Beam EDM: A Novel Technique to Measure the Neutron Electric Dipole Moment

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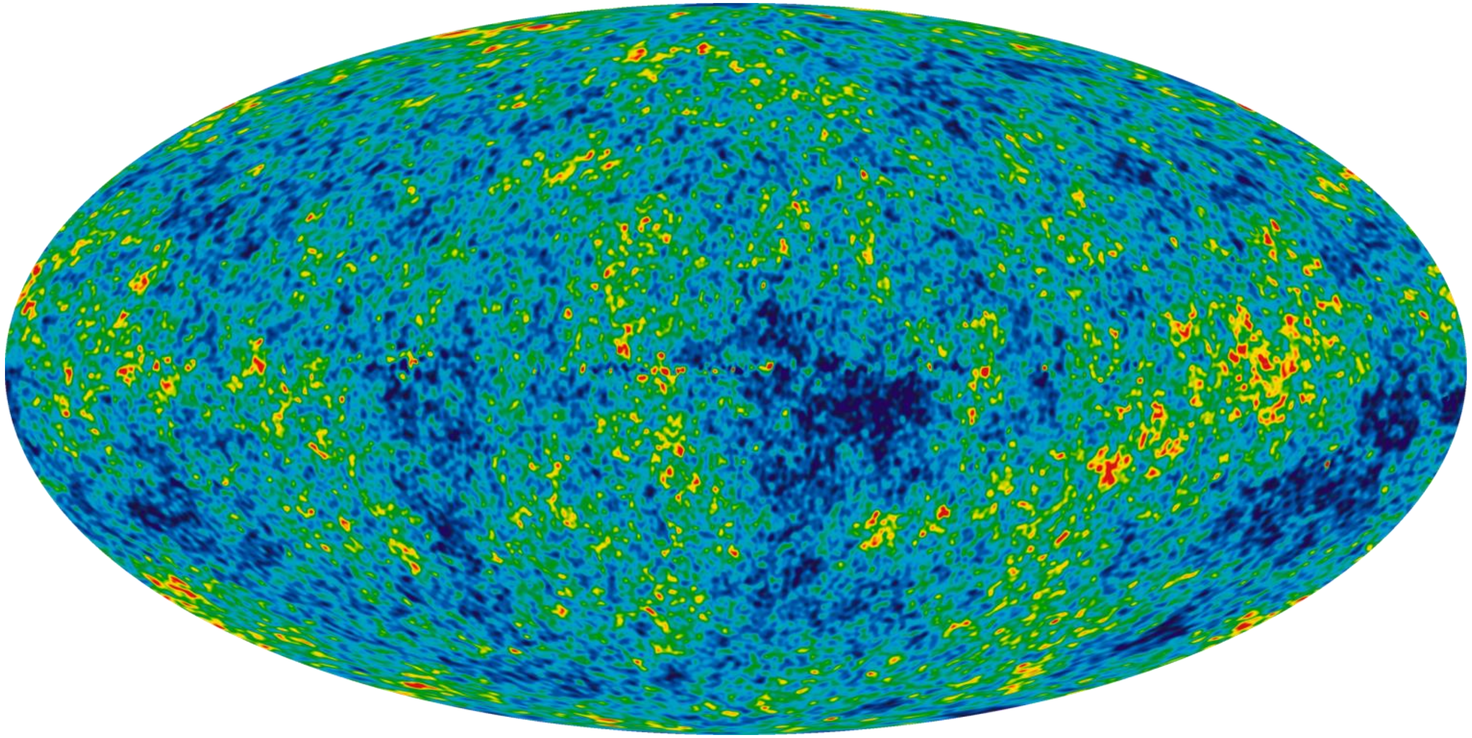
EPP Seminar – 3rd Oct. 2019

University of Sussex

Cosmic Microwave Background (CMB)



- CMB provides information of the early universe
- This can determine an asymmetry between baryons and anti baryons:

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

Baryogenesis

- Occurs in the early universe that produces the observed asymmetry of matter over anti-matter
- Sakharov conditions:
  - Baryon number violation
  - C-symmetry and CP-symmetry violation
  - Interactions out of thermal equilibrium
- Additional sources of CP-violation could explain this asymmetry, possible new physics

What is the neutron EDM?

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$$\mathcal{H} = -\mu_n \vec{\sigma} \cdot \vec{B} - d_n \vec{\sigma} \cdot \vec{E}$$

- Hamiltonian of the neutron under applied magnetic and electric fields
- μ_n is the neutron magnetic moment, d_n is the electric dipole moment

Quantity
Spin, $\vec{\sigma}$
Time, t
Electric field, $\vec{E}$
Magnetic field, $\vec{B}$
Position, $\vec{x}$

What is the neutron EDM?

$$\boldsymbol{P}(\mathcal{H}) = -\mu_n \vec{\sigma} \cdot \vec{B} - d_n \vec{\sigma} \cdot \left(-\vec{E}\right)$$

Quantity	Parity (**P**)
Spin, $\vec{\sigma}$	$\vec{\sigma}$
Time, t	t
Electric field, $\vec{E}$	-$\vec{E}$
Magnetic field, $\vec{B}$	$\vec{B}$
Position, $\vec{x}$	-$\vec{x}$

What is the neutron EDM?

$$\boldsymbol{T}(\mathcal{H}) = -\mu_n(-\vec{\sigma}) \cdot \left(-\vec{B}\right) - d_n(-\vec{\sigma}) \cdot \vec{E}$$

Quantity	Time reversal (**T**)
Spin, $\vec{\sigma}$	-$\vec{\sigma}$
Time, t	-t
Electric field, $\vec{E}$	$\vec{E}$
Magnetic field, $\vec{B}$	-$\vec{B}$
Position, $\vec{x}$	$\vec{x}$

What is the neutron EDM?

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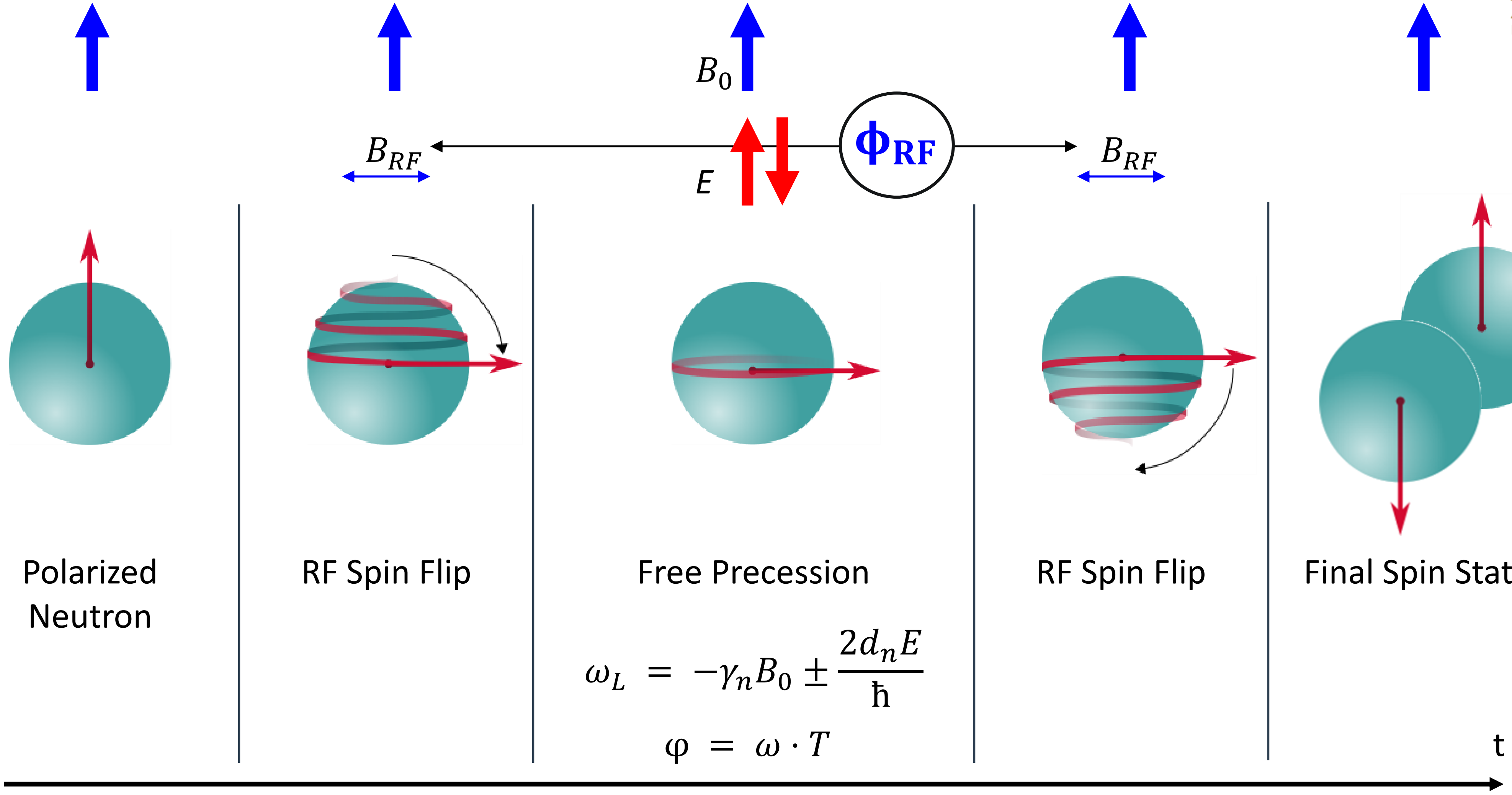
- Existence of non-zero d_n violates **P** and **T**
- CPT theorem, **T** = **CP**
- Standard Model (weak sector): $d_n \sim 10^{-31} - 10^{-34} e \cdot \text{cm}$
- Beyond Standard Model theories: $d_n > 10^{-31} e \cdot \text{cm}$

How to measure the neutron EDM - Ramsey Technique



How to measure the neutron EDM - Ramsey Fringe

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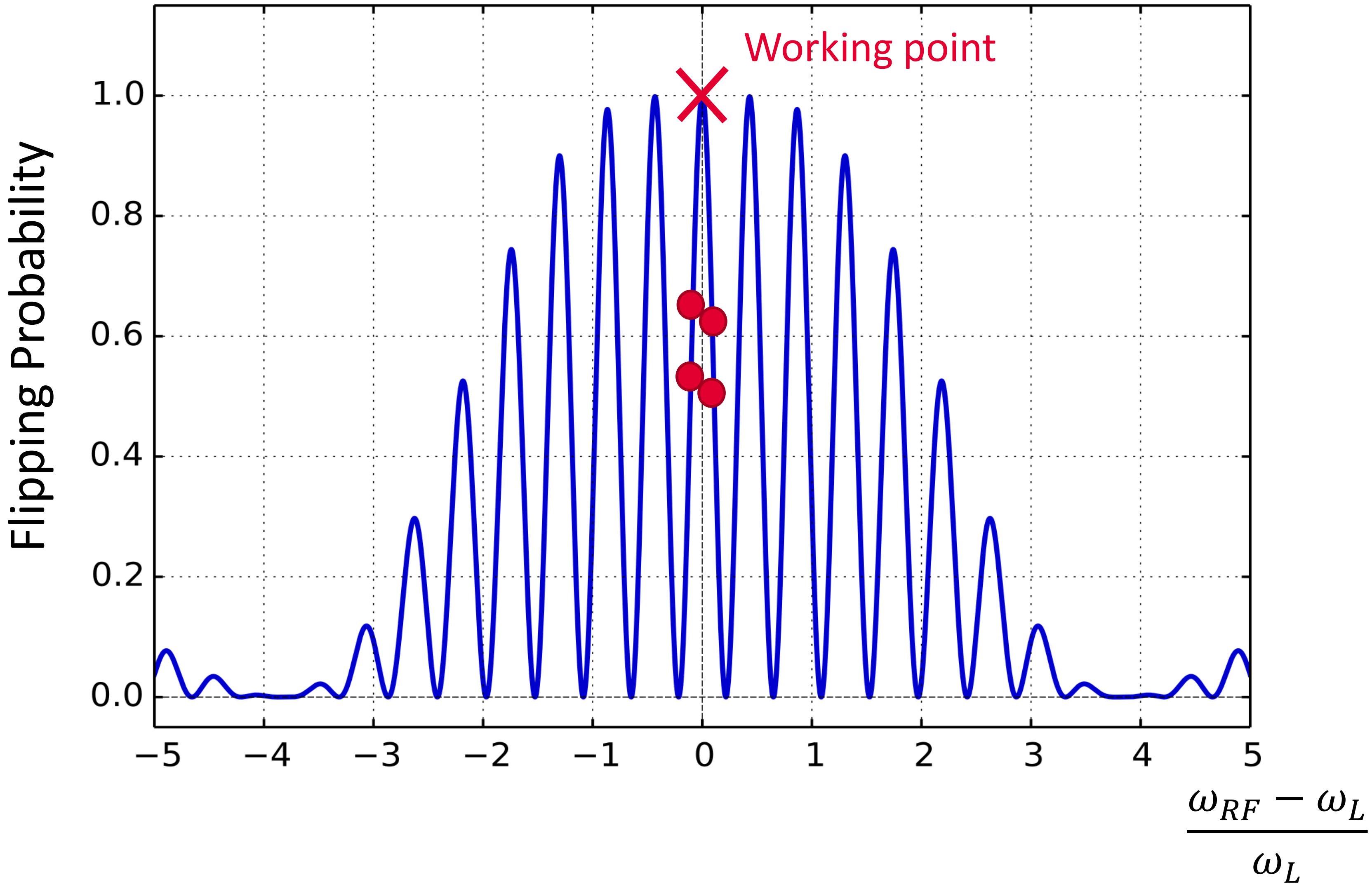

How to measure the neutron EDM - Phase Scan

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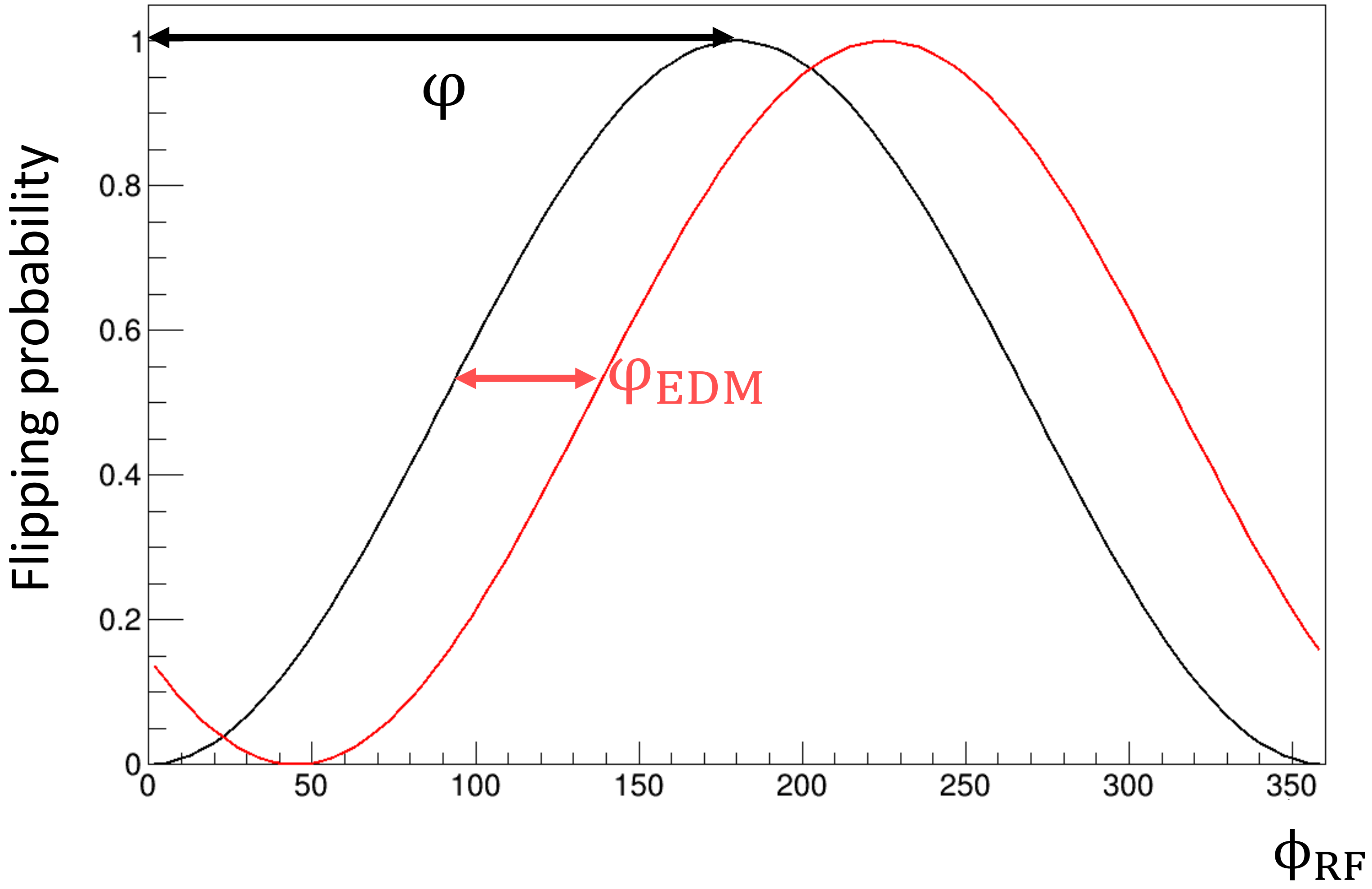
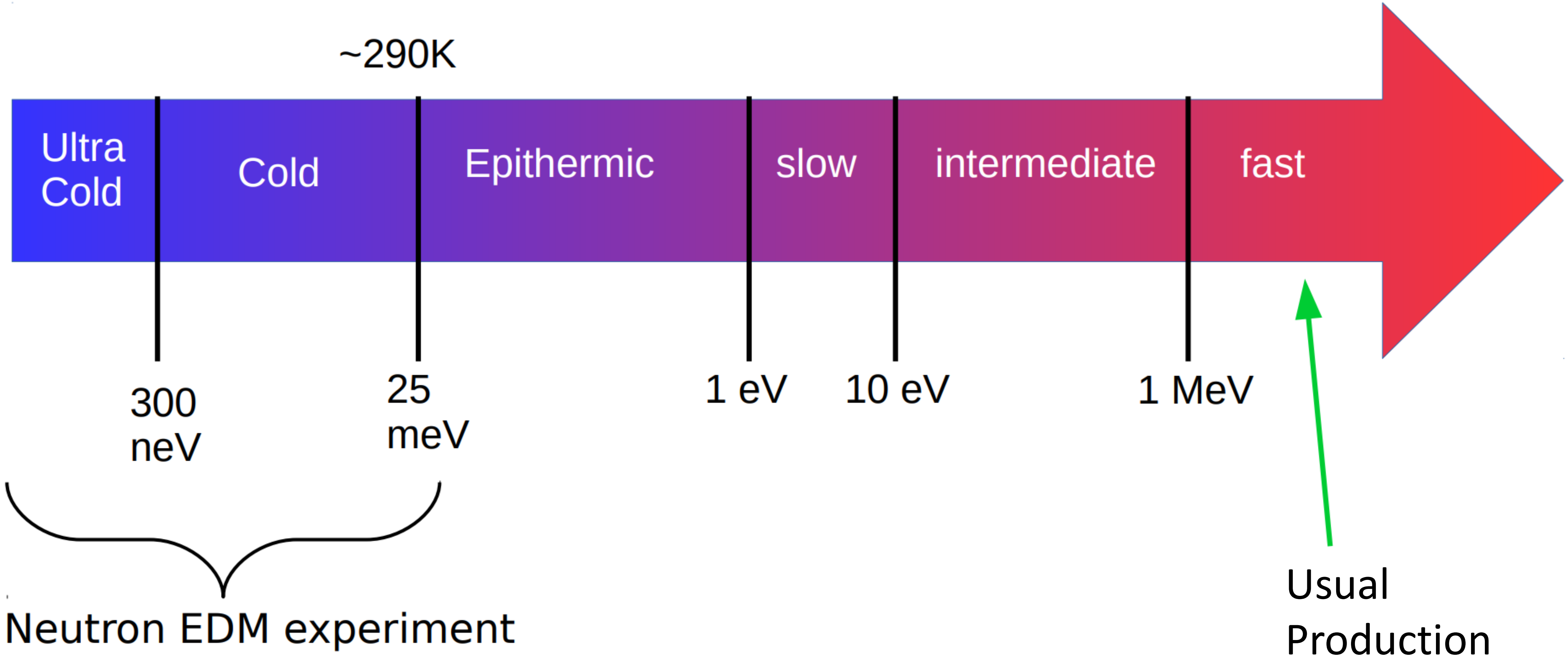


