COSY Proposal / Letter of Intent / Beam Request

For Lab. use

Exp. No.: 216	Session No. 40

Title of Experiment: **Search for Permanent Electric Dipole Moments at COSY**
Step 1: Spin coherence and systematic error studies

Collaborators: JEDI collaboration
Jülich **E**lectric **D**ipole Moment **I**nvestigations

Institute:

(Continue on separate sheet if necessary)

Spokesperson for collaboration: Name: **PD Dr. Andreas Lehrach**
PD Dr. Frank Rathmann
Prof. Dr. Jörg Pretz

Address:

Andreas Lehrach, Frank Rathmann
Institut für Kernpyhsik
Forschungszentrum Jülich
Leo-Brand Str.
52425 Jülich, Germany

Jörg Pretz
III. Physikalisches Institut
Physikzentrum 26C 212
RWTH Aachen
52056 Aachen, Germany

Is support from the LSF program of the EC requested?
~~Yes~~ No

Date: **10.04.2012**

Phone: +49 2461-616453 Fax: +49 2461-612356 E-mail: a.lehrach@fz-juelich.de
Phone: +49 2461-614558 Fax: +49 2461-612356 E-mail: f.rathmann@fz-juelich.de
Phone: +49 241 8027306 Fax: +49 241 8022244 E-mail: pretz@physik.rwth-aachen.de

Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second): minimum needed	Intensity or internal reaction rate (particles per second): maximum useful
5×10^8 / fill Vector polarized	0.5-3 GeV/c	3×10^8/store	10^9/store
Type of target	**Safety aspects (if any)**	**Earliest date of installation**	**Total beam time (weeks)**
EDDA Polarimeter with new read-out electronics	none	Fall 2012	EDM weeks

What equipment, floor space etc. is expected from Forschungszentrum Jülich/IKP?

EDDA polarimeter with new read-out electronics
Electron cooling at full energy
Installation and commissioning of new RF-B Spin Flipper

Summary of experiment (do not exceed this space):

Permanent EDMs (Electric Dipole Moments) of fundamental particle violate both time invariance and parity. Assuming the CPT theorem this implies CP violation. The standard model predicts non-vanishing EDMs; however, their magnitudes are expected to be unobservably small. Hence, discovery of a non-zero EDM would be a signal for “new physics”.

EDM experiments with charged particles are only possible at storage rings. As a first step towards EDM searches in storage rings, pursued by the recently founded JEDI collaboration, we propose research and development work to be carried out at COSY to maximize the spin coherence time and to reduce systematic spin rotations.
Both aspects focus on the first direct EDM measurement of a charged particle in a storage ring at COSY at the level of approximately 10^{-24} e·cm and on a longer time scale to reach an even higher sensitivity constructing a dedicated storage ring.

Attach scientific justification and a description of the experiment providing the following information:
For proposals:
Total beam time (or number of particles) needed; specification of all necessary resources
For beam requests:
Remaining beam time (allocations minus time already taken)

Scientific justification:
What are you trying to learn?
What is the relation to theory?
Why is this experiment unique?

Details of experiment:
Description of apparatus.
What is the status of the apparatus?
What targets will be used and who will supply them?
What parameters are to be measured and how are they measured?
Estimates of solid angle, counting rate, background, etc., and assumptions used to make these estimates.
Details which determine the time requested.
How will the analysis be performed and where?

General information:
Status of data taken in previous studies.
What makes COSY suitable for the experiment?
Other considerations relevant to the review of the proposal by the PAC.

EC-Support:
The European Commission supports access of new users from member and associated states to COSY. Travel and subsistence costs can be granted in the frame of the program Access to Large Scale Facilities (LSF).

Proposal

Search for Permanent Electric Dipole Moments at COSY

Step 1: Spin coherence and systematic error studies

($\mathcal{JEDI}$ Collaboration)

Jülich, May 2, 2012

submitted to the COSY Program Advisory Committee

Proposal

Search for Permanent Electric Dipole Moments at COSY

Step 1: Spin coherence and systematic error studies

($\mathcal{JEDI}$ Collaboration)

Abstract

Permanent EDMs (Electric Dipole Moments) of fundamental particle violate both time invariance and parity. Assuming the CPT theorem this implies CP violation. The standard model predicts non-vanishing EDMs, their magnitudes, however, are expected to be unobservably small. Hence, the discovery of a non-zero EDM would be a signal for "new physics".

EDM experiments with charged particles are only possible at storage rings. As a first step towards EDM searches in storage rings, pursued by the recently founded JEDI collaboration, we propose research and development work to be carried out at COSY to maximize the spin coherence time and to reduce systematic spin rotations. Both aspects focus on a first direct measurement of a charged particle EDM in a storage ring at COSY aiming at an upper limit of $\approx 10^{-24}$ e·cm, and on a longer time scale to reach an even higher sensitivity constructing a dedicated storage ring.

Spokespersons:

Andreas Lehrach
Institut für Kernphysik, Jülich Center for Hadron Physics
Forschungszentrum Jülich, 52428 Jülich, Germany
email: `a.lehrach@fz-juelich.de`

Jörg Pretz
III. Physikalisches Institut
RWTH Aachen, 52056 Aachen, Germany
email: `pretz@physik.rwth-aachen.de`

Frank Rathmann
Institut für Kernphysik, Jülich Center for Hadron Physics
Forschungszentrum Jülich, 52428 Jülich, Germany
email: `f.rathmann@fz-juelich.de`

JEDI collaboration

R. Engels, O. Felden, M. Gaisser, R. Gebel, F. Goldenbaum, D. Grzonka, C. Hanhart, A. Kacharava, V. Kamerdzhiev, S. Krewald, A. Lehrach, B. Lorentz, R. Maier, S. Martin, A. Nass, N. Nikolaev, A. Nogga, F. Rathmann, J. Ritman, Y. Senichev, H. Seyfarth, H. Stockhorst, H. Ströher, A. Wirzba, E. Zaplatin, and D. Zyuzin
Institut für Kernphysik, Jülich Center for Hadron Physics, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

P. Benati, S. Bertelli, C. Ciullo, M. Contalbrigo, M. Fiorini, G. Guidoboni, P. Lenisa, D. Oellers, L. Pappalardo, A. Pesce, M. Statera, and C. Weidemann
Universita di Ferrara and INFN, 44100 Ferrara, Italy

D. Chiladze, N. Lomidze, D. Mchedlishvili, M. Nioradze, and M. Tabidze
High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia

A. Dzyuba, K. Grigoryev, P. Kravtsov, and A. Vasilyev
St. Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia

A. Kulikov, V. Kurbatov, G. Macharashvili, and Yu. Uzikov
Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980 Dubna, Russia

W. Bernreuther, D. Eversmann, J. Pretz, and A. Stahl
III. Physikalisches Institut, RWTH Aachen, 52056 Aachen, Germany

F.M. Esser, H. Glückler, and H. Soltner
Zentralabteilung Technologie, Jülich Center for Hadron Physics, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

U.-G. Meißner and Y. Valdau
Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany

M. Berz
Michigan State University, East Lansing, MI 48824, USA

A. Khoukaz
Institut für Kernphysik, Universität Münster, 48149 Münster, Germany

A. Polyanskiy
Institut for Experimental and Theoretical Physics, 117218 Moscow, Russia

A. Silenko
Research Institute for Nuclear Problems, Belarusian State University, Minsk 220080, Belarus

R. Talman
Cornell University, Ithaca, NY 14853, USA

P. Thörngren Engblom
AlbaNova University Center, Royal Institute of Technology, Physics Department, SE-106 91 Stockholm, Sweden

C. Wilkin
Physics and Astronomy Department, UCL, London WC1E 6BT, United Kingdom

P. Zupranski
Department of Nuclear Reactions, Andrzej Soltan, Institute for Nuclear Studies, 00-681, Warsaw, Poland

Contents

1 Executive Summary

Although extremely successful in many aspects, the Standard Model of Particle Physics is not capable of explaining the apparent asymmetry in abundance of matter and antimatter 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 yrs).

