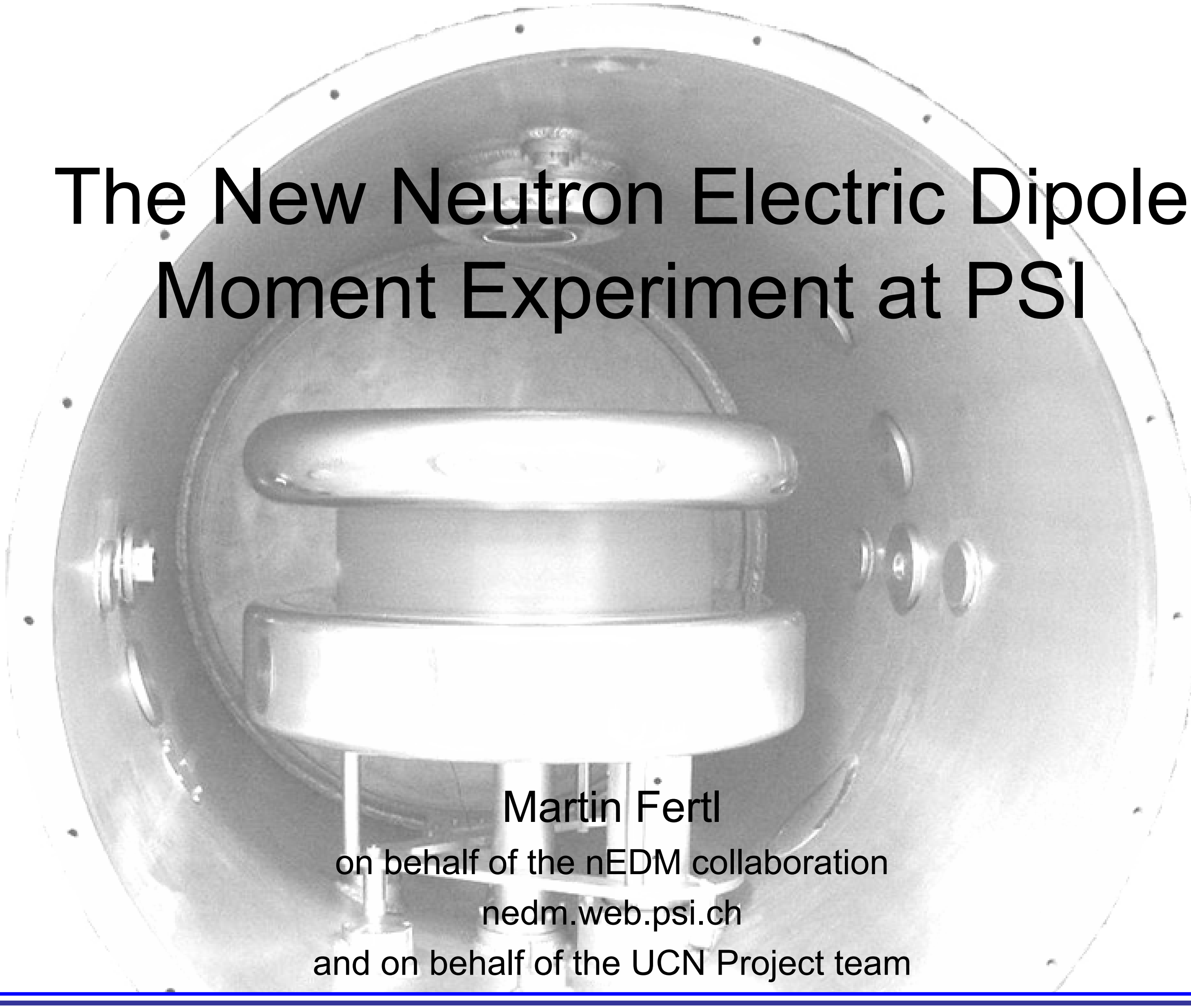


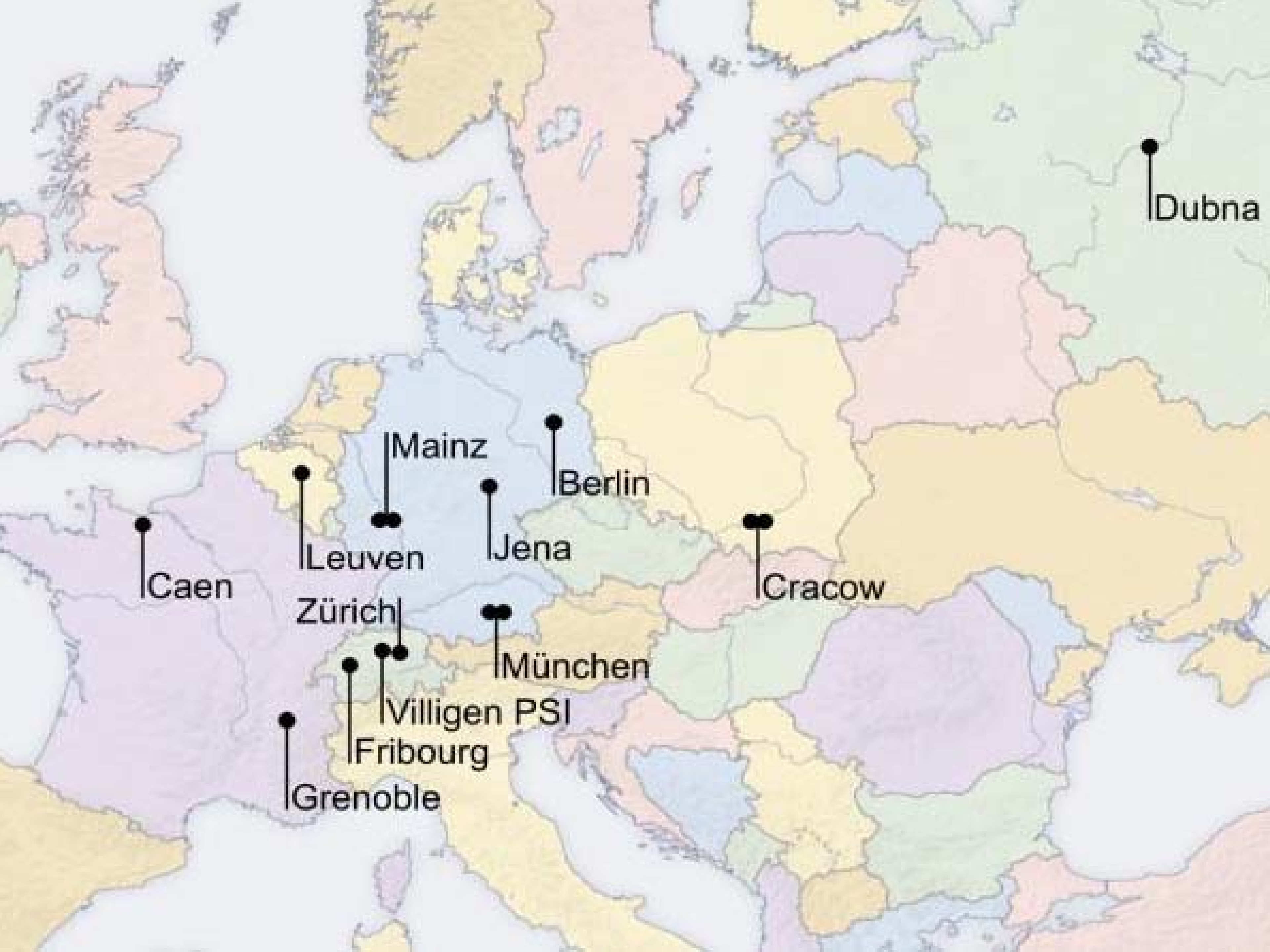
The New Neutron Electric Dipole Moment Experiment at PSI

Martin Fertl

on behalf of the nEDM collaboration

nedm.web.psi.ch

and on behalf of the UCN Project team


Dubna
Mainz
Berlin
Leuven
Jena
Caen
Cracow
Zürich
München
Villigen PSI
Fribourg
Grenoble

The neutron EDM collaboration

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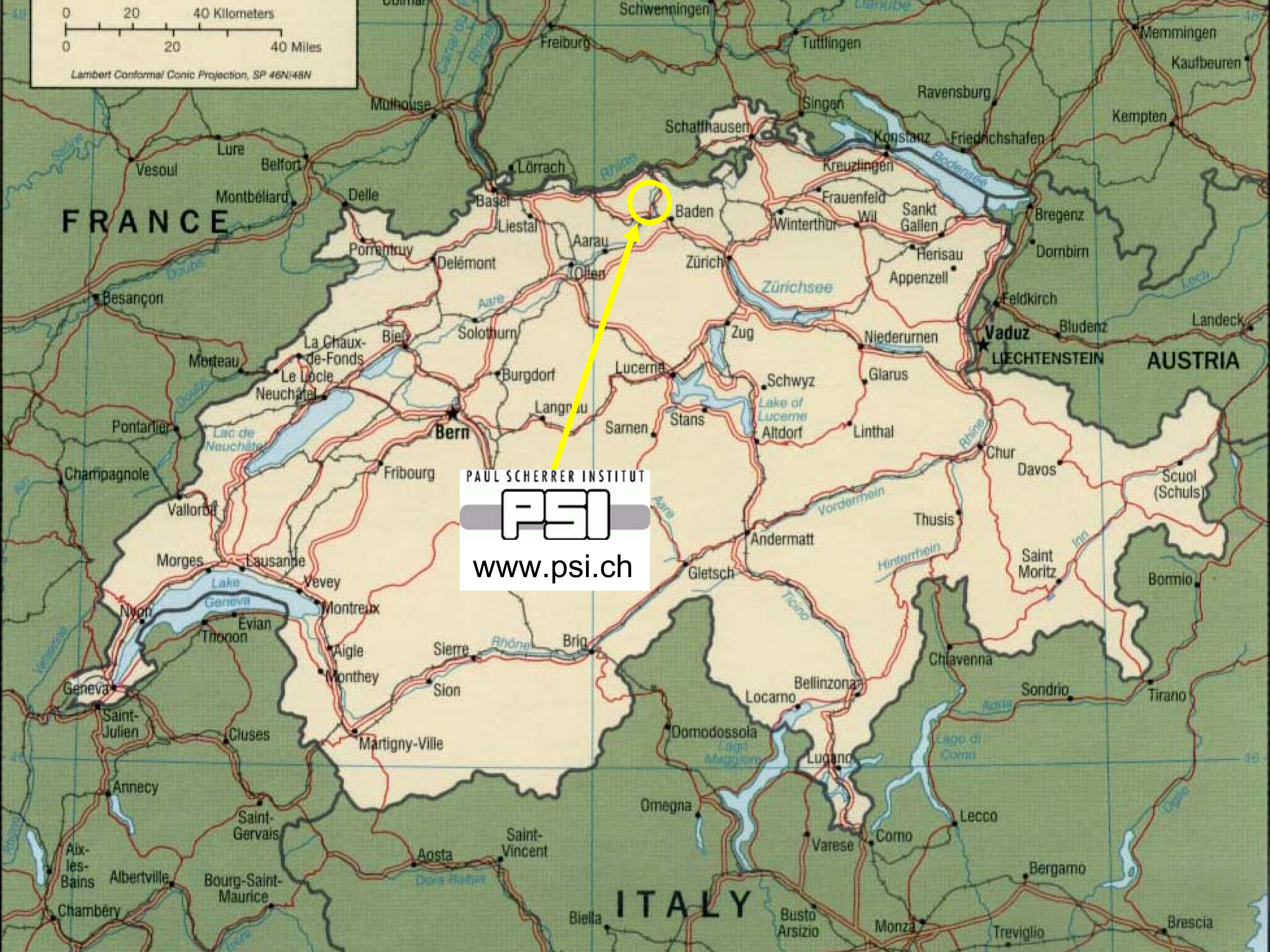
K. Kirch[1], F. Piegsa	*Eidgenössische Technische Hochschule, **Zürich***

