Beam EDM

Neutron pulsed beam experiment to search for an EDM

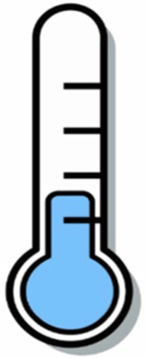
Florian Piegsa

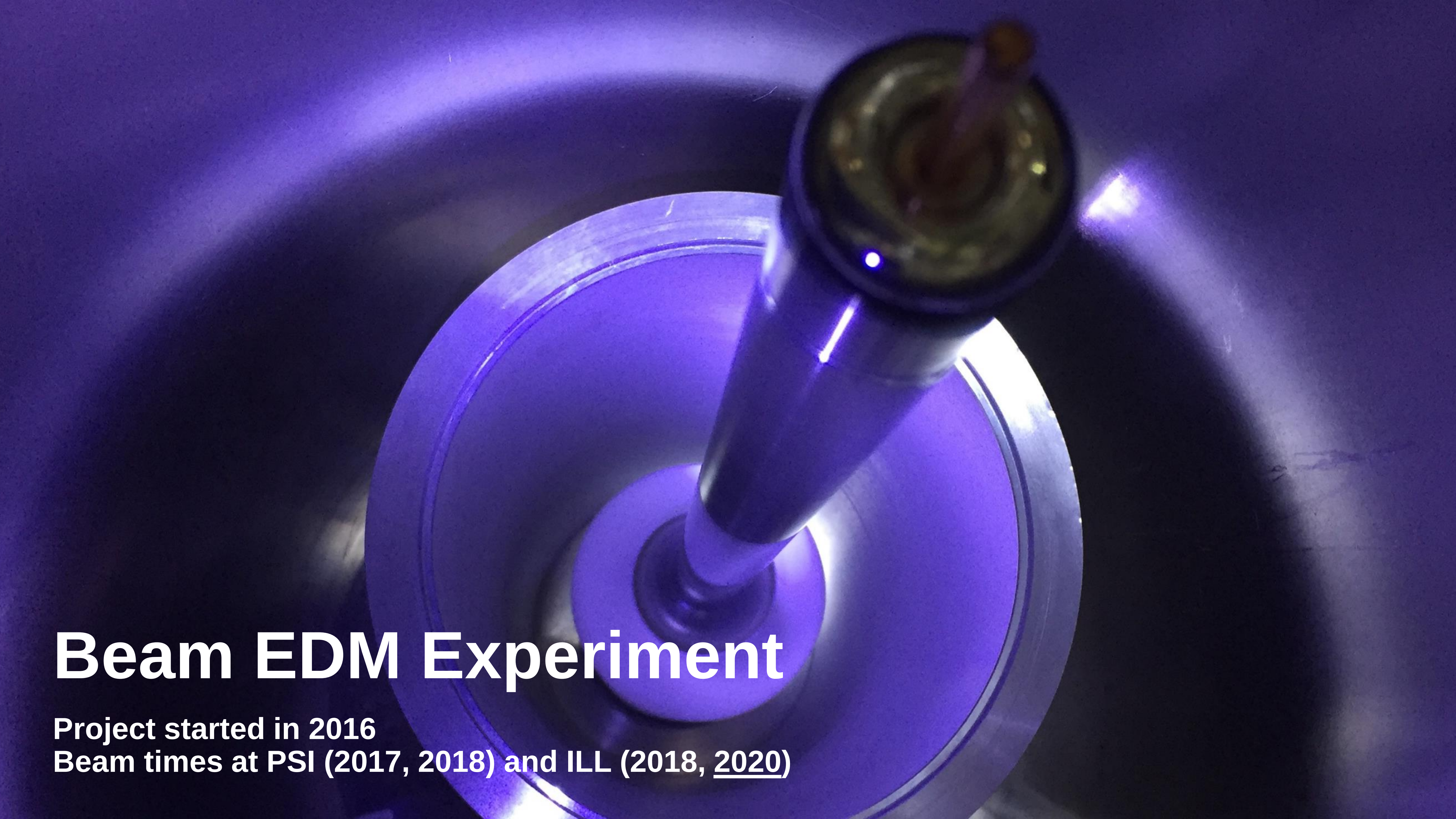
Laboratory for High Energy Physics
Albert Einstein Center for Fundamental Physics
University of Bern

UNIVERSITÄT BERN

Neutrons

Thermal (D_2O)	300 K	25 meV	2200 m/s
Cold (LD_2)	60 K	5 meV	1000 m/s
Ultracold (SD_2)	2 mK	200 neV	6 m/s

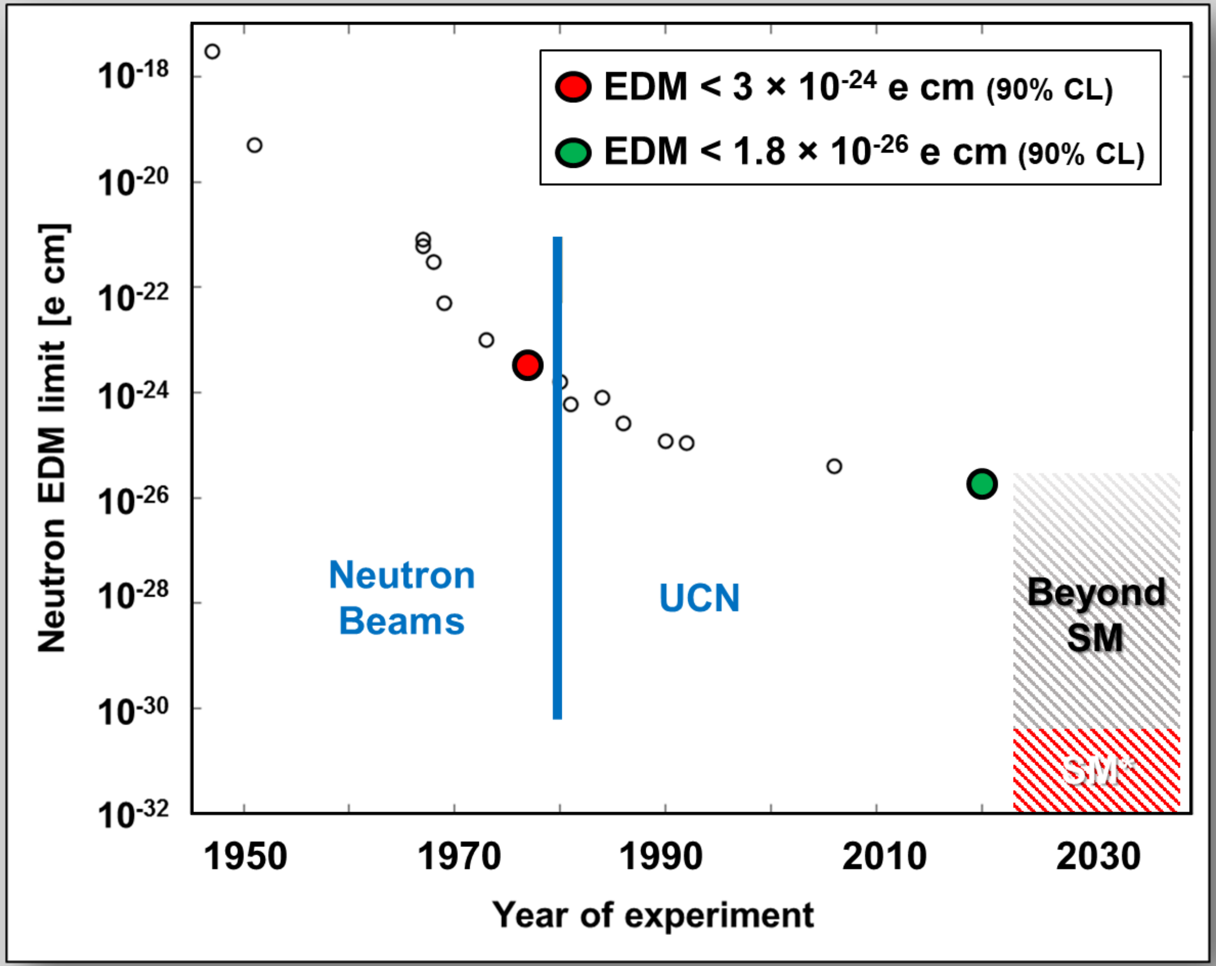




Beam EDM Experiment

Project started in 2016
Beam times at PSI (2017, 2018) and ILL (2018, <u>2020</u>)

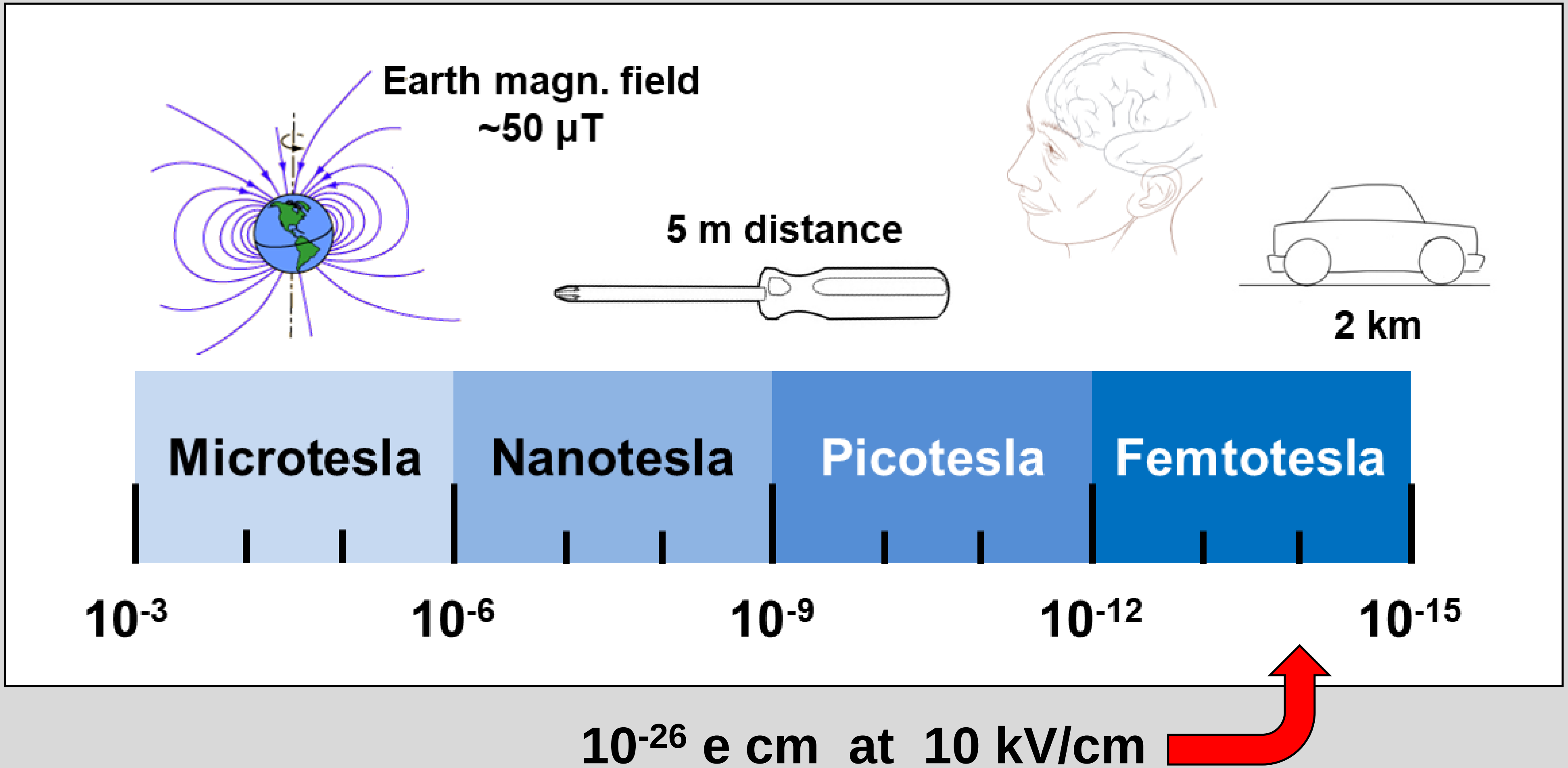
History of the neutron EDM



Dress et al., PRD 15, 9 (1977)
Abel et al., PRL 124, 081803 (2020)
* Seng, PRC 91, 025502 (2015)

How sensitive is this really?