It is essential to perform EDM measurements on different particles 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 direct measurements have been conducted yet for protons and other light nuclei due to special difficulties of applying electric fields on charged particles. It should be noted that EDM measurements of proton, deuteron, and ^{3}He nucleus could be performed in one and the same storage ring. 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. It is based on extensive work of the COSY EDM Study Group in 2011-2012 [1].

As a first step, we propose here research and development work to be carried out at COSY to maximize the spin coherence time and to reduce unwanted spin rotations induced by the magnetic moment. This includes:

i) measurements of the dependence of spin coherence time on the wave form applied to the horizontal RF–B spin flipper at different spin harmonics and beam energies for protons and deuterons,

ii) systematic studies of unwanted spin rotations utilizing a vertical RF–B field and investigations of unwanted spin rotations as a function of closed-orbit excitation and fluctuations, quadrupole magnet alignment and ring impedances.

We are planing to use a polarized proton and deuteron beam in a momentum range of $p \approx 0.5 - 3$ GeV/c and the EDDA detector system with modifications to target and electronics. This first step of the proposal concentrates on the studies mentioned above. Based on the results of these studies the second step will be prepared, focusing on the first direct measurement of an EDM of a charged particle with a sensitivity of $\approx 10^{-24} e$cm.

The directorate of the IKP and the management of Forschungszentrum Jülich strongly support this project. A collaboration with RWTH Aachen is established as well and will hopefully be extended in the framework of the "Exzellenzinitiative" (JARA-FAME). The tentatively estimated total amount of beam time to perform the research studies to start a first direct measurement amounts to about 12 weeks in total until end of 2014. We would like to ask the PAC for a scientific assessment of the physics case in general and the suggested stepwise approach using COSY.

We will also appreciate any further suggestion and advice. We intend to coordinate our project closely with the PAC and keep it informed about our progress and the future plans. The requested beam time is covered by the directorate's discretion beam time ("EDM weeks") foreseen for the rest of this year and 2013.

2 Physics case

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 $\approx 10^{-29}$ 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.

2.1 Motivation

Baryogenesis and Electric Dipole Moments of nucleons 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-antimatter 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 parametrized by the phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The SM, although extremely successful in many aspects, fails miserably in explaining the dominance of matter over anti-matter. Simultaneously, the SM predicts an exceedingly small electric dipole moment of nucleons of 10^{-33} e·cm $< d_N < 10^{-31}$ e·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 $d_N \approx 10^{-25}$ e·cm [4]. Indeed, a very crude, dynamics-short, estimate for the EDM of nucleons is a nuclear magneton times $\sim 10^{-7}$ (for parity violation) times $\sim 10^{-3}$ (for CP violation), *i.e.*, $d_N \approx 10^{-24}$ e·cm. 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 $\approx 0.01 \cdot (1\,\mathrm{TeV}/\Lambda_{\mathrm{NP}})^2 \cdot \tan\Phi_{\mathrm{NP}}$, where Φ_{NP} is the CP-violation angle, and Λ_{NP} is an energy scale for **N**on-SM **P**hysics. 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 $\approx (1\,\mathrm{TeV}/\Lambda_{\mathrm{NP}})^2 \cdot \tan\Phi_{\mathrm{NP}} < 10^{-7}$ [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 ultra-cold 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.

This ultimate goal for protons and deuterons will be realized at a later stage in a dedicated storage ring (we do not dwell further into details within the framework of the proposal presented here.

2.2 Current EDM Limits

In Table 1, 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 searches could at least be one order of magnitude more sensitive than currently planned neutron EDM experiments at SNS (Oak Ridge), ILL (Grenoble-France), and PSI (Villigen, Switzerland).

Particle	Current Limit	Goal	d_n equivalent	reference
Neutron	$< 2.9 \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	[6]
^{199}Hg	$< 3.1 \times 10^{-29}$	10^{-29}	10^{-26}	[7]
^{129}Xe	$< 6.0 \times 10^{-27}$	$\approx 10^{-30} - 10^{-33}$	$\approx 10^{-26} - 10^{-29}$	[8]
Proton	$< 7.9 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	[7]
Deuteron		$\approx 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-31}$	

Table 1: 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 the EDM value for the neutron to provide the same physics reach as the indicated system.

We emphasize that the above cited tentative upper bound for the proton EDM as part of a nucleus in an electrically neutral atom, $|d_p| < 7.9 \times 10^{-25}$ e·cm, derives from the theoretical reinterpretation of the upper bound for the EDM of ^{199}Hg [7]; there are no direct experimental data available on either proton or deuteron EDMs.

Before embarking into the endeavor of designing and constructing dedicated, special-purpose electrostatic and/or combined magnetic-electrostatic storage rings, one needs to improve by orders in magnitude the present understanding of spin dynamics and systematics. Here, COSY stands out as a unique facility on a worldwide scale that is ideally for such benchmarking studies. In the present proposal, we argue that a **first direct measurement** of the proton and deuteron EDMs with a sensitivity of $d_{p,d} \approx 10^{-24}$ e·cm is feasible with COSY essentially as it is, and as discussed above, the sensitivity aimed for with the present proposal is already in the ballpark of existing theoretical expectations.

3 Experimental method to measure EDMs in storage rings

The point about measuring EDMs in storage rings is that while magnetic dipole moments (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. Only electrically neutral atoms and neutrons can be held in traps, placing a charged particle in an electric field region becomes more challenging since the electric force will act on it, and this 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 a steering field the radial electric field is employed. Simultaneously, the same electric field provides the EDM signal that we are looking for. 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

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} + \vec{\mu} \times \vec{B} = \vec{\omega} \times \vec{s}\,. \tag{1}$$

Note that $\vec{d}$ is parallel to the spin vector $\vec{s}$. For particles with spin-$\frac{1}{2}$ (protons), $\frac{d\vec{s}}{dt} = \frac{1}{2} \cdot \hbar\vec{\omega}$, and for spin-1 particles (deuterons), $\frac{d\vec{s}}{dt} = 1 \cdot \hbar\vec{\omega}$, respectively. (Here we indicated rest frame equations; the full BMT formalism is redundant here.)

In this section we outline experimental methods to measure EDMs in storage rings starting with an approach to measure EDMs of protons and deuterons at COSY with an RF-E Flipper. The COSY measurement will be an intermediate step with a sensitivity of roughly 10^{-24}ecm towards the design of a dedicated storage ring discussed in Sec. 3.2.

3.1 Method proposed for COSY

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 $10^{10} - 10^{11}$, 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 $\alpha = 2.4 \times 10^{-12}$ rad 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. The mathematical derivations can be found in the App. A. 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 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.

3.2 Method proposed for dedicated rings

The proposed method, primarily developed at BNL, employs radial electric fields (for deuterons and ^{3}He, also magnetic fields) to steer the particle beam in the dedicated storage ring [9, 10].

