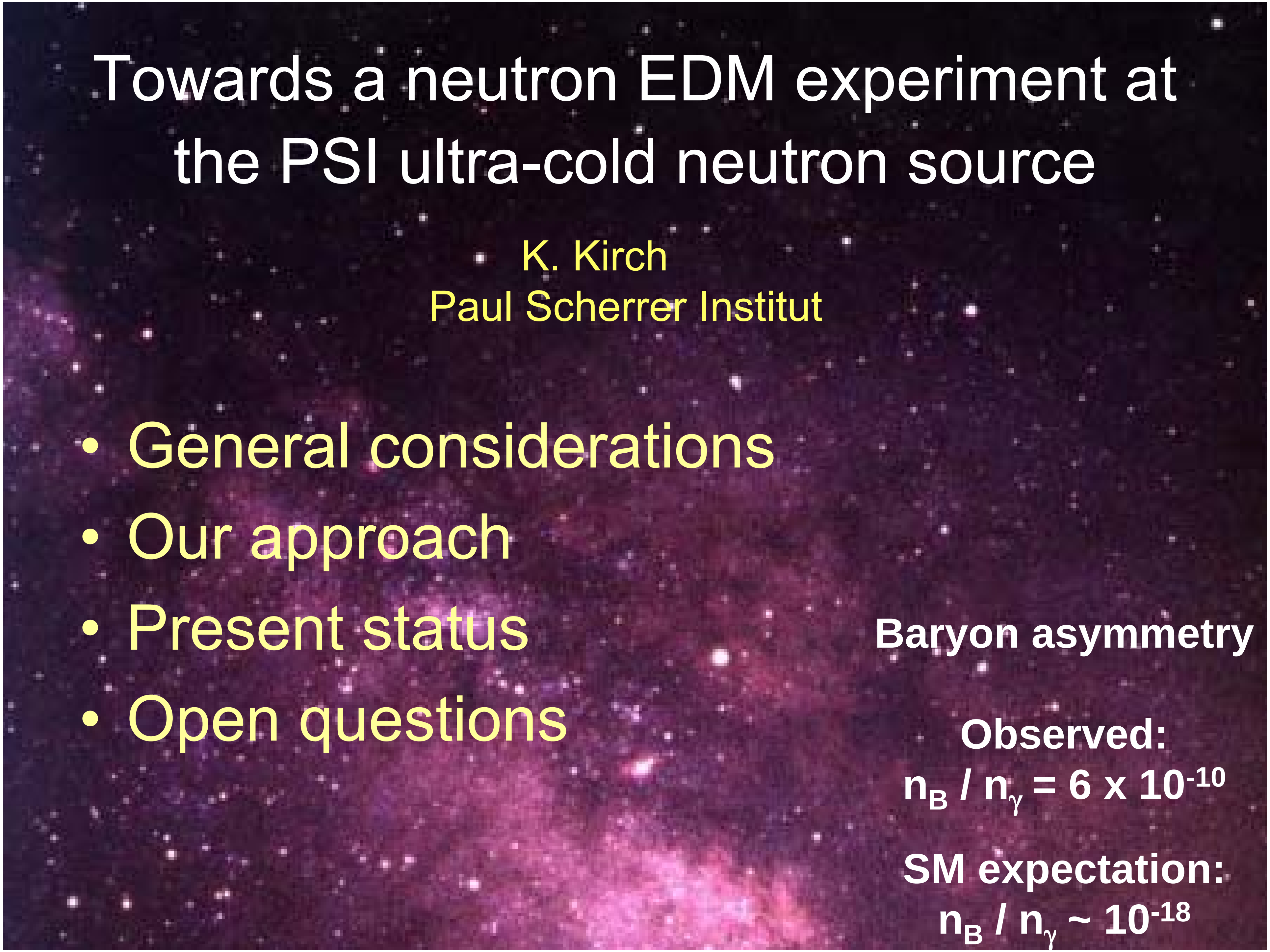


Towards a neutron EDM experiment at the PSI ultra-cold neutron source

K. Kirch
Paul Scherrer Institut

- General considerations
- Our approach
- Present status
- Open questions

Baryon asymmetry

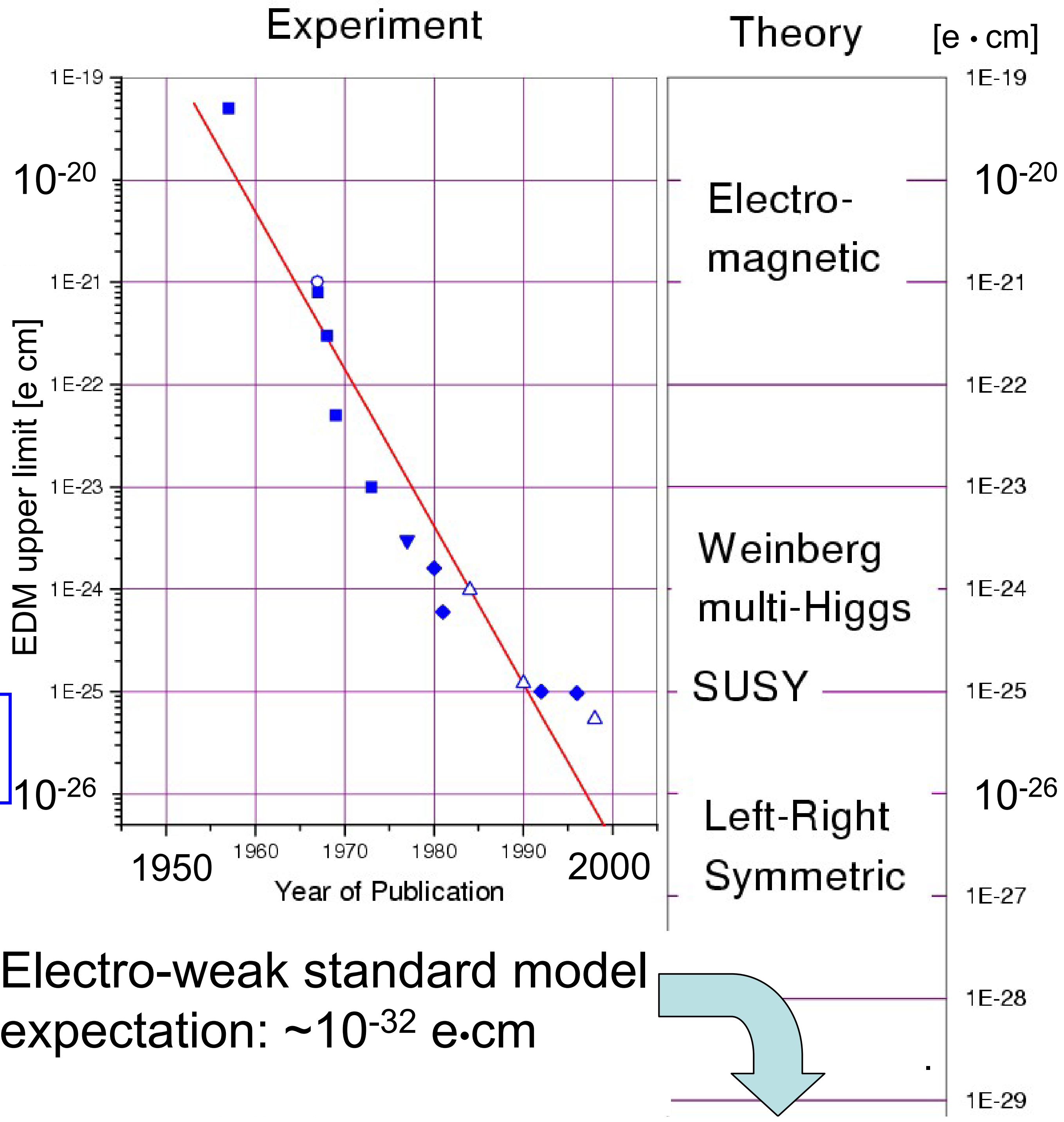
Observed:
$n_B / n_\gamma = 6 \times 10^{-10}$

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

The EDM limits to date

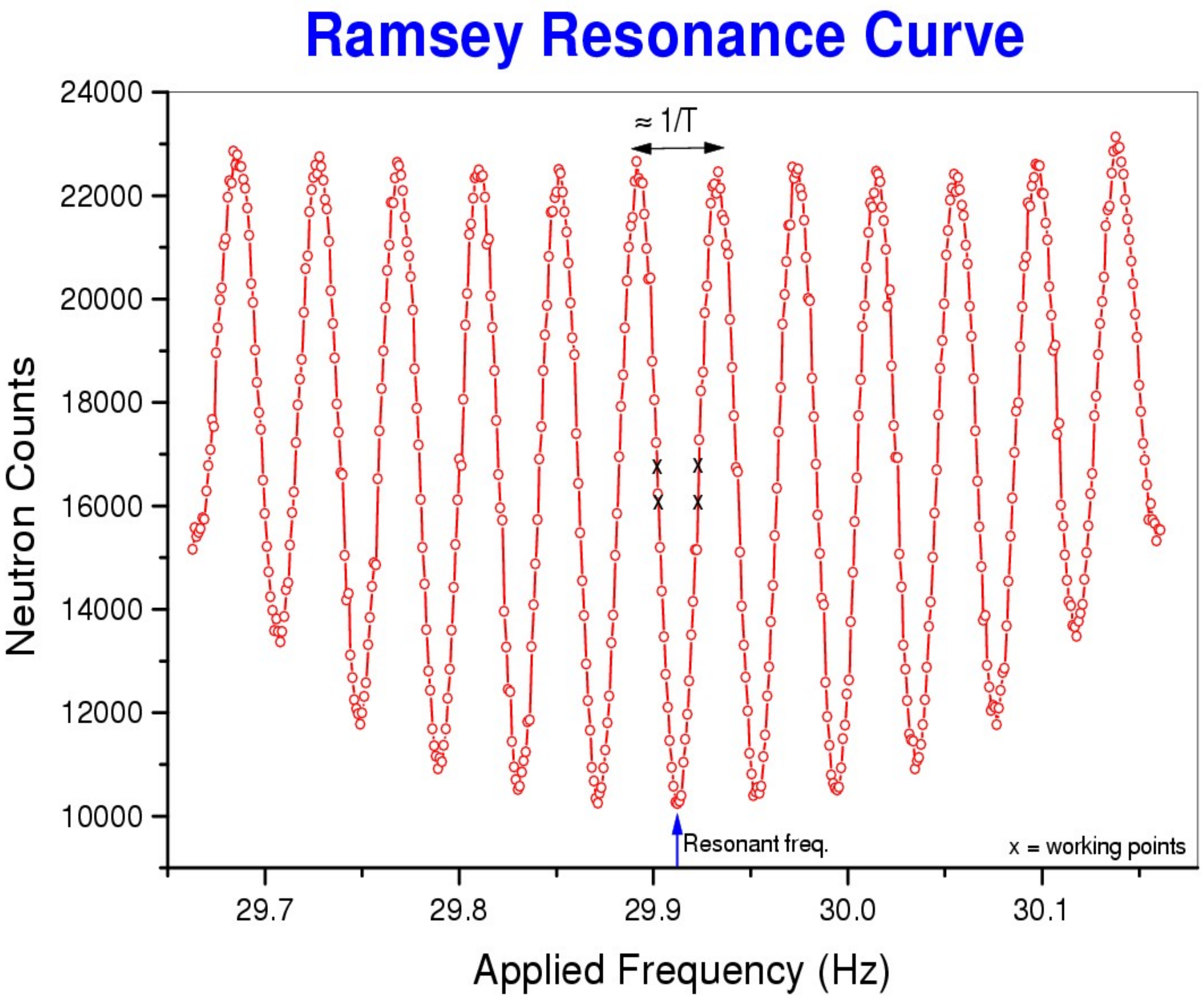
Smith, Purcell, Ramsey
PR108(1957)120

$d_n \leq 6.3 \cdot 10^{-26}$ e•cm
RAL-Sussex-ILL
PRL82(1999)904



Electro-weak standard model expectation: ~10^{-32} e•cm

How to measure the EDM ?



