ERC CONSOLIDATOR GRANT 2021

PART B2

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

ELECTRIC DIPOLE MOMENTS: A HIGH PRECISION PATH TO NEW PHYSICS

Symmetries [1] and the breaking of symmetries [2, 3, 4] played an essential role in the foundation of today's Standard Model of particle physics (SM). Electric dipole moments (EDMs) of fundamental particles violate time-reversal and, invoking the CPT-theorem [5], the combined symmetry of charge-conjugation and parity-inversion (CP). More than 70 years ago, E.M. Purcell, N.F. Ramsey and their student J.H. Smith [6] searched for an EDM of the neutron for the first time. Since then, many searches worldwide with increasing sensitivity on neutrons, atoms, and molecules [7, 8] were concluded, so far, without detection.

Intriguingly, the same fundamental CPV interaction provoking an EDM could also be the key for explaining the prevalence of matter over antimatter in our Universe. This well-grounded assertion, also known as baryon asymmetry of the Universe, is based on cosmological observations of the abundance of primordial light elements, baryon acoustic oscillations in the cosmic microwave background, and the absence of a relic antimatter horizon visible through monoenergetic photons from annihilation. An explanation to generate a matter-dominated universe from symmetric initial conditions requires three conditions. Sakharov [9] identified these as:

- Processes violating baryon-number (B) conservation, transforming the original B = 0 symmetric Universe into the Universe with the observed B-number;
- Processes, which violate charge (C) and charge-parity (CP) invariance;
- Departure from thermal equilibrium.

The SM provides with sphaleron processes an effective B-violating mechanism, while the electroweak phase transition, with a single Higgs of mass $125\ \mathrm{GeV}/c^2$ is not a sufficiently strong departure from thermal equilibrium [10], a clear indication for physics beyond the SM (BSM). Here, however, I will only discuss the CPV prerequisite.

CP-violation (CPV) discovered by J. Cronin, V. Fitch, and others in 1964 [4] was completely unexpected and is today an accurately studied effect in the quark sector of the weak interaction and part of the SM as CPV phase of the Cabibbo Kobayashi Maskawa (CKM) matrix [11]. Although this phase is close to maximal [12], it is insufficient for the observed matter-antimatter asymmetry, and the resulting values of all possible EDMs of fundamental particles are far too small [13, 14] for detection anytime soon.

While no new particles were found at LHC yet [15, 16], high precision measurements have access to energies exceeding the reach of LHC by testing indirect effects [17]. Intriguingly, the most substantial evidence for BSM appears in semileptonic B-meson decays with heavy leptons, especially with muons [18, 19, 20], at LHCb, Belle, and BaBar, violating lepton flavor universality (LFU), and in the substantiated evidence of the muon g-2 discrepancy with SM expectations [21, 22, 23]. These striking hints for new physics are incompatible with minimal flavor violation (MFV) in the lepton sector [24]. In effective-field theories, the imaginary part of the Wilson coefficient, see Figure 1, of which the real part gives rise to the g-2 of a lepton, also gives rise to the EDM [25, 26]. This intrinsic connection of the EDM to the g-2 and the tantalizing evidence for LFU violation can only be tested by searching for the muEDM.

The different EDM searches are sensitive to different, unique combinations of underlying CPV sources. These model-dependent interactions at very high energy scales can conveniently be translated to simple contact interactions, parametrized by low energy constants, sometimes called Wilson coefficients, using the framework of effective field theories [27, 28, 29, 30]. A prominent example is Fermi's beta decay theory, where the heavy W bosons are integrated out. Figure 1 illustrates the multiple connections between laboratory measurement of a CPV observable passing through parametrizations, considering, for example C_S and C_T in effective field theories at increasing energies (nuclear, electroweak scale), to finally connect to the in nature realized fundamental theory.

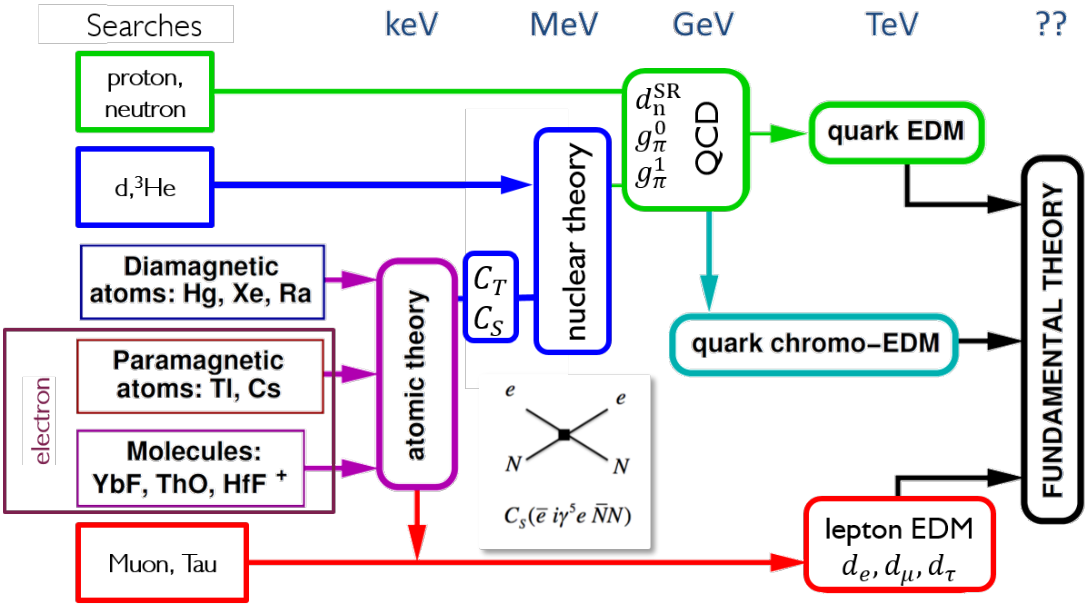

Figure 1: Illustration of the connection between underlying fundamental theories to laboratory measurement, passing through potential effective CPV sources at different energies. Note, that measurements on bare leptons have the cleanest unambigous connection to fundamental interactions.

In recent years, great progress has been made towards searching for charged hadron EDMs in dedicated storage rings [31, 32]. Establishing a dedicated search and making the first measurement of a bare muon's EDM in a table-top storage ring is the present proposal's motivation and background.

