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Research proposal (Part B section 1)

Search for permanent Electric Dipole Moments of light ions (p, d, ^{3}He) in storage rings

EDM

Cover Page:

- Name of the Principal Investigator (PI)	Dr. Frank Rathmann
- Name of the PI's host institution for the project	Forschungszentrum Jülich, Germany
- Proposal full title	Search for permanent electric dipole moments of light ions (p, d, ^{3}He) in storage rings
- Proposal short name	EDM
- Proposal duration in months	60

The Standard Model (SM) of Particle Physics fails to explain the reason for our very existence since it is not capable to account for the apparent matter-antimatter asymmetry of our Universe. Physics beyond the SM is required and is searched for by *(i)* employing highest energies (e.g., at LHC), and *(ii)* striving for ultimate precision and sensitivity (e.g., in the search for electric dipole moments (EDMs)). Permanent EDMs of particles violate both time reversal (T) and parity (P) invariance, and are – via the CPT-theorem – also CP-violating. Finding an EDM would be a strong indication for physics beyond the SM, and pushing upper limits further provides crucial tests for any corresponding theoretical model, e.g., SUSY. For about half a century, neutron EDM (nEDM) measurements at many laboratories worldwide are trying to extend the already impressive experimental limits even further. Searches for EDMs of the proton, the deuteron, and of heavier nuclei bear the potential to reach even higher levels of sensitivity ($\sim 10^{-29}$ e·cm). Since it is essential to perform EDM measurements on different targets in order to unfold the underlying physics, pEDM and dEDM searches are *must-do* experiments. EDM experiments with charged particles are only possible at storage rings. In the ultimate experiment with a sensitivity beyond $\sim 10^{-29}$ e·cm, the EDM signal would be the vertical polarization produced by the EDM-induced precession of the frozen horizontal spin in a permanent radial electric field of a dedicated electric storage ring. The present proposal aims at a *first direct measurement* of the EDMs of protons and deuterons at $\sim 10^{-24}$ e·cm sensitivity level, and will be carried out in the conventional magnetic storage ring COSY of Forschungszentrum Jülich. Here the EDM signal would be the horizontal polarization produced by the EDM-induced precession of the frozen vertical spin in a radio-frequency electric flipper with horizontal electric field. Apart from providing the first direct access to pEDM and dEDM, literally all the outstanding technological and instrumental challenges for the proposed studies at COSY constitute groundbreaking work for the next generation of dedicated electric storage rings. The research environment at Jülich coupled to the strong experienced groups of scientists and engineers from Jülich, RWTH-Aachen, Brookhaven National Laboratory, and Michigan State University, provides the ideal starting point, and constitutes, on a world-wide scale, the optimal basis for one of the most spectacular possibilities in modern science: Finding a signal for new physics beyond the Standard Model through the detection of permanent electric dipole moments in a storage ring.

Section 1: ***The Principal Investigator***

1(a) Curriculum Vitae (max 2 pages)

Dr. Frank Rathmann

Birthdate October 5, 1961

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Education	2000/07/26	Habilitation, Univ. Erlangen
	1994/1/31	PhD Physics, Univ. Marburg (Sehr Gut)
	1991	Second State Examination, State of Hesse
	1989	First State Examination, Univ. Marburg
Employment	since 2000	Staff member at Institut für Kernphysik, FZ-Jülich
	1997-2000	Scientific assistant (C1), Univ. Erlangen
	1994 – 1997	Assistant scientist, Univ. Madison, WI, USA
	1991 – 1994	Research associate, Univ. Marburg
	1989 – 1991	Traineeship at the Studienseminar Bensheim, Germany
Prizes and Awards	1994-1997	Feodor-Lynen Fellowship of the Alexander-von-Humboldt Foundation
Functions	since 2012	Co-spokesperson of the JEDI[1] collaboration (together with Jörg Pretz (RWTH-Aachen) and Andreas Lehrach (Jülich))
	since 2010	Coordinator of the Jülich EDM Study Group on the search for electric dipole moments in storage rings
	2003-2010	Elected member of the International Spin Physics Committee.
	2007-2009	Member of the Scientific and Technical Council of Forschungszentrum Jülich
	since 2004	Spokesperson of the PAX collaboration (together with Paolo Lenisa, Ferrara) http://www.fz-juelich.de/ikp/pax/portal/
	since 2002	Coordinator of the spin physics program at COSY

Research Areas Experimental Hadron Physics; Spin Physics with hadronic probes; double polarized meson production; fundamental symmetries of the strong interaction; polarization of hadrons; polarized antiprotons; polarized internal targets; spin manipulation of stored beams, searches for electric dipole moments in storage rings

[1] Jülich Electric Dipole moment Investigations

Funding ID	**2000 – 2010**: Attracted and managed funding from the Research and Development Program (FFE) of Forschungszentrum Jülich for equipment, PhD-students, and PostDoc positions. Various contracts have been granted to Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany; Tbilisi State University, Georgia; JINR, Dubna, Russia; Petersburg Nuclear Physics Institute, Gatchina, Russia; and Ferrara University, Ferrara, Italy.	Forschungszentrum Jülich, Germany ~567 k€
	2003 – 2010: Attracted and managed research funds in the framework of the ANKE/PAX collaboration within the JINR (Dubna, Russia) and BMBF agreement, in the amount of about 30k€/yr.	BMBF, Germany - JINR, Russia ~250 k€
	2003 – 2007: International Science and Technology Center Project (No. 1861) on *Polarized Molecules*, together with Petersburg Nuclear Physics Institute, Gatchina Russia, University of Cologne, Cologne, Germany, and Institut für Kernphysik, Forschungszentrum Jülich, Germany.	ISTC, Moscow, Russia 450 k$
	2006 – 2008: For the PAX Project, Prof. Dr. E. Steffens, Friedrich-Alexander Universität Erlangen-Nürnberg, received a grant for investment, a 3 yr PostDoc position, and a 3 yr PhD position.	BMBF, Bonn, Germany 540 k€
	2007: Funds granted from the "Impuls-and Vernetzungsfond" of the Helmholtz-Society in conjunction with the submission of a Design Study in the 7th European Framework Program, which I had written.	Helmholtz Society 25 k€
	2008: DFG Grant for work on polarized Antiprotons involving two Russian and one Georgian scientist.	Deutsche Forschungsgemeinschaft 40 k€
	2008 – 2011: International Science and Technology Center Project (No. 1861) on *Polarized Fusion*, together with Petersburg Nuclear Physics Institute, Gatchina Russia, University of Cologne, Cologne, Germany, and Institute für Kernphysik, Forschungszentrum Jülich, Jülich, Germany.	ISTC, Moscow, Russia ~300 k$
	2009 – 2011: Funds granted in the European Framework Program 7 for a Joint Research Activity (JRA) on Polarized Antiprotons, which I am coordinating.	European Union I3HP2 320 k€
	2010 – 2014: My contributions to a project aiming at the production of a beam of polarized antiprotons led to an ERC grant, which has been awarded to Hans Ströher, leader of my institute at Jülich.	European Union ERC 2500 k€
	2012 – 2015: Funds granted in the European Framework Program 7 for a Joint Research Activity (JRA) on Polarized Antiprotons, which I am coordinating.	European Union I3HP3 284 k€

1(b) 10-Year-Track-Record (max 2 pages)

During the past 10 years, I have been working at the Institute for Nuclear Physics (IKP 2) of Forschungszentrum Jülich, where we performed experiments with the ANKE detector and more recently, with the PAX experimental setup at COSY. During that period, I was also taking part in all experiments of the PINTEX collaboration at IUCF. Apart from a small scale experiment which was carried out at the Cologne tandem accelerator, we have begun a series of experimental investigations with PAX at COSY, which will be extended towards studies of the spin-dependence of the $\bar{p}p$ interaction at the AD ring of CERN. In this period, we published (with me as co-author):

- 19 physics papers (letter style) in Physical Review Letters, and in Physics Letters B,
- 21 physics papers (regular) in European Physical Journal, Physical Review C, Physical Review ST-AB, Nuclear Physics A, Journal of Physics G, Physica Scripta, and others,
- 9 instrumental papers in Nuclear Instruments and Methods, Review of Scientific Instruments, and IEEE Transactions on Nuclear Science, and
- 38 contributions to the proceedings of international conferences and symposia.
- Over the course of the past ten years, I have on record at the web of science 90 publications (57 articles in peer reviewed journals and 48 proceedings contributions). Up to now, my 109 papers received in total 1200 citations, were cited on average 11 times, and my current h-index is 19.

List of the top ten publications with myself as senior author:

1. V. Barone et al. [PAX Collaboration], http://arxiv.org/abs/hep-ex/0505054.
   Antiproton-proton scattering experiments with polarization
2. D. Oellers et al., Phys. Lett. B 674, 269 (2009)
   Polarizing a stored proton beam by spin flip?
3. F. Rathmann et al., Phys. Rev. Lett. 94, 014801 (2005).
   A method to polarize stored antiprotons to a high degree
4. T. Mersmann et al., Phys. Rev. Lett. 98, 242301 (2007).
   Precision study of the η^3He *system using the* $dp \to \eta^3He$ *reaction*
5. A. Kacharava, F. Rathmann, C. Wilkin [ANKE Collaboration], http://xxx.lanl.gov/abs/nucl-ex/0511028
   Spin Physics from COSY to FAIR
6. H.O. Meyer et al., Phys. Rev. Lett. 87, 022301 (2001).
   Measurement of partial-wave contributions in $\vec{p}\vec{p} \to pp\pi^0$
7. D. Chiladze et al., Phys. Rev. ST AB 9, 050101 (2006).
   Determination of deuteron beam polarizations at COSY
8. S. Yaschenko et al., Phys. Rev. Lett. 94, 072304 (2005).
   Measurement of the analyzing power in $pd \to (pp)n$ *with a fast forward* $1S_0$ *proton pair*
9. T. Wise et al., Phys. Rev. Lett. 87, 042701 (2001).
   Nuclear polarization of hydrogen molecules from recombination of polarized atoms
10. H. Seyfarth et al., Phys. Rev. Lett. 104, 222501 (2010).
    Production of a Beam of Tensor-Polarized Deuterons Using a Carbon Target

As a monograph, I have written my habilitation (*Polarized Internal Gas Targets, A New Tool for Nucleon-Nucleon Interaction Studies, 2000, Univ. Erlangen, Germany).*

I was invited to present talks at 21 topical international conferences.

I am serving as a referee of scientific papers for Physical Review (Letters), European Physical Journal, Physics Letters, and Nuclear Instruments and Methods.

I have served from 2003-2010 as member of the International Spin Physics Committee which oversees the scientific programs of the series of International Spin Physics Symposia (http://www.fz-juelich.de/ikp/pax/spin/).

