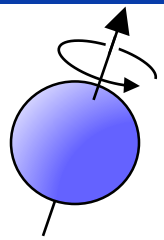
charged particle Electric Dipole Moment (cpEDM) – Status of the Collaboration and next Steps

C. Carli on behalf of the cpEDM Collaboration

PBC general WG Meeting, 2nd December 2021

- Physics Motivation
- Fully electro-static "Magic Energy Ring"
- Other schemes and Variants
  - "Hybrid Ring"
  - RF Wien Filter Method
  - Search for oscillating cpEDMs
- Staged Approach
- Status of Collaboration
- Summary

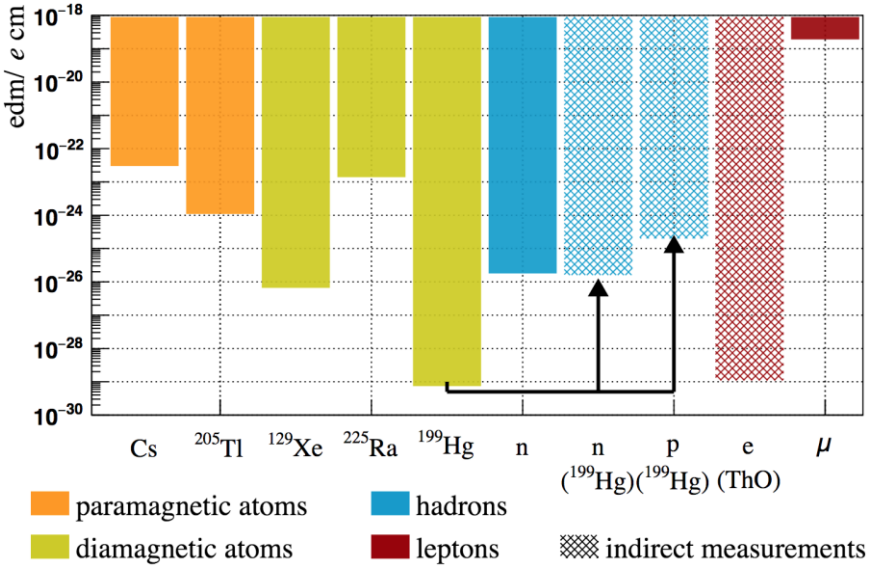
Physics Motivation



Spin $\vec{s}$
Magnetic moment $\vec{\mu}$
Electric moment $\vec{d}$?
(as well aligned with spin)

- 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

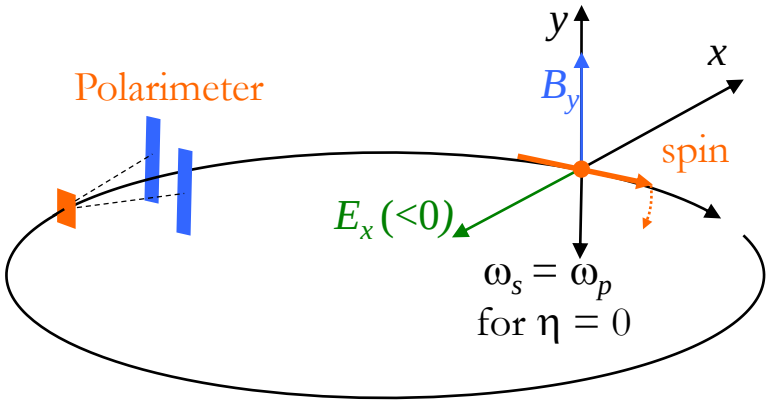


Measured upper bounds for EDMs
(from CERN 2021-003)

- CERN joined international effort within PBC study group

Fully electrostatic "magic Energy" Ring

- "Frozen spin" cpEDM ring
  - Initial longitudinal polarization of bunch maintained for vanishing EDM (only well known MDM)
  - Identical angular frequencies $\vec{\omega}_s$ and $\vec{\omega}_p$ describing rotation of spin and direction require



