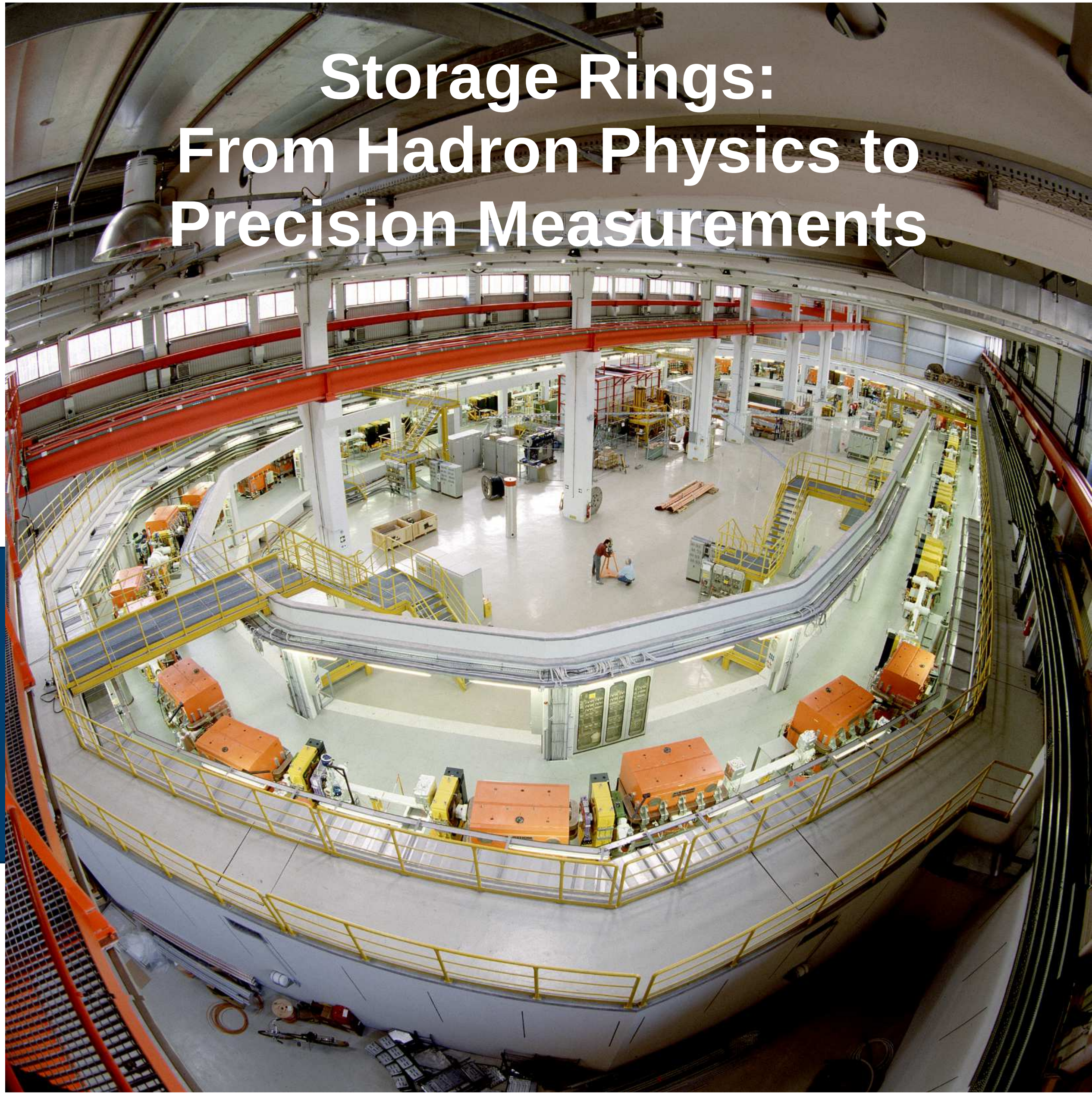
766. WE-Heraeus-Seminar

High-Precision Measurements and Searches for New Physics

09 – 13 May 2022 Physikzentrum Bad Honnef

Thursday, May 12, 2022

Storage Rings: From Hadron Physics to Precision Measurements



Cooler Synchrotron (**COSY**) at IKP of Forschungszentrum Jülich (Germany)

Hans Ströher

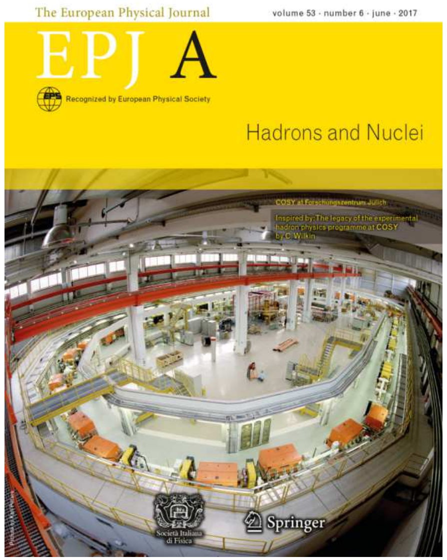
for the **JEDI-** and the **CPEDM** collaboration

PRELUDE – COSY HISTORY

- ➢ 1993 (April 1): Inauguration
- ➢ 1993: First experiment
- ➢ 1996: Polarized beams (p), 1998 (full energy), 2003 (d)

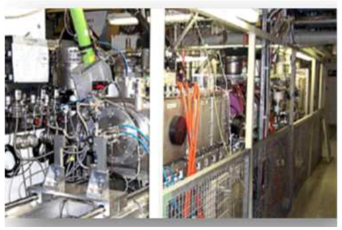
- ➢ **Hadron physics** (internal, external target stations)
  - Elastic pp- and pn-scattering
  - Threshold meson production (N*, Δ*)
  - Dibaryonic state d*(2380) in pn → $\Delta\Delta$ → $d\pi^0\pi^0$
- ➢ 2005: WASA detector (from TSL/Uppsala → COSY)
  - Rare η-decays
  - Search for Dark Photons
- ➢ 2016: Termination of Hadron Physics program

- ➢ 2010: **JEDI** (Jülich Electric Dipole moment Investigations)
  - 485. WE-Heraeus Seminar 2011 (and # 744. in 2021)



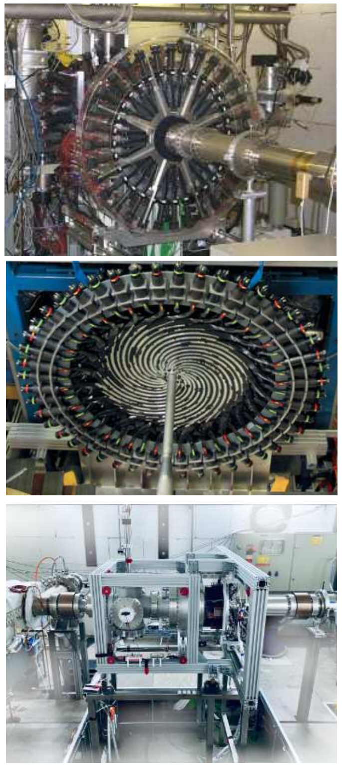
PRELUDE – COSY POLARIZATION HISTORY (I)

➢ Polarization **hardware**: sources, targets, polarimeter; manipulation tools

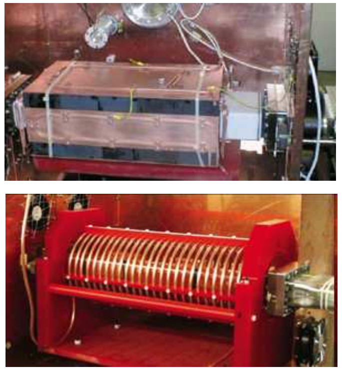


COSY polarized H^-,D^- source

ANKE, PAX polarized H^-, D^- target (ABS)