BNL is pursuing the proposed proton EDM with a purely electrostatic bending field whereas the feasibility of an "All-In-One" lattice design with combined electrostatic and magnetic field deflectors is investigated in Jülich to perform a deuteron or helium-3 EDM experiment, which is complimentary to the proton EDM measurement. These design will even reach a higher sensitivity than the first direct measurement proposed at COSY.

The idea worked out at BNL is to search for EDMs using the radial electric steering field of the ring [9, 10]. The method is most sensitive when the spin vector is kept along the momentum vector for the duration of the storage and the EDM signal is a vertical polarization which builds up because of the EDM induced precession of the spin out of the ring plane. Magnetic or electric quadrupole magnets form a weak focusing lattice and internal polarimeters probe the particle spin state as a function of storage time [11]. An RF cavity and sextupole magnets will be used to prolong the spin coherence time (SCT) of the beam. For protons, $\frac{g-2}{2} = G_p = 1.793$ is positive, thus in a purely electric machine at the so-called magic momentum of 0.7 GeV/c (232 MeV), the $(g-2)$ precession is zero, *i.e.*, the spins are always aligned along the momentum vector. A realization of the frozen spin regime for deuterons and helions call upon a combination of electric and magnetic steering fields, as indicated in Table 2.

The spins of vertically polarized protons injected into the EDM ring can be rotated

Particle	p (GeV/c)	E (MV/m)	B (T)
Proton	0.701	16.8	0
Deuteron	1.000	-4.03	0.16
^{3}He	1.285	17.0	-0.051

Table 2: Parameters for the transverse electric and magnetic fields required to freeze the spin in an EDM storage ring of radius $r = 30\,\mathrm{m}$.

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.

4 Strategy towards a first direct EDM measurement at COSY

The strategy towards a first direct EDM measurement contains preparatory measurements at COSY, development of simulation tools and a dedicated hardware:

1. Experimental and theoretical studies of the spin coherence time (SCT) in COSY,
2. investigation of systematic effects,
3. development of a precision simulation program for spin dynamics in a storage ring,
4. Polarimetry,
5. development of an RF-E flipper system capable to operate at electric fields around 1 MV/m.

These developments will lead to a first direct measurement of proton and deuteron EDMs at COSY with a statistical sensitivity goal of about $d = 10^{-24}$ e·cm. They will be outlined below with an emphasis on the first two items.

4.1 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 minuscule angle $10^{-13} - 10^{-12}$ rad 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 cancelation of the two principal decoherence mechanisms at judiciously chosen beam energies and RF-E flipper harmonics [1]. 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.

There is a perfect analogy between the EDM driven precession of the spin in an electric field and the magnetic moment (MDM) driven precession in a magnetic field. This analogy provides a unique way for diagnostics of unexplored aspects of spin precession in the COSY ring. A broad-band RF-B spin flipper has to be utilized to have the capability to apply magnetic fields with different wave forms and over a wide frequency range (roughly 80 kHz to 1 MHz). The required integral field strength depend on the momentum spread of the beam and will roughly be 0.025 $(\mathrm{T\,mm})^{-1}$. The intended system is able to deliver an RF B-Field over a wide frequency range and is based on a strip line design (transverse electromagnetic (TEM) transmission line).

Spin coherence time will be studied with different wave forms applied to the RF-B spin flipper at different spin harmonics and beam energies for protons and deuterons. For this part a horizontal RF-B field is required. The goal is to get optimum setting of the RF-B field for maximum spin coherence time to increase the statistical sensitivity of the final EDM measurement at COSY. Fig. 1 shows the dependence of spin coherence time for different wave forms applied to the RF–B flipper at different spin harmonics and beam energies for protons and deuterons. In this calculations an ideal COSY ring is assumed. The SCT of the idle precession (without RF–B flipper on) will limit the observable spin coherence time with spin flipper on. To perform these studies the SCT without RF–B flipper has to be optimized by means of a phase-space cooling and multipole correction. This is the main goal of the EDM@COSY proposal (spokespersons Ed Stephenson, P. Lenisa).

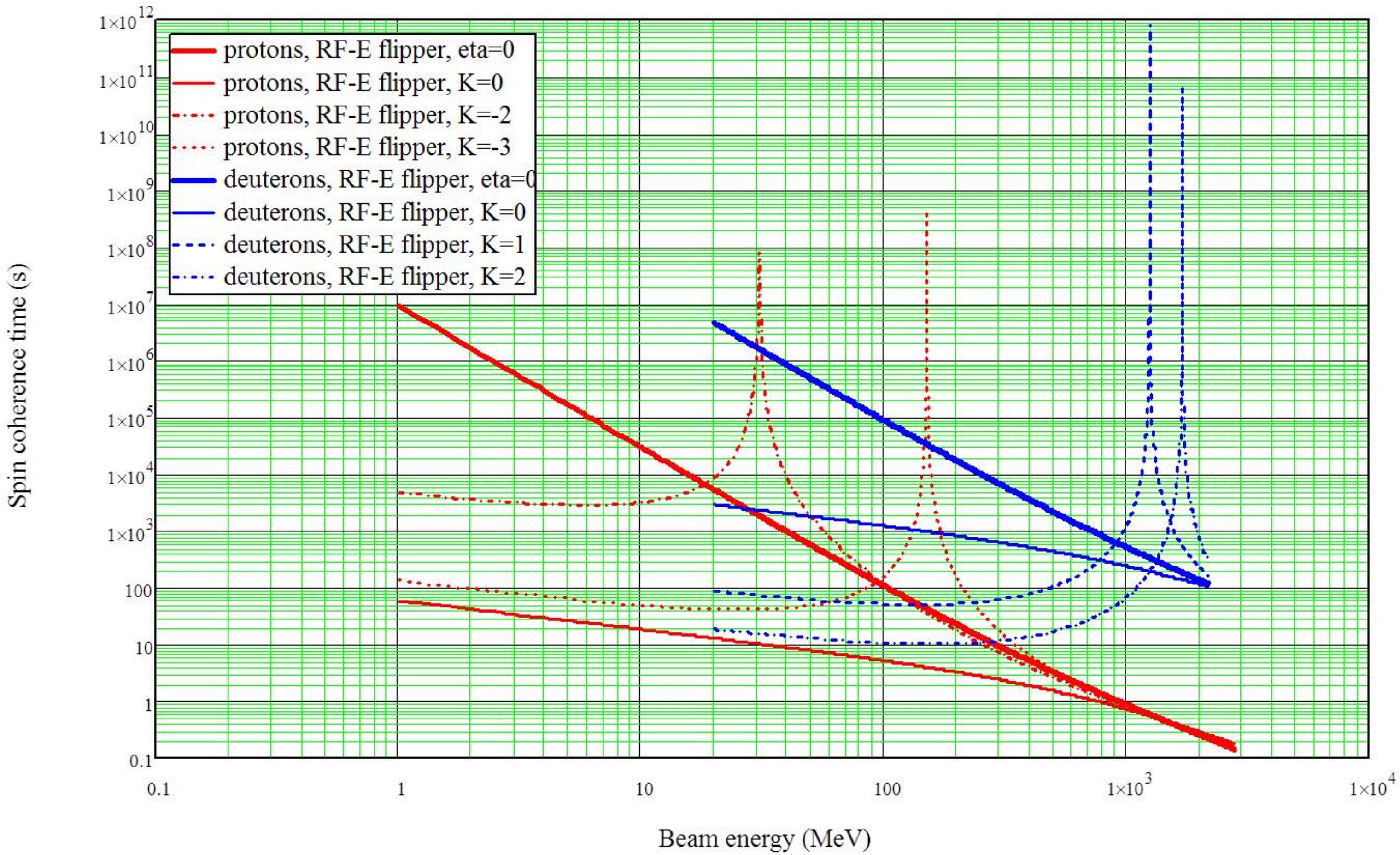

Figure 1: Pattern of the energy, RF-E flipper harmonics, and modulation mode, dependence of the spin coherence time for protons and deuterons as suggested by Eq. (24) in App. A at $\delta p/p = 10^{-4}$. The thick solid lines are for the flattop mode, which amounts to $\eta = 0$. For 100 MeV deuterons the flattop mode offers an enhancement of the SCT by about two orders in magnitude. In the first test run with 270 MeV deuterons we expect an enhancement of the SCT by approximately one order in magnitude from one harmonic to the other and to the flattop mode. (For more details see appendix.)