PRL82(1999)904

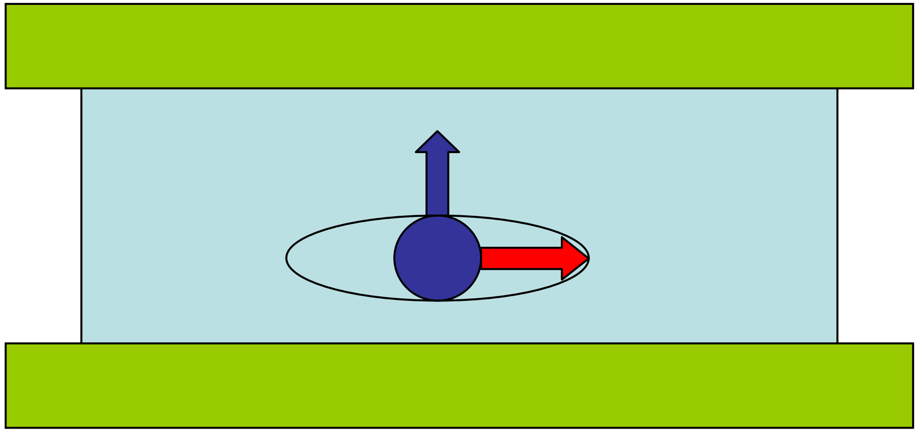
$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

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

al values for the
ex-RAL-ILL EDM:
75
30 s
0 kV/cm
8000 / cycle
2.5·10^{-24} e·cm / cycle
out 10^{-26} e·cm / year
ΔB < 800 fT

Major experimental questions

- How to get (many) UCN into the box ?
- How to make sure, B behaves well ?
- How to maximize E, α, T ?
- How to fight systematics (B, v x E, ….) ?



Different approaches …

Our approach

- Produce high UCN density separate from EDM
- EDM in vacuum and at room-temperature
- Double- or multi-chamber setup
- Cs laser optically pumped magnetometer (LsOPM) array
- Internal field stabilization
- Resonance frequency stabilization
- Digital frequency generation with possibility of phase shifts
- UCN velocity sensitive detection scheme
- Improve many details (coatings, polarization, DAQ, MC, …)
- Hands-on work with old Sussex-RAL experiment
- Setup improved experiment at PSI in 2008
- Aim first at 1•10^{-27} e•cm

The neutron EDM collaboration

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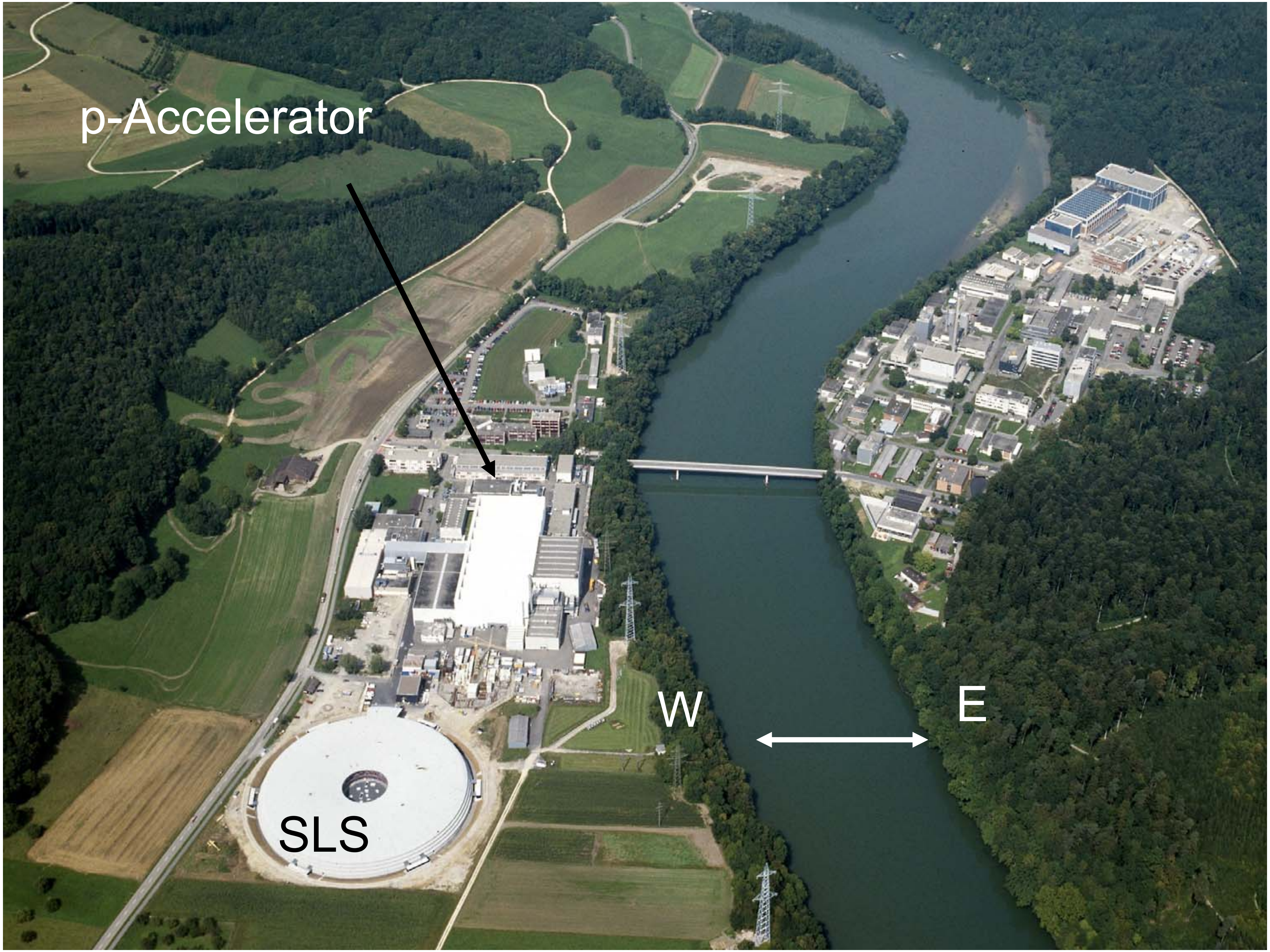
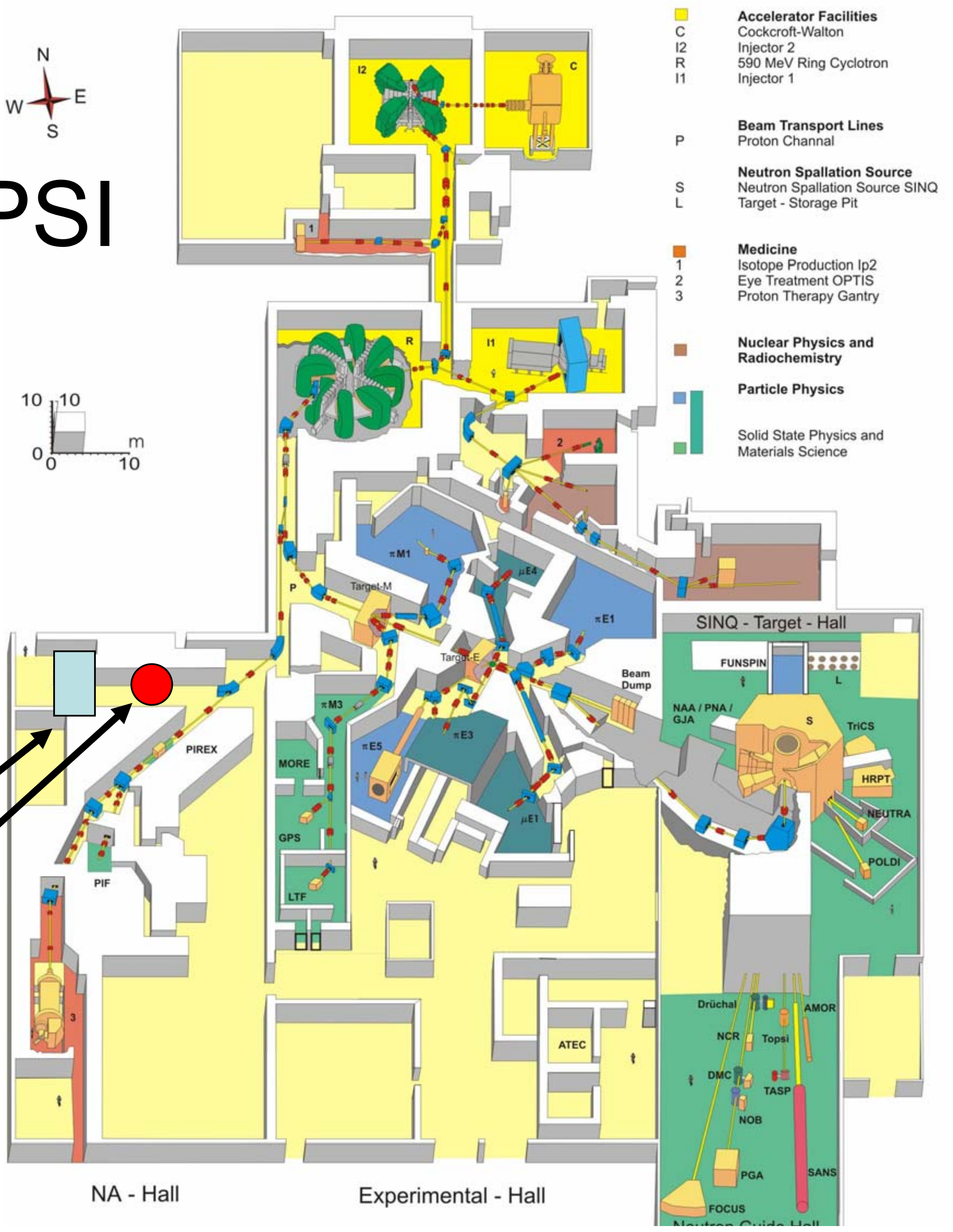
*Paul Scherrer Institute, **Villigen,** Switzerland*