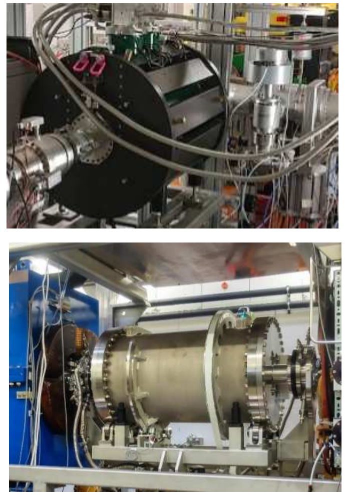
EDDA, WASA, JEDI polarimeter



RF dipole
RF solenoid

↑

A. Krisch et al.
(Spin-at-COSY)

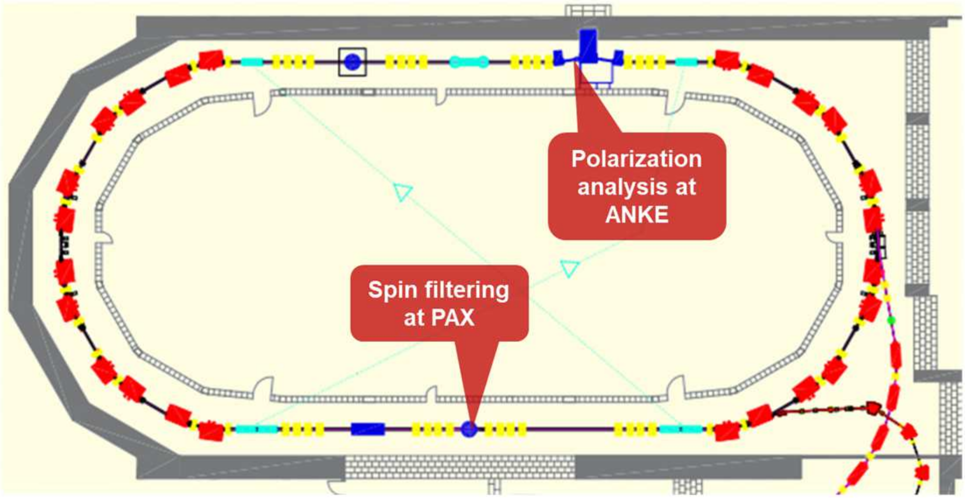


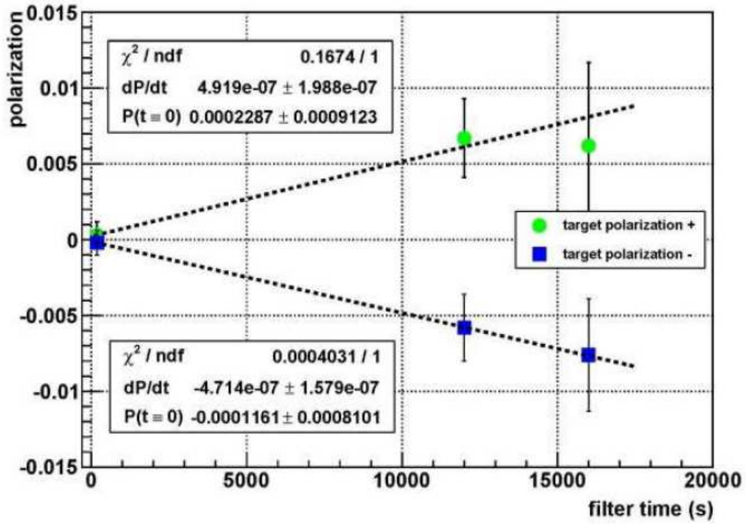
Siberian snake
RF Wien filter

PRELUDE – COSY POLARIZATION HISTORY (II)

- Polarization experiments at COSY:

PAX: towards **polarized anti-protons** ← proton "spin-filtering" expt. at COSY



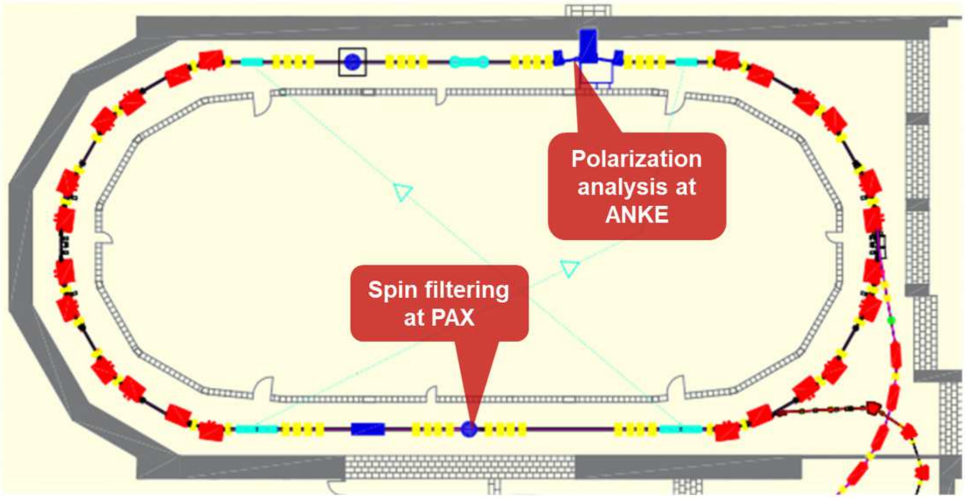


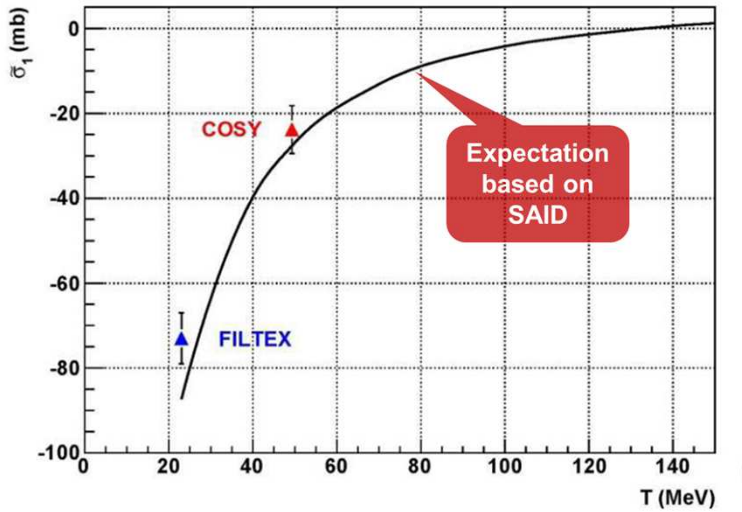
→ Proof-of principle experiment (ERC AdG "POLPBAR" 2010-2016)

PRELUDE – COSY POLARIZATION HISTORY (II)

➢ Polarization experiments at COSY:

<u>PAX</u>: towards **polarized anti-protons** ← proton “spin-filtering” expt. at COSY



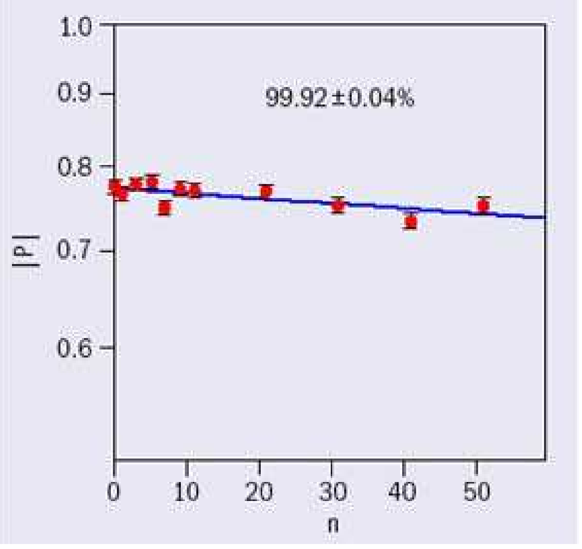


→ Proof-of principle experiment (ERC AdG “POLPBAR” 2010-2016)

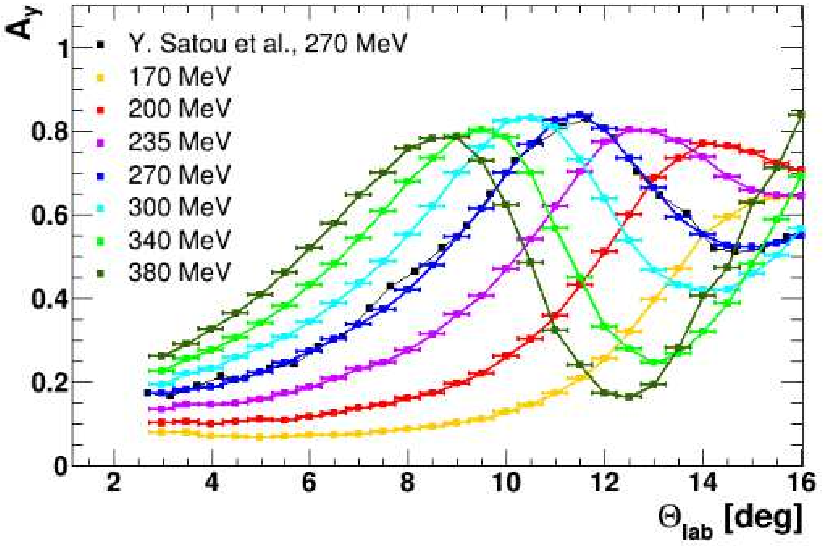
PRELUDE – COSY POLARIZATION HISTORY (III)

➢ Polarization experiments at COSY:

<u>Examples</u>: **spin manipulation**; hadronic reaction (→ **polarimetry**)



Spin flipping efficiency of a proton beam (2.1 GeV/c) with an RF dipole (A. Krisch et al., 2004)

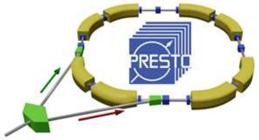


Vector analyzing power A_y for pC elastic scattering with WASA FW detector (F. Müller et al., 2020)