UNIVERSITÄT BERN



10^{-26} e cm at 10 kV/cm

Neutron EDM sensitivity

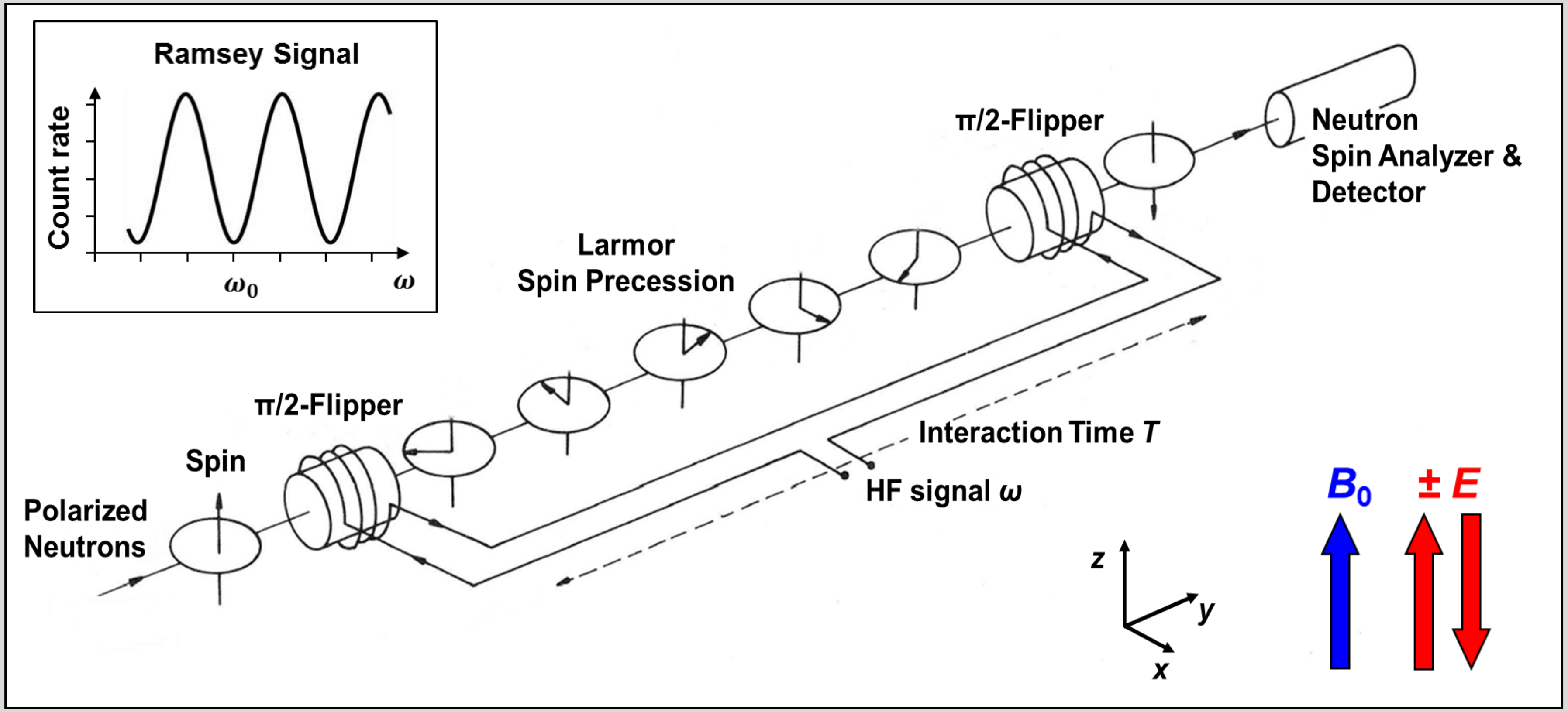
$$\sigma(d_n) \propto \frac{1}{ET\sqrt{N}}$$

BEAM ⟷ **UCN***

BEAM		UCN*	
E = 100 kV/cm		E = 11 kV/cm	
$\dot{N}$ ≈ 100 MHz	(ESS)	$\dot{N}$ = 11'400 / 300 s ≈ 40 Hz	
T ≈ 100 ms	(50 m)	T = 180 s	(storage)

* Abel et al. (*nEDM-collaboration*), PRL 124, 081803 (2020)

Ramsey's Technique



$$\Delta\varphi = (\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) \cdot T \propto d \cdot E$$

Ramsey, PR 76, 996 (1949)
Ramsey, PR 78, 695 (1950)

Why were beam experiments abandoned?

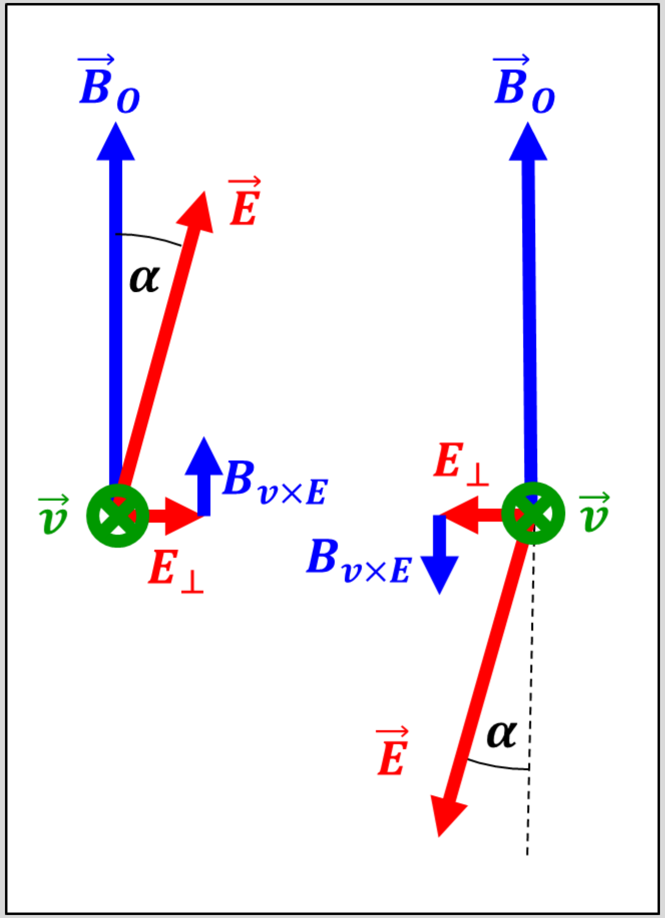
UNIVERSITÄT BERN

- **v×E – effect:** $$\vec{B}_{v\times E} = -\frac{\vec{v}\times\vec{E}}{c^2}$$

- **This can cause a false EDM signal, e.g.:**

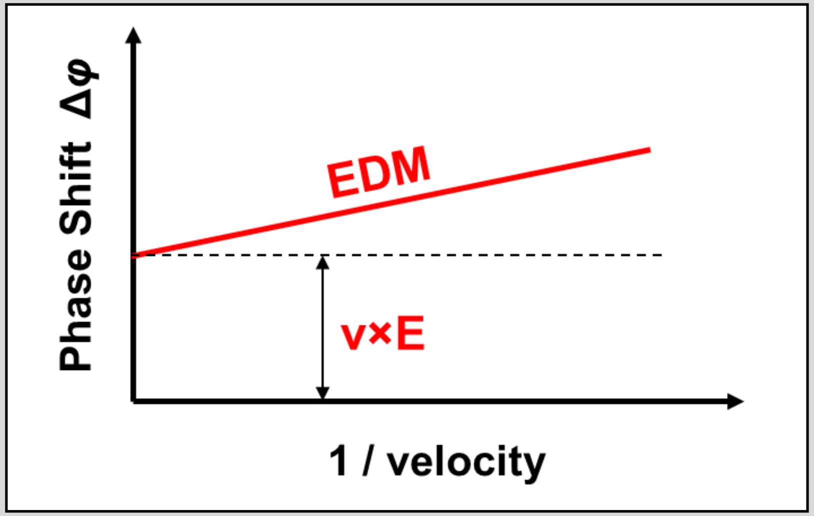
$$d_{\text{false}} \approx 10^{-20}\,\text{e cm}\cdot\sin\alpha \qquad \textbf{for:}\;\; v = 100\ \text{m/s}$$

- **The false effect is velocity-dependent, however, a real EDM signal is not !**



Novel concept using a pulsed beam

UNIVERSITÄT BERN



Length of experiment

$$\Delta\varphi = \frac{8 d_n E}{\hbar} T + \frac{4 \gamma_n E L}{c^2} \sin\alpha$$

slope = EDM   offset = v×E

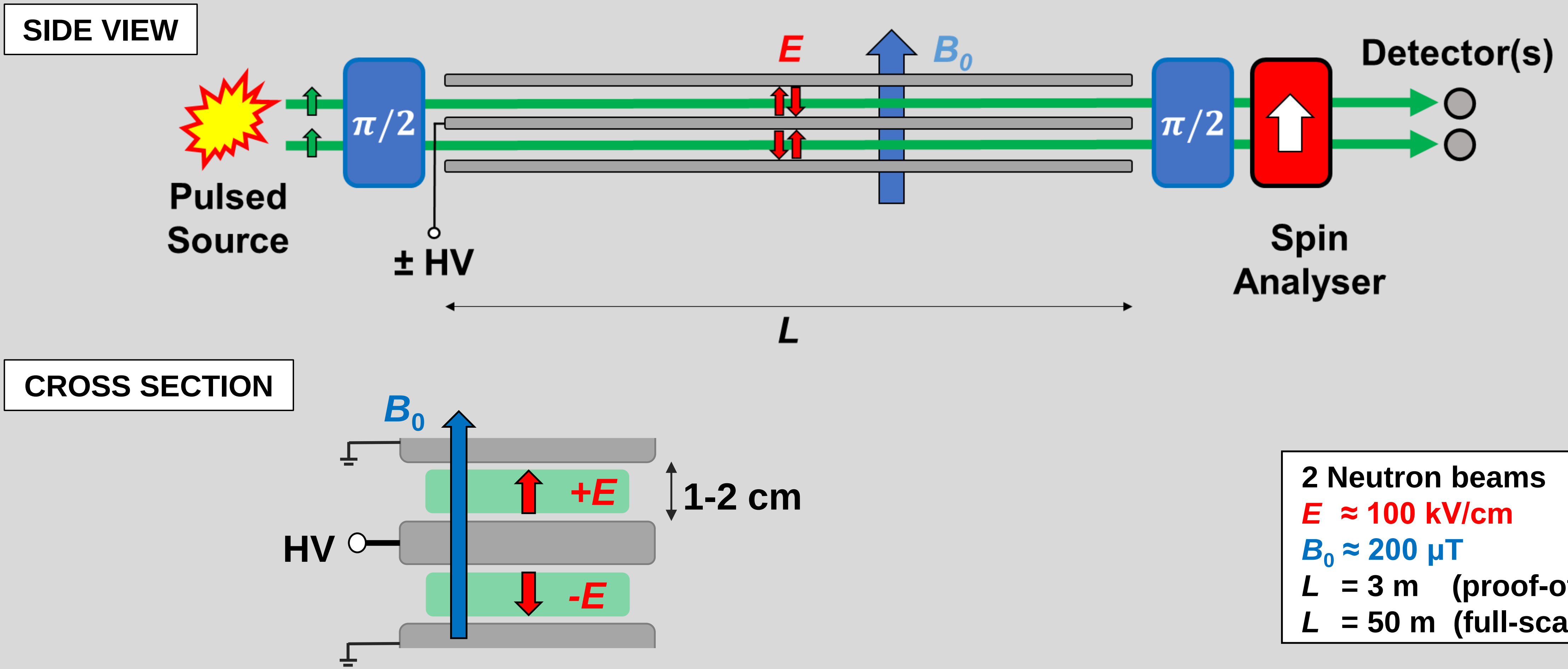
Concept is ideal for pulsed neutron spallation sources

e.g. at the European Spallation Source (ESS)

Start with proof-of-principle experiments

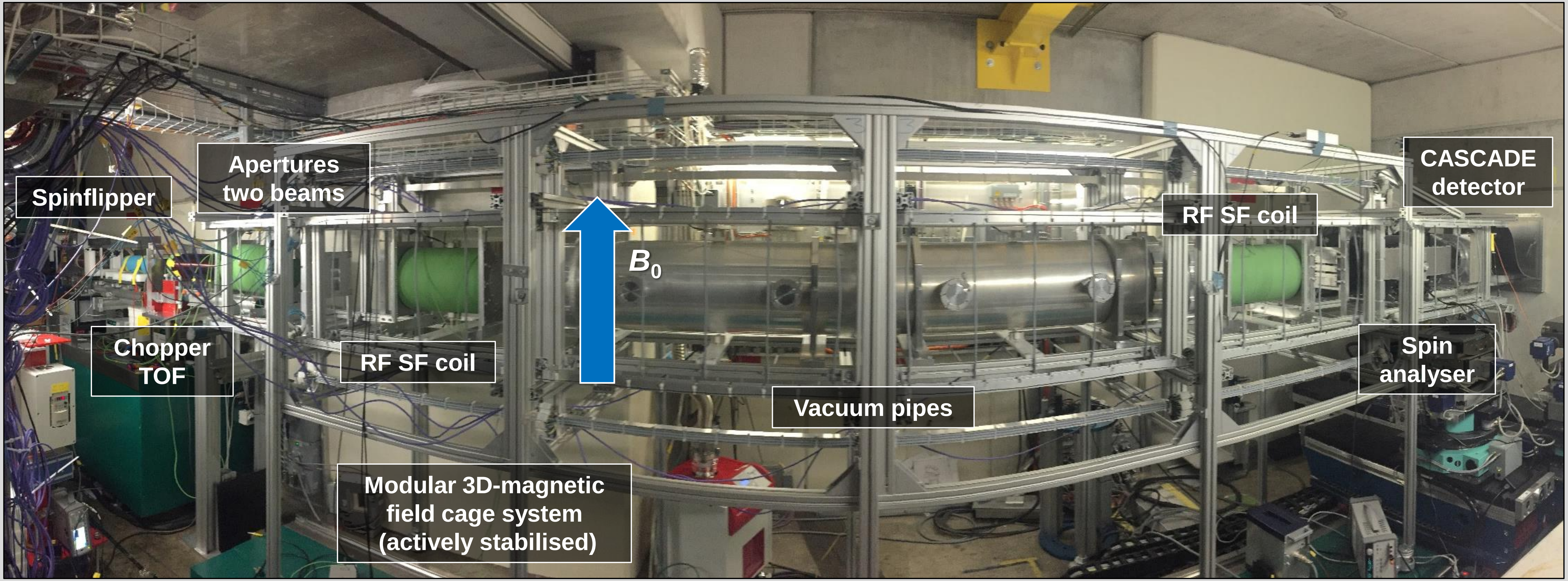
Piegsa, PRC 88, 045502 (2013)