4.2 Investigations of systematic effects

Studies with vertical RF-B Field

Main sources of systematic errors are the alignment of the RF-B fields with respect to the invariant spin field, opening angle of spin ensemble (action angle), and field quality (fringe fields) of the RF-B field.

First the alignment angle of the RF-B flipper will be modified to investigate and suppress false spin rotations. After that beam cooling and heating will be applied to change the opening angle of the spin ensemble.

Investigations for a required COSY upgrade

It is obvious that a substantial improvement of COSY is required in order to reach the desired EDM sensitivities. False spin rotations as a function of closed-orbit excitation, quadrupole alignment and ring impedances will be studied. The aim of this part is to reduce systematic errors and the results will be the bases to specify the required COSY upgrade (orbit correction system – steerer and BPMs, power supply stability, magnet alignment and ring impedances):

- 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. Systematic errors of the orbit measurement (e.g., temperature drift, beam current dependence) have to be studied in detail. In particular, a precise adjustment of the quadrupole and sextupole magnets is mandatory, and the BPMs have to be aligned with respect to the magnetic axis of these magnets. The geodetic alignment of COSY magnets has to be verified. Compensation of phase space coupling and multipole correction to high accuracy is absolutely crucial. Methods of orbit-response matrix, local orbit bumps, turn-by-turn orbit measurements, and beam-based orbit alignment have to be applied to significantly increase the precision of orbit control and knowledge of machine imperfections.

- 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.

- 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.

4.3 Development of a precision simulation program for spin dynamics

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 for the Jülich supercomputer is starting in May 2012. 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 dedicated storage ring has to be optimized by a full simulation of spin motion.

4.4 Polarimetry

For the studies described above the existing EDDA polarimeter will be used. The development of high precision polarimetry with highest attainable degree of stability for long measurement times over the COSY energy range will be pursued as well.

4.5 Development of an RF-E flipper

An RF-E 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 $\gamma \cdot G + k$. Test experiments with a pure magnetic field are planned to investigate and optimize the spin coherence time in COSY.

4.6 Timing of Activities

We expect that a series of runs with polarized protons and deuterons is needed in 2013/2014 to investigate spin coherence time and systematic errors. This investigations will require a horizontal and vertical RF-B field and the orbit correction system at COSY.

- In a first step a RF-B spin flipper was installed in COSY and coherence beam oscillations could be observed (week 13 of 2012).
- In a second step in week 20/21 the RF system will be commissioned with polarized beams.
- The aim of the first measurements in 2013 is to study SCT as a function of different wave forms, beam energy and harmonics of spin excitation.
- A second beam time period in 2013/14 will be dedicated to investigations of false rotations of a vertical RF-B field.

- Additional beam time is needed in 2014 to study systematic errors by the COSY ring elements and adjustment.

A Detailed Outline of proposed method

A.1 EDM at COSY: reversing the rôle of vertical and horizontal polarizations

In a future dedicated storage ring with a steering sideways electric field, the EDM signal is a precession of the initially frozen longitudinal spin out of the ring plane. Here, we suggest to supplement the purely magnetic storage ring COSY (ring magnetic field $\vec{B}$) with a radio-frequency electric spin flipper (RF-E flipper) placed in a section where $\vec{B} = 0$. A non-vanishing EDM, $\vec{d} = ed\vec{S}$, gives rise to the precession of the spin $\vec{S}$ in an electric field $\vec{E}$ with angular velocity $\omega_{\rm EDM} = edE$. A single pass through the flipper of length L with a sideways electric field $\vec{E}$ would tilt the initial vertical spin $\vec{S} \parallel S_y$, and generate a CP-violating component of the spin in the ring plane, $\Delta S_z = S_y \cdot \alpha$, where $\alpha = dEL/\beta c$. The system of coordinates is shown in Fig. 2. The corresponding change of the horizontal polarization per pass equals

$$\Delta S_{\parallel} = \sqrt{(S_z + \Delta S_z)^2 + S_x^2} - \sqrt{(S_z^2 + S_x^2)} = \frac{S_z}{S_{\parallel}} \Delta S_z = S_y \cdot \alpha \cdot \cos(\theta)\,, \qquad (2)$$

where θ is the angle of the horizontal spin with respect to the particle momentum. To

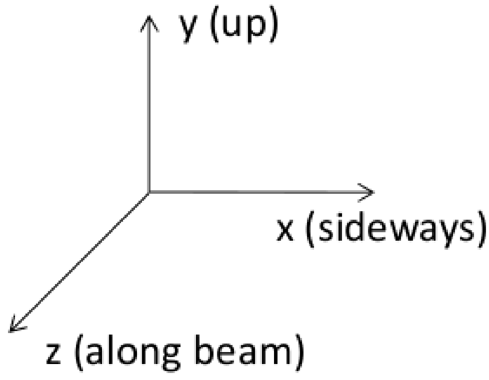

Figure 2: System of coordinates, the beam moves in z direction, the y-axis is vertical, and the x-axis is sideways.

appreciate the complexity of the task, for a beam of deuterons with $T = 100$ MeV, a RF-E flipper of length $L = 1$ m, a realistic electric field of $E = 15$ kV/cm, and $d = 10^{-23}$ e·cm, one finds $\alpha = 2.4 \cdot 10^{-12}$ rad (see Fig. 3). This entails that an observable CP-violating polarization of several per cent can only be accumulated at the expense of $\sim 10^{11}$ turns during $\sim 10^5$ s. Hence the crucial issue is to establish a possibility of maintaining a large in-plane spin coherence time, which is a principal risk factor in all storage ring EDM (srEDM) projects. Here we emphasize that the coherence and long-time preservation of the vertical polarization in a storage ring is the goal for most experiments with polarized beams, while up to now, no one payed attention to the horizontal components of the spin (see Fig. 4).

The spread of the spin precession rate may evolve the initial spin arrows into a spin hedgehog,) with a vanishing average horizontal polarization (see panel d) of Fig. 4). The issues which must be addressed before launching an actual EDM experiment are

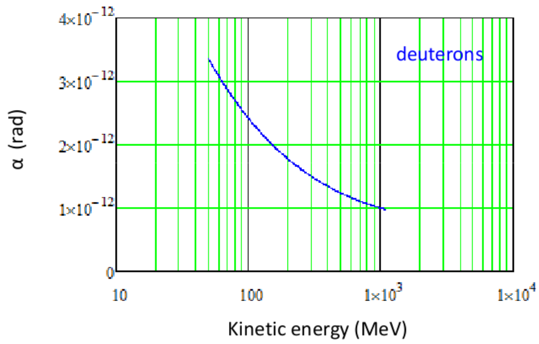

Figure 3: Energy dependence of the angle tilt per turn, α, in the RF-E flipper in the range accessible with COSY induced by an assumed deuteron EDM of $d = 10^{-23}$ e·cm.

a) how long is the horizontal spin coherence time, and

b) how it is affected by the RF-E flipper in the process of accumulation of the EDM signal.