I have been member of the organizing committees of a number of international workshops and conferences:

Conferences:

- 6th International Conference on Nuclear Physics at Storage Rings (2005) (http://www.fz-juelich.de/ikp/stori05/)
- 6th European Conference on Electromagnetic Interactions with Nucleons and Nuclei (2005), Workshop on Physics and Technology Frontiers of Facilities for Hadron Physics (http://www.iasa.gr/EINN_2005/)

- I was co-chair for the 19th International Spin Physics Symposium (2010, https://www.congressa.de/SPIN2010/), and one of the editors of the conference proceedings, published in *J. Phys.: Conf. Ser.* **295** (http://iopscience.iop.org/1742-6596/295/1).

Workshops:

- 1st Summer School and Workshop on COSY Physics (2002)
- 4th ANKE Workshop on Study of Proton-Deuteron Interactions (2002)
- Workshop on Hadron Physics at COSY (2003)
- First Caucasian-German School and Workshop on Hadron Physics (2004)
- Workshop on Hadron Physics at COSY (2005)
- 2nd Caucasian-German School and Workshop on Spin in Hadron Physics (2006)
- XIIth International Workshop on Polarized Sources, Targets & Polarimetry (2007, https://www.bnl.gov/pst2007/default.asp)
- I was co-chair of the 409th WE Heraeus Seminar on Polarized Antiprotons (2008, http://www.fe.infn.it/heraeus)
- XIIIth International Workshop on Polarized Sources, Targets & Polarimetry (2009, http://www.fe.infn.it/PST2009/)
- I was co-chair for the 485th WE Heraeus Seminar on Search for Electric Dipole Moments (EDMs) at Storage Rings (2011, http://www.fz-juelich.de/ikp/edm/en/)
- I am co-organizer of the workshop on EDM Searches at Storage Rings, to be held at ECT*, Trento, Italy (2012, http://www.ectstar.eu/)

Supervised students:

At IKP, we have diploma and PhD-students as well as PostDocs from many countries all over the world, e.g., Germany, Russia, China, Japan, Italy, Poland, and Georgia. Many of them do their experiments at COSY, analyze the data at IKP, and finally return back for defending their PhD at their home institutions. During the past decade, mostly in the framework of the ANKE and PAX collaborations, I have supervised many students to their diploma or PhD:

- Ralf Engels, Doctoral Thesis: Entwicklung eines universellen Lambshift-Polarimeters für polarisierte Atomstrahltargets an ANKE/COSY, Universität zu Köln, Germany (2002)
- Maxim Mikyrtichiants, Doctoral Thesis: Development and Investigations of an Atomic Beam Source for Experiments at internal cyclotron beams, Petersburg Nuclear Physics Institute, Gatchina, Russia (2003)
- Sergey Yaschenko, Doctoral Thesis: Deuteron Breakup p(pol)d → (pp)n with a fast forward diproton studied at ANKE-COSY, Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Germany (2004)
- David Chiladze, Diploma Thesis: Deuteron Polarimetry Studies at COSY-Jülich with the ANKE Spectrometer, Tbilisi State University, Tbilisi, Georgia (2004)
- Kirill Grigoriev, Doctoral Thesis: Creation of the polarized Hydrogen and Deuterium target for the ANKE experiment at COSY, Petersburg Nuclear Physics Institute, Gatchina, Russia (2007)
- David Chiladze, Doctoral Thesis: Polarised Charge–Exchange Reaction dp → (pp)n Studies at the ANKE-COSY Spectrometer, Tbilisi State University, Tbilisi, Georgia (2008)
- Susanna Bertelli, Diploma Thesis: Studio della reazione di deuteron breakup in esperimenti di spin-filtering per la polarizzazione di fasci di antiprotoni, Ferrara University, Ferrara, Italy (2008)
- Greta Guidoboni, Diploma Thesis: Design of the interlock system of a test-bench for silicon detectors, Ferrara University, Ferrara, Italy (2009)
- Colin Barschel, Diploma Thesis: Calibration of the Breit-Rabi Polarimeter for the PAX Spin-Filtering Experiment at COSY/Jülich and AD/CERN, RWTH Aachen, Aachen, Germany (2010)
- Dieter Oellers, Doctoral Thesis: Polarizing a Stored Proton Beam by Spin-Flip?, Universität zu Köln, Germany (2010)
- Christian Weidemann, Doctoral Thesis: Preparations for the Spin-Filtering Experiments at COSY/Jülich, Universität zu Köln, Germany (2011)

Section 1(c): *Extended Synopsis of the project proposal* (max 5 pages)

Executive Summary

Although extremely successful in many aspects, the Standard Model of Particle Physics is not capable of explaining the apparent matter-antimatter asymmetry of our Universe, and thus fails to explain the basis for our existence. It has way too little CP-violation. There are two strategies to hunt for physics beyond the Standard Model: one option is to explore higher energies, as presently done, e.g., at the LHC. The other alternative is to employ novel methods which offer very high precision and sensitivity. Permanent electric dipole moments violate both time reversal and parity invariance, and are, assuming CPT invariance therefore, CP-violating. Searches for permanent electric dipole moments of protons, deuterons and heavier nuclei provide highest sensitivity for the exploration of physics beyond the SM, thus possess an enormous physics potential. The reach in energy scale for finding new physics beyond the Standard Model is estimated to range up to 300 TeV for SUSY-like new physics and up to 3000 TeV for point-like interactions, way beyond that of the LHC. In turn, these searches require a long-term engagement (> 10 yr).

It is essential to perform EDM measurements on different targets with similar sensitivity in order to unfold the underlying physics and to unveil the baryogenesis process. While neutron EDM experiments are pursued at many different locations worldwide, no such measurements have been conducted yet for protons and other light nuclei due to special difficulties of applying electric fields on charged particles. However, since a measurement on the proton has the potential to reach at least an order of magnitude higher precision than corresponding neutron EDM experiments, the proton (and deuteron) EDM experiments constitute a *must-do*. It should be noted that EDM measurements of proton, deuteron, and ^{3}He could be performed in one-and-the same *unique* machine. This is the final goal in the 2-step approach at COSY, outlined below.

Freezing the horizontal spin motion in a dedicated electric storage ring, i.e., forcing the particles' spin to always point along the direction of motion, cancels the $(g-2)$ precession. The build-up of a vertical polarization component of the beam would indicate the signal for a finite EDM of the orbiting particles. Searches for EDMs of charged fundamental particles have hitherto been impossible because of the absence of the required new class of primarily electric storage rings. At the core of the present proposal is a modification of the storage ring approach, aiming at a first direct precision measurement of the EDMs of proton and deuteron using the conventional magnetic storage ring COSY.

Introduction

The question of whether particles possess permanent electric dipole moments has a long-standing history, starting from the proposal by Ramsey and Purcell to search for a neutron EDM as a signature for parity (P) and time-reversal (T or CP) violation, which, over the last 50 years or so, resulted in ever decreasing upper limits. With the present proposal, we would like to provide the foundation for future searches for EDMs of the proton and other charged particles in a storage ring with a statistical sensitivity of $\sim 1.22 \times 10^{-29}$ e·cm per year, pushing the limits even further and with the potential of an actual particle-EDM discovery. COSY at Forschungszentrum Jülich is ideally suited as a host for such a project.

The current physics program of COSY comprises *(i)* hadron spectroscopy, *(ii)* baryonic and baryon-meson interactions, and *(iii)* symmetries and symmetry breaking. While *(i)* and *(ii)* make heavily use of the spin degree of freedom, symmetry investigations (in hadronic reactions and eta-meson decays) up to now are performed without polarization; it is planned, however, to measure the isospin-violating reaction $dd \to \alpha\pi^0$ also with a polarized beam, once the signal has been established at the WASA detector. The current proposal is to make use of polarized stored beams in a cooler ring to study fundamental symmetries, starting from what is available at COSY and expanding it into a **precision facility for spin physics**.

COSY has a history of a highly successful operation of cooled polarized beams and targets – in fact, COSY is a unique facility for spin physics with hadronic probes on a world-wide scale. Many foreign groups have exploited its capabilities, e.g., the *Spin-at-COSY*- and the *dEDM*-collaboration. Over the course of the past decade, the accelerator group (led by R. Maier), together with the two experimental institutes (J. Ritman, H. Ströher) have acquired in-depth experience in polarized beam/target manipulation and polarimetry. The COSY environment at Jülich, including the theory group (U.-G. Meißner), is thus ideally suited for a major (medium-sized) project involving spin and storage rings as this will be required for the search for permanent electric dipole moments (EDM) of charged fundamental particles (e.g., protons, deuterons, and other light nuclei).

The proposed new method, developed primarily at BNL, employs radial electric fields (for deuterons and ^{3}He also magnetic fields) to steer the particle beam in the machine, magnetic or electric quadrupole magnets to form a strong focusing lattice (e.g., FODO), and internal polarimeters to probe the particle spin state as a function of storage time [1]. An RF cavity and sextupole magnets will be used to prolong the spin coherence time (SCT) of the beam. For protons, it requires building a storage ring with a highly uniform radial electric field with a strength of $\sim 12-17$ MV/m between stainless-steel plates $2-3$ cm apart. The bending radius of the machine will be $\sim 25 - 40$ m, including straight sections, a circumference of ~250 m is anticipated. The so-called magic momentum of 0.7 GeV/c (232 MeV) is the one where the $(g-2)$ precession for the proton is zero, i.e., the spin is always aligned along the momentum vector (see Table 1).

The spins of vertically polarized protons injected into the EDM ring can be rotated into the horizontal plane by turning on a solenoidal magnetic field in one of the straight sections of the machine, and turning it off at the appropriate time. The EDM signature shows up through the development of a vertical component of the particle spin as a function of storage time.

Particle	**Momentum (GeV/c)**	**Electric field (MV/m)**	**Magnetic field (T)**
Proton	0.701	16.8	0
Deuteron	1.000	-4.03	0.16
^{3}He	1.285	17.0	-0.051

Table 1: Parameters for the transverse electric and magnetic fields required for a storage ring of radius $r = 30$ m.

In Table 2, we give current and anticipated EDM bounds and corresponding sensitivities for nucleons, atoms, and the deuteron. The last column provides a rough measure of their probing power relative to the neutron (d_n). At this level, the storage ring based EDM search proposed here, will be at least one order of magnitude more sensitive than currently planned neutron EDM experiments at SNS (Oak Ridge), ILL (Grenoble-France), and PSI (Villigen, Switzerland).

Particle/Atom	**Current EDM Limit**	**Future Goal**	**$\sim d_n$ equivalent**
Neutron	$< 1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg	$< 3.1 \times 10^{-29}$	$\sim 10^{-29}$	10^{-26}
^{129}Xe	$< 6.0 \times 10^{-27}$	$\sim 10^{-30} - 10^{-33}$	$\sim 10^{-26} - 10^{-29}$
Proton	$< 7.9 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}
Deuteron		$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-31}$

Table 2: Current EDM limits in units of [e·cm], and long-term goals for the neutron, ^{199}Hg, ^{129}Xe, proton, and deuteron are given here. Neutron equivalent values indicate values to provide the same physics reach as the indicated system.

