# ERC Advanced Grant 2015
# Research proposal [Part B2]
# *(<u>not</u> evaluated in Step 1)*

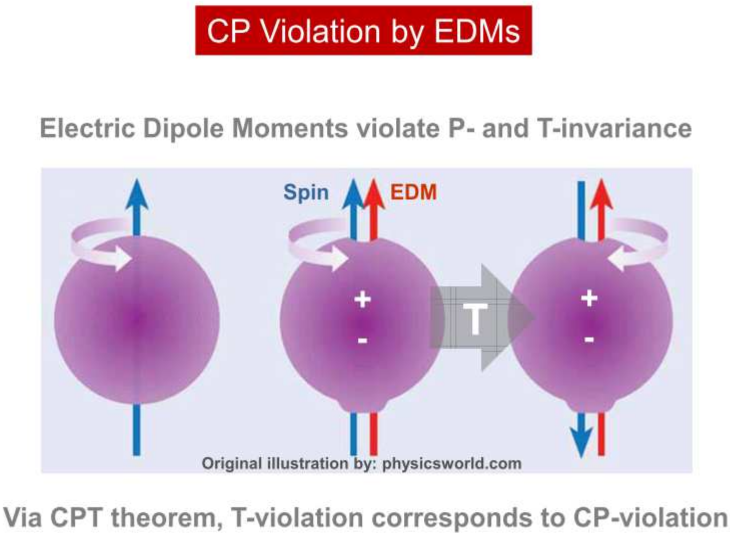
**Part B2: *<u>The scientific proposal</u>* (max. 15 pages)**

**Section a. State-of-the-art and objectives**

**Science case: WHY? – Explore the reason for the baryon-asymmetry of the Universe; uncover the reason for our existence!**

The search for permanent Electric Dipole Moments (EDM) in non-degenerate systems was initiated by Edward Purcell and Norman Ramsey more than 50 years ago for the neutron. Since then a long series of searches with ever increasing sensitivity on neutrons, atoms and molecules has been conducted, but no finite EDM has yet been found. Nevertheless, the experimental upper limits have already had a significant influence on theories of elementary particle physics like, e.g., for supersymmetric models. New generations of experiments are under way or are being planned, which may have the potential to find an EDM – in any case with additional far-reaching theoretical implications.

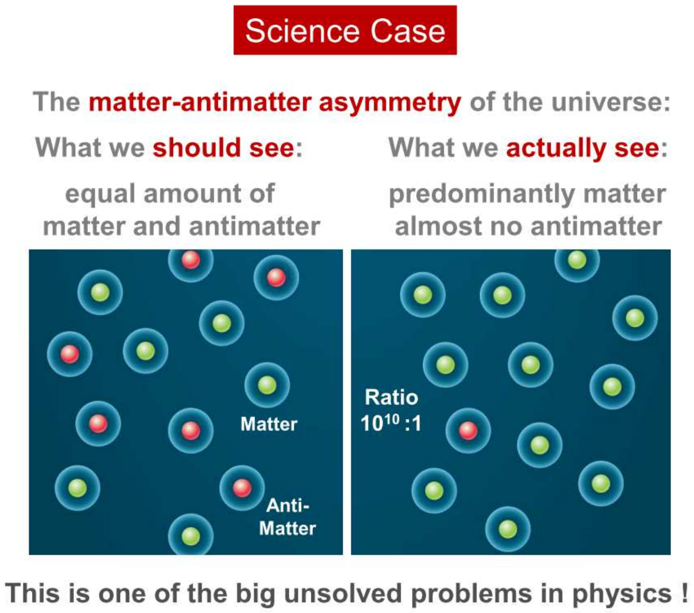
The interest in EDMs originates from the fact that they violate parity (P-) and time-reversal (T-) invariance – for the latter this is schematically shown in the figure below, where application of the T-operation results in a different state. By means of the CPT-theorem, T-violation corresponds to the violation of the combined charge (C-)-parity symmetry CP. Although the discovery of CP-violation (CPV) by James Cronin and Val Fitch (and others) in 1964 came as a complete surprise, it is nowadays a well-studied effect in the quark sector of the weak interaction and included in the Standard Model (SM) of elementary particle physics via the so called CKM mechanism. Given the knowledge of SM-CPV, the predicted size for EDMs of elementary particles is unmeasurably small – at least with current experimental techniques.




There may be, however, additional sources of SM-CPV, e.g., in the leptonic sector. It is intended to search for these in neutrino oscillations – but the corresponding projects are still in its infancy. It could as well be possible that new CPV sources are lurking in electric dipole moments. The existing experimental EDM limits for the neutron (dircctly measured to be $\sim 10^{-26}$ e·cm) and the proton ($\sim 10^{-24}$ e·cm – deduced from atomic EDM limits) indicate two things: (i) EDMs are very small compared to magnetic dipole moments (MDMs) and (ii) their smallness is not at all understood theoretically – via the so called Quantum Chromodynamics (QCD) $\theta$–term it establishes the *strong CP puzzle*, which is waiting to be be solved.

The strongest motivation for new CPV is obtained from the fact that apparently our Universe contains essentially only matter and almost no antimatter (see figure below) – one might call this the *puzzle of our existence*! There are strong arguments for this assertion based on the Big Bang Nucleosynthesis (abundance of the lightest nuclei), the Cosmic Microwave Background Radiation and on Supernovae, although relic antimatter is also searched for, e.g., with the “Alpha Magnetic Spectrometer” (AMS) on the “International Space Station” (ISS) – as of today without success.

Briefly after the Big Bang, matter was created from energy in the form of particle-antiparticle pairs. Why didn´t these pairs annihilate again into pure energy, leaving no matter behind? For yet unknown reasons, at some point in time, the part which we call matter has had a slight plus over antimatter – after the annihilation phase ended this surplus of matter established the Universe we live in (notwithstanding “Dark Matter” and “Dark Energy”). This process is called *baryogenesis*. Note that the electroweak CPV of the Standard Model would have left over much less matter, leading to a Universe largley devoid of galaxies.




In 1967, Andrei Sakharov determined which properties of Nature are required for baryogenesis, regardless of the exact mechanism. His three key assumptions – now known as *Sakharov conditions* – are:

- At least one baryon-number (B-) violating process, transforming the original B = 0 universe into the universe with a very high B-number ;
- Processes, which violate charge (C-) and charge-parity (CP-) invariance;
- Interactions outside of thermal equilibrium.

These conditions are necessary but not sufficient – one still needs to determine the specific mechanism through which baryogenesis happens. Here, however, we are only concerned with the CPV prerequisite: it exists (see above), but it is too small by many orders of magnitude – additional new sources are required, which most probably will also imply New Physics (NP)!

