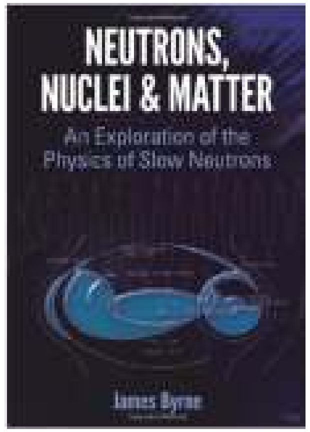
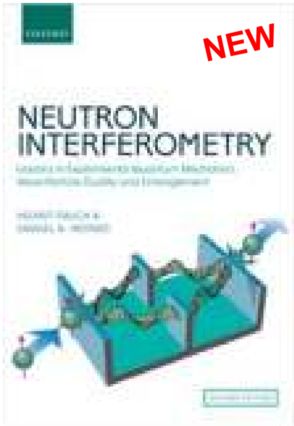
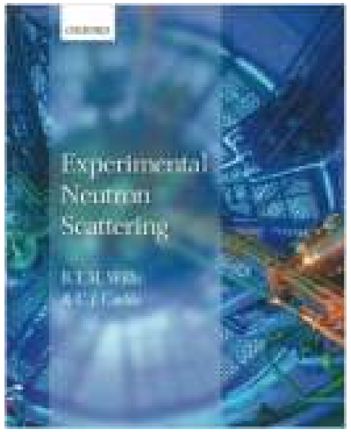
Neutron Electric Dipole Moment Search at Room Temperature

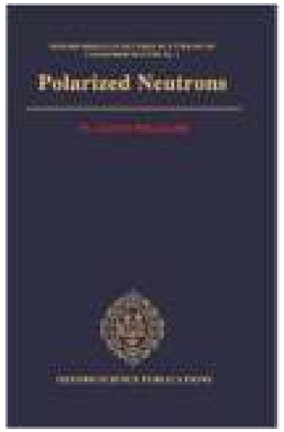
Florian Piegsa
ETH Zürich – Institute for Particle Physics

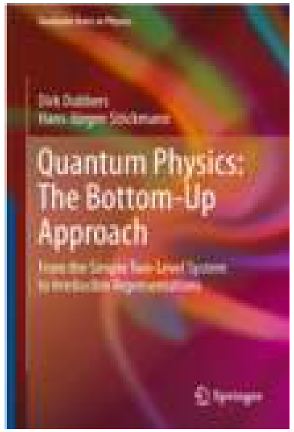
Fundamental Neutron Physics Summer School in Knoxville 2015











- **Byrne – Neutrons, Nuclei & Matter**
- **Golub, Richardson & Lamoreaux – Ultra-Cold Neutrons**
- **Rauch & Werner – Neutron Interferometry**
- **Willis & Carlile – Experimental Neutron Scattering**
- **Williams – Polarized Neutrons**
- **Dubbers & Stöckmann – Quantum Physics**

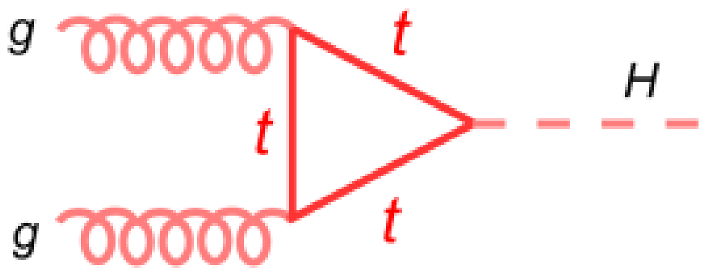
and others …

- Introduction & Motivation
- Rabi's & Ramsey's Method
- How to Measure a Neutron EDM
- The nEDM Experiment at PSI
- Future & Ramsey beyond the EDM

► Introduction & Motivation

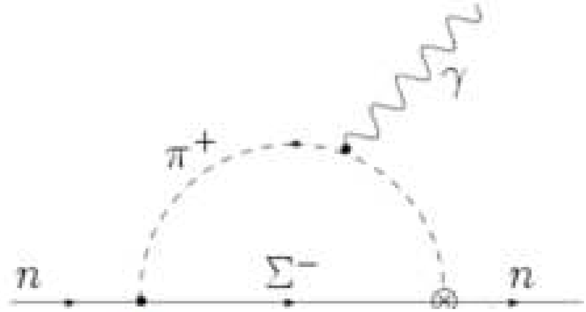
High Energy Frontier

Direct production of new particles

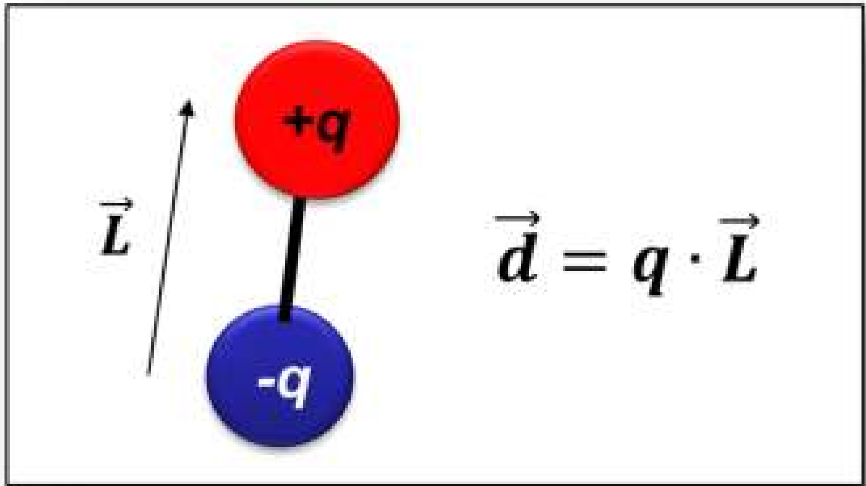


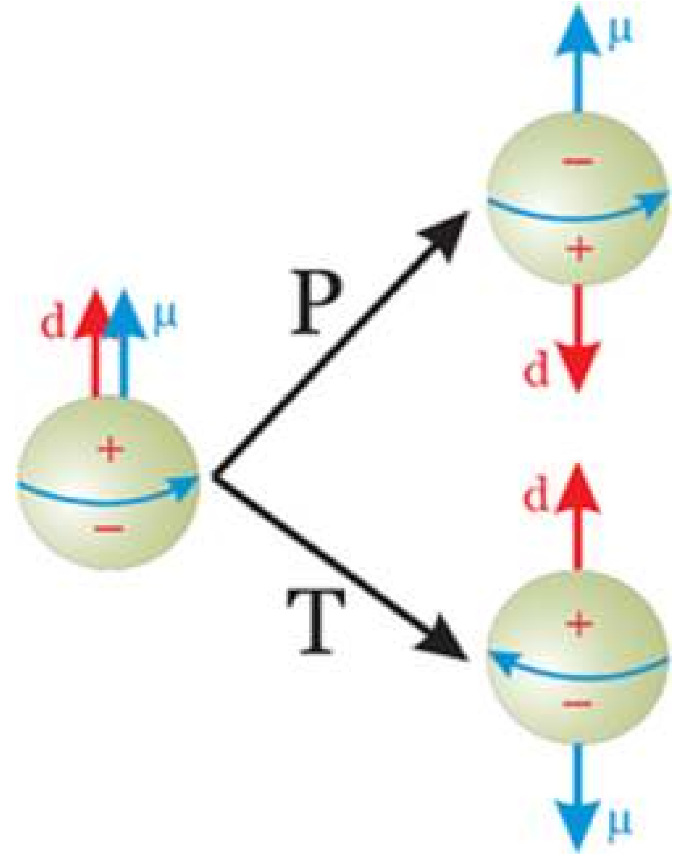
High Intensity/Precision Frontier

Search for a neutron EDM



EDM search describes promissing route for discovering new physics beyond the SM.





The classic picture of
P & T violation caused by an EDM

$$\mathcal{H} = -\mu \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} - d \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}$$

(non-relativistic interaction Hamiltonian)

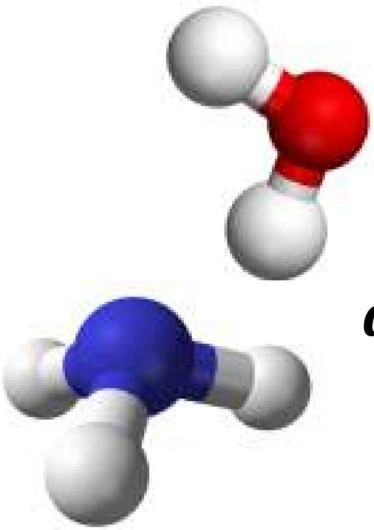
► A non-zero electric dipole moment (EDM) of a fundamental particle, e.g. of the neutron, violates parity (P) & time-reversal symmetry (T) *.

► With CPT conservation**, from T violation follows CP violation.

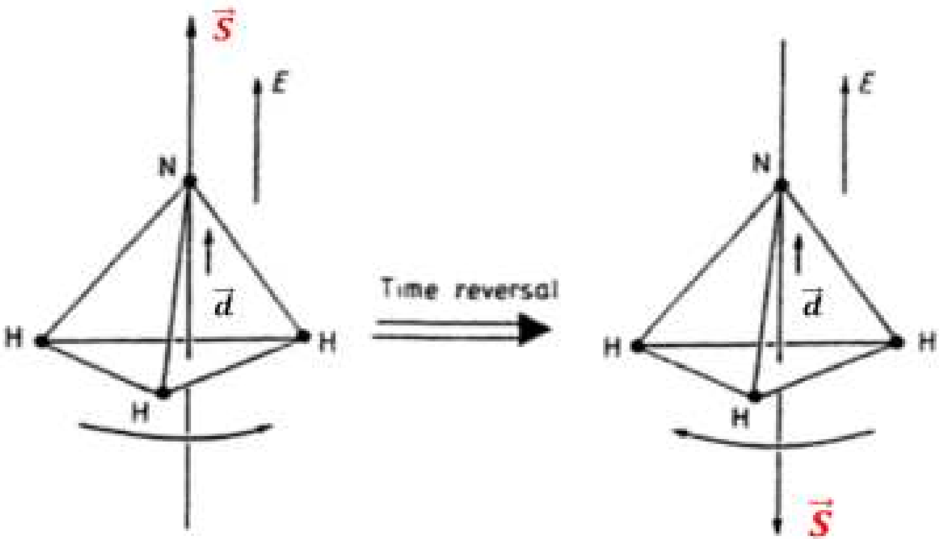
* Purcell & Ramsey, Phys. Rev. 78, 807 (1950)

** Lüders, Ann. Phys. 2, 1 (1957)

EDM of Polar Molecules



$$d_{H2O} \approx d_{NH3} \approx 10^{-8} \dots 10^{-9}\ \mathrm{e\ cm}$$



Polar molecules do NOT violate T or CP since they have degenerated states:

$$\vec{d} = \pm d \frac{\vec{S}}{|\vec{S}|}$$

This degeneracy allows them to have EDM's.

Electroweak SM expectation:

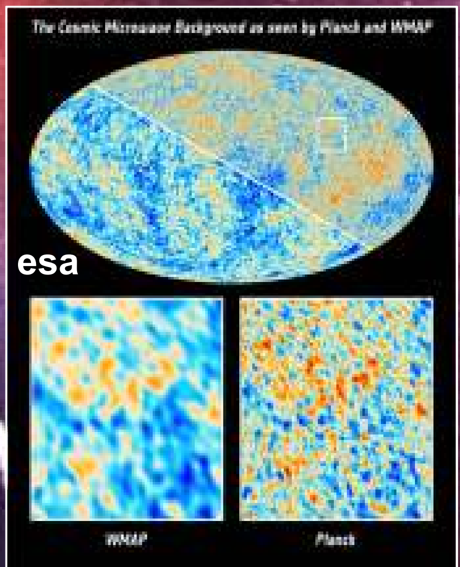
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

vs.

Observed*:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Connection between Cosmology and SM of Particle Physics !



Sakharov criteria for Baryogenesis in the early universe:

1. *Baryon number violation*
2. *C and CP violation*
3. *Thermal non-equilibrium*

JETP Lett. 5, 24 (1967)

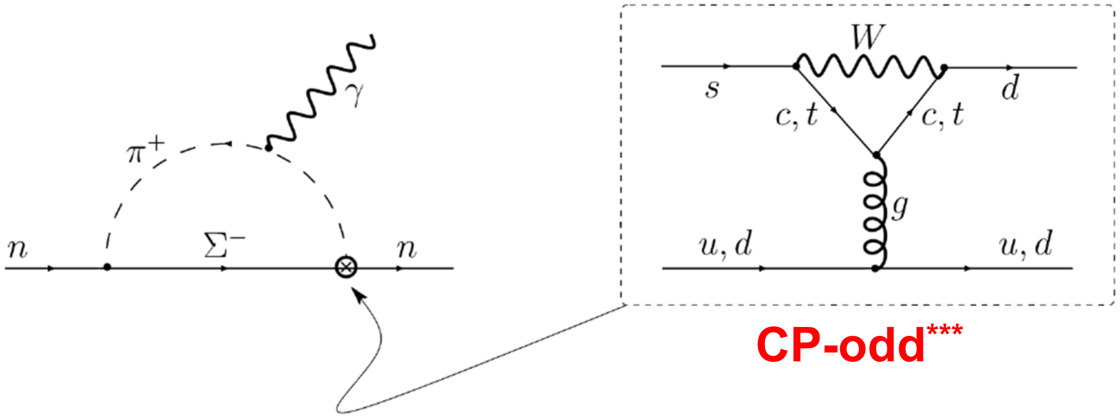
* e.g. WMAP, COBE, Planck

► Electroweak SM:

CP violation has been observed in weak interaction (K^0/B^0 systems) and is included in the SM via the phase δ in the quark mixing matrix (CKM).

However, the SM CP violation is very small and accounts for a neutron EDM of only about $10^{-31\pm1}$ e cm *,,***.**

$$\text{CKM} = \begin{bmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



* Mannel, Uraltsev, Phys. Rev. D 85, 096002 (2012)
** He, McKellar, Pakvasa, Int. J. Mod. Phys. A4, 5011 (1989)
*** Khriplovich, Zhitinitsky, Phys. Lett. B 109, 490 (1982)

► QCD – Strong CP-Problem:

QCD includes a CP violating term. The strength of the CP violation is characterized by the angle θ_{QCD}, which is expected to be of order one.

CP-odd 'θ-term'

$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\theta_{QCD}=0} + \frac{g^2}{32\pi^2}\theta_{QCD} G\tilde{G}$$

Gluon field

Lattice QCD*:

$$d_n^{QCD} = (-2.9 \pm 0.9) \cdot 10^{-16}\, \theta_{QCD} \text{ e cm}$$

$$d_p^{QCD} = (+1.1 \pm 1.1) \cdot 10^{-16}\, \theta_{QCD} \text{ e cm}$$

With current nEDM limit:** $\theta_{QCD} \lesssim 10^{-10}$

Why is θ_{QCD} so small ?

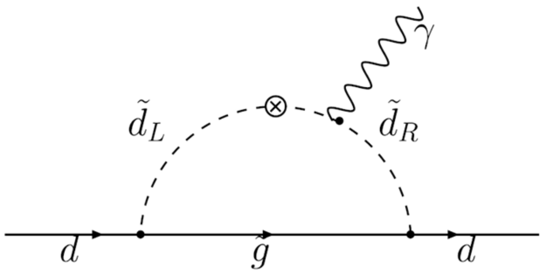
Axion's as a possible way out* ?!?!**

* Guo, Meissner, JHEP 12, 097 (2012)
** Baker et al., PRL 97, 131801 (2006)
*** Peccei & Quinn, PRL 38, 1440 (1977)

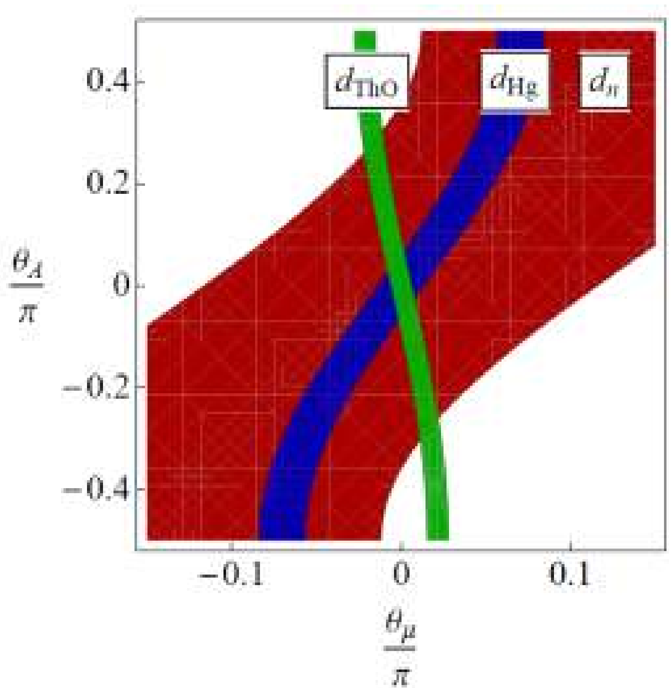
► SUSY CP-Problem:

$$d_n \approx 10^{-24}\ e\ cm \left(\frac{1\ TeV/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Probing for new physics at very high energies, even beyond the reach of large accelerators/colliders !



