Proposal

Spin–Filtering Studies at COSY

($\mathcal{PAX}$ Collaboration)

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Abstract

We propose to use an internal polarised target in the COSY ring to determine the polarisation build–up in a proton beam. Spin–filtering experiments at COSY would provide the necessary data to test our present understanding of spin–filtering processes in storage rings.

Measurements of the polarisation build–up of stored protons are crucial to progress towards the PAX goal to eventually produce stored polarised antiproton beams. The availability of intense stored beams of polarised antiprotons will provide access to a wealth of single– and double–spin observables, opening a new window on QCD spin physics. It is planned to realise this experimental programme at the new Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany.

A recent experiment at COSY revealed that $e\vec{p}$ spin–flip cross sections are too small to cause a detectable depolarisation of a stored proton beam. This measurement rules out a proposal to use polarised electrons to polarise a proton beam by $\vec{e}p$ spin–flip interactions. Thus, our approach to provide a beam of polarised protons is based on spin–filtering using an internal polarised gas target.

In total 22 weeks of beam time are needed to complete the experimental program at COSY. We now ask for two weeks of beam time for commissioning of the low–β section and measuring the machine acceptance.

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Contents

1 Introduction

In this proposal the PAX collaboration lays out a plan to measure the polarisation build–up in a proton beam at the COSY ring by spin–filtering with a polarised internal gas target. The proposed staging for the implementation of the experimental setup shall provide a smooth operation of COSY.

The scientific objectives of this experiment are twofold. Despite the fact that a proof of the spin–filtering principle has already been produced by the FILTEX experiment at the TSR–ring in Heidelberg with a proton beam of $T_\mathrm{p} = 23\,\mathrm{MeV}$ [1], a measurement of the polarisation build–up at COSY yields values for the proton–proton spin–dependent total cross sections at different energies, thus allowing us to match these cross sections to the spin–filtering process involving machine related issues. Therefore, spin–filtering experiments at COSY would provide the necessary data to test and improve our present understanding of spin–filtering processes in storage rings.

Secondly, understanding of the spin–filtering processes in storage rings would allow us to pave the way to produce stored polarised antiproton beams, which will open a window to a new unique physics, apart from the obvious interest for the general theory of $\bar{p}p$ interactions. Therefore, we would like to commission the setup, which will be used for the experiments with antiprotons at AD (CERN) [19, 22]. These measurements in turn will allow to define the optimum parameters of a future, dedicated large–acceptance Antiproton Polarizer Ring (APR). The latter is intended to feed a high–luminosity double–polarised asymmetric $\bar{p}p$ collider with polarised antiprotons, which would provide a unique laboratory to study transverse spin physics in the hard QCD regime. Such a collider has been proposed by the PAX Collaboration [2] for the new Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany, aiming at luminosities of $10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

A spin–$\frac{1}{2}$ beam could also be polarised if particles in one spin state would be moved into the other state (by spin flipping). The advantage over the spin filter method is that the precious stored beam is conserved by this process. However, a very recent dedicated experiment at COSY, in which the depolarisation of a stored, polarised proton beam scattering from unpolarised electrons, was measured, rules out the prospect of using spin flip to polarise a stored beam [3].

Thus, at this time, spin–filtering is the only known method that stands a reasonable chance of succeeding in the production of a stored beam of polarised particles.

2 Proposed Measurements

That a stored beam can be polarised by spin–filtering has been demonstrated in the FILTEX experiment at TSR, Heidelberg [1]. In this experiment, a 23 MeV stored proton beam was passing through an internal transversely polarised hydrogen gas target with a thickness of 6×10^{13} atoms/cm^2. The polarisation build–up of the beam as a function of filter time t can be expressed as [1]

$$P(t) = \tanh(t/\tau_1)\ , \tag{1}$$

provided that the effect of depolarising resonances can be neglected on a time scale of τ_1. Here, τ_1 is the polarising time constant. The induced beam polarisation is parallel to the target polarisation. In FILTEX, a polarisation build–up rate of

$$\frac{\mathrm{d}P}{\mathrm{d}t} \approx \frac{1}{\tau_1} = 0.0124 \pm 0.0006 \text{ per hour} \tag{2}$$

has been observed.