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

- Concept of "magic energy"
  - Possible for particles with positive anomalous magnetic moment factor $G = (g - 1)/2 > 0$
  - "frozen spin" fulfilled with electric field only by appropriate choice of "magic energy" $b_m g_m = G^{-1/2}$
  - Fully electrostatic machine (electro-static quads) and counter-rotating beams

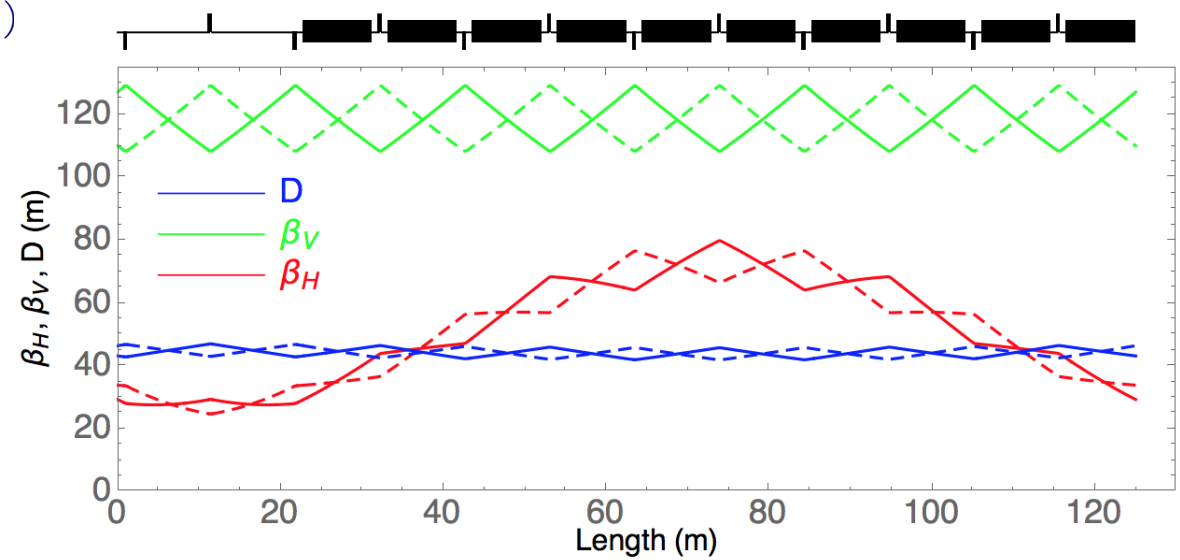
Sensitivity of 10^{-29} e.cm often quoted very challenging

- For protons with $G = 1.7928473\cdots$: $E_m = 232.79$ MeV and $p_m = 700.74$ MeV/c
  - Requires a ring with a circumference of at least 500 m
  - EDM of d = 10^{-29} e.cm (sensitivity target often given) rotates spin around radial axis by 1.6 nrad/s
  - Residual magnetic field inside shield probably main limitation
    - Scheme to measure orbit separation of counter-circulating beams with pm(!) accuracy for mitigation
  - Other challenges: spin (de-)coherence, understanding and handling of systematic effects

Other Schemes and Variants – Hybrid Ring Concept

- Ring operated at "magic energy" and focusing using magnetic quadrupoles
  - Gradients of electric bendings must be avoided (design field index $m = 0$)
  - As well operation with counter-rotating beams