Why is ϕ_{SUSY} so small or M_{SUSY} so large ?

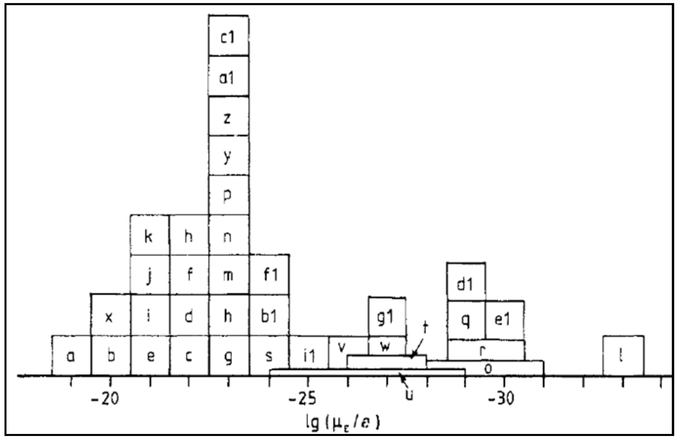


with: M_{SUSY} = 2 TeV, tan β = 3

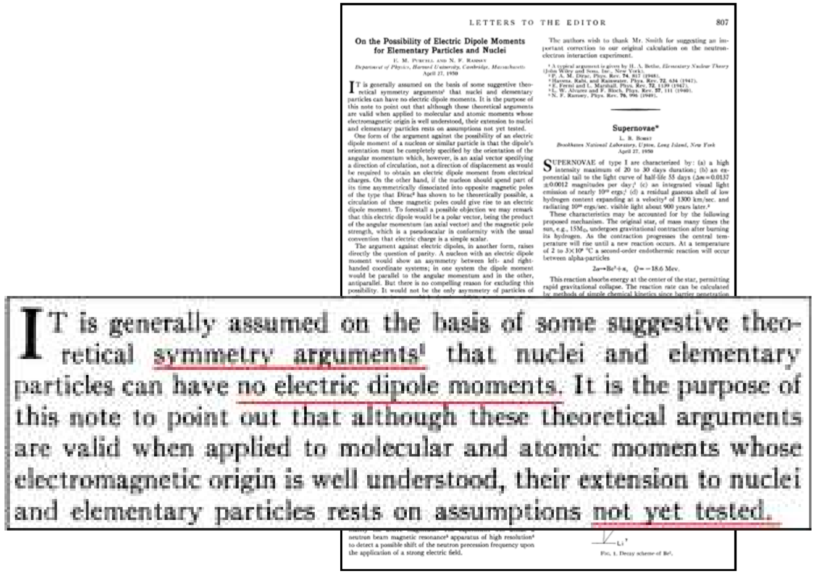
Combination of EDM constrains (e, n & Hg) to a constrain on CP violating SUSY phases

Pospelov, Ritz, Ann. Phys. 318, 119 (2005)

- ► Search for (neutron) EDM's has **ruled out many models of CP violation** – viable model must comply with EDM limits.
- ► EDM searches represent most promising probes for **beyond SM physics**. Small 'SM background' (complementary to LHC).
- ► Investigate different EDM's to learn about the origin of the CP violation (**e, μ, n, p, d, Hg, Xe**).



Ramsey, Rep. Prog. Phys. 45, 95 (1982)


LETTERS TO THE EDITOR 807

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

Supernovae*

IT is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

Ramsey, Phys. Rev. 87, 807 (1950)

- **First Ramsey measurement**

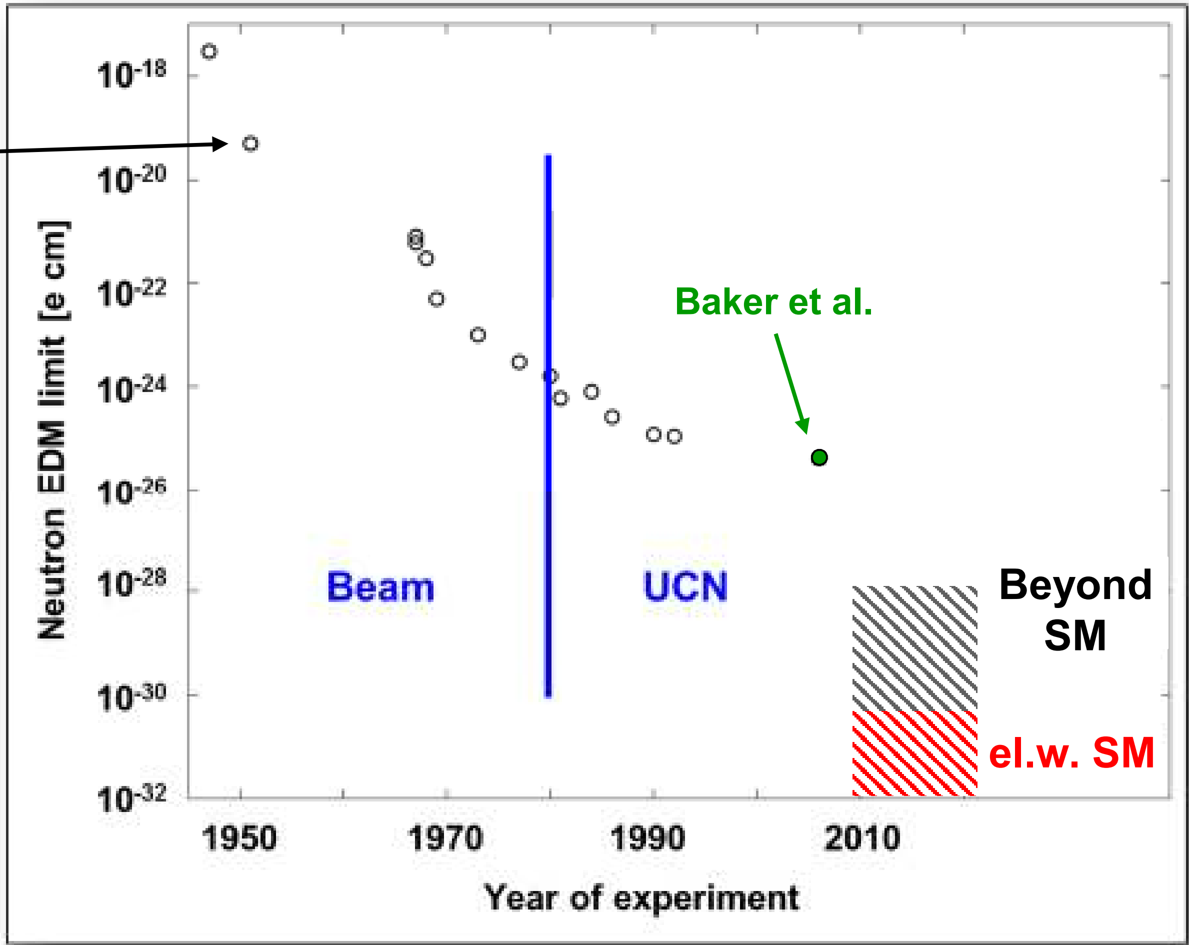
  Smith, Purcell & Ramsey, Phys. Rev. 108, 120 (1957)

- **Current limit:**

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

(90% CL)

Baker et al., PRL 97, 131801 (2006)



- **Several experiments world-wide, e.g. at PSI, SNS, FRM-2, LANL, TRIUMF and others, are aiming for improved sensitivities of about two orders of magnitude. All these efforts employ so-called ultracold neutrons.**

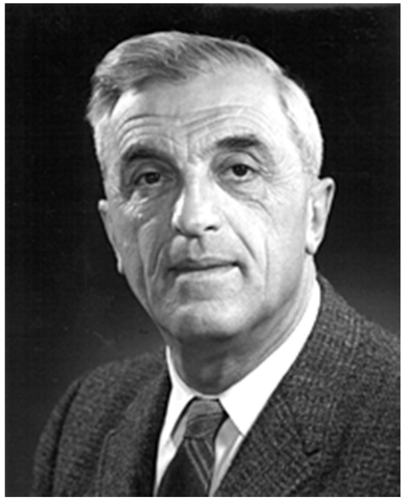
If a neutron were blown up to the size of the Earth, the current limit (3×10^{-26} ecm) on its EDM would correspond to a displacement of the positive and negative charge by about 10 µm.

► Rabi’s & Ramsey’s Method

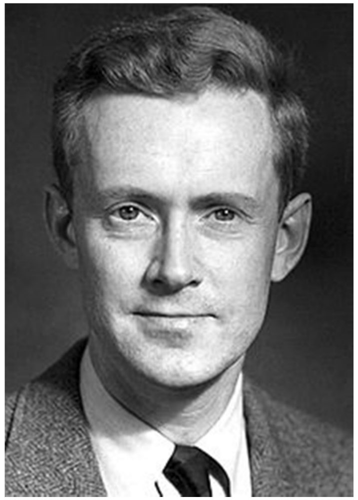
Isidor Rabi

Nobel Prize 1944

Molecular beam resoance method



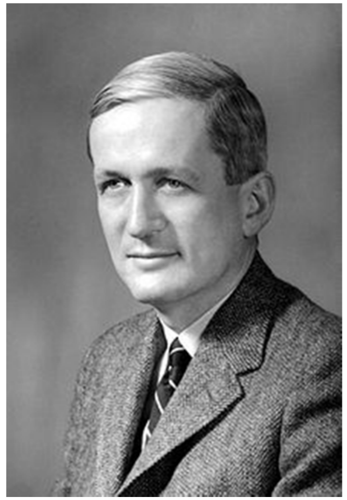
Felix Bloch



Edward Purcell

Nobel Prize 1952

Nuclear Magnetic Resonance (NMR)



Norman Ramsey

Nobel Prize 1989

Ramsey method

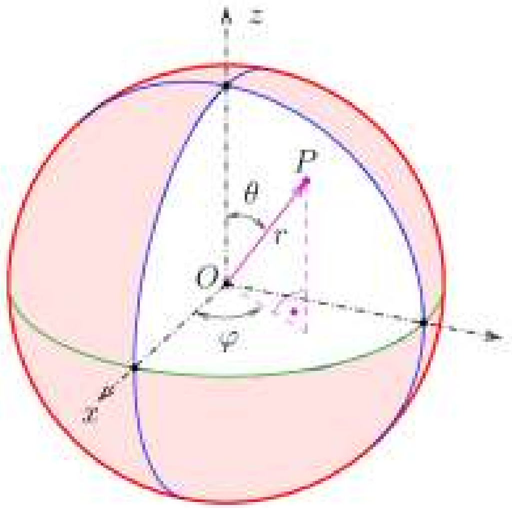
- **Bloch Equation:** Describes the interaction of a spin, i.e. a magnetic moment, with a magnetic field (here no relaxation):

$$\frac{\partial}{\partial t}\langle\vec{\mu}\rangle = \gamma\,\langle\vec{\mu}\rangle \times \vec{B}$$

$$\vec{\mu} = \gamma\frac{\hbar}{2}\vec{\sigma} = \gamma\vec{S}$$

Gyromagnetic Ratio

Vector of the Pauli matrices



$$\psi = \begin{pmatrix} e^{-i\varphi/2} cos\left(\frac{1}{2}\theta\right) \\ e^{+i\varphi/2} sin\left(\frac{1}{2}\theta\right) \end{pmatrix}$$

Most general representation of a Pauli Spinor

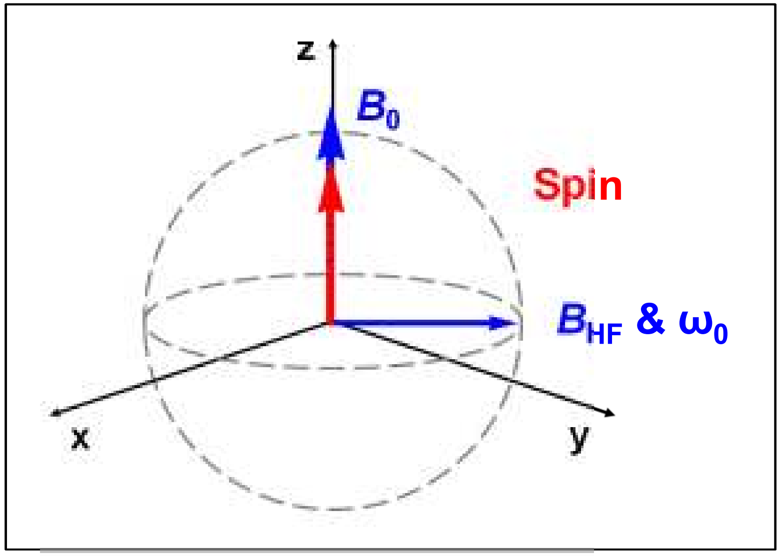
$$\langle\psi\,|\vec{\sigma}|\,\psi\rangle = \begin{pmatrix} sin(\theta)cos(\varphi) \\ sin(\theta)sin(\varphi) \\ cos(\theta) \end{pmatrix}$$

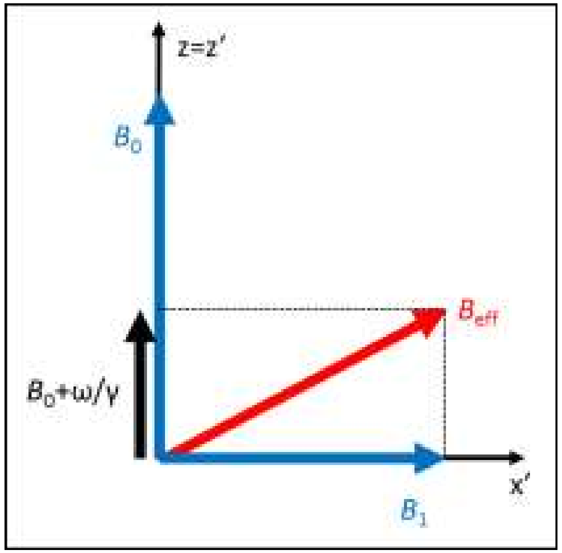
Expectation value of the Pauli Spinor

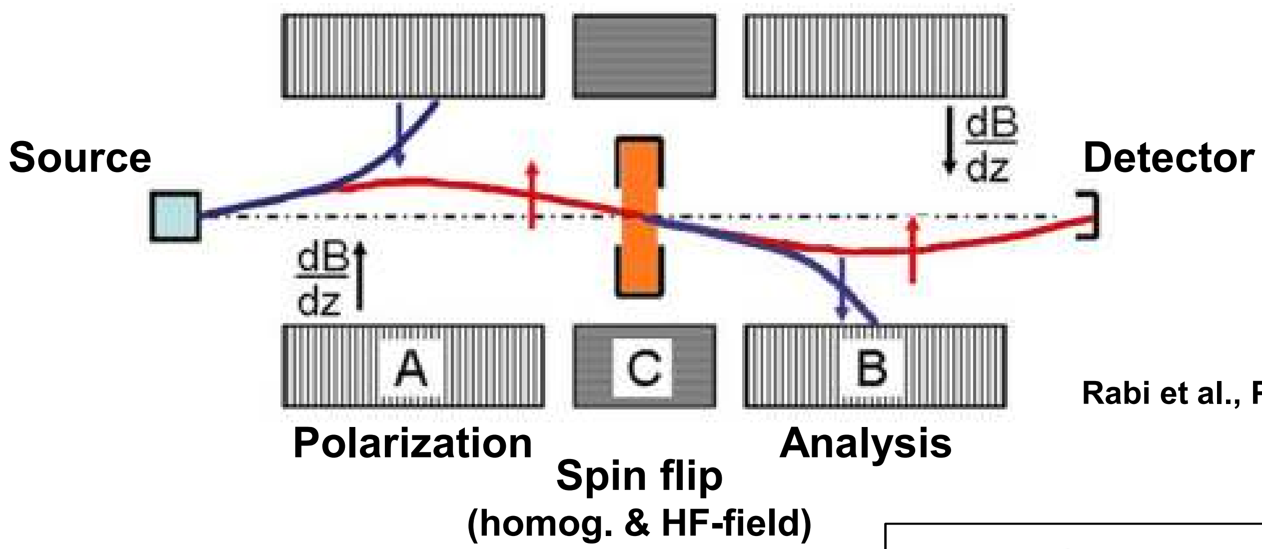
- **Rotating Frame:** When applying a circular oscillating field it is often easier to transform the problem into the so-called 'Rotating frame' system. The Bloch equ. becomes:

$$\frac{\delta}{\delta t}\langle\vec{\mu}\rangle = \gamma\,\langle\vec{\mu}\rangle \times \left(\vec{B} + \vec{\Omega}/_{\gamma}\right) = \gamma\,\langle\vec{\mu}\rangle \times \vec{B}_{eff}$$