The polarisation build–up has been interpreted in terms of the known *pp* spin–dependent interaction (see, e.g., [3, 4]). It can be shown that the time constants for transverse (⊥) or longitudinal (||) filtering are given by, respectively

$$\tau_1^{\perp} = \frac{1}{\tilde{\sigma}_1 Q d_t f} \quad \text{and} \quad \tau_1^{||} = \frac{1}{(\tilde{\sigma}_1 + \tilde{\sigma}_2) Q d_t f} \; . \tag{3}$$

Here, Q is the target polarisation, d_t the target thickness in atoms/cm^2 and f the revolution frequency of the particles in the ring. Knowledge of these parameters is crucial during spin–filtering experiments. The "filtering cross sections" $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$ are closely related to the spin–dependent total cross sections, σ_1 and σ_2, defined in the expression for the total hadronic cross section $\sigma_{\rm tot}$:

$$\sigma_{\rm tot} = \sigma_0 + \sigma_1(\vec{P} \cdot \vec{Q}) + \sigma_2(\vec{P} \cdot \hat{k})(\vec{Q} \cdot \hat{k}) \; , \tag{4}$$

where σ_0 denotes the total spin–independent hadronic cross section, σ_1 the total spin–dependent cross section for transverse orientation of beam polarisation P and target polarisation Q, σ_2 denotes the total spin–dependent cross section for longitudinal orientation of beam and target polarisations. (Here we use the nomenclature introduced by Bystricky, Lehar, and Winternitz [5], where $\hat{k} = \vec{k}/|\vec{k}|$ is the unit vector along the collision axis.) The difference arises because protons that scatter at a sufficiently small angle remain in the ring. This is the case for scattering events with θ less than the acceptance angle $\theta_{\rm acc}$ of the machine downstream of the target.

The acceptance angle can be determined by [10]:

$$\frac{1}{\theta_{\rm acc}^2} = \frac{1}{2\theta_{\rm x}^2} + \frac{1}{2\theta_{\rm y}^2} \quad \text{with} \quad \frac{1}{2\theta_{\rm x,y}^2} = \frac{\beta_{\rm x,y}}{A_{\rm x,y}}, \tag{5}$$

where $\beta_{\rm x,y}$ are the horizontal and vertical beta functions at the measuring spot and $A_{\rm x,y}$ the ring acceptances in the horizontal and vertical plane. Here it is assumed that the betatron oscillations in both planes are completely decoupled.

In order to extract both spin–dependent total cross sections σ_1 and σ_2 from the observed time constants [Eq. (3)], a measurement with transverse and longitudinal target (and therefore beam) polarisation is required. The latter involves the operation of a Siberian snake. In addition, the acceptance angle $\theta_{\rm acc}$ has to be known (see Sec. 3.1), because the spin–dependent filtering cross sections $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$ depend on $\theta_{\rm acc}$. Therefore, Coulomb–nuclear interference at extreme forward angles $\theta < \theta_{\rm acc}$ must be taken into account. For protons, where the interaction is purely elastic, this is accomplished using the existing NN scattering databases SAID [6] and Nijmegen [7].

In order to determine σ_2, the stable beam spin direction has to be longitudinal at the position of the Polarised Internal Target (PIT). The use of two solenoid belonging to the COSY electron cooler and WASA experiment, both located in the straight section opposite to the PAX place, are able to provide longitudinal beam polarisation for the PAX experiment at COSY. Since COSY has never been operated with longitudinally polarised beam, it is absolutely necessary to check first if it works. Therefore, a longitudinaly polarised beam has to be injected into the ring. This requires an installation of extra solenoids in the Injection Beam Line (IBL) to match the spin direction of the beam to the stable one of the COSY ring.

The primary quantity measured in this experiment is the polarisation of the stored beam. Because the analysing power in *pp* scattering is not larger than few per cent in the energy region where sizeable build–up can be obtained (see Fig. 1 in Sec. 3.4), the technique we propose assumes using an unpolarised deuterium gas injected into the target cell after filtering is completed. The analysing power in *pd* is large, it is well measured at $T_\mathrm{p} = 49.3\,\mathrm{MeV}$, and the measurement of the beam polarisation becomes straightforward, as we have demonstrated during the depolarisation studies at COSY [3].

