Storage Ring Electric Dipole Moment Measurement

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RWTH Aachen & FZ Jülich
on behalf of the JEDI & CPEDM collaboration

Liverpool, January 2020


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North
Atlantic
Ocean
Pavia
Lyon
Bordeaux
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PAPAL
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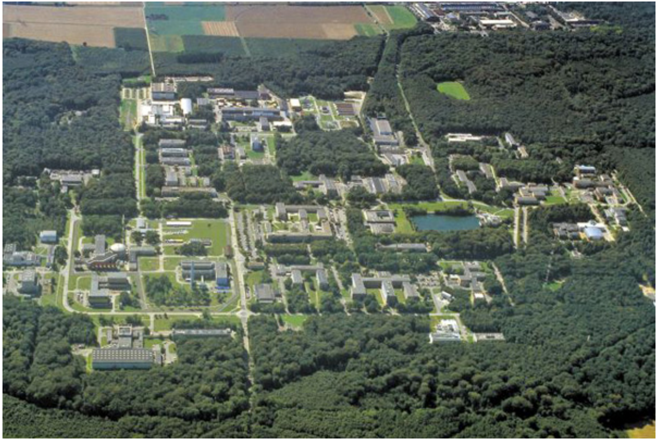
Bay of
Biscay
Rhône
Marseille
Rome
CORSICA
SPANISH
MARCH
MUSLIMS
Mediterranean
Sea
SPOLETO
Barcelona

- RWTH (Rheinisch-Westfälische Technische Hochschule)
- founded in 1870
- 45 000 students (total population 250 000)
- largest technical university in Germany



- one of the largest interdisciplinary research centers in Europe
- 6000 staff members (2000 scientists)
- “Forschungszentrum Jülich works on key technologies for the grand challenges facing society in the fields of information and the brain as well as energy and environment.”

Outline

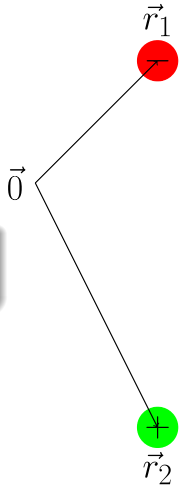
- Introduction & Motivation
  What are Electric Dipole Moments (EDMs)?, What do we know about EDMs?, Why are EDMs interesting?
- Experimental Methods
  How to measure **charged** particle EDMs?
- Towards a storage ring EDM measurement
  How to manipulate and measure a polarization with high precision.

Introduction & Motivation

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$



Order of magnitude

	atomic physics	**hadron physics**
charges	e	
$\|\vec{r}_1 - \vec{r}_2\|$	1 Å$= 10^{-8}$cm	
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	
observed	water molecule	
	$4 \cdot 10^{-9} e \cdot$ cm	

Order of magnitude

	atomic physics	**hadron physics**
charges	e	e
$\|\vec{r}_1 - \vec{r}_2\|$	1 Å$= 10^{-8}$cm	$1\,\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$4 \cdot 10^{-9} e\cdot$ cm	$< 3 \cdot 10^{-26} e\cdot$ cm

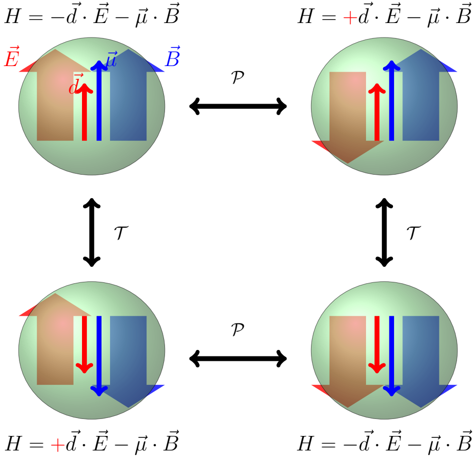
EDM Operator

	E (electric field)	P odd	
classical:	$\vec{d} = e\vec{r}$	P odd	large EDM possible, e.g. molecules with
	$H = -\vec{d} \cdot \vec{E}$	P even	degenerated ground states of different parity
spin	$\vec{d} = d\vec{s}/\lvert\vec{s}\rvert$	P even	
	$H = -\vec{d} \cdot \vec{E}$	P odd	EDM possible if P (and T) violated

$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

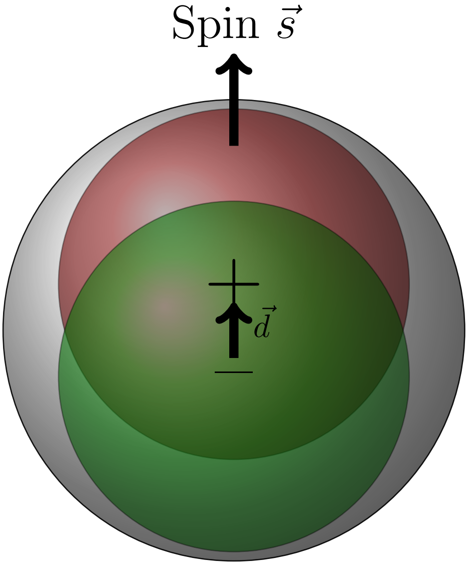
$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment (MDM)
both || to spin $\vec{s}$

	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}-d\frac{\vec{s}}{s}\cdot\vec{E}$
$\mathcal{T}$:	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E}$
$\mathcal{P}$:	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E}$



$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\overset{\mathcal{CPT}}{=}\mathcal{CP})$

Electric Dipole Moments (EDM)

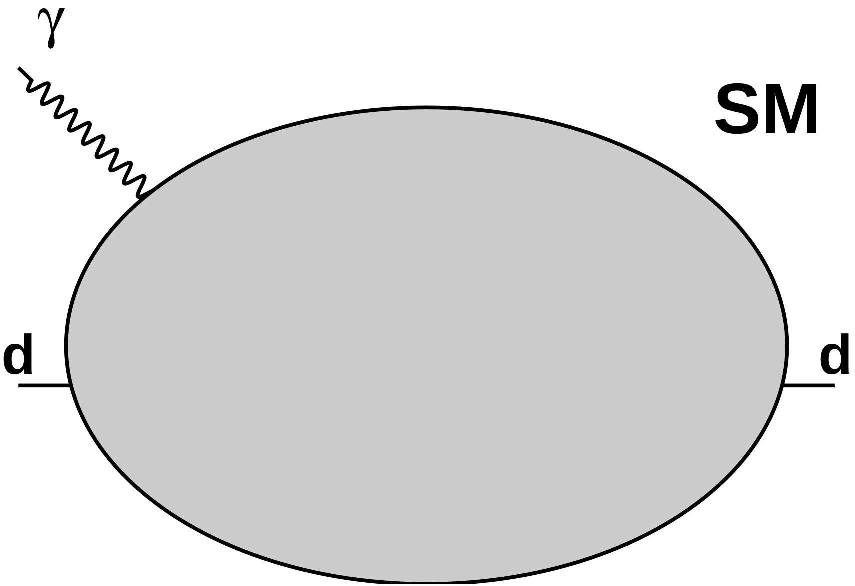


- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \overset{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to "matter-antimatter" asymmetry
- axion field leads to oscillating EDM

