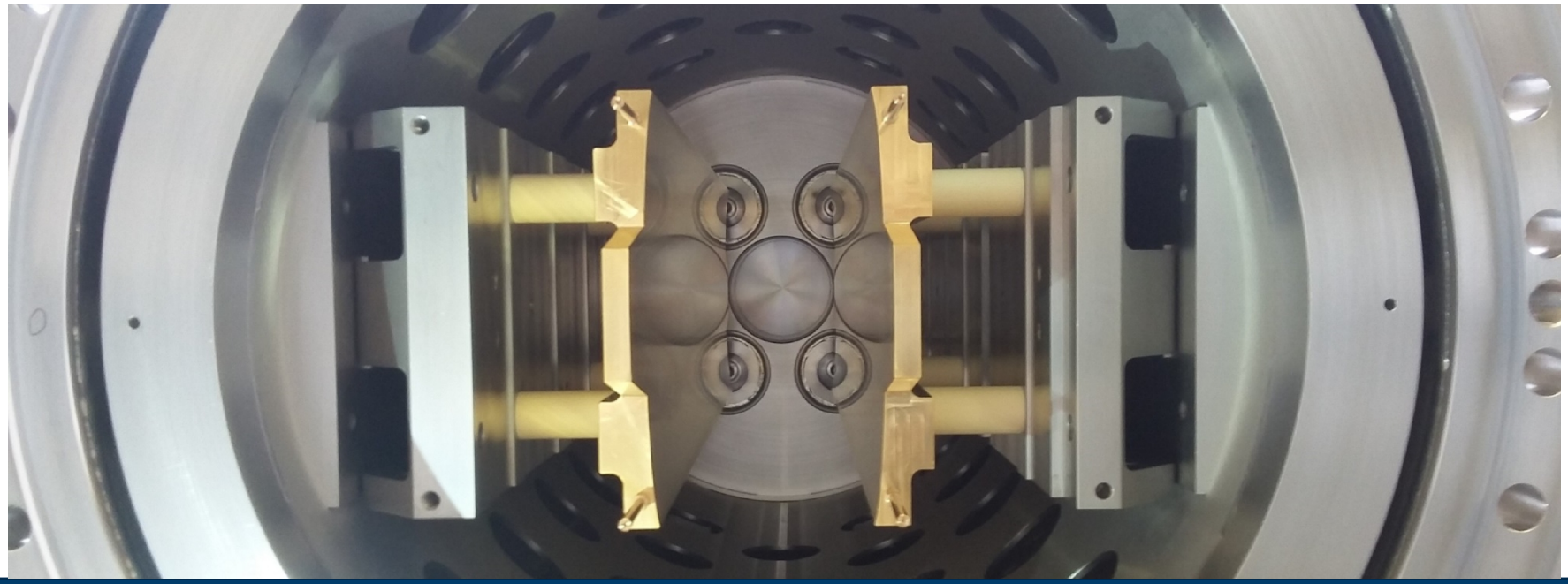

THE SEARCH FOR PROTON AND DEUTERON ELECTRIC DIPOLE MOMENTS USING STORAGE RINGS

JUNE 11TH 2020 I ALEXANDER NASS FOR THE JEDI COLLABORATION

Mitglied der Helmholtz-Gemeinschaft

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BARYON ASYMMETRY IN THE UNIVERSE

Carina Nebula: Largest-seen star-birth regions in the galaxy

(NASA, ESA und M. Livio und das Hubble 20th Anniversary Team (STScI))

Observation and expectation from the Standard Cosmological Model (SCM):

	$\eta = (n_b - n_{\bar{b}})/n_\gamma$	
Observation	$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$	Best Fit Cosmological Model [1]
	$(5.53 - 6.76) \times 10^{-10}$	WMAP [2]
Expectation from SCM	$\sim 10^{-18}$	Bernreuther (2002) [3]

There is a discrepancy of about 9 orders of magnitude.

ELECTRIC DIPOLE MOMENTS (EDM'S)

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$) :

- non-relativistic Hamiltonian:

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

- **Energy of magnetic dipole** invariant under P and T:

$$-\vec{\mu} \cdot \vec{B} \overset{P \text{ or } T}{\longrightarrow} -\vec{\mu} \cdot \vec{B}$$

  No other direction than spin $\Rightarrow \vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).

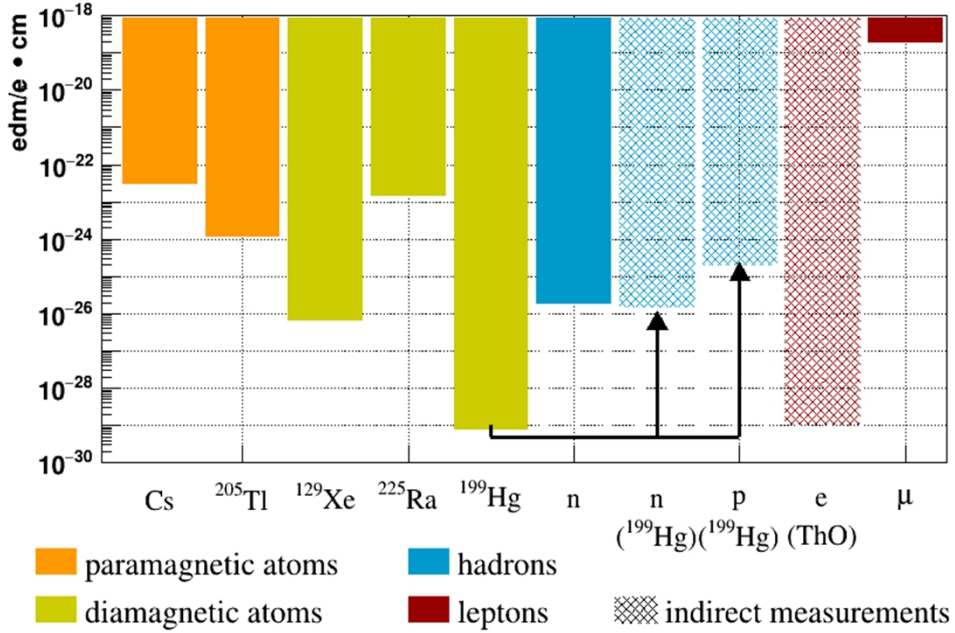
- **Energy of electric dipole** $H = -\vec{d} \cdot E$, includes term

$$\vec{s} \cdot \vec{E} \overset{P \text{ or } T}{\longrightarrow} -\vec{s} \cdot \vec{E},$$