Objectives and scientific concept: **Baryogenesis and Electric Dipole Moments of nucleons**

Electric dipole moments of elementary particles become possible only if P and T invariances are violated. By the CPT theorem, T-non-invariance amounts to CP violation.

The Universe as we know it has a microscopic net baryon number – about 0.2 baryons per cubic meter, or 10^{-10} of the density of relic photons. The Universe is electrically neutral and the electric charge of protons – free or bound in nuclei – is compensated for by electrons. The observed abundance of anti-nucleons and positrons seems exceedingly small and is consistent with zero. This constitutes the enigma of our existence from the physics point of view, since within the standard Big Bang cosmology the evolution of the Universe starts from an equal number of particle and antiparticle species.

In 1967 Andrei Sakharov formulated three conditions for the baryogenesis – the origin of the matter-anti-matter asymmetry in the Universe [2]:

1. Early in the evolution of the Universe, the baryon number conservation must be violated sufficiently strongly;
2. The C and CP invariances must be violated, so that baryons and anti-baryons are generated with different rates;
3. At the time when the baryon number is generated, and the generation is superseded by an expansion of the asymmetric matter, the evolution of the Universe must be outside thermal equilibrium.

CP violation in kaon decays is known since 1964. It has been more recently observed in B-decays and there are indications in charmed meson decays. Within the SM, CP violation can be economically parameterized by the phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The SM, although extremely successful in many aspects, however, has at least two weaknesses: neutrino oscillations do require extensions of the SM and, most importantly, the SM mechanisms fail miserably in the expected baryogenesis rate. Simultaneously, the SM predicts an exceedingly small electric dipole moment of nucleons of $10^{-33}\mathrm{e}\cdot\mathrm{cm} < d_N < 10^{-31}\mathrm{e}\cdot\mathrm{cm}$.

There is a consensus that supersymmetric and GUT extensions of the SM can do a much better job on baryogenesis. We simply refer here to the 2006 Les Houches lectures by J. Cline [3]. As early as in 1981, J. Ellis et al. noticed that some scenarios, tuned to the baryon number of the Universe, could predict large $d_N \sim 10^{-25}$ e·cm [4]. Weinberg's 1992 observation in his Dallas High Energy Physics conference summary talk remains very much valid today [5]:

"*Endemic in supersymmetric theories are CP violations that go beyond the SM. For this reason it may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron* *electric dipole moment. These electric dipole moments were just briefly mentioned at this conference, but they seem to me to offer one of the most exciting possibilities for progress in particle physics.*"

In a broad class of SUSY models, the electric dipole moment of the nucleon can be estimated as its magnetic moment times a parameter $\sim 0.01 \cdot (1\ \mathrm{TeV}/\Lambda_{\mathrm{NP}})^2 \cdot \tan\Phi_{\mathrm{NP}}$, where Φ_{NP} is the CP-violation angle, and Λ_{NP} is an energy scale for non-SM physics. In his recent review, "*Electric Dipole Moment Goals and "New Physics": d_p with 10^{-29} e·cm sensitivity! Why is it important?*", Bill Marciano of BNL has emphasized that such a level of accuracy would amount to a constraint on the new physics parameters $(1\sim\mathrm{TeV}/\Lambda_{\mathrm{NP}})^2 \cdot \tan\Phi_{\mathrm{NP}} < 10^{-7}$ [6]. If the CP-violating phase Φ_{NP} is large, which is plausible in SUSY and/or multiple Higgs models, one could set a lower bound on the energy scale for non-SM physics as high as 300 TeV, way beyond the reach of LHC. This energy scale of 300 TeV indicates the enormous potential of experimental investigations that favor higher sensitivity, instead of exploring the high energy frontier.

The finite lifetime of neutrons is an obvious restriction and, together with the practical limitations of obtaining a large number of ultracold neutrons, imposes a limit of $d_n \leq 10^{-28}$ e·cm on the sensitivity of neutron EDM experiments. Stable protons coupled with the fact that high intensity of highly polarized and cooled proton and deuteron beams are readily available, would allow one to surpass that limitation by at least an order of magnitude over the best projected neutron EDM sensitivities.

Experimental method to measure EDMs in storage rings

Electric Dipole Moments, EDMs $(\vec{d})$, couple to electric fields and Magnetic Dipole Moments, MDMs $(\vec{\mu})$, couple to magnetic fields. The spin precession in the presence of both electric and magnetic fields is given by

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B}, \tag{1}$$

where (assuming that the EDM vector $\vec{d}$ is orthogonal to the $\vec{E}$ and $\vec{B}$-fields)

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\omega} \times \vec{s}, \tag{2}$$

with $\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \frac{1}{2}\bar{h}\vec{\omega}$, for spin $\frac{1}{2}$ (protons), and $\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \bar{h}\vec{\omega}$ for spin 1 (deuteron), respectively. (Here we indicated rest frame equations; the full BMT formalism is redundant here.)

While MDMs of fundamental particles can be placed in a magnetic field for a considerable amount of time, this is generally not always possible with EDMs. Placing a charged particle in an electric field region becomes more challenging since the electric force will act on it, which needs to be compensated *without* canceling the EDM effect. One way to accomplish this is to place the charged particles in a storage ring, where as steering field a radial electric field is used. The method is most sensitive when the spin vector is kept along the momentum vector for the duration of the storage, and this ultimate goal will be realized at a later stage in a dedicated storage ring, and this subject will not be addressed within the framework of the proposal presented here.

First direct measurement of proton and deuteron EDMs using an RF-E flipper

It is obvious that COSY with its phase-space cooled polarized proton and deuteron beams, including new hardware (like a low-β section and a Siberian snake), and the available target and detector systems, provides not only a test-bench for preparatory studies on polarimetry, spin coherence time, etc., but that it could also be used essentially "as it is" for a first direct measurement, providing a solid upper limit number for the EDM of protons and deuterons. We continue studying the potential systematic errors. We have identified a novel approach using an RF-E flipper system which shall be employed in an experimental investigation at COSY with the goal to provide a first direct measurement of the EDM of protons and deuterons. One should keep in mind that all we presently know about the proton EDM is a highly model-dependent reinterpretation of the upper bound on the EDM of the ^{199}Hg atomic system. The first model-dependent assumption is the negligible contribution to atomic EDMs from electrons. The second model-dependent one concerns the contribution to nuclear EDMs from CP-violating nuclear forces on top of the contribution from the EDM of the constituent nucleons. For the latter, the uncertainty of the deuteron EDM could be substantially different from the (sum of) neutron and proton EDMs. It is fair to state that at the moment, both proton and deuteron EDMs have the status of being barely constrained.

Since the statistical accuracy of an EDM measurement hinges on the time interval during which the spins in the machine are coherently oscillating with a spin coherence time (SCT), understanding which effects limit the SCT is the prime issue which we will address first in the frame work of the present proposal.

As stated in the introduction, the COSY environment will provide a jump-start for the storage ring EDM project. Because of its complexity and the many involved technological challenges, the project will require, however, a significant preparation time and persistence to achieve the proposed sensitivities.

The project proposal is composed of studies related to four main aspects:

1. Experimental and theoretical studies of the SCT in COSY,

2. Development of a precision simulation program for spin dynamics in a storage ring, based on COSY-INFINITY that allow one to accurately simulate the behavior of a large sample of orbiting particles for a long period of time in COSY,
3. development of an RF-E flipper system capable to operate at electric fields around 1 MV/m, and
4. a **first direct measurement of proton and deuteron EDMs at COSY** with a statistical sensitivity goal of about $d = 10^{-24}\mathrm{e} \cdot \mathrm{cm}$.

These aspects will be briefly outlined below.

1. Experimental and theoretical studies of the spin coherence time in COSY: With the accessible RF-E flipper parameters, the vertical spin will be tipped by a miniscule angle $10^{-13} - 10^{-12}$ per single pass and the buildup of an observable horizontal polarization in the per cent range demands the horizontal spin coherence during $10^{10} - 10^{11}$ revolutions of the stored particles. The two principal decoherence mechanisms are dispersions of spin tunes and of revolution frequencies of stored particles. An important finding from the Jülich EDM Study Group is that the two spin tune and flipper dispersions are locked to each other making possible a mutual cancellation of the two principal decoherence mechanisms at judiciously chosen beam energies and RF-E flipper harmonics [7]. This prediction has far reaching consequences and needs to be tested experimentally at COSY. For deuterons, an enhancement of the SCT can be achieved in COSY by operating the RF-E flipper in a special flattop mode. Furthermore, theoretical arguments suggest that continuous synchrotron and betatron oscillations of the stored particles would only very weakly decohere the horizontal spin. The possibility that operating an RF-E flipper might suppress spin decoherence induced by the dispersion of the spin tune of stored particles is an entirely new observation, a search for these decoherence-free energies has never been performed before and emerges as one of top priority tasks for COSY in the upcoming years. Such a possibility is of potentially strong impact on the whole EDM program and its experimental study is one of principal points of this proposal. For stored deuterons, the flat-top modulation of the electric field in the RF-E flipper has never been experimentally studied before. For stored protons decoherence mechanisms can be avoided altogether by selection of the appropriate beam energy and the RF-E flipper harmonics.

2. Development of a precision simulation program for spin dynamics in a storage ring, based on COSY-INFINITY. Existing spin tracking codes like COSY- INFINITY (M. Berz, MSU) have to be extended to properly simulate spin motion in presence of an electric dipole moment. The appropriate EDM kick and electric field elements (static and RF) have to be implemented and benchmarked with simple first-order simulation codes. Furthermore, a symplectic description of fringe fields, field errors, and misalignments of magnets has to be adapted and verified. In order to provide the required CPU time for the simulations of spin motion with a time scale larger than tens of seconds, spin tracking programs have to be migrated to powerful computer systems or clusters. An MPI version of COSY-INFINITY is already running on the MSU cluster. A project application for the Jülich supercomputer (JUGENE and JUROPA) will be submitted soon. Finally, benchmarking experiments will be performed at COSY to check and to further improve the simulation tools. In a next step, the analysis of systematic spin rotations will be carried out. Spin tracking for a first measurement of a charged particle EDM in a storage ring can be performed to investigate the sensitivity of the proposed method. Finally, the layout of a precision storage ring with combined field deflectors has to be optimized by a "full" simulation of spin motion.

3. Development of an RF-E flipper: An RF-E(B) spin flipper will be utilized to perform a first direct measurement of a charged particle EDM in the storage ring at COSY. The fields provided by the system consist of a vertical magnetic field of roughly 70 G and a radial electric flipper field of up to 30 kV/cm. The spin flipper will run at a frequency tuned to the spin tune $G \cdot \gamma$. Test experiments with a pure magnetic field are planned to investigate and optimize the spin coherence time in COSY.