also at: [1]*Paul Scherrer Institut*, [2]*PNPI Gatchina*   PhD students


0 20 40 Kilometers
0 20 40 Miles
Lambert Conformal Conic Projection, SP 46N/48N
FRANCE
AUSTRIA
ITALY
LIECHTENSTEIN
Vaduz
Schwenningen
Freiburg
Tuttlingen
Memmingen
Kaufbeuren
Ravensburg
Kempten
Singen
Mulhouse
Schaffhausen
Konstanz
Friedrichshafen
Bodensee
Kreuzlingen
Lure
Vesoul
Belfort
Lörrach
Rhine
Montbéliard
Delle
Basel
Liestal
Baden
Frauenfeld
Sankt Gallen
Bregenz
Winterthur
Wil
Aarau
Porrentruy
Delémont
Zürich
Herisau
Dornbirn
Olten
Appenzell
Zürichsee
Besançon
Aare
Feldkirch
Doubs
Solothurn
Zug
Niederurnen
Bludenz
Landeck
La Chaux-de-Fonds
Biel
Morteau
Le Locle
Burgdorf
Lucerne
Schwyz
Glarus
Neuchâtel
Langnau
Lake of Lucerne
Pontarlier
Lac de Neuchâtel
Bern
Sarnen
Stans
Altdorf
Linthal
Chur
Davos
Champagnole
Fribourg
Scuol (Schuls)
Vallorbe
Thusis
Vorderrhein
Andermatt
Hinterrhein
Morges
Lausanne
Saint Moritz
Inn
Vevey
Gletsch
Bormio
Lake Geneva
Montreux
Nyon
Evian
Thonon
Aigle
Sierre
Rhône
Brig
Ticino
Chiavenna
Monthey
Sion
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Locarno
Sondrio
Tirano
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Martigny-Ville
Domodossola
Lago Maggiore
Lugano
Lago di Como
Annecy
Omegna
Lecco
Saint-Gervais
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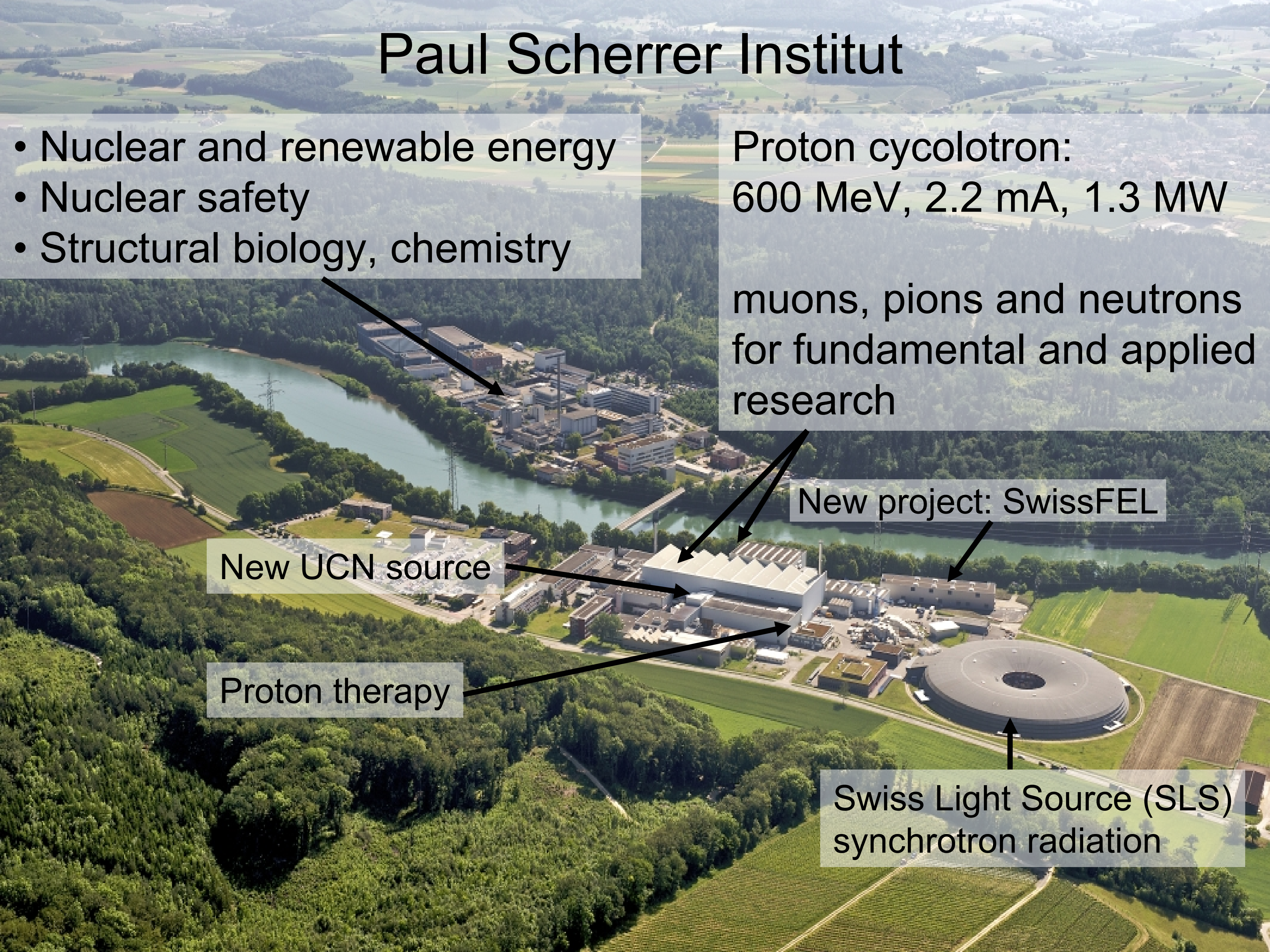


What caused the Baryon asymmetry ?

Observed (Cobe + WMAP, 2003) :

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = \left(6.1 \pm^{0.3}_{0.2}\right) \cdot 10^{-10}$$

SM expectation :

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

Andrei Sakharov 1967:
B-violation
C & CP-violation
thermal non-equilibrium
[JETP Lett. 5 (1967) 24]

EDMs and symmetries

Thus a nonzero electric dipole moment violates
P, T symmetry and, assuming CPT conservation, also CP.

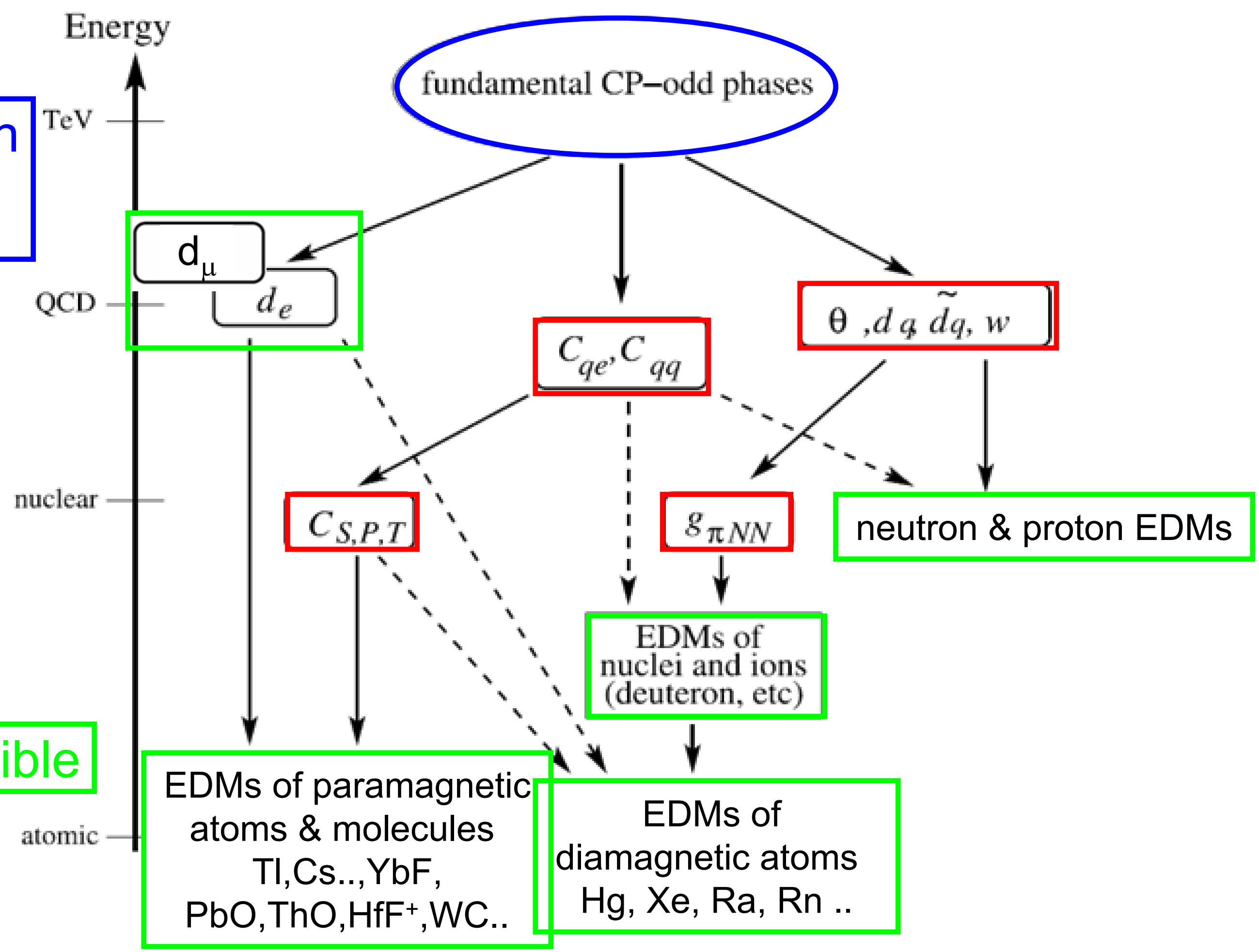
Purcell and Ramsey, Phys. Rev. 78, 807 (1950)
Landau, Nucl. Phys. 3, 127 (1958)
Ramsey, Phys. Rev. 109, 225 (1958)

Origin of EDMs

need CP-odd phases in fundamental theory

these values should be deduced

experimentally accessible



Adapted from:
A. Ritz, NIMA 611 (2009) 117-123

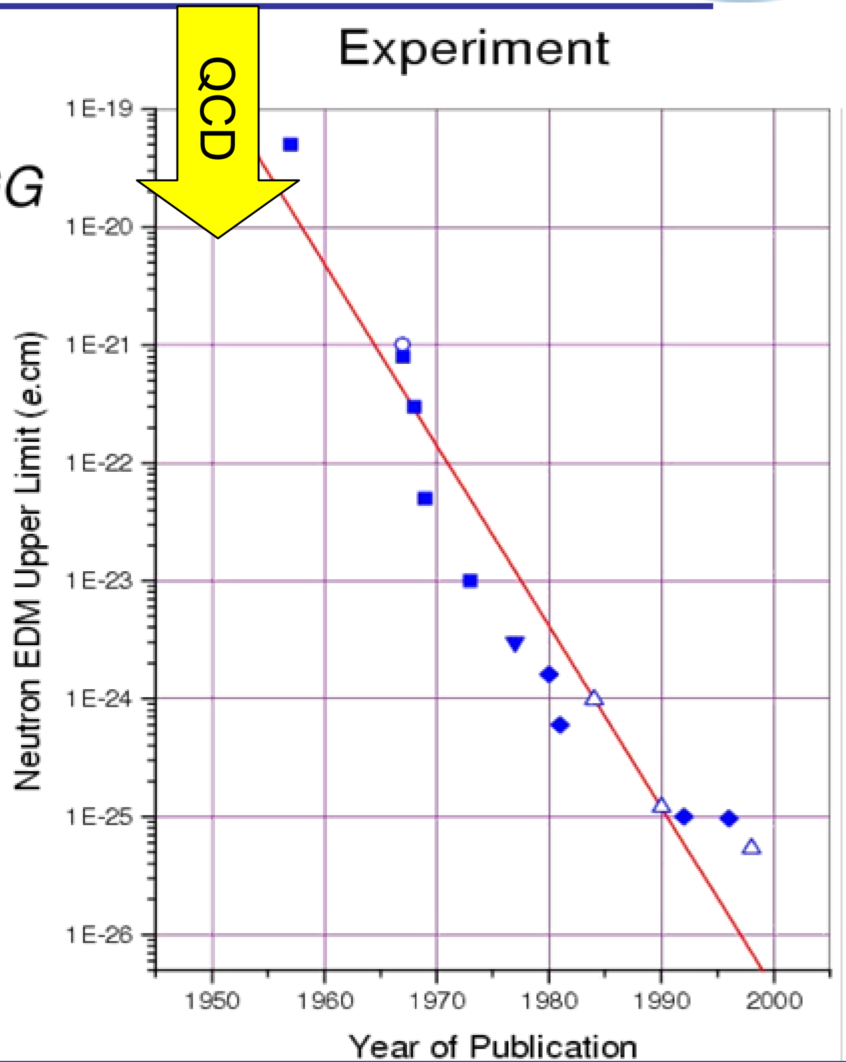
The strong CP problem

$$L_{QCD} \approx L_{QCD}^{(\theta_{QCD}=0)} + g^2/(32\pi^2)\theta_{QCD} GG$$

$$d_n \approx 10^{-16} ecm \cdot \theta_{QCD}$$

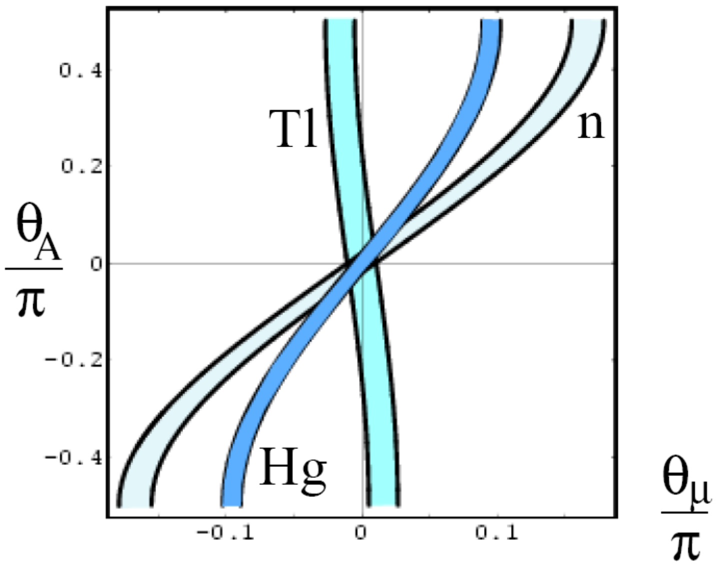
$$\theta_{QCD} \leq 10^{-10}$$

Why is θ_{QCD} so small?



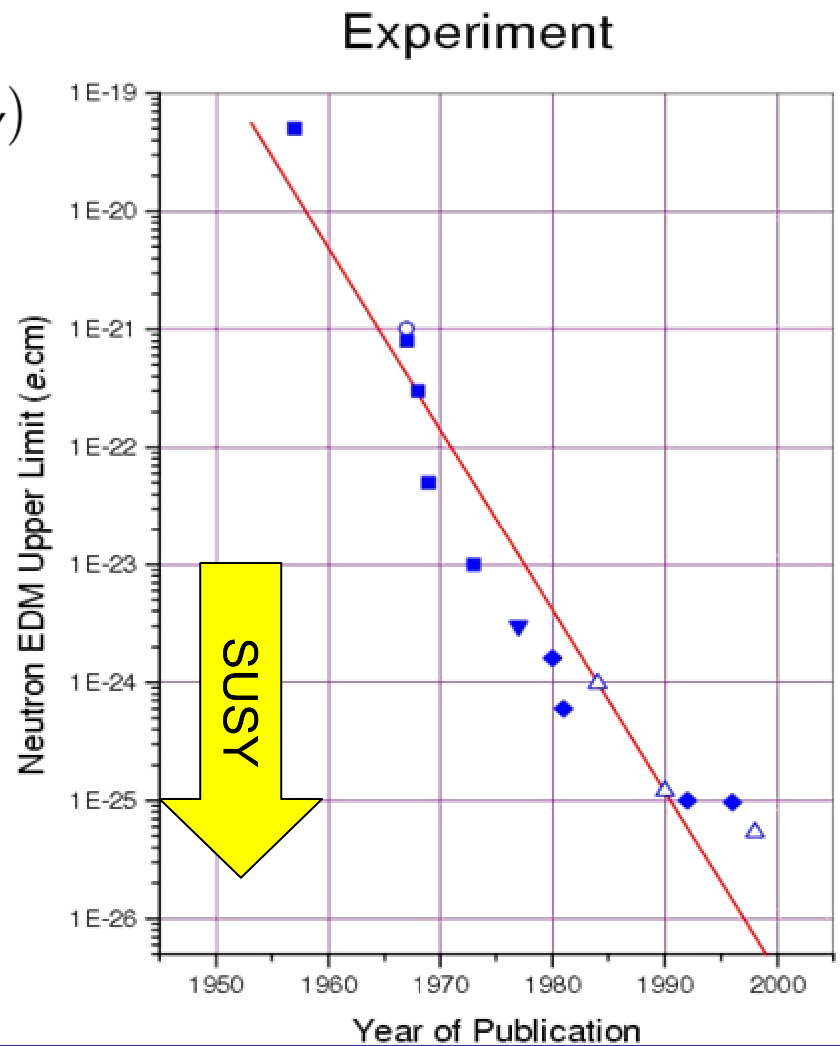
The SUSY CP problem

$$d_n \approx 10^{-23} ecm \left(\frac{300\text{GeV}/c^2}{M_{SUSY}} \right)^2 sin\left(\phi_{SUSY}\right)$$

