Search for an EDM of the neutron at PSI

K. Kirch, PSI
for the nEDM collaboration

- Collaboration
- Our approach
- Update

The Neutron EDM Collaboration

G. Ban, Th. Lefort, O. Naviliat-Cuncic
*Laboratoire de Physique Corpusculaire, **Caen,** France*

K. Bodek, St. Kistryn, M. Kuzniak[2], J. Zejma
*Institute of Physics, Jagiellonian University, **Cracow,** Poland*

N. Khomytov, B.M. Sabirov
*Joint Institute of Nuclear Reasearch, **Dubna,** Russia*

P. Knowles, M. Rebetez, A. Weis
*Departement de Physique, Université de Fribourg, **Fribourg,** Switzerland*

C. Plonka, G. Rogel[1]
*Institut Laue-Langevin, **Grenoble,** France*

G. Quéméner, D. Rebreyend, S. Roccia, M. Tur
*Laboratoire de Physique Subatomique et de Cosmologie, **Grenoble,** France*

M. Daum, R. Henneck, S. Heule[3], M. Kasprzak[4], K. Kirch, A. Knecht[3], A. Pichlmaier
*Paul Scherrer Institut, **Villigen,** Switzerland*

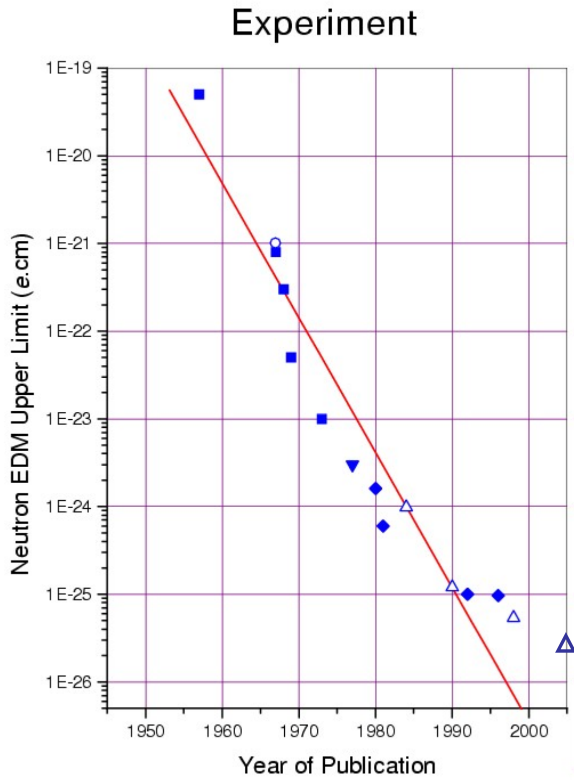
also at: [1]*LPC Caen,* [2]*Paul Scherrer Institut,* [3]*University of Zürich,* [4]*SMI Vienna*

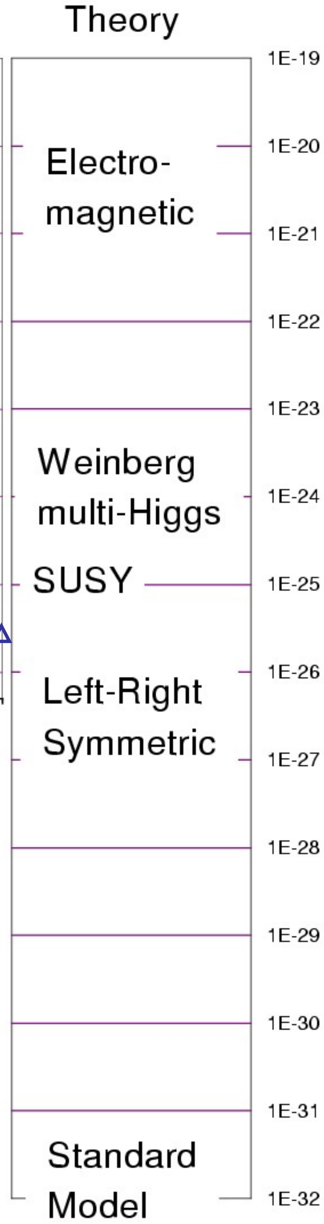
Context

What is needed for progress?

- larger sensitivity, much more UCN
- better control of systematics

$$\delta d_n = \frac{h}{4\pi\alpha} \cdot \frac{1}{T \cdot E \cdot \sqrt{N_0}}$$

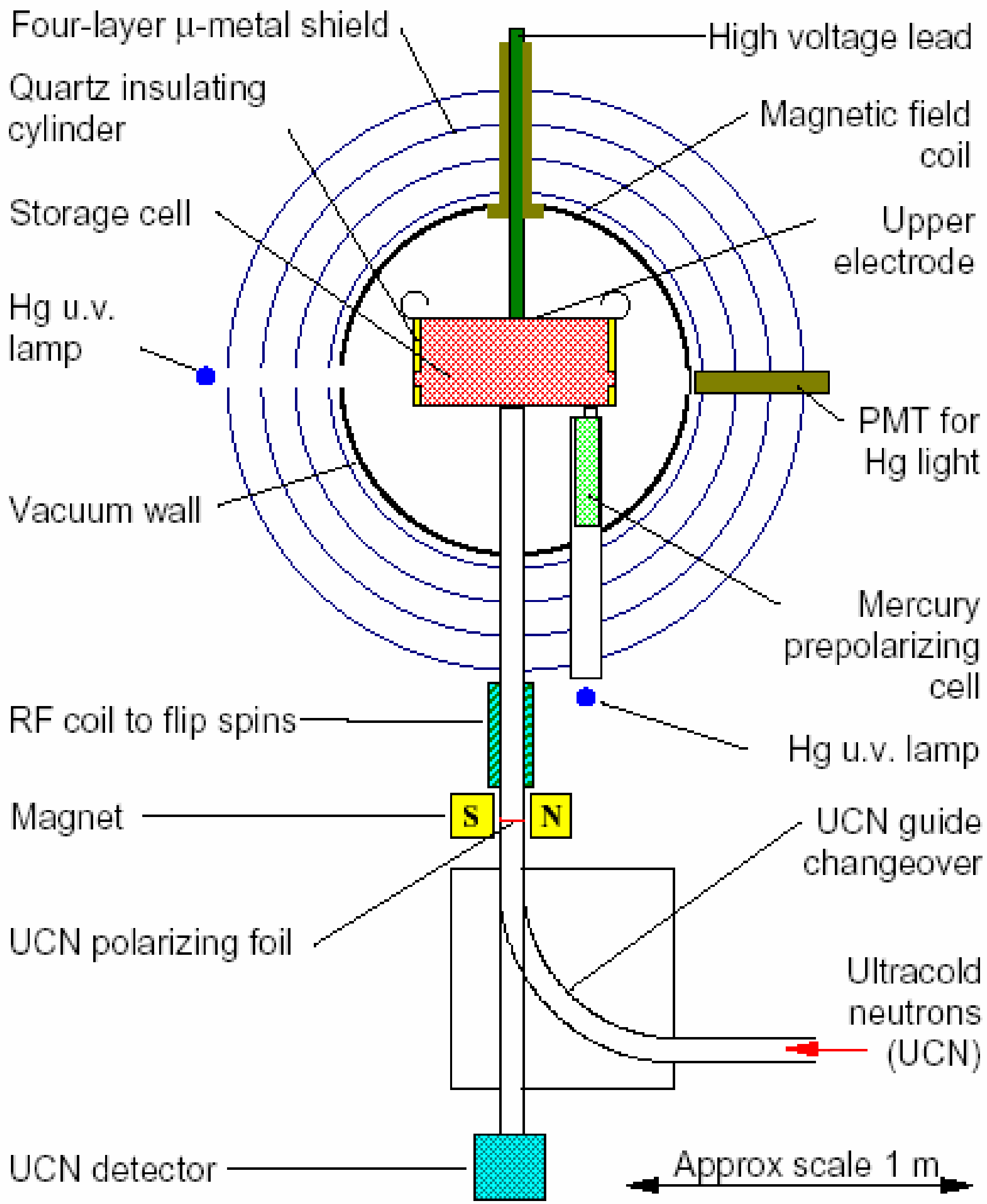




$$h\nu^+ = 2\,(\mu_n B + d_n E)$$
$$h\nu^- = 2\,(\mu_n B - d_n E)$$

$$h\Delta\nu = 4\, d_n\, E$$

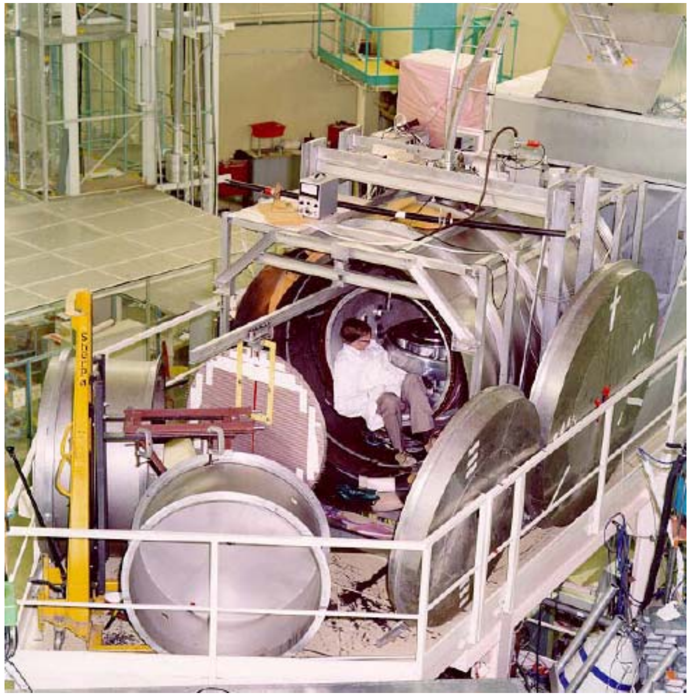
Context



Sussex-RAL-ILL experiment

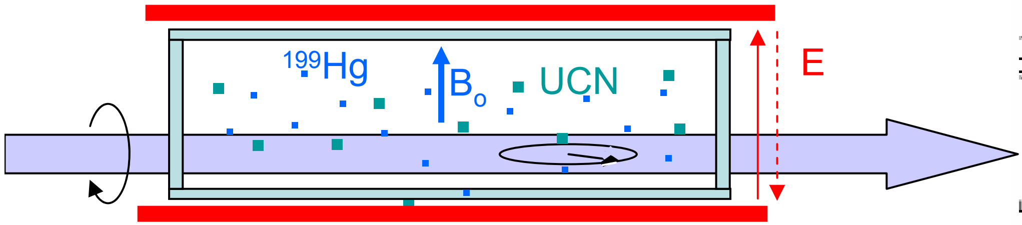
$d_n < 2.9 \times 10^{-26}$ e cm

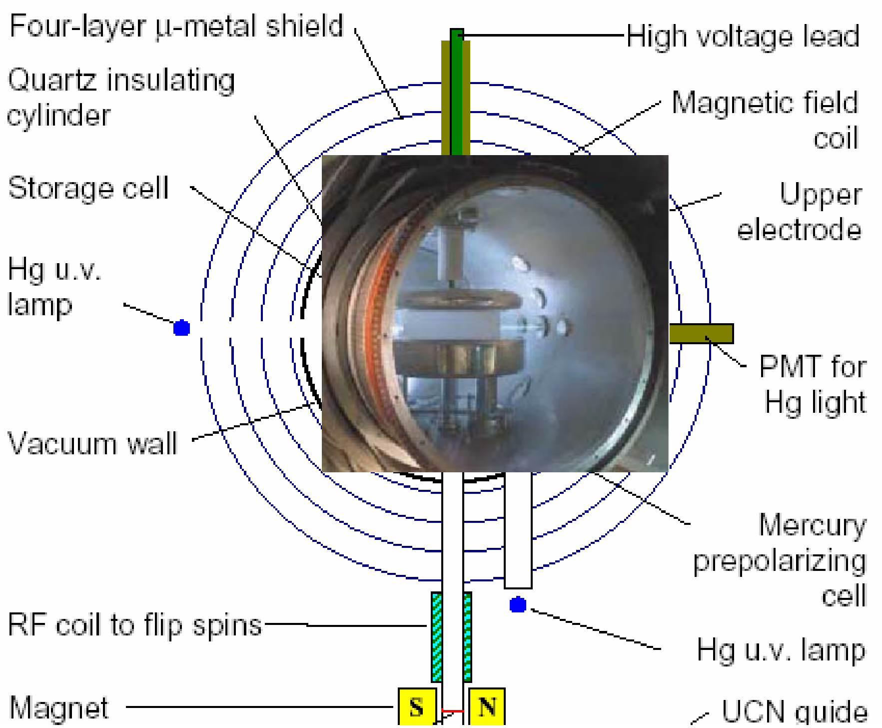
C. A. Baker et al., PRL 97 (2006) 131801
P. G. Harris et al., PRL 82 (1999) 904

