Storage Rings for the Search of Charged Particle Electric Dipole Moments

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Motivation

Addressing the most intriguing puzzles of contemporary physics

Problems

- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

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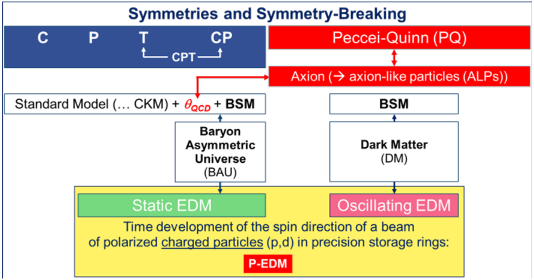
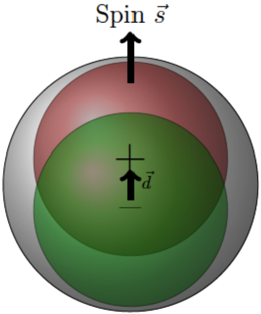
Approach

- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM



Electric Dipole Moment (EDM)



- Permanent separation of + and - charge
- Fundamental property of particles (like magnetic moment, mass, charge)
- Possible via violation of time-reversal (T) and parity (P)

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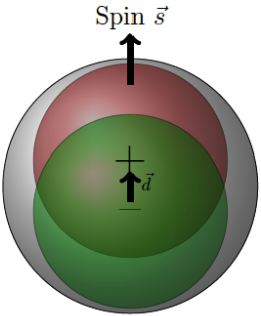

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EDM meas. test violation of P and T and ($\stackrel{CPT}{=}$ CP)

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

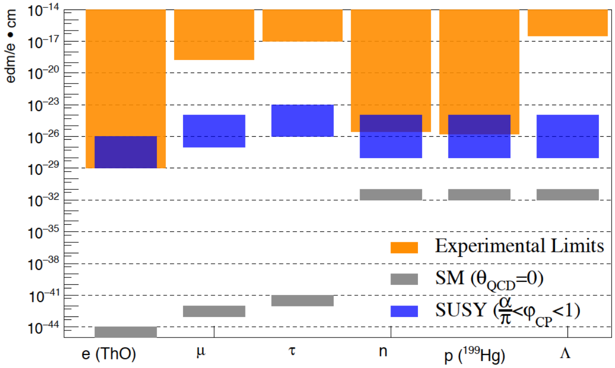
- Excess of Matter in the Universe:

	observed	SM prediction
$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

- Sacharov (1967): CP-violation needed for baryogenesis

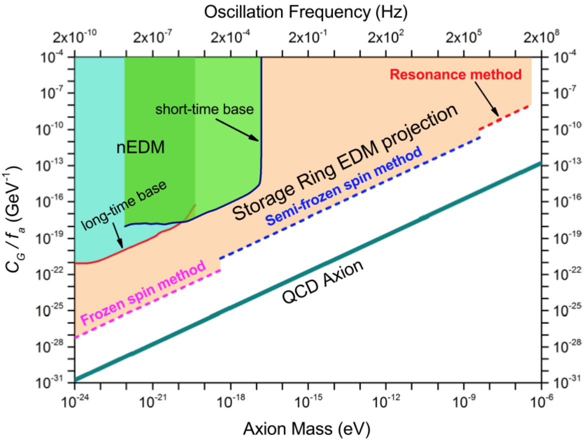
- $\Rightarrow$ New CP-V sources beyond SM needed
- Could show up in EDMs of elementary particles

STATIC EDM: current upper limits



- Objective: EDMs of charged hadrons: p, d, ^{3}He
  - Note: current limit on p-EDM: $2.0 \times 10^{-25} e \cdot cm$ (ind. from $d_p^{\downarrow 199Hg}$)
- Final goal: to bring the limit on p to 10^{-29} e · cm

OSCILLATING EDM: axion mass vs gluon coupling



[S. P. Chang et al. Phys. Rev. D 99, 083002]

- Experimental limits for the axion-gluon coupled oscillating EDM measurement.