A Dedicated Search For an Electric Dipole Moment of the Muon

The search for a non-zero EDM of the muon in a dedicated experiment is a unique opportunity to improve the current sensitivity towards $10^{-23}\ e\mathrm{cm}$ corresponding to:

- roughly three orders of magnitude improvement compared to the current experimental limit;
- a model-independent and complementary search for new physics in the lepton sector;
- a unique test of lepton flavor universality (LFU);
- and sets a first stringent limit on an otherwise poorly constraint Wilson coefficient.

If accomplished, this search will provide a significant advancement towards establishing a new standard model of particle physics.

The muon plays an exceedingly prominent role in unveiling cracks in the SM and might pioneer the experimentally guided foundation of a new physics model. Nearly all substantial evidence found in laboratory experiments for a departure from SM physics involves the muon. For example:

- the g-2 experiment at FNAL, corroborating the discrepancy between SM predicted [22] and experimentally measured anomalous magnetic moment $a_\mu = (g-2)/2$ to 4.2σ $[23, 21]$;
- the departure from LFU in B-meson decays, with $B \to K\ell\ell$ alone showing a 3.1σ evidence [20] and more than 5σ evidence [33, 19] when combining all LFU observable in B-meson decays

- the deficit in the 1st-row unitarity of the CKM matrix with about 4σ evidence [34] may also be interpreted as LFU violation [35].

Electric dipole moments of leptons (electron, muon, and tau) play a unique role, as contrary to nucleon EDMs (proton, neutrons, and heavier nuclei), these are much less susceptible to CPV generated by the vacuum polarization term of QCD [36].

In the past, a dedicated muEDM search seemed less attractive as the impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e < 1.1 \times 10^{-29} e\mathrm{cm}$ (CL 90%) [37], were rescaled, by the ratio m_μ/m_e, assuming minimal flavor violation (MFV). Naïve scaling results in a limit of $d_{\mu\leftarrow e} < 2.3 \times 10^{-27} e\mathrm{cm}$ (CL 90%), which is many orders of magnitude better than the direct limit $d_\mu < 1.5 \times 10^{-19} e\mathrm{cm}$ (CL 90%). However, MFV is a model-dependent assumption allowing a light particle spectrum, in principle observable at the LHC, where this reduces the degree of fine-tuning in the Higgs sector while respecting at the same time flavor constraints. Furthermore, the electron EDM result is deduced, assuming that possible time- and parity-violating electron-nuclear interactions, e.g. $C_s(\bar{e}\gamma^5 e\bar{N}N)$, are zero. Effectively a single measurement is insufficient, and only by combining the measurement with ^{199}Hg, which is sensitive to C_S and nearly insensitive to d_e, a global limit on C_S and d_e may be deduced [28].

In conclusion, the direct search for an EDM of a bare muon probes uncharted territory in BSM theories and makes the result independent from CPV in nuclear and atomic interactions and from MFV assumptions required when relying on the electron EDM results from molecules [37] or molecular ions [38]. The detection of a muon EDM would be a major discovery, comparable to the historical milestones by Wu, Lederman, Cronin, and Fitch, while a null result will serve as an important rail guard for models behind today's standard model.

Observe The Muon Spin Precession Due to the EDM in a Storage Ring

An electric dipole moment, $\vec{d}$ in an electric field will result in a spin precession $\vec{\omega}_e = -2d\vec{E}/\hbar$, where $d = \eta q\hbar/(4mc)$ is the strength of the parity-violating coupling between angular momentum, the spin of the particle, and the electric field $\vec{E}$. In a uniform magnetic field $\vec{B}$, a particle that moves with velocity $\vec{v} = \vec{\beta}c$ perpendicular to $\vec{B}$ will fulfill a closed orbit, and the spin will start to precess around the electric field $E^* = \gamma\vec{v} \times \vec{B}$, with $\gamma = (1-\beta^2)^{-1/2}$, in the restframe of the particle, denoted by $*$. It is convenient to describe the spin motion relative to the momentum vector in a reference frame moving collinear with the particle. In the general case where electric and magnetic fields will be used to steer the beam of particles around a storage ring, the spin precession is described by the T-BMT equation [39, 40, 41]

$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} - \frac{a\gamma(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\gamma+1} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \frac{\gamma c(\vec{\beta}\cdot\vec{E})\vec{\beta}}{\gamma+1}\right]. \quad (1)$$

In the design case of a storage ring, momentum, magnetic, and electric field form an orthogonal basis. Hence equation (1) simplifies to

$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{q}{m}\frac{\eta}{2}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]. \quad (2)$$

The first term describes the spin precession, $\vec{\omega}_a$, of the anomalous magnetic moment, $a = (g-2)/2$, of the particle with magnetic moment $\vec{\mu} = gq\vec{s}/(2m)$. The second term is the electric precession, ω_e, due to an EDM oriented perpendicular to $\vec{B}$. In the presence of a muEDM, the observed frequency will be $\omega = \sqrt{\omega_a^2 + \omega_e^2}$, and a tilt in the precession plane by a tiny angle, $\zeta = \arctan(\eta\beta/(2a))$, will lead to a vertical oscillation phase-shifted by $\pi/2$ with respect to the horizontal precession. The weak decay of muons is inherently parity-violating. Hence, the highest-energy positrons are emitted along with the muon spin, and the precession can be measured by detecting decay positrons with a detector system inside the storage ring.