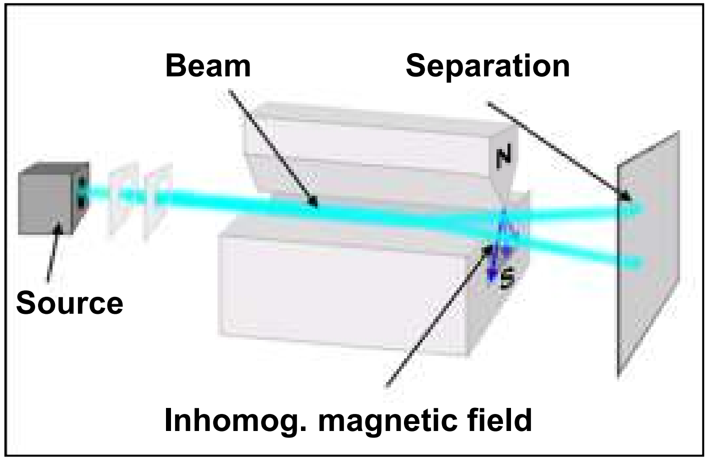
Transformed Bloch Equation





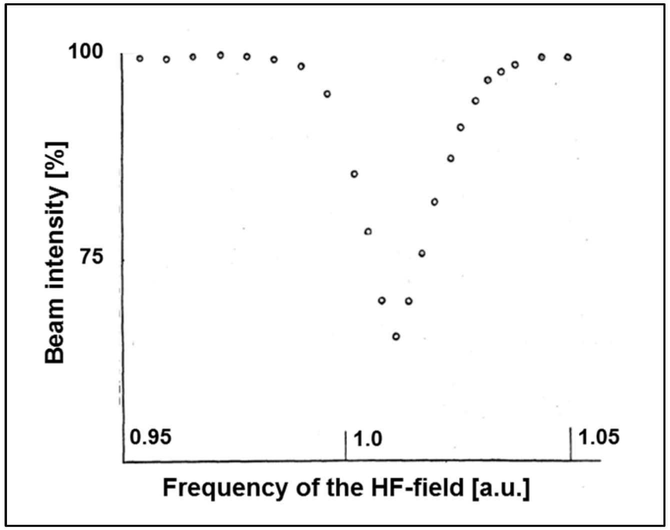


Rabi et al., PR 53, 318 (1938)



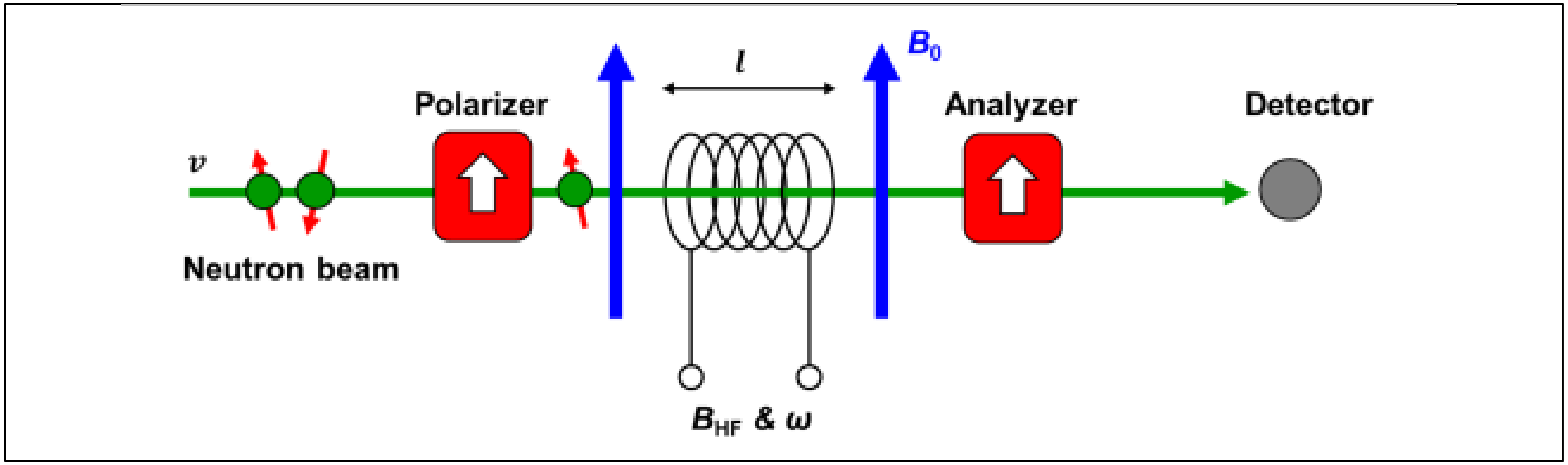
Stern-Gerlach setup as Polarizer

$$\vec{F} = \pm |\vec{\mu}| \nabla |\vec{B}|$$

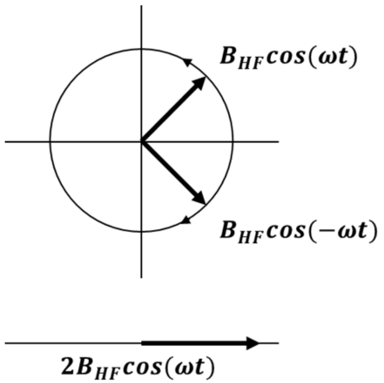


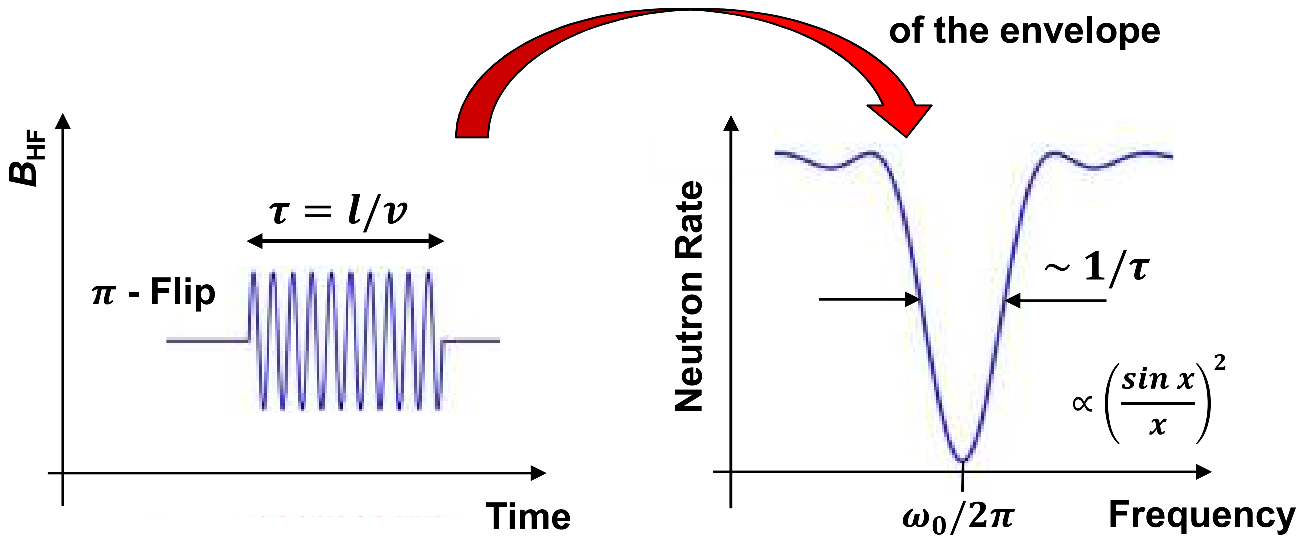
Resonance of ^{7}Li in LiCl

Rabi Experiment with Neutrons

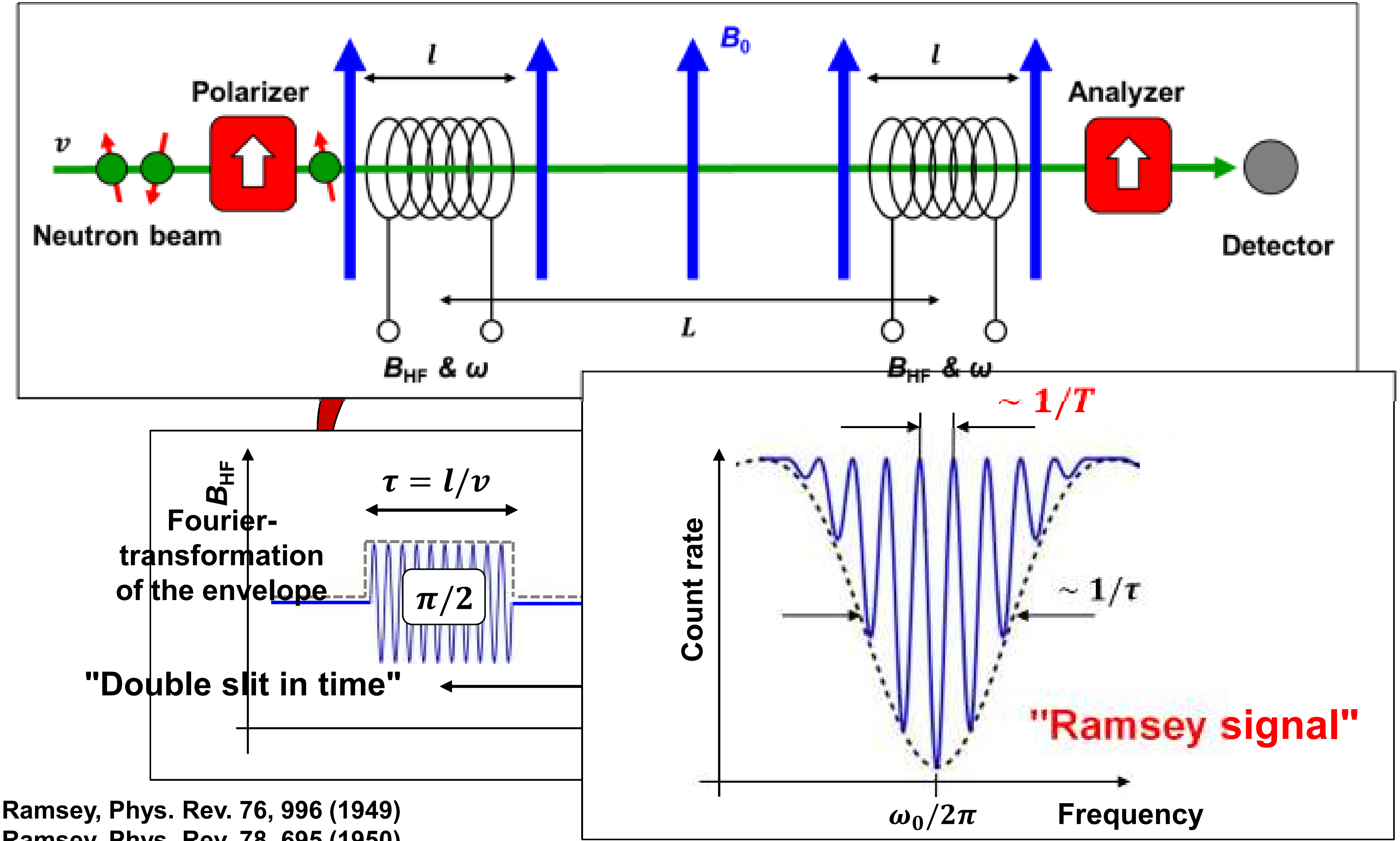


Fourier transformation of the envelope



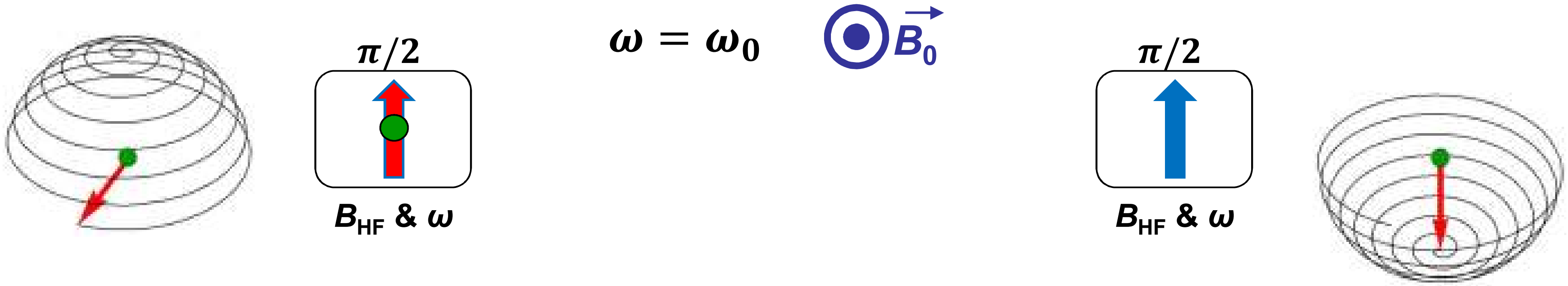


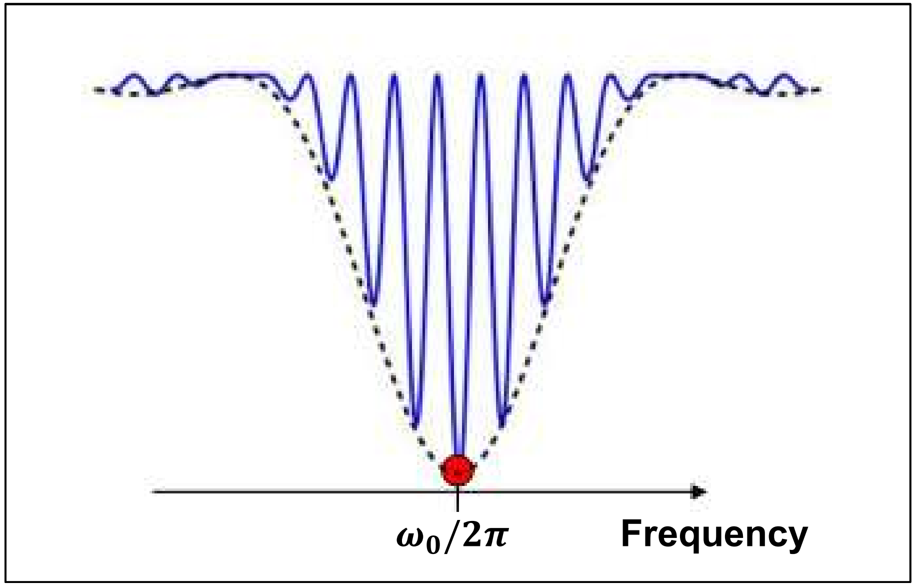
Divide the π-pulse into two separate, phase-locked $\pi/2$-pulses:



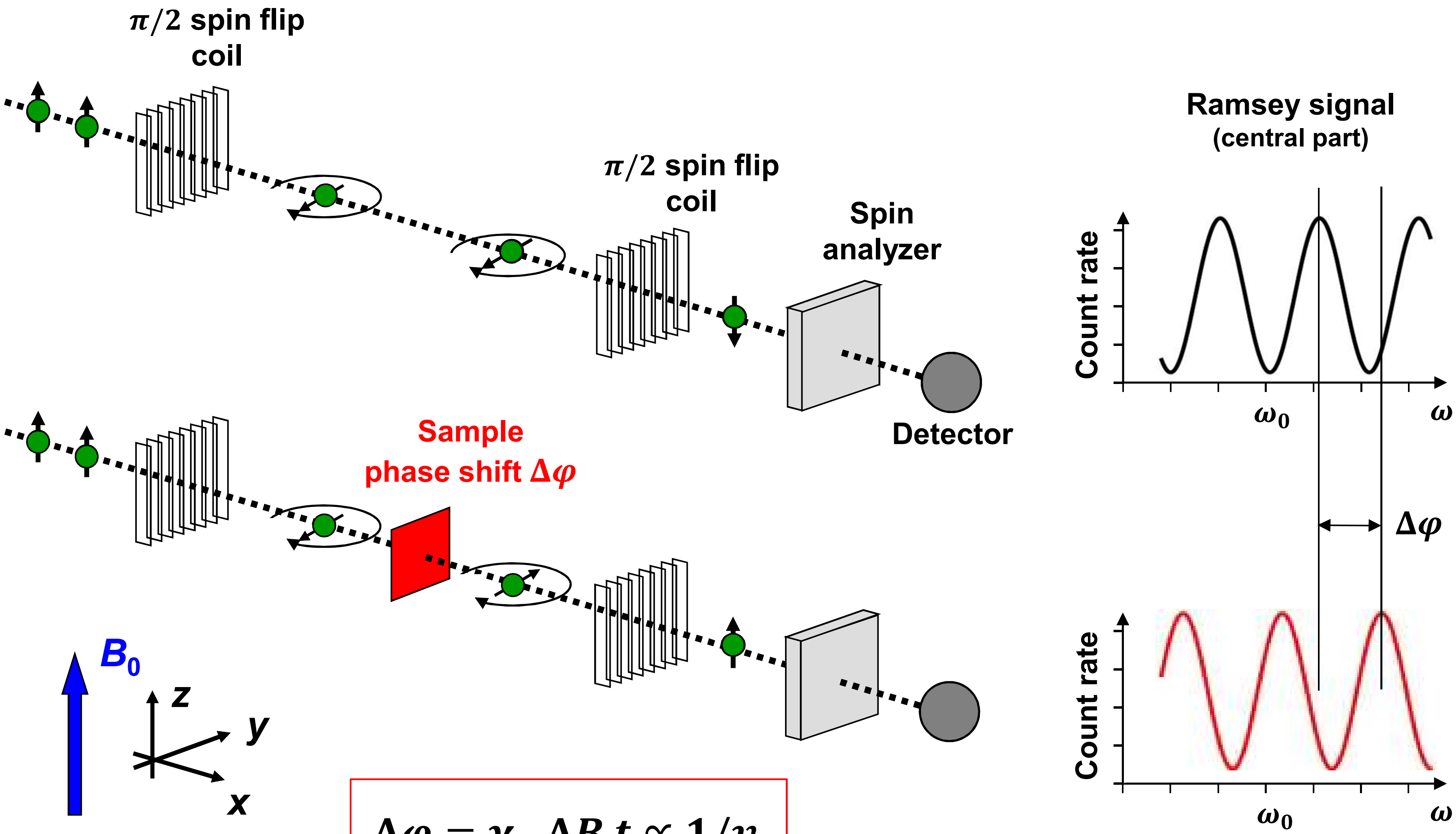
Ramsey, Phys. Rev. 76, 996 (1949)
Ramsey, Phys. Rev. 78, 695 (1950)

Why does the Ramsey signal shows this pattern ?



