Executive summary for “Measurement and Optimization of the Spin Coherence Time for Protons in COSY”

Exp. No.:	Session No.

Collaboration: JEDI Collaboration

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Is support* from the LSF program of the EU requested?

[✓ Yes] ~~No~~

Total number of particles and type of beam (p,d,polarization)	Momentum range (MeV/c)	Intensity or internal reaction rate (particles per second)	
		minimum needed	maximum useful
polarized protons	T = 140 MeV p = 531 MeV/c	10^9	10^{10}
Experimental area	Safety aspects (if any)	Earliest date of Installation	Total beam time (No.of shifts)
COSY ring (JEDI polarimeter, rf solenoid, electron cooler)		no further installation needed	2 weeks MD + 3 weeks experiment

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

***EU-Support:**
The European Commission supports access to COSY for users outside Germany from European and associated states within the STRONG-2020 integrating activity.
For details see http://www.ikp.fz-juelich.de/strong2020.

Description of request (motivation, milestone(s), goals; maximum 5 pages)

Measurement and Optimization of the Spin Coherence Time for Protons in COSY

Updated version of proposal E009

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July 15, 2021

The current strategy for measuring electric dipole moments (EDMs) using storage rings aims at a high-precision all-electric ring with counter-rotating beams running protons. As an intermediate step a demonstrator for key technologies for an electric storage ring as well as for frozen spin is planned. One prerequisite for a successful realization is a large spin coherence time in the order of 1000 s. So far the experimental program at COSY has focused on deuterons. After finishing the second precursor run in spring 2021, we would like to start a similar effort on the spin coherence time for protons by asking for an initial run of 5 weeks of beamtime (2 MD + 3 experiment) during the upcoming scheduling period.

The proposal had been presented initially at CBAC #11 and was then classified as high priority.

1 Introduction

The concept for the storage ring electric dipole moment (EDM) experiment grew out of the work on the precision measurement of the muon magnetic dipole moment (MDM) at Brookhaven. A novel analysis of the storage ring MDM data yielded the lowest value then available for an upper limit on the muon EDM [1]. A sensitive search for EDMs on charged particles could be made using a storage ring to confine the beam [2]. The EDM signal was a rotation of the polarization direction under the influence of a large electric field in the particle frame. It was also recognized that such a storage ring might serve as a general platform to investigate the EDM of several other nuclear species. The result from the muon MDM was just barely inconsistent with theory[1], leading to the expectation that new physics (such as supersymmetry) might be playing a role that would require further investigations such as the EDM search. A proposal was written for a deuteron experiment at Brookhaven [5, 6] that emphasized the added sensitivity of the deuteron nucleus to supersymmetry [7, 8]. This led to work, first at the KVI in Groningen and later at COSY (E174), on highly efficient deuteron polarimetry and the suppression of polarimeter errors [9].

It was clear that systematic error management would be central to the success of the EDM experiment. By comparing EDM-like effects for beams circulating in either direction in the storage ring (an experimental realization of time reversal), a large number of problems could be eliminated. For the deuteron, however, this required that the magnetic field of the storage ring be reversed along with the direction of the circulating beam. An attempt to create common-mode magnets and electric fields for two beams circulating simultaneously led to prohibitive costs. So the goal of the first experiment was changed to the proton EDM [10]. This choice was reinforced with the discovery of a Higgs boson that met Standard Model expectations and no indication in CERN experiments for supersymmetry. Work already underway with deuterons at COSY producing a horizontally polarized beam with a long polarization lifetime continued with the expectation that any results would generalize to the proton case.

Consequently, for several years the JEDI collaboration has performed a number of experiments on prolonging and understanding the spin coherence time (SCT) of cooled and bunched deuterons at a beam momentum of $p = 970\,\mathrm{MeV/c}$. This energy was chosen to optimize the use of the scintillators in the EDDA detector as a beam polarimeter. It has been shown that sextupole configurations leading to small chromaticities in the horizontal and vertical plane result in long SCTs on the order of $\tau = 1000\,\mathrm{s}$ [11, 12]. In order to achieve this a number of tools have been developed to measure the spin coherence time as well as the spin tune[2] in real time and to phase-lock the spin precession to an external rf resonator (rf solenoid, rf Wien filter) [13, 14]. In parallel, new technical equipment has been developed and installed in the COSY ring [15–18]. Systematic studies on ring imperfections and spin dynamics [19–21] and beam based alignment [22] completed these investigations. All the experimental work was accompanied by theoretical studies and lattice simulations of spin and particle tracking [23, 24]. From the accelerator point of view major efforts went into updating the control and monitoring systems of the machine as well as in the development of high intensities and stable beam conditions. Recent beam times showed that once the experimental requirements were met the beam conditions were stable over weeks.

