An EDM measurement using a pulsed cold neutron beam

b
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AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

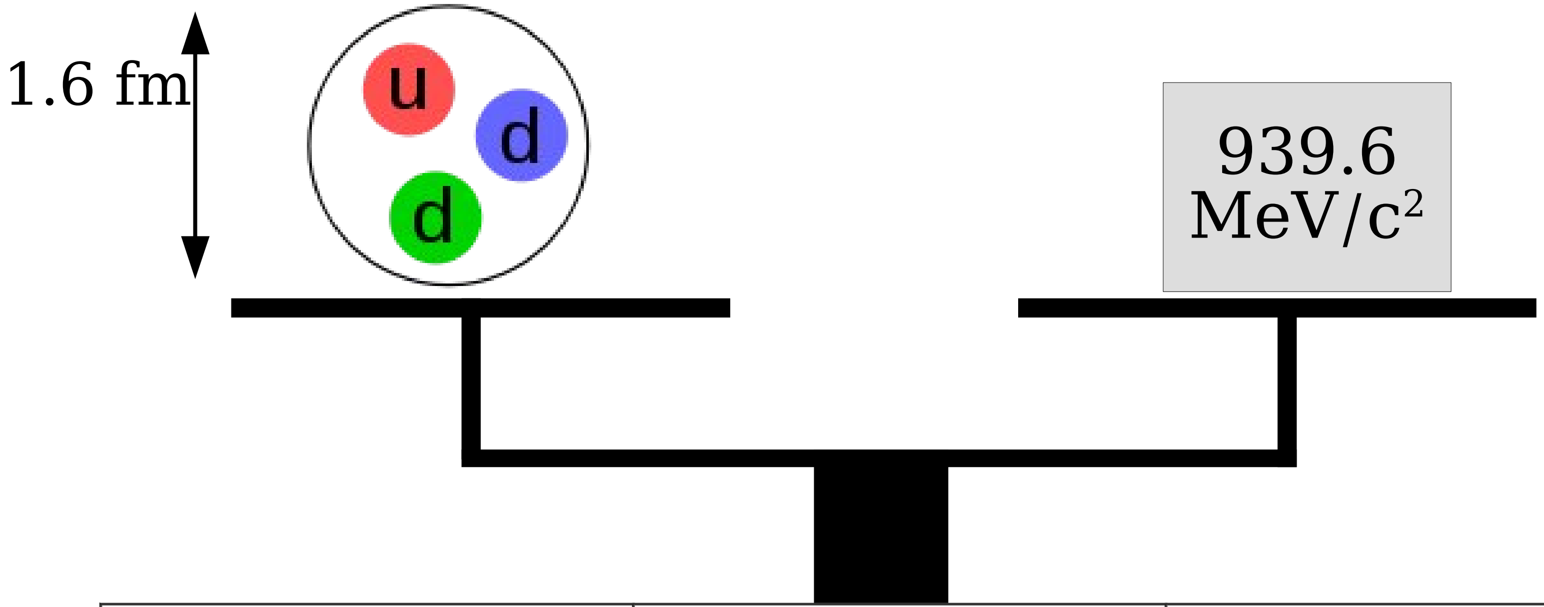
Beam EDM

AEC Graduate Student Seminar

Estelle Chanel

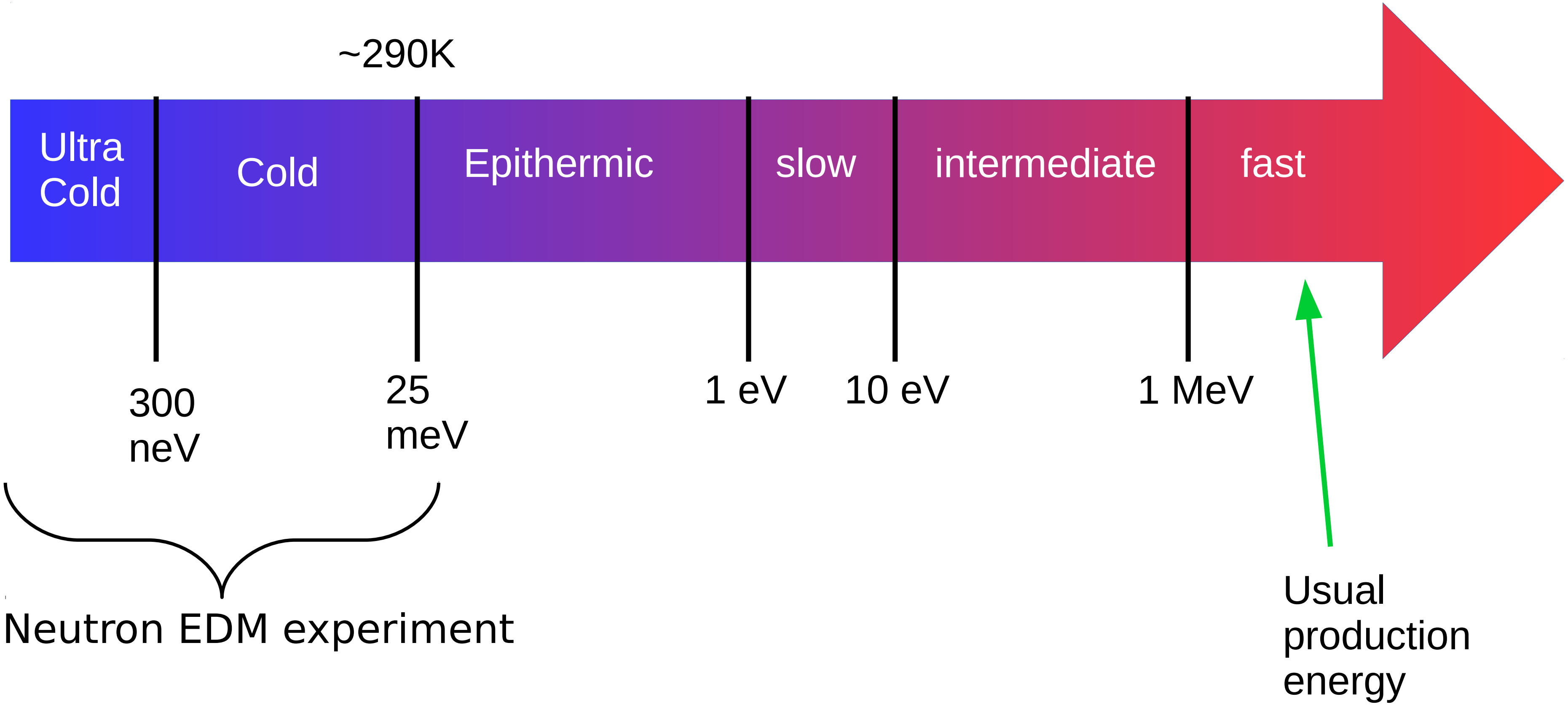
15th May 2019

Neutron properties

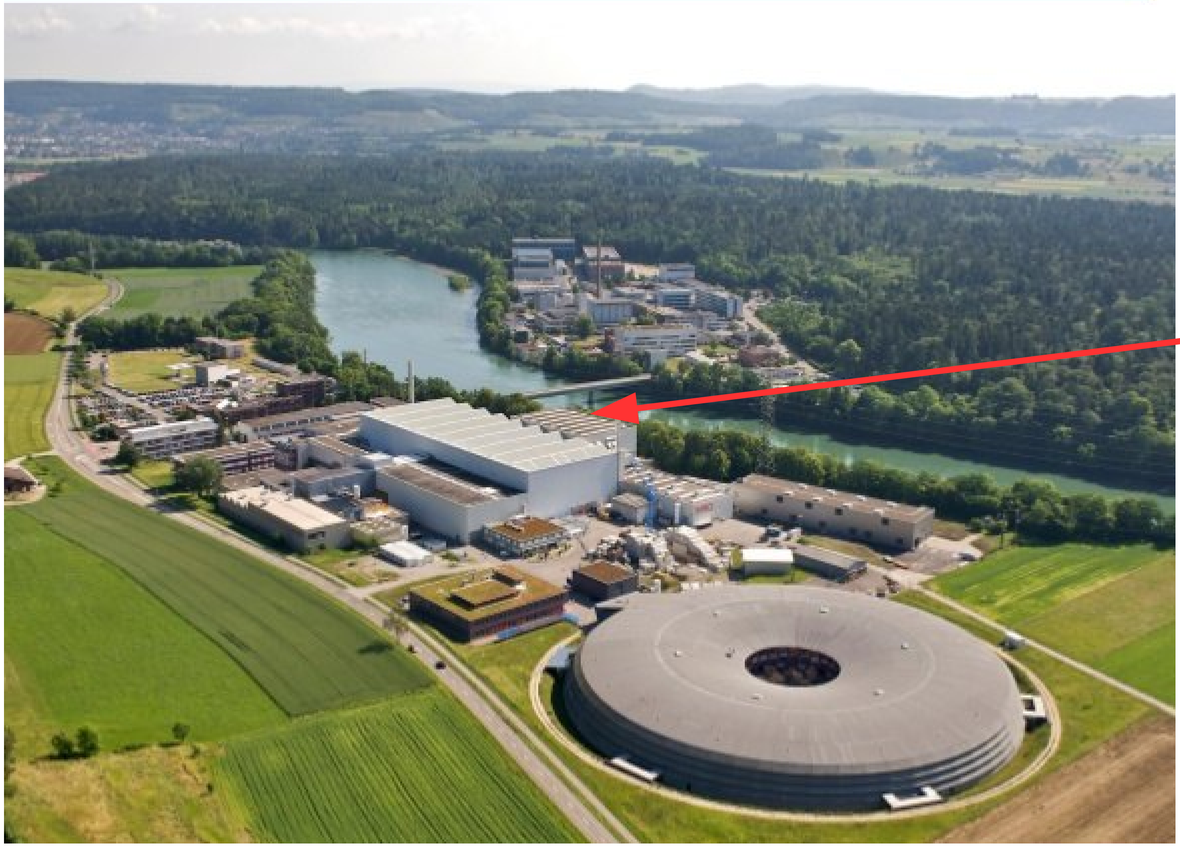


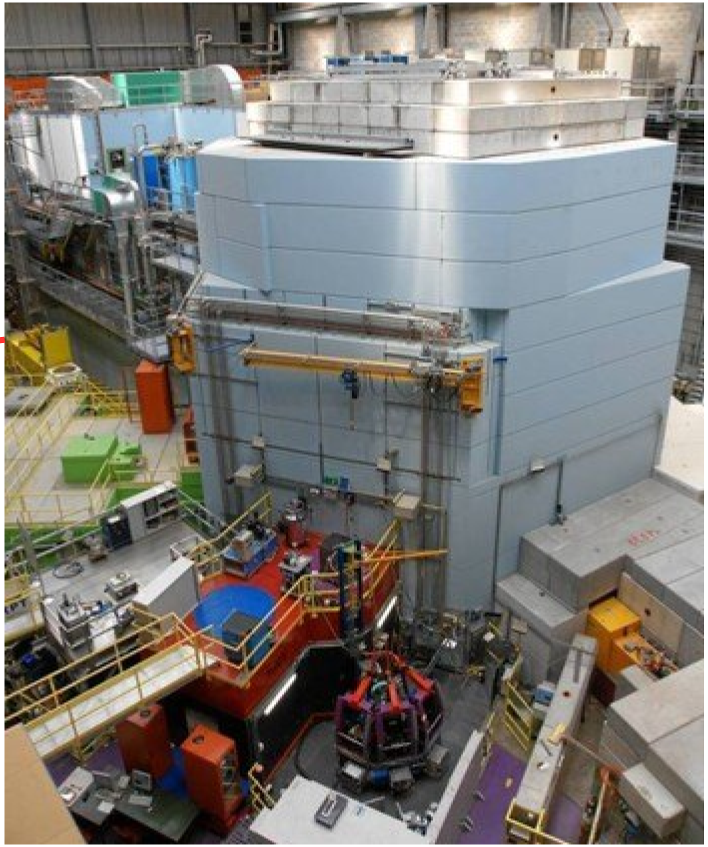
Spin 1/2	$\gamma_n \approx -2\pi\times 29$ MHzT^{-1}	Life time ≈ 880 s

Neutron kinetic Energy

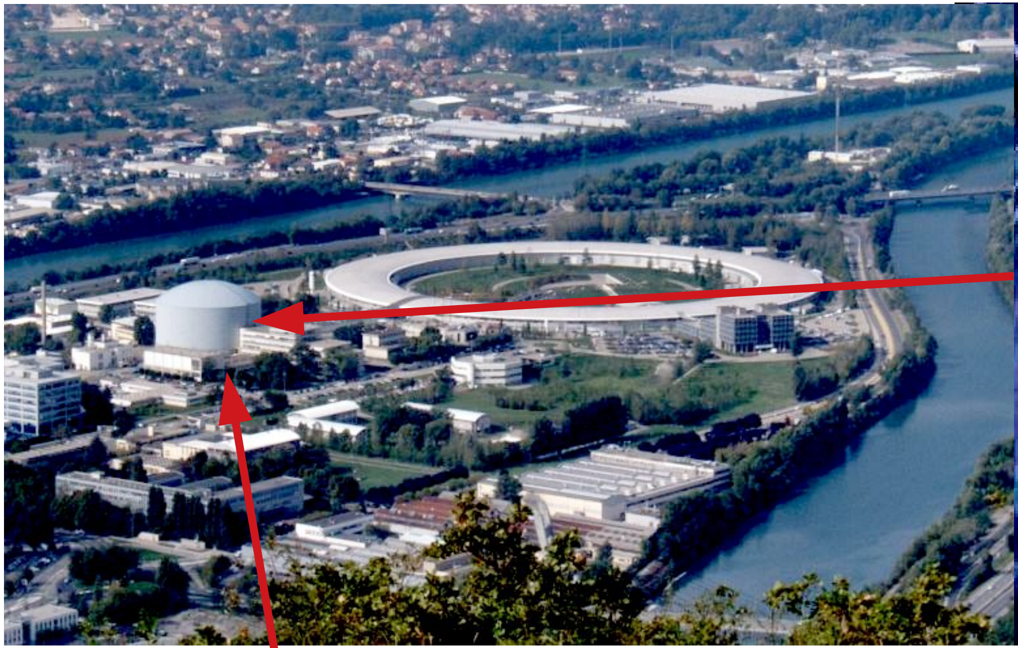


Neutron production at PSI


Paul Scherrer Institut


SINQ Spallation target building

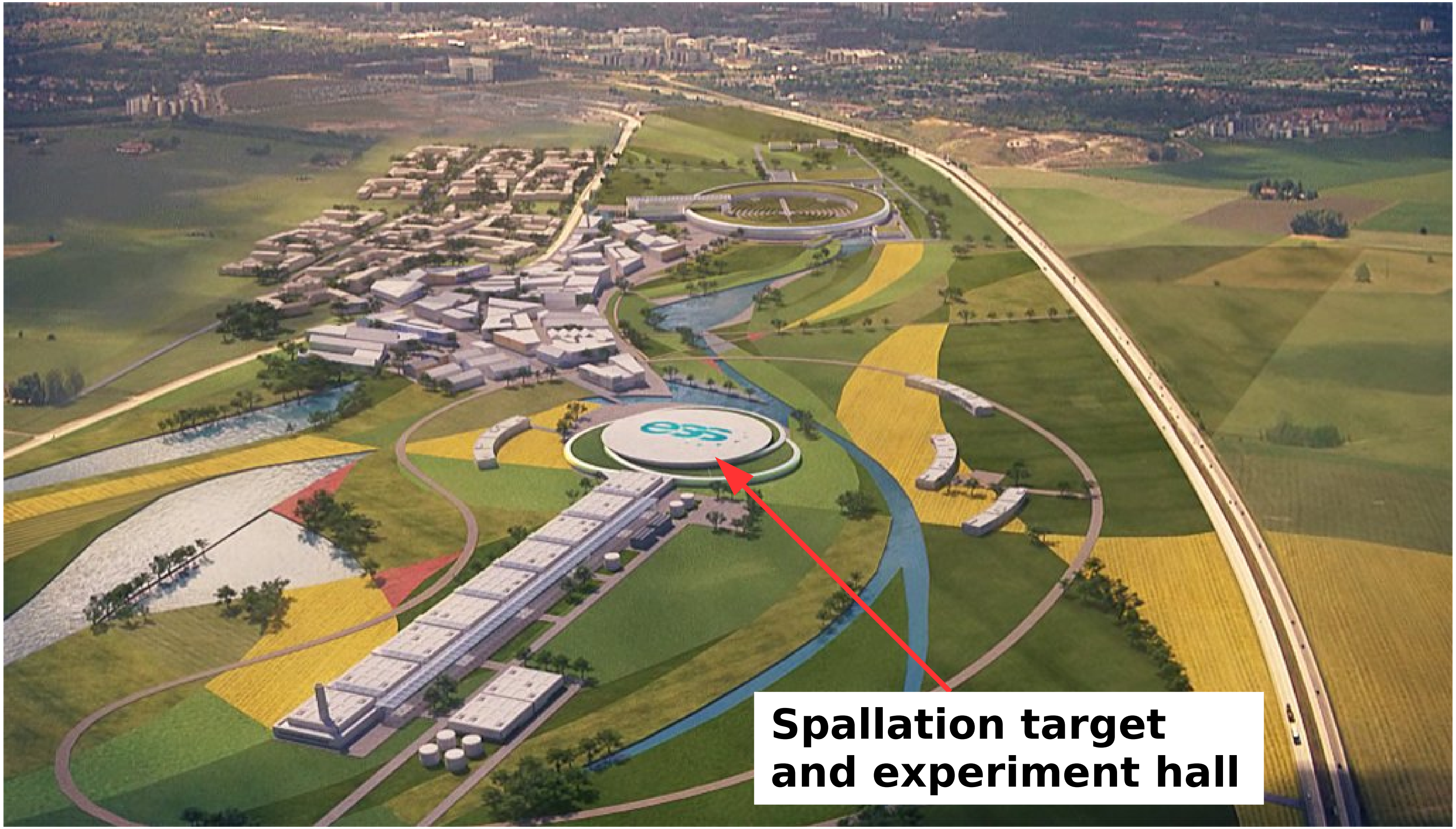
Neutron production at ILL



Institut Laue Langevin, Grenoble

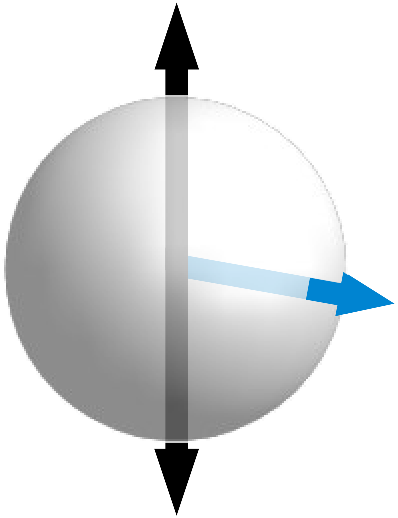
ILL Nuclear Reactor

Neutron production at ESS



What is an EDM?

