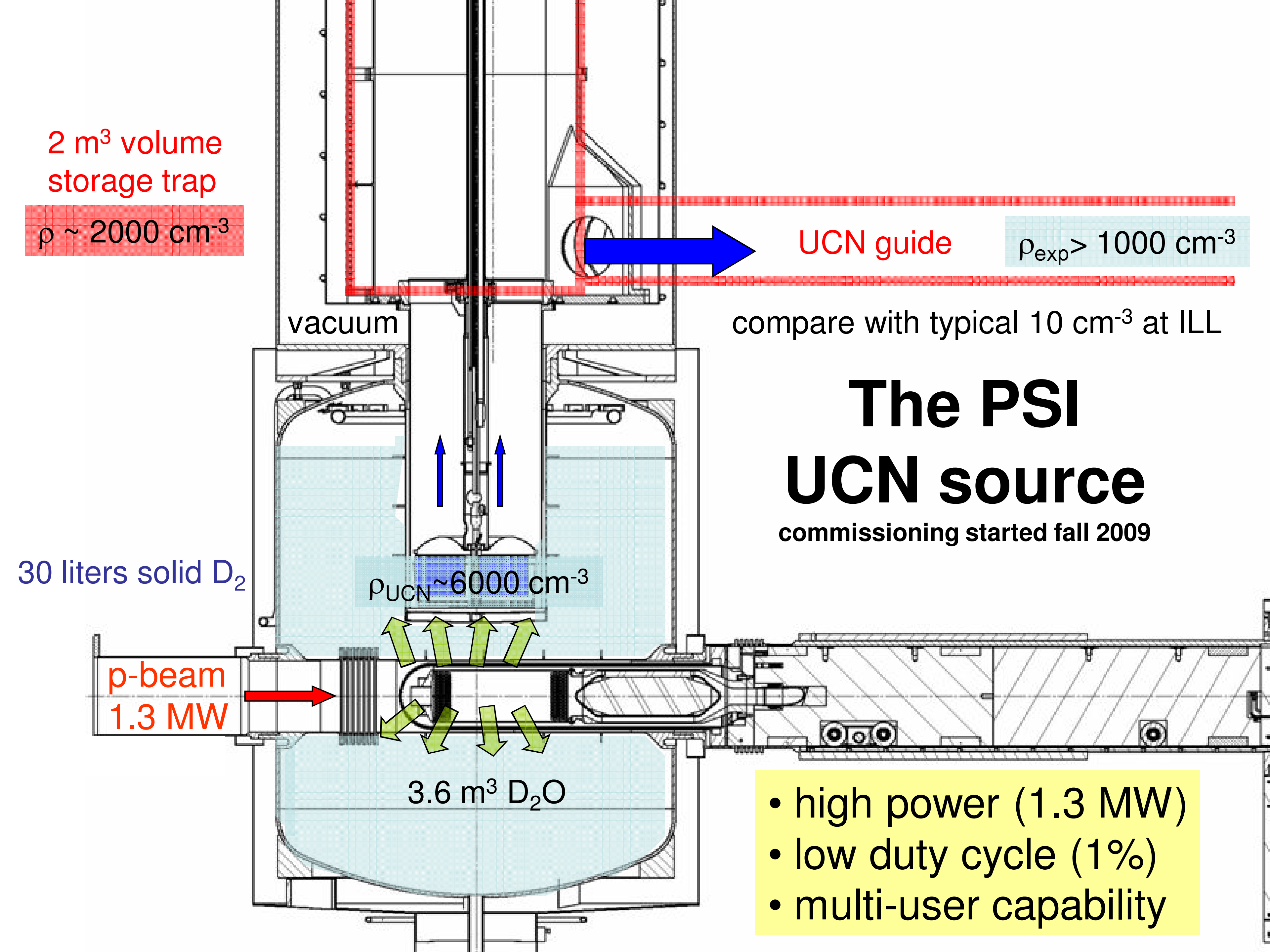
ILL, France	superfluid 4He	ρ ~ 1000 UCN/cm3

≥2012:

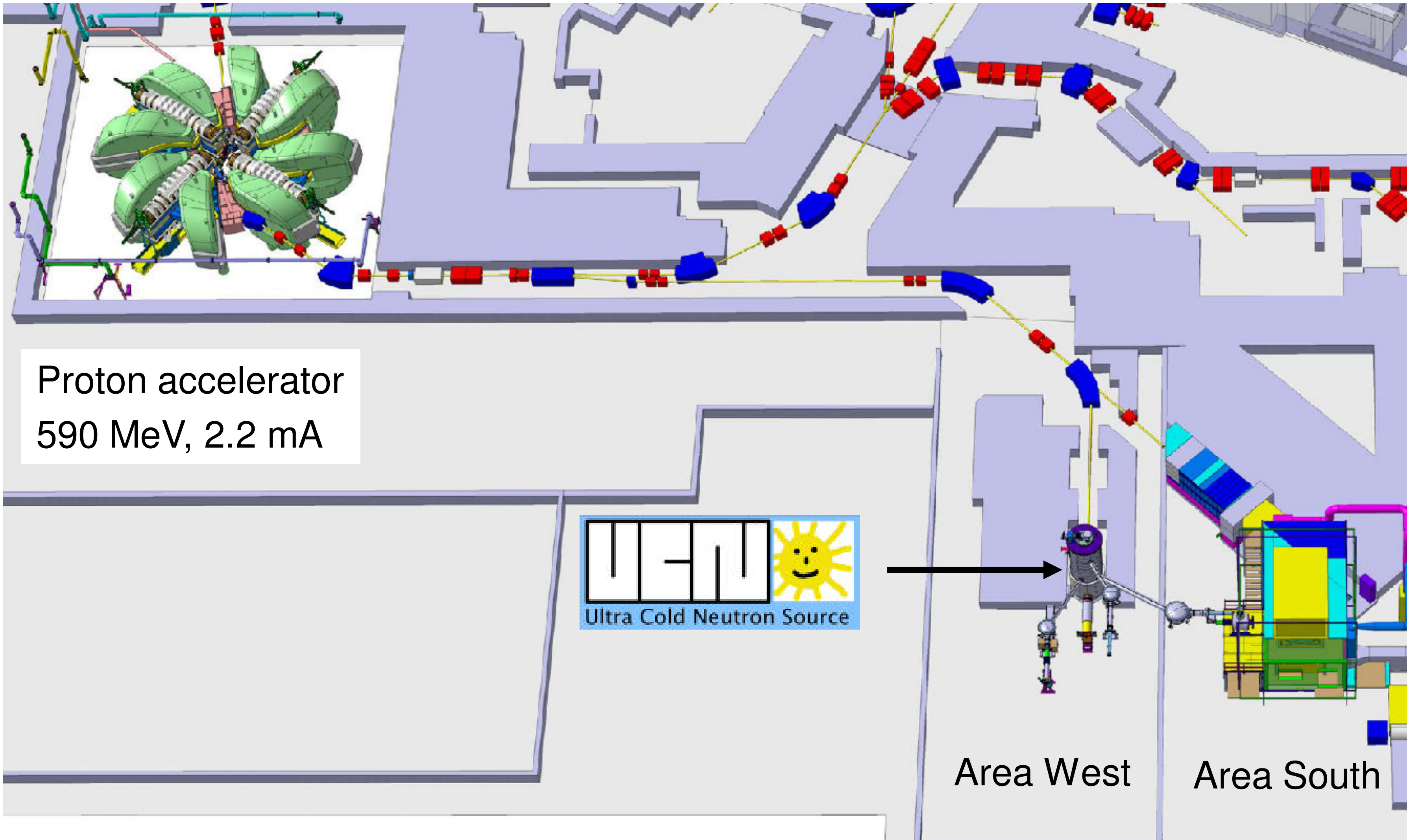
FRM-II, Germany	solid D_2	$\rho \sim 3000$ UCN/cm^3
PNPI, Russia	superfluid ^{4}He	$\rho \sim 10'000$ UCN/cm^3

≥2013:

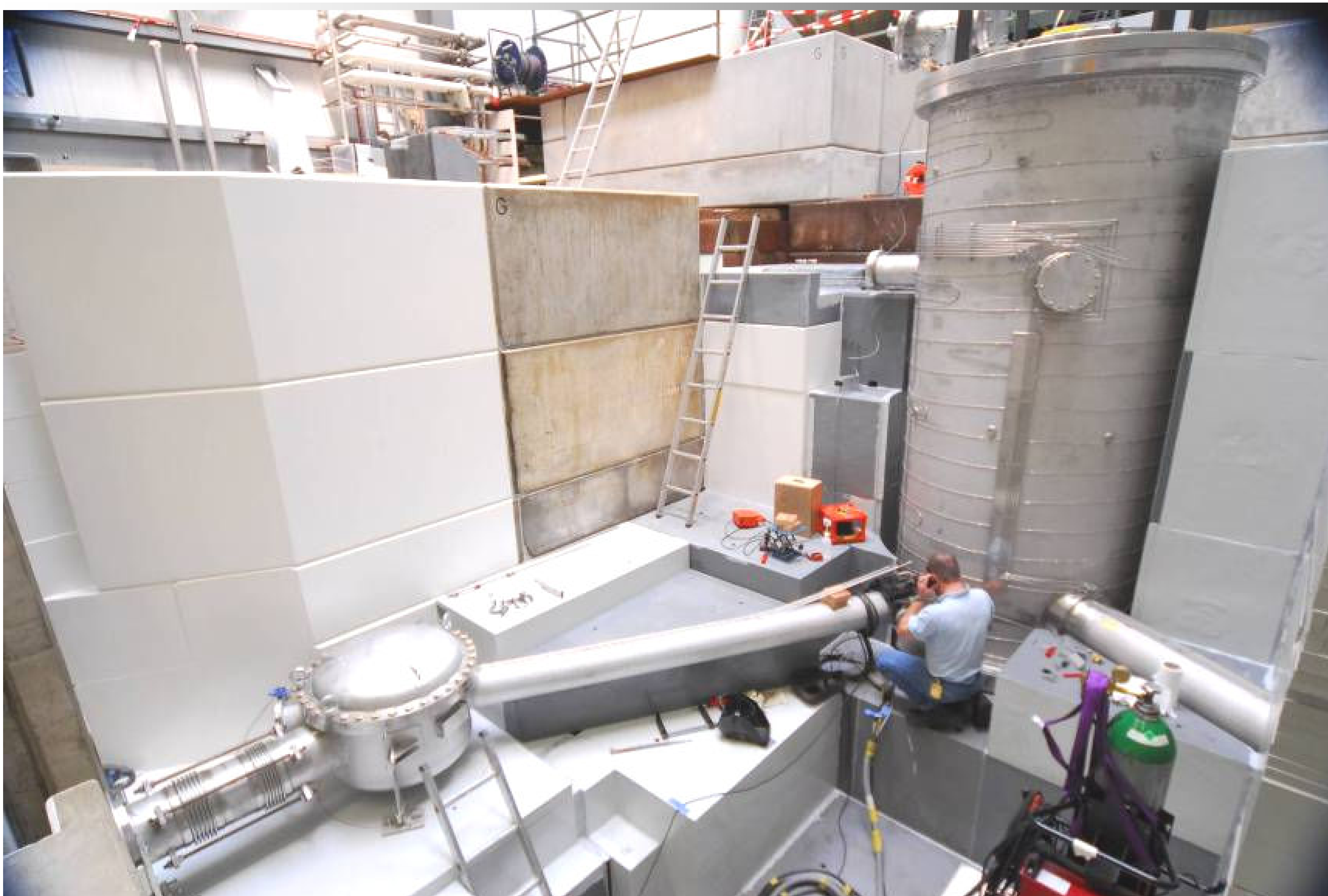
TRIUMF, Canada	superfluid ^{4}He	$\rho \sim 50'000$ UCN/cm^3


2 m³ volume
storage trap
ρ ~ 2000 cm⁻³
UCN guide
ρexp > 1000 cm⁻³
vacuum
compare with typical 10 cm⁻³ at ILL
The PSI
UCN source
commissioning started fall 2009
30 liters solid D₂
ρUCN ~6000 cm⁻³
p-beam
1.3 MW
3.6 m³ D₂O
• high power (1.3 MW)
• low duty cycle (1%)
• multi-user capability

UCN Source


Proton accelerator
590 MeV, 2.2 mA
UCN
Ultra Cold Neutron Source
Area West
Area South

UCN Source

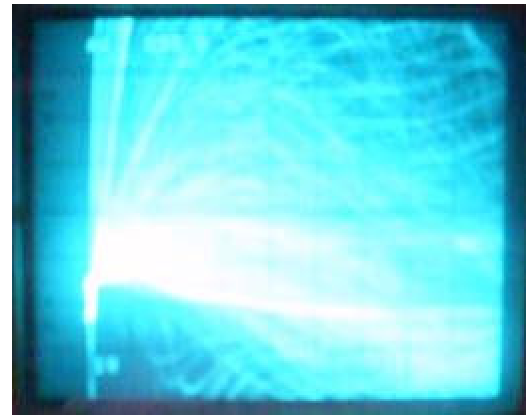


First Proton Pulse on Target
December 15, 2009

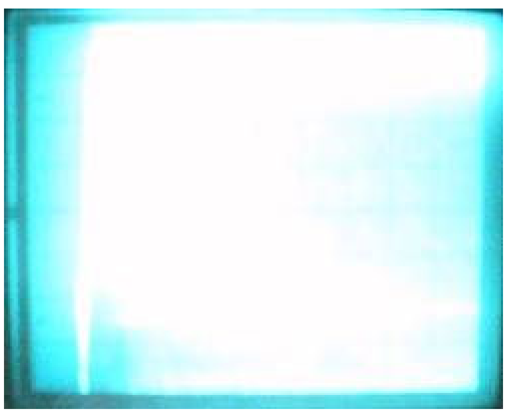
- Signal distribution on oscilloscope monitoring fast neutrons
- 100 μA beam current / 5 ms pulse length

before pulse (background)

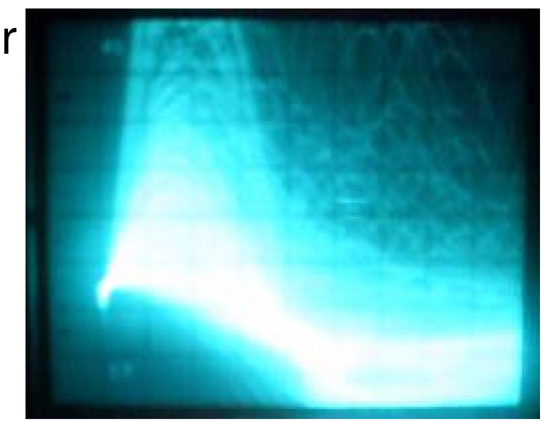
start of pulse



during pulse



2 s after pulse



B.Lauss / L.Goeltl Dec.15, 2009

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nEDM Experiment @ SNS

nEDM Experiment @ PSI

Current & Proposed nEDM Experiments

- CryoEDM experiment @ ILL (next slides, courtesy of P. Harris)
  Sussex – Rutherford – Oxford – ILL – Kure
- SNS EDM @ SNS (next slides, courtesy of B. Filippone)
  ASU – Berkeley – Brown – BU – Caltech – Duke – Indiana – Kentucky – LANL – Maryland – MIT – NCSU – ORNL – HMI – SFU – Tenn. – UIUC – Miss.State – Yale
- nEDM experiment @ PSI (next slides)
  PTB – LPC – JUC – HNI – JINR – FRAP – ECU – LPSC – BMZ – KUL – GUM – IKC – TUM – PSI – ETHZ