$\mathcal{CP}-$Violation & connection to EDMs

Standard Model	
Weak interaction	
CKM matrix	$\rightarrow$ unobservably small EDMs
Strong interaction	
θ_{QCD}	$\rightarrow$ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	$\rightarrow$ accessible by EDM measurements

EDM in SM and SUSY



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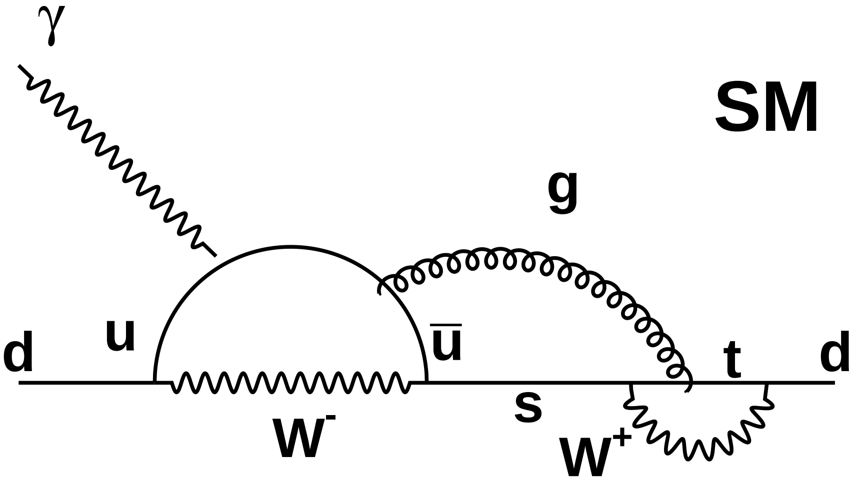

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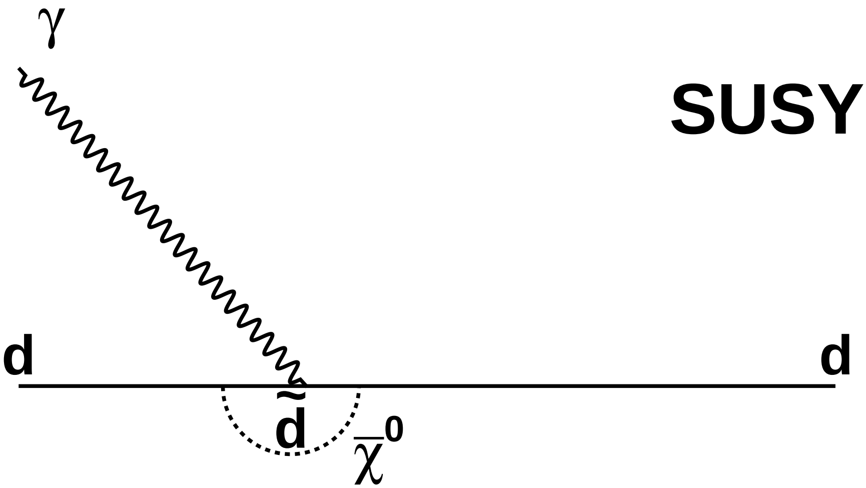
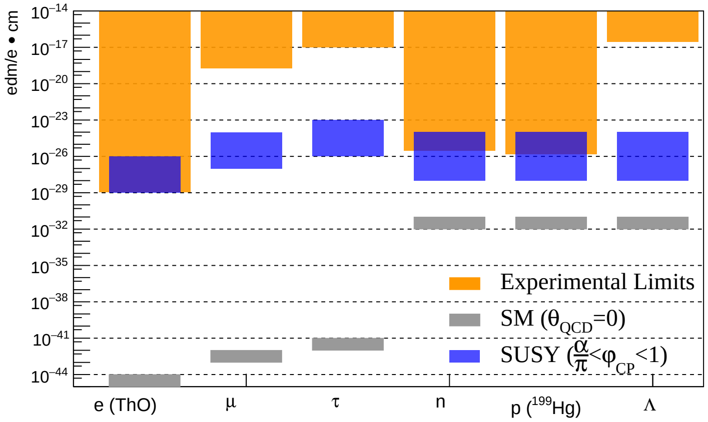
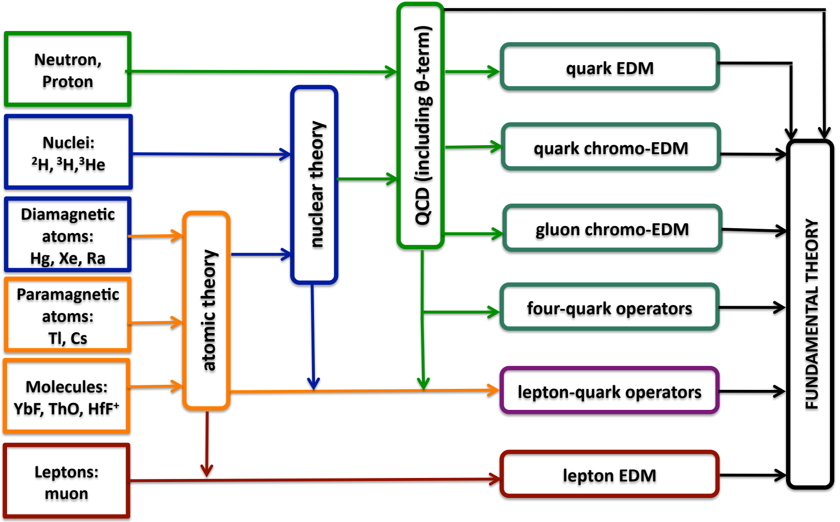


EDM: Current Upper Limits



storage rings: EDMs of **charged** hadrons: *p*, *d*, ^{3}He

Why Charged Particle EDMs?