Electric Dipole Moment quantifies the interaction between the spin and the electric field



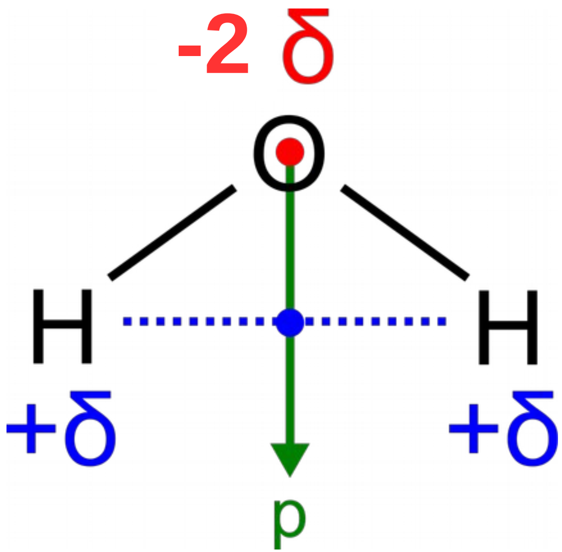
Spin & Bloch sphere

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

$$\gamma_n = \frac{2\mu_n}{\hbar}$$

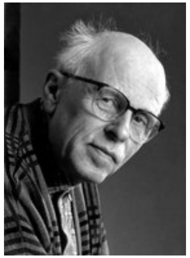
EDM in Water

$$\mathbf{p = 4\times10^{-9}\ ecm}$$



Water

Baryon asymmetry

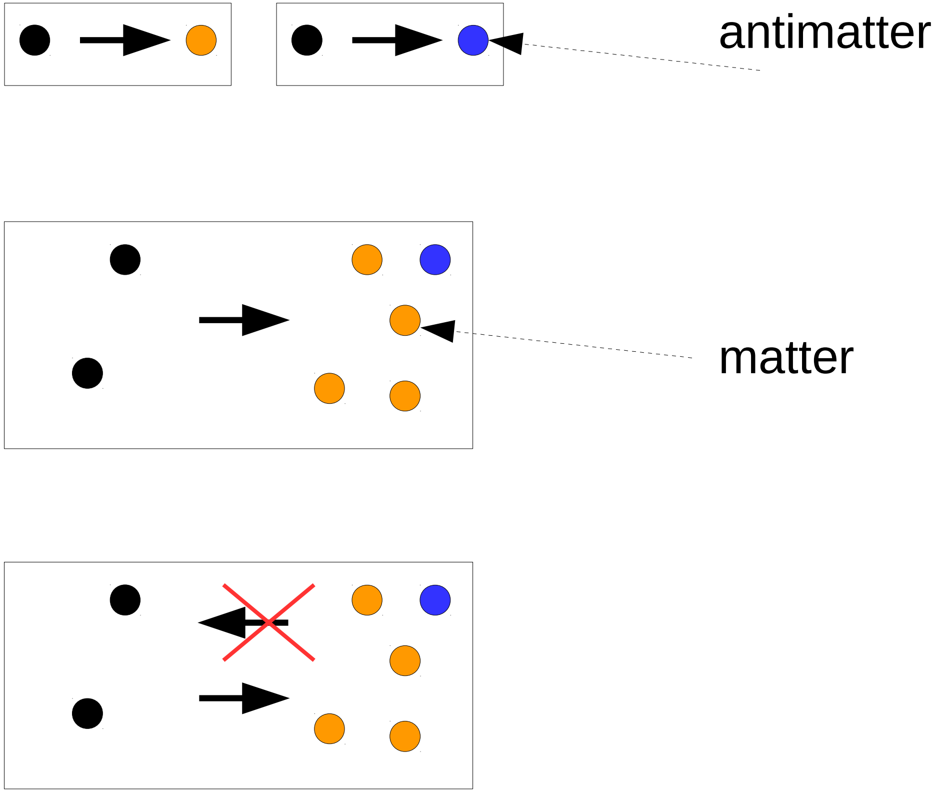


Sakharov conditions:

1. Bayon number violation

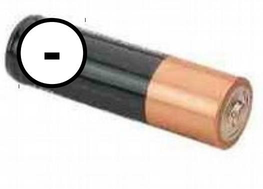
2. C and CP violation

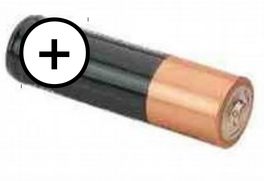
3. non thermal equilibrium



C,P,T symmetries

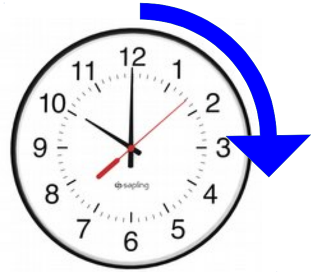
C Charge conjugation $q \rightarrow \bar{q}$

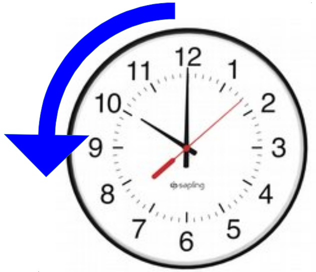




P Space inversion $r \rightarrow -r$

T Time reversal $t \rightarrow -t$





CPT theorem
CP violation ↔ T violation

EDM and P violation

$$H = -\mu_n \vec{\sigma}\,\vec{B} - d_n \vec{\sigma}\,(-\vec{E})$$

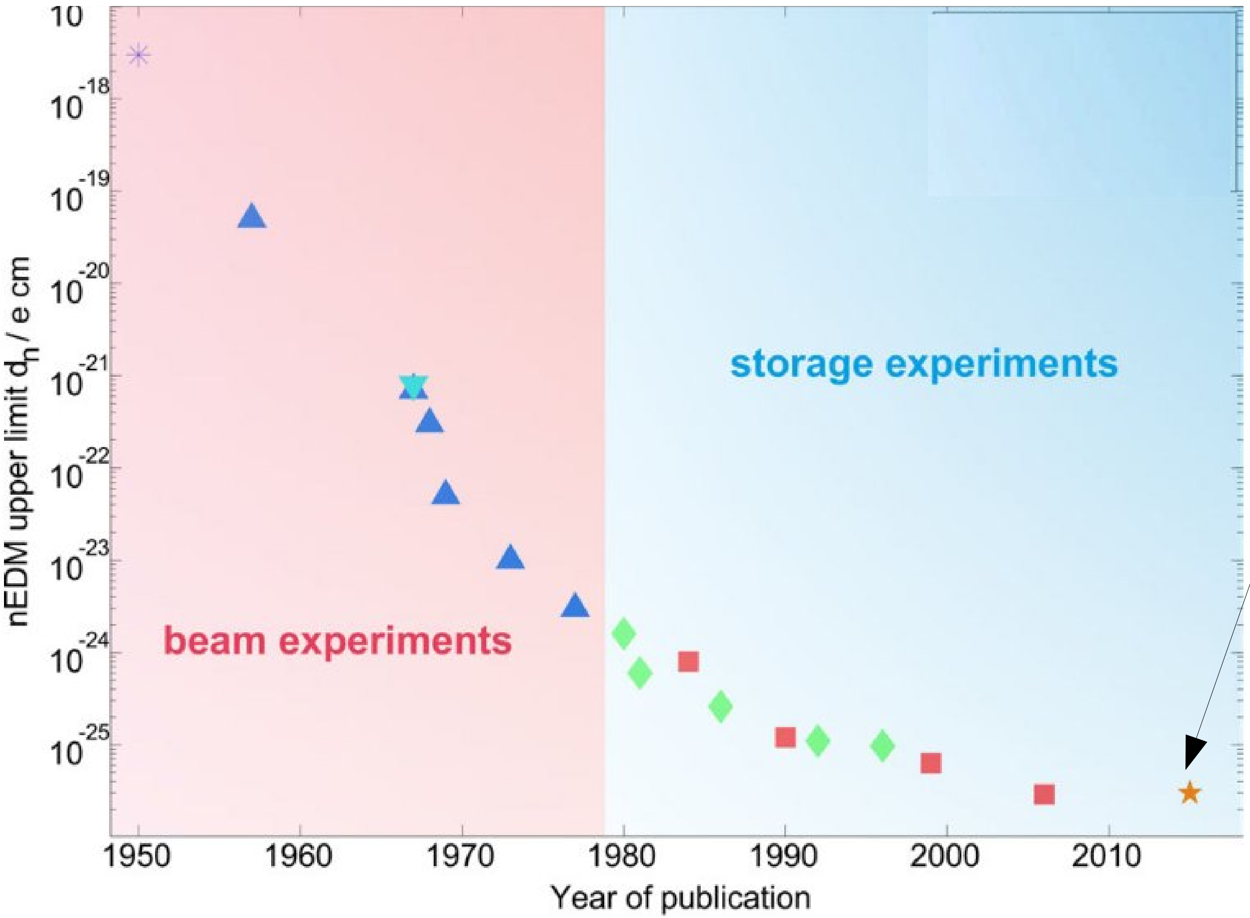
Quantity	Symbol	Parity (P)	Time (T)
Spin	$\vec{\sigma}$	$\vec{\sigma}$	$-\vec{\sigma}$
Time	t	t	- t
Electric field	$\vec{E}$	$-\vec{E}$	$\vec{E}$
Magnetic field	$\vec{B}$	$\vec{B}$	$-\vec{B}$
Position	$\vec{x}$	$-\vec{x}$	$\vec{x}$

EDM and T violation

$$H = -\mu_n(-\vec{\sigma})(-\vec{B}) - d_n(-\vec{\sigma})\vec{E}$$

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

Limit of the neutron EDM

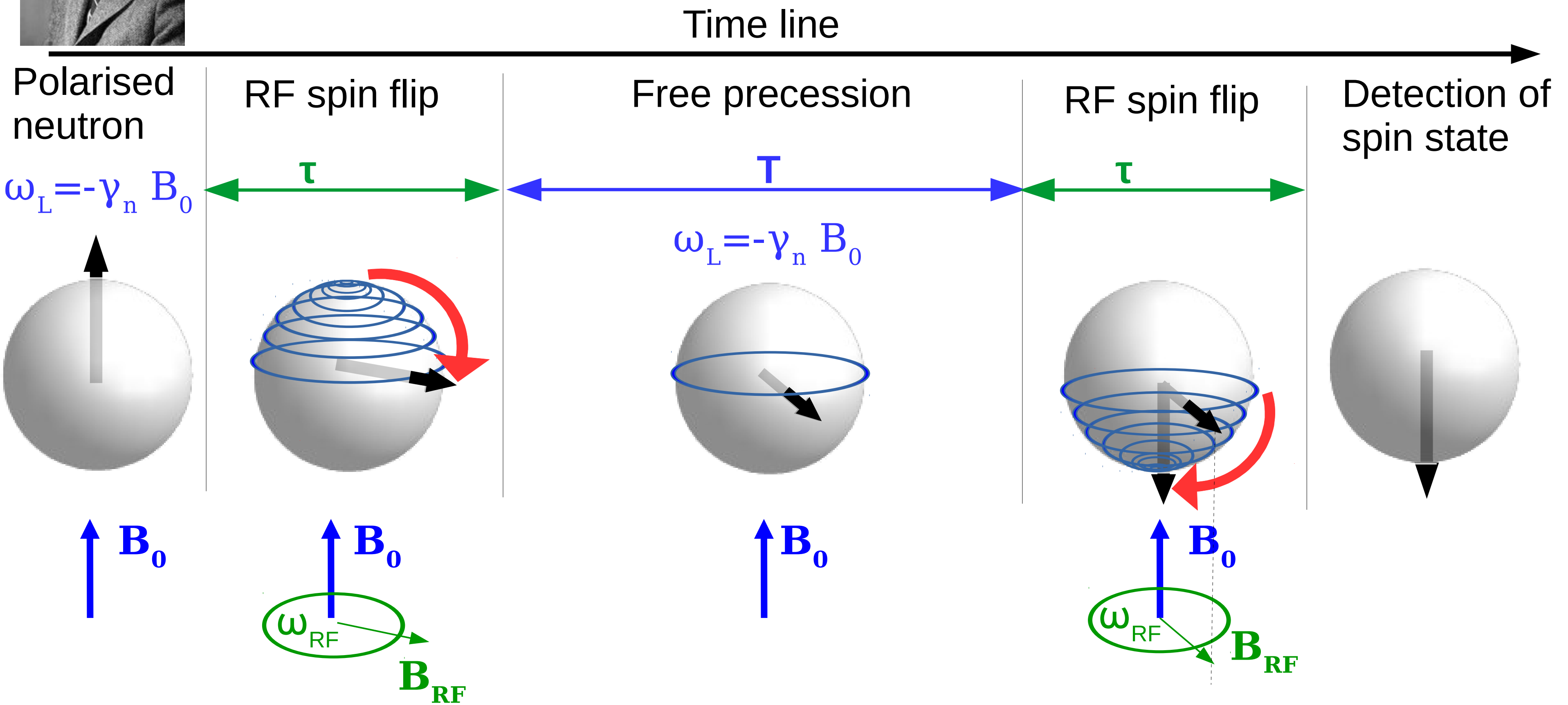


Current limit
$d_n = 3.0\ 10^{-26}$ ecm

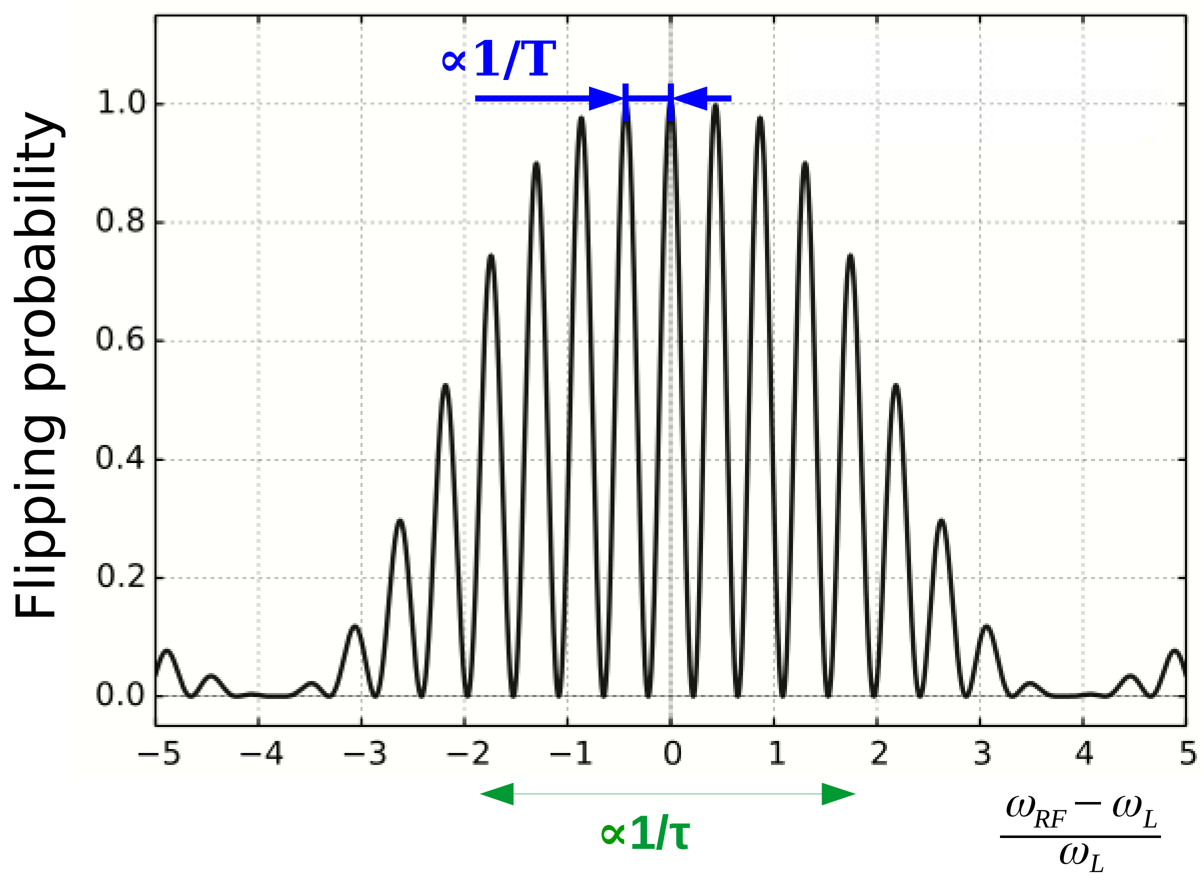
Standard model value
$d_n \in [10^{-32};10^{-30}]$ ecm