Permanent Electric Dipole Moments (EDM) of elementary particles can be a door towards NP: in fact, some theories like supersymmetry (SUSY), left-right symmetry and multi-Higgs scenarios, suggest that EDMs may be much larger than the SM predictions and can be within experimental reach.

EDMs are searched for worldwide in the neutron, in atoms, molecules, and solids, steadily pushing the upper limits further for the neutron (nEDM), the proton (pEDM) and the electron (eEDM). Future upgrades will continue to improve these limits, but some general limitations seem to be inevitable:

- Free neutrons are unstable, and thus the measurement time will be principally limited; ultracold neutrons (UCN) cannot be produced and stored in very large quantities – the future goal for nEDM is $\sim 10^{-28}$ e·cm);
- In complex systems like atoms, molecules or even solids, the EDMs of constituents need to be deduced indirectly with the help of sophisticated models.

A new idea to extend the direct measurements to new systems and with the potential to push limits even further is to search for *charged particle* EDMs in dedicated storage rings (srEDM). This is the background and motivation for the present proposal.

**Science case: WHAT? – Search for *charged-particle* Electric Dipole Moments in storage rings (srEDM)!**

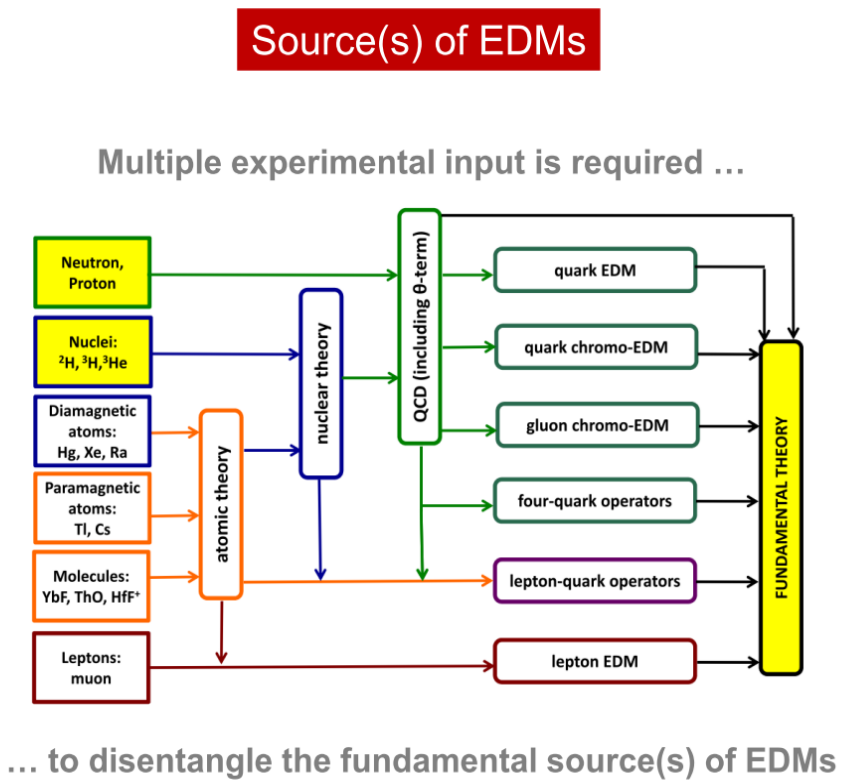
Searching for a non-zero proton and/or deuteron EDM in a dedicated storage ring represents an experimental opportunity to improve the current sensitivity towards $10^{-29}$ e·cm, which corresponds to:

- nearly 5 orders of magnitude compared to the indirectly obtained pEDM limit;
- roughly 3 orders of magnitude compared to the current nEDM limit, and
- at least an order of magnitude in comparison to the projected future nEDM figure.

For the deuteron, it will establish a first-ever measurement.

If achieved, these limits will provide a significant advancement towards the discovery of a finite permanent EDM in a non-degenerate system.

In addition to the sensitivity potential, it has also become evident in recent years that – after the observation of a finite EDM – it will be required to investigate different systems to elucidate the fundamental source(s): thus, besides the neutron, at least the proton but preferably also the deuteron must be investigated. A more complete picture, including atoms, molecules and leptons, is shown in the following figure: it is seen that for leptons, there is a direct link between experiment and the fundamental theory, while for hadrons (and more complex systems – nuclei, atoms, molecules) the connection becomes more sophisticated by intermediate theoretical steps, e.g., QCD. On the other hand, the possible fundamental insight into the underlying physics is much richer.



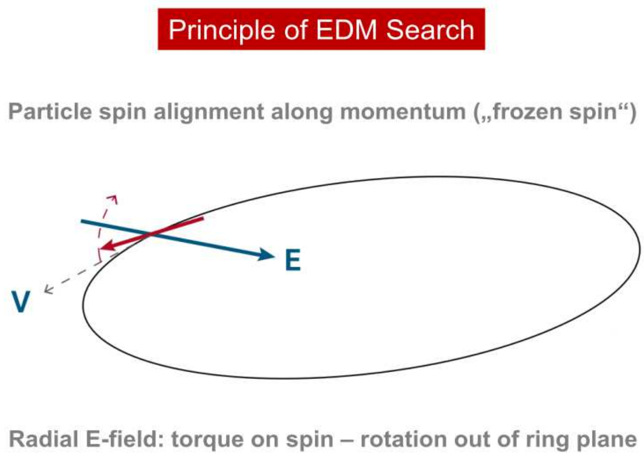

After the discovery of an EDM, e.g., for the neutron, one of the most important questions to be answered will be, whether it is caused by strong CP violation or whether it originates from physics beyond the Standard Model (BSM). The SM-Lagrangian contains a second source of CPV, the QCD vacuum angle ($\theta$-term), whose value is already strongly constrained by experimental neutron EDM limits. The extreme smallness of $|\theta|$ is a long-standing puzzle of the Standard Model. Experimental data on the EDMs of light ions (proton, deuteron) can provide an answer to it. While a single EDM measurement can be interpreted (fitted) by any source, two measurements, e.g., neutron and proton, will allow conclusions about the origin of the CP violation. As a check of the theory, the result for the bound neutron-proton system (deuteron) should as well be available. In recent years several calculations have been performed for EDMs of the nucleon and several light nuclei, using modern effective-field theory techniques, in order to determine how theory can be best constrained: it has been shown that the $\theta$-term could be identified with good accuracy, once results for EDMs of the neutron, proton and deuteron have been obtained. For this source the EDMs of these systems are all expected to be of the same order of magnitude, but the precise quantitative relations between the individual EDMs are a clear prediction of the $\theta$-term. In this way, the existence/smallness of strong CP violation – a puzzle which has been around for almost fifty years – can potentially be solved.