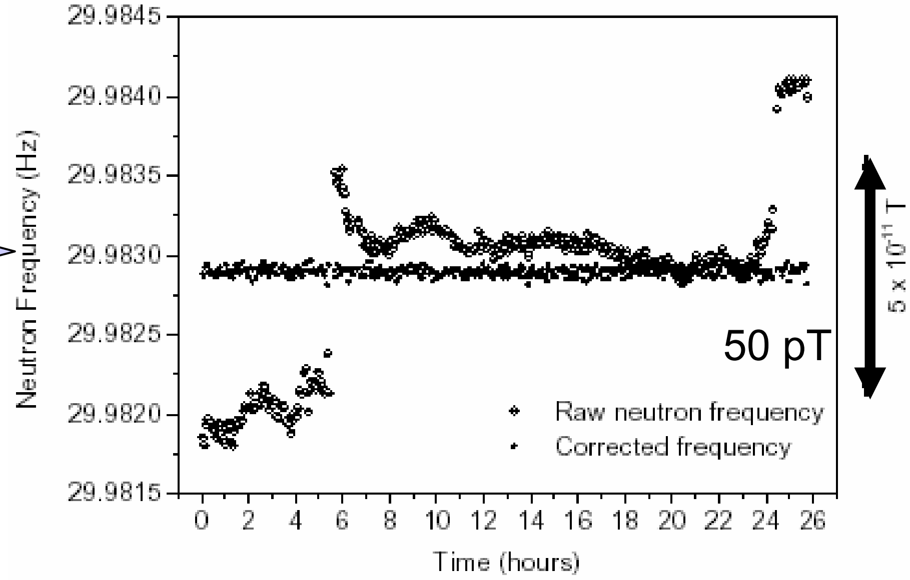


Context

^{199}Hg co-magnetometer







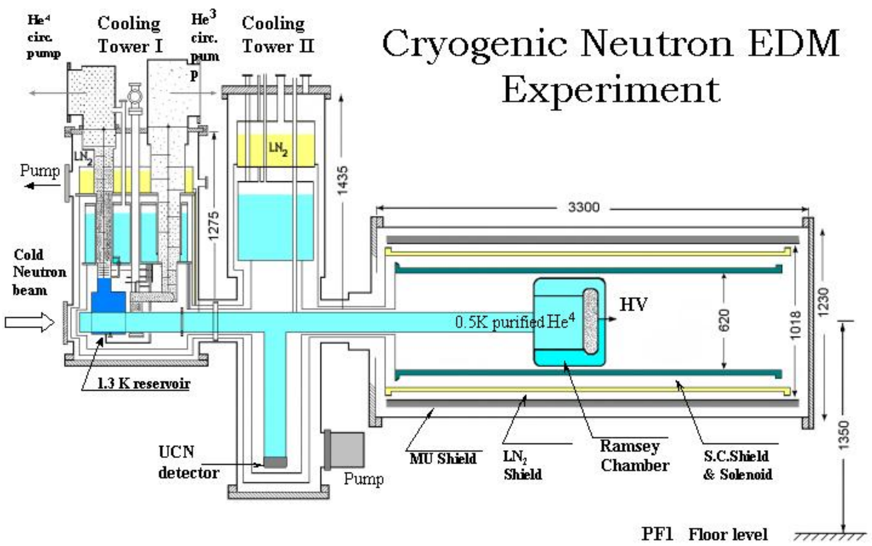
K.Green et al., NIM A 404 (1998) 381
P. G. Ha... 04

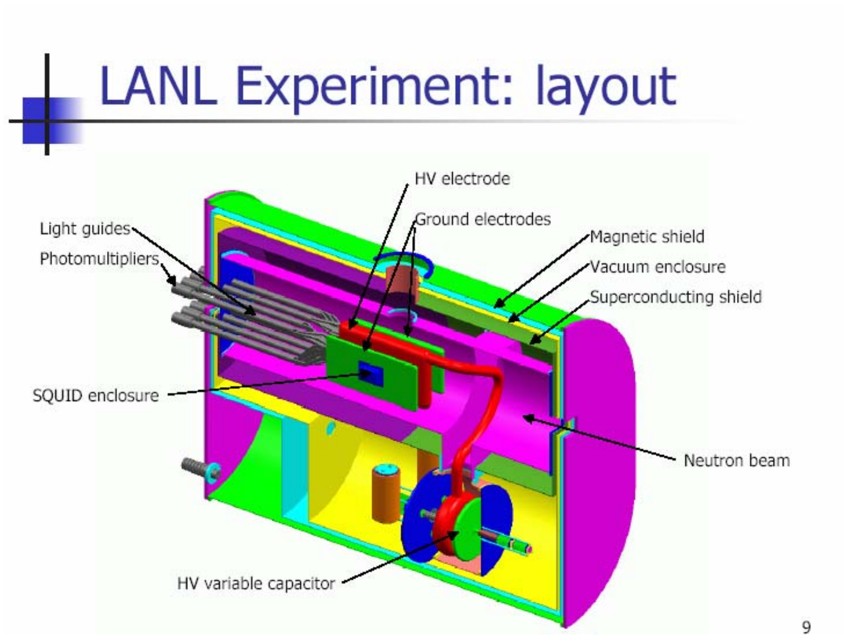
$$h\nu^{+} = 2\,(\mu_n B + d_n E)$$
$$h\nu^{-} = 2\,(\mu_n B - d_n E)$$
$$h\Delta\nu = 4\,d_n E$$

J.M.Pendlebu... 2102
S.K.Lamoreau... 005) 032104
P.G.Harris and J.M.Pendlebury, PR A 73 (2006) 014101
C.A.Baker et al., PRL 97 (2006) 131801

Context

Other projects: cryogenic experiments with UCN in superfluid ^{4}He below 1K





Our approach

Improve room-temperature, in-vacuum technique

At ILL:

- Work with the RT experiment of Sussex-RAL-ILL (measure, test, try, learn, repair, recuperate, ….)
- Improve magnetic field measurement
- Improve magnetic field stability and homogeneity
- Improve overall stability and control (+ many other issues)

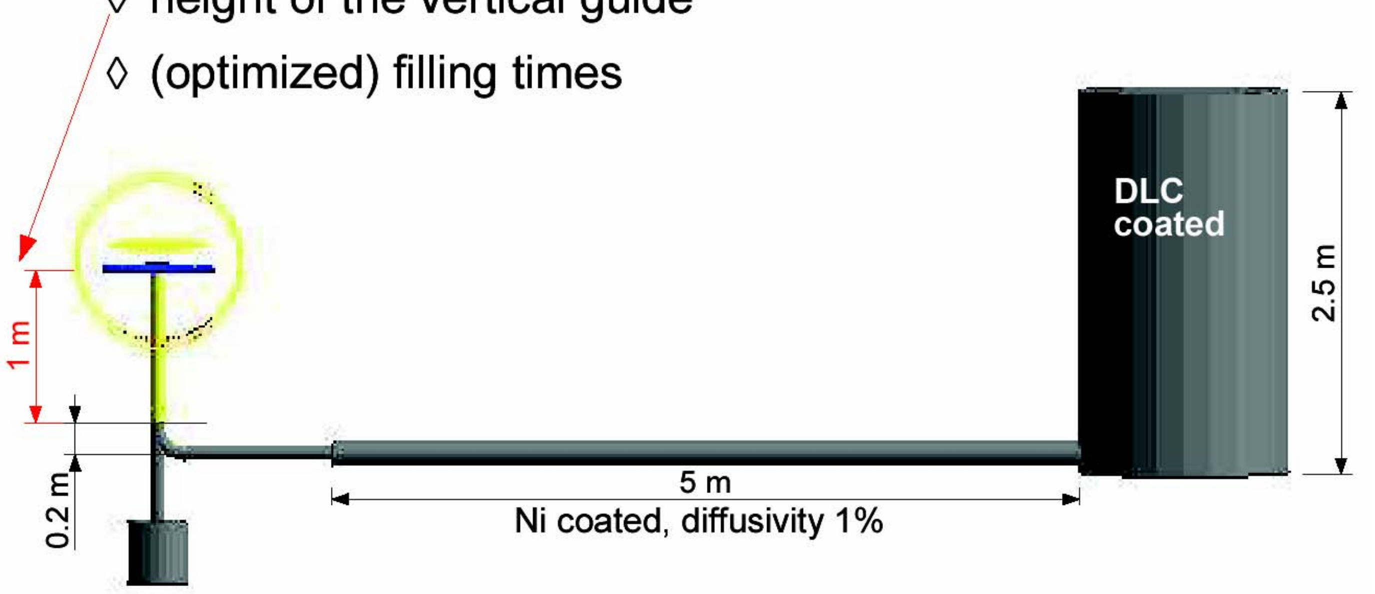
At PSI:

- Increase statistics
- New systematic control tools
- At some point: new system

UCN performance at ILL and at PSI

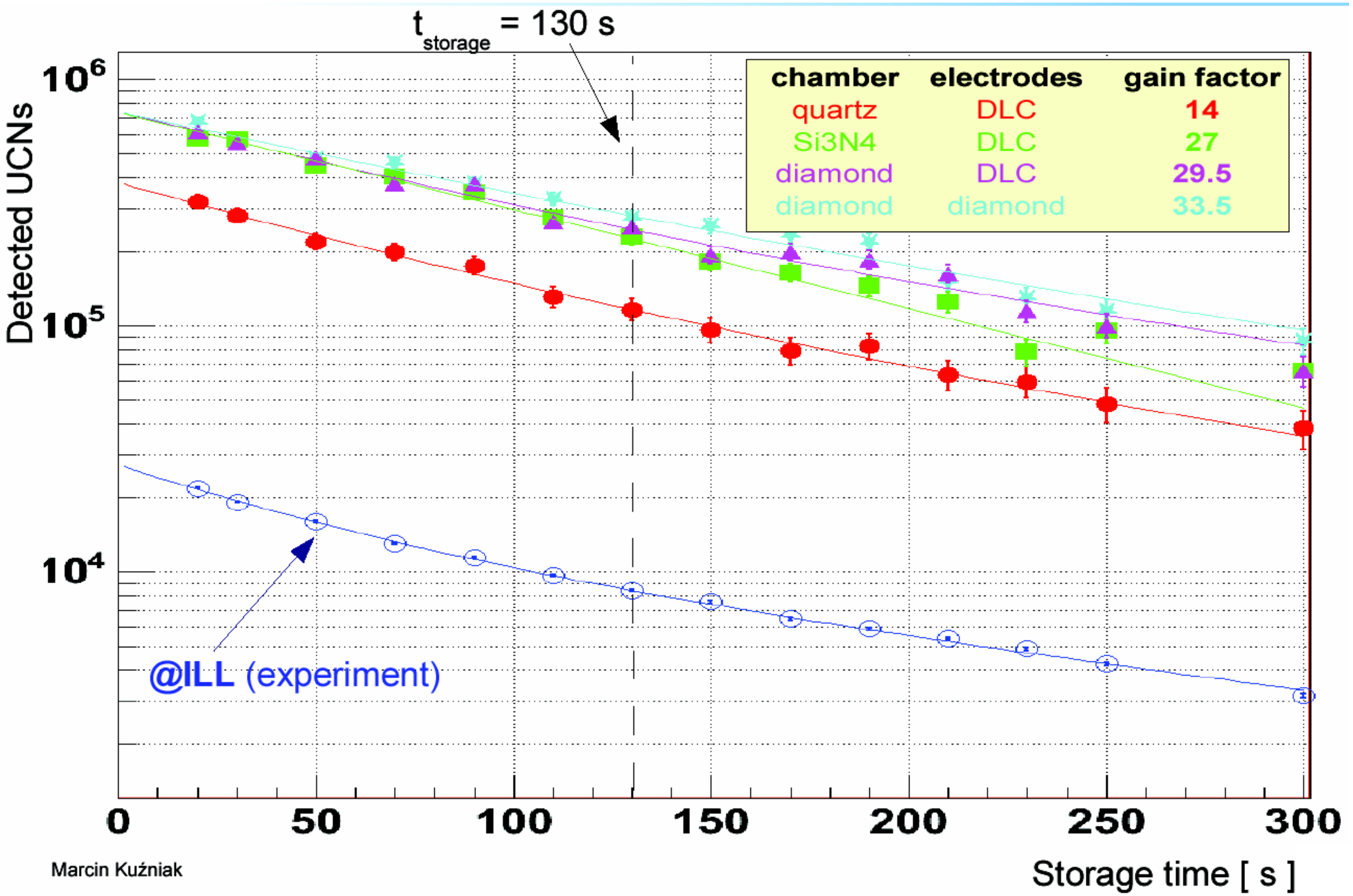
◊ Configurations with different:

- ◊ materials (Quartz, DLC, Si_3N_4, diamond)
- ◊ height of the vertical guide
- ◊ (optimized) filling times



Simulations using Geant4 (S. Agostinelli et al., NIM A 506 (2003) 250)
modified and extended for UCN:
P. Fierlinger, PhD thesis, UniZh, 2005; F. Atchison et al., NIM A 552 (2005) 513.
Further developed by **M. Kuzniak** and others in our collaboration.