One major goal for the activities with deuterons is a first direct measurement of the deuteron electric dipole moment (EDM) using the waveguide rf Wien filter [25]. A first run took place in Q4 2018, a second one in Q1/Q2 2021. Data analysis is currently in progress. The ongoing work at COSY is also the subject of the ERC Advanced Grant ”srEDM” [26] and the long term strategy for EDM searches utilizing storage rings is de-

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[1] For a summary of the BNL results see [3], recently confirmed and improved at Fermilab [4].

[2] Number of spin revolutions per particle revolution.

scribed in a feasibility study [27, 28] written as input for the discussion on the *European Particle Physics Strategy Update 2018 – 2020* [29, 30] and for the CERN *Physics Beyond Colliders study group* [31]. It foresees a step-wise plan starting with the current COSY activities. The project continues with an intermediate prototype ring as a demonstrator for key technologies for an electric ring as well as for frozen spin, and has as a final goal a high precision all-electric storage ring for protons with counter-rotating beams.

For the proposed EDM measurements a successful realization of a long spin coherence time also for protons is a mandatory requirement. Furthermore, it will verify theoretical predictions of simulations codes and the credibility of the theoretical calculations for these measurements.

A number of things suggest that, compared to the deuteron, the proton is the more challenging case including the increased size of the anomalous moment (and, thus, the speed of precession in the COSY ring), the greater abundance of intrinsic and imperfection spin resonances, and greater complications with the landscape of chromaticity leading to shorter polarization lifetimes. First results of more detailed simulation studies indicate that for the lattice configuration with minimized dispersion in the straights (which was used for the deuteron studies) a long spin coherence time could not be achieved by minimizing the chromaticities. Furthermore, the calculated required sextupole corrections for preserving the spin coherence lead to an unstable beam motion (see Sect. 2). What also needs to be kept in mind is that more polarimeter statistics acquired in shorter times will be needed to follow the proton spin manipulations.

With the beam time we ask for in this proposal we would like to initiate a similar program as we had it for deuterons in the past. During this first beam time and as an important first step all the techniques from the deuteron case have to be transferred to protons: extraction of the beam onto a carbon target by noise extraction to measure the beam polarization, spin rotation by means of the rf solenoid, and, the continuous measurement of the spin tune and the degree of polarisation of the spin-precessing particle ensemble. Subsequently, we can start investigating the effect of the COSY operation parameters (chromaticity, betatron tunes, cooling, lattice symmetries) on the SCT.

As for the proposed investigations a normalized emittance of $\epsilon \leq 1\,\mathrm{mm\,mrad}$ is crucial (see Sect. 2) efficient beam cooling is mandatory. For all previous experiments with deuterons electron cooling was the method of choice and has been continuously optimized. Therefore, we want to keep this cooling strategy for the initial run with protons (at least), although this puts an upper limit of $T = 140\,\mathrm{MeV}$ on the beam energy.

Initially, the parameters will be chosen based on most recent simulation results. The experimental data will then serve as further input to the simulations to properly prepare subsequent runs. While the development of long SCTs for deuterons was a continuous process over several years since 2012, the experience gained during that time should help to keep the total amount of time for protons considerably shorter. In total we estimate three separate runs with three weeks of beam time (excluding MD) each.

