Search for a Neutron EDM using a Pulsed Beam

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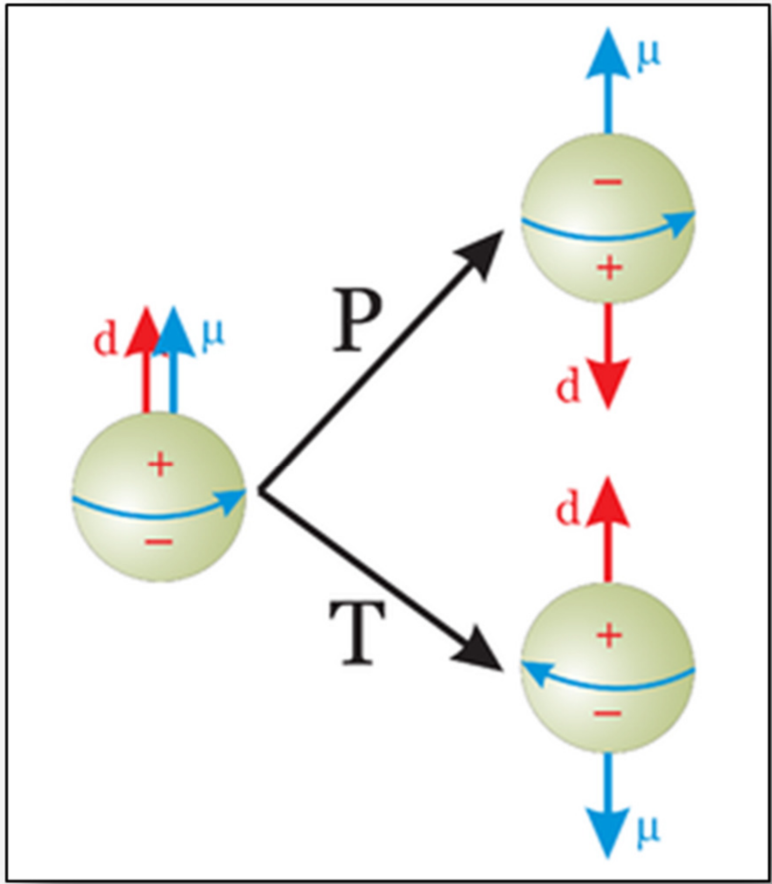
- ▶ Introduction & $v \times E$ - effect
- ▶ Proposed Pulsed Beam Exp.
- ▶ Systematic Effects
- ▶ First Test Experiments at PSI
- ▶ Conclusion

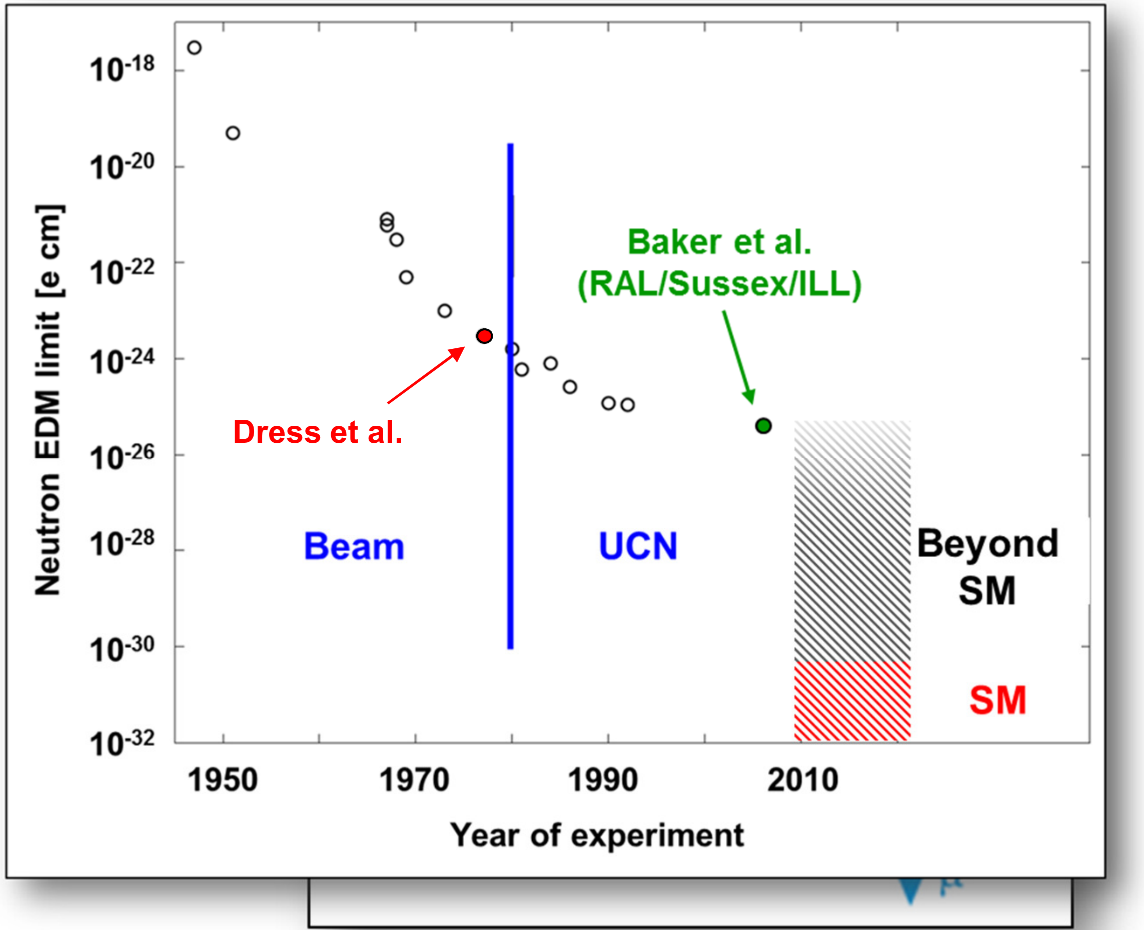


'Classic Picture'

Piegsa, PRC 88, 045502 (2013)

Neutron EDM – Situation & Perspective

- A neutron EDM violates CP, if CPT is conserved:



'Classic Picture'

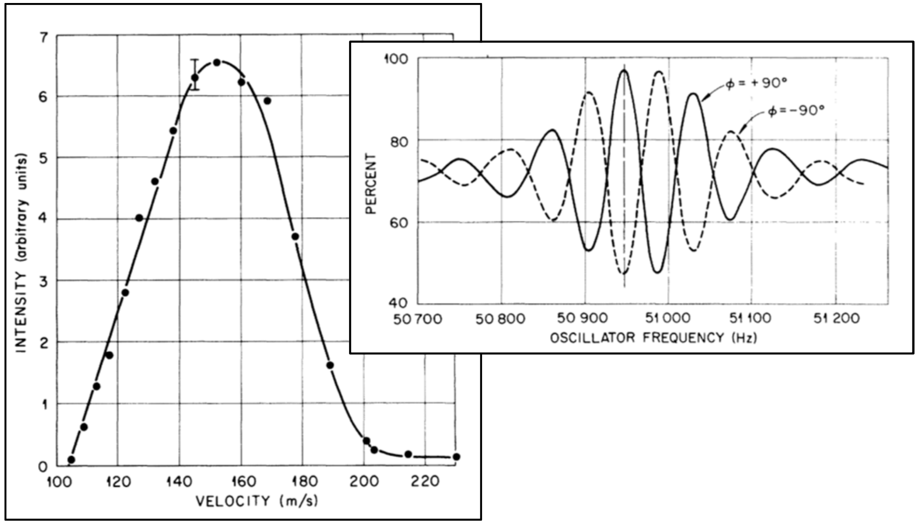
- Current limit:

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

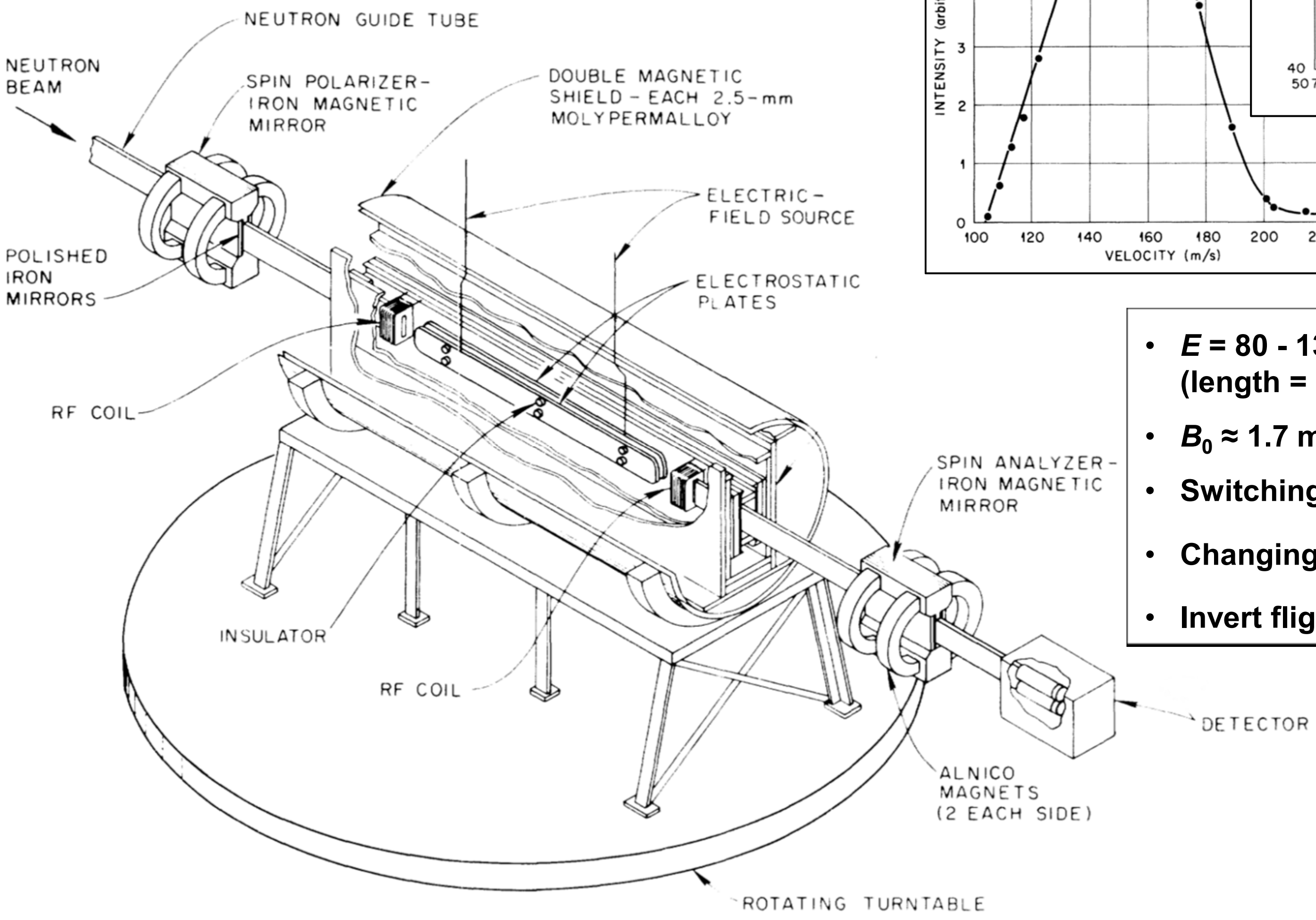
Baker et al., PRL 97, 131801 (2006)

- Several experiments worldwide are aiming for sensitivities of about 5×10^{-28} e cm, all are using ultracold neutrons.