MC of the experiment at PSI



Marcin Kuźniak

Sussex-RAL-ILL apparatus @ PSI

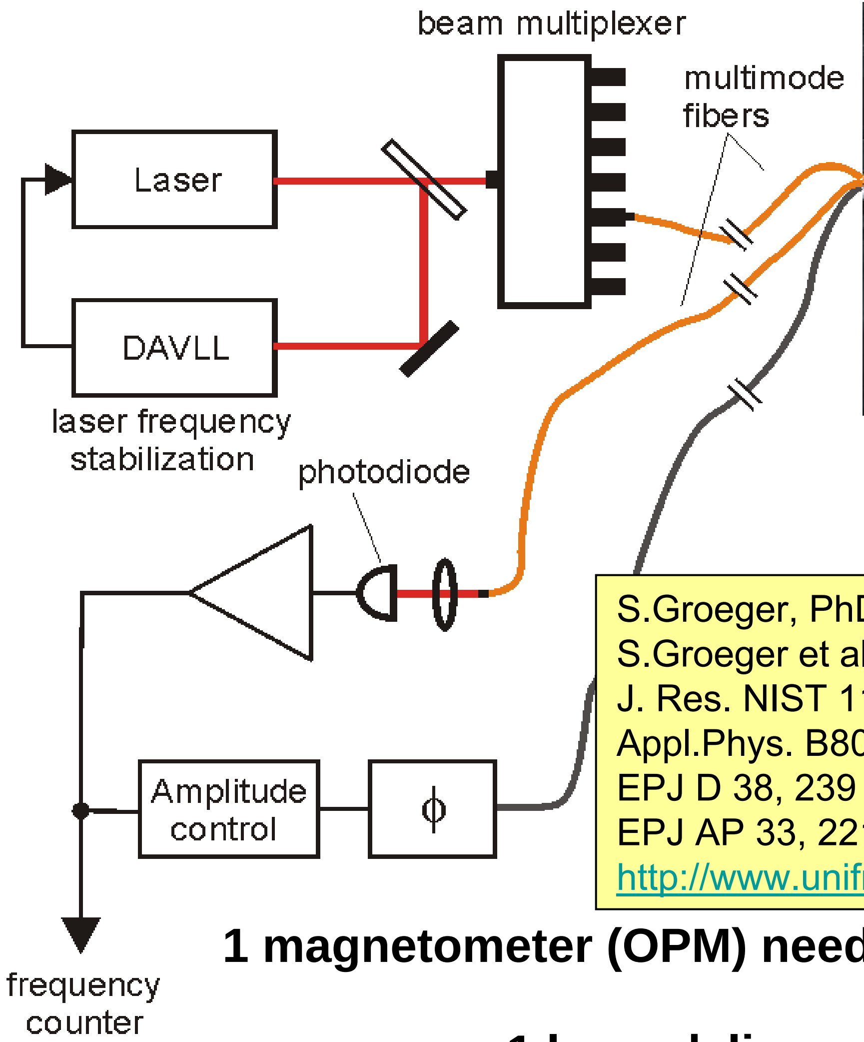
- gain factor 3-4 in sensitivity with the present setup
- gain factor 5-6 in sensitivity with new wall material
- need improved magnetic field stability, homogeneity and control
  - improved co-magnetometry
  - external magnetometry, outside but close to UCN

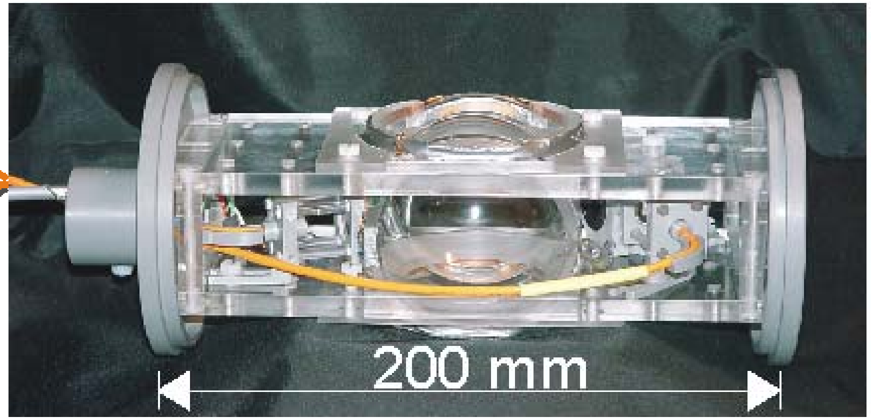
Co-magnetometry I

- Improve sensitivity of HgM
  200 fT → 40 fT or better
  - initial polarization
  - prepolarizer volume
  - lamp vs. laser ?
- Activities just starting

External magnetometry with

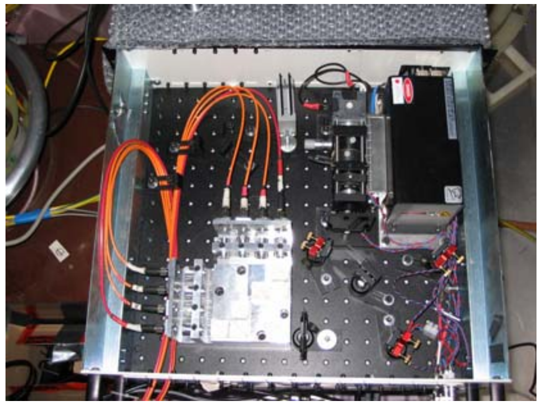
Self-oscillating laser-pumped Cs magnetometers





- non-magnetic sensor head
- Larmor frequency: 3.5 kHz @ 1 μT

S.Groeger, PhD thesis, UniFr, 2005
S.Groeger et al.,
J. Res. NIST 110, 179 (2005),
Appl.Phys. B80, 645 (2005),
EPJ D 38, 239 (2006),
EPJ AP 33, 221 (2006,)
http://www.unifr.ch/physics/frap/



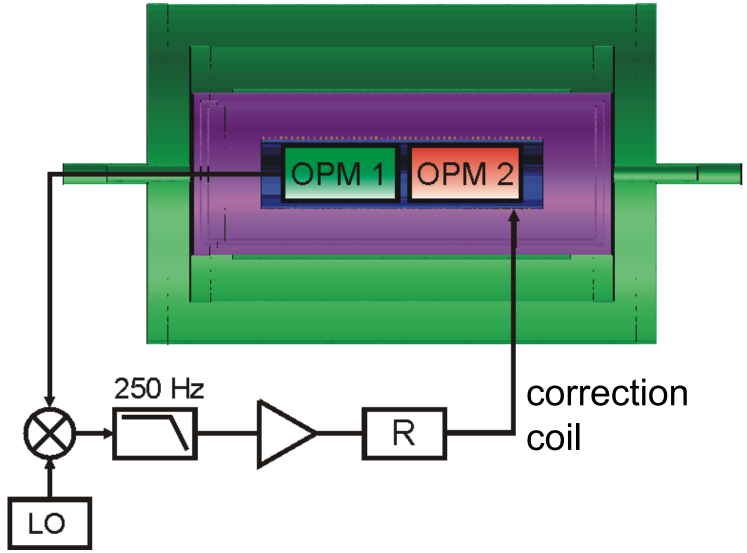
1 magnetometer (OPM) needs 25 μW

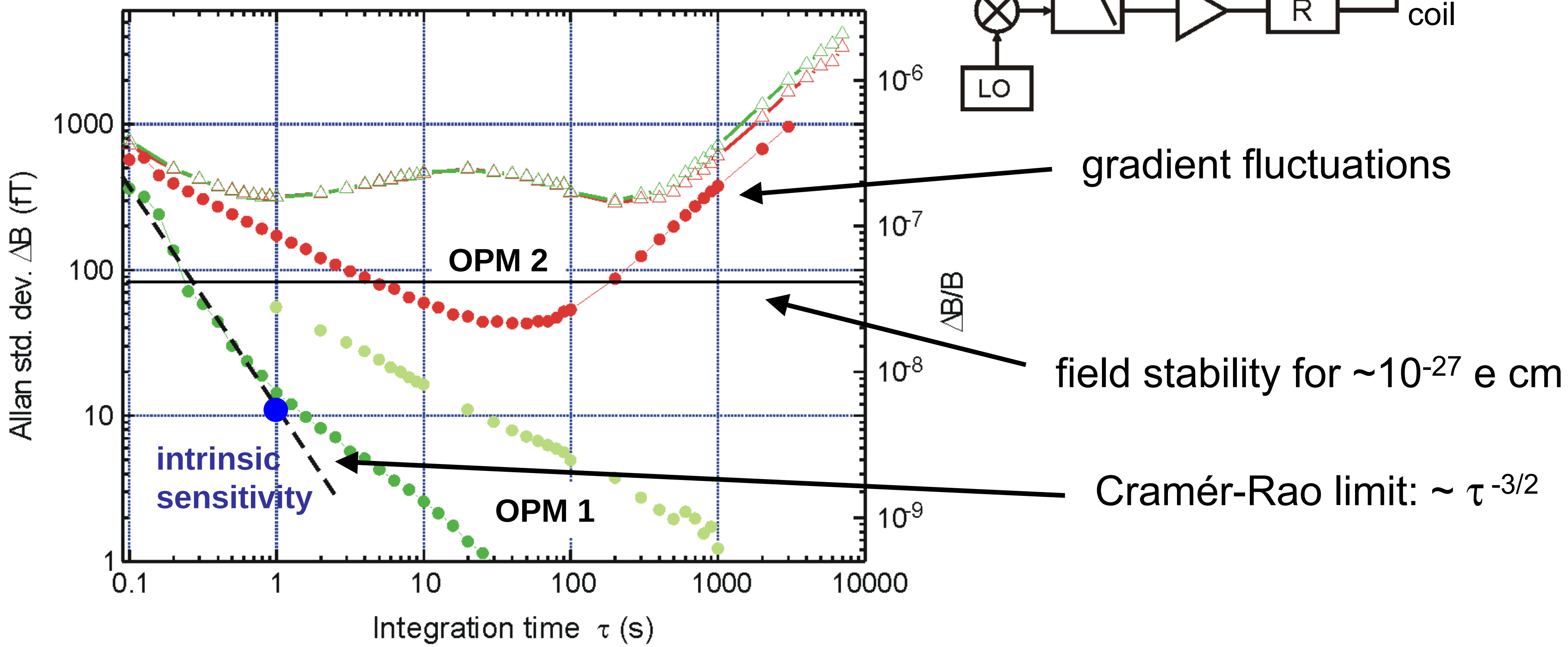
1 laser delivers >10 mW

→ 1 laser = many sensors

Active field stabilization

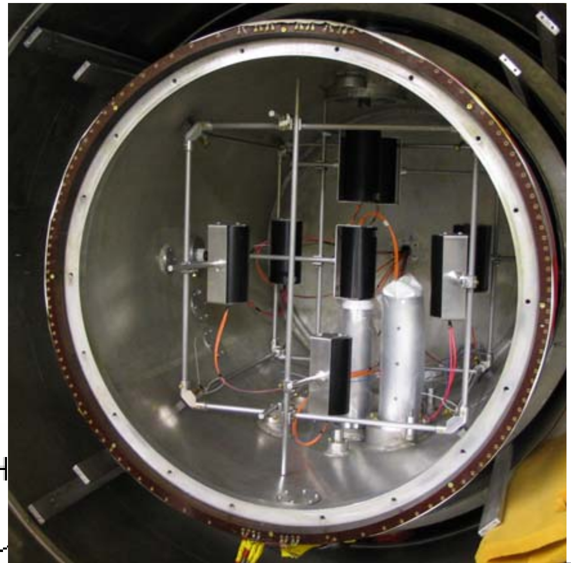
Simple field stabilization coils give 10^3 improvement at 100 s.
Gradient correction of the same order can be expected.