Neutron Energy



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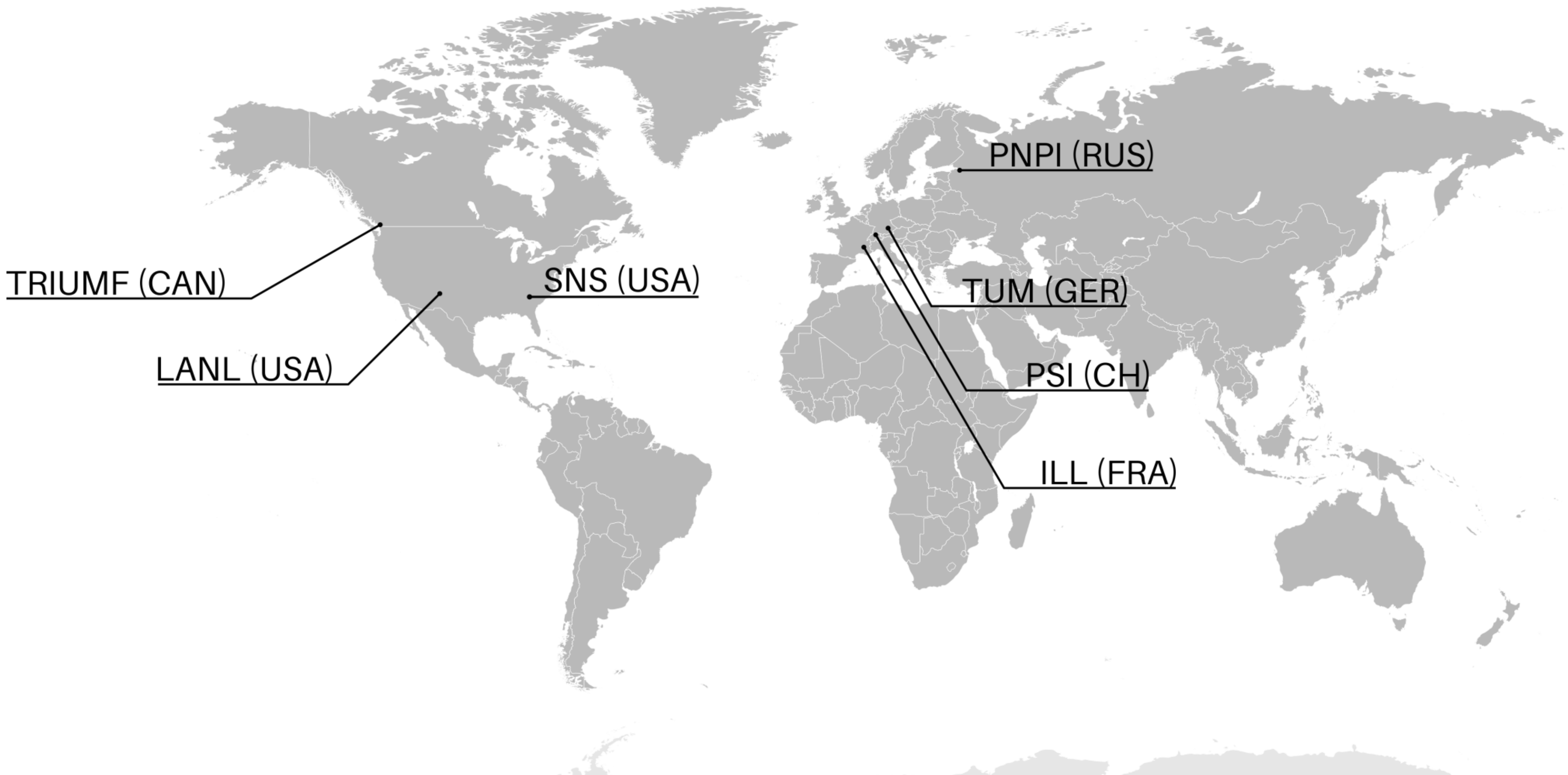
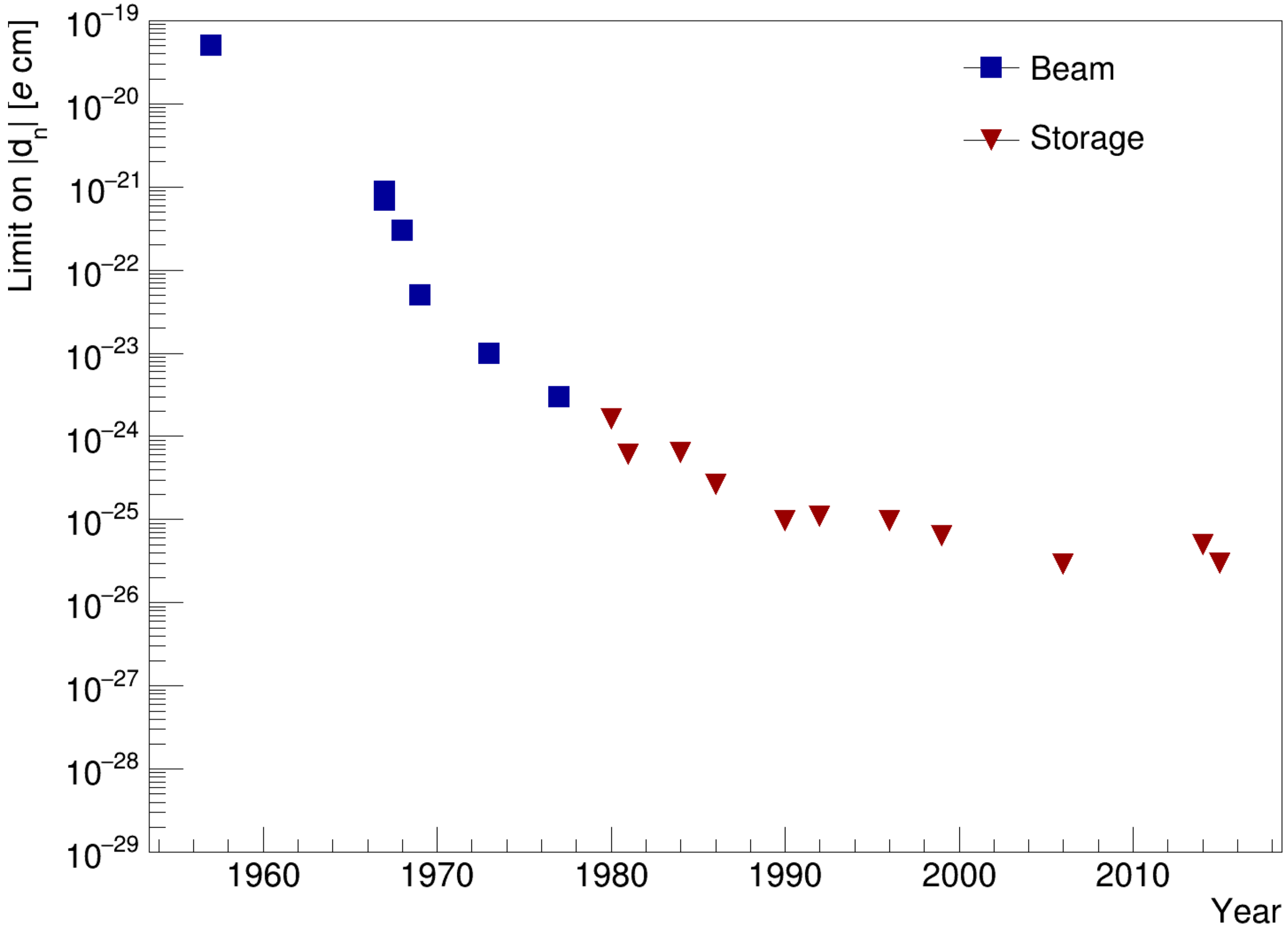
Neutron EDM Searches Worldwide



Current Neutron EDM Limit



- Switch to stored UCN experiments due to systematic limitations
- Sussex/RAL/ILL collaboration: $|d_n| < 3 \times\ 10^{-26}\mathrm{e\cdot cm}\ (95\%\ \mathrm{C.L.})$[1]
- Next generation experiments aim for $\mathcal{O}(10^{-27})$e·cm

[1] Pendlebury, J. M. et al. Physical Review D 92.092003 (2015)

Why cold neutron beam?

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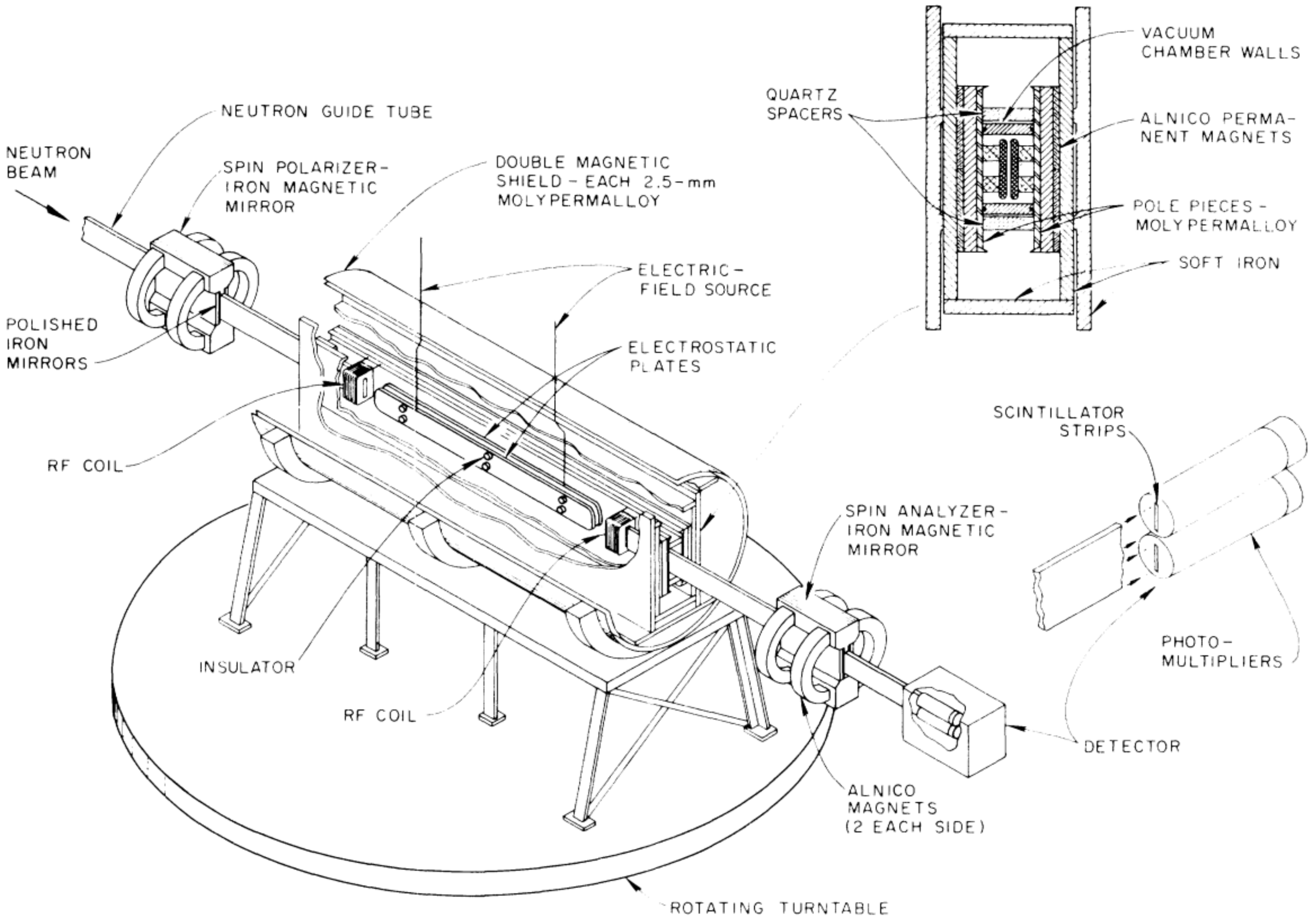
- General nEDM experimental sensitivity:

$$\sigma_{d_n} \propto \frac{\hbar}{\eta \tau E \sqrt{N}}$$

- Production of UCN produces lower densities compared to beams
- Storage experiments work with lower electric fields
- Velocity spectrum much faster for cold beams, observation time lower

Previous Neutron Beam EDM (1977)



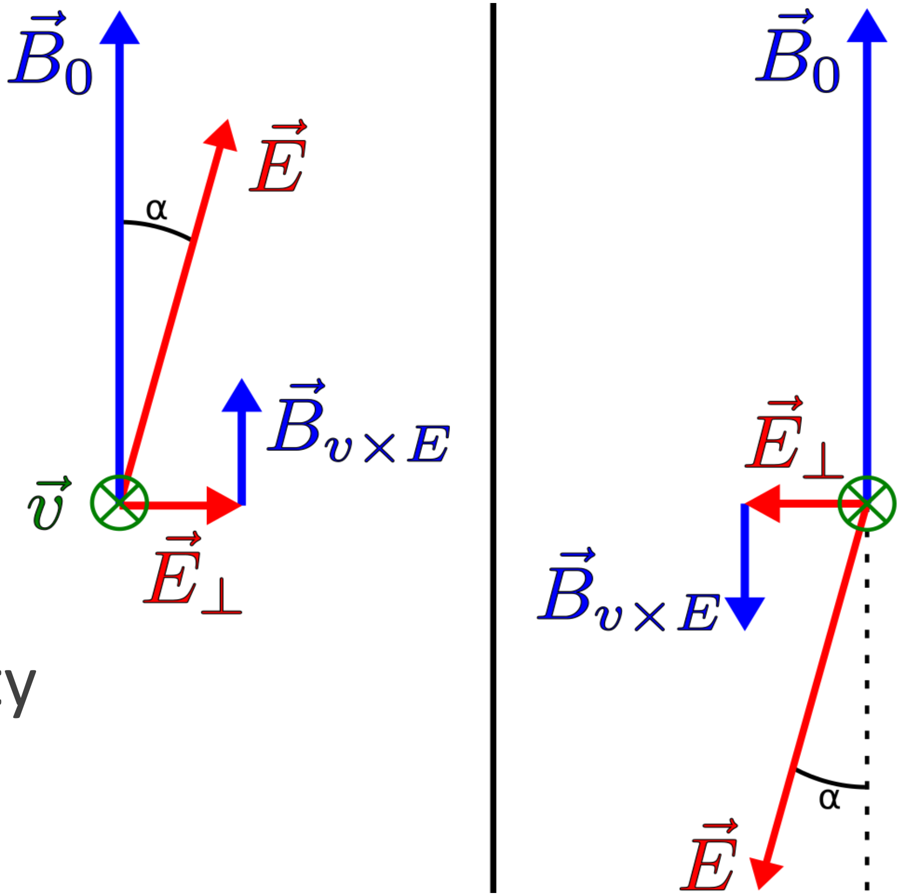
- Performed at ILL
- Systematic can occur due to relativistic $\vec{v} \times \vec{E}$ effect
- $|d_n| < 3 \times 10^{-24}$e·cm (90% C.L.)[2]

