Storage Rings for the Search of Charged-Particle Electric Dipole Moments*

C. Carli[1], P. Fierlinger[2], P. Lenisa[3], J. Pretz[4,5], F. Rathmann[4], E. Stephenson[6],
and H. Ströher[4]

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Abstract

Storage rings can be used to search for electric dipole moments (EDM) of charged particles with unprecedented sensitivity. A new type of accelerator is required, namely an all-electric storage ring capable of simultaneously maintaining clockwise and counter-clockwise beams polarized in the ring plane for adequate time. A strategy towards its realization is outlined.

Scientific background

Permanent Electric Dipole Moments (EDM) of particles violate both time reversal (T) and parity (P) invariance and, on the basis of the CPT theorem, they also violate the combined symmetry CP (CPV). Such a symmetry breaking is thought to be responsible for the different behavior of particles and antiparticles, leading, e.g., to the apparent matter-antimatter asymmetry in the Universe. CPV is found in the electroweak part of the Standard Model of particle physics (SM) but – since SM-CPV is much too weak to explain the matter-antimatter asymmetry – other sources must be sought. An obvious observable to investigate is an EDM – finding a finite EDM would very probably also indicate new physics, not contained in the SM [1]. After a possible discovery of an EDM, different systems will have to be investigated in order to identify the CPV-source. Because of its exceptional science case, EDMs are searched for in various systems, hitherto, e.g., for the electron bound in atoms and molecules or the free neutron, but only impressive upper limits have been obtained so far [2]. Recently, it has been proposed to use polarized charged particles, like proton, deuteron and ^{3}He, confined in a storage ring [3]. The measurement principle is based on the time development of the polarization vector – which is parallel to the EDM – subject to a radial electric field: a beam of particles, originally polarized in the horizontal plane, slowly develops a vertical component. In spite of its simplicity, this represents an enormously challenging project due to the smallness of the expected effect.

As of late, oscillating EDMs as an additional observable have come into focus [4]: axions and axion-like particles (ALPs) induce such oscillating EDMs with an oscillation frequency proportional to their mass. Since these yet unobserved particles are well motivated candidates for dark matter (DM) with largely unconstrained mass, they are also searched for with different approaches: srEDM storage rings are very well suited to allow for these searches over a wide range of mass/oscillation frequency. To observe axions/ALPs, the stored particle spins have to precess at the oscillation frequency of the axion field to produce a resonant build-up of the vertical polarization. It should be noted that this principle can already be applied in storage rings with magnetic bending, such as COSY (Jülich, Germany). In addition, axions/ALPs are considered to be less sensitive to systematic effects compared to static EDMs in a ring.

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Strategy towards Realization

As inferred from previous measurements, e.g., for the neutron, the smallness of EDMs requires significant efforts to further improve the experimental upper limits – ultimately to an EDM sensitivity of the order of $10^{-29}\,\mathrm{e\,cm}$. For the proton, this implies the design and construction of a dedicated all-electric precision storage ring, which can simultaneously store clockwise and counter-clockwise beams, polarized in the horizontal plane. The momentum of the beams should be "magic" (700.7 MeV/c, beam kinetic energy of 232.8 MeV). Under these conditions, the spin precession due to the magnetic dipole moment is vanishing, and the particle spins point along the momentum ("frozen spin condition"). For electric fields that appear technically achievable, the circumference of such a ring will be a few hundred meters (example: an E-field of 8 MV/m implies a ring of 500 m). Contrary to protons, the magnetic anomaly G of deuterons and ^{3}He ions is negative. Therefore, EDM measurements in a storage ring using the latter particles require a combination of E- and B-fields to fulfill the frozen spin condition. There are substantial technological and metrological challenges that need to be mastered, e.g., storage and spin-coherence time of the beams, residual radial magnetic fields that mimic an EDM, precision polarimetry and the required accuracy of beam position monitors. The conclusion of the JEDI (Jülich Electric Dipole moment Investigations [5]) and the CPEDM (Charged-Particle EDM) collaborations is that this requires a stepwise approach [6, 7]:

Step 1: Proof-of-capability

COSY-Jülich is a worldwide unique storage ring for polarized beams with magnetic deflection:

(i) perform a first-ever deuteron EDM „precursor experiment“,

(ii) conduct a proof-of-principle for axion/ALPs search,

(iii) optimize the proton spin-coherence time (SCT).

Step 2: Proof-of-principle

Design, build and operate a prototype ring (kinetic energy between 30 and 45 MeV) in two steps:

(i) an all-electric ring for CW/CCW operation, but not at the magic momentum,

(ii) complement ring with B-fields for „frozen spin“; perform first competitive proton (pEDM) experiment (with a sensitivity similar to the neutron EDM). Continue axion/ALP search.

Step 3: Precision experiment

Design, build and operate a dedicated storage ring (all-electric, kinetic energy 232.8 MeV) to push the pEDM sensitivity significantly below that of the neutron EDM:

(i) the final goal is $10^{-29}\,\mathrm{e\,cm}$. Continue axion/ALP search.

Optional Step 4: Measurements with deuteron and 3He ions

This will require a ring with combined E- and B-fields for the “frozen spin“-condition.

Step 1 is an ongoing effort of the JEDI-collaboration at COSY-Jülich (Germany). The major milestone towards a final precision storage ring will be Step-2, which requires cooperation of the accelerator community with the hadron and elementary particle physics communities.

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Affiliations

[1]CERN, CH-1211 Geneva-23, Switzerland
[2]Department of Physics, Technical University Munich, 85748 Garching b. München, Germany
[3]University of Ferrara and INFN, 44100 Ferrara, Italy
[4]Institut für Kernphysik, Forschungszentrum Jülich, 52428 Jülich, Germany
[5]III. Physikalisches Institut B, RWTH Aachen University, 52056 Aachen, Germany
[6]Center for Spacetime Symmetries, Indiana University, Bloomington, Indiana 47405, USA