S. Haciomeroglu and Y. K. Semertzidis, PRAB 22, 034001 (2019)



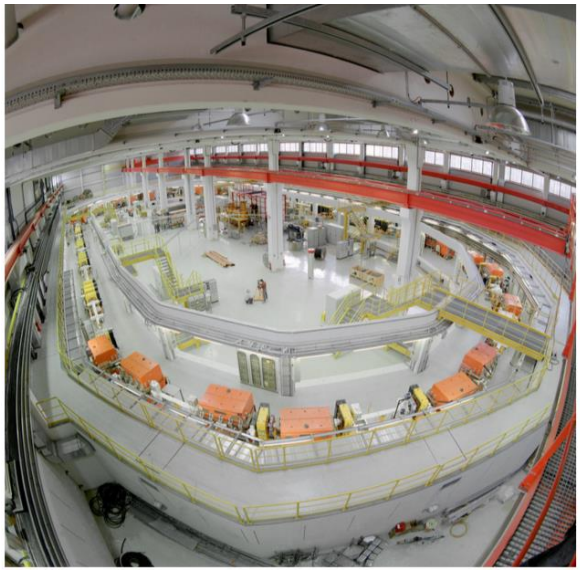
Twiss parameters for one out of four periods for the CW (solid lines) and the CCW (dashed lines) beam

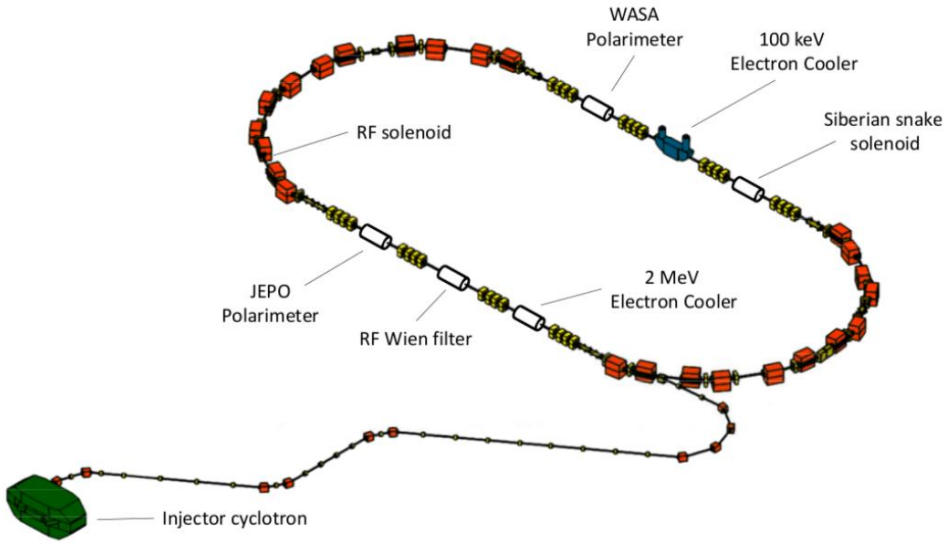
- Features and consequences
  - No spin rotation proportional to average radial magnetic field $\bar{B}_x$
  - Lattice different for counter-rotating beams – tuning more delicate (tunes, closed orbit, spin coherence)
  - Systematic effects to be evaluated with care
    - Unwanted electric gradients
    - Higher magnetic fields …..

Other Schemes and Variants –
RF Wien Filter Method

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

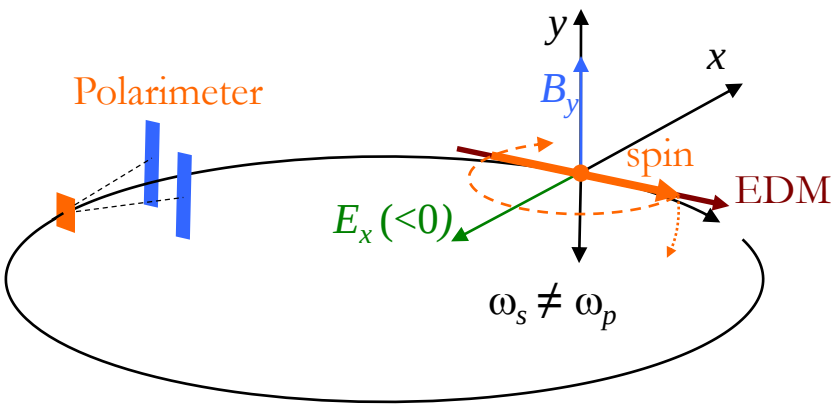
Note: many studies as spin feedback and spin decoherence studies, essential for cpEDM measurements in general, done with COSY