Beam EDM experiment

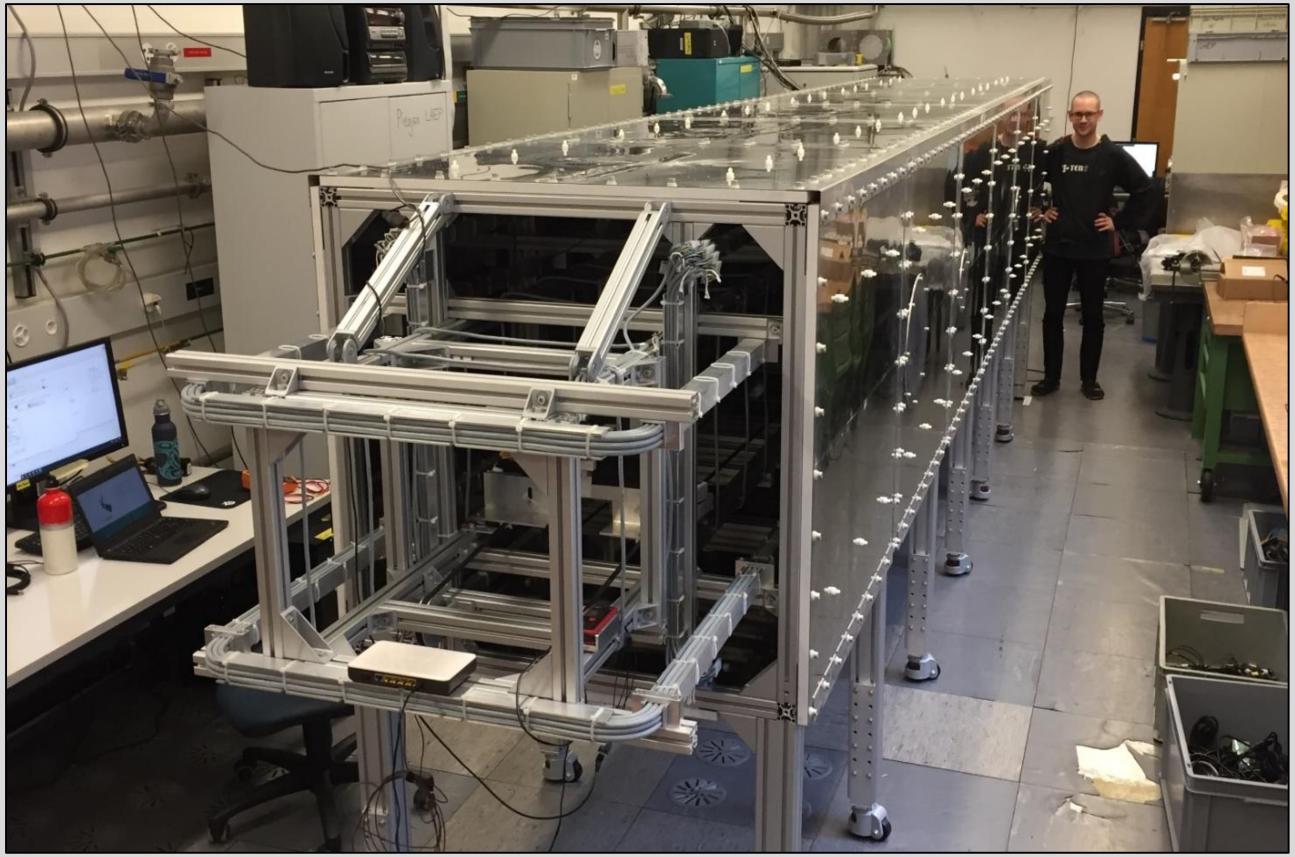


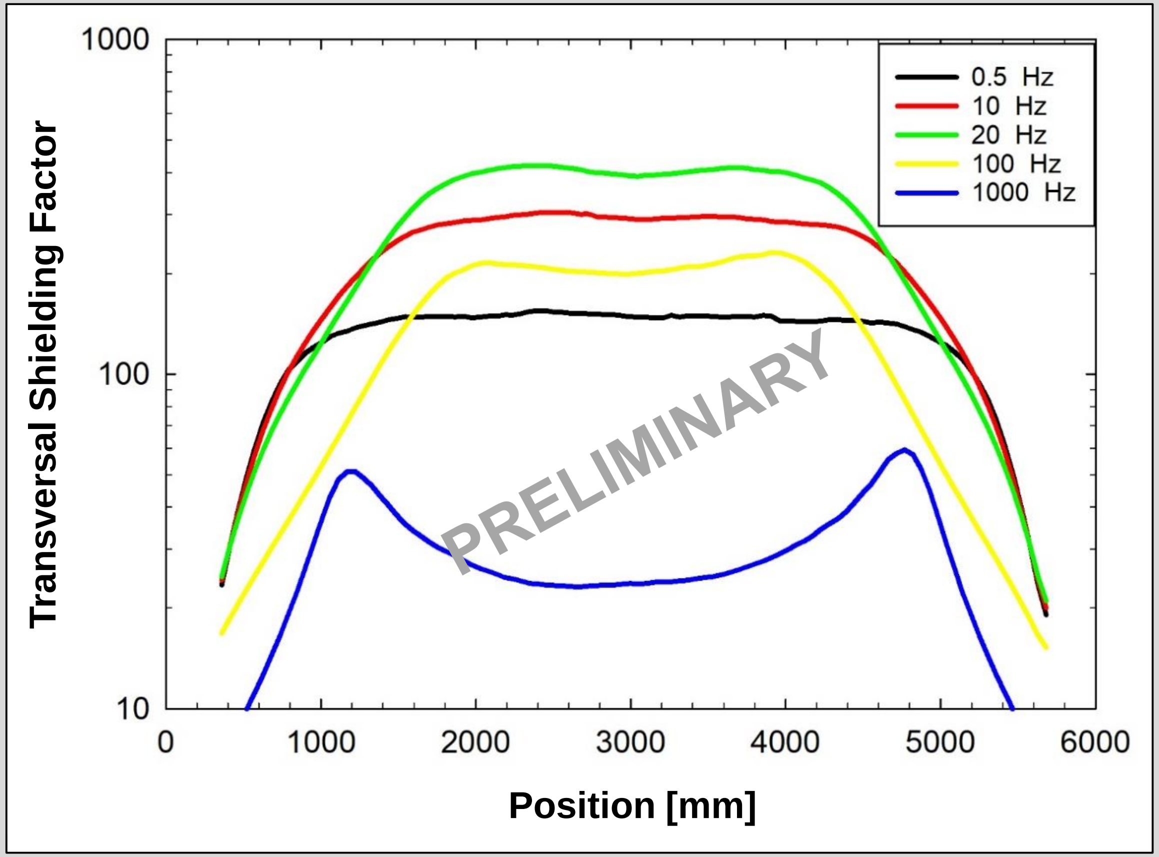
2 Neutron beams
$E \approx 100$ kV/cm
$B_0 \approx 200$ μT
L = 3 m (proof-of-prin.)
L = 50 m (full-scale)

Beam time at PSI (Sept./Oct. 2018)



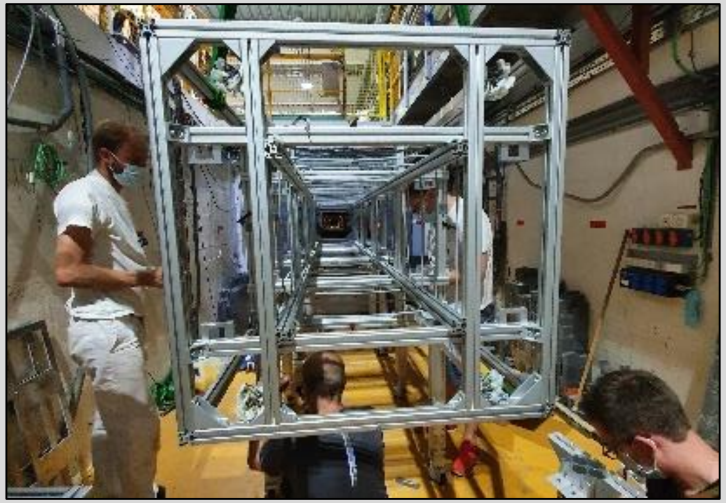
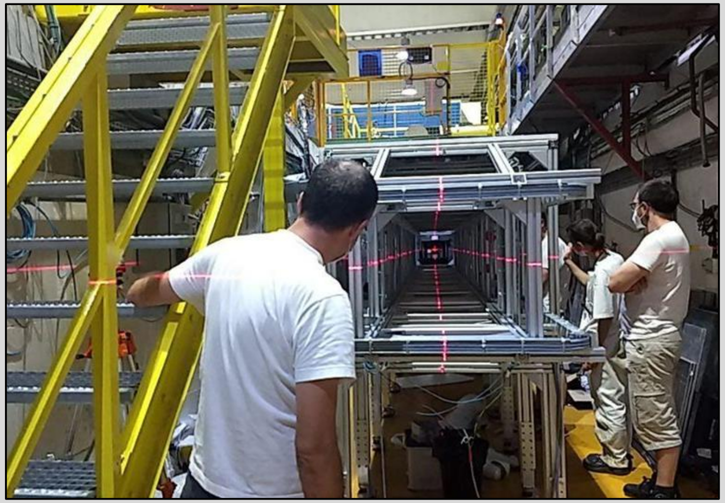
Two layer magnetic shield (2020)

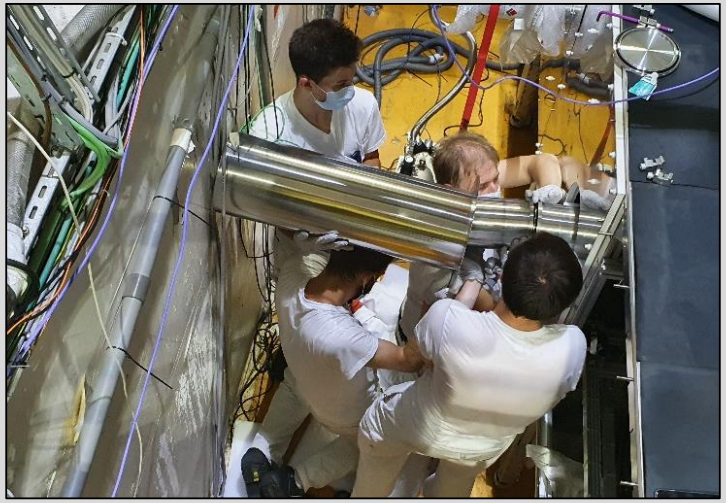




► **Passive shielding of external field inhomogeneities and fluctuations**

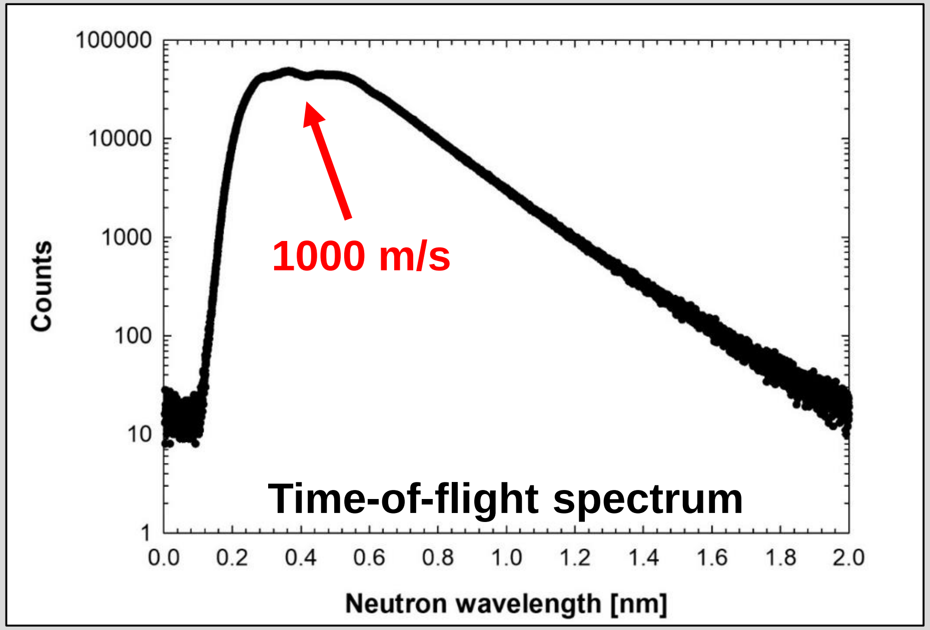
Beam time at ILL (Aug./Sept. 2020)

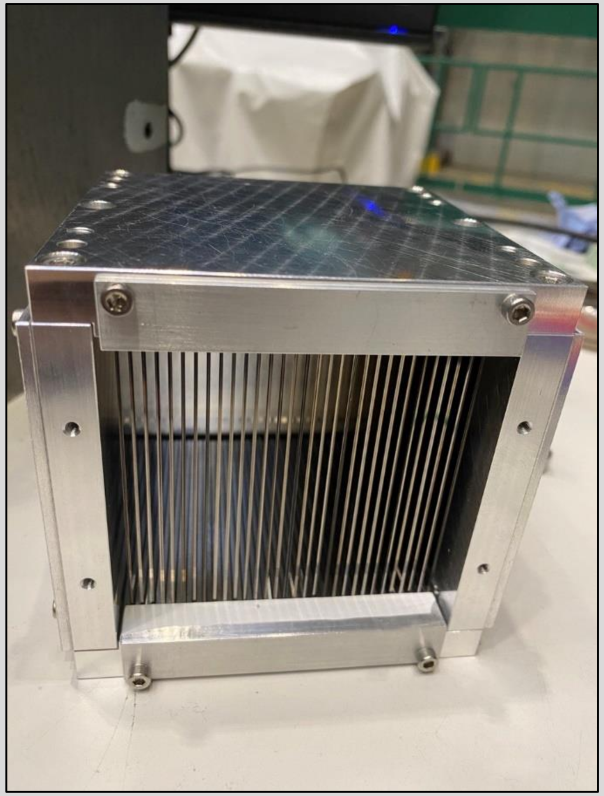

Ramsey apparatus at PF1b

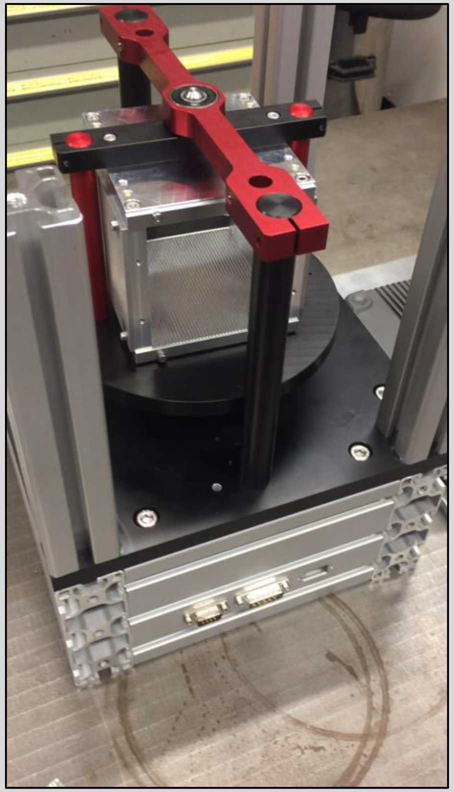
- Two beams each: 1 × 7 cm^2
- Main (vertical) magnetic field: B_0 = 220 µT
- 3 × 1-meter-long electrode sections/stacks
- 8 internal (stab.) and 5 external (monitor) fluxgates