p-Accelerator
W
E
SLS

UCN source at PSI

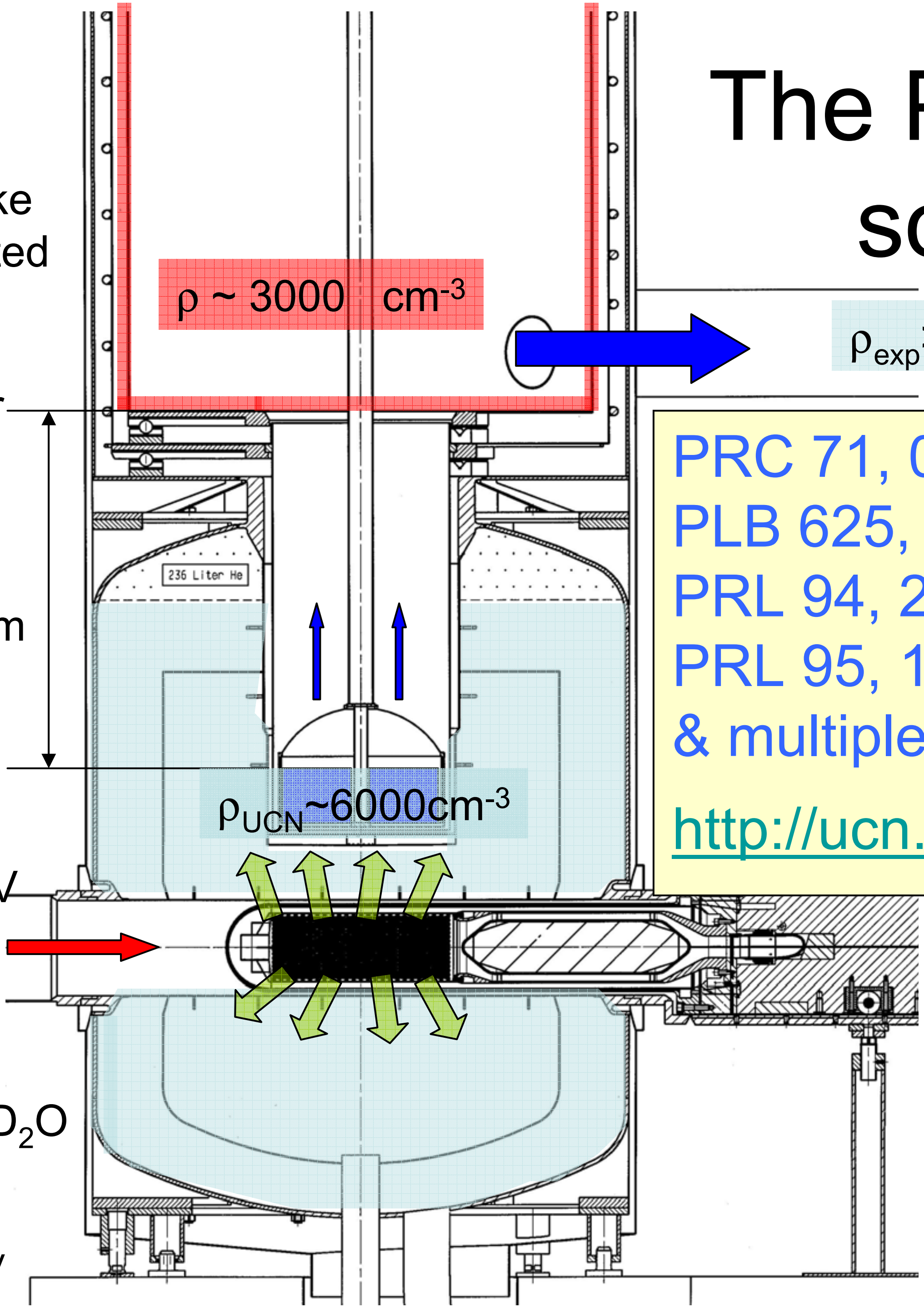
Deliver 600 MeV protons with 2mA, i.e. **1.2 MW** !, at 1% duty cycle to UCN target station

Ultra Cold Neutron Source



nEDM Source

The PSI UCN source



Diamond-Like
Carbon coated
~2 m^3 trap

UCN shutter

1.2m

$\rho \sim 3000\ cm^{-3}$

$\rho_{exp} > 1000\ cm^{-3}$

$\rho_{UCN} \sim 6000 cm^{-3}$

2 mA,600 MeV
proton beam
1% duty cycle

~3 m^3 D_2O

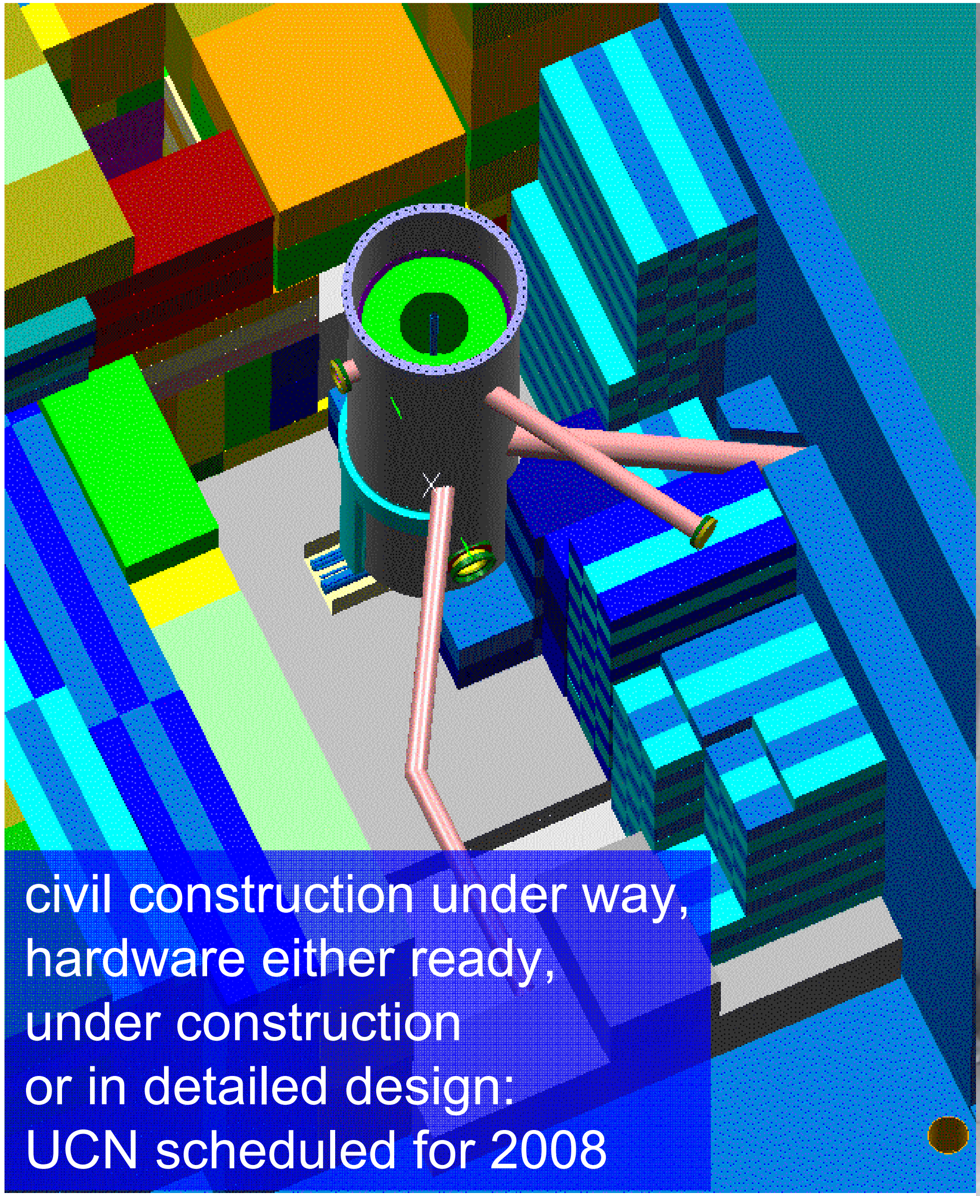
PRC 71, 054601 (2005)
PLB 625, 19 (2005)
PRL 94, 212502 (2005)
PRL 95, 182502 (2005)
& multiple NIM A

http://ucn.web.psi.ch

PSI - Cracow - ILL –
Vienna - Efremov

EDM FLAV

UCN source status: on track



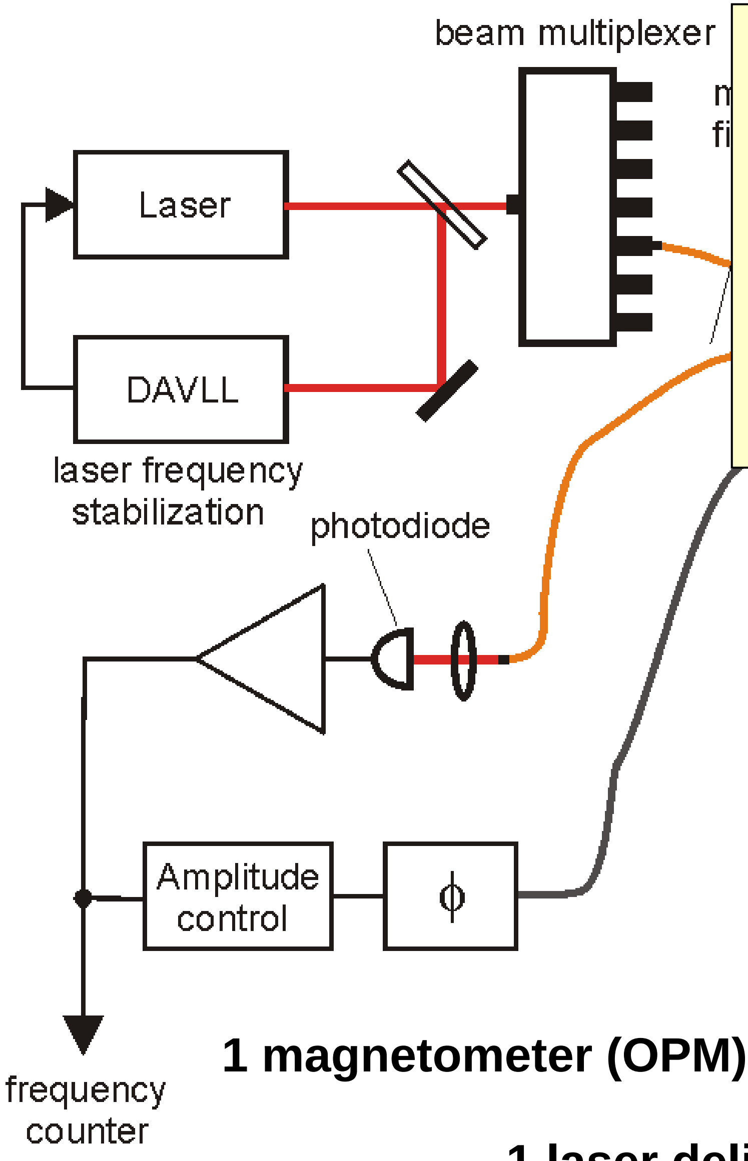
civil construction under way,
hardware either ready,
under construction
or in detailed design:
UCN scheduled for 2008

Oct 05

Magnetometry approach

- improve magnetic field measurement & control
- complement co-magnetometry approach
  (or even give up on it)
- use many highly sensitive sensors for scalar and gradient information
- use active feed-back stabilization of the magnetic field and gradients
- generate oscillatory field using (weighted) information of Cs magnetometers
- use double or multiple neutron chambers

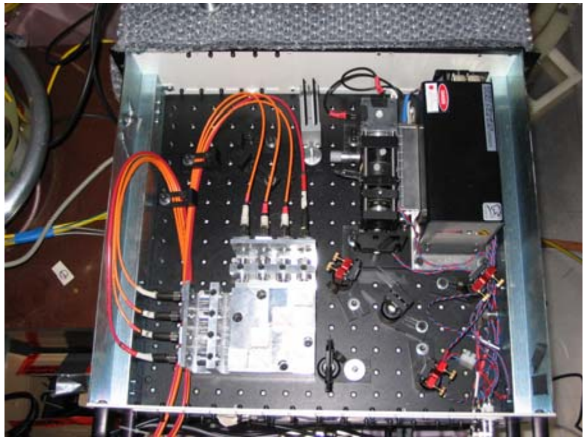
Self-oscillating laser-pumped Cs magnetometer



