Prototype Ring Facility for charged-particle EDM search

Toward a Technical Design Report

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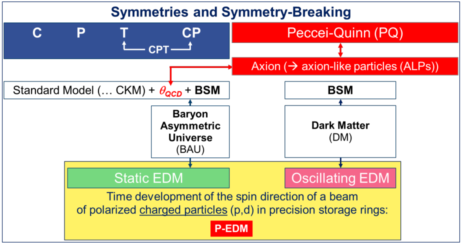
Contents

Search for electric dipole moments using storage rings

One of the most intriguing puzzles of contemporary physics

Open issues

- Predominance of matter over antimatter in the Universe
- Nature of Dark Matter



Approach

- Measurements of static EDMs of fundamental particles (p, d, ...).
- Searches for axions and axion-like particles (ALPs) as Dark Matter candidates through oscillating EDMs.

Grants and evaluations

- ERC Advanced Grant srEDM (Hans Ströher, Proposal No. 694340)
- Helmholtz Evaluation Report, Topic 2, Cosmic Matter in Lab., 01/2020:
  - **Goals** in Program Oriented Funding IV period
    - Initiation of the proton Electric Dipole Moment (EDM) project at COSY-ring to open an opportunity to explore physics beyond the standard model.
  - **Work program:**
    - Use COSY, the world's only storage ring for polarized proton and deuterium beams at the IKP facility at FZJ. This will explore the scientific potential for proton/deuteron EDM experiments in the COSY-ring.
    - Perform within PoF IV an Axion search via oscillating EDMs at COSY, which may open the way to new concepts that may extend the reach in precision down to 1×10^{-29} e cm.
- Deliberation Document 2020 Update European Strategy for Particle Physics:
  - [...] the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported. [...]

Strategy toward dedicated EDM ring

CPEDM Collaboration: http://pbc.web.cern.ch/edm/edm-default.htm

Project stages and time frame toward a dedicated EDM ring:

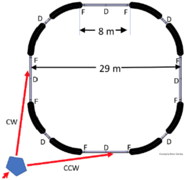
Stage 1

- precursor experiment

- magnetic storage ring
- Now

Stage 2

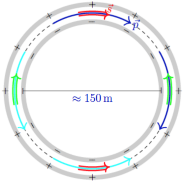
- prototype ring



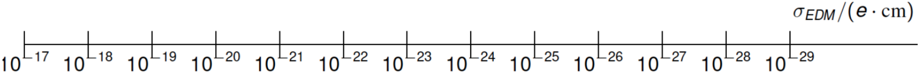
- electric/magnetic bends
- simultaneous ↻ and ↺ beams
- 5 years

Stage 3

- dedicated storage ring



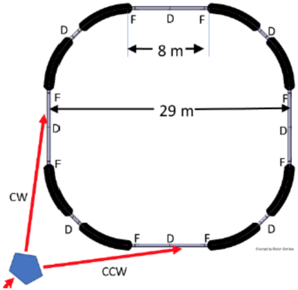
- at magic p momentum
- 10 years



Stage 2: Prototype EDM storage ring (PTR)

100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- p at 45 MeV frozen spin including additional vertical magnetic fields



Challenges – open issues

- All electric & E/B combined deflection
- Storage time
- CW-CCW
  - operation
  - orbit difference to pm
- Spin-coherence time
- Polarimetry
- Magnetic moment effects
- Stochastic cooling

Primary purpose of PTR

- study open issues.
- first direct proton EDM measurement.