3 Machine Properties

3.1 Acceptance and Beam Lifetime

For the planned PAX experiment to polarise the circulating proton beam a long beam lifetime is necessary. The stored beam intensity decreases with time because of reactions and scattering outside the machine acceptance. Most of these effects occur in the internal target, although general vacuum conditions do play an important role as well. The beam lifetime thus depends on the target thickness. For a given production rate of polarised atoms, the target thickness depends on the diameter of the storage cell. In certain cases, the opening of the storage cell, in turn, affects the machine acceptance, and one is faced with an optimisation problem. Possible optimisation criteria are the polarisation build–up rate, the beam remaining after filtering, or the statistical accuracy of the polarisation measurement. At COSY, nevertheless, once the low–β insertion is built (see Sec. 4.2), a cell of 10 mm diameter does not limit the ring acceptance even at injection (see Fig. 4, right panel). Among other limiting factors affecting the beam lifetime one can note lattice settings, tunes, chromaticity, possible orbit distortions, cooling performance, transverse beam oscillations due to instabilities.

In order to measure and optimise the ring acceptance dedicated studies have been carried out [8, 9] under various conditions, beam energy, tune, lattice setting, orbit, target thickness, proton beam intensity, and electron beam current. In addition, the application and test of a newly developed orbit correction procedure to reduce the large orbit distortions typical for COSY at injection energy was realised.

To achieve long beam as well as long polarisation lifetimes, one has to avoid machine and depolarising resonances. Before relevant measurements were done, tunes with best lifetimes were searched by a tune scan for different lattice settings of the ring.

During several measurements it has been discovered that the reduction of the orbit distortions and the accurate tuning of the chromaticity have a large effect on the COSY acceptance, allowing to increase the initially measured $14\,\mu$m acceptance at injection energy to more than $25\,\mu$m in both x and y.

It can also be stated, that the COSY vacuum conditions are the serious limiting factors for the future PAX polarising experiments with a target thickness around $0.5 \cdot 10^{14}\,\mathrm{atoms/cm^2}$ in the low–β section. The low–β section will increase the pure target lifetime but not the lifetime due to the residual gas in the ring. So far, the typical proton beam lifetime at injection of $t = 1.1\,\mathrm{h}$ could only be improved to $t = 1.7\,\mathrm{h}$ with the increased machine acceptance. Any further improvement, *e.g.* a possibility of baking the arcs, would seriously help spin–filtering experiments.

3.2 Beam Intensity

Keeping in mind that after spin–filtering for a few beam lifetimes a substantial remaining beam intensity is needed in order to measure the beam polarisation, it is fairly important to dedicate some development effort towards increasing the number of protons stored. Calculation show that the intensity limit in the COSY ring due to the space charge is close to 10^{11} protons per spill, thus, spin–filtering has to start with similar values.

3.3 Polarisation Lifetime

The spin tune is the number of rotations of the magnetic moment of a particle during one revolution. Depolarising resonances arise when the horizontal and vertical tune, the orbit frequency and the synchrotron frequency, or combinations thereof, are related in a simple way to the spin tune. As an example, an "intrinsic" resonance occurs when the (*e.g.*) horizontal tune and the spin tune are an integer multiple of each other. More complicated resonance conditions are possible and lead to (usually weaker) resonances. Near a resonance, the spin motions of individual particles start to differ, and the beam depolarises.

Experimental studies of the polarisation lifetime in a storage ring have been carried out at the Indiana Cooler [11, 12]. It was found that the polarisation lifetime increases rapidly with distance from the resonance, and quickly becomes so long as to be difficult to measure. Thus, for the cooler experiments it was sufficient to avoid the immediate proximity to any low-order resonance.