4. First direct measurement of proton and deuteron EDMs at COSY, using the resonant EDM effect with an RF-E flipper. The most promising scenario identified by the Jülich EDM Study Group is based on supplementing COSY with an RF-E flipper which runs at a frequency tuned to the spin tune ($\gamma \cdot G \pm K$, K integer). The radial electric field of the flipper would rotate the spin of stored particles away from the vertical stable spin axis, building up a CP-violating horizontal polarization. The minuscule effect from a small EDM can by amplified to an observable scale only at the expense of an extremely large number of revolutions of the beam of the order of 10^{10}, which requires the integrity of the coherently built-up horizontal polarization for an extremely long time scales of $10^4 - 10^5$s, i.e., a spin coherence time in that range must be ensured. This requirement is regarded as the principal risk factor behind all proposals for EDM searches in storage rings. Rapid precession of the horizontal polarization with the spin tune frequency further demands a polarimetry with very fast readout. The statistical accuracy of the RF-E flipper approach to the EDM at COSY is encouraging. Operating COSY supplemented with the flattop modulated RF-E flipper at $\nu_F = 77$ kHz, providing electric fields of $E = 15$ kV/cm, for an assumed deuteron EDM of

$d_d = 10^{-23}$ e·cm one finds for a single pass a rotation angle $\alpha = 2.4 \times 10^{-12}$ at 100 MeV. For a spin coherence time of $\tau_{SC} = 10^5$ s, the accumulated CP violating in-plane polarization of the deuteron could be as large as $P_{||} = 0.08$ (0.06 for a harmonic flipper). In order to reach an upper bound of $d_d = 10^{-24}$ e·cm, polarizations of $P_{||} = 0.008$ (0.006 for a harmonic flipper) need to be determined, a task within reach of state-of the art polarimetry. Such an upper bound on the deuteron EDM of $d_d = 10^{-24}$ e·cm would be comparable to the results from the model-dependent reinterpretation of upper bounds on atomic EDMs, and size wise close to the ballpark of presently available bounds on the neutron EDM. Regarding the systematic limitations involved in the operation of an RF-E flipper in EDM experiments, this remains a by and large uncharted territory experimentally, and from the accelerator theory side, only a very crude theoretical treatment has been applied so far. In the process of probing the EDM of the proton and deuteron using this technique we will study the systematic errors and will develop the necessary tools and prepare us for the next round of EDM experiments with much more statistical sensitivity. In summary the program outlined above will take several years for full execution at COSY and is considered a must-do towards the strategic goal of dedicated storage rings for EDM searches anywhere.

Commitment of PI and team

A large fraction of the time of the PI (~60%) will go into the leadership and coordination of the project. As the principle investigator I will instruct the core team at Jülich. Experiments are presently underway to determine for the first time the spin coherence time in a hadron machine. It should be emphasized here that all collaborating team members are absolutely vital for the success of the project. The team members around Y. Semertzidis at Brookhaven National Laboratory (BNL) have a long standing experience with record precision storage ring experiments, such as the celebrated muon $(g-2)$ experiment. The group is presently working on the machine design of a future electric pEDM ring, and possesses a large expertise in storage ring lattice studies. The RWTH-Aachen group (J. Pretz) is very experienced in large collaborations, in the research on the spin structure of the nucleon, and the measurement of the muon EDM of the BNL $(g-2)$ collaboration. In addition, the group has expertise in the coordination of data analysis and detector groups. The group at Michigan State University (M. Berz, principal developer of COSY-INFINITY) holds the world's expertise on the COSY-INFINITY tracking tool. This is considered an absolutely vital and indispensible ingredient to ensure the success of the proposed project.

Research environment

In the sector of nuclear and hadron physics, Jülich is the undisputed world leader in the operation of stored polarized beams of protons and deuterons. This expertise makes Jülich the ideal location for the envisioned search for permanent electric dipole moments. The present project involves both a tremendous challenge and an exceptional opportunity, which has the full backing of the management of IKP and FZJ as a possible future perspective of the institute. The role of the ERC Advanced Grant, if approved, will be a decisive step towards establishing COSY-Jülich as the leading hadron spin-physics laboratory in Europe. At the same time, the present proposal provides an international flagship project of highest visibility for Europe. It will pave the way for next generation EDM searches in dedicated storage rings.

Final Remark

The searches for EDMs using storage rings come along with many already identified technological challenges and experimental difficulties. In addition, there will most likely be additional ones that show up as the project moves forward. Nevertheless, despite the expected difficulties and uncertainties that may lie ahead of us, storage ring based searches for EDMs represent at present our best bet for the most sensitive EDM measurements worldwide. **The experimental investigations outlined here constitute one of the most *spectacular possibilities* to actually find a signal for new physics beyond the Standard Model. As such, the study proposed here, represents a chance that should not be missed.**

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ERC Advanced Grant 2012
Research proposal (Part B section 2)
(not evaluated in step 1)

Section 2: ***The Project proposal*** (max. 15 pages, excluding Ethical Issues Table and Annex)

a. State-of-the-art and objectives

WHAT? – Find a permanent EDM of p, d, or ^{3}He or push the limits as far as possible!

The search for permanent electric dipole moments (EDM) was initiated by Edward Purcell and Norman Ramsey more than 50 years ago. Since then, a long series of searches with ever more sensitive experiments on neutrons, atoms, and molecules has been conducted. Although no EDM has yet been found, the experimental upper limits have already had significant influence on theories of elementary particle physics. Now new generations of experiments are under way or are being planned, which may at last find an EDM – in any case with far-reaching implications. As will be explained in more detail in the next section, the radically new approach proposed here is based on utilizing a storage ring to determine EDMs of charged particles (p, d, or ^{3}He). Potentially, such an approach provides the highest sensitivity of all proposed searches for EDMs with a projected sensitivity of $\sim 10^{-29}$ e·cm per year.

The proposed searches for EDMs using storage rings come along with many already identified technological challenges and experimental difficulties. In addition, there will most likely be additional ones that show up as the project moves forward. Nevertheless, despite the expected difficulties and uncertainties that may lie ahead, storage ring based searches for EDMs constitute at present our best bet for the most sensitive EDM measurements, with the goal to actually find a signal for new physics beyond the Standard Model. As such, the proposed study represents a chance that must not be missed.

WHY? – Explore the reason for our baryon-asymmetric universe!

The modern understanding of the origin of the Universe rests upon the Big Bang cosmology supplemented by the inflationary expansion during the earliest stages of the universe. In conjunction with the Standard Electroweak Theory, this paradigm provides a perfect quantitative description of the primordial nucleosynthesis of the light elements. The CP violation, experimentally discovered in 1964 and crowned by the Nobel Prize to J. Cronin and V. Fitch, though tiny, implies that the laws of nature are not exactly the same for matter and antimatter; matter could have been dynamically generated in the earliest stages of the Big Bang. Presently, the wealth of experimental data on CP violation in the neutral kaon and B decays, and from $D\bar{D}$ mixing can be accommodated by the Cabibbo-Kobayashi-Maskawa parameterization (CKM) of the quark-mixing matrix (another Nobel Prize in physics to M. Kobayashi and T. Maskawa). Remarkably, in the Wolfenstein representation, the relevant CP-violating phases exhibit no particular smallness as compared to, for instance, the Cabibbo angle. The scale for the matter-radiation kinetics in the early phases of the Big Bang is set firmly by the experimentally observed density of the relic microwave radiation, and while the CKM mechanism is capable of reproducing the dynamical generation of the net baryon number of the universe, the predicted baryon density is orders of magnitude below the experimental observation. One would conclude that additional, yet unknown non-CKM mechanisms of CP-violation beyond the SM are at work. Arguably, permanent EDMs of particles could indicate such a mechanism and their discovery might just be around the corner.

The past 25 years have witnessed an extensive phenomenology of CP-violations in meson decays. Theorists have correctly suggested the most promising B decays (Sakurai prize in theoretical physics to I. Bigi and A. Sanda). One of the net results from these investigations of the potential of B decays suggests that mechanisms beyond the Standard Electroweak Mode could at most reveal themselves as small deviations from the CKM predictions. The D decays are much more difficult to analyze theoretically and their potential as a testing ground for non-CKM mechanisms is less promising. To summarize, non CKM-mechanisms might not be observable in meson decays at all.

The fundamental nature of CP violation demands a most vigorous effort with probes beyond meson decays. There are ideas about the CP violation in neutrino oscillations but this subject is still in its infancy. A much more established probe is an electric dipole moment of particles, light nuclei and atoms. One must not be discouraged by the extremely small neutron EDM values $d_n \sim 10^{-31} - 10^{-32}$ e·cm predicted by the Standard Model – the current upper bound on d_n has already ruled out some of the theoretical models and carves significantly into the domain of predictions of supersymmetric models. The crucial point is that once tuned to the experimentally established rate of the baryogenesis, supersymmetry-based models tend to predict $d_n \sim 10^{-28}$ e·cm or larger. The conclusion, one would draw from this brief discussion is that in the search for permanent EDMs of particles, no effort should be spared to reach and surpass the present levels of sensitivity.

b. Methodology

HOW? Employ a new class of storage rings for EDM searches!

The principal observable of every EDM experiment is the angle of precession of the spin in an electric field which boils down to the product of an electric field times the precession (observation) time. In the neutron beam magnetic resonance technique, a restriction comes from the short time of flight of neutrons through the magnet. Stored ultracold neutrons (UCN) allow one to increase the precession time by about four orders in magnitude. In addition, the precession time is bound from above by the neutron lifetime. Furthermore, considering the typical size of the UCN storage cell one loses in the strength of the applied electric field. The important virtues of dedicated proton (or d, ^{3}He) EDM storage rings experiments are:

- *i)* the large number of stored particles ($10^{10} - 10^{11}$), and
- *ii)* the envisioned use of electric fields, an order of magnitude larger than those in UCN experiments (srEDM experiments: $12 - 17$ MV/m *vs.* 10 kV/cm in UCN experiments).
- *iii)* Since contrary to neutrons, protons do not decay, the achievable observation (precession) times (also for d, ^{3}He) are potentially much longer than the neutron lifetime. Therefore, it is of critical importance to ascertain that large spin coherence times (SCT) – the highest risk factor in all proposals of storage ring EDM searches – can be achieved in dedicated pure electric and conventional magnetic storage rings.

The ultimate EDM experiment, capable of surpassing the sensitivity of the neutron EDM experiments and aiming at $d_{p,d} \sim 10^{-29}$ e·cm per year, is by all accounts within the reach of the approach of frozen longitudinal spins in a dedicated storage ring. In order to achieve the aspired goals, the basic storage-ring-related experimental and theoretical concepts need to be improved beyond state-of-art. Before embarking on the construction of dedicated storage rings, the most challenging aspects must be worked out at existing facilities. The cooler synchrotron COSY stands out uniquely as a facility well-suited to address such must-do experiments, due to its well-recognized experimental record with stored cooled beams of polarized protons and deuterons.