PHYSICAL REVIEW D 92, - (2015). DOI: 10.1103/PhysRevD.92.092003

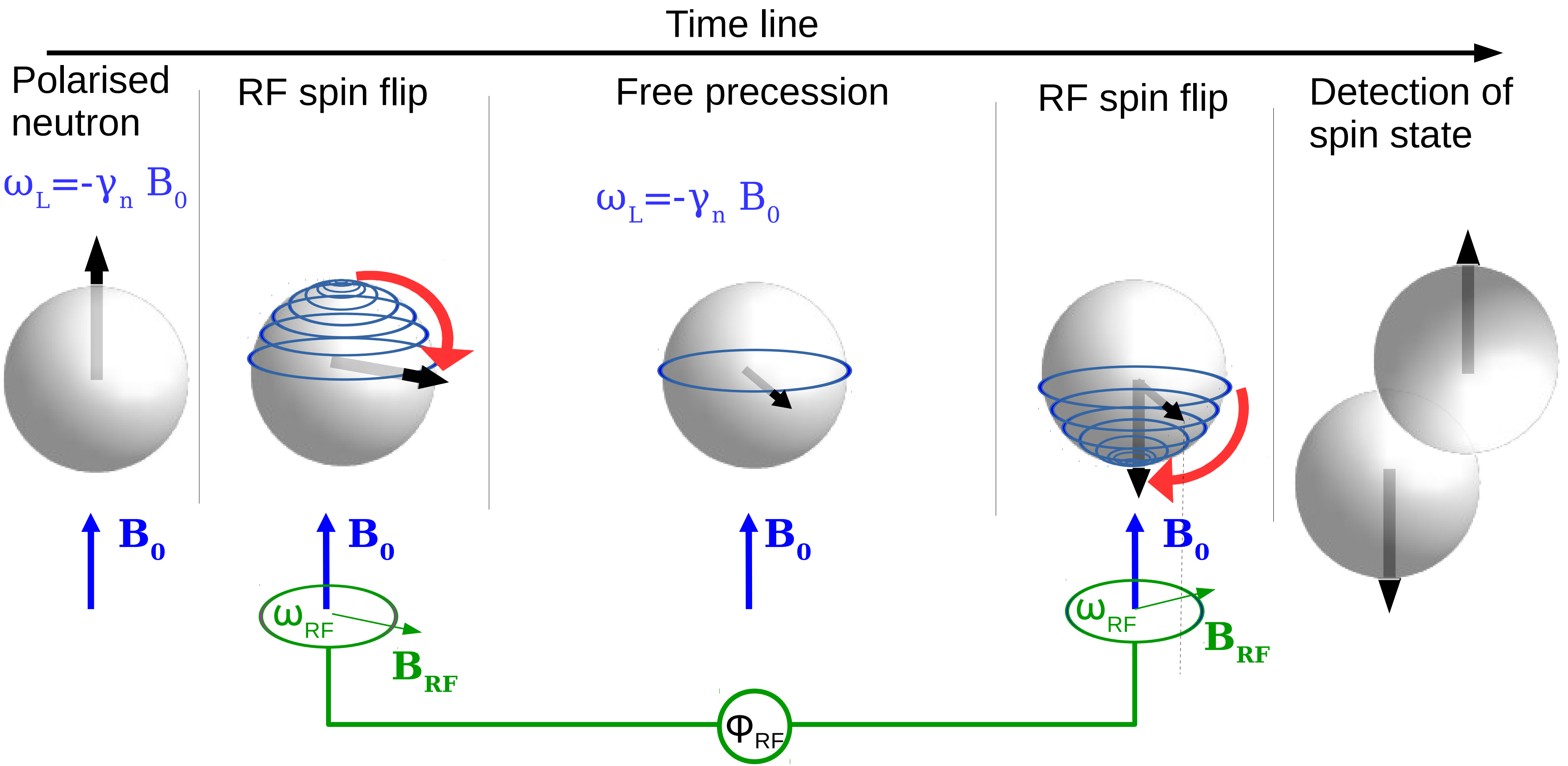
Ramsey technique



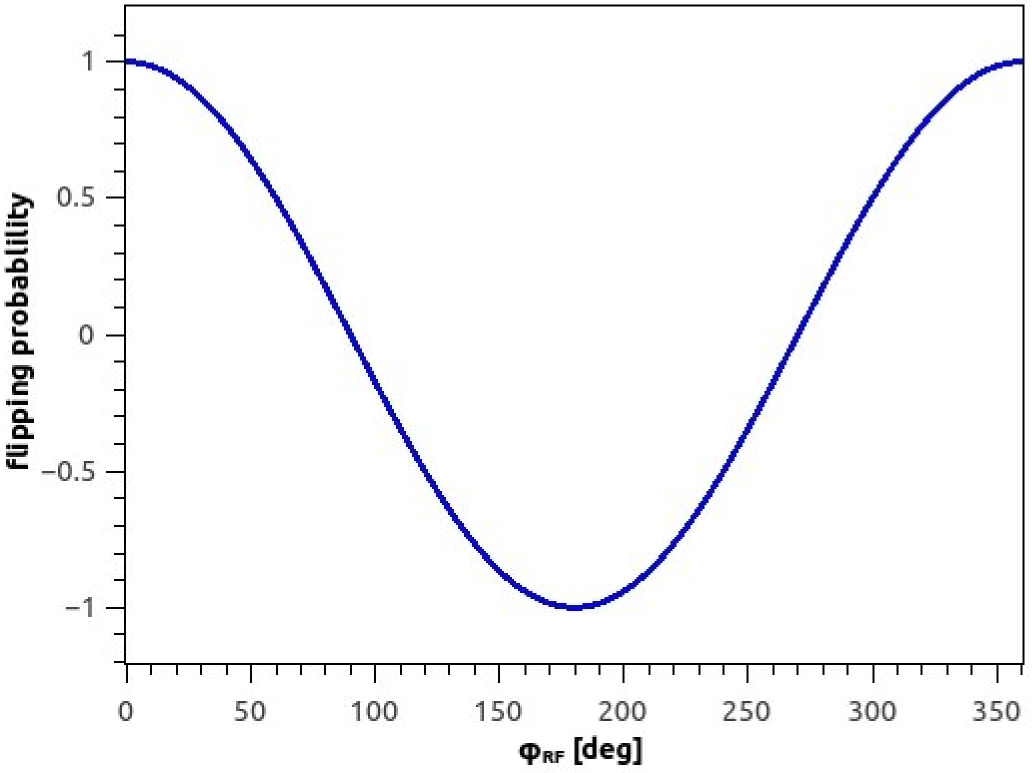
Ramsey fringes



Phase scan technique

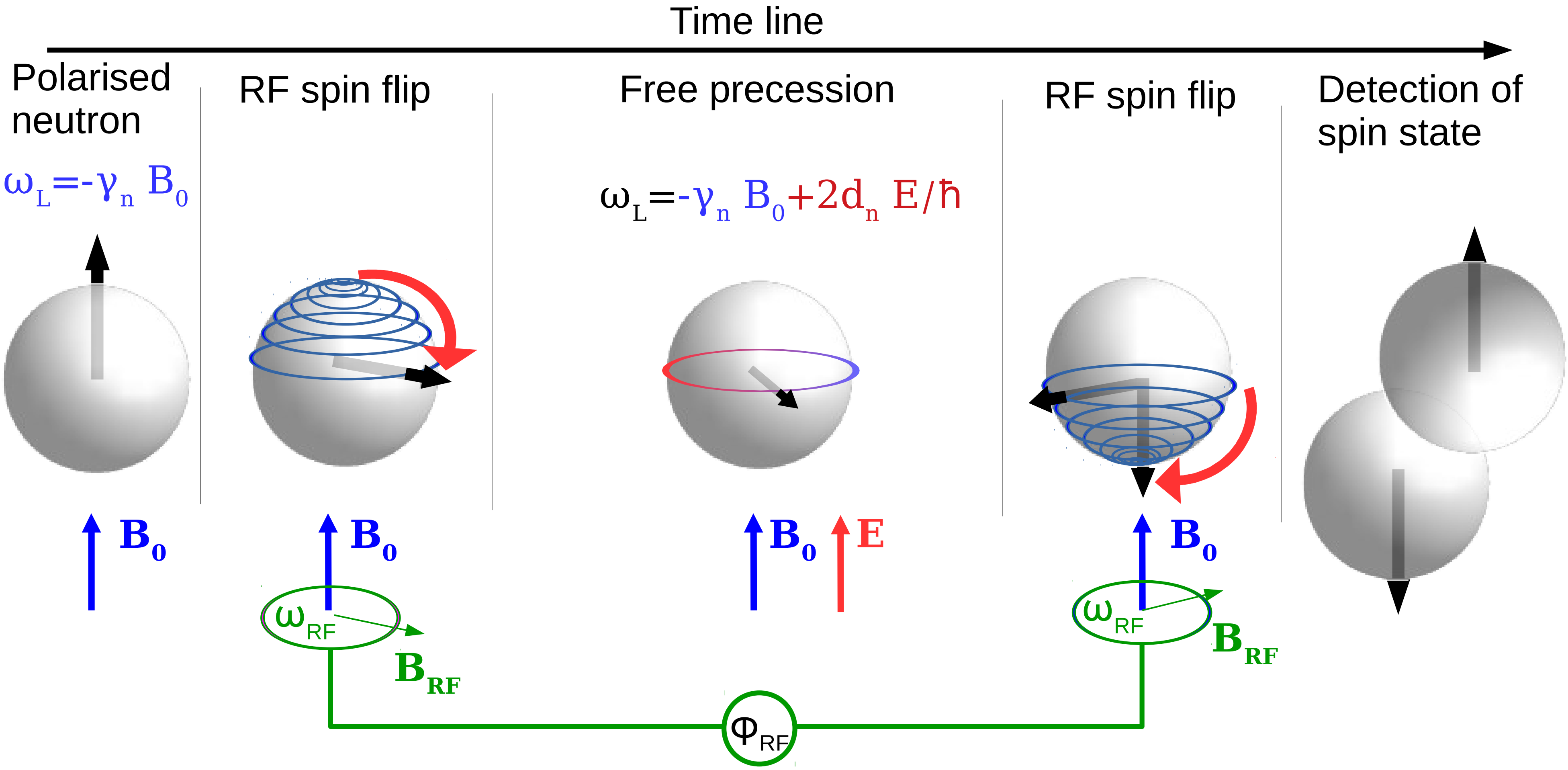


Phase scan with EDM

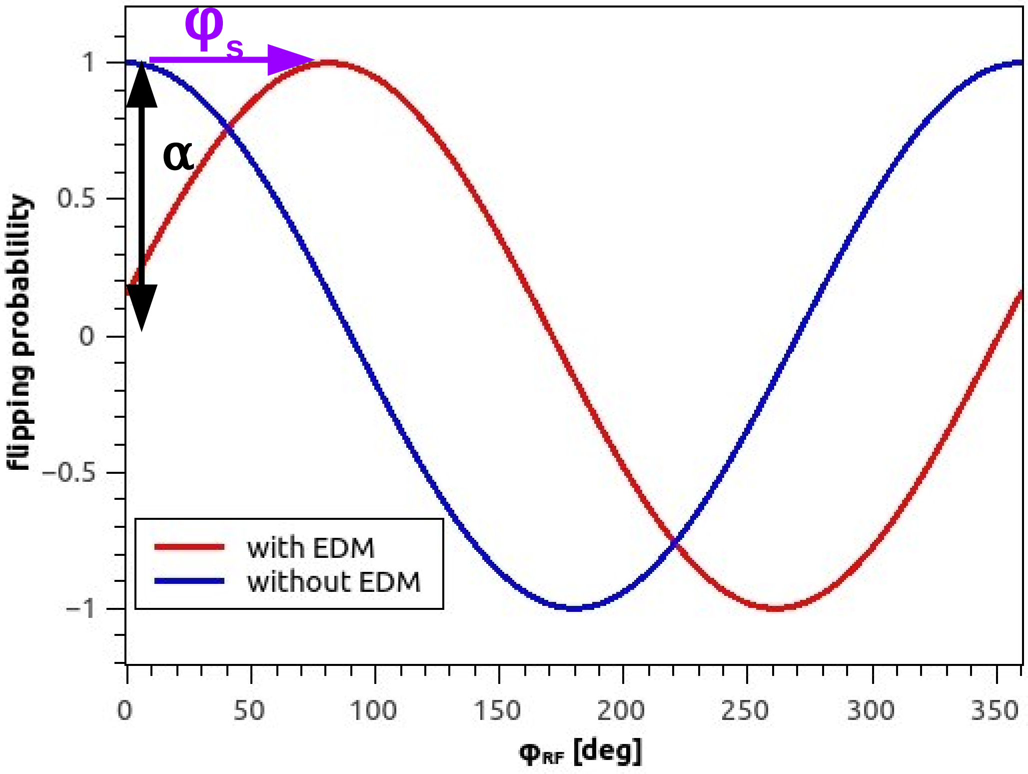


Advantage:
Always on resonance

Phase scan with EDM



Phase scan with EDM



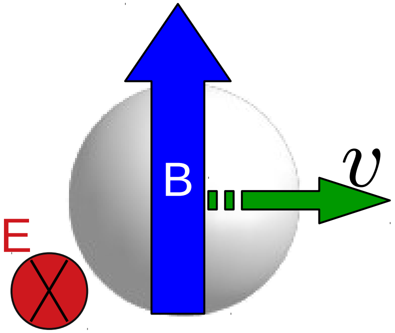
Advantage:
Always on resonance

$$\sigma_{d_n} \propto \frac{1}{\alpha \sqrt{N}\, T\, |E|}$$

Contributions

Relativistic
vxE effect

$$\vec{B}_{v\times E}=\frac{-\vec{v}\times\vec{E}}{c^2}=\frac{-\ell E}{tc^2}\hat{e}_{v\perp E}$$