Chopper

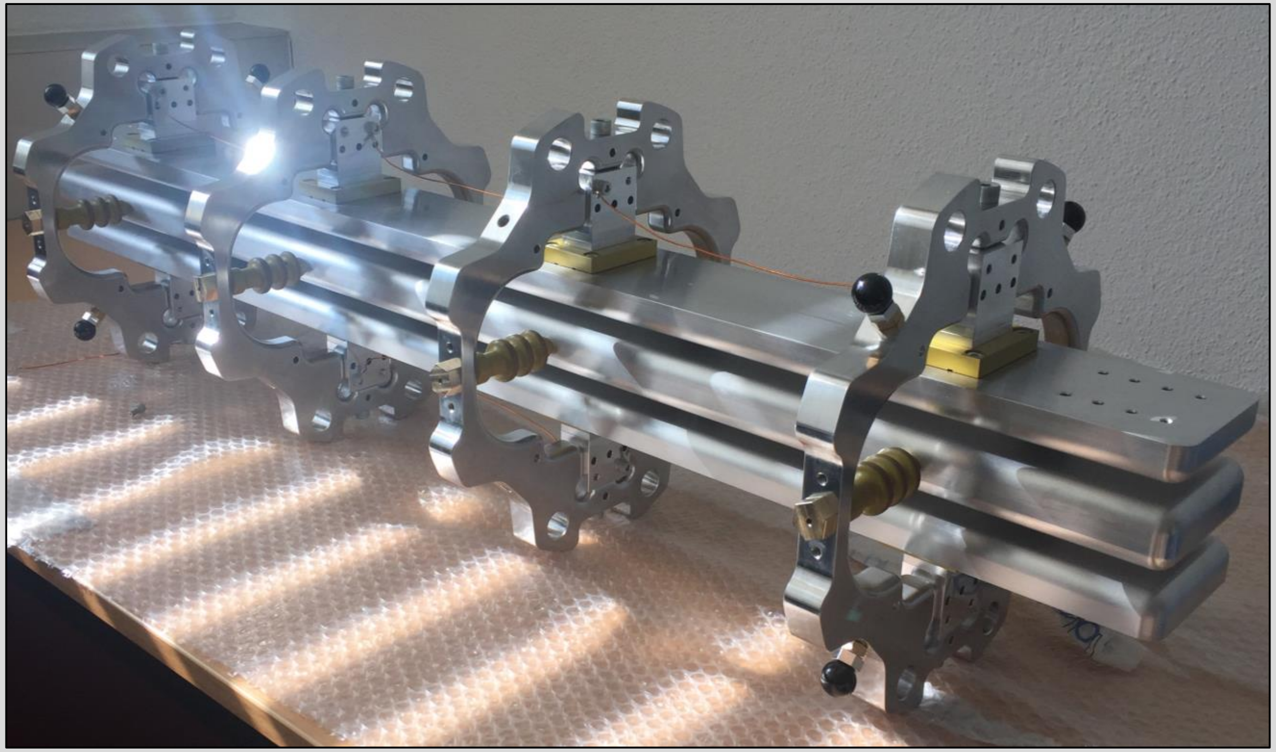
UNIVERSITÄT BERN

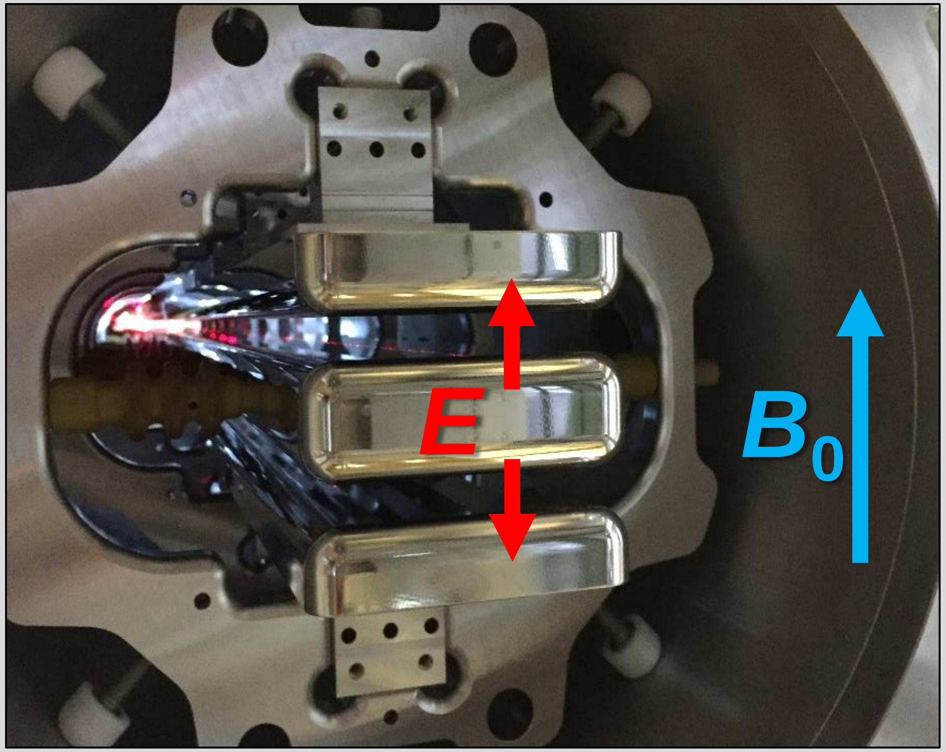




► **Collimator (Gd-coated wafers) installed on a motorized/spinning turntable (up to 15 Hz)**

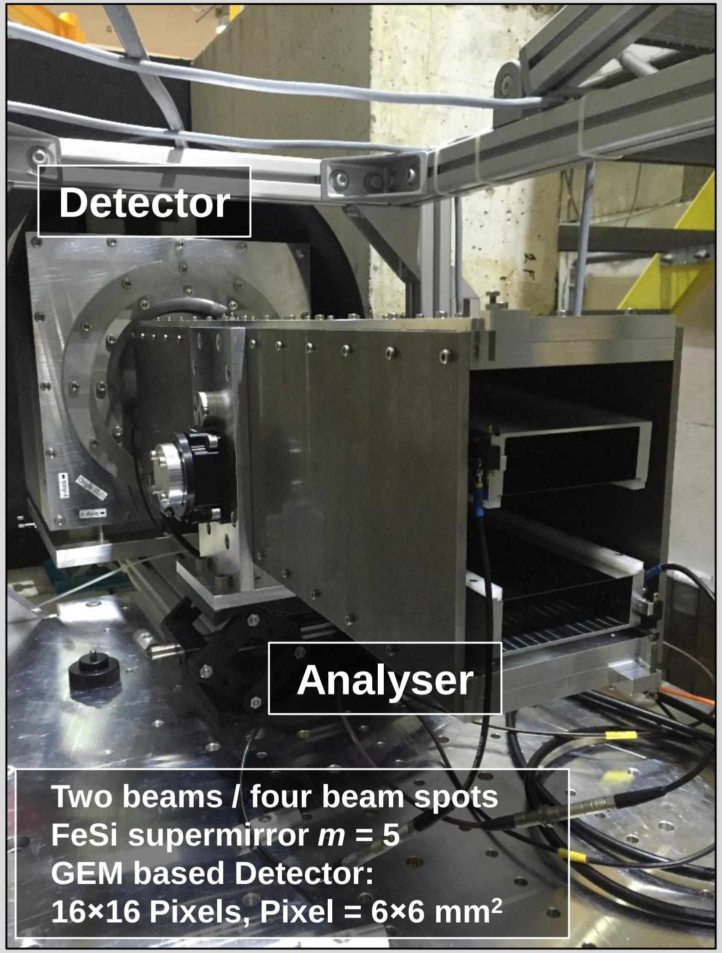
Electrode stacks

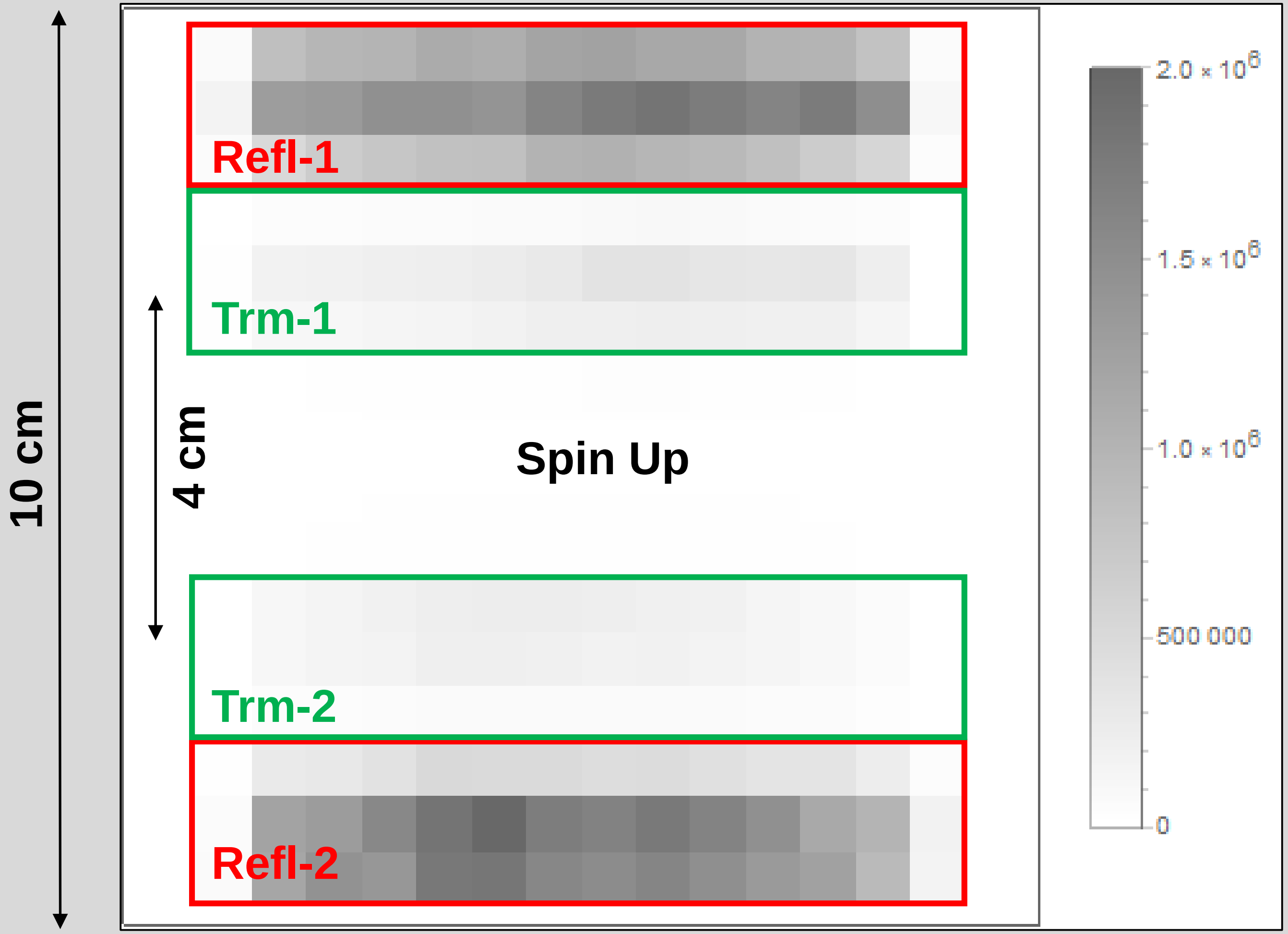




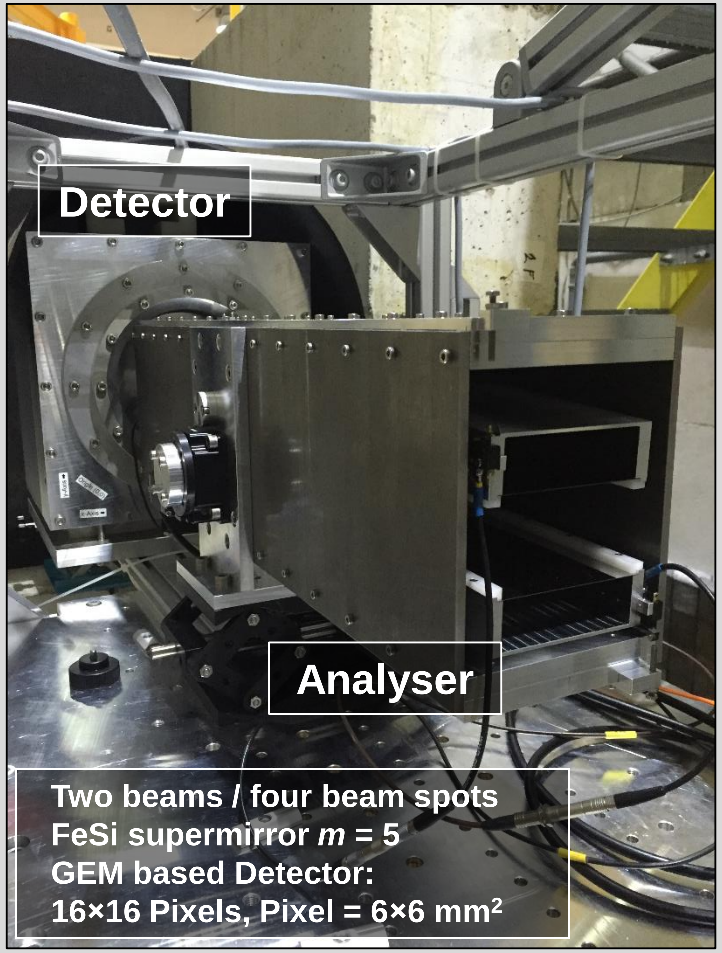
► **Length: 1 m, Separation: 1 cm, Achieved electric field (stable): ± 40 kV/cm**