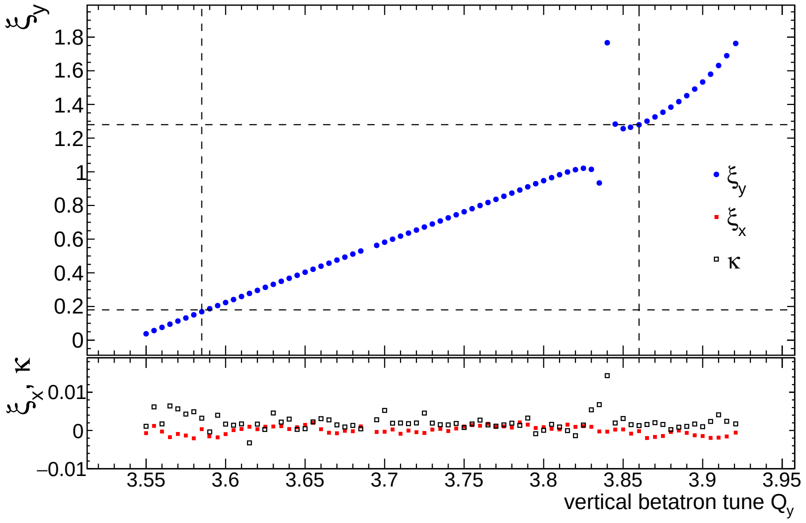

Figure 1: Simulated optimum settings of the chromaticities ξ_x and ξ_y and the second-order momentum compaction factor κ for a minimized spin tune spread as function of the vertical betatron tune Q_y for deuterons. A lattice setup with minimized dispersion in the straights and a deuteron reference momentum of $p = 970\,\mathrm{MeV/c}$ has been used. [32]

2 Spin dynamics

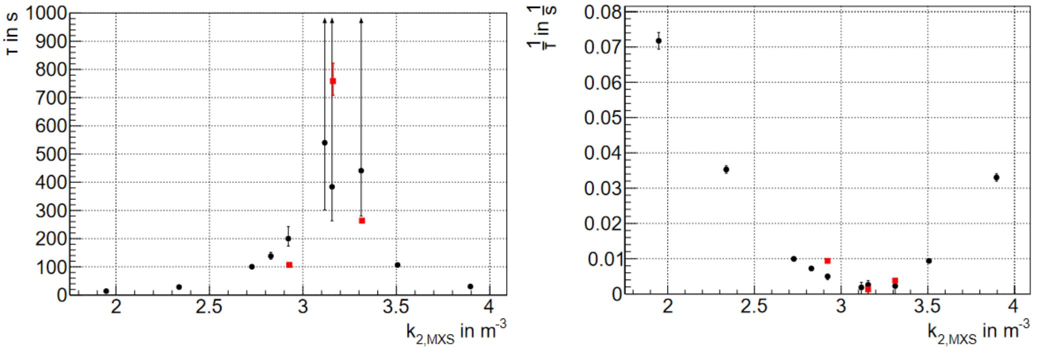

Figure 2: Spin coherence time τ measured for different sextupole settings at betatron tune $Q_y = 3.86$. The right figure illustrates the reciprocal of the SCT. The black circles correspond to runs with shorter, the red squares belong to runs with longer measurement intervals. The maximum SCT is reached at about $k_{2,\mathrm{MXS}} = 3.16\,\mathrm{m}^{-3}$ corresponding to $\xi_y \approx 1.14$. [32]

In general, the spin coherence time (SCT) of an ensemble of particles is determined by the deviations of the spin precession rates as well as the spin precession axes of the individual particles with respect to the reference particle. These deviations have to be kept small in order to achieve a long SCT. Variations in the precession rate (or spin tune) are caused by the impact of path lengthening on the individual particles distributed in the transverse and longitudinal phase space. In addition, intrinsic spin resonances introduce a vertical phase-space dependent tilt of the rotation axis. This is described by the extension of the invariant spin vector (rotation axis of the reference particle) to the invariant spin field, which depends on the phase space position of a particle. If the distance to an intrinsic resonance is large and/or its strength is weak, these tilts become small.