EDM

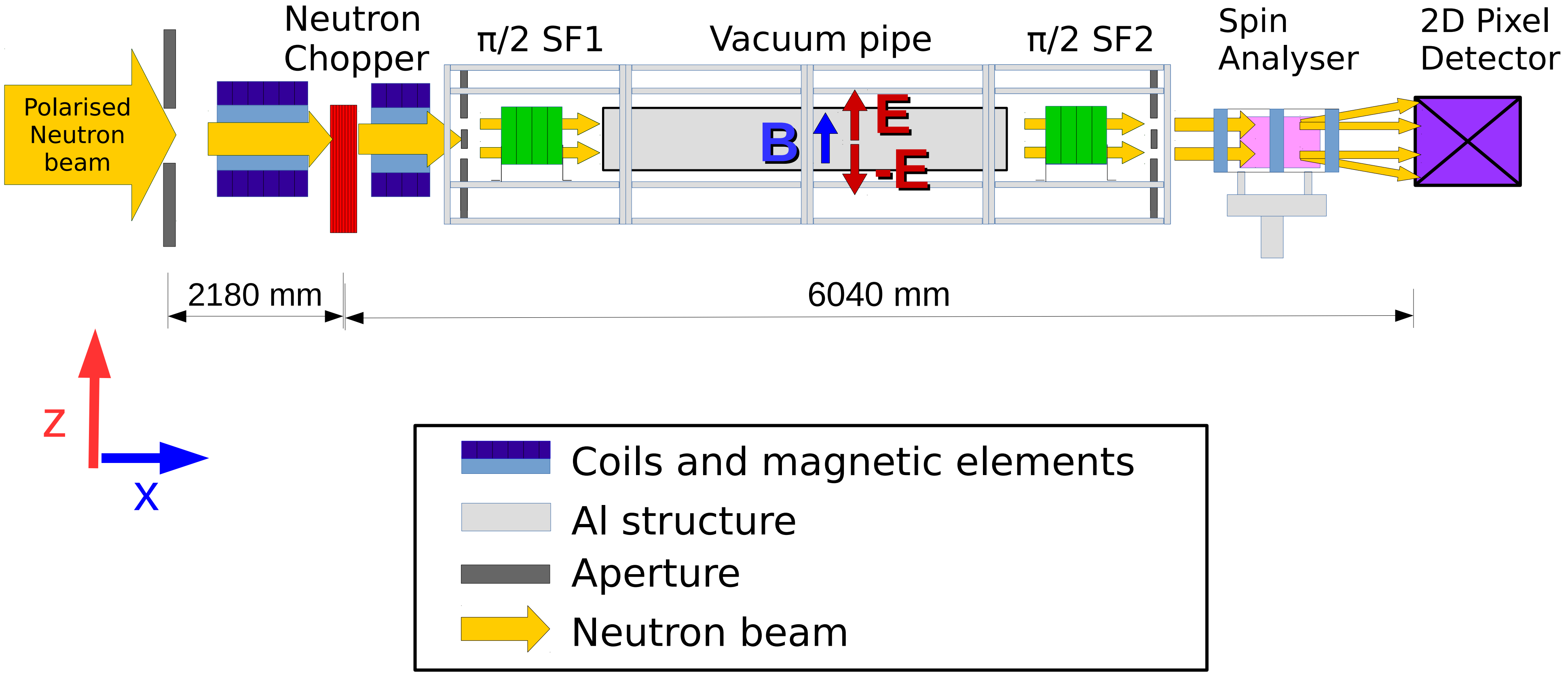
$$\vec{B}_{EDM}=\frac{2d_n\vec{E}}{\gamma_n\hbar}$$

$$\phi=-\gamma_n\sum B_i t$$
$$=\gamma_n\frac{\ell E_\perp}{c^2}$$
$$-\gamma_n(B_{EDM}+\Delta B)t$$