The size of the deuteron EDM, with respect to the EDM of proton and neutron, is an excellent probe for BSM physics: as mentioned, for the $\theta$-term one expects similar size EDMs for the nucleon and the deuteron, while certain BSM sources predict the dEDM to be significantly larger, up to an order of magnitude. Thus, it can be expected that dEDM has a particularly large discriminating power due to its unique spin-isospin properties.

The calculations are complicated because the models are formulated at very high energy and then need to be evolved down to the scales where experiments take place. Using a cascade of effective field theories such calculations become possible and the EDMs can be expressed in terms of the parameters appearing in the high-energy models. Preliminary results confirm that different classes of models predict different hierarchies of EDMs and thus can be disentangled once experimental results will be available.

**Technique: HOW? – Observation of EDM effect on spin motion**

The principle of storage-ring EDM measurements of charged particles is simple: if an electric dipole moment exists, the spin vector, which is oriented parallel to the EDM direction, will experience a torque in an external electric field, resulting in a change of the original spin direction (see figure below). This minuscule spin rotation can be determined with the help of a so called polarimeter (a detector to determine the spin direction). Alternatively, one can search for a tiny change of the spin precession frequency due to an EDM.




The spin motion (precession) of a particle, which possesses both a magnetic dipole moment (MDM) and an electric dipole moment (EDM), in electric (E) and magnetic (B) fields of a storage ring is governed by the Thomas-Bargmann-Michel-Telegdi (Thomas BMT-) equation:

$$\frac{d\vec{s}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}),$$

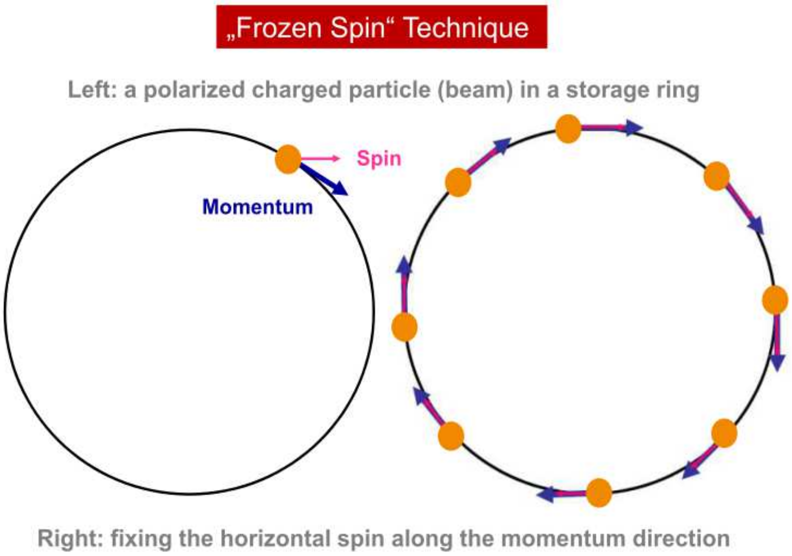
$$\vec{\Omega}_{MDM} = \frac{q}{m}\left[G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{B}\right) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right],$$

$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left[\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}\left(\vec{\beta}\cdot\vec{E}\right) + c\vec{\beta}\times\vec{B}\right].$$

($\beta$, $\gamma$ are the Lorentz factors, $G$ is the magnetic anomaly, and $\eta$ parametrizes the size of the EDM; $m$, $q$ represent mass and charge, and $c$ is the velocity of light). Here the angular velocities ($\Omega$) are defined with respect to the momentum vector of the particle.

The main challenge is that in general the spin precession due to the MDM is many orders of magnitude larger than the spin precession expected from an EDM. The aim is thus to find electro-magnetic field configurations where the contribution due to the MDM vanishes, i.e., where the spin vector does not precess and always points along the momentum vector in the absence of an EDM. This technique is called "frozen spin" (see figure below).

For protons with their positive anomalous magnetic moment, this condition can be achieved with *purely electric fields* for a “magic” beam momentum of $p$ = 700.74 MeV/c. For particles with negative anomalous magnetic moment (like deuterons) a *combination of electric and magnetic fields* has to be used. In either case a non-vanishing EDM results in a build-up of a vertical polarization component for a beam that was initially polarized in the horizontal plane.

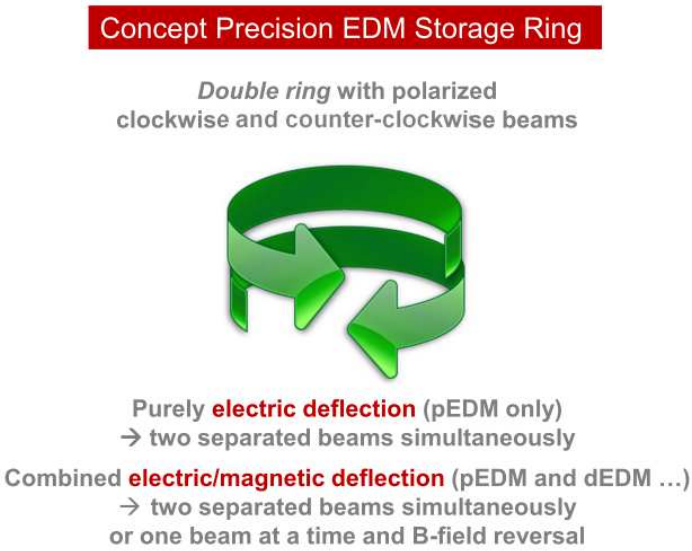



**Scholarly aspects**: **HOW? – Employ a new class of storage rings for charged-particle EDM searches!**

For the final high-precision ring with a EDM sensitivity goal of $10^{-29}$ e·cm or even better, both options require the use of clockwise (CW) and counter-clockwise (CCW) beams to remedy, e.g., the following systematic errors:

- Radial magnetic fields;
- Non-radial electric fields;
- Vertical quadrupole misalignments;
- rf cavity misalignments and unwanted field components.

The main systematic error will come from an unwanted spin precession due to the MDM in radial magnetic fields which will be indistinguishable from the EDM signal. A radial magnetic field, however, causes forces in different directions for the beams in opposite directions and thus it can be controlled to a very high accuracy. In addition there will be significant further experimental and technological challenges, for example shielding of external magnetic fields (below 1 nT everywhere), beam position monitoring (in the order of nm) and polarimetry (µrad/1000 s for $10^{-29}$ e·cm).




Such a dual-ring does not yet exist. The challenges briefly sketched above are basically due to the transition from the ideal physics case to its realization in a piece of equipment – two conclusions must be inferred:

- It will not be possible to reach the projected sensitivity goal in one step, essentially starting from scratch to design build and operate the dual-beam precision storage ring. Since such a facility also represents a significant investment it must only be made after a very careful assessment of all the risk factors has been performed and once all key-technologies are provided.
- An approach, in which these key-technologies are developed and demonstrated, combined with a series of experiments in which the EDM-sensitivity is increased step-by-step, based on the experience gained on the way, is compulsory.