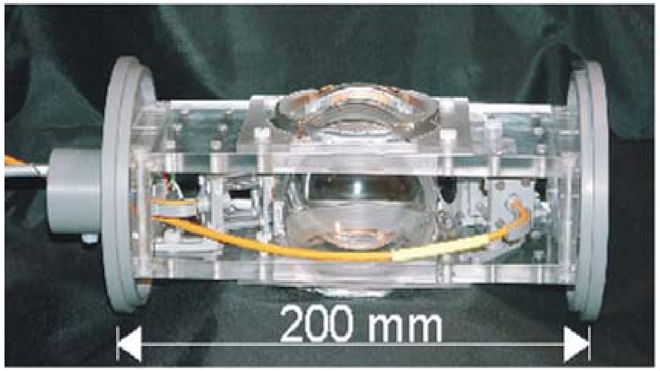


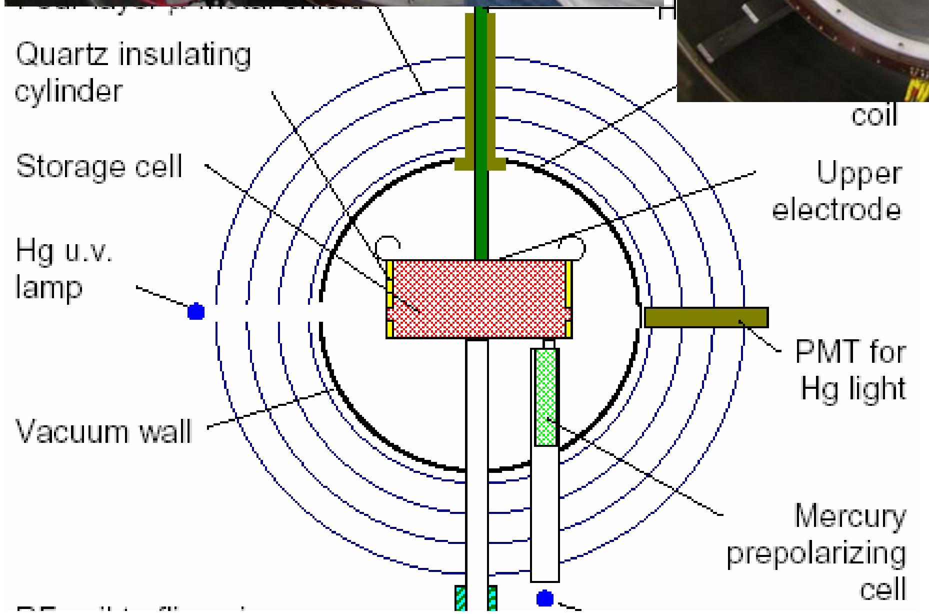


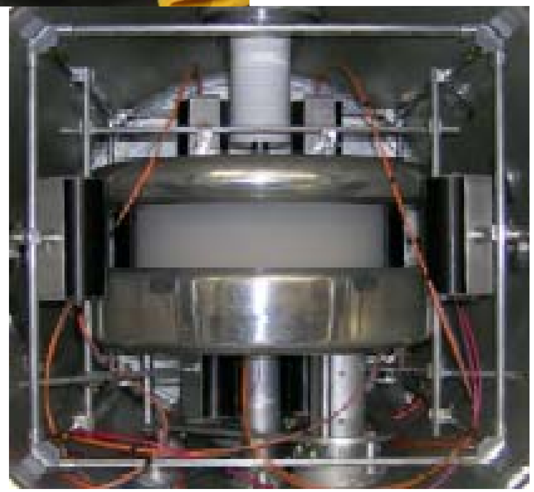
IPC CAEN | FRAP Fribourg Atomic Physics | ill | LPSC Grenoble | PAUL SCHERRER INSTITUT PSI

Cs magnetometers in EDM

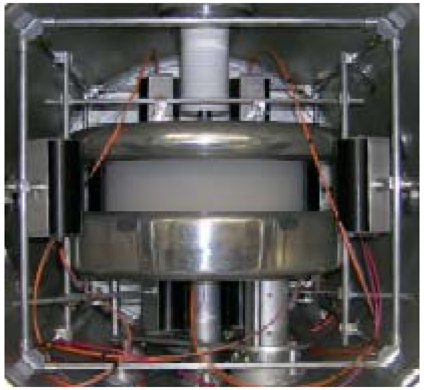






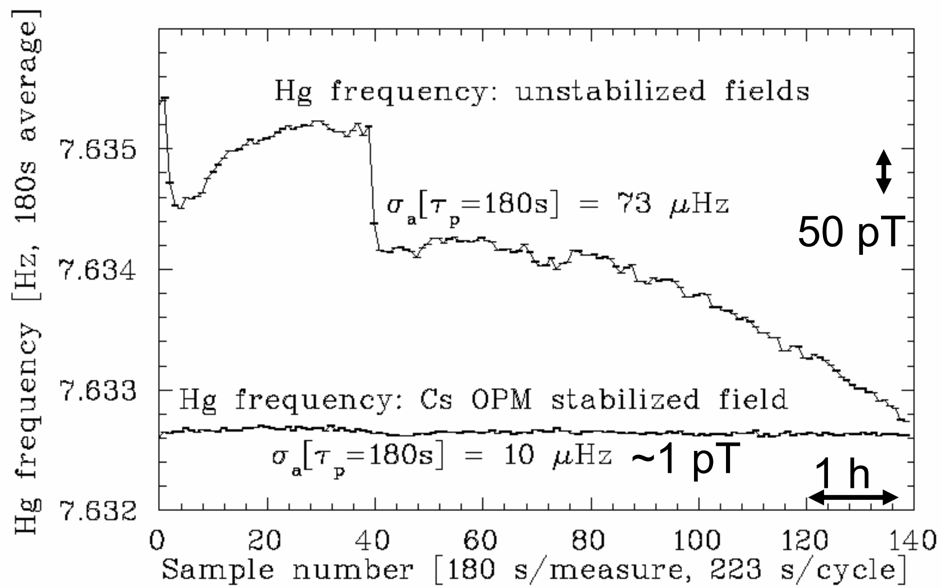


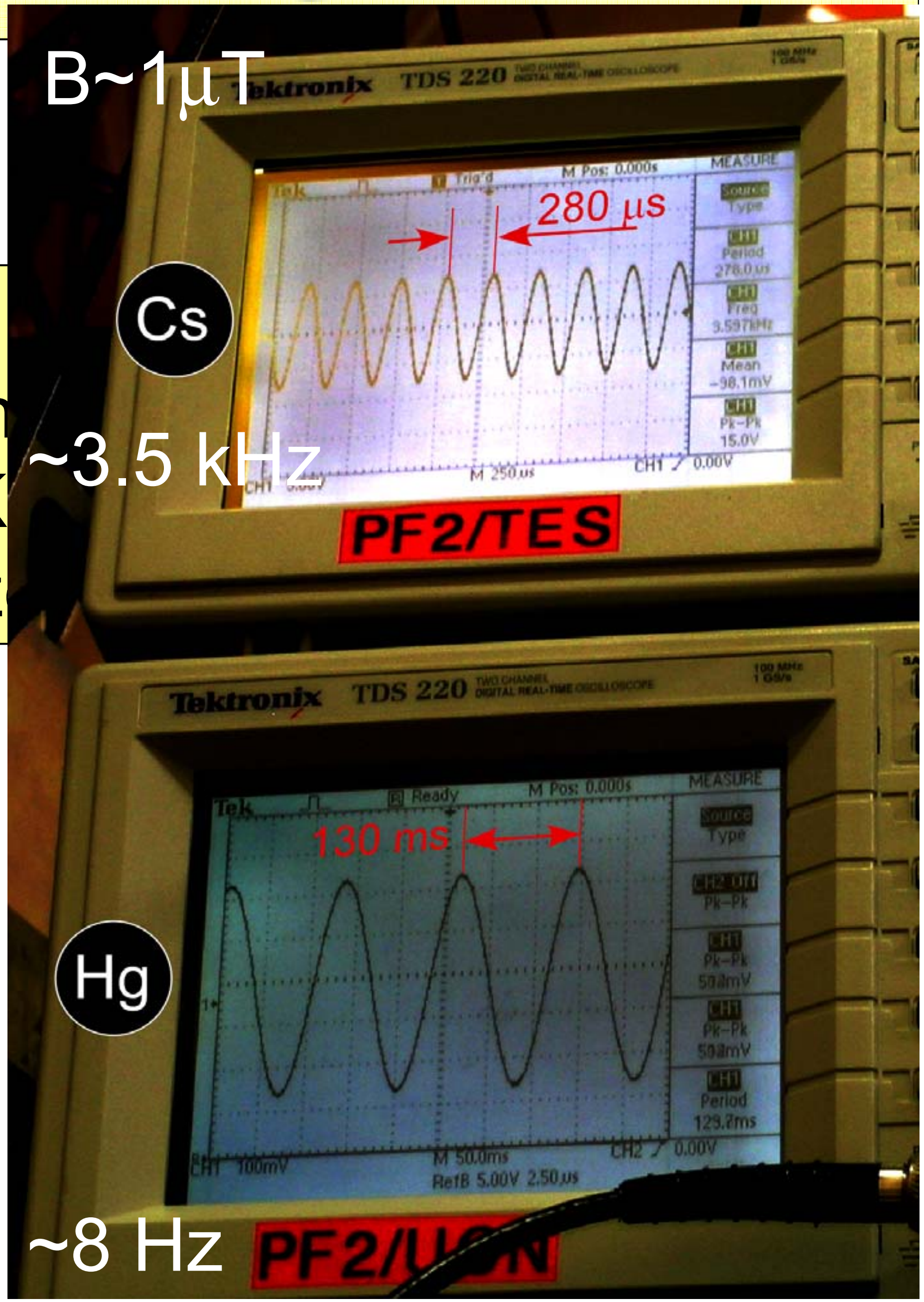
Operate Cs and Hg simultaneously



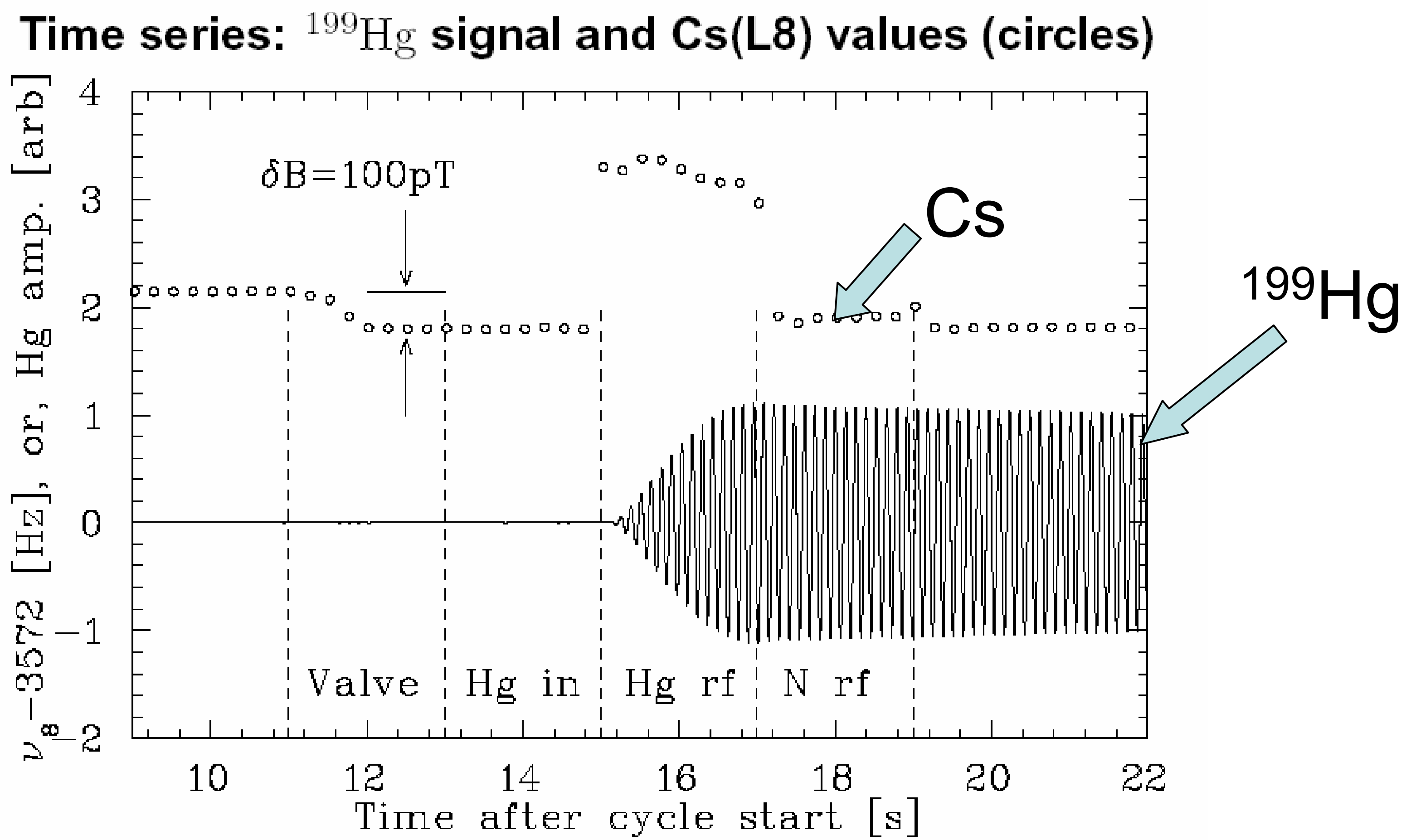
Active B-field
with Cs-magn
HV-tests: P.K
Next: stabiliz