In a dedicated electrostatic or combined electrostatic/magnetic ring, the radial static electric field causes an EDM driven rotation of the spin out of the machine plane, and this leads to the buildup of a (small) vertical polarization as function of time. This buildup can only accumulate as long as the in-plane polarization does not decohere (see Fig. 4). There are two important changes from the dedicated electrostatic (or combined electrostatic/magnetic) ring with frozen longitudinal spin. Firstly, the rôles of the vertical and horizontal spins are inverted. Secondly, in magnetic storage rings, the spin $\vec{S}$ precesses in the magnetic field of the machine with respect to the momentum vector with a frequency $f_S = \gamma G f_{\rm R}$, *i.e.*, by an angle $\theta_S = 2\pi\gamma G$ per revolution, where G is the anomalous magnetic moment and $f_{\rm R}$ is the ring frequency.

The crucial rôle of this spin precession is obvious already from Eq. (2). If the electric field of the flipper and the tilt angle α were kept constant, upon k turns the spin precession angle $\theta = k\theta_S$ would change $\Delta S_{||}$ in Eq. (2) from increment to decrement and so forth, and therefore, the net effect will be tiny oscillations of the horizontal spin around zero, as indicated in panel a) of Fig. 5.

Coherent accumulation occurs, though, if the RF-E flipper field oscillates in exact lock to the spin precession.

Specifically, for a harmonic modulation, $E = E_0\cos(l\theta_{\rm F}) = E_0\cos(\theta_{\rm F} f_{\rm R} t)$, where l is the number of periods of the RF-E flipper, *i.e.*, for tilt angles $\alpha = \alpha_E\cos(\theta_{\rm F} f_{\rm R} t)$, upon k turns,

$$S_{||}(t) = S_y \sum_{l=1}^{k} \alpha_E \cos(l\theta_S)\cos(l\theta_{\rm F}) = \frac{1}{2}\sum_{l=1}^{k}\left[\cos(l(\theta_S - \theta_{\rm F})) + \cos\left(l(\theta_S + \theta_{\rm F})\right)\right]\,, \qquad (3)$$

The coherent buildup of the CP-violation signal requires $\theta_{\rm F} = \pm\theta_S + 2\pi K$, *i.e.*,

$$f_{\rm F} = f_S \pm K f_{\rm R} = (\gamma G \pm K) f_{\rm R}\,, \qquad (4)$$

where K is an integer. (As a matter of fact, Eq. (4) is the standard condition for spin rotators.) In Fig. 6, a range of RF-E flipper frequencies for 100 MeV protons and deuterons

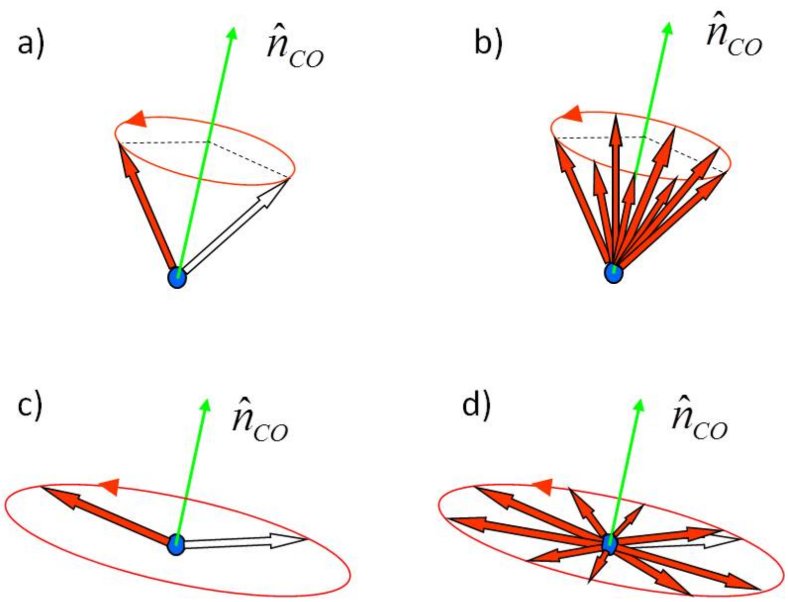

Figure 4: In experiments involving polarized beams in storage rings, one usually does not worry about the coherence of spins along the closed-orbit vector $\hat{n}_{\rm CO}$. Shortly after injection, as shown in panel a), all spin vectors are aligned (coherent). After some time, the spin vectors get out of phase and fully populate the cone, as shown in panel b), and this is the situation of a conventional polarization experiment using a stored beam, where the projection of spins *along* the closed orbit vector, $\vec{S} \parallel \hat{n}_{\rm CO}$, is the same with and without decoherence. When you deal with a beam polarized along a direction *perpendicular* to the closed orbit vector, $\vec{S} \perp \hat{n}_{\rm CO}$, as proposed for high-sensitivity srEDM searches (see Sec 2.1), the situation is very different. Shortly after injection, as shown in panel c), the particle spins may still be coherent, but once they are fully out of phase, as shown in panel d), the polarization component perpendicular to $\hat{n}_{\rm CO}$ has vanished. Therefore, in a dedicated EDM machine, the observation time is limited by the time it takes the ensemble of particles to decohere, the spin-coherence time.

is shown. Suppressing the small oscillations which do not rise as function of time, the Master Equation 3 yields

$$S_{||}(t) = \frac{1}{2} S_y \alpha_E f_{\rm R} t. \tag{5}$$

A rectangular (flattop) modulation of RF-E flipper is equally possible, it would enhance the EDM signal by a factor $4/\pi$,

$$S_{||}(t) = S_y \sum_{l=1}^{k} \alpha_E |\cos(l\theta_S)| = \frac{2}{\pi} S_y \alpha_E f_{\rm R} t\,, \tag{6}$$

and, furthermore, in the case of stored deuterons, it offers interesting possibilities to suppress certain spin decoherence mechanisms.

The above derivation holds for a pilot particle which enters the flipper at $t = 0$, particles in the beam bunch which are behind the pilot particle by a fraction $0 < z < 1$ of the ring circumference, are subjected to RF-E flipper fields with a phase advance of $\theta_z = f_S \Delta t$,