J. de Vries

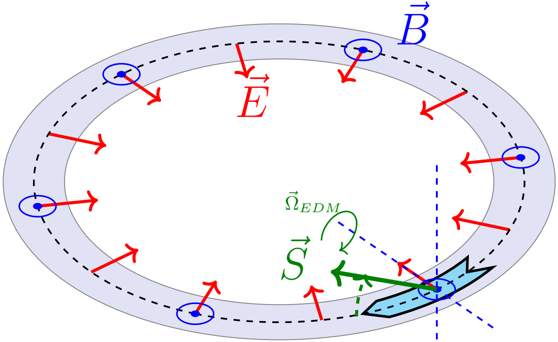
Experimental Methods

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, . . .):

Interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles: apply electric field in a storage ring:



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto d(\vec{E}+\vec{v}\times\vec{B})\times\vec{s}$$

build-up of vertical polarization $s_{\perp} \propto d$, if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**frozen spin**)

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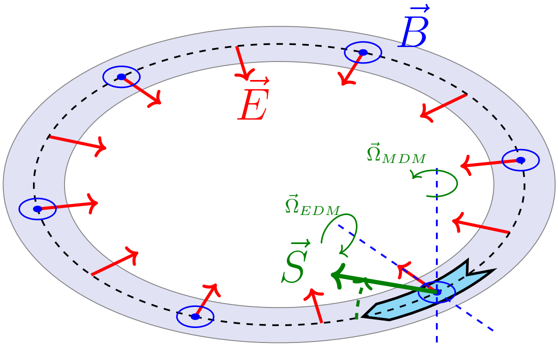


$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto d(\vec{E}+\vec{v}\times\vec{B})\times\vec{s}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega}\times\vec{s}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{\mathrm{horz}}||\vec{p}$ (**frozen spin**)

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{=\vec{\Omega}_{\mathrm{MDM}}} + \underbrace{\frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})}_{=\vec{\Omega}_{\mathrm{EDM}}}\right] \times \vec{s}$$

electric dipole moment (EDM): $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{s}$,

magnetic dipole moment (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$

Note: $\eta = 2 \cdot 10^{-15}$ for $d = 10^{-29}$ecm, $G \approx 1.79$ for protons

Spin Precession: Thomas-BMT Equation

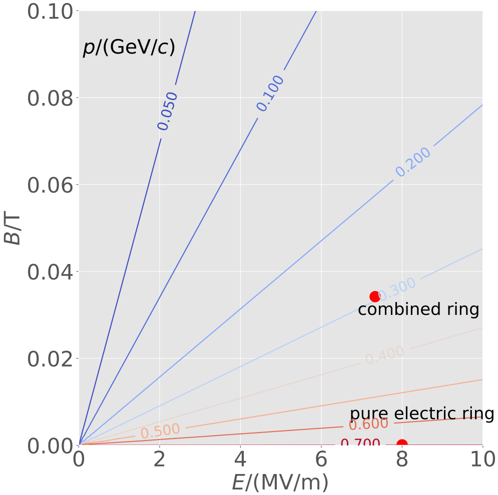
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B}) \right] \times \vec{s}$$

$\underbrace{\qquad\qquad\qquad}$ $\vec{\Omega}_{\mathrm{MDM}} = 0\,,$ **frozen spin**

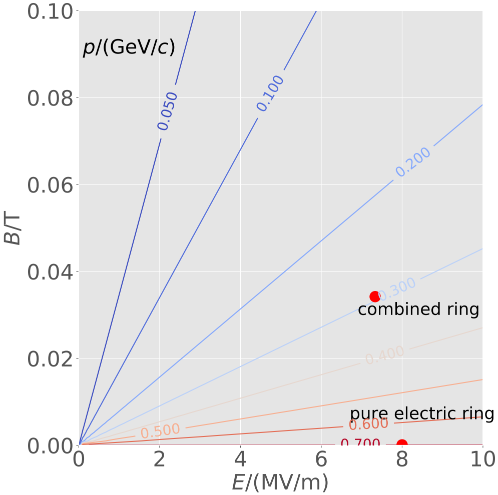
achievable with pure electric field if $G = \frac{1}{\gamma^2 - 1}$, works only for $G > 0$, e.g. proton

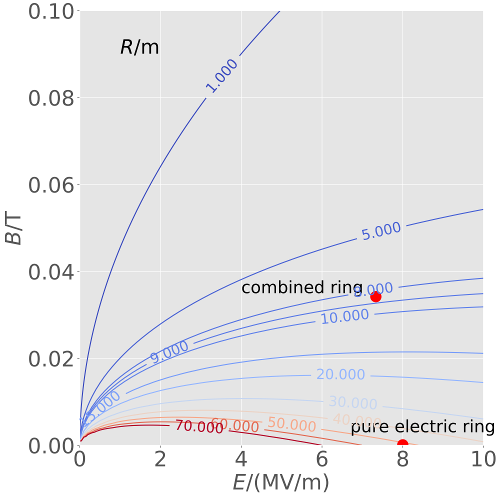
or with special combination of E, B fields and γ, i.e. momentum

Momentum and ring radius for proton in frozen spin condition



Momentum and ring radius for proton in frozen spin condition





Different Options

	☺	☹
1.) pure electric ring	no $\vec{B}$ field needed, $\circlearrowleft$, $\circlearrowright$ beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for p, d, ^{3}He, smaller ring radius	both $\vec{E}$ and $\vec{B}$ B field reversal for $\circlearrowleft$, $\circlearrowright$ required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to G, i.e. no **frozen spin**

Statistical Sensitivity

beam intensity	$N = 4 \cdot 10^{10}$ per fill
polarization	$P = 0.8$
spin coherence time	$\tau = 1000\,\mathrm{s}$
electric fields	$E = 8\,\mathrm{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

$$\sigma_{\text{stat}} \approx \frac{2\hbar}{\sqrt{N f \tau} P A E} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 2.4 \cdot 10^{-29}\, e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

Systematic Sensitivity

signal: $\Omega_{\text{EDM}} = \frac{dE}{s\hbar} = 2.4 \cdot 10^{-9}\,\text{s}^{-1}$ for $d = 10^{-29}\,e\,\text{cm}$

- radial B-field of $B_r = 10^{-17}\,\text{T}$:
  $\Omega_{B_r} = \frac{eGB_r}{m} = 1.7 \cdot 10^{-9}\,\text{s}^{-1}$
- geometric Phases (non-commutation of rotations), $B_{\text{long}}, B_{\text{vert}} \approx 1\text{nT}$
  $\Omega_{\text{GP}} = \left(\frac{eGB}{16m}\right)^2 \frac{1}{f_{\text{rev}}} = 3.7 \cdot 10^{-9}\,\text{s}^{-1}$
- General Relativity:
  $\Omega_{\text{GR}} = -\frac{\gamma}{\gamma^2+1}\frac{\beta g}{c} = -4.4 \cdot 10^{-8}\text{s}^{-1}$
- ...