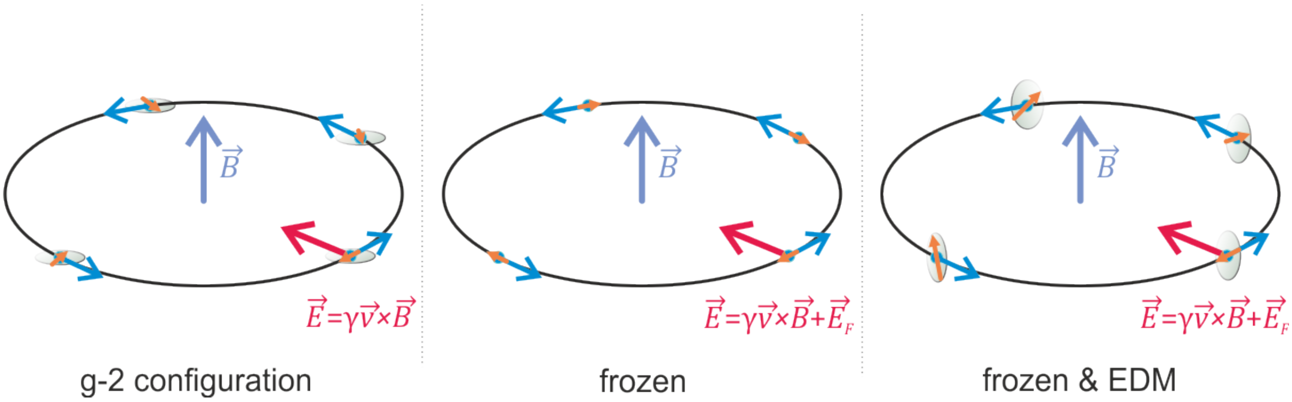

Figure 2: Illustration of spin and momentum evolution in a storage ring. The g-2 configuration uses the magic momentum with $\gamma = (1 - a_\mu)/a_\mu$. In the g-2 configuration the spin (orange arrow) precesses in the plane of the storage ring. Applying the radial electric field, the frozen-spin "frozen" condition is realized and the spin is always aligned with the momentum. In this case, an electric dipole moment will result in a vertical precession out of the storage ring plane.

Previous experiments were built and optimized to measure with the highest accuracy the anomalous magnetic moment $a_\mu = (g-2)/2$. The FNAL/BNL [42, 43, 23] storage ring has a large focusing field index $n \approx 0.1$ and electric fields for electrostatic focusing. Muons with a so-called "magic momentum" of $p = 3.1\mathrm{GeV}/c$ from backward decaying pions are used, cancelling the electric term in equation (1) and making the muon precession to first-order independent of electric fields. Figure 2 on the left illustrates the g-2 precession configuration without EDM. The decay positrons are recorded using calorimeters and straw tube trackers inside the storage ring [23]. It is planned to use the data to search for a vertical oscillation signal to improve the direct limit on the muEDM $|d_\mu| < 1.8 \times 10^{-19} e\mathrm{cm}$ [42] to better than $10^{-21} e\mathrm{cm}$ [44]. Using the magic momentum prevents this experiment from implementing the frozen-spin configuration; hence, the sensitivity to a muon EDM is limited by the resolution of the vertical amplitude, proportional to ζ, of the oscillation in the tilted precession plane.

The J-PARC experiment [45] uses muons with a much lower momentum of $p = 300\mathrm{MeV}/c$ from a reaccelerated thermal muon beam with a thousand times lower horizontal emittance. This permits a storage ring design without an electric field using a high fidelity compact NMR magnet with a magnetic field of $B = 3\mathrm{T}$. In this case, equation (1) simplifies to

$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right]. \qquad (3)$$

Again, the sensitivity to an EDM is limited by the resolution of the vertical amplitude. The g-2 frequency and an eventual EDM signal will be deduced from a measurement of the spiral tracks of decay positrons in the magnetic field using silicon-strip detectors arranged inside the storage orbit. Commissioning of the experiment with an EDM sensitivity of a few $10^{-21} e\mathrm{cm}$ is planned in 2025, while a first result is expected by the end of 2026.

Employ the Frozen-Spin Technique in High Fidelity NMR Magnet

A new technique, significantly increasing the sensitivity to an EDM of the muon, was first proposed in the seminal publication by Farley et al. [46]. It uses an electric field, $\vec{E}_f$, perpendicular to particle motion and the magnetic field fulfilling

$$a\vec{B} = \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}_f}{c}, \qquad (4)$$

and thereby canceling the anomalous precession term of equation (1).

My proposed high precision instrument with an EDM sensitivity goal of $6 \times 10^{-23} e\text{cm}$ [47], is a synthesis of the experiment proposed by Adelman et al. [48] and the vertical injection pioneered by the group of the J-PARC g-2/EDM experiment [49]. We will use muons with a momentum of $p = 125\text{MeV}/c$ and high polarization, $P = 93\%$, from backward decaying pions in the superconduting solenoid of $\mu E1$. The muons will enter the uniform 3T-magnet through a collimating injection channel from the bottom. The magnet's coil package is arranged such that the magnetic field gradient between injection zone and storage zone is less than 3mT/m resulting in a large acceptance phase space. On average, only one muon at a time will enter the spectrometer and spiral up to the central area, where a triggered magnetic quadrupole pulse, field lines sketched in Figure 3, produces a magnetic quadrupole field of about 100ns. Within the storage region the pulsed magnetic field points along the radial direction and turn the muon onto a stable orbit. The matched electric field $\vec{E}_f$ cancels the anomalous precession during storage and in the absence of an EDM the spin perfectly follows the momentum vector. An EDM will result in a precession of the spin along the radial direction, see Figure 2 on the right, and will be detected by tracking the decay positrons using a barrel detector of HV-MAPS detectors. A top and a bottom scintillator will be used to investigate the background and detect muons that punch through the detector's central area. Once a positron is detected or a punch-through is registered, the next muon will be accepted.

We will use clockwise and counterclockwise injected muons to cancel the dominant systematic effects to first order. Remaining systematic effects from

- Radial magnetic fields
- Misalignment of electric and magnetic field
- Periodic azimuthal magnetic field and imperfect canceling of the anomalous precession
- Misalignment of the positron detection system relative to electric and magnetic fields

will drive the final instruments design and define stringent specifications. The most dominant effect will come from unwanted spin precession of the magnetic dipole moment coupling to the radial magnetic field required for weakly focusing. However, using clockwise and counterclockwise propagating muons and binning the asymmetry over an integer multiple of a revolution period will suppress a false signal, while a remaining dilution of the statistical sensitivity might remain due to vertical betatron oscillations.

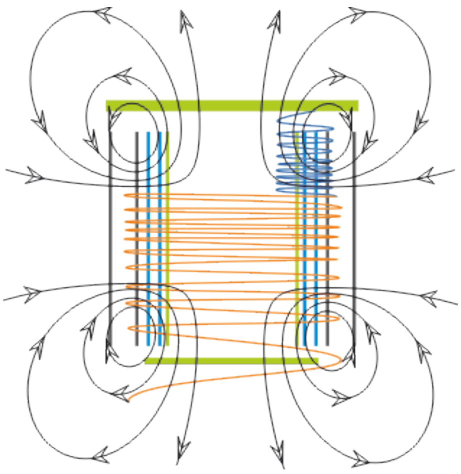

Figure 3: Central part of muEDM spectrometer. Orange spiral: incoming muon, grey vertical lines: electrodes; Blue and green: particle detectors; Vector field lines illustrate the pulsed magnetic quadrupole field.

