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Electric Dipole Moment Measurements at Storage Rings

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Electric Dipole Moments (EDMs) of subatomic particles, are considered as one of the most powerful tools to study CP-violation beyond the Standard Model. Such CP-violating mechanisms are searched for to explain the dominance of matter over anti-matter in our universe. This paper discusses EDM searches of charged hadrons in storage rings.
The document focuses on activities at the existing storage ring COSY at Forschungszentrum Jülich, Germany and the design of a 100 m circumference prototype ring able to demonstrate key technologies and components. These include simultaneous clockwise and counter-clockwise beam operation with electrostatic bending elements and, by adding a magnetic field, the frozen spin technique.

KEYWORDS: electric dipole moment, CP-violation, storage ring, axion searches

1. Introduction

The existence of electric dipole moments (EDMs) of subatomic particles (e.g. atoms, certain molecules, hadrons) is only possible if parity (P) and time reversal (T) symmetry are violated. Assuming that the CPT theorem holds, T-violation is equivalent to CP-violation. Note that in this context we talk only about *permanent* EDMs. The well known EDMs of certain molecules (e.g. H_20, NH_3) are not of this nature and don't require violation of P and T symmetries. These molecules appear to have a permanent EDM because of two almost degenerated energy levels of opposite parity. This implies that the energy levels grow linearly with an applied electric field – a sign of a permanent EDM. However, in very small electric fields E, the energy levels grow quadratically with the electric field strength (quadratic Stark effect). This is the case if the interaction energy eE, e being the elementary charge, is smaller than the energy difference of the two almost degenerated energy levels. A more detailed discussion can be found in reference [1].

The search for EDMs has a long history. Starting 60 years ago with the measurement of the neutron EDM by Smith, Purcell and Ramsey [2]. Figure 1 shows an overview of experimental results. Up to now all measurements show results consistent with zero. The resulting upper limits for various particles (lower edge of orange bar) together with predictions from super-symmetric models (SUSY) and the Standard Model are shown. Most of the measurements were performed on neutral systems. The proton limit was deduced from an EDM measurement of the mercury atom for example. One exception is the muon. The limit shown in figure 1 was obtained at a storage ring experiment where the main purpose was to measure the anomalous magnetic moment of the muon [3].

Based on the principle of the muon EDM measurement, experiments are proposed to measure EDMs of charged particles in storage rings [4]. The principle will be discussed in the next section. Section 3 describes measurements at the existing magnetic storage ring Cooloer Synchrotron COSY at Forschungszentrum Jülich, Germany. Section 4 discusses the next step, i.e. plans for a dedicated storage ring to measure EDMs of charged particles.

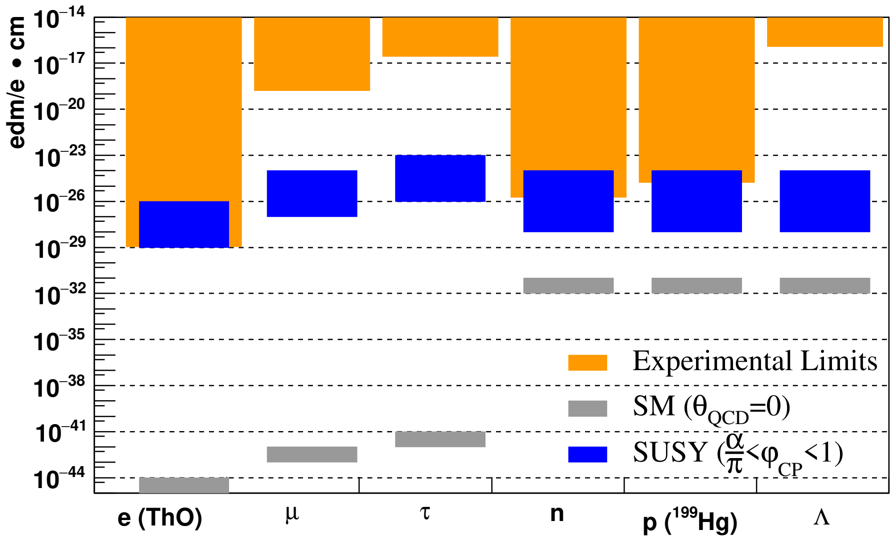

Fig. 1. 90% EDM limits for various particles, together with prediction from the Standard Model and Super Symmetry.