$d_n < 3 \times 10^{-24}$ e cm (90% 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., PRD 15 (1977) 9

- **In general:**

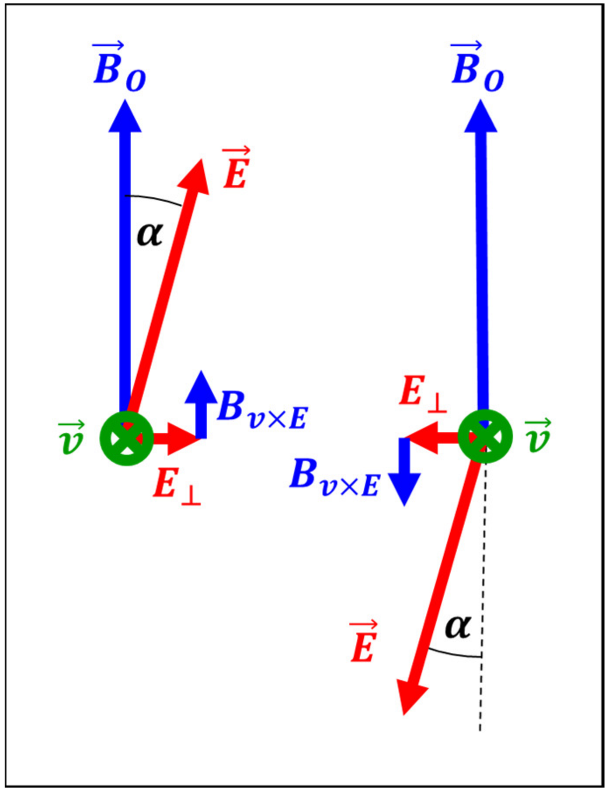
$$\vec{B} = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} + \begin{pmatrix} \delta B_x \\ \delta B_y \\ \delta B_z \end{pmatrix} \qquad |\vec{B}| \approx B_0 + \delta B_z + \underbrace{\frac{\delta B_x^2 + \delta B_y^2}{2\,B_0}}_{\text{transversal fields}} - \frac{\delta B_z \cdot (\delta B_x^2 + \delta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

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

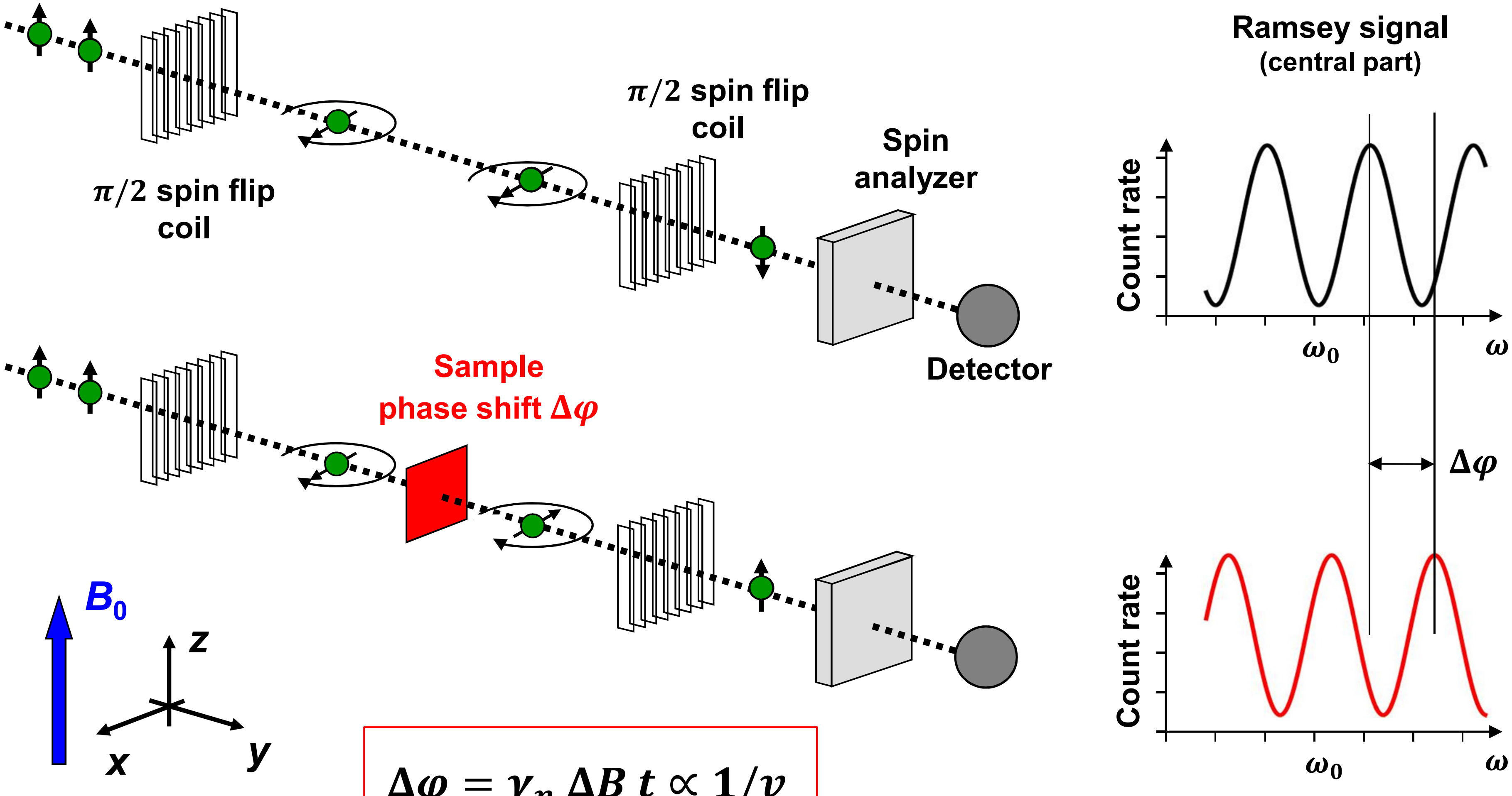
$$\boxed{\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}}$$

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

- ***v×E* effect is velocity dependent !!**
- $d_{n,false} \approx 10^{-19}\ \mathrm{e\,cm}\cdot\sin\alpha$ **for *v* = 1000 m/s**
- **2nd order term non-zero, even if *α* = 0.**



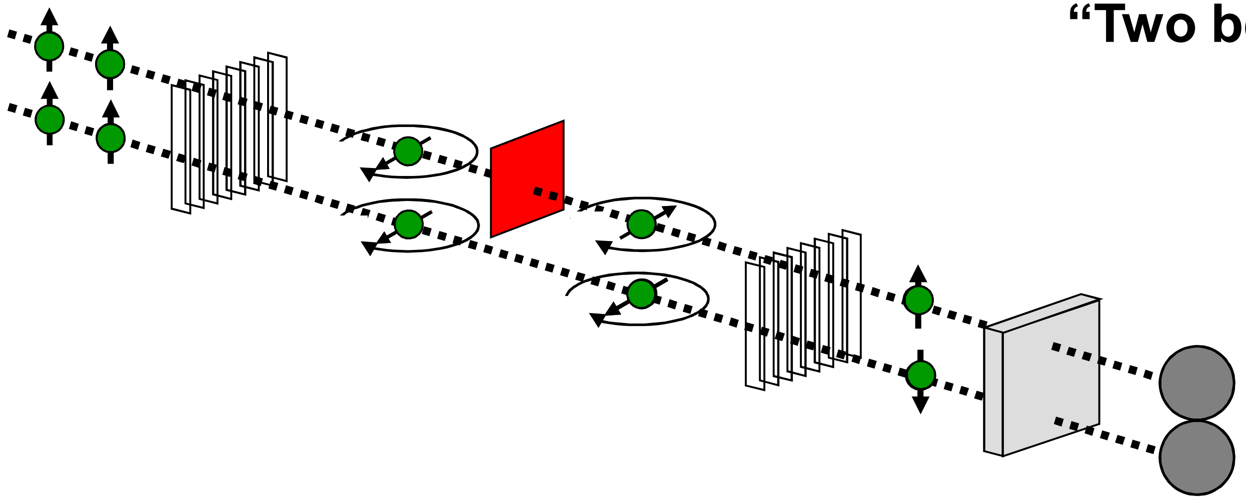
Measure (pseudo-) magnetic fields using neutrons:

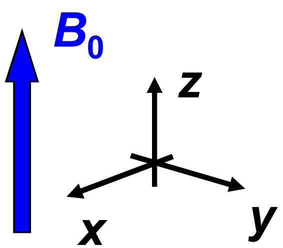


$$\boxed{\Delta\varphi = \gamma_n \, \Delta B \, t \propto 1/v}$$

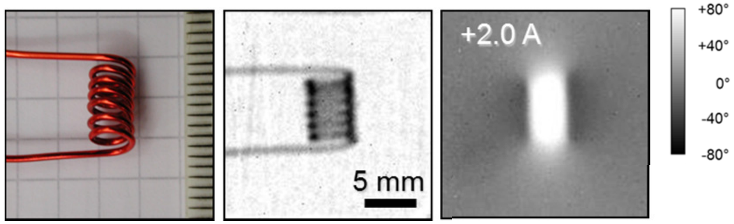
ΔB: change of the field in the sample

"Two beam method"

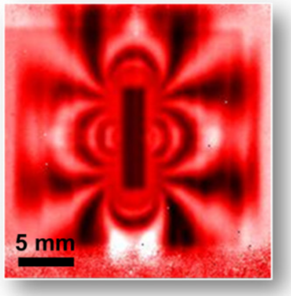




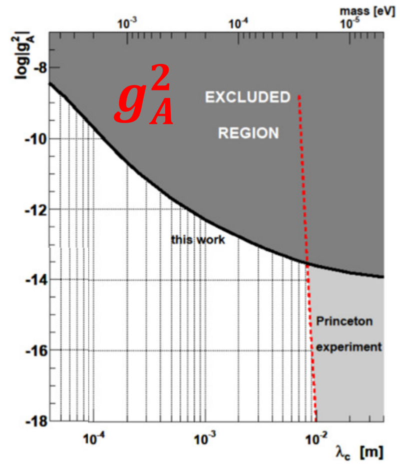
Suppression of common noise / global drifts
(magnetic field, HF-phase, temperature etc.)