3.4 Expected Polarisation Build–Up in COSY

The polarisation build–up rate, which can also be interpreted as polarising cross section [see Eq.(3)], from spin–filtering including nuclear elastic scattering and Coulomb–nuclear interference can be expressed as:

$$\tilde{\sigma}_1(\theta > \theta_{\rm acc}) = 2\pi \int_{\theta_{\rm acc}}^{\theta_{\rm max}} \frac{{\rm d}\sigma}{{\rm d}\Omega} \left[A_{\rm 00ss} + A_{\rm 00nn}\right] {\rm d}\Omega, \quad (6)$$

$$\tilde{\sigma}_1(\theta > \theta_{\rm acc}) + \tilde{\sigma}_2(\theta > \theta_{\rm acc}) = 2\pi \int_{\theta_{\rm acc}}^{\theta_{\rm max}} \frac{{\rm d}\sigma}{{\rm d}\Omega} A_{\rm 00kk}\, {\rm d}\Omega, \quad (7)$$

for transverse and longitudinal cases, respectively. Here Bystricky notation is used [5]. $\theta_{\rm max}$ is the maximum kinematically allowed angle. These quantities can be easily calculated using existing NN scattering databases SAID [6] and Nijmegen [7].

The four other important ingredients to derive beam polarisation from spin–filtering are:

1. the revolution frequency, precisely known at the time of experiment;
2. target density, which can be determined during experiment;
3. polarisation of the target. A special care has to be taken to measure and continuously monitor this parameter, as explained in Sec. 5;
4. machine acceptance angle $\theta_{\rm acc}$ at the target. It has to be measured in a dedicated experiment.

For the calculation of the anticipated polarisation build–up at $T_{\rm p} = 49.3\,{\rm MeV}$ the following target parameters have been assumed: polarisation $Q = 0.8$ and the areal density of $d_{\rm t} = 5 \cdot 10^{13}\,{\rm cm}^{-2}$. From the measured machine acceptance of $A_{\rm x,y} = 25\,\mu{\rm m}$ and projected β–functions (see Fig. 4) the acceptance angle at the target of $\theta_{\rm acc} = 8.4\,{\rm mrad}$ can be deduced [Eq.(5)].

The results of these calculations for spin–filtering for two beam lifetimes are shown in Fig. 1 for transverse (left) and longitudinal (right) beam polarisations for different energies. Realistic beam lifetimes due to residual gas are assumed. The dashed box displays the available COSY electron cooling range. The magenta curve (denoted with **1**) corresponds to the standard non–optimised COSY settings we have reported earlier during PAC session #36, the black one (**2**) is the realistic calculation with current optimum COSY settings. The blue curve (**3**) is obtained for the same conditions as the black one, only the beam lifetime due to the residual gas in the ring is twice the current value ($\tau = 3.3\,{\rm h}$).

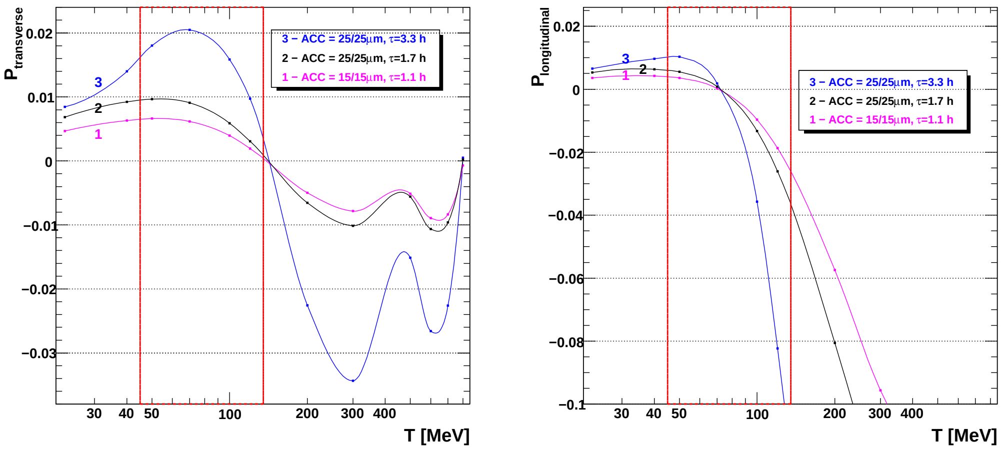

Figure 1: Calculated beam polarisation after two beam lifetimes of filtering (corresponding to a decrease in the number of stored protons by a factor of about $e^2 \approx 7$) as function of the beam energy. The panels on the left and on the right are for transverse and longitudinal polarisation, respectively. The magenta line (1) corresponds to the beam settings without optimisation (as presented at COSY-PAC #36), the black line (2) depicts the current conditions with optimised COSY settings, the blue one (3) stands for the same rings settings as (2), but with the beam lifetime due to the residual gas only improved twice. The red rectangle displays COSY electron cooling range.

