Beam EDM

Neutron beam experiment to search for an EDM

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FNSNF Fonds national suisse / Schweizerischer Nationalfonds / Fondo nazionale svizzero / Swiss National Science Foundation
erc European Research Council

Neutrons

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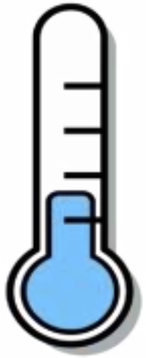
Thermal (D_2O)	300 K	25 meV	2200 m/s
Cold (LD_2)	60 K	5 meV	1000 m/s
Ultracold (SD_2)	2 mK	200 neV	6 m/s



Beam EDM Experiment

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

History of the neutron EDM

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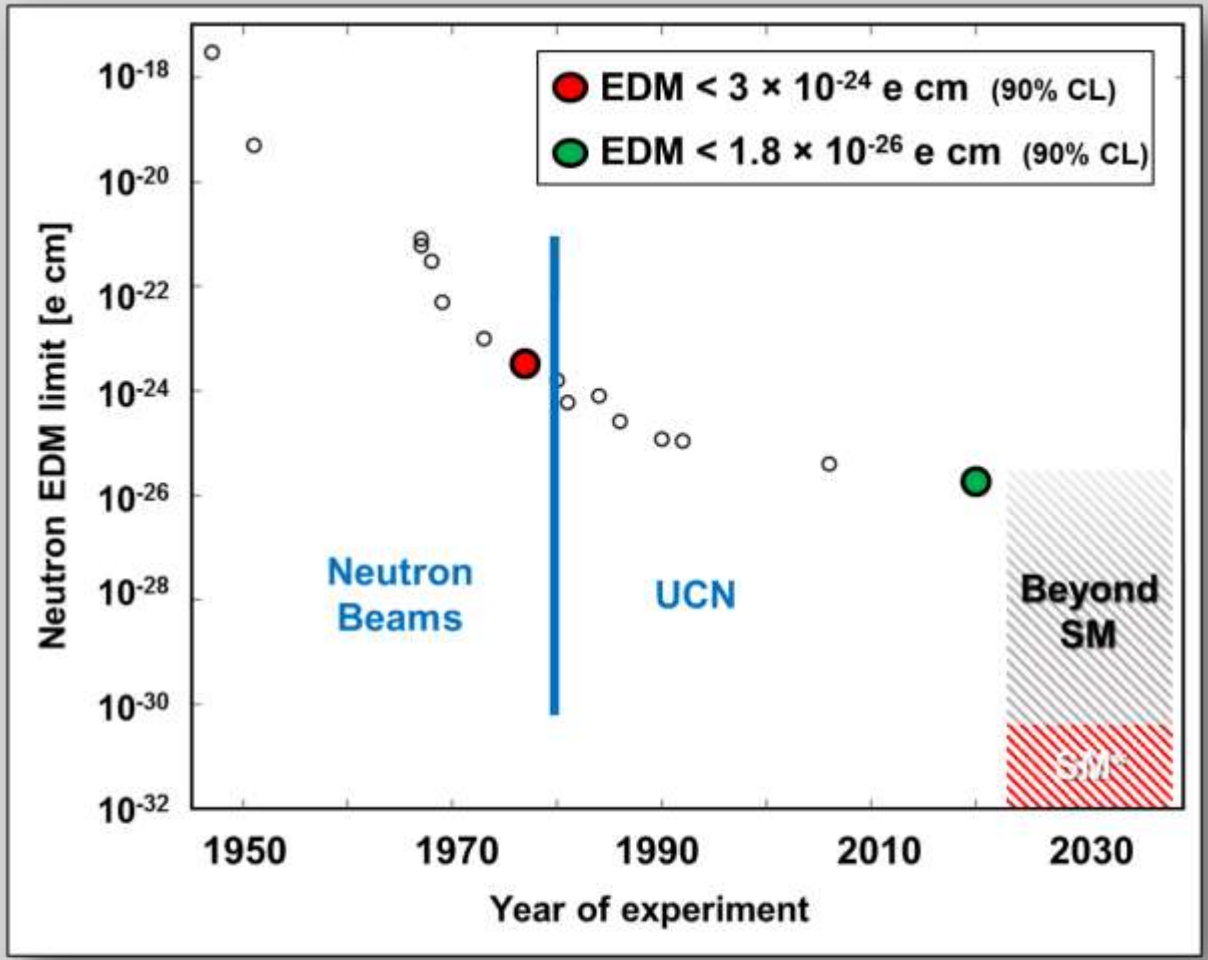
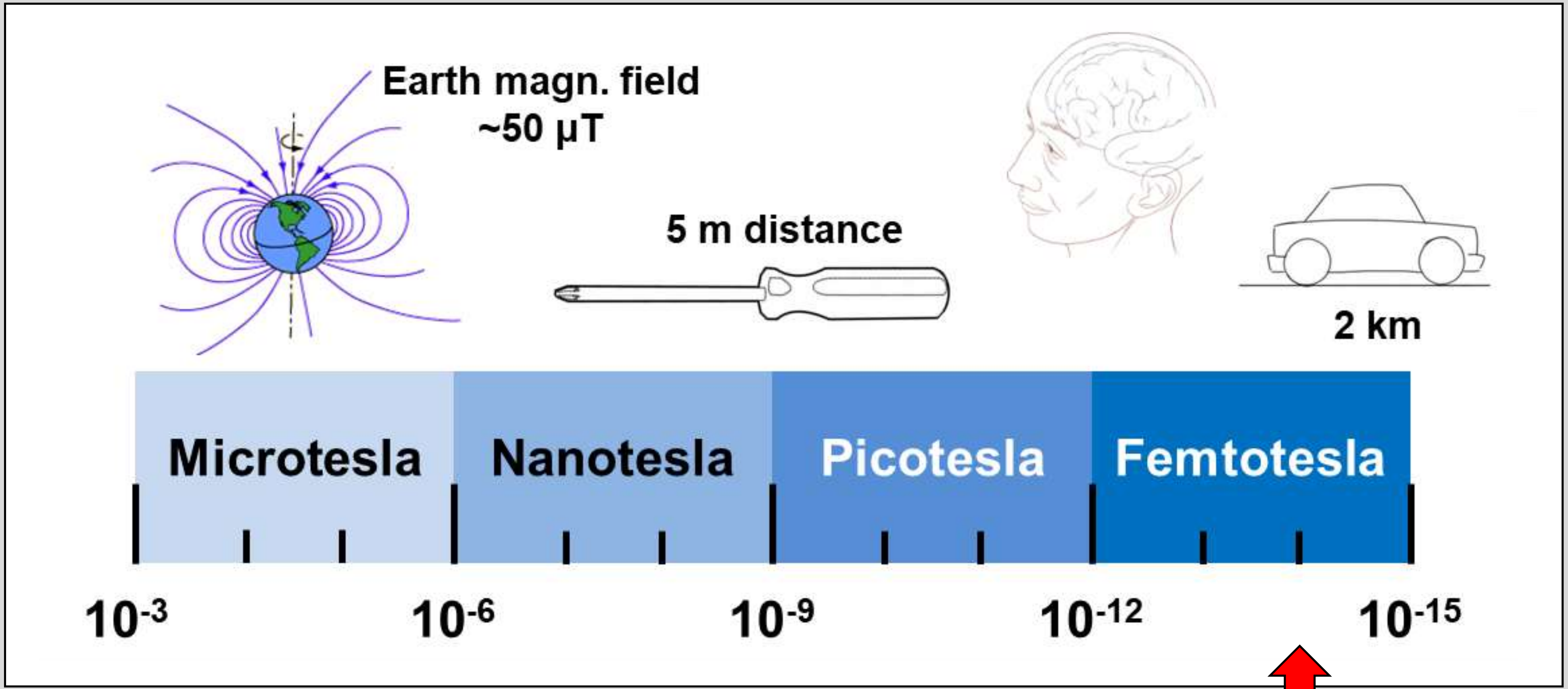


Dress et al., PRD 15, 9 (1977)
Abel et al., PRL 124, 081803 (2020)
* Seng, PRC 91, 025502 (2015)

How sensitive is this really?



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

Neutron EDM sensitivity

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

BEAM

E = 100 kV/cm

$\dot{N}$ ≈ 100 MHz (ESS)

T ≈ 100 ms (50 m)

UCN*

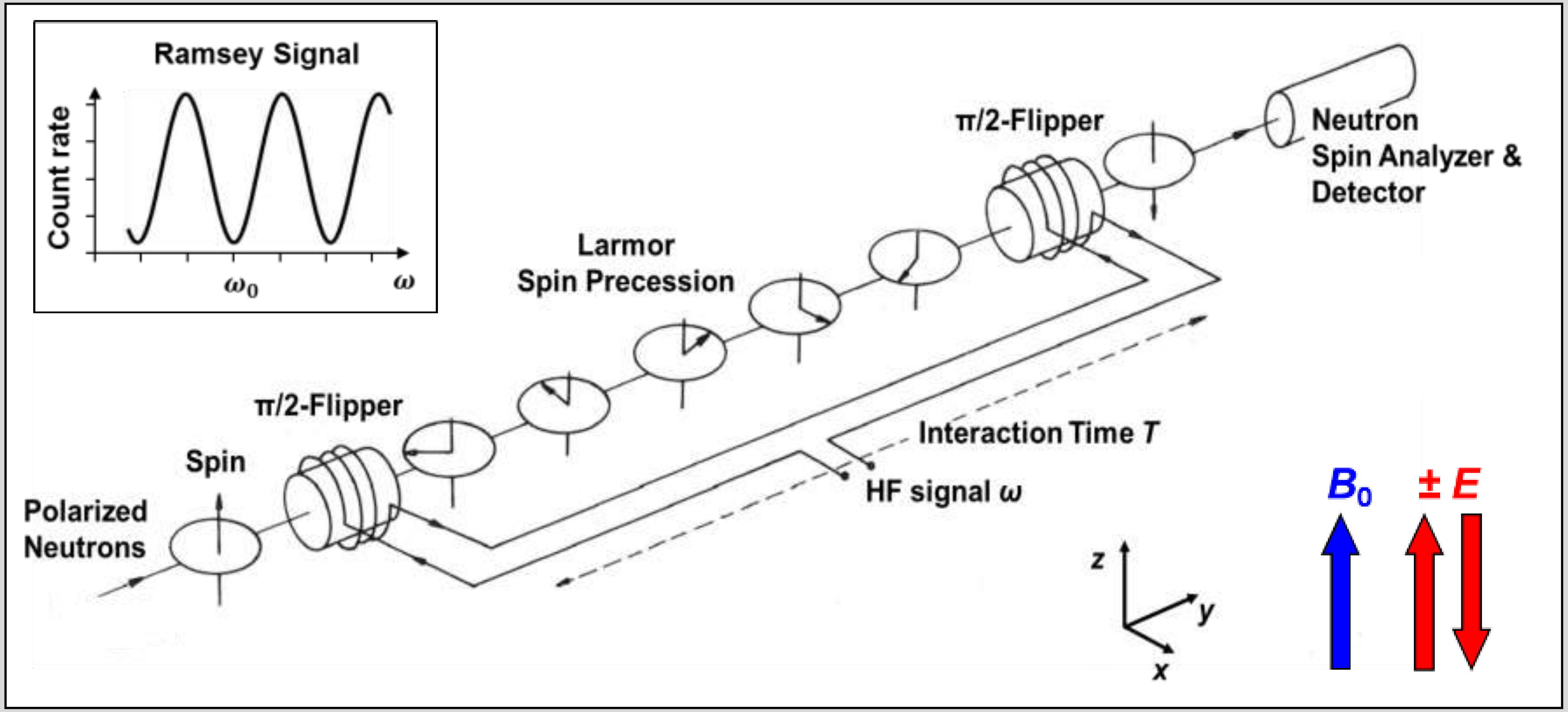
E = 11 kV/cm

$\dot{N}$ = 11’400 / 300 s ≈ 40 Hz

T = 180 s (storage)

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

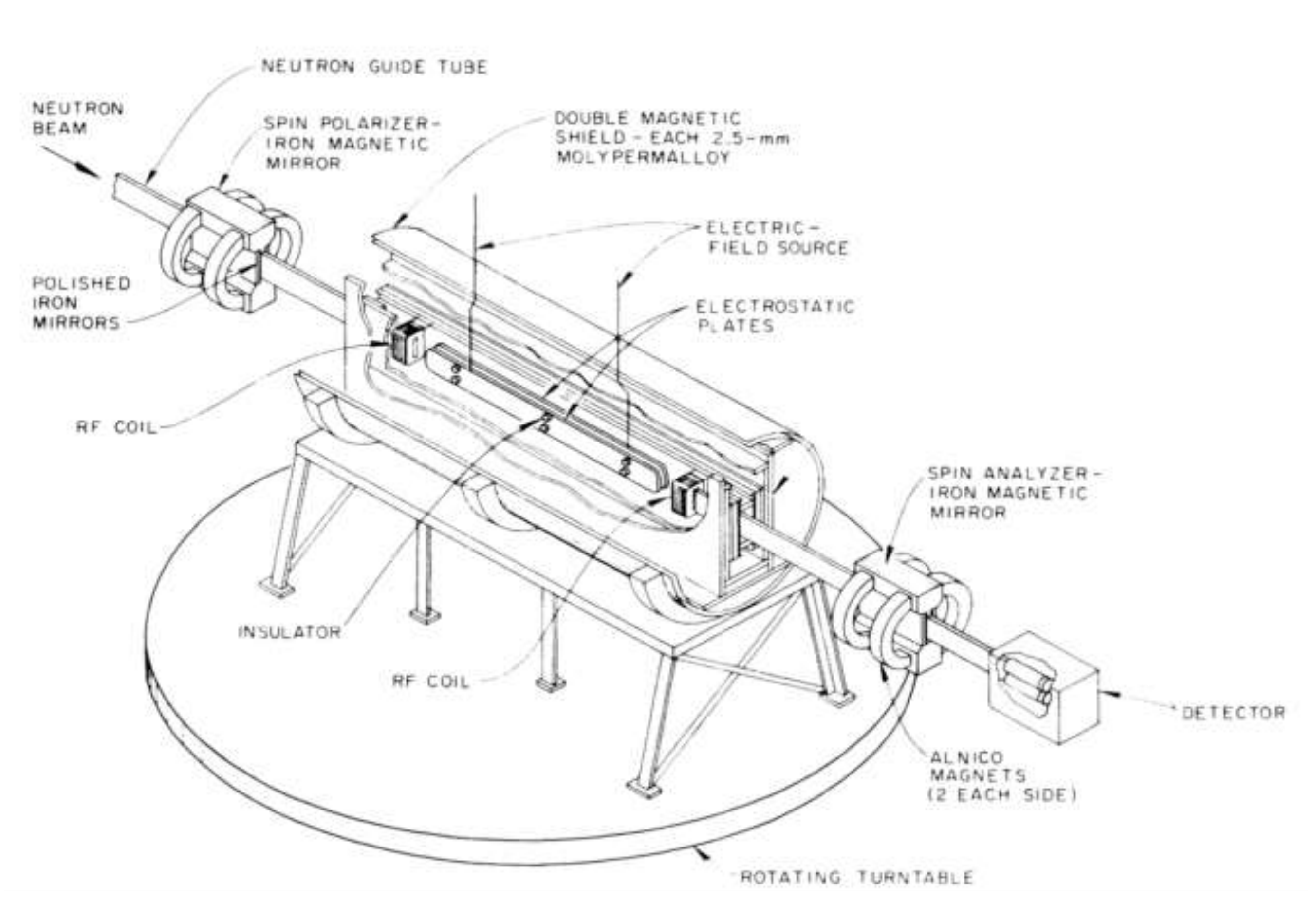
Ramsey‘s Technique



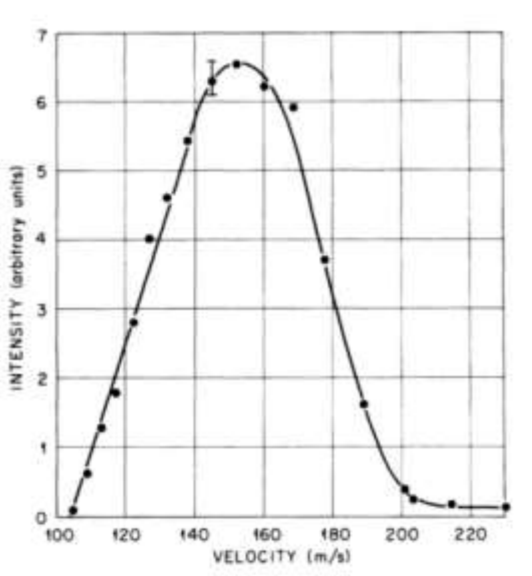
$$\Delta\varphi = (\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow}) \cdot T \propto d \cdot E$$