^{199}Hg **Allan variance**



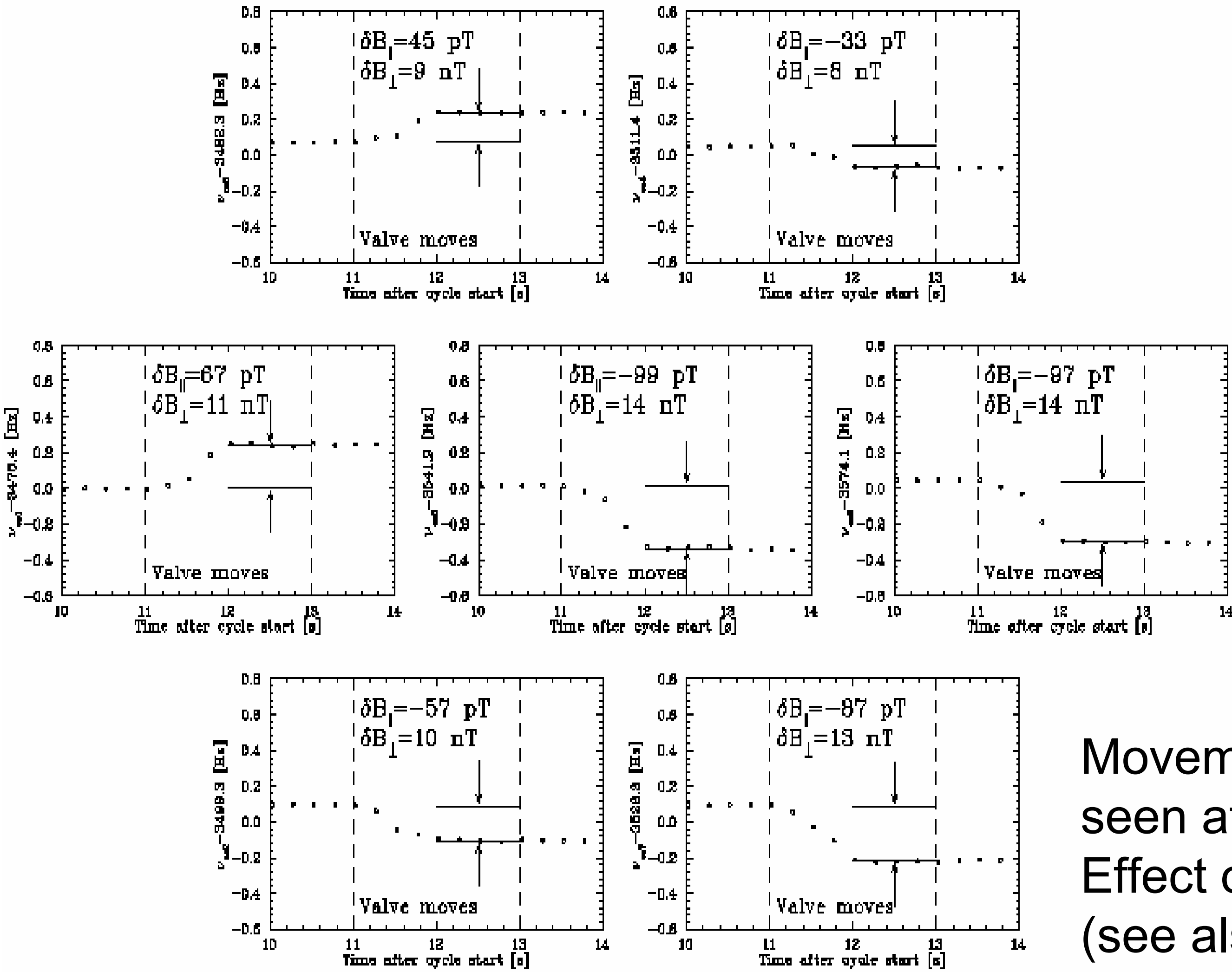


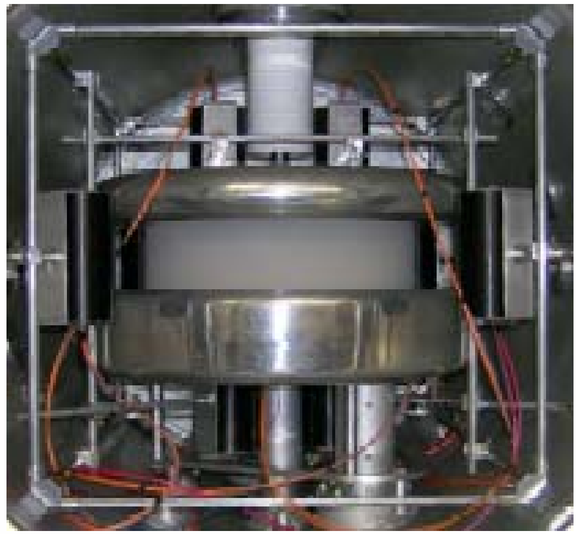
A new dimension in diagnostics ...



280 GB of data under analysis at FRAP

A new dimension in diagnostics ...





Movement of the UCN shutter seen at different locations: Effect of a magnetic impurity (see also PRL97(2006)131801)

External Cs magnetometry

- Many (vector) CsM desirable for monitoring of the magnetic field
- Stabilize magnetic field and gradients
- It appears feasible to stabilize the field to a level at least as good as was achieved by offline correction with the HgM before
- But: probably not sensitive enough to leakage currents and magnetic wall impurities

Improvements for a new EDM

- Double chamber setup, larger volumes
- Velocity sensitive UCN detection
  (false neutron EDM: $d_{af,n} \sim \langle v^2_{ucn} \rangle B_z^{-2} dB_z/dz$)
- Second co-magnetometer
  (go for no atomic false EDM: $d_{af,atom} \sim \gamma^2 R^2 dB_z/dz$)
- Stability, control and logging of the environmental data

Co-magnetometry II

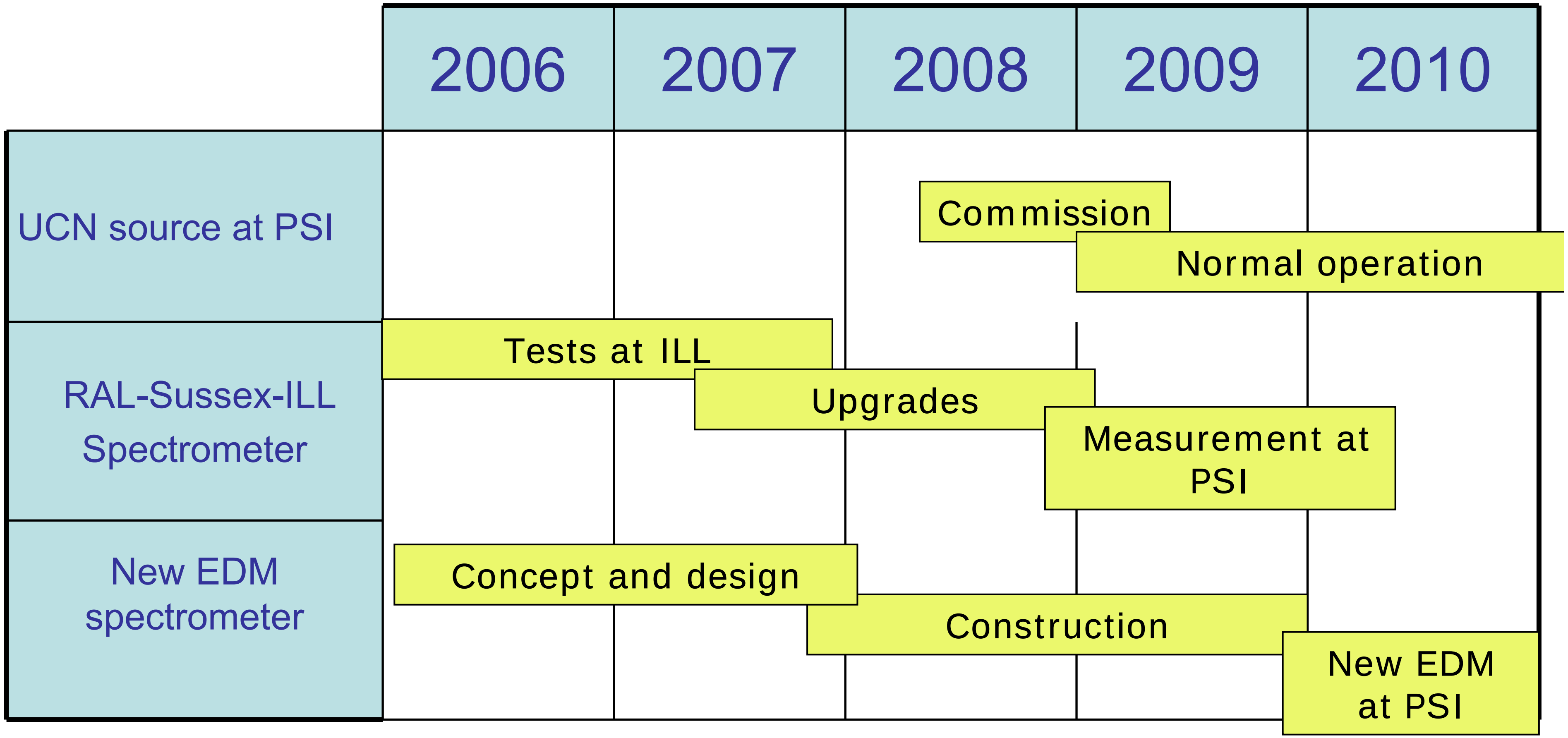
- Potential co-magnetometer candidates:
  ^{199}Hg (7.7 Hz/μT), ^{129}Xe (-11.8 Hz/μT), ^{3}He (-32.4 Hz/μT)
- Geometrical phase induced false effect:
  (Pendlebury et al., PRA70(2004)032102)
  $d_{af,atom} \sim \gamma^2 R^2 \, dB_z/dz$ $\quad$ $d_{af,n} \sim \langle v^2_{ucn} \rangle B_z^{-2} \, dB_z/dz$
- Example: B_z=1μT, dB_z/dz=1nT/m

$d_{af,n} \sim 10^{-27}$e cm

$d_{af,Hg} \sim 13 \times d_{af,n}$
$d_{af,Xe} \sim 2 \times d_{af,Hg}$
$d_{af,He} \sim 18 \times d_{af,Hg}$

Two null results for atomic co-magnetometers could prove the stability of the B-field magnitude **and** the absence of gradients

Present planning



We thank the members of the RAL-Sussex-ILL collaboration for allowing us to use their apparatus and for many interesting discussions.

