Search for electric dipole moments of charged particles in storage rings

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Motivation

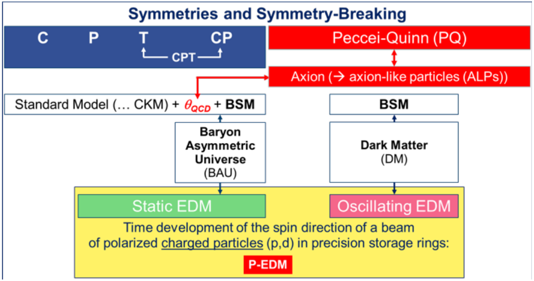
Physics case

Problems

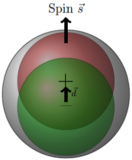
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

Approach

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

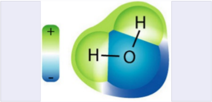


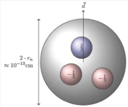
Electric Dipole Moment (EDM)



- Permanent separation of + and - charge
- Fund. property of particles (like mag. moment, mass, charge)

Orders of magnitude

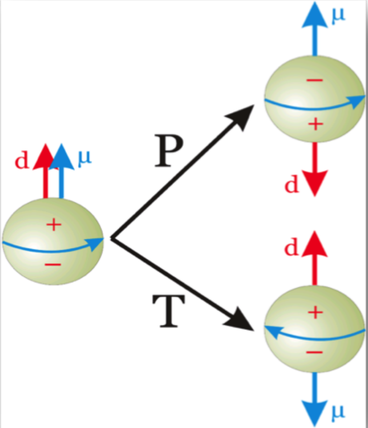




	Atomic Physics	Hadron Physics
$\lvert r_1 - r_2 \rvert$	Å= 10^{-8} cm	fm = 10^{-13} cm
naive exp.	10^{-8} e · cm	10^{-13} e · cm
observed	water molecule $2 \cdot 10^{-8}$ e · cm	neutron $< 10^{-26}$ e · cm

$\rightarrow$ possible via violation of time-reversal (T) and parity (P)

T and P violation of EDM



$$H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} - d \frac{\vec{s}}{s} \cdot \vec{E}$$

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

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

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

- Excess of Matter in the Universe:

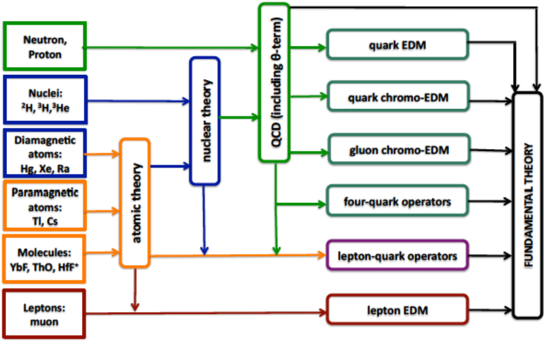
	observed	SM prediction
$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$	6×10^{-10}	10^{-18}

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

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

Why charged particles EDMs?

- Static EDM: complementary informations from different systems required
  - Direct measurement and statistical improvement with respect to neutron



J. de Vries

- Oscillating EDM: axion as a solution to the θ_{QCD} problem
  - Limit on θ_{QCD} comes from n_{EDM}

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= $10^{-29} e \cdot cm$)

Frozen spin

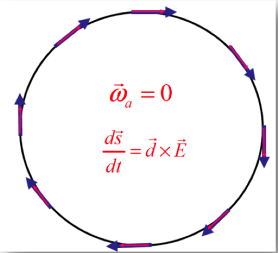
$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\Omega_{MDM} - \Omega_{cycl} = 0 \rightarrow \textbf{frozenspin}} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B}\right)\right] \times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

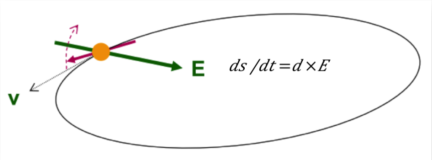
- Achievable with pure electric field for proton (G $>$ 0): $G = \frac{1}{\gamma^2 - 1}$
- Requires special combination of E, B fields and γ for d, ^3He (G $<$ 0)

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





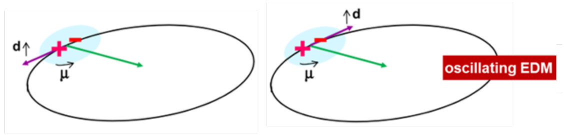
Frozen-spin condition:

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

Search for oscillating EDM in storage rings

Axions as light dark matter candidates

- Axion interaction with ordinary matter: $\frac{a}{f_0} F_{\mu\nu} \tilde{F}_{\mu\nu}$, $\frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \bar{\Psi} \gamma^\mu \gamma_5 \Psi$
- $\frac{a}{f_0} G_{\mu\nu} \tilde{G}_{\mu\nu}$ $\rightarrow$ coupling to gluons with same structure as QCD-θ term
- Generation of an oscillating EDM



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

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

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

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

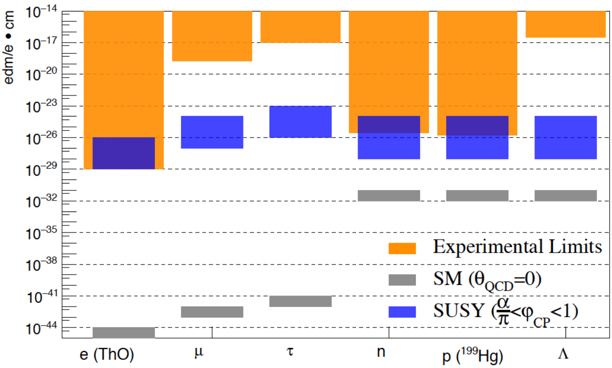
High precision, primarily electric storage ring

- 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

Expected statistical sensitivity in 1 year of data taking:

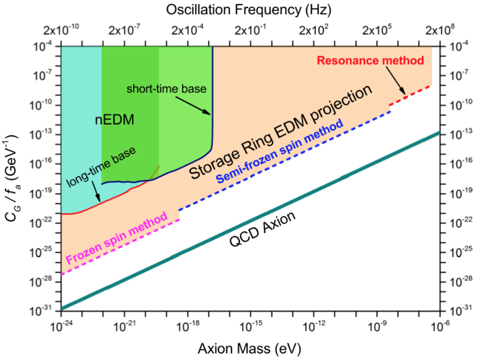
- $\sigma_{stat} = \frac{\hbar}{\sqrt{Nf}\tau PAE} \Rightarrow \sigma_{stat} = 2.6 \times 10^{-29} e \cdot cm$
- Experimentalist's goal: provide σ_{syst} to the same level.

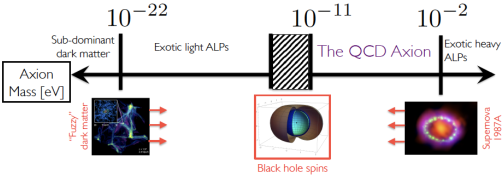
STATIC EDM: current upper limits



- **Objective:** EDMs of charged hadrons: p, d, $^{3}\mathrm{He}$
  - 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





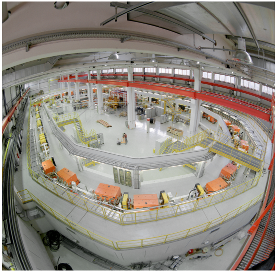
- Experimental limits accessible in one year per single frequency measurement.

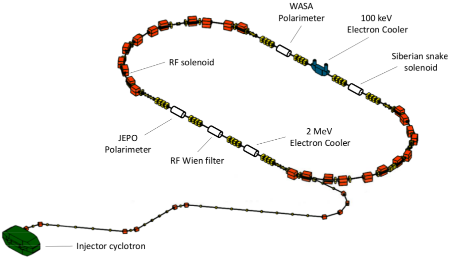
Achievements at COSY

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



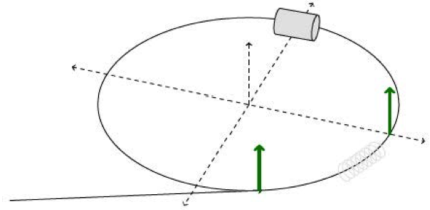


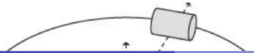
Previously used as spin-physics machine for hadron physics:

- Ideal starting point for Storage Ring EDM related R&D
- Dedicated and unique experimental effort worldwide