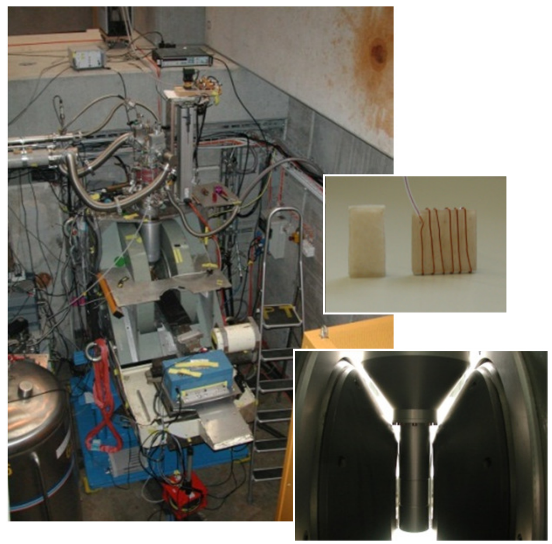
Piegsa et al., *NIM A* **605** (2009) 5



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



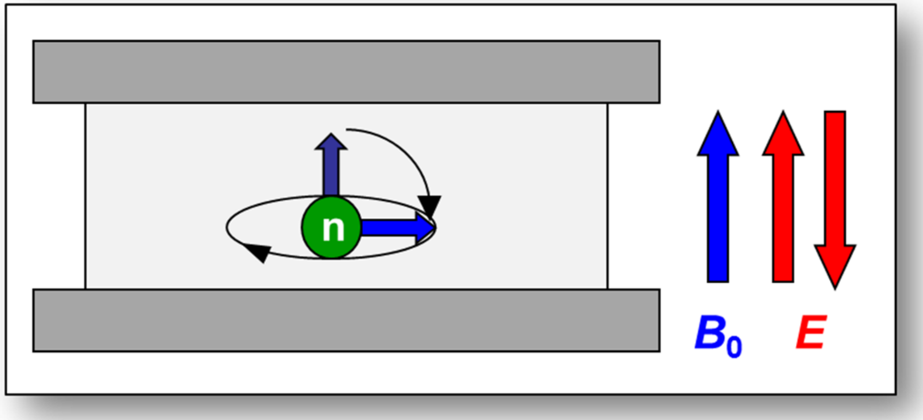
Piegsa & Pignol, *PRL* **108** (2012) 181801


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

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

► Proposed Pulsed Beam Experiment

- Determine the neutron Larmor frequency / neutron EDM with **Ramsey's technique** applied to ultracold neutrons:



$$\left.\begin{aligned} \hbar\omega_{\uparrow\uparrow} &= -2\mu_n B_0 - 2d_n E \\ \hbar\omega_{\uparrow\downarrow} &= -2\mu_n B_0 + 2d_n E \end{aligned}\right\} \Rightarrow \boxed{\hbar\Delta\omega = 4d_n E}$$

for B_0 = const.

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

angle between *E*- and B_0-field

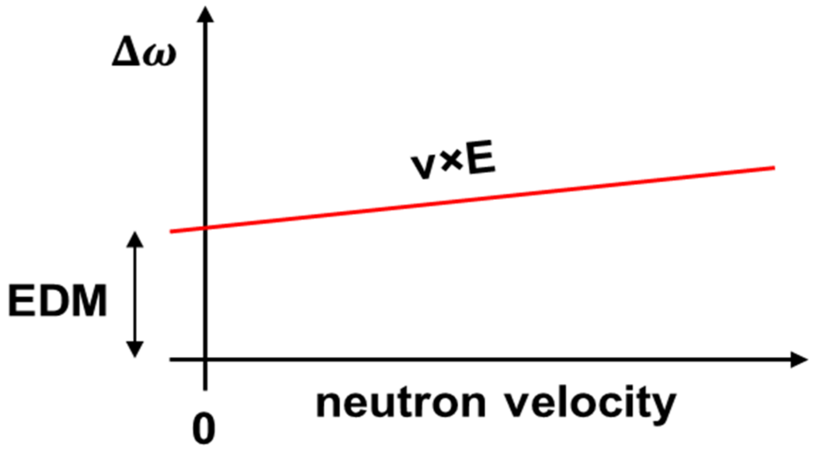
UCN

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

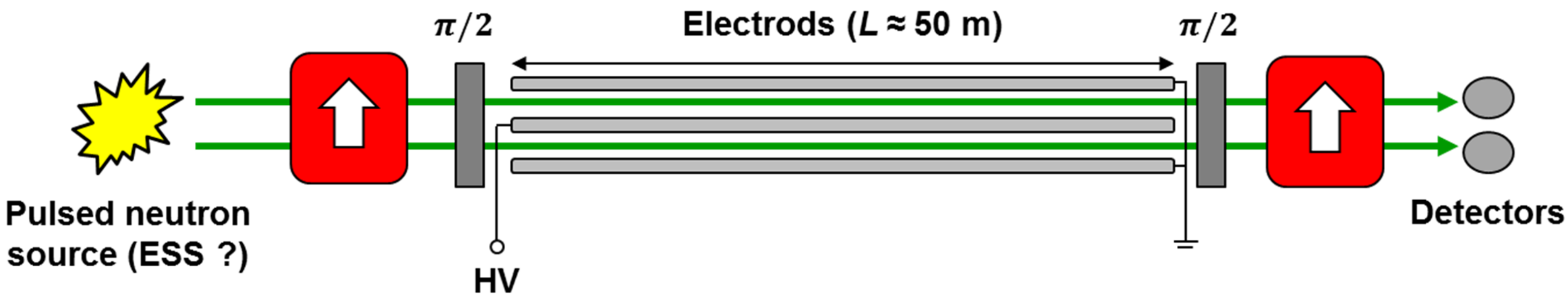
Beam

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

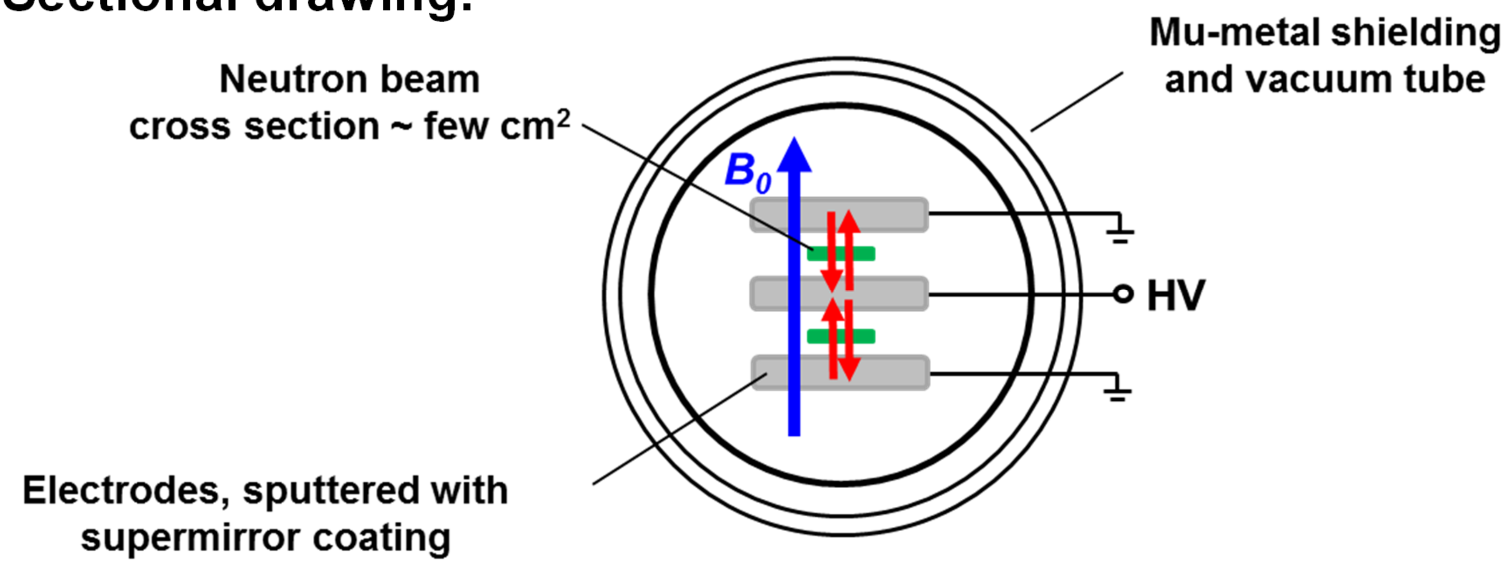
- **Idea: Separate the two effects by directly measuring the frequency shift as a function of the velocity:**