[2] Dress, W. B. et al. Physical Review D 15.9 (1977)

Relativistic $\vec{v} \times \vec{E}$ effect

$$\vec{B}_0 = \frac{-\vec{v} \times \vec{E}}{c^2}$$

- Misalignment of the $\vec{B}_0$ and $\vec{E}$ creates an additional magnetic field component
- Appears as shift in asymmetry against ϕ_{RF}
- This shift is velocity dependent
- Performing an EDM measurement with velocity spectrum overcomes this



Paul Scherrer Institut

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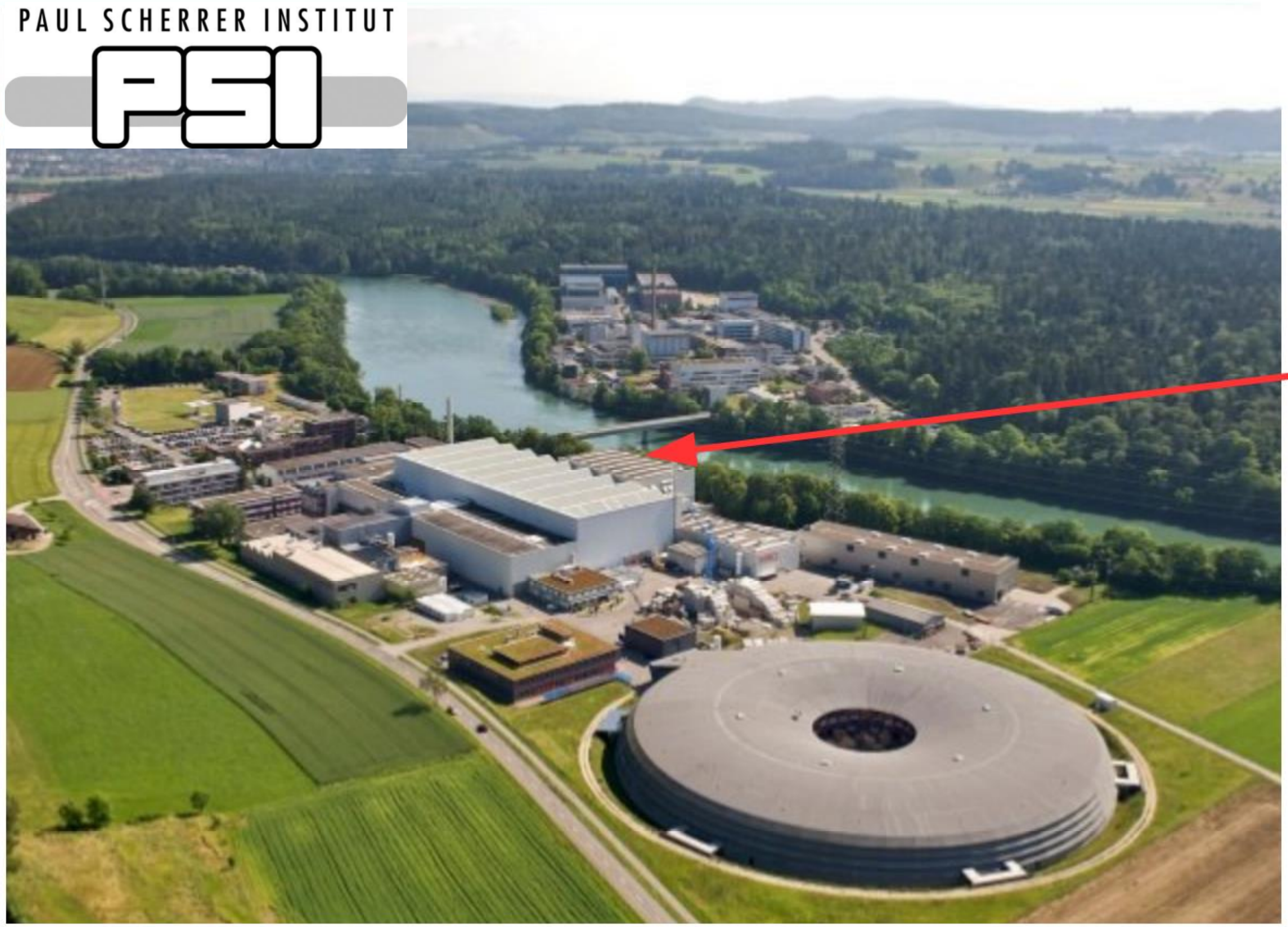
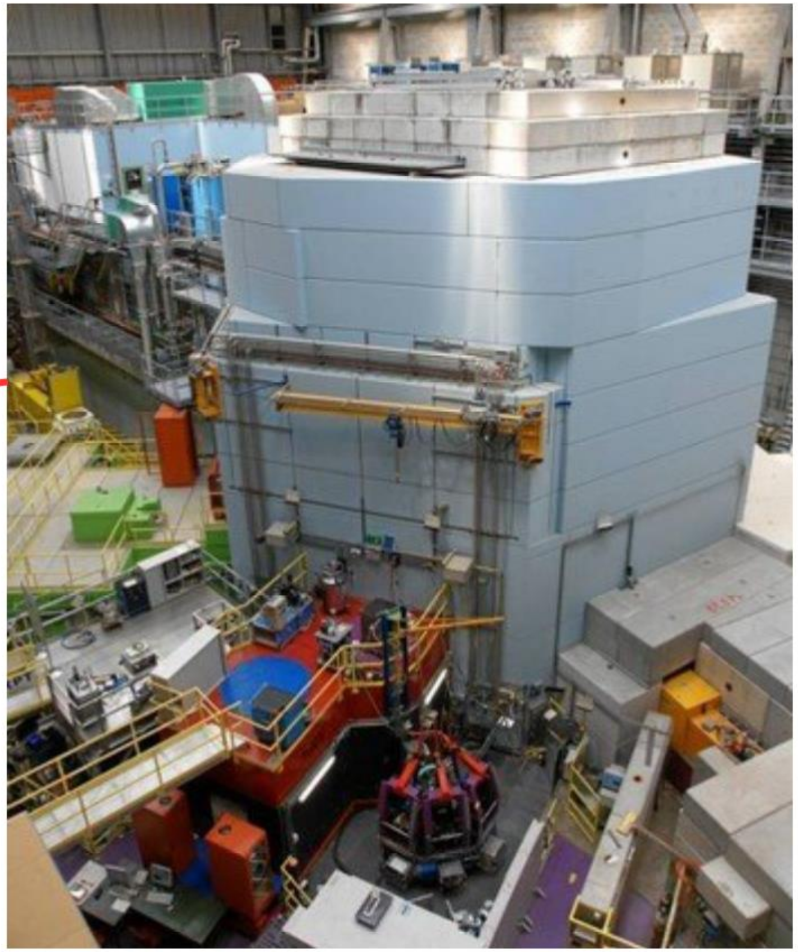


Paul Scherrer Institut



SINQ Spallation target building

Institute Laue-Langevin

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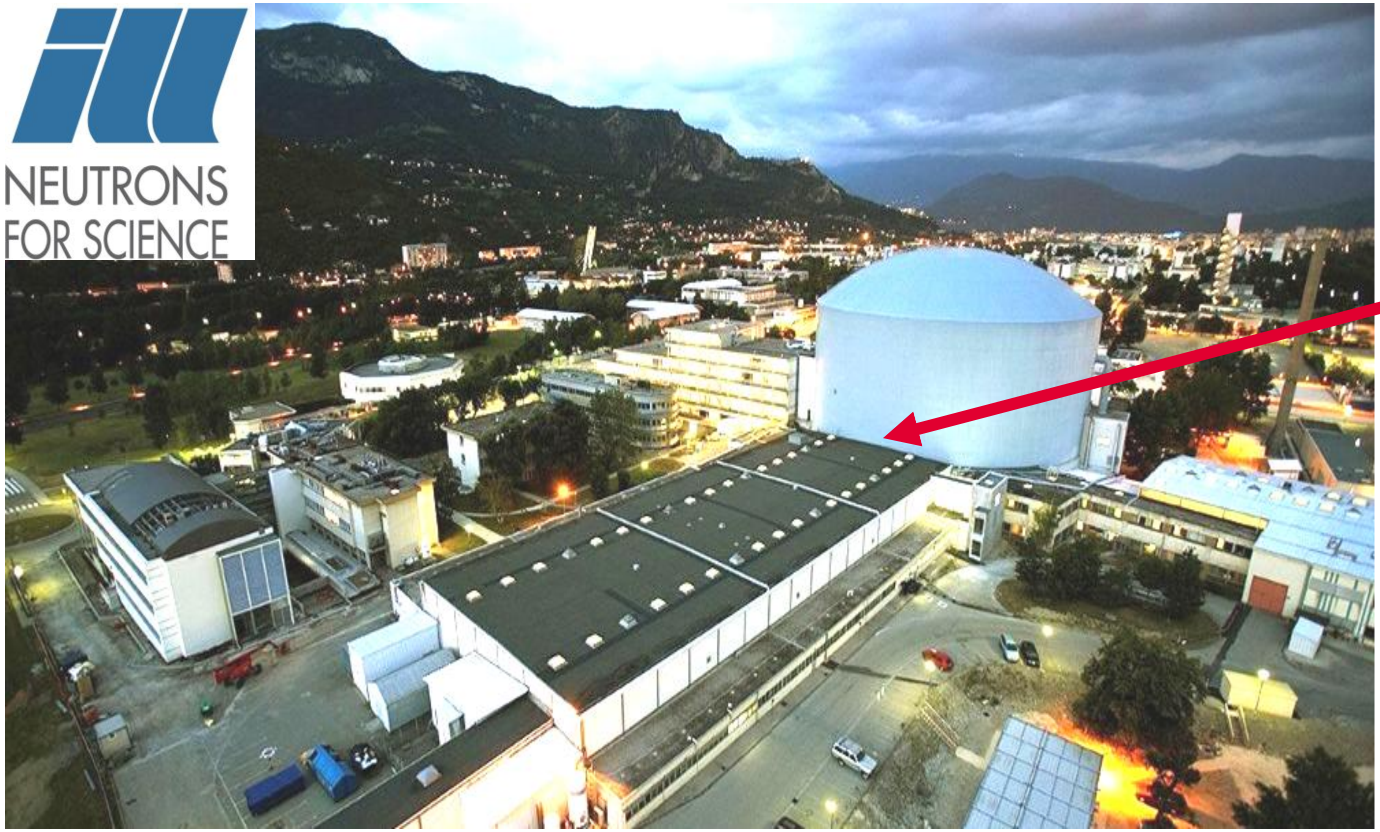
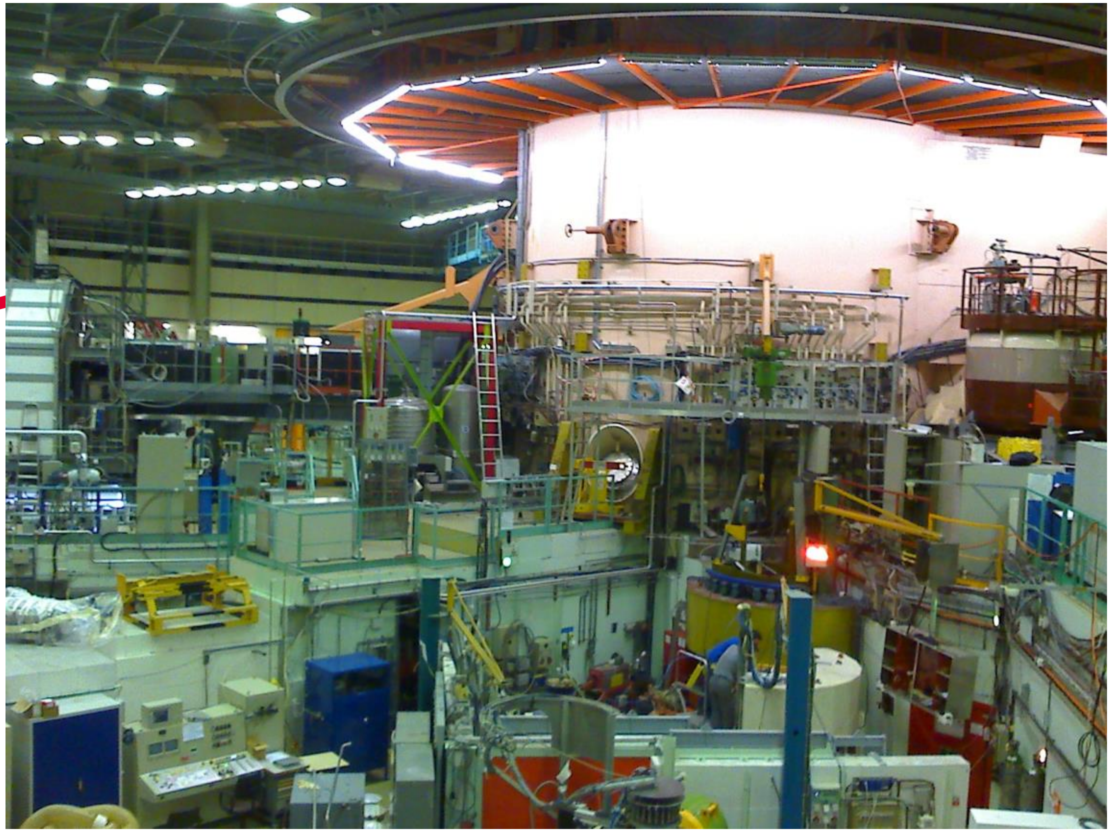


Institute Laue-Langevin



Inside the rector hall

Beam EDM, BOA @ PSI 2018

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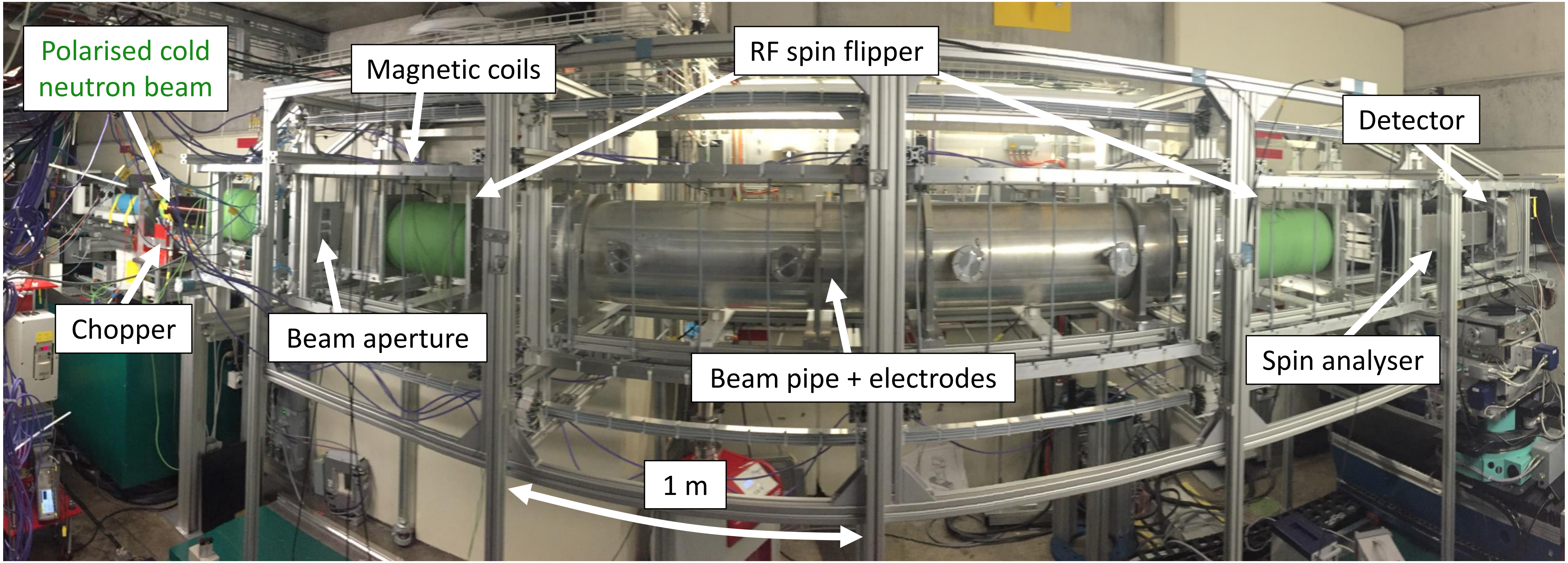