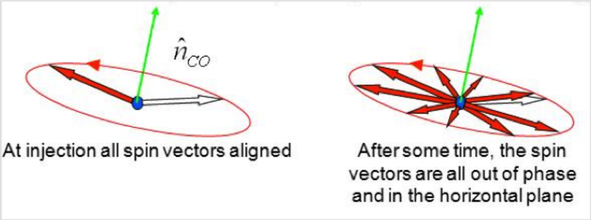
Experiment preparation

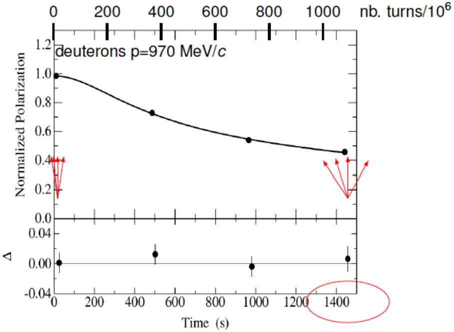
1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with RF-solenoid into horizontal plane
3. Extract beam slowly (100 s) on Carbon target
4. Measure asymmetry and determine spin precession





Optimization of spin-coherence time

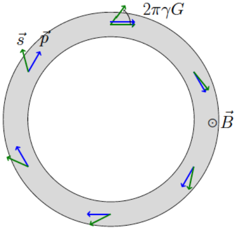


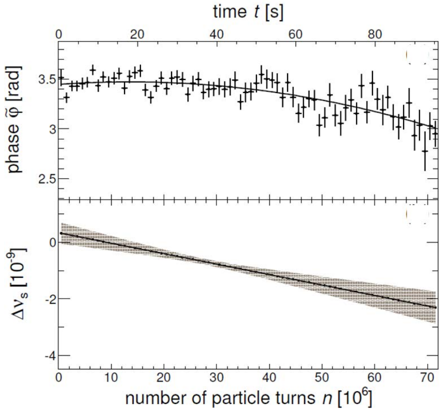


I major achievement
[Phys. Rev. Lett. 117 (2016) 054801]

- 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

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

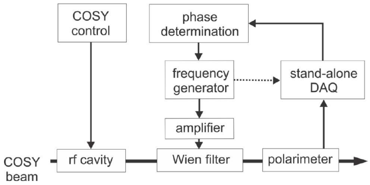
II major achievement *[Phys. Rev. Lett. 115 (2015) 094801]*

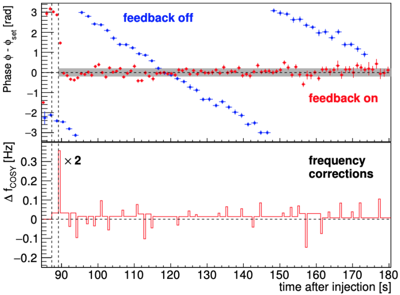
- Interpolated spin tune in 100 s:
- $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$ $(\Delta\nu_s/\nu_s \approx 10^{-10})$
- Angle precision: $2\pi \times 10^{-10}$ = 0.6 nrad
- Previous best: 3×10^{-8} per year (g-2 experiment)
- $\rightarrow$ new tool to study systematic effects in storage rings

Phase locking spin precession in machine to device RF

Spin-feedback system maintains:

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





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

Error of phase-lock σ_ϕ = 0.21 rad

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

COSY precursor experiment

EDM measurement in a magnetic storage ring

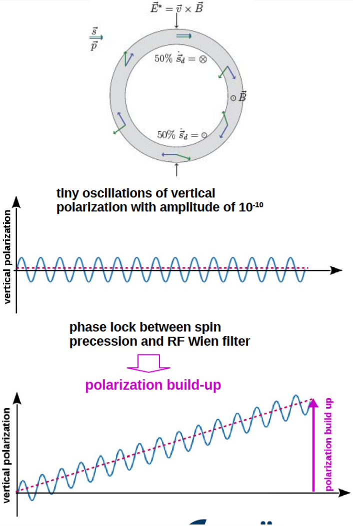
- Exploitation of motional electric field in particle rest frame: $E^* = v \times B$

Problem

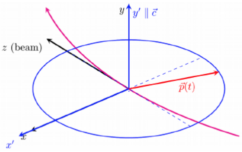
- Momentum ↑↑ spin
  spin ⇒ spin kicked up
- Momentum ↑↓ spin
  ⇒ spin kicked down
- ⇒ no accumulation of vert. asymmetry

Solution: RF-Wien filter

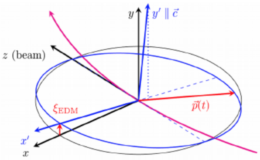
- Lorentz force:
  $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$



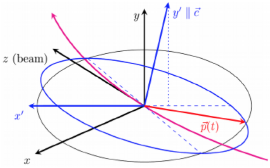
Effect of EDM on stable spin-axis



EDM absence



EDM effect

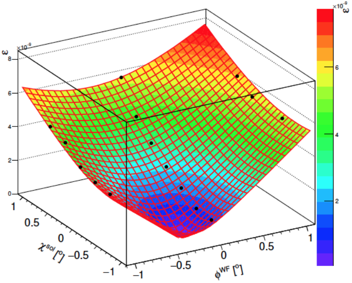


Magnetic misalignm.