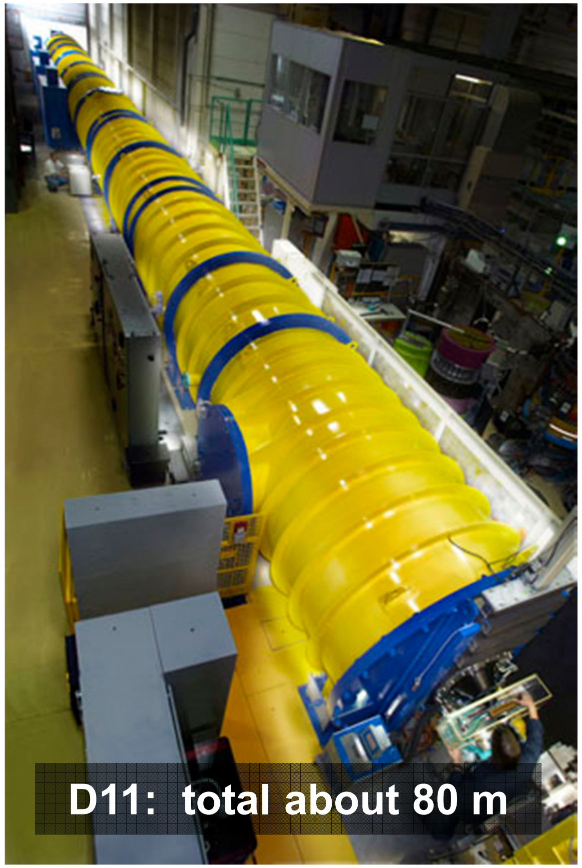
► **Side view:**

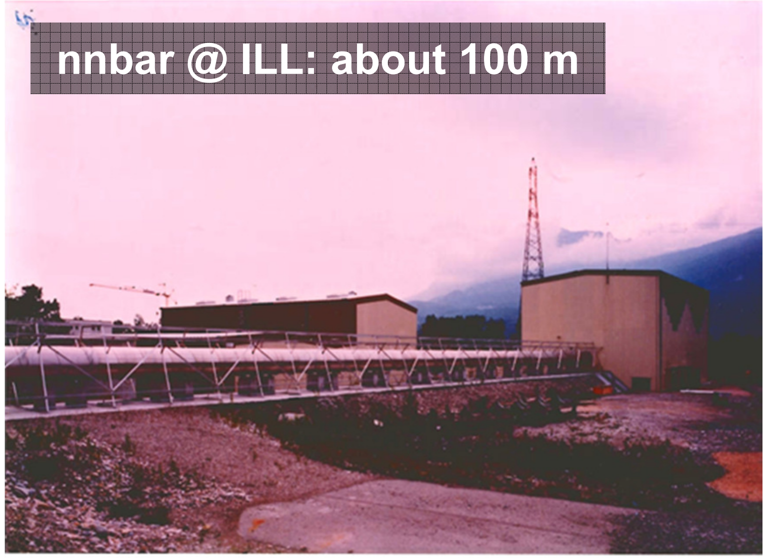


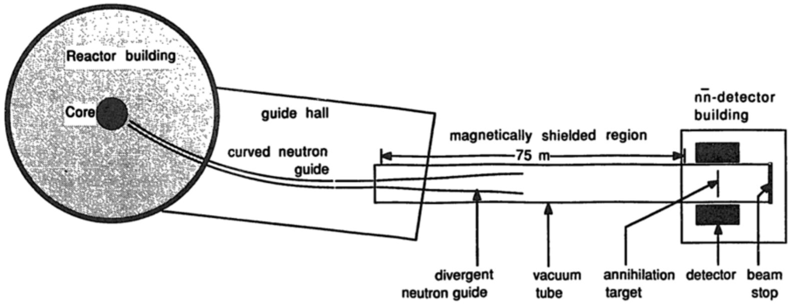
► **Sectional drawing:**



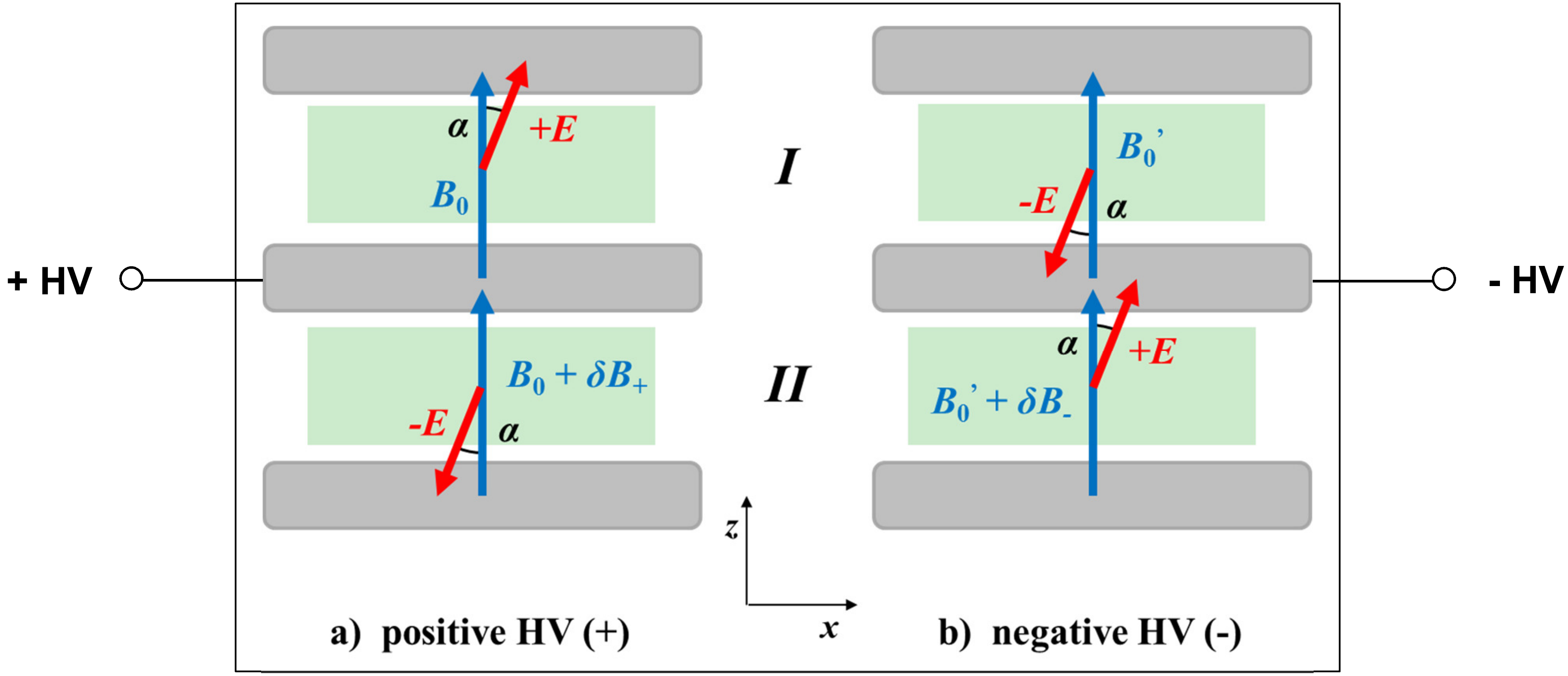
Isn't that horribly long ?







Baldo-Ceolin et al., Z. Phys C 63 (1994) 409



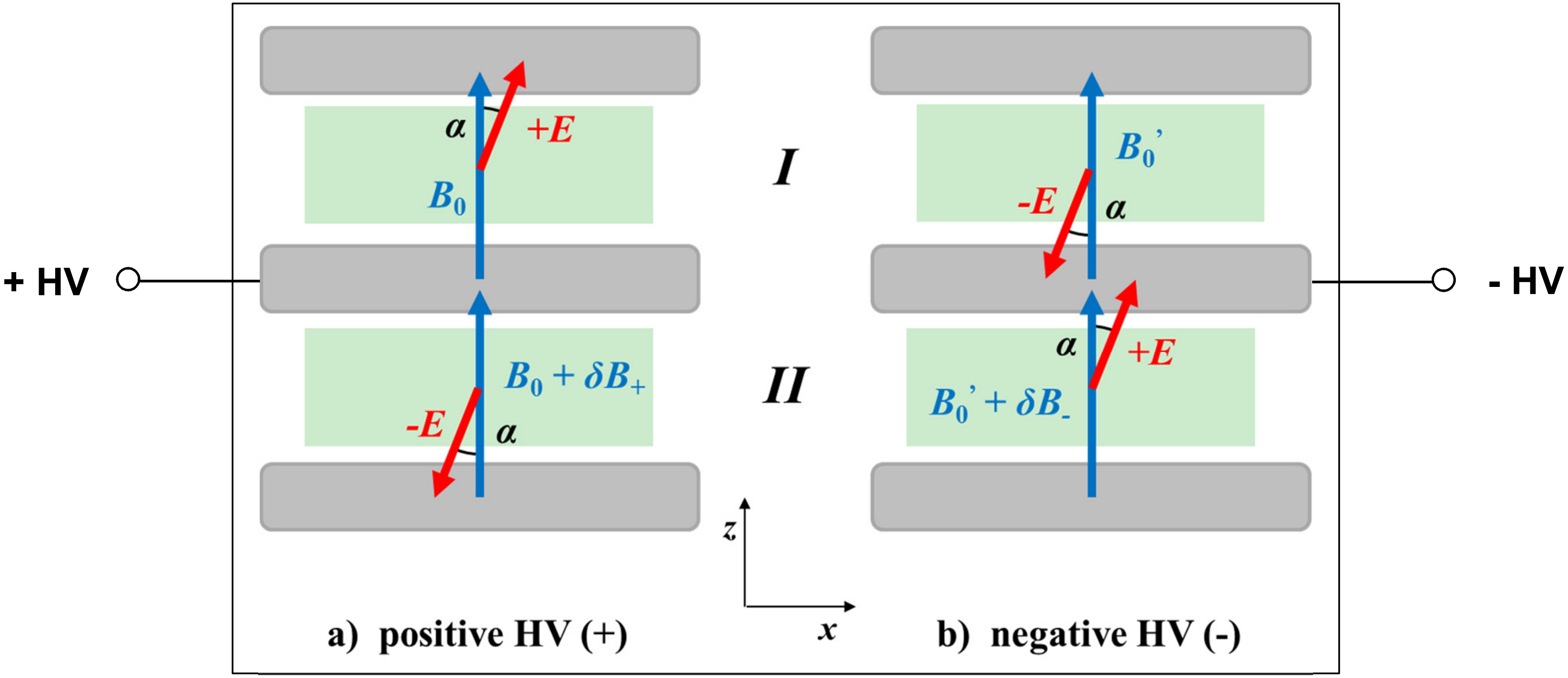
$$B_{I,+} = B_0 \qquad + B^* + \frac{vE}{c^2}\sin\alpha \qquad\qquad B_{I,-} = B_0' \qquad - B^* - \frac{vE}{c^2}\sin\alpha$$

$$B_{II,+} = B_0 + \delta B_+ - B^* - \frac{vE}{c^2}\sin\alpha \qquad\qquad B_{II,-} = B_0' + \delta B_- + B^* + \frac{vE}{c^2}\sin\alpha$$

nEDM: $B^* = \frac{2d_n E}{\hbar\gamma_n}$

$$\Delta\omega = \gamma_n\{(B_{I,+} - B_{II,+}) - (B_{I,-} - B_{II,-})\}$$

More general consideration: Piegsa, PRC 88, 045502 (2013)



$$\boxed{\Delta\omega = \gamma_n \left\{ 4B^* + 4\frac{vE}{c^2}\sin\alpha + \underbrace{(\delta B_- - \delta B_+)}_{\text{Drift of magn. field gradient}} + \mathcal{O}\left[E^2\right] \right\}}$$

nEDM: $B^* = \dfrac{2d_nE}{\hbar\gamma_n}$

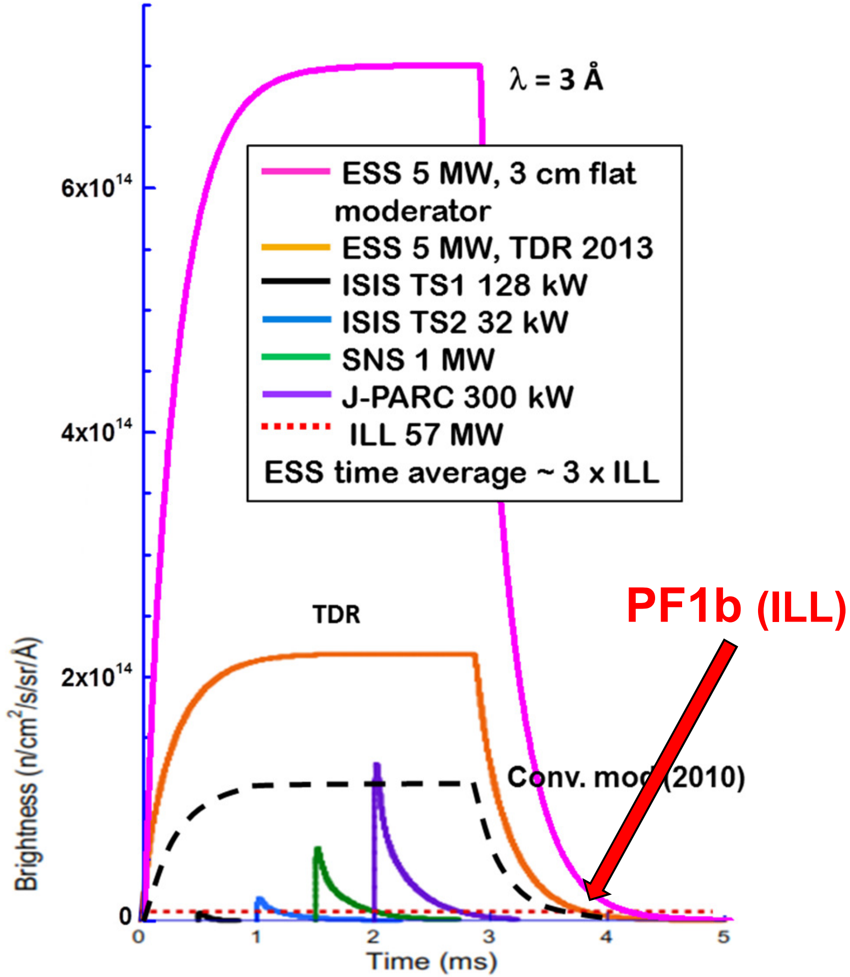
Limits on E_I, E_{II} and α_I, α_{II}

More general consideration: Piegsa, PRC 88, 045502 (2013)