The current proposal ("Electric Dipole Moment Search using Storage Rings") suggests such a step-wise approach: starting with existing equipment, in particular the cooler storage ring COSY at Forschungszentrum Jülich (COSY-Jülich, see below), two objectives will be pursued (WP-x refers to the work packages, described in more detail below):

- Develop the tool-box, comprising:
  - Beam position monitors (BPM), beam current transformers (BCT) [cf. WP-1and WP-4]
  - Electrostatic deflector and combined E-B "bender" [cf. WP-1 and WP-4]
  - Accelerator feedback system [cf. WP-1 and WP-4]
  - Beam polarimeter [cf. WP-2 and WP-4]
  - Spin tracking simulation codes [cf. WP-3]
- Perform EDM measurements with COSY:
  - Proof-of-principle for deuterons, using rf-elements ("Wien filter") [WP-5]
  - First direct measurements for protons and deuterons, using static E/B elements [WP-5]

The acquired know-how will be integrated in a design study (outside of the current srEDM project proposal) with the aim to provide a Conceptual Design Report (CDR) or even a Technical Design Report (TDR) for the final facility, which is a longer-term (>10 years) project.

**Section b. Methodology**

The srEDM project is a complex high-risk high-impact venture, which needs careful planning and execution. The following sections outline the structure of the necessary experienced team, the required (mostly available) hardware and the work packages (including the deliverables/intermediate milestones) on the way.

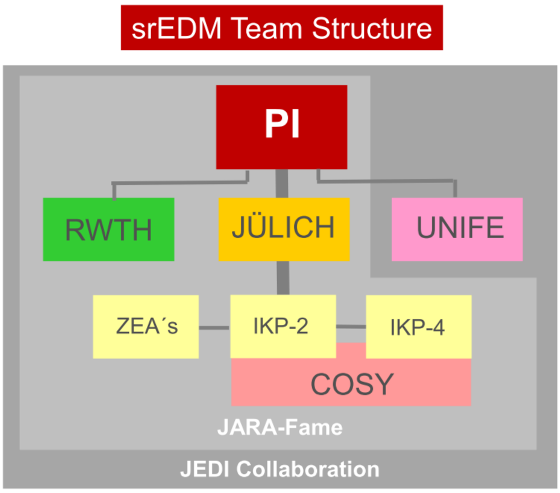
In order to keep track of progress (and possible problems which might lead to re-adjustments), it is planned to document and report all of the results in a timely fashion, e.g., on the srEDM-website, in conferences and in refereed scientific journals; best care and attention will be taken that results as well as the project itself will be presented to the broader scientific community and to the public. The dissemination of the results will be the responsibility of the PI and comprises:

- Implementation and maintenance of a website;
- Scientific internal and external reporting;
- Data and patent management (e.g., storage and access of experimental and technical data);
- Organization of topical internal and external review meetings.

## Strategy: HOW? – Structure of the team; partners

Although the Institut für Kernphysik of Forschungszentrum Jülich [JUELICH] – comprising the PI´s institute (IKP-2) and the accelerator department (IKP-4) as well as the central engineering institutes (ZEA-1 (mechanics) and ZEA-2 (electronics)) – provides a very solid basis for the proposed srEDM project, the diversity and complexity requires additional complementary expertise, which can be implemented with the following two partner institutions:

- The Physics Institute (III B) of RWTH Aachen University [RWTH] has internationally acknowledged expertise in design and construction of, e.g., LHC detector components as well as complex data analyses, which will be extremely helpful for the new polarimeter. In cooperation with engineering departments, they have recently started to build and test mock-up models for the electrostatic deflectors. Prof. J. Pretz has been a member of the BNL $(g\text{-}2)_\mu$ collaboration, the only previous precision storage ring experiment. Finally, the university provides access to well-prepared PhD students for the project.
- The group at the University of Ferrara and INFN (Ferrara, Italy) [UNIFE], led by Prof. P. Lenisa, is a long-term collaborator, e.g., in PAX (polarized antiprotons) and has acquired unique expertise in polarized sources, targets and polarimetry, which will be invaluable for the success of the beam polarimetry work package and for all of the experimental investigations at COSY. Also Ferrara will be a source of well-trained PhD students.

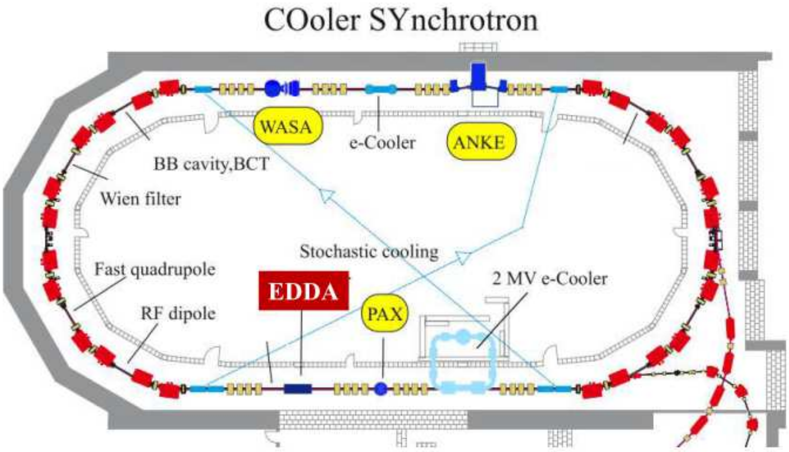



Forschungszentrum Jülich and RWTH Aachen University founded an institutional cooperation called JARA (Jülich Aachen Research Alliance) with one section FAME (Forces and Matter Experiments), which aims to answer the question about the fate of antimatter: all involved Jülich and Aachen institutions are members of JARA-Fame. The JEDI-collaboration (Jülich Electric Dipole Moment Investigations) encompasses all partners (see figure).

## Strategy: HOW? – Exploit COSY-Jülich as R&D and EDM-demonstrator facility

The COoler SYnchrotron (COSY) is a conventional single beam storage ring with a circumference of 184 m at the Institut für Kernphysik (IKP) of Forschungszentrum Jülich (FZJ) (see figure); it is the hadron storage ring worldwide which has most of the characteristics required for the charged particle EDM project and it can be employed for the first EDM measurements of this proposal, although it was never conceived as a precision storage ring for this purpose.