Chopper

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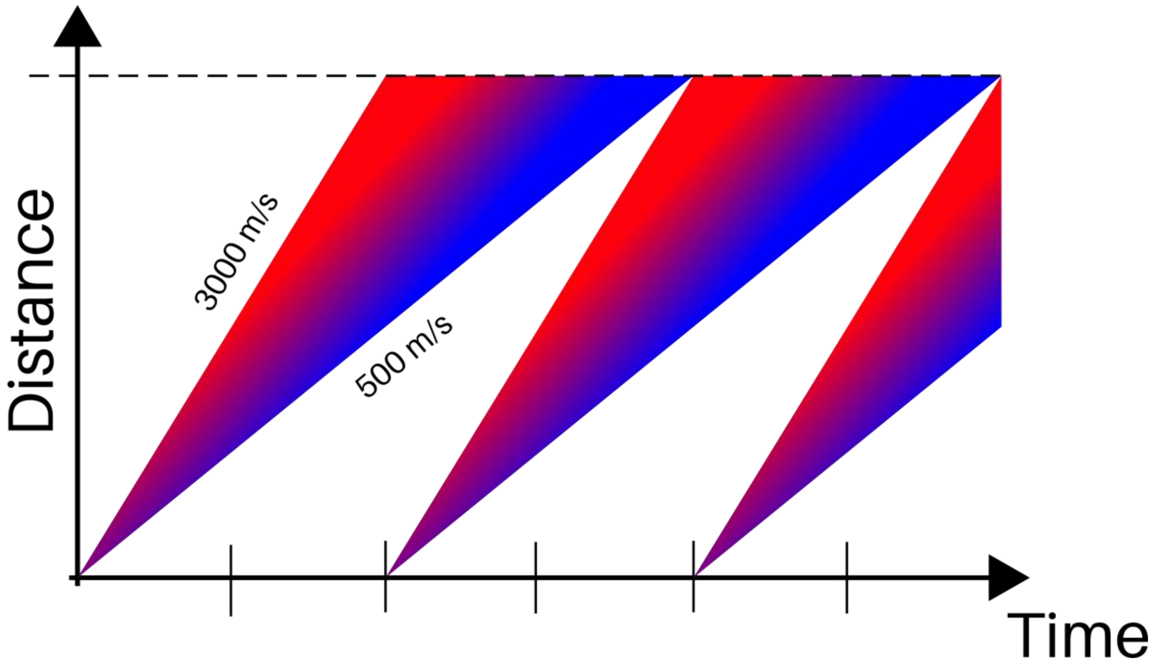
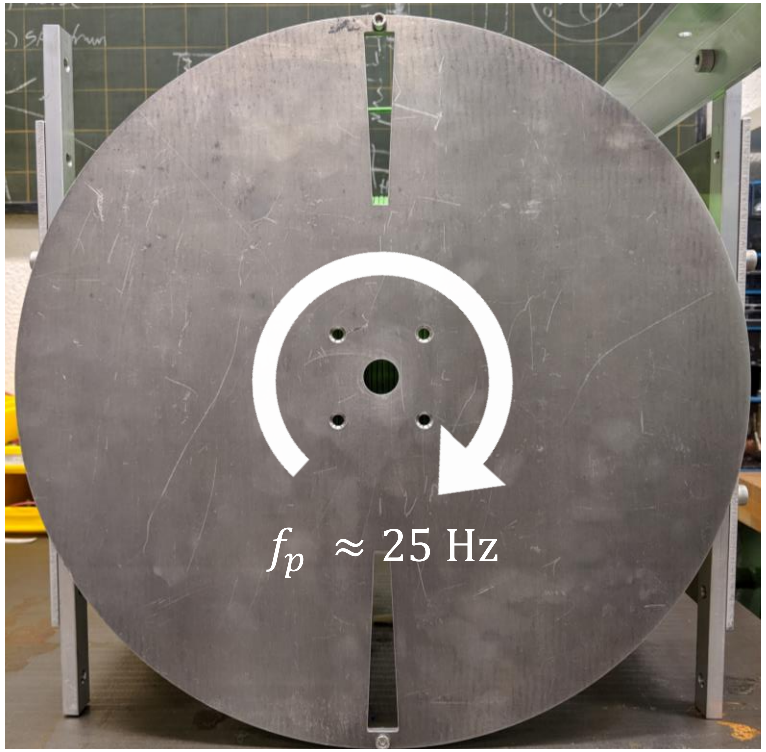
- Neutron absorbing disc, 30% borated aluminium
- Small opening slits, 2 pulses per rotation





Spin flipper

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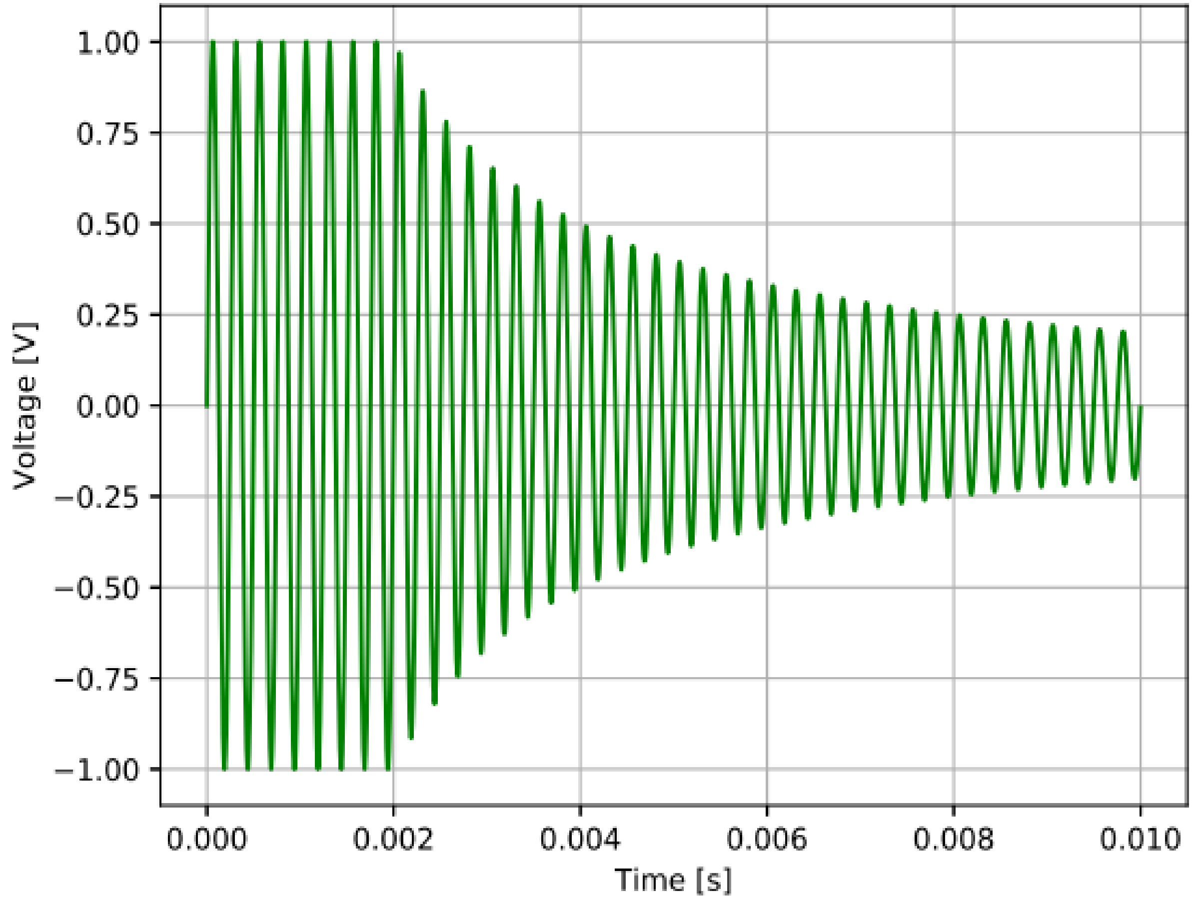
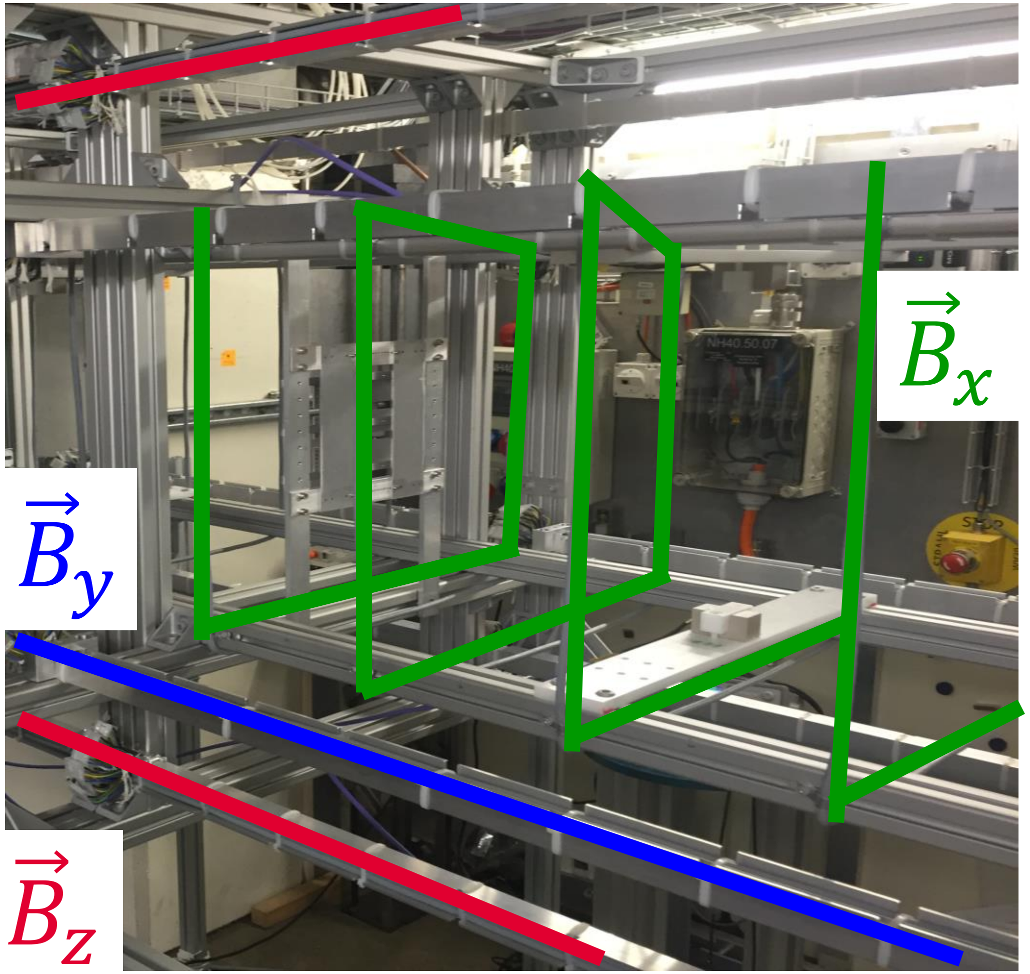
- Two spin flippers, one upstream, other downstream
- Require coils to flip spin of the neutrons
- Velocity of neutrons is Maxwellian, therefore, require a modulated $\frac{\pi}{2}$ flip



Magnetic field

- Three independent coils, $\vec{B}_x$, $\vec{B}_y$, $\vec{B}_z$, compensates for Earth's magnetic field.
- Main field in $\vec{B}_0 = 125\ \mu\text{T}$
- Actively stabilises over 7 m of the experiment to $< 10\ \text{nT}$.



Electric field

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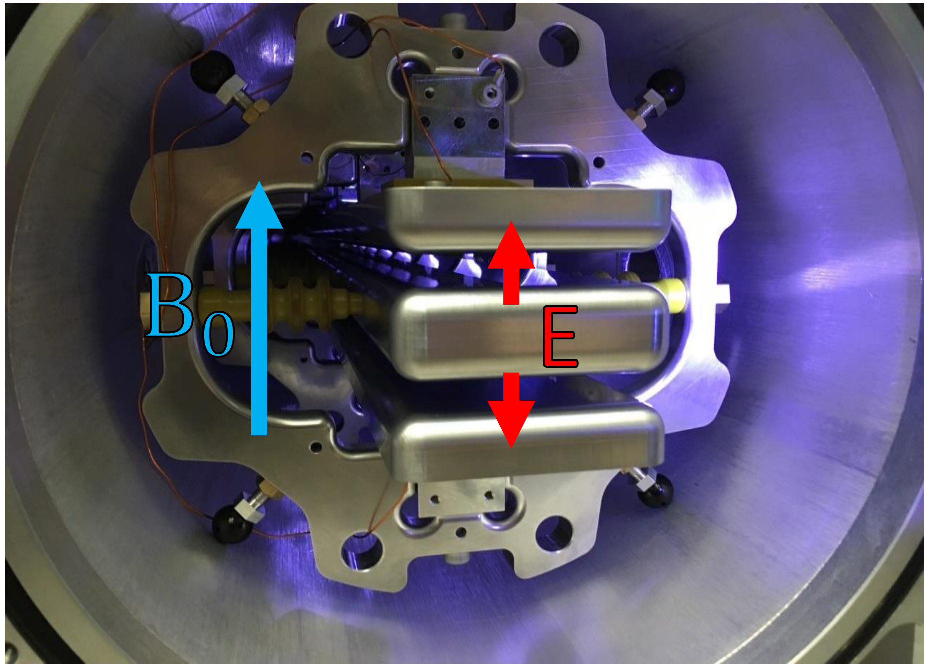
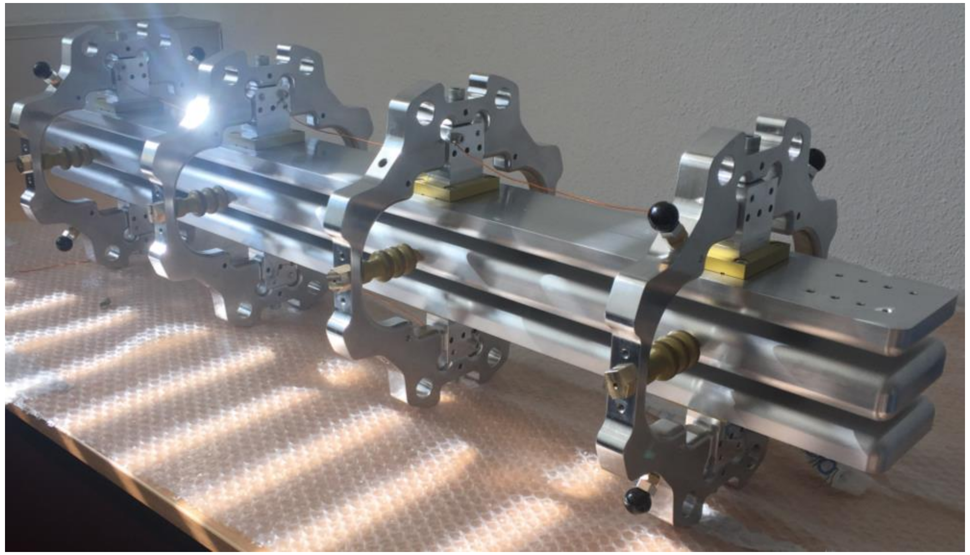
- Made of non-magnetic materials
- Each stack is 1 m long
- Electric field goal 100 kV/cm, 1 cm separation between electrodes
- Dual beams simultaneous measurement with opposite *E* field.





Spin Analyser

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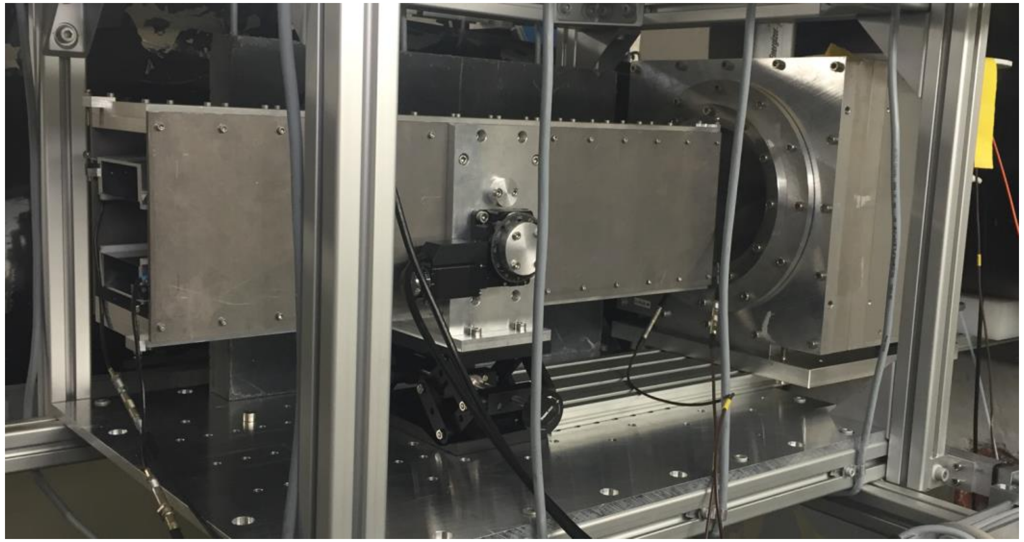
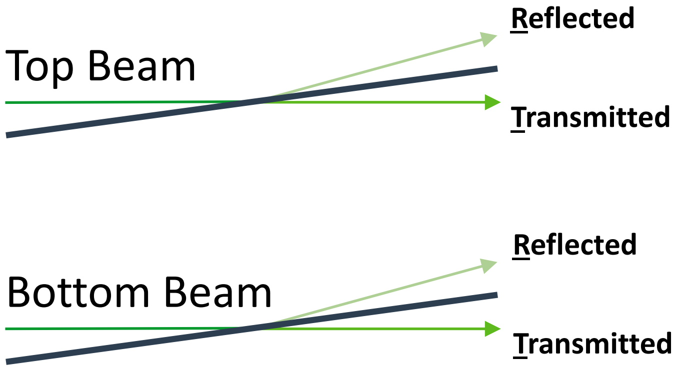
- Two sets of silicon wafers top and bottom.
- FeSi coated, m = 5 super mirrors.
- Reflects single spin state, produces 4 beam spots.
- Allows spatial separation of spin states to determine asymmetry.