JRNIST 110, 179 (2005)
Appl.Phys. B80, 645 (2005)
JOSA B 22, 77 (2005)

http://www.unifr.ch/physics/frap/

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

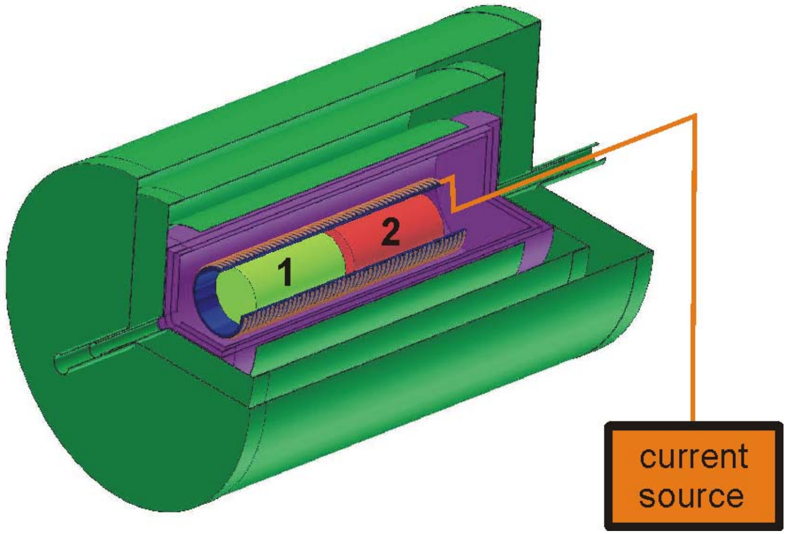


1 magnetometer (OPM) needs 25 µW

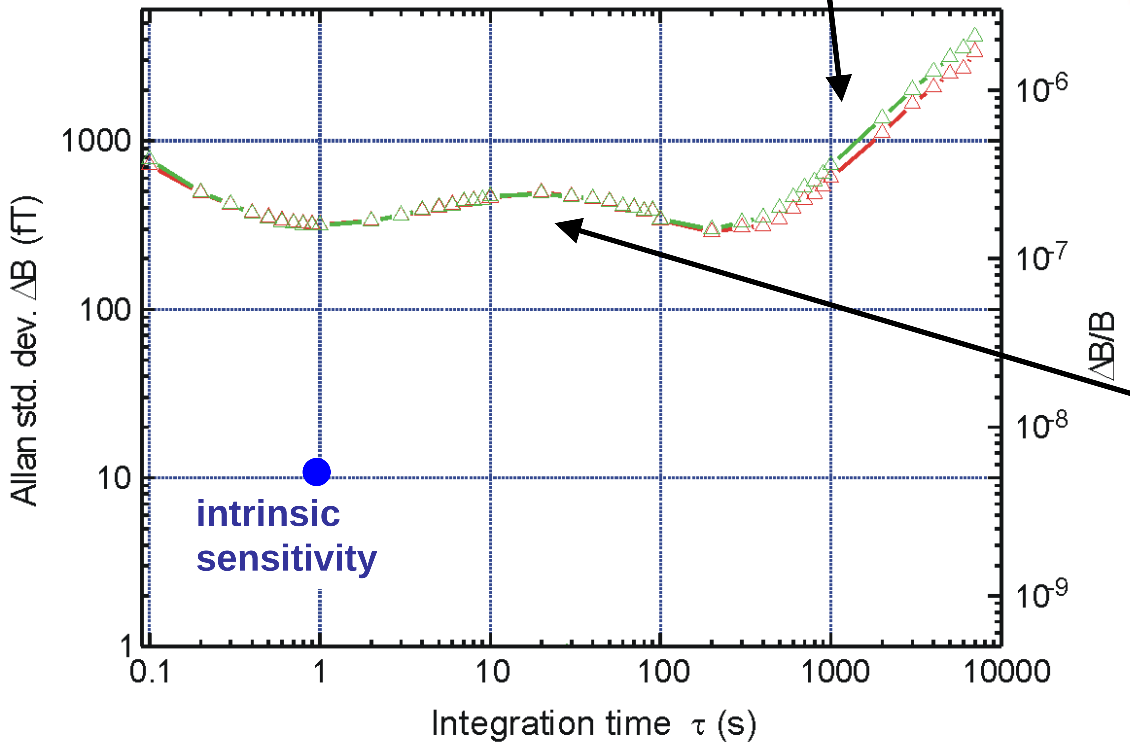
1 laser delivers >10 mW

1 laser = many sensors

Field fluctuations inside magnetic shield



long term drift

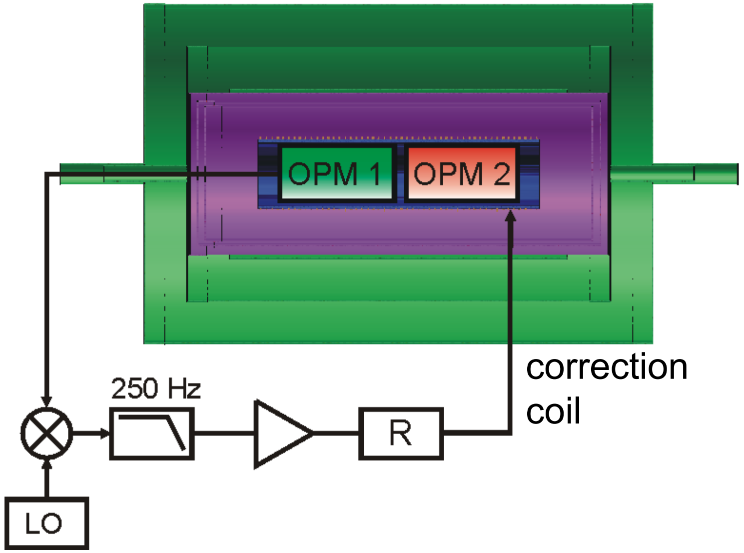


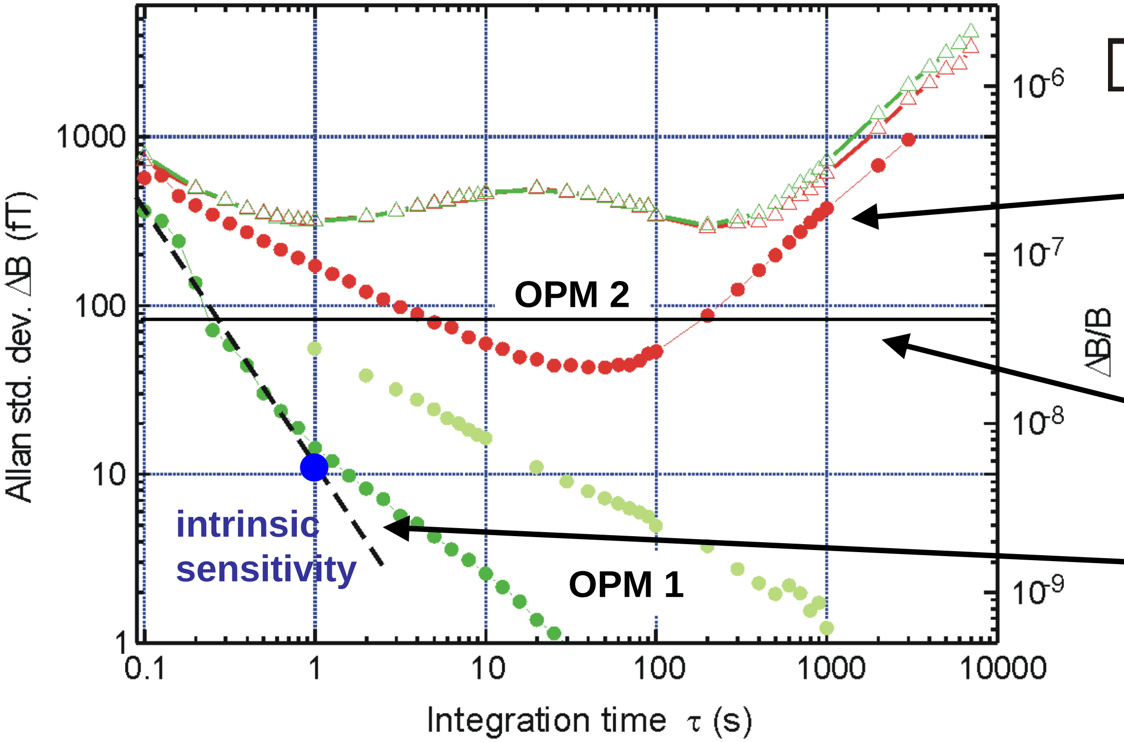
intrinsic sensitivity

limited by current source

Active field stabilization

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



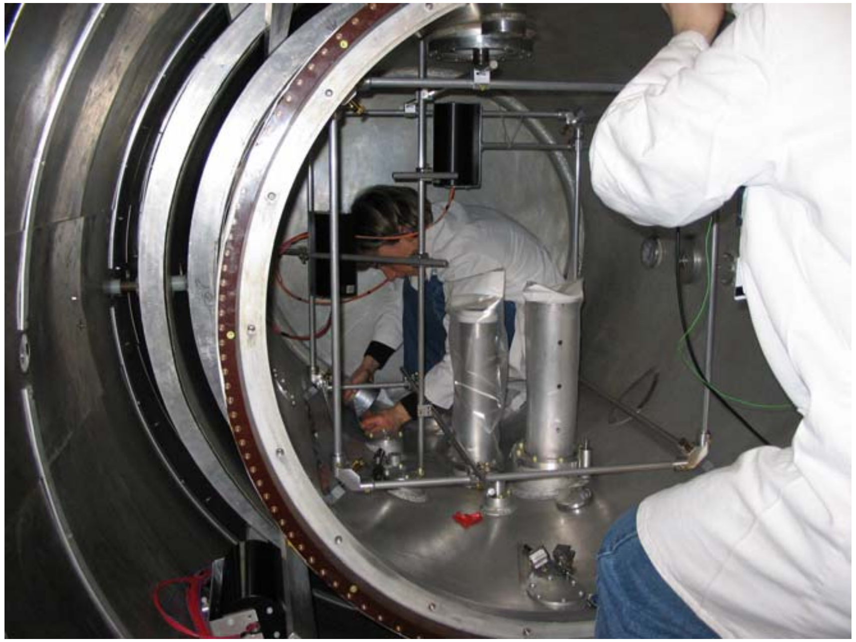


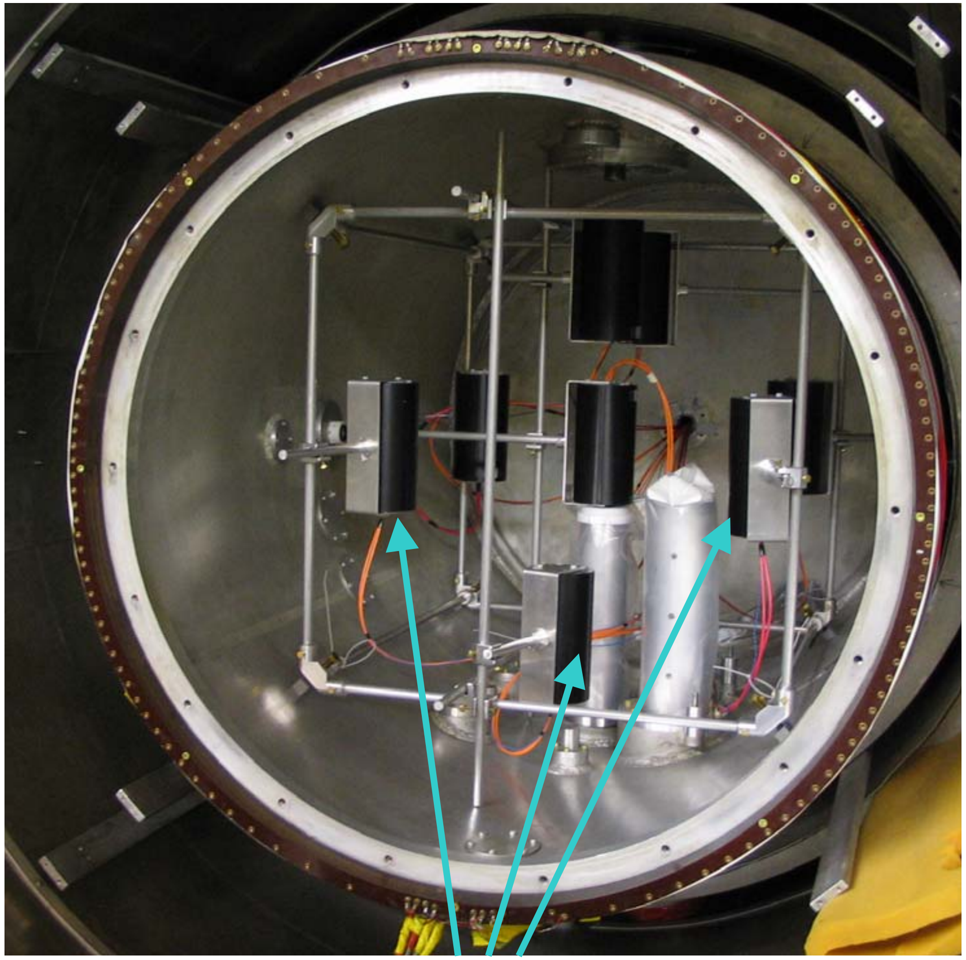
gradient fluctuations

field stability for ~10^{-27} e cm

Cramér-Rao limit: ~ $\tau^{-3/2}$

Magnetic field measurements in the Sussex/RAL/ILL EDM setup



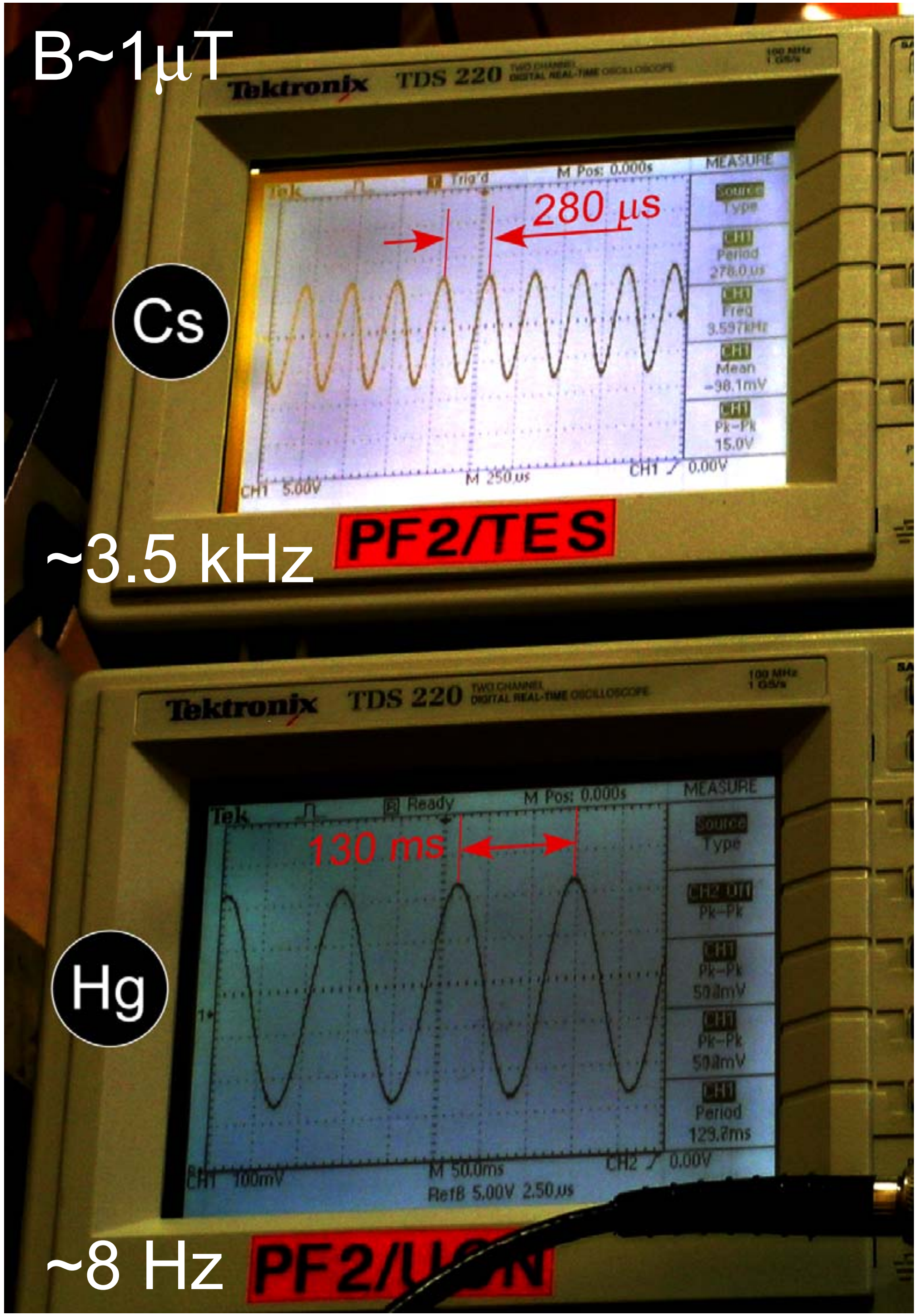


laser-pumped
Cs magnetometers

Simultaneously running Cs magnetometer and Hg co-magnetometer:

preliminary results:
~ 1 order of magnitude more stable Hg reading with active field stabilization using Cs magnetometer

field stability ASD ≤ 200 fT over 100s time scales measured with Cs magnetometers



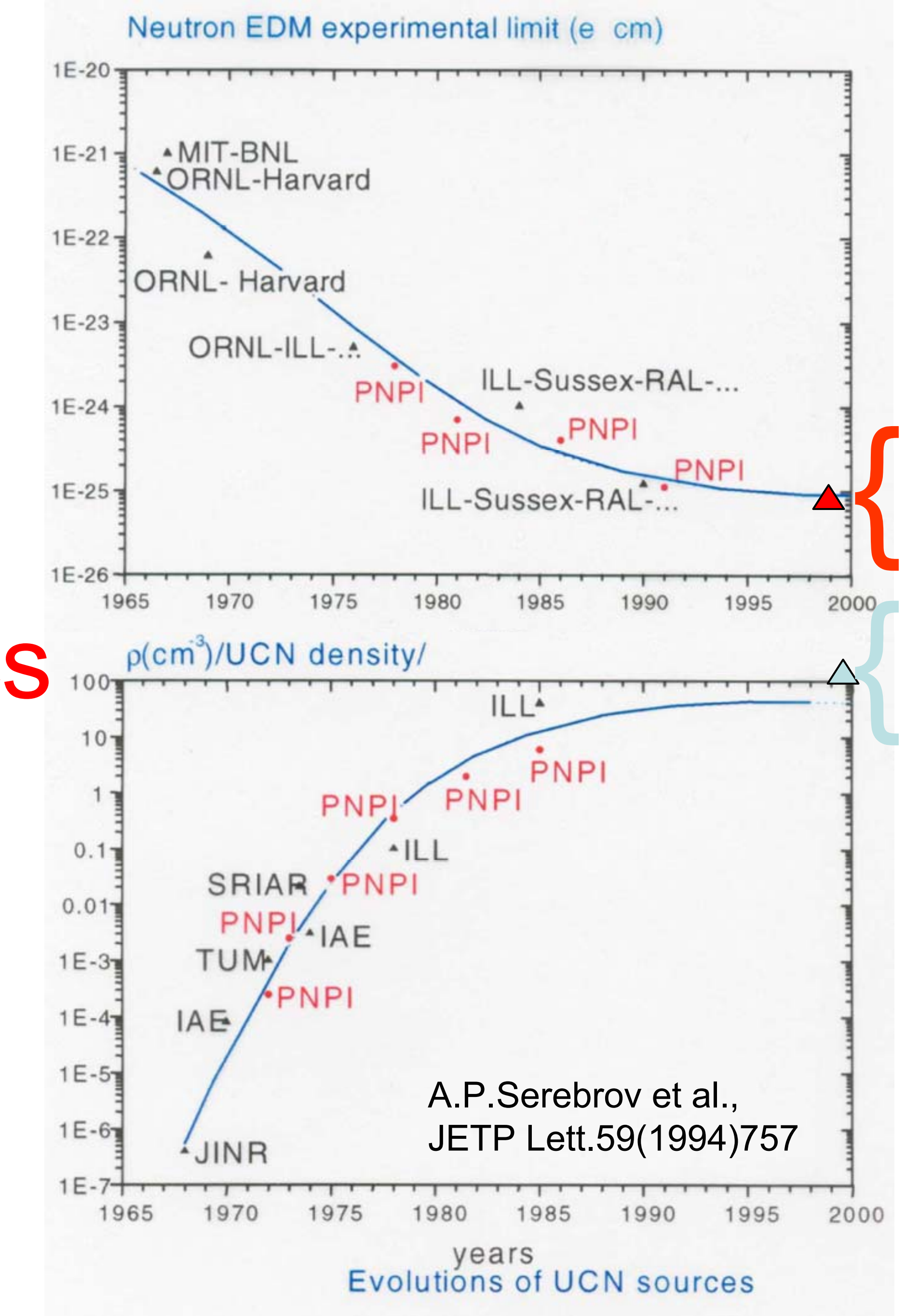
Other ongoing EDM research