Velocity sensitive UCN detection

Problem: UCN velocity dependent EDM systematics

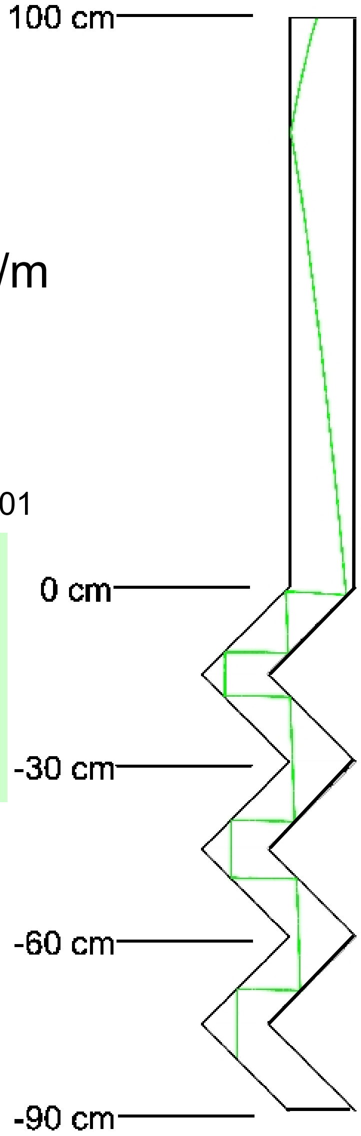
e.g. B = 1 μT, E = 10 kV/cm, dB/dz =1 nT/m

⇨ d_n(false)* = 3 x 10^{-27} e cm

*J.M.Pendlebury et al., Phys. Rev. A 70 (2004) 032102
S.K.Lamoreaux and R.Golub, Phys.Rev. A 71 (2005) 032104
P.G.Harris and J.M.Pendlebury, Phys. Rev. A 73 (2006) 014101

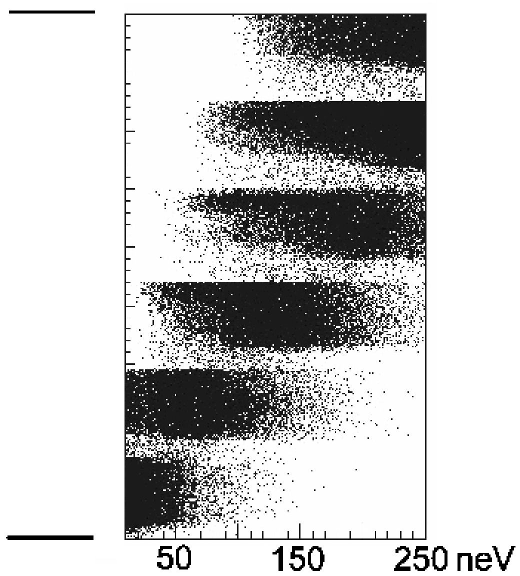
Idea: Measure EDM as function of UCN velocity with efficient simultaneous detection e.g. δd_n ⇨ $\sqrt{2}\,\delta d_n$ in 2 energy bins with according ability to test an EDM signal

- PhD project at PSI
- study of detector options
- realization of prototype
- comprehensive study of UCN velocity related systematics



G4-UCN** simulation of UCN with energies [0, 250] neV at 100 cm falling into a 6-fold segmented detector