$$A_i = \frac{T_i - R_i}{T_i + R_i}$$





CASCADE-E 100 Neutron Detector

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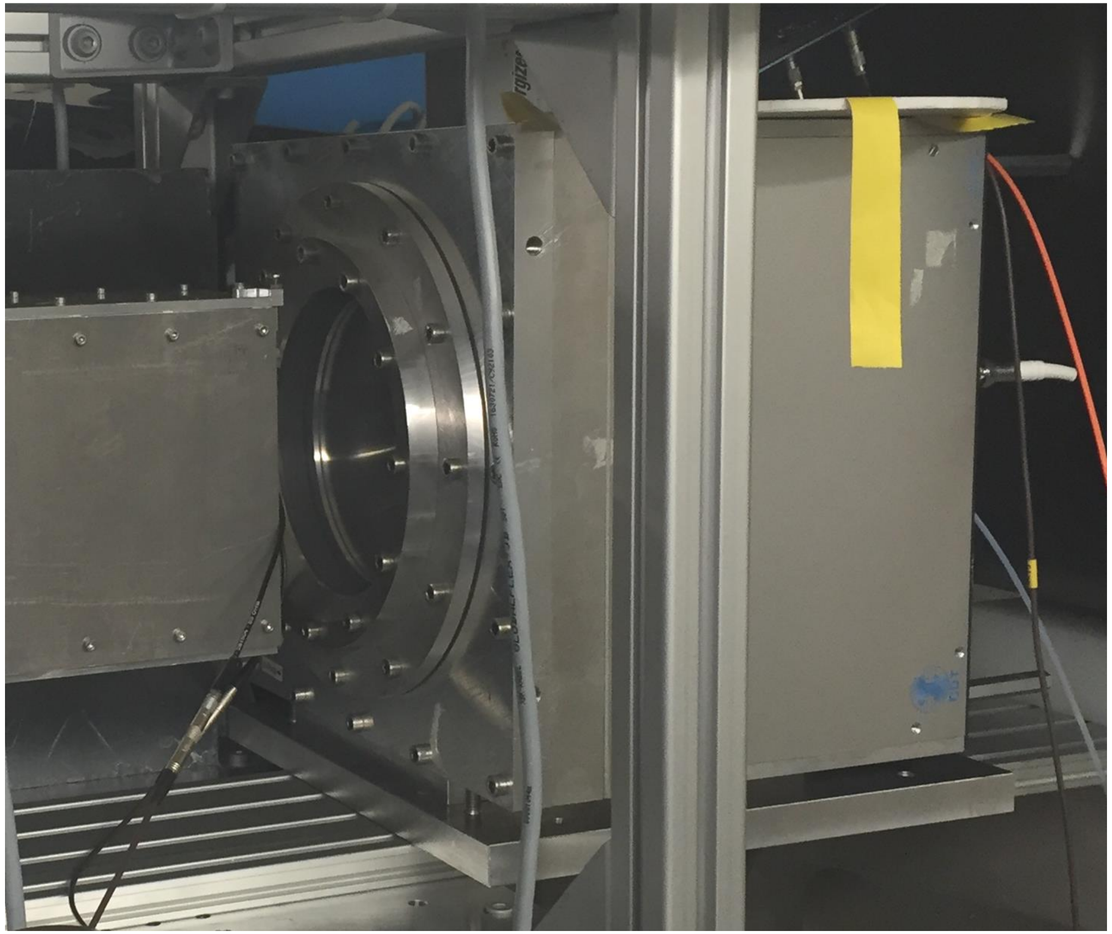
- Supplied by CDT GmbH
- GEM (gas electron multiplier)-based cold neutron detector
- Position sensitive
- 16x16 pixel array
- 6.5x6.5 mm^2 area per pixel
- Efficiency: ~35% @ 5Å



CASCADE-E 100 Neutron Detector

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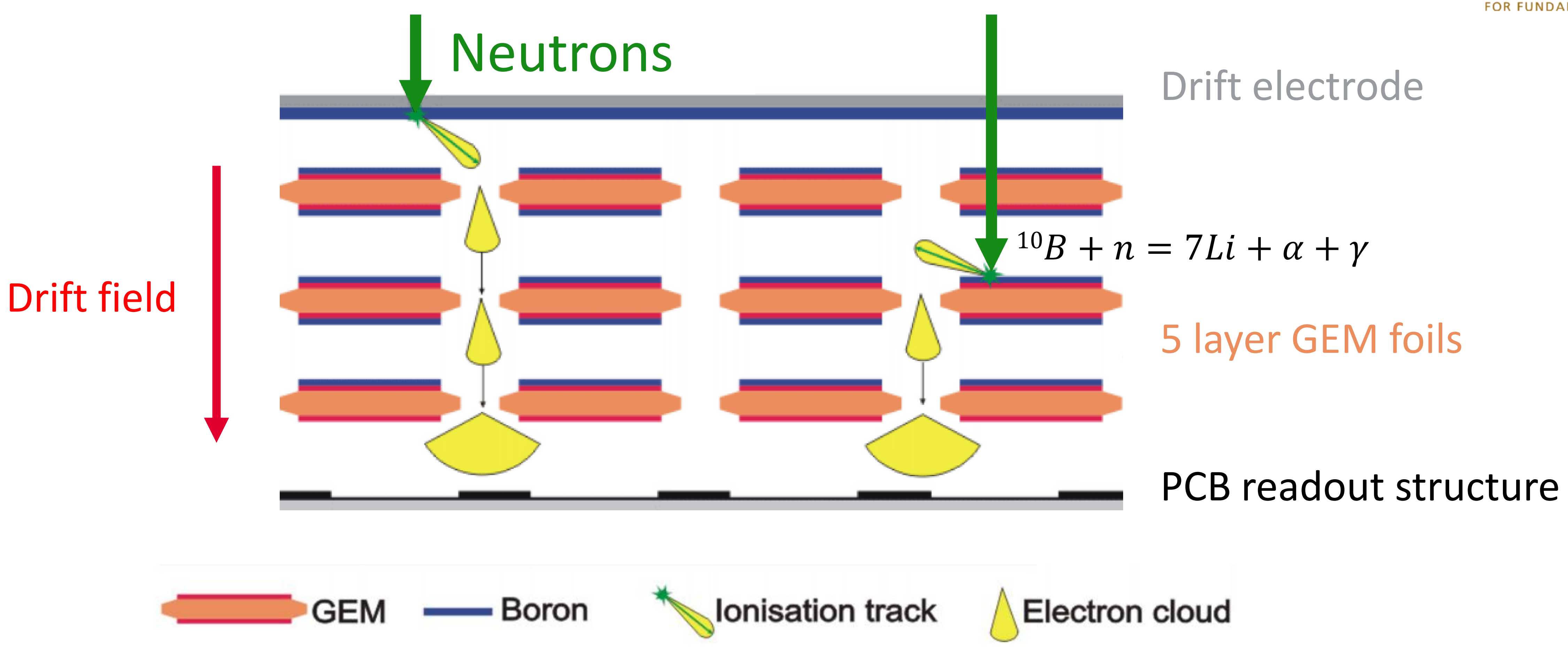

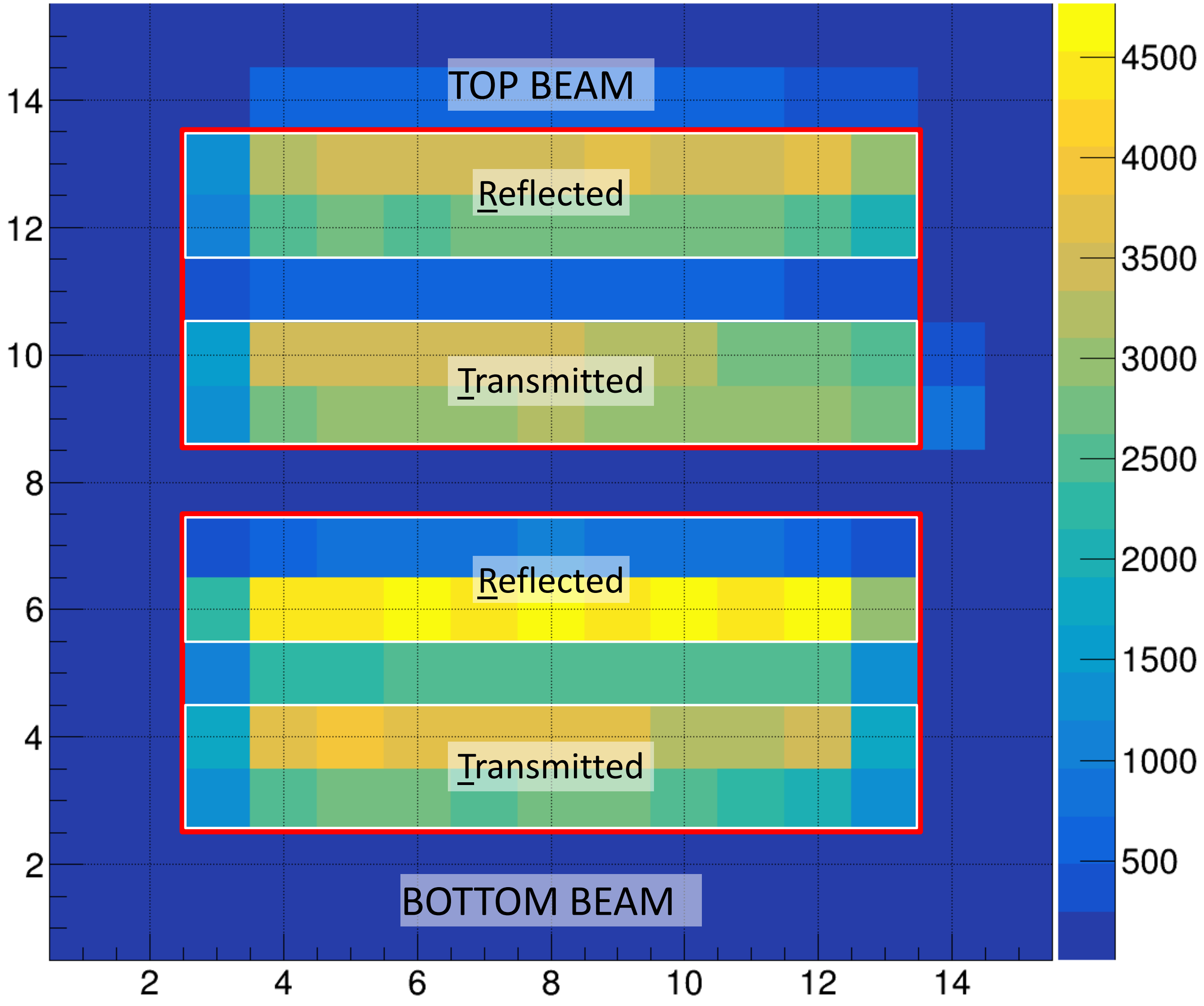

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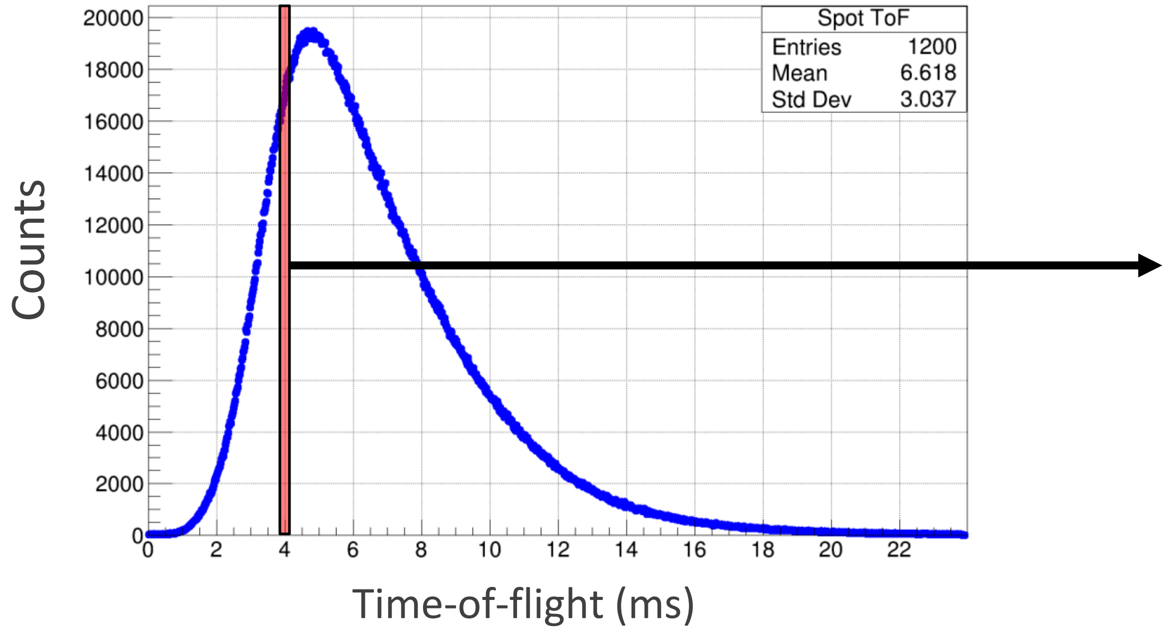
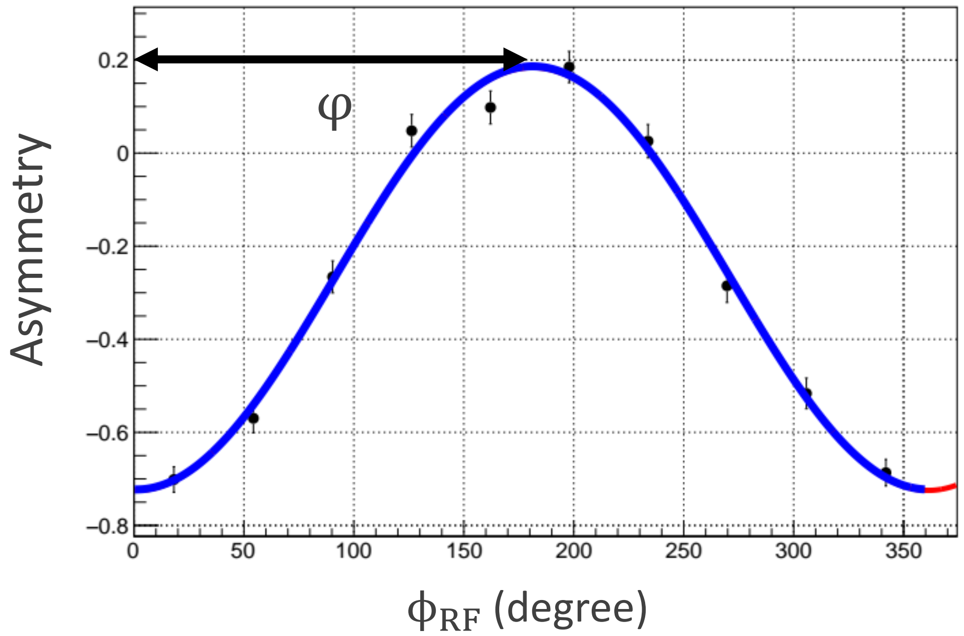
Measurement principle





- Measure neutron ToF
- Time bin 20 μs
- $L_{SD} = 6.5$ m

- Asymmetry: $A_i = \frac{T_i - R_i}{T_i + R_i}$
- Single time bin, φ determined by measuring asymmetry while scanning ϕ_{RF}
- Determine φ for every time bin in the ToF

Spin precession contributions – single beam

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$$B_{\vec{v}\times\vec{E}} = \frac{LE\sin\alpha}{Tc^2}$$ Relativistic $\vec{v} \times \vec{E}$ effect

$$B_{EDM} = \frac{2d_n E}{\gamma_n \hbar}$$ Pseudo-magnetic field due to EDM

$$B_{grad} = \delta B_0$$ Magnetic field gradient

$$B_{drift} = \frac{\omega_{RF}}{\gamma_n} - B_0$$ Off-Resonance spin flipper

$$\varphi_1 = \gamma_n\left(B_{\vec{v}\times\vec{E}} + B_{EDM} + B_{grad} + B_{drift}\right)T$$