Why Charged Particle EDMs?

- No direct measurement for charged hadron EDMs
- Potentially higher sensitivity (compared to neutrons):
  - no lifetime limitation;
  - more particles ($\rightarrow$ better statistics), different systematics;
  - required to deduce EDM source(s);
- complementary to neutron EDM:

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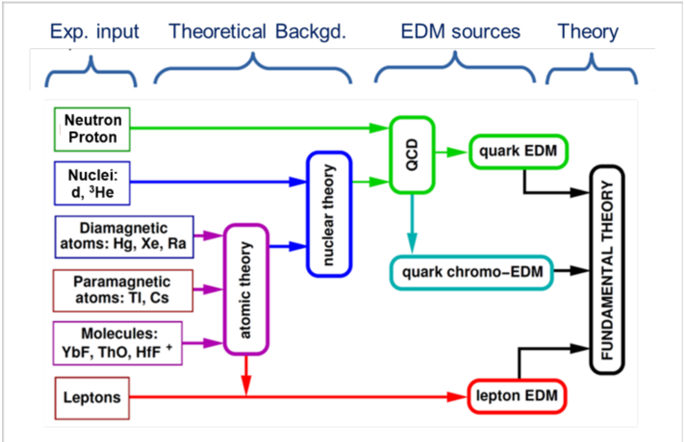
EDM of single particle not sufficient to identify CP-V source

Sources of CP Violation



Experimental method

Spin Precession in a storage ring

Thomas-BMT equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = [(\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) - \vec{\Omega}_{cycl}] \times \vec{s} =$$

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

- Mag. dip. mom. (MDM): $\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$ (G=1.79 for proton)
- El. dip. mom. (EDM): $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{s}$ ($\eta = 2 \cdot 10^{-15}$ for d= $10^{-29} e \cdot cm$)

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Frozen spin

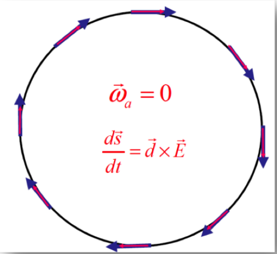
$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\Omega_{MDM}-\Omega_{cycl}=0 \rightarrow \textbf{frozenspin}} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right] \times \vec{s}$$

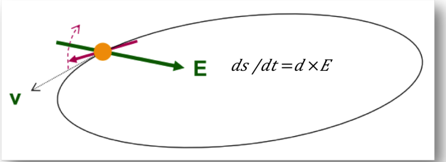
- Achievable with pure electric field for proton (G > 0): $G = \frac{1}{\gamma^2 - 1}$
- Requires special combination of E, B fields and γ for d, ^3He (G < 0)

Search for static EDM in storage rings

Measurement concept

1. Inject particles in storage ring
2. Align spin along momentum ($\rightarrow$ freeze horiz. spin-precession)
3. Search for time development of vertical polarization





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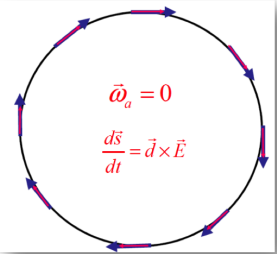
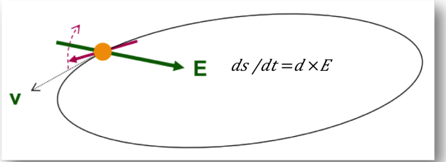
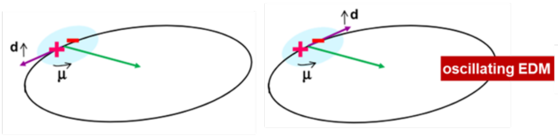




Frozen-spin condition:

- Pure E ring for *p*
- Combined E/B ring for *d* and ^{3}He

Search for oscillating EDM in storage rings



$$\vec{d} = \eta \frac{q\hbar}{2mc} \vec{S}$$

$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

Combined E/B ring

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect
- Oscillating EDM resonant condition $\rightarrow$ buildup of out-of-plane spin rotation
- Search of resonance (axion/ALP mass) via change of beam momentum

Requirements

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity and shielding from *unwanted* magnetic fields.
- High beam intensity: $N=4 \cdot 10^{10}$ per fill
- Polarized hadron beams: P=0.8
- Long spin coherence time: τ = 1000 s
- Large electric fields: $E \sim 10$ MV/m
- Efficient polarimetry with:
  - large analyzing power: A = 0.6
  - high efficiency detection: eff. = 0.005

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Expected statistical sensitivity in 1 year of data taking:

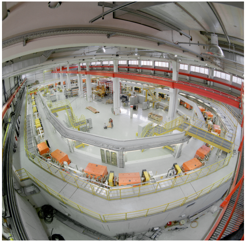
- $\sigma_{stat} = \frac{\hbar}{\sqrt{Nf\tau}PAE} \Rightarrow \sigma_{stat} = 2.6 \times 10^{-29} e \cdot cm$
- Experimentalist's goal: provide σ_{syst} to the same level.

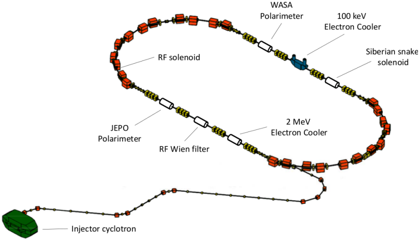
Achievements at COSY

The COSY storage ring at FZ-Jülich (Germany)

COoler SYnchrotron COSY

- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta p= 0.3-3.7 GeV/c
- Phase-space cooled internal and extracted beams



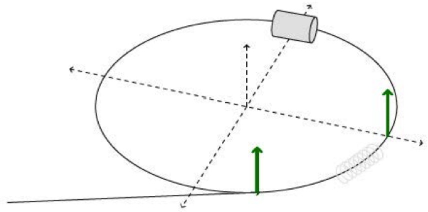


Previously used as spin-physics machine for hadron physics:

- Ideal starting point for srEDM related R&D
- Dedicated and unique experimental effort worldwide

Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c



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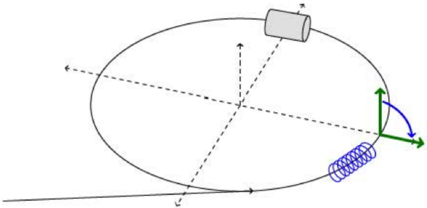
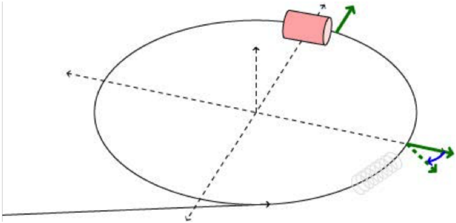
2. Flip spin with solenoid into horizontal plane

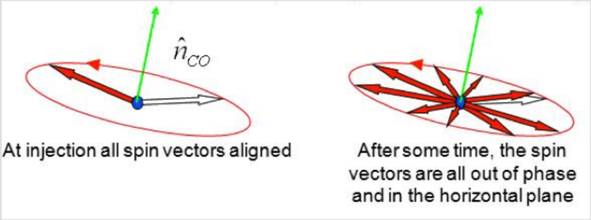


Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with solenoid into horizontal plane
3. Extract beam slowly (100 s) on Carbon target
4. Measure asymmetry and determine spin precession



