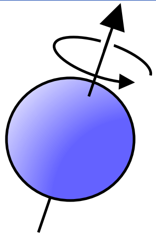
charged particle Electric Dipole Moment (cpEDM): recent Progress, Results and Prospects

C. Carli on behalf of the cpEDM Collaboration

PBC annual Workshop, 26th March 2024

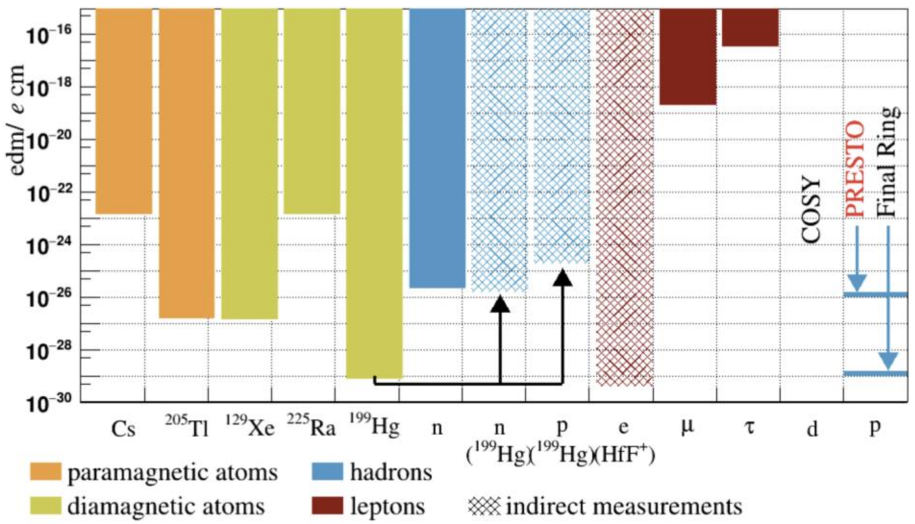
- Physics Motivation
- Measurement Principle
  - Frozen Spin Rings
  - Magic Energy Rings and Variants
  - Search for oscillating EDMs
  - Another Approach RF Wien Filter Method
- Vertical Offset of Quad and horizontal betatron Oscillations (Example of recent studies withing PBC)
- Design of a Prototype Ring as next Step
- Summary

Physics Motivation



- Search for (static) Electric Dipole Moment (EDM) of elementary particles
  - EDM aligned with spin and well known Magnetic Dipole Moment (MDM)
  - Would violate CP symmetry
  - Explanation of preponderance of Matter over Antimatter
  - (A tiny EDM compatible with standard model)
- Search for oscillating EDMs
  - May be caused by coupling with Axions
- Storage rings for direct cpEDM measurement
  - Direct measurement at rest requiring electric field not possible for charged particles

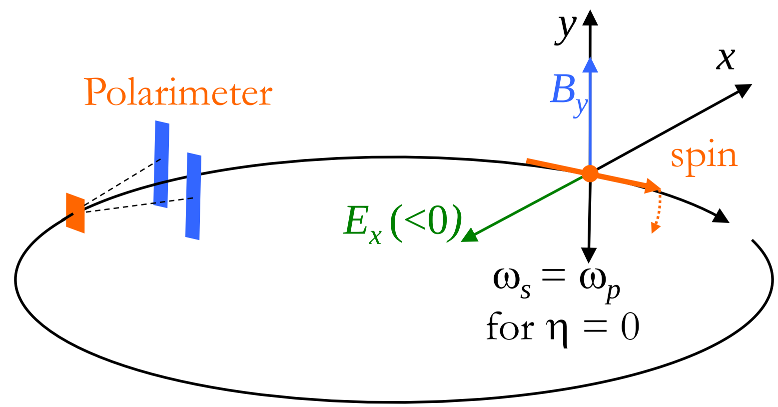
  => Measurement for particles in storage ring



Measured upper bounds for EDMs

Measurement Principle – Frozen Spin Rings

- "Frozen spin" cpEDM ring
  - Initial longitudinal polarization of bunch maintained for vanishing EDM (with well known Magnetic Dipole Moment (MDM) only)
  - Identical angular frequencies $\vec{\omega}_s$ and $\vec{\omega}_p$ describing rotation of spin and direction required
  - Finite EDM generates spin rotation around radial axis => very slow build-up of vertical spin component



Sketch of a "frozen spin" CP-EDM Ring (η describing EDM)

- Ring operated on spin resonance
  - Sensitivity to perturbations
  - Spin rotations due to imperfections (with MDM only) can be misinterpreted as signature of EDM

Sensitivity of 10^{-29} e.cm often quoted very challenging

- Spin (de-)coherence must be well understood and controlled
  - Frozen spin must be fulfilled for all particles with different longitudinal and transverse oscillation amplitudes
  - Operation with bunched beam
  - Compensations using sextupoles mandatory for sufficient spin coherence times

Measurement Principle – Frozen Spin Rings

- Spin dynamics described by Thomas-BMT equation extended for possible EDM

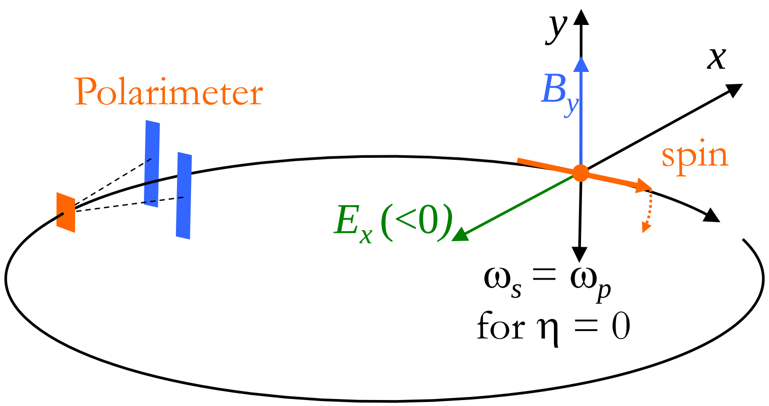
$$\frac{d\vec{S}}{dt} = \vec{\omega}_s \times \vec{S} = (\vec{\omega}_M + \vec{\omega}_E) \times \vec{S}$$