This high precision experiment does not exist yet. Its detailed technical design, including all relevant hardware, techniques and innovative methodologies, requires a phased approach and an effective collaboration. In particular, it will not be possible to reach the projected ultimate sensitivity goal of this technique in a single step, as the required total financial investment will only become available once the feasibility of all key technologies has been demonstrated and possible risks carefully accessed.

The current proposal, "Search for a Muon EDM using the frozen-spin Technique," will be the first step in this phased approach. The team I will recruit will develop key technologies for the injection and storage of muons and demonstrate the feasibility of the proposed concept by using an existing solenoid magnet with a wide bore at the Paul Scherrer Institute (PSI) for a precursor experiment with a sensitivity of a $3 \times 10^{-21} e\mathrm{cm}$. In particular, two objectives will be pursued (Txx define task numbers):

Objective A: Develop key technologies and design the final instrument (also required for precursor experiment)

- Full Monte Carlo and machine learning surrogate model (T01)
- Full finite element model of magnetic and electric fields including mechanical forces (T02)
- Analysis, data blinding, and DAQ (T03)
- Nested electrode system with a minimal material budget for the frozen-spin technique T(04)
- Pulsed magnetic field to kick muons on a stable orbit (T05)
- Injection channel made of a superconducting shield (T06)

Objective B: Perform a first EDM measurement using an existing solenoid at PSI

- Develop magnetic-field correction coils and field measurement device (T07)
- Develop dedicated positron and muon detectors (T08)
- Demonstrate injection
- Demonstrate for the first time electric-field tuning to frozen-spin condition
- First dedicated frozen-spin EDM measurement

The research will be pursued at PSI, with a newly recruited diverse and gender-balanced team of two post-doctoral researchers and three PhD students. The ERC project proposed here will provide essential guidance for the final instrument design, and acquired know-how and methodology will be a pivotal part of a conception and technical design report of the ultimate instrument. Intermediate results from individual tasks will seed new developments, leading eventually to a next-generation g-2 experiment crosschecking the final FNAL result [23].

Section b. Methodology

The muEDM project is a high-gain enterprise exploring new frontiers in particle physics off the beaten track, requiring thoughtful organization and execution. In the following, I will outline the new team's structure, the necessary developments and test measurements (tasks), and the required hardware, which partially exist at PSI.

All developments accomplished and progress made will be tracked using an internal wiki platform. I will take care that new achievements will be presented timely at conferences and workshops and published in open-access journals. To disseminate results and stimulate new ideas, we will organize a workshop on storage ring EDM searches. Code and data will be made public using the PSI standard open data infrastructure provided by the Swiss national supercomputing center[1]. I will have the lead in all key hardware developments profiting from my experience as technical coordinator of the neutron EDM experiment. Further, I will care of management tasks and organize internal and external audits as part of the PSI beam time allocation procedure.

[1] https://www.cscs.ch/

STRUCTURE OF THE TEAM AND ROLE OF PARTNERS

For this project of 60 months duration, I ask for 72 months post-doctoral positions and 135 months of PhD positions. I will personally supervise the PhD students on a day-to-day basis. They will enroll in PhD programs at ETH Zürich, Switzerland, through Prof. Klaus Kirch, or the University of Pisa, Italy, through Prof. Angela Papa. Prof. Angela Papa will support the required development of scintillator-based muon and positron detectors.
The team will have access to PSI resources. It will be supported by the muon physics group, the detector physics group, the accelerator division for beamline adjustment, magnet design and kicker power supplies, and the laboratory for scientific computing throughout the project. The mechanical and electric workshops at PSI have an excellent record in supporting high-impact particle physics experiments (e.g., nEDM, MEG, muonic atoms); all technical work will be done in-house.

Pivotal to the success of this project is my new dedicated team. In the following, I outline the desired profiles and indicate the tasks described in more detail later.

Post-doctoral researcher PD1 will have excellent skills in computational modeling. In particular, she/he should have worked with standard MC particle transportation codes (e.g., Geant4, FLUKA) and multiphysics finite element codes (Ansys, Comsol, Opera) **task 1&2**. Ideally, she/he has already worked with generic algorithms and applied machine-learning techniques successfully. Further, she/he will be involved in data acquisition and analysis of **task 3** and supporting the PhD students in all computing questions.

Post-doctoral researcher PD2 will have outstanding skills in applied experimental particle physics. In particular, she/he will need to have experience in DAQ, power electronics, and accelerator physics. Her/his focus will be on **tasks 3&4**, establishing a dedicated DAQ system, and supervising PhD2 in developing the pulsed magnetic field**.** She/he will lead the development of the magnetic field measurement device and support PhD students 2&3 the magnetic field coil design of **task 7.** More generally, she/he will support the PhD students in question concerning the technical and experimental realization of key developments.

PhD student PhD1 will have as central mission **task 4**, the development of the quadrupole magnetic pulse and parts of **task 7,** the generation of the weakly focusing field and magnetic field measurements.

PhD student PhD2 will have as central mission **task 5** the development of the injection channel shielded by a superconducting tube, parts of **tasks 7&8,** the development of the muon-entrance trigger, and the correction coil system.

PhD student PhD3 will have as central mission **task 6**, developing the electrode system to generate the electric field for the frozen-spin technique. To test and measure the g-2 precession as a function of the electric field, she/he will also contribute decisively to parts of **task 8,** the development of the positron detection system.

Integrate final year master students from ETHZ into PSI projects is a fruitful tradition and planned for non-time-critical subtasks. In particular, programming of hardware for DAQ, dedicated MC simulations, or participation in tests is well suited to the current project.

During recruitment and throughout the project, I will support gender equality and aim for a diverse team working together with mutual respect and complementing each other's capacities.