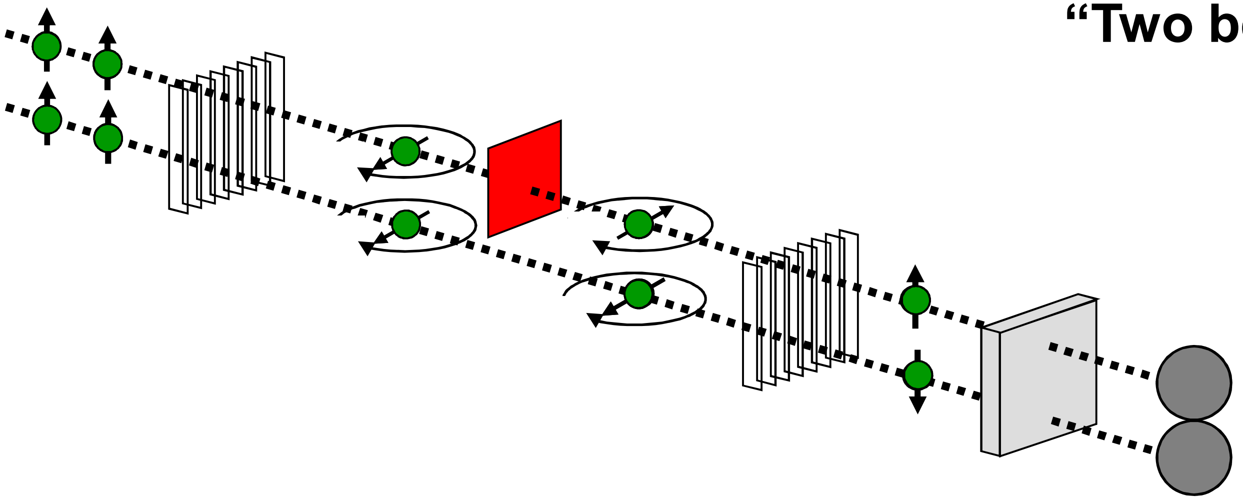


Clock comparison between neutron spin and HF signal.

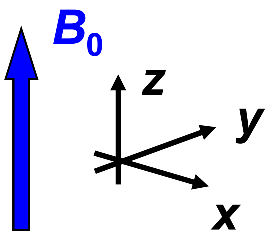


$$\Delta\varphi = \gamma_n \, \Delta B \, t \propto 1/v$$

ΔB: change of the field in the sample



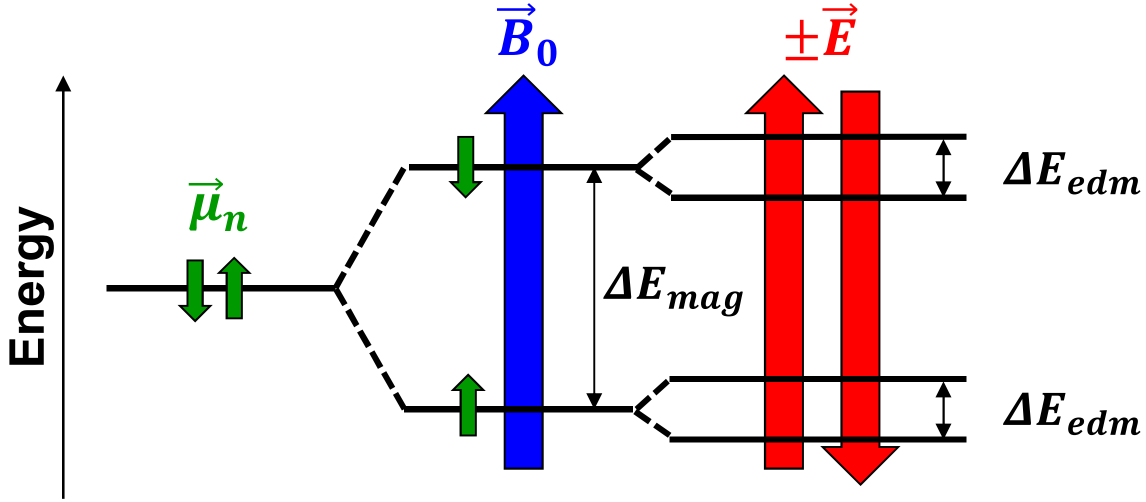
"Two beam method"



Suppression of common noise / global drifts
(global magnetic field, HF-phase, temperature etc.)

But, susceptible to drifting magn. field gradients !

► How to Measure a Neutron EDM



$$\mathcal{H} = -\vec{\mu}\cdot\vec{B}_0 - \vec{d}\cdot\vec{E}$$

$$\Delta E_{mag} = \hbar\omega_{mag} = 2\mu_n B_0 \quad \text{with: } \mu_n = \tfrac{1}{2}\hbar\gamma_n$$

$$\Delta E_{edm} = \hbar\omega_{edm} = 2 d_n E$$

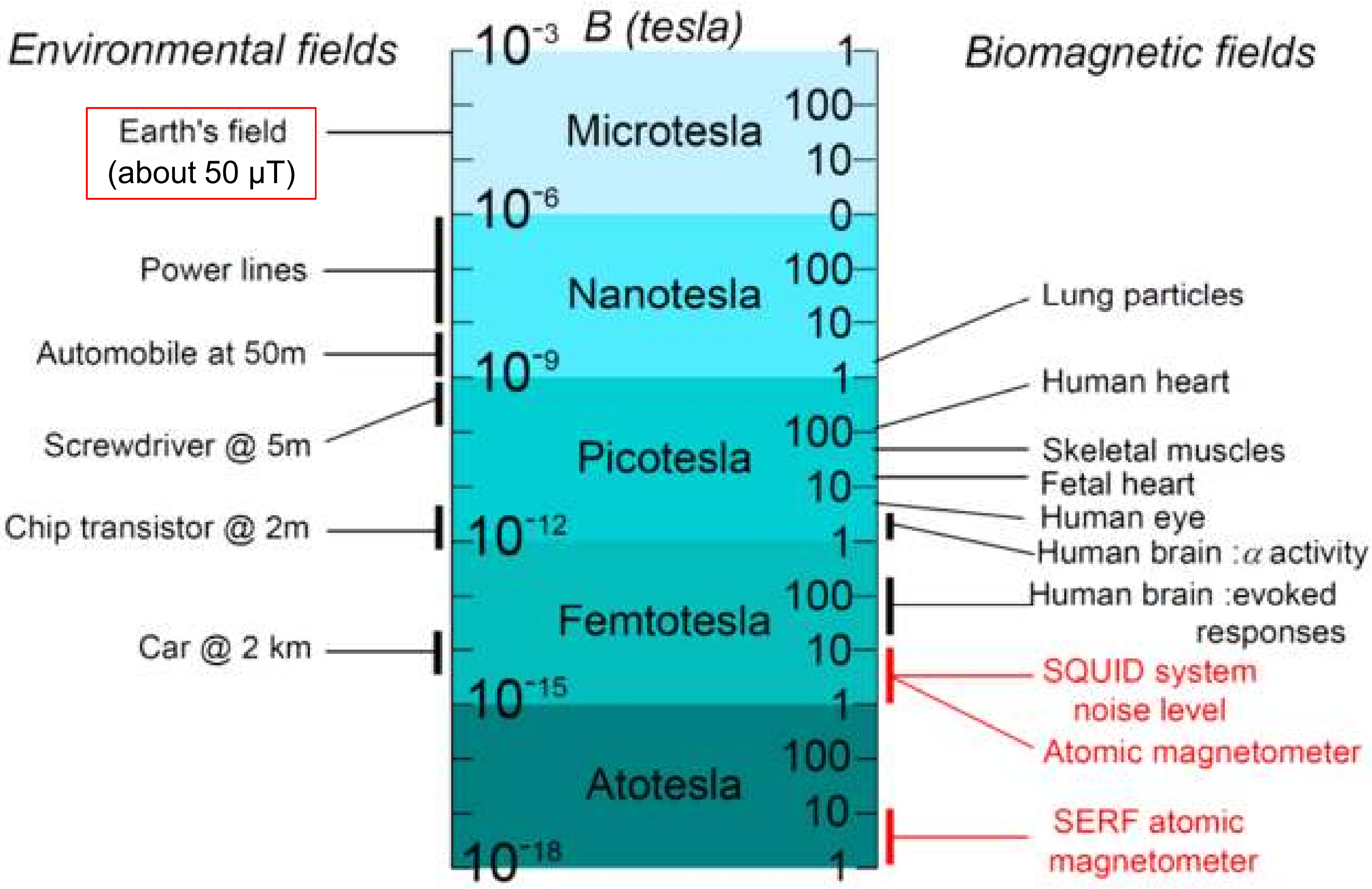
$B_0 \upuparrows E$ ⇨ $\hbar\omega_{\upuparrows} = \hbar\left(\omega_{mag} + \omega_{edm}\right) = 2\cdot(\mu_n B_0 + d_n E)$

$B_0 \uparrow\downarrow E$ ⇨ $\hbar\omega_{\uparrow\downarrow} = \hbar\left(\omega_{mag} - \omega_{edm}\right) = 2\cdot(\mu_n B_0 - d_n E)$

$$\hbar(\omega_{\upuparrows} - \omega_{\uparrow\downarrow}) = 4\, d_n E$$

← for B_0 = const.

How stable the Magnetic Field has to be ?



How stable the Magnetic Field has to be ?

- $\hbar\Delta\omega = 4\, d_n E + 2\mu_n \Delta B$

Magnetic field change during electric field polarity change

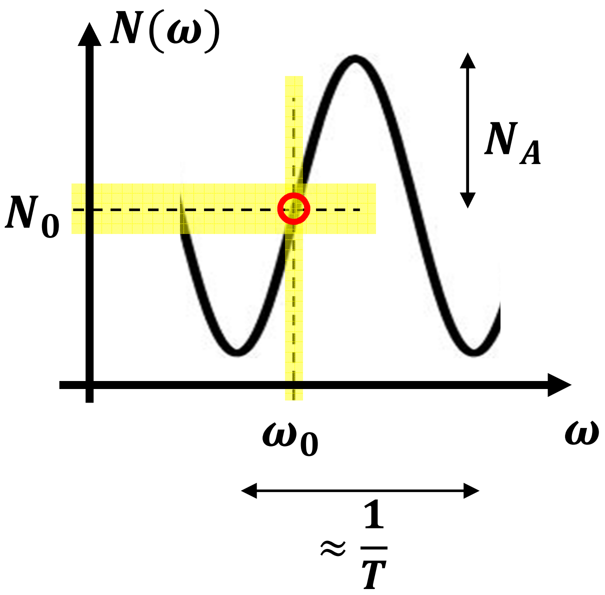
- $$d_{n,false} = \frac{\hbar\gamma_n}{4E} \cdot \Delta B$$

E = 1 MV/m

$d_{n,false} = 3 \times 10^{-27}$ e cm with: $\Delta B = 1$ fT

- **Is it necessary to stabalize the field on the below fT level ???**

YES	**NO**
for effects correlated with *E*-field direction, e.g. leakage currents, magnetisation due to charging of electrodes (gradients), geom. phases etc.	**for random noise effects, which will average out over time. However, …**



"visibility"

$$N(\omega) = N_0\left[1 + \eta \sin\left((\omega - \omega_0)T\right)\right] \qquad \text{with: } \eta = \frac{N_A}{N_0} \leq 1$$

$$\left.\frac{\partial N(\omega)}{\partial \omega}\right|_{\omega=\omega_0} = N_0 \eta T = \frac{\sigma_N}{\sigma_{\omega_0}} = \frac{\sqrt{N_0}}{\sigma_{\omega_0}} \qquad \text{slope at } \omega = \omega_0$$

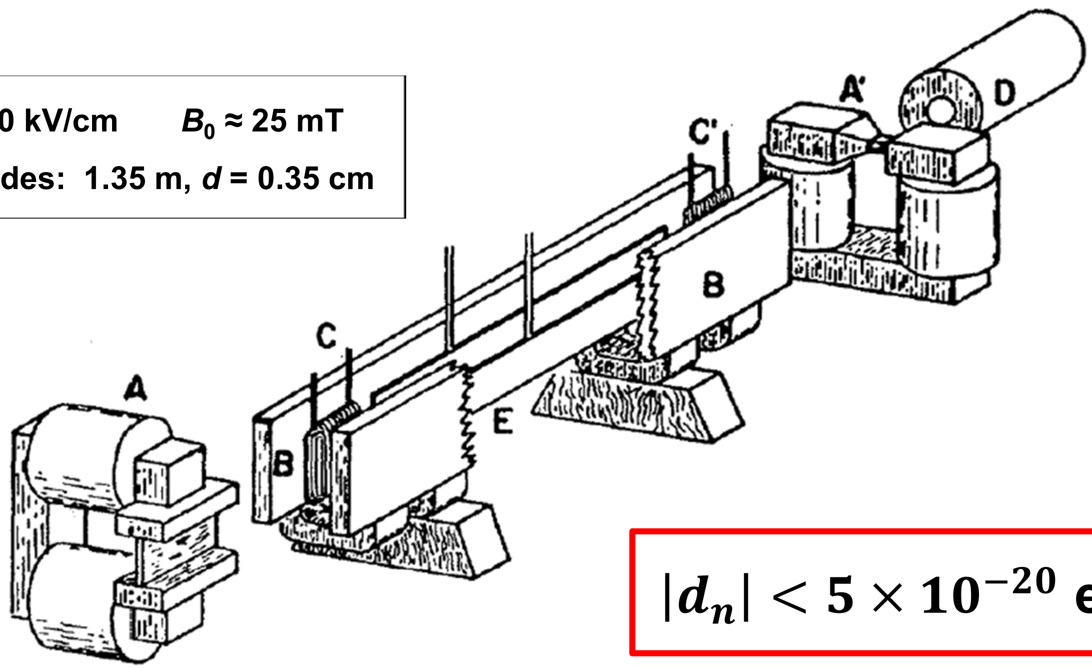
$$\Rightarrow \boxed{\sigma_{\omega_0} = \frac{1}{\eta T \sqrt{N_0}}}$$

► We want to measure a frequency/phase shift, i.e. make **two measurements** each with for instance ${N_0}/{2}$ detected neutrons:

$$\left.\begin{aligned} \sigma_{\Delta\omega} &= \frac{\sqrt{2} \cdot \sqrt{2}}{\eta T \sqrt{N_0}} \\ \Delta\omega &= \frac{4 d_n E}{\hbar} \end{aligned}\right\} \Rightarrow \boxed{\sigma(d_\mathrm{n}) = \frac{\hbar}{2 \eta T E \sqrt{N_0}}}$$