Thus EDMs violate both P and T symmetry

- EDMs possibly constitute the missing cornerstone to explain the surplus of matter over antimatter in the Universe
- Non-vanishing EDMs would add a 4th quantum number (d) to fundamental particles

STATUS OF EDM SEARCHES



Missing are direct EDM measurements:

- of the electron (limit obtained from ThO molecule)
- of the proton (limit obtained from $^{199}_{80}$Hg)
- of the deuteron

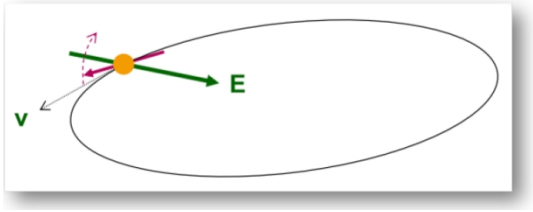
SPIN PRECESSION OF PARTICLES IN A STORAGE RING

Spin precession frequency of particle relative to direction of flight:

$$\vec{\Omega} = \vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}}$$
$$= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

For protons with $\vec{\Omega} = 0$ (frozen spin) in a pure electric ring:

$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\mathrm{MeV\,c^{-1}}}$$



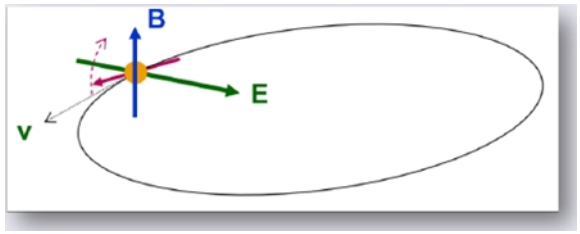
Proposed method to measure EDMs in an electric storage ring:

- place the particles in a storage ring (radial E-fields)
- freeze horizontal spin precession
- measure time development of vertical polarization ($d\vec{S}/dt = \vec{d} \times \vec{E}$)

EXPERIMENTAL REQUIREMENTS

Generalized solution for magic momentum:

particle	G	p [MeV c^{-1}]	T [MeV]	E_x [MV m^{-1}]	B_y [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



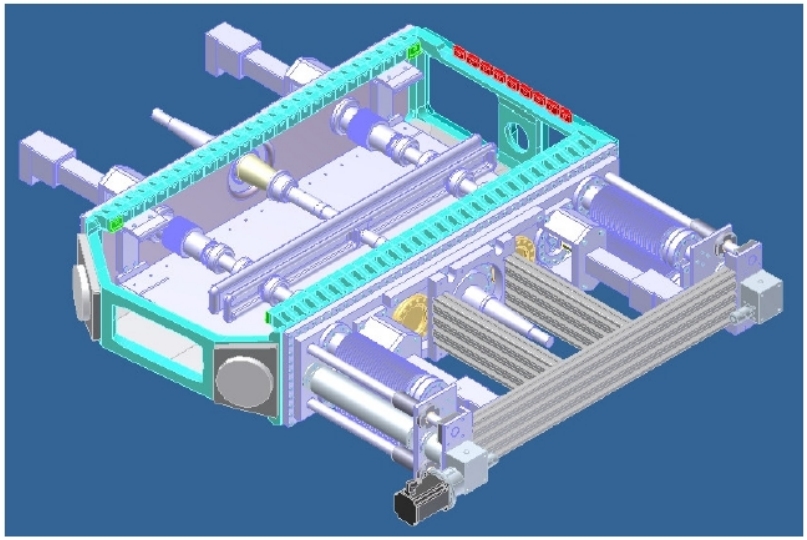
High precision, primarily electric storage ring:

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields
- High beam intensity ($4 \cdot 10^{10}$ particles per fill)
- High polarization of stores hadron (P = 0.8)
- Large electric fields (E = 10 MV/m)
- Long spin coherence time (τ_{SCT} = 1000 s)
- Efficient polarimetry with large analyzing power ($A_y \cong 0.6$) and high efficiency detection (f ≅ 0.005)

→ $\sigma_{stat}(1\,yr) = 10^{-29}$ e cm

The goal is to provide σ_{syst} at the same level

TECHNICAL DEVELOPMENTS: E/B DEFLECTOR



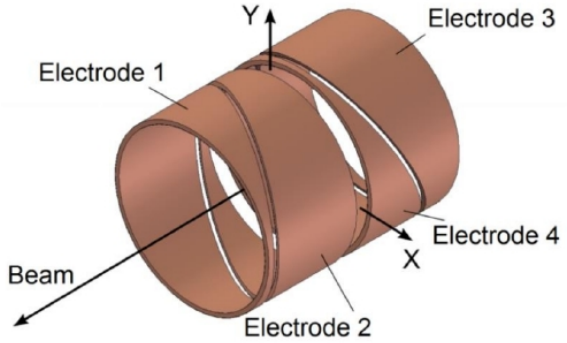
Equiment and parameters:

- Dipole magnet, B_{max} = 1.6 T, gap height = 200 mm
- Deflector material: TiN coated Aluminum
- Electrode length = 1020 mm, electrode height = 90 mm
- Electrode spacing = 20 … 80 mm
- Maximum voltage = ±200 MV