PRELUDE – COSY EDM HISTORY

- 2008: US **SREDM** collaboration
  EDM polarimetry experiments at COSY
- 2010: EDM at COSY starts
  JEDI collaboration: R&D, tests at COSY
- 2016: **ERC AdG** (PI H.S.)
  R&D, precursor experiment
- 2021: PBC, CYR, ESPP Update, JENAS EoI
  CPEDM collaboration

- 2022: Staged approach; **PRESTO** application



→ COSY: the **best place** for R&D, tests w/ beam, first EDM measurements

INTRODUCTION – MOTIVATION EDM SEARCHES

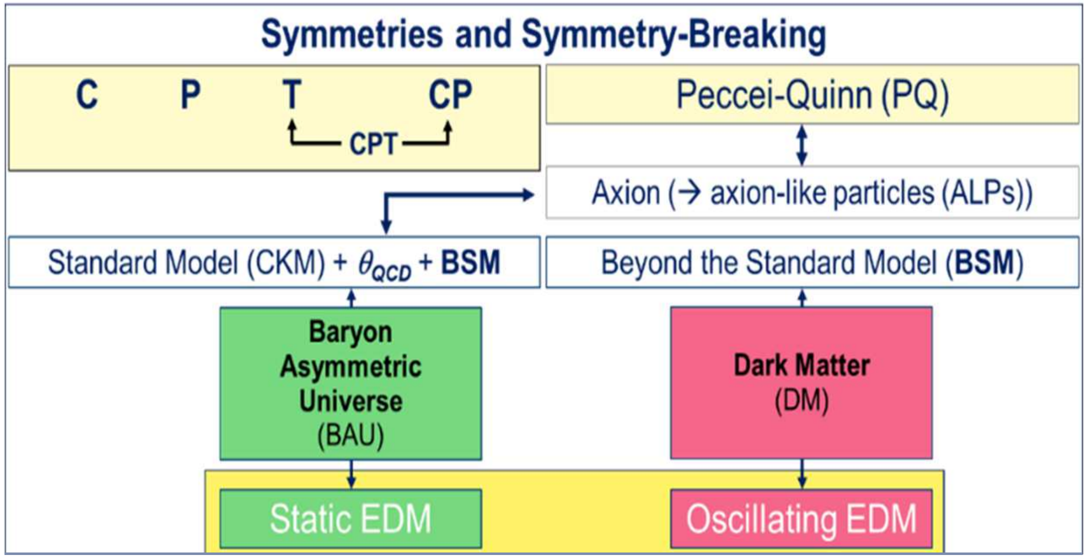
➢ Science case: **cosmology** and **particle physics**:

- Why is there **matter** and no **antimatter**?

  Additional CP-violation

- What is **Dark Matter** made of?

  Axion (Axion-like particles)

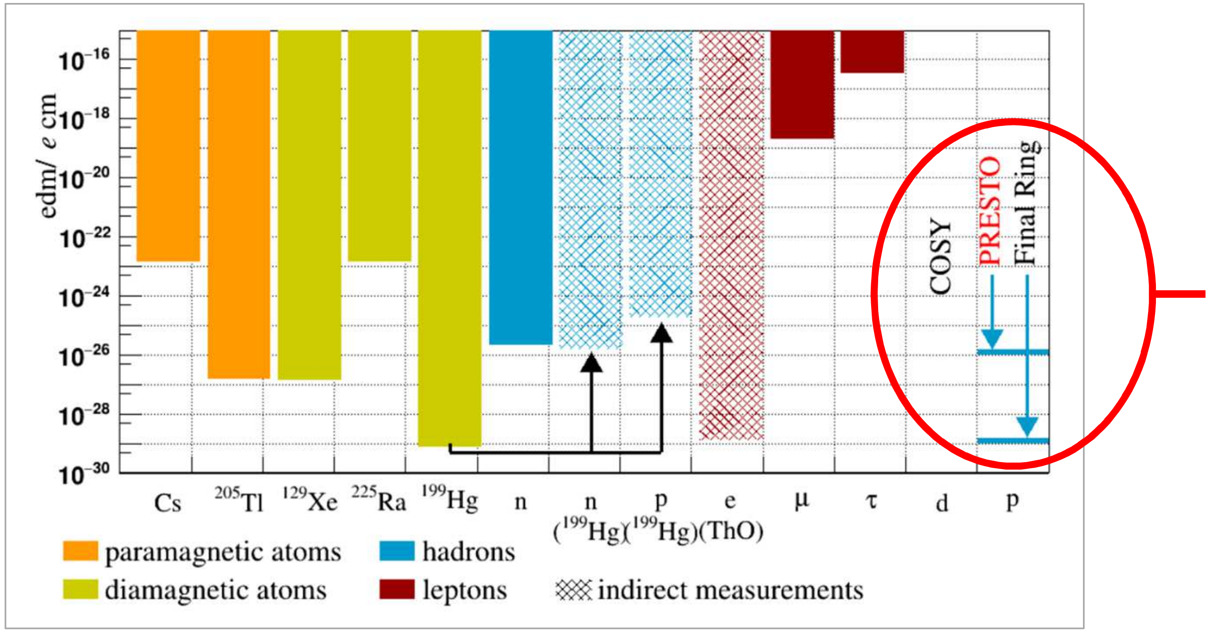


Electric Dipole Moments (EDM) of particles:

- CP-violation, since P- and T-violating
- Axion/ALP search

INTRODUCTION – MOTIVATION EDM SEARCHES

➢ Science case: status – **EDM searches**



→ no EDM found yet - excellent **direct (n) / indirect (e, p)** sensitivity limits (note: SM contribution negligible)

INTRODUCTION – MOTIVATION EDM SEARCHES

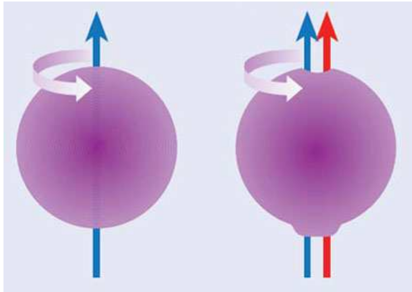
- Science case: **new approach** – charged particles

Experimental input		Theoretical input	EDM sources	Goal
Direct measurements	Neutron (n) **Proton (p)** **Deuteron (d)** Leptons: Electron (e), Muon (μ), Tau (τ)	Quantum Chromo-Dynamics (QCD) Nuclear Theory	Quark EDM Quark-Chromo EDM Lepton EDM	FUNDAMENTAL THEORY
Indirect measurements	Atoms: → Nucleon (n,p) → Electron (e)	Nuclear Theory Atomic Theory		

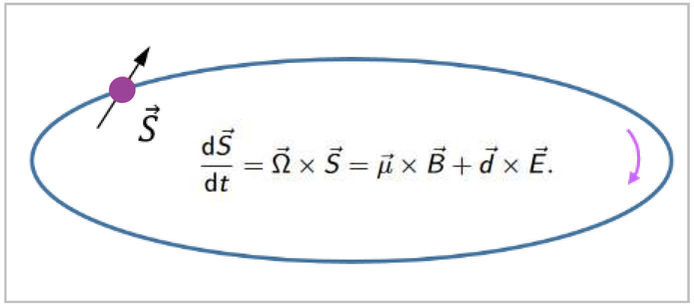
→ direct EDM search for proton, deuteron: **how?**

INTRODUCTION – MEASUREMENT PRINCIPLE (I)

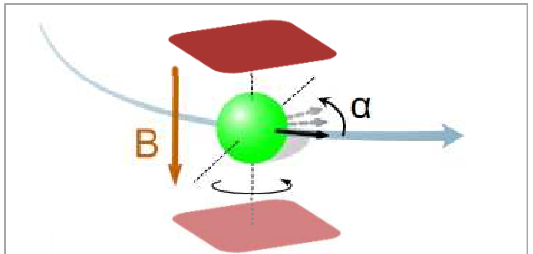
- **Dipole moment** (vector) || to **particle spin**:



- Movement of **particle spin** in external (magnetic, electric) fields:

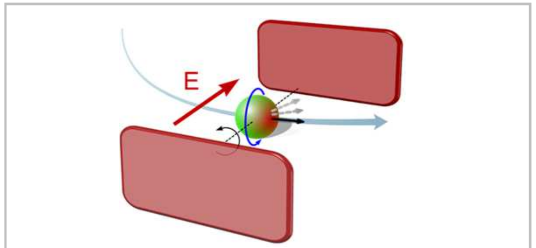


Storage ring



Magnetic dipole moment μ

in-plane “(g-2) precession”



Electric dipole moment *d*

out-of plane rotation

INTRODUCTION – MEASUREMENT PRINCIPLE (II)

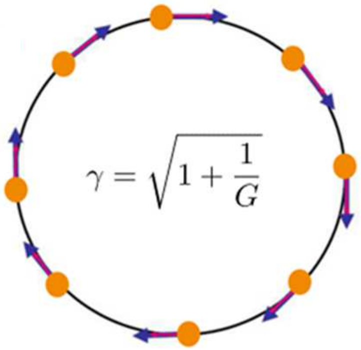
- Spin precession (**Thomas-BMT equation**):