It is obvious that the effect we are going to measure is small. Nevertheless, the optimum filtering time does not necessarily have to be equal to two beam lifetimes, the time evolution of the polarisation is roughly linear for small times (see Fig. 2). Therefore, one can filter longer and measure with just enough particles in the ring to determine beam polarisation after filtering. If $5 \cdot 10^{10}$ protons are initially injected, after four beam lifetimes – corresponding to a decrease in the number of stored particles by a factor of $e^4 \approx 55$ – one still has 10^9 protons to perform the measurements of the beam polarisation.

4 Experimental Setup

4.1 Overview

The measurement requires implementing a Polarised Internal storage cell Target (PIT) in the straight section. The target density depends strongly on the transverse dimension of the storage cell. In order to provide a high target density, the β–function at the storage cell should be about $\beta_x = \beta_y = 0.3$ m. In order to minimise the β–functions at the cell, a special insertion is proposed, which includes additional quadrupoles around the storage cell (see Fig. 3). The low–β section should be designed in such a way that the storage cell does not limit the machine acceptance. We will utilise the PIT formerly used at HERA/DESY [13, 14], which has already become available at the beginning of 2006, to feed the storage cell. The target will be operated in a weak magnetic guide field of a about 10 G. The orientation of the target polarisation can be maintained by a set of Helmholtz coils in transverse (x or y) and longitudinal (z) directions.

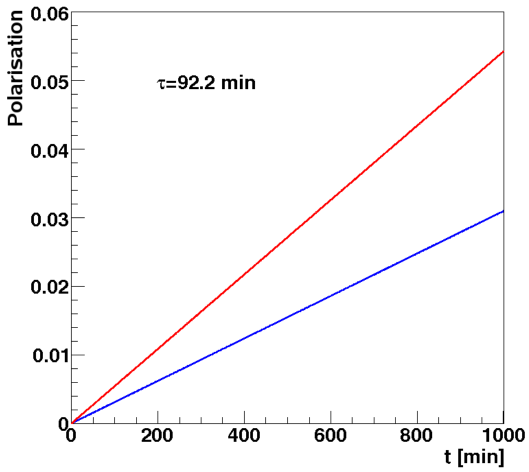

Figure 2: Time evolution of the beam polarisation for transverse (red) and longitudinal (blue) as function of the filtering time. The calculations are performed at $T_{\mathrm{p}} = 49.3\,\mathrm{MeV}$ for realistic COSY settings. A beam lifetime of $\tau = 92.2\,\mathrm{min}$ includes effects of both the target and the residual gas.