- nEDM experiment @ ILL/PNPI
  PNPI – ILL
  → currently running at ILL, needs new UCN source for competitive result
- nEDM experiment @ TRIUMF
  KEK – TIT – Osaka – RCNP – Winnipeg
  → ≥ 2013, LOI/proposal for TRIUMF expected in 2010/2011

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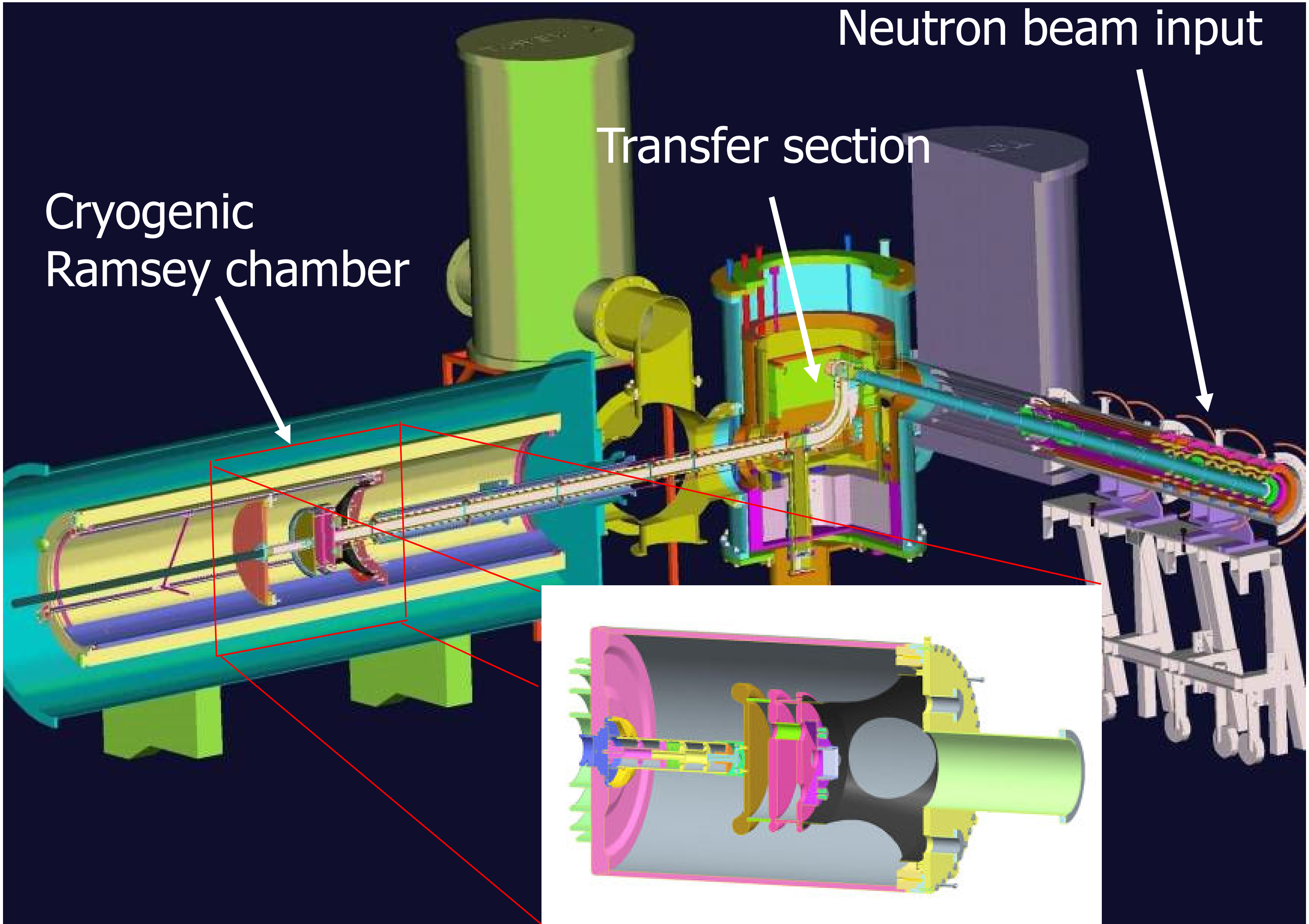
CryoEDM overview



Status & Plans

C.f. room-temp vacuum, liquid He offers:

- More neutrons *N*
- Higher electric field *E*
- Better polarisation α
- Longer NMR coherence time *T*

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

100-fold improvement in sensitivity

- Neutron production and detection in LHe works well.
- Commissioning underway – key components shown to work (but need improvement)
- Cryogenics are old and have caused numerous setbacks
- B shielding not yet optimal, and electric field needs to increase; but we know how
- First results anticipated ~2011-2 at ~$3\text{x}10^{-27}$ ecm level
- 2012-13: expt due to move to 6x brighter beamline
- Various upgrades proposed for implementation at that time – e.g. 4-cell Ramsey chamber, improved materials
- Anticipated ultimate sensitivity ~few 10^{-28} ecm

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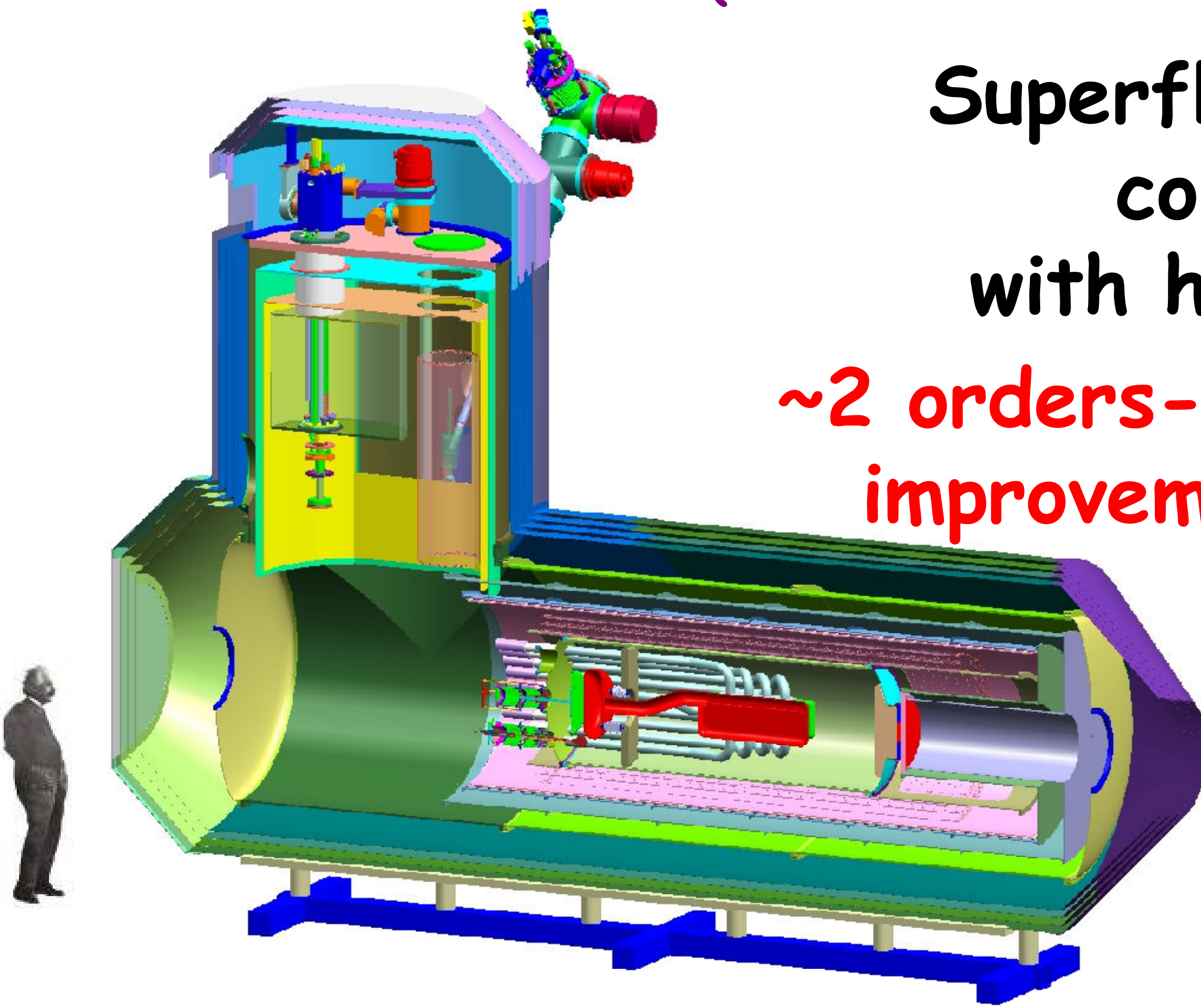
New EDM Experiment @ SNS

(ASU – Berkeley – Brown – BU – Caltech – Duke – Indiana – Kentucky – LANL – Maryland – MIT – NCSU – ORNL – HMI – SFU – Tenn. – UIUC – Miss.State – Yale)

(AMO – HEP – NP – Low Temp expertise)



Superfluid He UCN converter with high E-field

~2 orders-of-magnitude improvement possible

Concept:
Golub & Lamoreaux PHYSICS REPORTS 237,1,1994.

Status of SNS nEDM

- nEDM building at SNS recently completed
- Completing critical R&D
  - High Voltage test at Low Temperature in LHe
- Project Design will be completed 2010
  - Cost and Schedule also determined in 2010
- Construction time ~ 5 years

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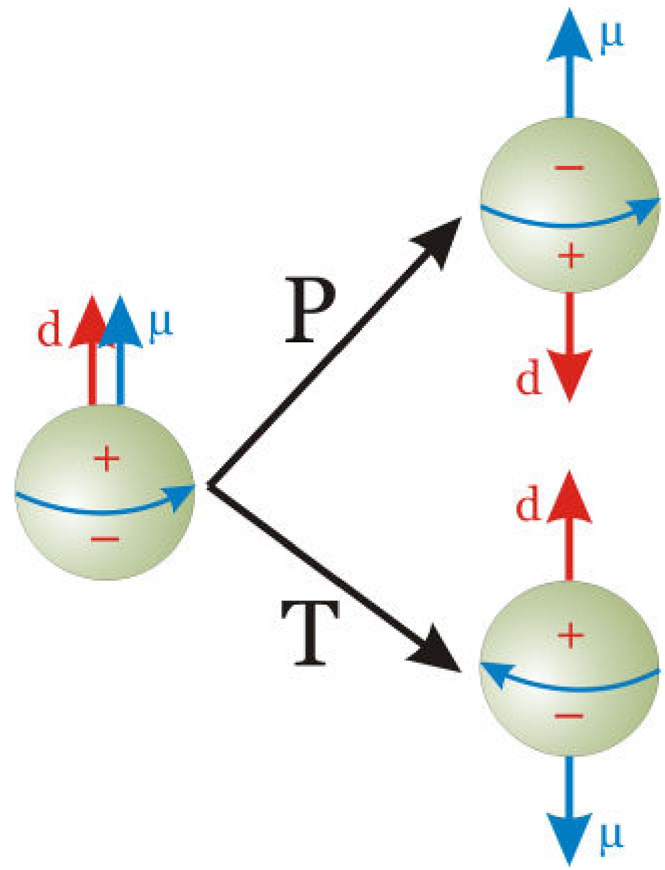
nEDM Strategy

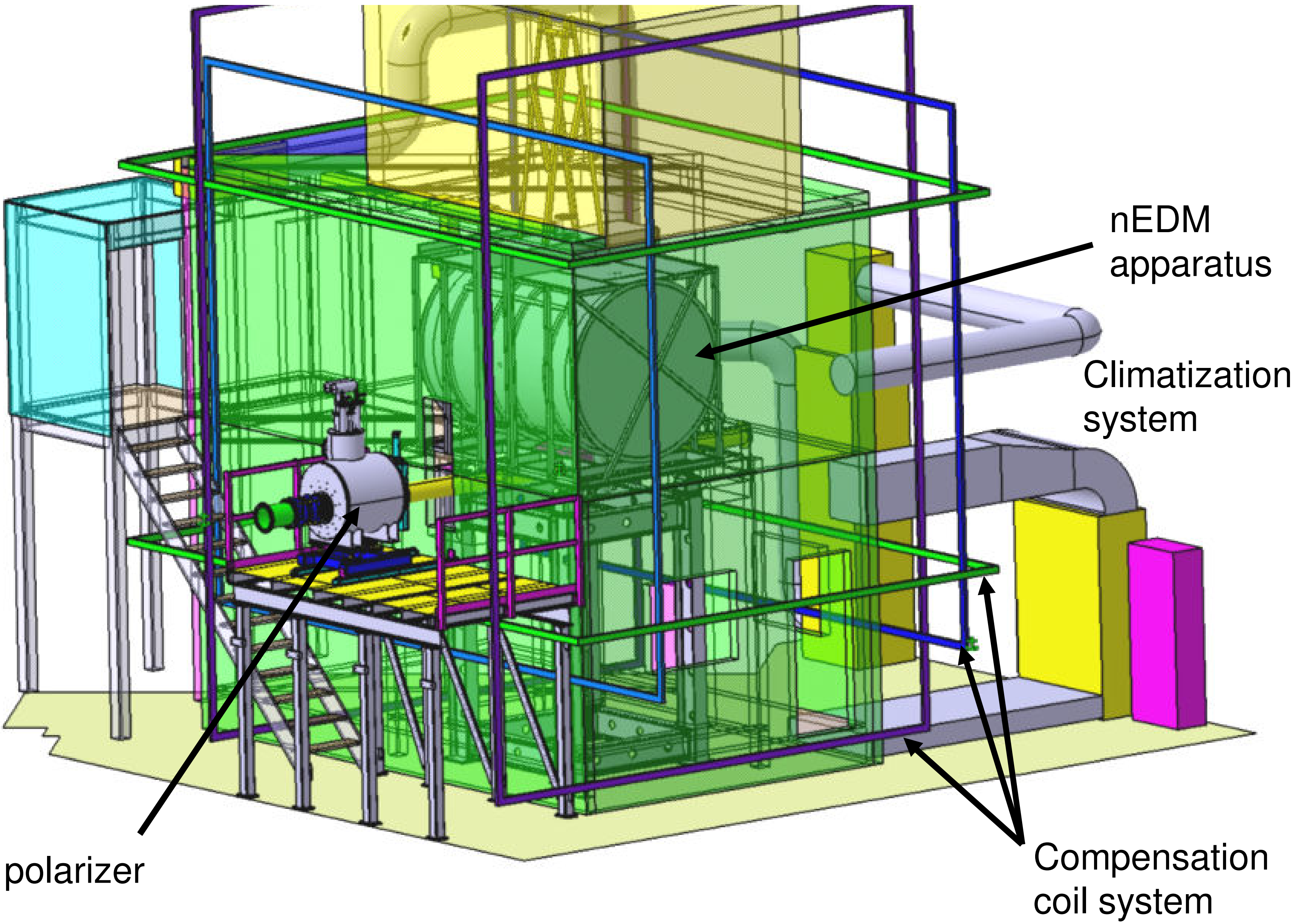
Universität Zürich

- **Phase I:**
  - Operate and improve Sussex-RAL-ILL apparatus at ILL
  - R&D for n2EDM
  - Move to PSI March 2009
- **Phase II:**
  - Operate Sussex-RAL-ILL apparatus at PSI (2009-2012)
  - Sensitivity goal: 5×10^{-27} *e*cm
  - Construction and setup of n2EDM
- **Phase III:**
  - Operate n2EDM (2012-2015)
  - Sensitivity goal: 5×10^{-28} *e*cm



Phase I: Sussex-RAL-ILL Apparatus at ILL

Phase II: Sussex-RAL-ILL Apparatus at PSI




Statistical Sensitivity

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

α = 0.75

E = 12 kV/cm

T = 150 s

N = 350'000

$\sigma(d_n)$ = 4 x 10^{-25} *e*cm / cycle$_{\text{400 s}}$

= 3 x 10^{-26} *e*cm / day

= 3 x 10^{-27} *e*cm / year$_{\text{200 nights}}$

Obtain same figures with
E=10kV/cm, T=130s, 200s cycle

After 2 years, statistics only
$d_n = 0$: $|d_n| < 4 \times 10^{-27}$ *e*cm (95% C.L.)