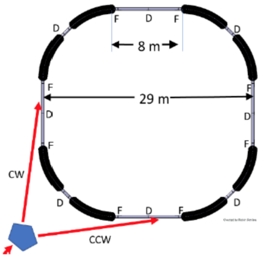
Technical Design Report (ready end of 2022)

- Present status summarized in CERN Yellow Report (CYR)
  - **Storage Ring to Search for Electric Dipole Moments of Charged Particles – Feasibility Study** [1]
- **Next step: CPEDM prepares Technical Design Report**
  - PTR Lattice design
  - Beam transfer and injection system
  - Electrostatic deflectors
  - Magnetic bends
  - Multipole elements
  - Ring vacuum system
  - Stochastic cooling
  - RF Cavity
  - Spin manipulation tools
  - Polarimeter
  - Beam diagnostics
- **Along with: Systematic studies, Spin tracking, error evaluation**

red: needs strong support (CERN, MPIK-HD, Liverpool U., ...)
green: already addressed

PTR lattice design (protons)

Basic beam parameters and layout [1, Chap. 7]



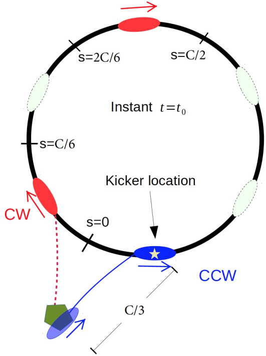
	E only	E & B frozen spin		unit
Bending radius	8.86	8.86		m
Kinetic energy	**30**	**30**	**45**	**MeV**
$\beta = v/c$	0.247	0.247	0.299	
γ (kinetic)	1.032	1.032	1.048	
Momentum	239	239	294	MeV/c
Electric field E	**6.67**	**4.56**	**7.00**	**MV/m**
Magnetic field B		**0.0285**	**0.0327**	**T**
rms $\epsilon_x = \epsilon_y$	1	1		π mm mrad
Transv. acc. $a_x = a_y$	> 10	> 10		π mm mrad

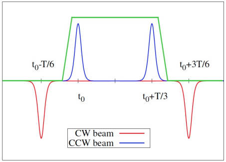
- p at 30 MeV all-electric CW-CCW beams operation
- p at 30 to 45 MeV frozen spin, with additional vertical B field

Needs strong support

Beam transfer and injection system

S. Martin, R. Talman, C. Carli, M. Haj Tahar: [1, Chapter 7.8]





Test at COSY: spin manipulation after injection appears feasible:

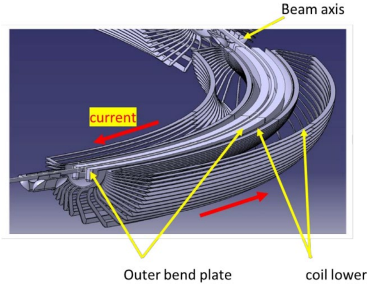
- could simplify injection scheme, no need for fast switches
- orient spin directions in bunches after injection of DC beam

Needs strong support

Electrostatic deflector

with additional magnetic bend

- Concept for electrostatic deflector element available [1, Ch. 7.6].



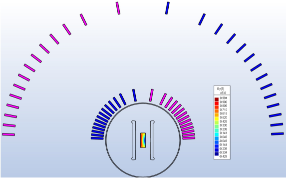
		units
Electric		
electric field	7.00	MV/m
gap between plates	**60**	**mm**
plate height (straight part)	**151.5**	**mm**
plate length	**6.959**	**m**
total bending length	55.673	m
total straight length	44.800	m
bend angle per unit	(45°)	**m**

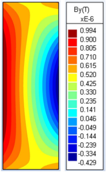
- **Next step:** build prototype with RWTH-Aachen (IAEW High Voltage)
- Studies of straight E/B deflector element to improve voltage holding capability ongoing at Jülich.

Needs some support/consulting

Magnetic bends

- Concept for magnetic add-on to deflector available [1, Ch. 7.6].
- Magnetic system ($\cos\theta$) placed outside the vacuum tube.





Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm^2
windings/element	60	

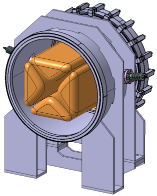
- Magnet system included in prototype development with RWTH-Aachen (IAEW High Voltage)

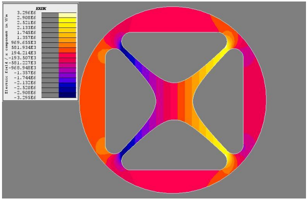
Needs some support/consulting

Multipole elements

Quadrupoles

- Design of electrostatic elements by J. Borburgh (CERN) [1, Chap. 9])
- Electrostatic quadrupoles
  - aperture diameter 80 mm, applied ±20 kV.
  - Simulated design with vacuum chamber of 400 mm diameter.





- PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
- 3D design available:
  - sextupole, octupole and higher harmonics reasonable
  - 800 mm longitudinal length and radial diameter of 620 mm.

Needs strong support

Vacuum system

- Ring vacuum given by minimum required beam lifetime of about 1000 s.
  - N_2 partial pressures below 10^{-12} mbar
  - H_2 partial pressures below 5×10^{-11} mbar.
- Stochastic cooling rate better than 5×10^{-3} mm mrad/s.
- non-vibrational system that avoids generation of magnetic fields
  - Cryogenic or NEG pumping systems may be used:
    1. NEG material becomes saturated after several pump-downs.
    2. Aging NEG material leaves dust particles in vacuum vessel.
    3. PTR will have significant number of pump-downs during program.
    4. High-voltage system requires excellent vacuum.
    5. System based on NEG cartouches [2] under discussion.
- Mechanical alignment of elements inside vacuum pipe of 400 mm diameter
  - active compensation of oscillations/ground motion
- Shielding (passive versus active)

Needs strong support

Stochastic cooling

- Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- Cooling should compensate emittance growth of 5×10^{-3} mm mrad/s.
  - Used successfully at COSY to compensate emittance growth of beam during interaction with internal gas targets.
  - Interplay between stochastic cooling and evolution of horizontally polarized ensemble of particles unknown.
  - **Studies of emittance growth and spin coherence time not possible at any other ring prior to PTR**.
- **Aim: provide basic design of stochastic cooling system for PTR.**

Needs some support/consulting

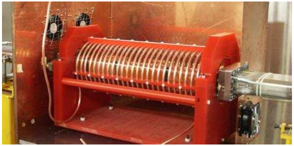
RF Cavity

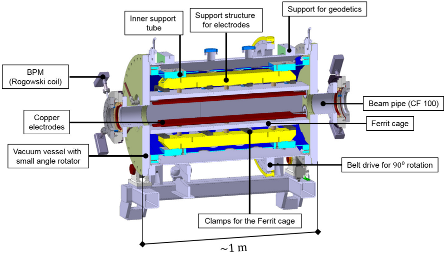
- Azimuthal magnetic fields of RF cavities lead to spin rotations of the magnetic moment.
- Even in case of a perfectly aligned cavity, individual particles experience horizontal magnetic fields and spin rotations into vertical and horizontal directions.
- Effect on EDM measurement strongly suppressed:
  - cancellation of effect for different particles crossing cavity gap each turn with different betatron phases and transverse positions.
- Design of RF cavity required that minimizes unwanted spin rotations.

Needs strong support

Spin manipulation tools

- Vertical polarisation of stored beam rotated into horizontal plane by **longitudinal field** of **RF solenoid**.
  - Typical ramp-up times from vertical to horizontal polarisation are $\approx 200\,\text{ms}$.
  - optimize design for PTR.





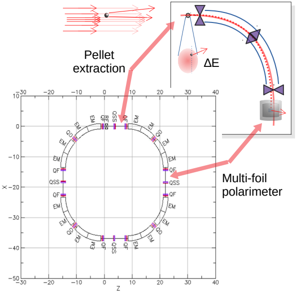
- **RF Wien filter** [3] applies **transverse magnetic fields** to spin, while excerting minimal Lorentz force on beam:
  - COSY: spin manipulation of individual bunches by fast RF switches feasible.
  - optimize design for PTR, need two of them for CW-CCW operations.

Needs some support/consulting

High-precision beam polarimeter (... with pellet extraction)

- dC (pC) scattering using white noise extraction works for relative polarization errors $\Delta p/p = 10^{-6}$ [4].
- Polarimeter system for dedicated ring described in [5–7].