→ Ready for tests, results to be expected soon

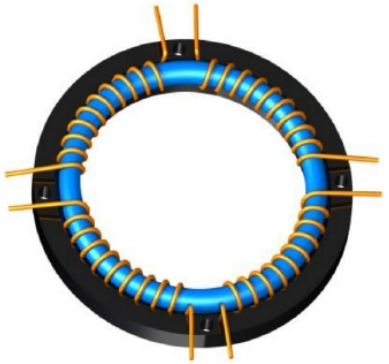
TECHNICAL DEVELOPMENTS: BPM

Conventional BPM



- Easy to manifacture
- Lenght = 20 cm
- Resolution ≈ 5 µm

Rogowski-BPM



- Excellent RF-signal response
- Lenght = 1 cm
- Resolution ≈ 1.25 µm

Two Rogowski Beam Position Monitors installed in COSY

CHARGED PARTICLE EDM COLLABORATION

Staged approach and time frame toward dedicated EDM ring [4]:

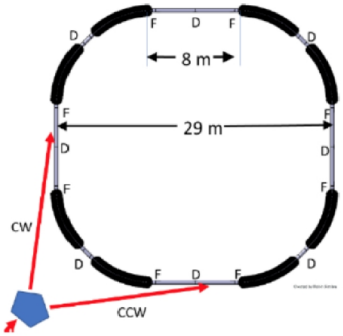
Stage 1

- precursor experiment

- magnetic storage ring
- Now

Stage 2

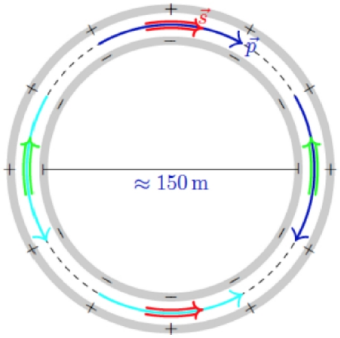
- prototype ring



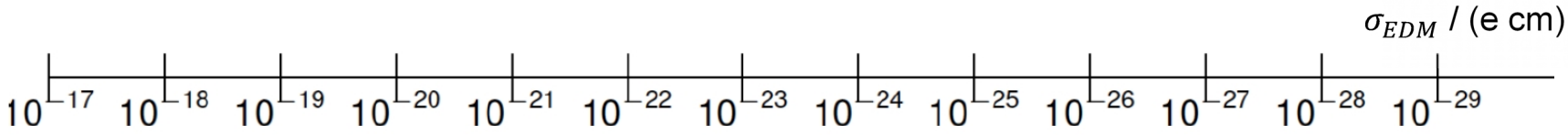
- electric/magnetic bends
- simultaneous ↻ and ↺ beams
- 5 years

Stage 3

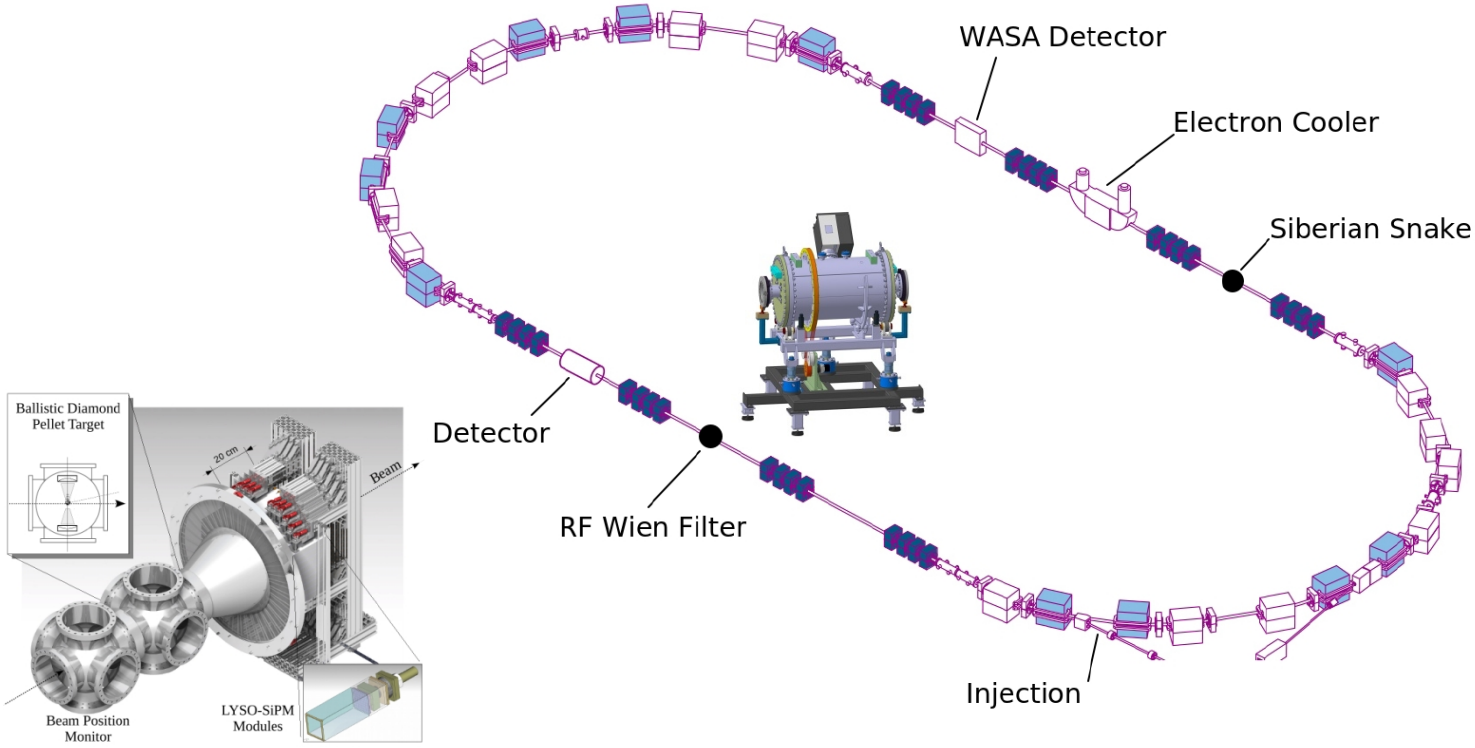
- dedicated storage ring



- at magic p momentum
- 10 years



THE COOLER SYNCHROTRON (COSY)