$E \approx 70$ kV/cm $B_0 \approx 25$ mT

Electrodes: 1.35 m, $d = 0.35$ cm

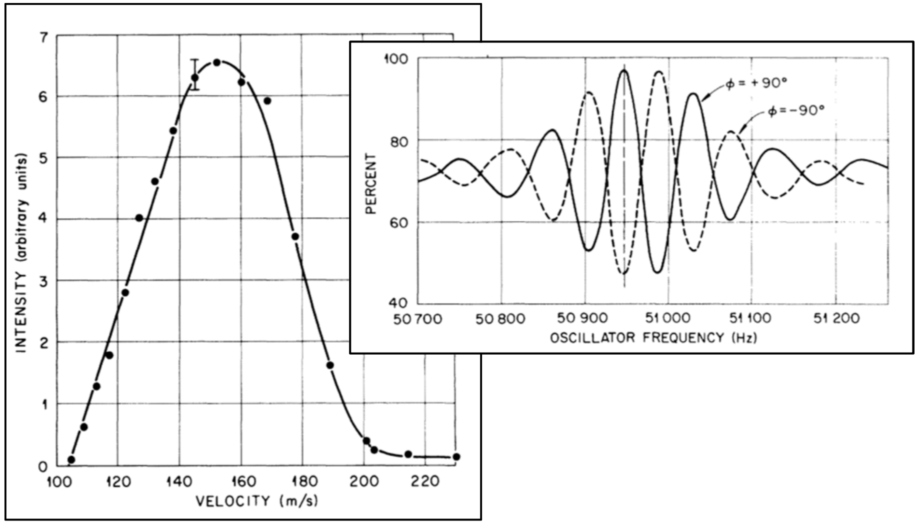


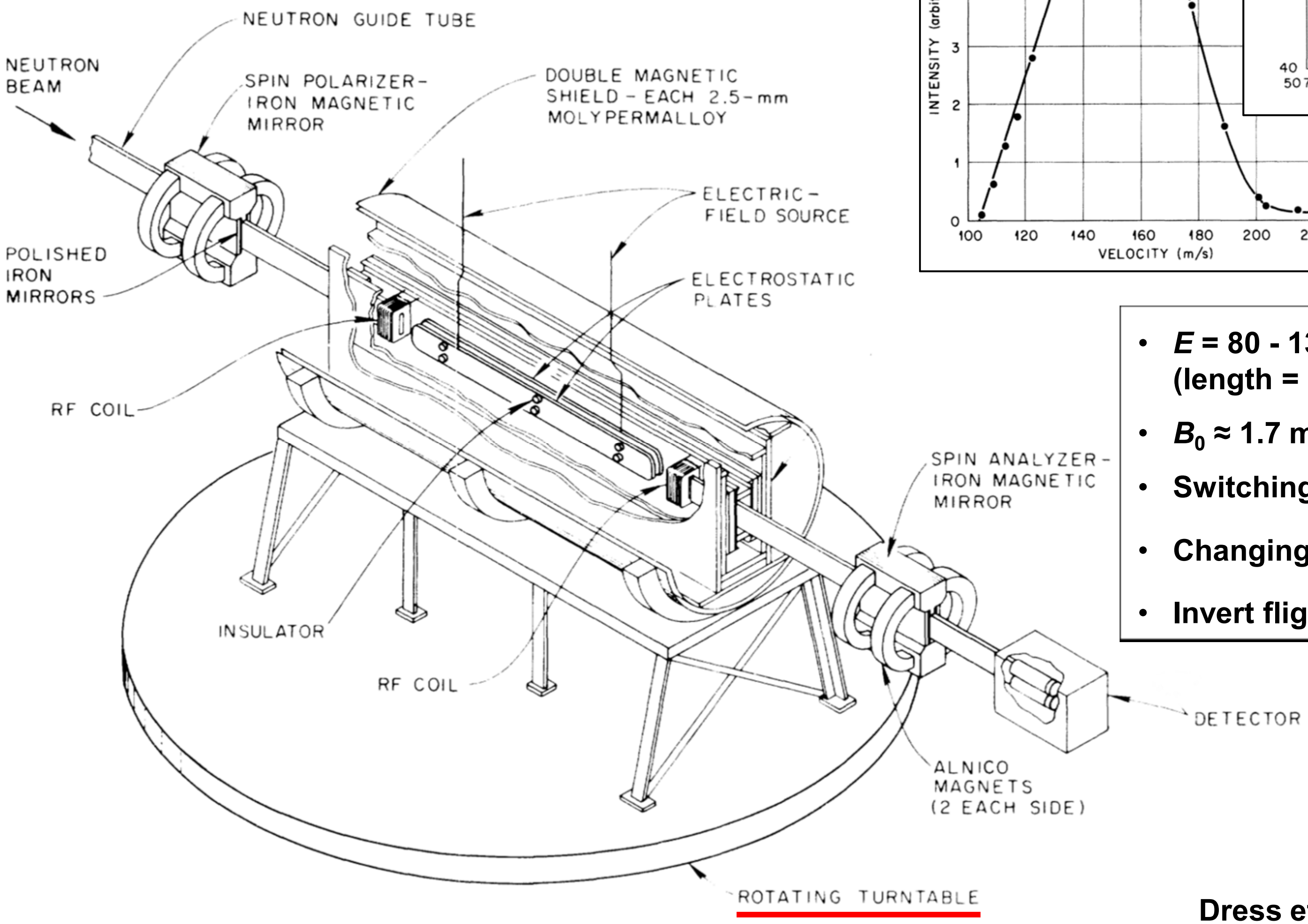
$|d_n| < 5 \times 10^{-20}$ e cm

FIG. 1. Schematic diagram of the apparatus. *A*, the magnetized iron mirror polarizer. *A'*, the magnetized iron transmission analyzer. *B*, the pole faces of the homogeneous field magnet. Note the horseshoe-like magnets bolted along the bottom. *C*, *C'*, the coils for the radio-frequency magnetic field. *D*, the BF_3 neutron counter. The magnetic fields in the polarizing magnet and the homogeneous field magnet are at right angles, and two twisted iron strips were used between them to rotate the neutron spins adiabatically.

Smith, Purcell, Ramsey, Phys. Rev. 108, 120 (1957)

$$|d_n| < 3 \times 10^{-24}\ \text{e cm} \quad (90\%\ \text{CL})$$





- E = 80 - 130 kV/cm (length = 1.8 m, gap = 1 cm)
- $B_0 \approx$ 1.7 mT (permanent magnets)
- Switching HV polarity every 200 s
- Changing RF-phase every 2 s ($+\frac{\pi}{2} \rightarrow -\frac{\pi}{2}$)
- Invert flight direction every other day

Dress et al., Phys. Rev. D 15, 9 (1977)

In general:

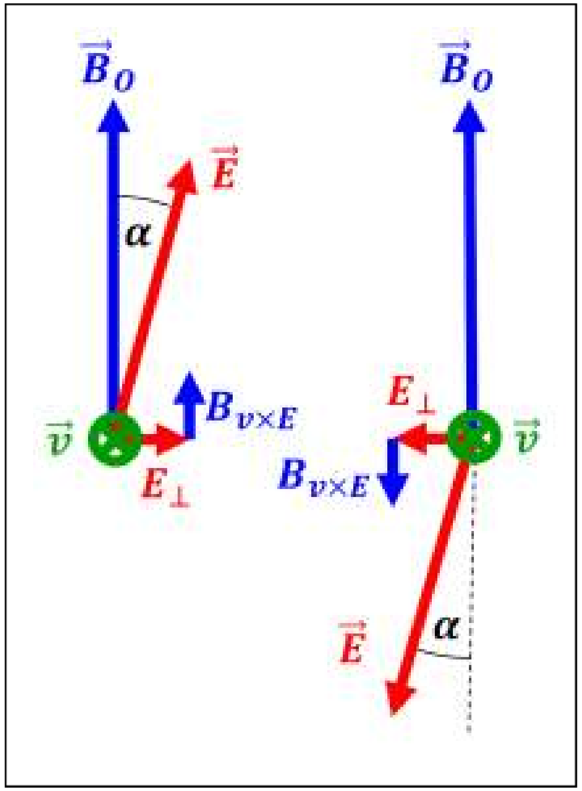
$$\vec{B} = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} + \begin{pmatrix} \delta B_x \\ \delta B_y \\ \delta B_z \end{pmatrix} \qquad |\vec{B}| \approx B_0 + \delta B_z + \underbrace{\frac{\delta B_x^2 + \delta B_y^2}{2\,B_0}}_{\text{transversal fields}} - \frac{\delta B_z \cdot (\delta B_x^2 + \delta B_y^2)}{2\,B_0^2} + \ \ldots$$

Relativistic *v×E* - effect (seen by moving neutron):

$$\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}$$

$$|\vec{B}| \approx B_0 + \frac{vE}{c^2}\sin\alpha + \frac{1}{2B_0}\left(\frac{vE}{c^2}\right)^2 + \ \ldots$$

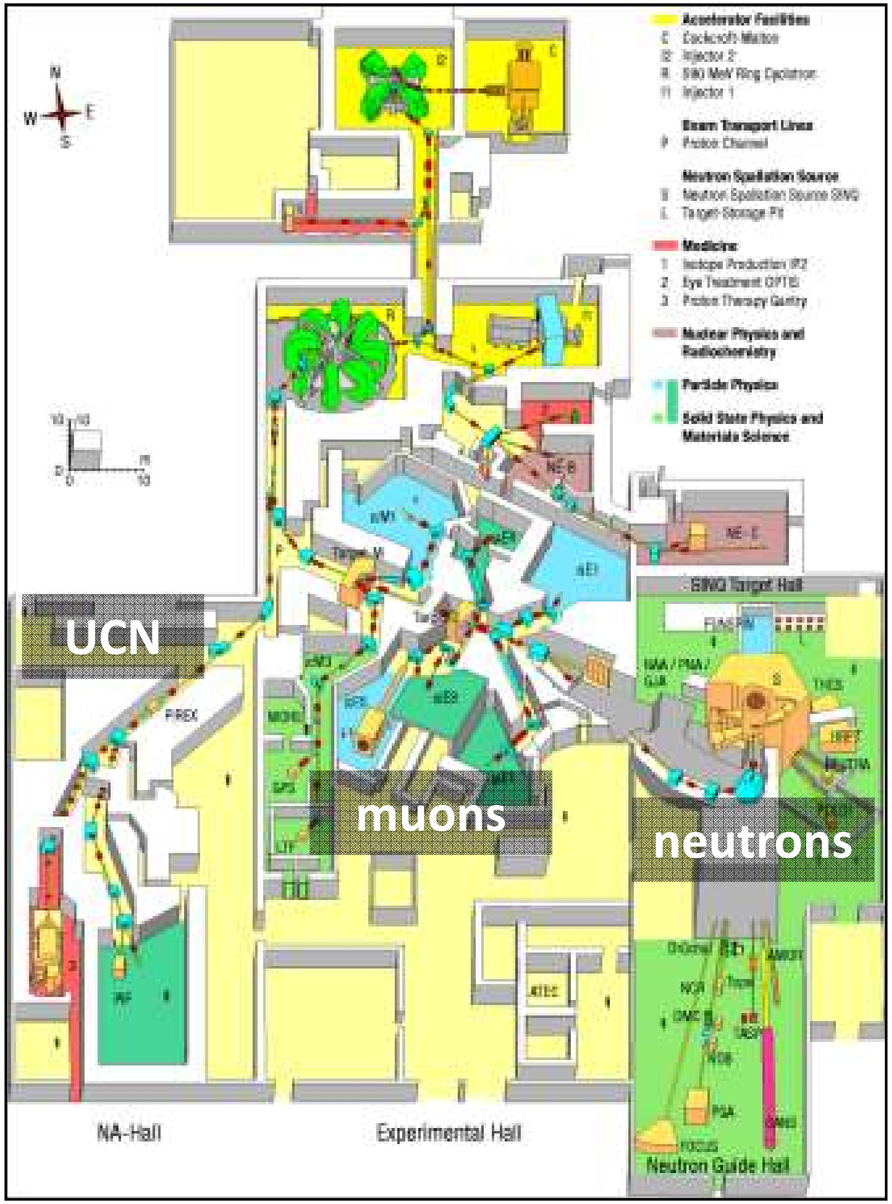
- *v×E* effect is velocity dependent !
- $d_{\text{n,false}} \approx 10^{-20}\ \text{e cm} \cdot \sin\alpha$ for: $v = 100$ m/s
- 2nd order term non-zero, even if $\alpha = 0$.
- Elsewhere effect responsible for spin-orbit coupling in atoms

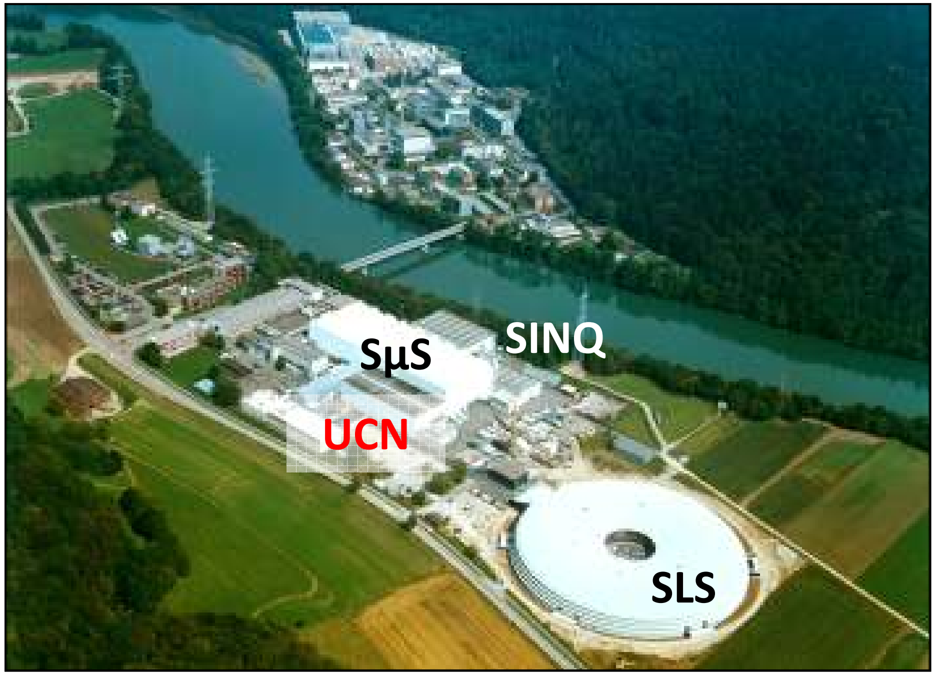


	Beam	UCN
Pro's	▶ Usually much larger *E*-fields ▶ More neutrons / Statistics ▶ Well-established neutron optics technology	▶ Lower velocity – *v*×*E*-effect smaller ▶ Much larger interaction times *T* (about 100 sec instead of 100 ms) ▶ Limited dimension – easier to control the magnetic field
Con's	▶ *v*×*E*-effect, however … ▶ Beam specific systematic effects	▶ UCN density still low ▶ UCN specific systematic effects due to gravity, wall collisions, and confinement (e.g. geometric phase) ▶ E-field is limited due to leakage currents & discharges