Systematics

Effect	Shift (see Ref.) [10^{-27} *e*cm]	σ (see Ref.) [10^{-27} *e*cm]	σ (at PSI) [10^{-27} *e*cm]
Door cavity dipole	-5.6	2.00	**0.10**
Other dipole fields	0.0	6.00	**0.40**
Quadrupole difference	-1.3	2.00	**0.60**
v×**E** translational	0.0	0.03	**0.04**
v×**E** rotational	0.0	1.00	**0.10**
Second-order **v**×**E**	0.0	0.02	**0.01**
ν_{Hg} light shift (geo phase)	3.5	0.80	**0.40**
ν_{Hg} light shift (direct)	0.0	0.20	**0.20**
Uncompensated *B* drift	0.0	2.40	**0.90**
Hg atom EDM	-0.4	0.30	***0.06***
Elastic forces	0.0	0.40	**0.40**
Leakage currents			**0.10**
ac fields			**0.01**
Total			**1.37**

After 2 years, statistics & systematics
$d_n = 0$: $|d_n| < 5 \times 10^{-27}$ *e*cm (95% C.L.)
or, e.g., $d_n = 1.3 \times 10^{-26}$ *e*cm (5σ)

PRL **97,** 131801 (2006)

Conclusions

Several new UCN sources are being built worldwide for fundamental physics experiments

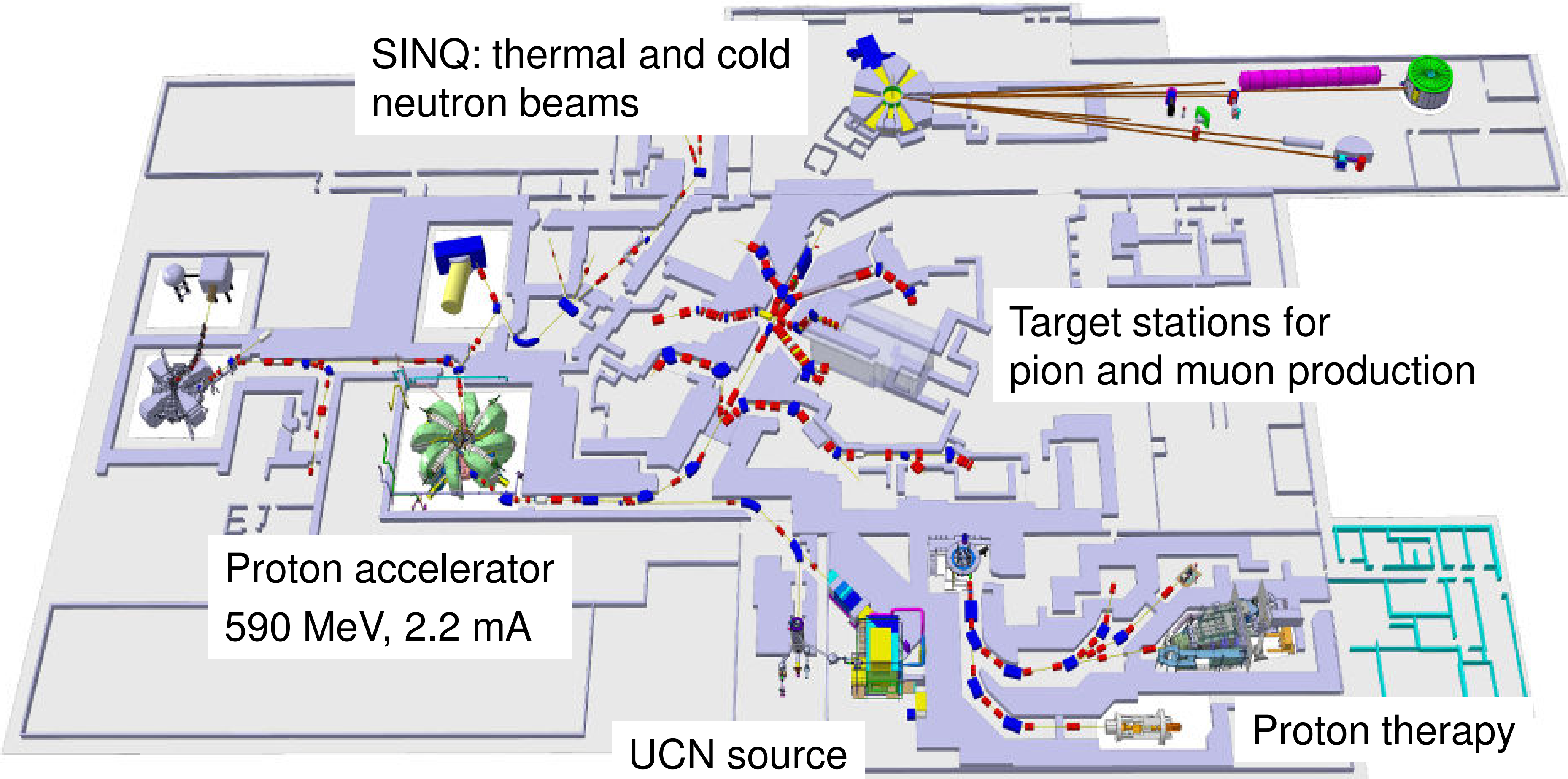
New sources will allow to push the statistical sensitivity in nEDM experiments by two orders of magnitude

Improved results of various nEDM experiments can be expected in the coming years

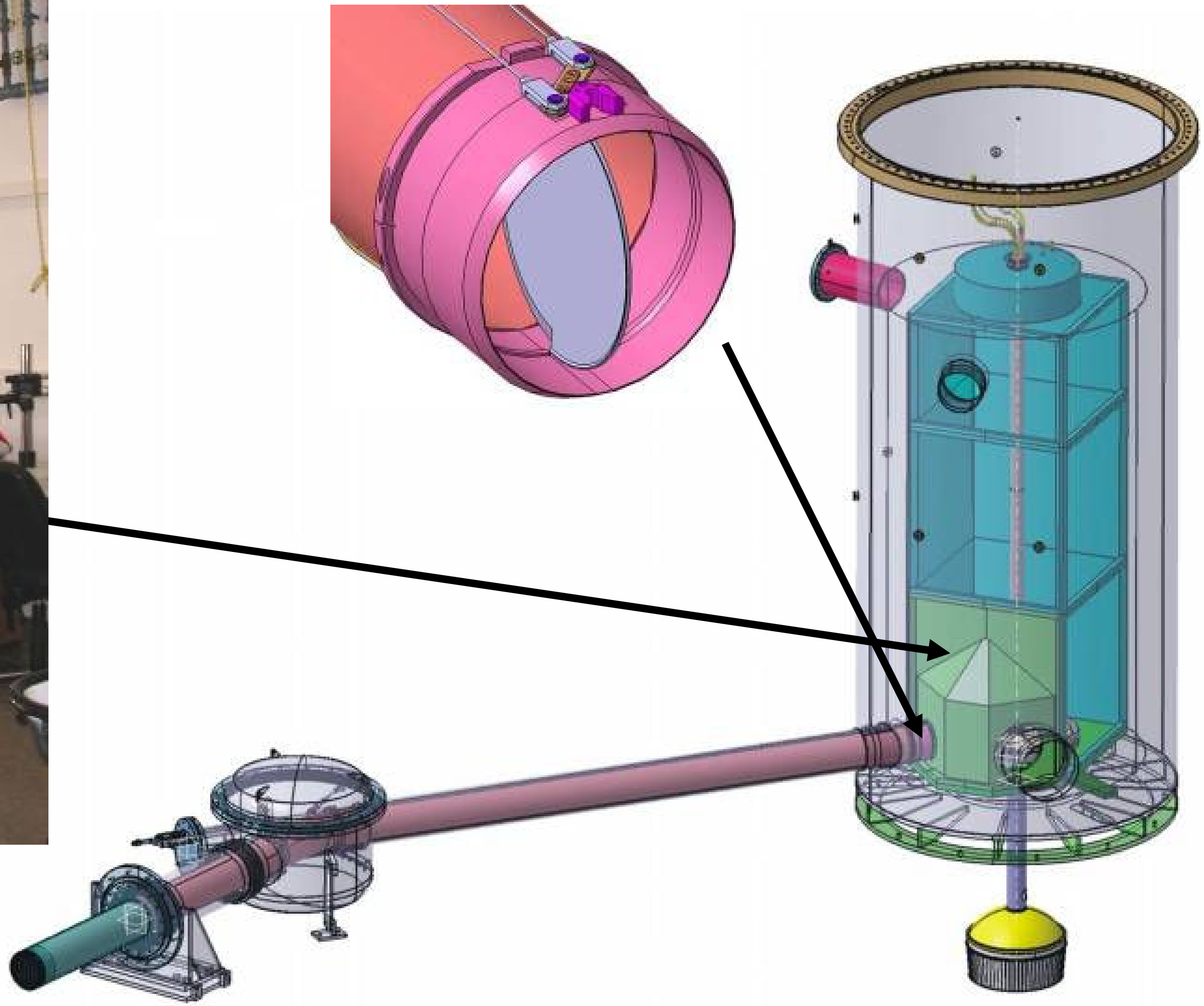
Backup

PSI UCN Source

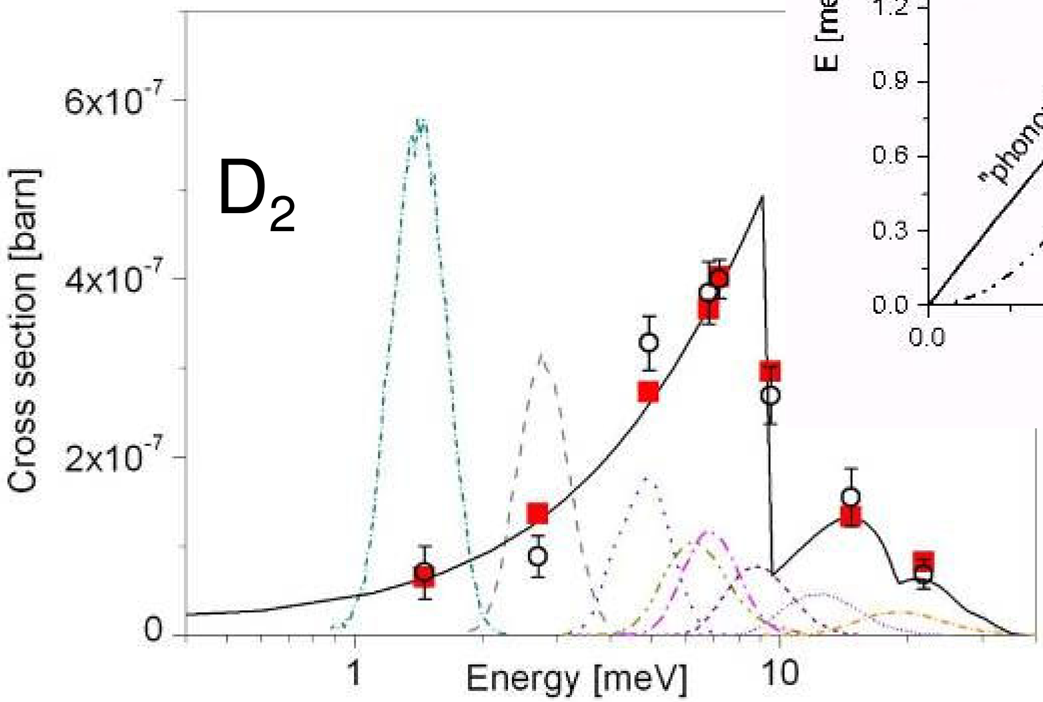
Proton Accelerator Facility @ PSI



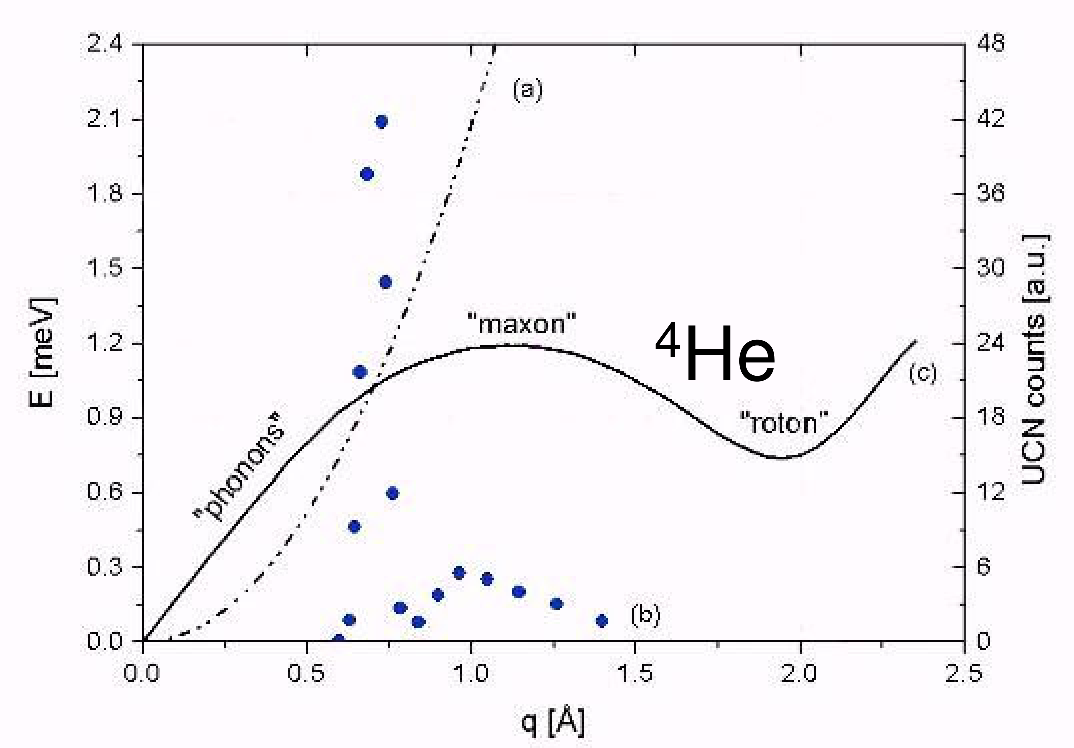
Storage Volume and Shutters



CN Energy Dependent UCN Production



F. Atchison et al., PRL 99, 262502 (2007)



C.A. Baker et al., PLA 308, 67 (2003)