EDM tilts the stable spin-axis

- Presence of EDM $\rightarrow \varepsilon_{EDM} > 0$
  - $\rightarrow$ spin precess around the $\vec{c}$ axis
  - $\rightarrow$ oscill. vert. polarization $p_y(t)$

Preliminary results from run in Dec. 18 + Feb./Apr. 21



(f) First 16 points on the map.

Spin-tracking simulations necessary

- Orientation of stable spin axis at location of RF Wien filter including EDM determined by minimum of map
- Spin tracking simulation shall provide orientation of stable spin axis without EDM
- Results foreseen by end of 2021

Compatible with $d_{EDM} < 10^{-17}$ e·cm

Strategy: staged approach

Strategy: staged approach to a storage ring for precision physics

On the basis of the preparedness of the required technological developments

Stage 1

precursor experiment

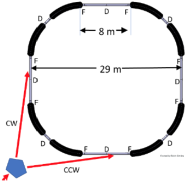
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

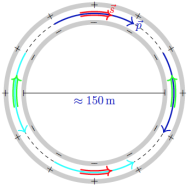


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

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}

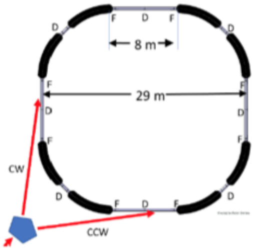
Planned Design Study application: Prototype Storage Ring for the Precision Frontier

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)

100 m circumference

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



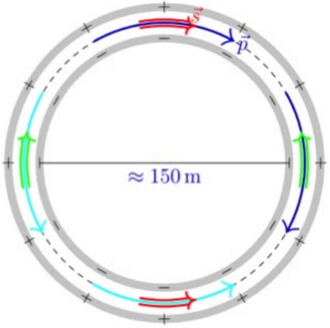
Challenges

- 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)



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)

Research Infrastructure Concept Development:

"Prototype Storage Ring for the Precision Frontier"

Framework

INFRADEV-01-01-2022 - Concept Development

- Application deadline: 10.01.22 - 20.04.22
- Duration: 4 years
  - Possible project development: 2023-2026
- Budget: total 3 M euro
- Coordinator + 6 beneficiaries

  INFN (Coord.), CERN, RWTH-Aachen, GSI, MPI-HD, Univ. Liverpool, Univ. Cracow
- Other potential participants
  - Research Institute for Nuclear Problems (Belarus), Joint Institute for Nuclear Research (Russia), Landau Institute for Theoretical Physics (Russia), Budker Institute of Nuclear Physics (Russia), Indiana University (USA), Cornell University (USA), Tbilisi State University (Georgia), Paul Scherrer Institute (CH), University of Ferrara (IT)

1 - Excellence

Science case

- Search for static charged particle EDMs
  - 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

Objectives

- New class of (precision) storage rings (p: all-E; d, $^3\mathrm{He}$: comb. E/B);
- design demonstrator as:
  key performance enabler for the final precision storage ring;
- capable of providing a wealth of science already.

2 - Impact

Fundamental Science

- Physics beyond the SM-BAU, DM

Accelerator Science

- New class of precision storage rings
- All-electric ring (high field, field homogeneity and stability)
- E/B combined bending
- Storage time
- CW-CCW injection and operation
- Spin-coherence time in electric machine
- Optimum orbit control
- Systematic effects from magnetic moments
- Multi-bunch approach to co-magnetometry
- Stochastic cooling

Metrology

- Polarimetry (efficient, sampling, non-destructive)

3 - Implementation

WP #	Item	MM	Institutions	Objectives
1	**Project coordination**	24	INFN (**Lenisa**)	
2	**Ring design** 1. Machine lattice 2. Beam transfer system	60+x	CERN (**Carli**) CERN/MPI-HD CERN/MPI-HD	 report report
3	**Ring elements** 1. Electrostatic bends 2. Electrostatic multipole elements 3. Magnetic bends 4. Injection hardware 5. Vacuum system	60+x	INFN (**Saputi**) RWTH-IAEW CERN IKP-GSI CERN INFN	 report report report report report
4	**Beam diagnostics and instrumentation** 1. Beam position monitors, incl phase-space detection (Rogowski type) 2. Beam profile restgas monitor 3. RF cavity 4. Stochastic cooling 5. Magnetic shielding 6. Alignment and metrology of elements	60+x	IKP-GSI (**Rathmann**) IKP-GSI IKP-GSI CERN IKP-GSI ZEA-FZJ CERN	 report report report report report report
5	**Polarimetry and spin manipulation tools** 1. Beam polarimeter 2. RF solenoid 3. RF Wien filter	60-x	LIV (**Vilella**) Liverpool IKP-GSI IKP-GSI	 report report report
6	**Parameter control and expected performance** 1. Systematics investigations 2. Spin tracking 3. Error evaluation	60-x	IKP-GSI (**Pretz**) CERN IKP-GSI/Krakow Krakow	 report report report
7	**Cost estimate**	12	INFN (**Variola**)	report
8	**Dissemination and outreach**	14	Krakow (**Wronska**)	publications, meetings, talks