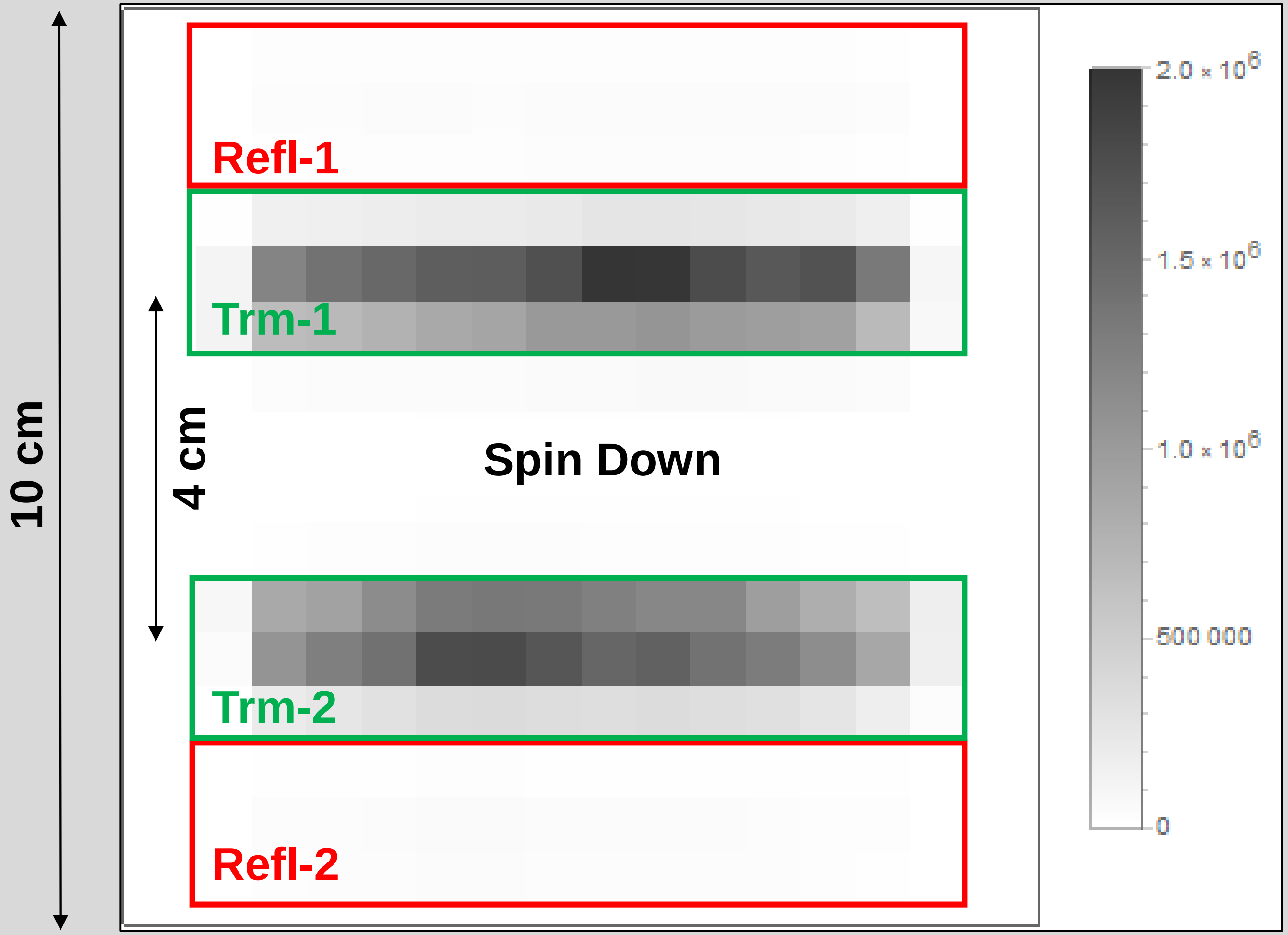
Spin analyser and detector





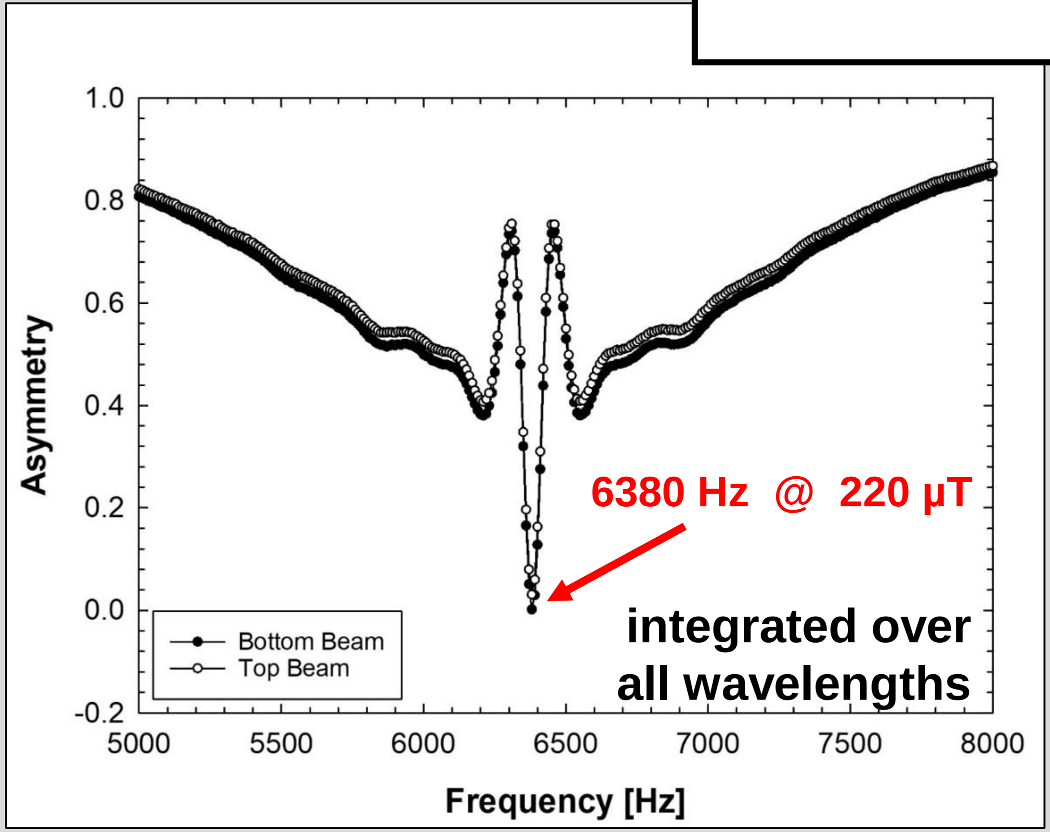
Spin analyser and detector

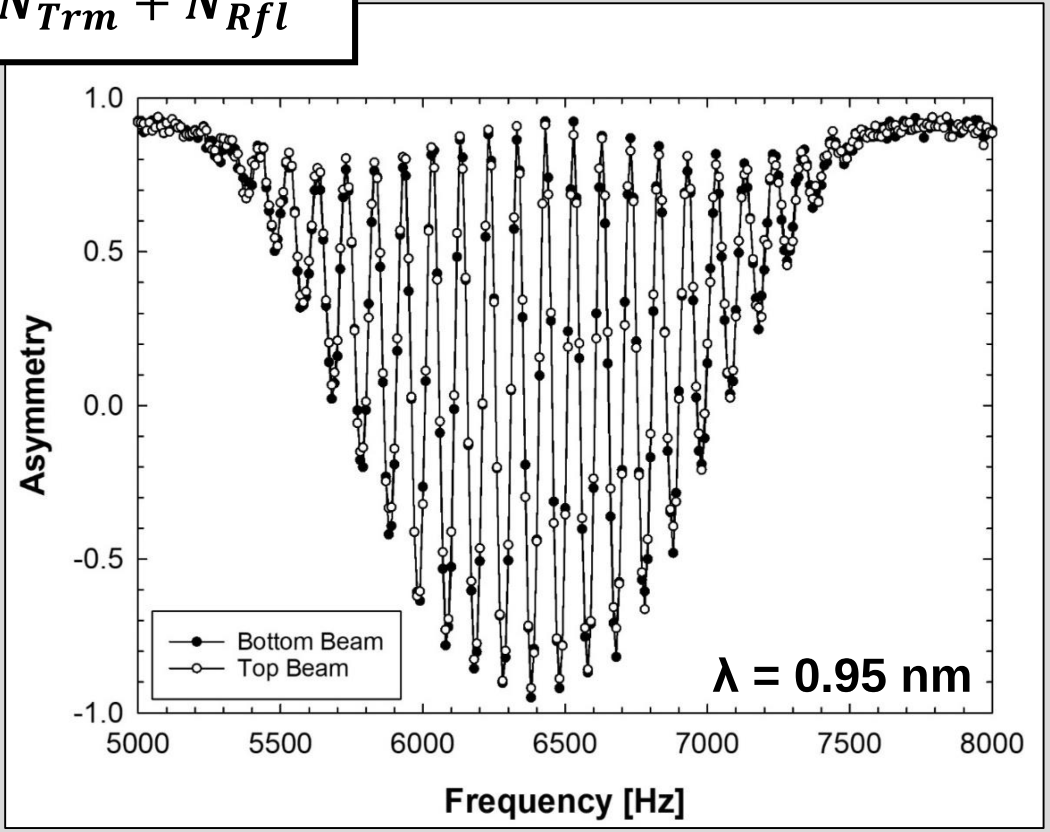




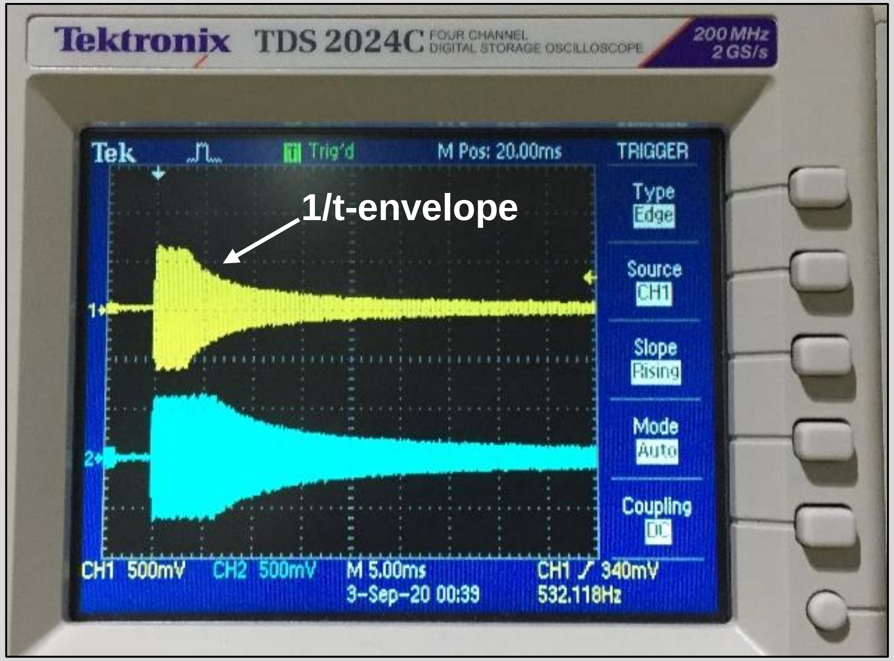
Classic Ramsey frequency scan

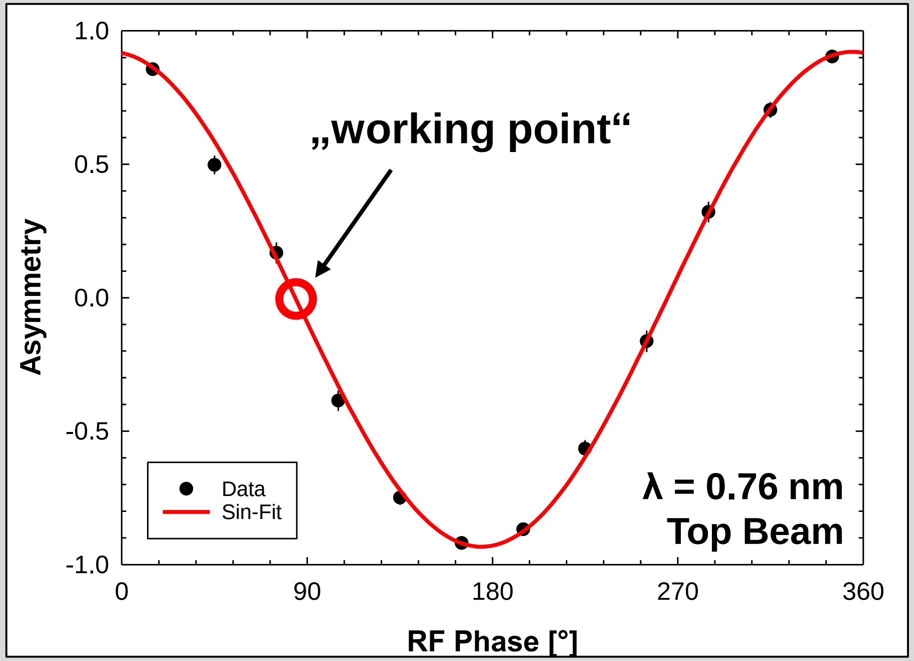
$$Asymmetry = \frac{N_{Trm} - N_{Rfl}}{N_{Trm} + N_{Rfl}}$$