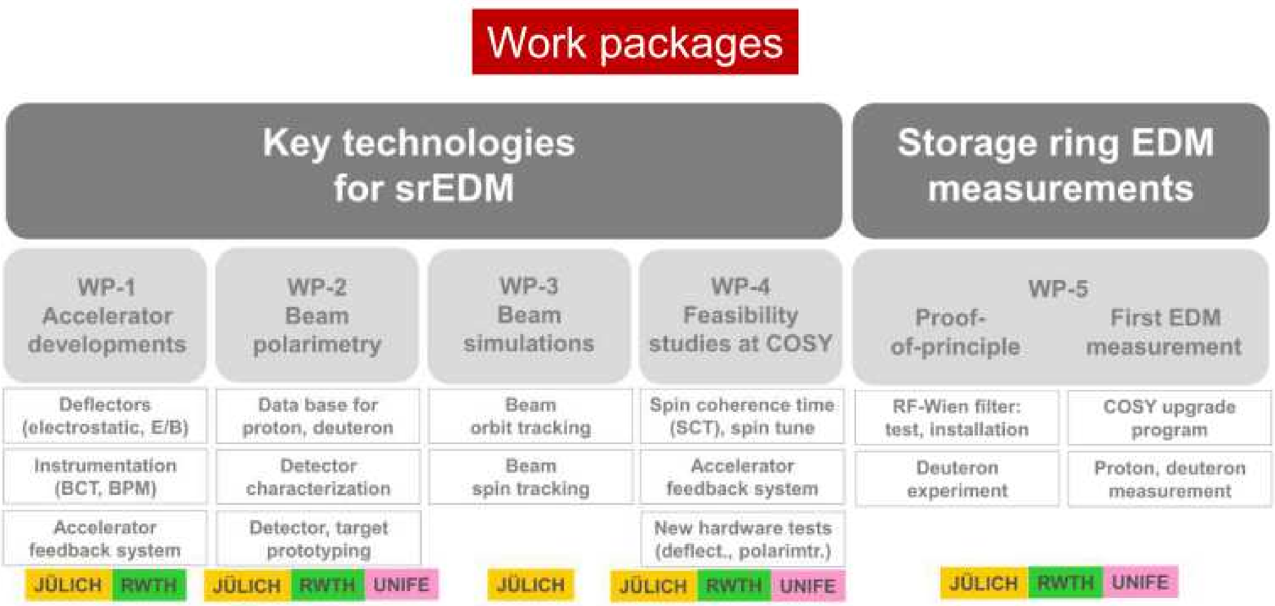
COSY stores and accelerates polarized proton and deuteron beams from the injector cyclotron JULIC to momenta between 0.3 GeV/c (value at injection) and 3.7 GeV/c. To preserve polarization during acceleration for polarized protons, well-established methods are employed: a fast tune-jumping system, consisting of two pulse air core quadrupoles, has been developed to overcome intrinsic resonances; polarization across imperfection resonances is preserved by the excitation of a vertical orbit bump using correcting dipoles to induce total spin flips. The polarization of the circulating beam in COSY can be monitored during acceleration with the internal EDDA detector. This unique tool simplifies the procedure of adjusting the accelerator for polarized beams. The achieved polarization for protons is higher than 75% up to the final momentum. Vector and tensor polarized deuterons are also routinely accelerated in COSY with polarizations up to 60%. COSY also provides phase space cooled beams over the whole momentum range by means of two electron coolers (low energy: up to 100 keV, high energy: up to 2.5 MeV) and a stochastic cooling system.




COSY has been operated for hadron physics experiments for more than 15 years. At the end of 2014 the hadron physics experiments have been stopped and the internal detector facilities (ANKE, WASA and PAX) will be decommissioned in future. For about 1/3 of the time (i.e. about 2000 hrs per year) COSY is now exploited for R&D in conjunction with the EDM project by the JEDI-collaboration. This fraction of beam time will increase once COSY is used as EDM-demonstrator facility (proof-of-principle, first measurements).

## Strategy: HOW? – Work packages

The following figure presents the overview of the work packages foreseen for the srEDM-project with the two major deliverables – key technologies and EDM measurements – details are described below:



## WP-1: Accelerator developments:
### Electrostatic and combined E-B bending elements, instrumentation of the storage ring

To carry out this kind of precision experiments, high-field electrostatic and combined E-B bending elements have to be developed and optimized. For the ultimate sensitivity goal of $10^{-29}$ $e\cdot$cm of a proton EDM experiment the development of high-field purely electrostatic bending elements are essential. Combined electrostatic - magnetic bending elements have to be developed for an "all-in-one" lattice design to perform a deuteron experiment – such a ring can also be used for protons as well as other light ions, e.g., $^3$He. For an EDM storage ring of radius $r$ = 30 m transverse electric fields of 17 MV/m with a magnetic field up to 1.6 kG are required.

The EDM measurement also requires a precise monitoring of the beam properties to understand systematic effects. The main systematic error of an EDM measurement is supposed to come from radial magnetic fields which will, via the interaction with the magnetic moment of the particle, mimic an EDM effect.

### Objectives

An electrostatic deflector from Fermi National Accelerator Laboratory (FNAL) has been transferred to Jülich to gain experience with ultra-high electrostatic fields. In cooperation with RWTH a clean room and test bench was set-up to test downscaled electrostatic deflector models. To handle systematic contributions by the two apertures of an "all-in-one" machine, the field polarity of the magnetic field has to be changed with very high precision while keeping the electric field completely constant. This will allow for consecutive runs of CW and CCW beams in the different apertures of the combined electrostatic - magnetic bending elements.

Major development steps for the final bending element are the optimization of the shape of electrostatic field plates with suitable magnet field configurations utilizing electromagnetic field simulation programs, electrical and mechanical layout of bending elements and R&D work on surface treatments that can yield ultra-high electric field gradients. Thus, the following steps are required:

1. Test and optimization of bending elements on the test bench:
   - Test and optimization of downscaled electrostatic bending elements;
   - Preparation of test bench and clean room at Jülich to test full-scale bending elements;
   - Refurbishing and performance optimization of FNAL deflector;
   - Development and of surface treatment utilizing the FNAL deflector to increase its performance;
   - Adding magnetic field coils and study field polarity change with very high precision.
2. Development of the final bending elements:
   - Optimization of the shape of electrostatic field plates with suitable magnet field configurations, using electromagnetic field simulation programs;
   - Electrical and mechanical layout of bending elements;
   - Construction of bending element, optimization of field configuration and strength;
   - Performance test and optimization on test bench.

One way of controlling systematic effects is the use of high precision BPMs. The idea is based on the exploitation of magnetic pick-ups in a *Rogowski coil* configuration (an electrical device for measuring alternating currents, which consists of a helical coil of wire). The main advantage of this coil design is the response to the particle bunch frequency and the compactness of the coil itself. In a first step the BPMs will be benchmarked in a laboratory test system. In the next step the calibrated BPMs will be installed and tested at the conventional storage ring COSY. In a further step an extension of the BPMs to measure the relative position of two counter-rotating particle beams must be foreseen.

3. *Rogowski* coil development:
   - Benchmarking in a laboratory test system;
   - Installation and performance testing at COSY.