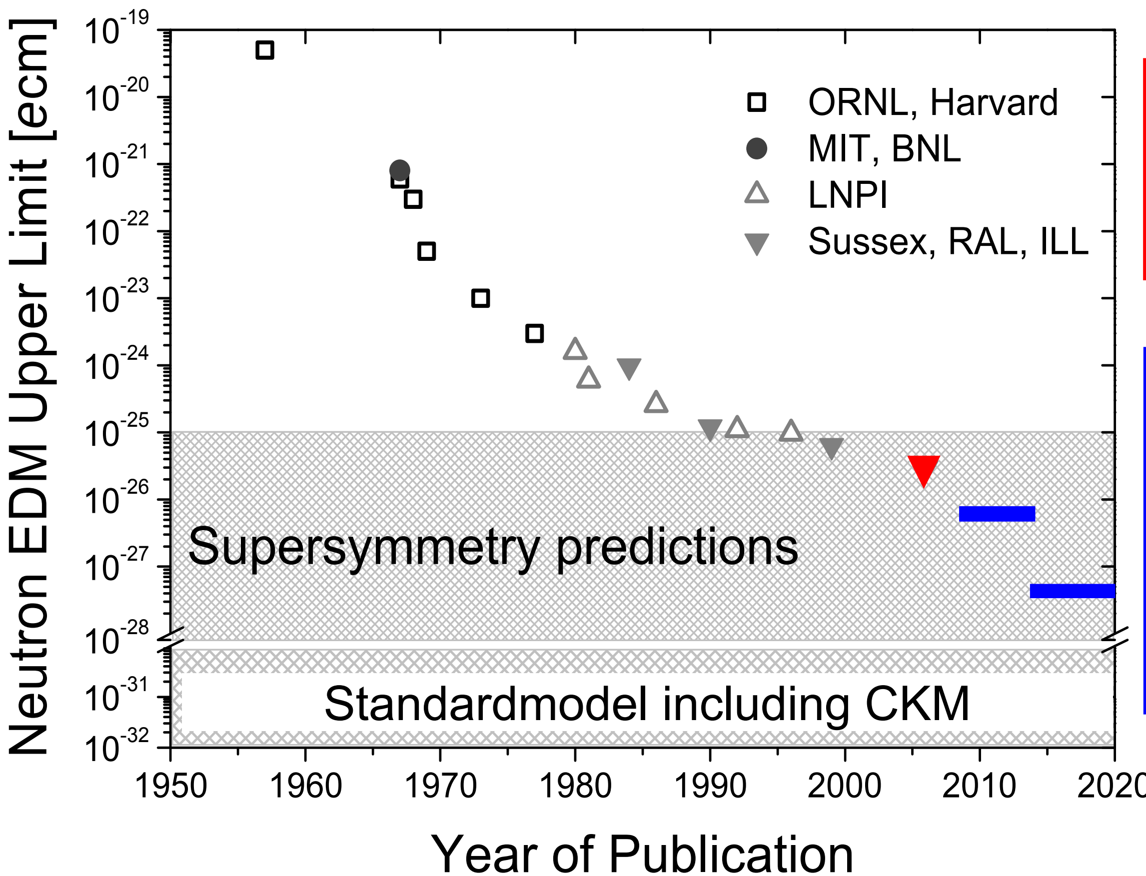


Pospelov, Ritz, Ann. Phys. 318(2005)119 for M_{SUSY} = 500GeV, tan b = 3

Why is Φ_{SUSY} so small?



History of nEDM searches



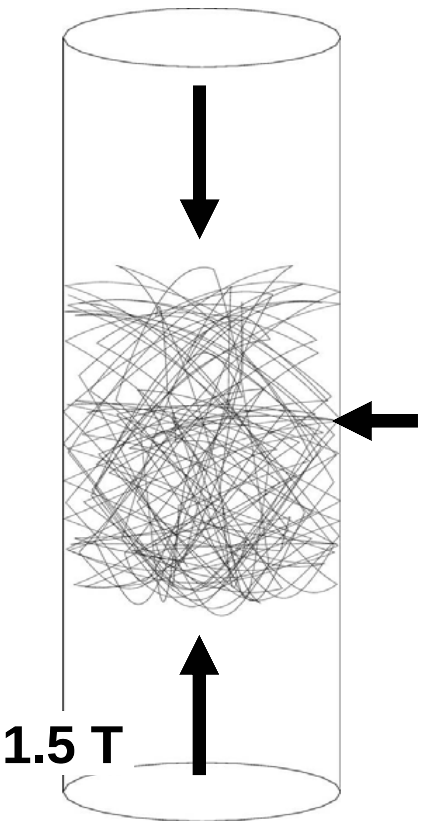
current best nEDM limit:
$d_n < 2.9 \cdot 10^{-26}$ e cm (90% C.L.)
C.A.Baker et al., PRL 97, 131801 (2006)

Sensitivity goals at PSI
Intermediate:
$d_n < 5 \times 10^{-27}$ e cm (95% C.L.)
Final:
$d_n < 5 \times 10^{-28}$ e cm (95% C.L.)

Ultracold neutrons

ultracold neutrons (UCN) are storable neutrons: E_{kin} < 330 neV, v < 8 m/s,

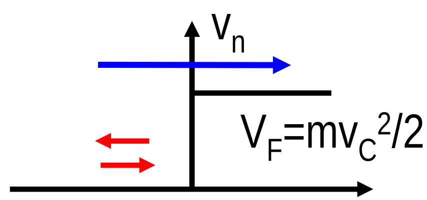
λ ≈ 500 Å, T ≈ 3 mK



Simulation of a neutron bottle with confining forces:

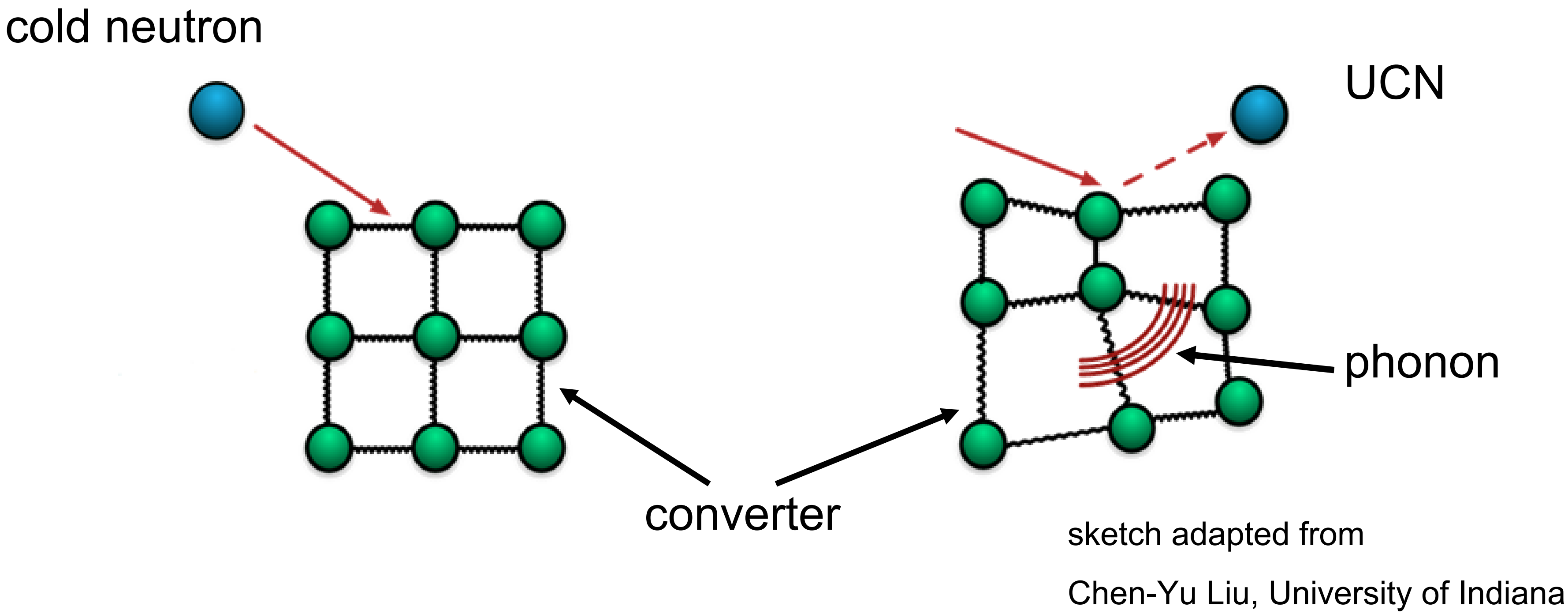
- Gravity: potential energy 100 neV/m
- Material optical potential: < 330 neV

E. Fermi, 1946 , Ya. B. Zeldovich Sov. Phys. JETP 9, 1389 (1959)



- Magnetic field gradient: potential energy ± 60 neV/T

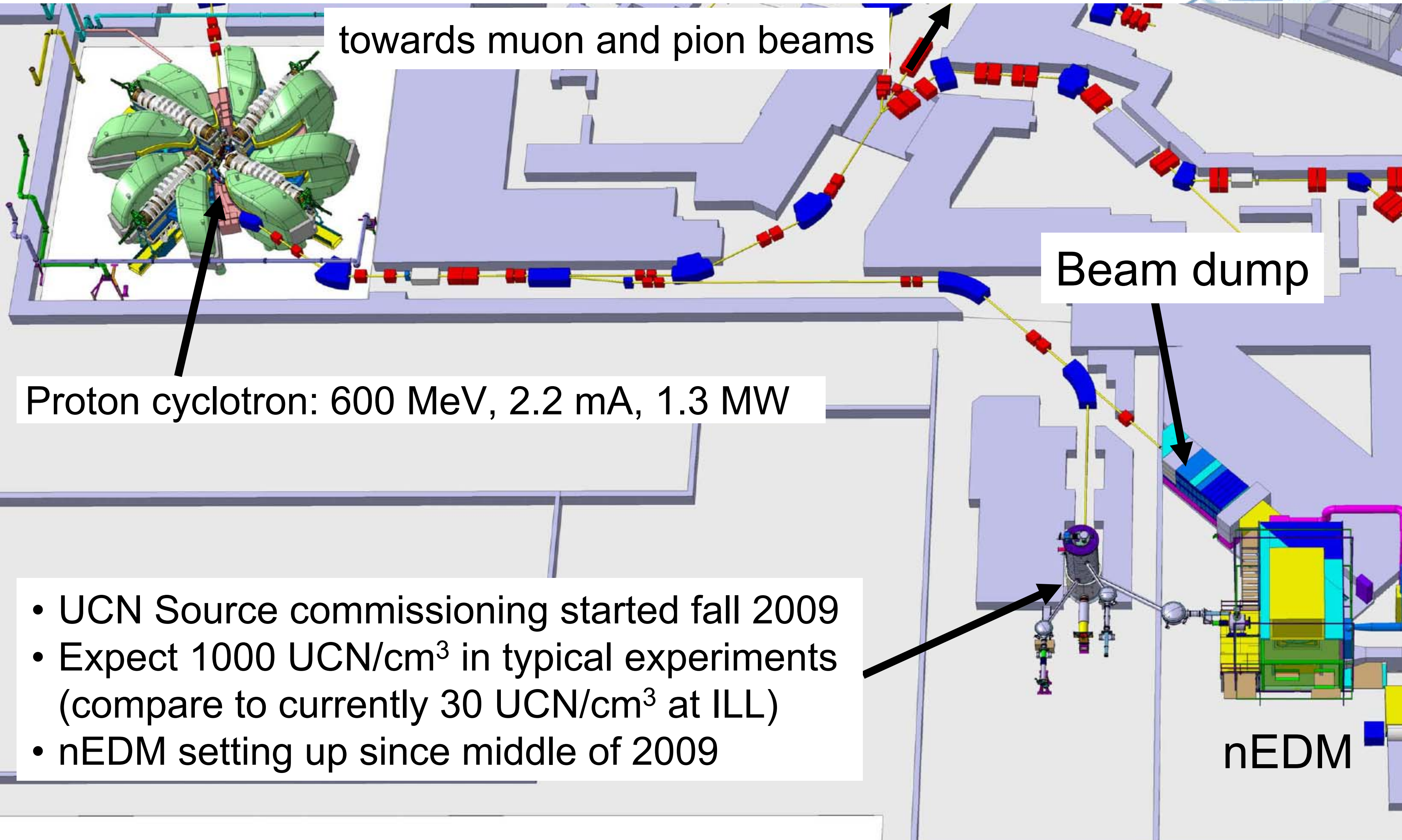
From cold to ultracold



converter types:

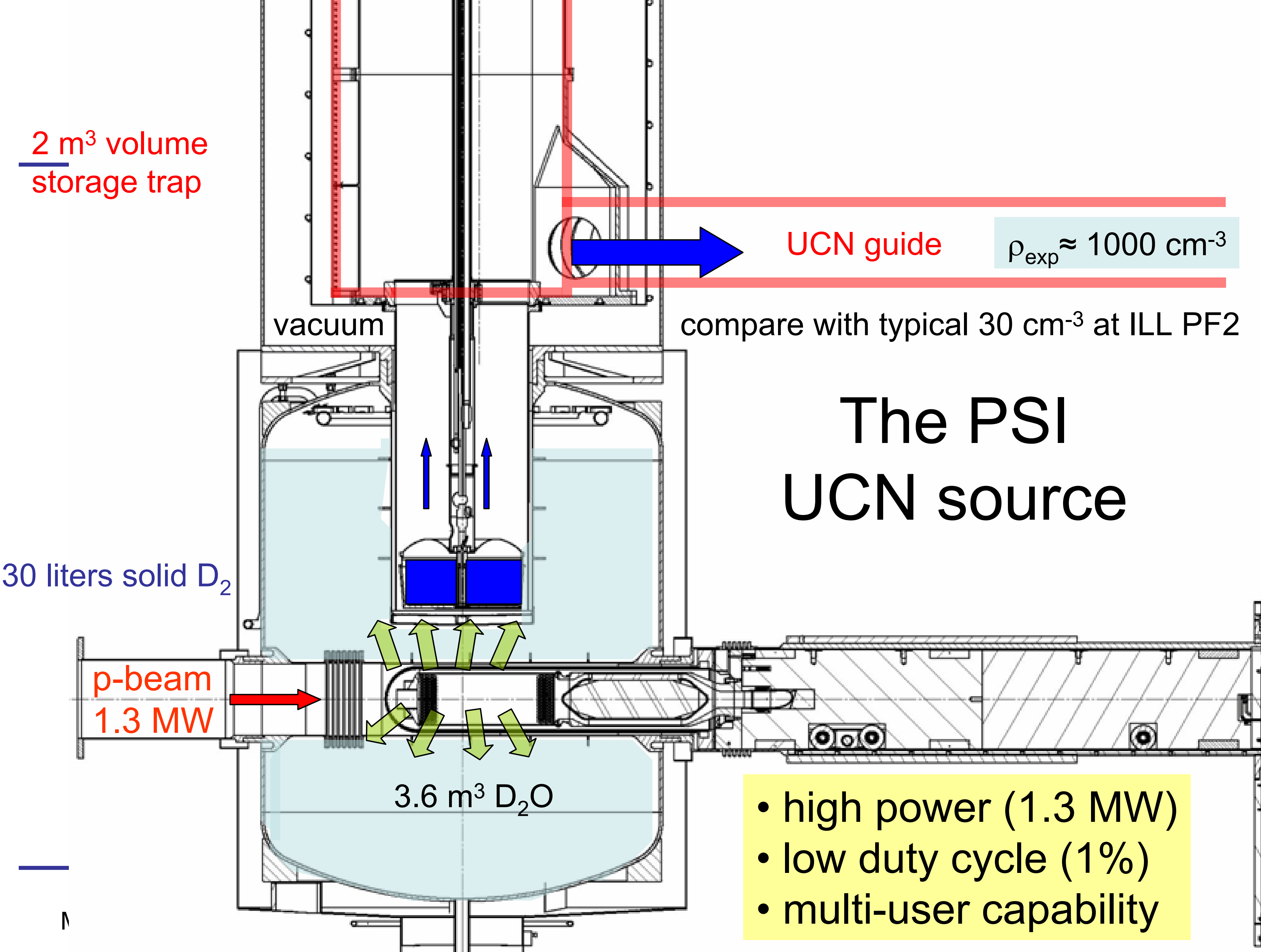
- sD_2 (PSI, LANL, NCSU, FRM2,…)
- sfHe (CryoEDM, SNS, ILL, PNPI,…)

The PSI UCN source



- UCN Source commissioning started fall 2009
- Expect 1000 UCN/cm^3 in typical experiments (compare to currently 30 UCN/cm^3 at ILL)
- nEDM setting up since middle of 2009

The PSI UCN source



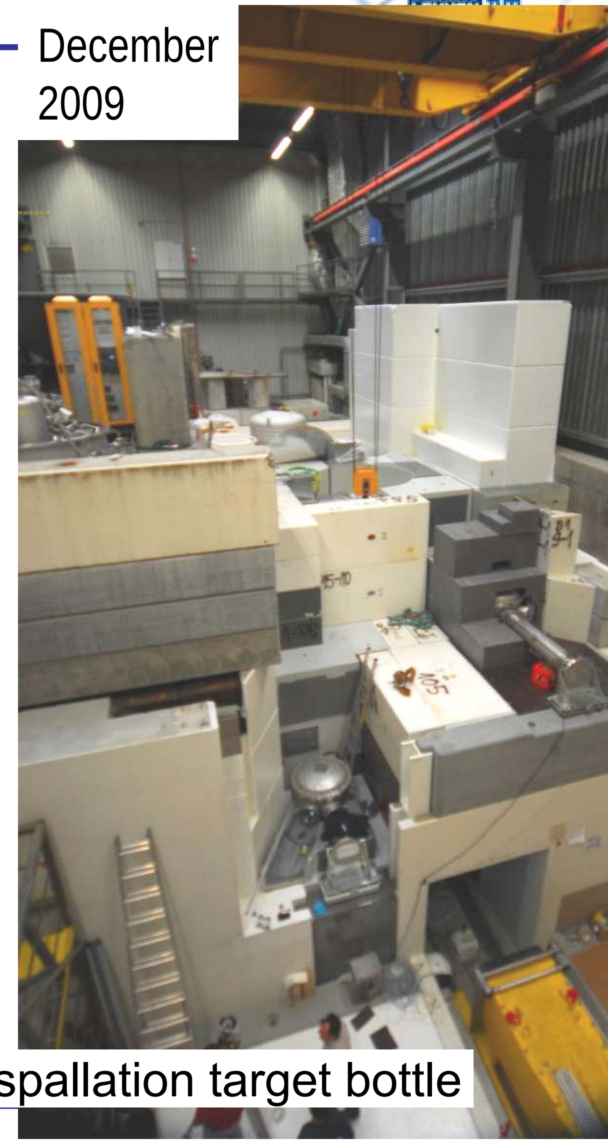
- high power (1.3 MW)
- low duty cycle (1%)
- multi-user capability