Optimization of spin-coherence time



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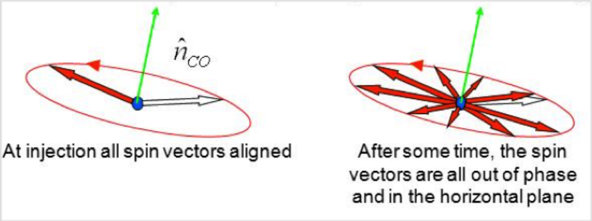
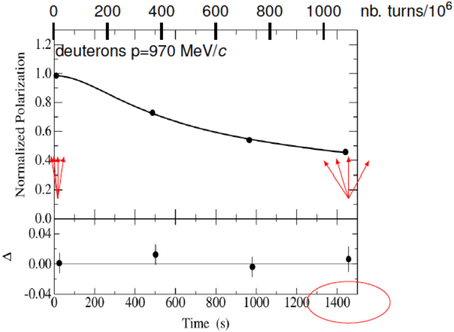
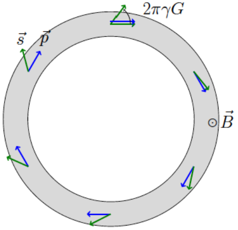




I major achievement
[Phys. Rev. Lett. 117 (2016) 054801]

- τ_{SCT} = (782 ± 117)s
- Previously: τ_{SCT}(VEPP) $\approx$ 0.5 s ($\approx 10^7$ spin revolutions)
- SCT of crucial importance, since $\sigma_{STAT} \propto \frac{1}{\tau_{SCT}}$

Precise determination of the spin-tune



Spin-tune ν_s

$$\nu_s = \gamma G = \frac{nb.spin-rotations}{nb.particle-revolutions}$$

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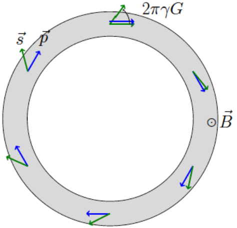

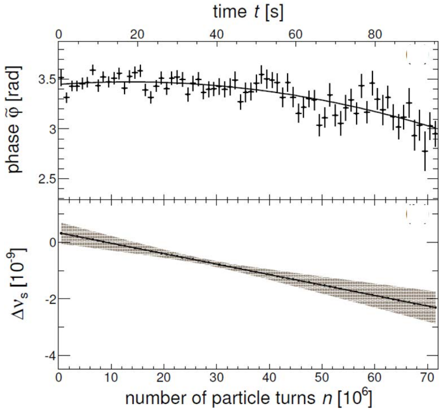

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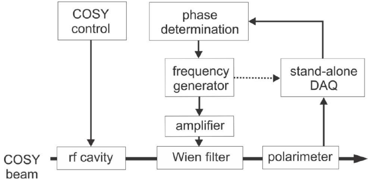
II major achievement *[Phys. Rev. Lett. 115 (2015) 094801]*

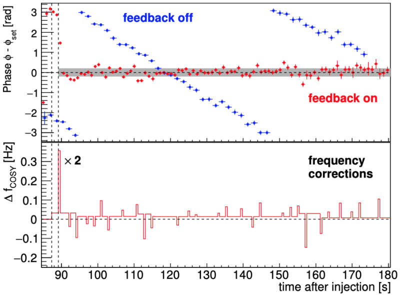
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ ($\Delta\nu_s/\nu_s \approx 10^{-10}$)
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: 3×10^{-8} per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage rings

Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

- resonance frequency
- phase between spin-precession and device RF





Ill major achievement *[Phys. Rev. Lett. 119 (2017) 014801]*:

Error of phase-lock σ_ϕ = 0.21 rad

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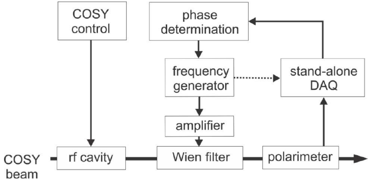

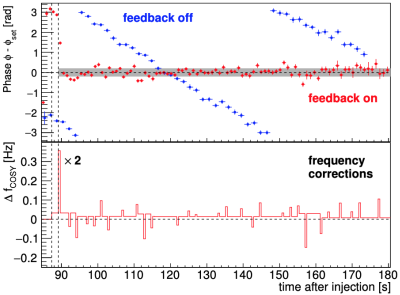

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At COSY freezing of spin precession not possible
$\rightarrow$ phase-locking required to achieve precision for EDM