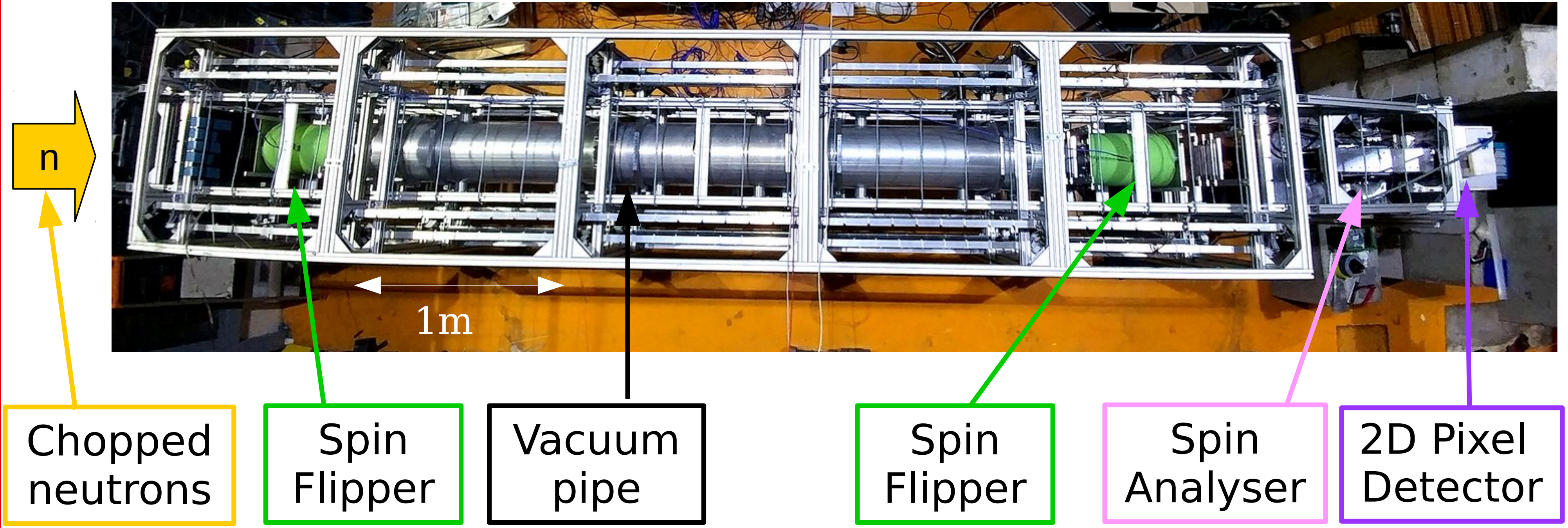
Off resonance

$$\Delta\vec{B}=\frac{\vec{\omega}_{RF}}{\gamma_n}-\vec{B}$$

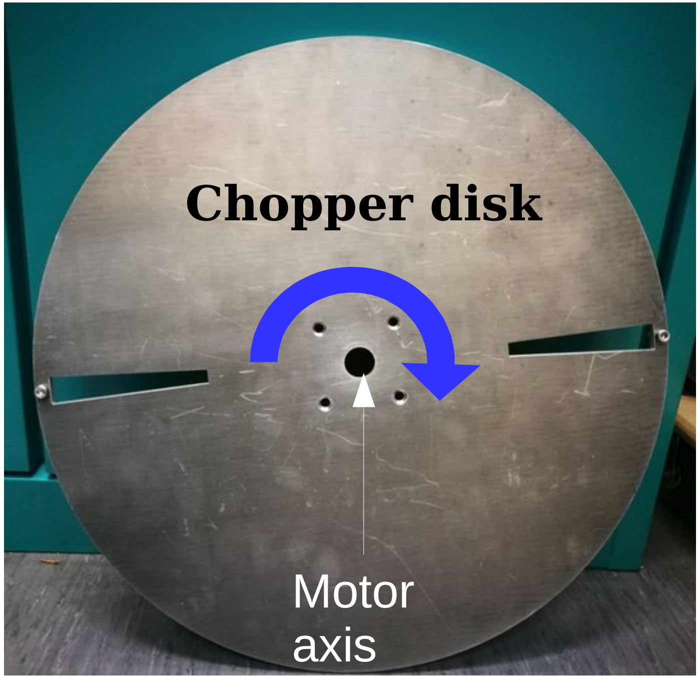
The Beam EDM setup

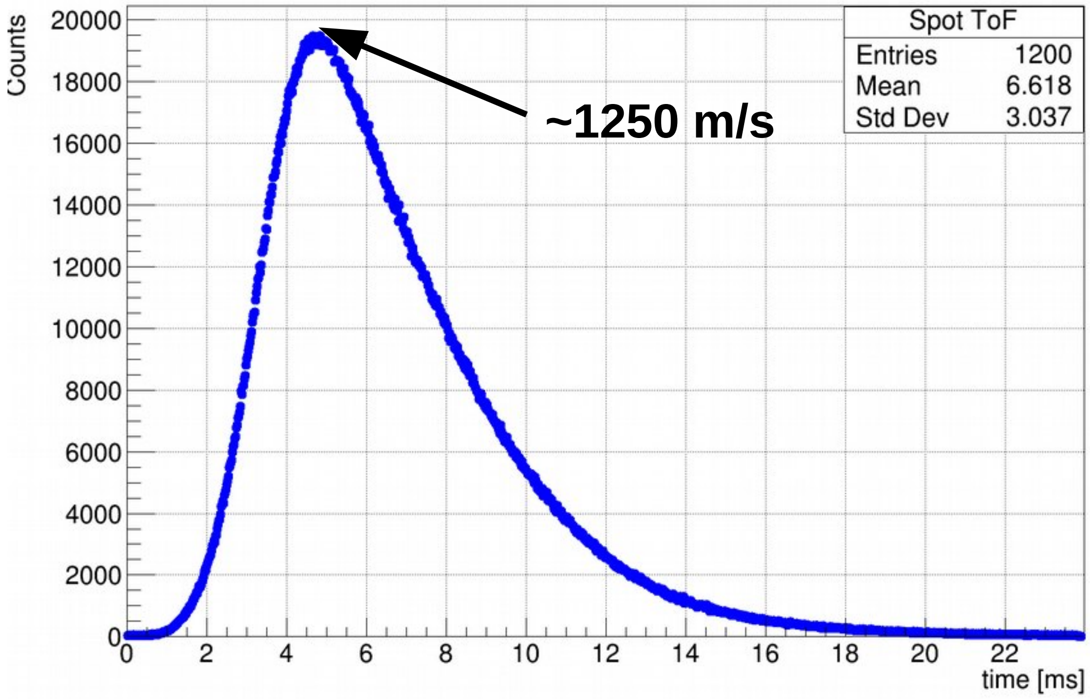


The Beam EDM setup



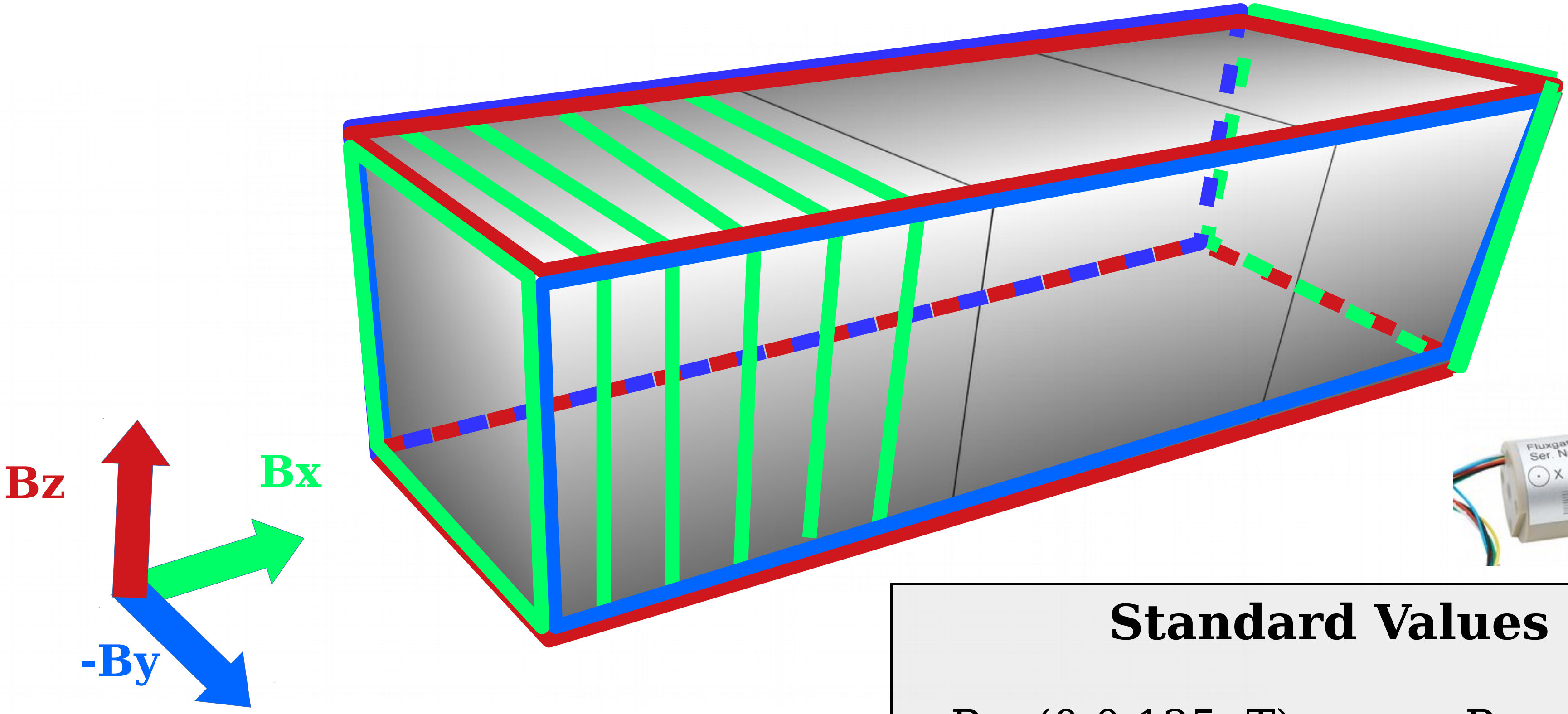
Neutron Chopper





Pulse frequency ~ 50 Hz

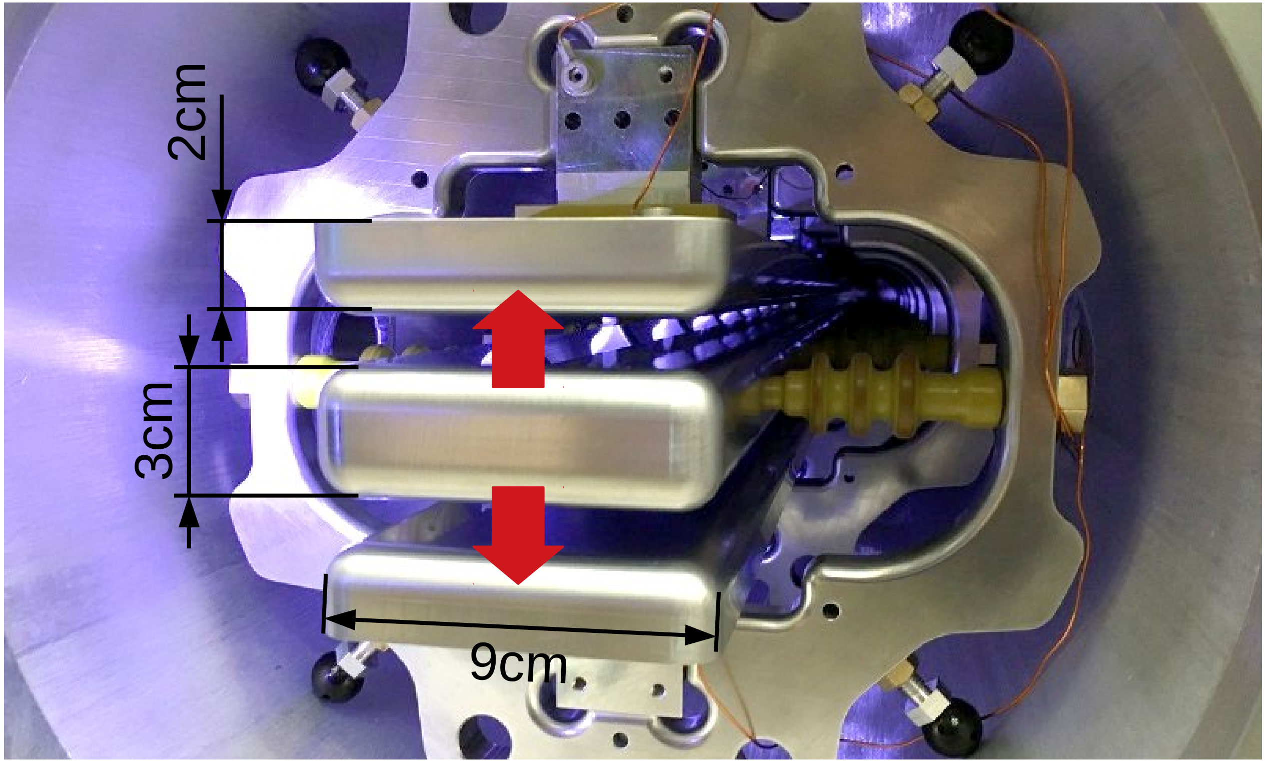
The Beam EDM setup: magnetic field



Standard Values

$B_0=(0,0,125\mu T)$ $B_{grad}=0$

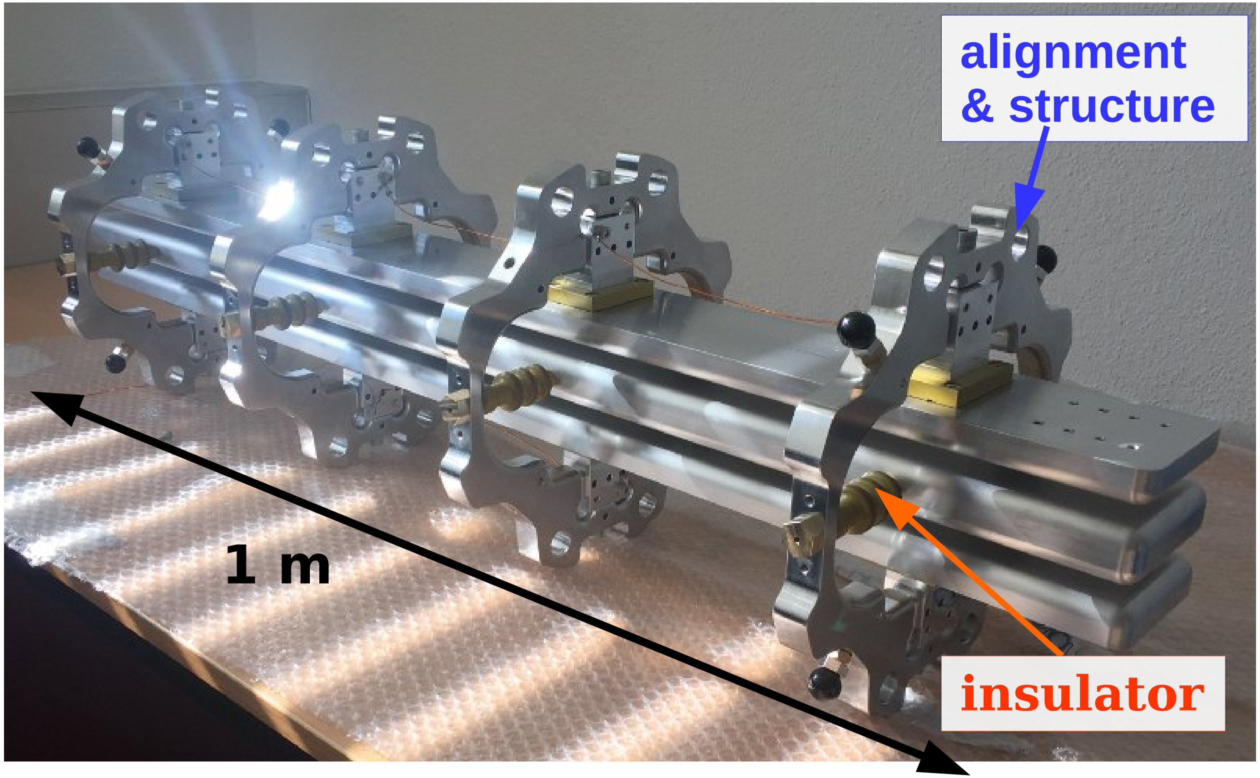
The Beam EDM setup: Electric field



Characteristics

- Material:
  Al electrodes
  ceramic insulator
- Dimension:
  1 m x 2 cm x 9 cm
  1 m x 3 cm x 9 cm
- Separation:
  from 5 mm to 1 cm
- Goal field:
  100 kV/cm @ 1 cm

The Beam EDM setup: Electric field



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  1 m x 2 cm x 9 cm
  1 m x 3 cm x 9 cm
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  from 5 mm to 1 cm
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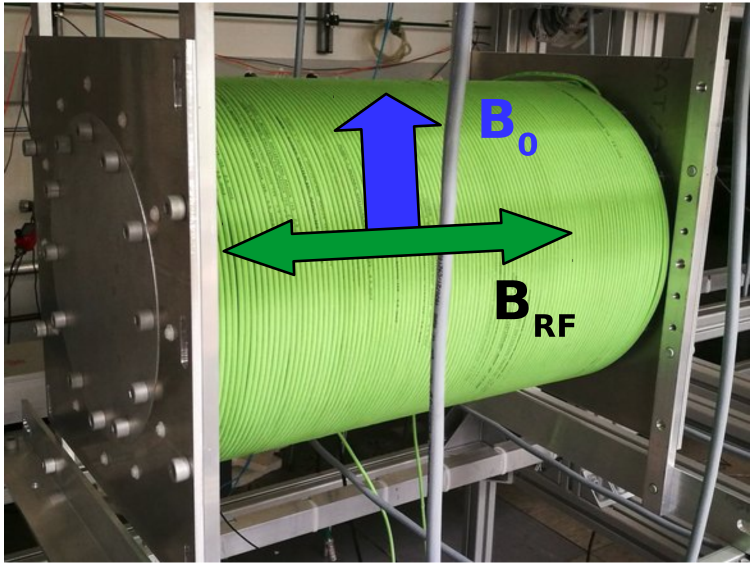
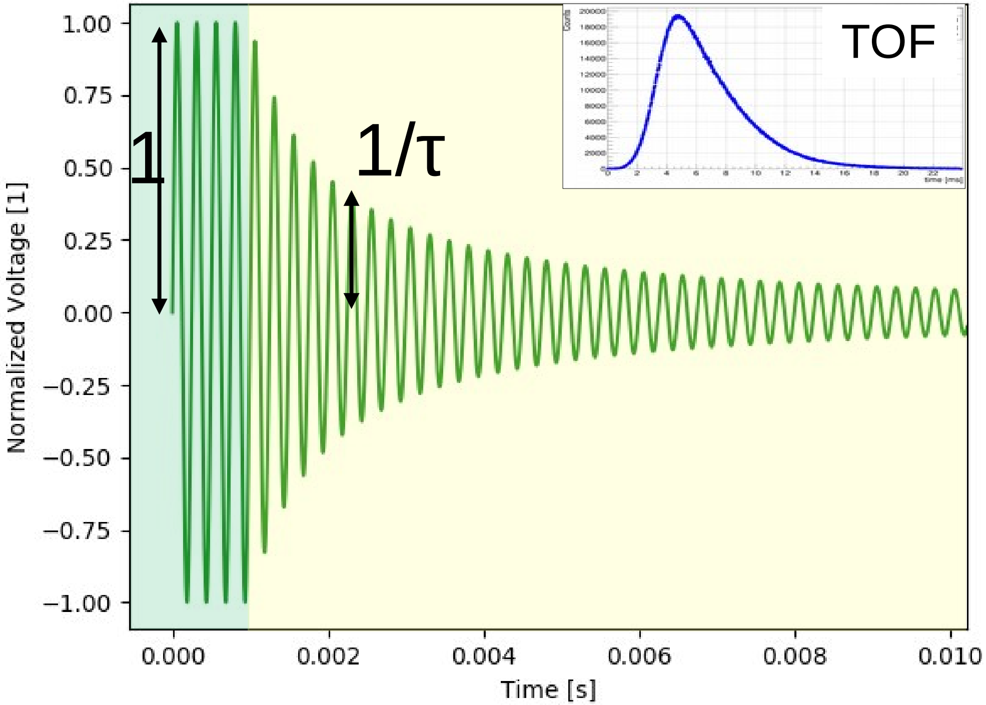
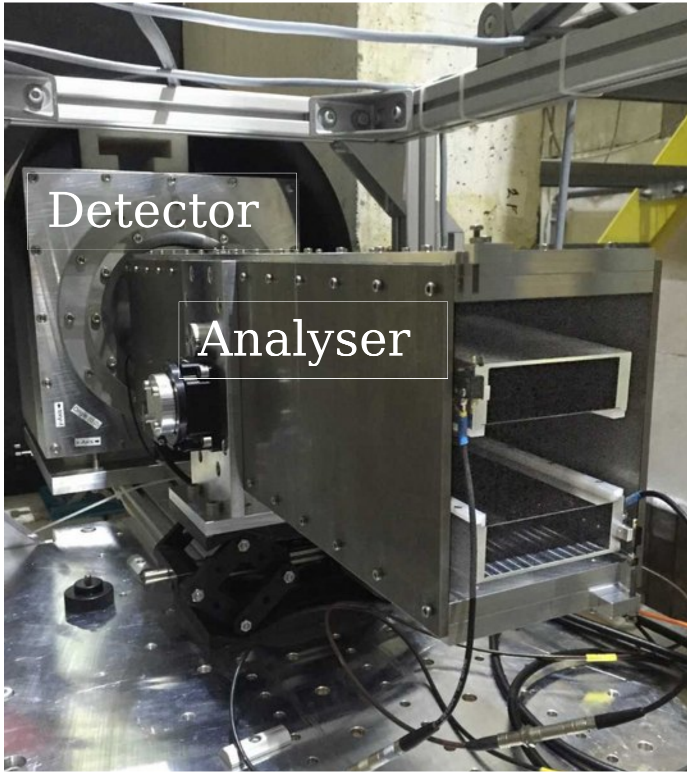
  100 kV/cm @ 1 cm