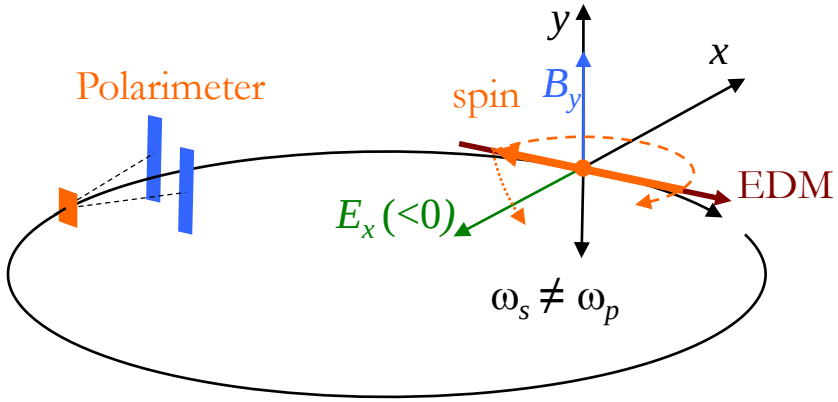


- RF Wien filter operated with suitable frequency and phase w.r.t. spin rotations
- EDM generates vertical spin build-up over duration of store
- First direct hadron cpEDM measurement result to come soon!

Other Schemes and Variants –
Search 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
  - Oscillating EDM means that ratio between EDM and spin oscillates $h = h_0 + \hbar \sin\left(w_{axion} t + j_0\right)$
  - Resonance condition $\left|w_s - w_p\right| = w_{axion}$!
  - 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!

Staged Approach

- All schemes for cpEDM measurements very challenging
- Design and construction of dedicated cpEDM ring as next step ruled ou
- 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

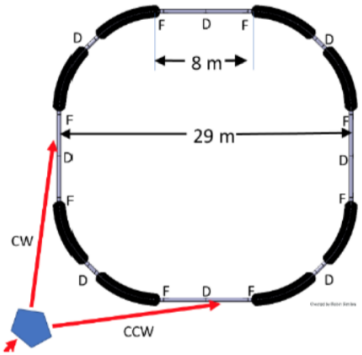
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

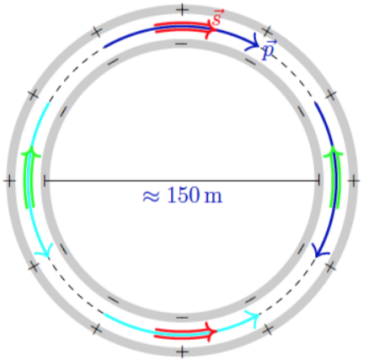


- electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

dedicated storage ring



- magic momentum

(701 MeV/*c*)

10 years

Next steps and Collaboration

- Concentrating on PTR design and construction as next steps
  - Phase 1: electro-static ring – "frozen spin" not possible
    - Gain experience with operation of large ring pushing electric fields to limits
    - Counter-rotating beams with observation of orbit separation
    - Spin control: optimization of spin coherence time, spin feedback …
    - Control of vertical orbit, operation with low vertical tunes, beam cooling …
  - Phase 2: additional magnetic field for "frozen spin" operation
    - First direct proton EDM measurement with (how much?) reduced sensitivity
  - Proposals for additional operational modes proposed and under discussion
- Structure for PTR design defined
  - Work packages and participating institutes defined
  - Regular meetings
  - Application for INFRADEV-01-01-2022 call being prepared
- In line with cpEDM PBC mandate (in addition further studies on systematic effects)
  - Main CERN contribution is ring design (lattice …) and injection concept
  - Contributions to hardware design: electro-static multipoles (quadrupoles)
  - RF system (system required expected to be simple) and alignment (expertise on state-of-the-art techniques and performance)

Status of Collaboration

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

Preliminary list with PTR design WPs and participating institutes

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
    - 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