Besides R&D for future dedicated EDM storage rings, the theoretical work of the past two years in the framework of the JEDI[1] collaboration uncovered some previously unattended facets of spin dynamics in magnetic storage rings with radiofrequency (RF) spin flippers. Within the longitudinal frozen spin approach, the EDM signal leads to the build-up of polarization from the frozen longitudinal one by the EDM-induced precession of the spins in the constant electric field of the machine. In a pure magnetic ring, one has to resort to RF-electric (RF-E) spin flippers with frequency locked to the spin tune of the stored particles. In this case, the frozen vertical spin is rotated onto the ring plane by the EDM-induced precession in the RF electric field of the flipper.

The principal challenge is that the expected spin tilt angle per single pass through the flipper is exceedingly small, $10^{-13} - 10^{-12}$ rad and the build-up of the observable polarization requires an exceedingly large number of turns, up to $10^{10} - 10^{11}$ turns. One needs to ensure that all spin tilts are in the same direction and that the spin coherence holds for a long time, i.e., for $10^4 - 10^5$ s. The recent theoretical finding from the Jülich EDM Study Group is the observation that spin-decoherence-free energies might exist such that spin decoherence from the dispersion of spin tunes of the stored particles is compensated for by operating the RF-E flipper at judiciously chosen harmonics. For stored deuterons, another possibility to suppress the spin decoherence is achieved when the RF-E flipper is operated in a special flattop mode. None of these techniques have ever been tried out before, their implementation at COSY is possible with moderate effort. Successful application of the spin decoherence free evolution of the build-up of horizontal polarization from a vertical one induced by the coupling of the electric dipole moment to the electric field in the flipper, would allow for the first direct experimental measurements of the EDMs of proton and deuteron with a statistical sensitivity of about 10^{-24} e·cm. It should be noted that this is close to the ballpark of sensitivity achieved in neutrons EDM experiments after about 50 years of experimentation.

[1] Jülich Electric Dipole moment Investigations

The entire challenging R&D for the first direct measurement of $d_{p,d}$ at COSY will be carried over to the ultimate frozen longitudinal spin storage rings. We specifically mention only radiofrequency and static deflectors with frontier electric field gradients; polarimetry of precessing spins with high reproducibility and stability, with the sensitivity to transverse and longitudinal polarizations at per mill and eventually several parts per million sensitivity level; fast readout of polarization asymmetries at MHz and beyond; extending the double polarization polarimetry for deuterons on polarized targets if the existing databse is found incomplete at energies optimal for the EDM experiments; beam-position monitoring at 5 ppm accuracy; high precision alignment of the ring elements; high precision alignment of stable spin axes of the polarized ion source and the storage ring; high precision chromaticity corrections etc. At the second stage when the ^{3}He EDM will be pursued, one will have to develop the polarimetry of polarized ^{3}He, where the experimental database is scarce.

Aim of the Proposal

The aim of the proposal is twofold. The main aim is to carry out the first direct measurement of the proton and deuteron EDM at COSY at $d_{p,d} \sim 10^{-24}$ e · cm sensitivity level. The second aim is to identify critical aspects of spin dynamics for future electric storage ring EDM experiments for proton, deuteron and ^{3}He for a common sensitivity level of 10^{-29} e · cm per year. The main deliverables of this proposal, which all constitute groundbreaking R&D for any future dedicated EDM storage ring, can be presented as follows:

a. Test of new ideas on stretching the spin coherence time in storage rings with a judicious operation of radiofrequency spin flippers. These tests can be carried out using radiofrequency magnetic flippers (RF-B flipper).
b. Development of radiofrequency electric flippers (RF-B(E) flipper) with strong electric fields.
c. Development of high precision polarimetry with highest attainable degree of reproducibility and stability for long measurement times over the COSY energy range.
d. Experimental studies of hitherto unattended aspects of spin response of the COSY ring.
e. The summit point of the proposal is the first direct experimental measurement of the proton and deuteron EDMs with sensitivity close to the ballpark achieved after half a century of neutron EDM experiments.

The underlying R&D of this proposal is absolutely crucial in order to reach a position to move forward to a design of the next generation electric storage rings EDM searches using the frozen spin concept that would aim experimentally at an initial level of sensitivity $10^{-24} - 10^{-25}$ e·cm, and would, over the course of a few years, eventually approach the final sensitivity of 10^{-29} e·cm.

Considering that the deuteron EDM has a specific sensitivity to CP-violating nuclear forces, it is not precluded that at a deuteron EDM machine one could already discover new physics at the 10^{-25} e·cm level. It remains to be seen whether that level of sensitivity requires the investment in the development of the frozen spin technique in a combined electric/magnetic machine, or that one can push to that frontier by modifying COSY.

Looking further ahead, a combined electric/magnetic ring for the deuteron EDM could be a cost saving option, as it is straightforward to employ this machine also for proton and ^{3}He EDM experiments. The operational parameters will be similar, but one needs to work on three more technical developments:

- A source of polarized ^{3}He ions, and
- an experimental program to determine polarization observables in the scattering of polarized ^{3}He.
- The development of a suitable polarimeter to detect the small polarization component of ^{3}He produced by the spin precession due to the EDM.

COSY is ideally suited to address the above-mentioned aspects.

Logistics, organization, and list of tasks

A working team is formed and the different activities related to the implementation of the project are structured into 9 main tasks. As principle investigator, I have identified a number of key persons for the team. These are presented in the next sections together with the resources for the project. These key persons are responsible for the accomplishment of the individual tasks.

Organization

Task 1: Management

First direct measurement of proton and deuteron EDMs using COSY

Task 2: Spin coherence time investigations at COSY

Task 3: Direct measurement of proton and deuteron EDM using RF-E flipper

Polarimetry

Task 4: Development of polarimeter concepts. This task might also involve the measurement of additional polarization observables.

Spin tracking

Task 5: Development of spin-tracking codes, based on COSY infinity and a custom-built simulation tool, including benchmarking

Systematic errors

Task 6: Systematic error studies

Technical developments

Task 7: Development of RF-E flipper system

Task 8: Development of beam-position monitors

Theory

Task 9: Theoretical studies

A brief description of the foreseen activity in each of the tasks is given below. As stated before, although the goals are quite clear, the task list contains only those aspects that could be clearly identified up to now. It is quite likely that there will be additional aspects coming into the focus as the project moves along that have either been overlooked or that have been underestimated: all of these will be added to and investigated by the corresponding task teams.

Task 1: Management

The management team of the project will have three members, one from Jülich (H. Ströher), one from RWTH-Aachen (J. Pretz), and one from BNL (Y. Semertzidis) – all three are very experienced in managing complex multi-national projects. In addition, Jülich, RWTH-Aachen, and BNL have organizational departments to provide support whenever necessary.

Task 2: Spin coherence time investigations at COSY

A number of different options for a first direct measurement of the proton, deuteron, and eventually also ^{3}He at COSY have been scrutinized recently by the Jülich EDM Study Group, in close collaboration with the BNL EDM collaboration[2]. Targeting a stringent bound on EDMs of stored particles demands for large spin coherence time of $10^4 - 10^5$ s. In order to achieve this goal, it is imperative to study extensively the spin dynamics in COSY as a spin storage ring in the extremely long time regimes which have not been explored hitherto. The experimental studies of the spin coherence time are presently in their formative stage, the first experimental look into the problem gave indications that the spin coherence time could be as large as several hundred seconds.

The theoretical studies of spin decoherence mechanisms is in an equally formative stage, already visible are several very encouraging results of work carried out by the Jülich EDM Study Group, in close collaboration with the BNL EDM collaboration. Of prime interest is to understand under which conditions, the spin decoherence would stop the build-up of CP-violating horizontal polarization by running the RF-E flipper. The principal source of spin decoherence is the dispersion of spin tunes of the stored particles. Depending on particle and energy, the present as yet incomplete theoretical understanding suggests different strategies:

- For stored deuterons, a promising technique could consist of using a flat-top modulated RF electric field, a system that has never been experimentally used before.
- For stored protons, one can suppress decoherence mechanisms by judicious choice of the beam energy and the RF-E flipper harmonics. The possibility that running a flipper might suppress spin decoherence induced by the dispersion of

[2] Storage Ring Electric Dipole Moment Collaboration http://www.bnl.gov/edm/

the spin tune of stored particles is an entirely new option, a search for these decoherence-free energies has never been performed before and emerges as one of top priority tasks for COSY in the upcoming years.

An opportune observation is that for diagnostics purposes, the EDM-caused rotation of the spin in an electric field can be swapped for the rotation caused by the magnetic moment of the spin in a magnetic field. Therefore, all the current ideas on spin decoherence mechanisms can be tested with already available (magnetic) RF-B flippers which can be realized as either radiofrequency solenoids or by using a dipole magnet (strip line). The requirements for such RF-B flippers include

i. support of both the harmonic and flattop modes of operation,

ii. a broad range of frequencies comprising several harmonics, which is especially important in the search for decoherence free energies for protons at intermediate energies and high energy deuterons,

iii. amplifiers to support half-integer, third-integer etc. flattop modes needed to optimize the deuteron energy,

iv. close, better equal magnetic flipper fields in the harmonic and flattop modes of operation.

In the present proposal, the EDM signal is a buildup of the horizontal polarization from the stable vertical one. However, the horizontal polarization can inadvertently be injected into the storage ring, if the stable spin axes of the polarized ion source and of the storage ring are misaligned. Opportune feature of RF-B flippers is that spin rotation angles can be made large, so that all three components of the spin can be measured simultaneously. This would allow for a thorough check of the existing theoretical studies that suggest that when RF-E and RF-B flippers are employed, the spin decoherence is different for the three polarization components of the stored particles. The theory predicts that only one of rotating components of the horizontal spin will be affected by the RF B-driven buildup, an experimental test of this feature is imperative. On the other hand, the experimental determination of the longitudinal polarization of protons demands for the development of polarimeters with polarized target (for more details, see Task 4). At this stage it might be advantageous to supplement the injection beam line with a special spin rotator to control the misalignment angle of the spin axes.

Full understanding of spin decoherence mechanisms requires an extensive studies of SCT as a function of the beam momentum dispersion, the impact of the synchrotron and betatron oscillations, which could be achieved by controlled pre-cooling of the beam.

At the final stage of RF-B flipper studies, there will be experiments at ultralow magnetic fields such that the spin tilt angle per turn is in the range anticipated for EDM induced effects with RF-E flippers. The prime purpose of such investigations is to identify possible false effects from the COSY ring, and to test the performance and attainable stability of the radiofrequency flippers.