** F.Atchison et al., NIM A552(2005)513



PAUL-SCHERRER-INSTITUT

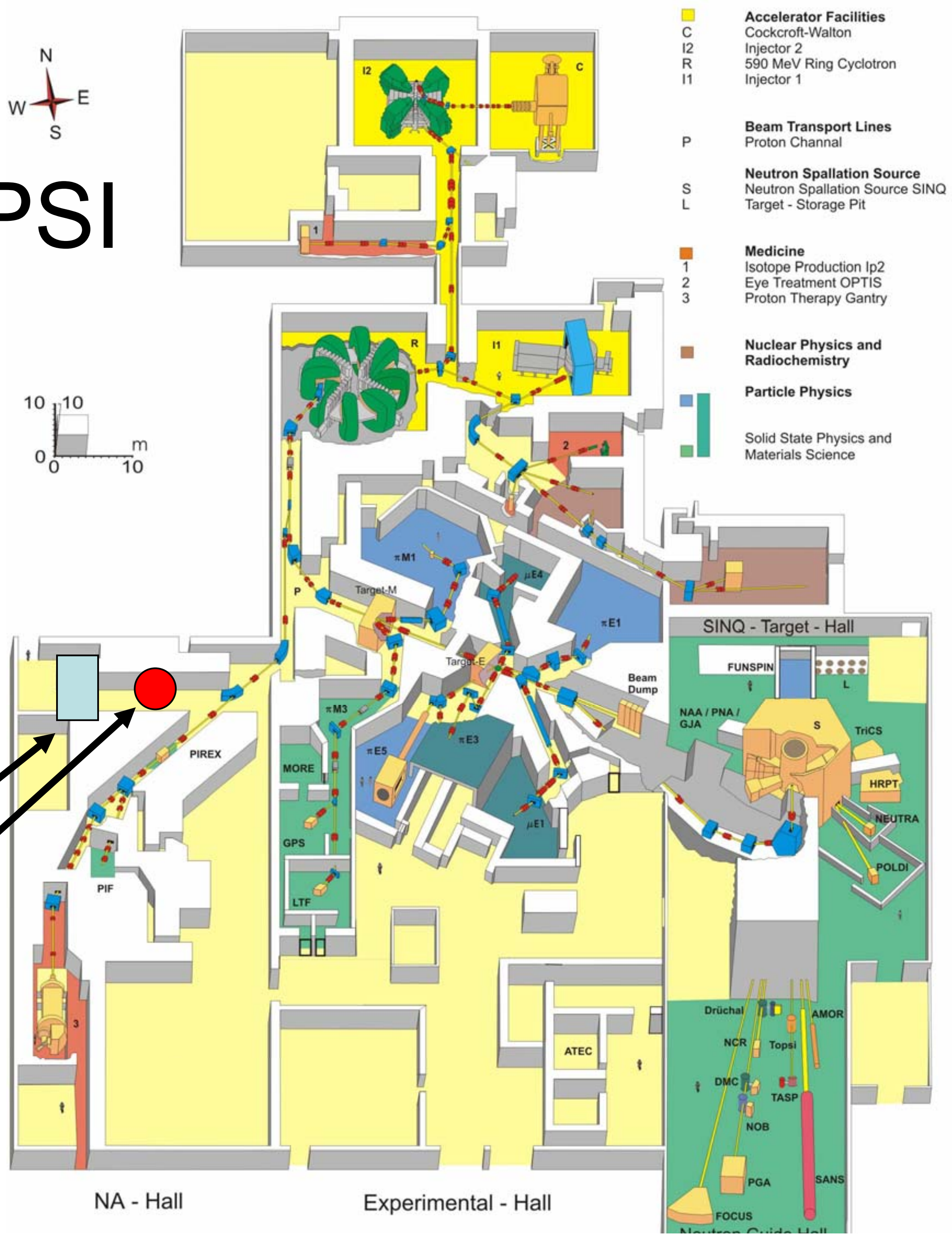
PSI

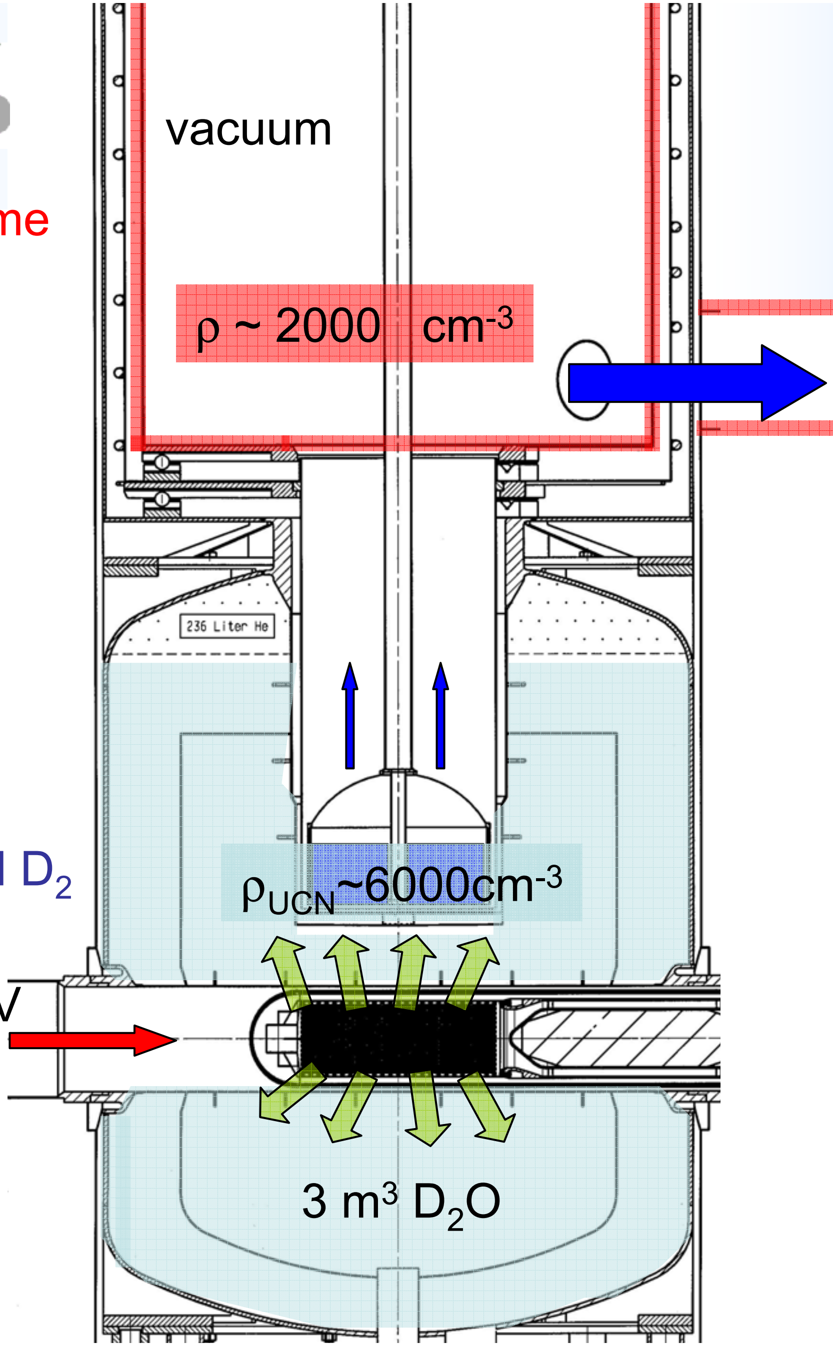
UCN source at PSI

Deliver 600 MeV, 2mA
at 1% duty cycle to
UCN target station

Ultra Cold Neutron Source

nEDM
Source





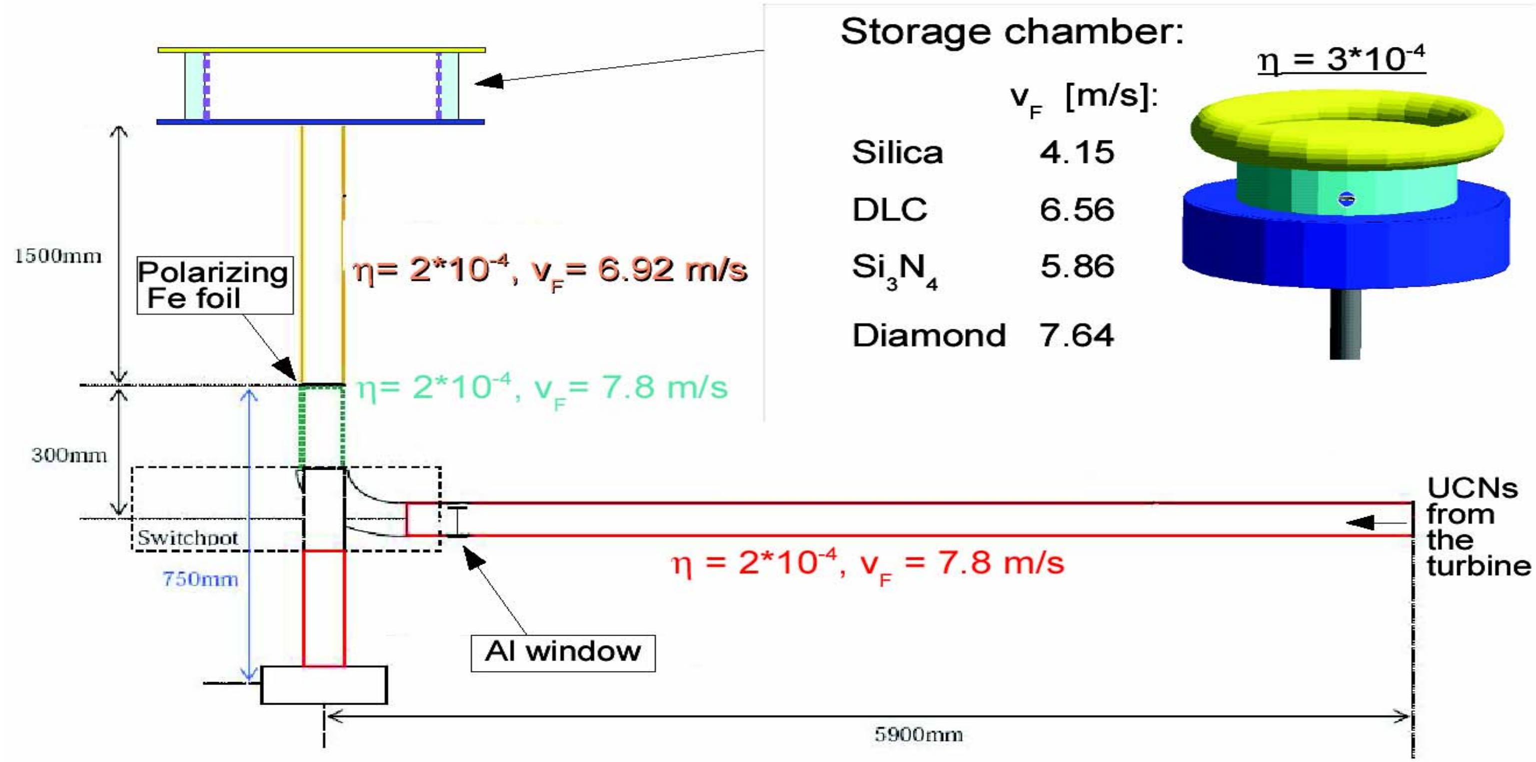
Ultra Cold Neutron Source

The PSI UCN source

- high power
- low duty cycle
- starts 2008 with 1 area
- multi-user capability with 2nd area, year xx?

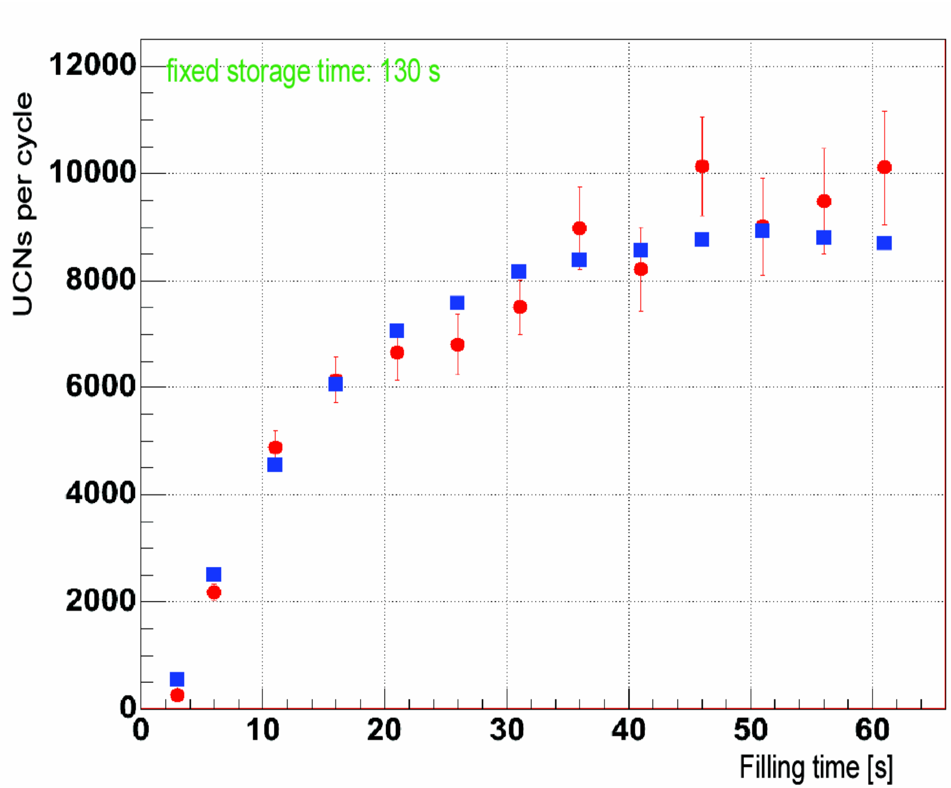
Papers by the PSI UCN group concerning related source and UCN physics at http://ucn.web.psi.ch

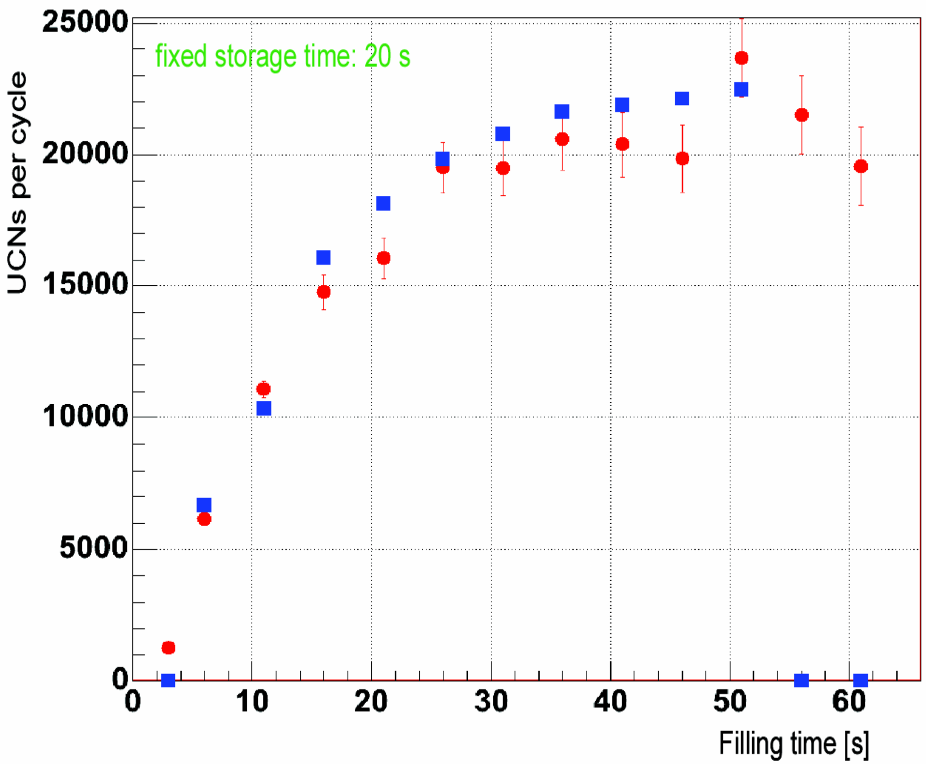
UCN transport and counting: Understand Statistics



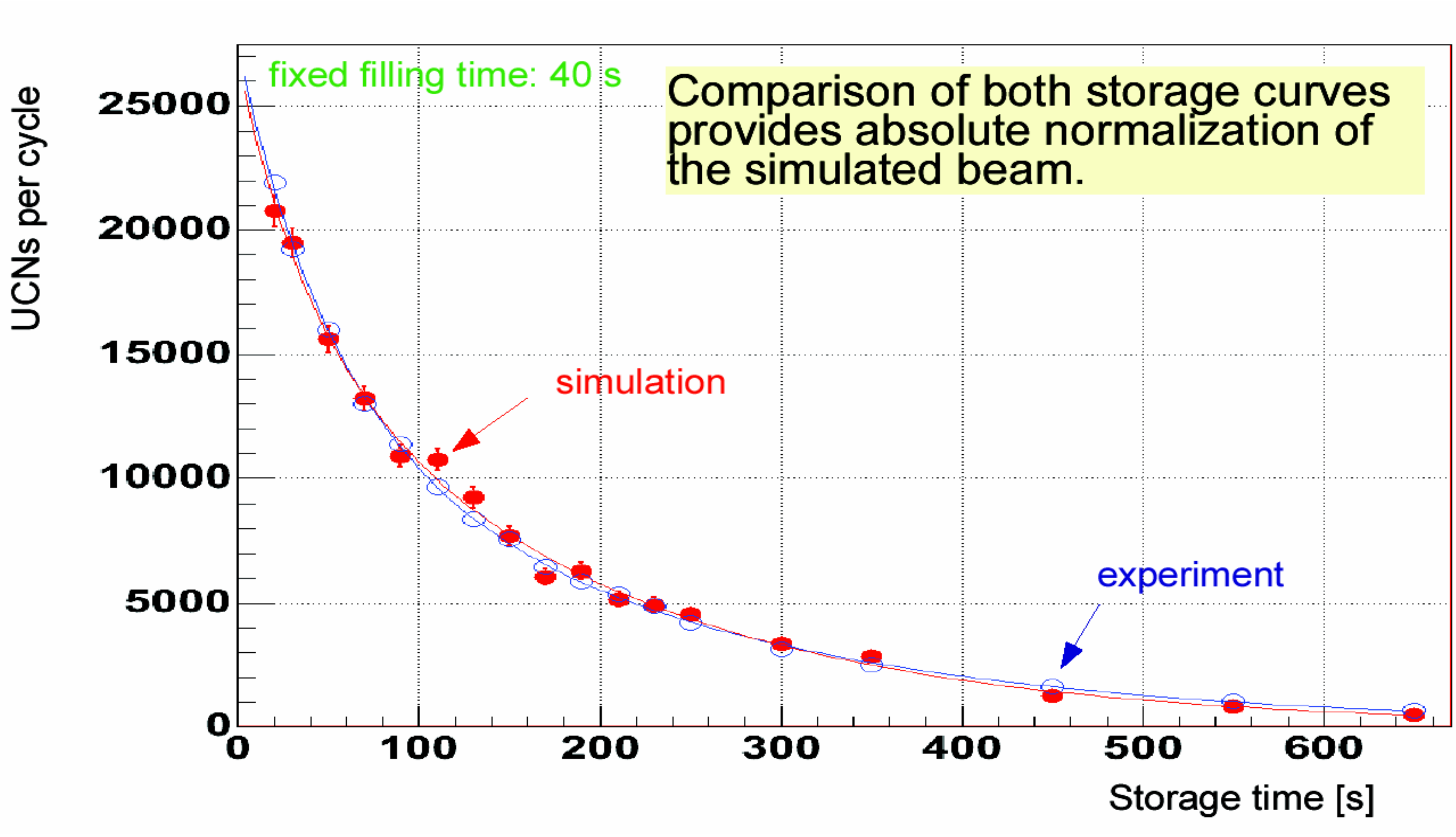
Simulations using Geant4 (S. Agostinelli et al., NIM A 506 (2003) 250) modified and extended for UCN:
P. Fierlinger, PhD thesis, UniZh, 2005; F. Atchison et al., NIM A 552 (2005) 513.
Further developed by **M. Kuzniak** and others in our collaboration.