nEDM Experiment

Strong CP Problem

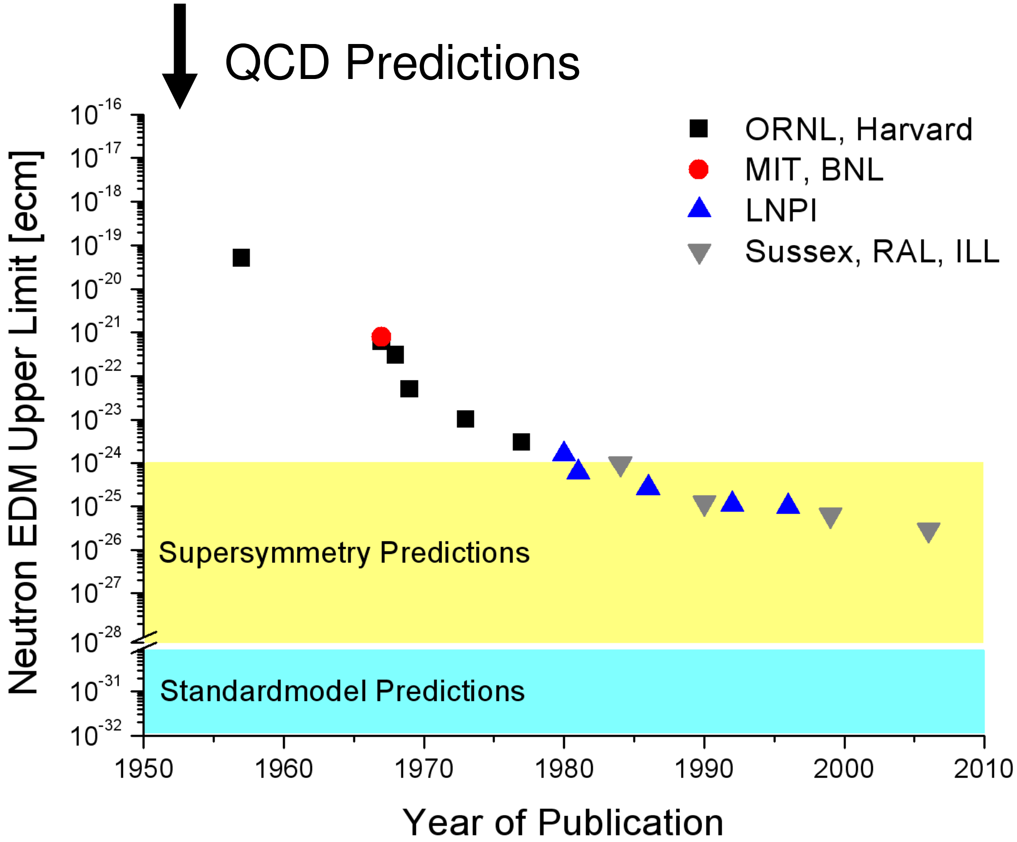
CP violating term in the QCD Lagrangian (θ-term):

$$\mathcal{L}_\theta = -\theta \frac{\alpha_s}{8\pi} \tilde{G}^a_{\mu\nu} G^a_{\mu\nu}$$

nEDM: $|d_n| \sim \theta \cdot 10^{-16}$ *e*cm

Current limit on $d_n \rightarrow \theta < 10^{-10}$

Why so small?



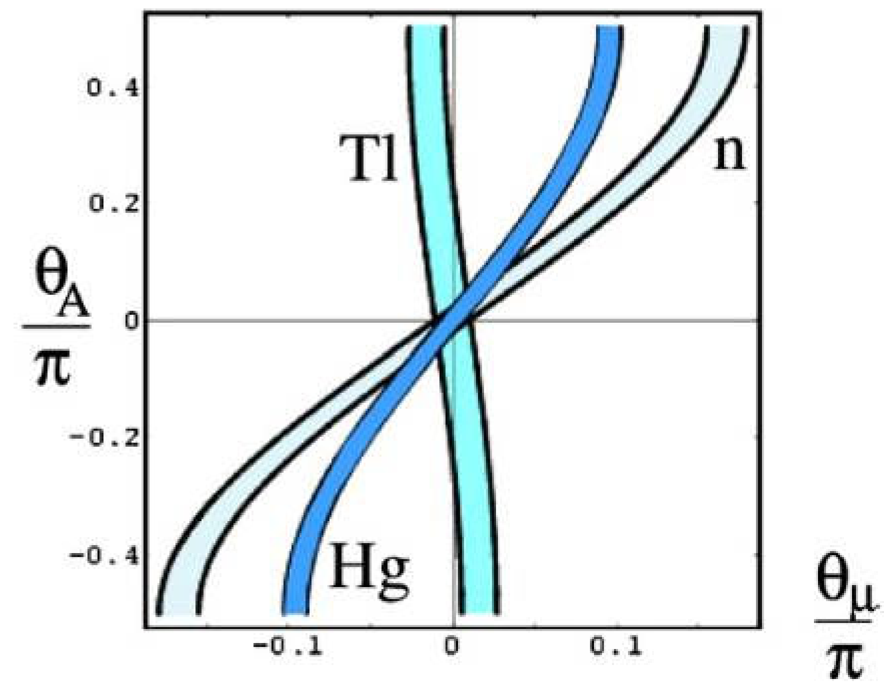
SUSY CP Problem

Larger CP violation in supersymmetric models than in the Standard Model

→ Simplified model: $d_n \sim \left(\frac{300\,\mathrm{GeV}}{M}\right)^2 \sin\phi \times 10^{-24}\, e\mathrm{cm}$

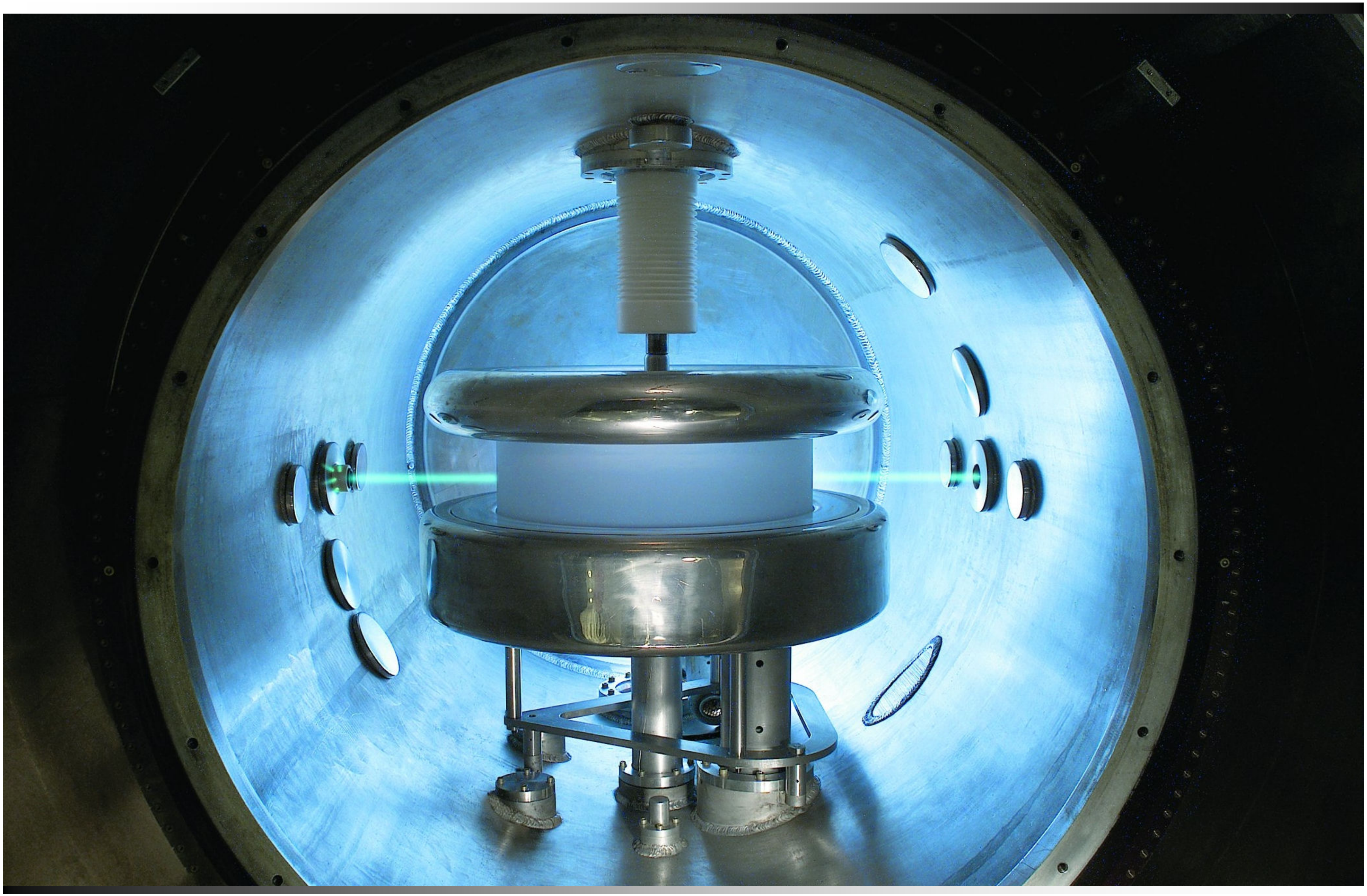
Limits on different electric dipole moments constrain SUSY phases already now

Why (so) small?



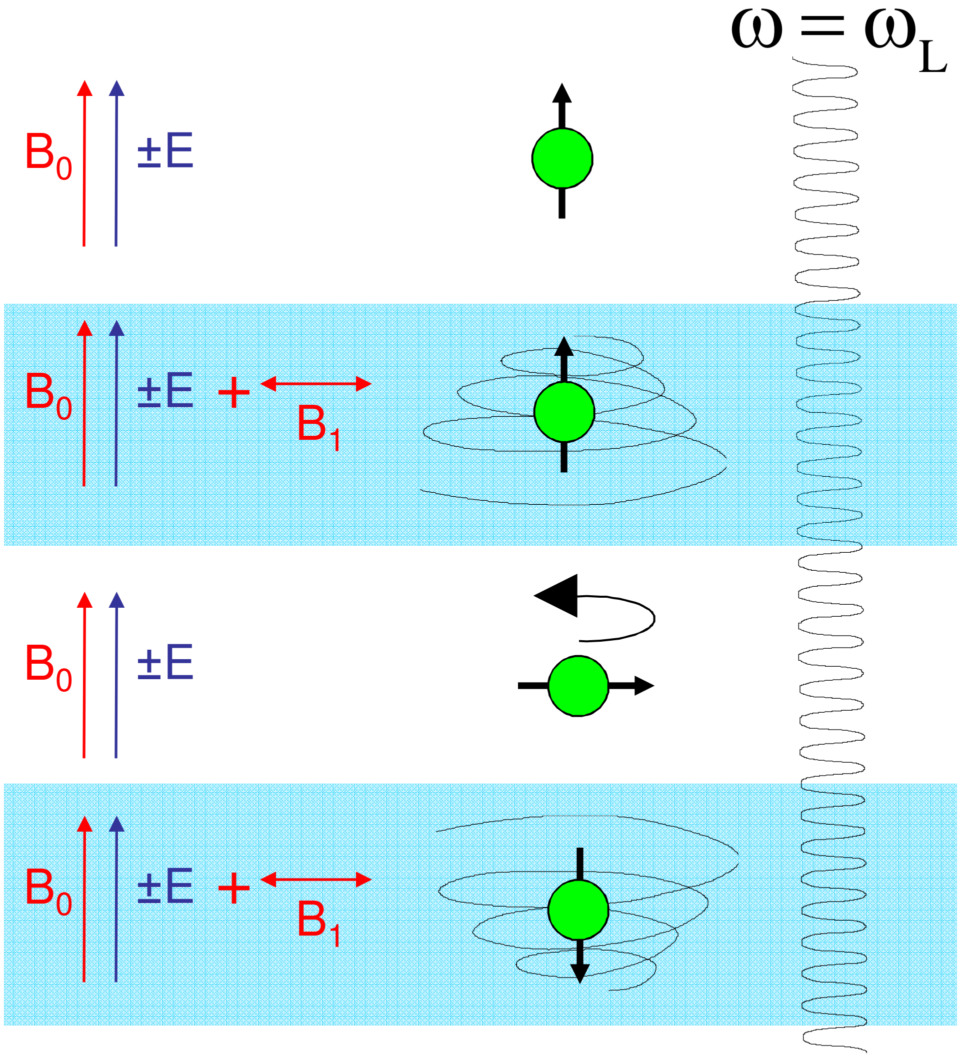
Ann. Phys. **318**, 119 (2005)

The Neutron EDM Collaboration

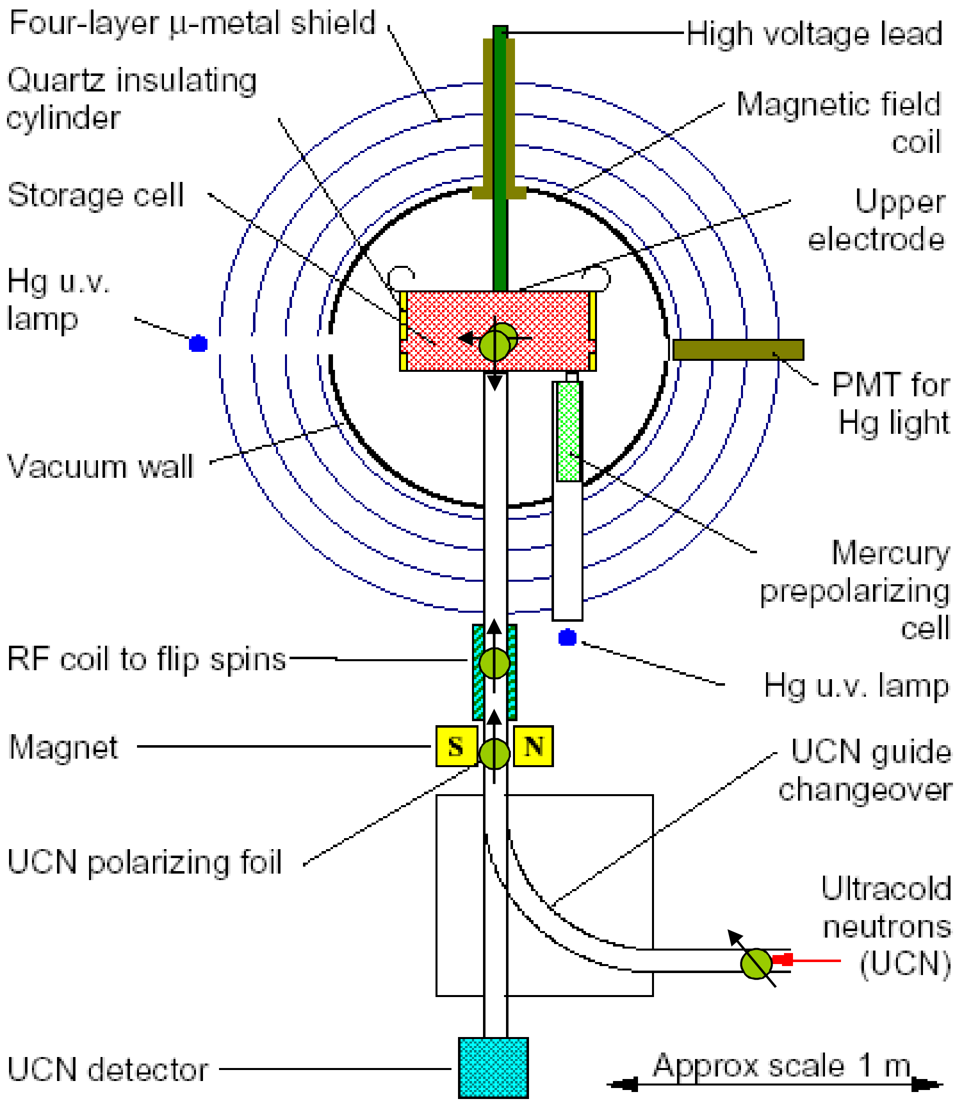


Ramsey resonance

- Polarized neutrons in a homogeneous static field (*+z*-direction, spin up).
- Linear oscillating field turning the spin in *xy*-plane.
- Free precession time (~100s) with μ_n and d_n coupling to static **B** and **E** field.
- Linear oscillating field turning the spin in *-z*-direction (spin down).