$$\sigma(d_{\mathrm{n}}) = \frac{\hbar}{2\eta T E \sqrt{N}}$$

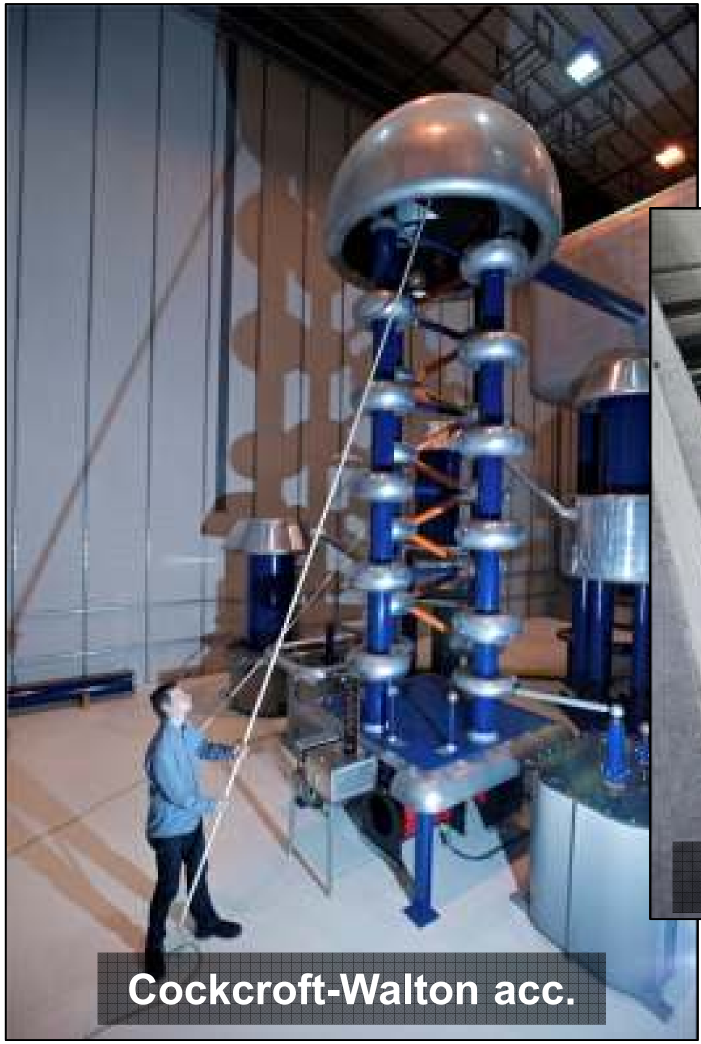
► Neutron EDM Experiment at PSI





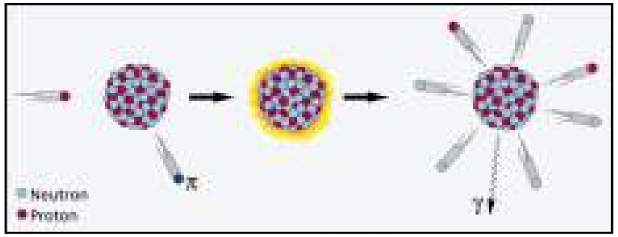
590 MeV × 2.2 mA = 1.3 MW

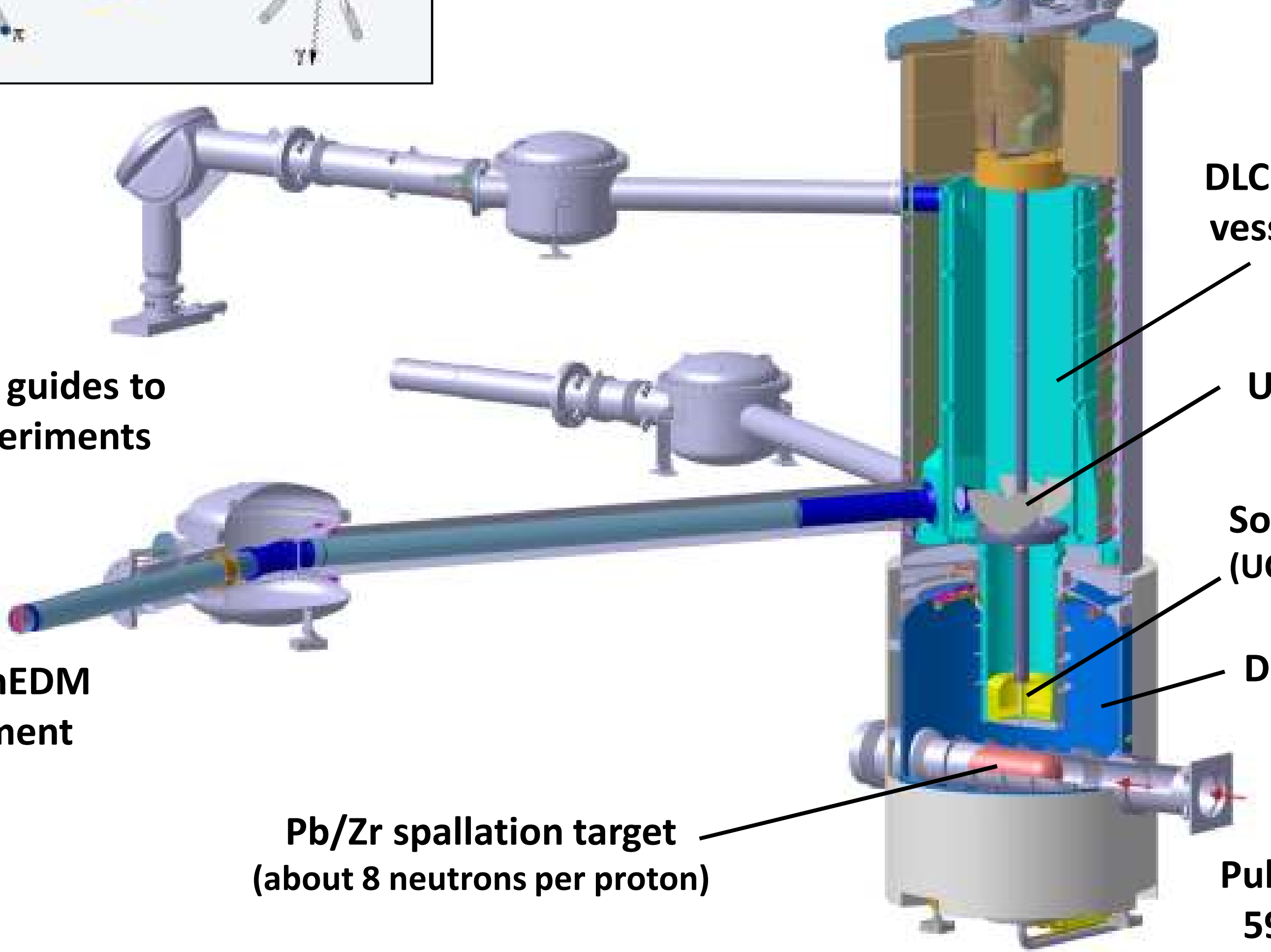
proton current 10^{16} p+/s



1. Stage: Cockcroft-Walton accelerator (800 keV)
2. Stage: "Injektor-2" – small ring cyclotron (72 MeV, 37% c)
3. Stage: Large Ring Cyclotron (590 MeV, 80% c)

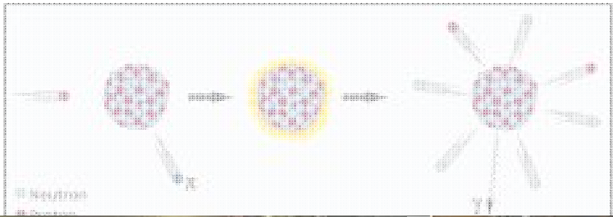
Solid Deuterium UCN source at PSI





Designed for 1000 UCN cm^{-3} - currently about 30 UCN cm^{-3}
Running since 2012

Solid Deuterium UCN source at PSI

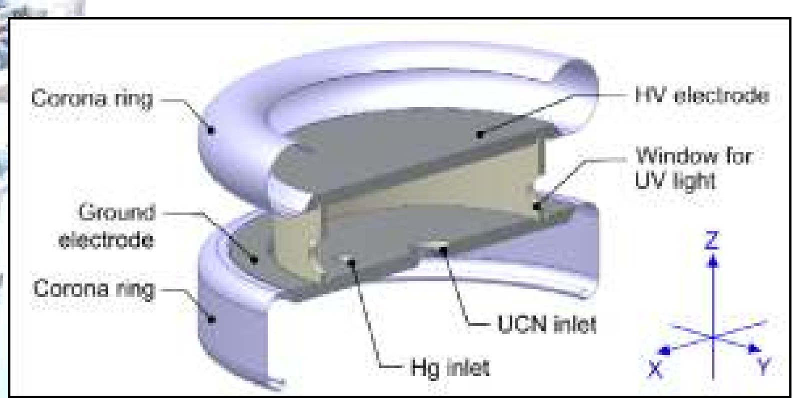


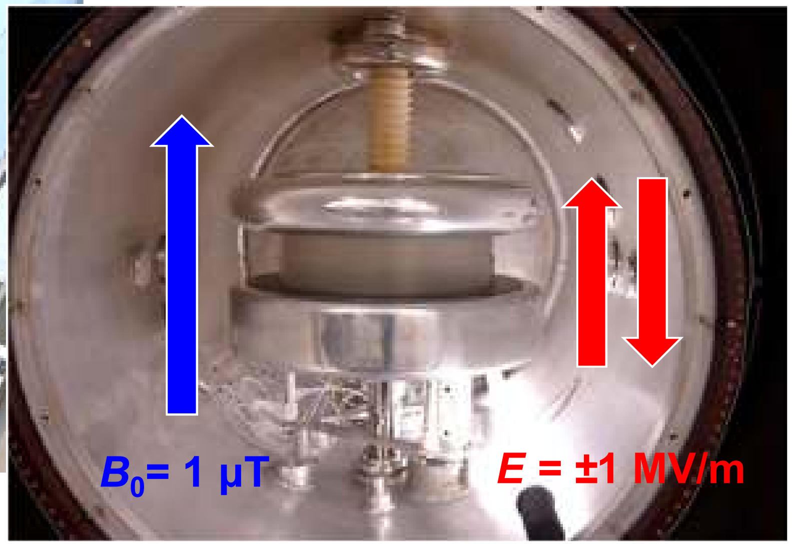
Pb/Zr spallation target
(about 8 neutrons per proton)

oton beam
V, 2.2 mA
pulse length = sec)

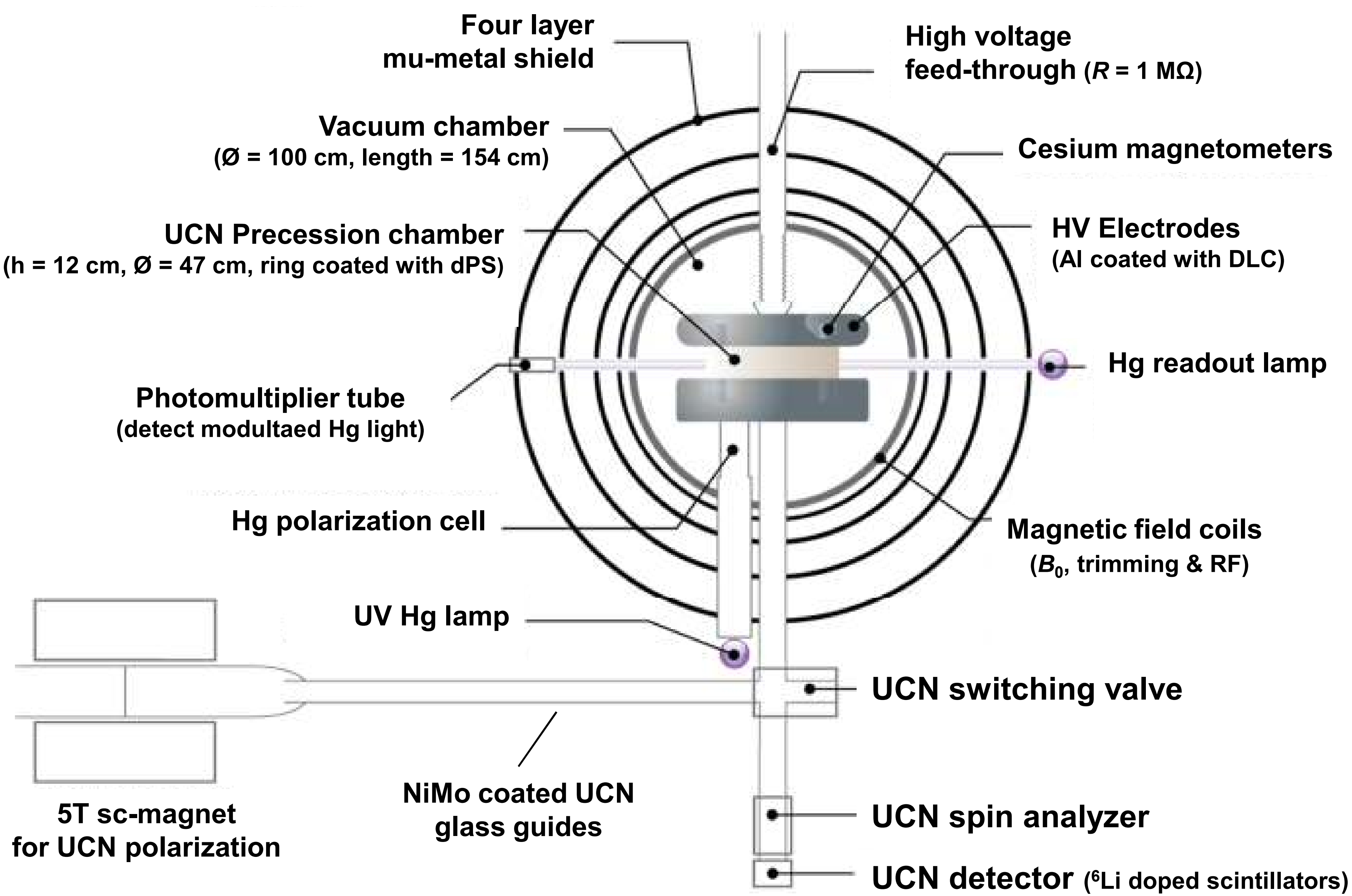
Designed for 1000 UCN cm^{-3} - currently about 30 UCN cm^{-3}
Running since 2012

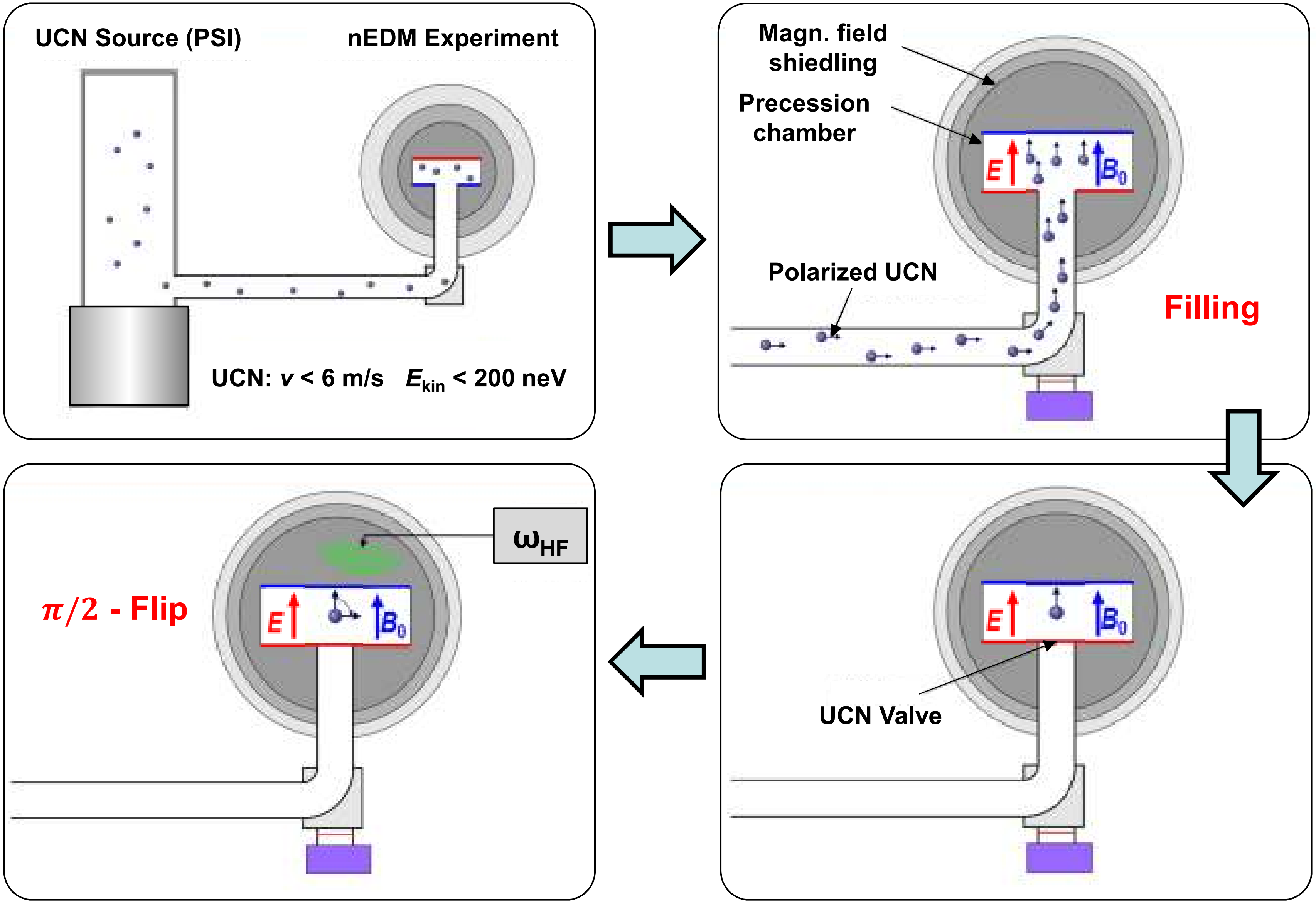
Improved setup of the old RAL/Sussex/ILL Experiment ('oILL')