2. Principle of Storage Ring EDM Experiments

For an elementary particle, the spin is the only vector defining a direction. A permanent EDM has to be aligned along this axis. If an EDM exists, the spin vector will experience a torque in addition to the one caused by the magnetic moment. For a polarization direction aligned along the momentum vector, this torque causes a polarization component in the vertical direction. The polarization direction can be determined by scattering the beam off a carbon target and analyzing the azimuthal distribution of the scattered particles. Expected EDMs are of the order of $10^{-27}\,e\,$cm. This means that the spin precession due to an EDM is orders of magnitude smaller than the precession caused by the magnetic dipole moment (MDM). The magnetic moment causes a precession of the spins in the horizontal plane as indicated in Fig. 2.

Quantitatively the spin motion with respect to the cyclotron motion is described by the Thomas-BMT equation [5–7]. Assuming $\vec{\beta} \cdot \vec{E} = \vec{\beta} \cdot \vec{B} = 0$, it is given by

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

The variables are explained in Tab. I.

The vertical polarization component will oscillate with a small amplitude $\beta\eta/(2G)$ and a angular frequency $\Omega_{\mathrm{MDM}} \approx -qGB/m$ in a magnetic storage ring. This oscillation was used in in the muon $g-2$ experiment [3] to set a limit on the muon EDM, parameterized by the dimensionless variable η. For leptons with G-values of approximately 10^{-3} this amplitude is three orders of magnitude larger compared to hadrons where $G \approx O(1)$. Therefore, other ways are being sought to obtain a larger signal.

Several methods are proposed. One solution is to run in a so called frozen-spin condition where the precession in the horizontal plane is suppressed ($\vec{\Omega}_{\mathrm{MDM}} = 0$) by a suitable electric and magnetic field combination [4]. Possible combinations of electric and magnetic fields leading to such a frozen

Table I. Definition of variables used in the text.

s	spin in the particle rest frame
t	time in the laboratory frame
q	electric charge
$d = \eta \frac{q\hbar}{2mc} \vec{s}$	electric dipole moment
η	dimensionless parameter describing the strength of the EDM
$\vec{\mu} = 2(G+1)\frac{q\hbar}{2m}\vec{s}$	magnetic dipole moment
G	anomalous magnetic moment
	$= -0.1425617662(22)$ for deuterons
	$= \quad 1.7928473447(8)$ for protons
	$= \quad 0.00116592061(41) \approx \frac{\alpha}{2\pi}$ for muons
c	speed of light
m	particle mass
$\vec{E}, \vec{B}$	electric and magnetic field in the laboratory frame
$\hbar$	Planck constant/(2π)
β	velocity in units of speed of light c
$\gamma = \frac{1}{\sqrt{1-\beta^2}}$	

spin condition are shown in figure 3. In this case the vertical polarization will grow to a larger amplitude and not just perform a fast oscillation. In a second method, which can be applied at a pure magnetic storage ring, the horizontal spin precession is influenced by an additional element in the storage ring, a radio frequency Wien filter in such a way that a build-up due to the EDM can also be observed [8, 9].

For the first method a dedicated storage ring has yet to be designed and built. The second option can be performed at an existing magnetic storage ring COSY. In the next section first deuteron EDM measurements at COSY will be discussed.