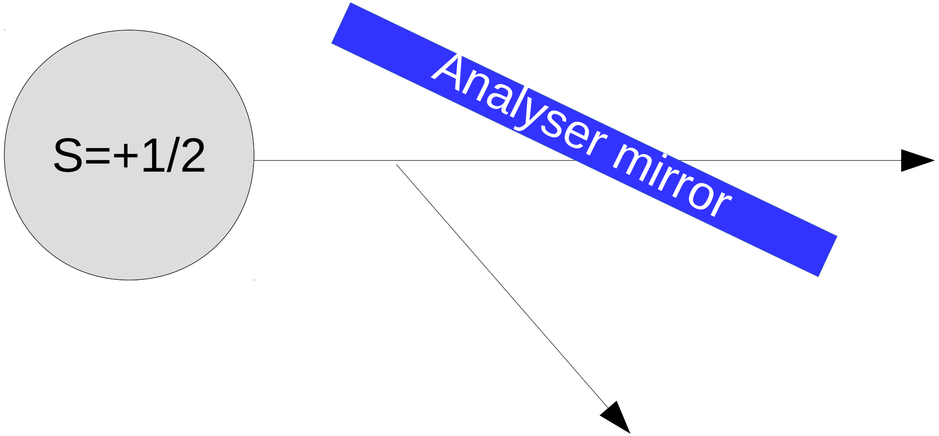
The Beam EDM setup: Spin Flipper



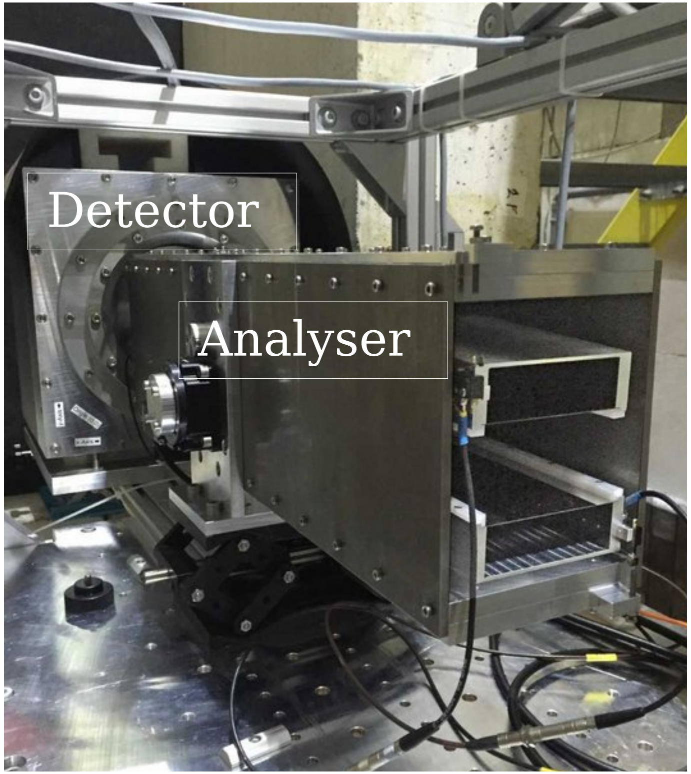


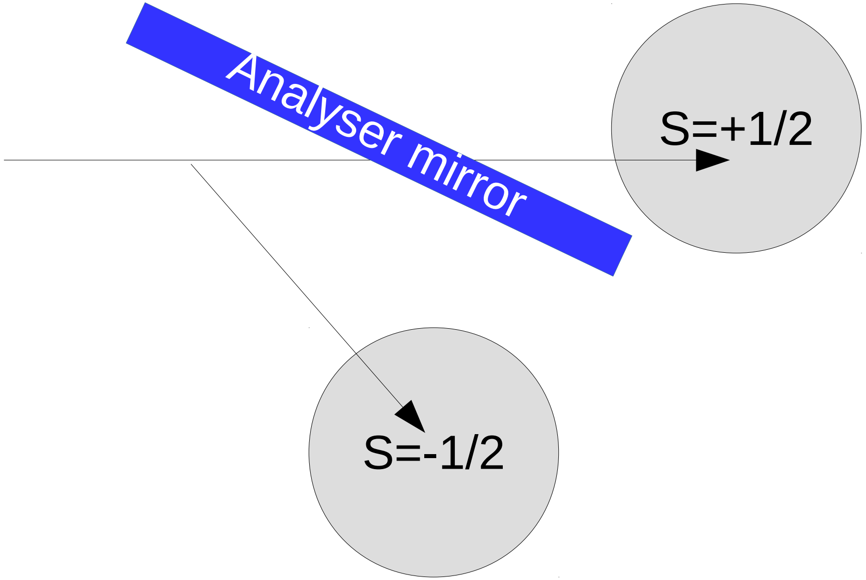
The Beam EDM setup: Spin Analyser



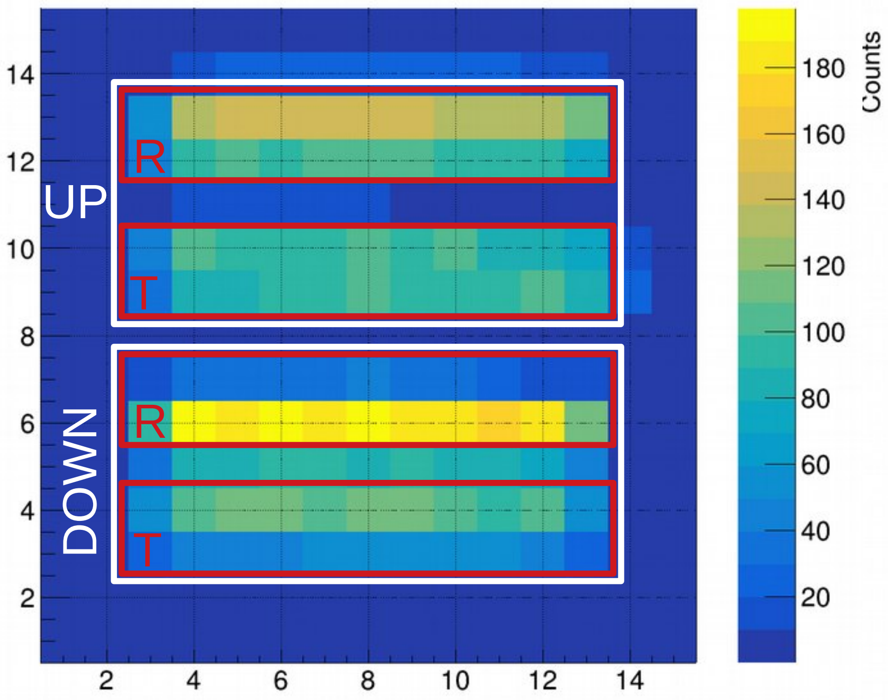


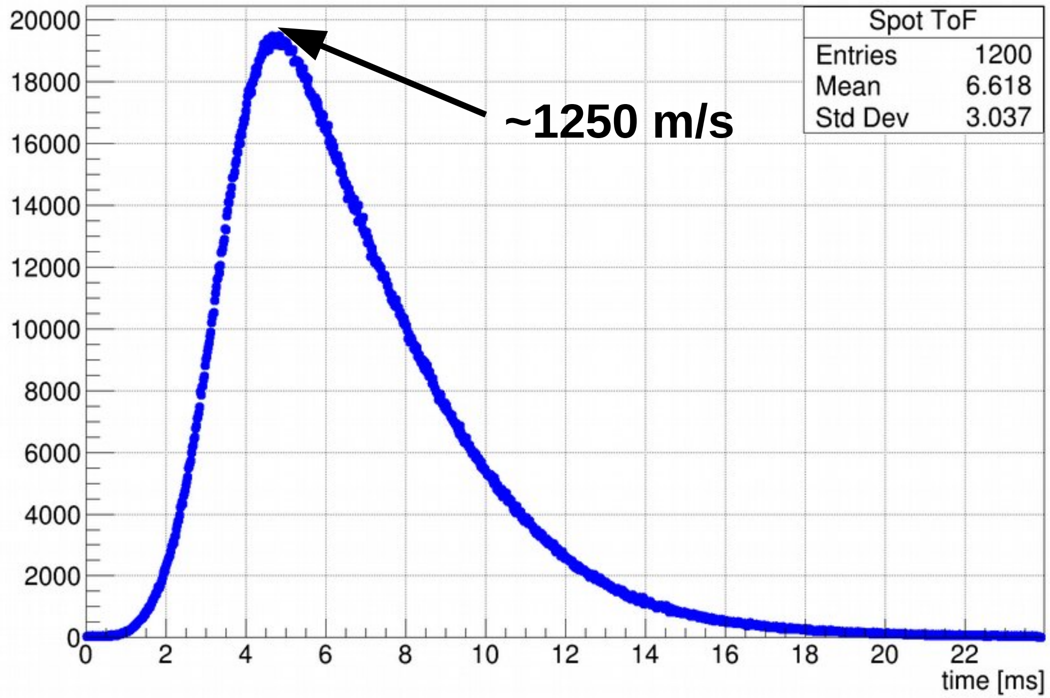
The Beam EDM setup: Spin Analyser



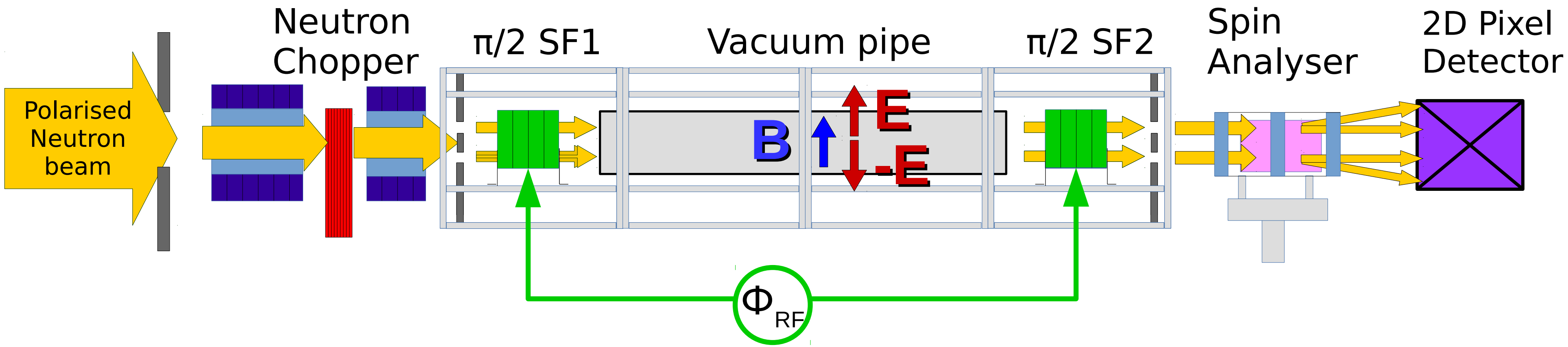


The Beam EDM setup: Detector





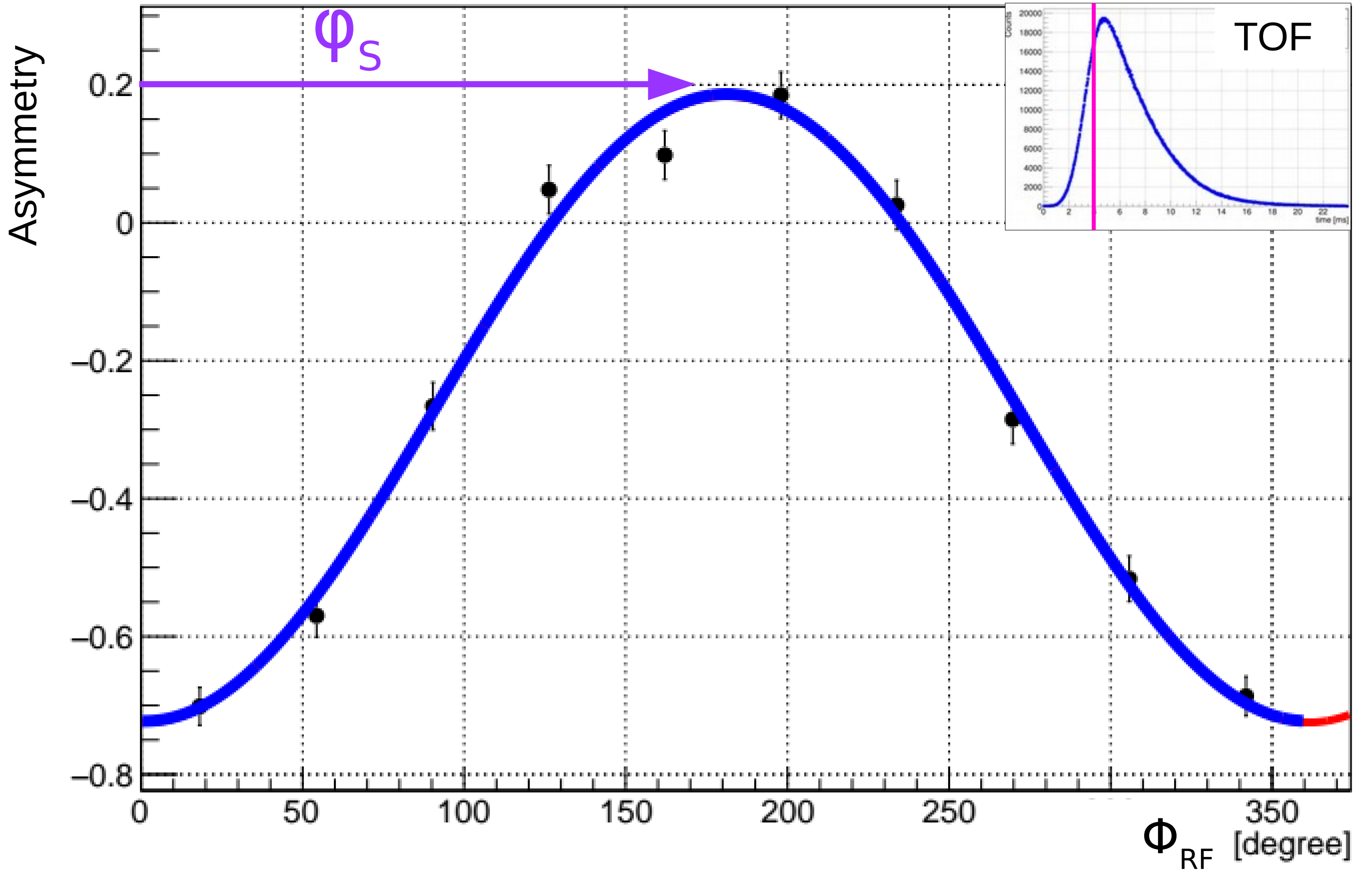
Standard measurement



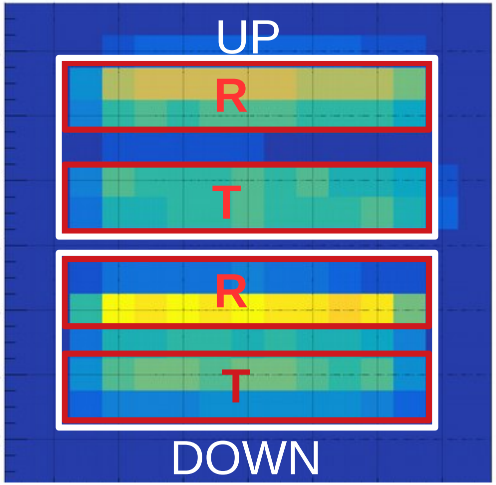
Phase scan: $\Phi_{RF} \in [0;2\pi]$

$B=\{B_0, B_0+\Delta B, \ldots\}$ $E=\{-E_0;0;E_0\}$

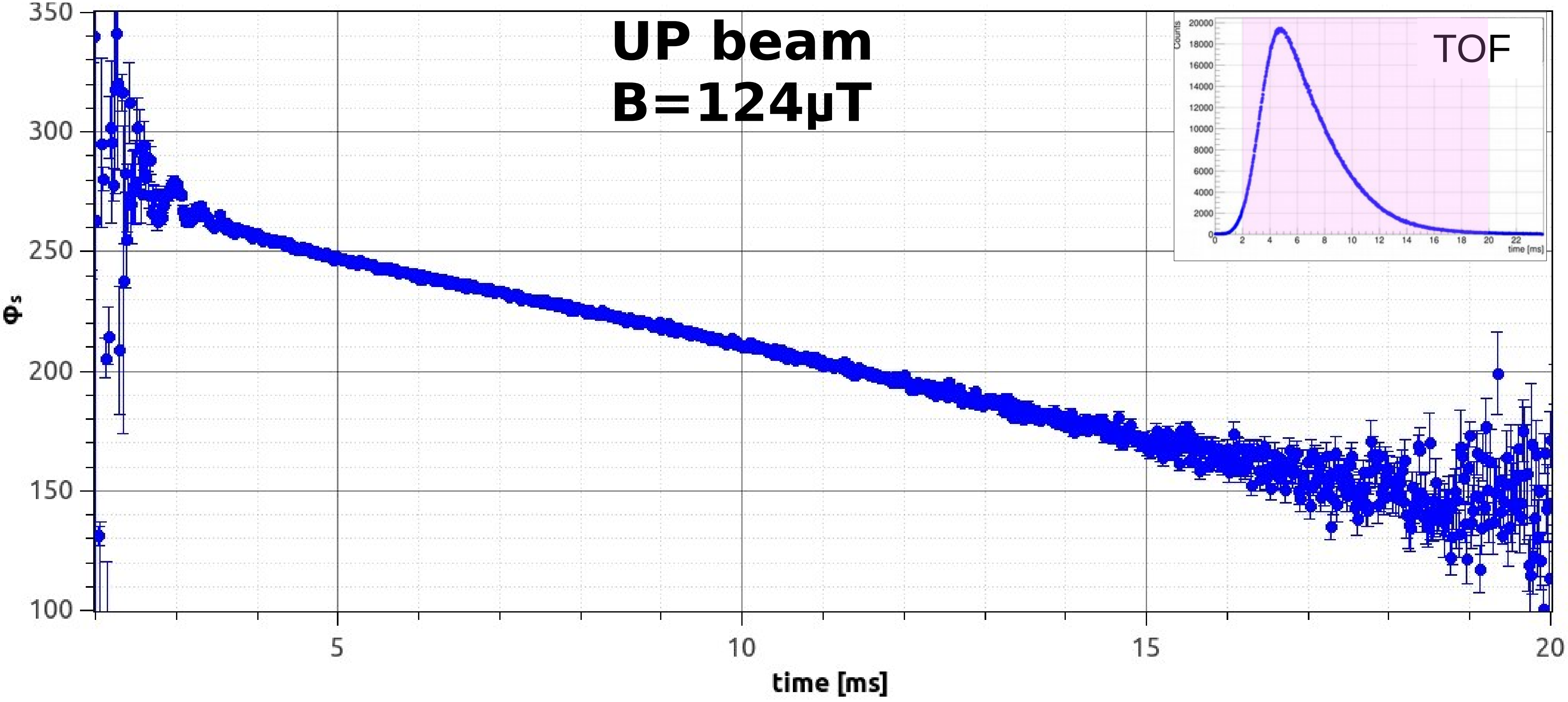
Phase scan



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



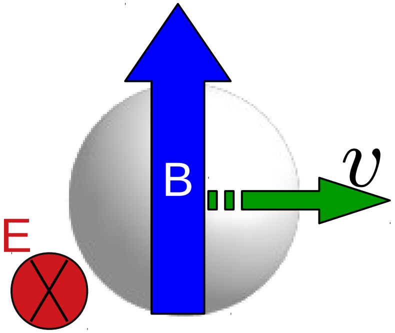
φ_s vs time



Contributions

Relativistic vxE effect

$$\vec{B}_{v\times E} = \frac{-\vec{v}\times\vec{E}}{c^2} = \frac{-\ell E}{tc^2}\hat{e}_{v\perp E}$$



EDM

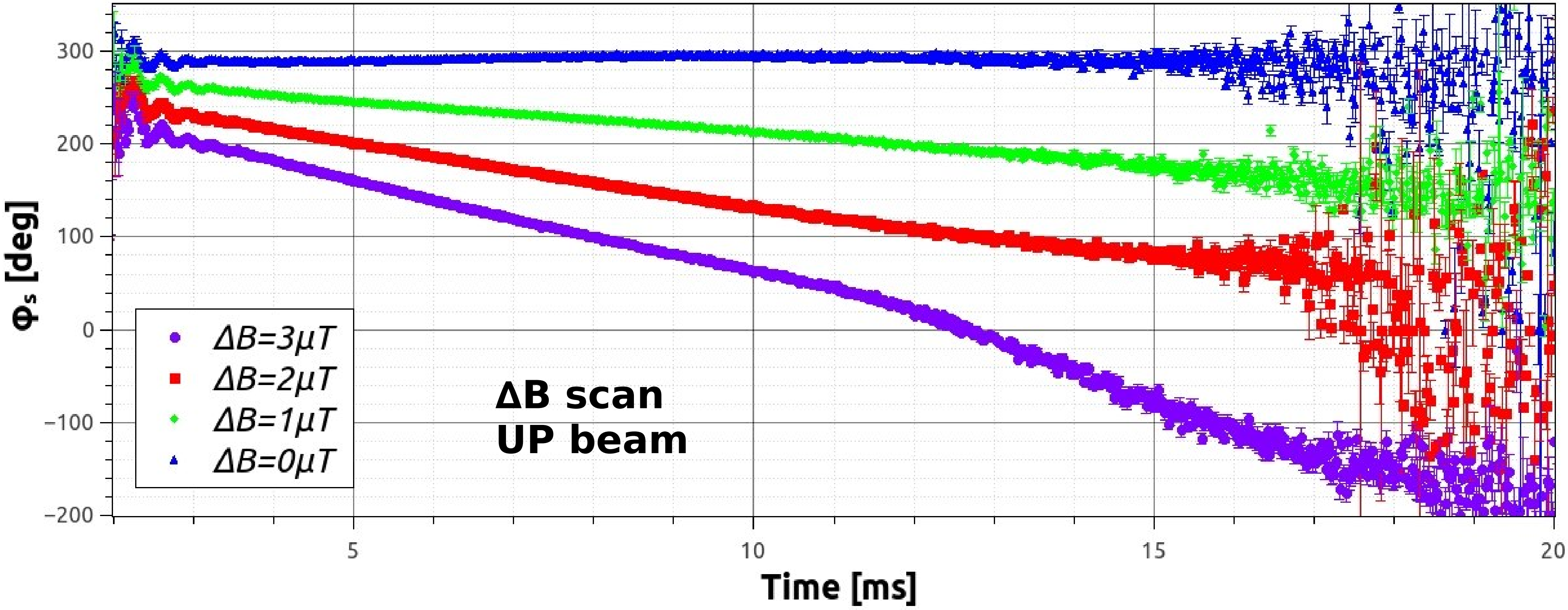
$$\vec{B}_{EDM} = \frac{2 d_n \vec{E}}{\gamma_n \hbar}$$

Off resonance

$$\Delta\vec{B} = \frac{\vec{\omega}_{RF}}{\gamma_n} - \vec{B}$$

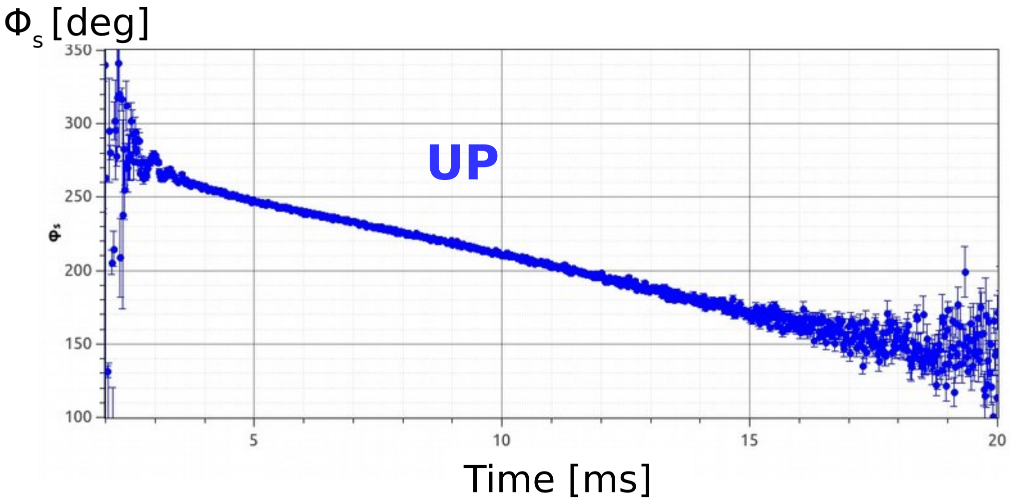
$$\boxed{\begin{aligned}\phi &= -\gamma_n \sum B_i t \\ &= \gamma_n \frac{\ell E_\perp}{c^2} \\ &\quad - \gamma_n \left(B_{EDM} + \Delta B\right) t\end{aligned}}$$