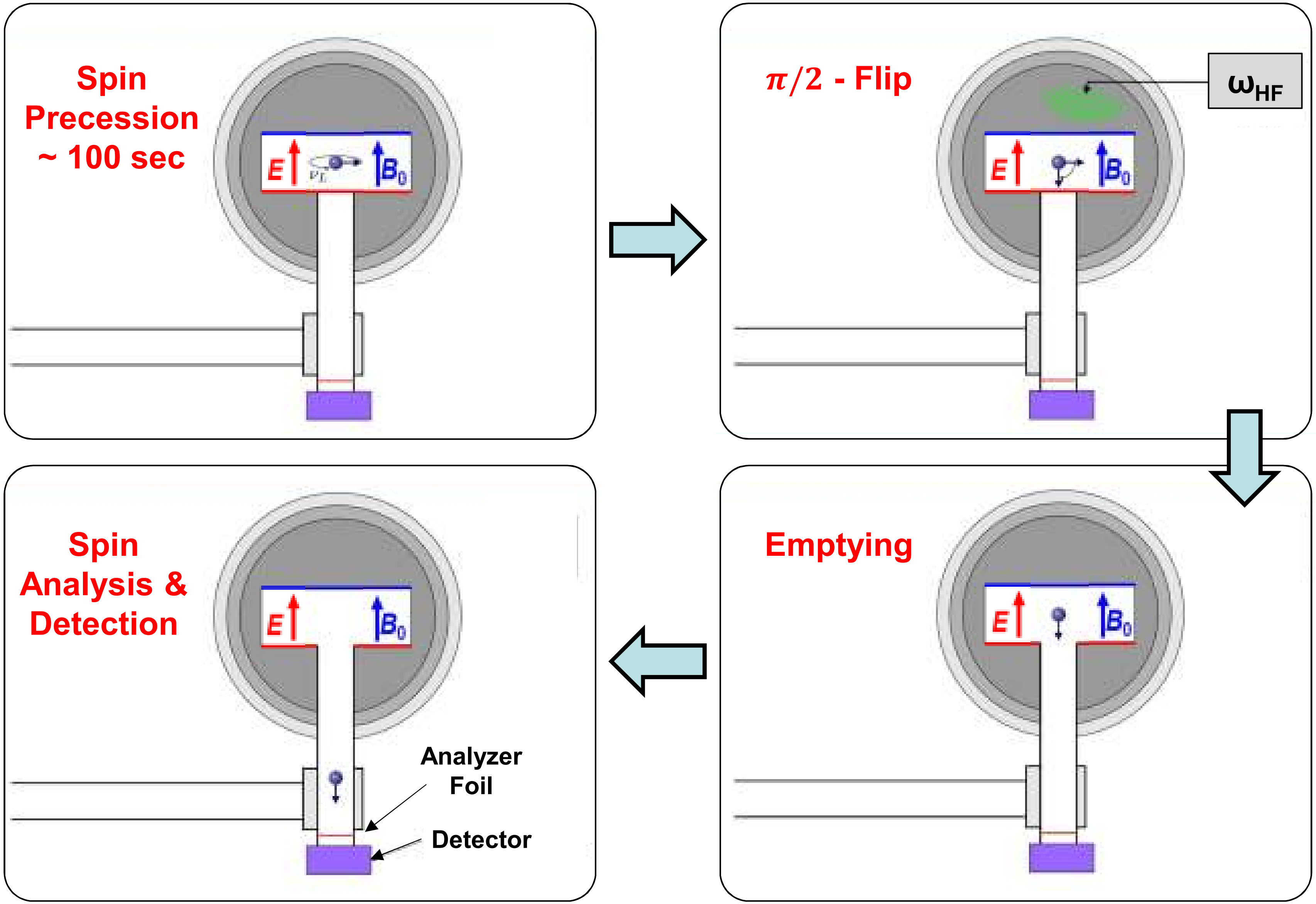


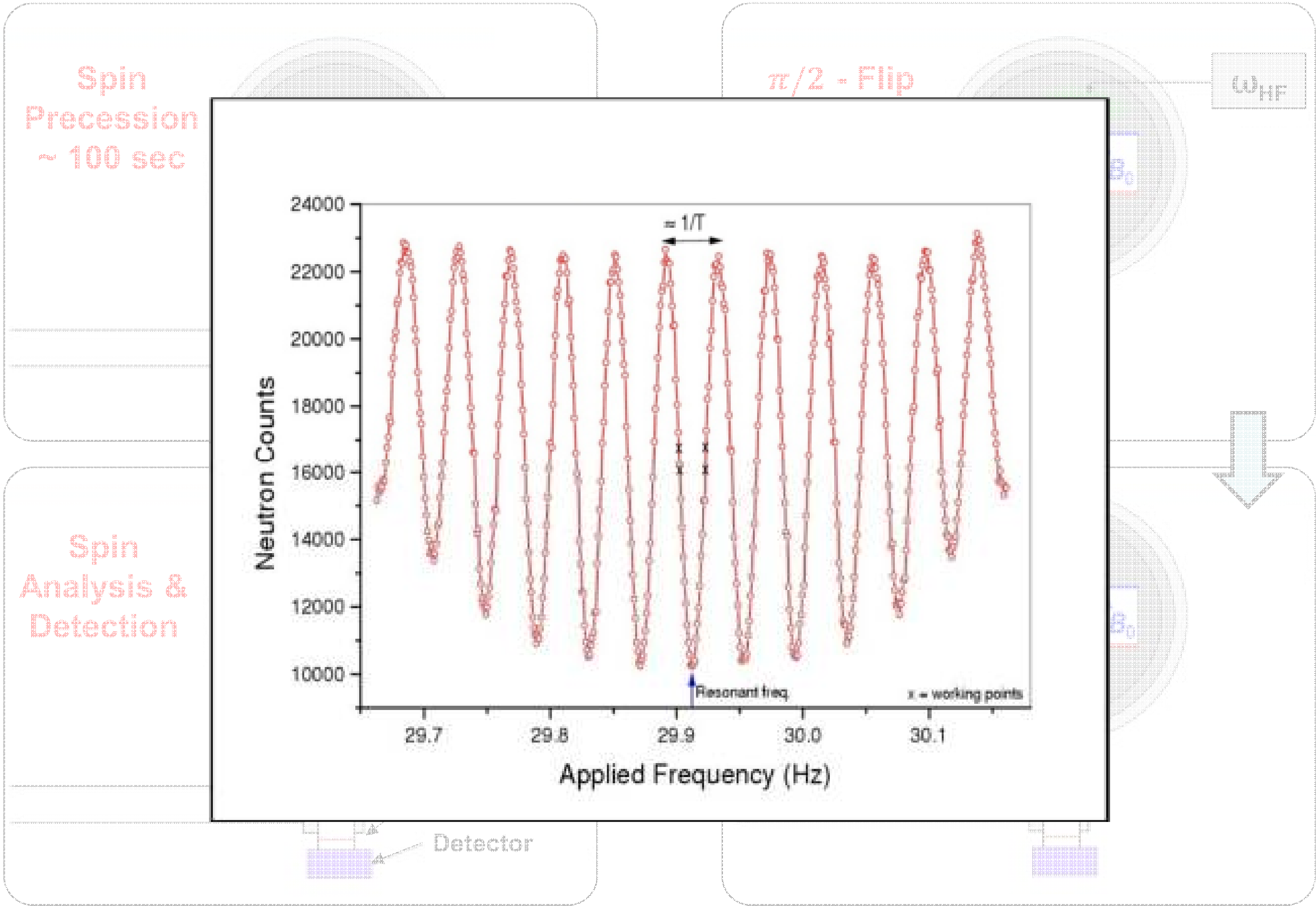
nEDM Experiment at PSI



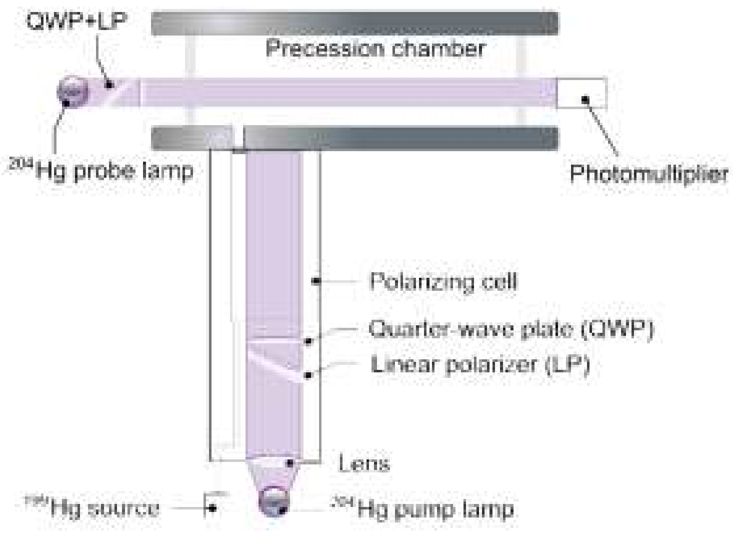


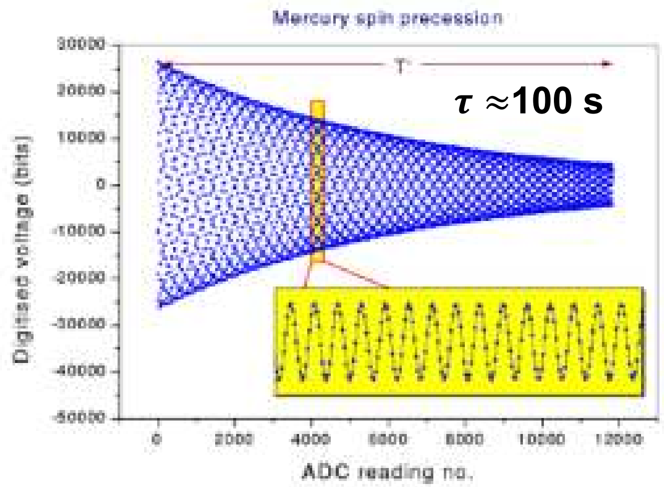
UCN Source (PSI)
nEDM Experiment
UCN: v < 6 m/s E_{kin} < 200 neV
Magn. field shiedling
Precession chamber
Polarized UCN
Filling
E
B_0
UCN Valve
ω_{HF}
$\pi/2$ - Flip

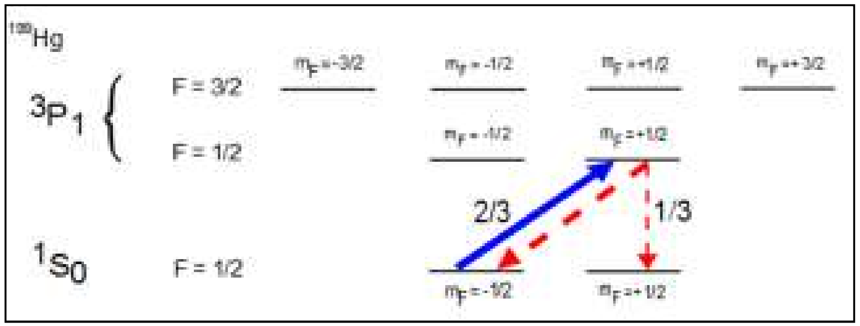

Spin
Precession
~ 100 sec
E
B0
$\pi/2$ - Flip
ωHF
E
B0
Emptying
E
B0
Spin
Analysis &
Detection
E
B0
Analyzer
Foil
Detector

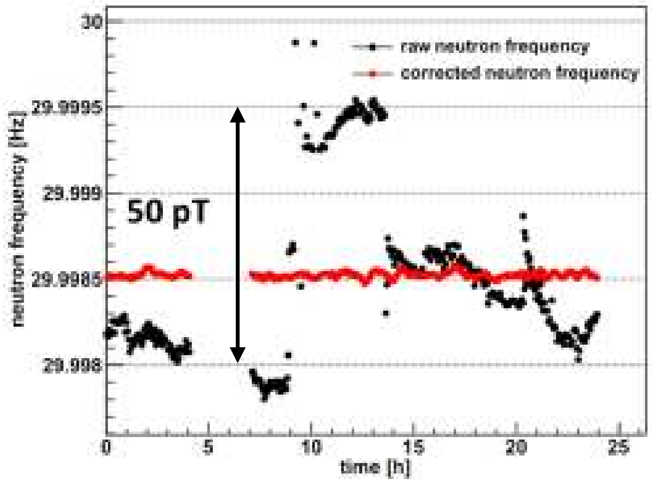

Spin
Precession
~ 100 sec
π/2 - Flip
Spin
Analysis &
Detection
Detector
Neutron Counts
Applied Frequency (Hz)
≈ 1/T
Resonant freq.
x = working points
24000
22000
20000
18000
16000
14000
12000
10000
29.7
29.8
29.9
30.0
30.1

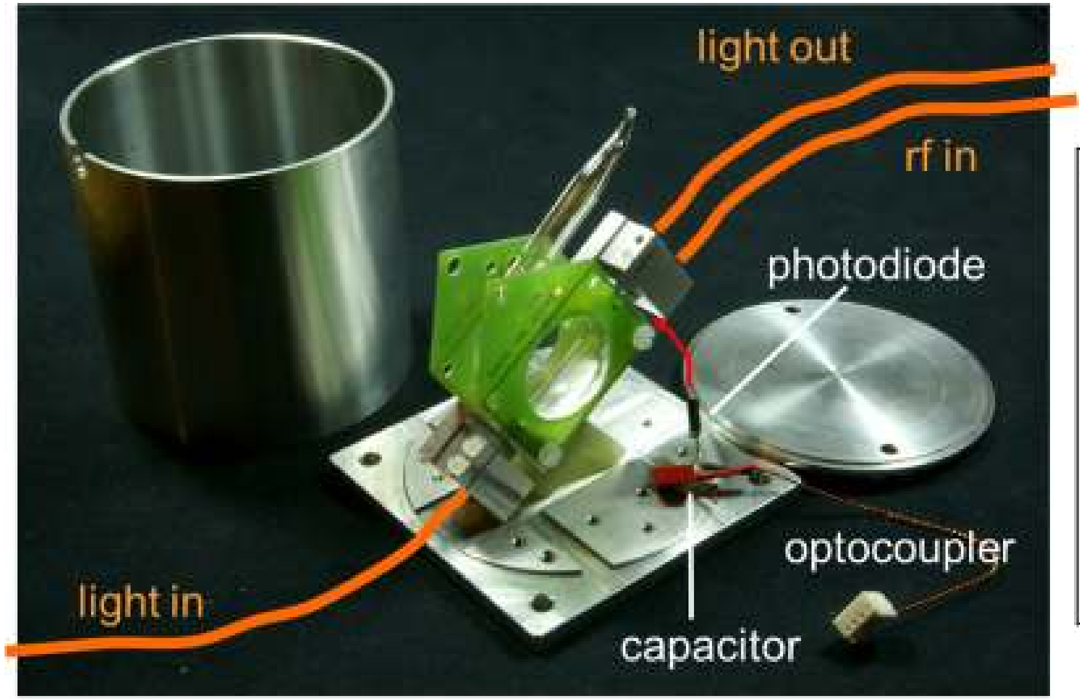
^{199}Hg-atoms are polarized using **circular polarized UV light** (254 nm). They are then filled in the same precession volume as the UCN (‘co-magnetometer’). The average (time & volume) magnetic field is measured by a **free induction decay of the Hg nuclear spins** (8 Hz @ 1μT) using a UV reading light – **absorption of the light depends on the orientation of the spin** and causes a modulation of the light intensity detected with a photo-multiplier tube (**sensitivity ≈ 100 fT** for approx. 100 s measurements).

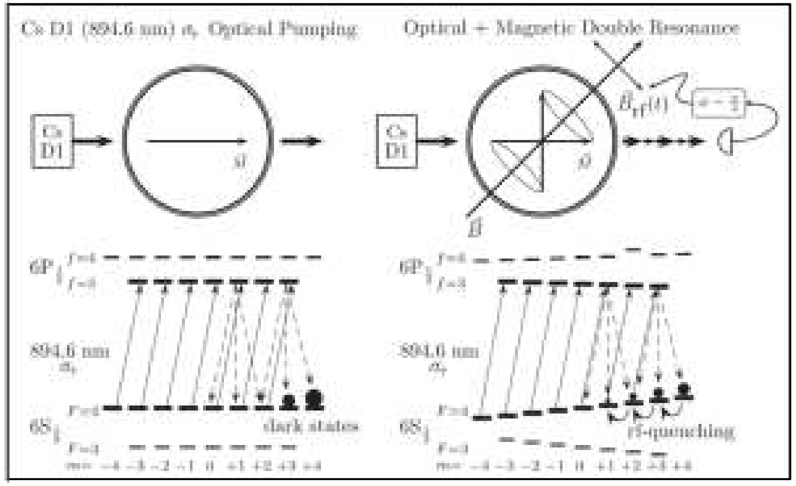












- A pump laser (about 895 nm) generates a macroscopic magnetization in the Cs-vapour, which precesses at its Larmor frequency in an external magnetic field (Nuclear Spin = 7/2, Electron Spin = ½ - F = 3 or 4).
- A small oscillating rf-field applied perpendicular destroys the magnetization (the Cs-vapour gets opaque). This effect is maximized, if the osc. frequency equals the Larmor frequency ($\omega_{RF} = \omega_L$, about 3.5 kHz/µT).
- Glass bulb with Cs-vapour has a diameter of about 2 cm.

Knowles et al., NIM A 611, 306 (2009)

- Biggest challange remains the stability of the magnetic field and the accuracy/precision of the magnetic field measurement/correction.
- Systematic effects can be separated in direct and indirect effects:

$$\left.\begin{aligned}\hbar\omega_n &= -\hbar\gamma_n B_0 - 2d_n E\\ \hbar\omega_{Hg} &= -\hbar\gamma_{Hg} B_0 - 2d_{Hg} E\end{aligned}\right\} \quad R' \equiv \frac{\gamma_n}{\gamma_{Hg}} - \frac{2E}{\hbar\omega_{Hg}}\underbrace{\left[d_n - d_{Hg}\frac{\gamma_n}{\gamma_{Hg}}\right]}_{= d_{n,meas}}$$

$$\Downarrow$$

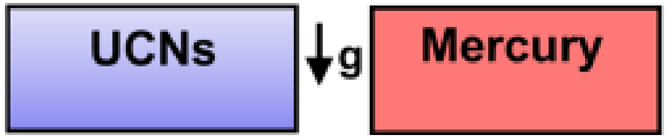
$$d_{n,meas} = d_n + d'_{n,false} + \underbrace{\left|\frac{\gamma_n}{\gamma_{Hg}}\right|}_{\approx 3.84} \cdot d_{Hg,false}$$

Systematic Effects – Direct

$$d_{n,meas} = d_n + d'_{n,false}$$

- ‘Uncompensated *B* drift’ – due to field gradients and gravitational effect on UCN

In the precession chamber



Center-of-mass shift ≈ mm

(measurable at *E*=0)

- UCN vxE effect (rotat. motion, 2nd order)

- UCN and Hg experience different fields ($v_{UCN} \ll v_{Hg}$)

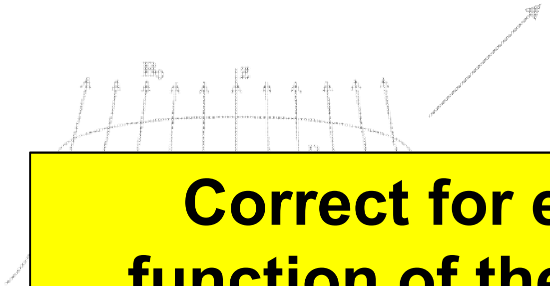
$$\begin{cases} f_n \propto \langle\, |\vec{B}|\, \rangle = B_0 + \dfrac{\langle B_T^2 \rangle}{2B_0} & \textit{adiabatic} \\ f_{\mathrm{Hg}} \propto |\, \langle\, \vec{B}\, \rangle\, | = B_0 & \textit{non-adiabatic} \end{cases}$$

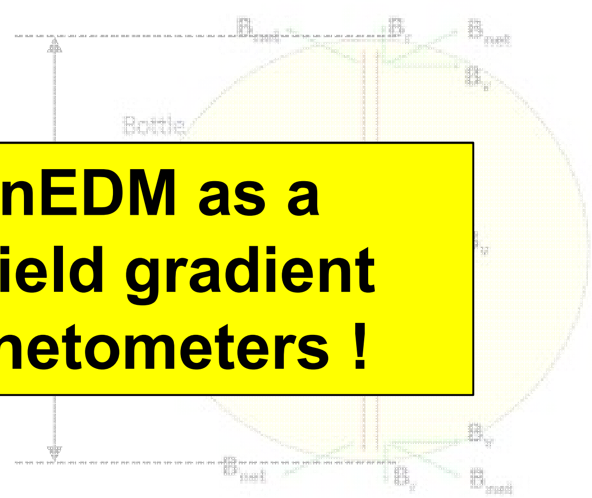
Systematic Effects – Indirect

$$d_{n,false} = \underbrace{\left|\frac{\gamma_n}{\gamma_{Hg}}\right|}_{\approx 3.84} \cdot d_{Hg,false}$$