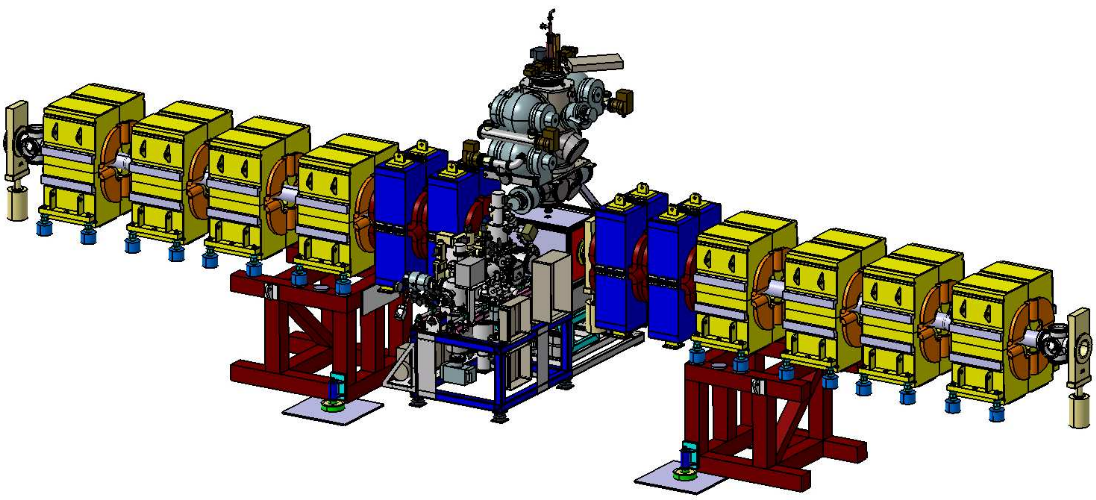

Figure 3: Full installation foreseen at COSY. Shown in yellow are the existing COSY quadrupole magnets that define the up and downstream boundaries of the low-β insertion. The magnets shown in blue are former CELSIUS quadrupole magnets. The atomic beam source is mounted above the target chamber that houses the detector system and the storage cell. Three sets of Helmholtz coils providing magnetic holding fields along x, y, and z are mounted on the edges of the target chamber (brown). The Breit-Rabi target polarimeter is mounted outward of the ring. Fast shutters are used on the target chamber on all four main ports.

4.2 Low–β Section

The operation of the polarised target requires transporting the stored beam through the narrow storage cell. Since at injection into COSY, the beam is not yet cooled, the apertures in the target region shall not be restricted by the storage cell. The machine optics at injection energy in terms of the betatron amplitudes in the low–β insertion are depicted in Fig. 4 (left), and the beam envelopes $E(x)$ and $E(y)$ in the cell region, based on the β–functions and the machine acceptances from the lattice model of COSY using $E(x, y) = \sqrt{A_{x,y} \cdot \beta_{x,y}}$ are shown in Fig. 4 (right).

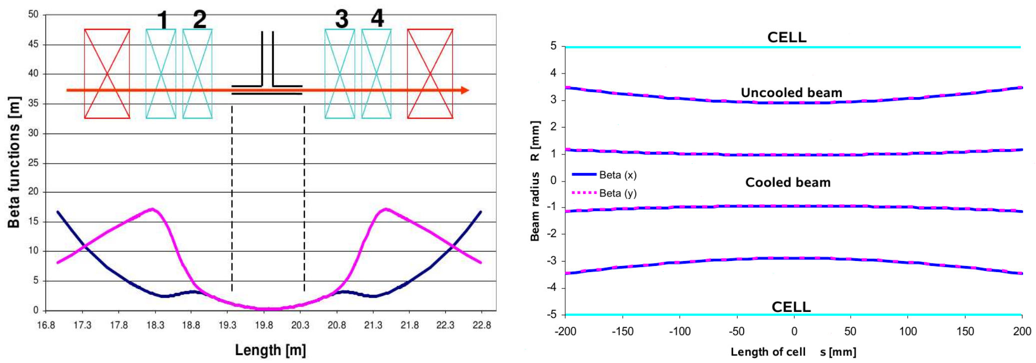

Figure 4: **Left**: Twiss β functions in the low-β insertion for the PAX installation at COSY at injection energy. The blue curve denotes β_x, the magenta one β_y. **Right**: Beam envelops in the storage cell region at injection energy with electron cooled and uncooled beams.

The low–β section comprised of four additional quadrupole magnets (blue ones in Fig. 3), which can be switched on adiabatically, four steerer magnets mounted directly on the surrounding COSY quadrupoles, a Beam Position Monitor (BPM), and fast shutters will be installed together with the improved vacuum system in this section.

4.3 Polarised Internal Target

Polarised internal targets represent nowadays a well established technique with high performance and reliability shown in many different experiments with hadronic and leptonic probes. Targets of this kind have been operated successfully at TSR in Heidelberg [15], later on they were also used at HERA/DESY [14], at Indiana University Cyclotron Facility and at MIT–Bates. A new PIT is presently operated at ANKE–COSY [16, 17]. A recent review can be found in Ref. [18]. Typical target densities range from a few 10^{13} to 2×10^{14} atoms/cm^2 [14].

The PAX target arrangement is depicted in Fig. 5. It consists of an Atomic Beam Source (ABS), a storage cell, and a Breit–Rabi polarimeter (BRP). H or D atoms in a single hyperfine–state are prepared in the ABS and injected into the thin–walled storage cell. Inside the target chamber, the cell is surrounded by the detector system (see Sec. 4.5). A small sample of the target gas propagates from the centre of the cell into the BRP where the atomic polarisation is measured. Simultaneously the sampled gas enters the Target Gas Analyzer (TGA) where the ratio of atoms to molecules in the gas is determined. A weak magnetic holding field of $\sim 10\,\mathrm{G}$ around the storage cell provides the quantisation axis for the target atoms (coils indicated in brown on the edges of the target chamber in Fig. 5); it can be oriented along the horizontal (x), vertical (y), or longitudinal (z) direction.