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

Last neutron beam-type experiment (1977)



- E ≈ 100 kV/cm (1.8 m, gap = 1 cm)
- B_0 ≈ 1.7 mT (permanent magnets)
- Switching HV polarity every 200 s
- Invert flight direction every other day to overcome systematic $v \times E$-effect



Dress et al., PRD 15, 9 (1977)

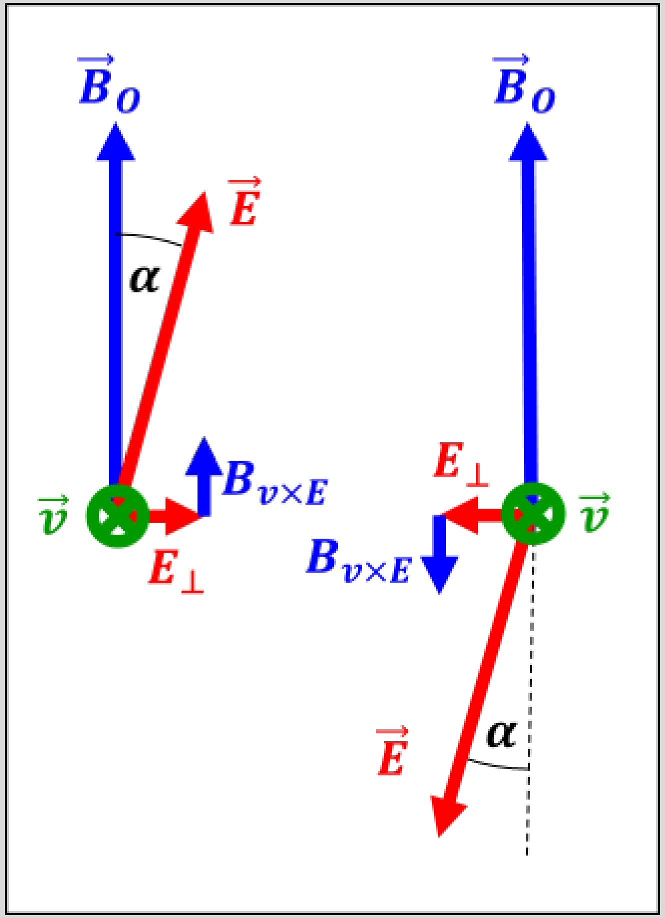
Why were beam experiments abandoned?

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

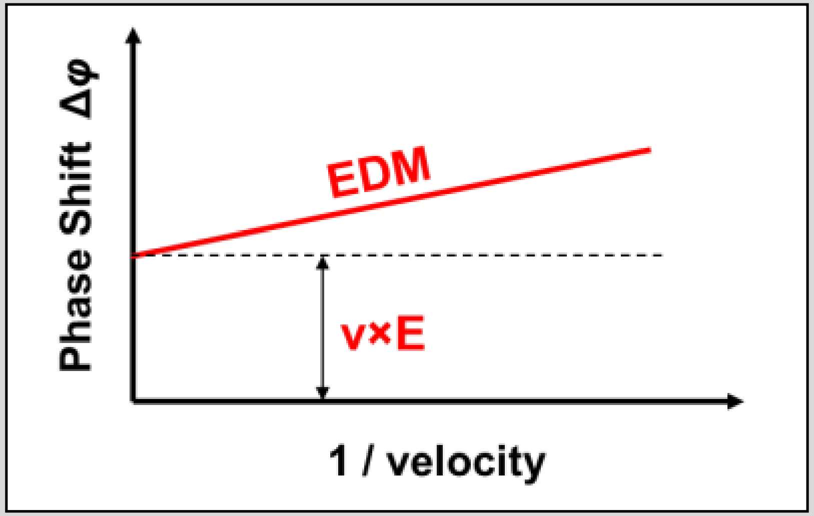
- **This can cause a false EDM signal, e.g.:**

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

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



Novel concept using a pulsed beam



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

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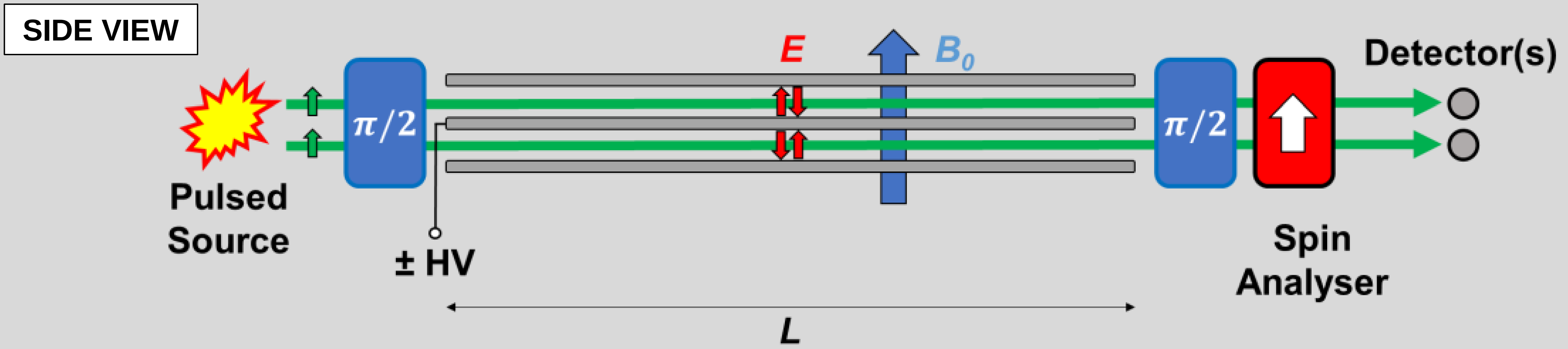
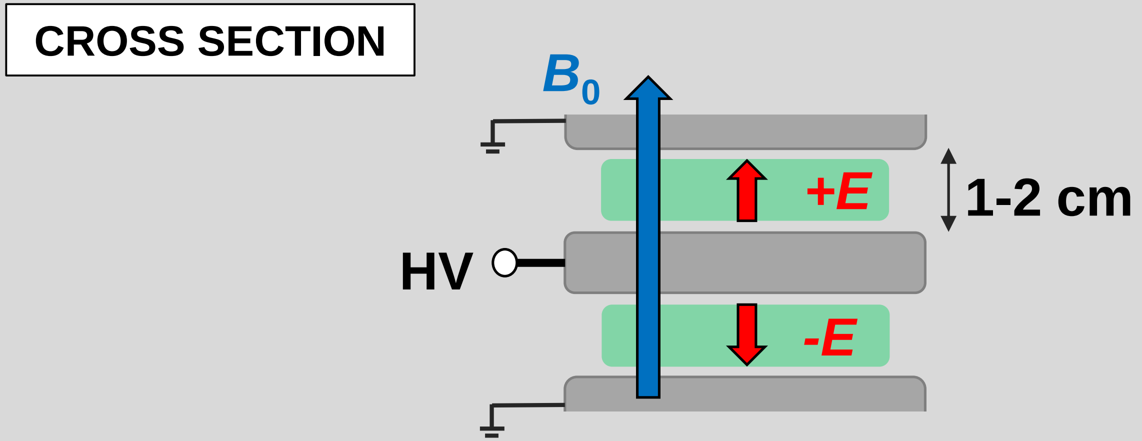
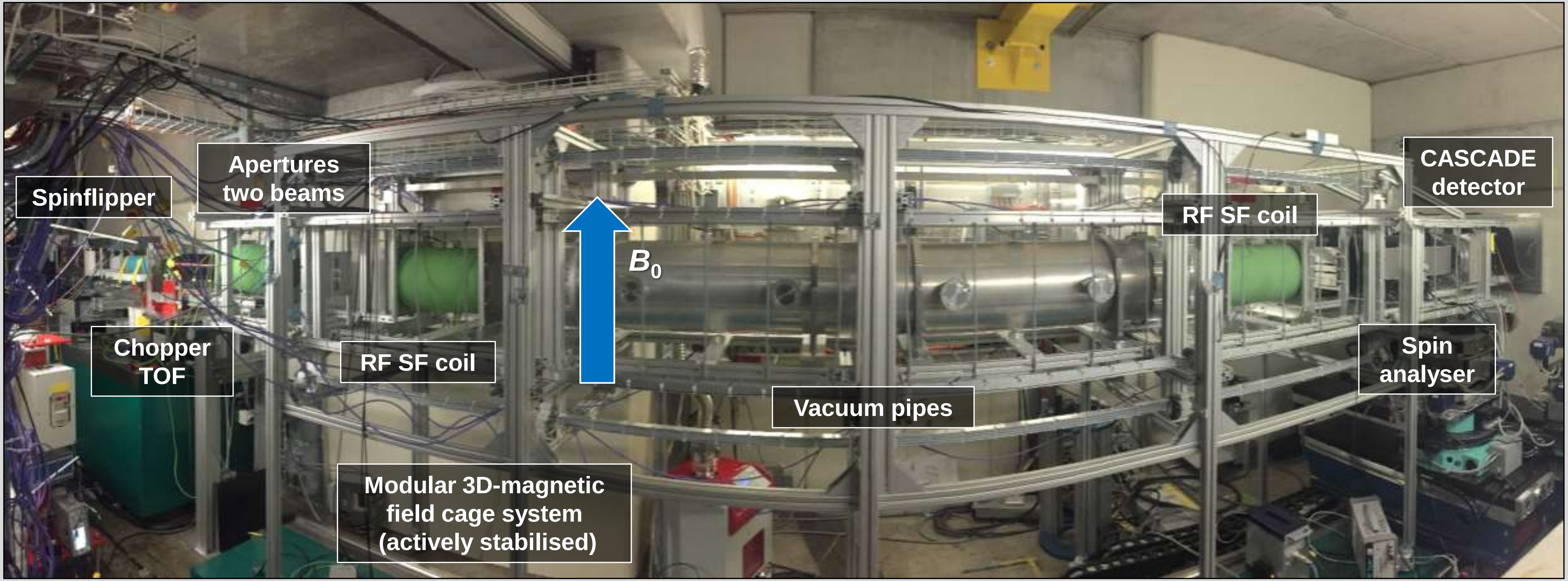