Strategy: staged approach

Staged approach

On the basis of the preparedness of the required technological developments

Stage 1

precursor experiment

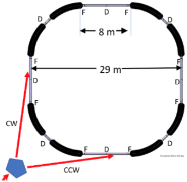
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

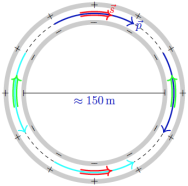


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

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}

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	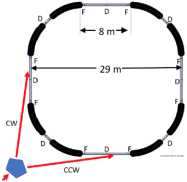	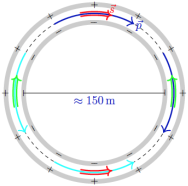
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ERC-AdG application: Pathfinder for a Charged-Particle EDM Storage Ring (P-EDM)

Stage 2: prototype EDM storage ring

- Build demonstrator for charged particle EDM
  - Key-performance enabler for the final ring
- Project prepared by CPEDM working group (CERN+JEDI)
  - P.B.C. process (CERN) & European Strategy for Particle Physics Update
- Possible host sites: COSY or CERN
- S.R. to Search for EDMs of Charg. Part. - Feas. Study (arXiv:1912.07881)

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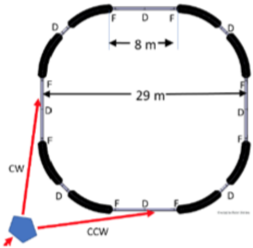
100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- Frozen spin including additional vertical magnetic fields



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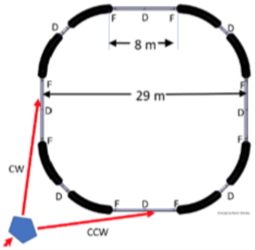


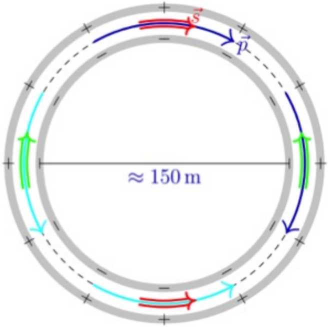
Challenges

- All electric & E-B combined deflection
- Storage and spin-coher. time in elec. machine
- CW-CCW operation
- Orbit control
- Polarimetry
- Magnetic moment effects
- Stochastic cooling

Stage 3: precision EDM ring

500 m circumference (with E = 8 MV/m)

- All-electric deflection
- Magic momentum for protons (p = 701 MeV/c)



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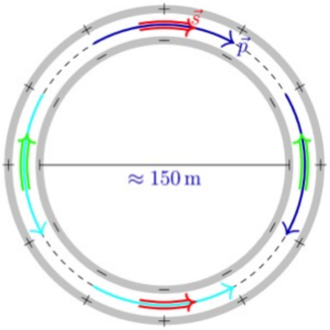

Challenges

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($>$ 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual (intentional) B_r field

"Holy Grail" of storage rings (largest electrostatic ever conceived)

Conclusions

EDM searches in Storage Rings

- Outstanding scientific case with high discovery potential
- Important developments in accelerator technology

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- Design of a small-scale prototype ring
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- Submitted: ERC-AdG: P-EDM (P.I. P. Lenisa)
- Planned: Design Study in Horizon Europe

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Unique chance that Europe should not miss!