Gravity neglected

$$\vec{\omega}_M = -\frac{q}{m}\left[\left(G + \frac{1}{\gamma}\right)\vec{B}_\perp + (G+1)\frac{\vec{B}_\parallel}{\gamma} - \left(G + \frac{1}{\gamma+1}\right)\vec{\beta} \times \frac{\vec{E}}{c}\right]$$

$$\vec{\omega}_E = -\frac{q\eta}{2m}\left[\frac{\vec{E}_\perp}{c} + \frac{1}{\gamma}\frac{\vec{E}_\parallel}{c} + \vec{\beta} \times \vec{B}\right]$$

with G describing the well-known MDM and η the EDM
(e.g., for protons $G \approx 1.792\,..$ and $\eta \approx 1.9 \cdot 10^{-19}$ for $\vec{d} = 10^{-29} e \cdot \mathrm{cm}$)



Sketch of a "frozen spin" CP-EDM Ring
(η describing EDM)

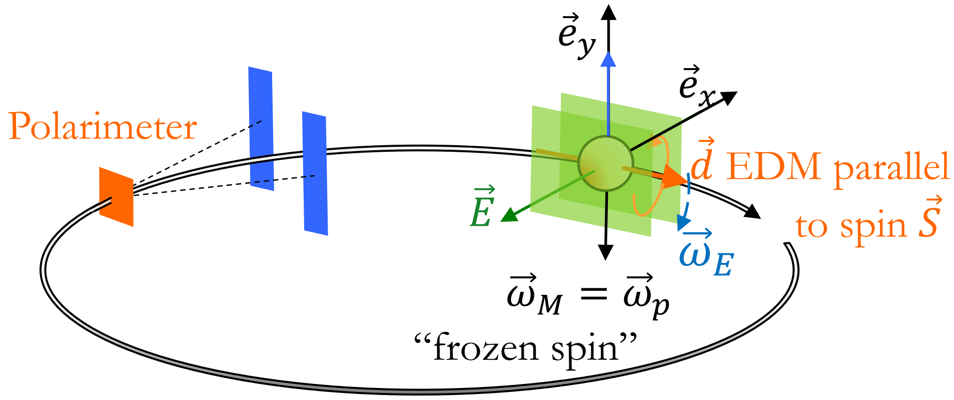
- Frozen spin condition with electric and magnetic fields

$$\omega_{p,y} = \frac{q}{\gamma m}\left(-B_y + \frac{E_x}{\beta c}\right) = \omega_{M,y} = \frac{q}{m}\left(G + \frac{1}{\gamma+1}\right)\frac{\beta\, E_x}{c}$$

leads to

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

Measurement Principle – Magic Energy Ring



Sketch of a "magic energy" cp-EDM Ring

- Concept of "magic energy"
  - Frozen spin ring with purely electric bends by choosing appropriate beam energy
    $$B_y = \frac{(\beta\gamma)^2 G - 1}{\gamma^2 \beta c\, G} E_x = 0$$
  - Leads to condition $\beta_m \gamma_m = G^{-1/2}$ with index "m" for magic energy
  - Possible for particles with $G > 0$ (not possible, e.g., for deuterons with $G < 0$)

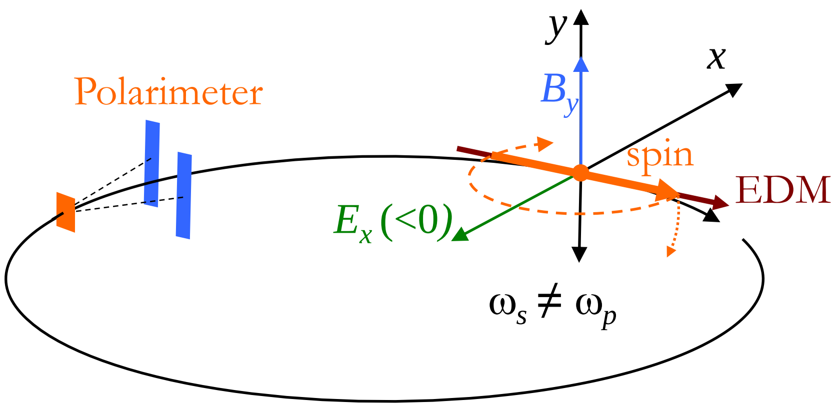
$E_m = 232.79$ MeV $\quad p_m = 700.74$ MeV/c

- For protons with
  - Magic energy and momentum $E_m = 232.79$ MeV and $p_m = 700.74$ MeV/c
  - Requires a ring with a circumference of at least 500 m (average bending field 5.27 MV/m)
    - EDM of d = 10^{-29} e.cm (sensitivity target often given) rotates spin around radial axis by 1.6 nrad/s

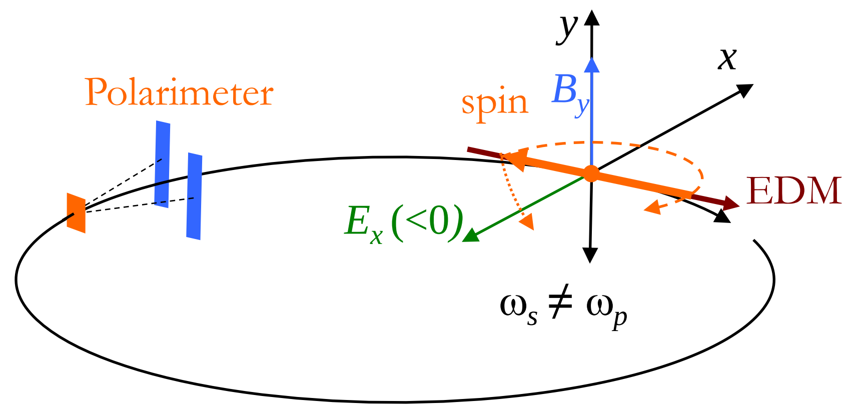
Measurement Principle – Variants of "magic Energy Rings"