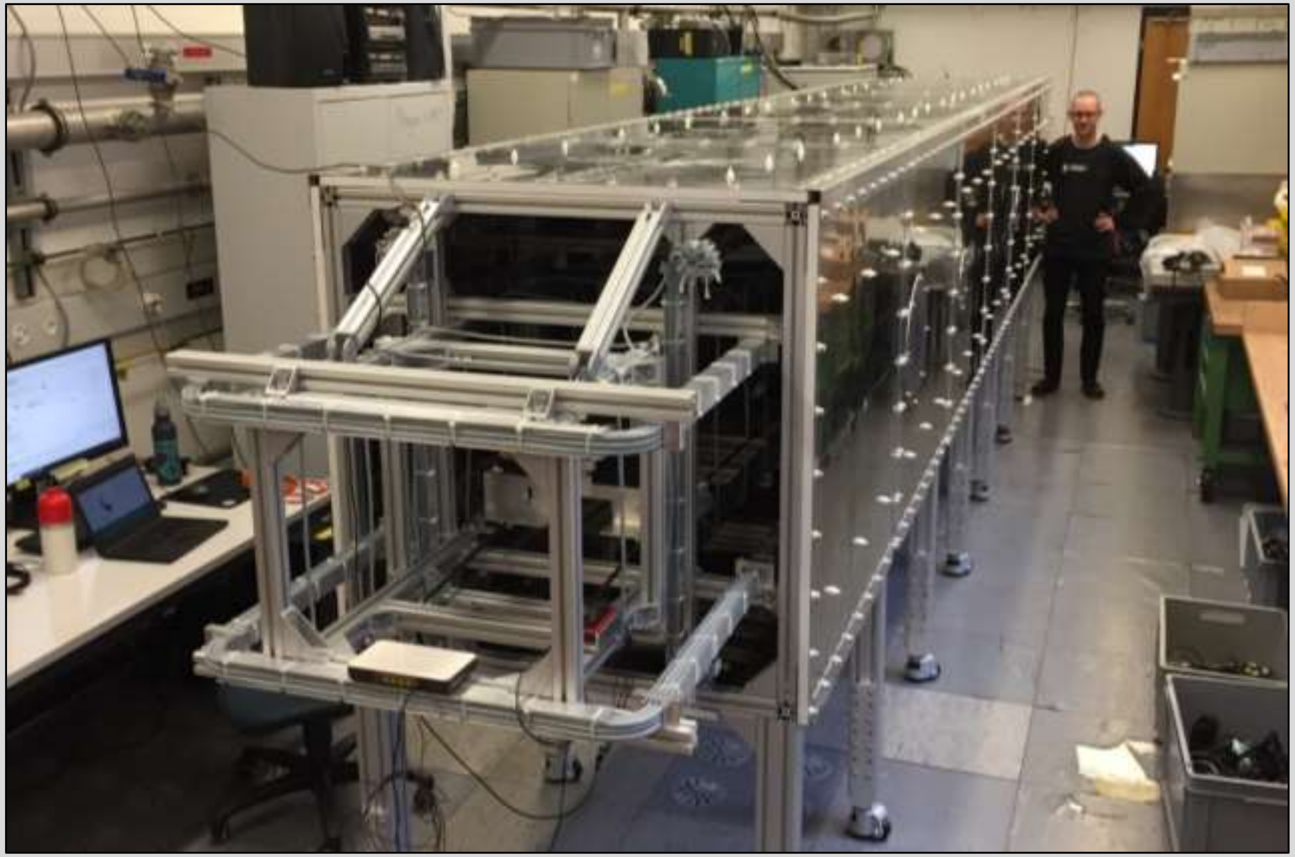


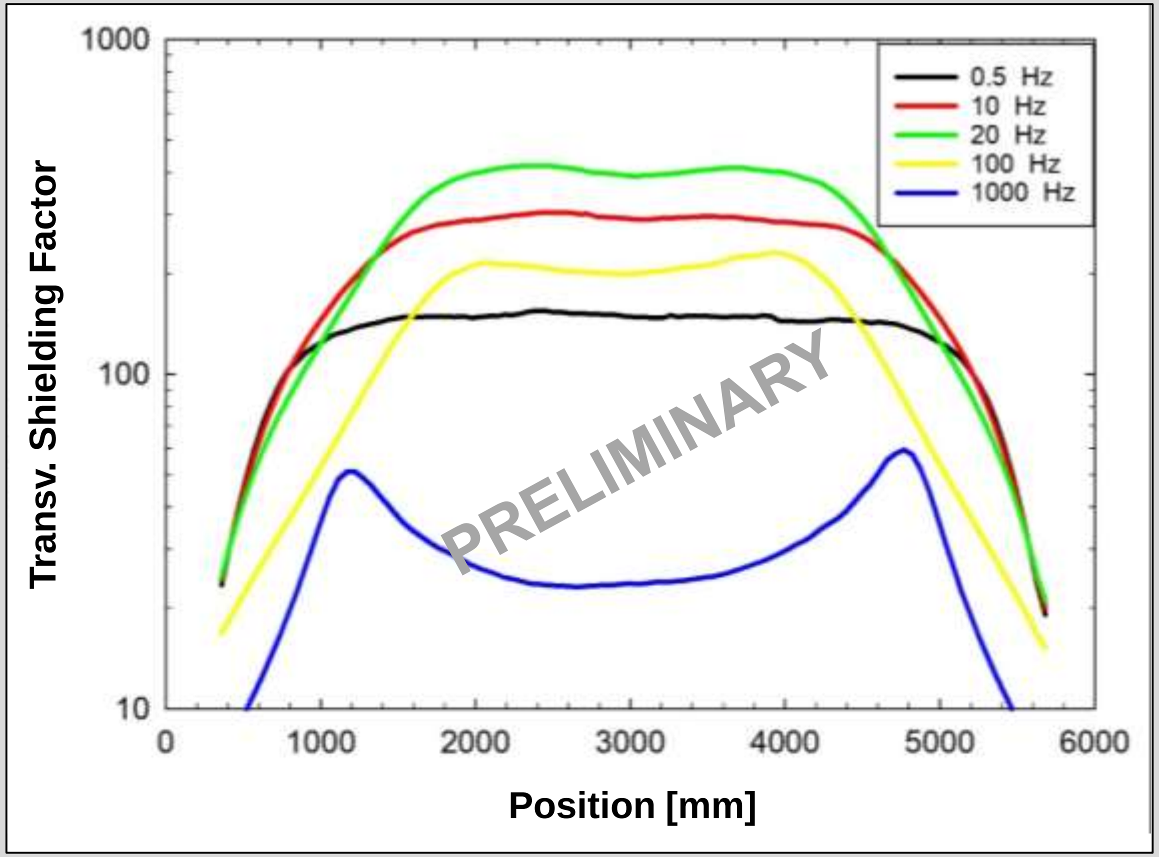
2 Neutron beams
$E \approx 100$ kV/cm
$B_0 \approx 200$ μT
L = 3 m (proof-of-prin.)
L = 50 m (full-scale)

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



Two layer magnetic shield (2020)

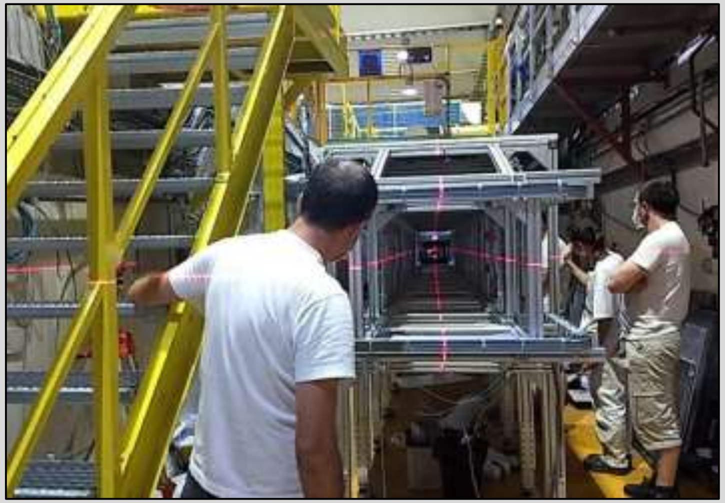




► **Passive shielding of external field inhomogeneities and fluctuations**

Shipping the experiment to ILL

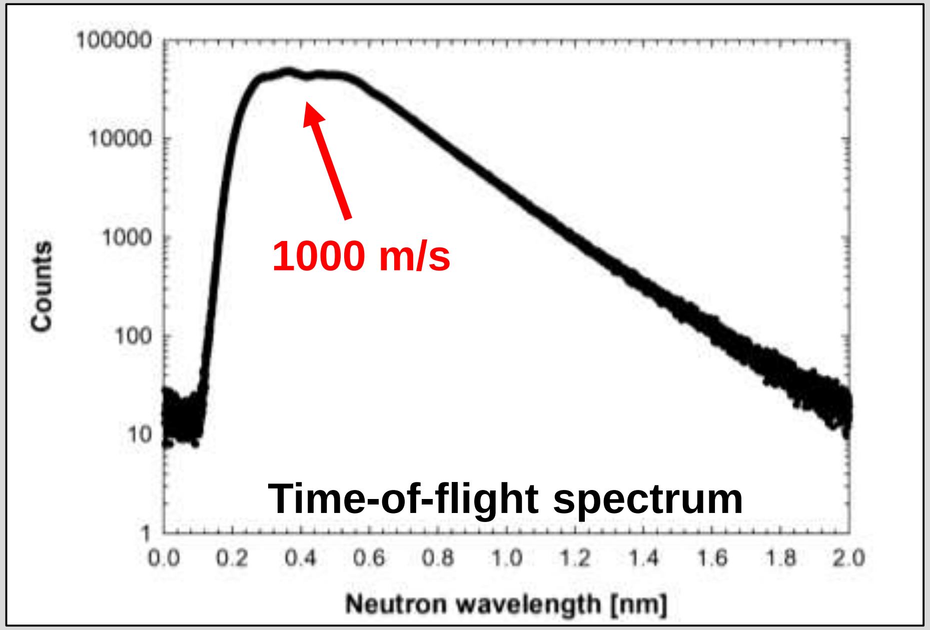
Beam time at ILL (Aug./Sept. 2020)

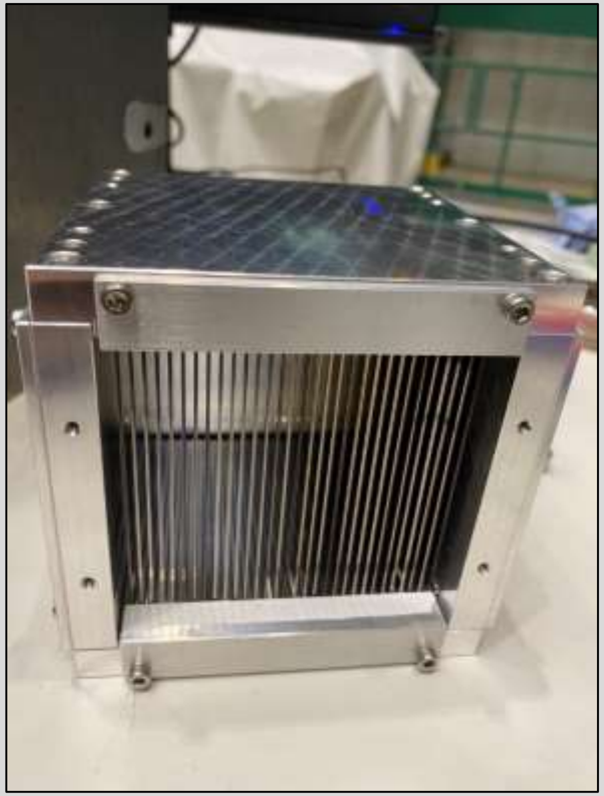


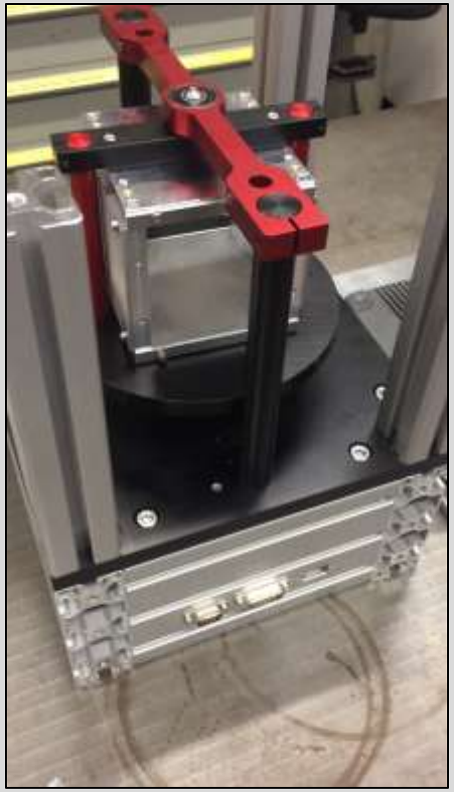
Ramsey apparatus at PF1b

- 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



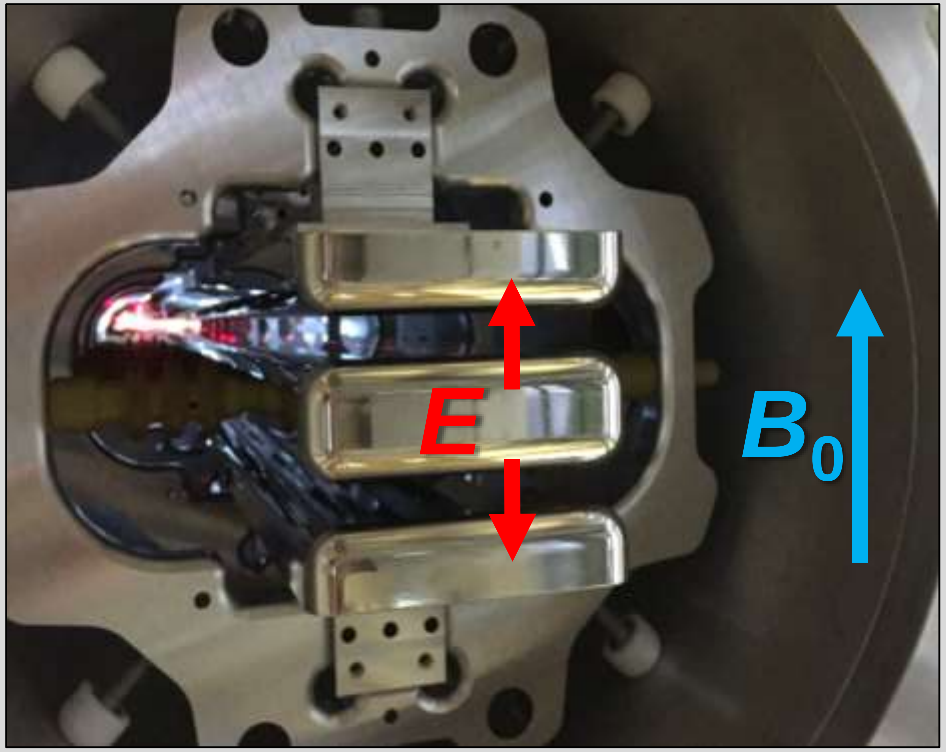
Chopper





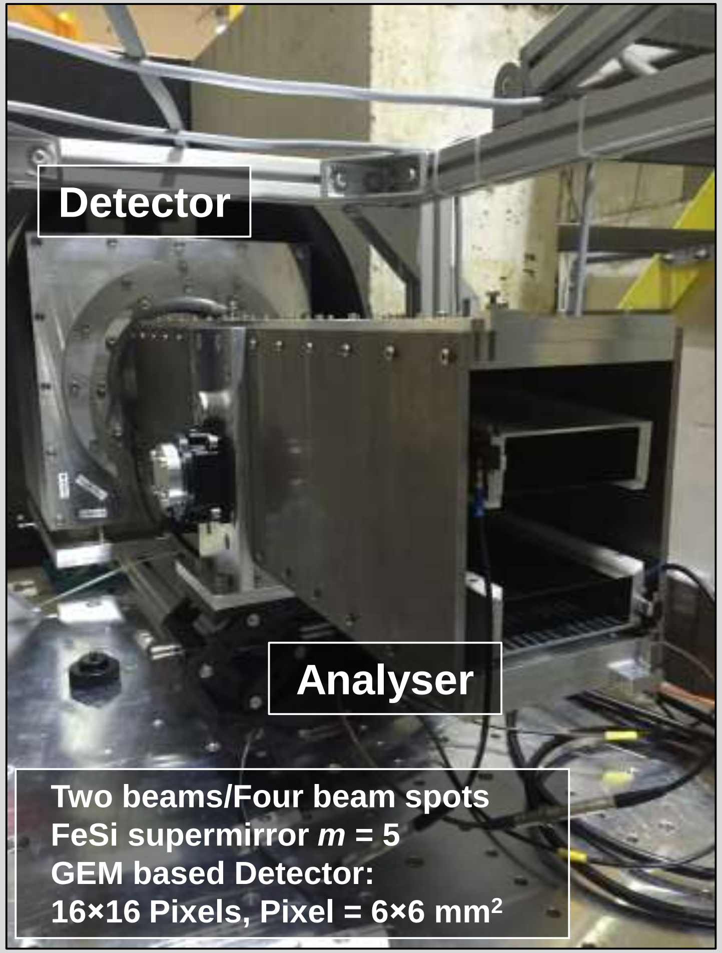
► **Collimator (Gd-coated wafers) installed on a motorized/spinning turntable (up to 15 Hz)**