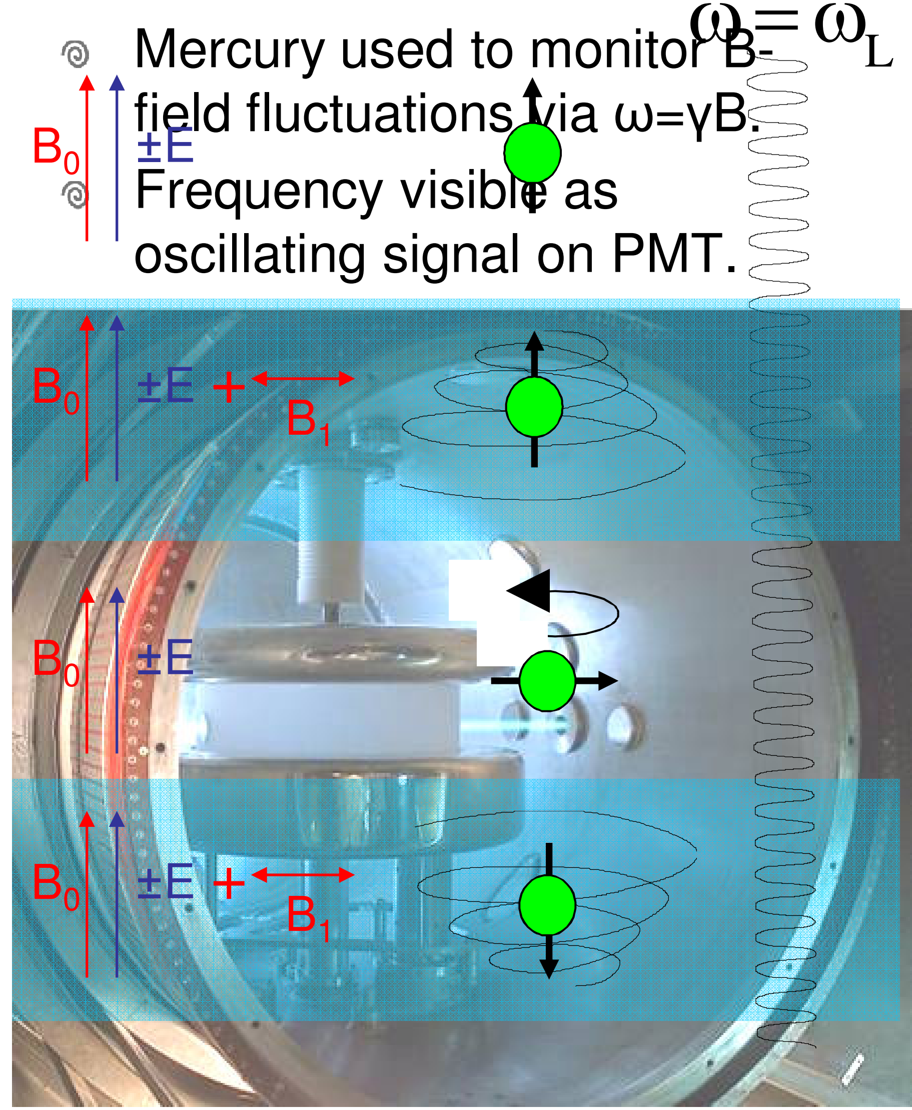


nEDM

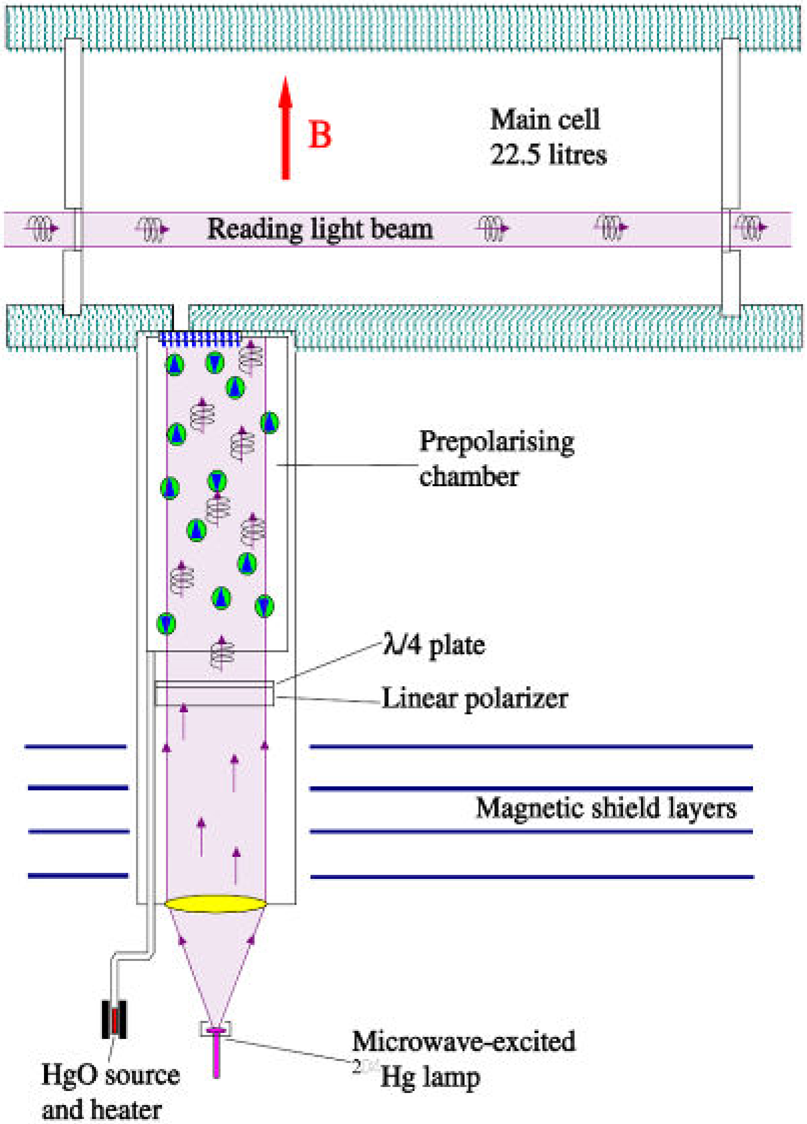


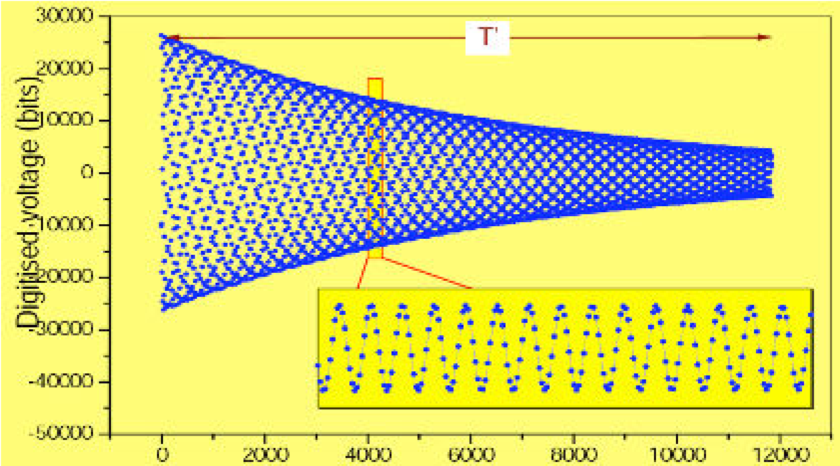
Mercury used to monitor B-field fluctuations via ω=γB.

Frequency visible as oscillating signal on PMT.



Hg magnetometer





Direct Measurement of ω_{Hg}!

The Neutron EDM Collaboration

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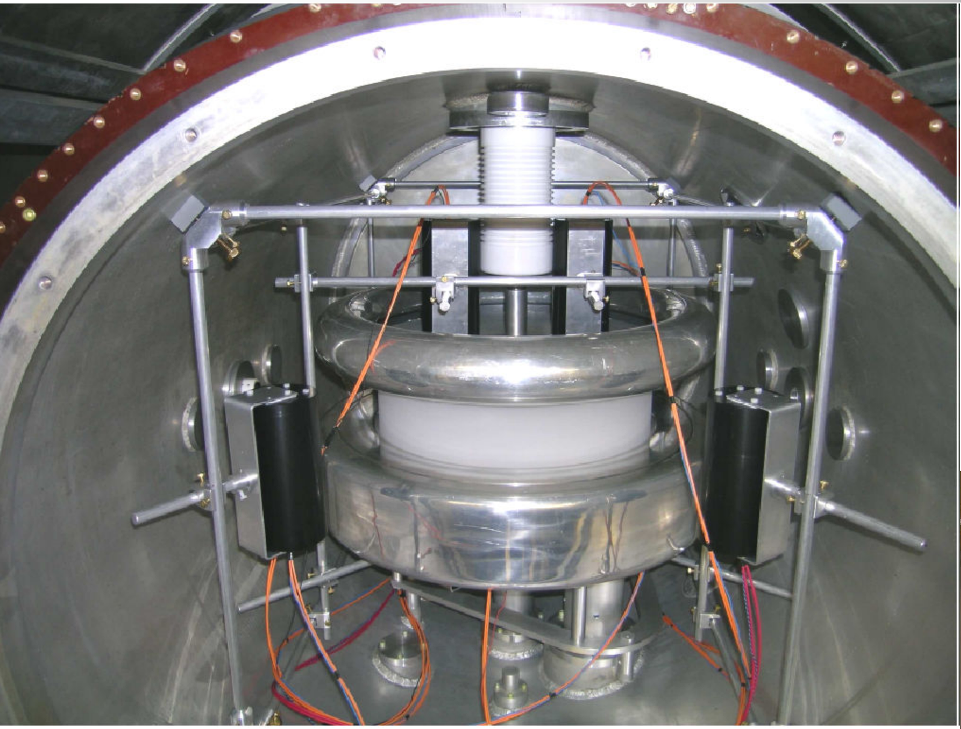
also at: [1]*Paul Scherrer Institut,* [2]*ILL Grenoble,* [3]*PNPI Gatchina,* [4]*University of Zürich*

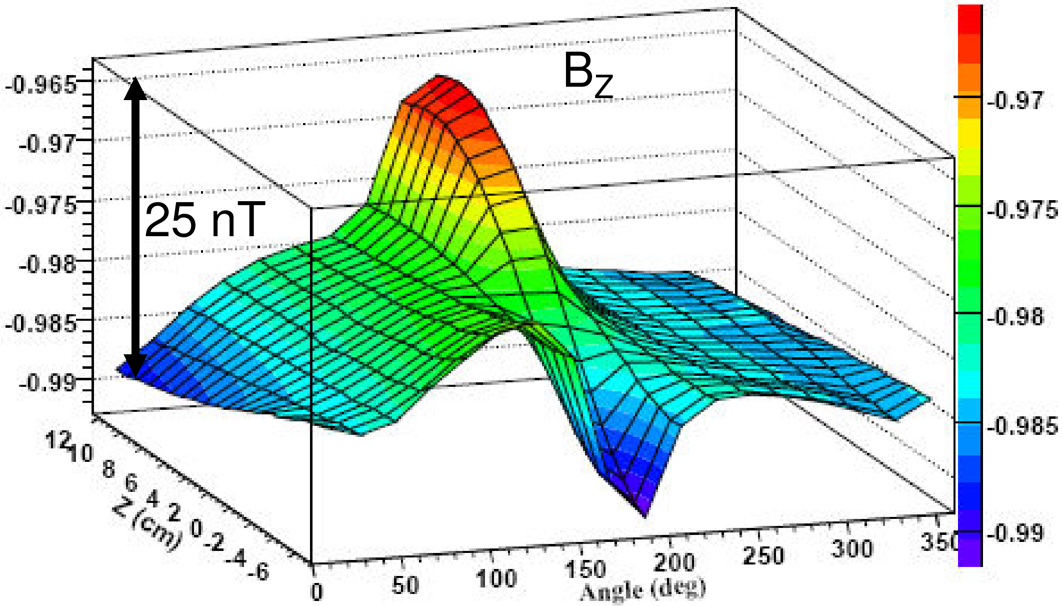
R&D during Phase I



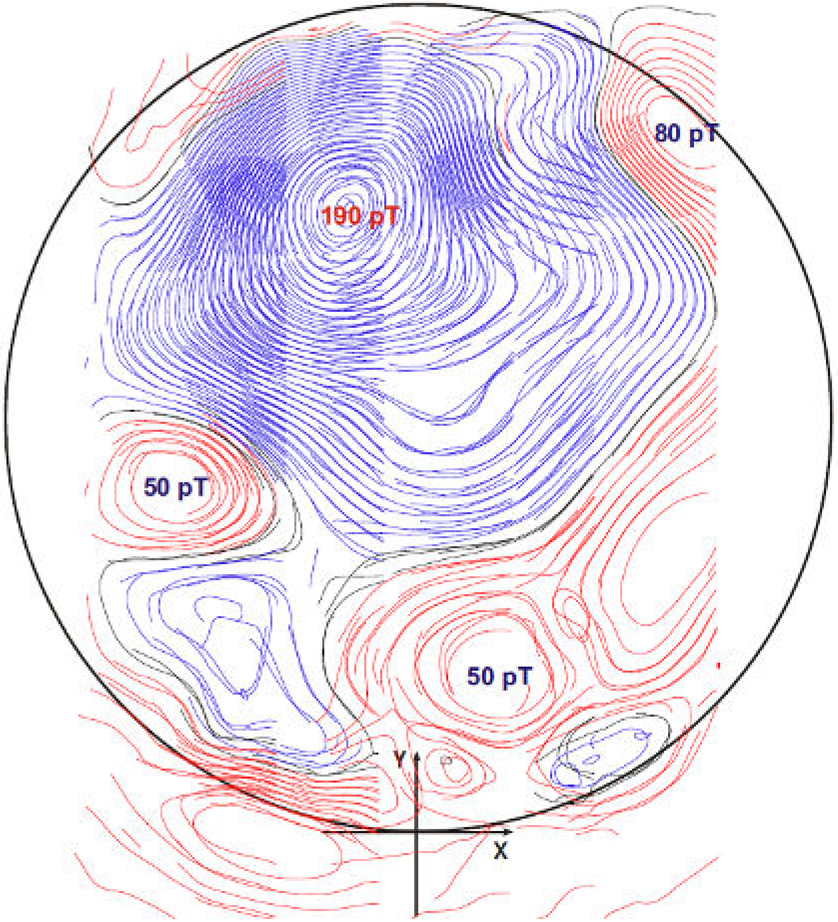
- Addition of Cs magnetometers
- Magnetic field diagnostics, field stabilisation