Modulated RF-signal & Ramsey phase scan

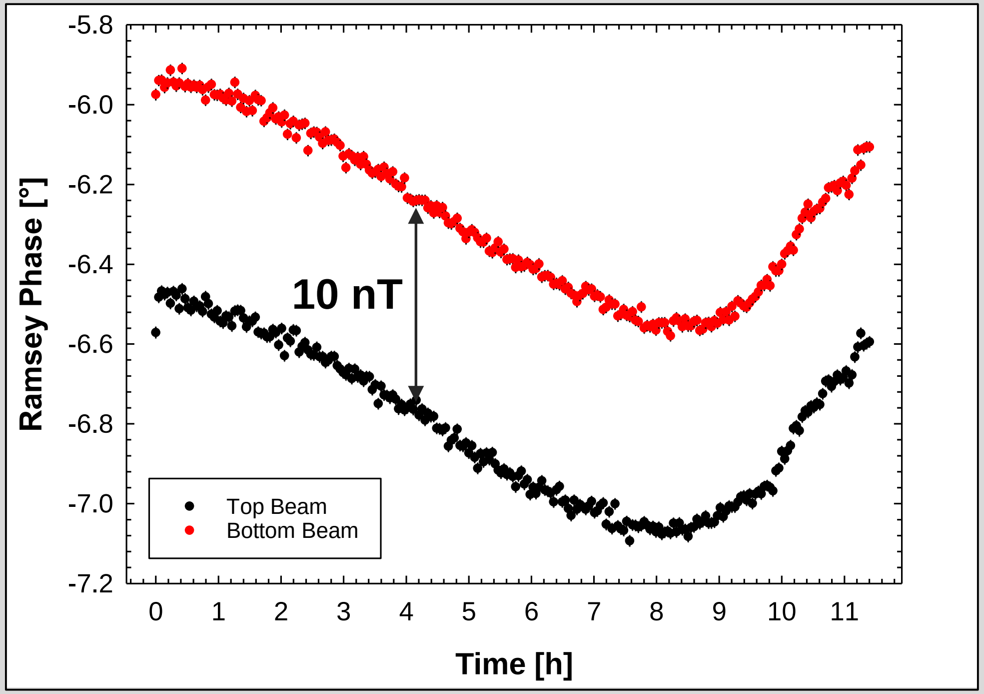




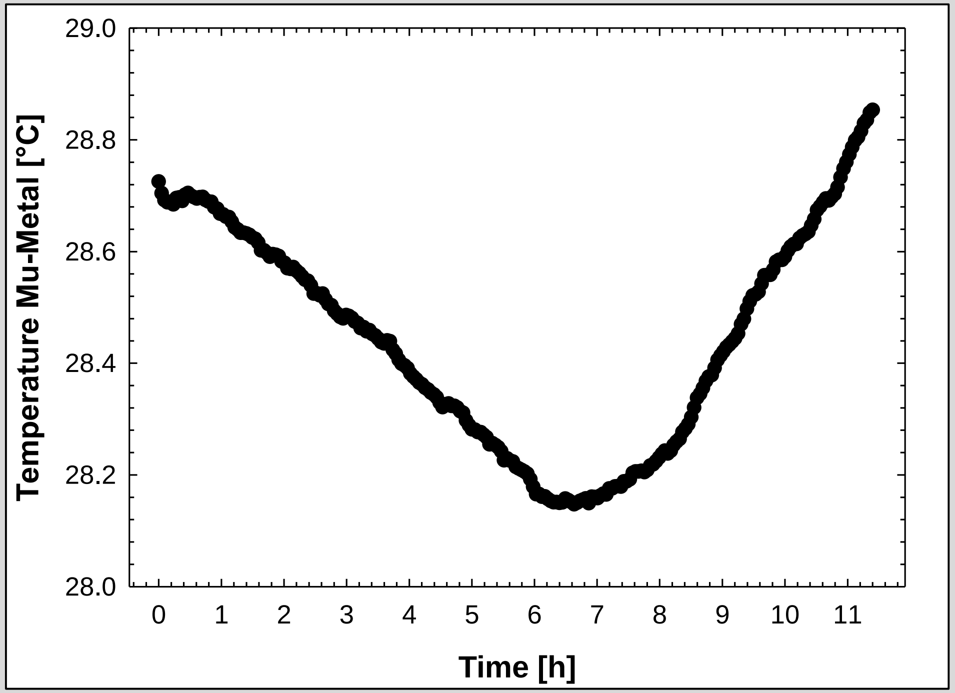
- **Modulated RF-amplitude triggered by chopper to achieve π/2 flip for all wavelengths**
- **Scan RF-phase between two spin-flippers with fixed frequency**
- **Option: measure only at „working point", i.e. Asymmetry = 0**