- Phase space cooled (polarized) proton and deuteron beams
- Momenta p = 0.3 … 3.7 GeV /c
- Provides an ideal starting point for srEDM related R&D
- First direct deuteron EDM measurement

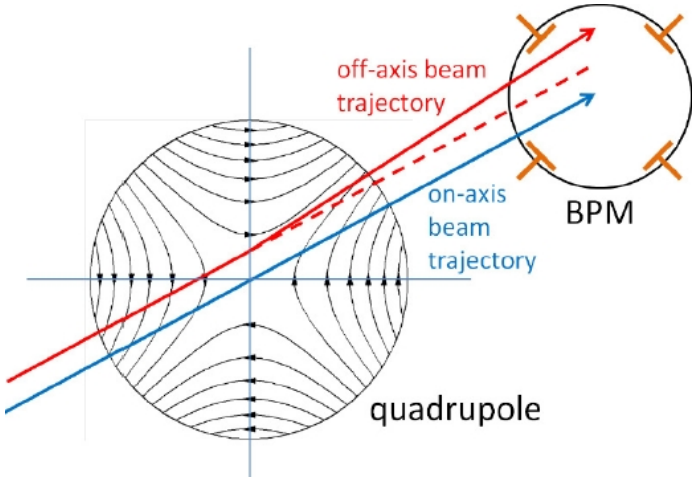
BEAM BASED ALIGNMENT

Alignment is crucial for a successful EDM measurement:

- Alignment surveys use markers on magnets
- Beam positions monitors don‘t have markers

→ Determination of positions of the BPMs

- Beam is deflected when it passes off-center through quadrupoles



Remarkable precision of better than 10 µm reached

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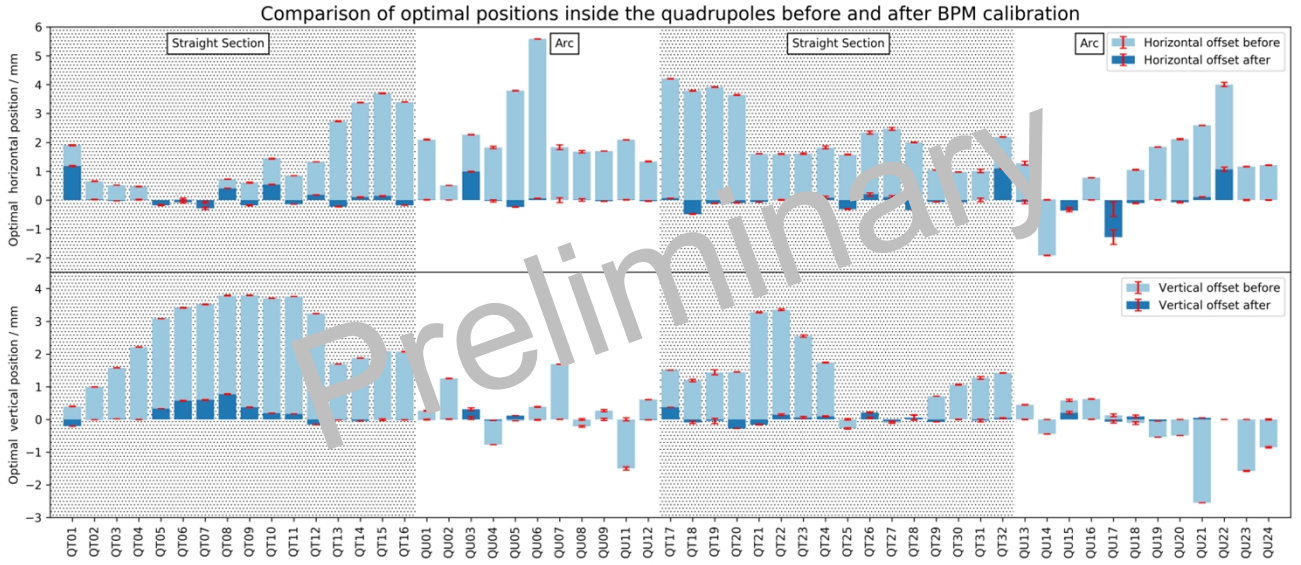

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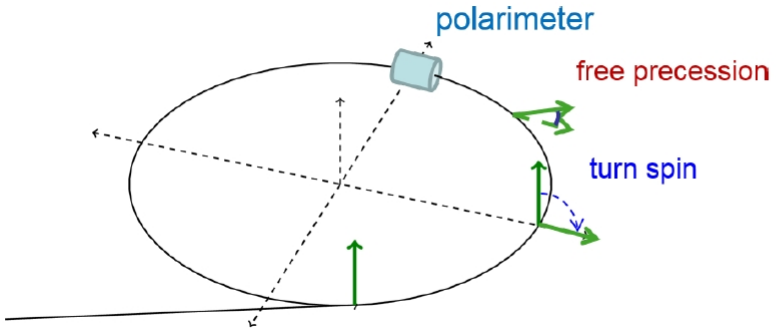
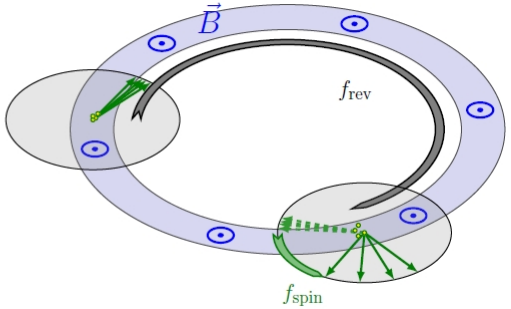
SPIN TUNE MEASUREMENT [5]