- Polarization profile determination at low energies:
  - Carbon multifoil polarimeter [8] based on Silicon detectors with pellet extraction
    - (PhD J. Gooding, University of Liverpool).
  - Ballistic Si pellet target for homogeneous beam sampling [1, App. K].
  - Eloss of 100 keV in 50 μm pellet $\rightarrow$ track displaced by 2.5 cm behind 90° bend.



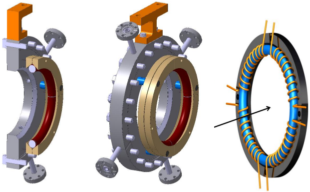
Needs strong support

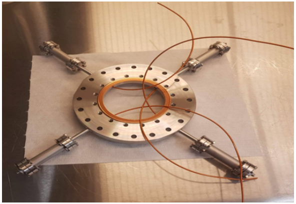
Beam diagnostics

Beam Position Monitors

Development of prototype BPM based on segmented toroidal coil [9]

- Rogowski coil





- advantages over conventional split-cylinder BPMs
  - short insertion length → many BPMs can be installed
  - inexpensive
  - high sensitivity to position of bunched beams
- Other diagnostics needed:
  - Beam profile monitor, non-destructive for emittance measurement
  - BCT, also to adjust CW/CCW beam currents

Needs some support/consulting

Conclusion

Search for charged hadron particle EDMs (p, d, light ions):

- New window to disentangle sources of CP violation, and to possibly explain matter-antimatter asymmetry of the Universe.
  - Search for static charged particle EDMs (p, d, ^{3}He)
    - EDMs $\rightarrow$ probes of CP-violating interactions
    - Matter-antimatter asymmetry
  - Search for oscillating EDMs
    - Axion gluon coupling
    - Dark matter search
  - Potential sensitivity to gravitational effects [10].
- Results and achievements at COSY are summarized in [1, App. A].

Staged approach:

- **Next:** Design of the prototype ring (PTR)
  - key components
  - first direct proton EDM measurement
- Contributions/support from PBC community / CERN required

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[5] I. Keshelashvili, F. Müller, D. Mchedlishvili, and D. Shergelashvili, "A new approach: LYSO based polarimetry for the EDM measurements," *J. Phys. Conf. Ser.*, vol. 1162, no. 1, p. 012029, 2019.

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[8] M. Ieiri, H. Sakaguchi, M. Nakamura, H. Sakamoto, H. Ogawa, M. Yosol, T. Ichihara, N. Isshiki, Y. Takeuchi, H. Togawa, T. Tsutsumi, S. Hirata, T. Nakano, S. Kobayashi, T. Noro, and H. Ikegami, "A multifoil carbon polarimeter for protons between 20 and 84 mev," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 257, no. 2, pp. 253–278, 1987.

References III

[9] F. Abusaif, “Development of compact highly sensitive beam position monitors for storage rings,” *Hyperfine Interactions*, vol. 240, p. 4, 2019.

[10] see, e.g., the presentations at the ARIES WP6 Workshop: Storage Rings and Gravitational Waves "SRGW2021", 2 February - 11 March 2021, available from `https://indico.cern.ch/event/982987`.

Spare slides

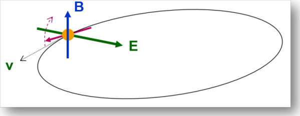
Search for charged particle EDMs with frozen spins

Magic storage rings see CERN Yellow Report [1]

For any sign of G, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \qquad (1)$$



where E_x is radial, and B_y vertical field.

- Some configurations for circular machine with fixed radius $r = 25\,\mathrm{m}$:

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
proton	1.793	700.740	232.792	16.772	0.000
deuteron	−0.143	1000.000	249.928	−4.032	0.162
helion	−4.184	1200.000	245.633	14.654	−0.044

Offers possibility to determine EDMs of

protons, deuterons, and helions in one and the same machine.