Systematic Sensitivity

Remedy:

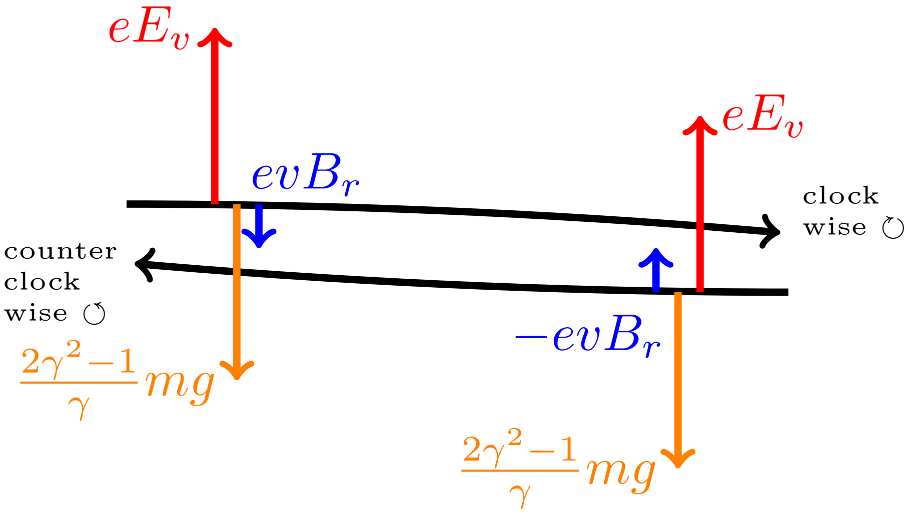
$$
\begin{aligned}
\circlearrowright: \quad \Omega_{\mathrm{CW}} &= \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}} + \Omega_{B_r}\,, \\
\circlearrowleft: \quad \Omega_{\mathrm{CCW}} &= \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} - \Omega_{\mathrm{GR}} + \Omega_{B_r}\,.
\end{aligned}
$$

$\Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}}$ drops out in sum, $\Omega_{\mathrm{CW}} + \Omega_{\mathrm{CCW}}$, effect of B_r can be subtracted by observing displacement of the two beams.

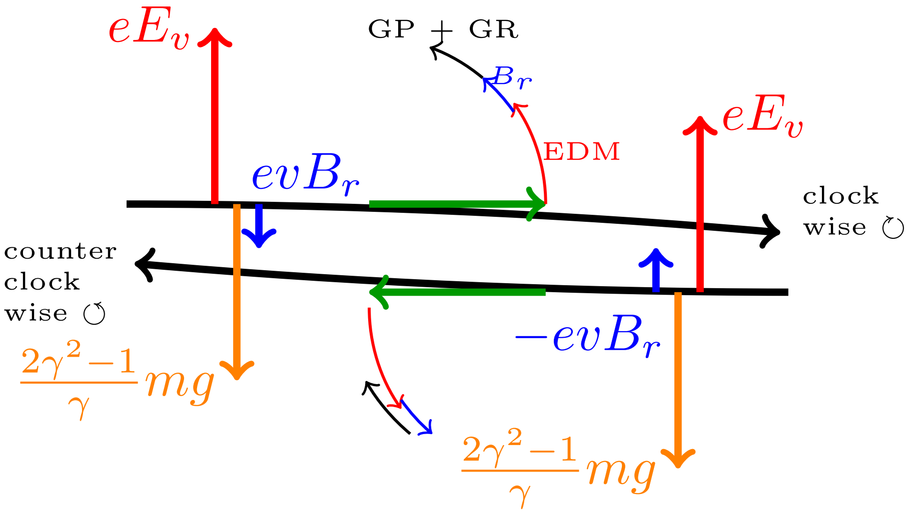
Conclusion:

Statistically one can reach sensitivity of $\approx 10^{-29}\,e\,\mathrm{cm}$, many systematic effects can be controlled using $\circlearrowleft$ and $\circlearrowright$ beams, needs further investigation
$\rightarrow$ **staged approach**

Systematics



Systematics



Towards an storage ring EDM measurement

Staged approach

Stage 1

precursor experiment

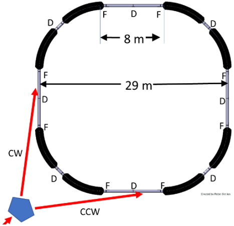
at Cooler Synchrotron COSY

- magnetic storage ring

now

Stage 2

prototype ring

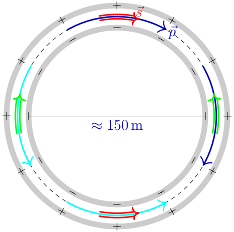


- initially electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

dedicated storage ring



- magic momentum

(701 MeV/c)

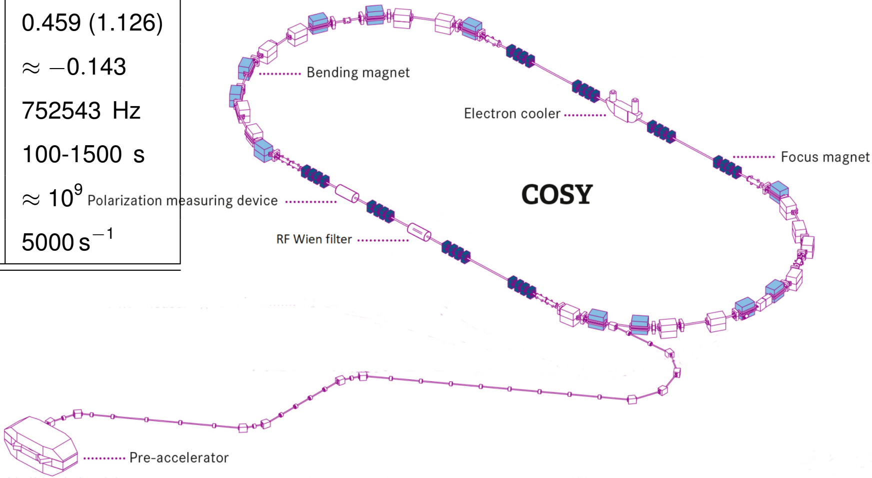
10 years

$\sigma_{EDM}/(e \cdot \mathrm{cm})$

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

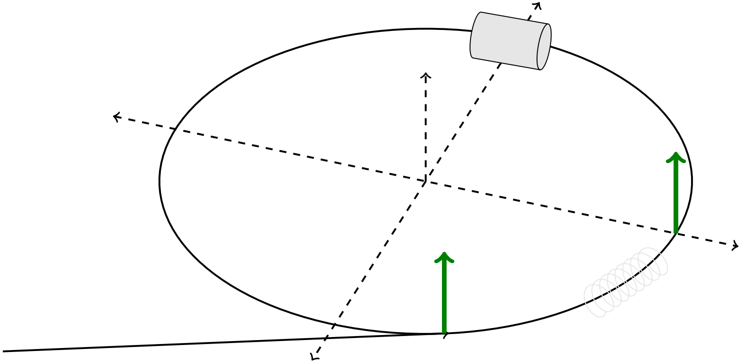
Stage 1: Precursor Experiment

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{rev}	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$
event rate at $t = 0$	5000 s^{-1}