- Development of superior UCN materials:
    - high critical velocity (or very low)
    - low UCN loss
    - low UCN depolarization
    - high specific resistivity
    - non-magnetic (or fully magnetized)
- High rate, high stability UCN detection
- State of the art DAQ
- Efficient UCN polarization and analysis
- Improved calculational tools
- Analysis of systematics

The EDM limitations to date:

A) Statistics

(UCN density,
storage time,
electric field strength,
polarization and
depolarization, ….)



A.P.Serebrov et al.,
JETP Lett.59(1994)757

Evolutions of UCN sources

$d_n \leq 6.3 \cdot 10^{-26}$ e•cm
RAL-Sussex-ILL
PRL82(1999)904

$\rho_{UCN} = 145 \pm 7$ cm^{-3}
A.Saunders et al.
PLB593(2004)55

UCN source
development
in CH, USA, F,
Germany, Japan

The EDM limitations to date: B) Systematics

- magnetic field homogeneity
- magnetic field gradients
- magnetic field drifts
- motional magnetic fields
- electric field uniformity
- electric field II magnetic field
- electric field reproducibility
- leakage currents
- depolarization
-
-
-
-

Joint Institute for Nuclear Research

FRAP
Fribourg
Atomic Physics

ill

LPSC
Grenoble

LPC
CAEN

PAUL SCHERRER INSTITUT
PSI

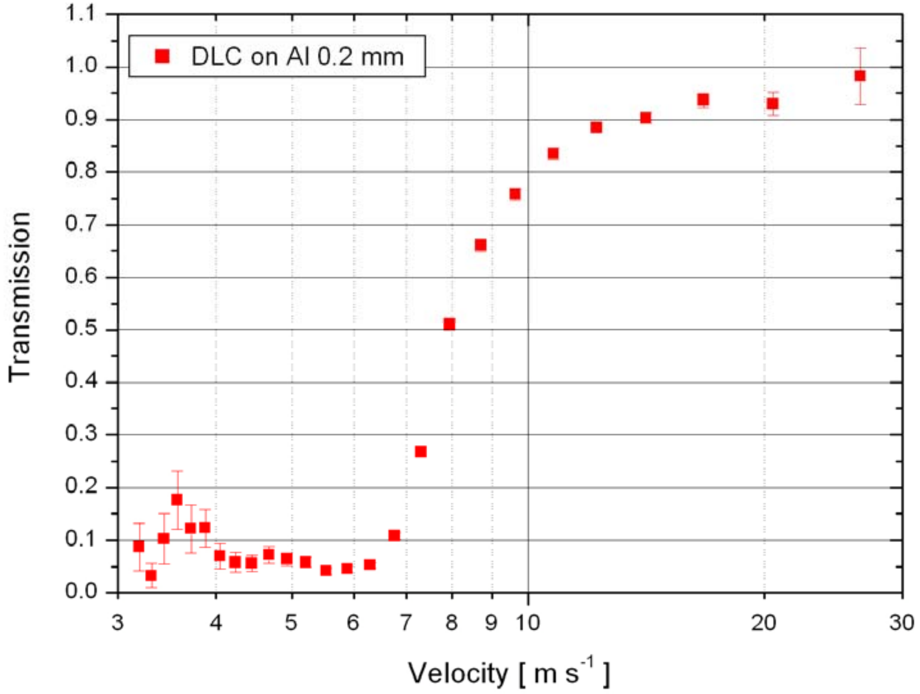
Thank you!