FIRST DEMONSTRATION OF A FROZEN-SPIN EDM MEASUREMENT

The PSI provides the world's most intense muon beams at low energies produced by the world's most powerful proton accelerator, the high-intensity proton accelerator, impinging on a carbon target. Pions produced in this reaction quickly decay into muons which then can be transported in secondary beamlines to experimental areas. For the ultimate sensitivity of the final experiment, we require a beam with tiny emittance and high flux at a momentum of about $200\ \mathrm{MeV}/c$. Such a beam does not yet exist but is planned with the advent of the high-intensity muon beam (HIMB) combined with a reaccelerated beam from a cold muon source [50, 51] for the end of the decade.

In 2019/2020, I led the characterization and analysis of the phase space and polarization of two existing beamlines, πE1[2] and μE1[3], which could serve for tests and the precursor experiment and the final measurement using the definite spectrometer, respectively. Both have a high polarization of $P > 0.93$. μE1 has a large vertical and horizontal emittance of about $1000\,\pi$ mm mrad each and provides a flux of up to $2 \times 10^8 \mu^+/s$ at $p = 125\mathrm{MeV}/c$, while πE1 has a five-time smaller emittance and 100 times smaller flux. A muEDM experiment tailored to the μE1 beamline could provide a measurement with a sensitivity of better than $6 \times 10^{-23} e\mathrm{cm}$, an improvement of three orders of magnitude compared to the present result of $d_\mu = (0.0 \pm 0.9) \times 10^{-20} e\mathrm{cm}$ [42]. Both beams are perfectly suited for the precursor experiment to measure an EDM and measurements to characterize and qualify the developments proposed in this grant request. As $\mu E1$ hosts a dedicated instrument which would need to be removed, I will apply for the work described here for test time on the πE1 beamline. Beam time allocation on $\pi E1$ by the particle physics research committee is uncritical.

Figure 4 sketches the precursor experiment using an existing superconducting solenoid, PSC, at πE1. It includes all prototype developments, part of this proposal, necessary for the final experiment: a superconducting injection channel, nested cylindrical high voltage electrodes, and the pulsed magnetic field coil. A dedicated correction coil system is also needed to adapt the field to the required uniformity and provide a weakly focusing field in the center for muon storage. Furthermore, a detection and trigger system based on scintillators and silicon photomultipliers (SiPM) will be deployed to measure the vertical asymmetry, the g-2 precession as a function of the electric field, and to provide a trigger for the magnetic pulse. We will use muons from pion decay at the carbon

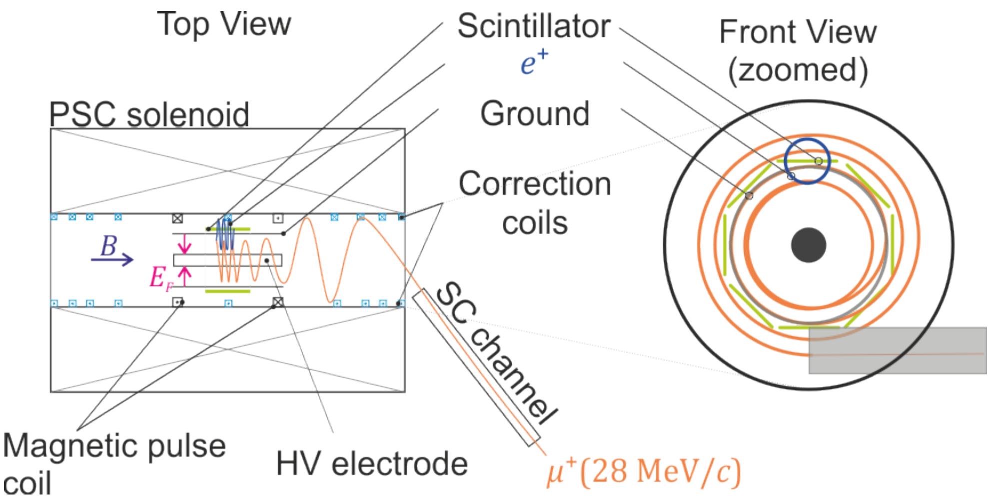

Figure 4: Frozen-spin precursor experiment on $\pi E1$, using an existing superconducting soleonoid (PSC) of the muon physics group. All key developments will be tested individually and a first measurement of the muEDM using the frozen-spin technique will be performed.

target surface with a momentum of $p = 28\ \mathrm{MeV}/c$ injected into a magnetic field of $B = 2\mathrm{T}$ resulting in a radius of about $r = 0.05\ \mathrm{m}$. For the frozen-spin technique, we will apply an electric field of about $E = 2\mathrm{kV}/\mathrm{cm}$. While the better lateral phase space improves the injection, the large magnetic field gradient of the solenoid decreases the efficiency. With a 1% injection efficiency, we reach a

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[2] https://www.psi.ch/en/sbl/pie1-beamline

[3] https://www.psi.ch/en/smus/e1

sensitivity of a $33 \times 10^{-21} e\mathrm{cm}$ in 20 days of measurement, similar to the target discussed for the J-PARC experiment [45].

WORK BREAKDOWN STRUCTURE INTO TASKS

Figure 5 shows an overview of the work breakdown structure into individual tasks with the two deliverables, key developments for the final muEDM instrument, and a first-ever muEDM experiment using the frozen-spin technique.