The strengths of intrinsic resonances strongly depend on the amplitudes of the vertical phase space motion. Thus, the spin motion of different particles is affected incoherently, which could introduce spin tune deviations. The impact of a single isolated intrinsic resonance on the spin tune has been discussed in detail in [32]. The simulations also predict a strong dependence of the SCT on the beam parameters like emittances and momentum spread paired with lattice parameters like chromaticities. It has also been shown that the resulting spin tune spread from intrinsic resonances can be compensated by an opposite deviation due to path lengthening by choosing a non-zero vertical chromaticity. For example, for deuterons with a nominal COSY betatron tune of about $Q = 3.6$, there are no strong intrinsic spin resonances that appear close by. Consequently, the calculations predict only a small positive vertical chromaticity ξ_y close to zero (and a second-order momentum compaction factor $\kappa = 0$). The simulations show that if one changes the vertical betatron tune to $Q_y \approx 3.86$, the vertical chromaticity has to be adjusted to roughly ξ_y = 1.29 (see Fig. 1).

In order to verify these predictions, a polarized beam with about 10^9 deuterons per injection was accelerated to its final momentum of 970 MeV/c. The beam was then electron cooled for about 75 s. At the nominal vertical betatron tune of $Q_y = 3.585$ a vertical chromaticity close to zero had to be used to reach a long spin coherence time. In a next step COSY was adjusted to a higher betatron tune. For this, several betatron resonances had to be crossed between the nominal tunes at injection and the desired higher betatron tunes. Additional quadrupoles in the arcs of COSY were utilized to shift the vertical betatron tune up to Q_y = 3.86. Due to beam heating during the betatron resonance crossing, additional electron cooling time was employed to reduce the emittance again after the final betatron tune was reached. With this setup, SCTs of several hundred seconds were experimentally achieved using chromaticities close to the predicted values (see Fig. 2) [32]. This result has been achieved during a night shift at COSY [33].

The effect of intrinsic resonances on the SCT for protons is much stronger. Intrinsic resonances appear at $\gamma G = n \cdot P \pm (Q_y - 2)$, where P is the super periodicity and Q_y the vertical betatron tune. Detailed simulations over a wide momentum range have been performed to further investigate the contributions from the different intrinsic resonances [32]. The results are summarized in Fig. 3. For comparison the deuteron case is shown in the right plot: there is no intrinsic resonance in the momentum range accessible with COSY and the spin tune deviations are in the order of $\nu_s \approx 10^{-9}$. For protons the situation is different: intrinsic resonances cause spin tune deviations that are larger by up to three orders

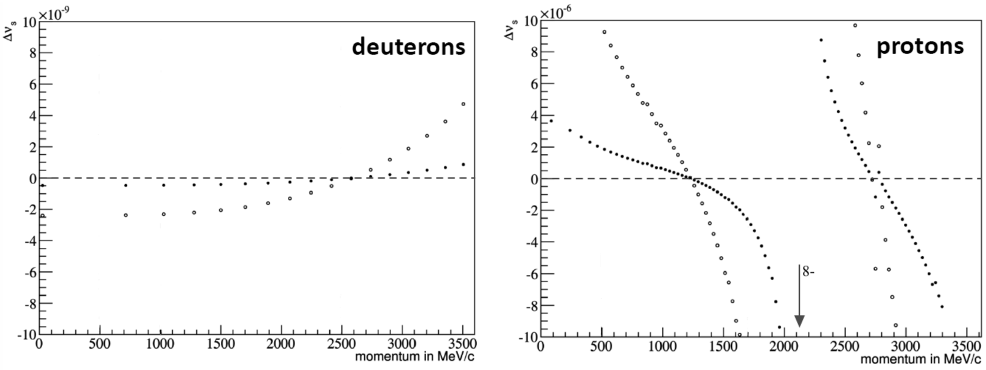

Figure 3: Spin tune deviations as function of beam momentum for a normalized emittance of 1 mm mrad (solid dots) and 5 mm mrad (open dots), respectively. The left plot shows deuterons, the right one protons. For each point an ensemble of 320 particle was randomly distributed in the six dimensional phase space. For protons the location of the 8- resonance is indicated. Note the different scale on the y-axis.

of magnitude. The longest spin coherence times are expected to be reached at the zero crossings. The induced shifts of these zero crossing locations are proportional to the vertical chromaticity, which controls the amount of path lengthening for individual particles induced by intrinsic resonances. Adjusting the vertical chromaticity using sextupole magnets allows one to move the zero crossing location to a desired reference beam momentum. The actual value of the SCT finally depends on the beam emittances and the distance to the zero crossing momenta. However, there are currently no experimental data on proton spin coherence times in order to verify these predictions. Thus, new expertimental data are urgently required to benchmark the spin tracking code for protons with respect to spin tune deviations and spin coherence time.