Task 3: Direct measurement of proton and deuteron EDM using RF-E flipper

The basic idea is to supplement COSY with an RF-E flipper which shall run at a frequency that is tuned to the spin tune ($\gamma \cdot G \pm K,\ K$ integer). The radial electric field of the flipper would rotate the spin of stored particles away from the vertical stable spin axis, thereby building up a CP-violating horizontal polarization. In order to appreciate the complexity of the task, for a beam of deuterons with $T = 100$ MeV, and an RF-E flipper of length $L = 1$ m, providing electric fields of $E = 15$ kV/cm, for an assumed electric dipole moment and $d_d = 10^{-23}$ e $\cdot$ cm, one finds a single pass rotation angle $a = 2.4 \times 10^{-12}$ rad. Such a minuscule effect can by amplified to an observable scale only when the beam is stored in the machine for an extremely large number of revolutions of the order of 10^{10}. And this requires that during the corresponding period of time of $10^4 - 10^5$ s, the build-up of horizontal polarization takes place *coherently*. Spin coherence times in that range must be ensured — this requirement is regarded as the principal risk factor behind all proposals for EDM searches in storage rings. Rapid precession of the horizontal polarization with the spin tune frequency further demands a polarimetry with very fast readout.

A feasibility test of such a mode of operation and the attainable accuracy of full polarimetry of the horizontal spin also needs an experimental scrutiny. The statistical accuracy of the RF-E flipper approach to the EDM at COSY is encouraging. With 100 MeV deuterons stored in COSY, supplemented with the above specified flattop modulated RF-E flipper, operated at $\nu_F = \gamma \cdot |G_d| \cdot \nu \sim 77$ kHz, for $\tau_d^{SC} = 10^5$ s and $d_d = 10^{-23}$ e · cm, the accumulated CP violating in-plane polarization of the stored ensemble of deuterons could be as large as $P_{||} = 0.08$ (0.06 for the harmonic flipper). In turn, for an upper bound of $d_d = 10^{-24}$ e · cm, polarizations of $P_{||} = 0.008$ (0.006 for the harmonic flipper) need to be determined. Such accuracies are within the reach of state-of the art polarimetry, although, depending on the beam energy and type stored particle, most likely, additional data on polarization observables need to be collected (task 5). As stated before, such an upper bound on the deuteron EDM of $d_d = 10^{-24}$ e · cm would be comparable to the results from model-dependent reinterpretations of upper bounds on atomic EDMs, and size wise close to the ballpark of state-of-the-art neutron EDM bounds. On the experimental side, there is the opportunity to probe systematic effects in the COSY ring in-situ using very slow RF *magnetic* flippers to reproduce the conditions to be encountered in the RF-E flipper EDM experiments (task 3). In summary, the program outlined in this proposal will take several years for full execution at COSY. It is considered a must-to-do towards reaching the strategic goal of future dedicated EDM storage rings.

Task 4: Development of polarimeter concepts

A simultaneous measurement of both P_x and P_z components of the horizontal polarization would be an important cross check of the appearing EDM signal. Only one component can reliably be extracted by standard polarimetry with an unpolarized target, while a polarized target is called upon for a full-fledged polarimetry. However, when such a polarized target is employed, in-plane magnetic fields are forbidden since the ordinary magnetic moment would cause a false spin precession from vertical to in-plane. This seems to preclude the polarimetry using e.g., a longitudinally polarized internal gas target with longitudinal holding magnetic field. The use of a dense transversely polarized internal storage cell target, however, seems possible, though during the horizontal polarization build-up process, the target must run with empty cell but vertical guide field switched on. One would inject polarized particles into the storage cell only at the polarimetry stage, and, since one does not want to change polarity of the holding field during the measurement, the injection of different hyperfine states from the polarized atomic beam source seems necessary.

Called upon here is the development of a new line of thinking towards a complete EDM polarimetry, where all three components of the beam polarization can be mapped out during the build-up of polarization induced by an EDM. In the long run, it may prove inadequate to observe only transverse polarizations in EDM build-up experiments. According to current theoretical ideas, only one of rotating components of the horizontal spin will be affected by the RF B-driven buildup, an experimental test of this feature and finding ways to separate the RF-B flipper generated horizontal polarization from false signals, for instance, from the injection of slight horizontal polarization from the polarized ion source, are imperative. While the pp data base in the beam energy range of interest for EDM studies is reasonably well established, the pd data base, and especially data involving ^{3}He are much scarcer, in particular those involving polarized beams and targets.

Once the spin coherence time studies (task 2) have shown that decoherence-free energies do exist in magnetic machine, the goal of this task is to identify suitable scenarios that lead to polarimeter concepts for reaching the EDM limits. Depending on the preferred energy for the deuteron EDM experiment, there might be a need to complement the polarization observable database for a single- and double-spin polarimetry purposes. The required instrumentation is to a large extent already available at COSY. At the ^{3}He stages of EDM searches at COSY, which is beyond the direct target of this proposal, there will definitely be a need to extend the existing spin observable database for ^{3}He polarimetry.

Task 5: Development of spin-tracking codes, based on COSY-INFINITY and a custom-built simulation tool, including benchmarking

One badly needs spin tracking tools capable of handling with controlled precision up to 10^{11} turns in a realistically modeled machine and for large samples of particles. Full spin-tracking simulations of the entire experiment are absolutely crucial to explore in a systematic way the feasibility to reach the desired spin coherence times (SCT) of $10^4 - 10^5$ s. Even if the required SCTs are attainable, one needs to check thoroughly whether systematic errors do not block the anticipated sensitivity to EDMs. It is planned to use the COSY-INFINITY code and its updates to include higher-order nonlinearities, normal form analysis, symplectic tracking and especially spin tracking upon incorporation of RF-E and RF-B flippers into the code. Given the complexity of the task, and in order to ensure the credibility of the results, at least two generic simulation codes must be developed with the required accuracy and efficiency but using different approaches. One such code is COSY-INFINITY based on the differential algebra. The second candidate is UAL[3]-Teapod based on discrete field kicks and originally developed for particle tracking for the SSC accelerator. The upgrade of COSY-INFINITY will be supervised by M. Berz (MSU), the principal developer of the presently available version of this powerful tracking tool.

Adding the spin degree of freedom substantially enhances the need for the computing power. In order to study subtle effects and simulate the particle and especially spin dynamics during the storage and build-up of the EDM signal, one needs custom-tailored fast trackers capable of following up to 10-100 billion turns for samples of up to $10^4 - 10^6$ particles. The spin coherence time, for instance, is of special multi-parametric nature and demands extensive exploratory simulations, where the demand for fast tracking for large ensembles is more important than going after all fine workings of the machine; in many cases, it might be sufficient to reproduce only the gross features of COSY or any other machine in a first stage. A comparison of very fast trackers using simplified model descriptions of the machine with results from COSY- INFINITY and UAL-Teapod will be reserved for the later stages of the simulation development when radiofrequency spin rotator elements will be incorporated into the generic trackers.

The spin and beam dynamics differential equations describing a particle in a combination of electric and magnetic fields are solved using Runge-Kutta integration. They have been shown to be accurate to sub-part per billion levels in describing the muon $g - 2$ precession frequency. The integration step size is 0.5 ps, making it rather slow with a possible maximum tracking time of about 10 ms for a particle in the ring. This method, even though it is slow, can be used for bench-marking the results of the much more efficient COSY- INFINITY or other efficient spin tracking program.

In addition, spin coherence time studies at COSY, at the core of this proposal, will benchmark all simulation codes. Preliminary first tests are possible with results obtained from a recent experiment conducted at COSY in early 2011. The analysis of the experimental data is in progress and the preliminary data suggest SCTs for deuterons of larger than several hundred seconds.

Task 6: Systematic error studies

While R&D on RF-E flippers would be one of the important tasks, in the course of discussions within the Jülich EDM Study Group, it has been understood that principal issues related to the spin coherence time could be clarified with RF-B flippers. Specifically, on the experimental side, there is the opportunity to probe systematic effects in the COSY ring in-situ using very slow magnetic RF-B flippers to reproduce the very slow spin rotation conditions to be encountered in the EDM experiments using RF-E flippers. Therefore, much of the spin decoherence mechanisms can be explored at the expense of a relatively minor upgrade of the RF equipment already available at COSY.

Regarding the systematic limitations of the RF-E flipper scenario, it remains a by and large uncharted territory experimentally, and from the accelerator theory side, only a very crude theoretical treatment has been applied so far. Specifically, as stated elsewhere, one badly needs spin tracking tools capable of handling with controlled precision up to 10^{11} turns in a realistically modeled machine. While spin tracking codes are indispensable, full insight into the results is only possible at the expense of analytic investigations which are still to be developed. To this end, important groundbreaking theoretical work has already been carried out by the IKP accelerator theory group which will be complemented by more PhD students, working specifically on this project.

While R&D on RF-E flippers would be one of the important tasks, in the course of discussions the Jülich EDM Study Group, it has been understood that, on the experimental side, principal issues on the spin response of the COSY ring could be clarified with a RF-B flippers. Specifically, there is an opportunity to probe systematic effects in the COSY ring in-situ using very slow magnetic RF-B flippers to reproduce the conditions to be encountered in the EDM experiments using RF-E flippers. Therefore, much of the spin decoherence mechanism and other limitations on the buildup of the EDM signal can be explored at the expense of a relatively minor upgrade of the RF equipment already available at COSY. Regarding the flipper alignment issues see the following task 8.

[3] Unified Accelerator Libraries

Because of a finite beam bunch, particles will cross the flipper at different phases of the flipper field for early and later particles in the bunch. The resulting spread of the spin tilt angle within the bunch is one of the systematic effects of the RF-E and RF-B flipper technique. A finite length of the flipper itself plays a role similar to the bunch length. The impact of both bunch and flipper lengths can be studied theoretically, it is amenable to tracking tools, the bunch length in a ring is controllable and these systematic effects can readily be studied experimentally with RF-B flippers.

It is obvious that a substantial improvement of COSY is required in order to reach the desired EDM sensitivities. The directorate of IKP and the board of directors at Forschungszentrum Jülich are fully aware of the implications of such a program in terms of manpower and hardware necessary to further pursue the goals of this project. Some items have already been identified, and are briefly discussed below:

- An improved closed-orbit control system for orbit correction in the micrometer range is necessary, which requires increasing the stability of correction-dipole power supplies by at least one order in magnitude. The number of correction dipoles and beam-position monitors (BPMs) has to be increased significantly, since the orbit has to be controlled along the entire path length of the beam in the COSY machine.
- The BPM accuracy, presently limited by electronic offset and amplifier linearity, has to be substantially improved as well. In particular, a precise adjustment of the quadrupole magnets is mandatory, and the BPMs have to be aligned with respect to the magnetic axis of the quadrupole magnets.
- Beam oscillations can be excited by vibrations of magnetic fields induced by the jitter of power supplies. Investigations have to be carried out with the aim to understand and suppress these beam oscillations to a sufficiently low level, where they do not interfere anymore with the design EDM sensitivity goal of 10^{-24} e · cm.
- The interaction of the circulating beam with the surrounding vacuum chamber produces longitudinal and transverse wake fields, which can lead to transverse and longitudinal beam kicks and excite instabilities. The main sources of wake fields are generally RF cavities and kickers, finite conductivity of wall material, discontinuities of the chamber geometry due to transitions, bellows and beam-position monitors. Transitions of the vacuum chamber profile can have a large impact on transverse and longitudinal beam motion. An accurate estimation of the total impedance budget of the COSY machine has to be carried out, and, depending on the outcome, those sections in conflict with the goals of this proposal will be modified.