- Purely electro-static machine with focusing by electric fields
  - Stray magnetic fields probably the most limiting systematic effect despite state-of-art shielding
  - Counter-rotating beams to control some systematic effects
  - Deflection by average radial magnetic field $\bar{B}_x$ compensate by electric field $\bar{E}_y = -\beta_m c \bar{B}_x$
  - With Thomas-BMT angular frequency $\bar{\omega}_{m,x} = -\frac{q}{m}\frac{G+1}{\gamma_m^2}\bar{B}_x$ (for $\bar{B}_x = 9.3\ aT$ gives $\bar{\omega}_{m,x} = 1.6$ nrad/s)
  - Cannot be disentangled from EDM combining measurements with counter-rotating beams
  - Mitigation using vertical orbit differences by how many orders of magnitude?
- Hybrid cpEDM ring (pursued by team around BNL and KAIST (South Korea))
  - Focusing by magnetic quadrupoles - Radial magnetic stray field compensated by magnetic quad field => no spin rotation proportional to perturbation
  - Vertical electric field from bends generates spin rotations around radial axis => very fast, but can in principle be disentangled from EDM observing counter-rotating beams
  - High periodicity 800 m ring proposed, operation with different polarities
  - Separation of counter-rotating beams and unwanted electric gradients - mitigations proposed
- Possible limitation due to geometric phase effects and other higher order effects to be understood for both variants

Measurement principle –
Variant searching for oscillating cpEDM



Initial situation
Spin and EDM parallel



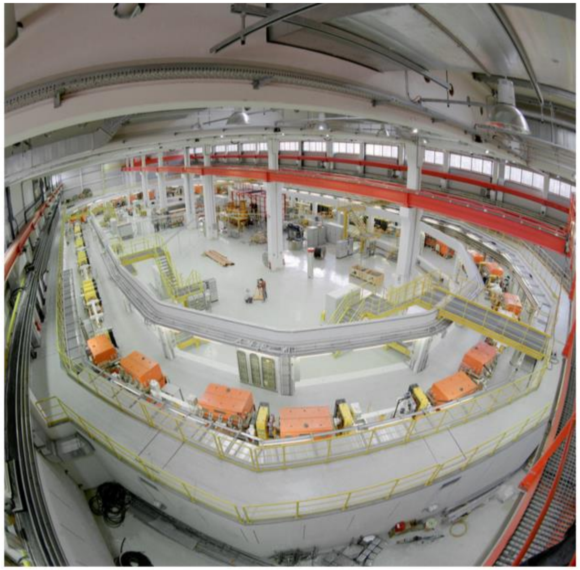
Half an oscillation period later
Spin and EDM antiparallel

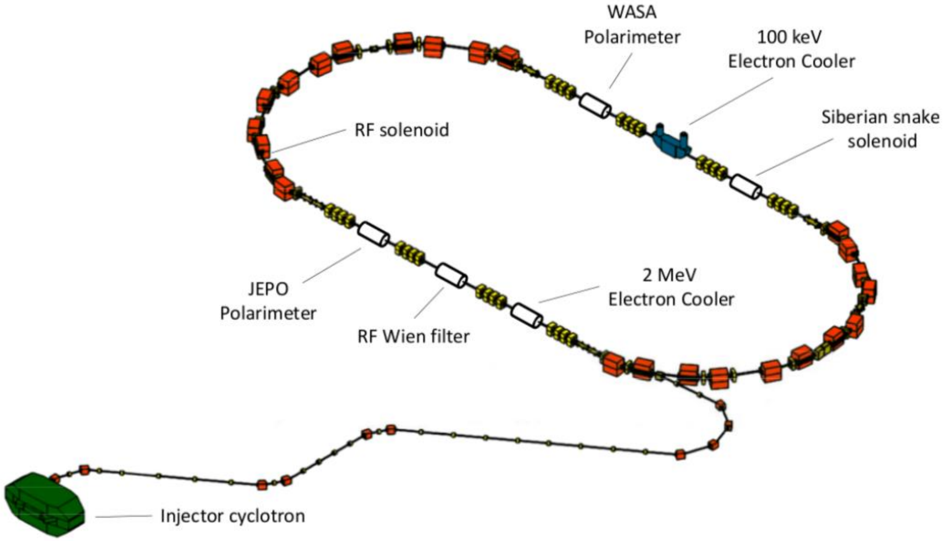
- Spin rotation w.r.t. particle direction with frequency equal to EDM oscillation (Not frozen spin!)
  - Oscillating EDM means that ratio between EDM and spin oscillates $\eta = \eta_0 + \hat{\eta}\sin\left(\omega_{axion} t + \varphi_0\right)$
  - Resonance condition $\left|\omega_s - \omega_p\right| = \omega_{axion}$!
  - Long-term build up of vertical spin component
  - Limited by agreement between frequencies for spin oscillation and rotation of spin in horizontal plane
  - Limitations due to statistics (need for runs with different possible spin oscillation frequencies)?
  - Many systematic effects strongly mitigated!

Measurement Principle – Another approach RF Wien Filter Methoid

- First direct cpEDM measurements done with COSY
  - "Frozen spin" operation not possible with existing magnetic ring

Note: many studies as spin feedback and spin decoherence studies, essential for cpEDM measurements in general, done with COSY