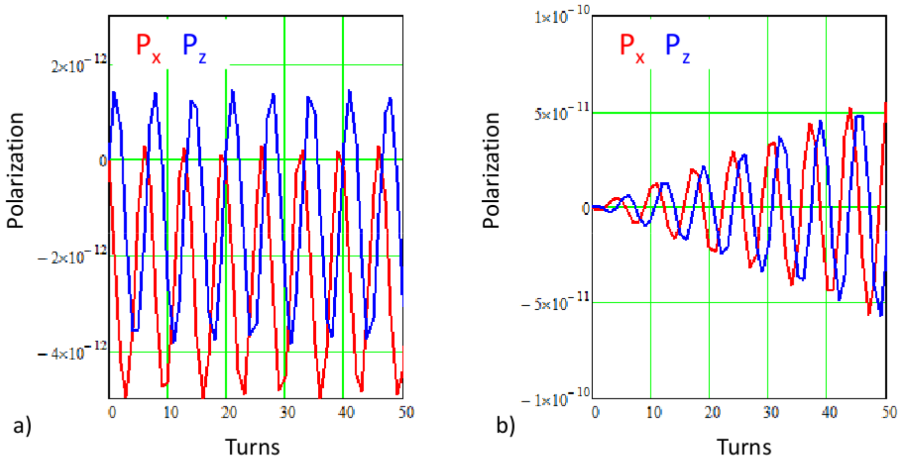

Figure 5: Panel a): Polarization components P_x and P_z of 100 MeV deuterons as function of the number of turns in COSY. Initially, the beam is polarized along the vertical (y) axis. Oscillations are induced by an RF-E flipper of length $L = 1$ m, operated with a *static* in-plane electric field of $E_x = 1.5$ MV/m, where a deuteron EDM of 10^{-23} e·cm is used. As shown in panel b), the spin precessions accumulate when the RF-E flipper is operated with harmonic excitation at $K = 0$ at a frequency of $f_\mathrm{F} = (\gamma G \pm K) \cdot f_\mathrm{R} = -77.083$ kHz.

where $\Delta t = z/f_\mathrm{R}$. The modified Master Equation reads

$$S_{||}(z,t) = S_y \alpha_E \sum_{l=1}^{k} \cos(l\theta_S) \cos\left(l\theta_S + \frac{f_\mathrm{F}}{f_S} z\theta_S\right) = \frac{1}{2} S_y \alpha_E f_\mathrm{R} t \cos\left(\frac{f_\mathrm{F}}{f_S} z\theta_S\right) . \tag{7}$$

The bunch can be viewed point-like, and its polarization is uniform if the bunch length z_b satisfies the condition $\frac{f_\mathrm{F}}{f_S} z_b \theta_S \ll 1$.

A.2 Impact of the RF-E flipper on the spin coherence time

There is an important difference between the horizontal spin coherence time (SCT) for idle precession, and the SCT when the RF-E flipper is driving the buildup of the horizontal polarization from the initially vertical one. The spin tune $\theta_S = 2\pi\gamma G$ varies from revolution to revolution and from one stored particle to another because of momentum variations about the nominal one, $\theta = \theta_S + 2\pi\, \delta\gamma\, G = \theta_S + \delta\theta$, where

$$\delta\theta = 2\pi\, \delta\gamma\, G = 2\pi\gamma\beta^2 \frac{\delta p}{p} G . \tag{8}$$

Our previous discussion was for a particle with nominal momentum, and hereafter, $\theta_S = \gamma_0 G$ and γ_0 is defined for the nominal beam momentum.

The average in-plane spin $\langle S_{||} \rangle$ points at an angle $\theta = \theta_S f_\mathrm{R} t$, while for the precession of an individual particle, there is the accumulating phase slip, $\Delta(k) = \sum_{l=1}^{k} \delta\theta_l$. This phase slip is the principal source of the spin decoherence in the case of idle precession,

$$S_{||}(t) = S_{||}(0) \langle \cos[\Delta(k)] \rangle_\mathrm{ens} = S_{||}(0) \left\{ 1 - \frac{1}{2} \langle \Delta^2(k) \rangle_\mathrm{ens} \right\} , \tag{9}$$

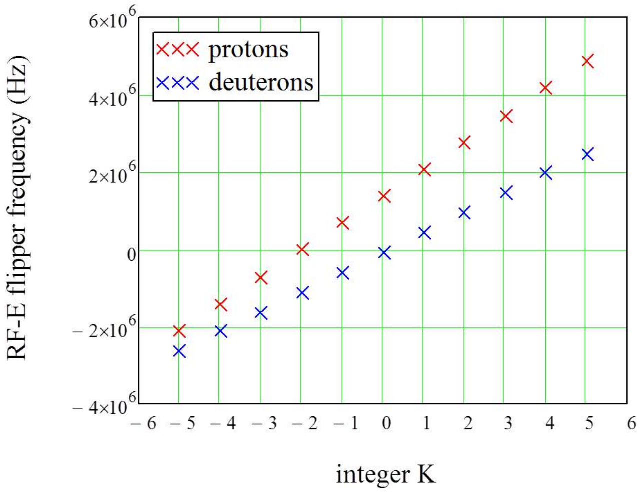

Figure 6: Based on Eq. (4), RF-E flipper frequencies for protons and deuterons at a kinetic energy of 100 MeV are plotted as function of harmonic number K.

where $\langle ... \rangle_{\rm ens}$ stand for the expectation value of an ensemble of particles in a bunch. If $\langle \Delta^2(k) \rangle$ rises with number of turns, *i.e.*, with time,

$$\langle \Delta^2(k) \rangle_{\rm ens} = k\Delta_0^2 = f_{\rm R} t \Delta_0^2 \,, \tag{10}$$

i.e., the horizontal **S**pin **C**oherence under idle (I) precession is characterized by the spin coherence time (SCT)

$$\tau_{\rm SC,I} = \frac{2}{f_{\rm R}\Delta_0^2} \,. \tag{11}$$

On the other hand, if the precession angle for an individual particle oscillates about its nominal value, *i.e.*, the cumulant $\langle \Delta^2(k) \rangle$ remains constant as function of time, then the envelope of $S_{||}(t)$ wouldn't decrease with time.

Examples of such steady oscillations are the synchrotron and betatron oscillations, whereas intra-beam and residual gas scattering, power supply or other instabilities in the machine are likely sources of randomization. Much more theoretical scrutiny, spin tracking with trackers like COSY-INFINITY supplemented with RF–B rotators, and experimental studies within the present proposal are needed to ascertain the importance and relative significance of random and steady spread of spin tunes; at the moment it remains an open issue.

The spread of the particle momenta changes the revolution (transit) time τ,

$$\frac{\delta\tau}{\tau} = \eta\frac{\delta p}{p} = \eta\frac{\delta\gamma}{\gamma\beta^2} \,, \tag{12}$$

where the slip factor equals

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2} \,. \tag{13}$$

γ_{tr} is the transition gamma-factor [12]. It produces a slip of the RF-E flipper phase per pass of

$$\delta\theta_{\rm F} = 2\pi f_{\rm F}\delta\tau = \frac{f_{\rm F}}{f_S}\cdot\frac{\eta}{\beta^2}\delta\theta_S \,. \tag{14}$$

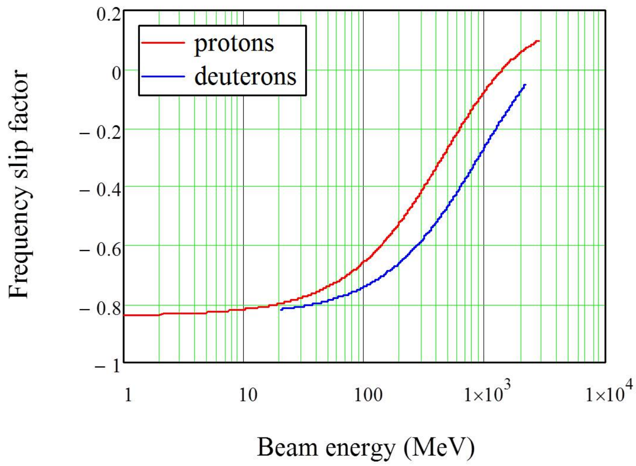

Figure 7: Energy dependence of the slip factor η for protons and deuterons in the energy range accessible at COSY at $\gamma_{tr} = 2.5$.