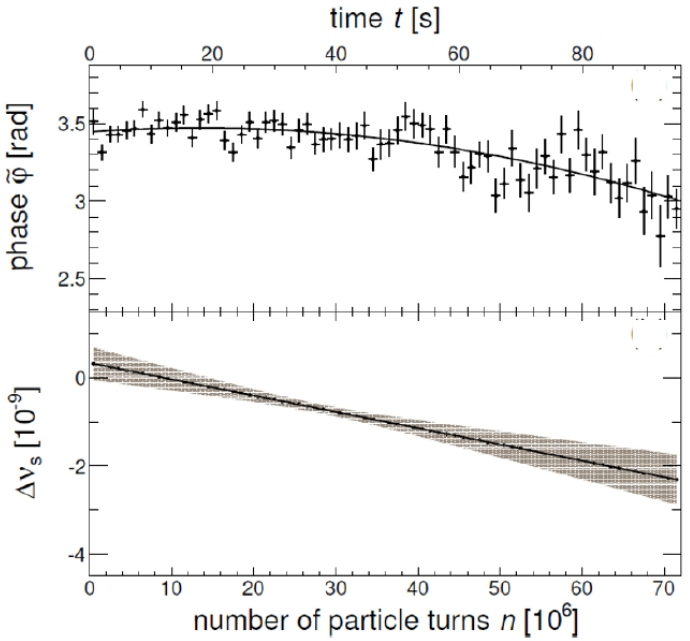


Measurement principle:

- COSY magnet ring, spins are not frozen and precess in the horiz. plane
- In-plane polarization determined by extracting particles on a carbon target and measure up-down asymmetry in polarimeter
- Spin tune can be determined to

$$\Delta\nu_S/\nu_S \approx 10^{-10}$$

→ New precision tool to study systematic effects in storage rings

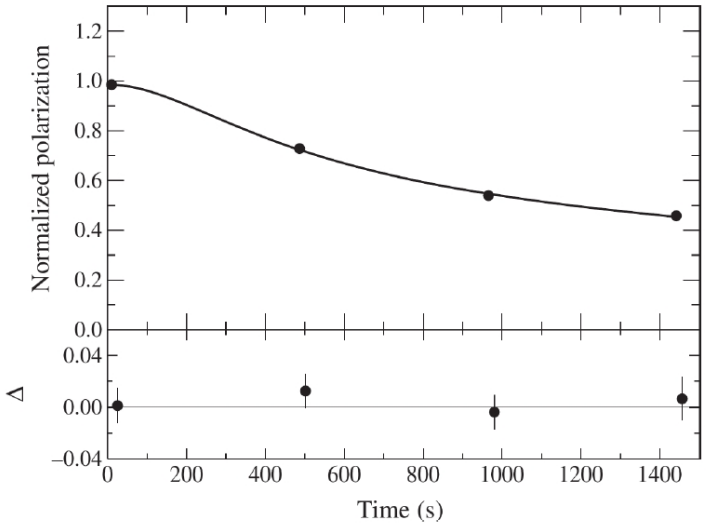


SPIN COHERENCE TIME AND PHASE LOCKING

JEDI progress on SCT [6]:

$\tau_{SCT} = (782 \pm 117)$ s

Previous record:
$\tau_{SCT}(VEPP) \approx 0.5$ s



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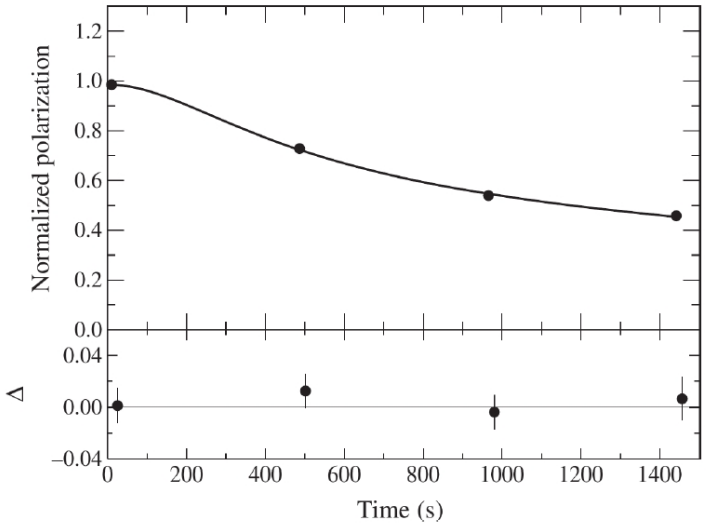
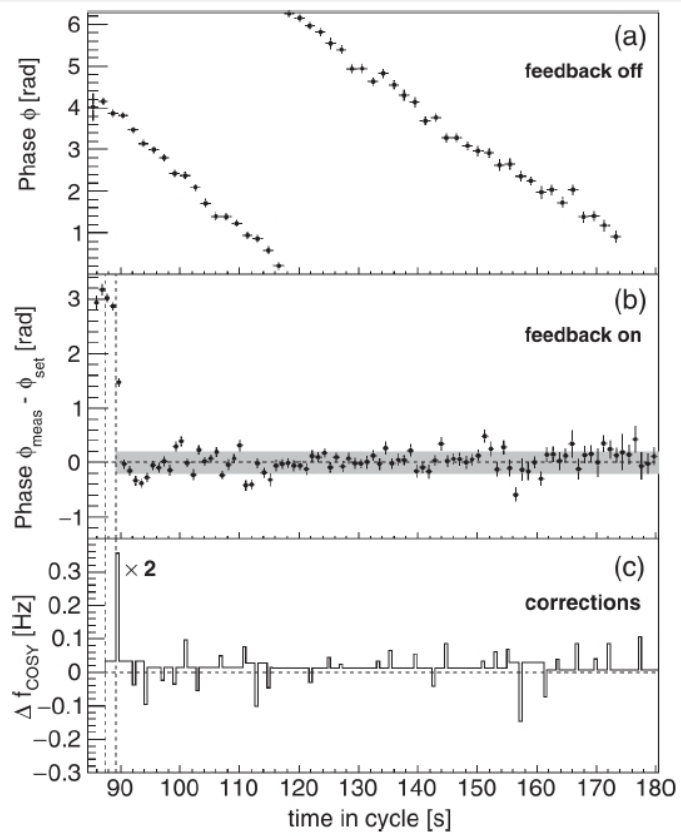