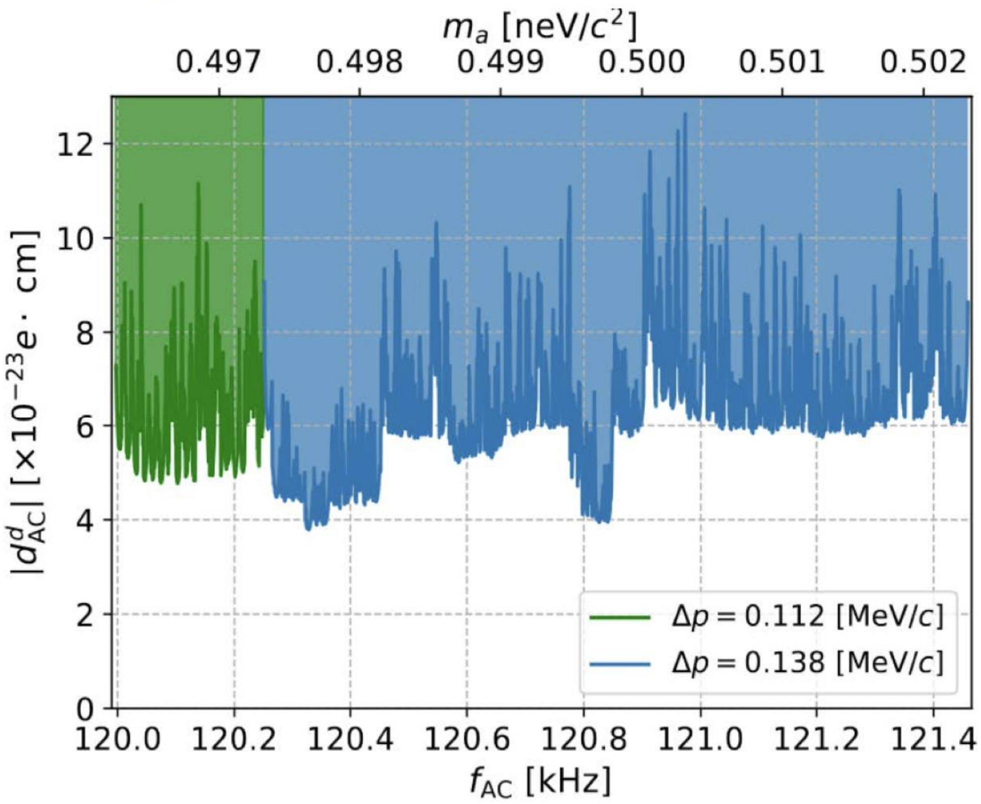


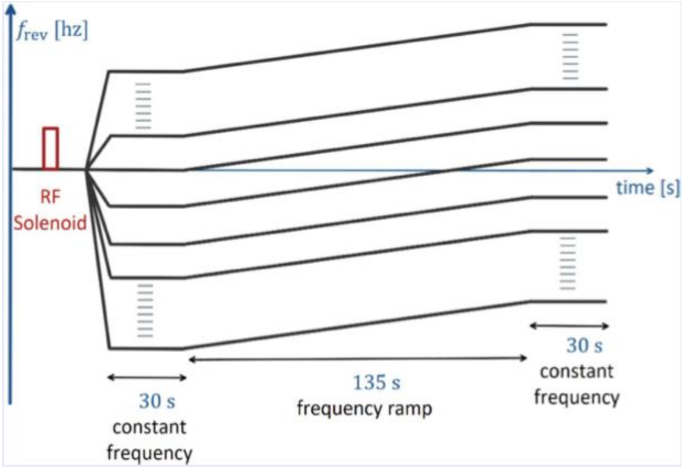


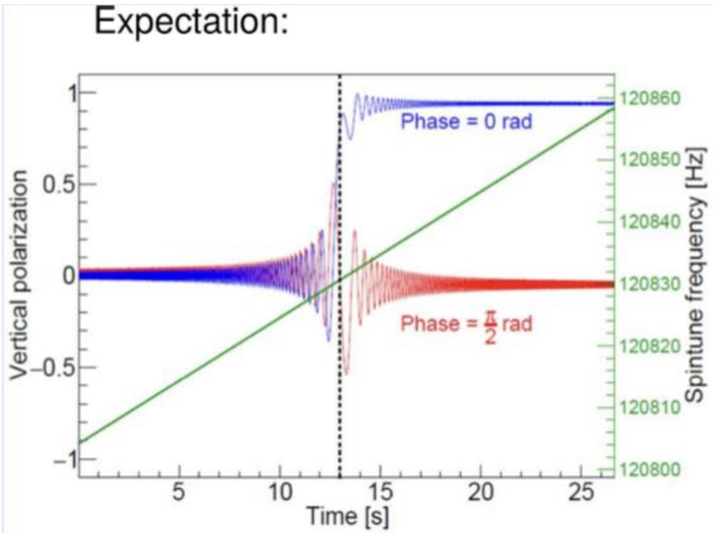
  - RF Wien filter operated with suitable frequency and phase w.r.t. spin rotations
  - EDM generates vertical spin build-up over duration of store
  - First direct hadron cpEDM measurement result to come soon

Measurement Principle –
Another approach RF Wien Filter Methoid

- Recent studies and results by COSY team
  - Upper bounds for oscillating EDMs (no Wien filter needed)