The PSI UCN Source

delivery of tank:
Sept. 04, 2008

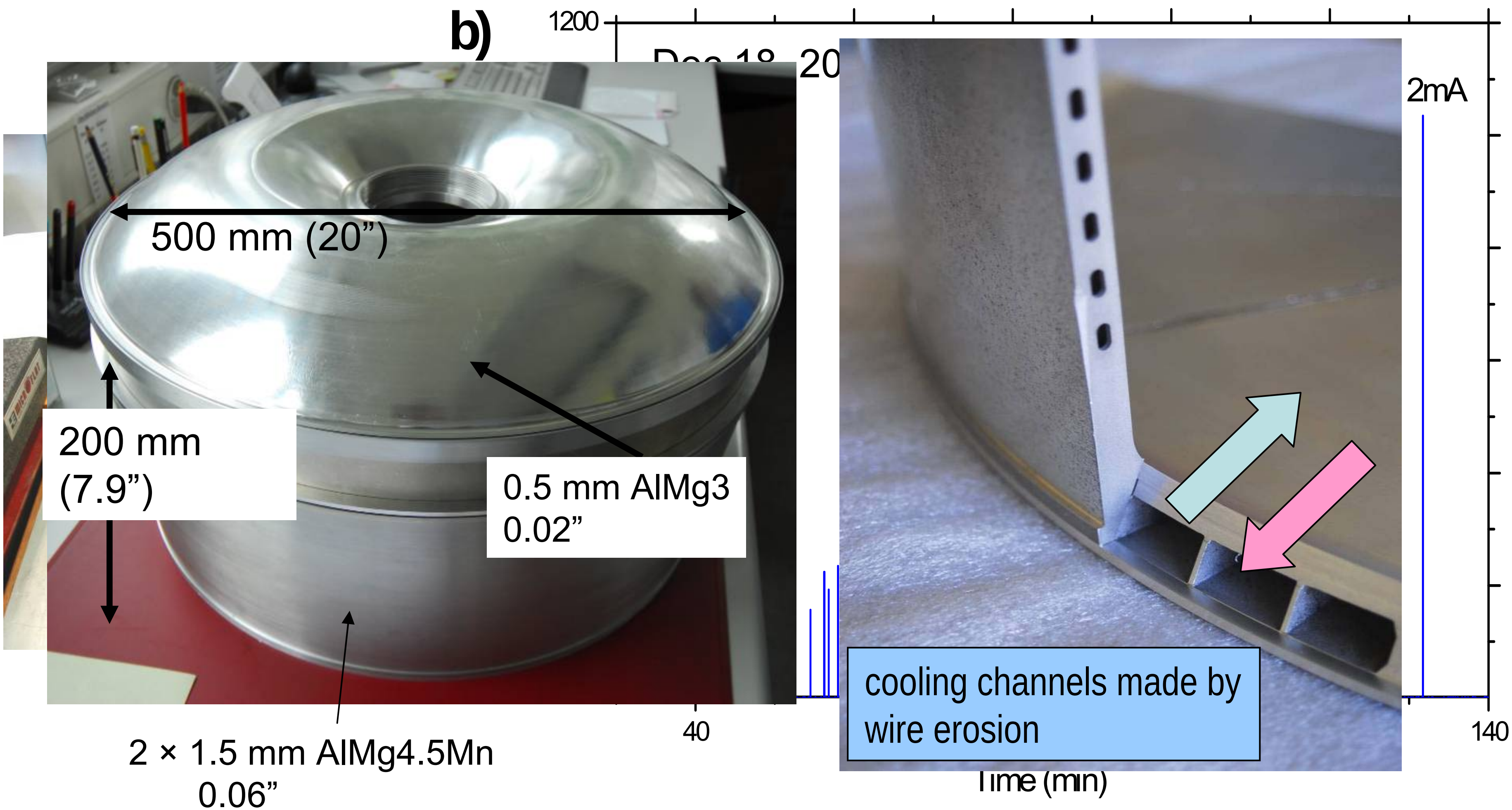
June
2009

December
2009

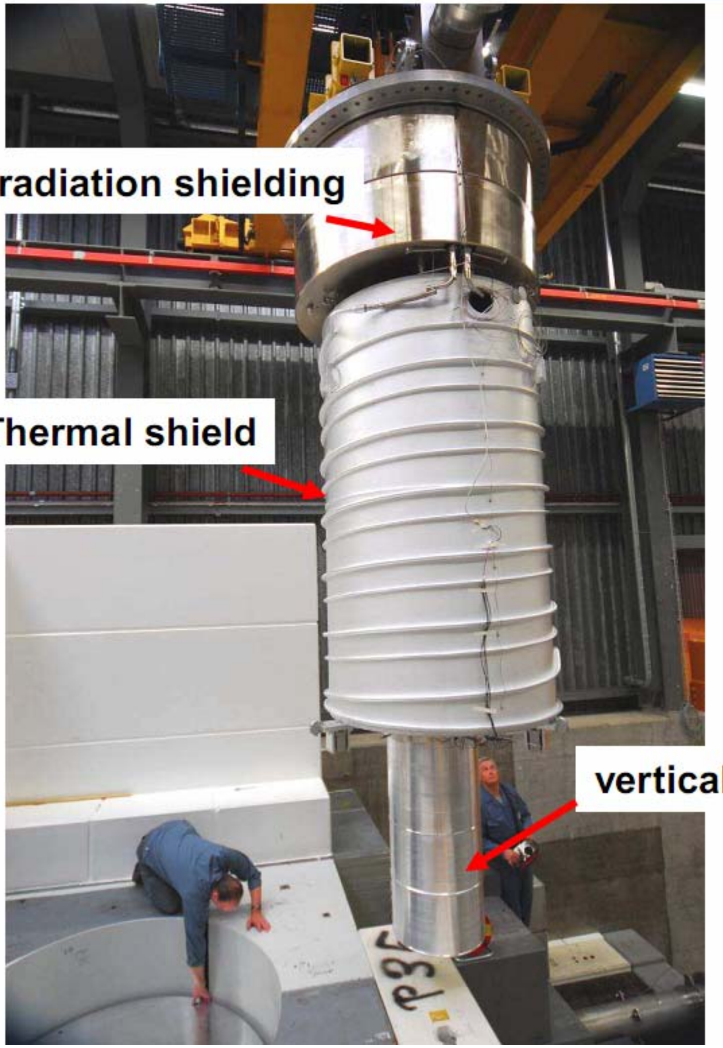


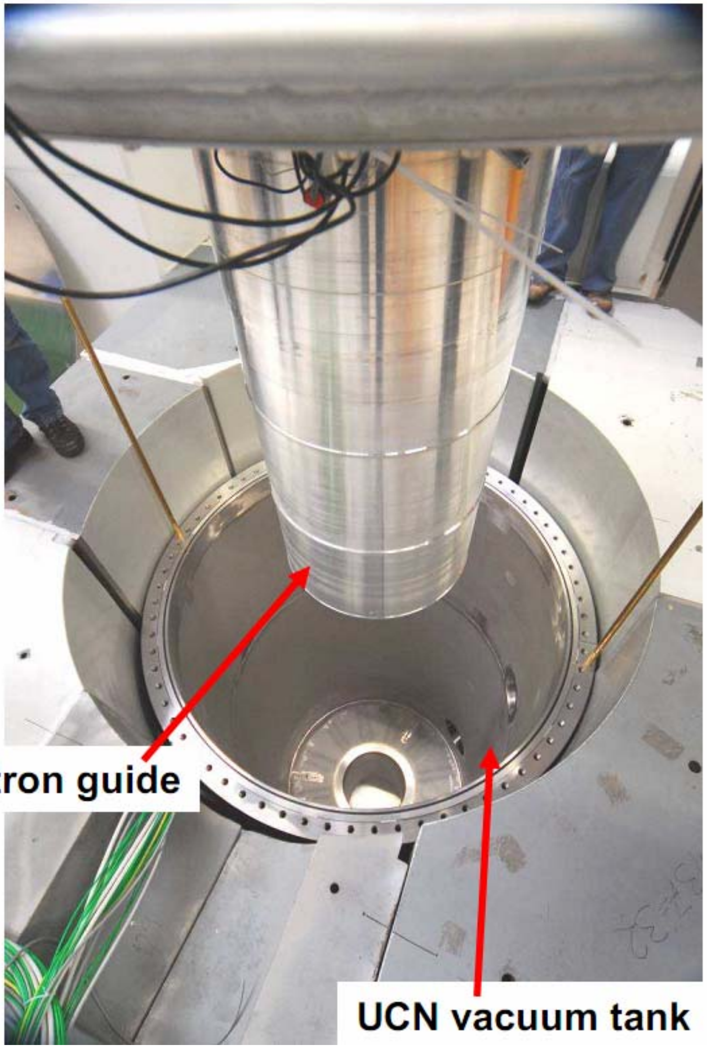
spallation target bottle

The PSI UCN Source

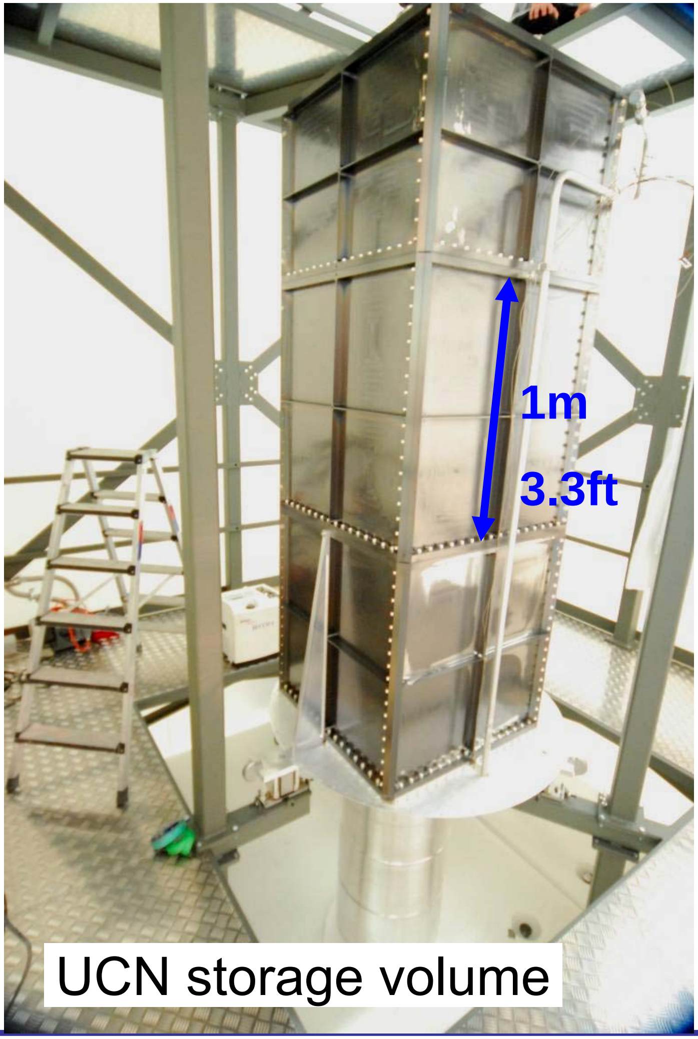


The PSI UCN Source

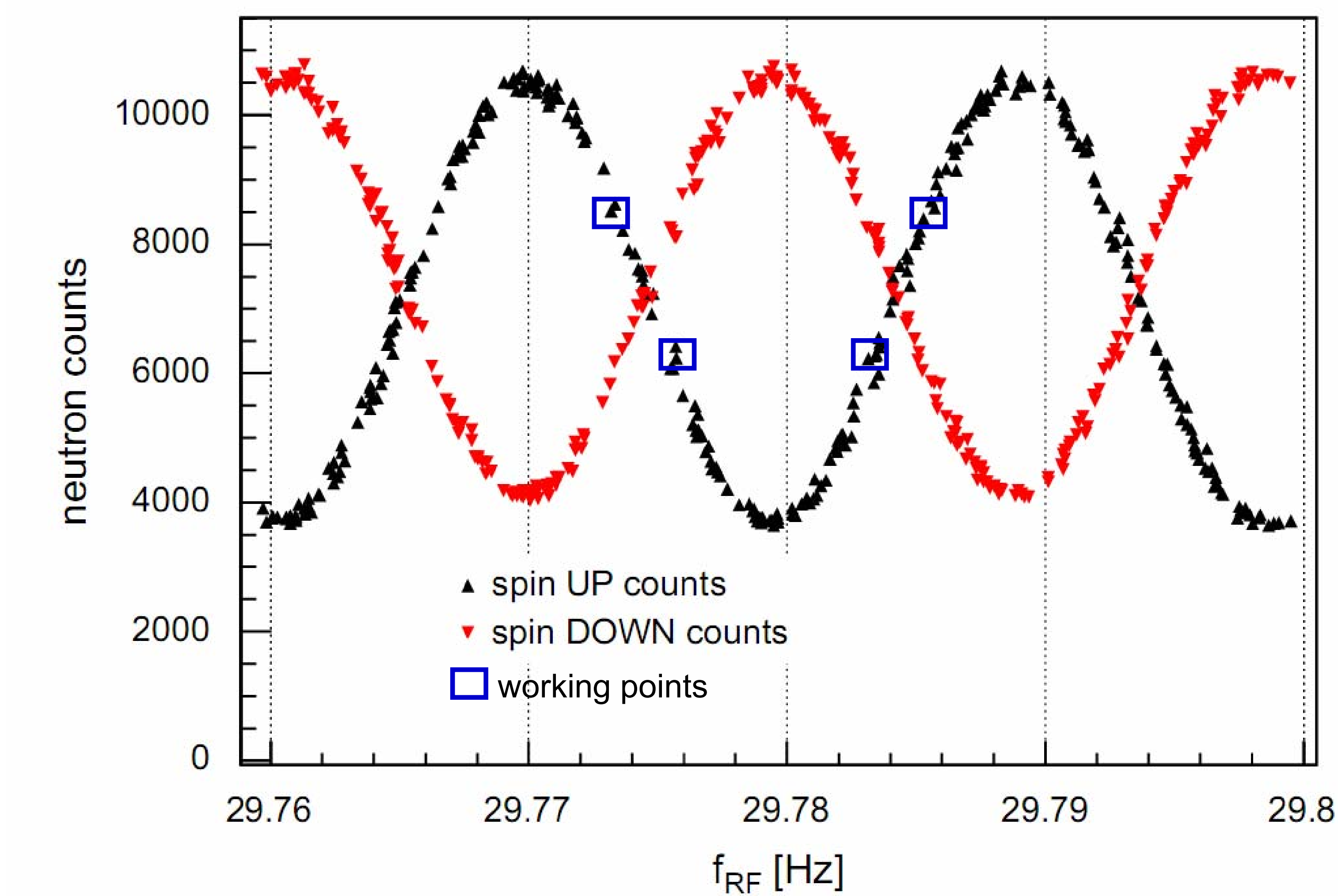




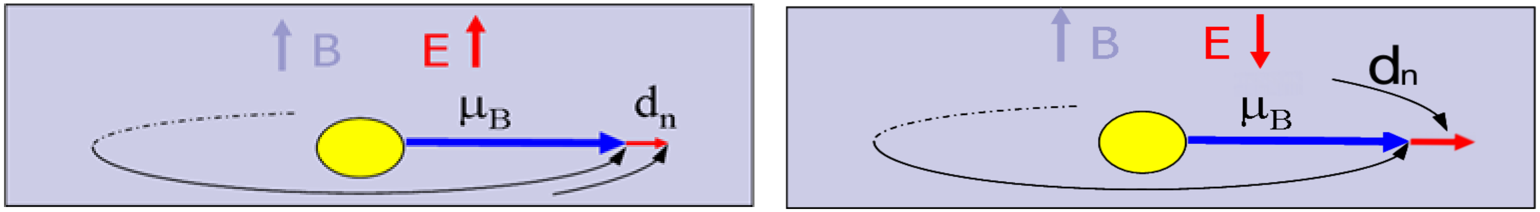
The PSI UCN source



Ramsey technique for nEDM



Measurement principle



try to detect a change of the Larmor precession frequency $\Delta\nu$ for parallel and anti-parallel B (~1 μT) and E fields (~10 kV/cm)

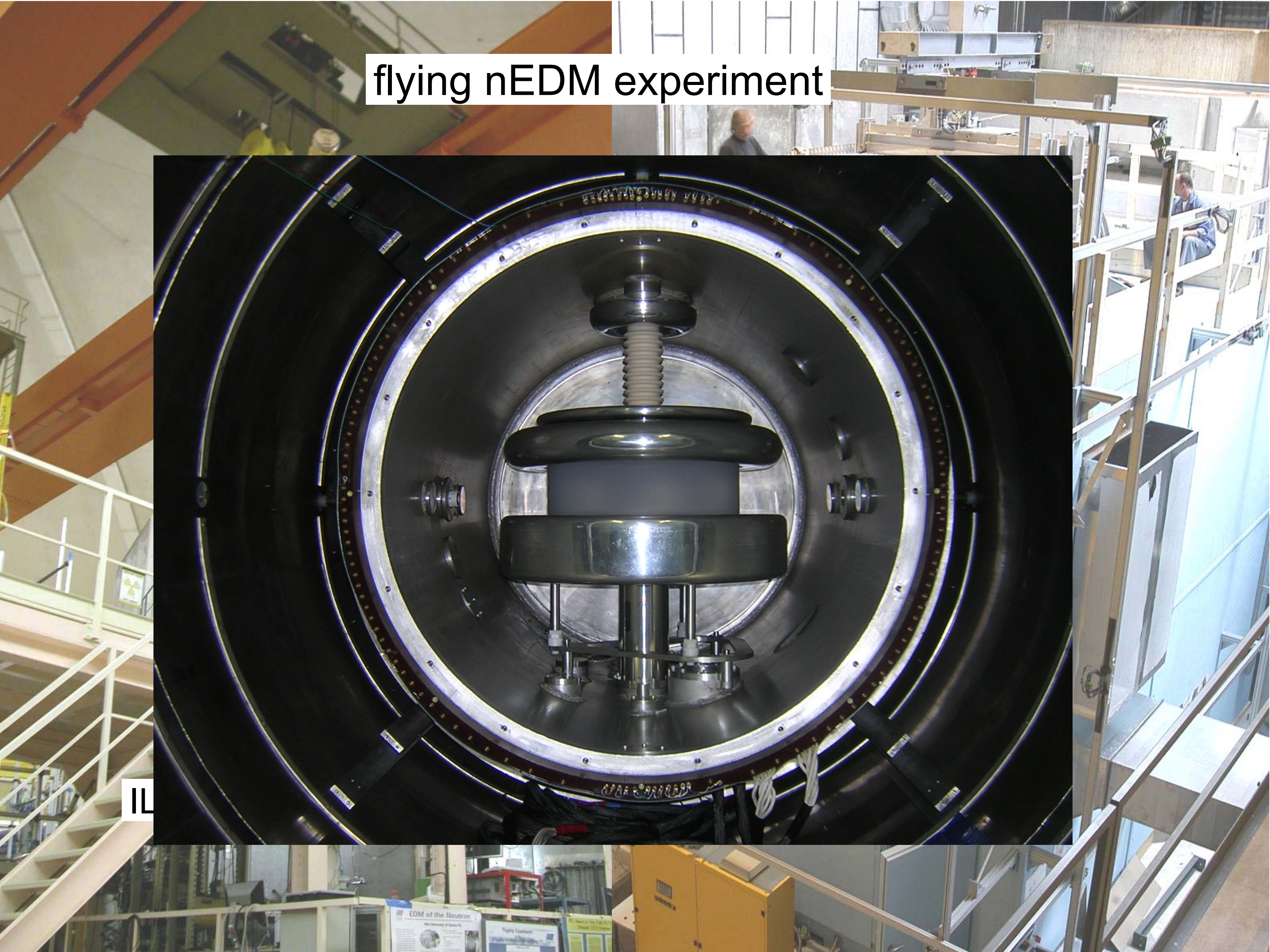
$$d_n = \frac{h\Delta\nu - 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}{2\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right)}$$

statistical sensitivity only limited by the uncertainty principle:

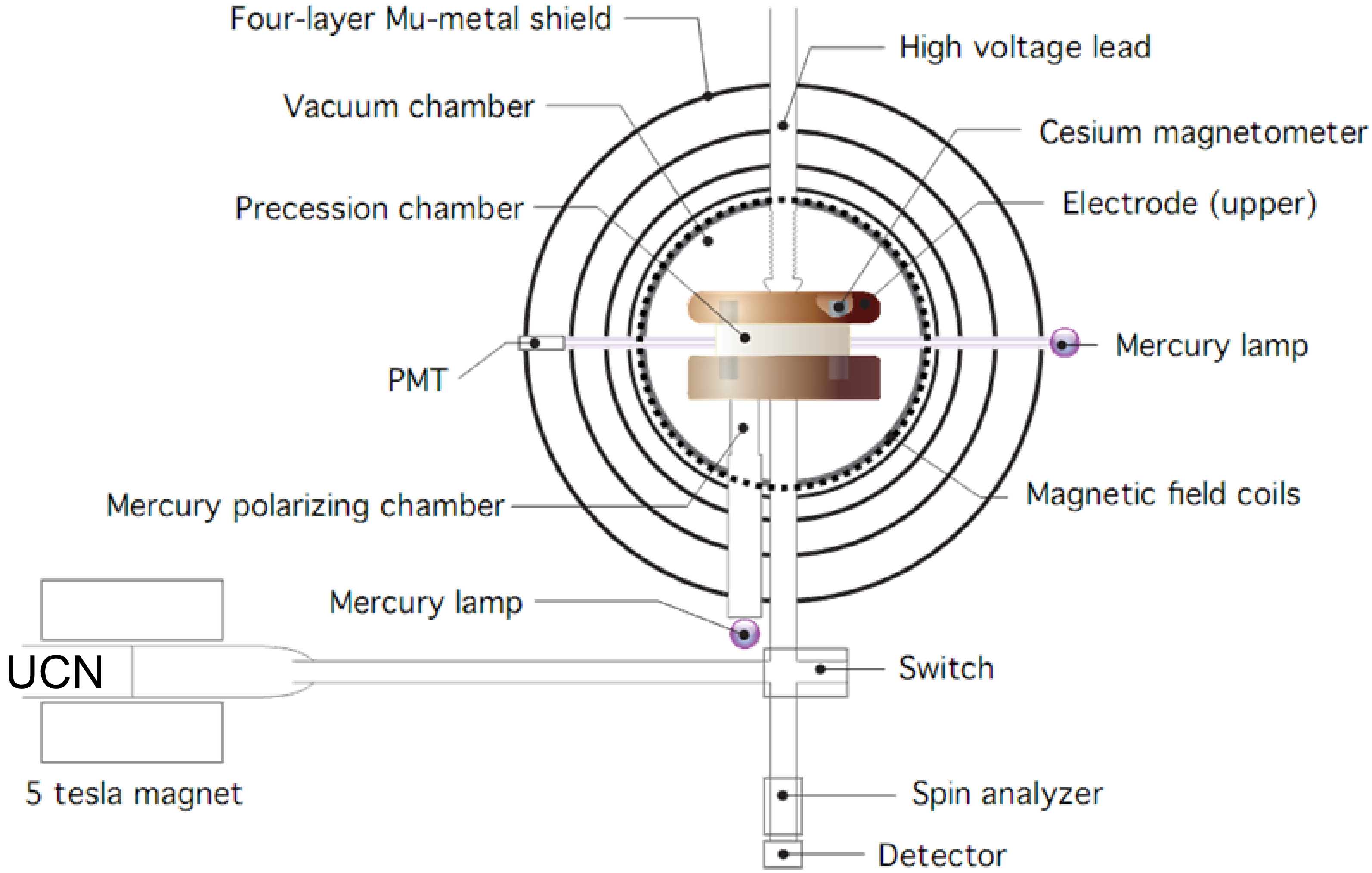
$$\sigma\left(d_n\right) = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

α	Visibility of resonance
E	Electric field
T	Time of free precession
N	Number of neutrons

flying nEDM experiment



nEDM apparatus



magnetic field requirements I

$$d_n = \frac{h\Delta\nu - 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}{2\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right)} \Rightarrow d_n = \frac{h\Delta\nu}{4E}$$

only if

$$2\mu_n\left(B_{\uparrow\downarrow} - B_{\uparrow\uparrow}\right) \ll h\Delta\nu = 4Ed_n \rightarrow \sigma\left(\Delta B\right) \ll \frac{2E\sigma\left(d_n\right)}{\mu_n}$$