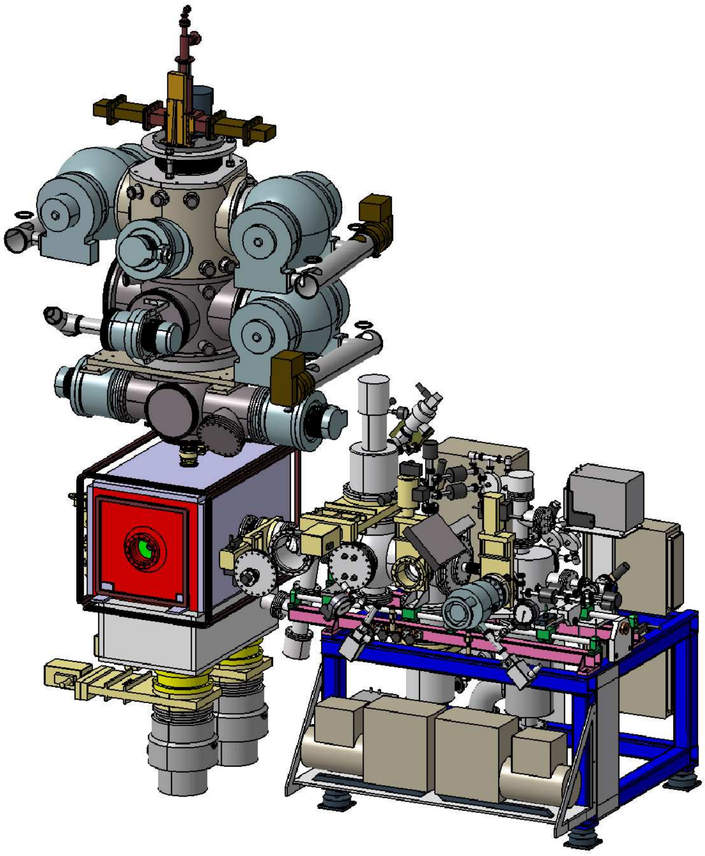

Figure 5: The PAX target at COSY. The atomic beam source (ABS) is mounted on top of the target chamber which houses the storage cell and the detector system. The proton beam passes through the target from behind. The Breit–Rabi polarimeter (BRP) on the right is fed by a small sample beam extracted from the storage cell.

4.4 Target Chamber and Vacuum System

The target chamber hosts the storage cell and the detector system. The target section has to be equipped with a powerful differential pumping system, that is capable to maintain good vacuum conditions in the adjacent sections of COSY. The vacuum system of the target chamber includes two turbo molecular pumps with 1600 ℓ/s pumping speed, backed by smaller turbo molecular pumps and a dry fore vacuum pump. In addition, a large cryogenic pump with a nominal pumping speed of about 20000 ℓ/s, mounted directly below the target chamber, presently developed by the Gatchina group, will ensure that most of the target gas exiting the storage cell is pumped away in the target chamber (see Fig. 6).