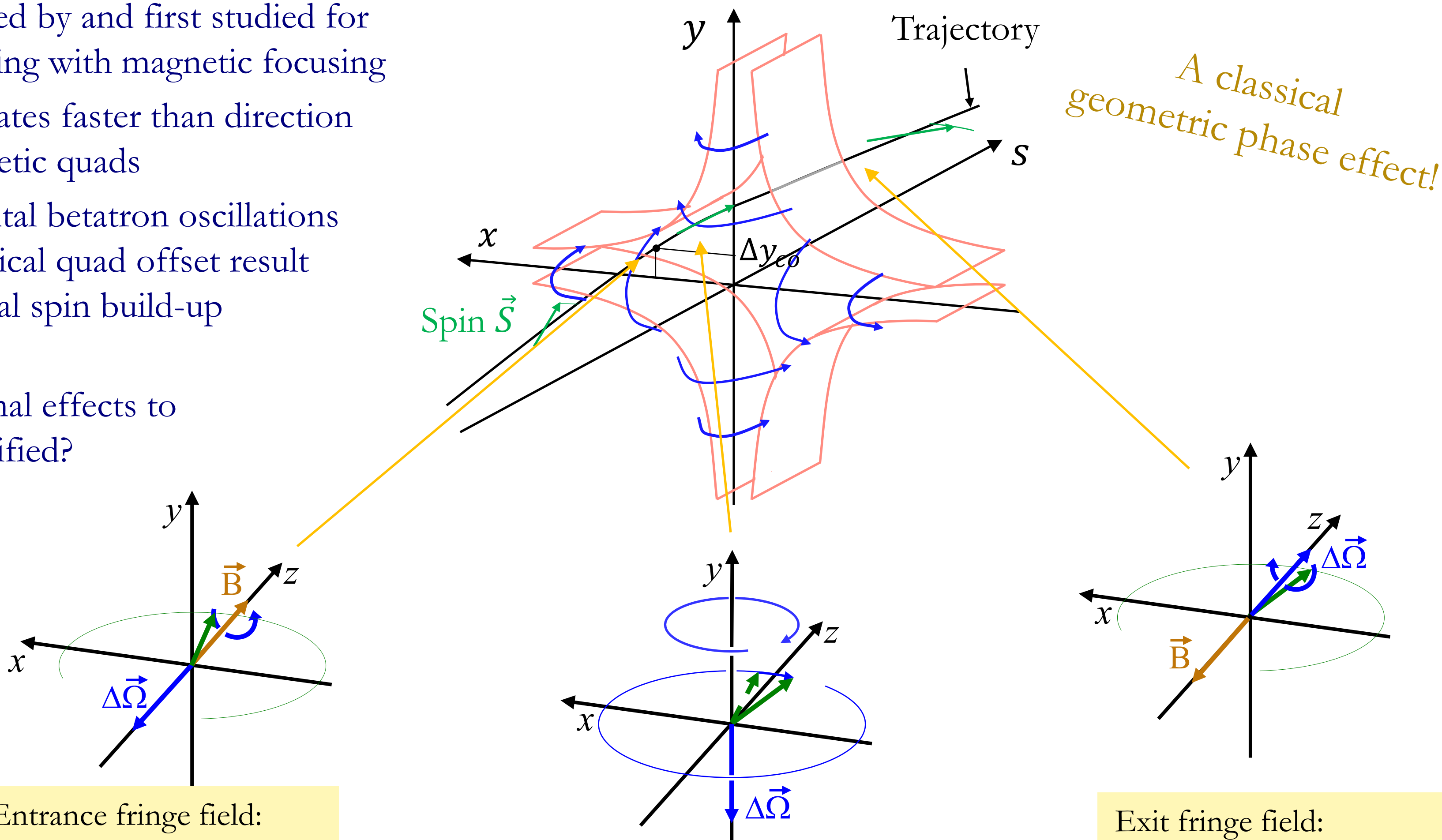


  - Measurement campaign to for first storage ring deuteron EDM

Vertical Offset of quad and horizontal betatron Oscillations

- Motivated by and first studied for hybrid ring with magnetic focusing
- Spin rotates faster than direction in magnetic quads
- Horizontal betatron oscillations and vertical quad offset result in vertical spin build-up

- Additional effects to be identified?



Entrance fringe field:
Positive longitudinal B
& positive radial spin
=> Negative vertical spin

Inside Quadrupole
Spin rotates faster than direction motion

Exit fringe field:
Negative longitudinal B
& negative radial spin
=> Negative vertical spin

Vertical offset of quad and horizontal betatron oscillations – hybrid ring

CP EDM

- Inside magnetic quadrupole and considering vertical component of angular frequencies for spin rotation $\omega_{s,y} = -\frac{q}{m}\left(G + \frac{1}{\gamma}\right) B_y$
  rotation of particle direction $\omega_{p,y} = -\frac{q}{m\gamma} B_y$

=> Radial spin component: $S_x \approx (\omega_{s,y}/\omega_{p,y})x' = (\gamma G + 1)x'$ and $S_x - x' \approx \gamma G\, x'$ (somewhat smaller for hybrid ring with part of focusing from electric bendings?)

Upper (lower) sign for quad entrance (exit)

- Integrated longitudinal magnetic field region of focusing magnet with strength k with x and Δy_{co} the transverse coordinates
  - Generates rotation around longitudinal axis

$$\int B_s\, ds = \pm \frac{m\gamma\beta c}{q} k\, x\, \Delta y_{co}$$

$$\Delta\alpha_s = -\frac{q}{m}\frac{G+1}{\gamma}\int B_s \frac{ds}{\beta c} = \mp(G+1)k\, x\, \Delta y_{co}$$

- Gives vertical spin component

$$\Delta S_y = \Delta\alpha_s(S_x - x') = \mp(G+1)k\Delta y_{co}\, x\,(S_x - x') \approx \mp\gamma\, G(G+1)k\, \Delta y_{co}\, x\, x'$$

- Averaging $x\,x'$ over betatron oscillations with β_x and α_x the Twiss parameters and J_x the action variable

$$\langle xx'\rangle = \frac{1}{2\pi}\int d\mu\, \sqrt{2J_x\beta_x}\, \cos\mu\sqrt{2J_x/\beta_x}\,(\sin\mu - \alpha_x\cos\mu) = -J_x\alpha_x$$

- Average spin buil-up rate with indices i and o for quadrupole entrance and exit

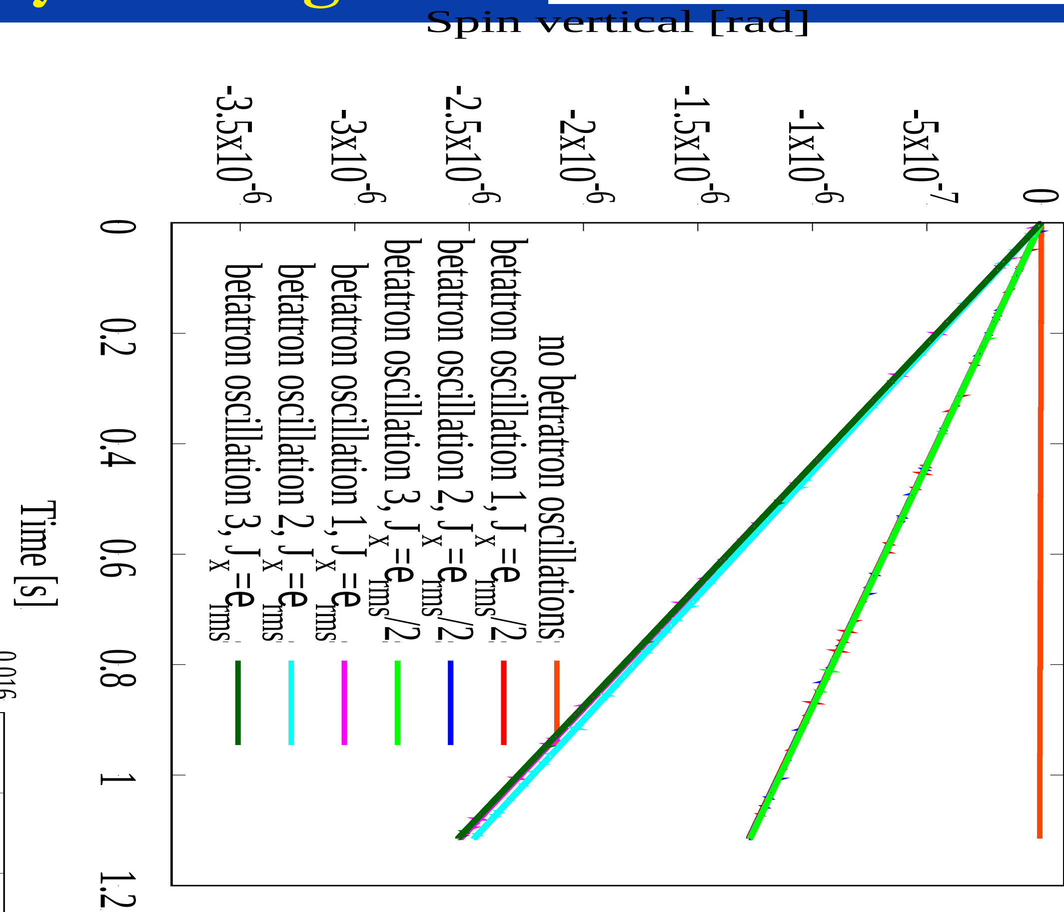
$$\dot{S}_y = \frac{\gamma\, G(G+1)k}{C/(\beta c)}\left(\Delta y_{co,i}\alpha_{x,i} - \Delta y_{co,o}\alpha_{x,o}\right) J_x$$