A radial magnetic field will lead to a vertical separation of the two beams which leads to a non-vanishing magnetic field which could be measured with SQUIDs (superconducting quantum interference device, consists of two superconductors separated by thin insulating layers to form two parallel Josephson junctions; they may be configured as a magnetometer to detect very small magnetic fields). A first estimate shows that one needs sensitivity of the order of 1fT/√Hz. SQUIDs with this sensitivity are available but were never tested in an accelerator environment. SQUIDs were used as a beam current monitor but never as a beam position monitor where a new 4-fold coil setup to measure up-down and left-right positions will be used. This will be addressed in this work package. Note that only the relative positions of the two beams have to be measured. This method only works if the beam currents and phase space of the two beams are the same or are determined very precisely.

4. SQUID BPM development:
   - Design and layout of a SQUID BPM;
   - Installation and performance tested at COSY.

For stabilization of COSY (and any future precision EMD storage ring), signals of as many ring and beam parameters as possible (magnets, rf-systems, spin and betatron tune, closed orbit, chromaticity etc.) need to be monitored and put into a feedback system. Such systems will be developed and then tested in COSY (WP-4).

### Deliverables

The list of items given in the subsections 1.- 4. above comprises the tasks that need to be worked off in this work package. As the final goal of this WP, a technical report will be delivered after month 48. Intermediate steps will be topical and review meetings.

### Contributions by the partners

The institute where most of the accelerator know-how for storage rings resides, IKP-4 of Forschungszentrum Jülich, will take over the largest fraction of the workload of the work package. The IKP-4 director Prof. M. Bai is committed to lead this WP. IKP-2 with its experience in polarized beams will also contribute under leadership of Dr. F. Rathmann (one of the JEDI-spokespersons). ZEA-1 of FZJ will be strongly involved in all technological developments. RWTH will be responsible for the downscaled electrostatic bending elements. For these tasks, one PostDoc position at FZJ and one at RWTH will be foreseen from this project (see figure below).

For the SQUID-BPM development, cooperation with one of the world experts of SQUIDs (Dr. H.J. Krause, PGI-8 of FZJ) has been started.

## WP-2: Polarimetry

The polarimeter for the EDM Storage Ring must operate continuously with high efficiency and high polarization sensitivity (analyzing power) so that polarization rotations of the beam as small as a µrad may be detected if they happen within a time of about 1000 s. There also needs to be control of the systematic errors in detecting this change to a similar level of precision. The conditions of high efficiency (1%) and analyzing power (~0.6) are fulfilled for medium energy protons and deuterons when using a thick (few cm) carbon block onto which the beam particles are directed continuously during the experiment. Elastic scattering of the beam particles from the atomic nuclei in the carbon target will be observed in a series of detectors installed behind the target.

Feasibility studies conducted at COSY have already demonstrated this level of performance and error suppression for a carbon block mounted at the edge of the circulating beam. In an experiment in which the polarization direction is periodically reversed, first-order errors arising from beam position or angle errors, or rate-induced acceptance changes in the detector system, may be cancelled using combinations of the elastic scattering rates for different azimuthal angles. Higher-order systematic effects related to the shape of the beam profile may be corrected based on the information from a reconstruction of individual scattering events if the carbon target is supplemented with a hydrogen gas jet (or frozen pellet beam) that crosses the beam. So part of the polarimeter detector will be a tracking system that allows tracing each particle back to its point or origin, and another outside the first that identifies particles that have scattered elastically. The hydrogen target will also give rise to Coulomb scattered (with spin independence) particles that oscillate about the beam center line and strike the thick carbon blocks on subsequent trips around the storage ring.

### Objectives

The goal of the WP will be the design, construction and testing of a prototype polarimeter for use in the first EDM storage ring experiment. This will comprise the following steps:

- Development of a broad-band database for p-C and d-C scattering;
- Detector characterization;
- Polarimeter modelling and Monte Carlo simulations;
- Realization and test of a prototype.

One exciting novel project which has recently been started, is to shoot small diamond pellets (size 1-100 µm) through the beam as target instead of using a bulk carbon block – this has many attractive features, like, e.g., instantly switching the target on/off and obtaining a beam profile, but it requires a new development.

A dedicated target-station in COSY for the data base measurements will be provided at the WASA place (see figure of COSY above); test experiments for detectors can also use the extracted COSY beam.

### Deliverables

The data base on polarized proton-carbon and deuteron-carbon scattering will be provided in month 30 (after the start of the project); a polarimeter prototype will be constructed and tested after 36 months, and the feasibility study for the new target system will also be finalized after 3 years.

### Contributions by the partners

Forschungszentrum Jülich (the group of the PI in IKP) will develop the polarimeter prototype and work on the new diamond pellet target system; for this purpose a new IKP-2 staff member (Irakli Keshelashvili) has been hired recently, and a cooperation with ZEA-1 (mechanical engineering of FZJ) has been started.

RWTH Aachen will perform detector modelling and MC simulations: under the supervision of Prof. J. Pretz, students will work off this task.

Ferrara will be responsible for the data base. A PostDoc with experience in polarized hadronic reactions will be hired for the group of Prof. P. Lenisa in order to provide the required precision polarization data (analysing power, cross section) from literature and from new measurements at COSY.

## WP-3: Beam simulations

Spin tracking simulations of the complete experiment are crucial to explore the feasibility of the planned storage ring EDM searches and to investigate the systematic limitations. For a detailed study during particle storage and build-up of an EDM signal, a large sample of particles must be tracked for billions of turns. The “COSY INFINITY” and “MODE” simulation programs are utilized for this purpose, both based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle. An MPI version is running on the Jülich supercomputer cluster. Given the complexity of the tasks, particle and spin dynamics simulation programs must also be benchmarked by comparing simulation results and experimental data from measurements at the Cooler Synchrotron COSY.

### Objectives

Spin tracking simulations to support the first direct measurements and quantify systematic errors have to be performed. In order to identify the best approach using numerical simulation codes, meetings of the world-leading experts will be organized – recently a kick-off meeting was held during the International Particle Accelerator Conference (IPAC15) in Richmond, Virginia (USA). In addition to “COSY INFINITY” and “MODE”, integrating programs also have to be used for benchmarking. These simulation programs are suitable to study effects that occur on short time scales.