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

Note: $\Omega_{MDM} >> \Omega_{EDM}$

- Make Ω_{MDM} **= 0**:

→ B = 0: **All-electric** storage ring
→ "Frozen spin" – "magic momentum" (for G > 0; proton)

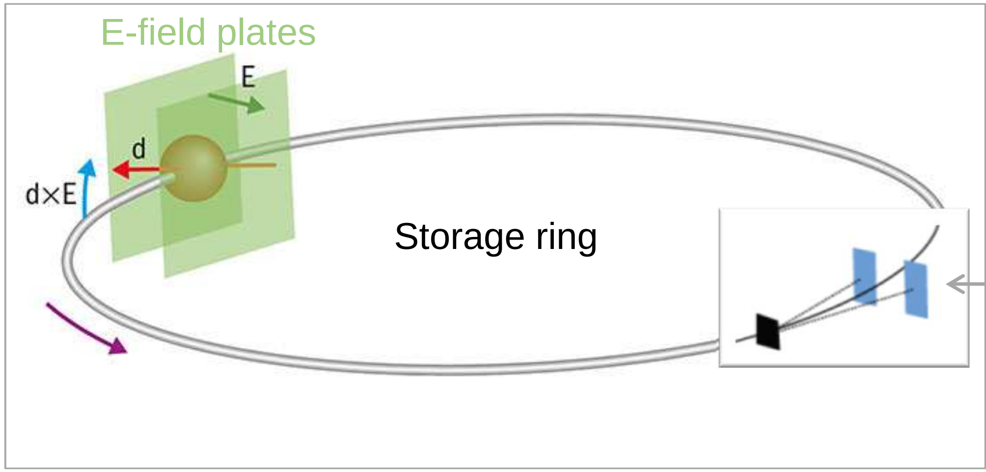


$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[\underbrace{\cancel{G\vec{B}} + \cancel{\left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}}_{=\vec{\Omega}_{\mathrm{MDM}}} + \underbrace{\frac{\eta}{2}(\vec{E} + \cancel{\vec{v} \times \vec{B}})}_{=\vec{\Omega}_{\mathrm{EDM}}}\right]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

INTRODUCTION – MEASUREMENT PRINCIPLE (III)

- EDM search for charged particles: **beam of polarized protons** (deuterons) in a storage ring - apply a radial electric field E:

Torque on the EDM: → originally polarized in-plane … develops **out-of-plane polarization**



Polarimeter to observe the vertical polarization build-up due to EDM

Statistical uncertainty: with reasonable assumptions (beam intensity, EDM-spin interaction time, polarimeter efficiency, …), a sensitivity of **10^{-29} e.cm** can be achieved in one year of total measurement time :

→ Goal: reduce **systematic** uncertainty to a comparable level

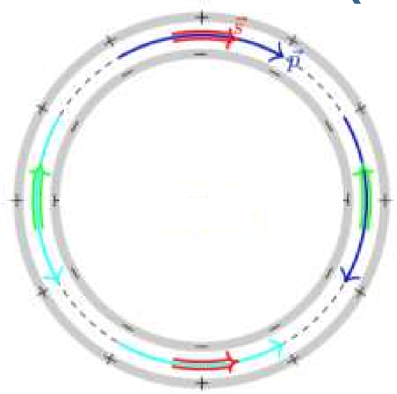
INTRODUCTION – CHALLENGES (I)

- Particle´s spin-response vastly different in for MDM and EDM:

  EDM of 10^{-29} e.cm (target sensitivity frequently given): spin rotation by **1.6 nrad/s**
  A radial magnetic field of ~ **10 aT** mimics effects of a 10^{-29} e.cm EDM

  → **Clockwise (CW)** and **counter-clockwise (CCW)** circulating particles

All-electric:
simultaneous
CW-CCW operation



Combined E/B fields:
subsequent
CW-CCW operation

- Realization:

  bunch(es) of (10^{10}) **polarized particles** (momentum spread, non-ideal orbits, …)
  storage ring (technical limitations: alignment, field imperfections, stability, …)
  polarimetry (efficiency, stability)
  …

INTRODUCTION – CHALLENGES (II)

➢ Beam characteristics:

Storage time of high intensity beam(s)
Measurement time (→ SCT)
Beam emittance (phase-space cooling?)

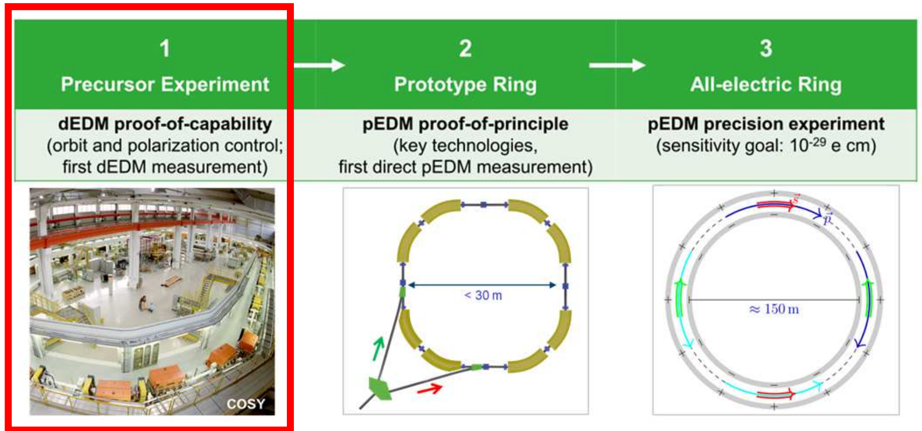
➢ Hardware:

Electric bends (MV/m, electric discharge)
Storage ring vacuum (cryogenics?)
Polarimetry (non-destructive?)
Large-scale magnetic shielding

➢ Other:

Alignment of ring elements, corrections
Beam orbit determination and feedback
Co-magnetometry
…

→ **Strategy**



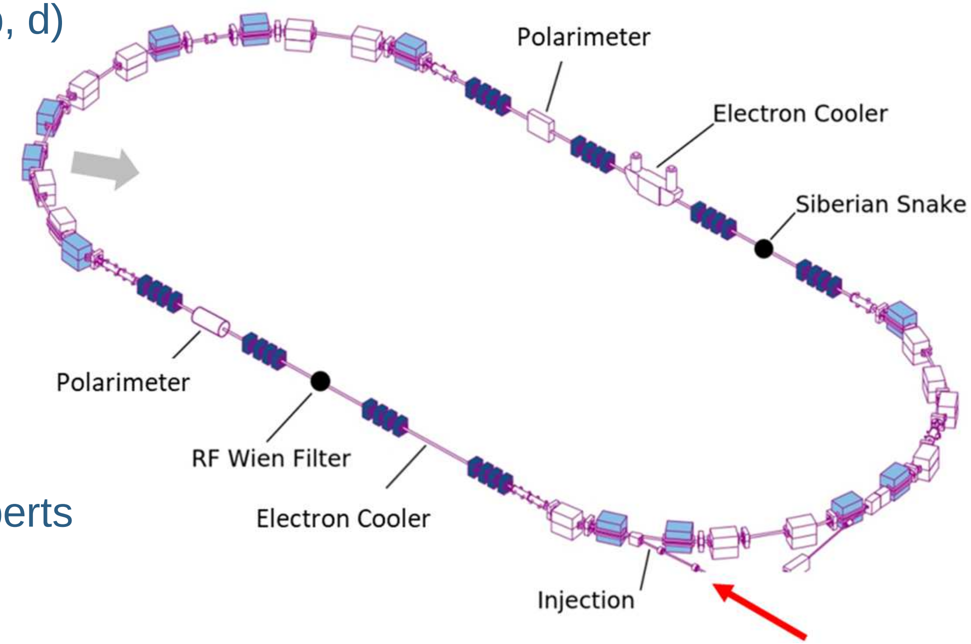
Ongoing activity at COSY

EDM STAGE 1 – COSY AS R&D FACILITY

- Worldwide unique:

  polarized beams (p, d)
  spin manipulation
  energy range fits
  cooling techniques
  …

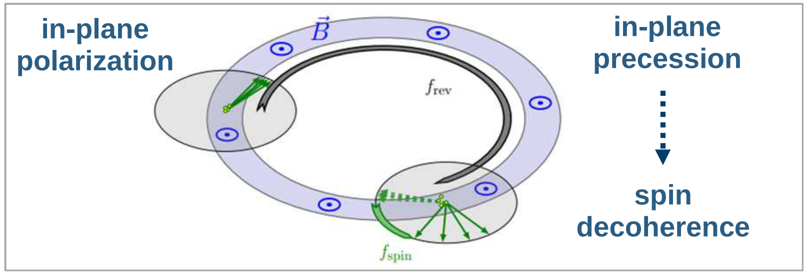
  experienced staff:
  scientists
  technicians
  operators
  \+ international experts