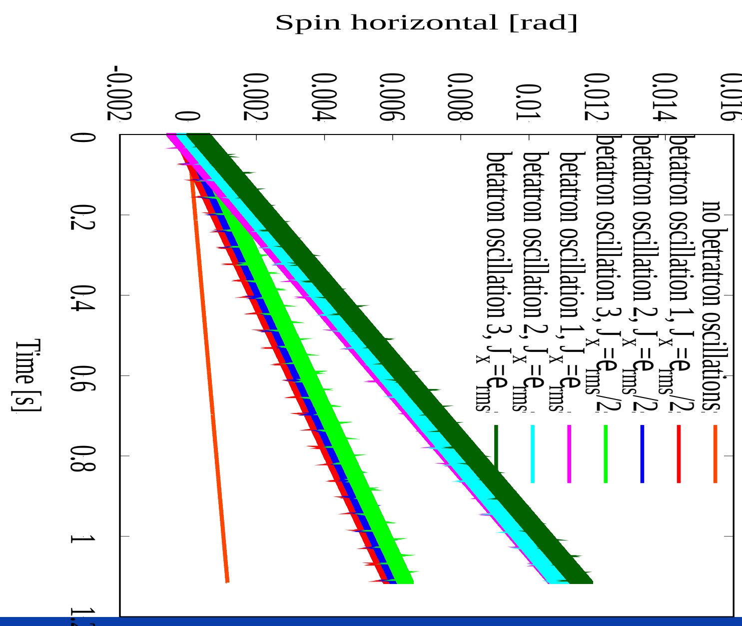
(rather upper limit for hybrid ring - should be exact for structure without bendings)

Vertical offset of quad and horizontal betatron oscillations – hybrid ring

- Case of an offset of 0.1 mm
- Local orbit deformation with magnetic correctors before and after quad

- Observed spin rotations about -1/2 times the expected ones
- Effect proportional to action variable (as expected)