European Spallation Source (ESS)

***F. Mezei (ESS):** A new 2D moderator concept (“**pancake**” moderator).*

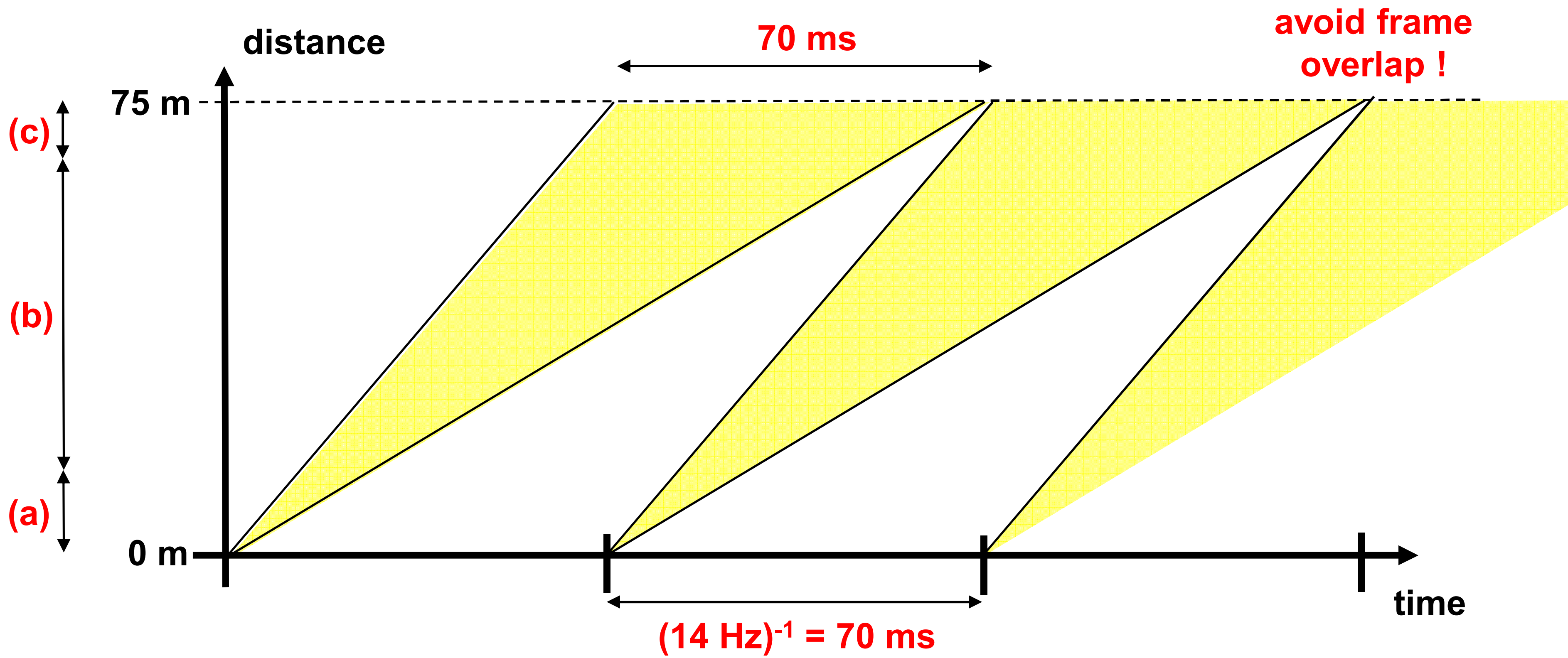
*The gains are expected to land at a **factor of 2 to 3**, compared to the performance expectations in the ESS baseline of 2012, i.e. **time average flux of ILL**.*



Pulse: 3 ms **Rate: 14 Hz**

Batkov et al., NIM A 729 (2013) 500
Mezei et al., Jour. of Neutron Research 17 (2014) 101

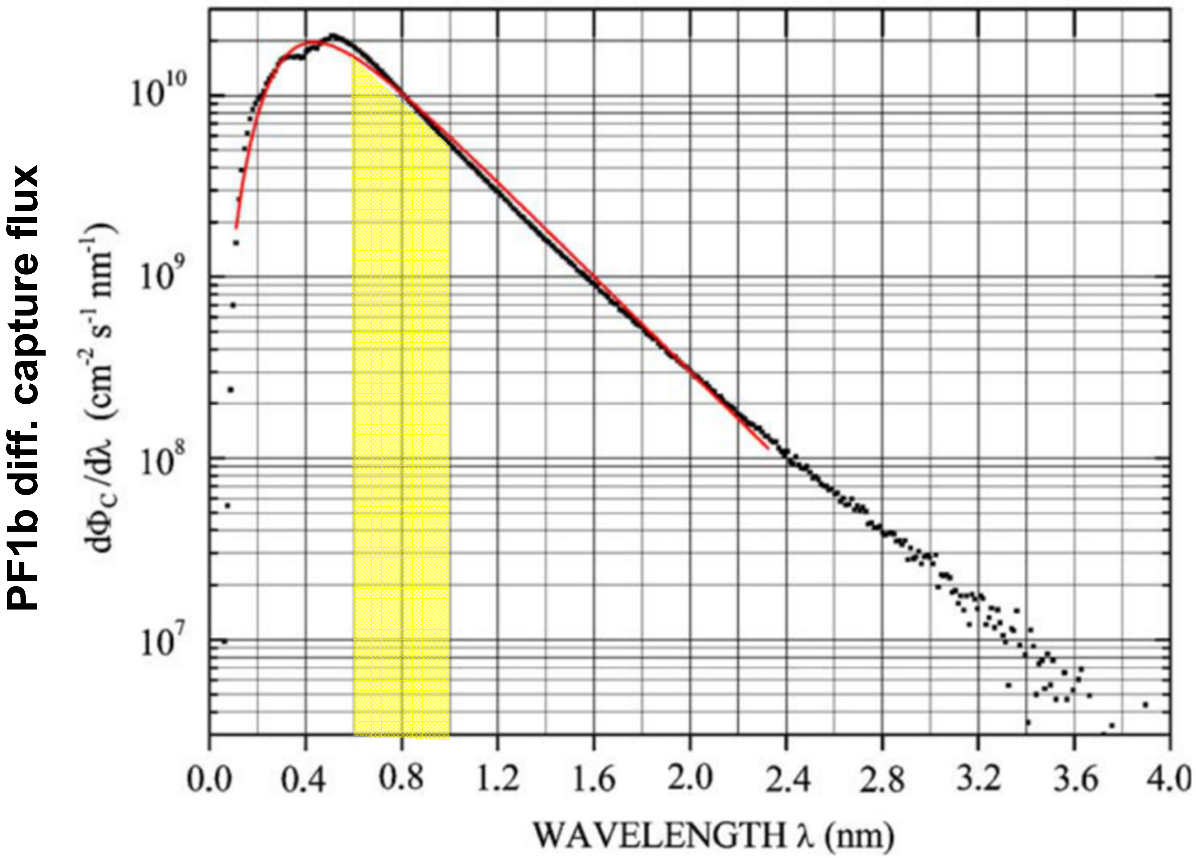
ESS Pulse Structure – Wavelength Selection



(a) Beam extraction & wavelength selection
(b) Ramsey precession region (~ 50 m)
(c) Spin analysis & detector

⇒ **Possible wavelength band**

- 0.6 nm: $t_{flight} = 75\ \text{m} / 660\ \text{m/s} \approx 115\ \text{ms}$
- 1.0 nm: $t_{flight} = 75\ \text{m} / 400\ \text{m/s} \approx 185\ \text{ms}$



$$\Phi_P = \int_{0.6}^{1.0} \frac{\lambda_0}{\lambda} \frac{\partial \Phi_C}{\partial \lambda} d\lambda \quad \Rightarrow \quad \Phi_P = 1.5 \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$$

unpolarized particle flux (0.6 – 1.0 nm)

$$\lambda_0 = 0.18 \text{ nm}$$

Abele et al., NIM A 562 (2006) 407

► **Statistical sensitivity:**

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

η = 0.75, T = 0.1 s, E ~ 100 kV/cm *

$$N = \underbrace{1.5 \times 10^{9}\,\mathrm{cm^{-2}s^{-1}}}_{\text{PF1B part. flux (ILL)}} \times \overbrace{1/3}^{\text{Polarization}} \times \underbrace{1/100}_{\text{Divergence losses (1D)}} \times \overbrace{2}^{\text{'Pancake target' (factor \sim 3)}} \times \underbrace{(2 \times 20\,\mathrm{cm^{2}})}_{\text{Beam cross sections}} \sim 4 \times 10^{8}\,/\,\mathrm{s}$$

distributed on at least 4 detectors

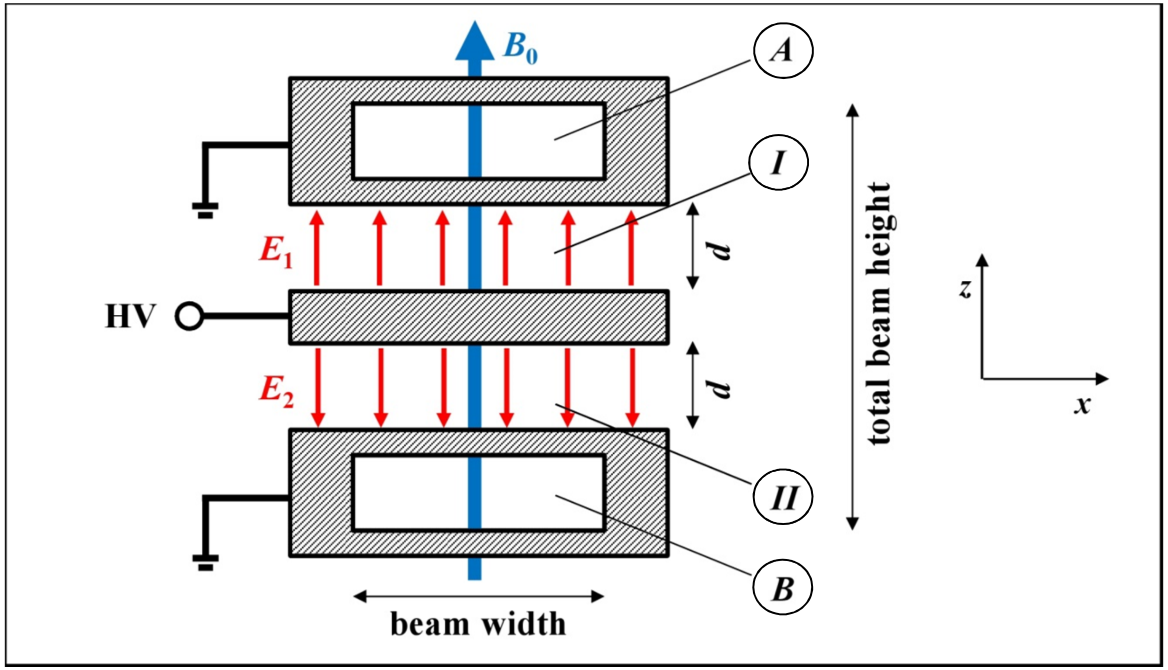
$$\boxed{\sigma(d_\mathrm{n}) \approx 8 \times 10^{-27}\ \text{e cm / day}}$$