Time-of-flight phase scan

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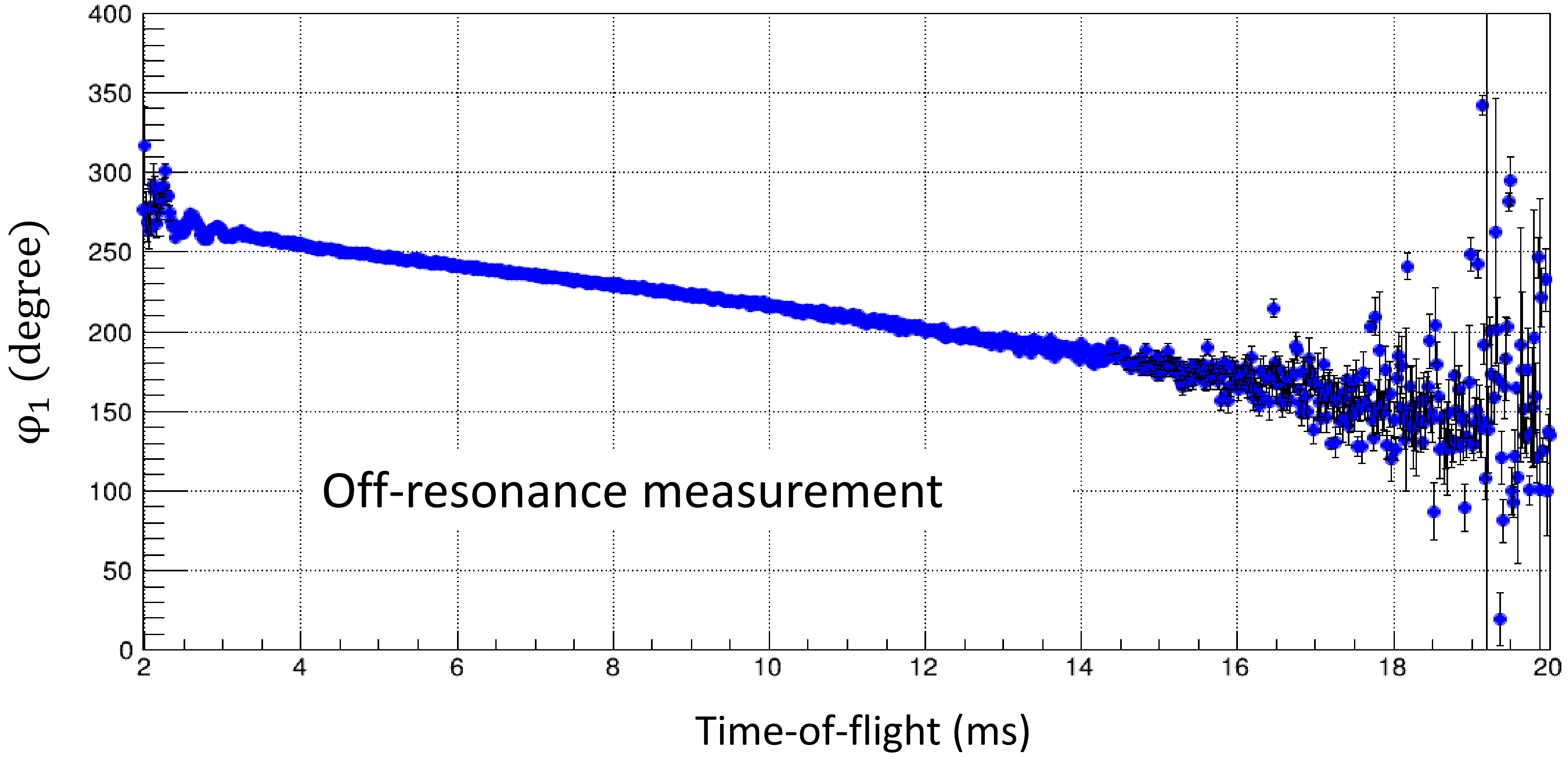
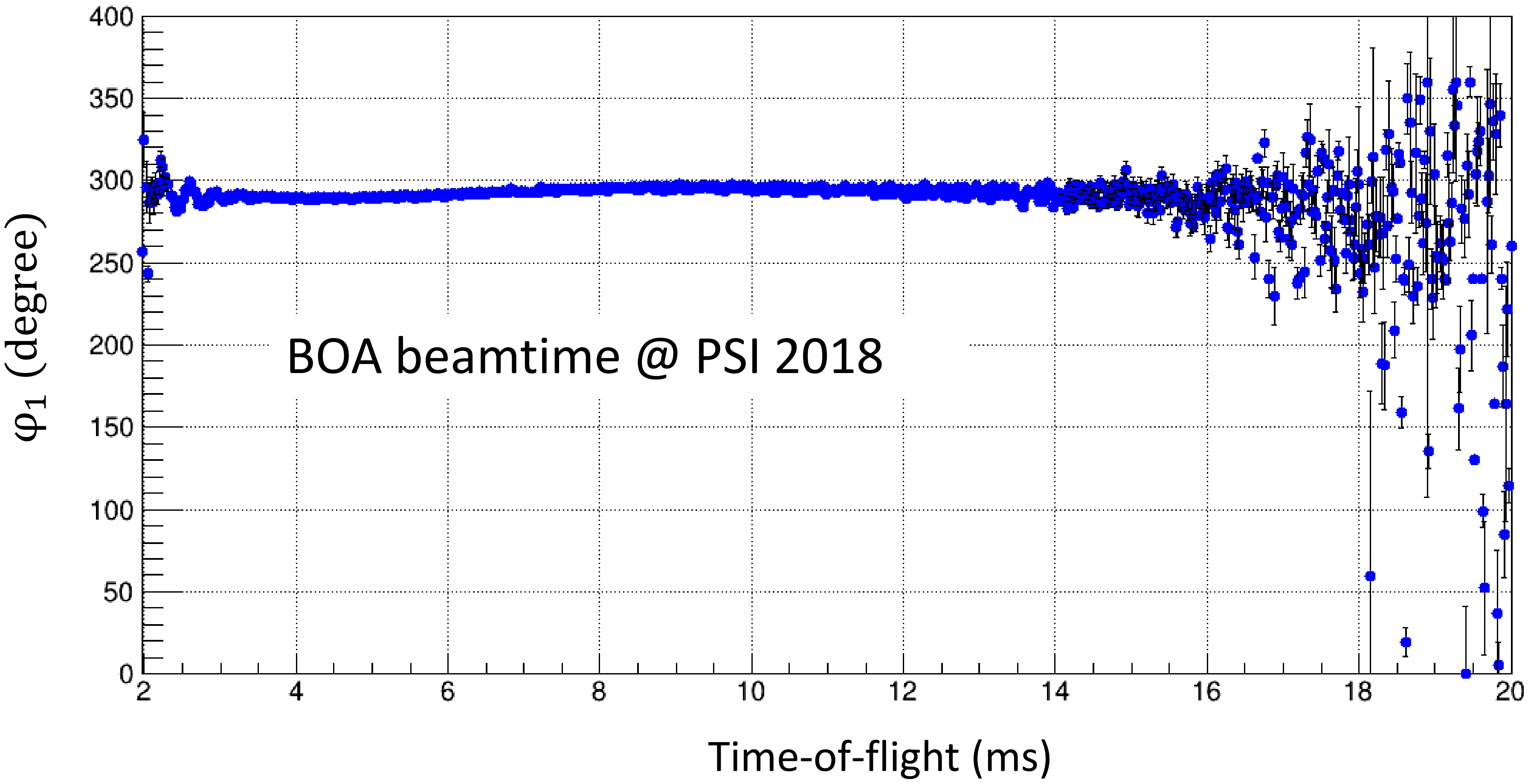


Time-of-flight phase scan



Systematic magnetic field gradients

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$$\Delta\varphi_1 = \left[\gamma_n \delta B - \frac{4d_n E}{\hbar}\right] \cdot T - \frac{2\gamma_n L E}{c^2} \sin\alpha$$

$$\Delta\varphi_2 = \left[\gamma_n (\delta B + \beta_- - \beta_+) + \frac{4d_n E}{\hbar}\right] \cdot T + \frac{2\gamma_n L E}{c^2} \sin\alpha$$

$$\Delta\varphi_1 - \Delta\varphi_2 = \gamma_n \left[(\beta_- - \beta_+) + \frac{8d_n E}{\hbar}\right] \cdot T + \frac{4\gamma_n L E \sin\alpha}{c^2}$$

- Use of two beams cancels global magnetic field drifts
- If field drift correlates to HV reversal, a systematic effect occurs

Ultimate goal

$$\sigma_{d_n} \approx \frac{2\hbar}{\eta \tau E \sqrt{N}}$$

- E = 100 kV/cm
- $\dot{N}$ = 400 MHz (10^6 larger then current UCN experiments)
- $\tau = 50$ ms ($L_{SD} = 75$ m)
- η = 0.75

$\sigma_{d_n} \sim 5 \times 10^{-26} e \cdot cm$ (per day @ ANNI[3])

[3] Torsten Soldner et al. arXiv:1811.11692v1 (2018)

Future Prospects

- Upcoming beamtime @ ILL 2020, goal to achieve better than:

$$|d_n| < 3 \times 10^{-24} \mathrm{e} \cdot \mathrm{cm}$$

  - Multi-layer mu-metal shielding
  - Electric field 100 kV/cm
  - Improved modulated spin flipper
  - Novel chopper system
- Additional measurement for Axion like particle

Thanks for your attention!

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Backup slides

nEDM in the Standard Model (weak sector)

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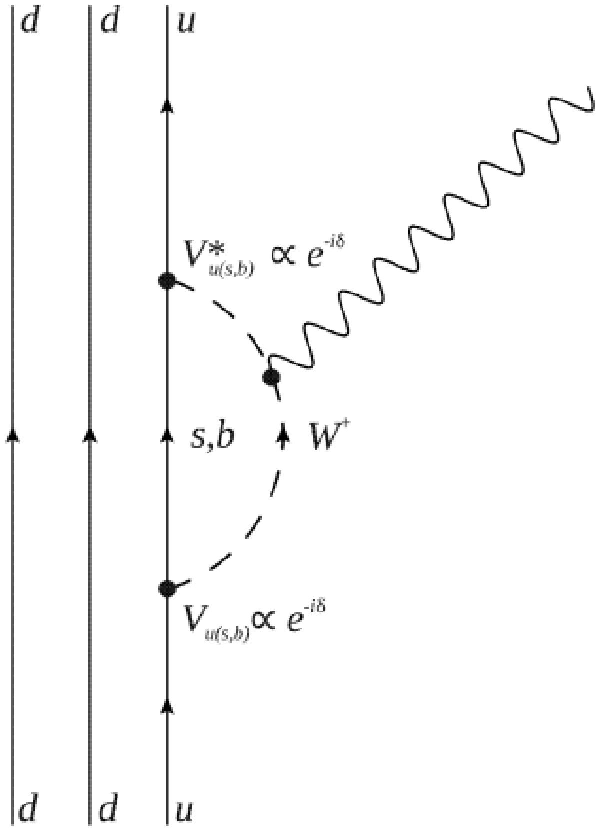

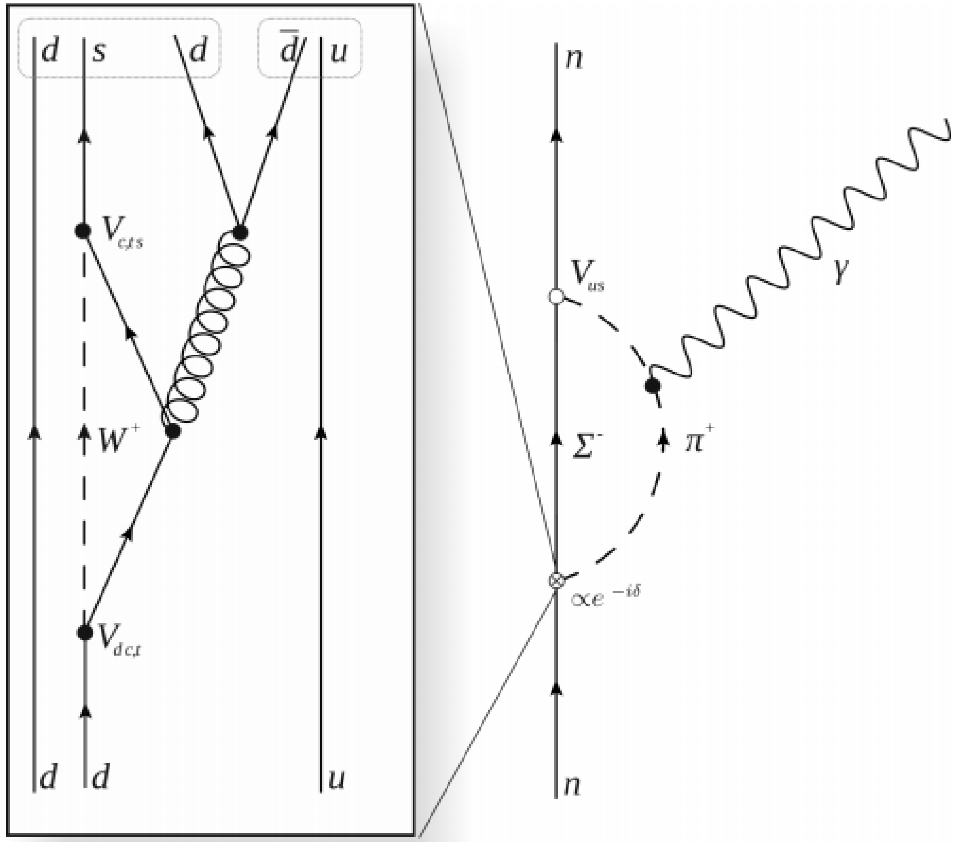

nEDM in the Standard Model (strong sector)

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$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_0 + \mathcal{L}_\theta$$

$$\mathcal{L}_\theta = -\theta\left(\frac{g^2}{32\pi^2}\right)\bar{G}^{\alpha}_{\mu\nu}G^{\alpha}_{\mu\nu}$$

$$d_n = \frac{e}{m_p}\frac{g_{\pi NN}\bar{g}_{\pi NN}}{4\pi^2}\ln\frac{m_p}{m_\pi}$$

$$|\theta| < 10^{-10}$$

Neutron EDM experiments worldwide

Facility, location	**UCN (CN) source**	**Spectrometer**	**Magnetometry**	**Sensitivity** $\mathcal{O}(10^{-27}\,e\cdot\mathrm{cm})$
LANL, USA	sD_2	dbl. chamber	^{199}Hg	1
ILL, France	cold source turbine	dbl. chamber	Cs-OPM	10
ILL, France	He-II to vacuum	dbl. chamber	^{199}Hg, Cs-OPM	1
ILL, France	CN beam	crystal-diffraction	-	10
ESS, Sweden	pulsed CN	dbl. chamber	-	0.1 -10
FRM-II, Germany	sD_2	dbl. chamber	^{199}Hg, Cs-OPM	0.1
SNS, Oakridge	He-II in-situ	dbl. chamber	^{3}He, squids	$<$0.1
PNPI, Russia	He-II to vacuum	dbl. chamber	Cs-OPM	0.1-1
TRIUMF, Canada	He-II to vacuum	dbl. chamber	^{199}Hg, ^{129}Xe	0.1-1
PSI, Switzerland	sD_2	sgl./dbl. chamber	^{199}Hg, ^{3}He, Cs-OPM	1-10

Comparison of cold beams

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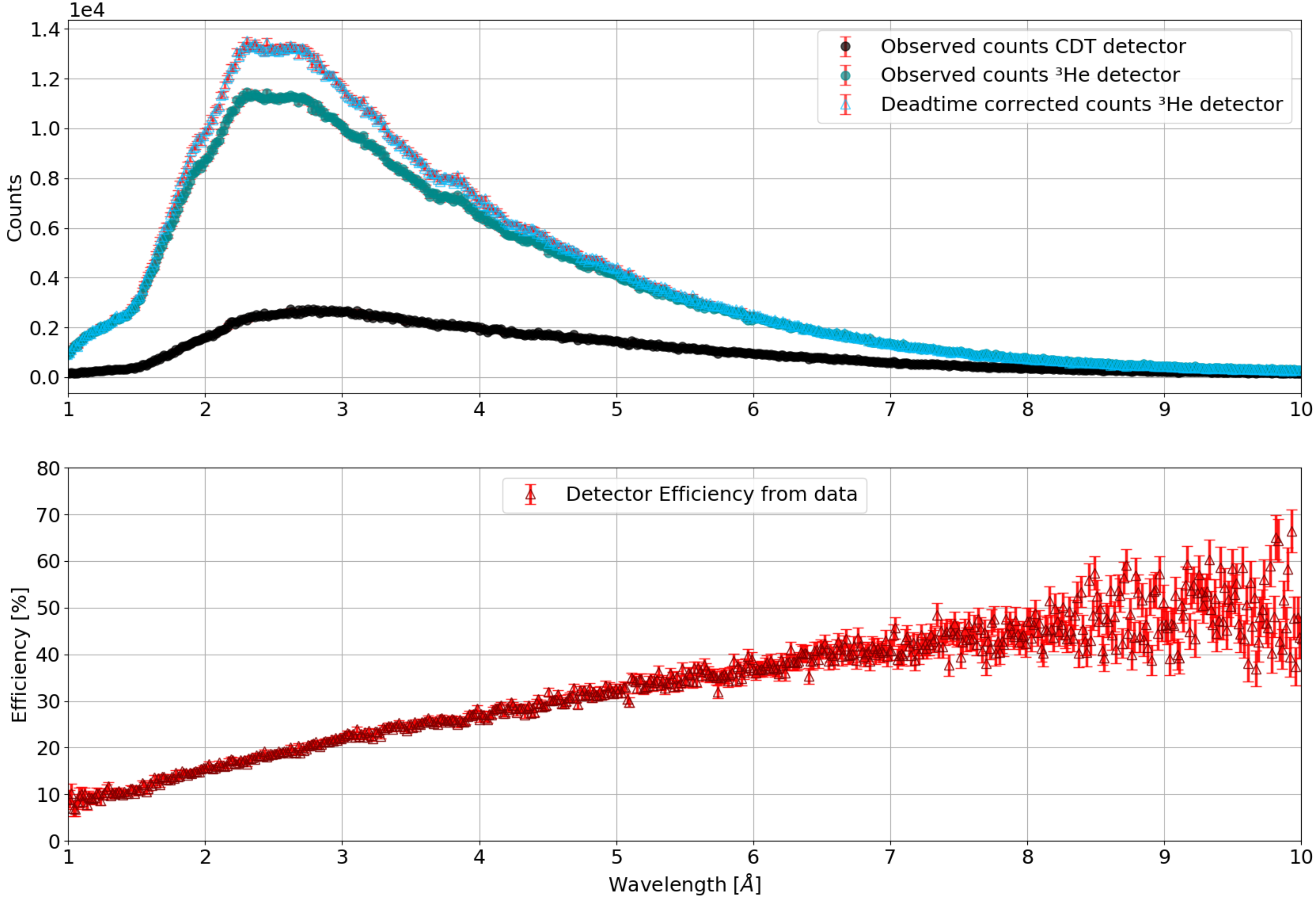
- PSI (BOA) - ~ 10^8/cm^2/s
- ILL (PF1b) - ~ 10^9/cm^2/s
- ESS (ANNI) - ~ 10^{10}/cm^2/s

Including chopper, only ~3% of beam rate.