### Deliverables

The goal of the WP will be to deduce the systematic limitations of the resonant method (RF Wien filter; see WP-5 below) with the simulation programs and perform lattice design and spin tracking for the design work of a dedicated EDM storage ring. In a first step the development and implementation of time-dependent transfer maps as well as the EDM extension to spin motion need to be tested and used to investigate the resonant method and its systematic limitations with COSY INFINITY and MODE. Main sources of systematic errors for the resonance method are the alignment of the RF Wien filter, the opening angle of spin ensemble, field quality (fringe fields), the relative frequency slip of the RF Wien filter and the closed orbit deviation of the beam due to misalignments and field errors of ring magnets. In order to improve the systematic EDM limit for this method the closed orbit correction system of COSY has to be improved significantly. For this task detailed beam and spin tracking simulation are essential. The results will be the bases to specify the required COSY upgrade (orbit correction system, beam-position monitors (BPMs), power supply stability, magnet alignment and ring impedances).

For the design study of a dedicated EDM storage ring, lattice design and spin tracking will be the major task in the upcoming years to identify the systematic EDM limit of the experimental methods in conjunction with the design of all accelerator elements.

The WP needs to be dealt with over the full period of the srEDM project, but some parts have to be finalized after about 2 years, since results are needed for the measurements of WP-5.

### Contributions by the partners

The simulations within this project will be performed in the IKP accelerator division (Prof. M. Bai) of FZJ with PhD students under the leadership of Prof. A. Lehrach (FZ Jülich / RWTH Aachen). The upgrade of COSY INFINITY will be supervised by Prof. M. Berz (MSU, USA), who is the principal developer of the presently available version and who is a member of the JEDI collaboration.

## WP-4: Feasibility studies at COSY

COSY with its polarized proton and deuteron beams offers unique possibilities for test measurements, benchmarking orbit and spin tracking codes (cf. WP-3) and testing new equipment: deflectors, beam position monitors and feedback systems (cf. WP-1) and, e.g., the polarimeter (cf. WP-2). In addition to these tasks, preparatory measurements for EDM experiments will be performed – in the following they are described in more detail.

One of the prerequisites for an EDM measurement in storage rings is the provision of long spin coherence times (SCT – the equivalent of the $T_2$ relaxation time in NMR). Recently, SCT of several hundred seconds were obtained for a p = 1 GeV/c deuteron beam. Such a large SCT made it possible to measure the spin tune of the beam with an unprecedented precision of $10^{-10}$ in a measurement time of 100 s (the corresponding paper has been submitted to PRL; see Ref. 5 in part B1 of this project). In a pure magnetic ring the spin tune, defined as the number of spin revolutions per particle turn, is given by the product of relativistic gamma-factor and the anomalous magnetic moment: $\nu_s = \gamma G$. With this measurement the spin tune has been established as a tool to investigate systematic effects. One observation of the measurement was that the spin tune varies within one cycle as well as from cycle to cycle by about $10^{-8}$. In a perfectly stable machine there should be no such variations. It is planned to investigate where these changes come from (temperature effects, magnetic field instabilities, etc.). Understanding these systematic effects is one objective of this work package. A second one is to provide long SCTs also for protons.

### Objectives

The goal of the WP will be to exploit COSY for feasibility investigations in connection with EDM storage ring experiments. These comprise the following items:

- Investigations to understand systematic effects for spin tune measurements;
- Benchmarking of simulation tools for orbit and spin tracking;
- Provision of large spin coherence times for protons:
- Implementation and test of the feedback systems.

### Deliverables

A comprehensive report on systematic errors for EDM measurement will be provided after 42 months. It is planned to publish the SCT results for protons in a refereed journal subsequently.

### Contributions by the partners

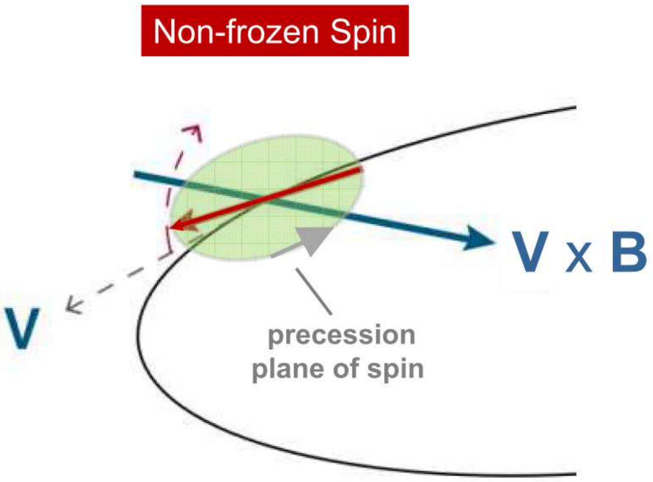
The studies of WP-4 are a task where all three partners contribute (see figure below); a PostDoc for RWTH (4 years) and another one for UNIFE (2 years) are foreseen.

## WP-5: Proof-of-principle and First EDM measurements using COSY

A storage ring charged hadron EDM-search has never been conducted (except for the muon (see above) which represents a very special case due to its weak decay), and, given the potential impact of such measurements, a demonstration of the method, i.e., the storage of a polarized beam with large spin coherence time and the application of an E×B field such that no Lorentz-force acts on the particles ("Magic rf Wien filter"), must be conducted as a first step.

During last year (2014), a prototype rf E×B dipole has been successfully commissioned and tested at COSY. The force due to a radial magnetic field is cancelled by a vertical electric one. In this configuration, the dipole fields form a Wien filter that directly rotates the particles' polarization vector. It was verified that the device can be used to continuously flip the vertical polarization of a 970 MeV/c deuteron beam without exciting any coherent beam oscillations. For a first EDM-experiment the rf E×B dipole in Wien-filter mode will be rotated by 90° around the beam axis. This configuration will be used for systematic investigations of sources for false EDM signals.

The magic rf Wien filter will allow us to perform a polarization build-up experiment (see figure below). Since we are using a magnetic machine, the direction of the spin of the particles is not frozen. In order for this technique to work, the frequency of the rf Wien filter must be locked to the spin motion. This will be accomplished by dedicated feedback systems (see WP-1 and WP-4).




The reach in EDM sensitivity using an rf Wien filter is, however, limited by the fact that any magnetic imperfection present in the machine will be amplified by the rf device. Therefore, the machine performance must be controlled to high accuracy, and this will required moderate upgrades. Using the rf E×B Wien filter, we are aiming at a first measurement of the deuteron EDM, which will serve as proof-of-principle measurement for the storage ring EDM technique.

After the experimental demonstration that storage ring EDM measurements can be performed, experiments will be conducted to obtain a first directly measured EDM for the proton and to deduce a first-ever measurement for the deuteron. As mentioned before, it must be understood that in a magnetic storage ring like COSY, there is no frozen spin. Therefore, later on in WP5, we will use a dedicated insertion composed of static electric and magnetic fields that decouples from the magnetic imperfection of the machine. In such an arrangement, the EDM signal will be solely produced by the insertion itself. Such a system will act as a miniature electrostatic storage ring, located inside a magnetic machine. As such, it will pave the way towards the new class of electrostatic storage rings for EDM searches.