* Dress et al., PRD 15 (1977) 9 (80-130 kV/cm)
Baumann et al., PRD 37 (1988) 3107 (60 kV/cm)

►Systematic Effects

► **False nEDM due to gradient drifts:**

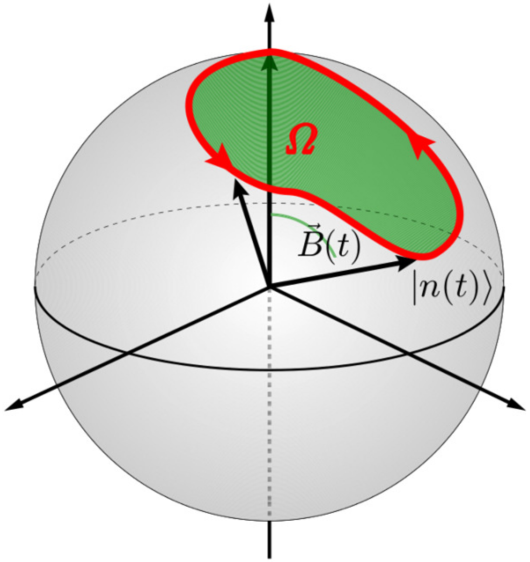
$$d_{n,false} = \hbar\gamma_n \frac{\delta B_- - \delta B_+}{8\,E} \propto \frac{1}{E}$$



Measure gradient either with 4 neutron beams or alternatively with polarized ^{3}He beam or other atomic magnetometers.

Avoid spin dephasing (field homogeneity): $\frac{\partial B_0}{\partial x} \approx \frac{\partial B_0}{\partial z} \ll$ **10 nT/cm**

► **Geometric phase accumulated at entrance and exit of electric field region – equivalent to electron EDM searches with ^{205}Tl (Berkeley):**



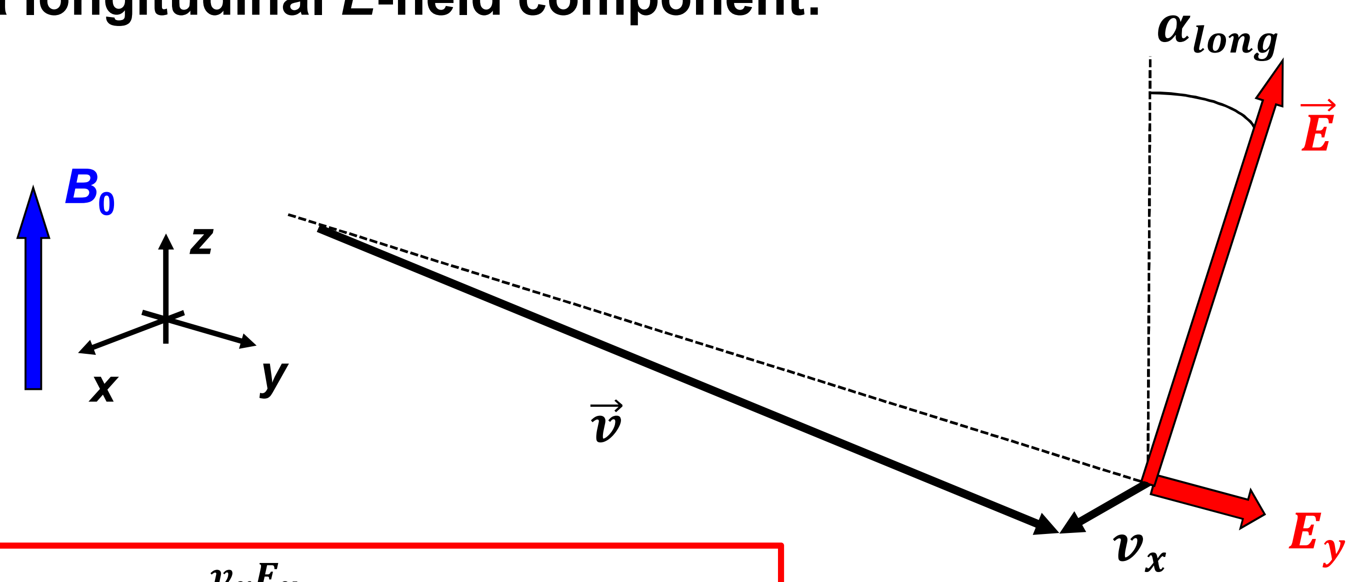
$$\Omega = 4\,\frac{\Delta B_{long}}{B_0^2}\cdot\frac{v\cdot E}{c^2} \quad\rightarrow\quad \text{Phase shift} = \Omega/2$$

ΔB_{long} = difference of long. magn. field at E-field entrance / exit

- **Measure at different & inverted B_0 (especially: $\Delta B_{long} \propto B_0$).**
- **Limit ΔB_{long} < 20 nT - for suppression below 5×10^{-28} e cm**

Commins, Am. J. Phys. 59, 1077 (1991)
Abdullah et al.. PRL 65, 2347 (1990)
Commins et al., PRA 50, 2960 (1994)

► **Due to a transversal momentum of the entire neutron beam and a longitudinal *E*-field component:**



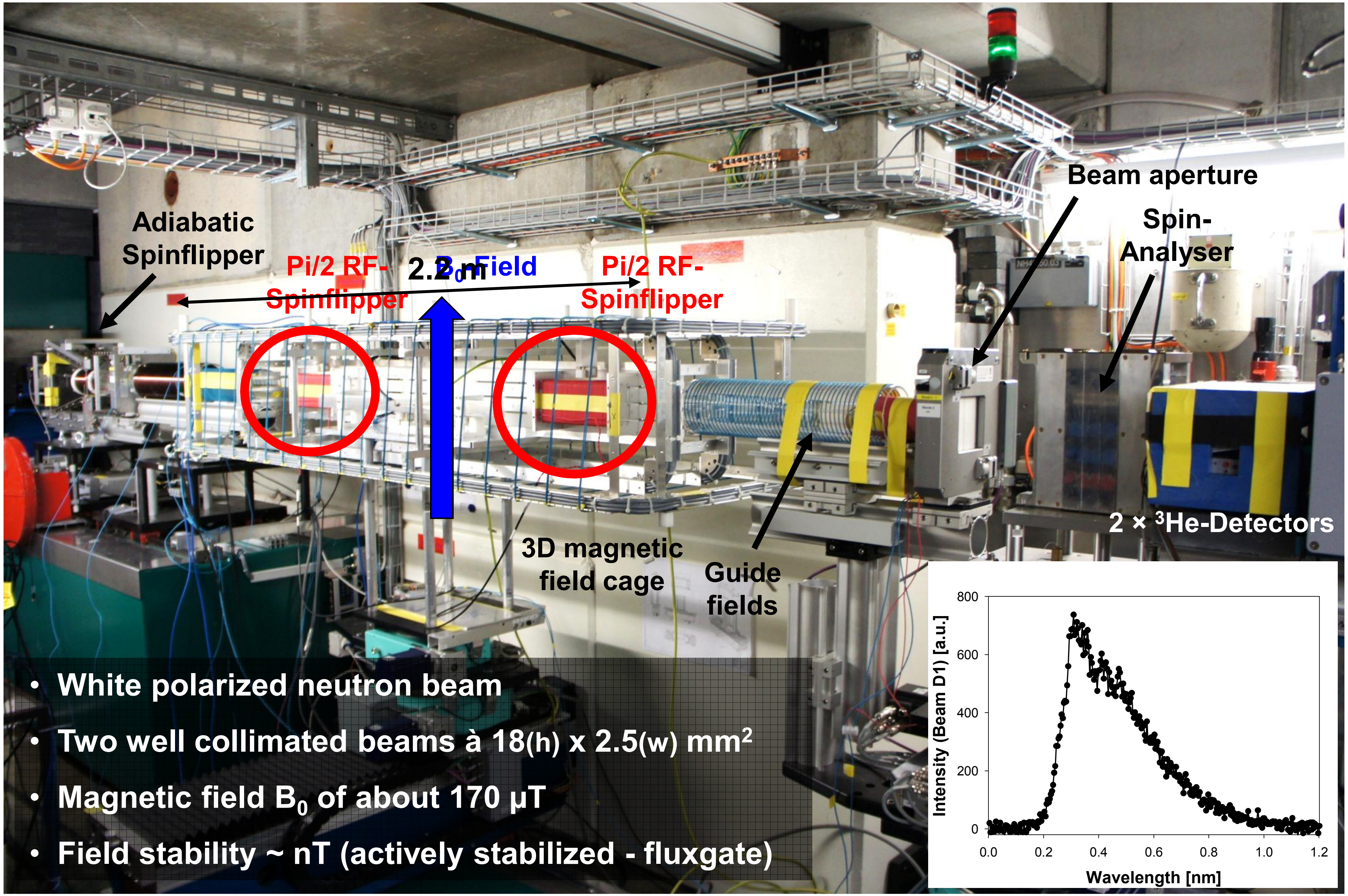
$$B_{v\times E} = \frac{v_x E_y}{c^2} \propto E \quad \text{(along } z\text{-axis)}$$

- **To reduce effect below 5×10^-28 e cm: $v_x < 2$ mm/s and $\alpha_{long} < 0.2°$**
- **Upper limit of the effect can be determined by intentionally misalignment of field & increasing of v_x (using apertures).**

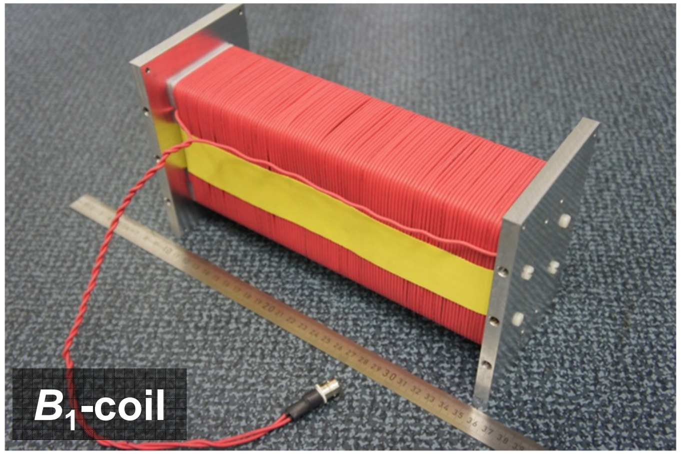
►First Test Experiments at PSI

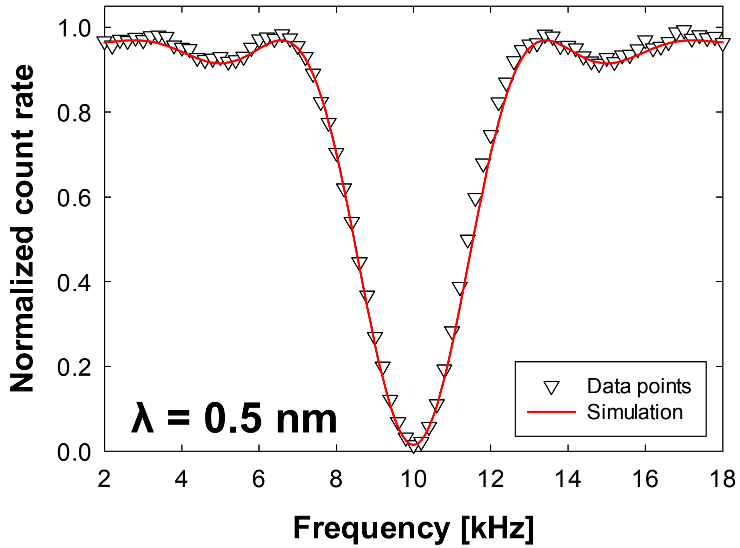
Martin Fertl, Klaus Kirch, Jochen Krempel & FP