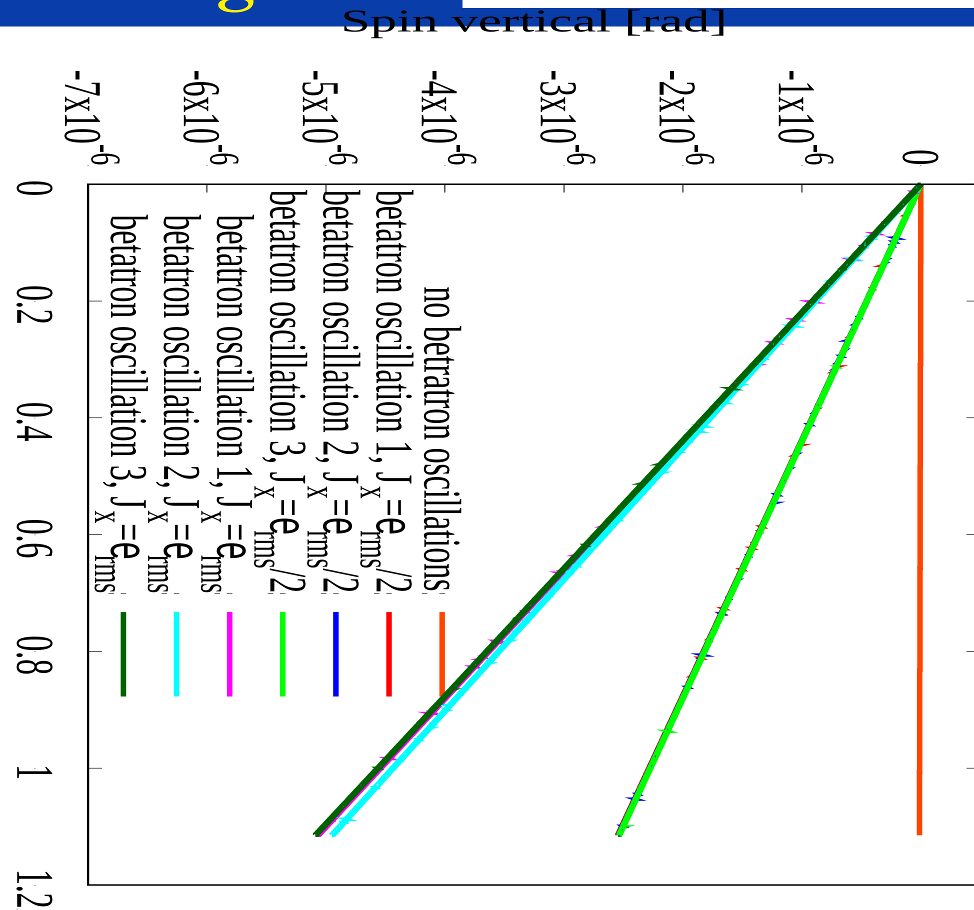


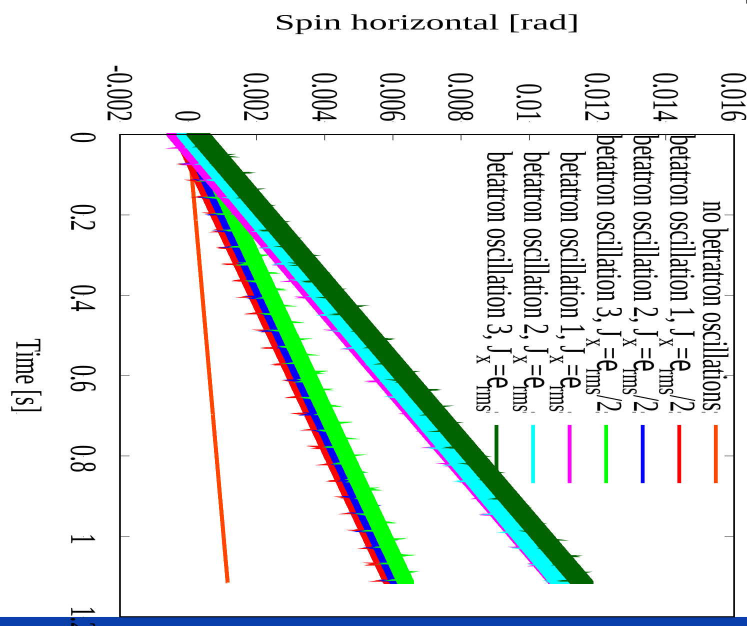
Study by Vera Cilento

Vertical offset of quad and horizontal betatron oscillations – hybrid ring

- Case of an offset of 0.2 mm

- Observed spin rotations about -1/2 times the expected ones
- Effect proportional to action variable (as expected)
- Effect proportional to vertical quad offset (as expected)



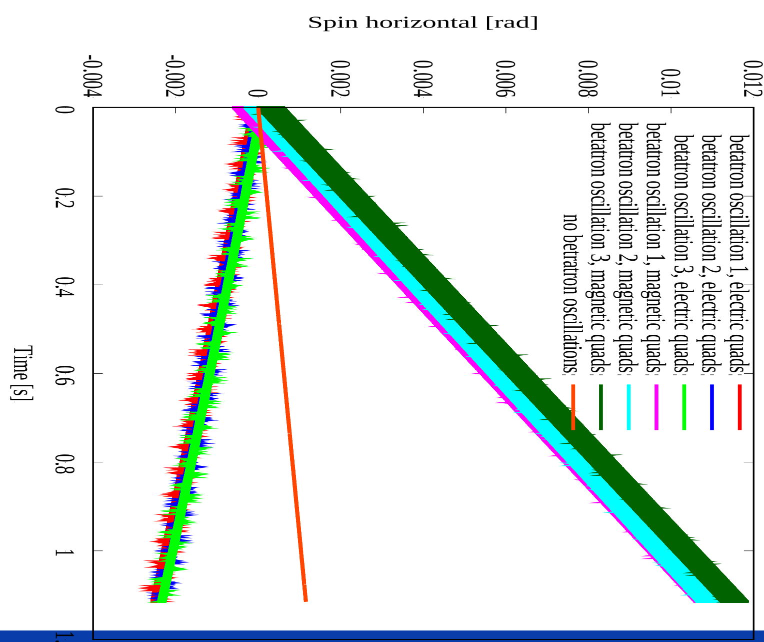


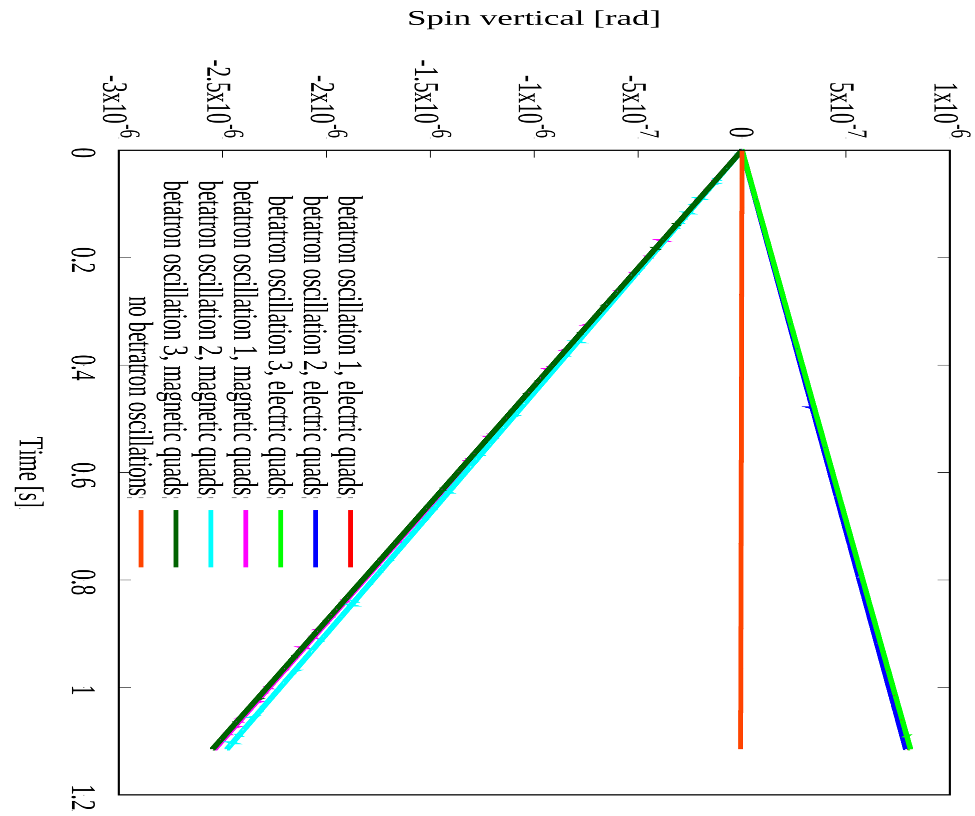
Study by Vera Cilento

Vertical offset of quad and horizontal betatron oscillations – comparison

- Case of an offset of 0.1 mm

- In addition, simulation with offset of electro-static quad and correctors to close orbit bump
- Effect proportional to vertical quad offset (as expected)