Collaboration

JEDI = Jülich Electric Dipole moment Investigations

- Spokespersons: P. L. & J. Pretz (RWTH-Aachen and FZ-Jülich)
- 90 members (Aachen, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...)
- http://collaborations.fz-juelich.de/ikp/jedi

CPEDM Collaboration: JENAA - EoI

- St. Rings for the search of Charged-Particles EDMs
- Submitters: C. Carli (CERN) P. L. & J. Pretz
- 119 endorsers
- https://indico.ph.tum.de/event/4482/overview

Collaboration

JEDI = Jülich Electric Dipole moment Investigations

- Spokespersons: P. L. & J. Pretz (RWTH-Aachen and FZ-Jülich)
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744. WE-Heraeus-Seminar (Bad-Honnef, Germany)

- *Towards Storage Ring Electric Dipole Moment Measurements*
- Organizers: M. Lamont (CERN), J. Pretz, A. Wirzba (FZ-Jülich)
- https://www.we-heraeus-stiftung.de/index.php?id=1567

Spares

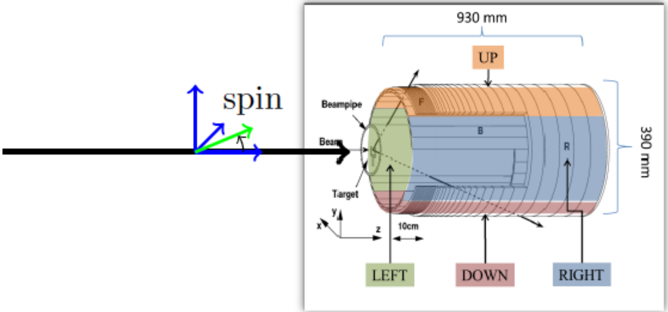
Status preparedness levels for the full-scale all-electric ring.

Operations	Rank	Comment	Reference
spin control feed-back	G	COSY R&D	App. A.1.3
spin coherence time	G(-)	COSY R&D	App. A.1.2
polarimetry	Y	polarimetry is destructive	Chap. 11
beam current limit	R	enough protons for EDM	Sect. 7.2
CW/CCW operation	R	systematic EDM error reduction	Ref. [1]
Theory			
GR gravity effect	G(+)	this paper, standard candle bonus	App. D
frozen spin fixed point stable?	G	stable, this paper	App. G.5.5
intrabeam scattering	Y	may limit run duration	Ref. [3]
geometric/Berry phase theory	Y	needs further study	Ref. [4]
Components			
quads	G	e.g. CSR design	Chap. 9
polarimeter	G	COSY R&D	Chap. 11
waveguide Wien filter	G	COSY R&D precursor	App. A.1.5
electric bends	R(+)	sparking/cost compromise	App. A.1.10
Physics & Engineering			
cryogenic vacuum	Y	required?—cost issue only	Ref. [5]
stochastic cooling	Y	ultraweak focusing issue	Ref. [6]
power supply stability	Y(-)	may prevent phase lock	Chap. 7
regenerative breakdown	R(+)	specific to mainly-electric, not seen in E-separators	
EDM systematics			
polarimetry	G(-)	COSY R&D	Chap. 11
CW/CCW beam shape matching	Y		Chap. 10
beam sample extraction	Y	systematic error?	Chap. 11, App. K
control current resettability	Y		Ref. [7]
BPM precision	Y(-)	Rogowski? Squids?	Chap. 7, Chap. 10
element positioning & rigidity	Y(-)	must match light source stability	Ref. [8]
theoretical analysis			Chap. 10 and refs.
Radial B-field B_r	R	assumed to be dominant	Ref. [1]

Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study (arXiv:1912.07881 [hep-ex])

Polarimeter

- Elastic deuteron-carbon scattering
- Up/Down asymmetry $\propto$ *horizontal polarization* $\rightarrow \nu_s = \gamma G$
- Left/Right asymmetry $\propto$ *vertical polarization* $\rightarrow$ d



Time-stamp system

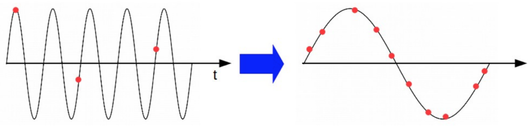
$$\text{Asymmetry: } \epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = p_z A_y \sin\left(2\pi \cdot \nu_s \cdot n_{turns}\right)$$

Challenge

- Spin precession frequency: 126 kHz
- ν_s = 0.16 $\rightarrow$ 6 turns/precession
- event rate: 5000 s^{-1} $\rightarrow$ 1 hit / 25 precessions $\rightarrow$ no direct fit of rates