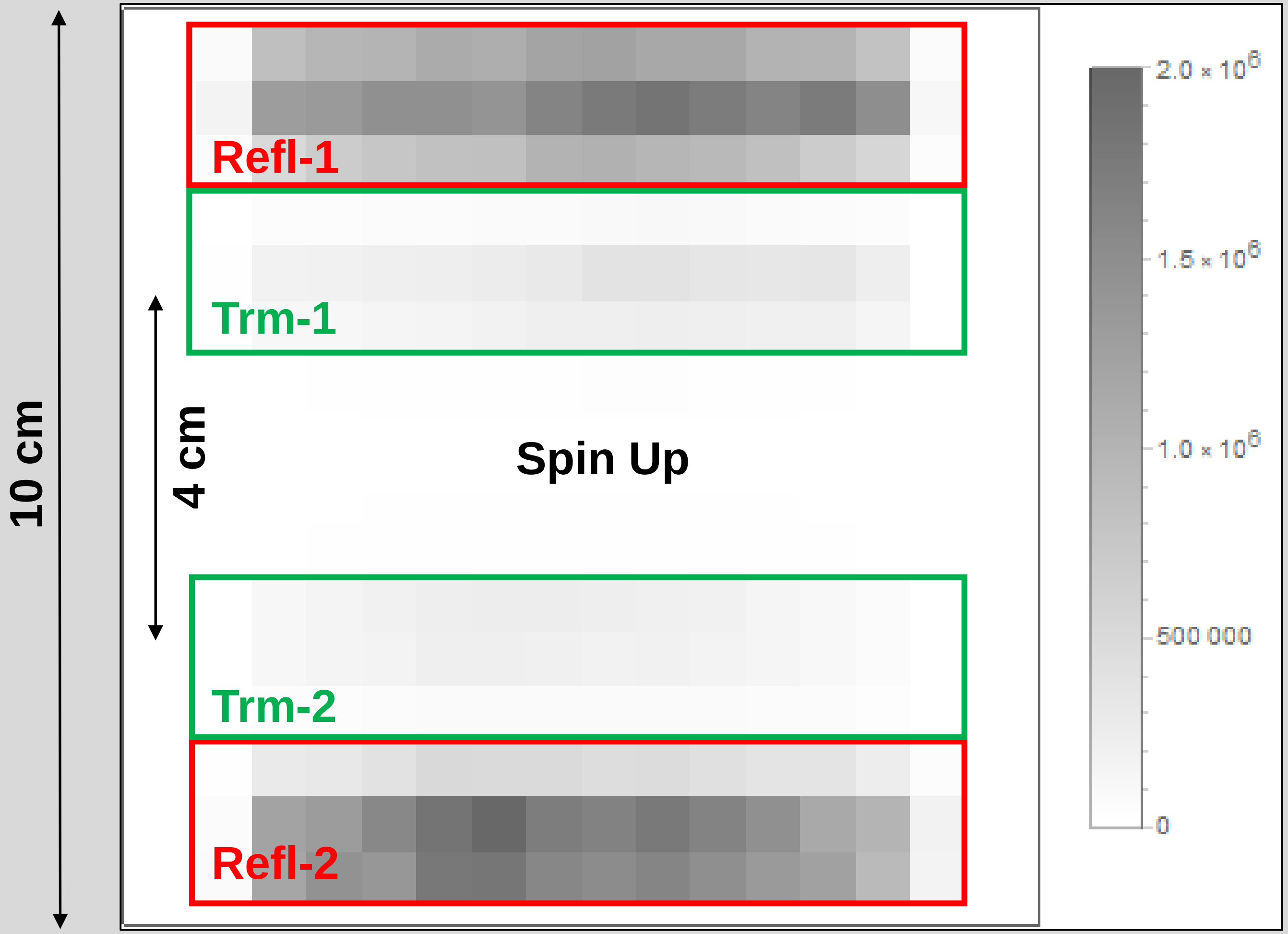
Electrode stacks



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

Spin analyser and detector





Spin analyser and detector

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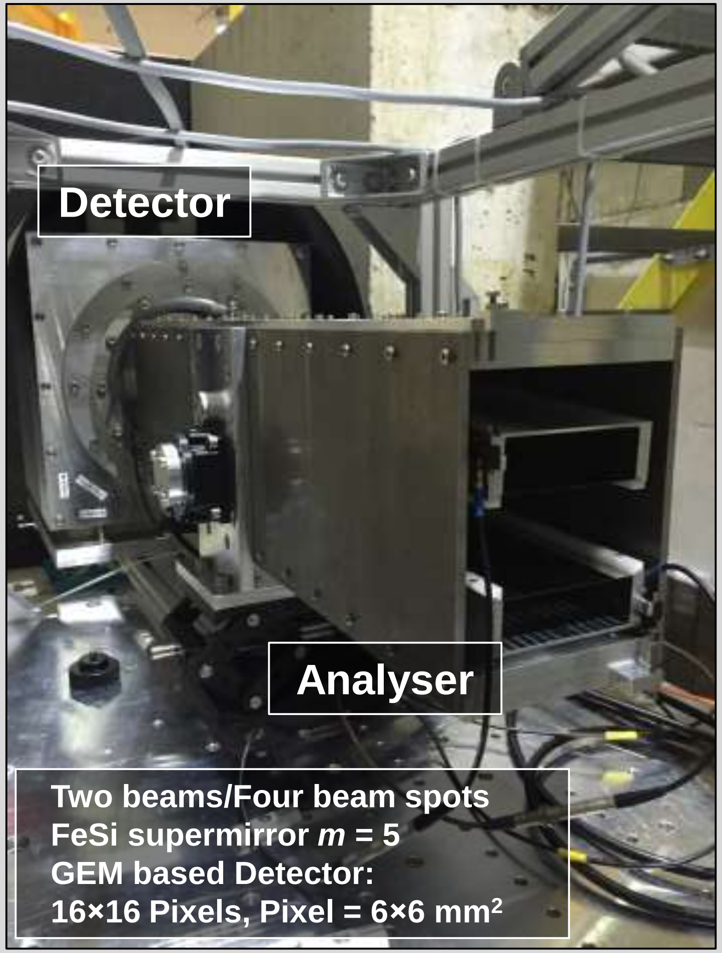
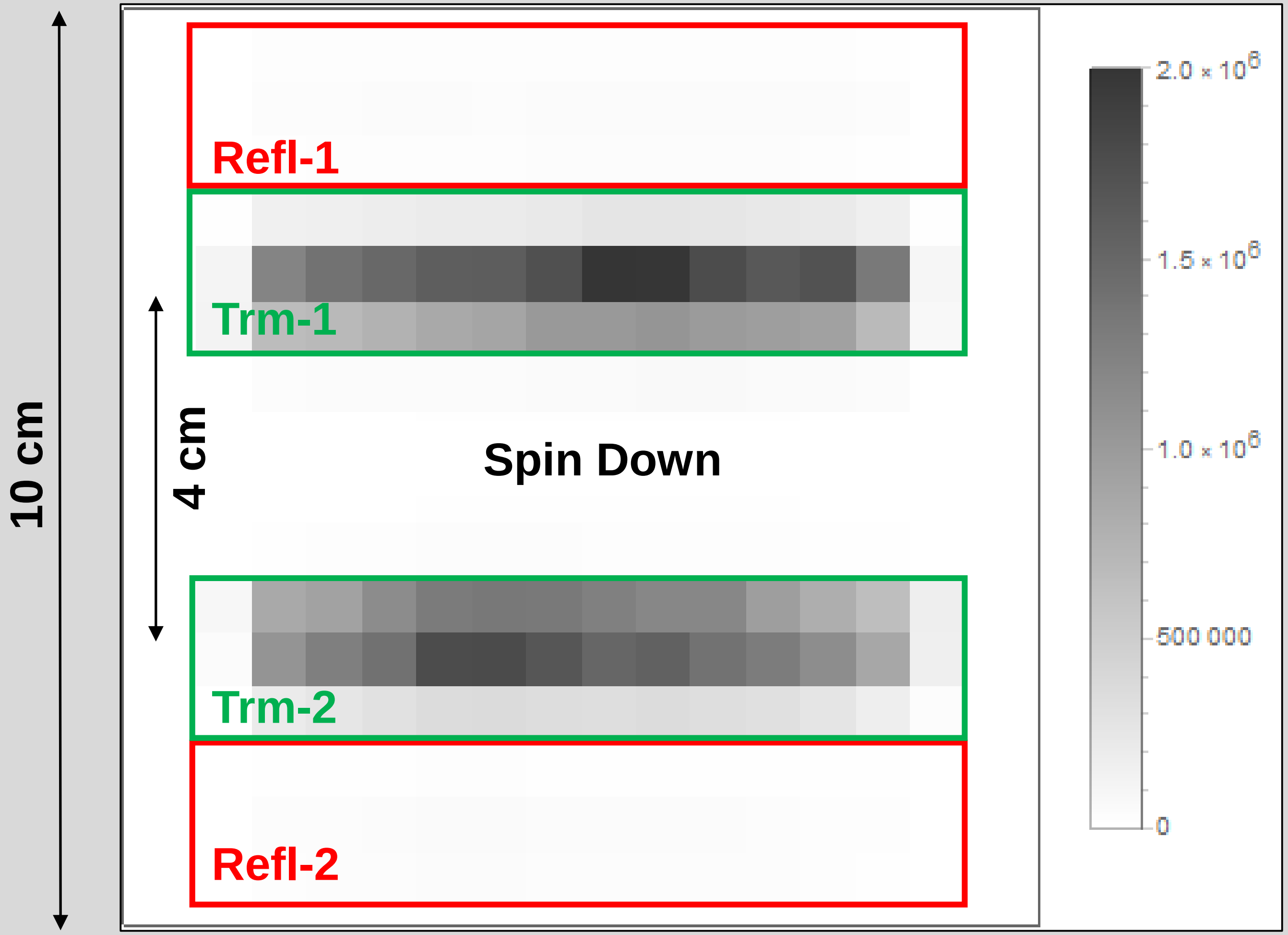
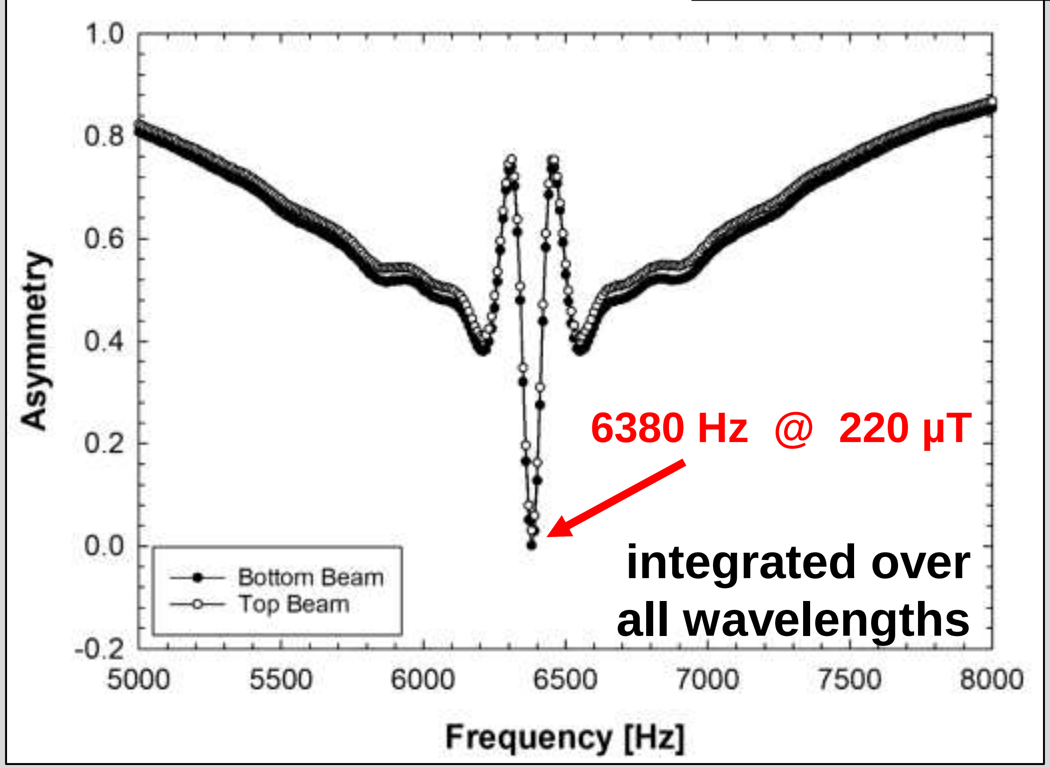
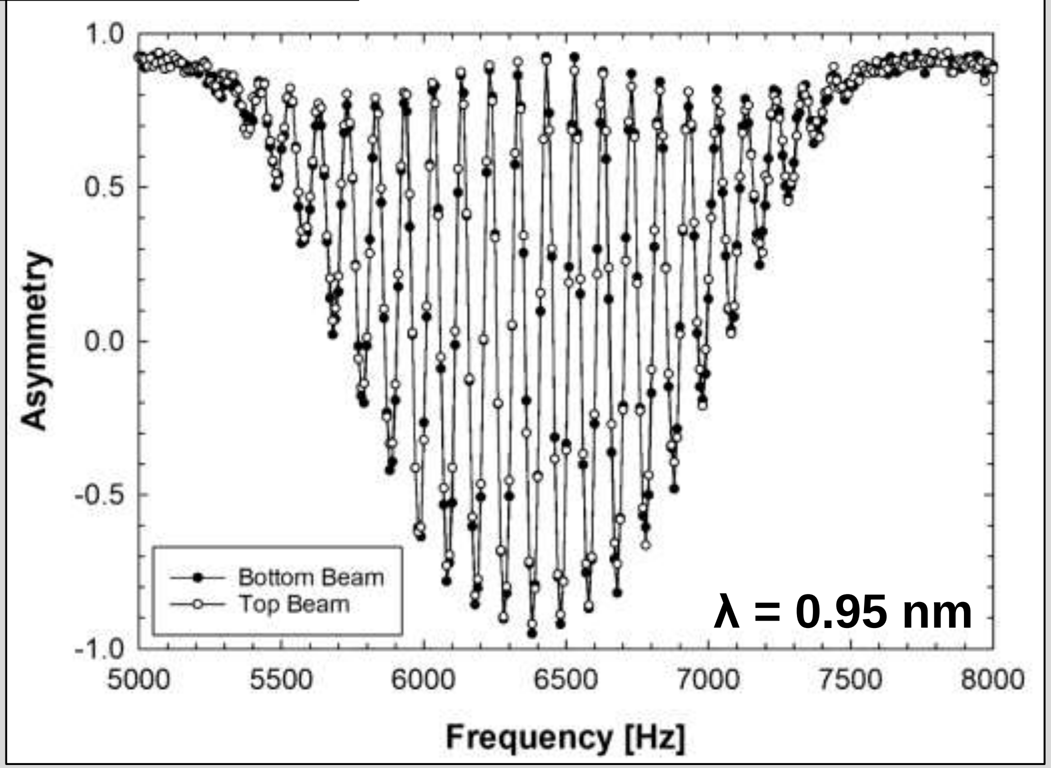




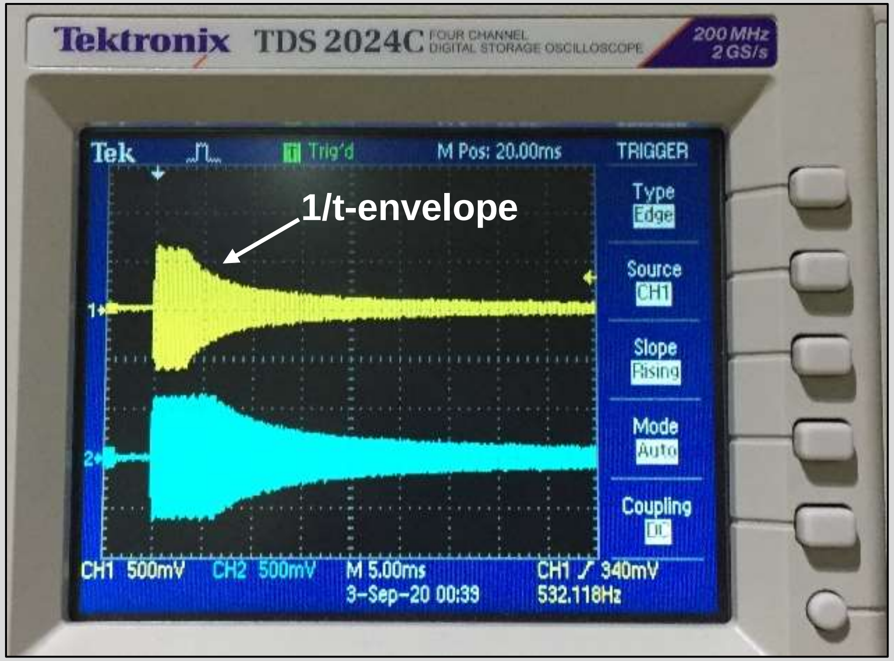
Classic Ramsey frequency scan

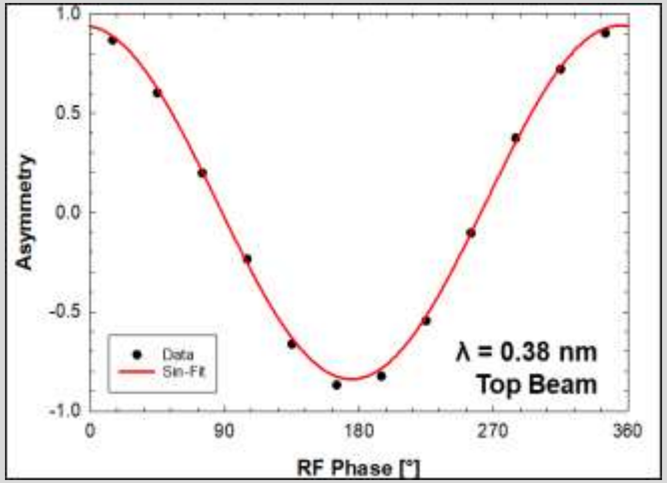
$$Asymmetry = \frac{N_{Trm} - N_{Rfl}}{N_{Trm} + N_{Rfl}}$$