Ramsey setup at BOA (December 2013)

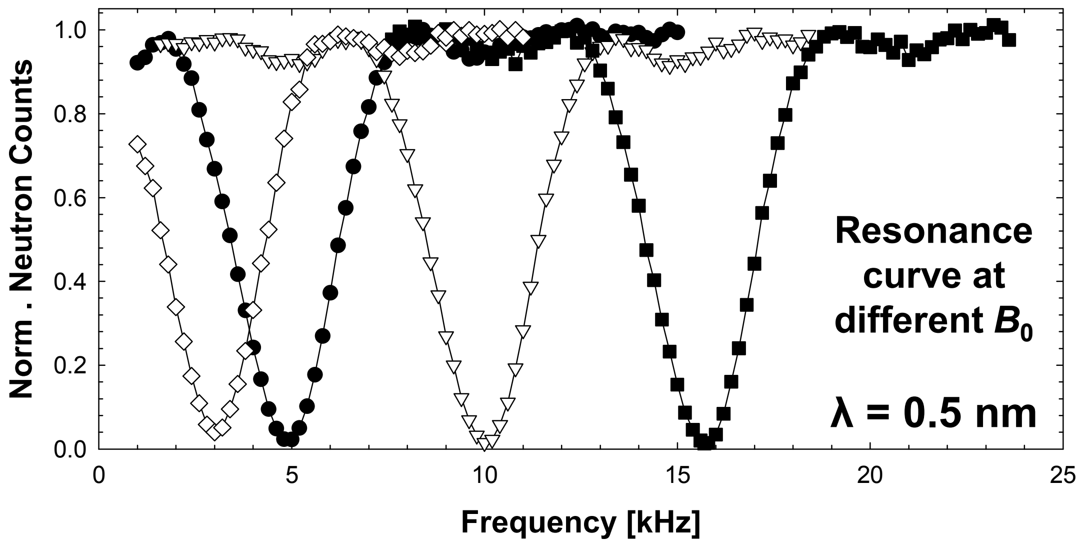


- White polarized neutron beam
- Two well collimated beams à 18(h) x 2.5(w) mm^2
- Magnetic field B_0 of about 170 µT
- Field stability ~ nT (actively stabilized - fluxgate)

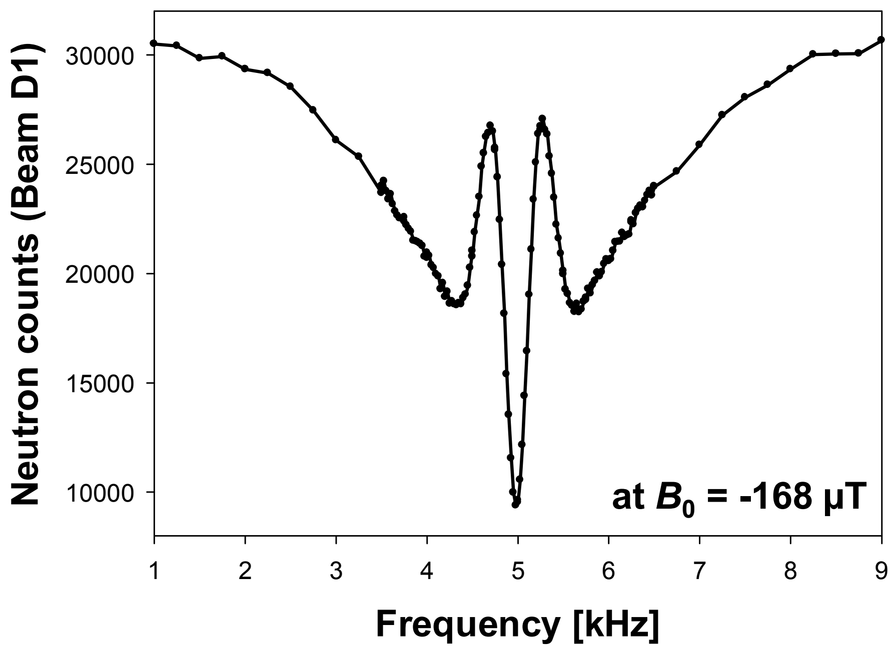




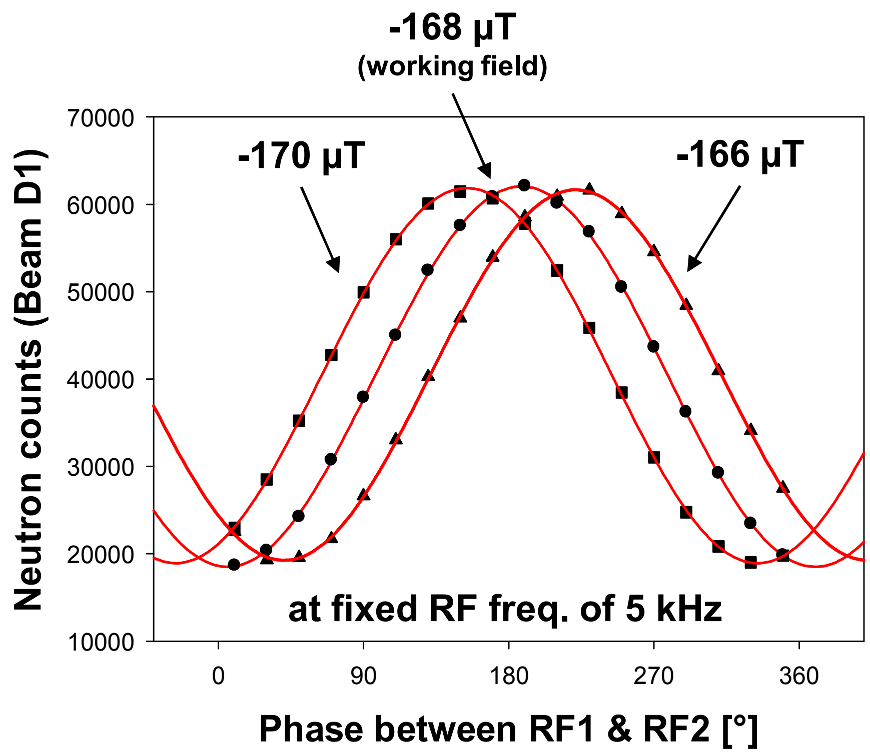
- Length = 25 cm
- Driven with audio-amp
- Longitudinal oscillating field
- Works fine down to ~ 100 μT
- Flip efficiency close to 100%



"Classic Ramsey" (Frequency scan) with a white neutron beam



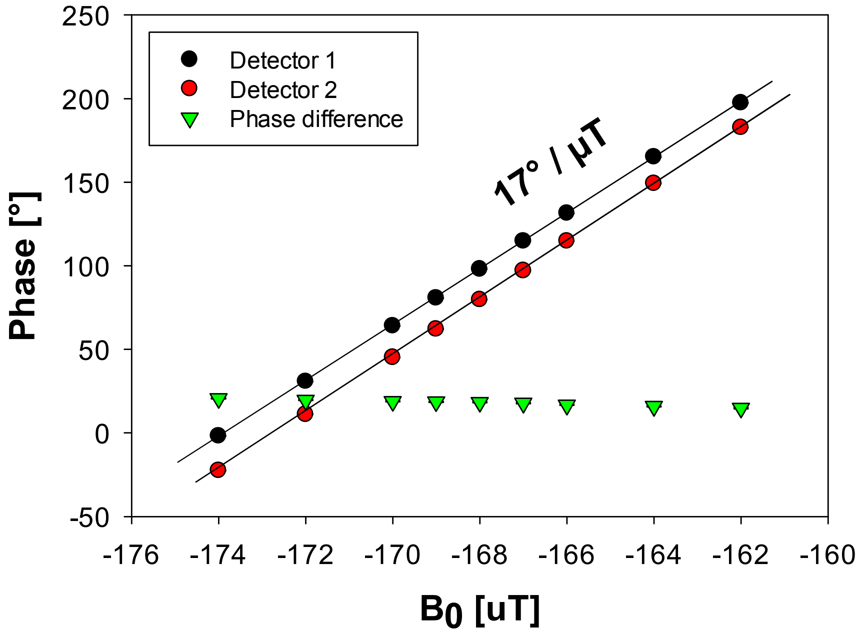
Alternatively: Ramsey phase-scan (about 5 min)



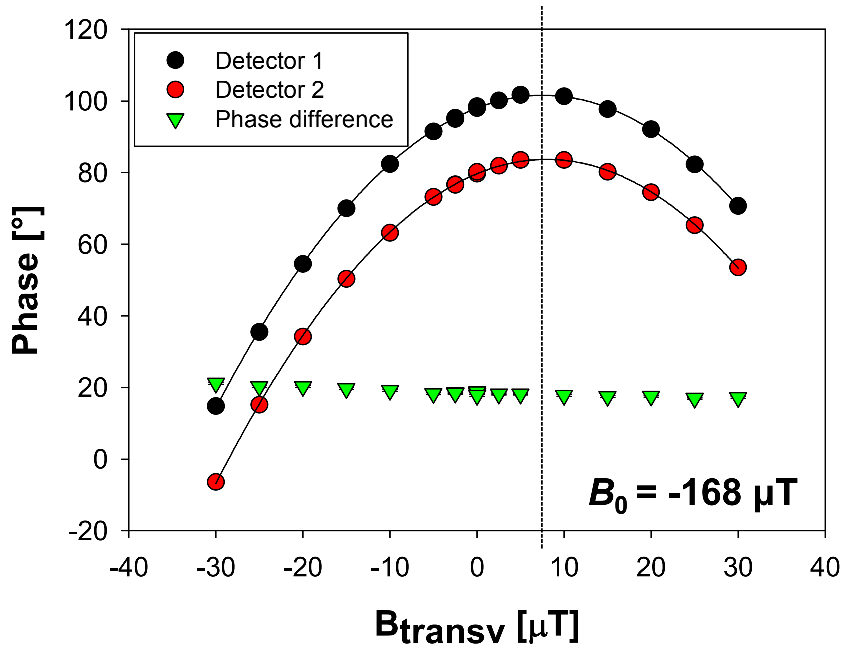
Phase shift ≈ 17° / µT

$$\left|\vec{B}\right| \approx B_0 + \delta B_z + \frac{\delta B_x^2 + \delta B_y^2}{2\,B_0} + \cdots$$