3 Polarimetry

Proton beam polarization measurements will be made using the JEDI polarimeter (JEPO) [17] by recording proton-carbon forward elastic scattering events. As discussed before, due to cooling contrainsts the beam energy is limited to $T = 140\,\mathrm{MeV}$. While the detector originally has been constructed for deuterons, also for protons at this energy cross sections as well as analyzing powers are large within its acceptance range. A compilation of cross section and analyzing power measurements made between 90 and 200 MeV beam energy are shown in Fig. 4.

The JEDI polarimeter is installed at the site previously used for the EDDA detector. Figure 5 shows two views of the system featuring $3 \times 3 \times 8$ cm^3 LYSO crystals and a 2 cm thick plastic ΔE detector with fine angular resolution. The readout uses SiPM silicon chips. The configuration can measure both horizontal and vertical asymmetries. As target

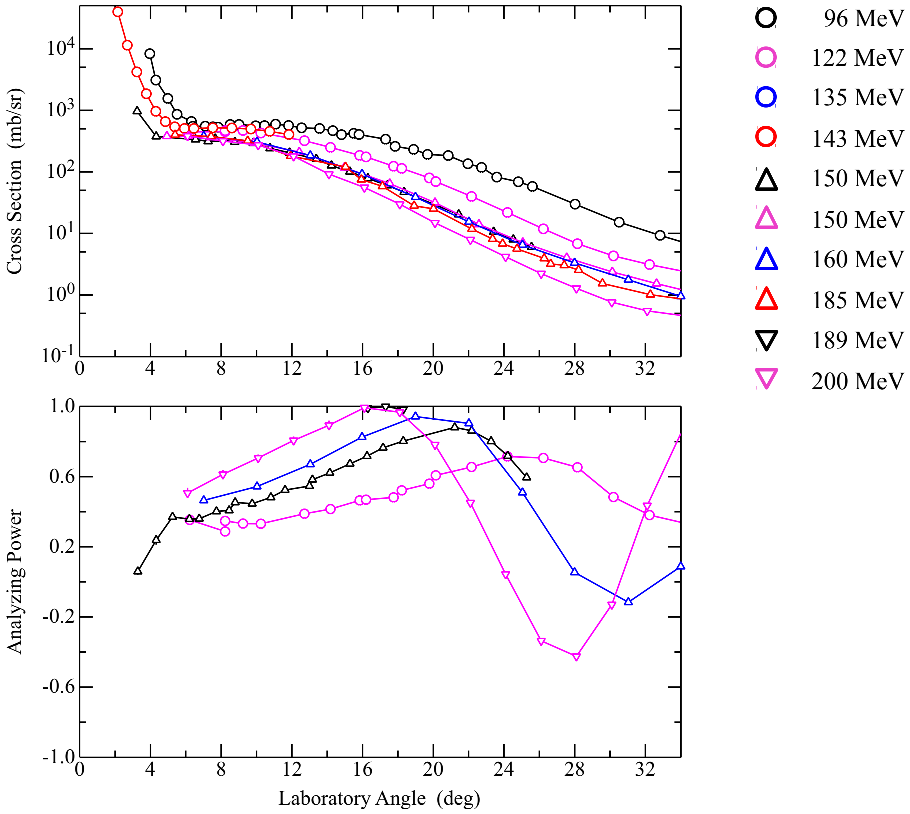

Figure 4: Top: Compilation of measured proton-carbon cross sections for beam energies between 96 and 200 MeV for proton-carbon elastic scattering as a function of laboratory scattering angle. Bottom: Analyzing power as function of the laboratory scattering angle. Data taken from [34–41].

a 2 cm thick carbon block situated next to the beam will be used[3]. Particles from the beam are moved onto the target using beam heating with a white noise source operating on a harmonic of the beam tune.