### Objectives

The goal of the WP is to provide a proof-of-principle measurement of the deuteron EDM using an rf E×B Wien filter. Once the dedicated insertion using a combination of electric and magnetic fields is available, a first-ever measurement of protons and deuterons using a magnetic storage ring will be carried out. Such an insertion is mandatory, as it will use the very same techniques that are required for a dedicated electrostatic machine.

### Deliverables

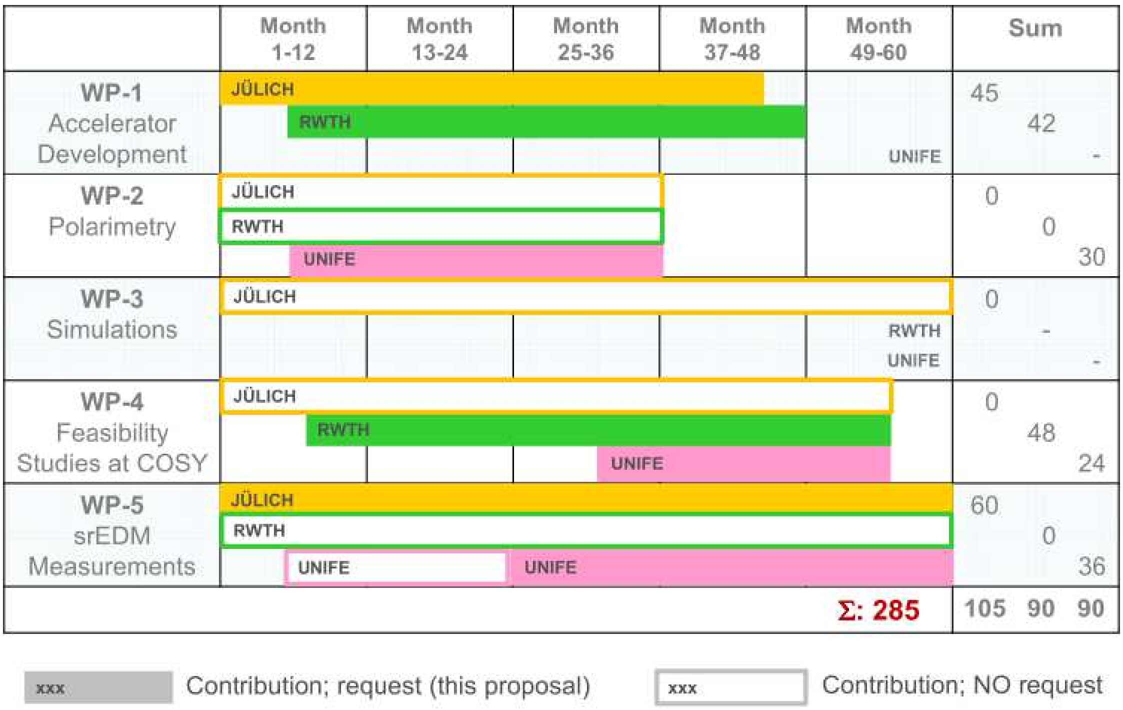
- Proof-of-principle experiment with deuterons using rf E×B Wien filter
- Design study of static insertion, including simulation studies and error estimates
- Technical realization
- Proton and deuteron EDM measurements

All of the above-mentioned items will be scheduled in the second half of the 5 year duration of the srEDM project.

### Contributions by the partners

The tasks of WP-5 will constitute a common effort of all three partners. More than one third of the requested personnel resources (one PostDoc for JUELICH for 5 years, necessary for the preparations, and another one for UNIFE for 3 years) will be attributed to this task.

As a summary the following figure shows the distribution of resources of the srEDM project with respect to the five work packages. A distinction is made between resources requested from ERC and additional resources which will be brought in from the PI´s institute and the partner institutions. It should finally be mentioned that the investments will be supplied by IKP of FZJ.




### Strategy: WHY NOW? – The right time and the right place

The Institut für Kernphysik of Forschungszentrum Jülich has recently changed the focus of the scientific use of COSY: hadron physics experiments have been completed and – during the next funding period (2015 – 2020) and beyond – COSY will be primarily used to exploit the possibilities of charged particle EDM searches. There is thus a unique time window to demonstrate the principle and to develop all the tools for srEDM – inevitable preconditions for a new dedicated precision (double-beam) storage ring, which undoubtedly would be a European flagship facility.

The current srEDM proposal – if successful – will provide a major boost to this project!

**Section c. Resources (including project costs)**

In the following table the cost for the srEDM project are specified according to the PI´s institute and the two partner institutions:

| **Cost Category** | | | **Total in Euro** | | | |
|---|---|---|---|---|---|---|
| | | | **JÜLICH** | **RWTH** | **UNIFE** | **Total** |
| **Direct Costs**[1] | **Personnel** | PI | 193456 | | | 193456 |
| | | Senior Staff | | | | |
| | | Postdocs | 619060 | 447127 | 376528 | 1442715 |
| | | Students | | | | |
| | | Other | | | | |
| | *i. Total Direct costs for Personnel (in Euro)* | | 812516 | 447127 | 376528 | 1636171 |
| | **Travel** | | 30000 | 30000 | 60000 | 120000 |
| | **Equipment** | | | | | |
| | **Other goods and services** | Consumables | 60000 | 60000 | 60000 | 180000 |
| | | Publications (including Open Access fees), etc. | | | | |
| | | Other: Audits | 6000 | 6000 | 6000 | 18000 |
| | | Other: Workshops | 20000 | | | 20000 |
| | *ii. Total Other Direct Costs (in Euro)* | | 116000 | 96000 | 126000 | 338000 |
| **A – Total Direct Costs (i + ii)** (in Euro) | | | 928516 | 543127 | 502528 | 1974171 |
| **B – Indirect Costs (overheads)** 25% of Direct Costs (in Euro) | | | 232128 | 135782 | 125632 | 493542 |
| **C1 – Subcontracting Costs** (no overheads) (in Euro) | | | 0 | 0 | 0 | |
| **C2 – Other Direct Costs with no overheads** (in Euro) | | | 0 | 0 | 0 | |
| **Total Estimated Eligible Costs (A + B + C)** (in Euro) | | | 1160644 | 678909 | 628160 | 2467713 |
| **Total Requested Grant** (in Euro) | | | 1160644 | 678909 | 628160 | **2467713** |

| | |
|---|---|
| **For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:** | **41,67 %** |

Remarks:

1) UNIFE has higher travel cost than JÜLICH and RWTH, since they frequently have to travel to Forschungszentrum Jülich for tests and COSY beam times.
2) The workshop costs comprise travel support for invited speakers as well as for students.
3) As mentioned previously no equipment cost is included, since the investments are covered by IKP funds. The consumables comprise repair of equipment, spare parts and, e.g., detector gases.