Competition

- At least 3 new EDM projects worldwide within the next 5 years (and maybe more (both 3 and 5))
  - all aim at sensitivities below 10^{-27} e•cm
  - all use at least two differential HV chambers
  - 2 will use superfluid Helium below 0.5K,
    1 will be operated in vacuum
  - 2 will rely on „external“ magnetometry,
    1 will have a co-magnetometer
  - 2 will measure the neutron precession frequency using the Ramsey method of separated oscillatory fields,
    1 will measure the difference frequency of neutrons and ^{3}He
  - 2 will detect the UCN in external detectors, 1 has the detection combined with the magnetometry
  - 2 detection schemes do not depend on UCN velocity,
    1 aims for velocity dependence
  - 1 will have zero E-field chambers,
    one doesn‘t, one didn‘t decide

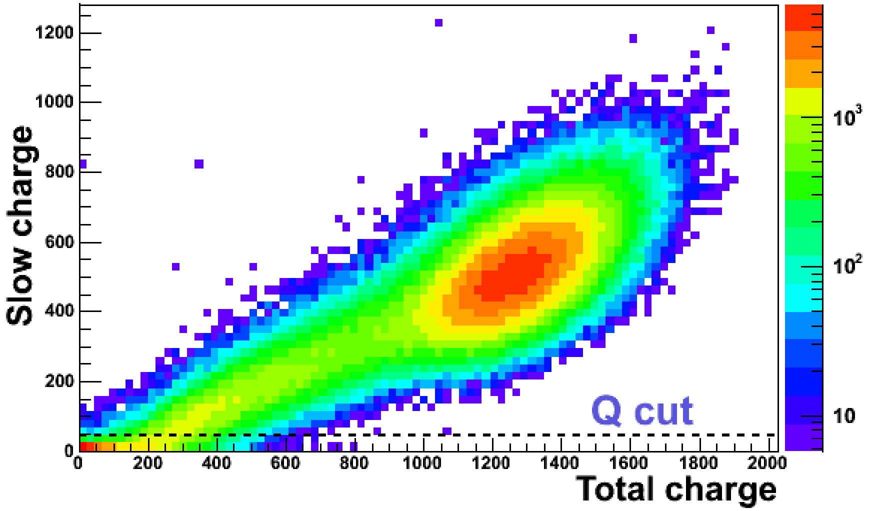
Diamond Like Carbon Coating

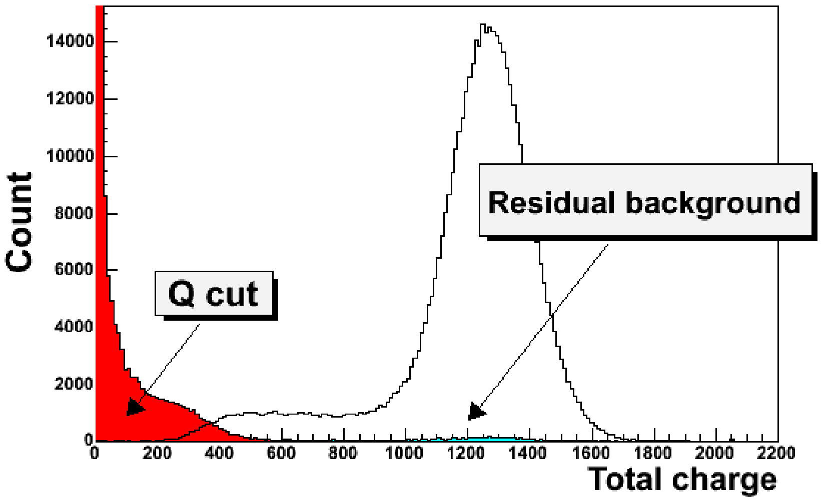
- Developed reliable DLC characterization
- Large area DLC coatings with high critical velocity, low loss and depolarization
- Prototype for UCN source storage tank with DLC coating under construction
- Pulsed Laser Deposition (PLD) of DLC presently being optimized
- PLD for UCN guide tubes under construction
- Research into high resistivity DLC coatings



Detector development

Various options, e.g.
thin GS10 Li glass scintillator,
4 m/s critical velocity,
25% resolution, fast, radiation hard,
easily shaped and segmented

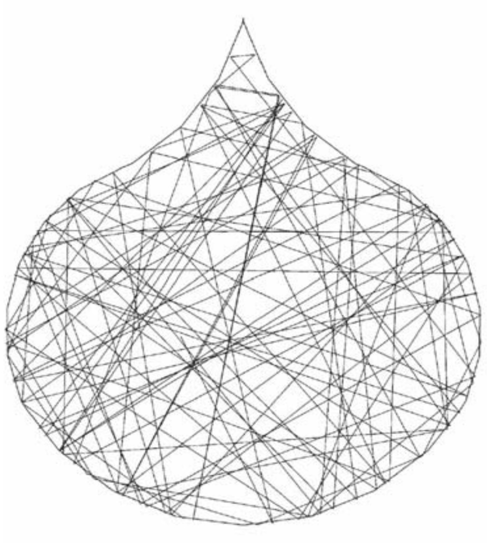


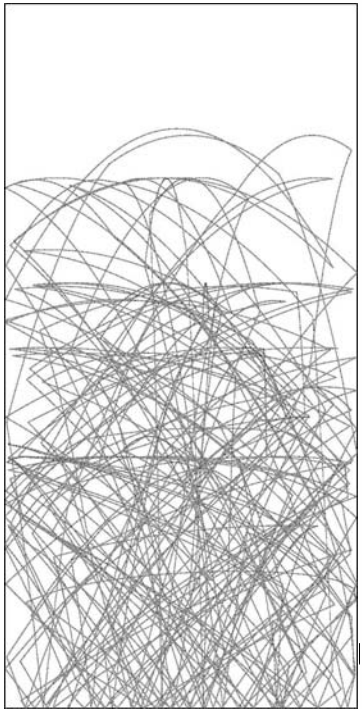


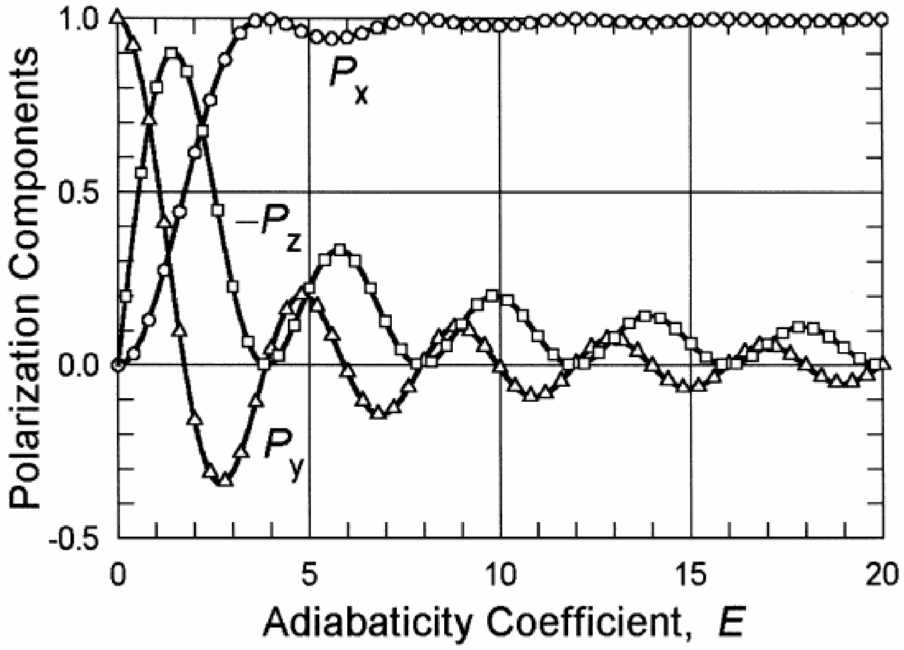
Adapted Geant4 for UCN

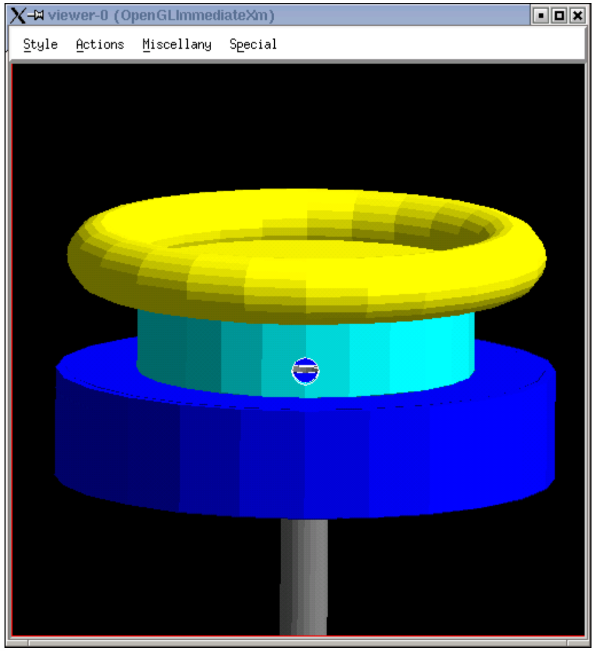
UCN specific features:

- 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









PHYSICAL REVIEW VOLUME 84, NUMBER 3 NOVEMBER 1, 1951

Phase Shifts in the Molecular Beam Method of Separated Oscillating Fields*

NORMAN F. RAMSEY AND HENRY B. SILSBEE
Harvard University, Cambridge, Massachusetts

(Received July 20, 1950)

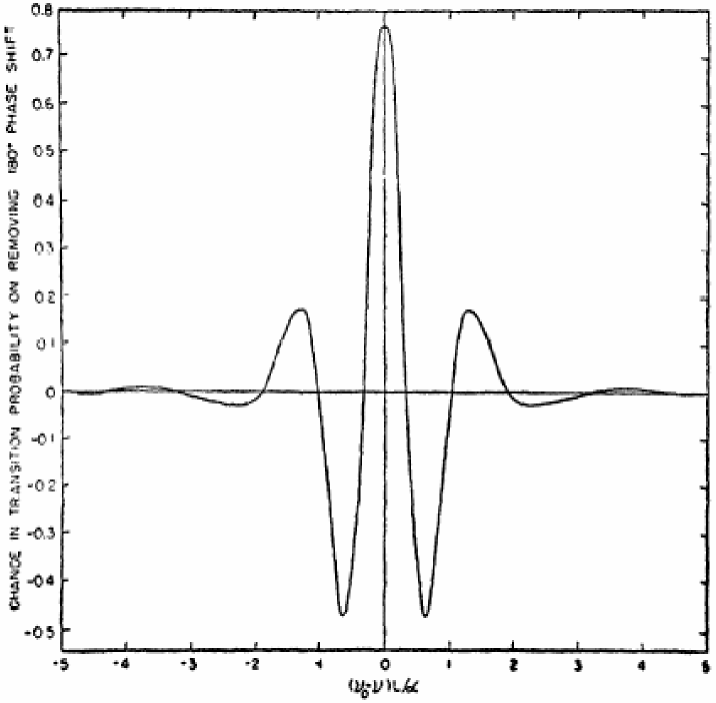


FIG. 1. Theoretical change in transition probability on removing 180° phase shift.