Figure 6 shows the Geant4 model of the JEDI polarimeter with all of its essential parts. The two-dimensional histograms show the ΔE vs. E spectra for the beam conditions corresponding to the current proposal. The expected energy loss for the elastic events in the plastic scintillator averages to 14 MeV and the total energy deposition in the LYSO crystals corresponds to 107 MeV. These are ideal conditions for the detector to select elastically scattered protons with very high efficiency.

Figure 7 shows the overall acceptance of the JEDI polarimeter for a realistic azimuthal event distribution following the differential cross section at 140 MeV proton beam kinetic energy. The expected detector efficiency with a 90 MeV energy cut in LYSO crystals averages at around 85 %. The detector can be operated in different configurations with slightly different angular coverage. In standard configuration the polar angular range is $4^\circ < \theta < 14^\circ$, in more expanded configuration where the individual arms have been

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[3] The thickness of the target is based on studies done at IUCF [42].

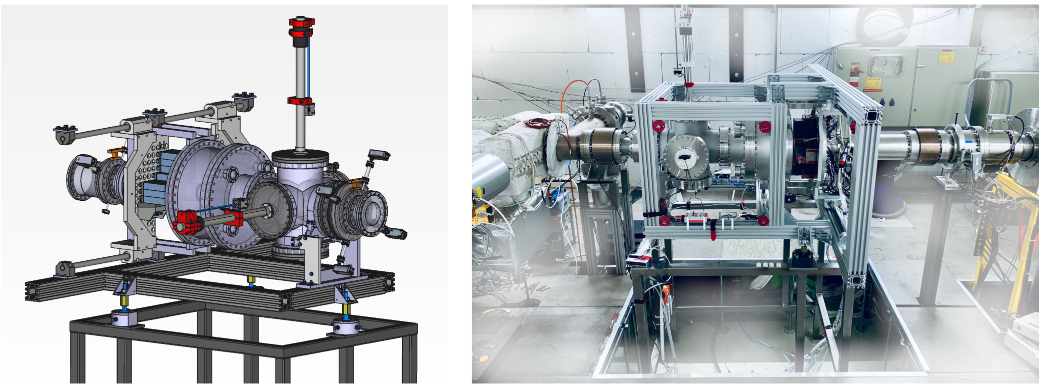

Figure 5: Left: CAD drawing of polarimeter with the vertical and horizontal targets. Right: picture of JEDI polarimeter (JePo) installed in the COSY ring at the former EDDA spectrometer place.

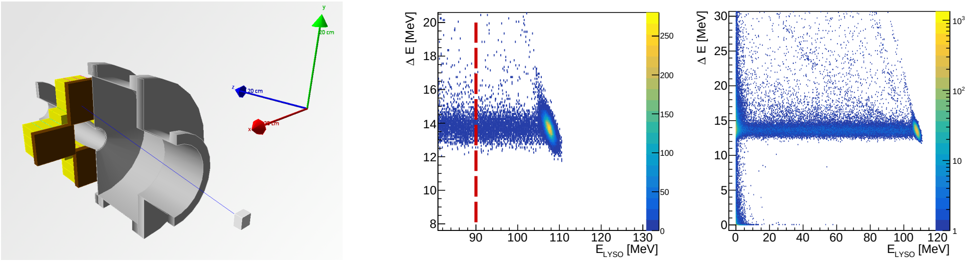

Figure 6: Left: Geant4 model of the polarimeter with a carbon target and LYSO modules shadowed by plastic scintillators. Middle and right: simulated ΔE vs. E spectra for a 140 MeV proton beam for two neighbored (2^{nd} and 3^{rd} row) crystals of the left arm. The red line indicates the energy cut to select elastic events.

shifted outwards it is between 7° and 16°. The overall figure of merit ($\sigma \cdot A^2$) is quite similar for both setups.