Comparison of MC and experiment





Comparison of MC and experiment



Example calculation: #(Cs)

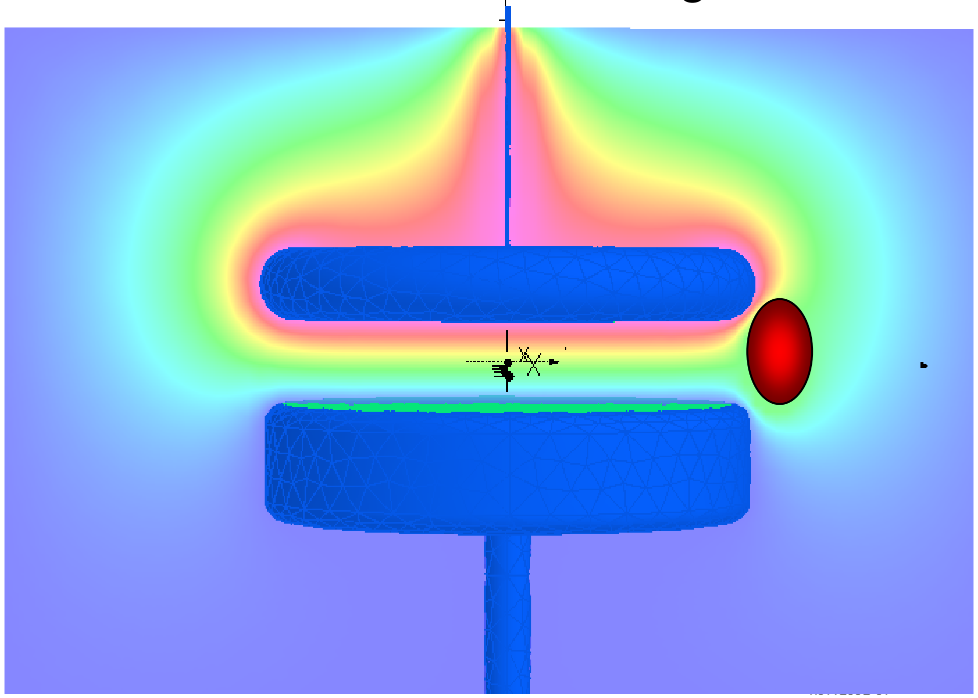
Use a spherical harmonics expansion formalism in order to calculate the number of sensors, their optimum locations, optimum (correction) coil configurations, etc.
Caveat: Assume no magnetization and no currents inside the volume surrounded by the magnetometers.

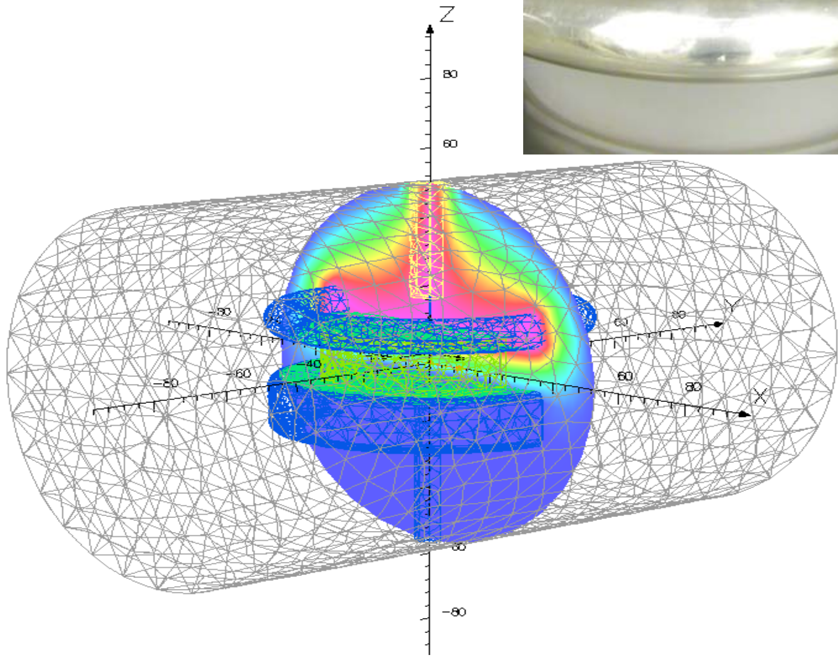
$\ell_{\max}$	Number of $\mathcal{A}_{\ell m}$, $\mathcal{B}_{\ell m}$	Number of vectorial magnetometers	Number of $\mathcal{A}^2_{\ell m}$, $\mathcal{A}_{\ell m}\mathcal{A}_{\ell' m'}$ $\mathcal{B}^2_{\ell m}$, $\mathcal{A}_{\ell m}\mathcal{B}_{\ell' m'}$	Number of scalar magnetometers
1	3	1		6
2	8	3		36
3	15	5		120
4	24	8		300
5	35	12		605
…	…	…		…
L	$L(L+2)$	$\left\lceil \frac{L}{3}(L+2) \right\rceil$		$L+2)(L+1)^2$

Clearly prefer vector type magnetometers !

Calculations: E-fields

Opera 3D models are used to predict the electric fields in the experiment and calculate the influence of external magnetometers.





E-fields from 2D and 3D models serve as input for UCN simulations in the investigation of systematic effects, due to, e.g. motional magnetic fields

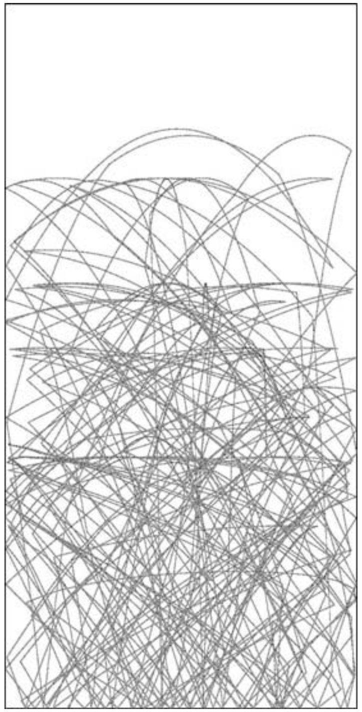
Adapted Geant4* for UCN

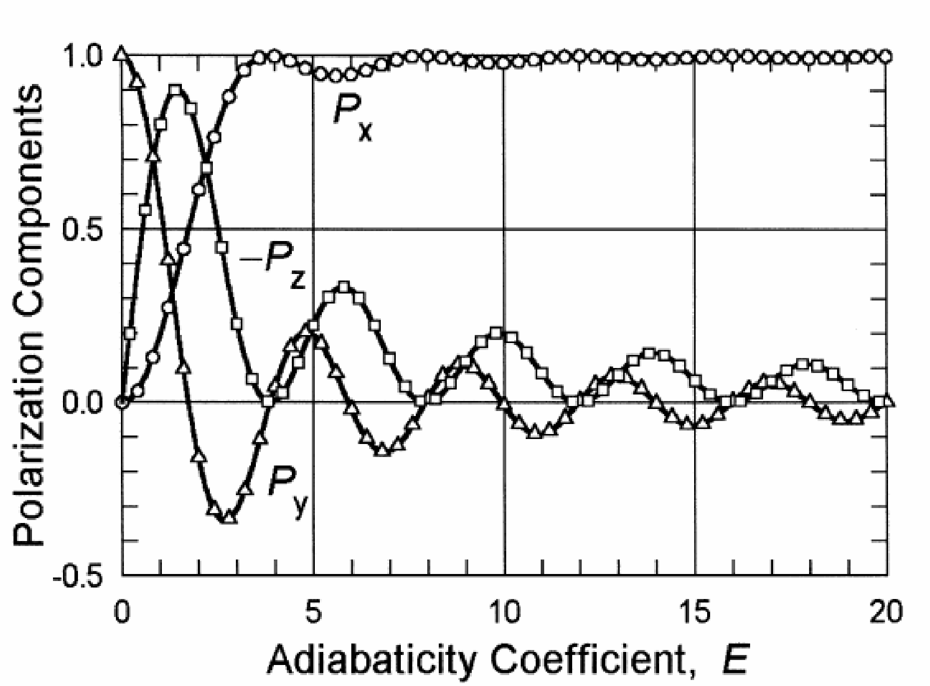
UCN specific features:

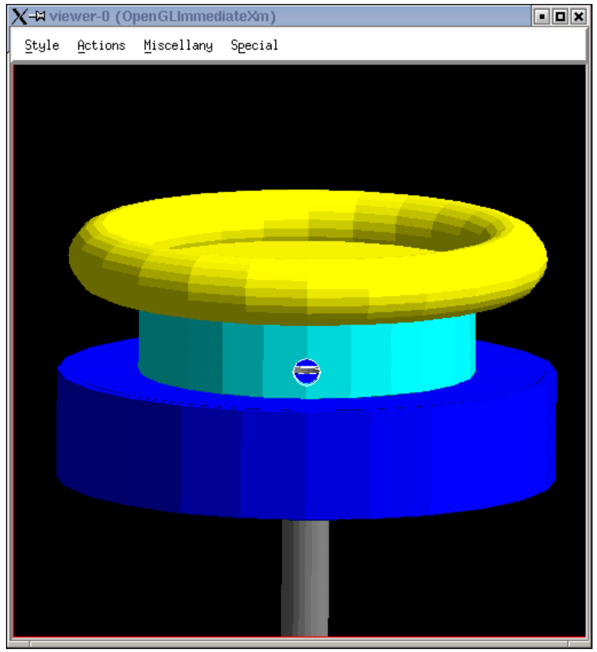
– Boundary and bulk material interaction
– Particle tracking with gravity
– Particle tracking through arbitrary (in general: inhomogenous, dynamic) magnetic fields
– Spin tracking through arbitrary magnetic fields

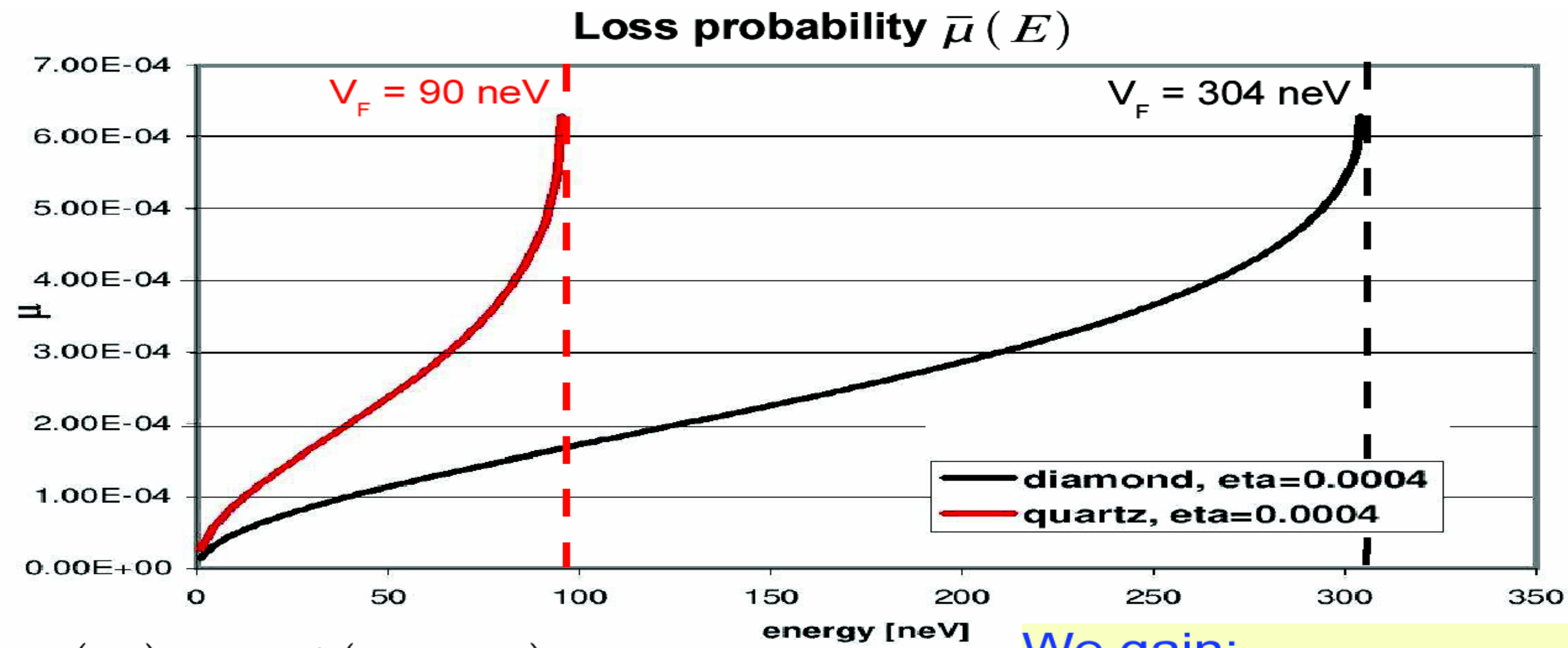
* S. Agostinelli et al., NIM A 506 (2003) 250

P. Fierlinger, PhD thesis, UniZh, 2005
T. Brys et al., NIM A 550 (2005) 637
F. Atchison et al., PL B 625 (2005) 19
F. Atchison et al., NIM A 551 (2005) 429









$$\bar{\mu}(E) = \eta \cdot f(E, V_F)$$

η – loss coefficient per wall collision

V_F – Fermi potential

We gain:

- ◊ fast UCNs
- ◊ more slow UCNs