→ since 2010, significant fraction of beamtime for **JEDI** experiments

EDM STAGE 1 – COSY ACHIEVEMENTS (I)

- Optimization of **spin-coherence-time** (SCT):

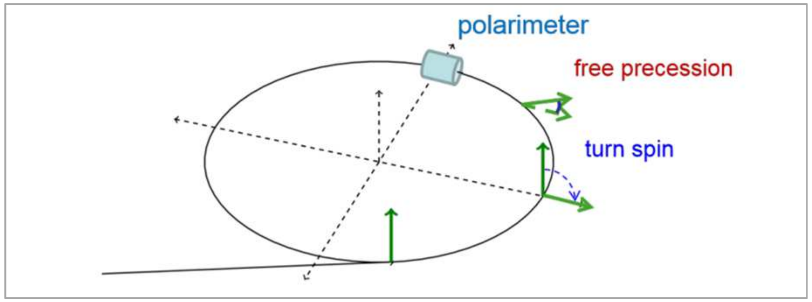


rapid depolarization (momentum variations)

→ beam bunching (isochronicity)

→ electron cooling (momentum spread)

→ sextupole field corrections, beam current limitation



measurement (deuteron beam)

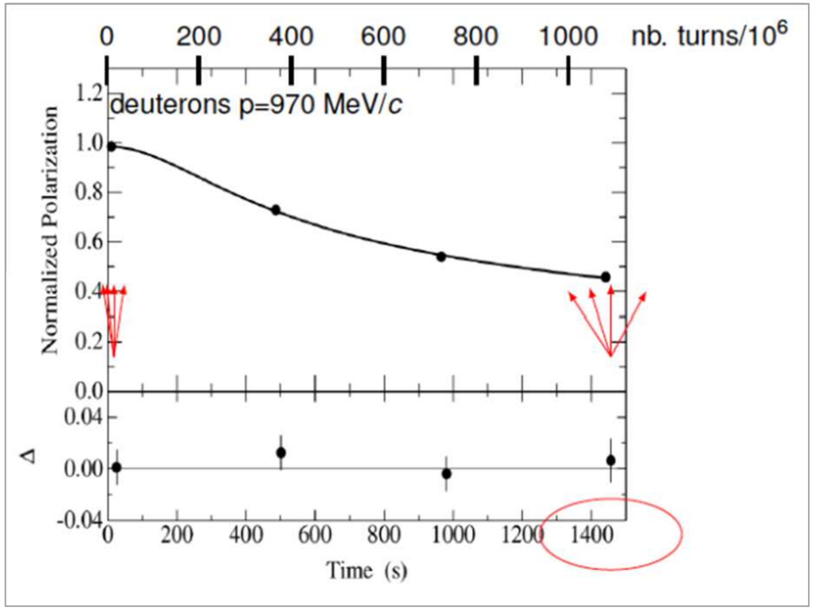
→ vertically polarized beam injected into COSY

→ rotation of spins by RF solenoid; free precession

→ 4x polarization determination (EDDA polarimeter)

EDM STAGE 1 – COSY ACHIEVEMENTS (I)

➢ Optimization of **spin-coherence-time** (SCT): $\sigma_{stat} \propto {\tau_{SCT}}^{-1}$



PRL 117, 054801 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

How to Reach a Thousand-Second in-Plane Polarization Lifetime with 0.97-GeV/c Deuterons in a Storage Ring

G. Guidoboni,[1] E. Stephenson,[2] S. Andrianov,[3] W. Augustyniak,[4] Z. Bagdasarian,[5,6] M. Bai,[6,7] M. Baylac,[8]

Nuclear Inst. and Methods in Physics Research, A 987 (2021) 164797

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

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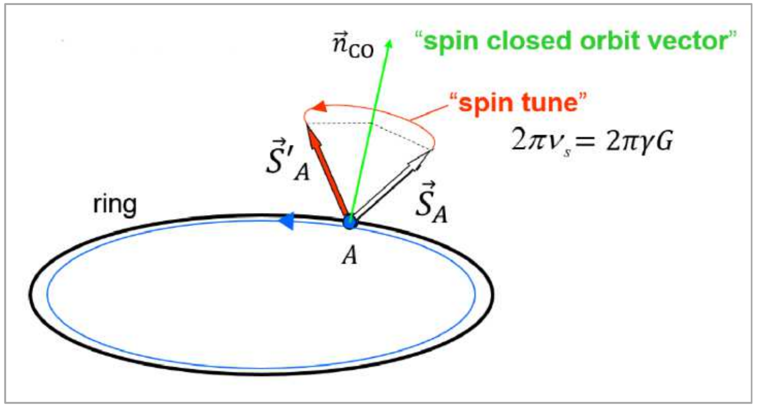
Technical Notes

Influence of electron cooling on the polarization lifetime of a horizontally polarized storage ring beam

→ **~1000 s** (orders-of-magnitude improvement; **EDM observation time**!)

EDM STAGE 1 – COSY ACHIEVEMENTS (II)

- Precision determination of **spin tune** (ST): (ν_s, # spin precessions per turn)



ideal magnetic storage ring on closed orbit $\nu_s = \gamma G$

real machine:

→ field imperfections

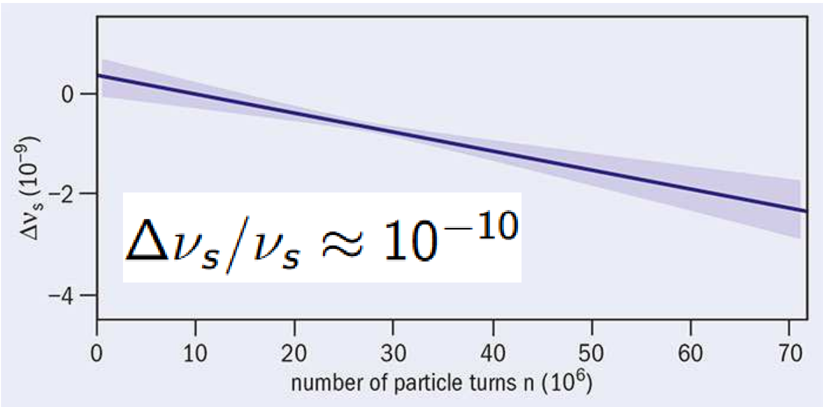
→ magnet misalignments

→ finite emittance

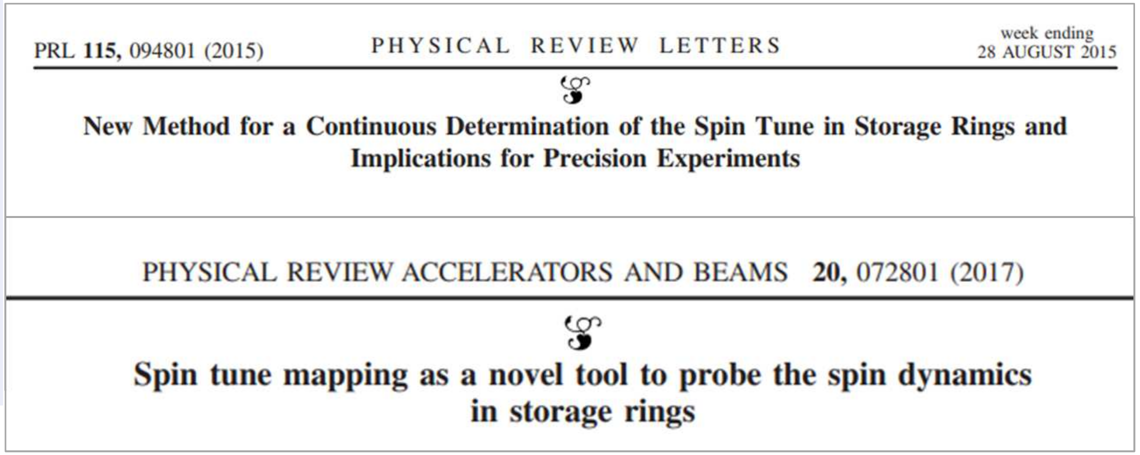
deviation of spin tune ν_s

EDM STAGE 1 – COSY ACHIEVEMENTS (II)

- Precision determination of **spin tune** (ST): (ν_s, # spin precessions per turn)



Deviation of the spin tune ν_s.
At t = 38 s (about 28 × 10^6 turns), the interpolated spin tune amounts to 16097540628.3±9.7 × 10^{-11}.
This represents the most precise measurement of this quantity ever performed.