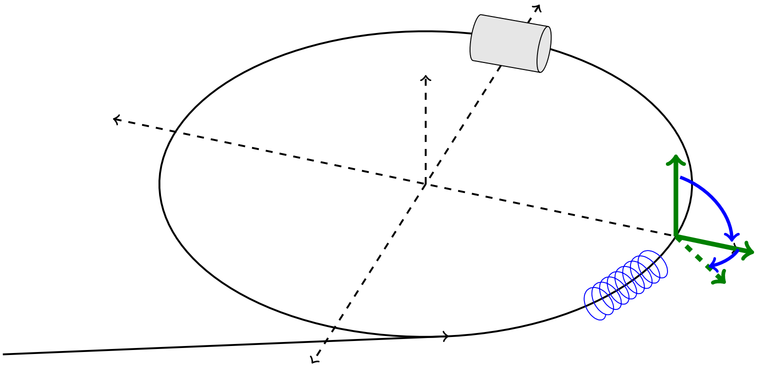
Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c



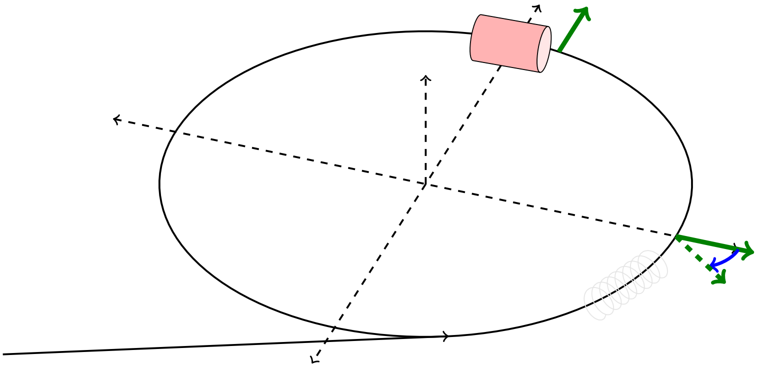
Experimental Setup at COSY

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts



Experimental Setup at COSY

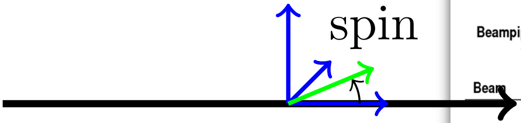
- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in $\approx$ 100-1000 s) on target
- Measure asymmetry and determine spin precession

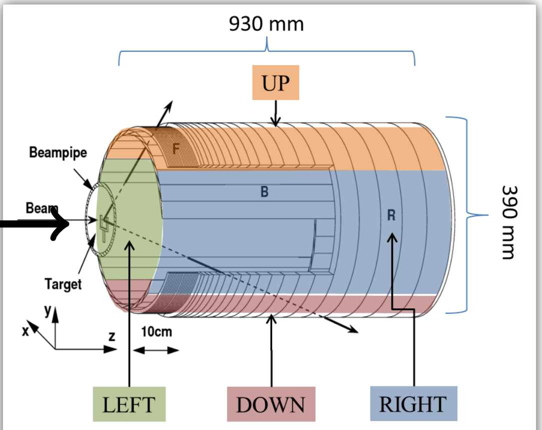


Polarimeter

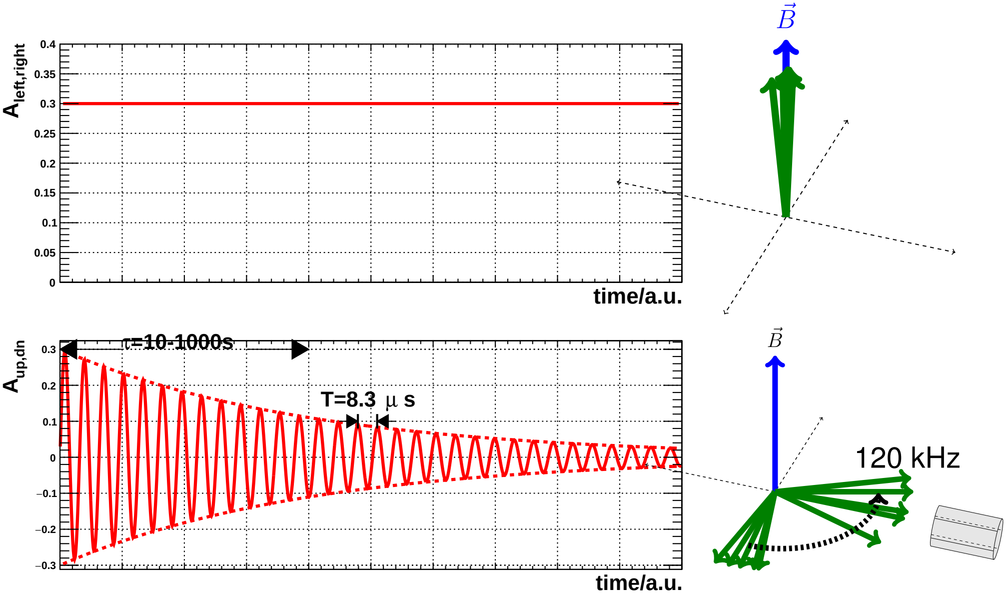
elastic deuteron-carbon scattering,
consists of four scintillator segments: left, right, up, down

asymmetry $A_{up,down} \propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
asymmetry $A_{left,right} \propto$ vertical polarization $\rightarrow d$



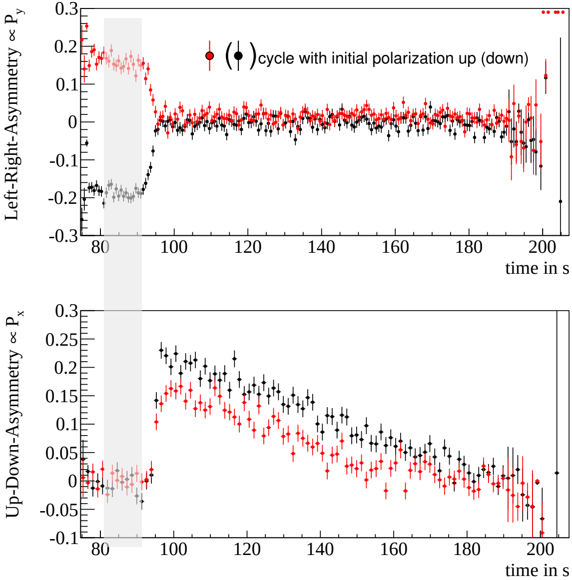


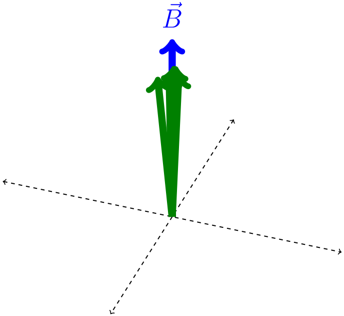
Asymmetries



Polarization Flip

envelope of





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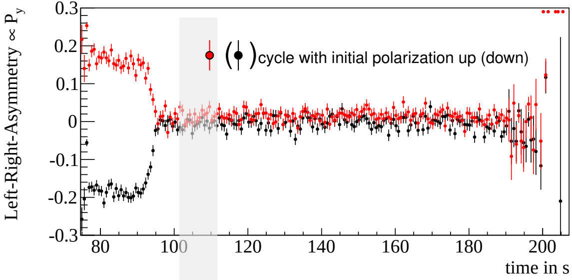