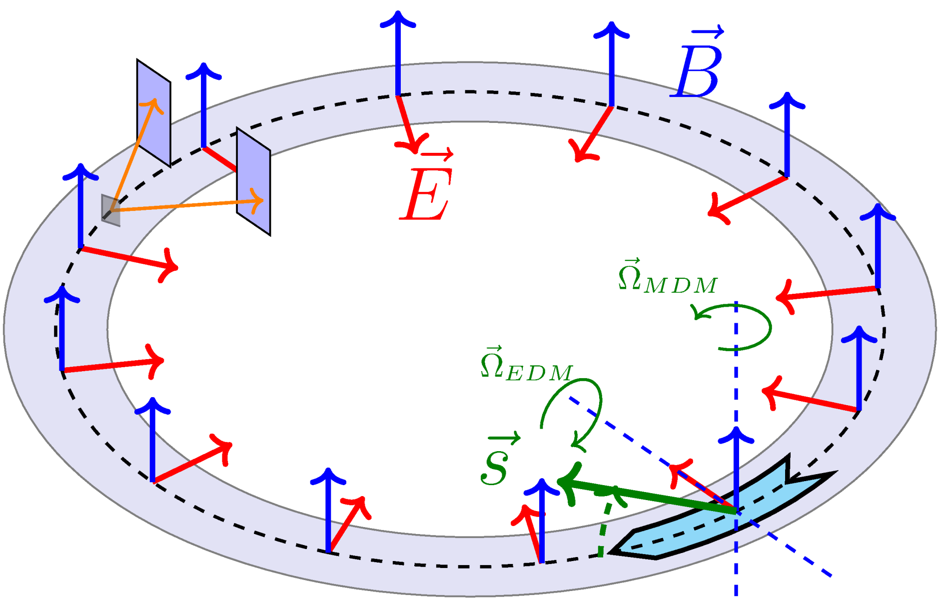

Fig. 2. Principle of a storage ring EDM measurement.

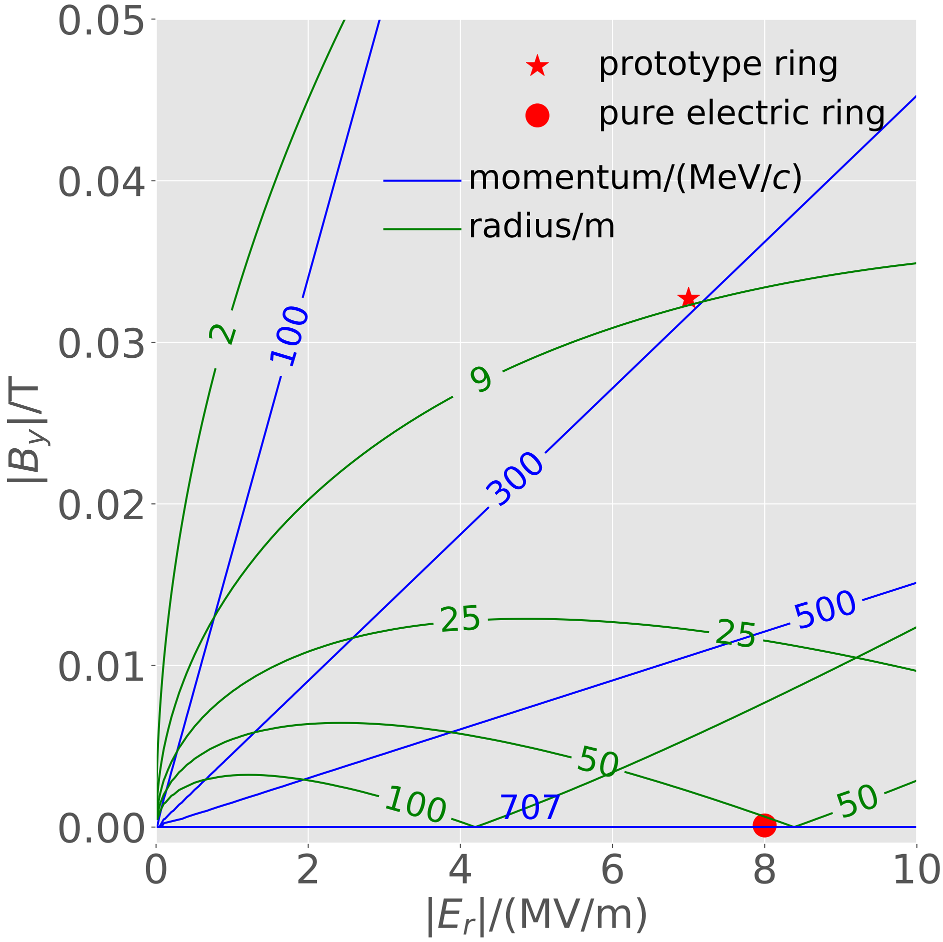

Fig. 3. Bending radius and momentum as a function of the electric and magnetic bending fields for the frozen spin condition.