Phase stability

Two beams



Temperature drift

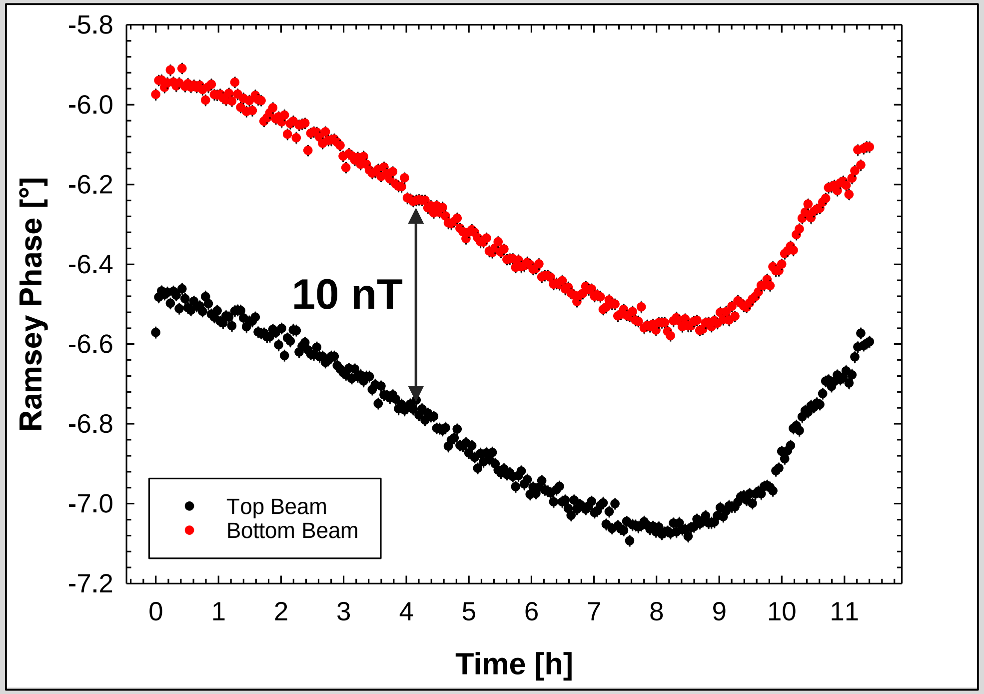


► **Two beam method allows for correction of (magnetic) drifts**

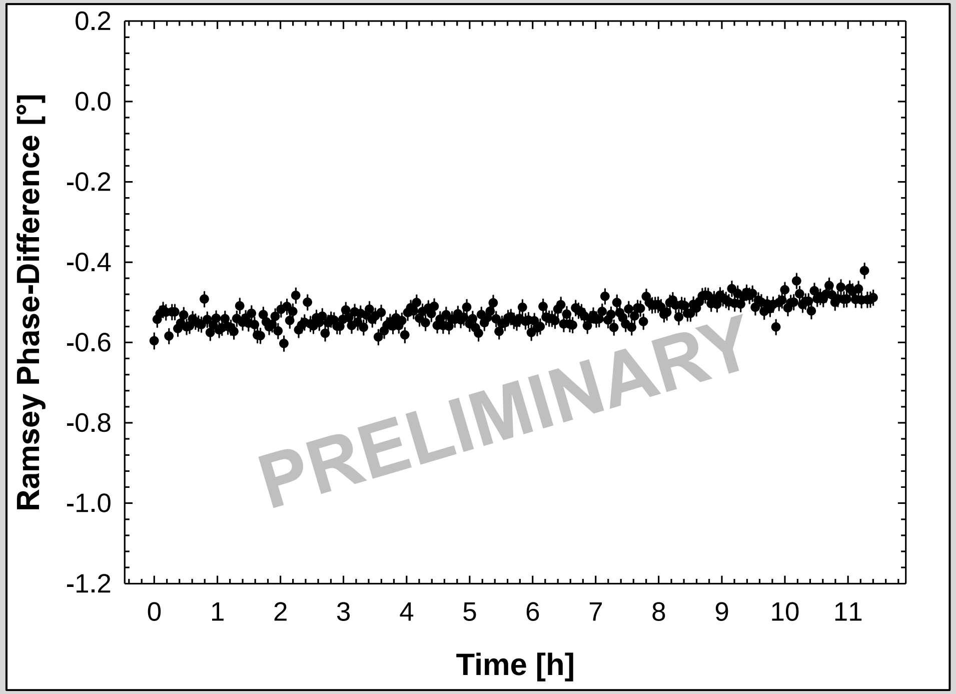
Phase stability

UNIVERSITÄT
BERN

Two beams

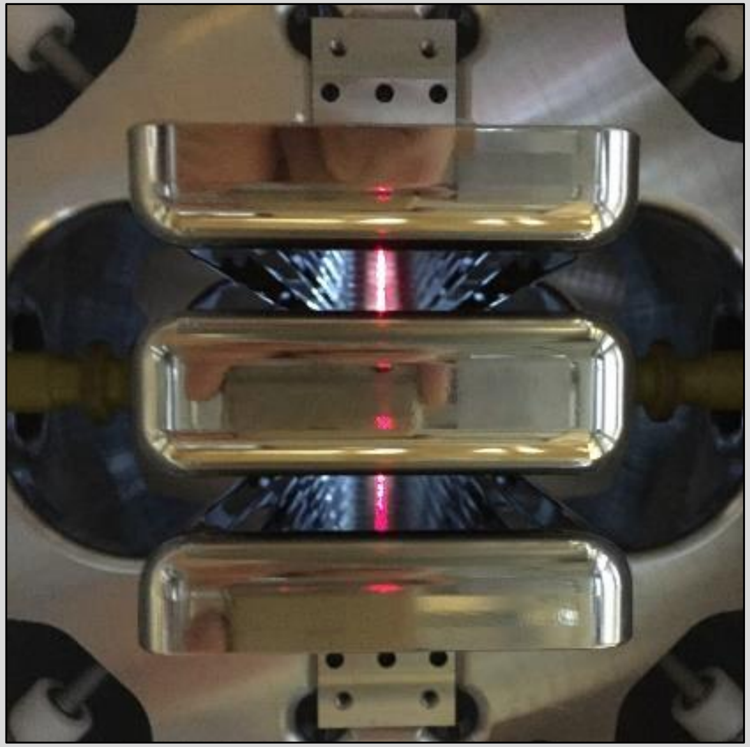


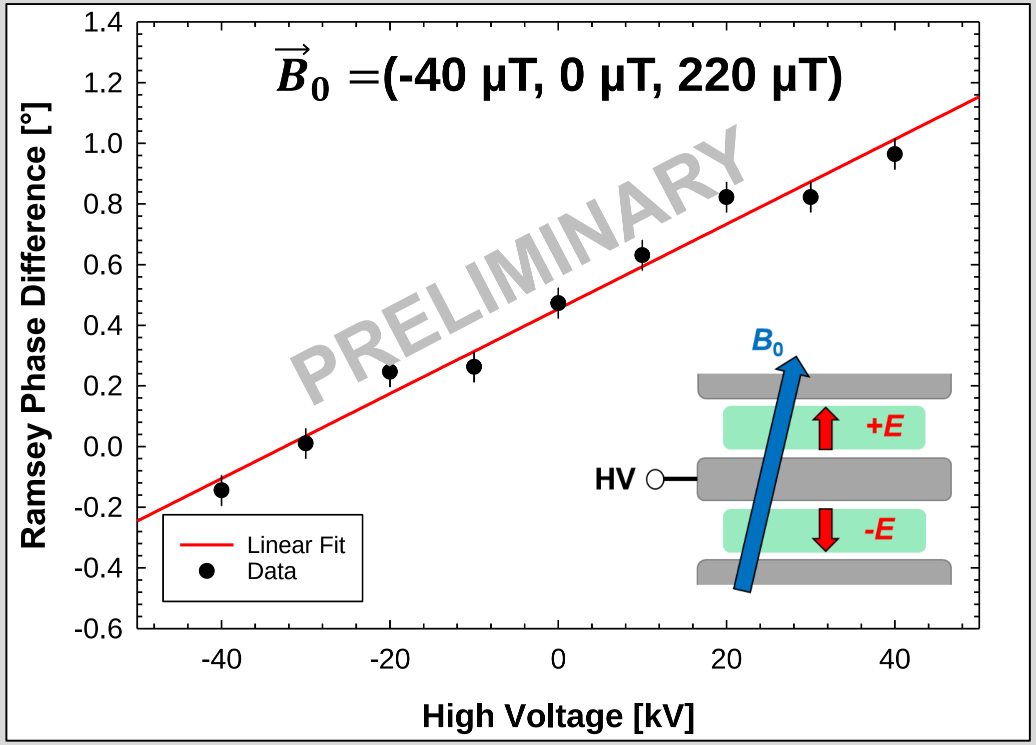
Phase-difference of two beams



► **Two beam method allows for correction of (magnetic) drifts**

Relativistic v×E effect

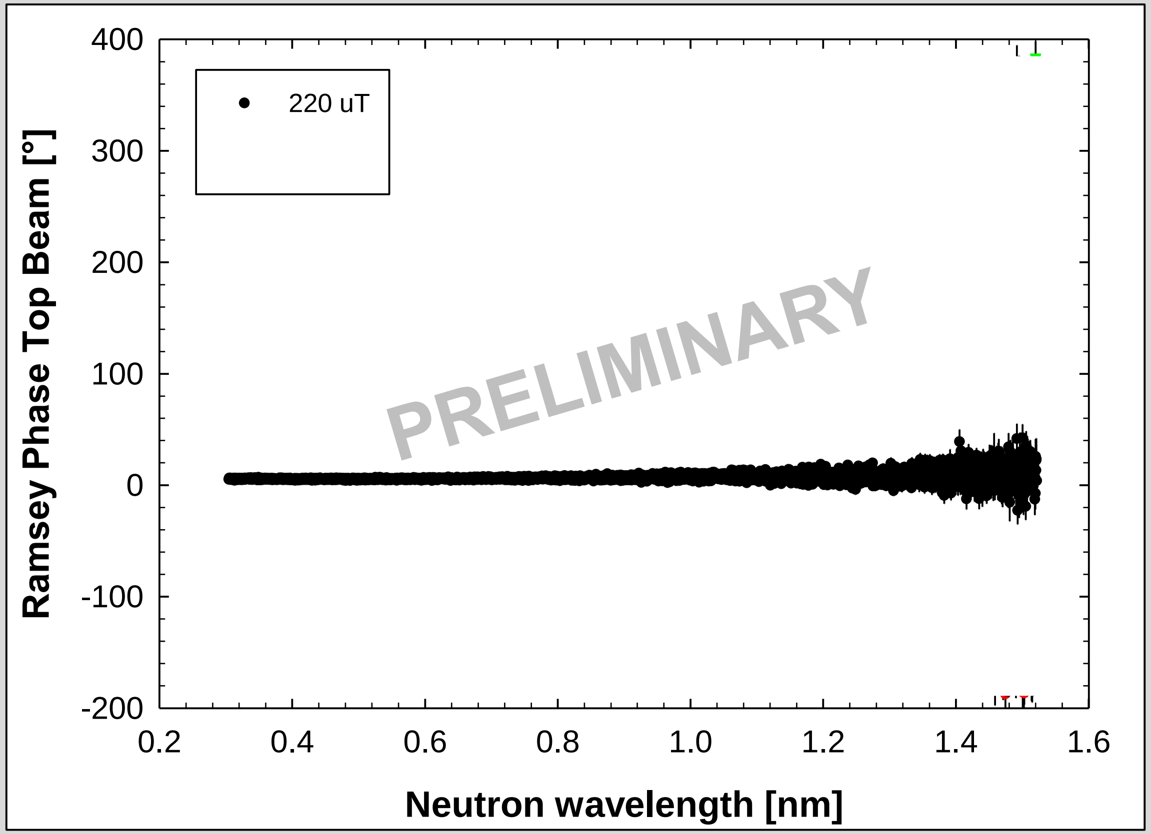




- v×E effect allows for a direct measurement of the electric field seen by the neutrons
- Here: magnetic field was intentionally tilted with respect to electric field direction

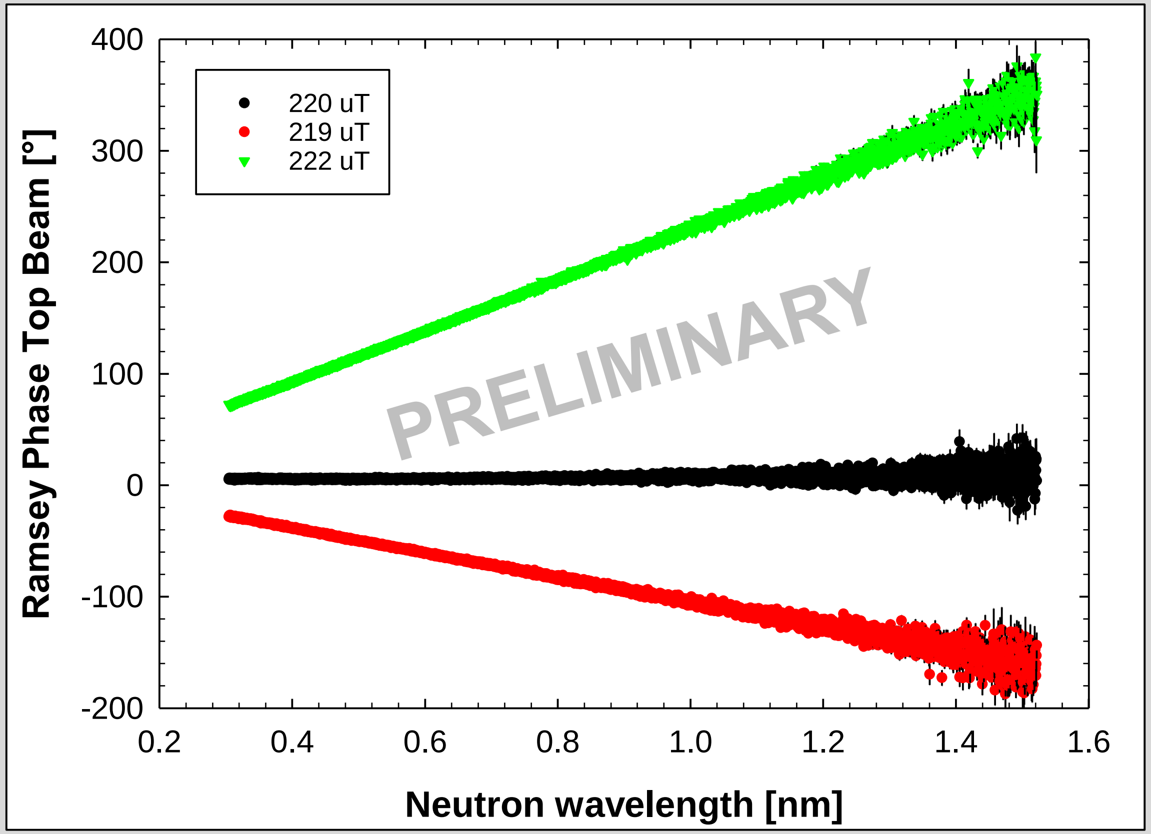
Magnetic field scan – emulating an EDM

UNIVERSITÄT BERN



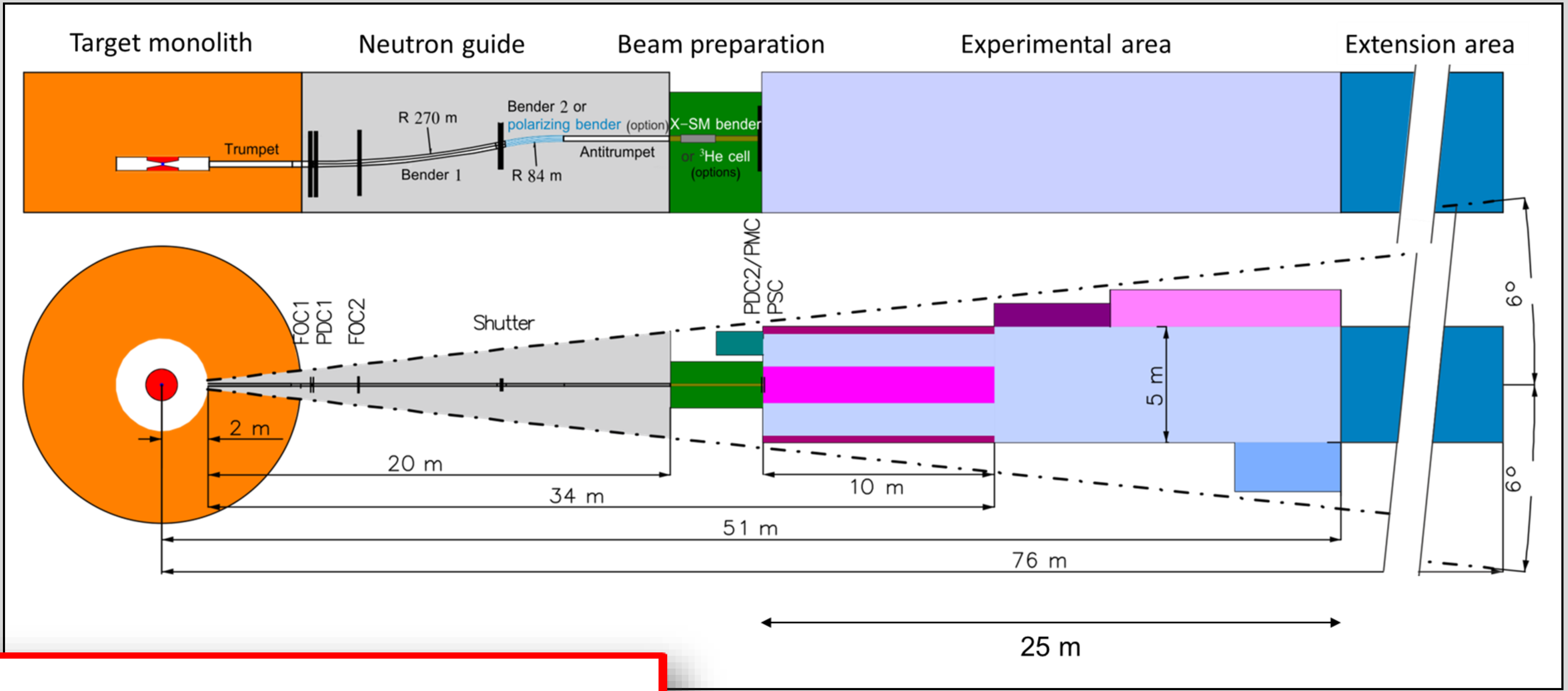
- Ramsey signal phase measured as a function of TOF, i.e. neutron wavelength
- An offset magnetic field causes a change of the slope, similar to an EDM interaction
- „Real EDM measurement“: determine slopes for both electric field polarities

Magnetic field scan – emulating an EDM



- **Ramsey signal phase measured as a function of TOF, i.e. neutron wavelength**
- **An offset magnetic field causes a change of the slope, similar to an EDM interaction**
- **„Real EDM measurement“: determine slopes for both electric field polarities**

Projected sensitivity at ANNI beamline (ESS)



$$\sigma(d_\mathrm{n}) \approx 5 \times 10^{-26}$$ **e cm per day**

E. Chanel et al., EPJ Web Conf. 219, 02004 (2019)
E. Klinkby, T. Soldner, J. Phys. Conf. Ser. 746, 012051 (2016)

Current status & next steps

- Performed proof-of-principle experiments at PSI and ILL
- Future competitive full-scale experiment intended for ESS
- Next steps:
  - McStas simulations of ESS performance on-going
  - Looking into new detector options for high rates

Axions and ALPs

Axions and ALPs

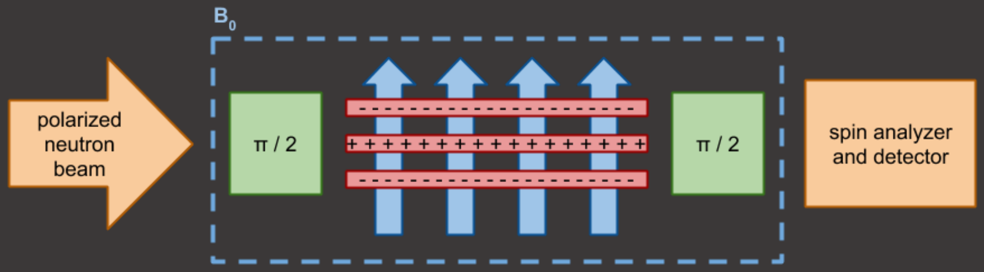
$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\theta_{QCD}=0} + \frac{g^2}{32\pi^2}\theta_{QCD} G\tilde{G} + Axionfield$$

- Limit on θ_{QCD} from neutron EDM measurements: $\boldsymbol{\theta_{QCD} < 10^{-10}}$
- Axion = light pseudoscalar particle postulated to solve „**Strong CP problem**" *
- Triggered many new experimental searches for **Axions and Axion-like particles** as they could potentially also solve Dark Matter „problem" – **so far no observation**
- One possibility: **ALP-gluon coupling could induce oscillating neutron EDM signal**

*** Peccei & Quinn, PRL 38, 1440 (1977)**

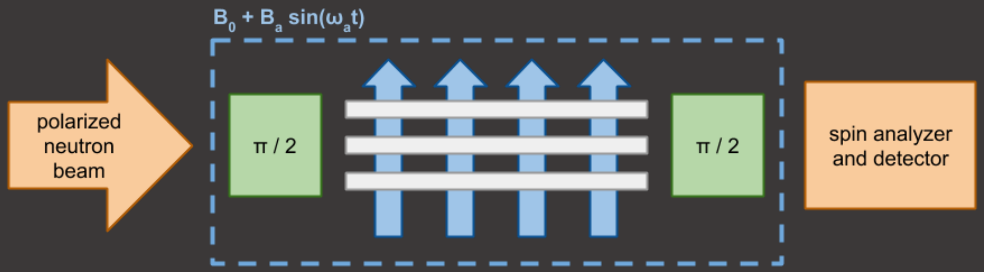
Beam EDM apparatus in „continuous mode“

Axion measurement



$$\underbrace{\frac{C_G}{f_a} a_0 \cos(\omega_a t) \times E}_{\text{time dependent moment}}$$