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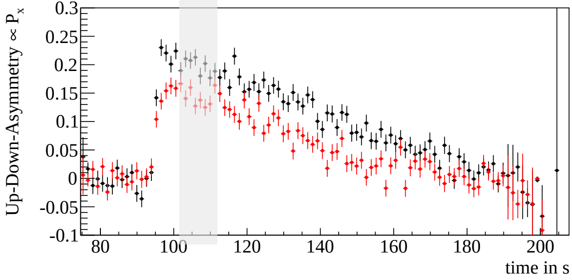

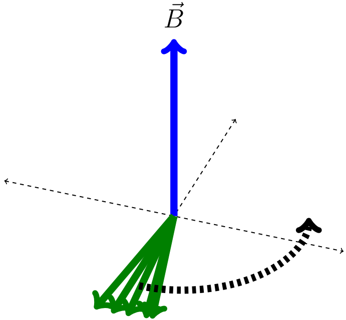

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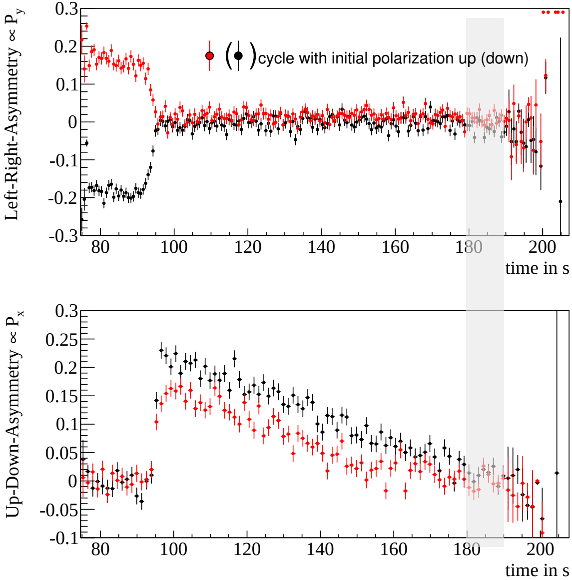
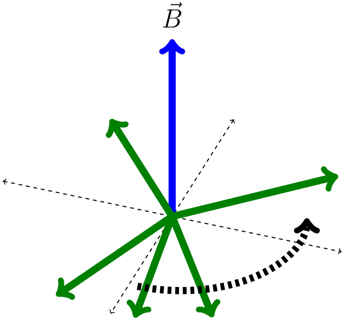
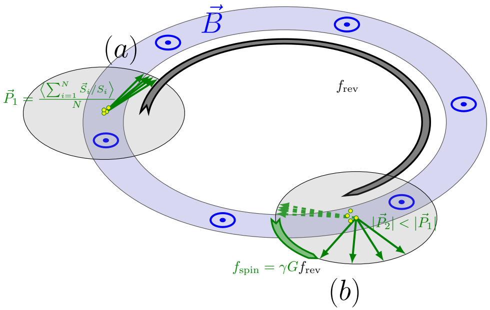
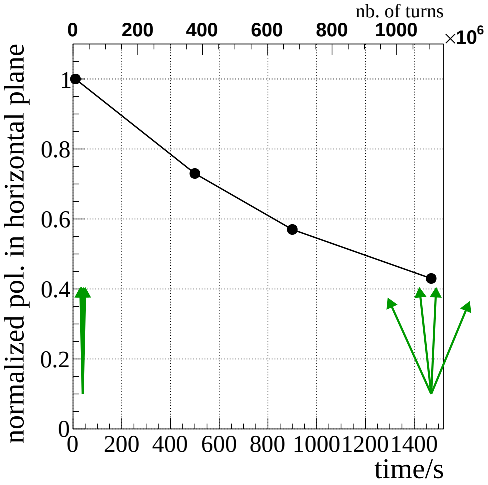




Long Spin Coherence Time (SCT)

Long Spin Coherence time $>$ 1000 s reached





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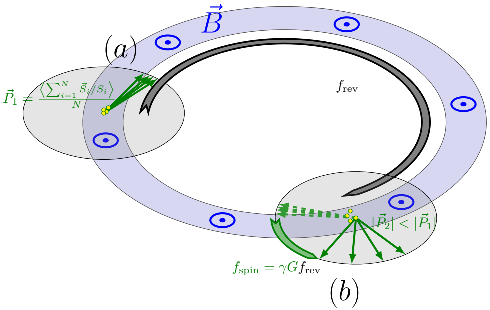
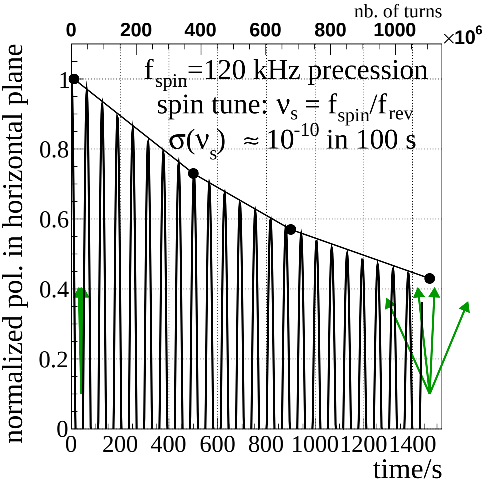
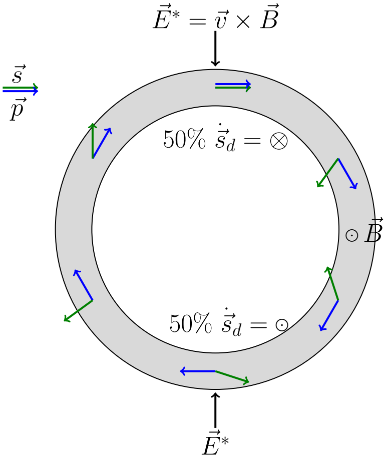




Principle of EDM measurement at magnetic storage ring

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.