The overall RF-E flipper phase slip is a cumulant quantity and the Master Equation will take the form

$$\begin{aligned} S_{||} &= S_y \alpha_E \sum_{l=1}^{k} \cos[l\theta_S + \Delta(l)] \cos\left(l\theta_{\rm F} + \frac{f_F}{f_S} \cdot \frac{\eta}{\beta^2}\Delta(l)\right) = \\ &= \frac{1}{2} S_y \alpha_E \sum_{l=1}^{k} \cos\left[C\Delta(l)\right] = \\ &= \frac{1}{2} S_y \alpha_E \sum_{l=1}^{k} \left\{1 - \frac{1}{2} C^2 \Delta^2(l)\right\} , \end{aligned} \tag{15}$$

where

$$C = 1 - \frac{f_{\rm F}}{f_S} \cdot \frac{\eta}{\beta^2} = 1 - \frac{\eta}{\beta^2} \cdot \left(1 + \frac{K}{\gamma G}\right) . \tag{16}$$

If $\Delta(k)$ only oscillates about zero with a constant amplitude (does not grow with k), then the net effect is a certain reduction of the CP-violating horizontal spin accumulation rate. However, if phase slips do once in a while randomize, then

$$\begin{aligned} S_{||}(t) &= \frac{1}{2} S_y \alpha_E k \left\{1 - \frac{1}{4} k C^2 \Delta_0^2\right\} \\ &= \frac{1}{2} S_y \alpha_E k \left\{1 - \frac{1}{4} C^2 \langle \Delta^2(k) \rangle_{ens}\right\} \\ &= \frac{1}{2} S_y \alpha_E f_{\rm R} t \left\{1 - \frac{1}{4} f_{\rm R} t C^2 \Delta_0^2\right\} . \end{aligned} \tag{17}$$

The above implies that the buildup process is impeded by decoherence with a SCT given by

$$\tau_{\rm SC} = \frac{2}{C^2} \tau_{\rm SC,I} \, . \tag{18}$$

Suppressing for the time being special features coming from C^2, Eq. (8) suggests some obvious scaling properties:

- decoherence effects for protons are stronger than for deuterons by the factor

$$G_d^2/G_p^2 \sim 160\,,$$

  which might appear as a show stopper for protons,

- decoherence effects are $\propto \gamma^2\beta^4$ and are weaker for non-relativistic particles,

- decoherence effects are $\propto \langle\delta p^2/p^2\rangle_{\rm ens}$ and are weaker for cooled beams.

A.3 Conspiracy of spin tune and flipper phase slip and the possibility of spin decoherence free energies

To the linear approximation in δp the spin precession and flipper phase shift are locked to each other and could conspire. There emerges a unique possibility of a cancelation of the two phase slip effects by judicious choice of beam energy and flipper harmonics, such that

$$C = 1 - \frac{1}{\beta^2}\cdot\left(\frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}\right)\left(1+\frac{K}{G\gamma}\right) = 0\,. \tag{19}$$

which amounts to

$$\gamma^3 = -\frac{K}{G} + \frac{\gamma^3}{\gamma_{tr}^2}\left(\frac{K}{\gamma G_p}+1\right)\,. \tag{20}$$

For protons $G_p = 1.793$ and solutions do exist for $-K = N = 2, 3, \ldots.$ For instance, with $\gamma_{tr}^2 = 3.3$, the lowest magic energy at $N = 2$ equals $T_p \approx 29$ MeV, the second root at $N = 3$ corresponds to $T_p \approx 133$ MeV, the third root yields $T_p \approx 210$ MeV etc. As we commented above, proton SCTs are generally suppressed by a large factor, $G_d^2/G_p^2 \sim 160$. To this end, if confirmed, such decoherence free energies are extremely opportune, since they remove the suppression for the proton SCTs, and pave the way to high sensitivity proton EDM searches at COSY and elsewhere.

Deuterons also possess a sequence of magic energies, albeit at much higher energies. Since $G_d < 0$, here we look for $K = +1, 2, \ldots.$ To a first approximation, deuterons and protons do share the same γ_{tr}. Assuming above γ_{tr}, the lowest magic energy at $K = 1$ equals $T_d \approx 0.9$ GeV, while at $K = 2$ our estimate is $T_d \approx 1.15$ GeV, still accessible with COSY. The transition energy is tunable, for instance at $\gamma_{tr}^2 = 4$, the deuteron magic energy yields $T_d(K = 1) \approx 1.03$ GeV and $T_d(K = 2) \approx 1.35$ GeV.

A.4 Flattop vs harmonic RF-E flippers

For non-relativistic deuterons the flipper phase slip is a show stopper. Indeed, because of large $-\eta/\beta^2 \approx 1/\beta^2 \gg 1$, at $K = 0$ it entails

$$C^2 \sim 1/\beta^4 \gg 1 \tag{21}$$

which strongly enhances spin decoherence effects. Going to higher flipper harmonics further aggravates the situation even more

$$C^2 \sim K^2/G_d^2\beta^4\,. \tag{22}$$

Our point is that the influence of the troublesome flipper phase slip can be entirely eliminated running the RF-E flipper in the flattop mode. Indeed, in such a mode the tipping electric field simply is the same for all particles in the bunch, which effectively amounts to having a situation with $\eta = 0$. The exact rectangular modulation is not imperative, what we are asking for is a flat top when the bunch passes through the flipper, and the E-field must be inverted when the bunch is at 180 degree, *i.e.*, on the opposite side in the machine.

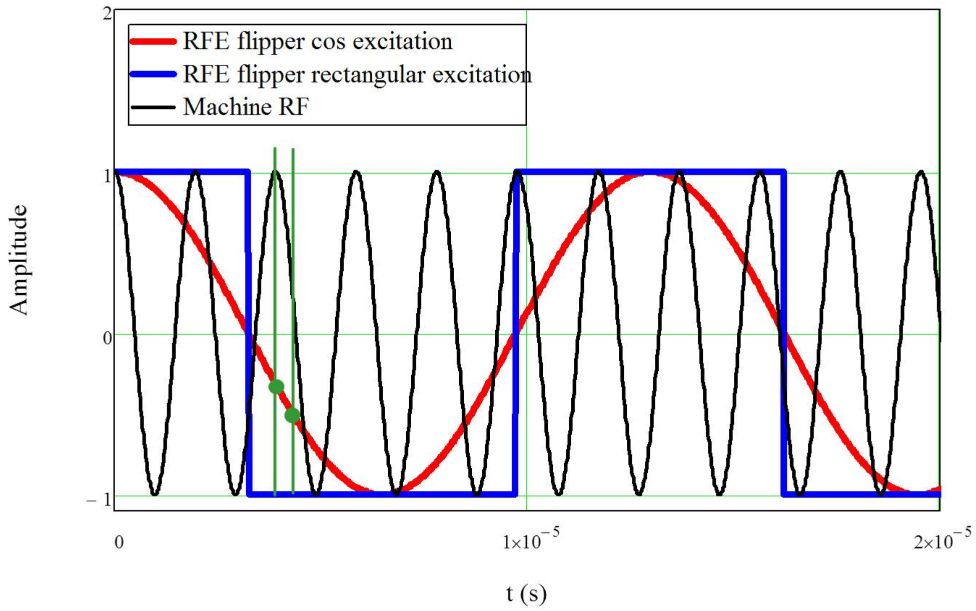

Figure 8: Illustration of the flattop mode (blue rectangular line) vs harmonic modulation (red cosine) for 100 MeV deuterons of the RF-E flipper at a frequency of $f_{\mathrm{F}} = (\gamma G \pm K) \cdot f_{\mathrm{R}} = -77.083$ kHz. The thin black cosine curve, $\cos(2\pi f_{\mathrm{R}} t)$, indicates the revolution of a particle in the ring. A particle with nominal momentum traverses the flipper at integer values of $2\pi f_{\mathrm{R}} t$, *i.e.*, at $\cos(2\pi f_{\mathrm{R}} t) = +1$, indicated by the first vertical green bar. A spread of the particle momentum generates a spread in revolution time, thus for a harmonic modulation the jitter generates a phase slip of the flipper (second vertical green bar), which leads to a spread in the electric field of the flipper. Flattop modulation of the electric field of the flipper is much less sensitive to such fluctuations.