PRL **115,** 094801 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 072801 (2017)

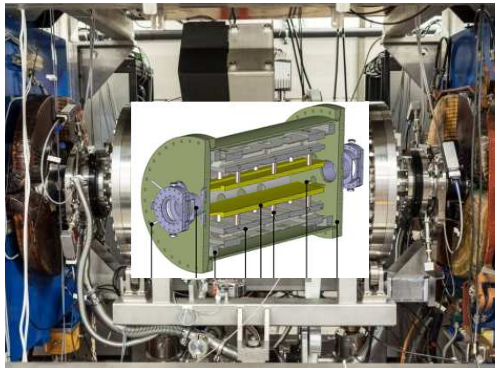
Spin tune mapping as a novel tool to probe the spin dynamics in storage rings

Determination of stable spin axis
First-ever *in-situ* measurement **(accuracy ~ 2.8 μrad)**

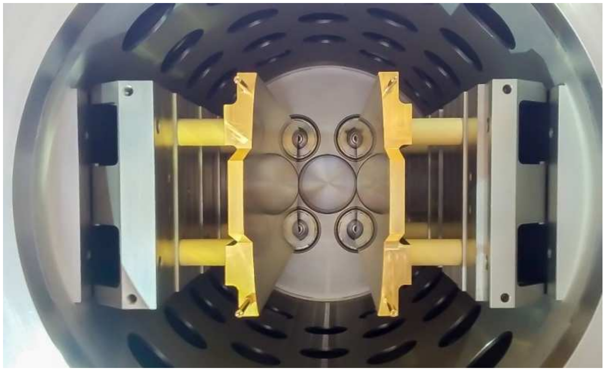
→ Study accelerator stability, machine imperfections; "phase-lock": new precision tool for **systematic effects** in storage rings

EDM STAGE 1 – COSY ACHIEVEMENTS (III)

- Bunch-selective spin manipulation with radio-frequency **(RF) Wien filter**



RF WF in COSY ring



Field plates inside **RF WF**

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 828, 21 August 2016, Pages 116-124

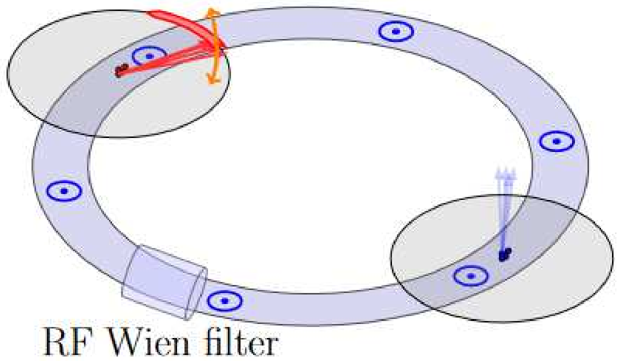
Electromagnetic Simulation and Design of a Novel Waveguide RF Wien Filter for Electric Dipole Moment Measurements of Protons and Deuterons https://doi.org/10.1016/j.nima.2016.05.012

COSY in multi-bunch (e.g., 2) operation

RF Wien filter in "**switching mode**" [on-off: $\tau \sim 20$ ns]

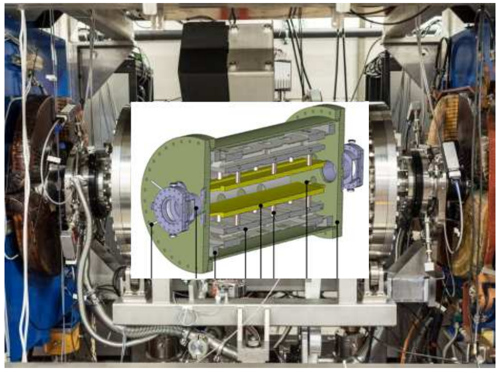
(in contrast to "continuous mode")

One bunch unaffected by Wien filter ("pilot bunch")

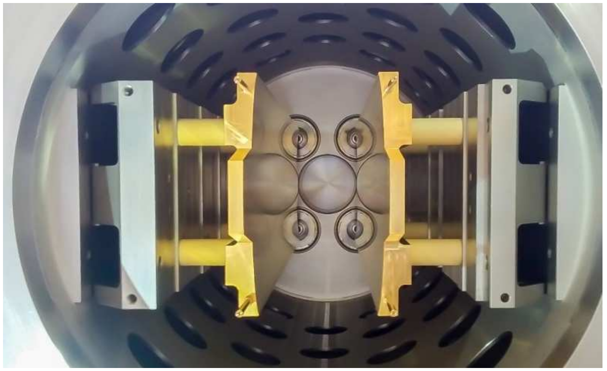


EDM STAGE 1 – COSY ACHIEVEMENTS (III)

- Bunch-selective spin manipulation with radio-frequency **(RF) Wien filter**



RF WF in COSY ring



Field plates inside **RF WF**

ELSEVIER

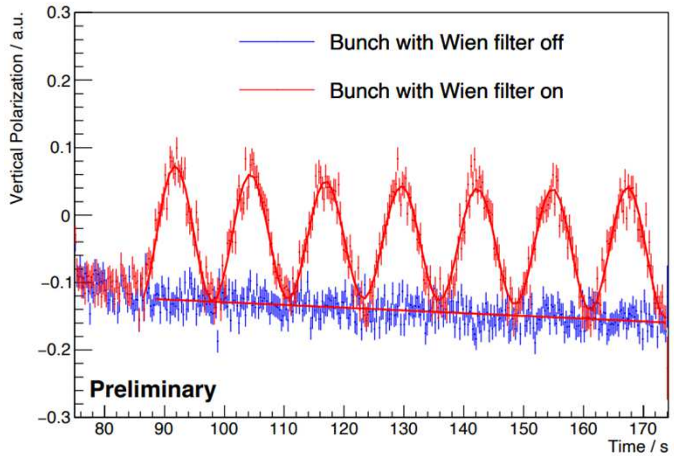
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 828, 21 August 2016, Pages 116-124

Electromagnetic Simulation and Design of a Novel Waveguide RF Wien Filter for Electric Dipole Moment Measurements of Protons and Deuterons https://doi.org/10.1016/j.nima.2016.05.012

COSY in multi-bunch (e.g., 2) operation
RF Wien filter in "**switching mode**" [on-off: $\tau \sim 20$ ns]
(in contrast to "continuous mode")
One bunch unaffected by Wien filter ("pilot bunch")

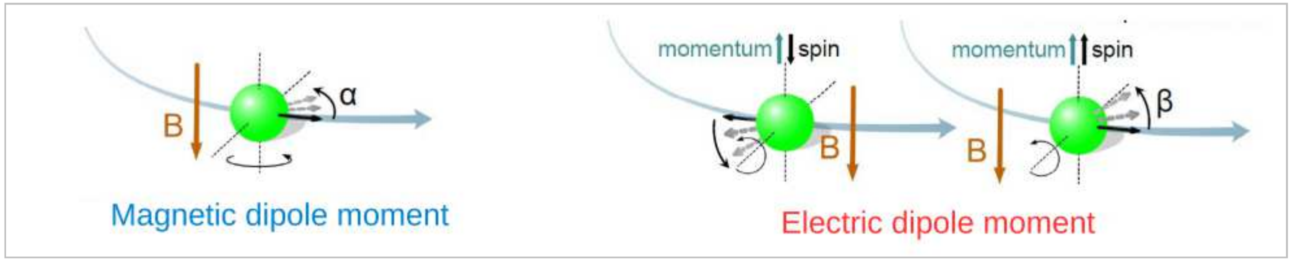
→ opportunity for **EDM measurement at COSY**
applied in 2nd "precursor" dEDM experiment



EDM STAGE 1 – COSY RESULTS (I)

- **EDM search**: polarized deuteron beam

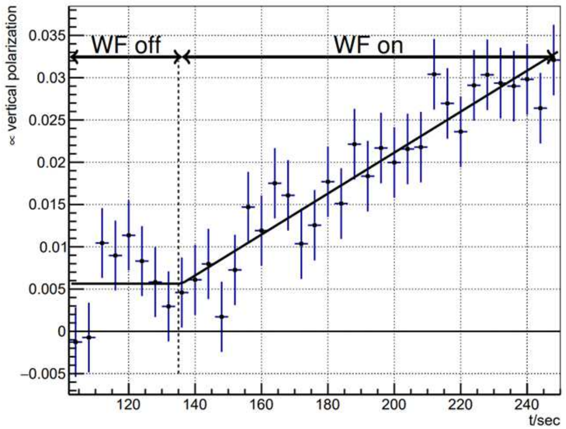
Magnetic ring:



EDM effect
exactly cancels

RF Wien filter (operation on harmonic of spin precession frequency) with **radial RF-E** and **vertical RF-B** fields: partially "frozen spin" → EDM produces a vertical spin rotation

First result:



increase observed as expected!