Fake axion measurement & field mapping

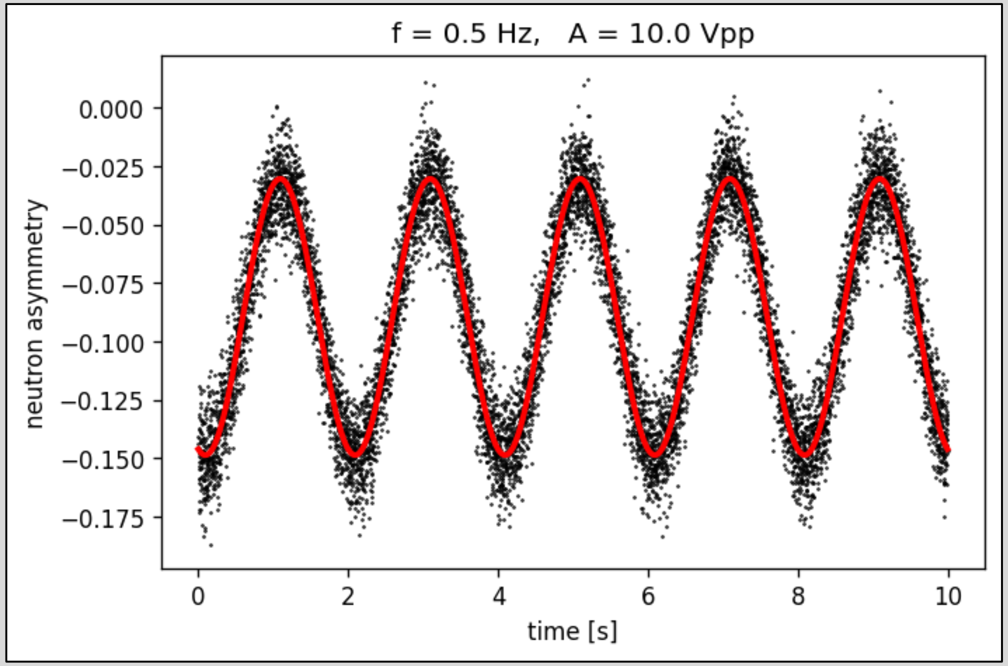


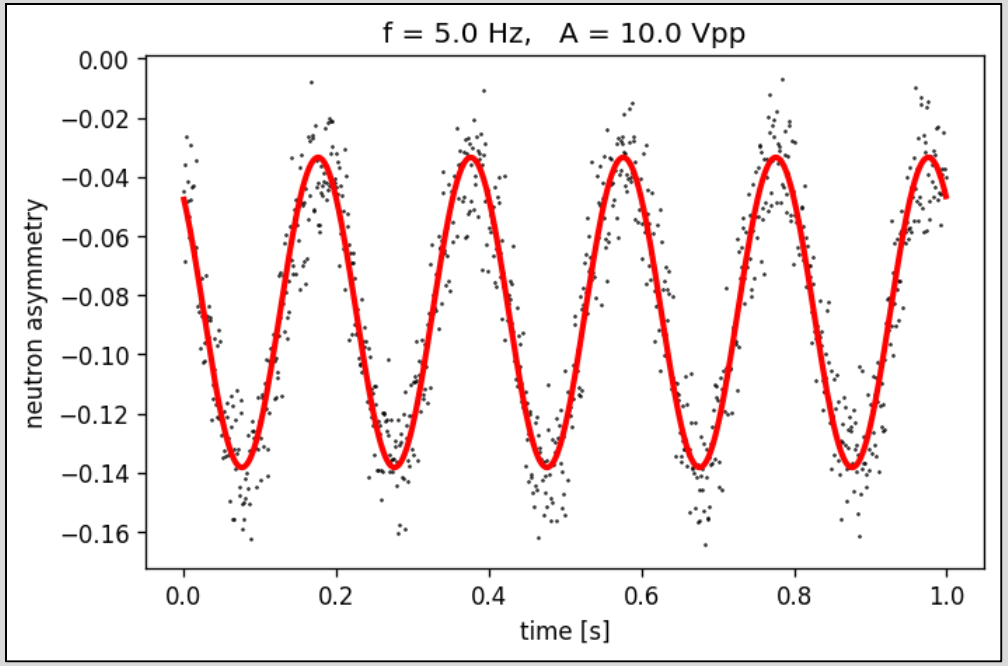
$$\underbrace{\gamma_n \times B_a \sin(\omega_a t)}_{\text{time dependent field}}$$

→ **Actual ALPs search data (*E* = 35 kV/cm)**

→ **Extract apparatus sensitivity**

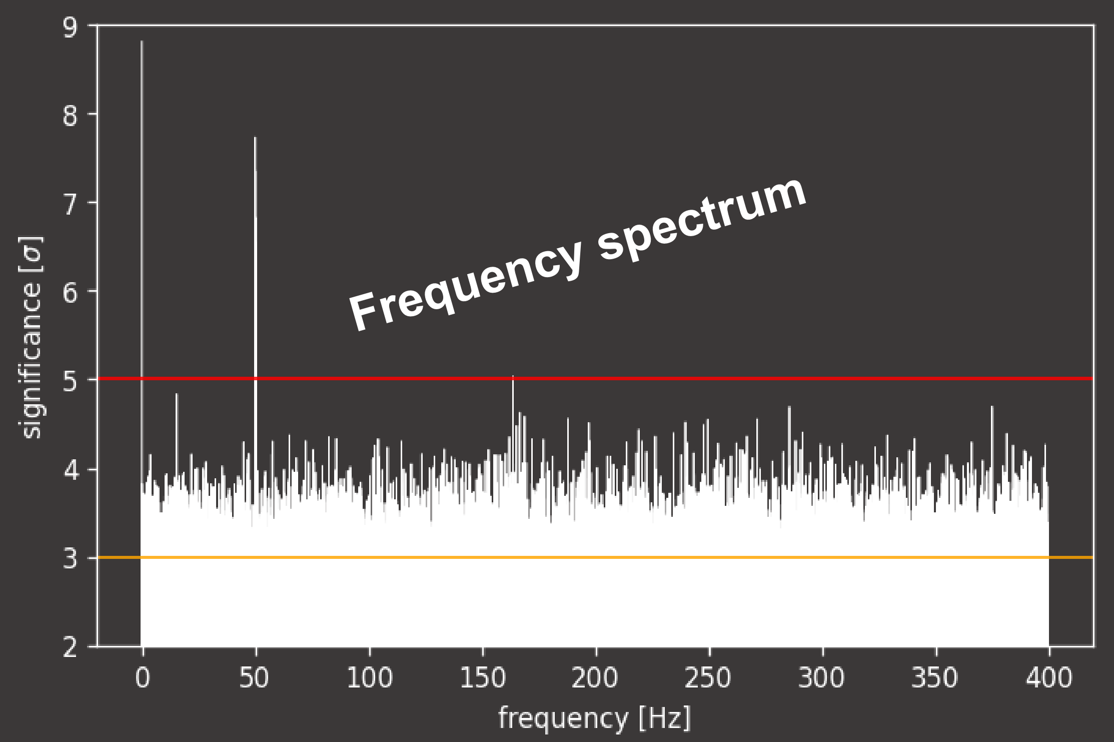
Example for „Fake Axion“ signals





- **Neutron data sampled with 4 kHz, i.e. 0.25 ms time bins**
- **„Injected“ Fake Axion signals from DC to 1000 Hz**

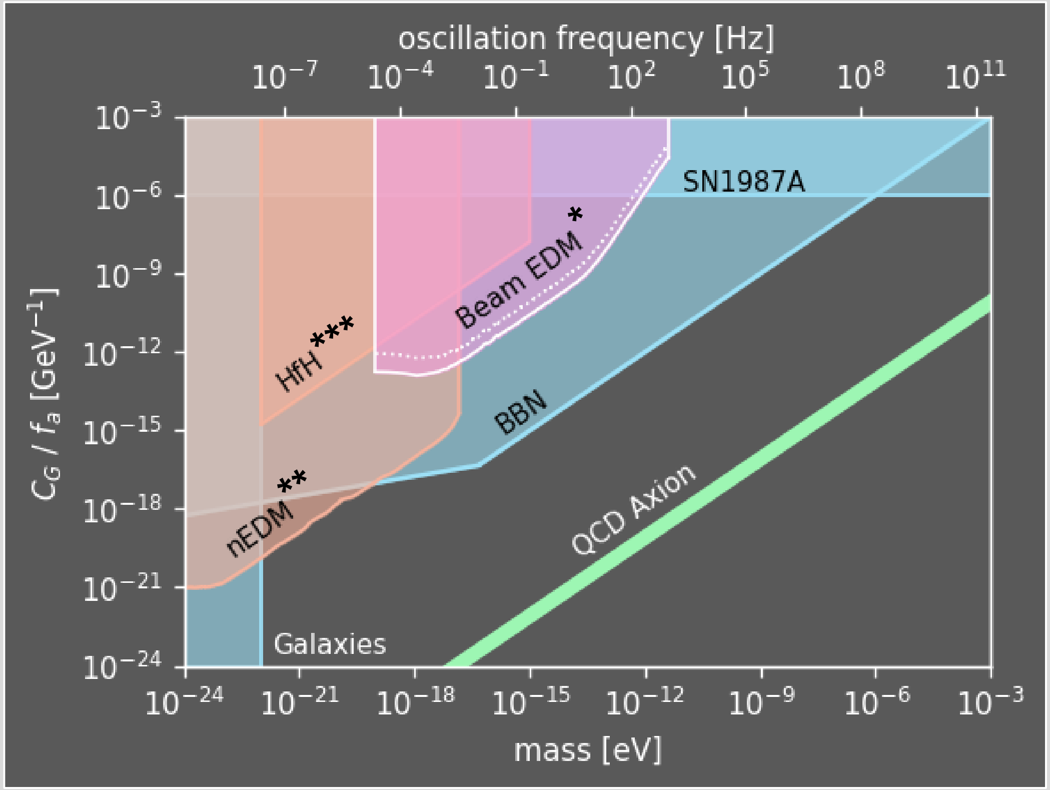
ALPs analysis



Conditions for a real Axion signal:

1. no signal for $E = 0$
2. peak with same amplitude for $B\uparrow\uparrow E$ and $B\uparrow\downarrow E$
3. 180° phase shift for $B\uparrow\uparrow E$ compared to $B\uparrow\downarrow E$

Landscape (Axion-gluon coupling)



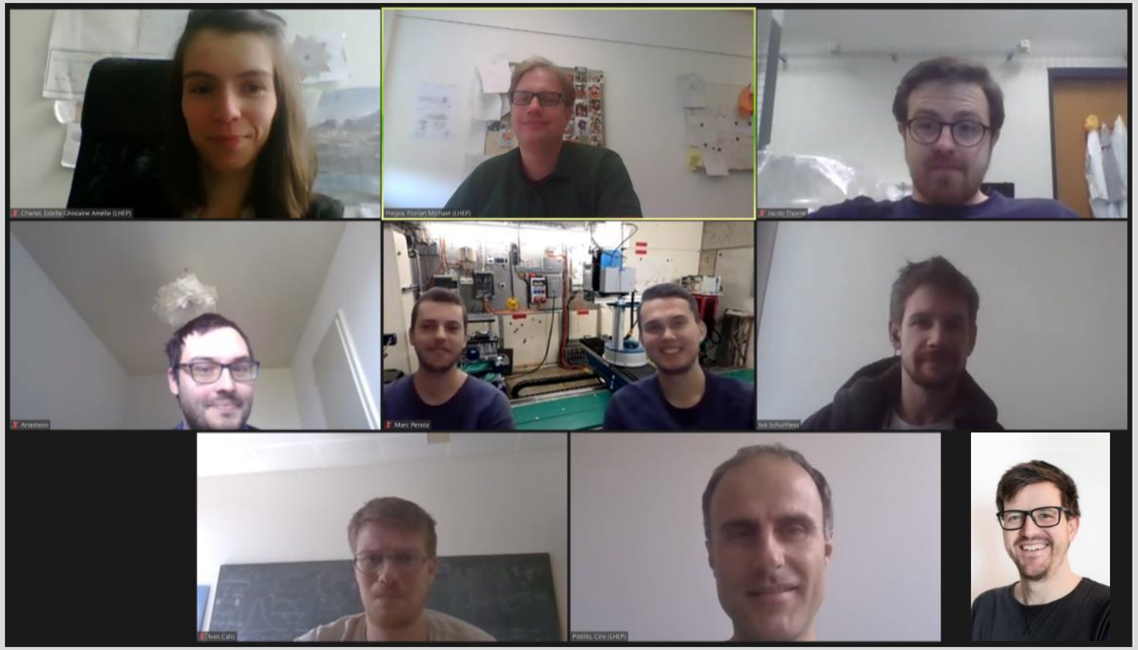
An ultralight axion-like particle can induce an oscillating neutron EDM:

$$d_n(t) \approx \frac{C_G}{f_a} \cdot a_0 \cdot \cos(m_a t) \cdot 2.4 \times 10^{-16} \text{ e cm}$$

C_G: model dependent parameter
f_a: axion decay constant
a_0: axion field amplitude
m_a: axion mass

*** Schulthess et al., arXiv:2204.01454**
**** Abel et al., PRX 7, 041034 (2017)**
***** Roussy et al., PRL 126, 171301 (2021)**

- New complimentary neutron EDM experiment
- Use apparatus to search for ALPs via oscillating EDM



Thank you for your attention !