Feedback system maintains [7]:

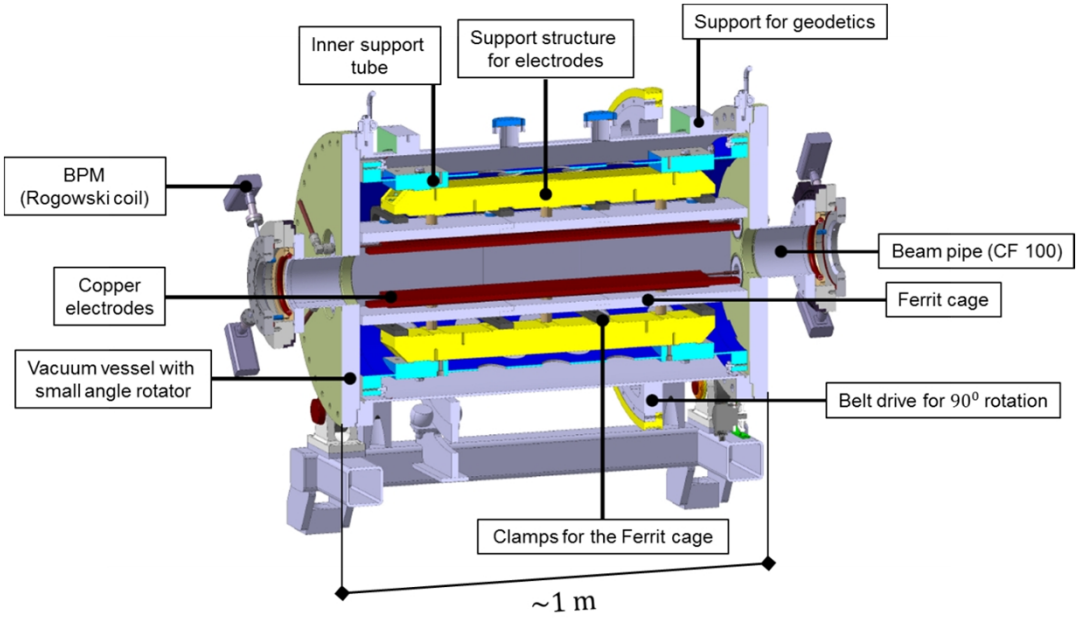
- Resonance frequency
- Phase between spin precession and RF device (solenoid or RF Wien filter)

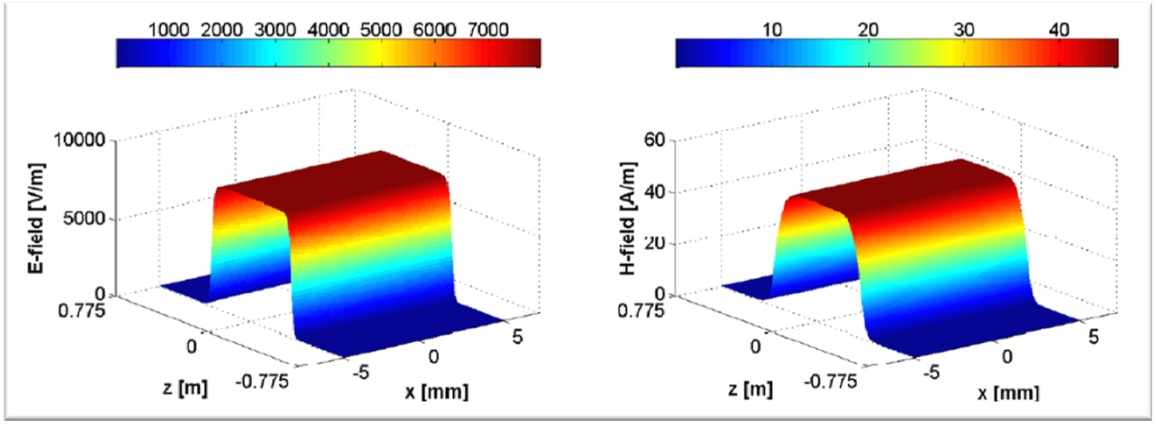
→ Error of phase lock $\sigma_\varphi = 0.21$ rad

WAVEGUIDE RF WIEN FILTER

Joint RWTH Aachen – FZ Jülich development [8]:

- Waveguide provides $E \times B$ by design
- Minimal $\overrightarrow{F_L}$ by carful design of components
- Driving circuit has tunable elements to match the phase and the impedance to the β of the beam
- Measurement of the beam excitation for perfect matching





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PROOF-OF-PRINCIPLE EXPERIMENT @ COSY