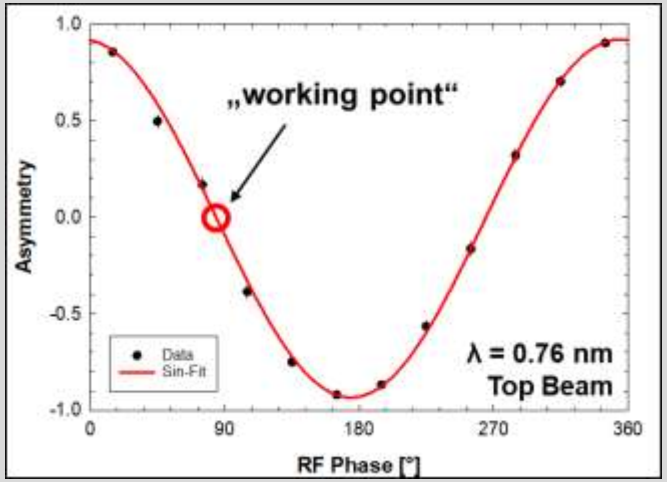




Modulated RF-signal & Ramsey phase scan







- Modulated RF-amplitude triggered by chopper: 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

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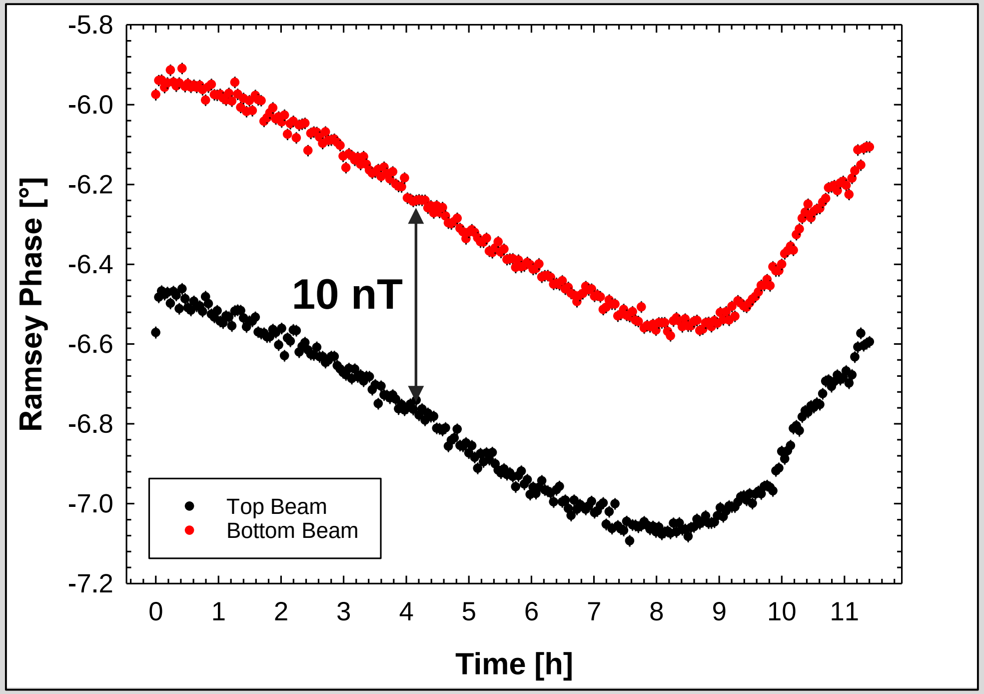
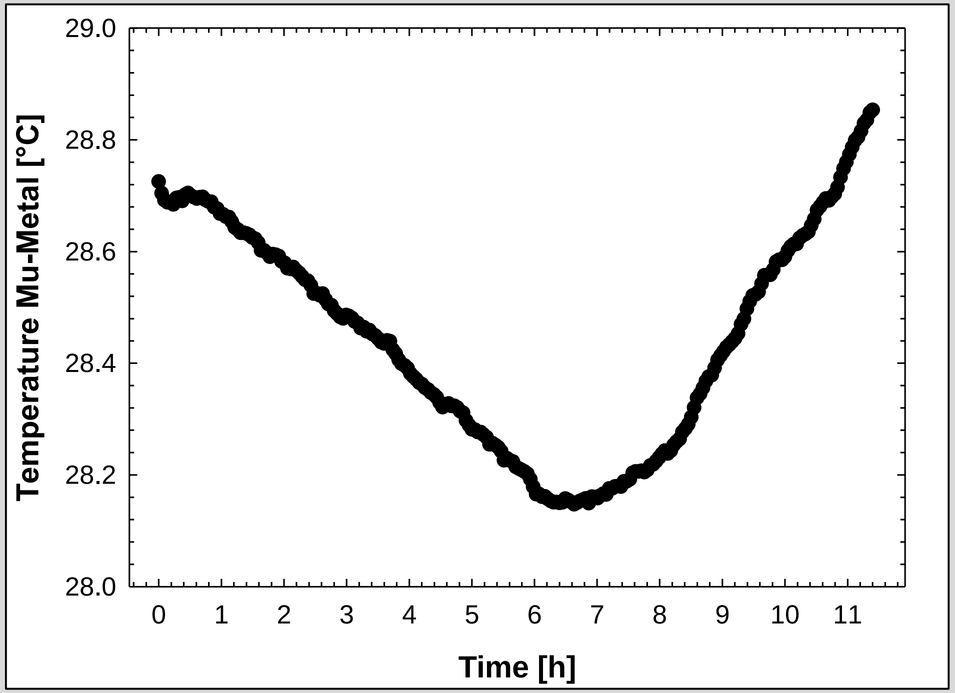
Two beams



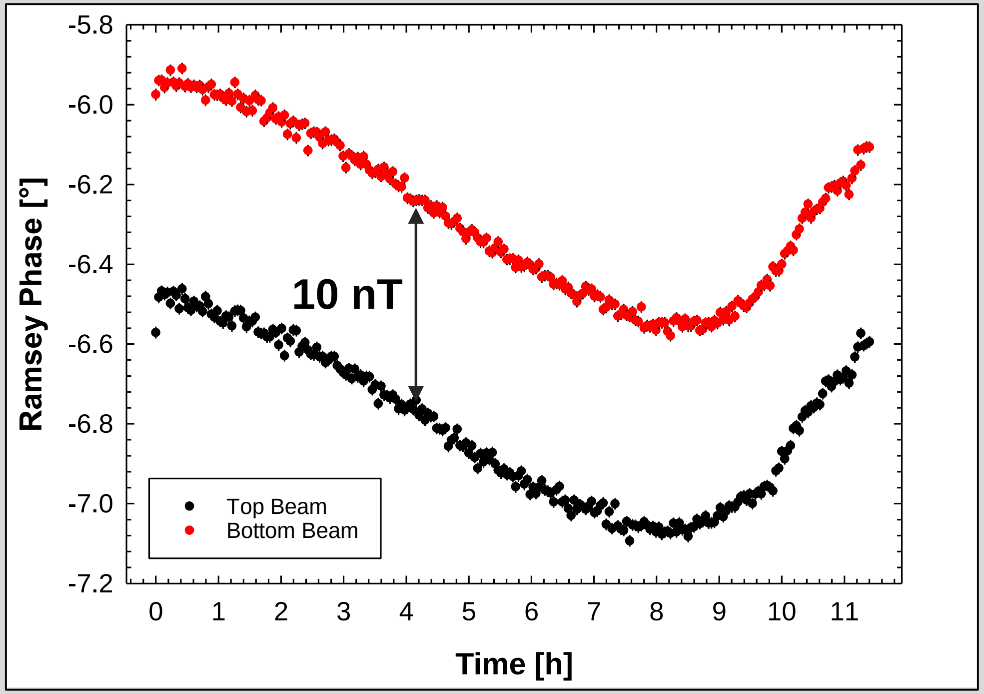
Temperature drift



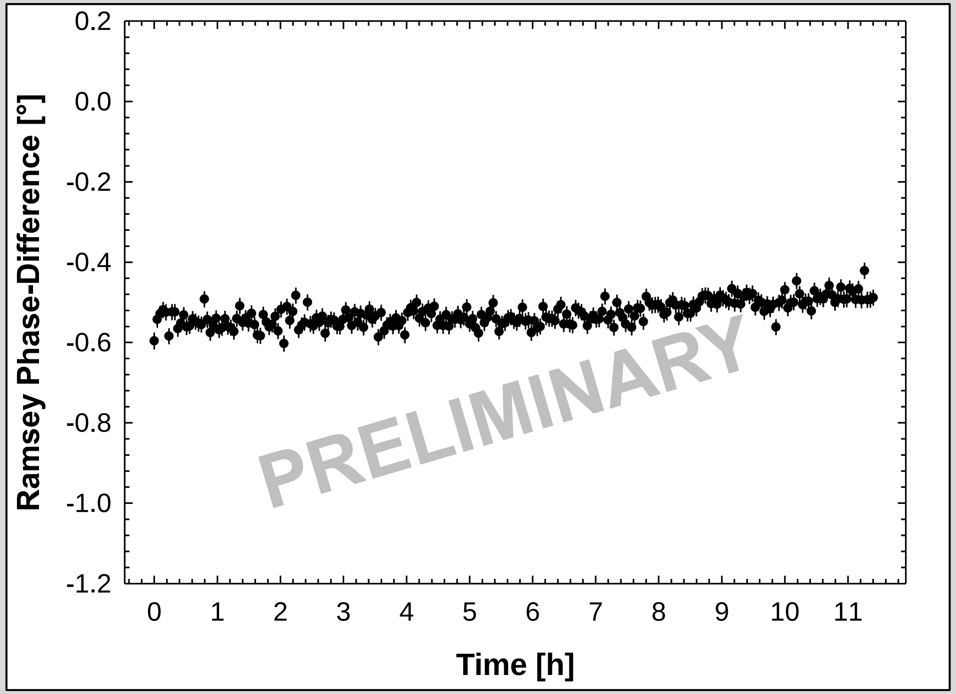
► **Two beam method allows for correction of (magnetic) drifts**