Conclusions

EDM searches in Storage Rings

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

Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Staged approach to face challenges in accelerator technology

- Precursor measurements at COSY
- Feasibility study of a *pure electrostatic* EDM proton ring

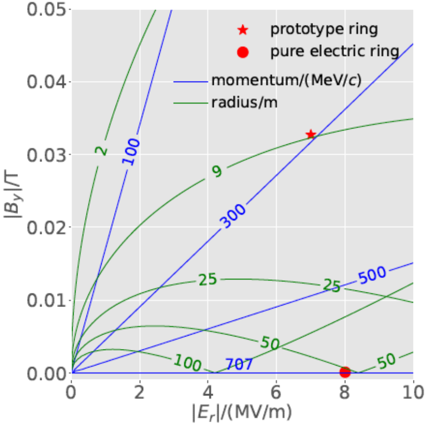
Funding

- Ongoing: ERC-AdG: srEDM (2016-2022) (FZJ, RWTH, Univ. Ferrara)
- Planned: Research Infrastructure Concept Development
  - Interdisciplinary impact
    - Fundamental and particle physics
    - Astroparticle and hadron physics
    - Accelerator and data science

Unique chance that Europe should not miss!

Spares

Momentum and ring radius for proton in frozen spin condition



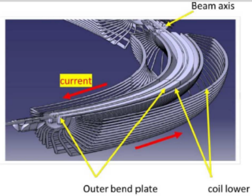
Two options:

- Pure electric ring:
p = 707MeV, bending radius≈ 50 m at E=8 MV/m

⋆ combined prototype ring:
p = 300MeV, bending radius≈ 9 m at E=7 MV/m

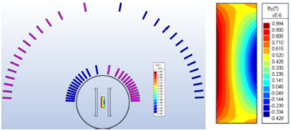
Electrostatic deflectors & magnetic bends

- Concept for electrostatic deflector available
- Next step: build prototype with RWTH Aachen
- Studies of straight E/B deflector to improve voltage holding capability at Jülich



		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

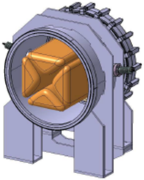
- Concept for magnetic add-on to deflector available.
- Magnetic system (cosθ) outside the vacuum tube.
- System included in prototype developm. with RWTH-Aachen

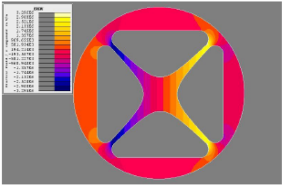


Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm^2
windings/element	60	

Electrostatic multipole elements

- Design of electrostatic elements by J. Burbough (CERN)
- Electrostatic quadrupoles
  - aperture diameter 80mm, applied $\pm$ 20 kV.
  - Simulated design with vacuum chamber of 400mm diameter.



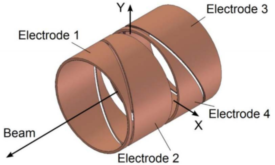


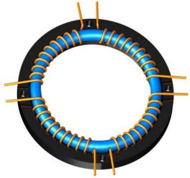
- PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
  - 3D design available;
  - sextupole, octupole and higher harmonics reasonable

Beam position monitors for srEDM experiments

Development of compact BPM based on Rogowski coil

- Main adv.: short install. length ($\approx$ 1 cm in beam direction)





Conventional BPM

- Easy to manifacture
- Length = 20 cm
- Resolution $\approx$ 10 μm

Rogowski BPM (warm)

- Excellent RF-signal response
- Length = 1 cm
- Resolution $\approx$ 1.25 μm

- 2 coils installed at entrance and exit of RF Wien filter

Simulations

- Beam and spin-tracking simulations to scrutinise and validate concepts and ideas
- Code bench-marking on existing COSY data
- Working group established