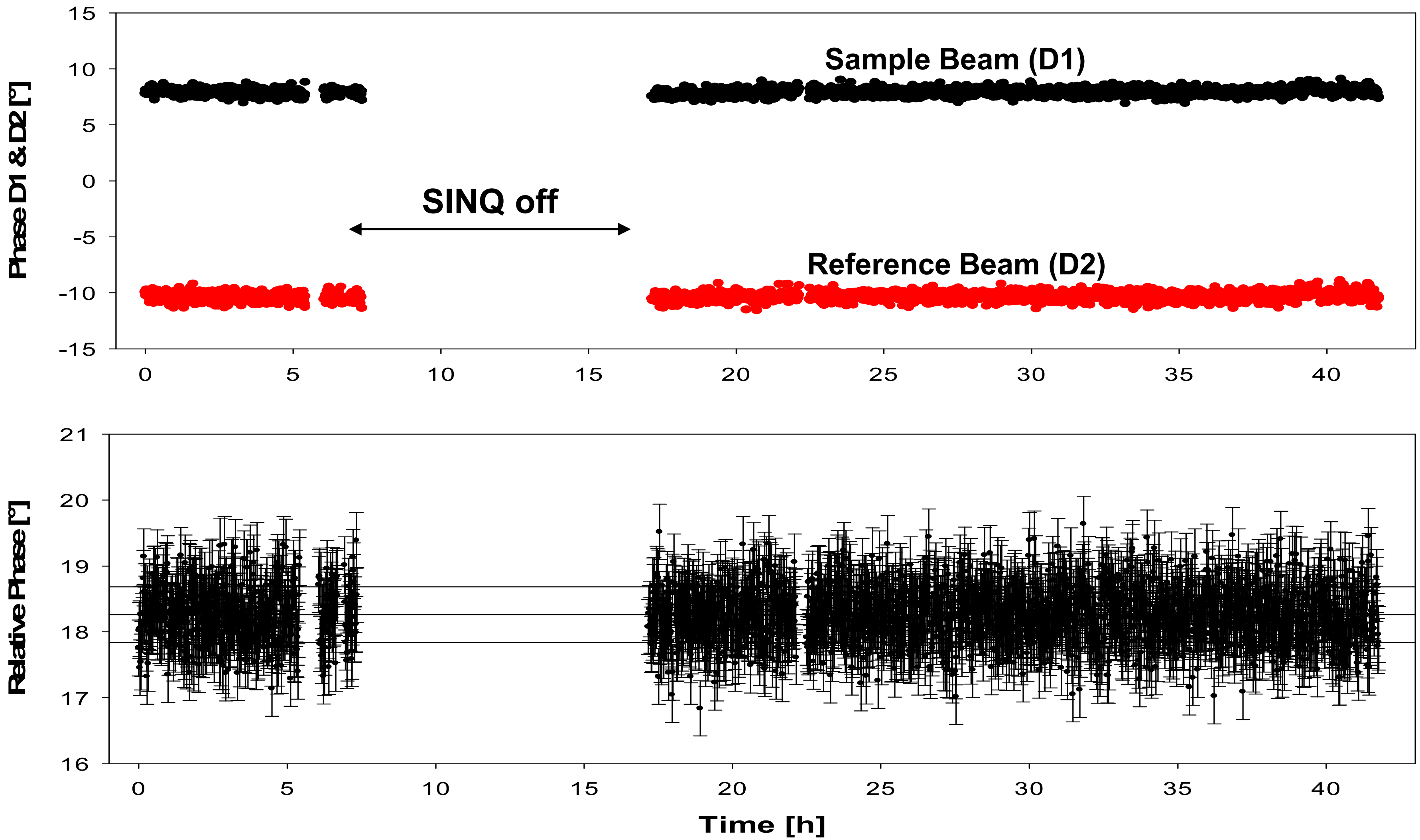
in *z*-direction



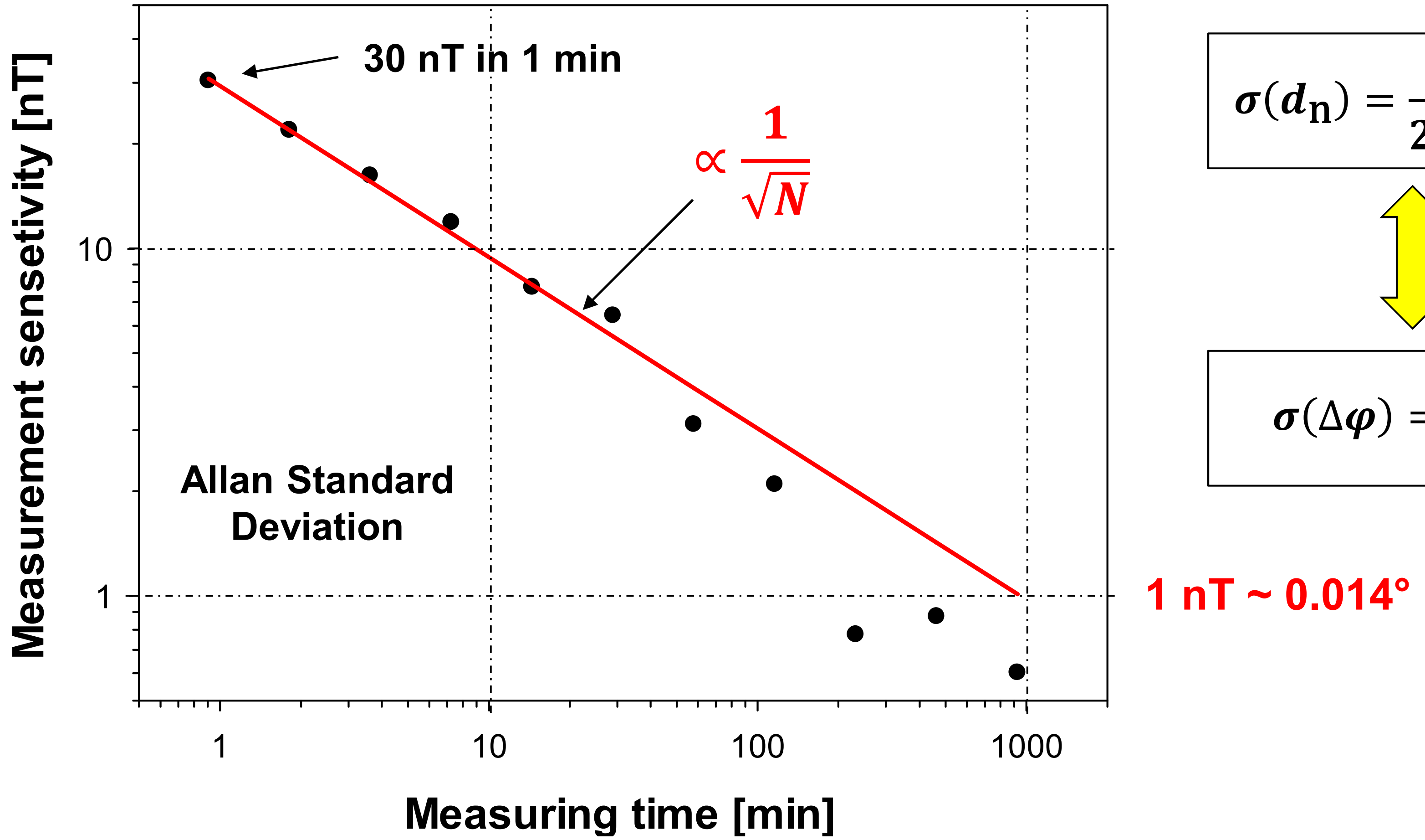
transversal field



Magnetic Field & Phase Stability



Magnetic field stabilization and two beam method work very good !



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

$$\sigma(\Delta\varphi) = \frac{2}{\eta\sqrt{N}}$$

So far no systematic limitation – purely statistical !

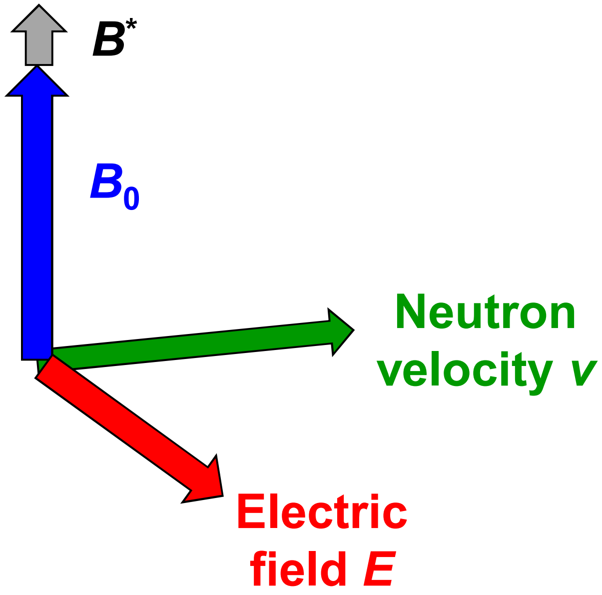
Use formula: $\eta \approx 0.7$ & $N_{D1+D2} = 5000\ s^{-1}$: $\sigma(\Delta\varphi) \approx 0.01°$ (at 1000 min)

► **Maximize $v \times E$ - effect – B and E perpendicular:**

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

Magnetic field "seen" by the neutron in its frame of reference, due to electric field.

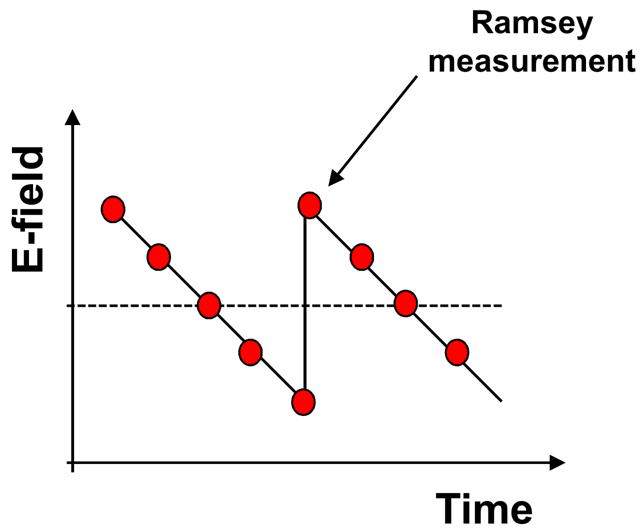
v = 1000 m/s & E = ± 1 MV/m ⇒ **B^* = ± 10 nT**



$$B_{tot} = B_0 + B^*$$

Measure Relativistic $v \times E$ - effect

Perform measurements in cycles:



- A measurement of the neutron EDM with a pulsed beam is complementary and can deliver a competitive result.

- The systematic effects need to be carefully considered.

- Probably offers the possibility for parasitic physics measurements (e.g. neutron magn. moment & exotics).

- New beam time starts next week at PSI.
  Goal: direct measurement of the $v \times E$ - effect

Mike Snow: *'The idea is not completely insane …'*

Thank you for your attention.