- **Hg-EDM*:** $|d_{Hg}| < 3.1 \times 10^{-29}$ **e cm (95% CL)**
- **Geometric phase effect due to transversal fields****

$$B_\perp = \frac{E \times v}{c^2} + \left(\frac{\partial B_{0,z}}{\partial z}\right)\frac{r}{2} \quad \Rightarrow \quad d_{Hg,false} = \frac{\hbar \gamma_{Hg}^2}{32c^2} D^2 \frac{\partial B_{0,z}}{\partial z}$$



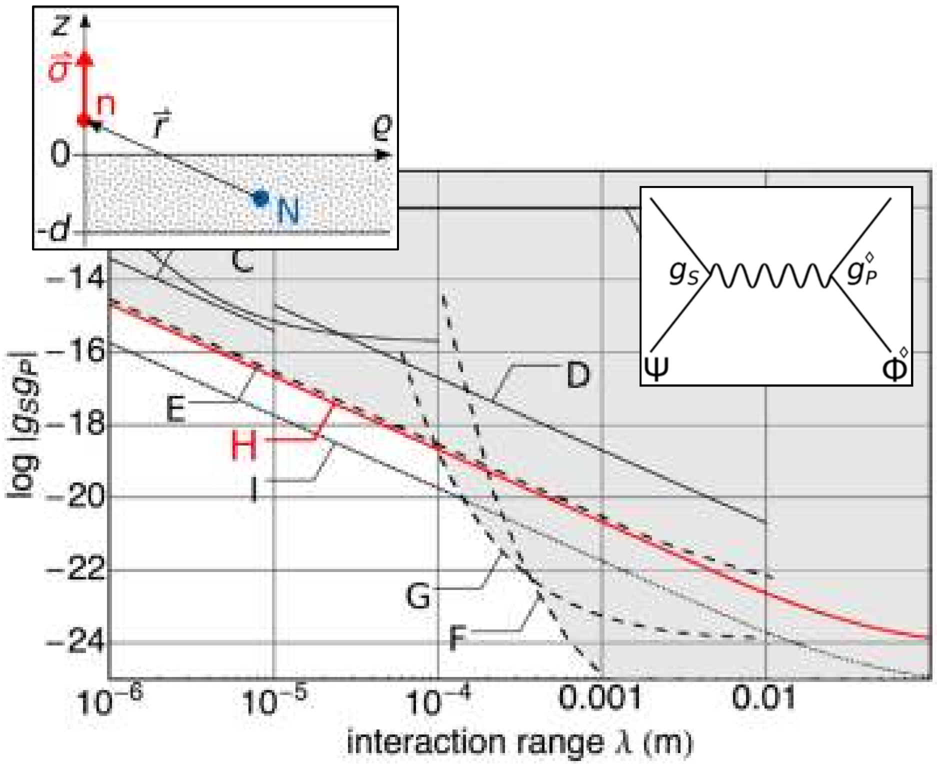


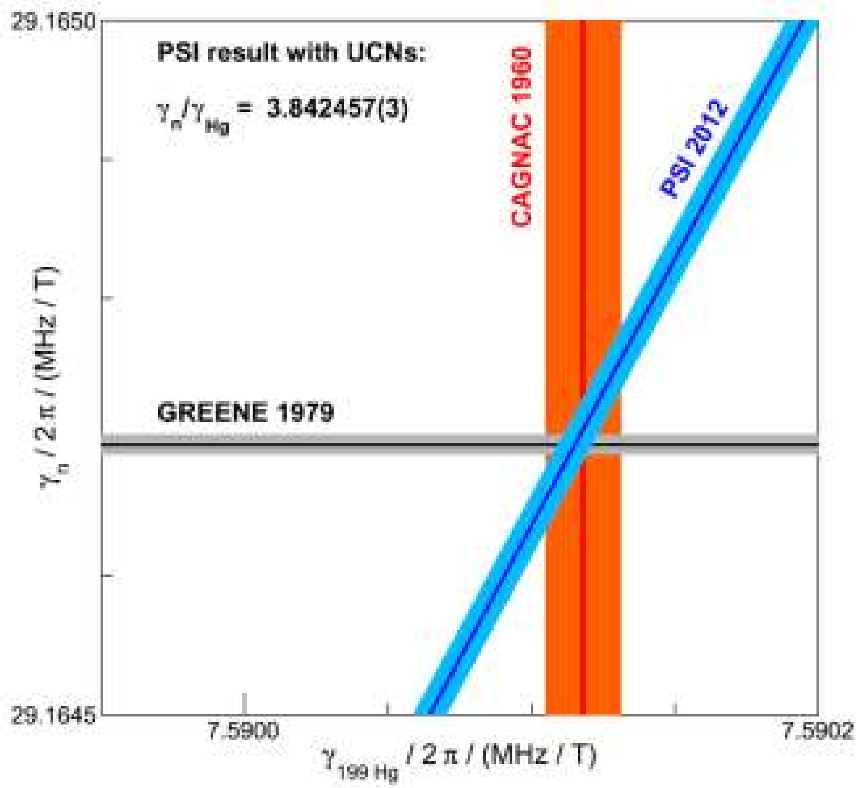
Correct for effect by measuring nEDM as a function of the vertical magnetic field gradient which is determined with Cs magnetometers !

* Griffith et al., PRL 102, 101601 (2009)
** Afach et al., arxiv 1503.08651

► Future & Ramsey beyond the EDM

► **Physics Results obtained with the same nEDM Apparatus:**



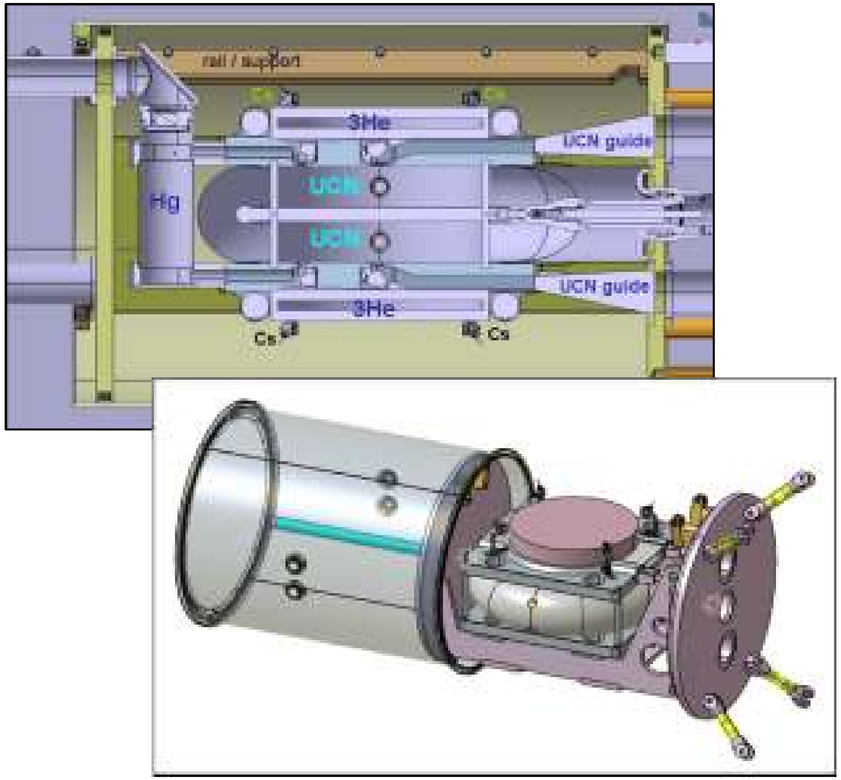


Search for new exotic interactions (Axion-Like-Particles) *

n/^{199}Hg - magnetic moment ratio **

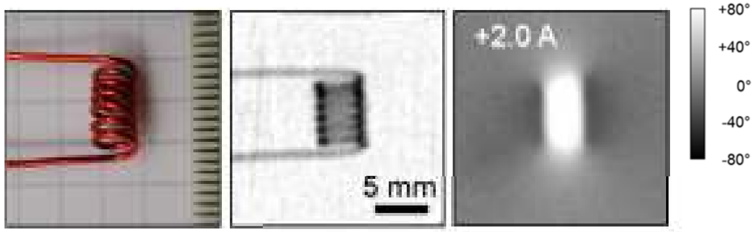
* Afach et al., Phys. Lett. B 745, 58 (2015)

** Afach et al., Phys. Lett. B 739, 128 (2014)

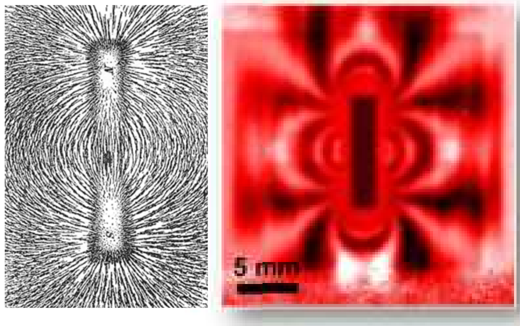


► **New features/improvements:**

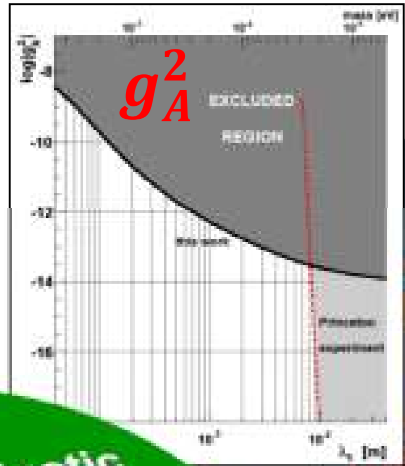
- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetic enviornment due to better shielding & compensation**
- **Higher neutron statistics due to better adaption to PSI UCN source**
- **Improved magnetometry (Hg, Vector-Cs, ^{3}He)**



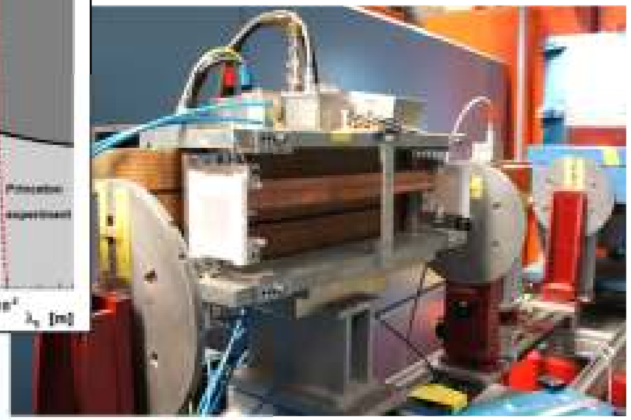
Piegsa et al., *NIM A* 605, 5 (2009)



Piegsa et al.,
PRL 102, 145501 (2009)



Piegsa & Pignol,
PRL 108, 181801 (2012)



Ramsey's technique using neutron beams is very powerful – maybe one should reconsider a beam nEDM measurement !?

van den Brandt et al., *NIM A* 611, 231 (2009)

A new nEDM Beam Experiment (at ESS) ?!

► **Main systematic in nEDM beam experiment caused by *v×E* - effect:**

UCN

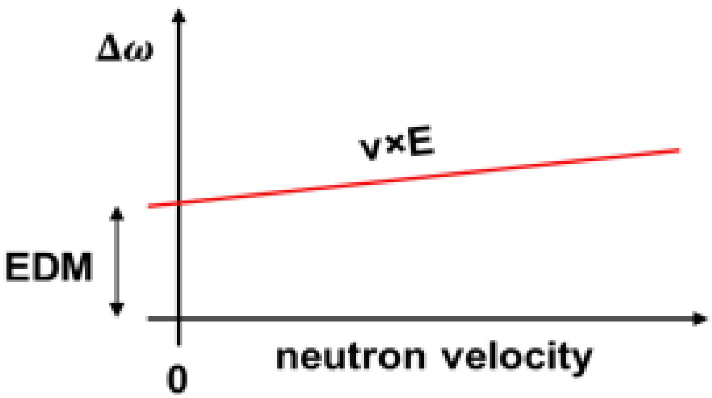
$$\hbar\Delta\omega = 4d_{\mathrm{n}}E$$

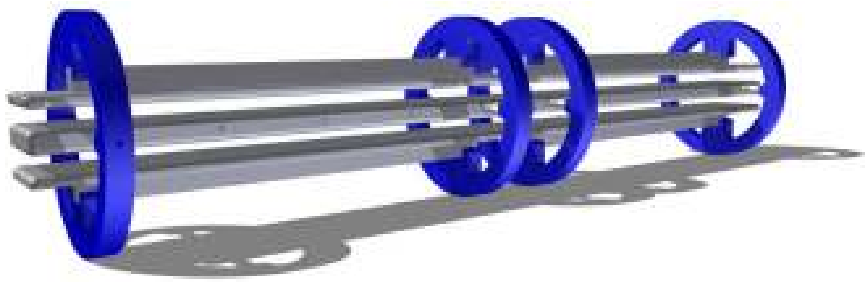
Beam

$$\hbar\Delta\omega = 4d_{\mathrm{n}}E - 4\mu_{\mathrm{n}}\frac{vE}{c^2}\sin\alpha$$

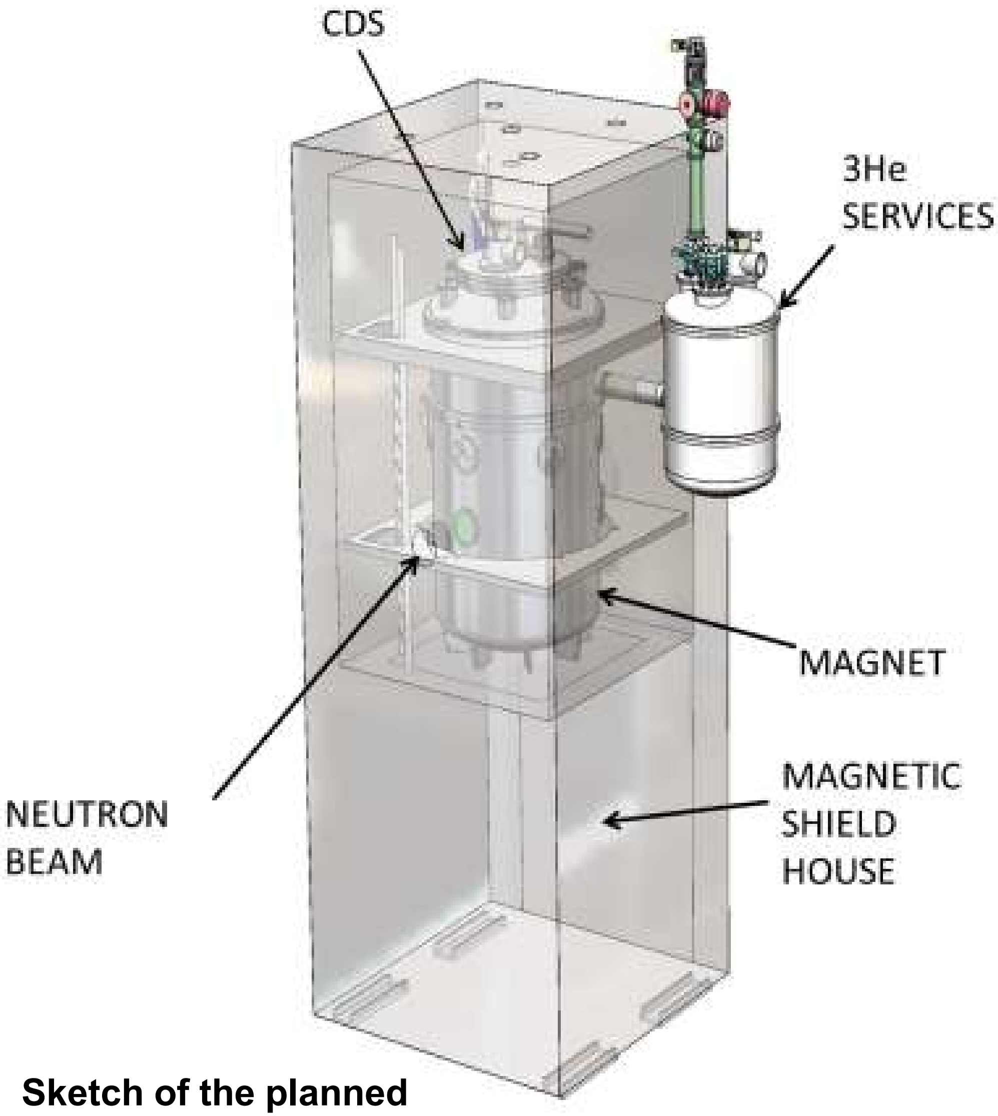
angle between *E*- and B_0-field

► **<u>Idea:</u> Separate the two effects by directly measuring the frequency shift as a function of the velocity at a pulsed neutron source:**



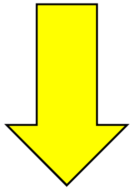


Piegsa, PRC 88, 045502 (2013)



Sketch of the planned SNS setup by R. Golub

Intriguing alternative approach and measurement scheme



Talk by T. Ito

Thank you for your attention.