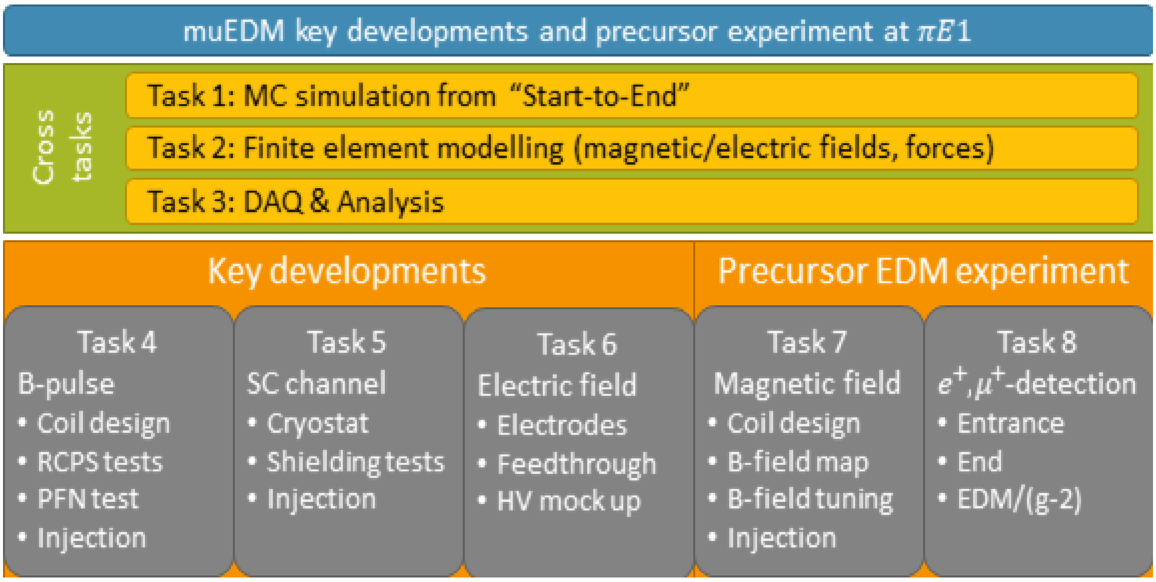

Figure 5: Work breakdown structure of the muEDM project into tasks.Task 1-3 provide support across the entire project, and need to be established in the first three years. Task 4-8 will be performed in parallel. All tasks will be combined in the final precursor measurement of an EDM using the frozen-spin technique.

Task 1: Monte Carlo Simulation of the Entire Experiment

Trajectories of muons and positrons moving in electric and magnetic fields are intrinsically connected and make high-fidelity Monte-Carlo simulations indispensable for a new instrument's successful design. Due to the strong link to task 2, which provides the field configurations for the MC simulation, I will implement an innovative, iterative genetic path for optimization. For this purpose, we will implement a fast algorithm based on machine learning to create a rapidly executing surrogate model of the field configuration and injection parameters [52].

Objectives and deliverables:

- Monte Carlo physics simulation of the final experiment from start-to-end
- Machine learning neural network surrogate model of the final experiment from start-to-end
- Monte Carlo simulation of the precursor experiment from start to end
- Machine learning neural network surrogate model of the precursor experiment
- Provision of MC data to the analysis task

The starting point will be a full physics simulation model from the exit of the pion decay channel, the muon source, to the muon's decay inside the experiment into a positron and its detection. We will create an initial random sample of the parameter space using the full physics model. This sample we use in a generic algorithm to train the surrogate model, a neural network. The results obtained are used in a short genetic optimization using the full physics model to verify and fine-tune the result. This iterative approach will be repeated until a stable solution is reached. Results from the simulation will be benchmarked to test measurements.

Task 2: Finite Element Modelling (FEM) of the Instrument

A final instrument model will be set up, using discrete coil blocks with static currents and dynamic currents in coils generating the magnetic pulse. The electric field will be superimposed by defining electric potentials. The coil placement will be at first optimized using a region of interest and standard single value decomposition into eigenmodes of discrete coils [53]. The field configuration will be further optimized by using an iterative, machine-learning-based process with the MC simulation optimizing a set of observables:

- injection efficiency,
- vertical and horizontal betatron oscillations,
- positron detection efficiency as a function of electrode and positron tracker placement.

This optimized field model will be used to derive an engineering model estimating physical forces and defining the type of superconductor, standard low-temperature NbTi or high-temperature superconducting ribbon, and henceforth temperature requirements.

Objectives and deliverables:

- Detailed 3D em-field model of the final experiment
- Multiphysics model
- Electrical, mechanical, and thermal specifications for engineering model

Task 3: DAQ, Analysis & Open Data

We will design and take into operation a data acquisition for more than 64 scintillating tiles and a slow recording of environmental parameters, for example, magnetic-field sensors, power-supply currents and voltages, and temperatures and vacuum pressures in the precursor experiment. The precursor experiment's main data acquisition needs to meet tight timing requirements with a synchronization frequency of about 10GHz, requiring a common clock generating the experiment's heartbeat.

Objectives and deliverables:

- data blinding and data analysis demonstrated on Monte Carlo data
- data acquisition of the precursor experiment
- publication of data and codes under the PSI open data scheme.

The signal of an EDM is a vertical precession of the spin. Taking the current EDM limit of $d_\mu < 1.8 \times 10^{-19}$, the oscillation term $\sin(\omega_e t + \phi)$ can be approximated by a rising slope, as the initial phase ϕ is small. We will record the decay positrons using vertically segmented scintillating tiles placed around the muon orbit (Task 8). By taking the ratio $A = (\mathrm{up} - \mathrm{down})/(\mathrm{down} + \mathrm{up})$ as a function of time, we can extract a slope. Magnetic field non-uniformities, timing and phase uncertainties, and detector misalignment will complicate the analysis. Therefore, we will study the analysis using toy data from the MC simulation, parametrizing possible effects, and devising mitigation strategies. Another important source of error in any analysis is an unintentional bias favoring a certain result. Thus, we will develop, implement, and test a data-blinding method before starting the precursor experiment. All codes used for data analysis will be documented and saved along with the original data to permit open reuse. Before starting a defined measurement, a digital objected identifier and a metadata folder will be created on the PetaByte archive of the CSCS[4] to prepare open data accessibility. The data will be recorded in a binary file format and stored initially on PSI data servers.

[4] https://www.psi.ch/de/photon-science-data-services/data-catalog-and-archive

After publication, the latest seven years after the end of data-taking, the entire dataset and analysis code will be made publicly accessible on the PetaByte archive.

Task 4: Pulsed magnetic field

The exactly timed and repeated application of the pulsed magnetic quadrupole field to twist the muons onto a stable orbit in the weakly-focusing magnetic field was not yet demonstrated in a similar configuration. Nevertheless, strong magnetic field kicks with a latency of less than 100ns are commonly used in muon-on-request kickers at PSI.

Objectives and deliverables:

- Study of systematic effects due to Eddy currents
- Pulse coil design in final and precursor experiment
- Specification and participation in the construction of the kicker power supply
- Test setup in air/vacuum, magnetic field measurement
- Demonstration of injection and operation in precursor experiment

The magnetic pulse turns the muon around the radial axis by applying a radial field pulse of about $B_r^{\text{pulse}} = 4\text{ mT}$ for a duration of about $t^{\text{pulse}} = 100\text{ns}$, with a pulse shape similar to a half-sine wave. The exact duration will result from optimization (task 1&2), considering that a longer duration is favorable as the electrodes from (task 6) damp the magnetic pulse considerably due to Eddy currents.