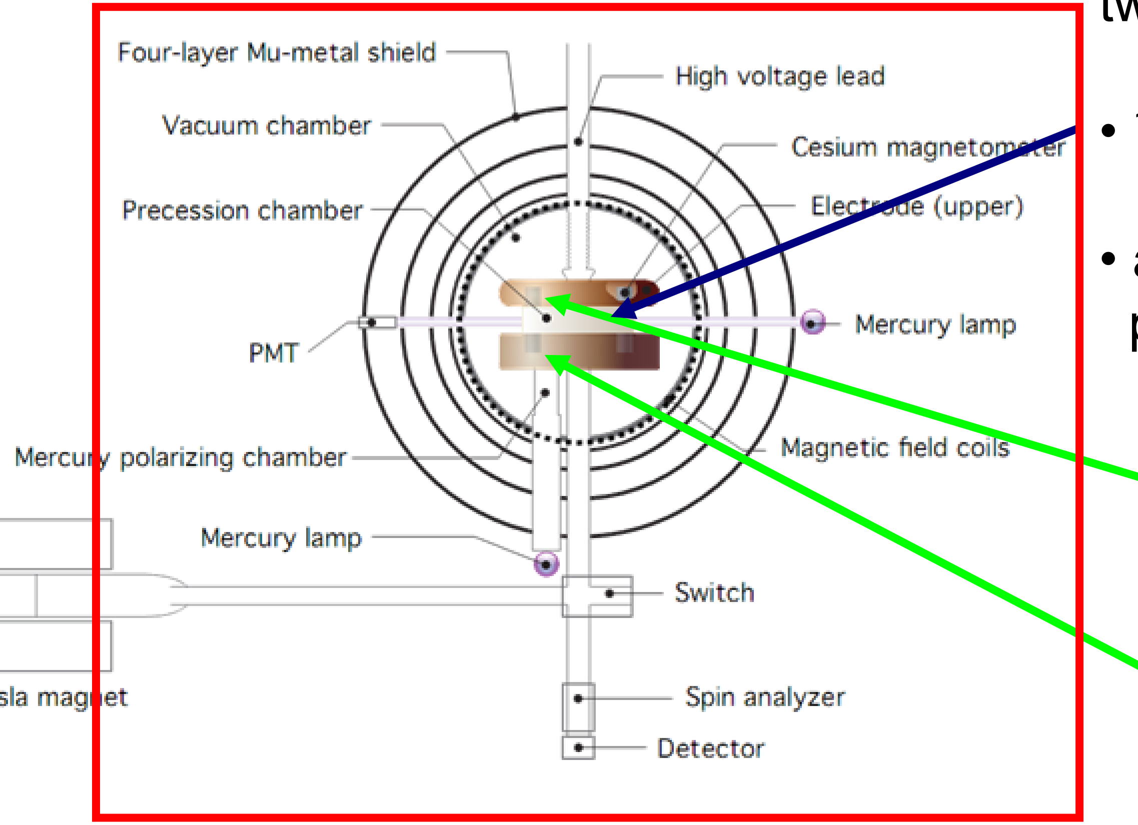
statistical sensitivity goal:

$$\sigma\left(d_{\mathrm{n}}\right) = \frac{\hbar}{2\alpha ET\sqrt{N}} = 4 \cdot 10^{-25}\,\mathrm{e\,cm}$$

- α Visibility of resonance (0.75)
- E Electric field strength (12 kV/cm)
- T Time of free precession (150 s)
- N Number of neutrons (350000)

B field requirement: $\sigma(B) = 100\,\mathrm{fT}$ per one Ramsey cycle (~500s)

magnetometers and SFC



two magnetometer systems:

- ^{199}Hg comagnetometer
- array of laser-driven optically pumped Cs-magnetometers:

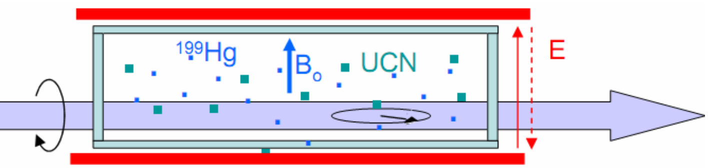
4 HV - compatible sensors

8 sensors on ground potential

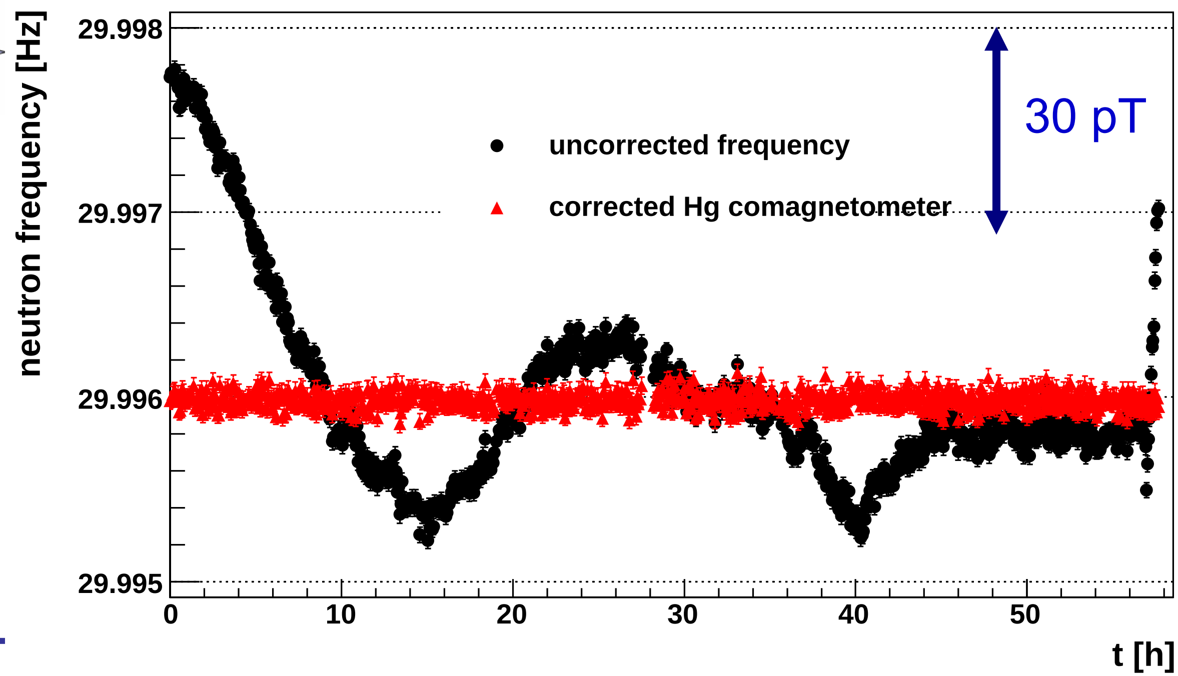
6 current coils for active sourrounding field compensation (SFC)

^{199}Hg comagnetometer

- polarized ^{199}Hg atoms sample magnetic field inside the UCN precession chamber at the same time as the UCN (cohabiting)
- optical readout of free spin precession with light from ^{204}Hg lamp
- performance: σ(B) ~ 40 fT per 100 s run

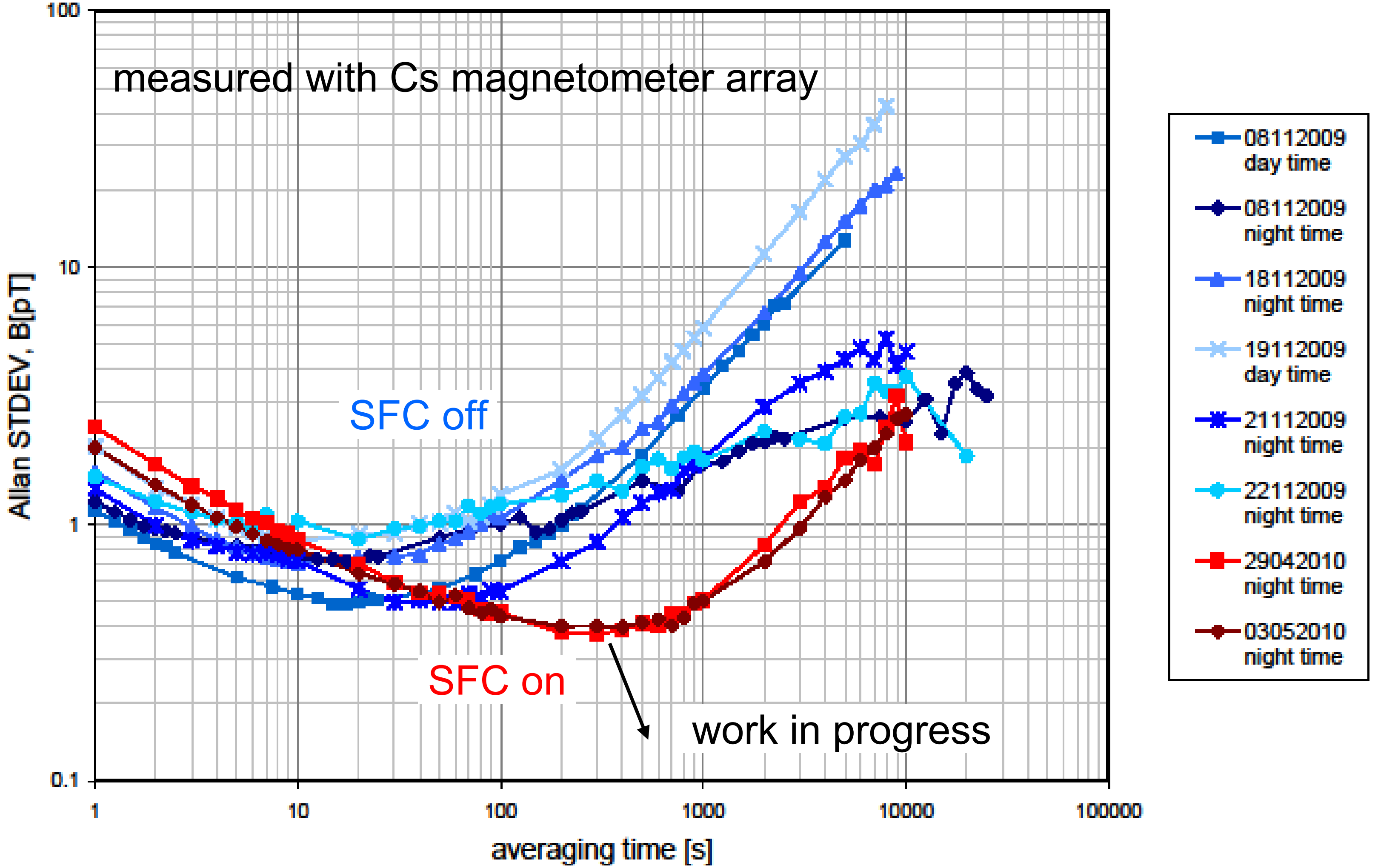


correct the UCN precession frequency with Hg precession frequency



SFC performance

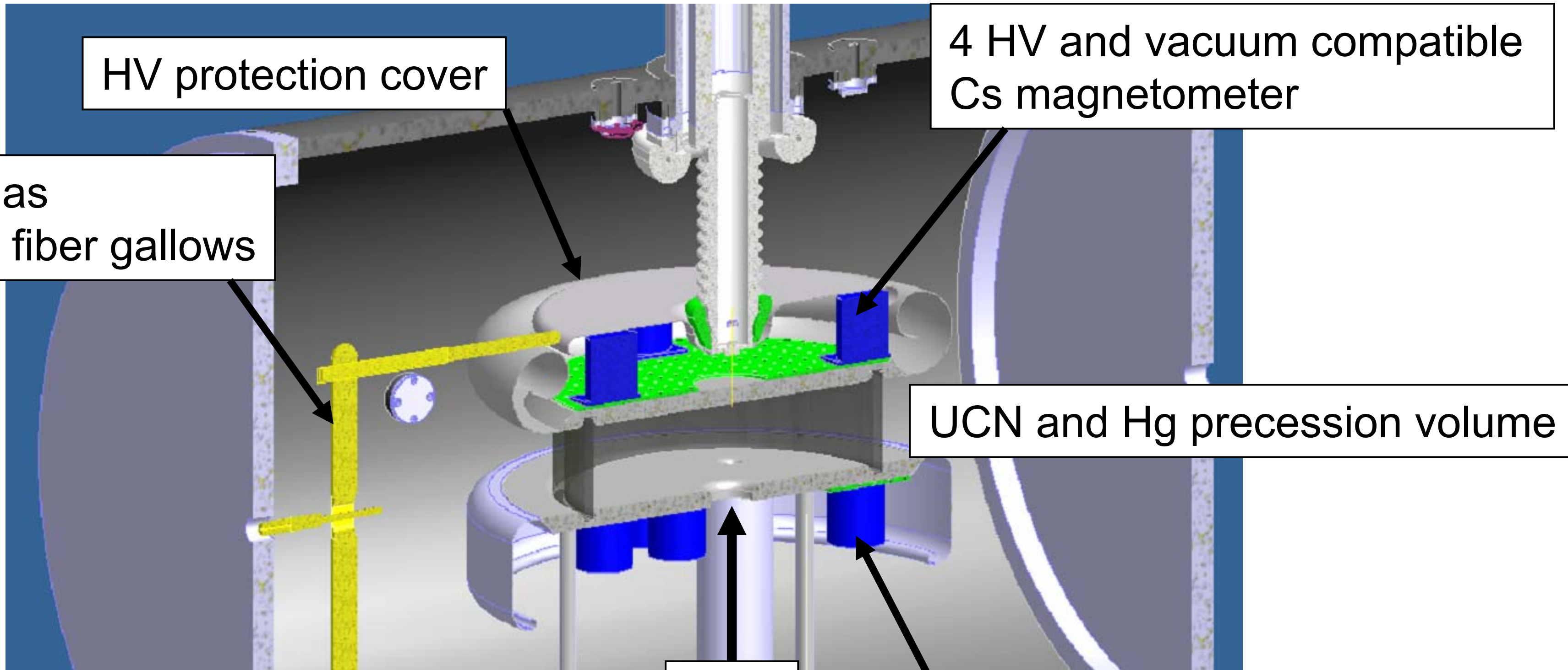
6 rectangular coils to actively stabilize the surrounding magnetic field



systematic error contributions

No.	Effect	Shift (Ref. [26]) $[10^{-27}\, e\mathrm{cm}]$	σ (Ref. [26]) $[10^{-27}\, e\mathrm{cm}]$	σ (Phase II) $[10^{-27}\, e\mathrm{cm}]$
1.	Door cavity dipole	-5.60	2.00	**0.10**
2.	Other dipole fields	0.00	6.00	**0.40**
3.	Quadrupole difference	-1.30	2.00	**0.60**
4.	$\mathbf{v} \times \mathbf{E}$ translational	0.00	0.03	0.04
5.	$\mathbf{v} \times \mathbf{E}$ rotational	0.00	1.00	**0.10**
6.	Second-order $\mathbf{v} \times \mathbf{E}$	0.00	0.02	0.01
7.	ν_{Hg} light shift (geo phase)	3.50	0.80	**0.40**
8.	ν_{Hg} light shift (direct)	0.00	0.20	0.20
9.	Uncompensated B drift	0.00	2.40	**0.90**
10.	Hg atom EDM	-0.40	0.30	*0.06*
11.	Electric forces	0.00	0.40	0.40
12.	Leakage currents	0.00	0.10	0.10
13.	ac fields	0.00	0.01	0.01
	Total	-3.80	7.19	**1.31**