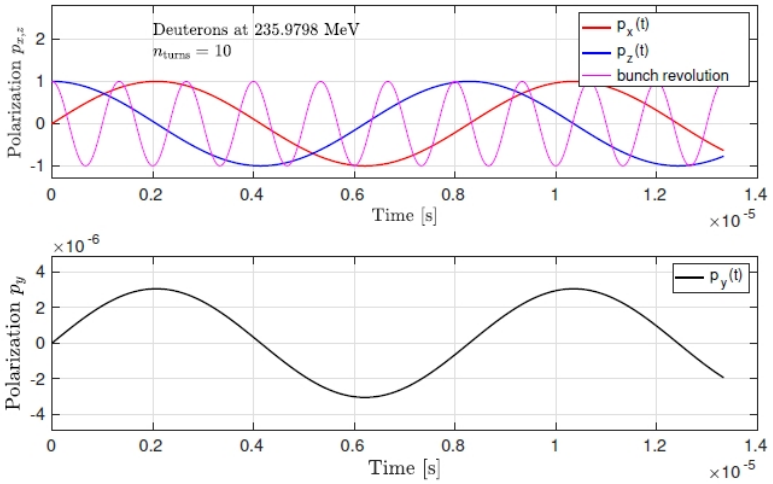
Without RF Wien filter

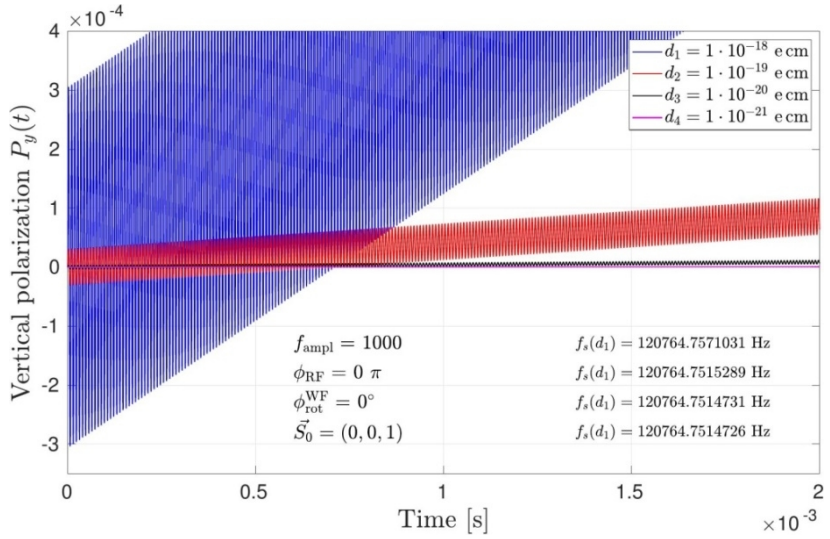
- Presence of EDM tilts stable spin axis in COSY
- Spins precess around this axis

→ Oscillating vertical polarization component $P_y(t)$ is generated

With RF Wien filter [9]

- In COSY $f_S \approx 120$ kHz
- Electric field of RF Wien filter $\int E_{WF} \cdot dl \approx 2.2$ KV
- EDM accumulates in $P_y(t) \propto d_{EDM}$
- Generally: $P_y(t) = a \cdot \sin(\Omega^{P_y} t + \phi_{RF})$





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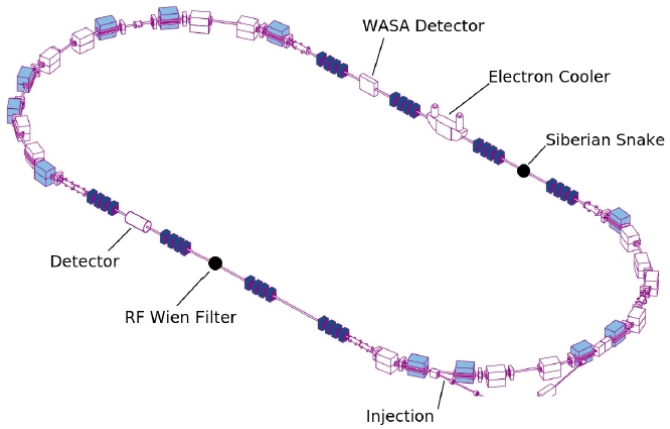
HOW DO WE MEASURE THE EDM EFFECT ?

Two features in the COSY ring affect the spin evolution

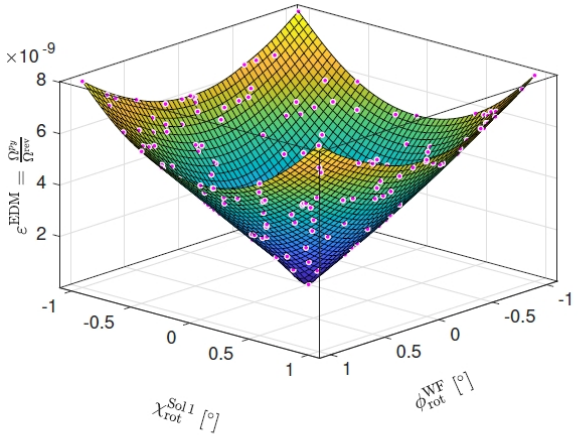
- RF Wien filter can be rotated by small angles
  → small radial magnetic field
- Siberian Snake
  (longitudinal magnetic field)



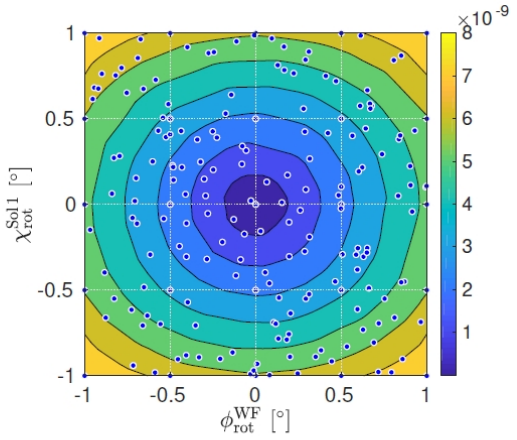
EDM resonance strength:

$$\varepsilon^{EDM} = \frac{\Omega^{P_y}}{\Omega^{rev}}$$

Expectation [9]



(a) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}$ e cm.



(b) Contour plot of (a).