Task 5: Superconducting injection channel

A magnetic-field-free region is required to bring muons from the beamline exit into the injection region with a magnetic field of up to 3 Tesla.

Objectives and deliverables:

- Design of test cryostat, which also connects to the precursor's solenoid
- Preparation of superconducting shield made of HTS ribbon wound onto a copper tube
- Preparation of superconducting shield made of sheets from Nb-Ti/Nb/Cu
- Test and characterization measurement in a superconducting solenoid with NMR and Hall probes
- Demonstration of injection through the channel
- Installation and operation in precursor experiment

The injection channel, a collimating, magnetic field-free tube with an inner square cross-section of $10 \times 10\text{ mm}^2$ connects the end of the muon delivery beamline to the 3T injection region at the bottom of the magnet. This technique was pioneered more than fifty years ago by Firth and coworkers for a 1.75T bubble chamber at CERN [54] and used for the BNL/FNAL (g-2) experiment [55]. The principal idea is that once the superconducting shield is cooled below the critical temperature T_c the field within the shield is "frozen" even when the outside field is ramped to its nominal strength. Essentially, ramping the outside field will induce persistent currents inside the superconductor counteracting to the outside field. This effect persists if the shield is sufficiently thick and the shielding current's mean lifetime is long enough. Once the field starts to penetrate, the outside field needs to be ramped down, and the superconducting shield can be reset by warming up above the critical temperature. We will test Nb-Ti/Nb/Cu sheets from the Wigner research center in Budapest embedded in a copper block, and a design based on high-temperature superconducting ribbons/tapes wound helically onto a copper tube. Similar tests [56, 57] showed promising results for the Nb-Ti/Nb/Cu sheets, while the HTS ribbon design did not sufficiently shield against the outside field. We will investigate whether different welding and mounting techniques and more layers of the helical wound HTS result in a sufficient shielding factor, which would be favorable if the final experiment's magnet is deploying HTS coils.

Task 6: Electric field

The accurate application of a radial electric field, matching the frozen-spin condition, is essential for the project's success. This task will develop, test, and implement a nested electrode design made of thin graphite or aluminum-coated Mylar foils and a support structure with minimal radiation length for positrons.

Objectives and deliverables:

- Design of cylindrical, nested electrode system for final and precursor experiment
- A full-scale prototype of the final version for tests
- Full-scale system for precursor experiment
- Assembly of test setup for voltages of up to $\mathrm{U} = \pm 60\mathrm{kV}$ and fields of up to $E = 2\ \mathrm{MV/m}$ in vacuum
- Qualification measurement of prototype and precursor electrode system
- Operation and control in precursor experiment.

The electrode system will be a cylindrical cage covered with a conducting foil. The effective radiation length should be as small as possible to reduce multiple scattering of decay positrons, leading to a misidentification of the track's direction. As the entire setup will be mounted in vacuum, excellent heat conduction needs to be guaranteed, as the energy deposited by induced Eddy currents inside the metal layer from a single magnetic pulse (task 4) might be small, but a repetition rate of about 50kHz will lead to considerable heating.

Task 7: Magnetic field

The design calculations defining the magnetic field is part of task 1&2. In this task, we develop methods and techniques to tune the solenoid field and add a weakly-focusing field in the solenoid center for the precursor experiment.

Objectives and deliverables:

- Specification of the weakly focusing field in the precursor field (together with task 1&2)
- Design of a magnetic field mapping device using NMR and Hall sensors
- Magnetic field map of the precursor solenoid magnet
- Design and realization of a correction and weakly-focusing coil system
- Qualification of the coil system and tuning of currents
- Field control and monitoring during precursor experiment

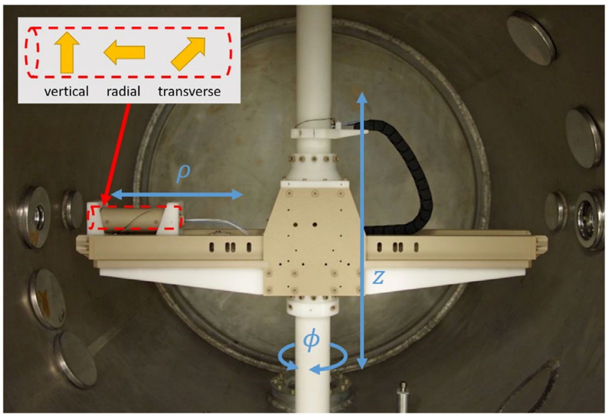

Figure 6: Field mapper in nEDM experiment (image Ref. [58]). A similar 3-axis design will be used to measure precisely the magnetic field of the storage solenoids for muEDM.

The magnetic-field mapping device is essential to measure and fine-tune the magnetic field and design the correction coils. It will feature a central axis with a perpendicular arm on which a cart will move a magnetic field sensor, similar to the one we built and operated for the nEDM experiment [58] at PSI shown in Figure 6. In the muEDM case, the axis will be mounted along the center of the solenoid. In the precursor experiment, we will demonstrate the capability to measure the field with a precision better than 1ppm using an NMR sensor from Metrolab and high precision 3D Hall sensors from lakeshore. The field will be expanded in cylindrical harmonics using a Fourier analysis [59], providing a convenient description of the magnetic field and permitting an efficient design of corrections coils.

Task 8: Positron and muon detection

We will request test beam times to qualify developments in dedicated experiments with muons during all project phases. For the detection of muons during these tests and in the precursor EDM measurement on πE1 we need muon and positron detectors.

Objectives and deliverables:

- Design, construction, and test of scintillator based muon and positron detectors
- Deployment and operation of the muon acceptance trigger in the EDM precursor experiment
- Deployment and operation of positron detectors in test experiments and precursor EDM measurement

To detect muons and decay positrons, we will use scintillating tiles and fibers read out by SiPM, which can be operated in high magnetic fields. The muon acceptance trigger is made of a signal from a thin scintillation tile mounted at the injection channel's entrance. The injection channels inside walls' will be covered with four $1\mathrm{mm}$ thick scintillators to detect muons that enter but do not exit the injection channel. Creating an anti-coincidence between the entrance and channel detectors makes it possible to trigger the pulsed magnetic field only for muons within the divergence defined by the channel's cross-section and length.