The simplest solution is to lock the RF-E flipper frequency to the ring frequency

$$f_F = \frac{1}{2N} f_R \,. \tag{23}$$

For deuterons $N = 3$, *i.e.*, $\gamma|G_d| = 1/2N = 1/6$, a somewhat higher energy $T_d = 317$ MeV is a convenient option, where the flipper field is inverted once per $N = 3$ revolutions of the beam.

However, using modern RF generators other attractive flattop flipper cycles are possible, allowing for lower energies:

- Half-integer cycle $1/\gamma|G_d| = 6.5$ at $T_d = 148.5$ MeV. The flipper period would comprise two spin turns and 13 revolutions of the beam: One would keep constant $E > 0$ for revolutions 1, 2, and 3; invert to $E < 0$ for revolutions 4, 5, and 6; keep $E = 0$ during the 7-th revolution; invert to $E > 0$ for revolutions 8, 9, and 10 and $E < 0$ for revolutions 11, 12, and 13.

- A still more interesting option is the third-integer cycle $1/|G_d| = 20/3$ at $T_d =$ 98 MeV, with a flipper cycle of 3 spin turns and 20 revolutions of the beam. The flipper field inversion pattern is as follows: $E > 0$ for revolutions 1, 2, and 3; $E < 0$ for revolutions 4, 5, 6, and 7; $E > 0$ for revolutions 8, 9, and 10; $E < 0$ for revolutions 11, 12, and 13 $E > 0$ for revolutions 14, 15, 16, and 17, and $E < 0$ for revolutions 18, 19, and 20.

As a reference point, we discuss in the following an evaluation of the SCT using an Ansatz of violent randomization of the particle momentum: we assign to each particle momentum a random kick, $p_k = p_0 + \delta p_k$, on the turn by turn basis, such that $\langle \delta p_k^2 \rangle_t = \langle \delta p_k^2 \rangle_{\rm ens} = \langle \delta p^2 \rangle$. Such an Ansatz grossly enhances the cumulant phase slip and is entirely unrealistic, but has one positive virtue - an exact relationship between SCT and $\delta p/p$:

$$\tau_{SC} = \frac{1}{2\pi^2 C^2 f_R G^2 \gamma^2 \beta^4} \cdot \left\langle \left(\frac{\delta p}{p} \right)^2 \right\rangle^{-1} . \tag{24}$$

For the reference case of 100 MeV deuterons, $f_{\rm R} \approx 511$ kHz, flattop flipper, *i.e.*, $C = 1$, and cooled beam with $\delta p/p = 10^{-4}$, our estimate yields $\tau_{SC}^d(\eta = 0) \sim 10^5$ s, which must be regarded as a lower bound for the deuteron SCT.

In Fig. 1 we plot the energy dependence of SCT τ_{SC} for protons and deuterons as a function of energy for different flipper harmonics. There is a strong sensitivity to the flipper harmonics and strong change of SCT from harmonic to flattop modulation. The peaks at $C = 0$ are clearly visible.

References

[1] A. Lehrach, B. Lorentz, W. Morse, N. Nikolaev, and F. Rathmann, "Precursor Experiments to Search for Permanent Electric Dipole Moments (EDMs) of Protons and Deuterons at COSY," `http://arxiv.org/abs:1201.5773`. Invited talk at Advanced XIV Workshop on High Energy Spin Physics, Dubna, Russia, September 20-24, 2011.

[2] A. Sakharov, "Violation of CP Invariance, c Asymmetry, and Baryon Asymmetry of the Universe," *Pisma Zh.Eksp.Teor.Fiz.* **5** (1967) 32–35. Reprinted in *Kolb, E.W. (ed.), Turner, M.S. (ed.): The early universe* 371-373, and in *Lindley, D. (ed.) et al.: Cosmology and particle physics* 106-109, and in Sov. Phys. Usp. 34 (1991) 392-393 [Usp. Fiz. Nauk 161 (1991) No. 5 61-64].

[3] J. M. Cline, "Baryogenesis," `arXiv:hep-ph/0609145 [hep-ph]`. 63 pages, many figures: lectures at Les Houches Summer School, Session 86: Particle Physics and Cosmology: the Fabric of Spacetime, 7-11 Aug. 2006. Fixed more minor errors and omissions.

[4] J. R. Ellis, M. K. Gaillard, D. V. Nanopoulos, and S. Rudaz, "A COSMOLOGICAL LOWER BOUND ON THE NEUTRON ELECTRIC DIPOLE MOMENT," *Phys.Lett.* **B99** (1981) 101.

[5] S. Weinberg, "Conference summary (HEP Dallas conference 1992)," *AIP Conf.Proc.* **272** (1993) 346–366, `arXiv:hep-ph/9211298 [hep-ph]`.

[6] C. Baker *et al.*, "Reply to comment on 'An Improved experimental limit on the electric dipole moment of the neutron'," *Phys.Rev.Lett.* **98** (2007) 149102, `arXiv:0704.1354 [hep-ex]`.

[7] W. Griffith *et al.*, "Improved Limit on the Permanent Electric Dipole Moment of Hg-199," *Phys.Rev.Lett.* **102** (2009) 101601.

[8] M. A. Rosenberry and T. E. Chupp, "Atomic electric dipole moment measurement using spin exchange pumped masers of ^{129}xe and ^{3}he," *Phys. Rev. Lett.* **86** no. 1, (Jan, 2001) 22–25.

[9] **Storage Ring EDM Collaboration** Collaboration, Y. K. Semertzidis, "The status of the storage ring EDM experiment," *AIP Conf.Proc.* **1182** (2009) 730–736.

[10] B. L. Roberts, J. P. Miller, and Y. K. Semertzidis, *Lepton Dipole Moments*, vol. 20 of *Advanced Series on Directions in High Energy Physics*, ch. 2, p. 655. World Scientific, 2010.

[11] N. Brantjes, V. Dzordzhadze, R. Gebel, F. Gonnella, F. Gray, D. van der Hoek, A. Imig, W. Kruithof, D. Lazarus, A. Lehrach, B. Lorentz, R. Messi, D. Moricciani, W. Morse, G. Noid, C. Onderwater, C. zben, D. Prasuhn, P. L. Sandri, Y. Semertzidis, M. da Silva e Silva, E. Stephenson, H. Stockhorst, G. Venanzoni, and O. Versolato, "Correcting systematic errors in high-sensitivity deuteron polarization measurements," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **664** no. 1, (2012) 49 – 64. `http://www.sciencedirect.com/science/article/pii/S016890021101850X`.

[12] A. Chao and M. Tigner, eds., *Handbook of accelerator physics and engineering.* World Scientific, 1999.