Task 7: Development of the RF-E flipper system

The goal of this proposal is to perform the first direct EDM measurement of protons and deuterons at COSY at a sensitivity level of 10^{-24} e · cm. This is within reach with an RF-E flipper of length $L = 1$ m, an electric field of $E = 15$ kV/cm. Such a device would generate a single pass rotation angle $\alpha = 2.4 \cdot 10^{-13}$ rad for a beam of deuterons with $T = 100$ MeV.

The required vertical magnetic field strength and radial electric field gradient for such a measurement can be reached with state-of-the-art technology. The main challenge is to provide a high-quality field with relative field errors of less that 10^{-7} or 10^{-8} (depending on the intended sensitivity limit) within a good field region where the beam passes through. The ends of the electric plates and magnet coil geometry have to be carefully designed and manufactured. It should be noted that in the muon $g - 2$ experiment, the vertical B-field varied azimuthally by about 100 ppm, while for the integrated field uniformity values of better than 1 ppm were reached. High-precision magnetic field measurements and determination of plate distances have to ensure the performance of the system. The alignment of the spin-flipper device with respect to the magnetic axis of the accelerator is of major concern. Piezo actuators will be used for precise motion control. They provide the highest accuracy, speed and resolution with sub-millisecond response and sub-nanometer resolution for static and dynamic compensation of positioning. Static offsets and time-dependent fluctuations (temperature drift, ground motion, etc.) can be easily handled by piezoelectric positioning technology. The main task is to build a combined alternating field device that includes diagnostic tools for the observation of magnetic fields and plate distance, and as well, an active feedback system to compensate for short term vibrations.

The effect of fringe fields of all other elements of the ring but RF-B and RF-E flipper will be determined directly during experiments with slow RF-B flippers. The fringe fields of the RF-E flipper itself can be reliably simulated theoretically; the collaboration members have the necessary expertise, and measured for both magnetic and electric cases.

The beam bunch must be sufficiently short so that all particles cross the flipper at a negligible small shift of the phase of the flipper. A finite length of the flipper itself plays a role similar to that of the bunch length. The impact of both lengths can be studied theoretically, it is amenable to tracking tools and the dependence on the bunch length can readily be studied experimentally with RF-B flipper.

High precision beam-position monitoring is required to exclude drifts caused by changing fringe field effects from the run to run and to minimize and eliminate the false effects caused by vertical electric fields. The motional radial magnetic fields generated by such stray vertical electric fields would produce a background rotation of the magnetic moment, and of the spin thereof, of stored particles. Apart from fringe fields, the unwanted vertical electric field can be induced by misalignment of the flipper. The precision alignment of electric deflectors is a generic problem to all storage rings with horizontal electric fields. To this end, the BNL team of this collaboration has a required expertise. In the E821 muon $(g-2)$-experiment, the alignment precision of the pole pieces was better than 25 μm, and using a number of passive (wedges) or active (pole-face winding) shims, the fields were made more uniform.

Task 8: Development of beam-position monitors

Here we reiterate why precision beam-position monitoring (BPM) is so important and how such studies carry over to future EDM storage rings? In the ultimate pure electric EDM machine, a high degree of cancellation of the systematic effects can be achieved by a simultaneous measurement of EDM signals for the counter-rotating proton beams. To this end, precision BPMs are needed for the proton EDM experiments with a resolution of 5 pm, i.e., the system of beam-position monitors should be capable to detect the relative beam position between the counter-rotating beams at the 5 pm level. This is beyond the current state-of-the-art by several orders of magnitude. The separation depends on the vertical tune of the machine, which can be modulated in such a way that any signal will be present at a known frequency and thus will be easier to detect. The magnetic field due to a single beam with 10^{10} particles and velocity of $\beta = 0.6$ creates a magnetic field of order 1 mG at a distance of 1 cm. When counter-rotating beams with the same intensity are used and completely overlap, this magnetic field cancels exactly. However, if the beams do not overlap by about 5 pm in the vertical direction, a vertical magnetic field of about 0.1 pG will be created on top/bottom and left/right of the beam location. If the overlap is offset in the horizontal direction, the induced magnetic field is going to be in the horizontal direction.

Of course, such a magnetic field is very small and can be easily generated by other unforeseen effects. In order to avoid possible systematic errors, the vertical tune can be modulated, which will also modulate the 0.1 pG magnetic field at the same frequency. The solution is to first inject a single beam, and align the magnetometers in such a way that the total signal is zero. This method will also eliminate any systematic error sources. Next, the additional beam will be injected in the counter-rotating direction. Any remaining signal will then be an indication of the presence of a background radial B-field.

SQUID gradiometers are anticipated to detect this magnetic field. As an alternative option the use of optical magnetometers with vector B-field detection capability is foreseen. These two methods have different requirements but both of them would have the statistical capability of detecting the very small magnetic fields created by the non-overlap between the counter-rotating beams. Applying them to an accelerator environment will require a special effort in shielding them from the inherent electronic noise present there.

Task 9: Theoretical studies

Permanent electric dipole moments (EDMs) of elementary particles and nuclei are among the most promising potential signatures for CP-violating physics beyond the Cabibbo-Kobayashi-Maskawa (CKM) phase of the Standard Model. However, an experimental signal of a non-vanishing EDM of the neutron, say, would not suffice to pinpoint the specific mechanism (e.g., the theta-angle of QCD, supersymmetric extensions of the SM, Left-Right symmetric models, multi-Higgs scenarios, etc.)

responsible for this result. Thus information on the EDMs of the proton, the deuteron and the ^{3}He will prove crucial in unfolding the source of the CP violation, since the various mechanisms give different strengths to the isoscalar and isovector combinations of the one-nucleon and few-nucleon contributions, respectively. In addition, because of CP-violating nuclear forces, the EDMs of light nuclei might potentially be larger than the counter parts of individual nucleons.

The task of theoretical physics is to provide quantitative predictions of the above-mentioned EDM signals assuming specific input values for the parameter(s) of the potential CP-violating mechanics (e.g., for the QCD theta angle, the various SUSY phases etc.), such that eventually the direction of deduction may be inverted if sufficiently many independent experimental results will have been established.

Since the experimental EDM signals themselves belong to the low-energy realm of the Standard Model, low-energy theoretical tools are applicable, specifically the methods of low-energy effective field theory, which is a specialty of the Jülich Nuclear Theory group. Chiral Perturbation Theory (ChPT), the established low-energy effective field theory of QCD, together with chiral effective field theory, the generalization of ChPT to light nuclei, is the correct tool to describe quantitatively the hadronic EDMs resulting from the various CP-violating operators in terms of a systematic expansion in the quark masses, external momenta and derivatives of the operators. In fact, the Bonn, Groningen, Tucson, and Jülich theory groups have already started by analyzing the electric dipole form factors of the neutron and proton in the framework of ChPT, the QCD vacuum angle, and other alternatives for the underlying CP-violating operators. Moreover, systematic studies of the EDMs of the light nuclei, deuteron and ^{3}He, are presently being developed. It should be noted that most of the theoretical predictions of the EDMs of these nuclei have been based on phenomenological studies which do not allow estimating the uncertainties of the calculations – this holds especially for the case of ^{3}He.

The task of the Jülich theory group is, in a first step, a systematic expansion of the one-nucleon and two-nucleon contributions to the deuteron EDM in the framework of chiral effective field theory. As the deuteron does not carry any isospin, it serves already as a filter for the isospin-dependent contribution of the quark-color mechanism. In a second step, in order to identify the role of the theta-term contributions, the isospin-independent part of the quark-color mechanism and the quark EDM scenario this investigation must be generalized to nuclei composed of three nucleons, the tritium and the ^{3}He, to allow also for a simultaneous and systematical description of the isoscalar and isovector components of the CP-breaking nucleon-nucleon interaction.

In summary, the measurements of the EDMs of the neutron, proton, deuteron, and ^{3}He as well as the systematical theoretical analyses of these systems are necessary to understand the underlying physics. The IKP Theory group has an expertise and manpower to provide an adequate theoretical support for the EDM experiments at COSY.

c. Resources (incl. Project costs)

Presentation of the Team

Crucial for the success of the project is the composition of the team which reflects the areas of expertise required. What we are going to do within the duration of the project is beyond state-of-the-art and only a team of experienced scientist and engineers has a chance of being successful. It will be my duty as PI of the project to coordinate the tasks and the team members, and to scientifically lead/guide the efforts.

As principal investigator, I will devote a large fraction of my time ($> 60\%$) to the project, and I will instruct the core team at Jülich. Experiments are presently underway at COSY to determine for the first time the spin coherence time in a hadron machine. It should be emphasized here that all collaborating team members are absolutely vital for the success of the project.

COSY as a facility together with its staff is specialized on spin physics with strong emphasis on spin manipulation of stored cooled beams of protons and deuterons; and on a worldwide scale COSY is a unique location to pursue searches for EDMs of charged particles. There is already ongoing preparatory work for the next stage of spin coherence time studies using the strip line techniques and analyzing the requirements to radiofrequency magnetic spin rotators, capable to operate in a broad range of frequencies and in the flattop mode. The COSY accelerator theory group is active in developing a theoretical framework for EDM studies at COSY and has a good record of collaboration on this subject with the team at BNL.

The team members at BNL have a long standing experience with record precision storage ring experiments, such as the muon $(g-2)$ experiment. The group is presently working on the machine design for a pEDM ring, and possesses a large expertise in lattice studies. The RWTH-Aachen group (J. Pretz) is very experienced in large collaborations, in the research on the spin structure of the nucleon, and the measurement of the muon EDM of the BNL $(g-2)$ collaboration.

The MSU group is a holder of the world expertise on the COSY-INFINITY tracking tool, internationally acknowledged by an Honorary Doctoral degree from Saint Petersburg University, awarded for the mathematical basis of the algorithms in COSY-INFINITY, and by the R.E. Moore Prize for newest additions to COSY-INFINITY based on the solutions of flows or maps of ordinary differential equations, granted to the principal developer of COSY-INFINITY, M. Berz, also author of a monograph on “Modern Map Methods in Particle Beam Physics”, and of the forthcoming book on “An Introduction to the Physics of Beams”.