3. Measurements at COSY

3.1 Deuteron EDM measurement

Two successful deuteron electric dipole moment (EDM) runs have been performed at the Cooler Synchrotron COSY in December 2018 and March 2021. Goal of the measurement was the determination of the so-called invariant spin axis $\hat{n}$, which is directly related to the EDM. In an ideal accelerator, the invariant spin axis points in vertical direction along the magnetic guiding field, if the particle has only a magnetic dipole moment and no EDM ($\hat{n} \parallel \vec{\Omega}_{MDM}$). The invariant spin axis defines the spin rotation axis. The component of the polarization vector along the invariant spin axis does not rotate. The presence of an EDM tilts this axis towards the radial direction by an angle $\eta\beta/(2G)$, i.e. $\hat{n} \propto \vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}$. The experiment has been performed with the radio frequency Wien filter [10] causing a build-up of a vertical polarization component, if the invariant spin axis is tilted with respect to magnetic field axis of the Wien filter. Rotating the Wien filter around the beam axis and by adding a solenoidal field the invariant spin axis could be deliberately tilted in radial and longitudinal direction, respectively. Measuring the polarization build-up (in accelerator terminology this means measuring a resonance strength ϵ) as a function of both rotations allows one to measure a two dimensional map, where the minimum indicates the position of the invariant spin axis with the Wien filter in its nominal position and zero solenoidal field.

Table II. Parameters of the COSY experiment to measure the deuteron EDM.

COSY circumference	183 m
deuteron momentum p	0.970 GeV/c
rel. velocity β	0.459
Lorentz factor γ	1.126
revolution frequency f_{cosy}	750.6 kHz
spin precession frequency $\lvert f_s \rvert$	120.9 kHz
nb. of stored particle	$\approx 10^9$
Wien filter resonance frequency $\lvert f_{\mathrm{rf}} \rvert$	873 kHz
Wien filter magnetic field	$2 \cdot 10^{-6}$Tm

Figure 4 shows the development of $\alpha = \mathrm{atan}(P_v/P_h)$ as a function of time for a fixed setting of the Wien filter and the solenoid. Here, $P_{v(h)}$ denotes the vertical (horizontal) polarization component. As soon as the Wien filter is switched on, α, i.e. the vertical polarization starts to raise. The slope is proportional to the resonance strength ϵ. Figure 5 shows the resonance strength as a function of the the Wien filter rotation angle Φ^{WF} and the rotation χ^{sol} caused by the solenoidal field. The minimum of the map indicates the position of the invariant spin axis for the Wien filter in its nominal position and no solenoidal field. As mentioned above, in an ideal ring one would only expect a tilt of the invariant spin axis in radial direction due to an EDM. However, here we observe both longitudinal and radial direction tilts of the order of a few mrad, caused by systematic effects (e.g. misalignments of elements) which are currently under investigation using beam and spin tracking simulations. Note that a tilt in radial direction of 1mrad is equivalent to an EDM of $10^{-17}e$cm.

The most important parameter of the experiment are given in Tab. II. More details are discussed in the conference contributions [11–14].

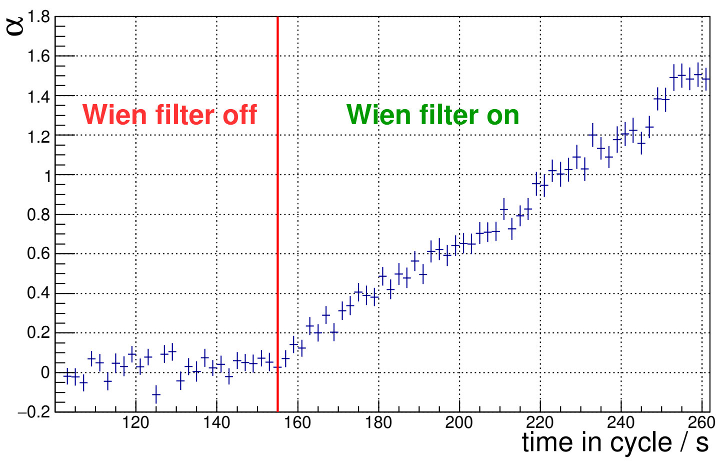

Fig. 4. Ratio $\alpha = \arctan(P_v/P_h)$ of vertical to horizontal polarization component as a function of time. The time derivative of the slope is directly related to the resonance strength ϵ.