Phase stability

Two beams

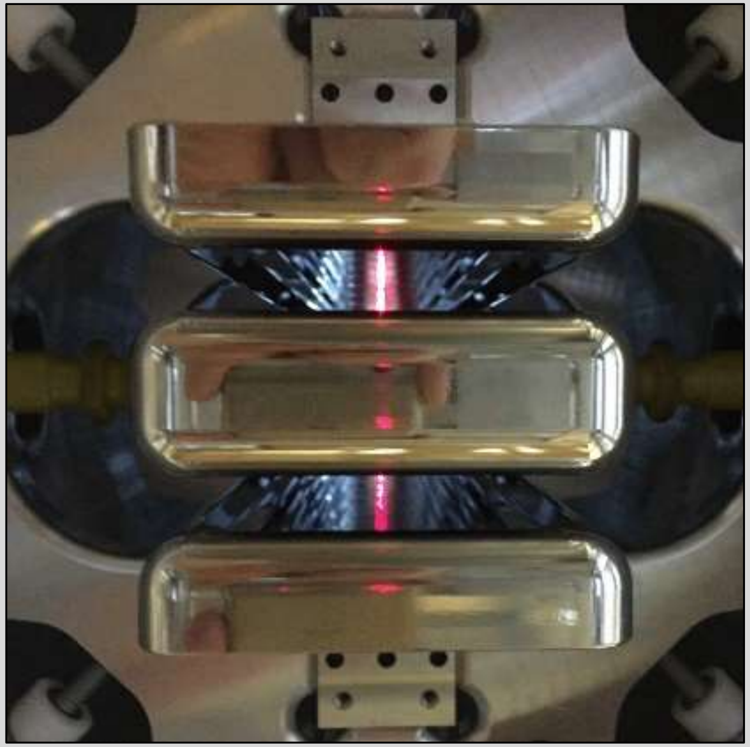


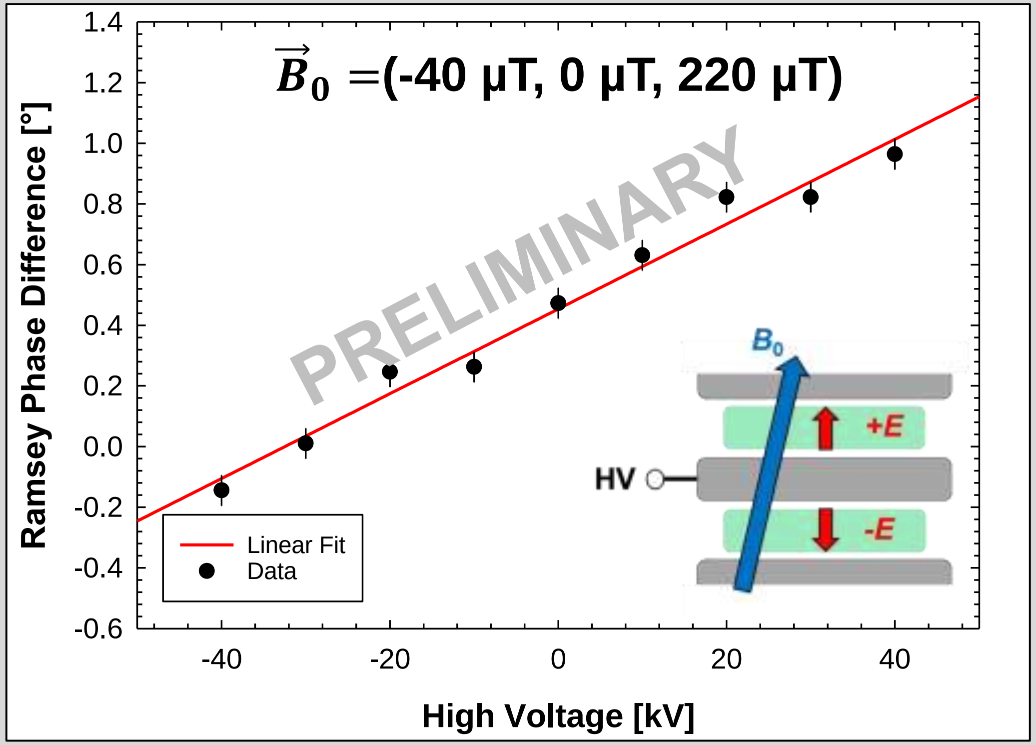
Phase-difference of two beams



► **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

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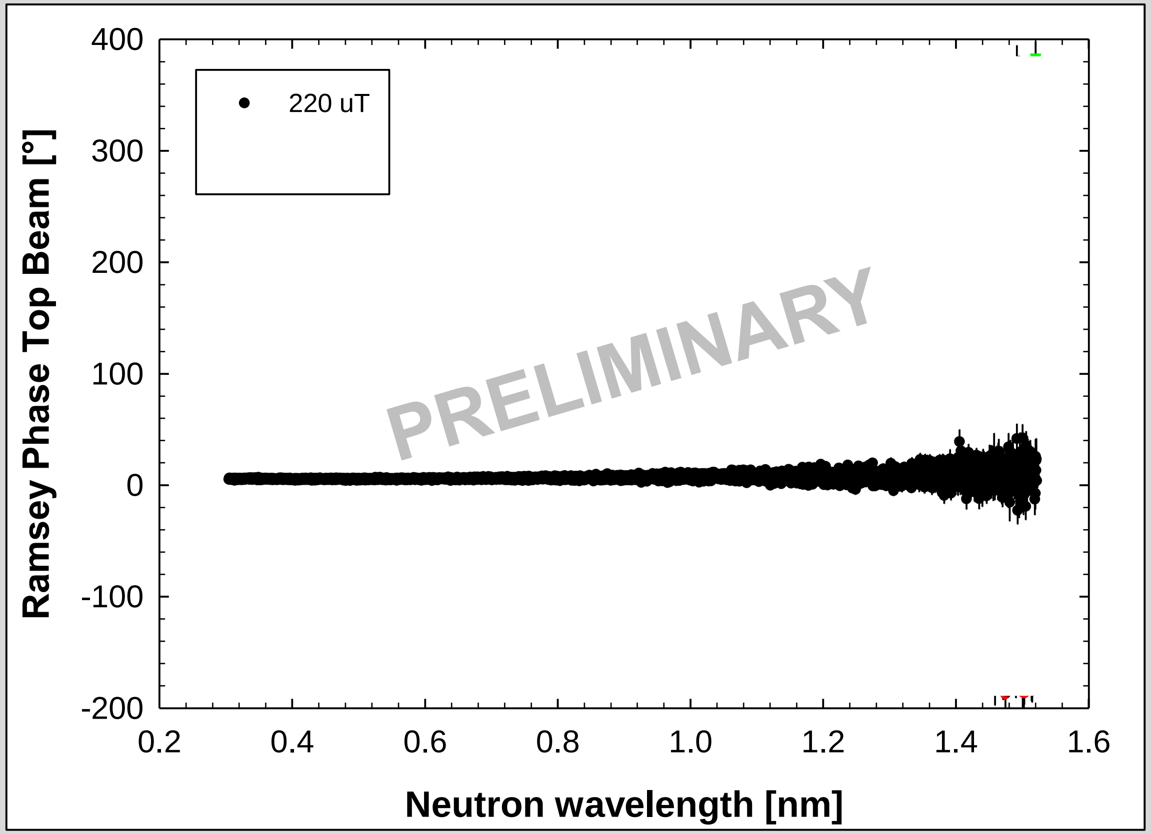
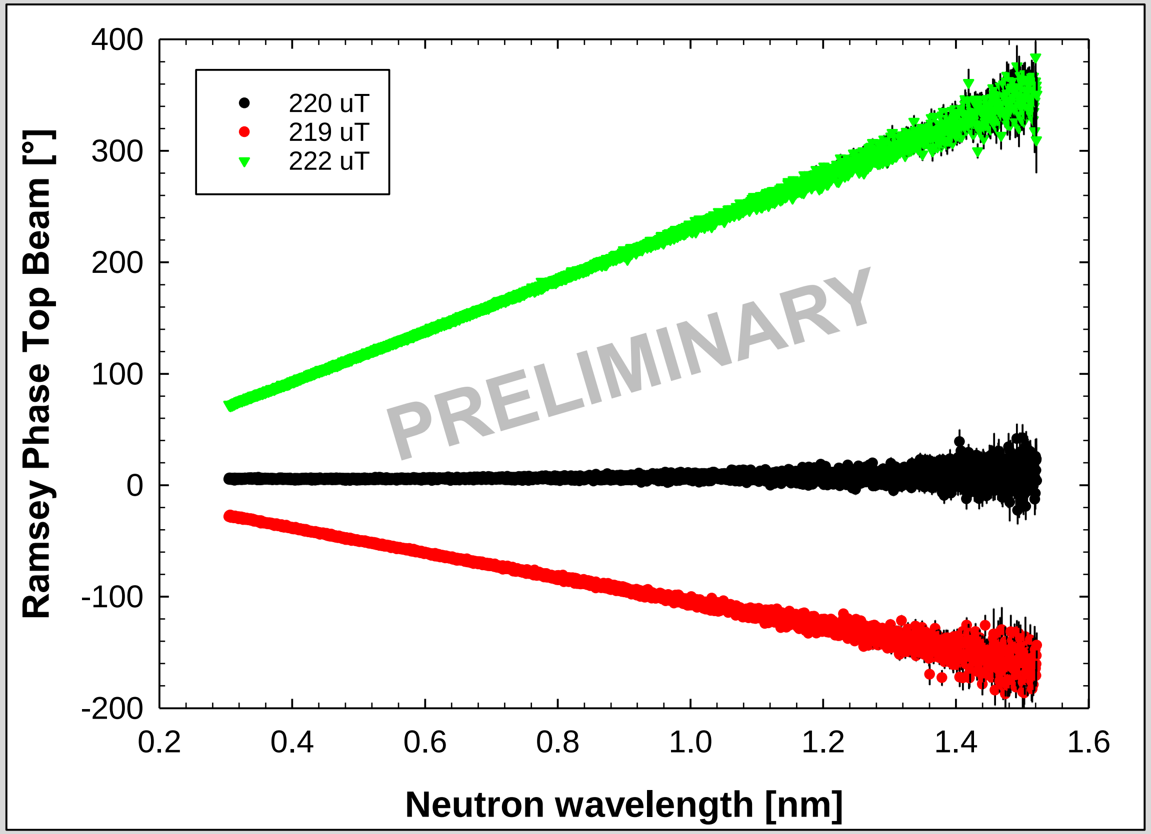


- **Ramsey signal phase measured as a function of TOF, i.e. neutron wavelength**
- **An offset magnetic field causes a change of the slope, similar to an EDM interaction**
- **„Real EDM measurement“: determine slopes for both electric field polarities**

Magnetic field scan – emulating an EDM



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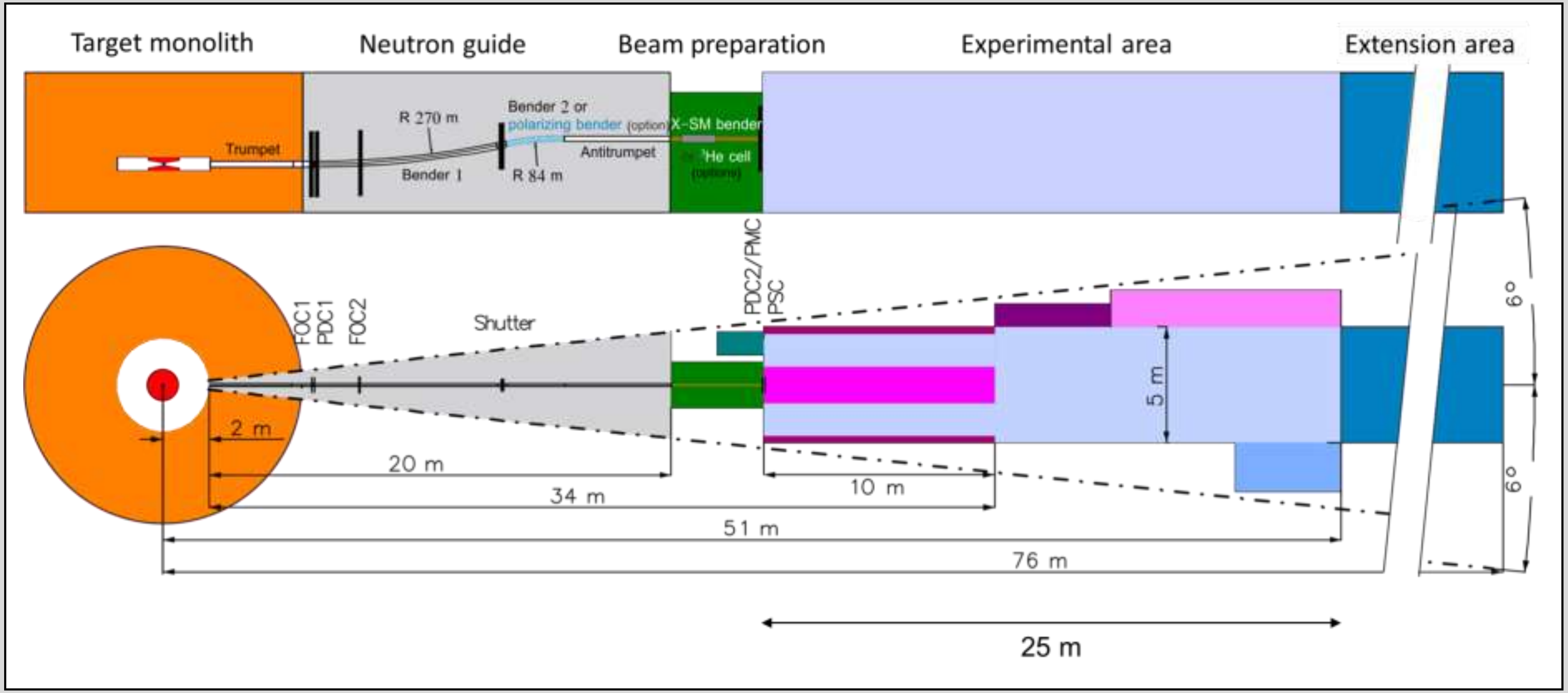
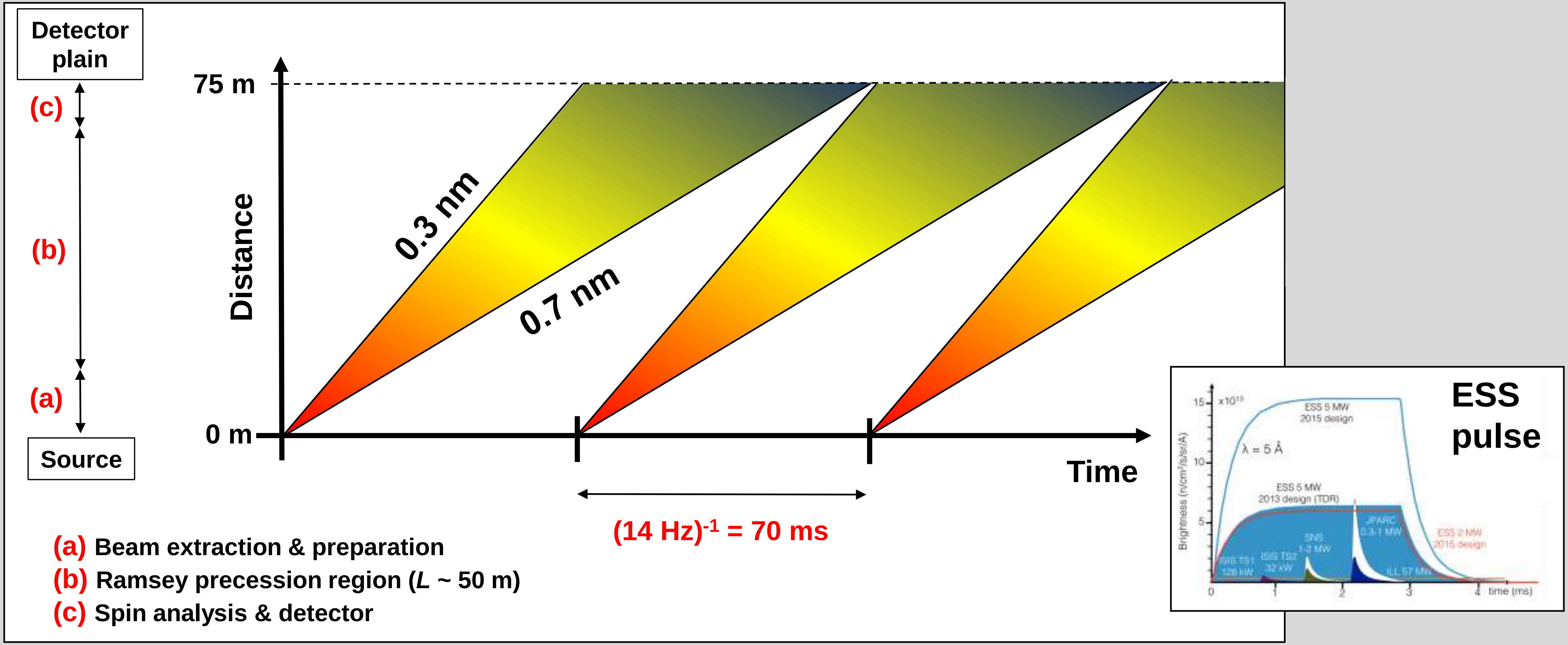
Proposed ANNI beamline at ESS



E. Klinkby, T. Soldner, J. Phys. Conf. Ser. 746, 012051 (2016)

Beam EDM at ESS / Time-of-flight



Projected sensitivity at ESS

$\eta = 0.75$, $L = 50$ m, $L_{TOF} = 75$ m, $\tau = 50$ ms, $E = 100$ kV/cm

$$N = \underbrace{1.3 \times 10^{13}\,\mathrm{cm^{-2}s^{-1}sr^{-1}}}_{\text{PF1B particle brightness (ILL)}} \times \overbrace{1/3}^{\text{Polarization}} \times \underbrace{1}_{\text{ESS} \approx \text{ILL}} \times \overbrace{(2 \times 20\,\mathrm{cm^2})}^{\text{Cross section of two beams}} \times \underbrace{2 \times 10^{-7}\,\mathrm{sr}}_{20\,\mathrm{cm^2} / (100\,\mathrm{m})^2} \sim 40\,\mathrm{MHz}$$

$\sigma(d_n) \approx 1.8 \times 10^{-25}$ e cm per day

Neutron absorbing electrodes

E. Chanel et al., EPJ Web Conf. 219, 02004 (2019)

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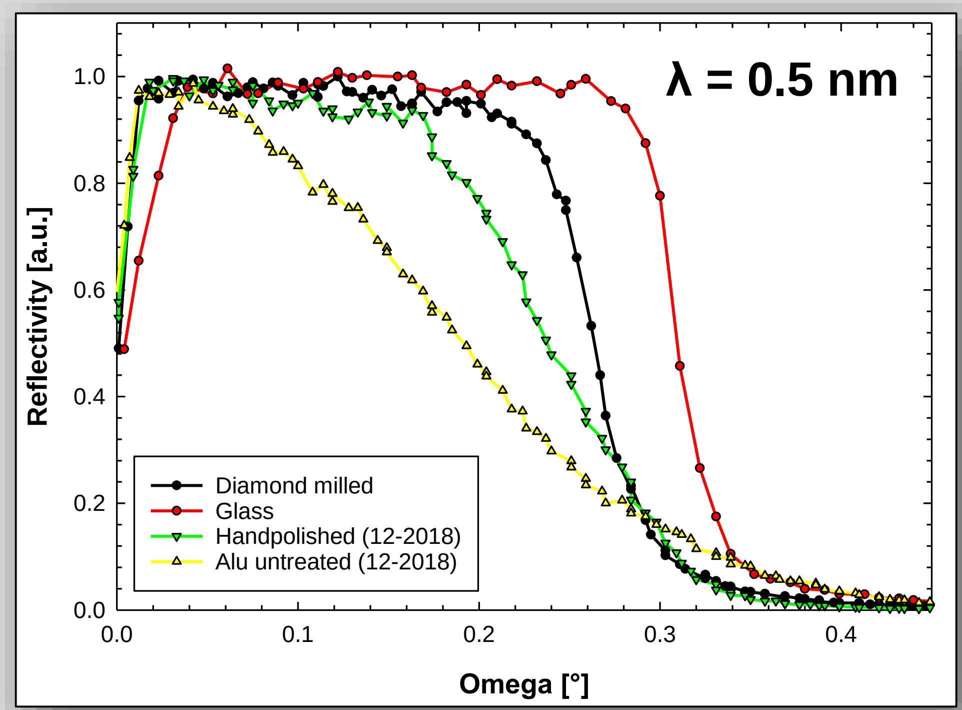
$$\sigma(d_n) \approx 5 \times 10^{-26}\ \text{e cm per day}$$