The key team members and their responsibilities are listed in the table below:

#	Task	Key persons
1	Management	H. Ströher (Jülich, Director Institute for Nuclear Physics 2) Y. Semertzidis (BNL, staff member) J. Pretz (RWTH-Aachen, III Physikalisches Institut)
2	Spin coherence time investigations at COSY	A. Lehrach (Jülich, staff member) B. Lorentz (Jülich, staff member)
3	Direct measurement of proton and deuteron EDM using RF-E flipper	A. Lehrach (Jülich, staff member) J. Pretz (RWTH-Aachen, III Physikalisches Institut) F. Rathmann (Jülich, staff member and PI of project)
4	Development of polarimeter concepts	J. Pretz (RWTH-Aachen, III Physikalisches Institut) A. Kacharava (Jülich, staff member)
5	Development of spin-tracking codes, based on COSY infinity and a custom-built simulation tool, including benchmarking	M. Berz (MSU, staff member) A. Lehrach (Jülich, staff member) Y. Semertzidis (BNL, staff member)
6	Systematic error studies	B. Morse (BNL, staff member) Y. Semertzidis (BNL, staff member)
7	Development of RF-E flipper system	R. Stassen (Jülich, staff member) R. Gebel (Jülich, staff member)
8	Beam-position monitors	V. Kamerdzhiev (Jülich, staff member) J. Pretz (RWTH-Aachen, III Physikalisches Institut)
9	Theoretical studies	A. Wirzba (Jülich, staff member) U.-G. Meißner (Jülich, Director Institute for Nuclear Physics 3)

Presentation of the status of the resources

Storage rings are being operated since half a century. All basic machine-related experimental and theoretical concepts and techniques are available and well established; now is the time to apply and commit this knowledge to the search for permanent electric dipole moments in storage rings. With the proposal, the work program towards storage ring based EDM searches is clearly defined; there are no principle show stoppers that would keep us from uncovering for the first time in history of science the scientific reason behind our existence, along with the determination of a proton or deuteron EDM different from zero. As the principal investigator, I would like to emphasize here that the time is ripe for this study.

The personnel applied for with this application would be based at Jülich, RWTH-Aachen, BNL, and MSU:

- Jülich would hire an experienced PostDoc for the duration of 5 years to contribute to the effort of performing a first direct EDM measurement of proton and deuteron employing COSY “as it is”. The PostDoc would be also involved on the development of spin-tracking and lattice simulation tools for present and future EDM storage ring studies.
- A PostDoc (5 years) would be hired at RWTH-Aachen to work in the group of J. Pretz on the development of an efficient polarimeter concept, capable to overcome the shortfall of present concepts that are incapable to measure the longitudinal beam polarization components.
- A five year PostDoc at BNL would devote a large part of his time on the development of the required precision beam-position monitors and magnetometers, and, assisted by the

experienced team around Y. Semertzidis, shall also work on the study of systematic errors for storage ring EDM experiments.

- A five year PostDoc at MSU working in the group of M. Berz would mainly be involved in the further development of the COSY-INFINITY, incorporating EDM kicks, RF-E and RF-B spin flipper devices, etc. Benchmarking against analytical simulation programs or integrating tracking codes is foreseen as well.

The Quest for the Unknown: Uncovering the reason for our existence

Searches for EDMs constitute extremely difficult high risk frontier experiments. As the very recent summary of delays with the next generation neutron EDM experiments at ORNL (Oak Ridge), PSI (Villigen), ILL (Grenoble) or in the January 31, 2012 article in Nature has put it, “Measuring the EDM could reveal clues to physics as profound as that sought at the Large Hadron Collider (LHC)... Unlike the LHC experiments, which rely on sheer energy, dipole measurements are so subtle and easily foiled that the three leading efforts are woefully behind schedule. Despite the problems, nuclear and particle physicists continue to express broad support for the neutron EDM studies, which they say are a unique complement to the LHC work. "It's a constellation of experiments that is critical," says Michael Ramsey-Musolf, a theoretical physicist at the University of Wisconsin-Madison.”

The aim of the proposal is to lay the foundation for EDM searches at storage rings, so that in a next step, the concrete work of building dedicated storage rings for EDM searches for protons, deuterons, and ^{3}He can be tackled. COSY with its experienced crew will be operational for the duration of the project to perform all the necessary tests, eventually leading to the first direct measurement of the EDMs of proton and deuteron. It is obvious that at a later stage of all possible sites worldwide to host a dedicated EDM machine, COSY is ideally suited to serve both as a site to benchmark new equipment, and, later on, as an injector srEDM experiments, providing polarized beams of protons, deuterons, and at later stage, also ^{3}He..

The present project involves both a tremendous challenge and an exceptional opportunity, which has the full backing of the management of IKP and FZJ as a possible future perspective of the institute. The role of the ERC Advanced Grant, if approved, will be a decisive step towards establishing COSY-Jülich as the leading hadron spin-physics laboratory in Europe. **At the same time, the present proposal provides an international flagship project of highest visibility for Europe: *The scientific prospects of finding a permanent EDM of protons or deuterons are absolutely terrific and spectacular.*** And yes, to the best of our knowledge, it can be done!

Project costs:

A summary of the costs over the five years duration of the project is presented in the following table. All listed costs of subcontracting for the different institutions address the audits.

	Cost Category	**Month 01-18**	**Month 19-36**	**Month 37-54**	**Month 55-60**	**Total (M1-60)**
Direct Costs:	*Personnel:*					
	PI Dr. F. Rathmann (60%)	74376	75867	81514	29923	261678
	Senior Staff JÜLICH	127502	130058	133325	44884	435768
	Post docs					
	RWTH-Aachen (J. Pretz)	91255	93085	95423	32124	311887
	BNL (Y. Semertzidis)	139126	140146	151069	49643	479985
	MSU (M. Berz)	138476	139494	150395	49420	477785
	Total Personnel:	570734	578649	611727	205994	1967103
	Other Direct Costs:					
	Consumables					
	JÜLICH	1500	1500	1500	500	5000
	RWTH-Aachen (J. Pretz)	1500	1500	1500	500	5000
	BNL (Y. Semertzidis)	1500	1500	1500	500	5000
	MSU (M. Berz)	1500	1500	1500	500	5000
	Travel					
	JÜLICH	7500	7500	7500	2500	25000
	RWTH-Aachen (J. Pretz)	5250	4750	4500	1500	16000
	BNL (Y. Semertzidis)	6000	6000	6000	2000	20000
	MSU (M. Berz)	4500	4500	4500	1500	15000
	Total Other Direct Costs:	29250	28750	28500	9500	96000
	Total Direct Costs:	599984	607399	640227	215494	2063103
Indirect Costs (overheads):	Max 20% of Direct Costs	119997	121480	128045	43099	412621
Subcontracting Costs: Jülich	(by reporting period and total)	0	3000	1500	1500	6000
Subcontracting Costs: RWTH	(by reporting period and total)	0	3000	1500	1500	6000
Subcontracting Costs: BNL	(by reporting period and total)	0	3000	1500	1500	6000
Subcontracting Costs: MSU	(by reporting period and total)	0	3000	1500	1500	6000
Total Costs of project:	(by reporting period and total)	719981	740879	774272	264592	2499724
Requested Grant:		719981	740879	774272	264592	2499724

For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:	**60%**

Specify briefly your commitment to the project and how much time you are willing to devote to the proposed project in the resources section.

Please note that you are expected to devote at least 30% of your total working time to the ERC-funded project and spend at least 50% of your total working time in an EU Member State or Associated Country (see ERC Work Programme 2012).

d. Ethical and security-sensitive issues

ETHICS ISSUES TABLE

Areas Excluded From Funding Under FP7 ***(Art. 6)***

(i) Research activity aiming at human cloning for reproductive purposes;

(ii) Research activity intended to modify the genetic heritage of human beings which could make such changes heritable (Research relating to cancer treatment of the gonads can be financed);

(iii) Research activities intended to create human embryos solely for the purpose of research or for the purpose of stem cell procurement, including by means of somatic cell nuclear transfer;

All FP7 funded research shall comply with the relevant national, EU and international ethics-related rules and professional codes of conduct. Where necessary, the beneficiary(ies) shall provide the responsible Commission services with a written confirmation that it has received (a) favourable opinion(s) of the relevant ethics committee(s) and, if applicable, the regulatory approval(s) of the competent national or local authority(ies) in the country in which the research is to be carried out, before beginning any Commission approved research requiring such opinions or approvals. The copy of the official approval from the relevant national or local ethics committees must also be provided to the responsible Commission services.

	Research on Human Embryo/ Foetus	YES	Page
	Does the proposed research involve human Embryos?		
	Does the proposed research involve human Foetal Tissues/ Cells?		
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?		
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?		
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

	Research on Humans	YES	Page
	Does the proposed research involve children?		
	Does the proposed research involve patients?		
	Does the proposed research involve persons not able to give consent?		
	Does the proposed research involve adult healthy volunteers?		
	Does the proposed research involve Human genetic material?		
	Does the proposed research involve Human biological samples?		
	Does the proposed research involve Human data collection?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

	Privacy	YES	Page
	Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?		
	Does the proposed research involve tracking the location or observation of people?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

	Research on Animals[4]	YES	Page
	Does the proposed research involve research on animals?		
	Are those animals transgenic small laboratory animals?		
	Are those animals transgenic farm animals?		
	Are those animals non-human primates?		
	Are those animals cloned farm animals?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

	Research Involving non-EU Countries (ICPC Countries[5]) [6]	YES	Page
	Is the proposed research (or parts of it) going to take place in one or more of the ICPC Countries?		
	Is any material used in the research (e.g. personal data, animal and/or human tissue samples, genetic material, live animals, etc) : a) Collected in any of the ICPC countries?		
	b) Exported to any other country (including ICPC and EU Member States)?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

	Dual Use	YES	Page
	Research having direct military use		
	Research having the potential for terrorist abuse		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	yes	

If any of the above issues apply to your proposal, you are required to complete and upload the "B2_Ethical Issues Annex" (template provided).

Without this Annex, your application cannot be properly evaluated and even if successful the granting process will not proceed.
Please see the Guide for Applicants for the Advanced Grant 2012 Call for further details and CORDIS http://cordis.europa.eu/fp7/ethics_en.html for further information on how to deal with Ethical Issues in your proposal.

[4] The type of animals involved in the research that fall under the scope of the Commission's Ethical Scrutiny procedures are defined in the Council Directive 86/609/EEC of 24 November 1986 on the approximation of laws, regulations and administrative provisions of the Member States regarding the protection of animals used for experimental and other scientific purposes Official Journal L 358 , 18/12/1986 p. 0001 - 0028

[5] In accordance with Article 12(1) of the Rules for Participation in FP7, 'International Cooperation Partner Country (ICPC) means a third country which the Commission classifies as a low-income (L), lower-middle-income (LM) or upper-middle-income (UM) country. Countries associated to the Seventh EC Framework Programme do not qualify as ICP Countries and therefore do not appear in this list.

[6] A guidance note on how to deal with ethical issues arising out of the involvement of non-EU countries is available at: ftp://ftp.cordis.europa.eu/pub/fp7/docs/developing-countries_en.pdf