E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

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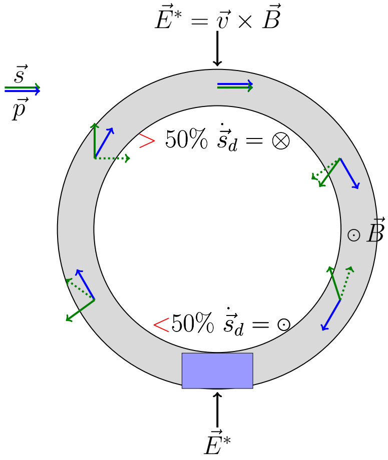
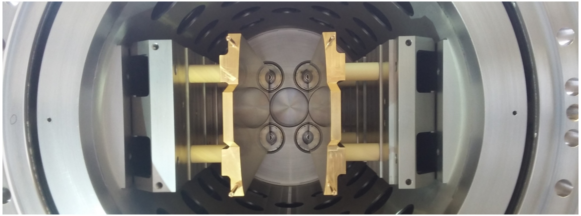
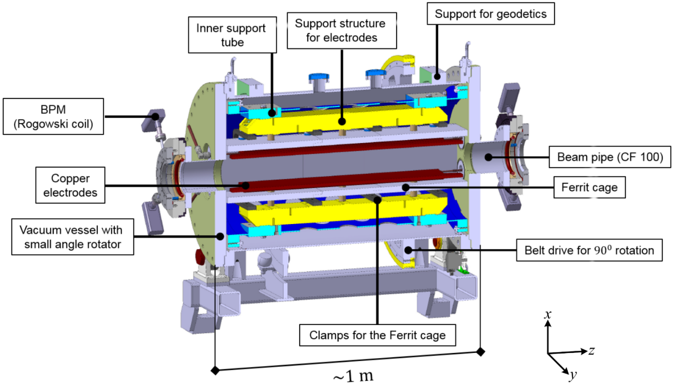


E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

Use resonant "magic Wien-Filter" in ring ($\vec{E}_W + \vec{v} \times \vec{B}_W = 0$):
$E^*_W = 0 \rightarrow$ part. trajectory is not affected but
$B^*_W \neq 0 \rightarrow$ mag. mom. is influenced
$\Rightarrow$ **net EDM effect can be observed!**

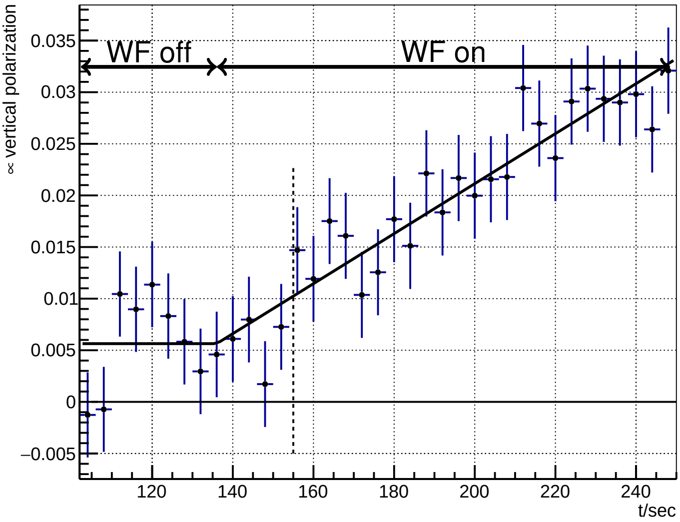
Wien filter





- field: $2.7 \cdot 10^{-2}$Tmm for 1kW input power
- frequency range: 100 kHz-2MHz

Observation of polarization build-up

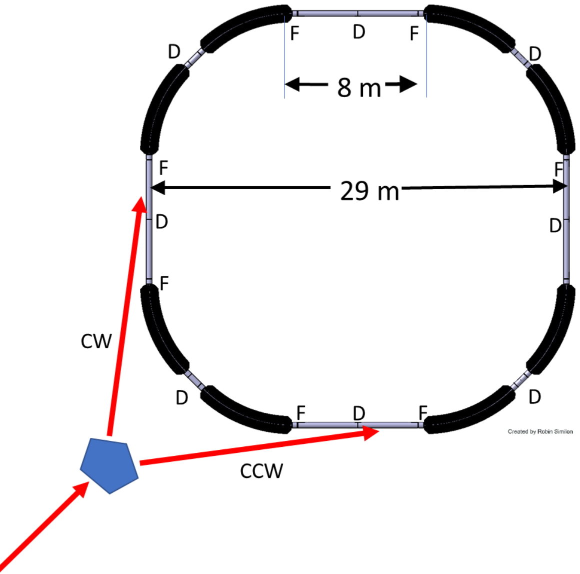


- polarization build-up proportional to EDM . . . and many perturbations
- perturbations are under investigation

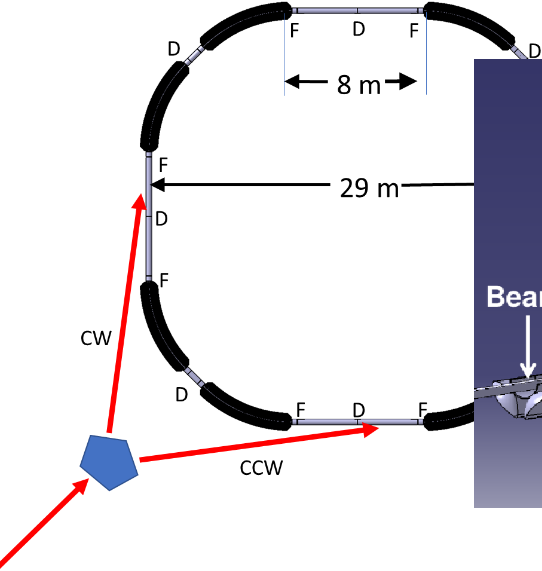
Stage 2: Prototype Ring

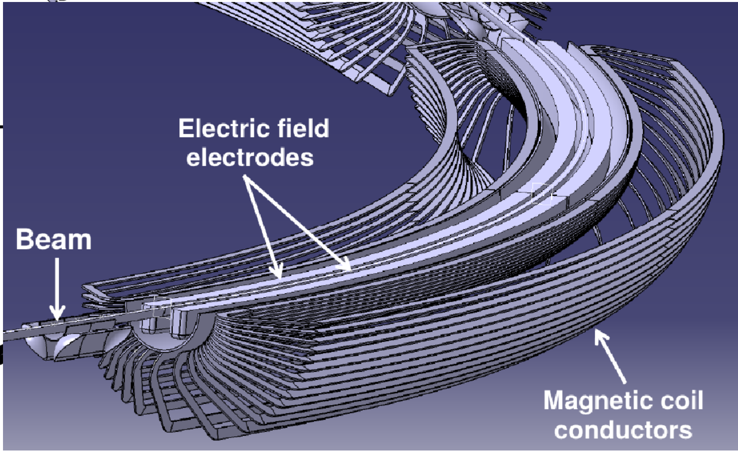
- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding ...
- perform EDM measurement