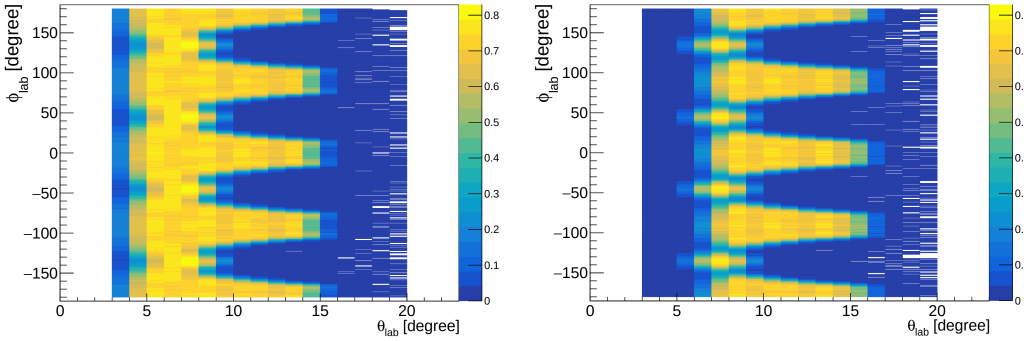

Figure 7: The detection efficiency calculated by the detected to generated event ratio. Left: the LYSO modules are squeezed close to the beam pipe. Right: all arms are shifted outwards by 3 cm to increase the minimum scattering angle. In both cases, the 90 MeV energy cut in LYSO energy is used to select elastic scattering events.

Starting last year the JEPO setup has been used regularly as standard polarimeter for all JEDI beam times (E010, E005.6, E005.7). Continuous spin tune analysis and the determination of the in-plane polarisation by unfolding the spin precession using time stamps has been established. The DAQ and the online analysis also matches the rate requirements of this proposals: event rates of $\gtrsim 10^6\,\mathrm{s}^{-1}$ could be processed.

4 Run plan

While it would be desirable to start at a zero crossing of the spin-tune spread, also other constraints, namely beam cooling and polarimetry, need to be considered. As discussed before this defines the (initial) proton kinetic energy as $T = 140\,\mathrm{MeV}$. While this energy is still higher than the energies of the planned demonstrator ring and lower than the 232.8 MeV ($p = 0.7007$ GeV/c) of the final proton EDM experiment [27, 28], we expect that any results concerning polarization measurement and lifetime can be transferred to different energies and ring lattices once the simulation codes have been validated.

The main goals for the initial beam time are the following:

1. Establish a routine COSY operation with $N \geq 10^9$ polarized and electron-cooled protons at a kinetic energy of $T = 140\,\mathrm{MeV}$ in flat top.
2. Extract the proton beam onto a carbon block target by noise excitation and measure the polarization.
3. Operate the rf solenoid at resonance frequency to rotate the spin into the horizontal plane.
4. Measure — for the first time — the spin tune and the SCT of the proton beam using the same technique as for deuterons.
5. Study the influence of sextupole corrections on the SCT.

6. Verify simulation results and provide a database for benchmarking future simulations.
7. Depending on the results: change the lattice configuration of COSY.

In the following, a more detailed run plan is discussed together with the estimated time needed for individual tasks.

4.1 Machine development

The last COSY beam time with polarized protons was the pC database run [43] in summer 2018; however it was without cooling or a strong demand on the beam intensity. We learned from the deuteron runs that it is advisable to switch off the e-cooler magnets after cooling to establish a better orbit, which needs a special setup. Also, a minimum number of particles of $N \geq 10^9$ is needed to perform a continuous measurement of the horizontal polarization. Furthermore, the EDDA polarimeter — which has been used for monitoring while crossing machine resonances — has been replaced by the LYSO polarimeter since then. In the range up to $T = 140\,\mathrm{MeV}$ intrinsic resonances are not present, however, higher order spin resonances as well as the imperfection resonance at $\nu_s = 2$ ($T = 108\,\mathrm{MeV}$) have to be considered. Taking into account also the time for optimizing the polarized source, this demands a prolonged machine development time of 2-3 weeks. (This already assumes that the initial preparation of the polarized source starts before the machine development as usual.)