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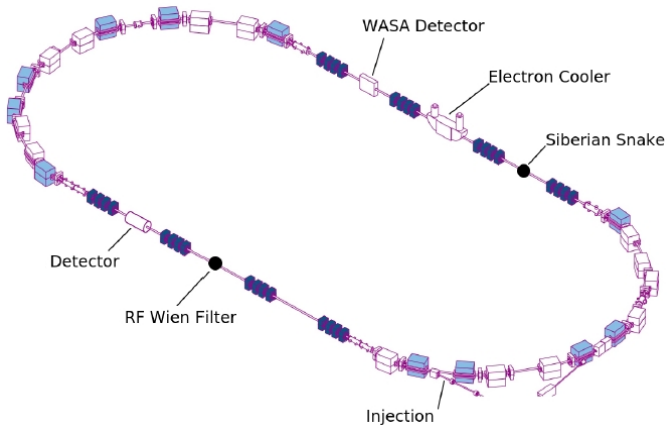

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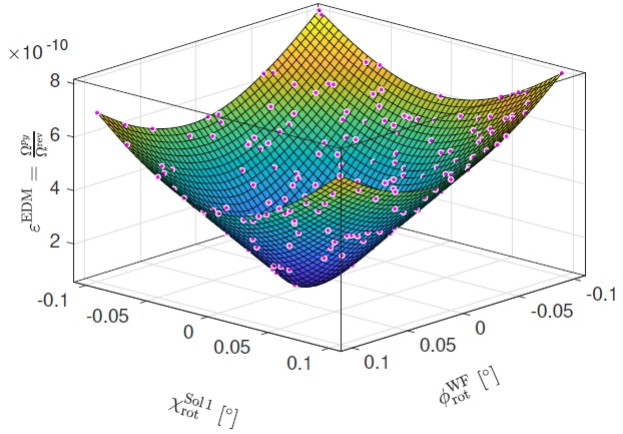
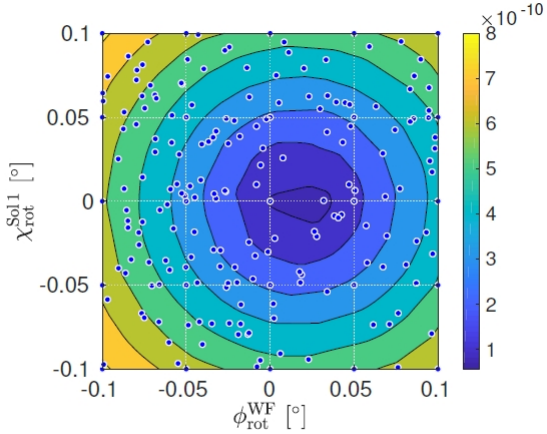


(c) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-18}$ e cm.



(d) Contour plot of (c).

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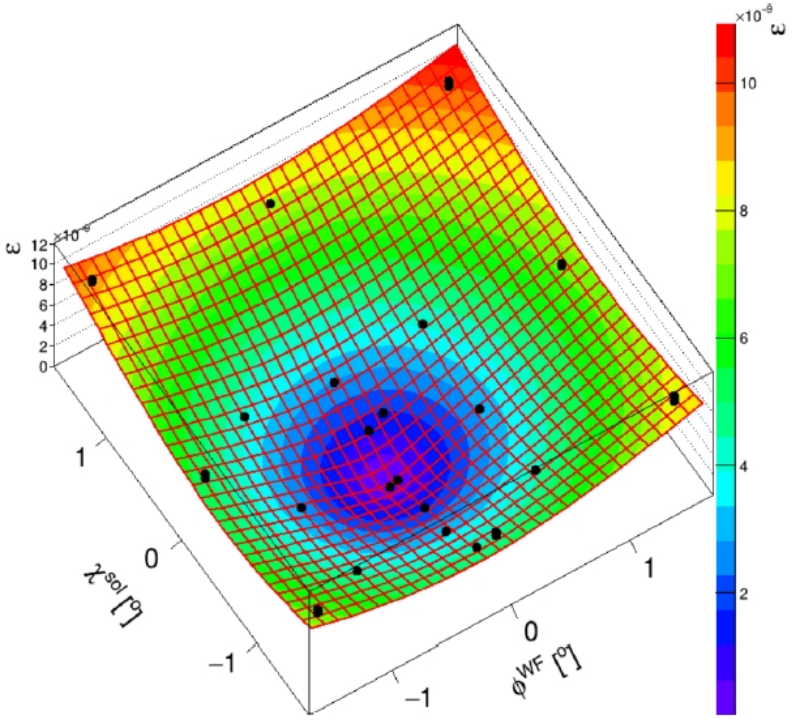
PRELIMINARY RESULTS

First measurement campaign (Nov. / Dec. 2018):

- 32 data points in 3 maps
- 2 weeks of pure measuring time
- Preliminary results of fit:

$$\phi_{min}^{WF} = -3.9 \pm 0.05 \text{ mrad}$$
$$\chi_{min}^{sol} = -6.8 \pm 0.04 \text{ mrad}$$



Current status:

1. Minimum represents spin rotation axis (3-vector) *including* EDM
2. Spin tracking shall determine orientation of stable spin axis without EDM
3. EDM is determined from the difference of 1. and 2.

SUMMARY

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

New window to disentangle sources of CP violation, and to possibly explain matter-antimatter asymmerty of the universe

Present status of the EDM measurement @COSY:

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM
- COSY remains a unique facility for such studies
- First direct deuteron EDM measurement underway
  - 6 week run in Nov./Dec. 2018, foreseen 6 week run in 2020/2021
  - Planned upgrades
    - Consolidation of beam based alignment
    - Test of pilot bunch technique
    - Measurement of spin tune change as function of orbit bumps
  - Sensitivity 10^{-18} … 10^{-20} e cm

Strong interest of high energy physics community in storage ring EDM searches

- Physics Beyond Collider process (CERN), and
- European Strategy for Particle Physics Update
- As part of this process: Proposal for prototype EDM storage ring prepared by CPEDM

JEDI COLLABORATION

Jülich **E**lectric **D**ipole moment **I**nvestigations

- ~ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, …)
- http://collaborations.fz-juelich.de/ikp/jedi

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