- Development of a new insulating UCN storage chamber: deuterated PS coated PS
- Potential: 162 neV (Quartz: 95 neV)

R&D during Phase I



- Fluxgate scans revealed large magnetic inhomogeneities
- Sources located and removed



- Capabilities to scan large parts at PTB Berlin using a SQUID array and inside the world's best shielded room (10^6)
- Resolution: 10 pT

Phase III: n2EDM

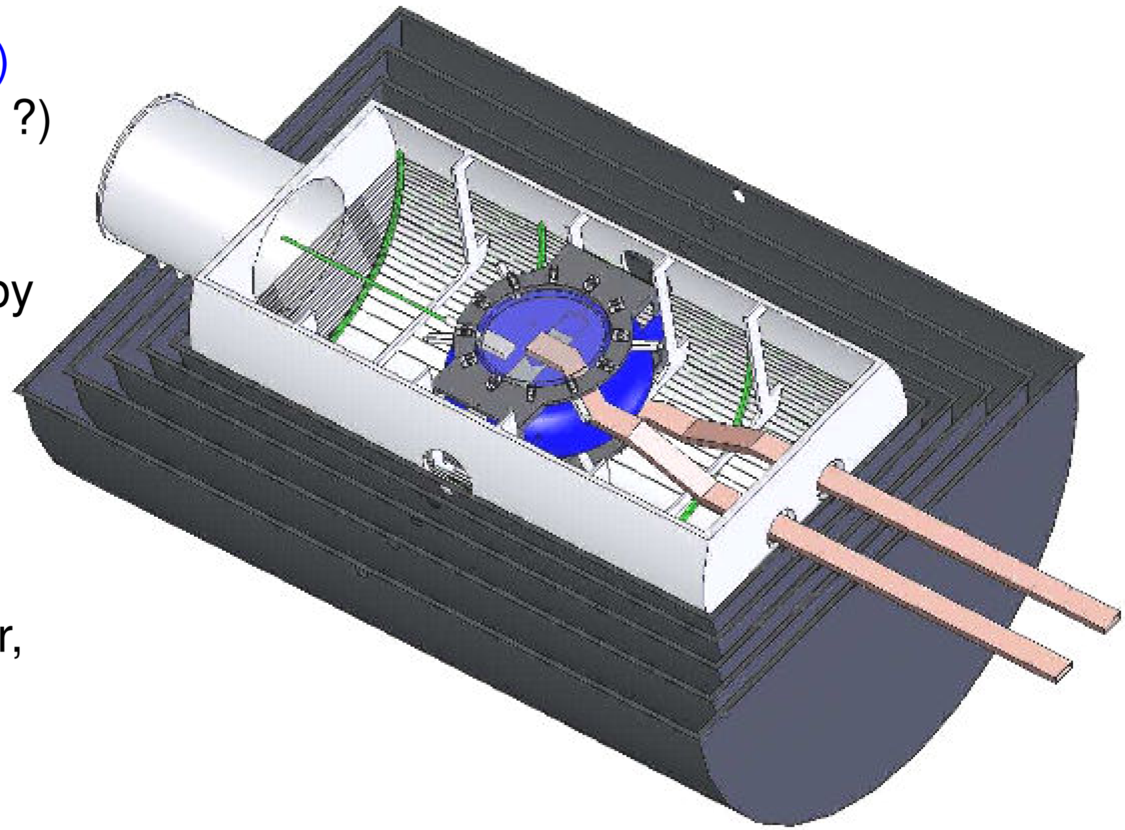
- Double chamber system, vertical stack of cylindrical chambers

- Co-magnetometer (Hg, Xe?, He?)
- Cs magnetometer array (64, 128, ?)
- 2 large He-3 magnetometers with He-3 read-out by CsM
- B-field and gradient stabilization by CsM

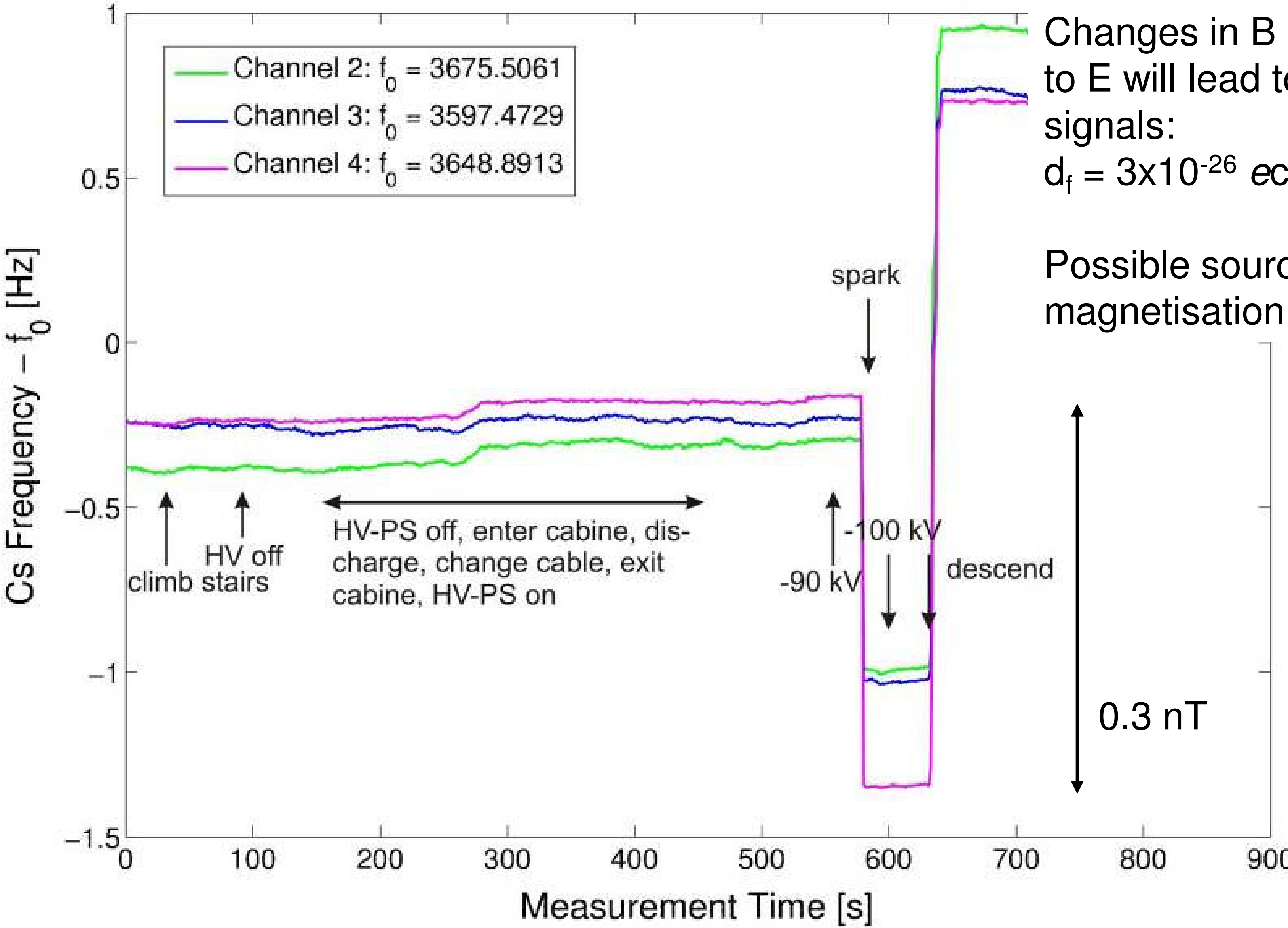
- 5-layer mu-metal shield

- UCN polarized by SC polarizer
- UCN spin analysis above detector, eventually simultaneous analysis

- Flexible DAQ



Example: B drift



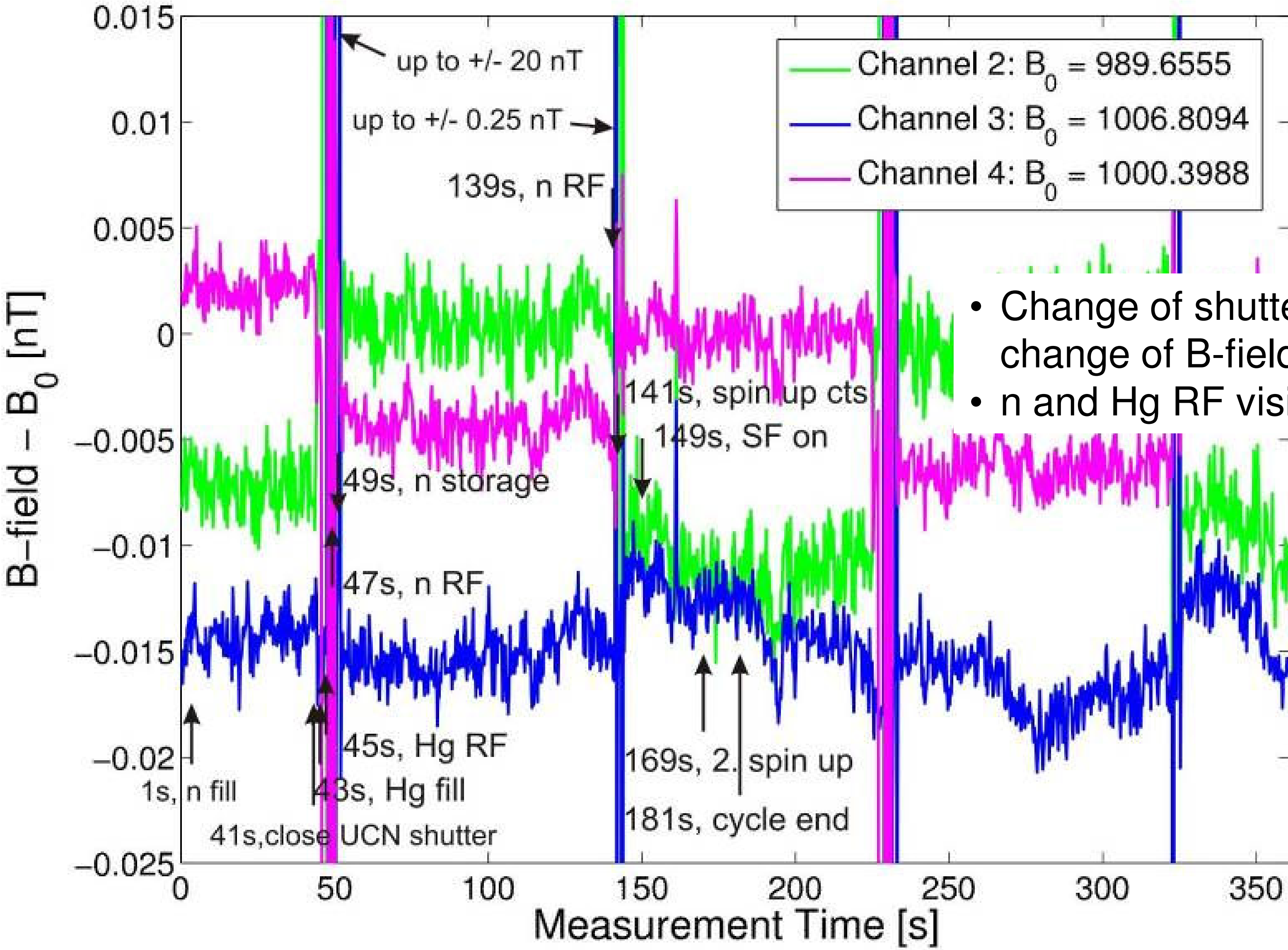
Changes in B proportional to E will lead to false EDM signals:

$d_f = 3\text{x}10^{-26}\ e\text{cm}\ \Delta B/(10\ \text{fT})$

Possible sources: sparks, magnetisation of mumetal

0.3 nT

Shutter Movement

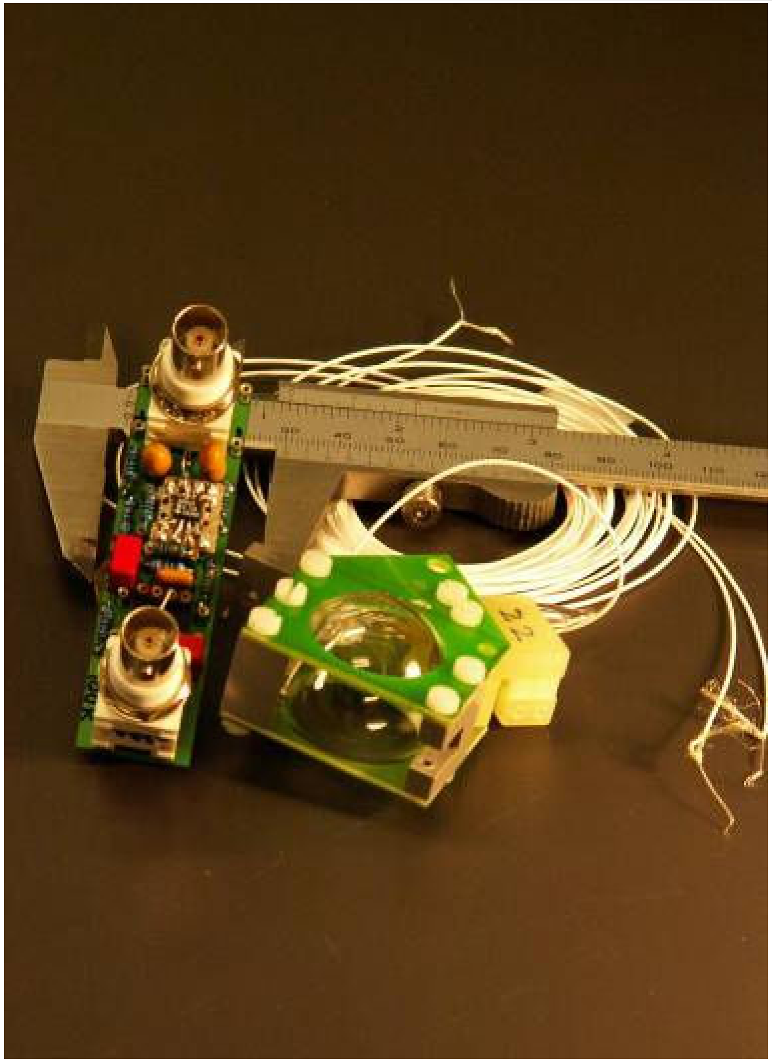


- Change of shutter position → change of B-field
- n and Hg RF visible

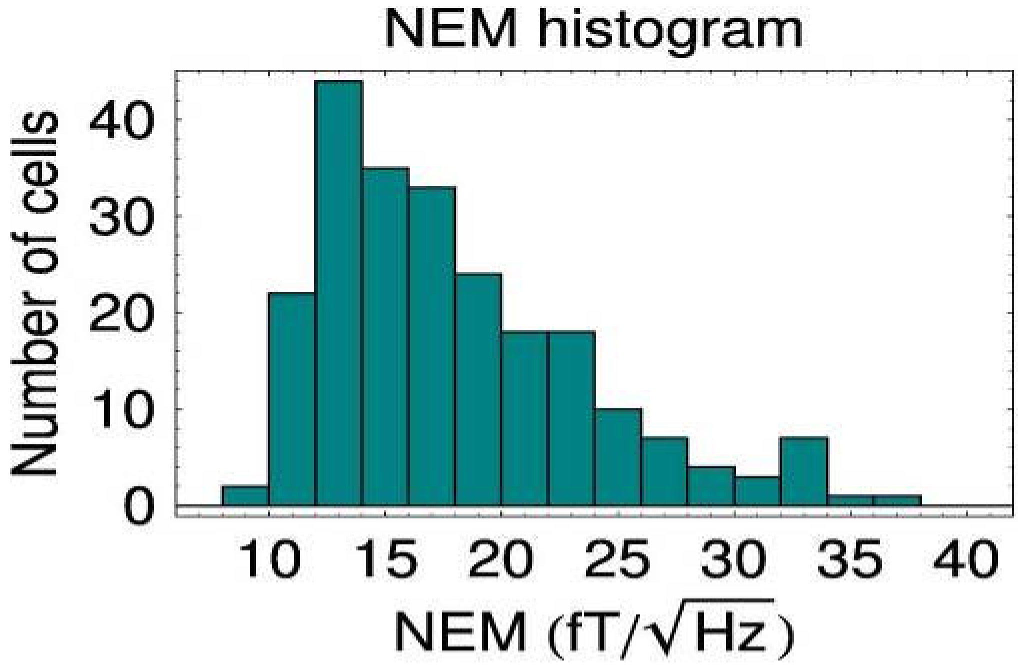
B-field Sensitivity

- Statistical sensitivity: $$\sigma_B = \frac{1}{\gamma_n 2\pi\alpha T\sqrt{N}}$$
- Sussex (nEDM NIMA, 2000): α = 0.5, T = 130 s, N = 13‘000
  → σ_B = 0.7 pT
- We: α = 0.3, T = 150 s, N = 5‘000 (!)
  → σ_B = 1.7 pT or ~1.7 x 10^{-6}
- From data: $< \sigma(f_n) >/< f_n > \approx 10^{-6}$
  $< \sigma(f_{Hg}) >/< f_{Hg} > \approx 7 \times 10^{-8}$ (~ 70 fT)
- Normalising the neutron data with Hg reduces the deviations to the level of statistical fluctuations!
- The fluctuations seen are magnetic fluctuations, they are bigger the further away from the center

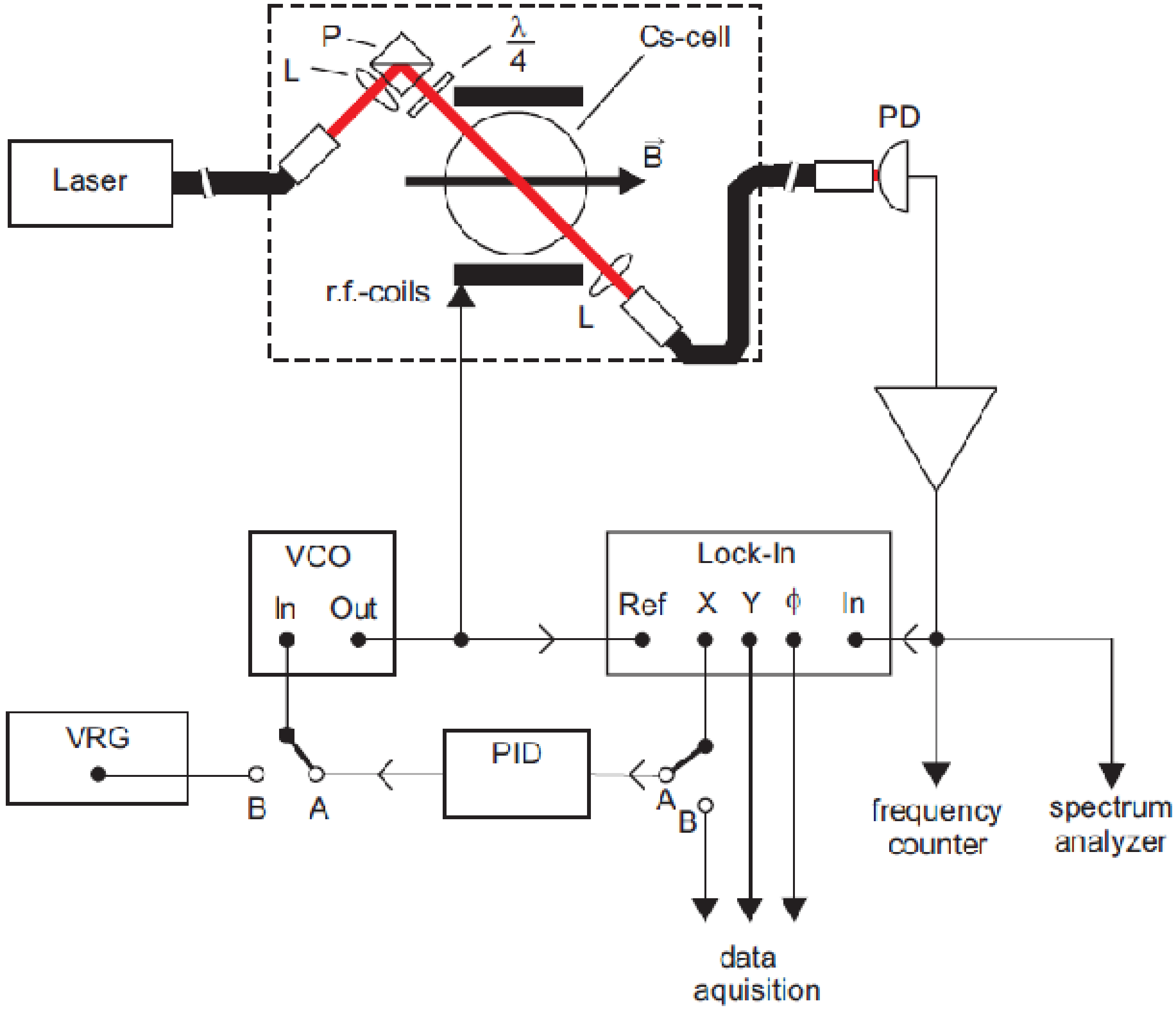
Cs Magnetometers



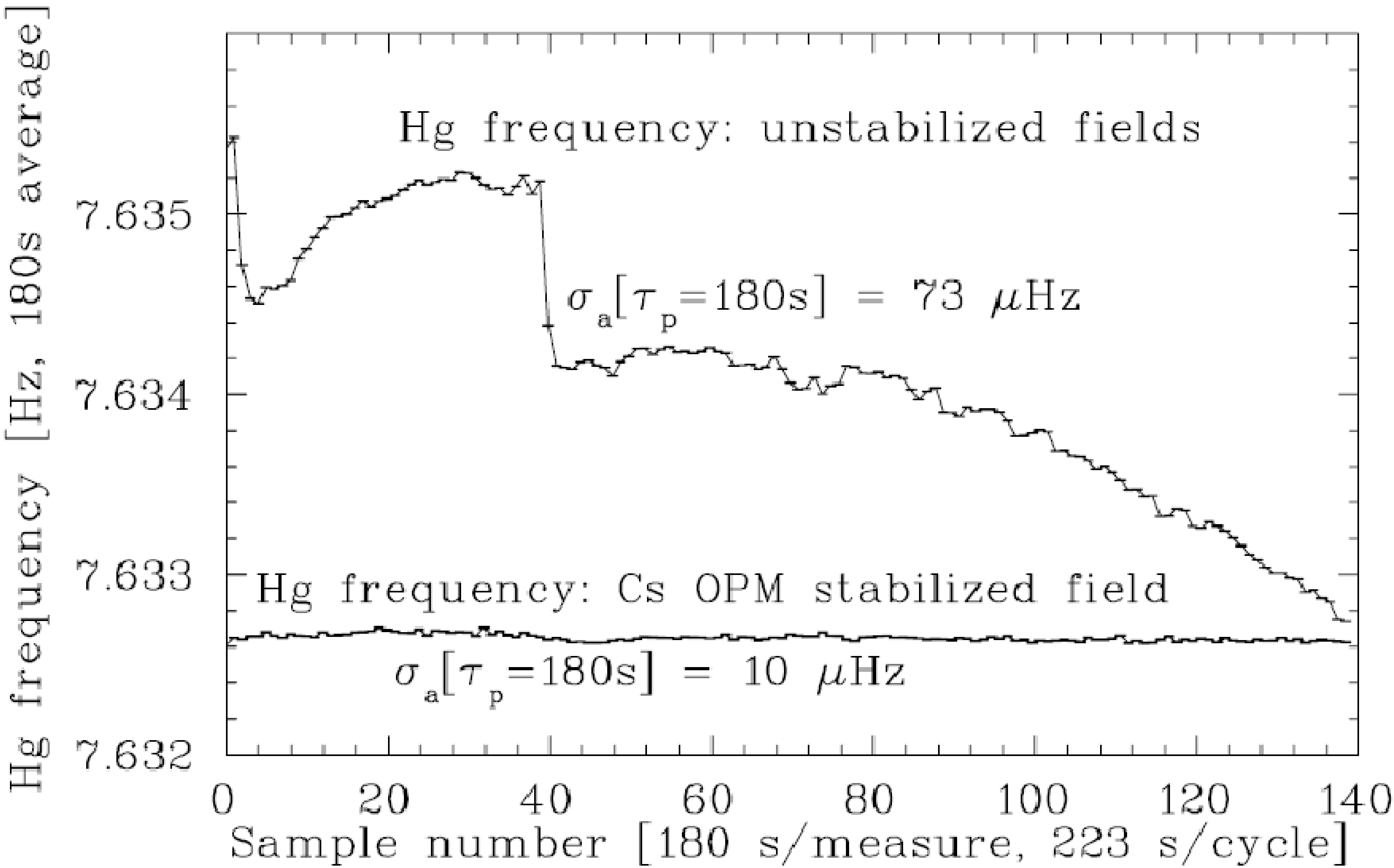
- Mechanical and optics for 25 sensors
- Prototype preamps work
- Ultimate sensitivity 10 fT/sqrt(Hz)
- 240 cells made and tested



Cs Magnetometers



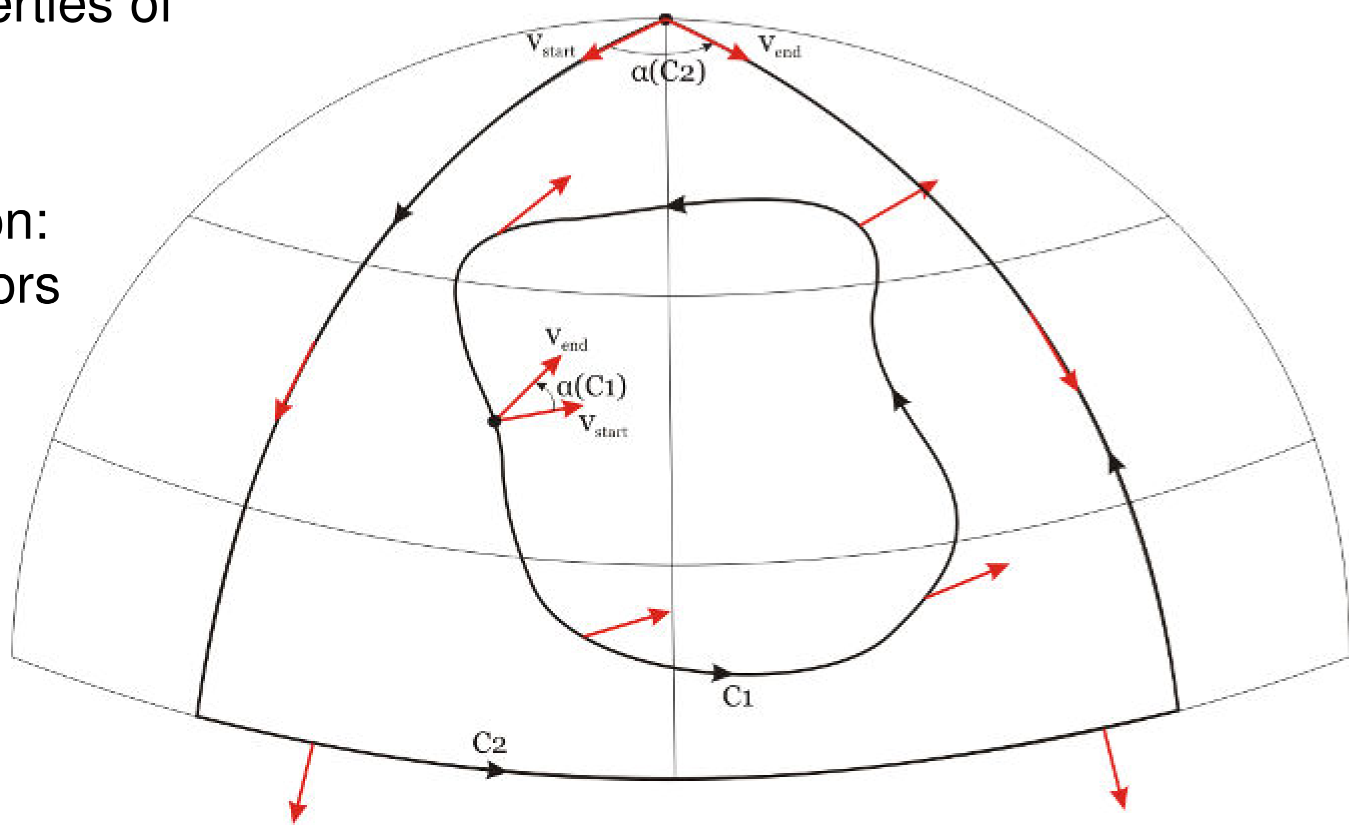
Cs Magnetometers



Systematics

Geometric Phase

- Quantum mechanical system acquires additional phase due to geometrical properties of parameter space
- Classical analogon: Transport of vectors along a sphere



Systematics

- Sources of magnetic inhomogeneities:

$$\vec{B}_{0xy} = -\partial B_{0z} \frac{\vec{r}}{2} \qquad \vec{B}_v = \frac{\vec{E} \times \vec{v}}{c^2}$$

- UCN moves around the trap with speed ω_r
  $\rightarrow$ experiences oscillating fields
  $\rightarrow$ shift of resonant frequency (Ramsey-Bloch-Siegert shift):

$$\omega = \omega_0 + \frac{\left(\gamma \vec{B}_{xy}\right)^2}{2(\omega_0 - \omega_r)}$$

- Expanding the square:

$$\vec{B}_{xy}^2 = \left(\vec{B}_v + \vec{B}_{0xy}\right)^2 = \vec{B}_{0xy}^2 + 2\vec{B}_{0xy} \cdot \vec{B}_v + \vec{B}_v^2$$