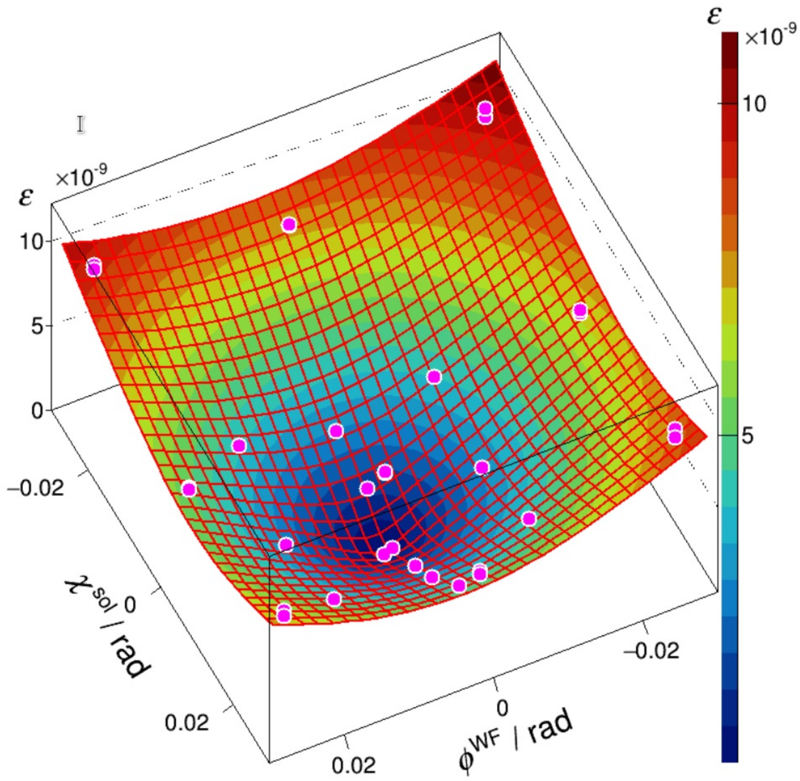

Fig. 5. Measured resonance strength ϵ (points) as a function of the Wien filter rotation angle Φ^{WF} and the rotation (spin kick) χ^{sol} caused by the solenoidal field. The colored area shows a fit with a two dimensional parboloid to the data. The minimum of the map indicates the position of the invariant spin axis.

3.2 Searches for axions and axion-like-particle (ALPs)

An axion or an axion like particle (ALP) induces an oscillating EDM, where the oscillation frequency is directly proportional to the axion/ALP mass m_a:

$$d = d_0 + d_1 \cos(\omega_a t + \varphi_a) \quad \text{with} \quad \omega_a = m_a c^2/\hbar\,. \tag{2}$$

If $d_1 \neq 0$ a resonance resulting in a build-up of a vertical polarization occurs. The resonance condition is $\omega_a = \Omega_{\text{MDM}}$. Ω_{MDM} is given by γG in a pure magnetic ring (see eq. 1). Thus be scanning γ, axion searches for different possible axion masses can be performed. The JEDI collaboration scanned in a limited range corresponding a mass range from 4.95 to 5.02 $\times 10^{-9} e$V. The big advantage of this method is that in principle one can search at a given mass by running at the corresponding frequency. One difficulty one has to overcome is the fact that the phase φ_a of the axion field with respect to the spin precession phase is not known. For this reason four bunches are stored in the accelerator with relative polarisation phases of about $\pi/2$. More details on the analysis can be found in reference [15].

No signal was observed. Preliminary results for the resulting 90% confidence limits based on the statistical sensitivity are shown in figure 6. The sensitivity interpreted as an oscillating EDM d_1 corresponds to approximately to $10^{-22} e$ cm for d_1. Compared to the search of a permanent EDM (the parameter d_0 in equation 2) the search for an AC effect d_1 is less affected by systematic effects. Note that influence on the spin motion due the axion wind effect is expected to be orders of magnitudes larger [16] in storage rings due to the larger velocity ($\beta \approx 1/2$) compared to MRT experiments. This effect is still being studied for the current experiment.