Guiding electrodes
estimated flux gain ~ 10

E. Chanel et al., EPJ Web Conf. 219, 02004 (2019)

Electrode reflectometry



Absorbing Electrodes: 20 mm / 50 m → 0.02° (max. vertical divergence)

Guiding Electrodes: about 0.20° @ 0.5 nm (Diamond milled aluminum)

Factor × 10

Current status & next steps

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- **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

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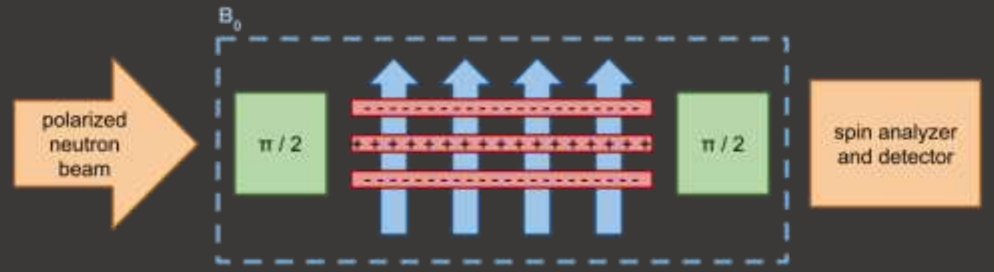
$$\mathcal{L}_{QCD} = \mathcal{L}_{QCD}^{\theta_{QCD}=0} + \frac{g^2}{32\pi^2}\theta_{QCD} G\tilde{G} + Axionfield$$

- 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)**

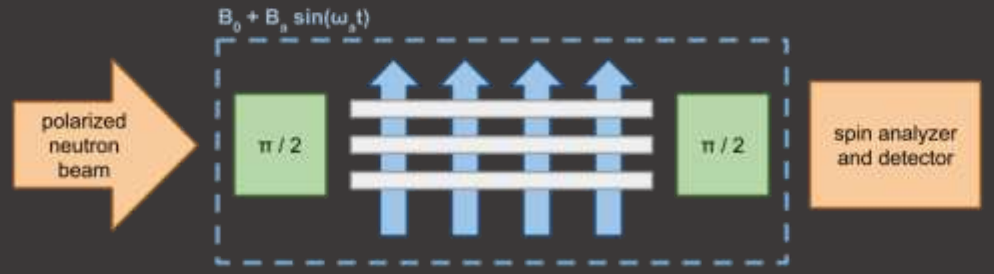
Beam EDM apparatus in „continuous mode“

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

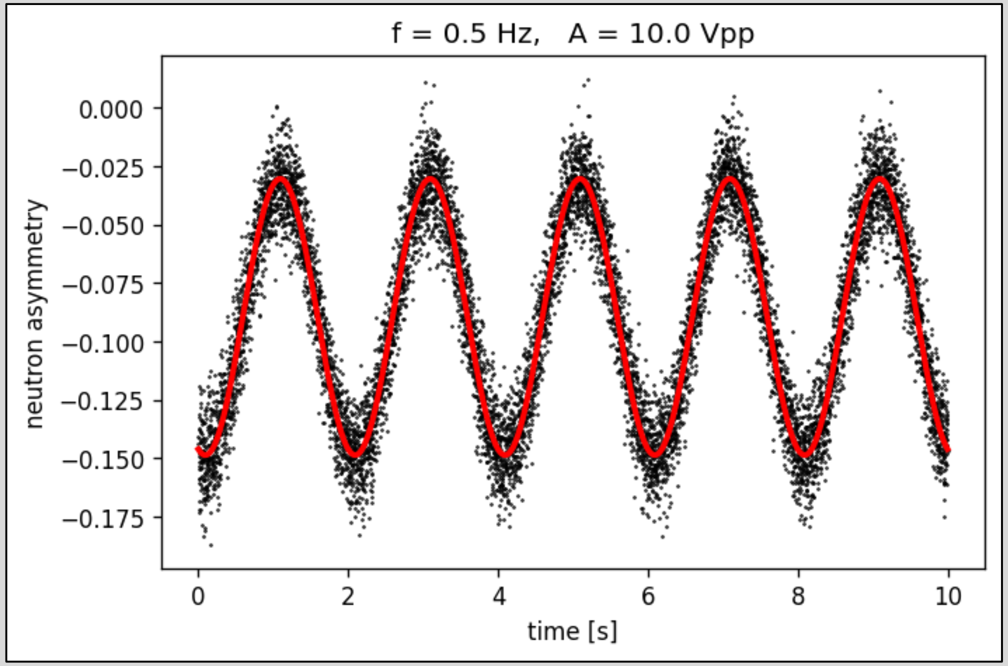


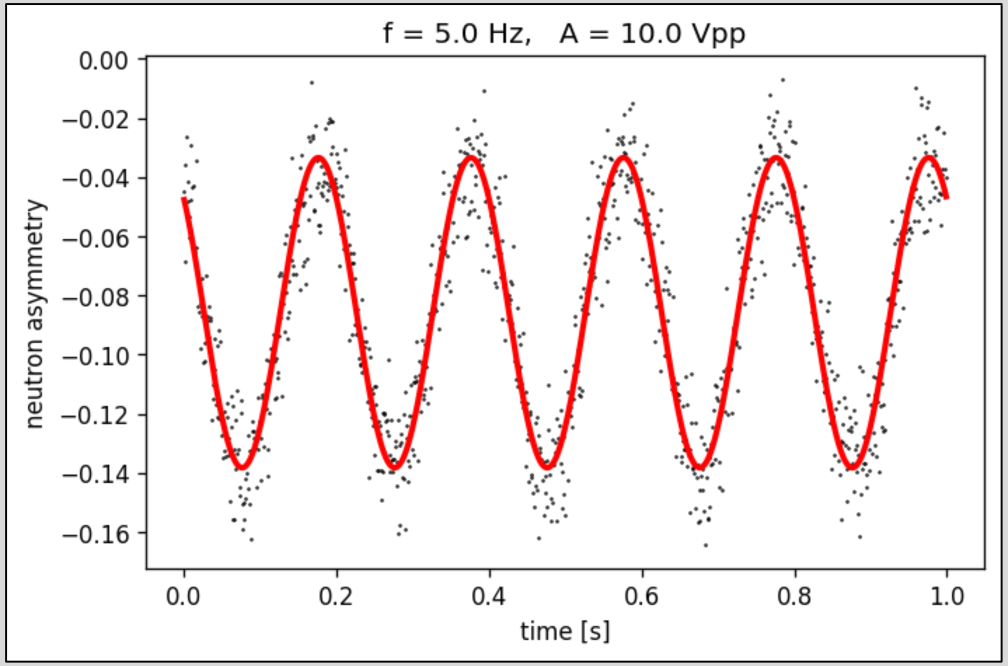
$$\underbrace{\gamma_n \times B_a \sin(\omega_a t)}_{\text{time dependent field}}$$

Actual ALPs search data (± 35 kV/cm)

Extract apparatus sensitivity

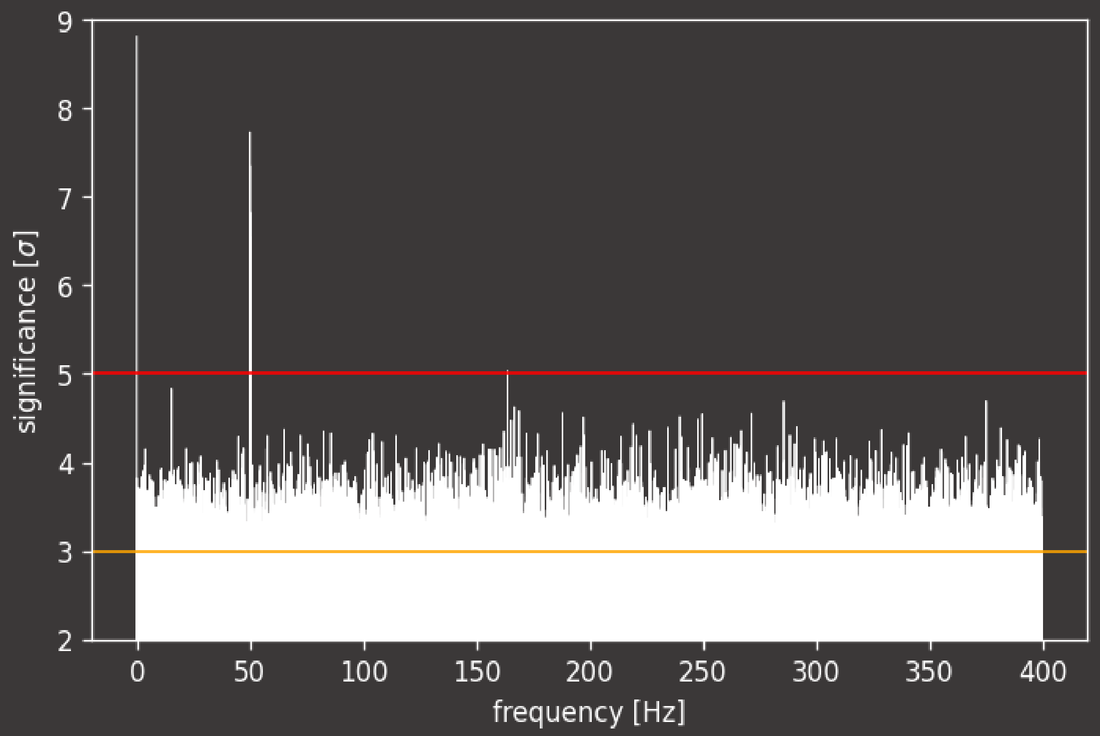
Example for „Fake Axion“ signals





- **Neutron data sampled with 4 kHz**
- **„Injected“ Fake Axion signals from DC to 1000 Hz**

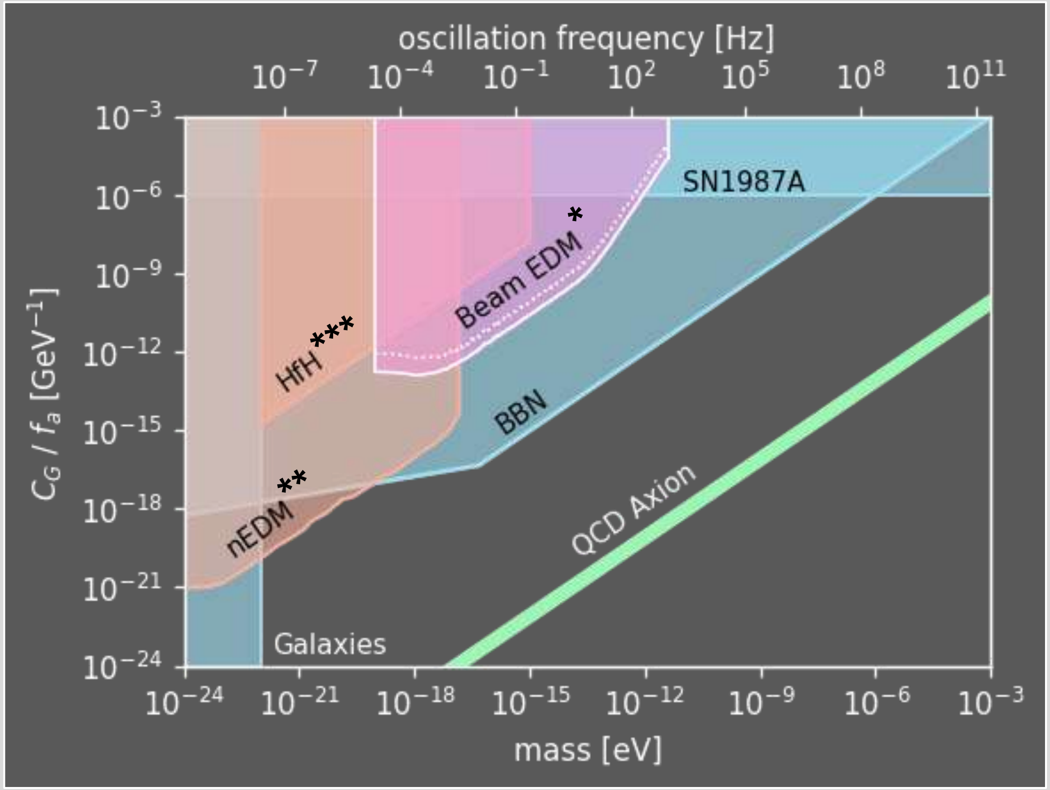
Axion conditions and spectrum



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)

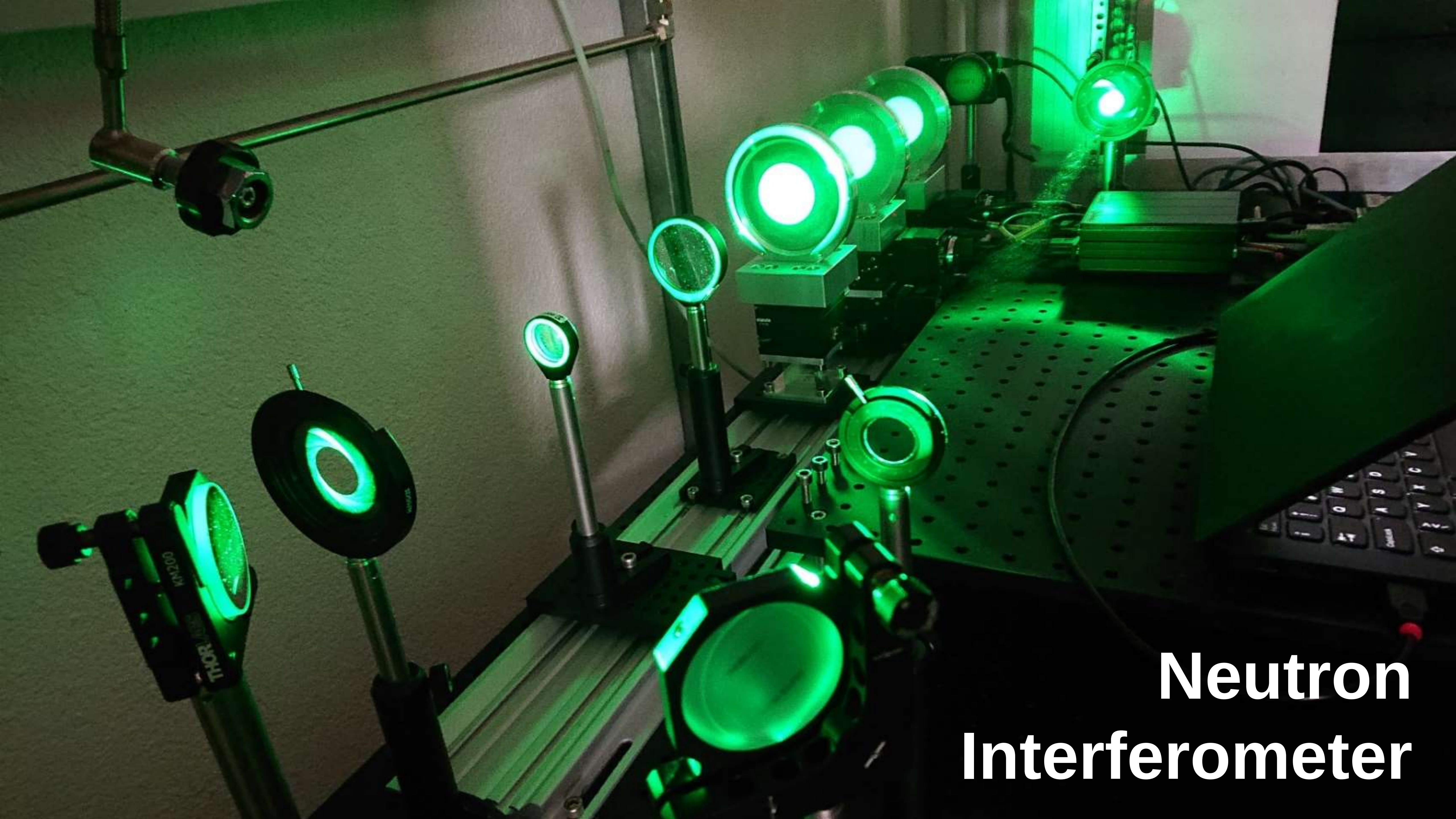


An ultralight axion-like particle (Dark Matter candidate) can induce an oscillating neutron EDM:

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

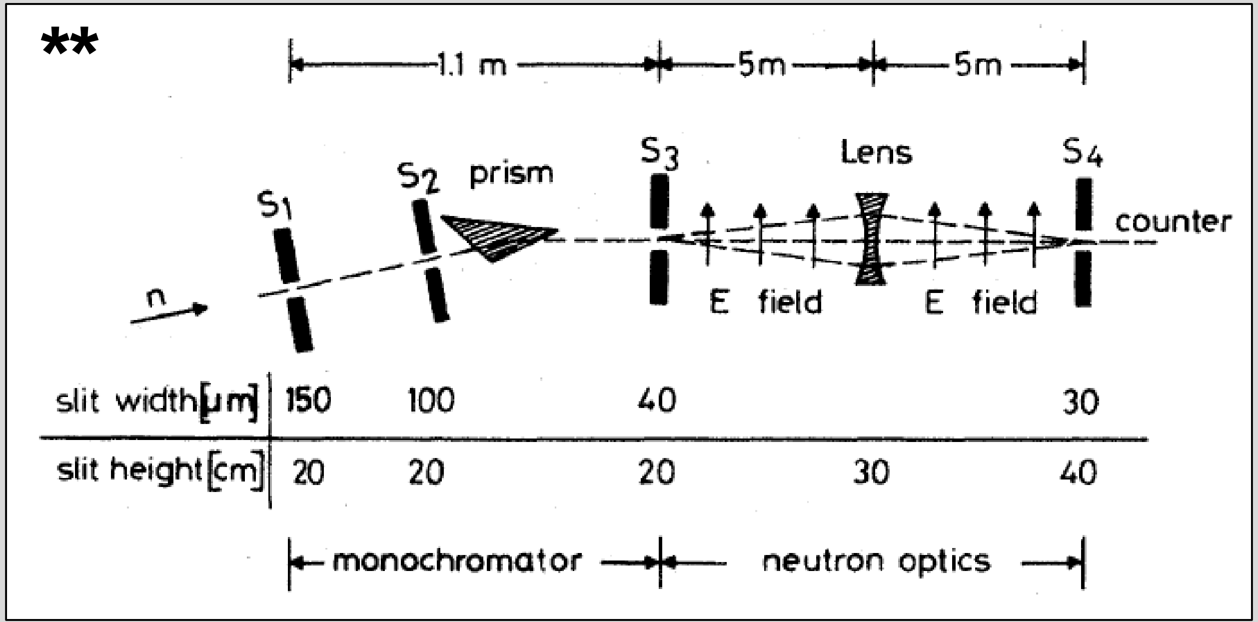
C_G: model dependent parameter
f_a: axion decay constant
a_0: axion field amplitude
m_a: axion mass

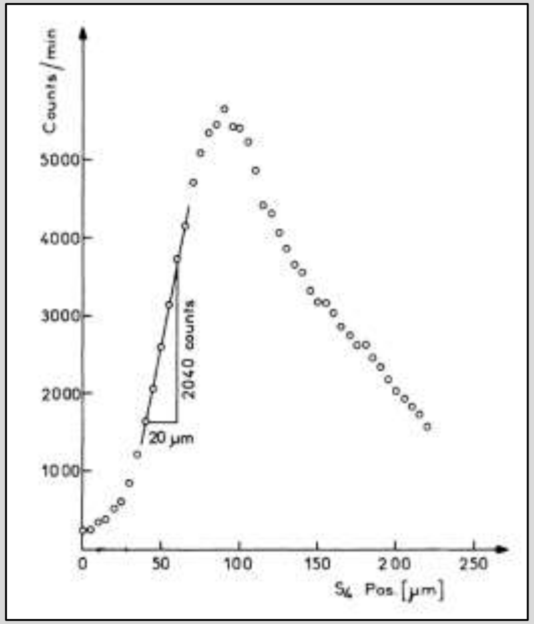
*** Schulthess et al., arXiv:2204.01454**
**** Abel et al., PRX 7, 041034 (2017)**
***** Roussy et al., PRL 126, 171301 (2021)**


Neutron
Interferometer

How neutral is the neutron?

Present best value*: $Q_n = (-0.4 \pm 1.1) \times 10^{-21}$ e





* Baumann et al., PRD 37, 3107 (1988)
** Gähler et al., PRD 25, 2887 (1982)

QNeutron – Talbot-Lau interferometer

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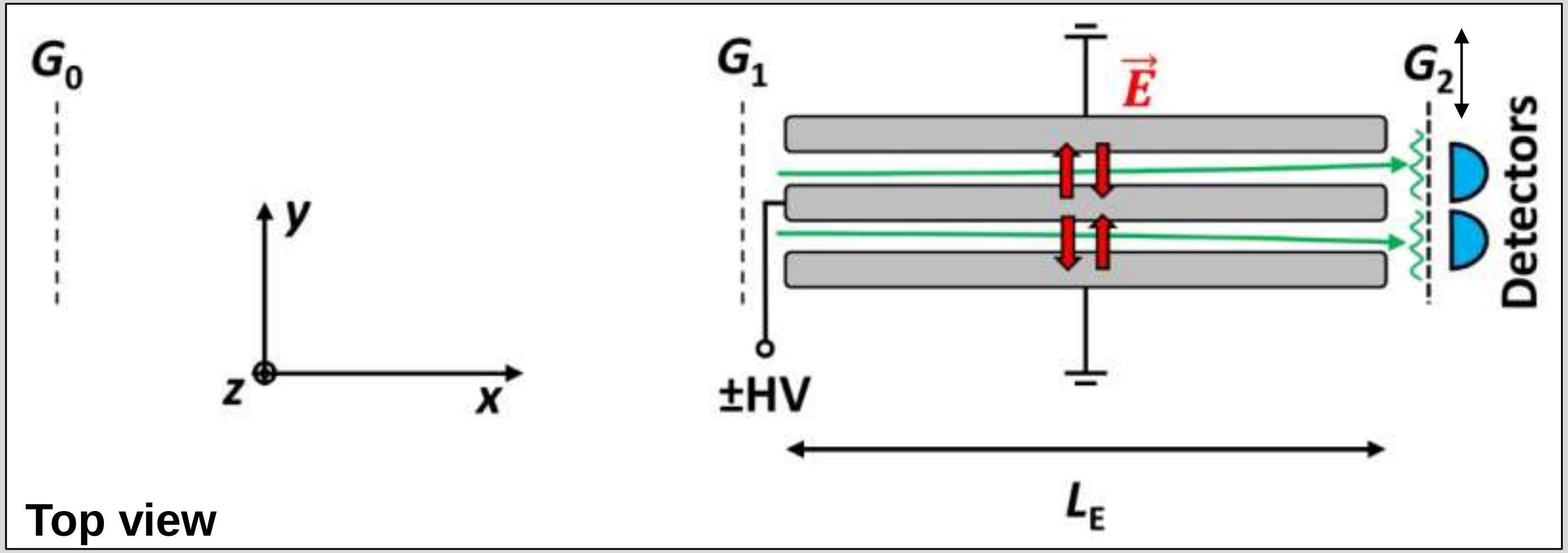
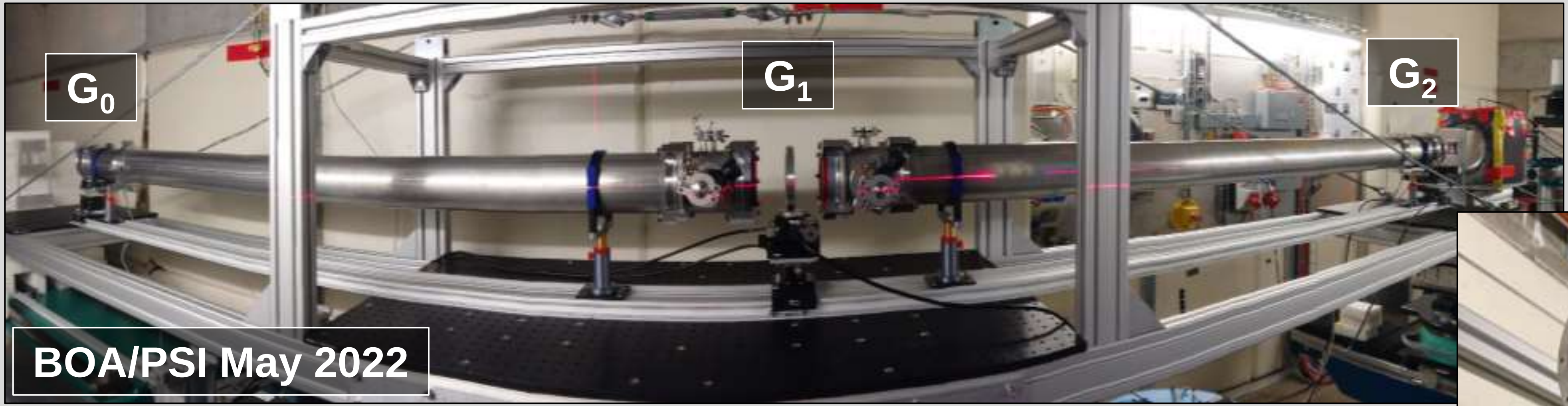
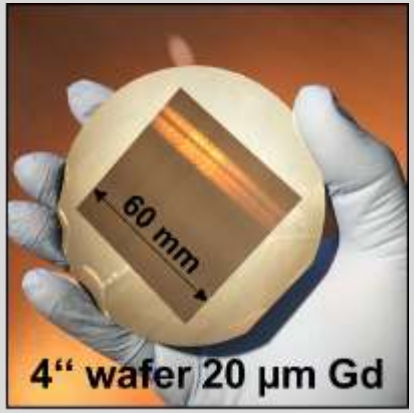


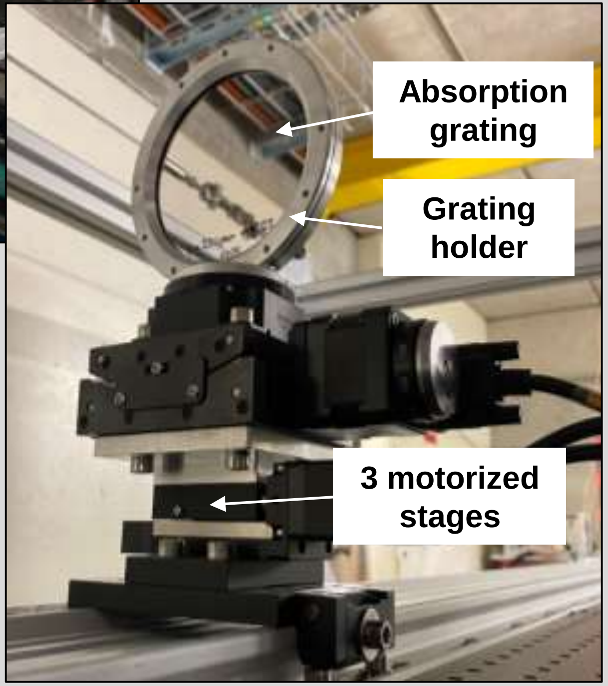
- **Three identical absorption gratings with sub-mm periods (~ 0.1 mm)**
  G_0: Coherence, G_1: Diffraction and G_2: Analyser
- **Detector cannot resolve interferometric pattern – scan analyser grating G_2**
- **Two beams with opposite effect – cancel common-noise/drifts**

Piegsa, PRC 98, 045503 (2018)

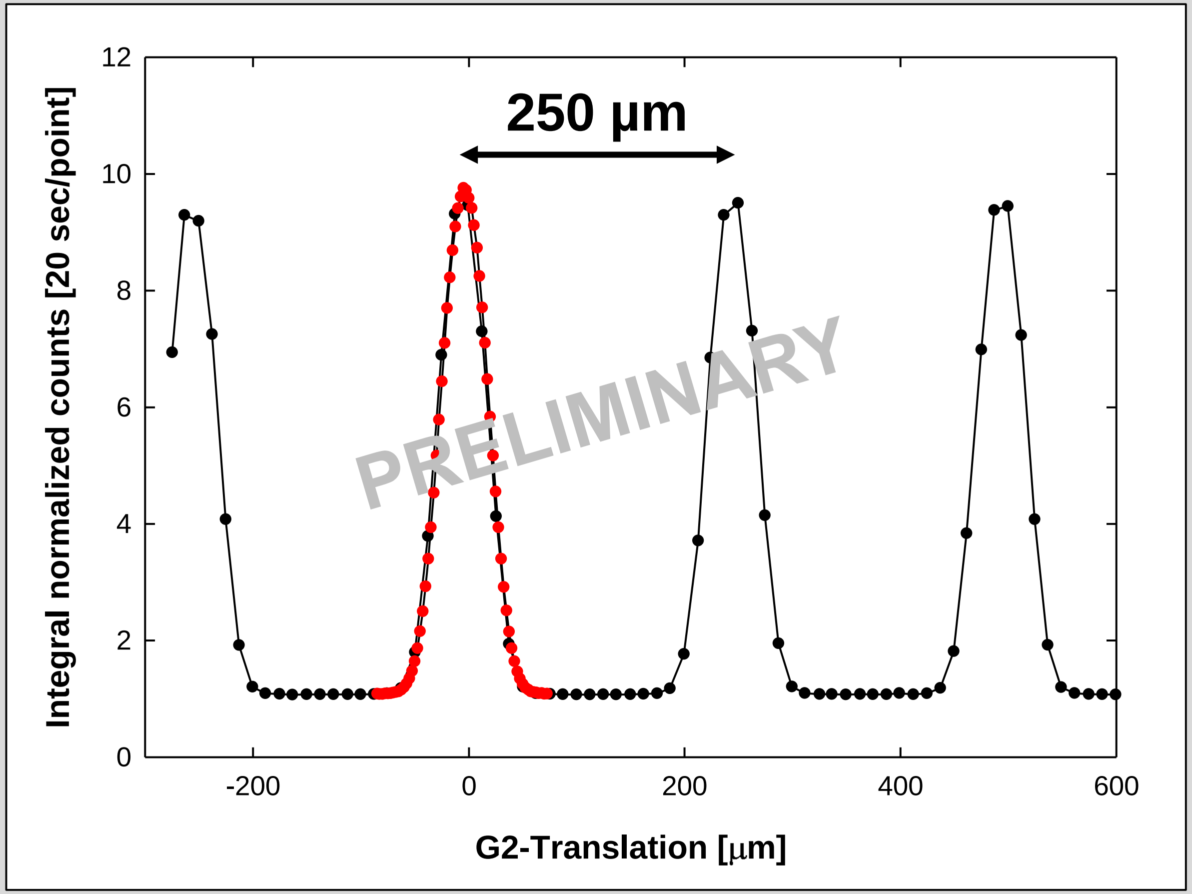
QNeutron – Experimental setup







First successful interferometer scan



to be continued …

Summary

UNIVERSITÄT BERN

- New complimentary neutron EDM experiment
- Axion search via an oscillating EDM
- Novel neutron interferometer with the goal to measure the electric charge of the neutron