$\propto E^0$ $\qquad \propto E^1$ $\qquad \propto E^2$

Systematics

- Averaging over possible paths for the two regimes $\omega_r < \omega_0$ (neutrons) and $\omega_r > \omega_0$ (mercury):

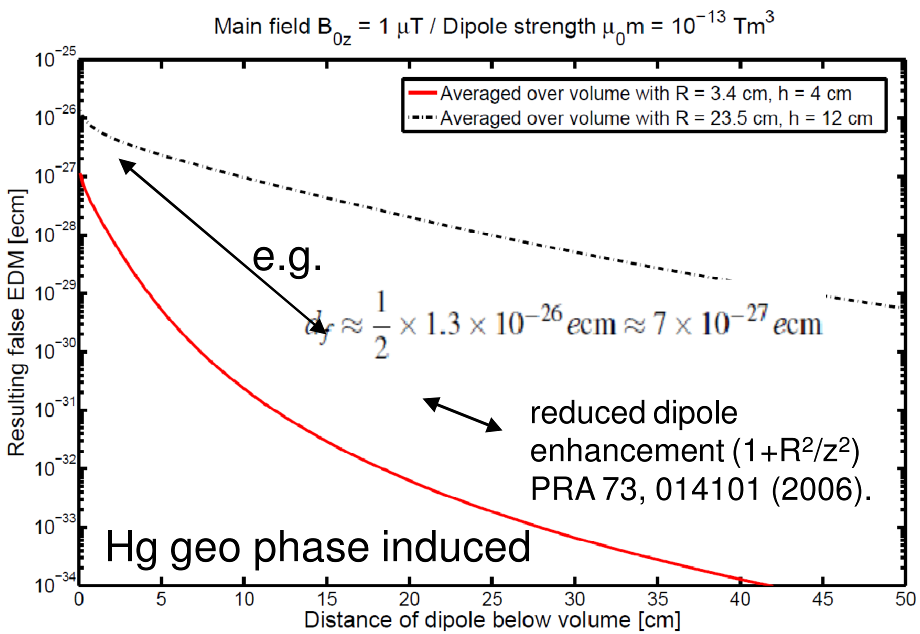
$$d_{fn} \propto \frac{\partial_z B_{0z}}{B_{0z}^2} v^2 \approx -10^{-27} \ e\text{cm}$$

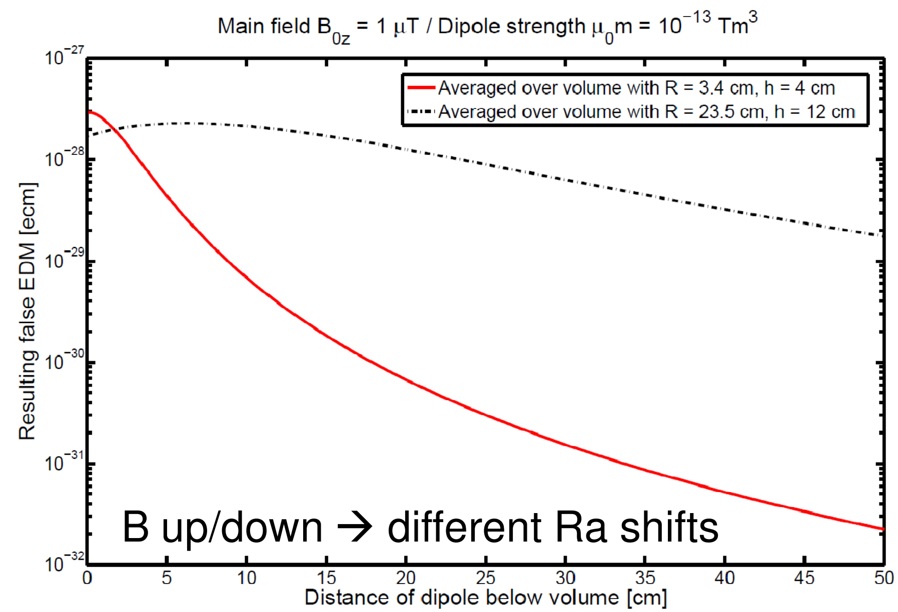
$$d_{fHg} \propto \partial_z B_{0z} R^2 \approx 10^{-26} \ e\text{cm}$$

- Mercury is used to correct for possible fluctuations of magnetic field (ratios of resonant frequencies)
$\rightarrow$ false Hg-EDM is imparted onto the neutron measurement:

$$d_{fHgn} = \frac{|\gamma_n|}{|\gamma_{Hg}|} d_{fHg} \approx 5 \times 10^{-26} \ e\text{cm}$$

Dipole fields





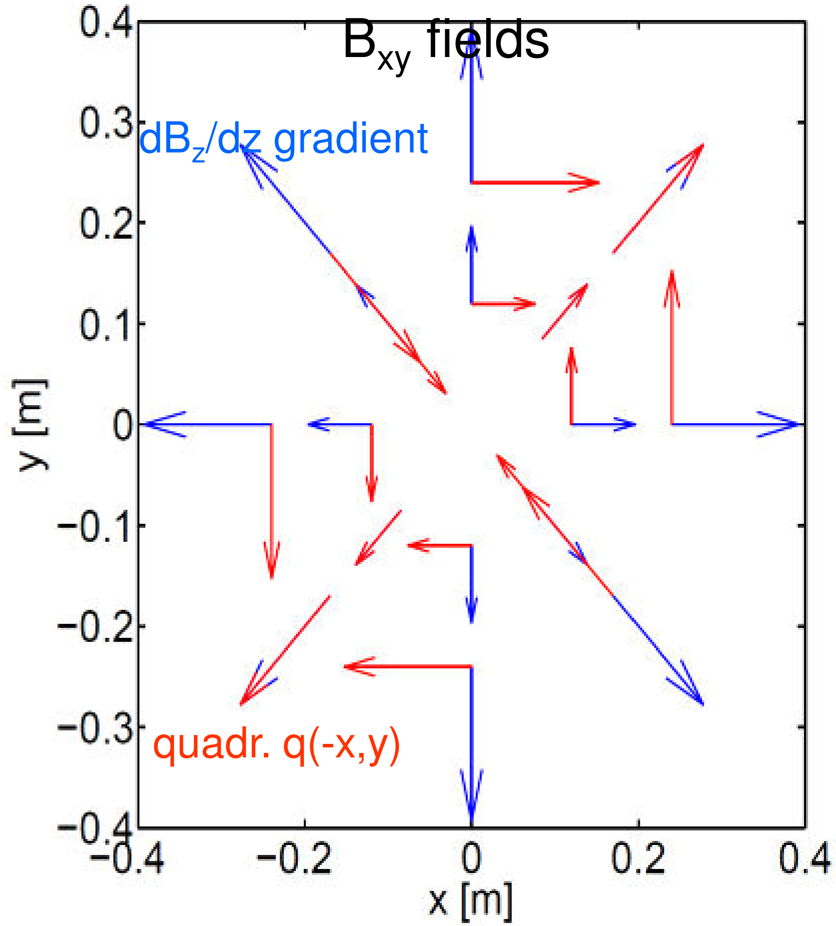
Reduce dipole contaminations to < 0.5 x 10^{-14} Tm^3/μ_0 → d_{false} < 5 x 10^{-28} *e*cm

Quadrupole fields

$$R_a = \left| \frac{\omega_n}{\omega_{Hg}} \frac{\gamma_{Hg}}{\gamma_n} \right| = 1 + \frac{q^2 R^2}{4B_0^2}$$

Quadrupole difference matters!

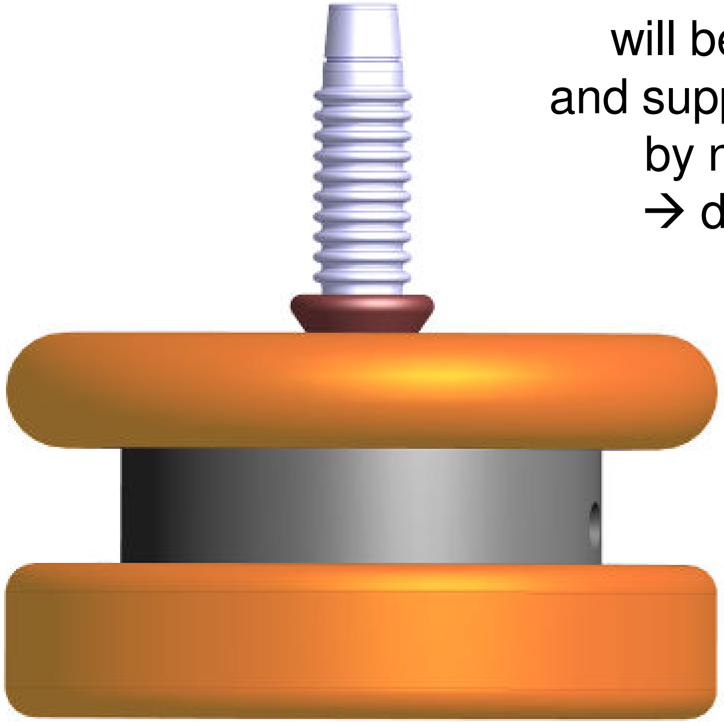
With transverse CsM, extract changes in B_{xy} down to
qR ~ 100 pT → $d_{false} < 6 \times 10^{-28}$ *e*cm

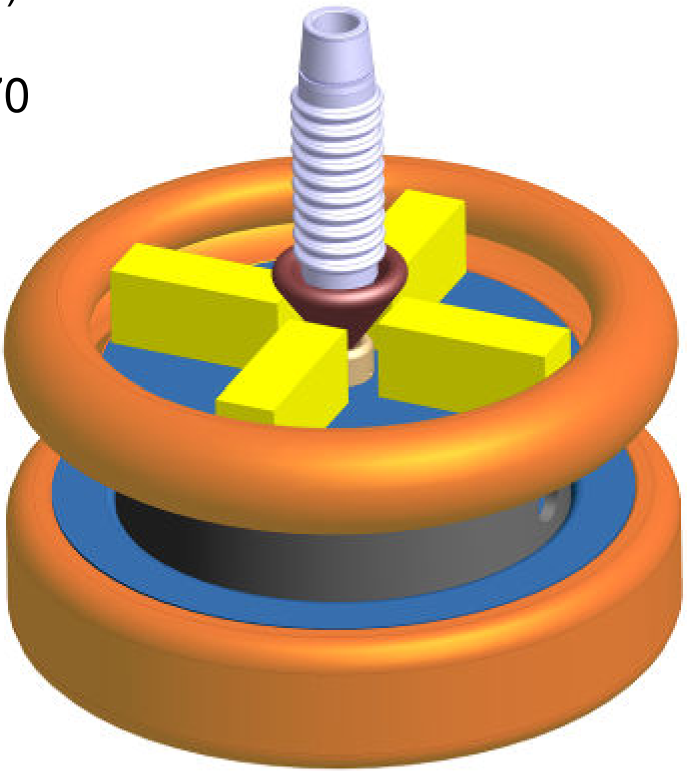


Uncompensated B-drift

Measure HV correlated gradients top-bottom with CsM

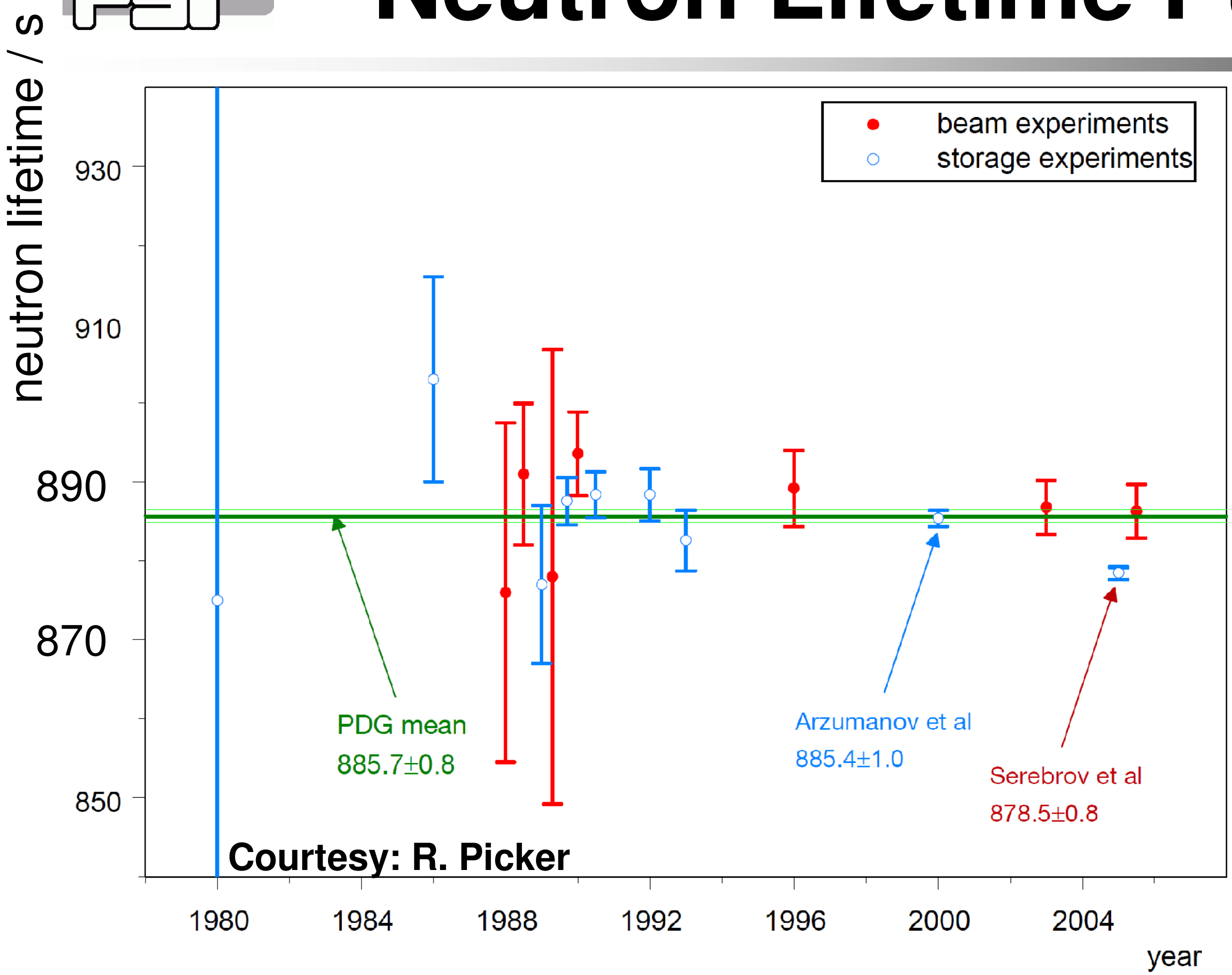
10 fT difference (6 x 10^{-26} *e*cm)
will be detected in one day
and suppressed by a factor ~70
by normalizing with Hg
→ $d_{false} < 9 \times 10^{-28}$ *e*cm





Neutron Lifetime

Neutron Lifetime Puzzle



New improved neutron lifetime experiments must be of high priority: Aim at 0.1s precision !

Various projects in preparation, emphasis on magnetic trapping

- permanent magnetic traps
- superconducting traps

PDG: The most recent result, that of SEREBROV 05, is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of 885.7 ± 0.8 s must be suspect.