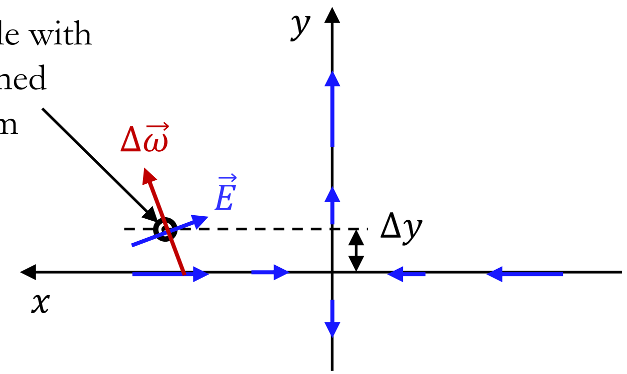


Study by Vera Cilento

Vertical offset of quad and horizontal betatron oscillations – electric quads

- Electric field $\vec{E} = k\frac{\gamma\beta^2 mc^2}{q}(-x, y)$
- Electric potential $U = k\frac{\gamma\beta^2 mc^2}{q}\frac{x^2-y^2}{2}$
- Change of Lorentz factor
  $\Delta\gamma = -\frac{qU}{mc^2} = k\,\gamma\beta^2\,\frac{y^2-x^2}{2}$
- Offset of beam w.r.t quad Δy results in (replace y by Δy)

Trajectory of particle with spin (almost) aligned with momentum



Direct spin rotation inside electric quad
From longitudinal into vertical direction

$$\Delta\omega_x = -\frac{q}{m}\left(G - \frac{1}{\gamma^2-1}\right)\frac{\beta E_y}{c} = -\frac{\beta c}{\gamma}k^2(\Delta y^2 - x^2)\Delta y \approx \frac{\beta c}{\gamma}k^2 x^2 \Delta y$$

$$\Delta\left(\frac{-1}{\gamma^2-1}\right) = \frac{2\gamma\,\Delta\gamma}{(\gamma^2-1)^2}$$

Skipping higher orders $\propto \Delta y^3$

Neglected effect proportional to Δy^3 (quad and correctors) significant?

Similar effect with vertical betatron oscillation to be studied?

- Factors L_{quad}/C for averaging over circumference and replacing x^2 by average $\langle x^2\rangle = \beta_x J_x$ gives for initial polarization parallel to movement

$$\dot{S}_y = -\widehat{\Delta\omega}_x = -\frac{L_{quad}}{C}\frac{\beta c}{\gamma}k^2\beta_x J_x\,\Delta y$$

- For hybrid ring lattice after replacing magnetic quads by electric ones with $\Delta y = -0.1$ mm,
  $L_{quad} = 0.4$ m, $C = 800$ m, $k = 0.0877\ \text{m}^{-2}$, $\beta_x = 64$ m and $J_x = \varepsilon_{rms} = 0.214\ \mu$m $\quad \dot{S}_y = 0.757\ \mu\text{rad/s}$
- From simulations: $\dot{S}_y = 0.788\ \mu\text{rad/s}$

showing good agreement with simulations…

Design of a Protoype Ring as next Step As Part of staged Approach

- All schemes for cpEDM measurements very challenging
- Design and construction of dedicated cpEDM ring as next step ruled out
- Agreement within community on staged approach
  - First direct cpEDM measurement (deuterons) and many basic studies with COSY
  - Next step: prototype ring to gain experience and better understand limitations and their mitigations

Stage 1

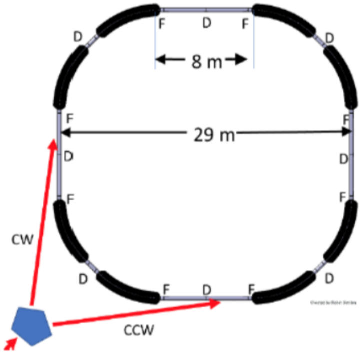
precursor experiment at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

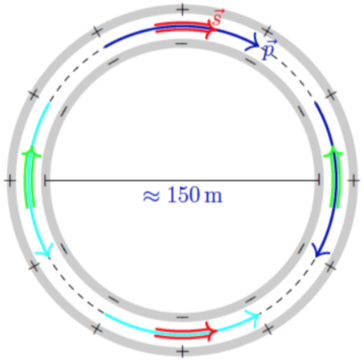


- electrostatic storage ring
- simultaneous ⟳ and ⟲ beams

5 years

Stage 3

dedicated storage ring



- magic momentum (701 MeV/c)

10 years

Design of a Protoype Ring as next Step Application for INFRADEV Grant

CP EDM

- Similar application almost successful (1st on reserve list)
- Collaboration of 8 institutes with different expertise
- Aim is a protoype ring design to test:
  - Gain expertise with operation with high electric fields
  - Study spin (de-)coherence and optimization if spin coherence time
  - Polarimetry
  - Magnetic fields in addition for “frozen spin” operation and first storage ring proton EDM measurement
  - Operation with low vertical tune and orbit separation measurements to estimate stray field
  - Improved understanding of systematic effects?
  - Beam cooling?

Design of a Protoype Ring as next Step Application for INFRADEV Grant

WP Number	WP title	Lead Participant Number	Lead Participant Short name	Person Months	Start month	End month
1	Project coordination	1	INFN	18	1	48
2	Ring design	3	CERN	48	1	42
3	Ring elements	5	RWTH	60	1	42
4	Beam diagnostics and instrumentation	2	GSI	24	1	42
5	Polarimetry and spin manipulation tools	6	LIV	84	1	42
6	Parameter control and expected performance	5	RWTH	90	1	42
7	Cost estimate	1	INFN	12	1	45
8	Dissemination and outreach	7	JAG	36	1	48
				372		

Participant number & short name	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	Total PM participant
1 INFN	18		6			12	12	12	60
2 GSI			12	12	12				36
3 CERN		24	18	12		6			60
4 MPG		24	12						36
5 RWTH			12			24			36
6 LIV					48				36
7 JAG						24		24	48
8 TSU					24	24			48
	18	48	60	36	84	90	12	36	372

Summary

- cpEDM measurements
  - of high interest for physics …
    - CP violation (larger than compatible with SM) a possible hint to explain matter preponderance ..
  - … but as well very challenging (for all variants proposed)
    - Systematic effects, spin (de-)coherence, beam life-time, spin manipulations, high precision polarimetry
    - Optimum scheme and achievable sensitivity to be determined
- Prototype ring PTR
  - Next step before construction on cpEDM ring can be envisaged
    - Gain experience with operation of large-scale high field electric ring
    - Assess main limitations and device mitigation strategies
  - First direct measurement of proton EDM in phase 2
  - Create base to define "magic energy" proton EDM ring
    - Together with studies and simulations on limitations in parallel
- Collaboration concentrating on PTR design
  - Work packages and participating institutes defined