4.2 Experiment week 1

The experimental run will start with setting up beam extraction onto the carbon block target by exciting the beam with white noise generated within a narrow band around the betatron frequency. In order to keep the detector rates constant, the so-called “Schneider box” is used, which houses a control loop that connects the detector rate to the noise amplitude. In addition the orbit needs to be adjusted such that (i) the rates in the detector are symmetric for unpolarized beam and (ii) the background in the detector is minimized. This part is completed by optimizing the detector (*e.g.* thresholds, trigger conditions) and starting up the time-stamping system for spin tune and SCT measurements. Once the measurement of the vertical polarization is established, the measurement cycle can be set up. A typical outline is:

t [s]	task
0…5	injection and acceleration
5…75	electron cooling
75…80	switch off e-cooler magnets and set-up orbit
80	start noise extraction onto the target
90	switch on rf solenoid for spin rotation

The next step is to run the rf solenoid at a harmonic of the spin precession frequency ($f_{\mathrm{sol}} = |k + \gamma G| \cdot f_{\mathrm{cosy}}, k \in \mathbb{Z}$) inducing driven oscillations and to identify the best option

kinetic energy	$140\,\mathrm{MeV}$
momentum	$531.3\,\mathrm{MeV/c}$
β	0.49276
γ	1.14921
f_{cosy}	$804736.7\,\mathrm{Hz}$
anomalous magnetic moment G	1.793
spin tune ν_s	2.060
f_{sol} $(k = -1)$	$853309.7\,\mathrm{Hz}$
f_{sol} $(k = -3)$	$756163.6\,\mathrm{Hz}$

Table 1: Basic beam parameters and first estimates for possible rf-solenoid resonance frequencies.

to rotate the spin into the horizontal plane. This includes a number of Froissart-Stora scans as well as a series of fixed frequency runs to locate the resonance frequency and to adjust the rf amplitude.

For kinetic energy of $T = 140\,\mathrm{MeV}$ the basic beam parameters together with possible resonance frequencies for the rf solenoid are summarized in Table 1.

4.3 Experiment weeks 2 and 3

We will start with the standard COSY setting with dispersion zero in the straights and chromaticity zero. With this setup the longest spin coherence times for deuterons were achieved. Measuring the spin decoherence of protons at this point will be a challenge as the SCT might be in the order of seconds or less, but necessary to compare experimental and simulation results for protons and deuterons at similar settings. This means that the rate in the detector has to be increased such that the time bins for extracting the horizontal polarization are small enough to sample a rapidly changing polarization. Compared to the WASA detector, which has been used for the deuteron runs, the new JEDI polarimeter allows trigger rates of at least a factor of 10 larger.

Once the measurement of the spin coherence time is established the COSY parameters will be varied systematically in order to maximize it starting with the sextupoles MXS, MXG and MXL as for deuterons. As predicted, one probably has to adjust the vertical chromaticity to a large positive value to compensate the phase-space dependent effect of intrinsic resonances on the SCT [32].

4.4 Subsequent runs

Based on the results from the first we expect to have two more runs on investigating the proton spin coherence time in the coming years.

The further strategy depends on the results obtained with the standard COSY beam optics and optimized sextupole settings. If a long spin coherence time can not be reached, a dedicated beam optics with high super-periodicity P has to be adjusted in order to minimize the number of intrinsic resonances and/or reduce their strength [44]. At the cooler synchrotron COSY the standard beam optics to accelerate the beam has a reduced super-periodicity $P = 2$, if the two straight sections are matched to a betatron phase advanced of exactly 2π in both transverse directions. After having the quadrupoles in the arcs and straight sections adjusted accordingly, the strength of intrinsic resonance will be significantly lower. This way, a super-periodicity of $P = 6$ can be reached, where only one intrinsic resonance $\gamma G = 8 - Q_y$ will contribute to the spin tune spread. By varying the sexupoles MXS, MXG and MXL in a systematic way, one can again find the best COSY setting for a long SCT.

Another options is to use a different beam energy based on simulation results where intrinsic resonances are less harmful and $\Delta\nu_s \approx 0$. However, as this will likely be a larger change in beam energy compared to the previous setting, it is not possible to estimate the total beam time for this option at this point, as the implications for beam cooling and polarimetry would need to be evaluated based on the selected beam energy.

5 Beam request

In order to make efficient use of the available beam time and personnel — given the overhead for setting up the experimental environment — we ask for **five weeks (two weeks of machine development followed by three weeks of measurement time)** within the current scheduling period using cooled polarized protons at a kinetic energy of $T = 140\,\mathrm{MeV}$.

Within the next years until 2024 we expect to ask for two more blocks of similar size.

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