Ring Lattice & Bending Element



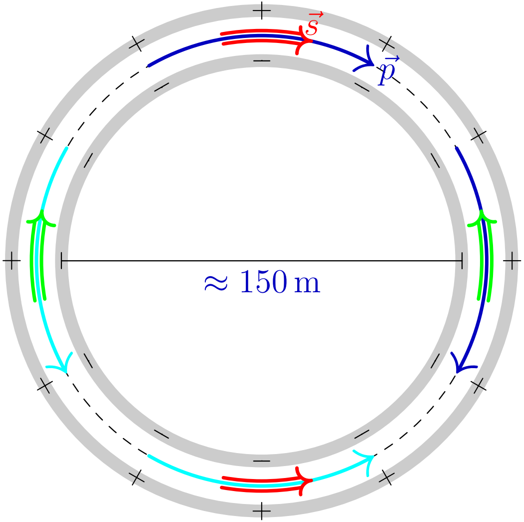
Ring Lattice & Bending Element





Stage 3: Dedicated Ring

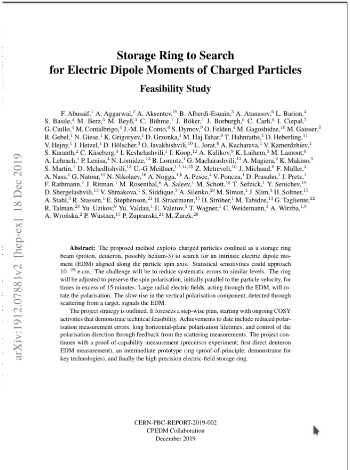
- pure electric ring:
  frozen spin ($p = 701$ MeV/c E_{kin}=233 MeV):



Collaborations

- **J**ülich **E**lectric **D**ipole Moment **I**nvestigations activities at Cooler Synchrotron COSY in Jülich
- CPEDM collaboration (CERN,JEDI,Korea, . . .) prototype/dedicated ring

Document submitted to ESPP in Dec. 2018
http://arxiv.org/abs/1912.07881



arXiv:1912.07881v2 [hep-ex] 18 Dec 2019

Storage Ring to Search
for Electric Dipole Moments of Charged Particles

Feasibility Study

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Abstract: The proposed method exploits charged particles confined as a storage ring beam (proton, deuteron, possibly helium-3) to search for an intrinsic electric dipole moment (EDM) aligned along the particle spin axis. Statistical sensitivities could approach 10^{-29} e.cm. The challenge will be to reduce systematic errors to similar levels. The ring will be adjusted to preserve the spin polarisation, initially parallel to the particle velocity, for times in excess of 15 minutes. Large radial electric fields, acting through the EDM, will rotate the polarisation. The slow rise in the vertical polarisation component, detected through scattering from a target, signals the EDM.

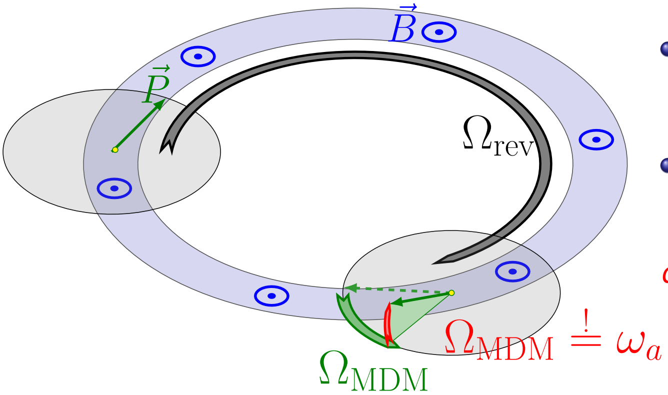
The project strategy is outlined. It foresees a step-wise plan, starting with ongoing COSY activities that demonstrate technical feasibility. Achievements to date include reduced polarisation measurement errors, long horizontal-plane polarisation lifetimes, and control of the polarisation direction through feedback from the scattering measurements. The project continues with a proof-of-capability measurement (precursor experiment; first direct deuteron EDM measurement), an intermediate prototype ring (proof-of-principle; demonstrator for key technologies), and finally the high precision electric-field storage ring.

CERN-PBC-REPORT-2019-002
CPEDM Collaboration
December 2019

Activities

- required for first EDM measurement:
  - maximize spin coherence time (SCT)
  - precise measurement of spin precession (spin tune)
  - polarisation feed back
  - RF- Wien filter
- to reduce systematic errors:
  - development of high precision beam position monitors
  - beam based alignment
- Interpretation of results:
  - spin tracking simulation (measured polarisation $\rightarrow$ EDM)
  - theory (pEDM, dEDM, eEDM, $\ldots \rightarrow$ underlying theory)
- Design of dedicated storage ring:
  - accelerator lattice
  - polarimeter development
  - development of electro static deflectors
- other observables:
  - axion searches
    (axions may lead to oscillating EDM)

Principle of storage ring axion experiment

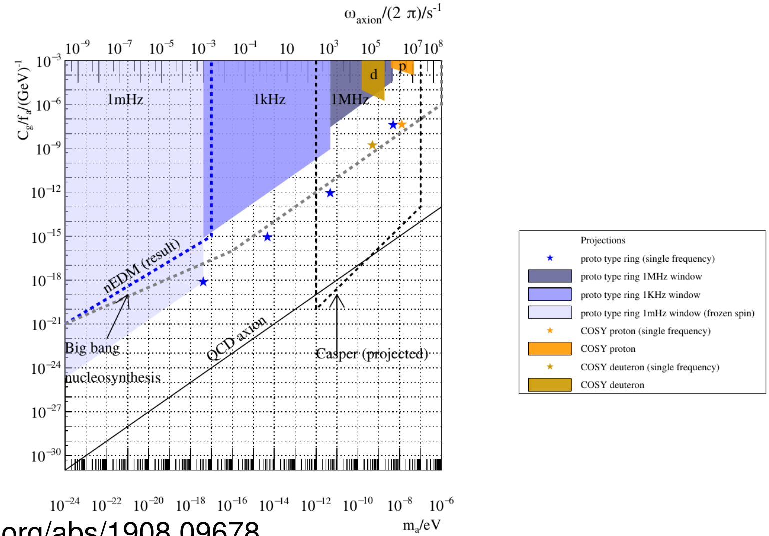


- Axion field gives rise to an effective time-dependent θ-term
- This gives rise to an oscillating electric dipole moment EDM d.

$$d = d_{DC} + d_{AC}\sin(\omega_a t + \varphi_a)$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

Axion Search



http://arxiv.org/abs/1908.09678

Summary

- EDMs are unique probe to search for new CP-violating interactions (and contribute to axion searches)
- **charged** particle EDMs can be measured in storage rings
- staged approach:
  precursor at COSY $\rightarrow$ prototype (100 m) $\rightarrow$ dedicated ring (500 m)

erc European Research Council

Spare

Connection to cosmology

Excess of matter in the universe:

	observed	SCM* prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

$\Rightarrow$ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

Momentum and ring radius for deuteron in frozen spin condition