Comments:

- polarization build-up ~ EDM
- **BUT**: many perturbations in COSY can produce such an effect
- need to be understood in order to deduce EDM limit: **currently investigated** … paper in preparation …

EDM STAGE 1 – COSY RESULTS (II)

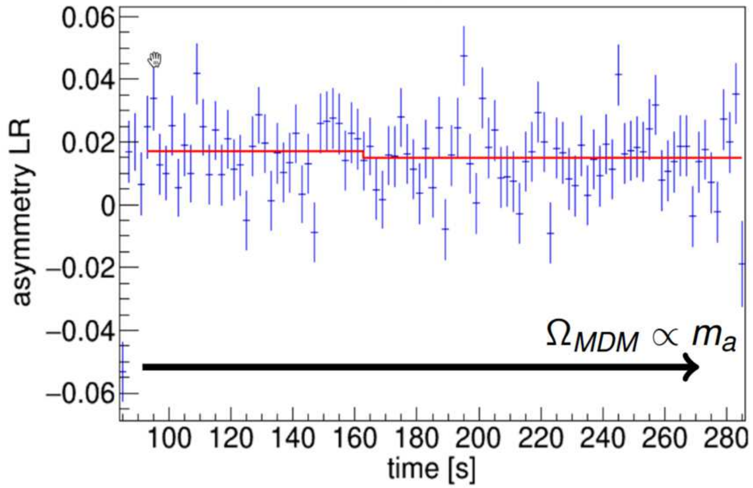
- **Axion search**: polarized deuteron beam

  Axion field gives rise to effective time-dependent θ_{QCD} term → **oscillating electric dipole moment**

  If precession frequency in magnetic ring (Ω_{MDM}) equal to $\omega_a = \frac{m_a c^2}{\hbar}$ (m_a … axion mass) → **resonant build-up**

  Beam momentum change: Ω_{MDM} (→ m_a) scan: mass range covered: (4.96 – 5.02) x 10^{-10} eV

  Axion will show up as **jump in vertical polarization**



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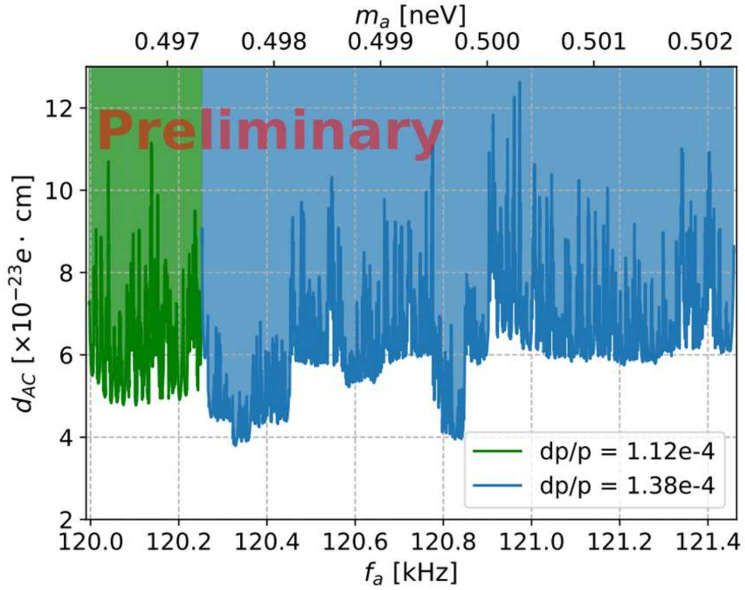
  Axion will show up as **jump in vertical polarization**



EDM STAGE 1 – COSY RESULTS (II)

- **Axion search**: polarized deuteron beam

Axion field gives rise to effective time-dependent θ_{QCD} term → **oscillating electric dipole moment**

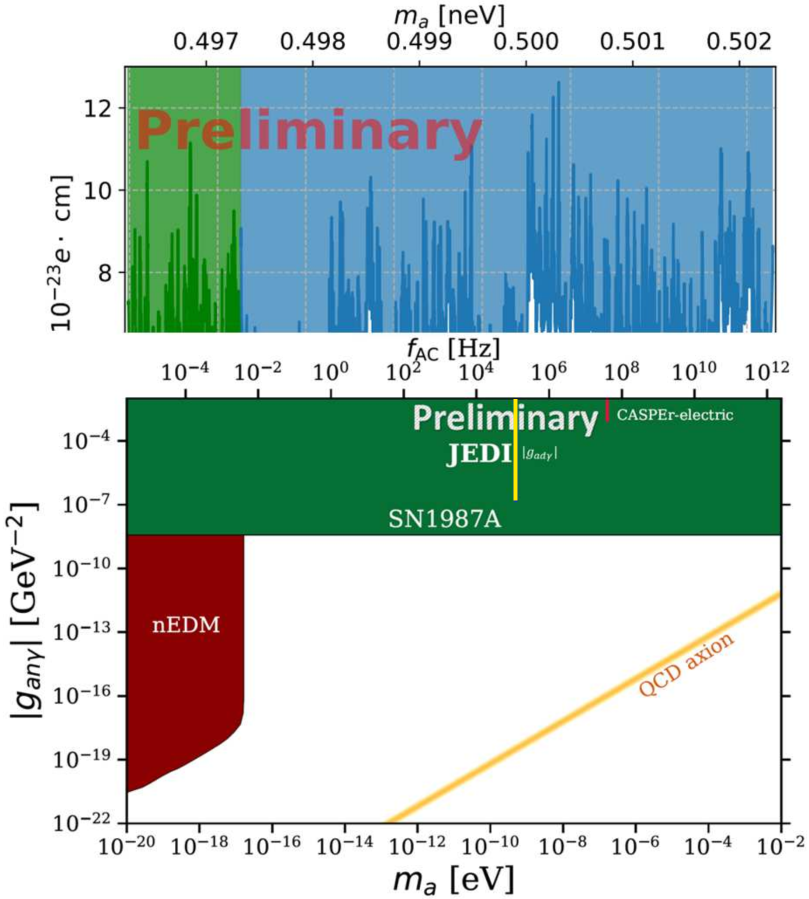
If precession frequency in magnetic ring (Ω_{MDM}) equal to $\omega_a = \frac{m_a c^2}{\hbar}$ (m_a … axion mass) → **resonant build-up**

Beam momentum change: Ω_{MDM} (→ m_a) scan: mass range covered: (4.96 – 5.02) x 10^{-10} eV

Axion will show up as **jump in vertical polarization**

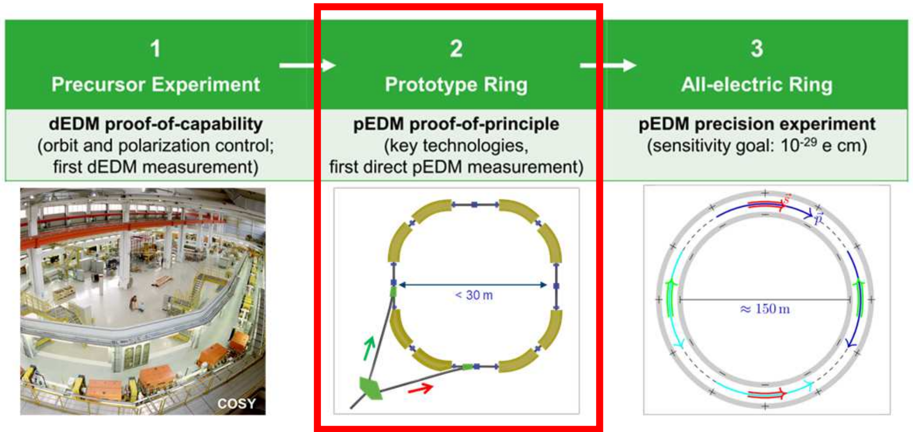
Axion anomalous **coupling to gluons** $g_{an\gamma}$

→ **Proof-of-principle**; paper in preparation



EDM STAGE 2 – PROTOTYPE RING (I)

- **1st step**: Design Study



PSR objectives:

(i) **All-electric**: demonstrate CW/CCW beam storage, spin-coherence time, …

(ii) **Combined E/B**: frozen spin → first direct proton EDM measurement

Pathfinder Facility
for a new Class of
Precision Physics Storage Rings
(PRESTO)