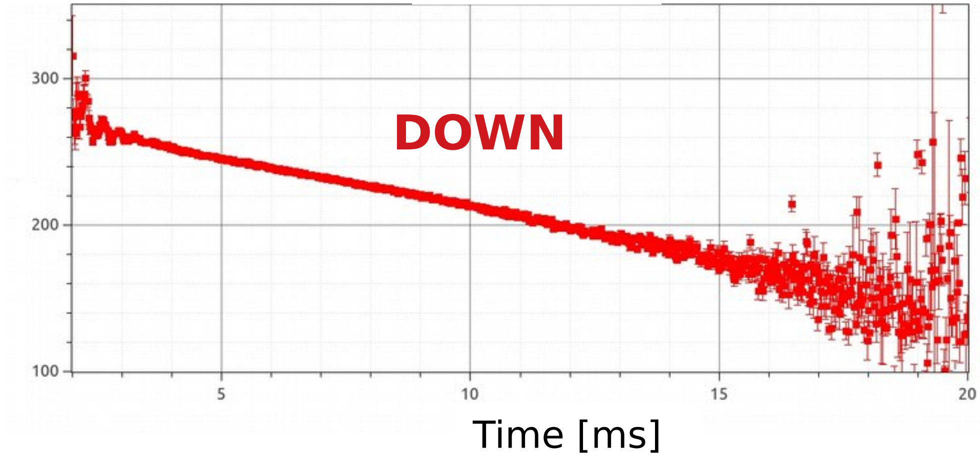
Phase VS TOF

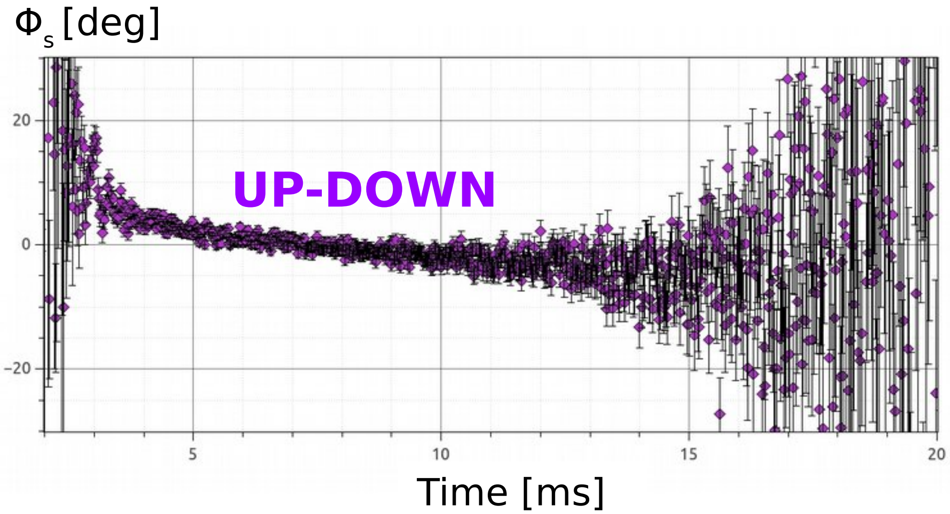


Φs [deg]
300
200
100
0
−100
−200
5
10
15
20
Time [ms]
ΔB=3μT
ΔB=2μT
ΔB=1μT
ΔB=0μT
ΔB scan
UP beam

Case B=124μT


Φ_s [deg]
350
300
250
200
150
100
Φ_s
UP
5
10
15
20
Time [ms]


300
200
100
DOWN
5
10
15
20
Time [ms]


Φ_s [deg]
20
0
−20
UP-DOWN
5
10
15
20
Time [ms]

Conclusion

Up to now:

- Novel technique with pulsed beam
- Design, construction and improvement of the apparatus over 2 years
- 3 Beam times performed
  - → 1st EDM measurement
  - → Several other physics results

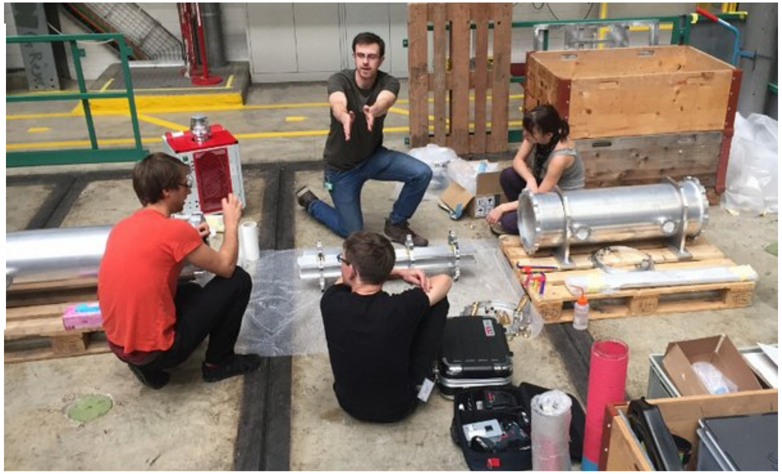
Yet to come:

- Beam time at ILL 2020
  - → Improve B and E
  - → Long EDM measurement
- Opportunity for students
  - → PhD
  - → Master/ bachelor