In the precursor experiment, scintillating tiles mounted outside of the thin ground electrode detect the decay positron, see Figure 4. The detectors are vertically segmented to permit the measurement of the vertical asymmetry. At the solenoid's far side, a scintillating detector will detect muons punching through the central region. It quantifies the injection efficiency by taking the ratio of detected muons with and without a triggered magnetic field and releases the veto from the acceptance trigger if the muon was not stored.

Risks and mitigation

This project's success builds on my proven experience with high electric and uniform magnetic fields, demonstrated in the high precision measurement of the neutron EDM [60] as technical coordinator and co-spokesperson. I joined the nEDM project in 2009 after my PhD where I developed a UCN source and built a ^{3}He cryostat [61, 62] connected to a beamline for which I performed the Monte Carlo simulations and developed a neutron monochromator for large wavelengths [63, 64, 65]. In my years at PSI, I supervised several innovative developments and measurements [58, 66, 67, 68] and demonstrated creativity in finding innovative solutions by inventing the UCN spin-echo method to measure the energy spectrum of stored neutrons [69]. In summary, I demonstrated my ability to lead and spearhead innovative research projects while also contributing at all levels to detailed and minute developments.

All tasks propose new innovative developments with a non-negligible potential to fail or delay the project. For this reason, I set a special focus on hiring two post-doctoral researchers who complement my skills and expertise with experience in accelerator physics, one with a stronger focus on computing, the other on hardware. If necessary, the accelerator and the muon group at PSI will consult and support.

A serious risk is to find the right balance for the design of thin electrodes. Too thick electrodes will dampen the required magnetic field pulse, making it inefficient or requiring much larger power, while too thin electrodes might melt or evaporate due to Eddy current heating. Dynamic finite element calculations will give a good indication; however, predictions for material thicknesses below 100 μm in large volumes are not reliable. Therefore, we will study the properties of different sheets made of freestanding graphite, metals, and very thin evaporated metal layers on Kapton or Mylar. Another option is to use very thin wolfram wires with small spacing.

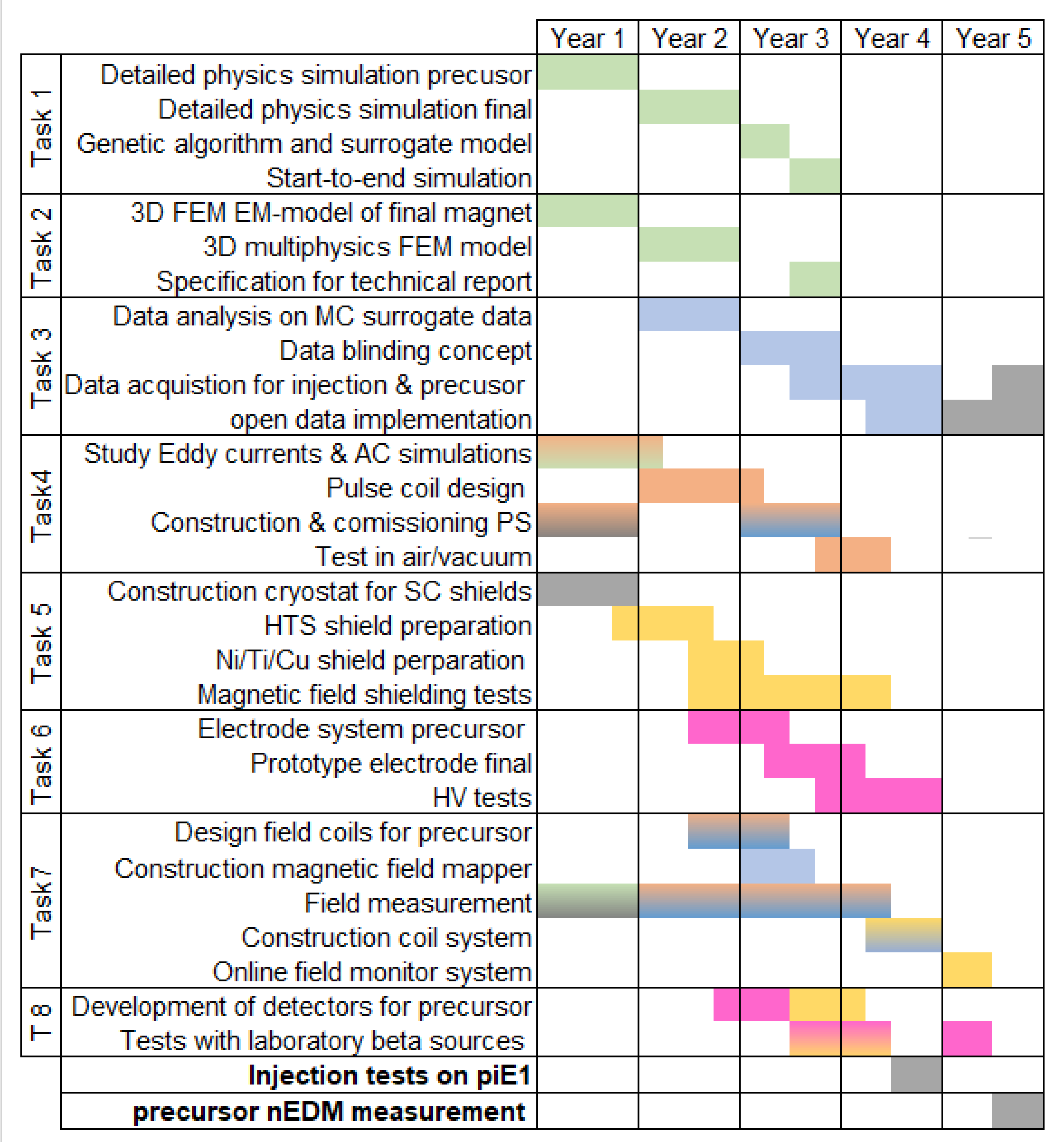

Figure 7: Task schedule indicating team members contributions: PD 1 PD2 PhD1 PhD2 PhD3 principle investigator/all .

A Unique Opportunity for Europe at PSI

This project permits Europe to remain at the forefront in the search for new physics. Combining my excellent skills and knowledge in high-precision experiments searching for an electric dipole moment with the unique muon beams at PSI, this ERC proposal will open the door to test CPV in the heavy lepton sector with muons. Now is the right moment, after the confirmation of the BNL muon g-2 result and the accumulation of hints and evidence for BSM involving muons, to set the sails for a new endeavor in high precision particle physics.

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