Solution: map many event to one cycle

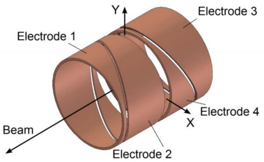
- Counting turn number n $\rightarrow$ phase advance $\phi_s = 2\pi\nu_s n$
- For intervals of $\Delta n = 10^6$ turns: $\phi_s \rightarrow \phi_s$ mod 2π

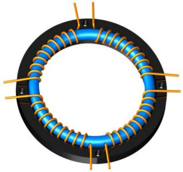


Beam position monitors for srEDM experiments

Development of compact BPM based on Rogowski coil

- Main adv.: short install. length ($\approx$ 6 cm in beam direction)





Conventional BPM

- Easy to manifacture
- Length = 20 cm
- Resolution $\approx$ 5 μm

Rogowski BPM (warm)

- Excellent RF-signal response
- Length = 1 cm
- Resolution $< 1 \mu$m

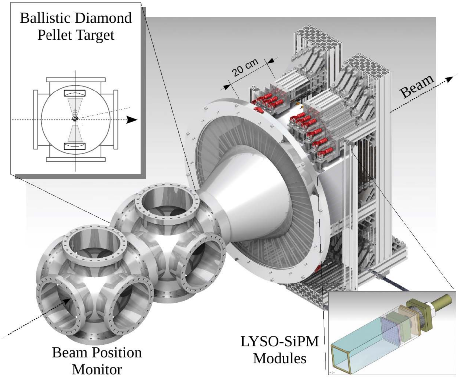
High-precision beam polarimeter with internal C target

Based on LYSO scintillator readout by SiPM

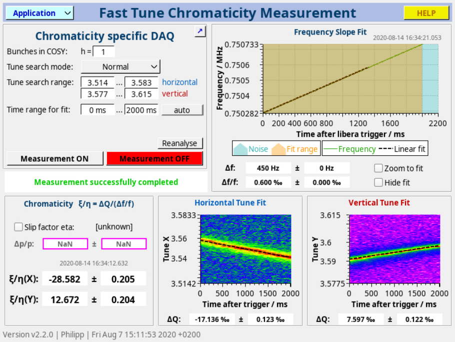
- Compared to NaI:
  - high density (7.1 vs 3.67 g/cm^3),
  - fast decay time (45 vs 250 ns).

Perspectives:

- Capable of operating with CW and CCW beams
- System installed in Spring 2020.
- Under study: Ballistic diamond pellet target for homogeneous beam sampling.
- Possibility of determining polarization profile of the beam



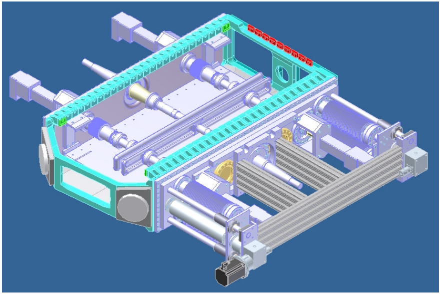
New tool for fast tune and chromaticity measurement



Fast tune measurement within a few milliseconds

- Fast tune meas. based on bunch-by-bunch beam position meas.:
  Betatron oscillations excited through stripline electrodes
  → resonant transverse oscillations observed through beam position pick-ups.
- Determination of the chromaticity:
  Particle momentum changed by small frequency change
  → observed tune change provides a measure for the chromaticity.

E/B deflector development using real-scale setup



Equipment

- Dipole magnet B_{max} = 1.6 T
- Mass = 64 t
- Gap height = 200 mm
- Protection foil between chamber wall and detector

Parameters

- Electr. length = 1020 mm
- Electr. height = 90 mm
- Electr. spacing = 20 to 80 mm
- Max potential = $\pm$ 200 kV
- Material: Al coated with TiN

- First results expected soon