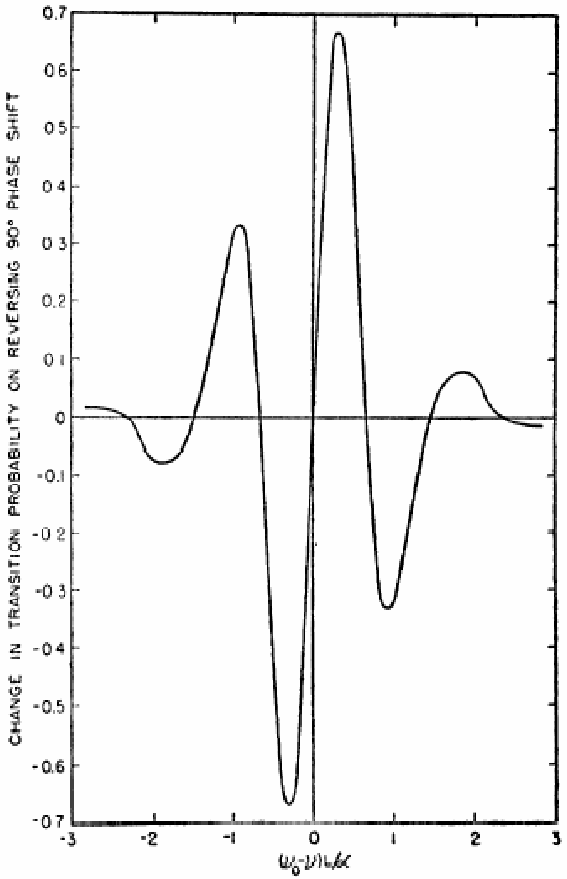


FIG. 3. Theoretical change in transition probability on reversing 90° phase shift.

VOLUME 82, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1999

New Experimental Limit on the Electric Dipole Moment of the Neutron

P. G. Harris,* C. A. Baker, K. Green, P. Iaydjiev,† and S. Ivanov‡
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D. J. R. May, J. M. Pendlebury, D. Shiers, K. F. Smith, and M. van der Grinten
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P. Geltenbort
Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France

(Received 17 September 1998)

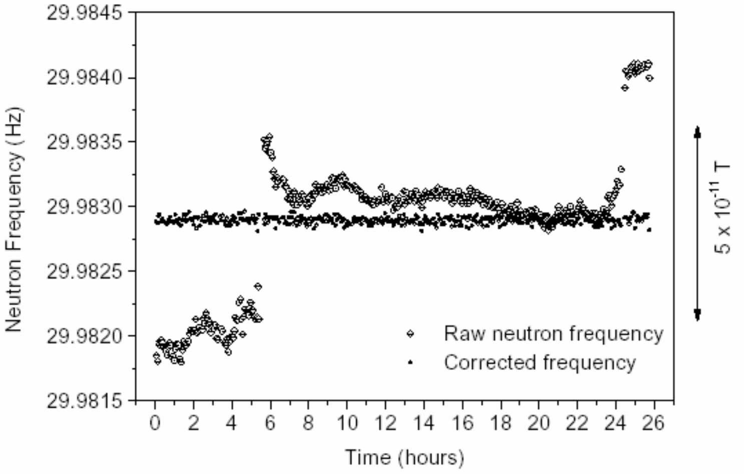


FIG. 3. Neutron resonant frequency measurements, showing both the raw and the mercury-corrected measurements.

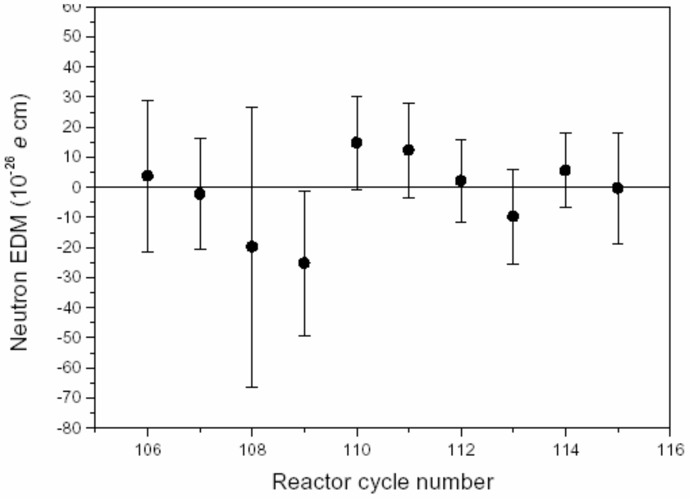


FIG. 4. Results of the neutron EDM measurements, grouped by reactor cycle.

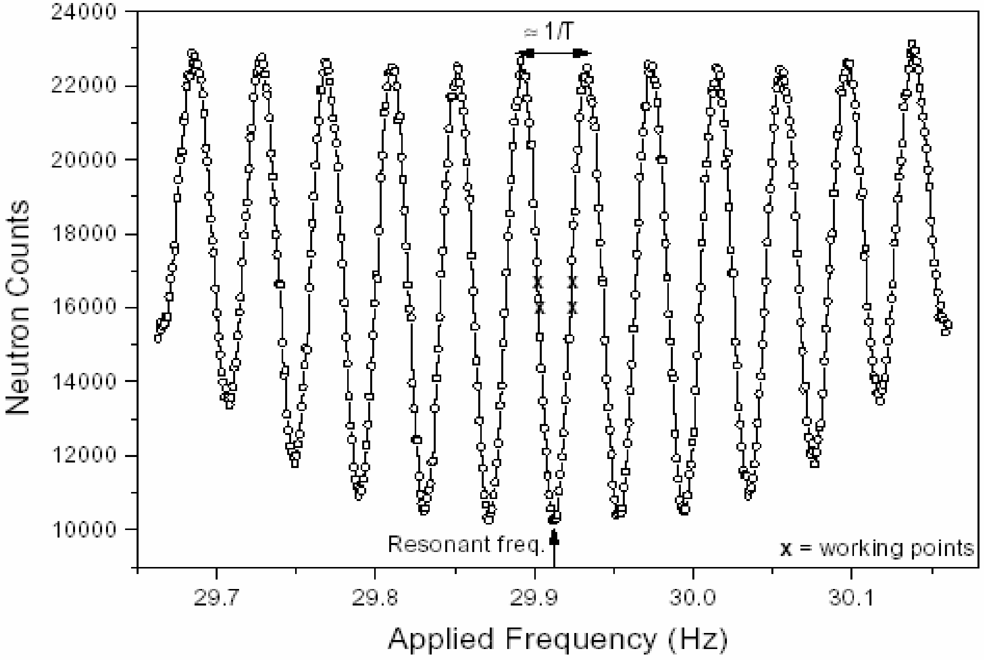


FIG. 2. The Ramsey resonance curve for spin-up neutrons, $N_\uparrow$. The corresponding pattern for $N_\downarrow$ is inverted but otherwise identical.

Ramsey resonances with phase shift

I. S. Altarev et al. / Electric dipole moment 279

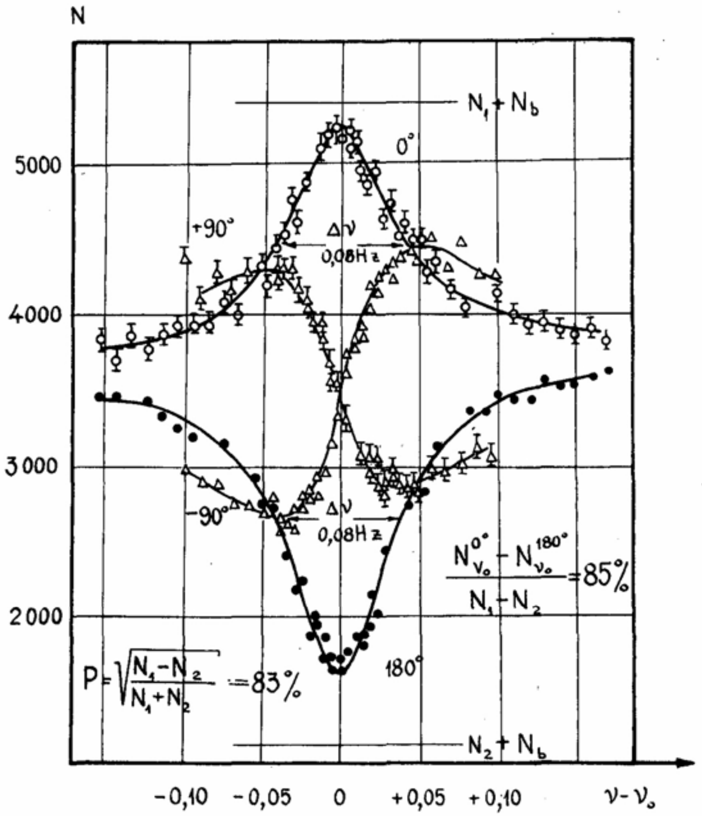


Fig. 5. Experimental resonance curves for different phase shifts between variable fields at the spectrometer input and output. N_1: neutron intensity with field H_1 turned off; N_2: neutron intensity with spin flip within the region between the polarizer and analyzer; N_b: thermal neutron background; P: degree of neutron polarization.

I.S. Altarev et al.,
NPA341(1980)269

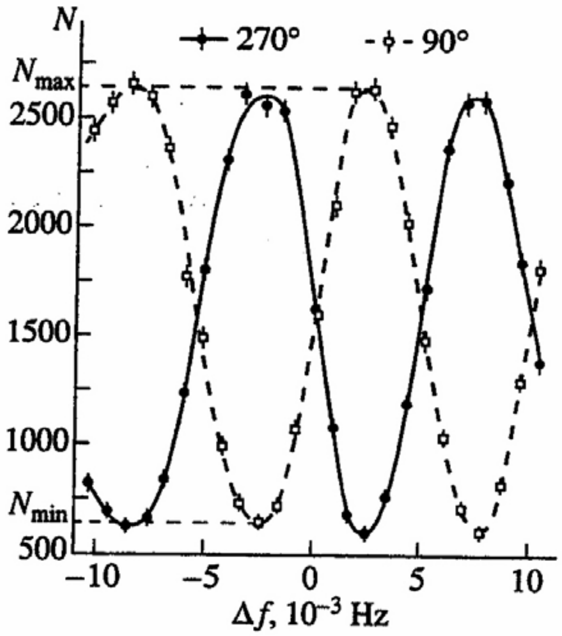
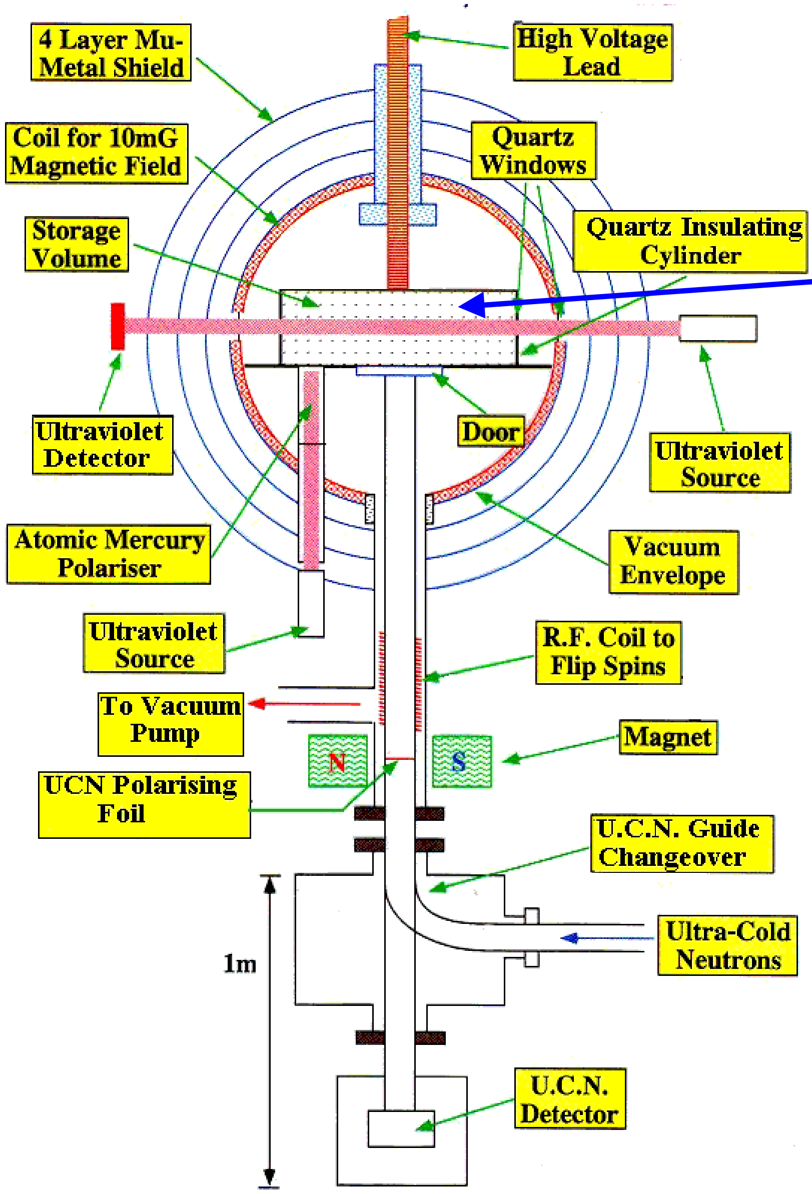


Fig. 5. Resonance curves obtained for the neutron-storage time $T_s = 100$ s.