Cs magnetometer array



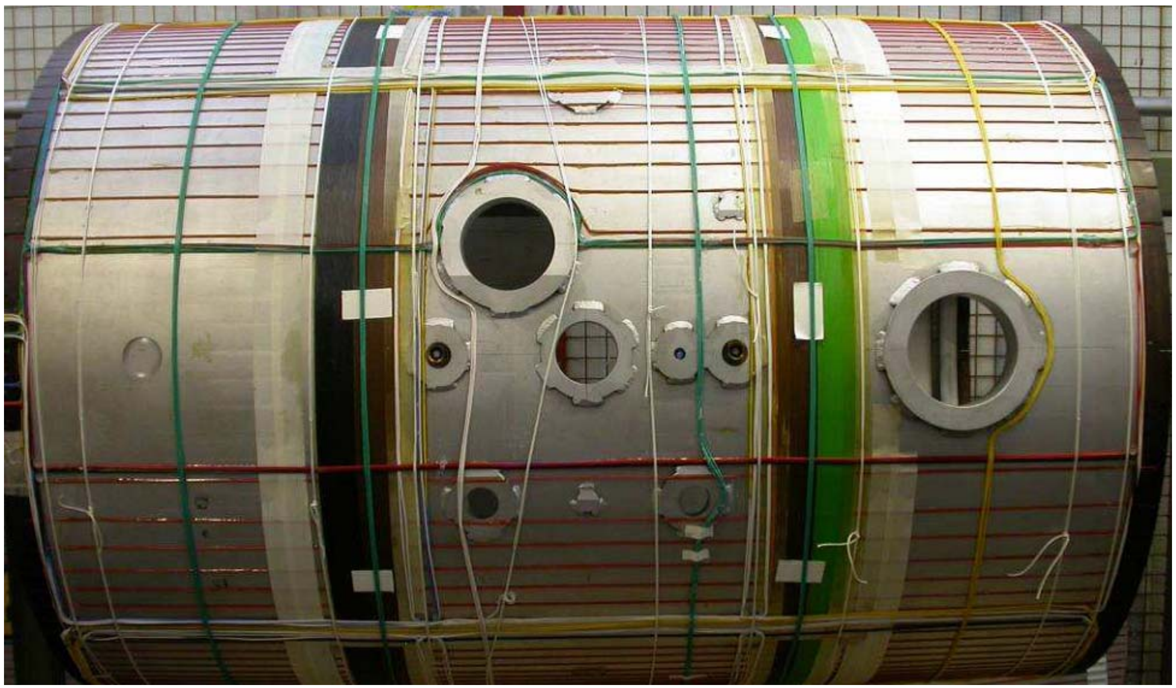
survey magnetic fields related to the doors/shutters (“door cavity dipole”)

measure the “uncompensated B drift” (HV reversal related)

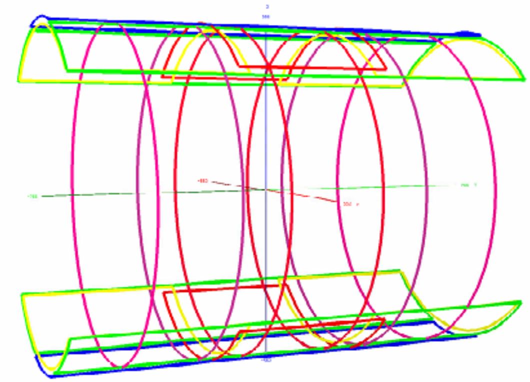
magnetic field gradients (geometric phase effect)

magnetic field requirements II

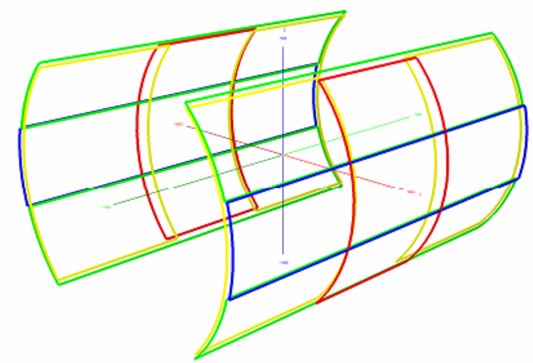
spatial magnetic field gradients → UCN depolarization (center of mass effect)
geometric phase effect



33 individual trim coils outside the vacuum tank
to shape the magnetic field

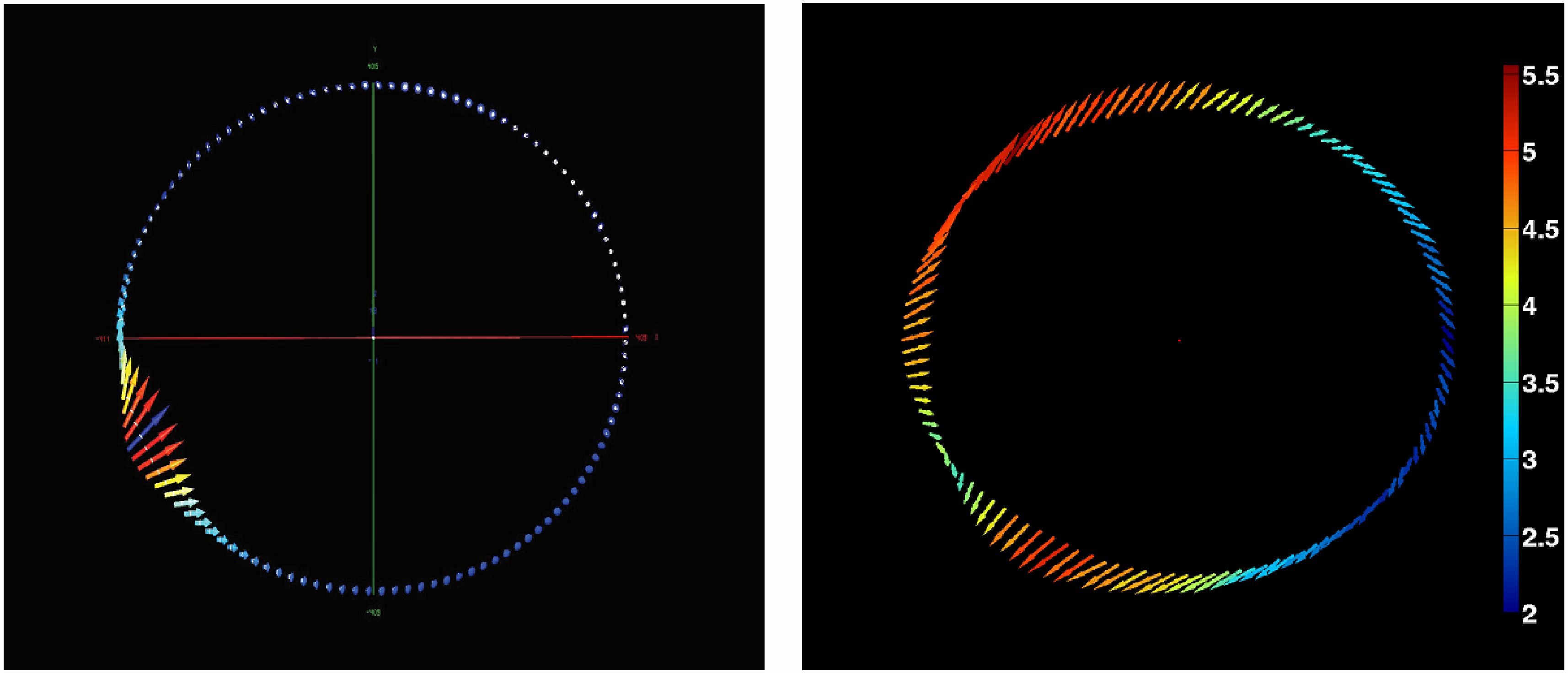


Top, bottom, and Helmholtz



Left & right side coils

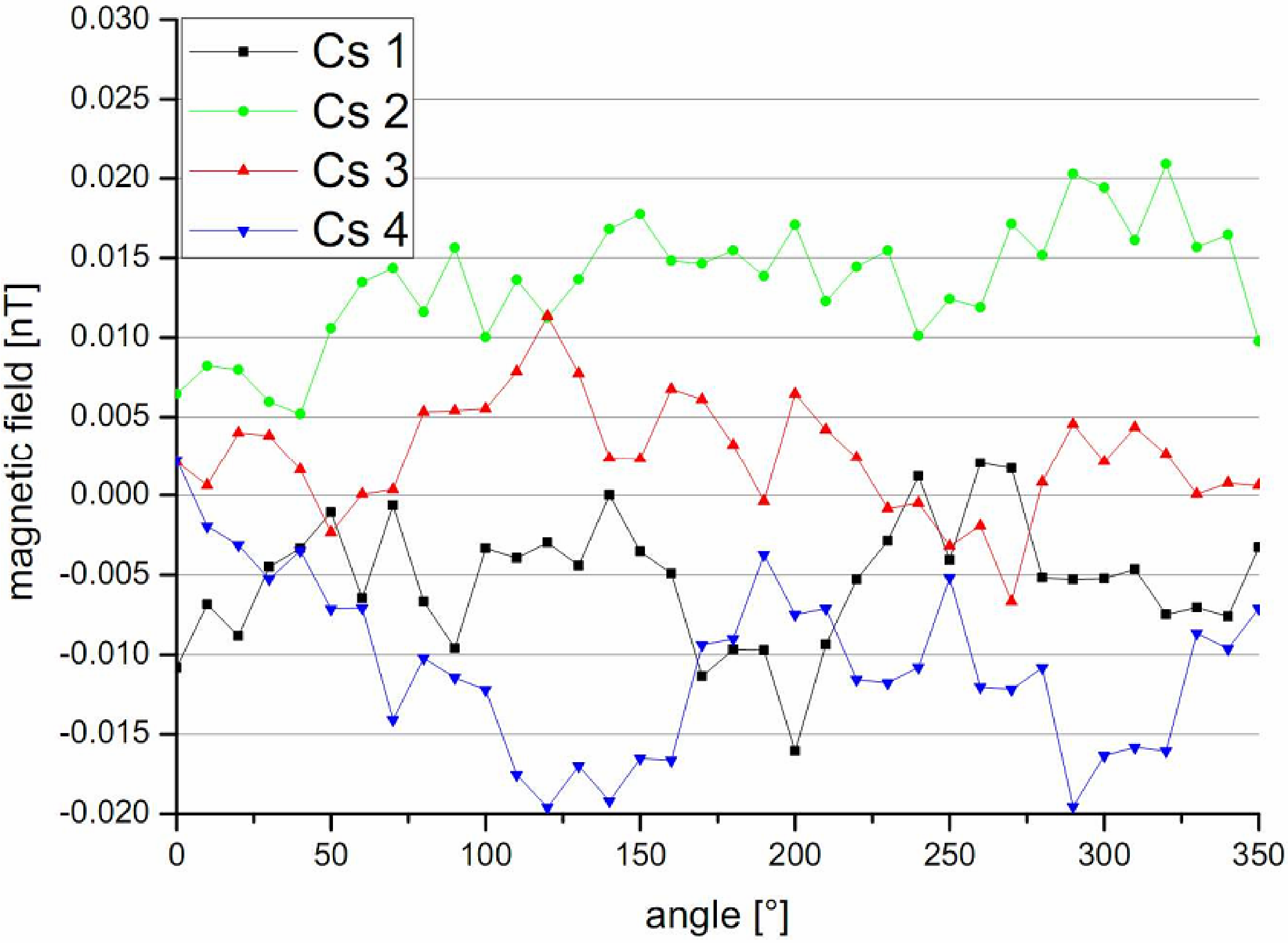
magnetic field mapping



(a) With magnetic nut. (b) Without magnetic nut.

Figure 46: Magnetic field after degaussing at $r = 40$ cm circle ($z = 0$) inside OILL without vacuum tank. (a) A maximum of 59 nT is caused by a magnetic nut on the left inside the shield. (b) Magnetic field after removal of the nut and degaussing again. The field is now about ten times smaller. The scale is in nT.

magnetic field mapping



average deviation from mean:

Cs 1: - 5 ± 4 pT

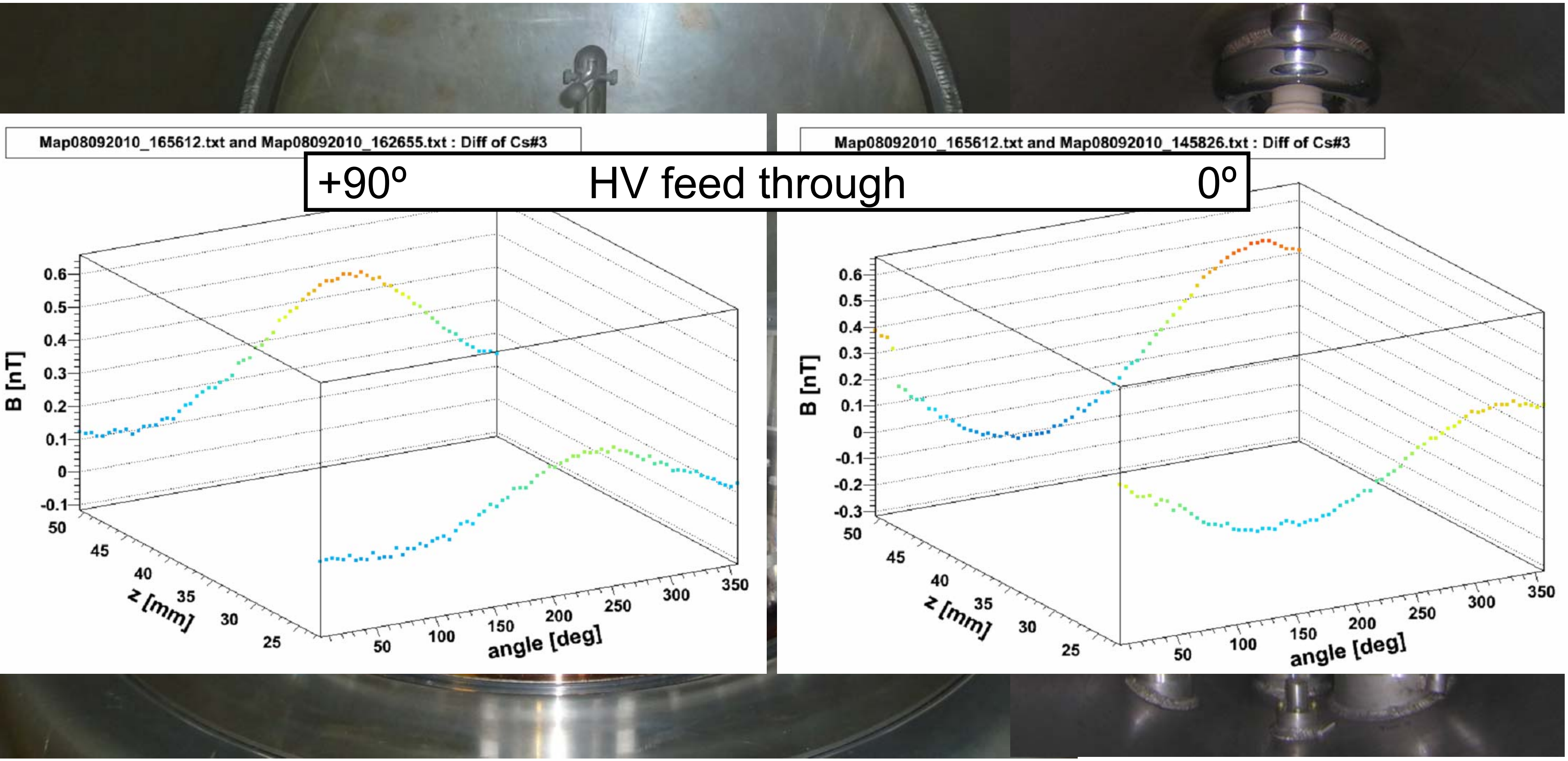
Cs 2: + 14 ± 4 pT

Cs 3: + 2 ± 4 pT

Cs 4: -11 ± 5 pT

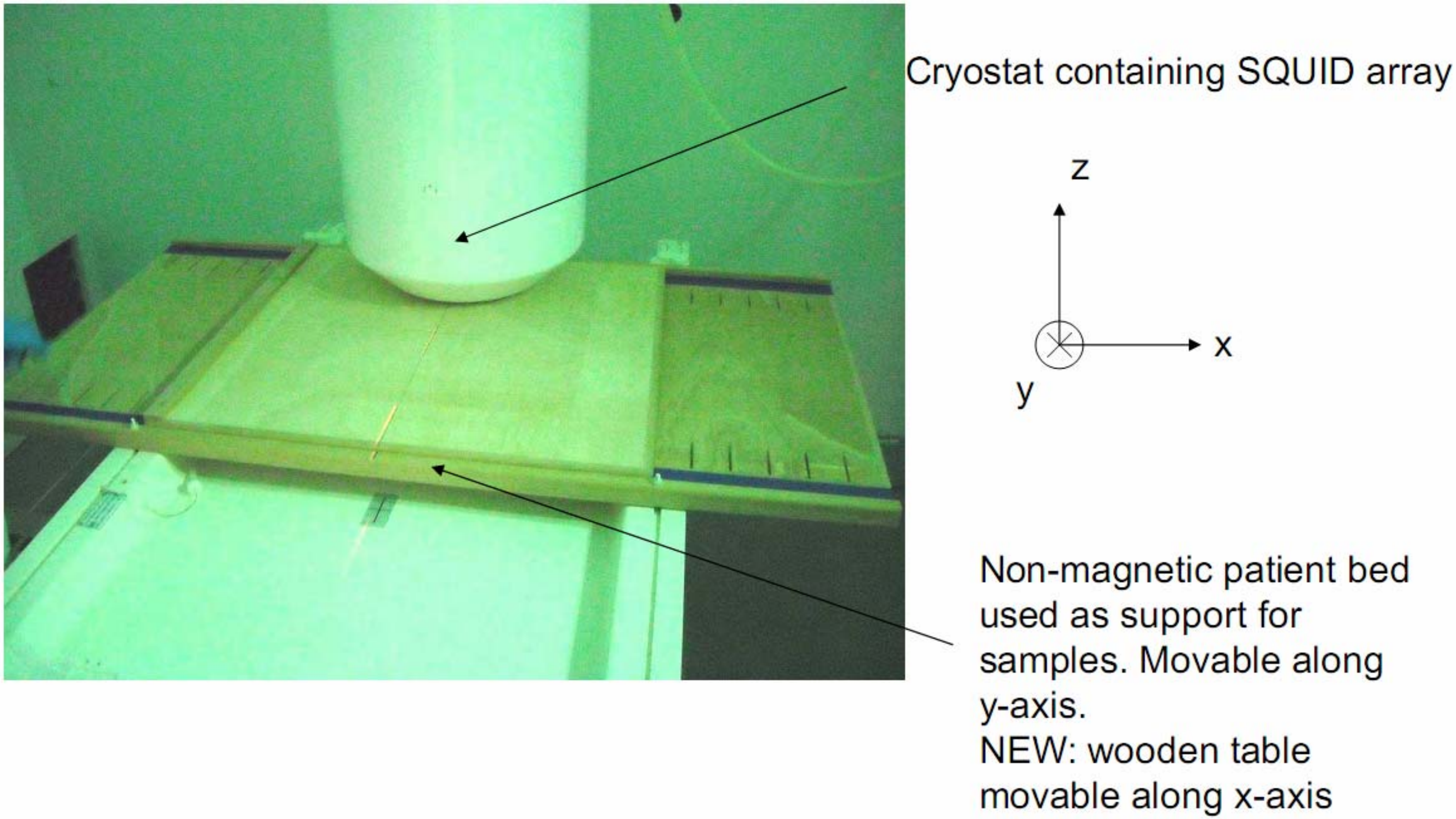
magnetic field mapping

map magnetic field in UCN precession chamber with all subsystems installed



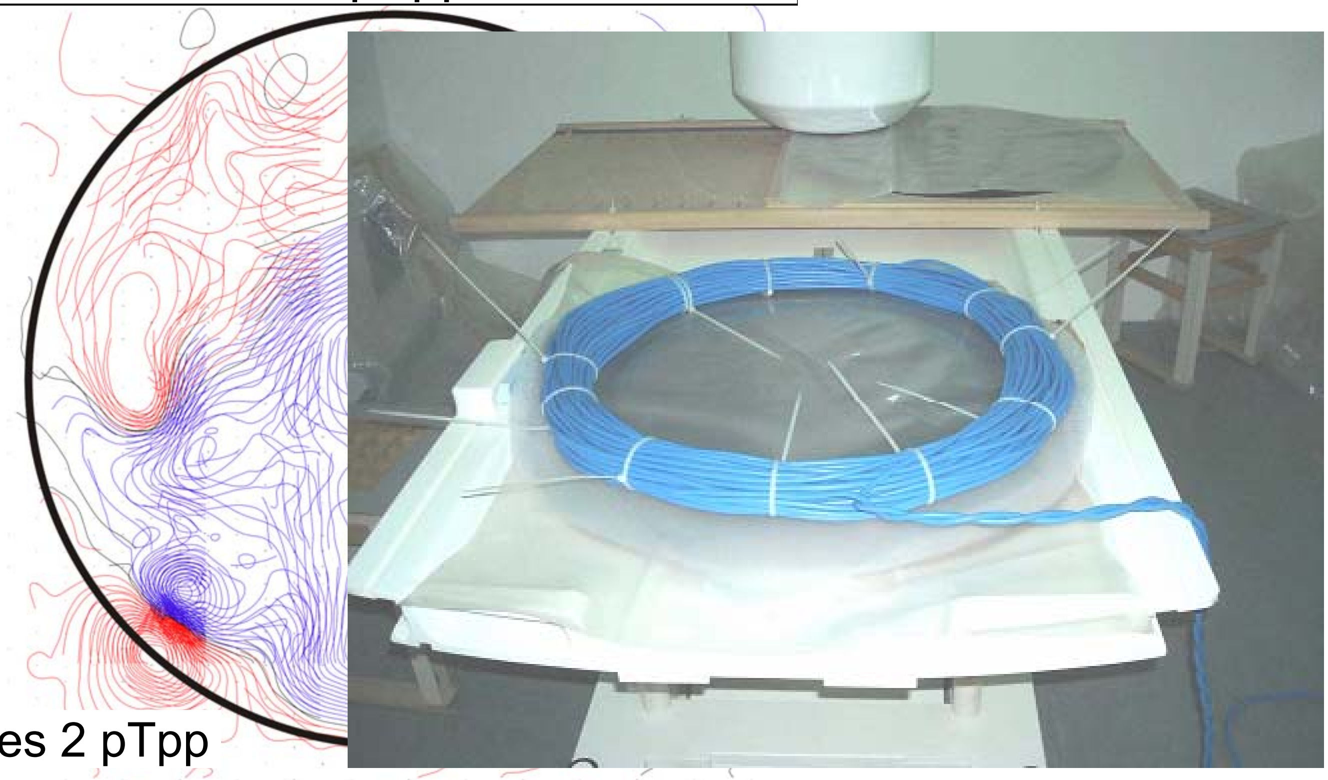
Magnetic screening

large pieces are magnetically screened with SQUID array at PTB Berlin BMSR2



Magnetic screening

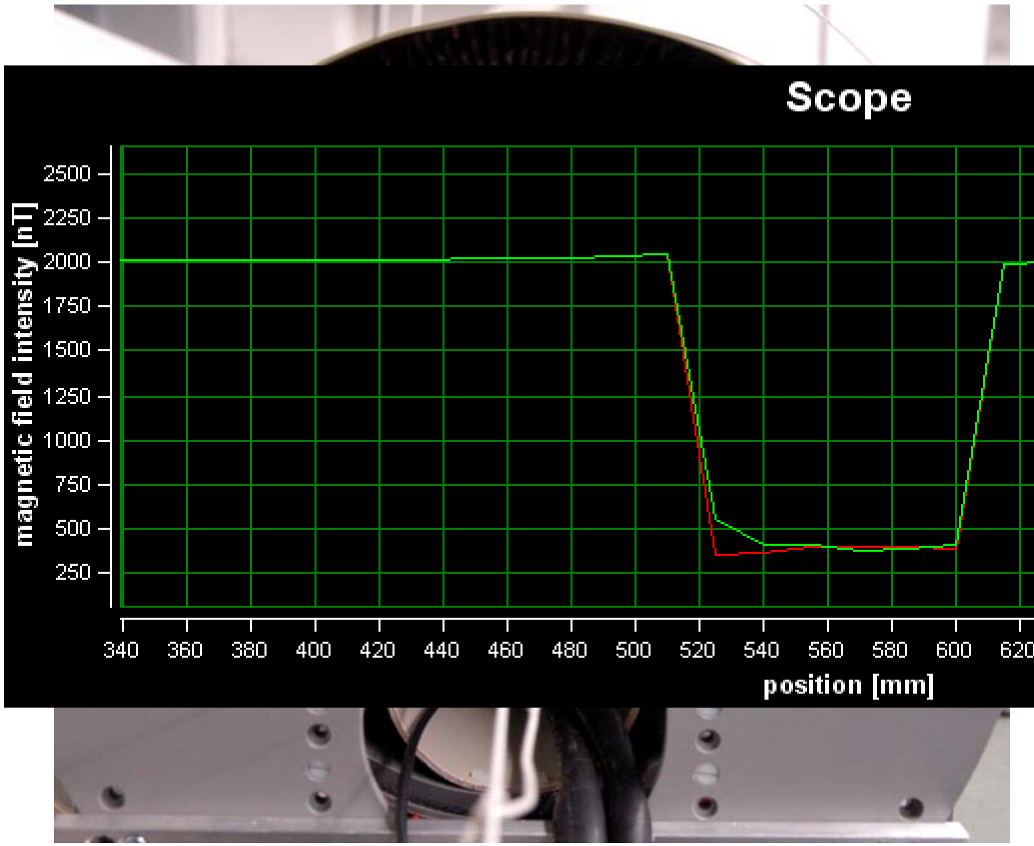
bottom electrode before degaussing
200 pTpp

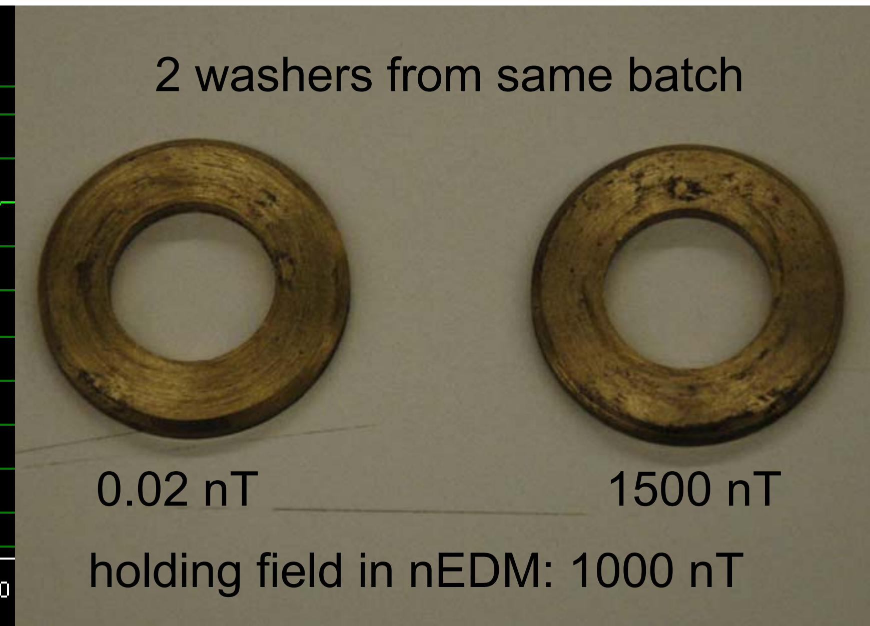


isolines 2 pTpp

Magnetic screening

gradiometer setup to magnetically screen small parts before implementation





Further developments

several further improvements have been developed in the collaboration and will be used in the new nEDM measurement:

- new high count rate UCN detectors (~10^5 cts/s each, 9 detectors)
- new spin analyzing foil (single crystal iron foil)
- thermal stabilization of Mu-metal shield
- new degaussing system for the Mu-metal shield
- new bipolar HV power supply
- replace massive metal pieces with metal coated plastics

Summary and outlook

- nEDM experiment successfully transferred to PSI
- PSI UCN source at the end of commissioning
  → cool down in November 2010
- Design of n2EDM experiment has started to improve sensitivity to 5×10^{-28} ecm (2012+).

Thank you!