Participants →

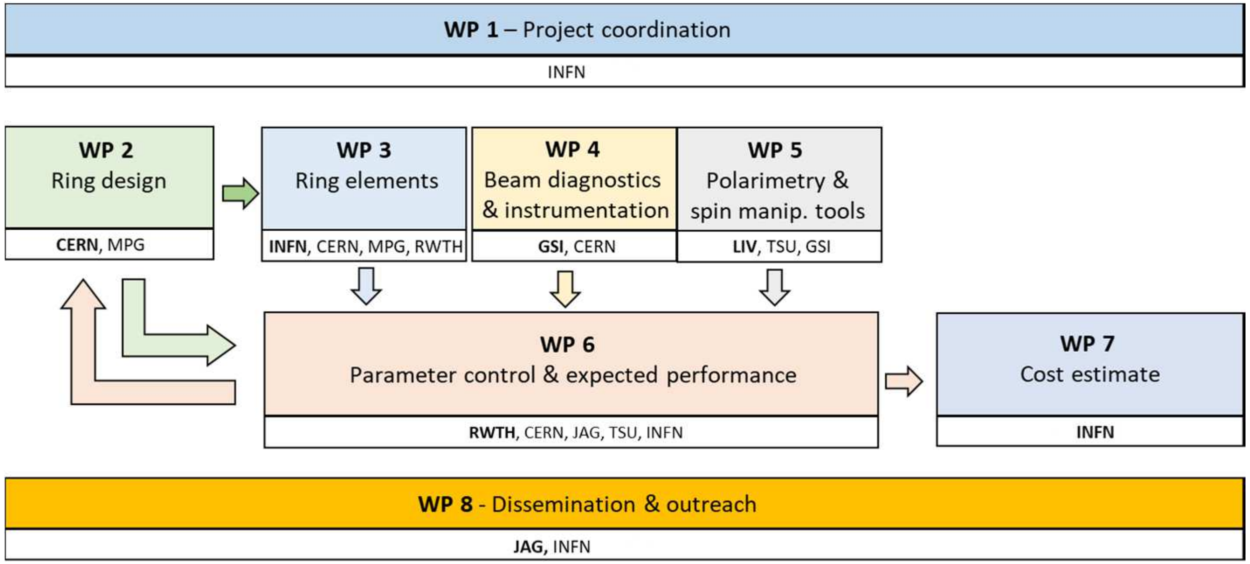
Part. No.	Part. Short Name	Participant Organisation Name	Country
1	INFN	Istituto Nazionale di Fisica Nucleare	Italy
2	GSI	GSI Helmholtzzentrum für Schwerionenforschung	Germany
3	CERN	Organisation Européen pour la Recherche Nucléaire	Switzerland
4	MPG	Max-Planck-Gesellschaft zur Förderung der Wissenschaften EV	Germany
5	RWTH	Rheinisch-Westfälische Technische Hochschule Aachen	Germany
6	LIV	The University of Liverpool	United Kingdom
7	JAG	Uniwersitatet Jagiellonsky	Poland
8	TSU	Ivane Javakhishvili Tbilisi State University	Georgia

→ **ERC** application (*Research Infrastructure Concept Development*) 4/22

EDM STAGE 2 – PROTOTYPE RING (II)

- **1st step**: Design Study

PRESTO work packages:



→ **Conceptual Design Report** (CDR) after 48 months

EDM STAGE 2 – PROTOTYPE RING (III)

- **2nd step**: Realization

Host site: PRESTO aims at a **site-independent** design study

Green Field Lab	Pre-prepared Lab	Fully-receptive Lab
No buildings available to house the EDM facility; **no** previous accelerator expertise; **no** experience with polarization measurements	Buildings to house the EDM facility available; accelerator expertise available; **no** polarization experience yet	Buildings to house the EDM facility available; storage ring expertise and polarization experience available
▪ Optimal facility planning from scratch	▪ Moderate additional investment cost	▪ Minimal investment cost ▪ Shortest lead time ▪ Available expertise
▪ Infrastructure (building) & facility costs largest ▪ Longest lead time ▪ Missing experience to build/run facility	▪ Some additional investments (e.g., polarized source …) required	▪ Possible compromises due to existing boundary conditions

Funding: PRESTO will develop **strategy** for next steps (e.g., EU: ERIC, ESFRI, …) and to acquire necessary resources

EDM STAGE 3 – FINAL PRECISION RING

- **Status:**

CERN Yellow Report:

Storage ring to search for electric dipole moments of charged particles

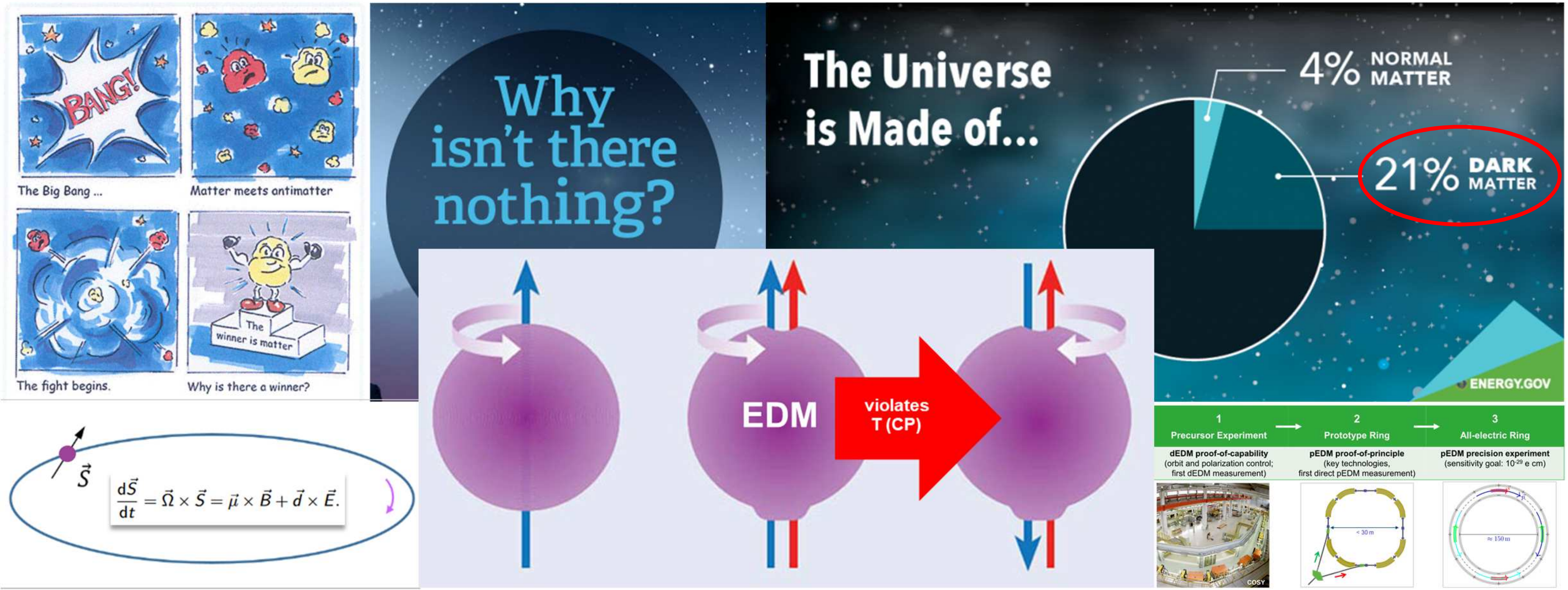
Storage ring to search for electric dipole moments of charged particles: Feasibility study,
CPEDM Collaboration
CERN Yellow Reports: Monographs, CERN-2021-003 (CERN, Geneva, 2021)
https://doi.org/10.23731/CYRM-2021-003.

Nuclear Physics News:

CPEDM: A Storage Ring Facility for Charged-Particle EDM Searches

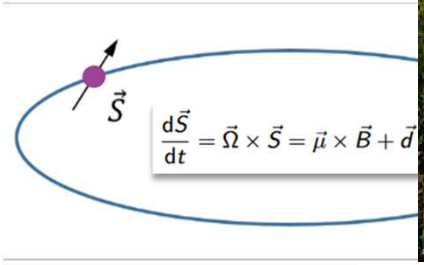
Carli Christian, Lenisa Paolo, Jörg Pretz, Frank Rathmann & Ströher Hans (2021)
CPEDM: A Storage Ring Facility for Charged-Particle EDM Searches,
Nuclear Physics News, 31:2, 27-29,
DOI: 10.1080/10619127.2021.1915027

SUMMARY

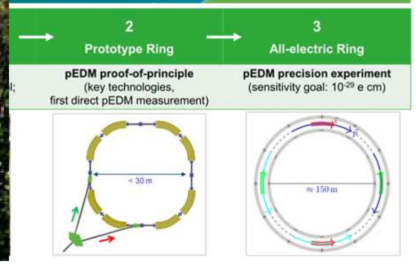

BANG!
The Big Bang ...
Matter meets antimatter
The fight begins.
The winner is matter
Why is there a winner?
Why isn't there nothing?
The Universe is Made of...
4% NORMAL MATTER
21% DARK MATTER
ENERGY.GOV
EDM
violates T (CP)
$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}.$
1 Precursor Experiment
dEDM proof-of-capability
(orbit and polarization control; first dEDM measurement)
2 Prototype Ring
pEDM proof-of-principle
(key technologies, first direct pEDM measurement)
3 All-electric Ring
pEDM precision experiment
(sensitivity goal: 10^{-29} e cm)
COSY
< 30 m

SUMMARY


BANG!
The Big Bang ...
The fight begins.
The winner is matter


$\vec{S}$
$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d}$


4% NORMAL MATTER
21% DARK MATTER
ENERGY.GOV


2
Prototype Ring
pEDM proof-of-principle
(key technologies,
first direct pEDM measurement)
3
All-electric Ring
pEDM precision experiment
(sensitivity goal: 10^{-29} e cm)

STORAGE RINGS: From Hadron Physics to Precision Measurements

Prof. Dr. Dr. h.c. mult. Hans Ströher
h.stroeher@fz-juelich.de

European Research Council
erc
ERC AdG srEDM (694340)