I.S. Altarev et al.,
Phys.At.Nucl. 59(1996)1152

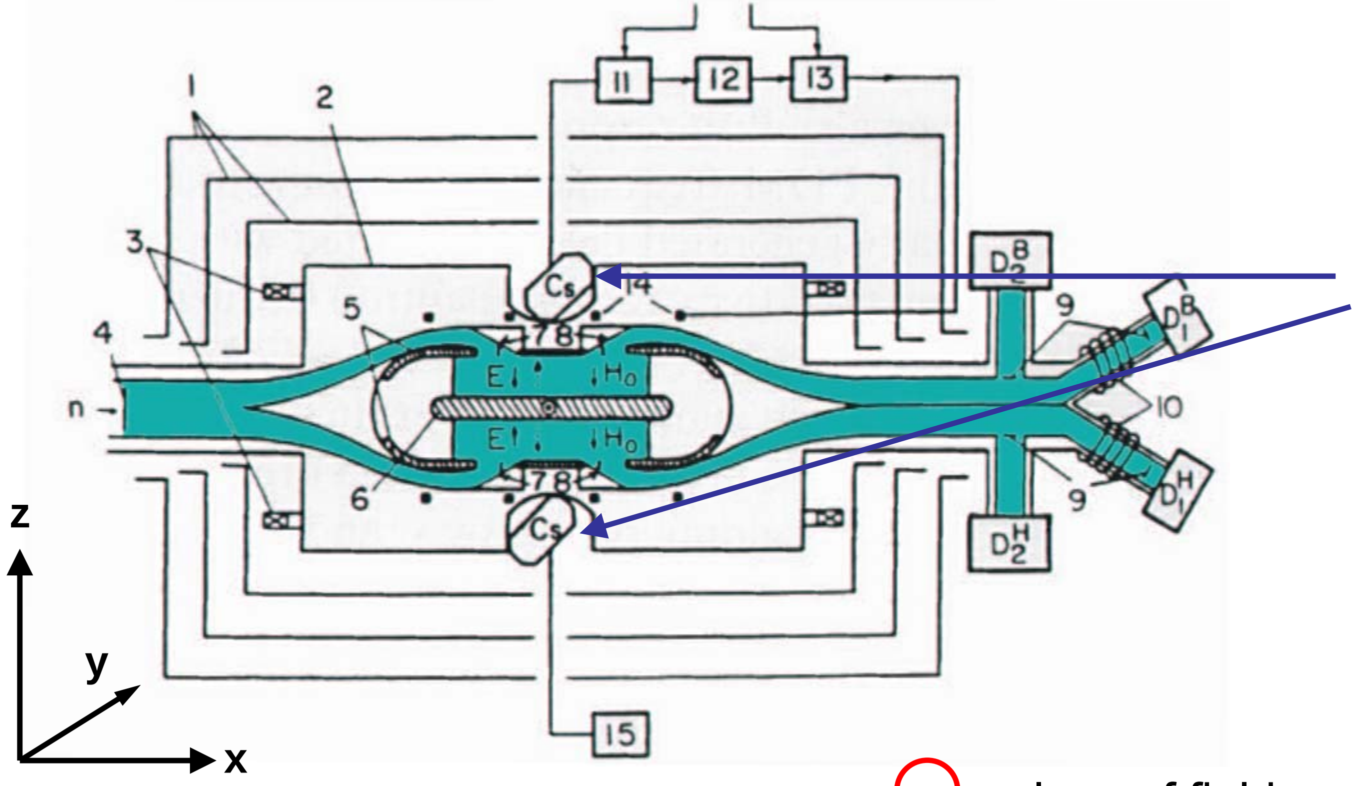
The Sussex-RAL-ILL EDM experiment



Hg co-magnetometer

- + neutron volume = Hg volume
- − low bandwidth (8 Hz)
- − integration over the whole volume
- − no information about gradients
- − no active field stabilization

The PNPI EDM experiment



Lamp-pumped
Cs magnetometers

⊕ high bandwidth ⟶ active field stabilization

⊕ information about linear gradient $\partial B / \partial z$

⊖ place of field measurement ≠ neutron volume

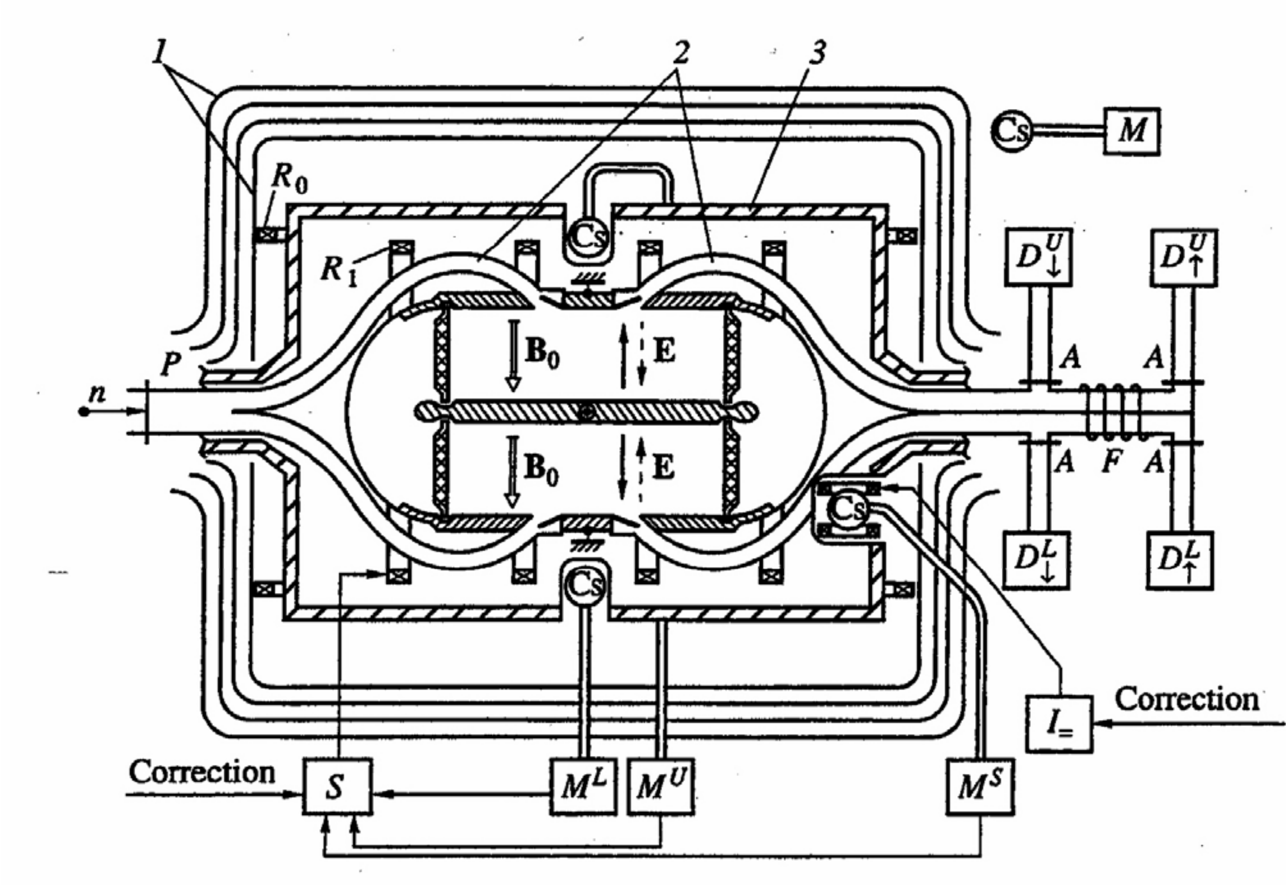
⊖ no information about component gradients $\partial B_i / \partial x_j \quad (i, j = 1,2,3)$

⊖ each sensor needs its own light source

The PNPI experiment

$d_n \leq 9.7 \cdot 10^{-26}$ e•cm
I.S. Altarev et al.,
Phys.At.Nucl. 59(1996)1152

ALTAREV *et al.*



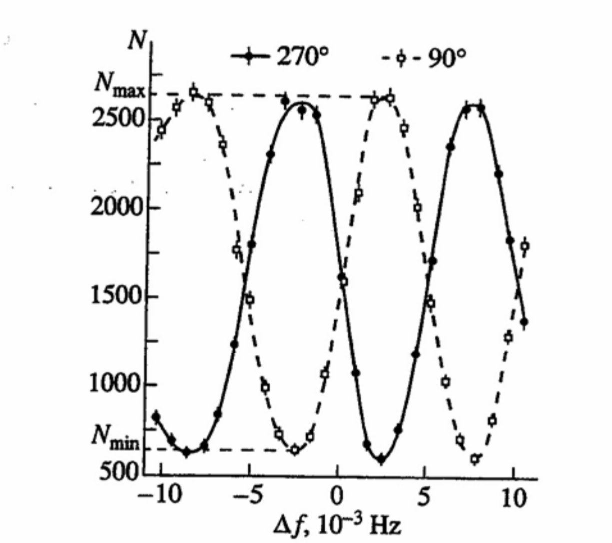


Fig. 5. Resonance curves obtained for the neutron-storage time $T_s = 100$ s.

Main advantages
- Double chamber
- Resonance stabilization

Some requirements for the B-field

$2 \cdot \mu_n \cdot \Delta B < 4 \cdot \delta d_n \cdot E$ for uncorrelated B-field noise per cycle

$\Delta B\ [\,\mathrm{fT}\,] < 3.3 \cdot 10^{26} \cdot E\ [\,\mathrm{kV / cm}] \cdot \delta d_n\ [\,e \cdot \mathrm{cm}]$

typical values
$E = 10$ kV / cm, $\delta dn = 2.5 \cdot 10^{-24}$ e•cm yield $\Delta B < 800$ fT

Obviously for an order of magnitude improvement
in sensitivity per cycle we need $\Delta B < 80$ fT.

However, things are more subtle …

- stable magnetic field:
  $\Delta B<80$ fT noise per cycle, see above
- E-field correlated changes are extremely dangerous
- homogenous field:
  $dB/dz<200$ fT/m, see PRA 70 (2004) 032102
- restrictions on
  - leakage currents,
  - field parallelity E,B
  - ΔE upon field reversal
- field control for other, also yet unknown effects
- realize v_{UCN} dependence of many systematics