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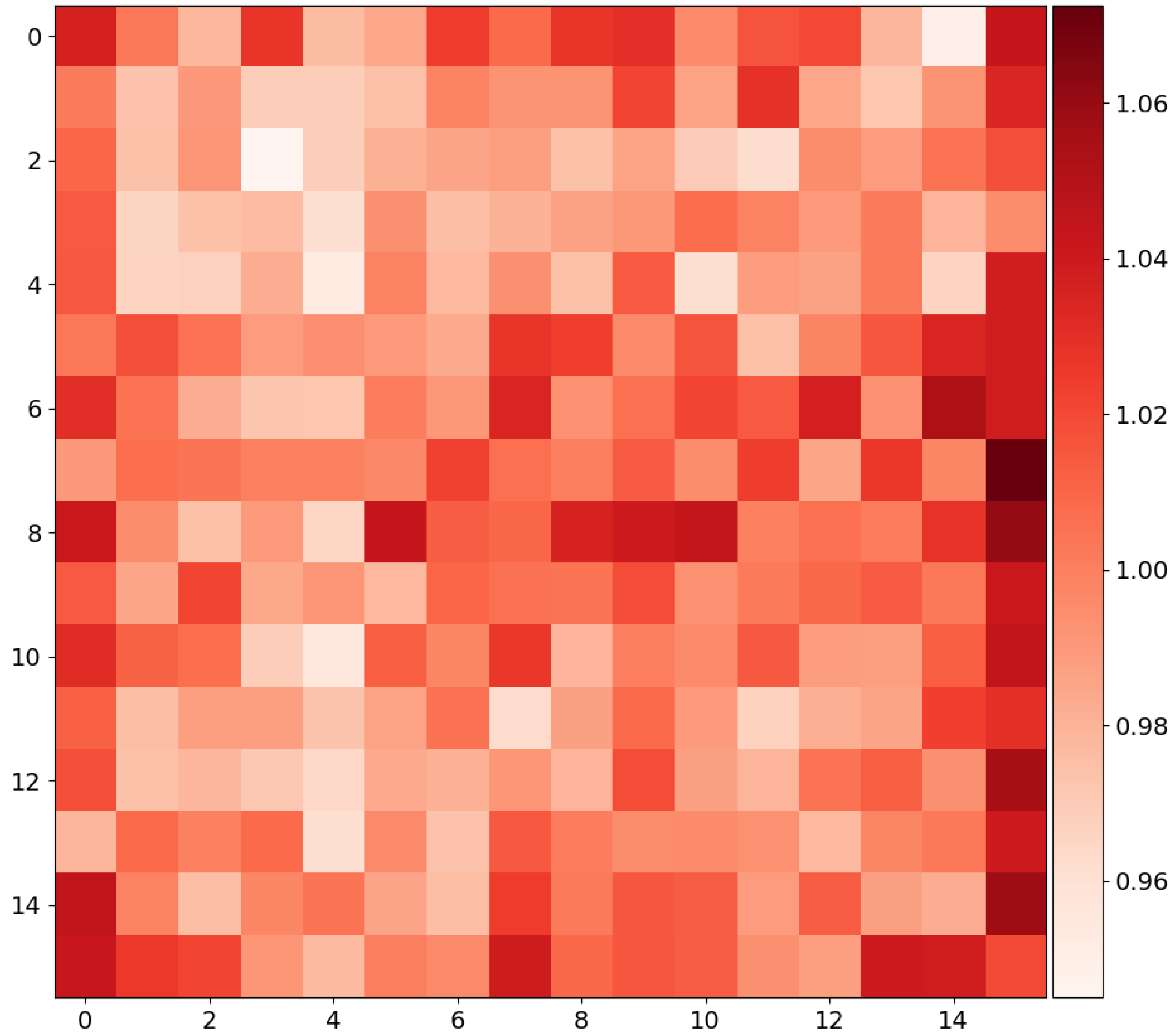

$\sigma_{stat} = 1.03\%$
$\sigma_{det} = 1.26\%$
$\sigma_{tot} = 2.29\%$

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Measurement principle

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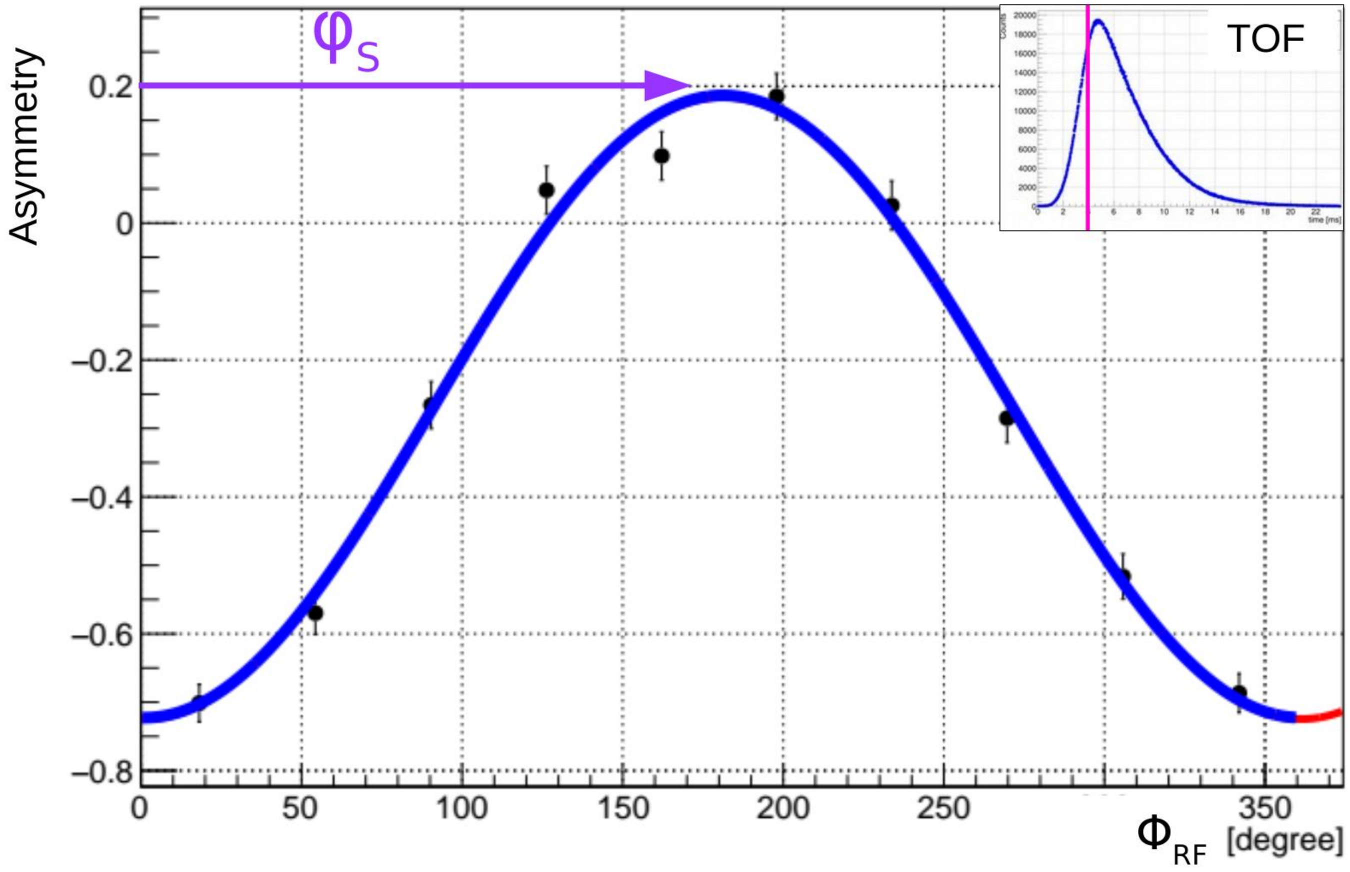
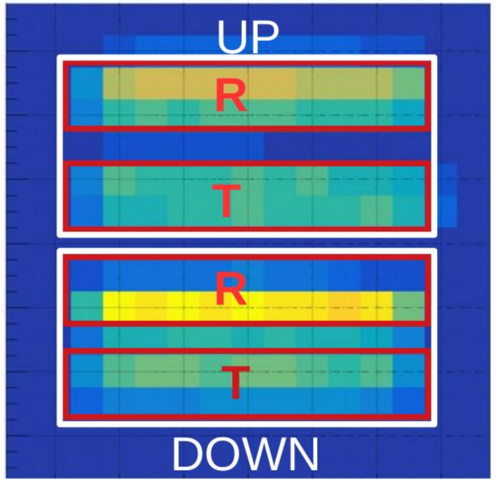
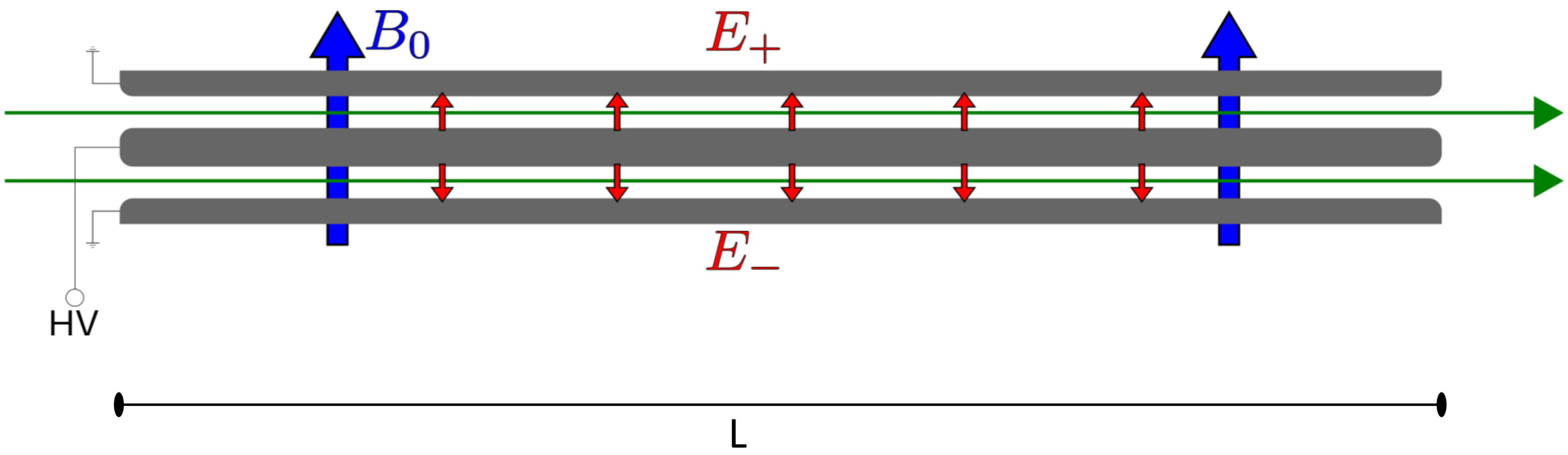
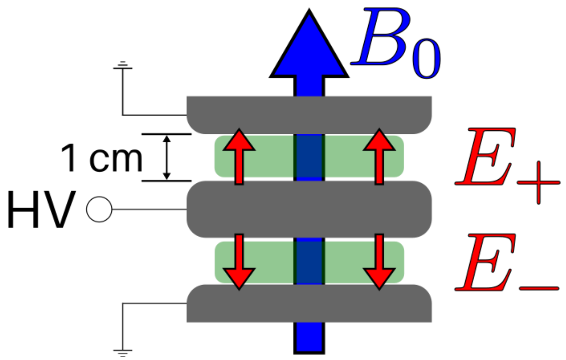


$$A = \frac{T - R}{T + R}$$



Vacuum pipe





*Cross-sectional View

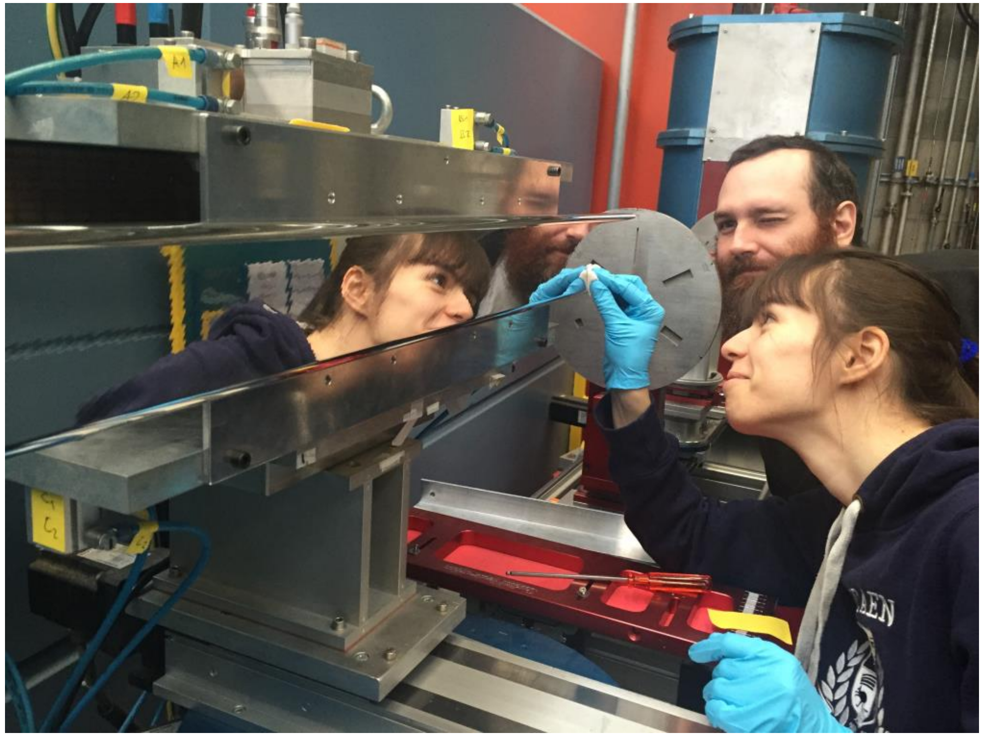
Two neutron beams

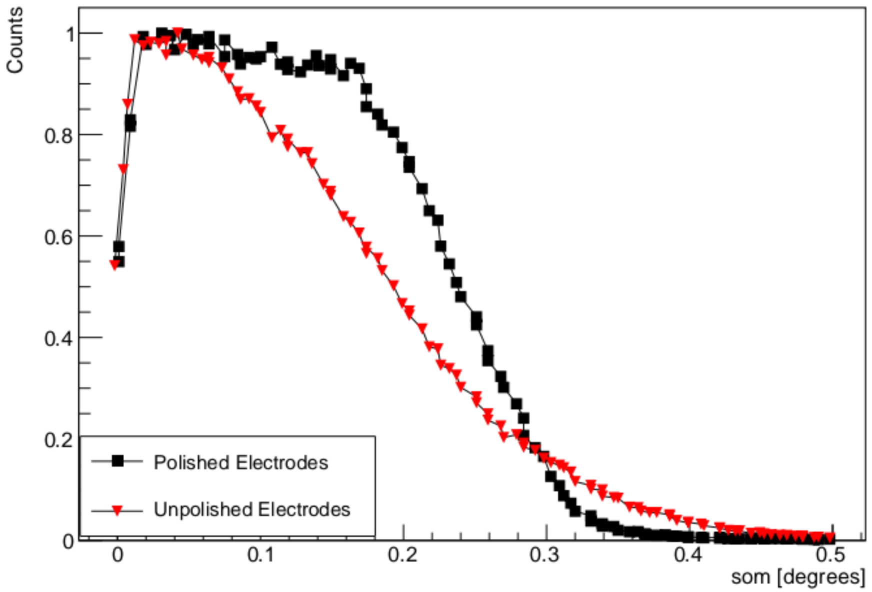
Magnetic field $\vec{B}_0 = 125\ \mu T$

Electric field $\vec{E} = 100\ kV/cm$

L = 4 m, $\tau \sim 4\ ms$

Neutron reflectivity measurement: NARZISS





Novel chopper design

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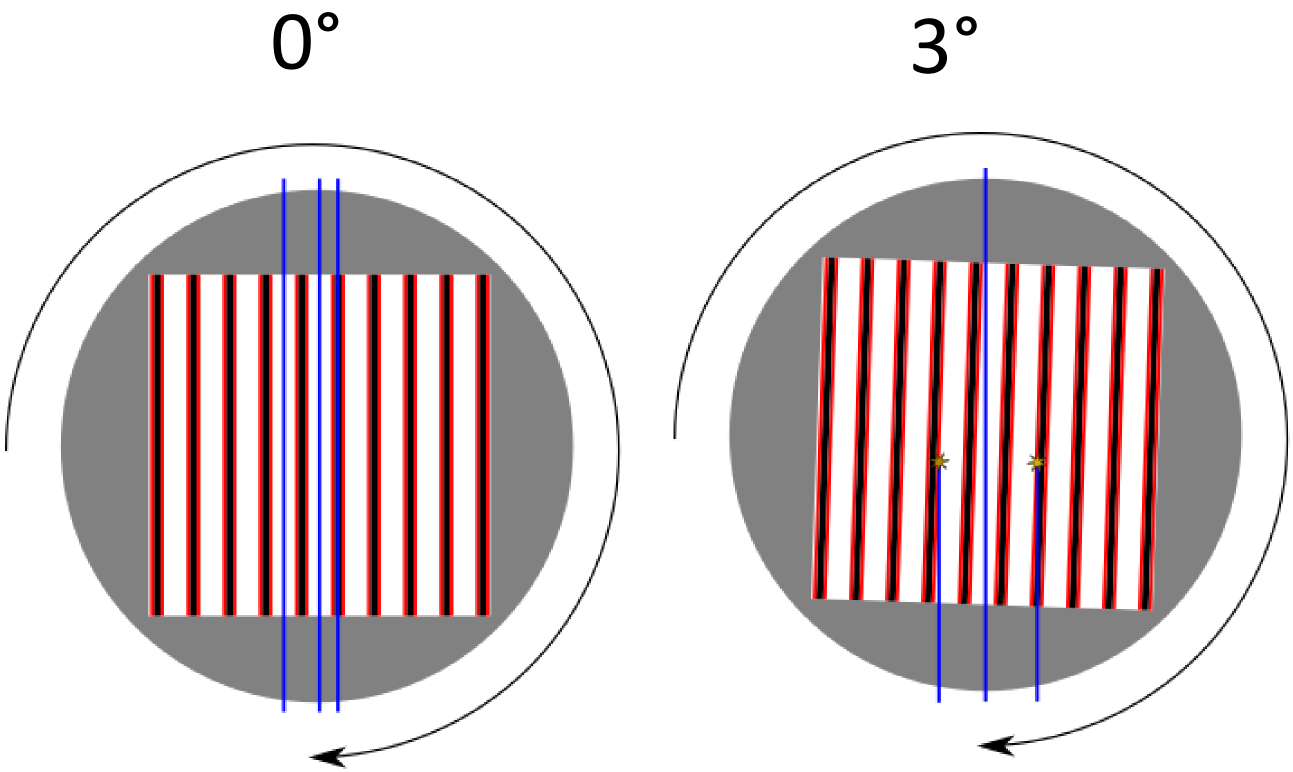