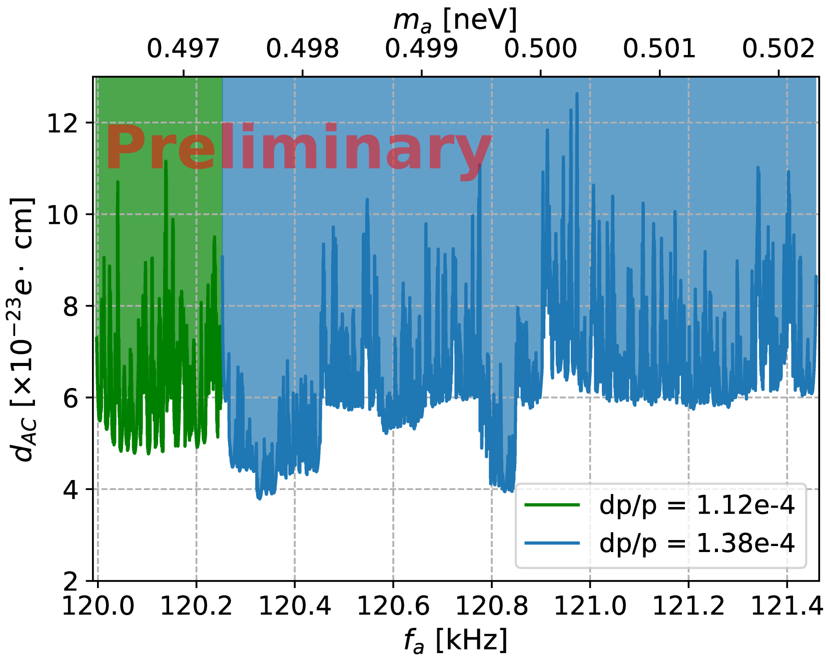

Fig. 6. Preliminary 90% upper confidence level sensitivity for an oscillating EDM (d_1 in equation 2, d_{AC} in the figure) in the frequency range from 120.0 to 121.4 kHz (mass = $4.95 - 5.02 \times 10^{-9} eV$). The green and blue colors show two scanning ramp rates in momentum change.

4. Design of a dedicated storage ring

From the studies at COSY it is evident, that a dedicated storage ring is needed to get a better handle on systematic effects. The most important remedy to fight systematics is the possibility to operate clockwise and counter clockwise beams in the so-called frozen spin mode, where the spin precession due to the magnetic moment is suppressed.

This can be achieved with certain combinations of electric and magnetic fields. Figure 3 shows the "playground" for constructing a storage where the frozen spin condition ($\vec{\Omega}_{\mathrm{MDM}} = 0$) is fulfilled for protons. Indicated by the red cicle is an option using a pure electric storage ring. The main advantage is that two proton beams can run clockwise and anti-clockwise simultaneously in the ring. The disadvantage is that, assuming that one is able to operate electrostatic bends with an electric field strength of $E = 8\,\mathrm{MeV/m}$, the bending radius of the ring is large ($r = 50\,\mathrm{m}$). The proton momentum has to be $p = 700.7\,\mathrm{MeV/c}$ in this case.

Another option indicated by the red star in Fig. 3 is to operate a ring with a combined electric and magnetic field. Using a field strength of $E = 7\,\mathrm{MeV/m}$ and a moderate radial magnetic field of $B = 0.03\,\mathrm{T}$. In this case the proton momentum is $p \approx 300\,\mathrm{MeV/c}$. For this so called prototype ring the bending radius is only $r = 9\,\mathrm{m}$. In order to operate the beams clockwise and counter clockwise, the magnetic field has to be reversed. The CPEDM (charged particle EDM) collaboration is pursuing the design of such a so called prototype ring. More details are discussed in the conference contributions [17–19] and reference [20].

5. Summary and Conclusions

Electric Dipole Moments are a unique probe to search fot CP-violating interactions outside the Standard Model. To directly measure EDMs of charged particles, like protons, deuterons or muons, storage rings are needed. First measurements of the deuteron EDM have been performed at the Cooler Synchrotron COSY at Forschungszentrum Jülich, Germany.

To reduce systematic uncertainties a new type of storage ring has to be constructed which allows one to operate clockwise and counter-clockwise circulating beams in the so called frozen spin condition, where the spin precession due to the magnetic moment is suppressed. Plans for such a ring were presented.

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