Beam EDM

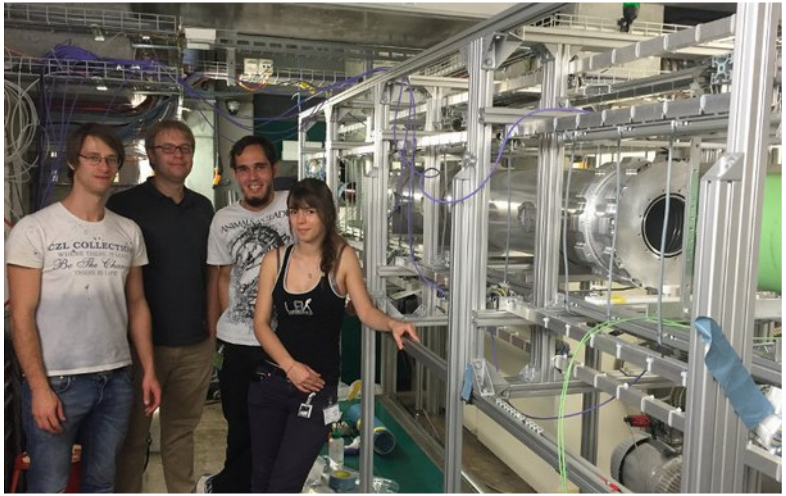
Acknolegements

erc
European Research Council
Established by the European Commission



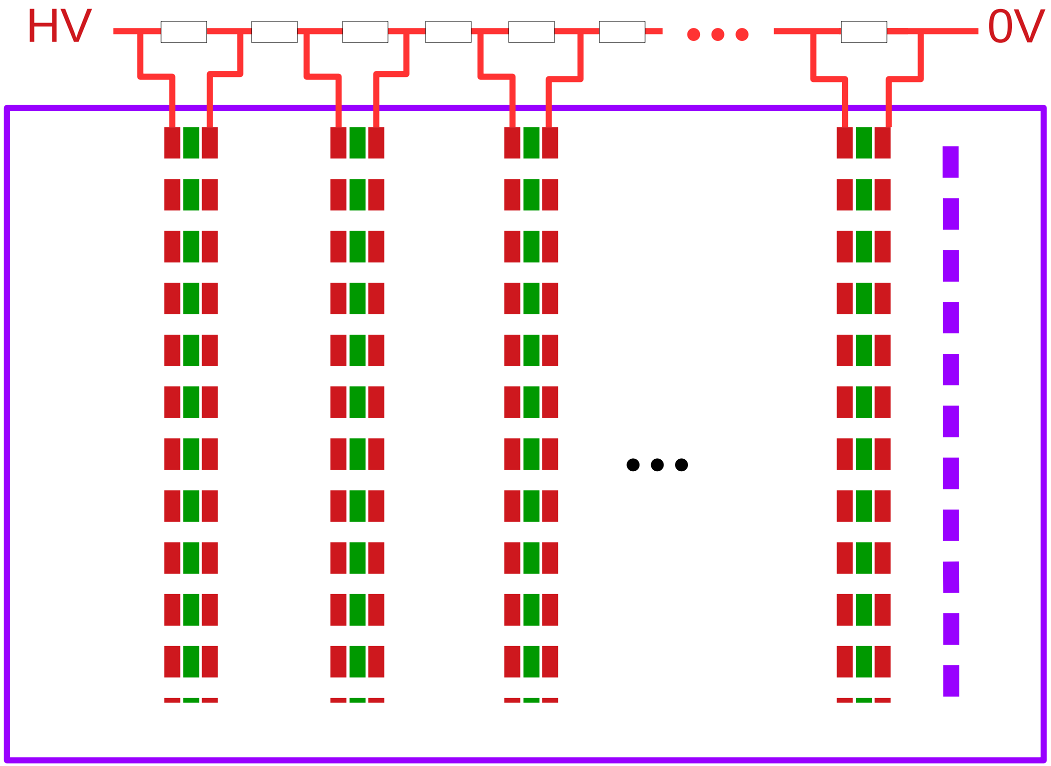
FNSNF

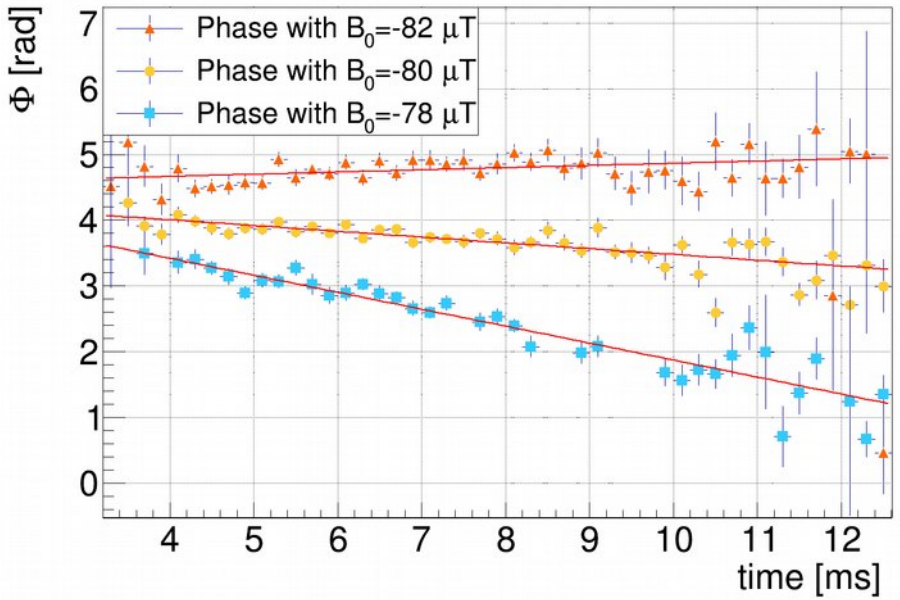
NEUTRONS FOR SOCIETY

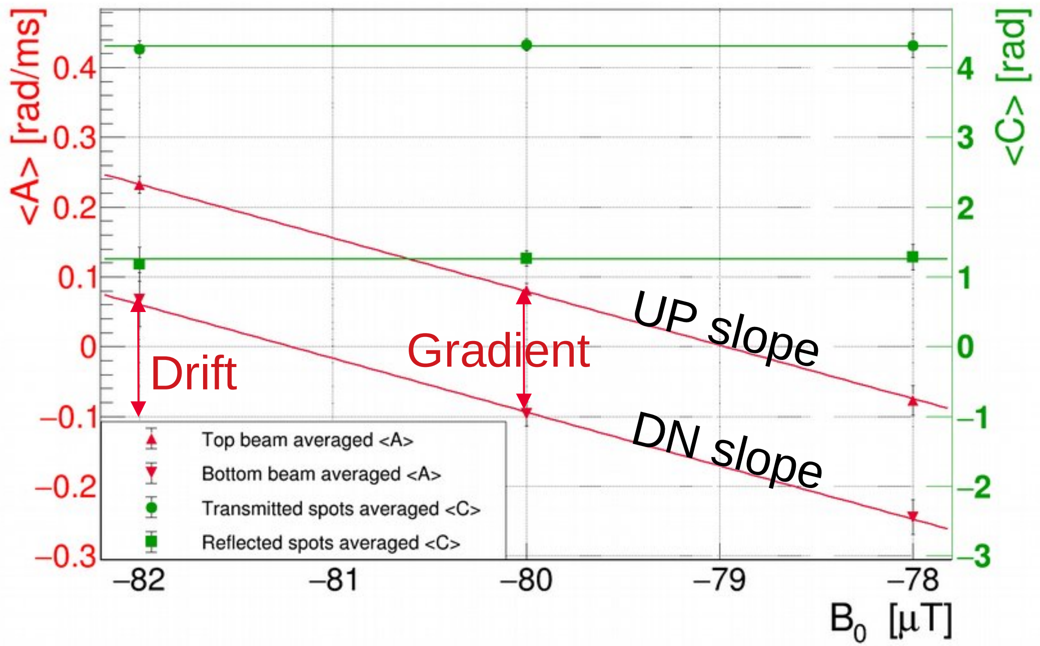


PAUL SCHERRER INSTITUT
PSI

CASCADE Detector



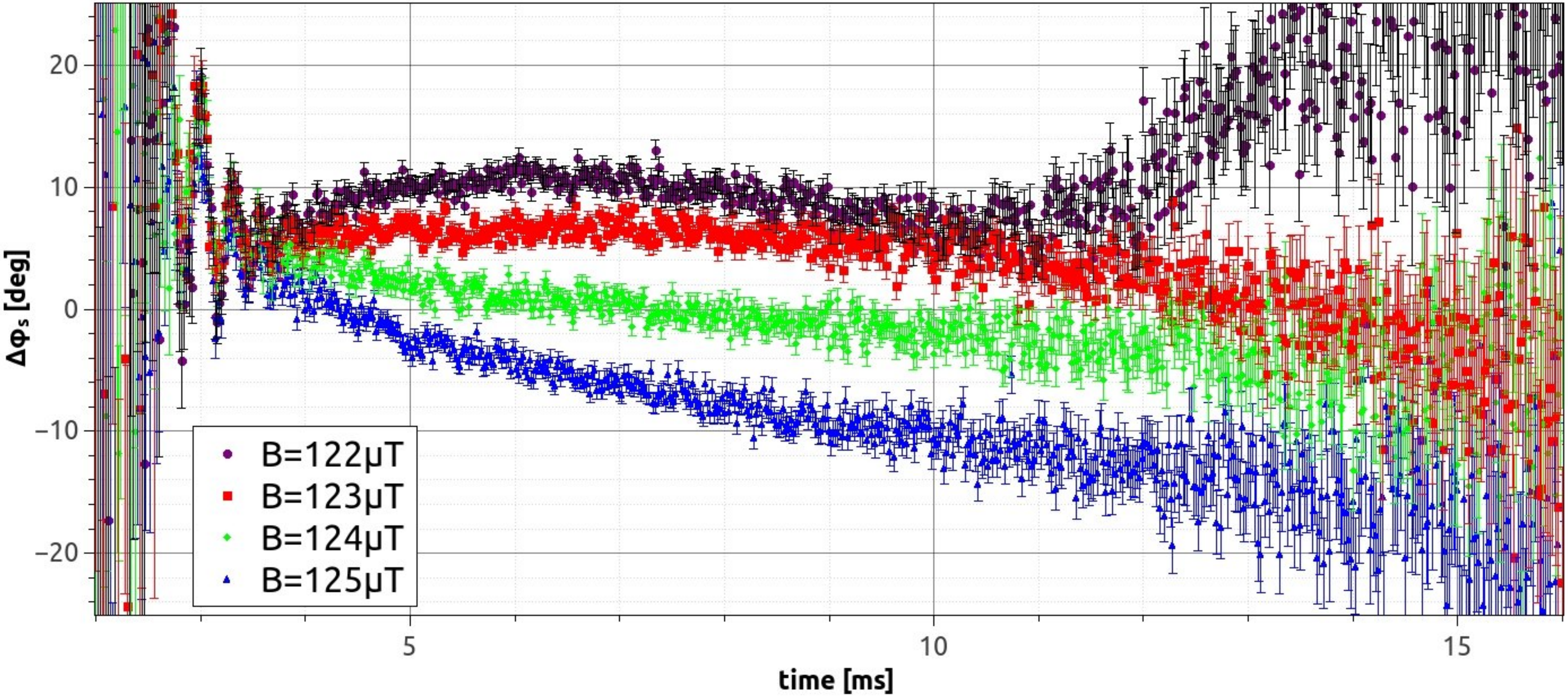




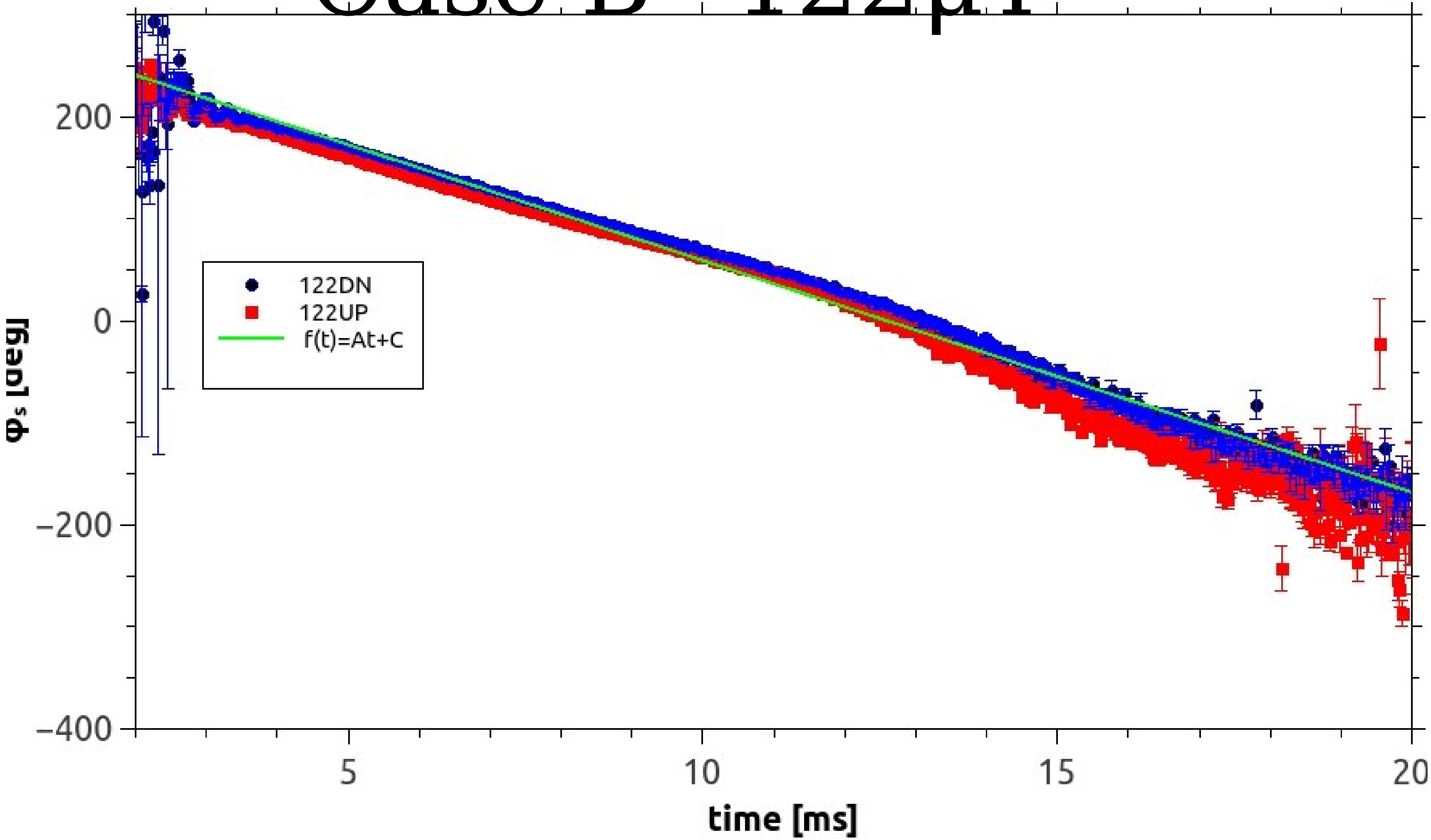
$$\Delta \phi = \gamma_n \sum B_i t_i = \cancel{\gamma_n \frac{L E_\perp}{c^2}} + \gamma_n \left(B_{Grad} + B_{Drift} \right) t_{PR} + \cancel{d_n \frac{E}{\hbar}} t_E$$

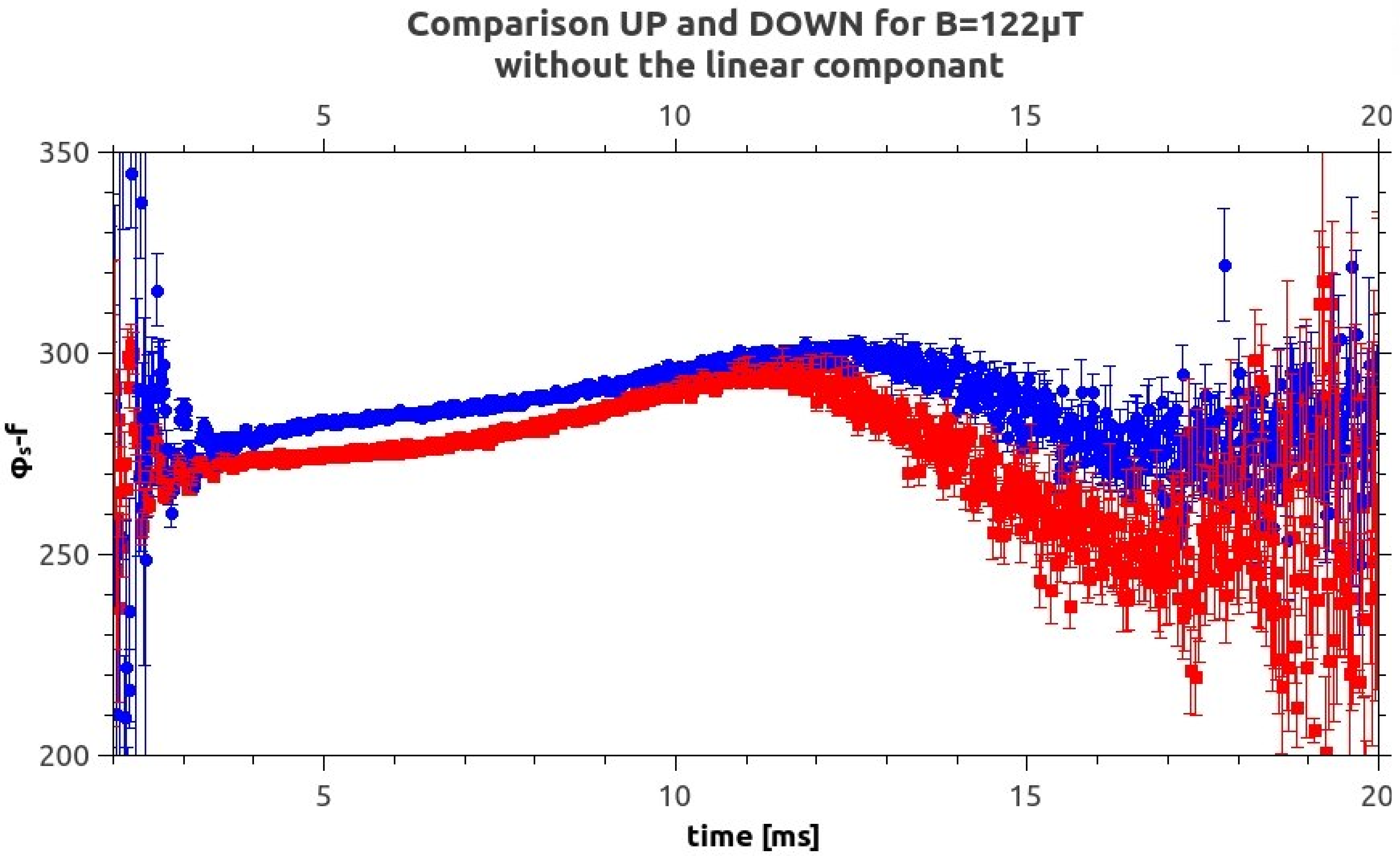
Phase VS TOF

B scan UP -DOWN

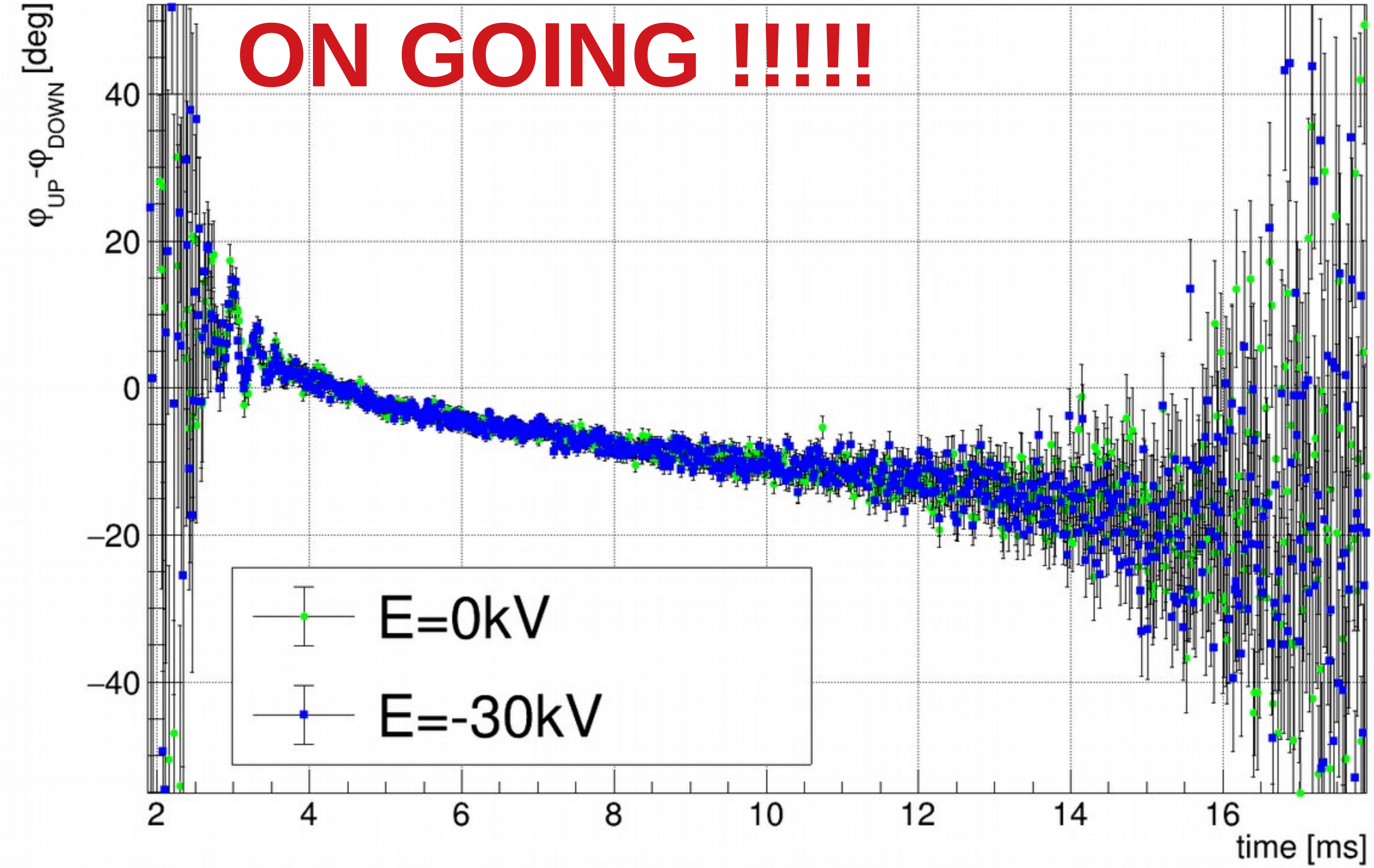


Case B=122μT

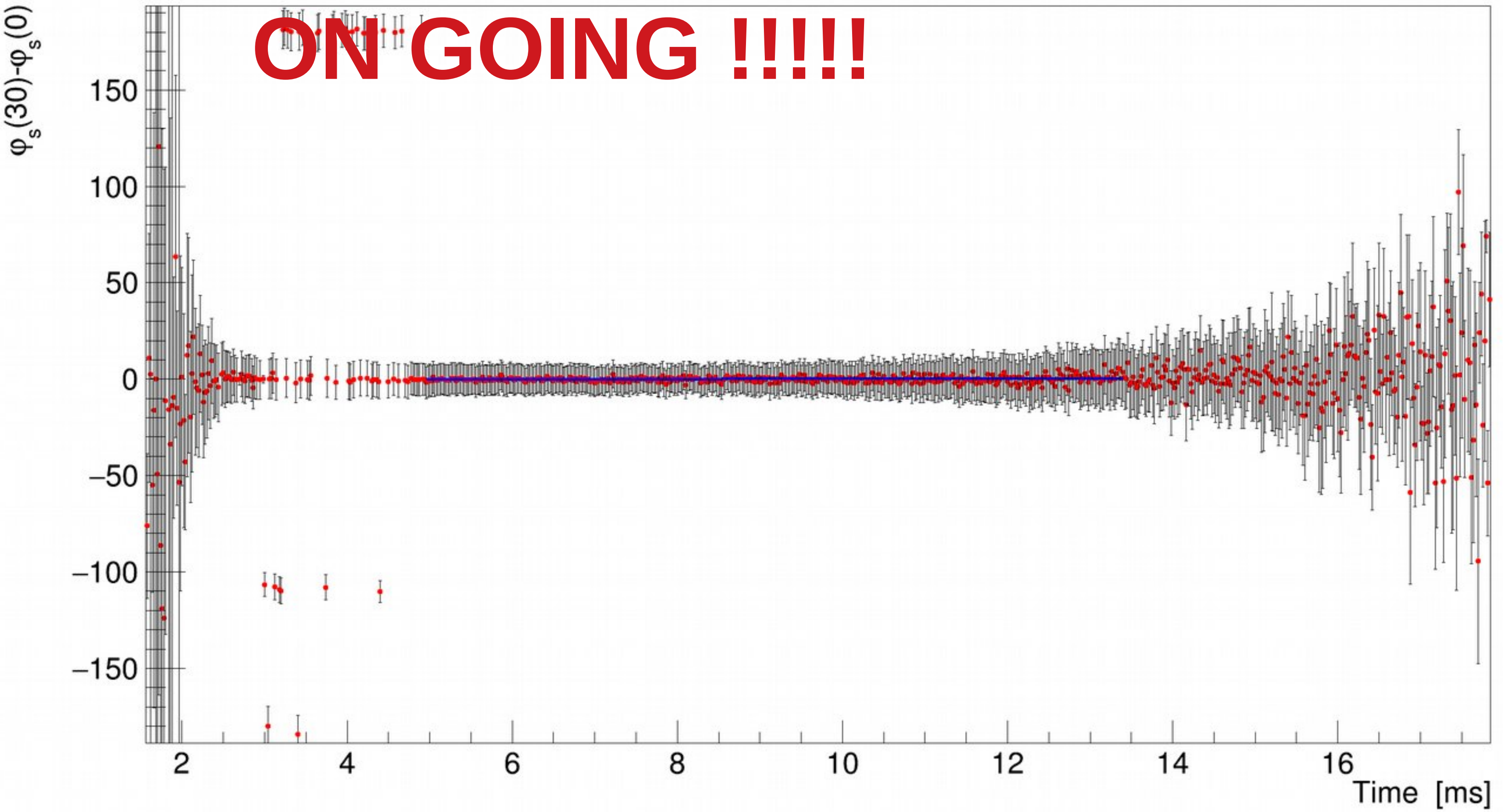



Comparison UP and DOWN for B=122µT
without the linear componant
5
10
15
20
350
300
250
200
φs-f
time [ms]

Beam Time PSI 2018: first EDM measurement

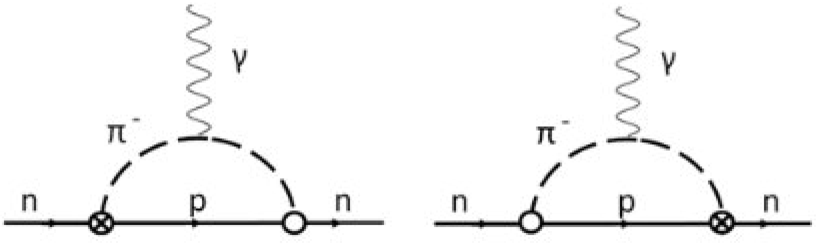


Beam Time PSI 2018: first EDM measurement



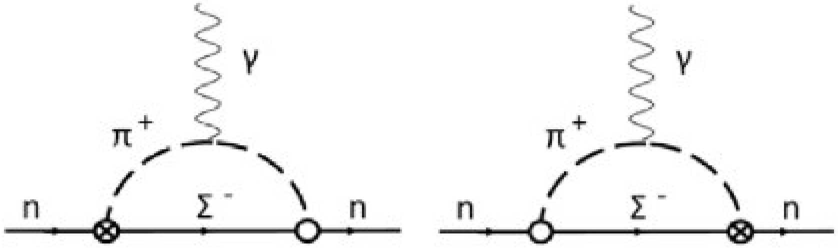
Feynman diagrams stong and weak

STRONG
sector
contribution



(a) **CP** violating 1st vertex (b) **CP** violating 2nd vertex

WEAK
sector
contribution



(a) CP violating 1st vertex (b) CP violating 2nd vertex