- Box structure, rotates about central axis
- Silicon wafer internal structure, coated with Gadolinium paint
- Symmetric opening/closing
- Wafer separation <1 mm
- 10 Hz rotation
- 3° opening
- 800 µs opening time
- x5 instantaneous rate

Spin analyser

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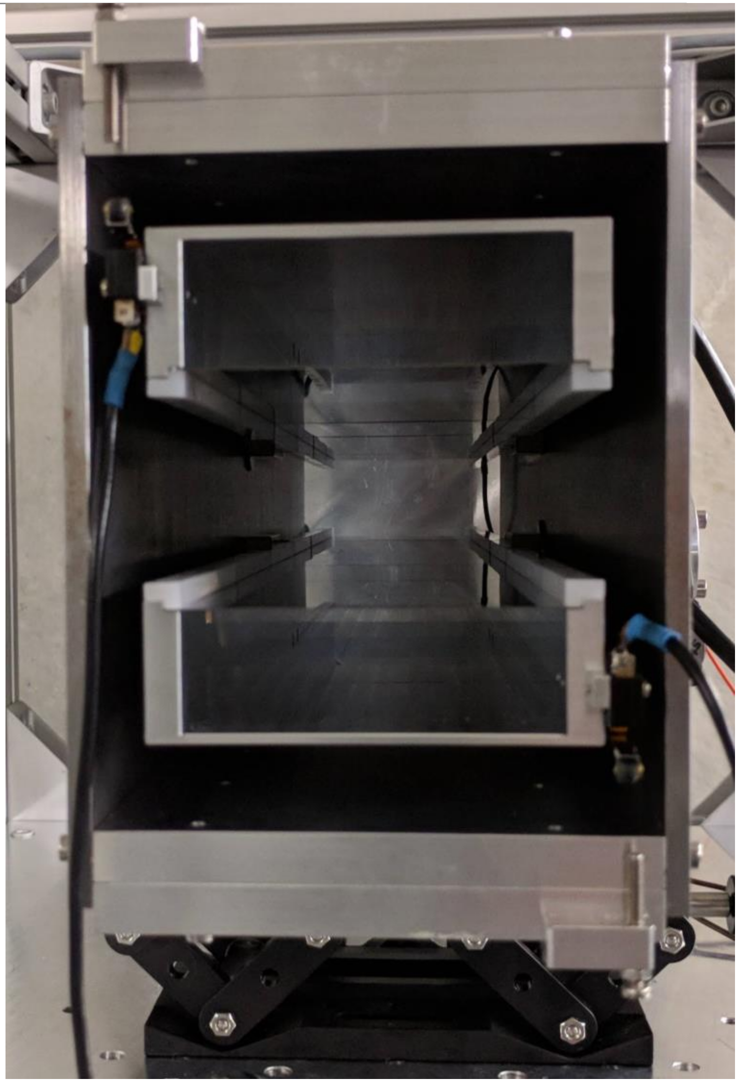
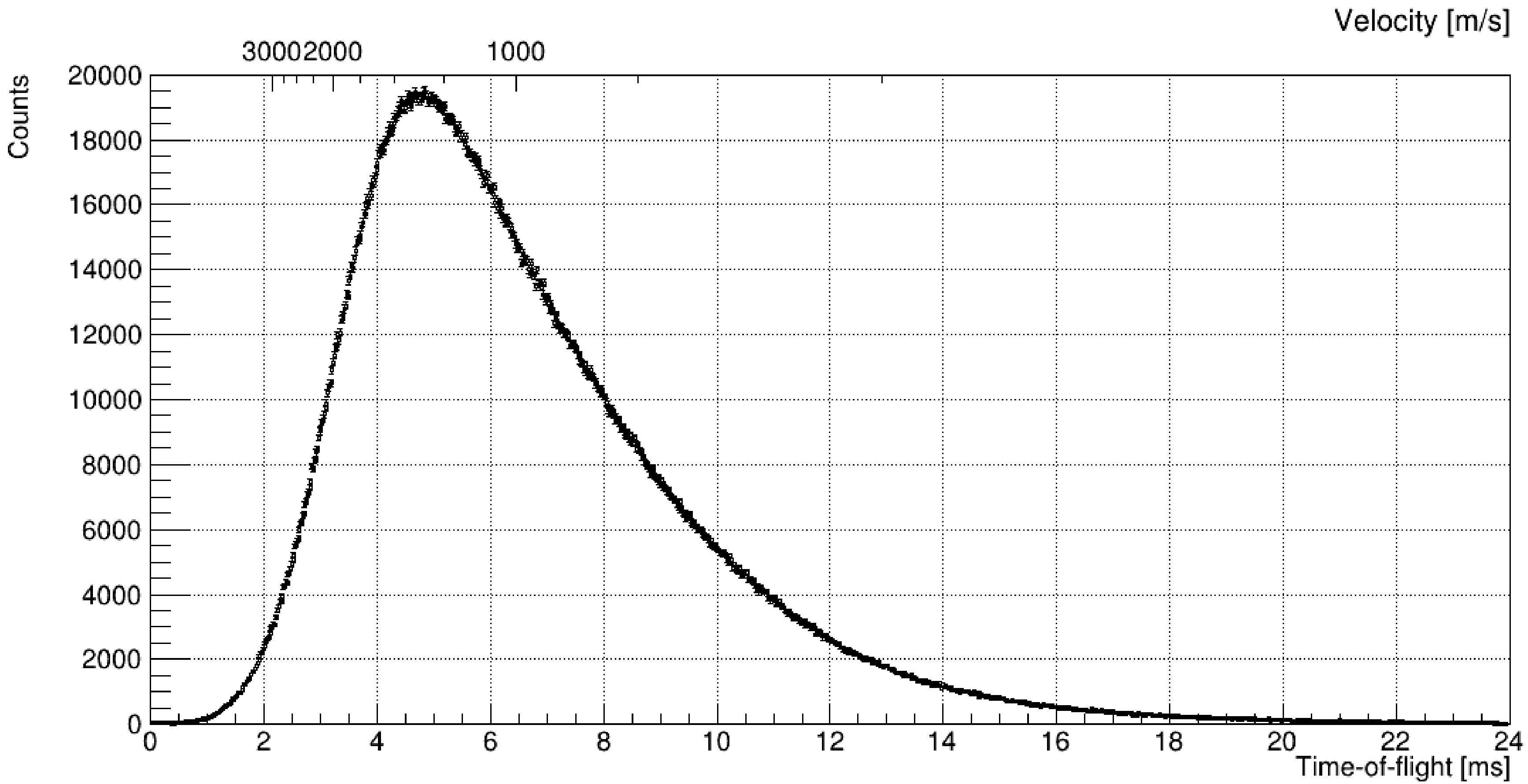
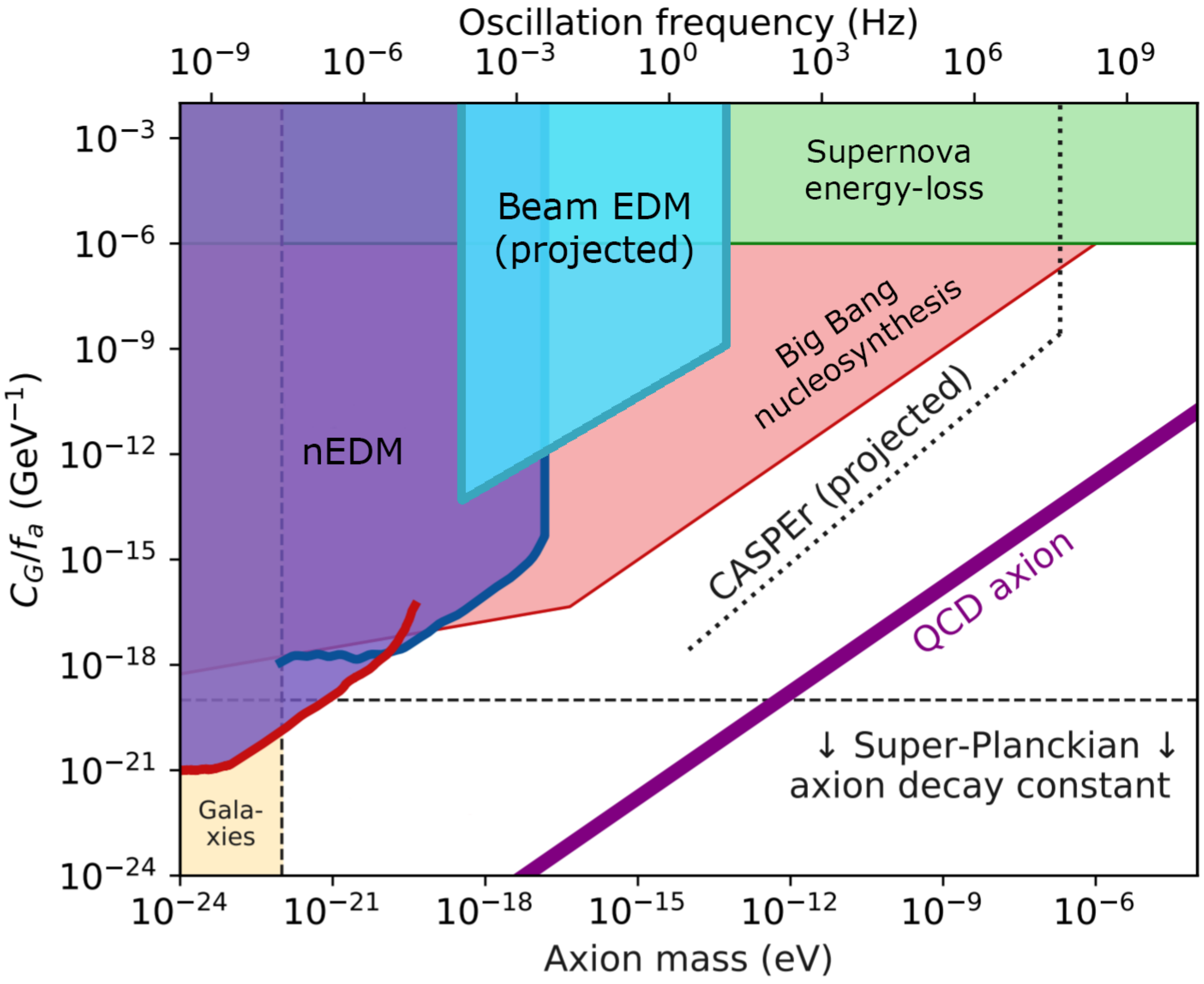
- Beamline view of the spin analyser



BOA @ PSI Neutron beam spectrum 2018





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

Axion-like-particle interaction

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non-gravitational interaction:

$$\mathcal{L} = \frac{C_\gamma}{f_a}\frac{\alpha}{8\pi} a \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu} + \frac{C_G}{f_a}\frac{\alpha_s}{8\pi} a \mathcal{G}_{\mu\nu}\tilde{\mathcal{G}}^{\mu\nu} - \sum_F \frac{C_F}{2f_a} a \bar{N}\gamma^\mu\gamma_5 N$$

axion-gluon coupling
➔ oscillating neutron EDM

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

C: model dependent parameter
α: coupling constant
f_a: axion decay constant
a: axion field
F: electromagnetic field tensor
G: gluonic field tensor
N: nucleon field
a_0: axion field amplitude
m_a: axion mass

Faxion measurement

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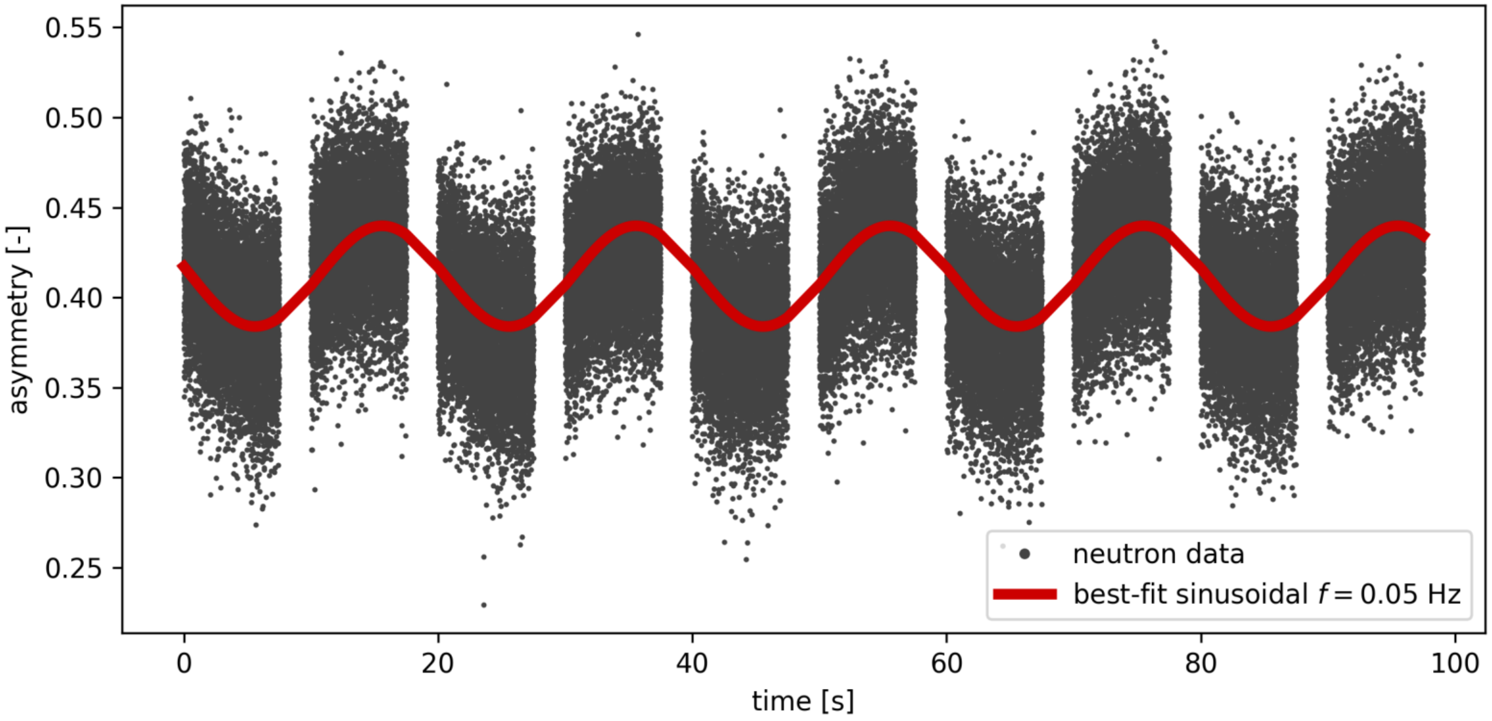

Faxion sensitivity

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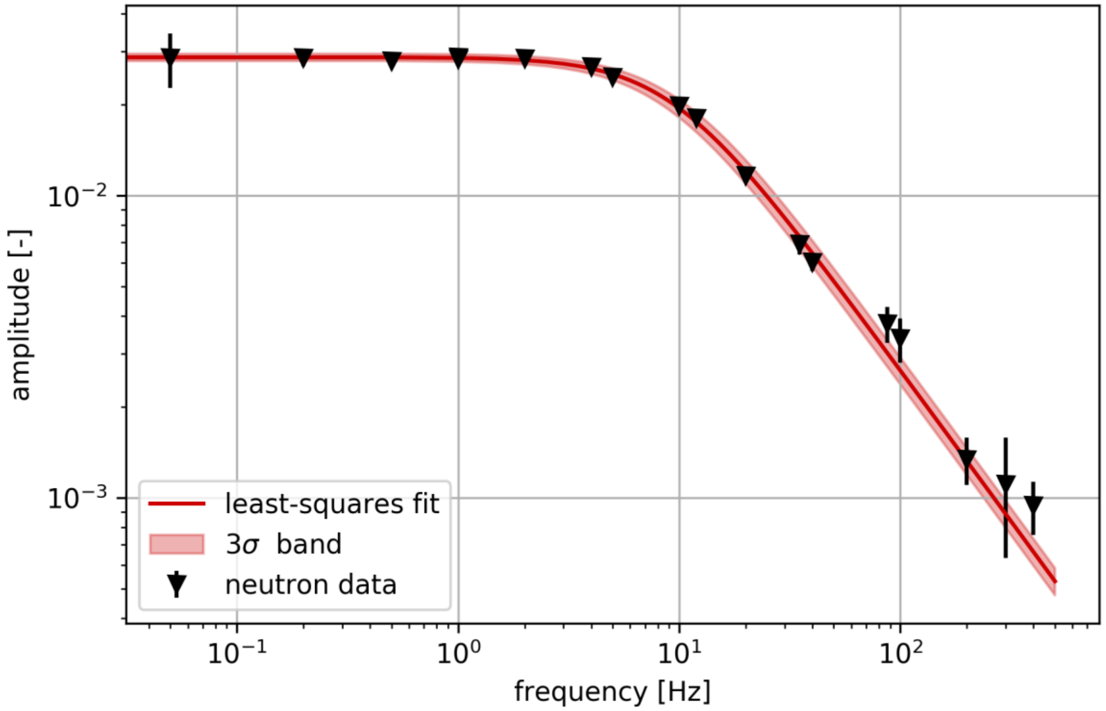

Axion measurement principle