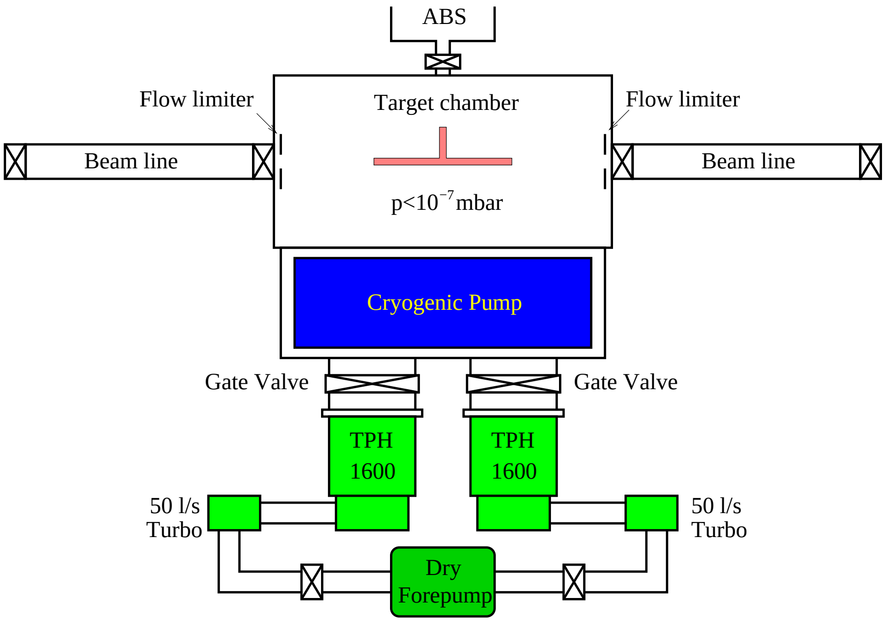

Figure 6: Vacuum system at the target chamber.

Movable flow limiters installed between the target chamber and the adjacent up– and downstream beam pipes reduce the gas load into these sections. These beam pipes will be coated with Non–Evaporable Getter (NEG) material to ensure a pumping speed per section of ≈ 2500 ℓ/s. It is necessary to activate and regenerate the NEG material at temperatures of 230–250°C. Assuming an atomic beam intensity of 6×10^{16} atoms/s (two states injected) and a pumping speed of 20000 ℓ/s in the target chamber, the expected chamber pressure during target operation would be about 6×10^{-8} mbar. With flow limiters of 30 mm diameter at the exit and entrance of the target chamber, the total flux from the storage cell and the target chamber into the adjacent beam pipes will correspond to about 5×10^{14} molecules/s, resulting in a pressure in the 10^{-8} mbar range in the up– and downstream sections.

4.5 Detection System

The PAX collaboration is setting up a detector system to determine the polarisations of beam (or target) by measuring the polarisation observables in elastic scattering.

The detector has to meet the following requirements:

1. provide a measurement of polarisation observables;
2. operate in vacuum to track low–momentum particles in the kinetic energy range from a few to a few tens of MeV;

3. provide large coverage of solid angle and luminous volume.

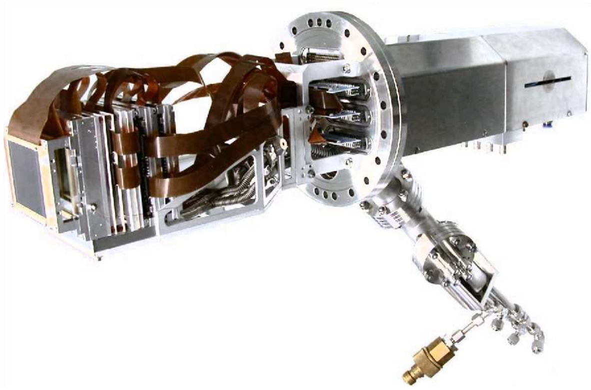

Figure 7: Single ANKE Silicon Tracking Telescope.

The detector system is based on silicon micro-strip detectors and the design follows closely the one recently developed at IKP for the ANKE experiment at Jülich (see photo of the single tracking telescope in Fig. 7). A detailed description of the ANKE detector system can be found in Refs. [20, 21].

The detector setup, shown in Fig. 8, left panel, is placed left and right to the the storage cell, which is 400 mm long and has a diameter of 10 mm. Two adjacent detector layers along the beam direction cover the central and forward sections of the storage cell in order to maximise the acceptance for elastic scattering both in necessary *pd* and *dp* measurements (see Fig. 8, centre and right panels). In $d\vec{p}$ case at $T_\mathrm{d} = 98.6\,\mathrm{MeV}$ the target polarisation will be measured, while $\vec{p}d$ reaction at $T_\mathrm{p} = 49.3\,\mathrm{MeV}$ serves determination of the beam polarisation (see Sec. 5). Events occur mainly in the central region of the cell where the target density has its maximum, therefore the detectors are placed downstream of the cell feeding tube. The 10 mm radial distance between two silicon layers is chosen to maximise the azimuthal acceptance while preserving the resolution on the vertex. In the event distributions shown in Fig. 8 the acceptance (geometrical one plus detection threshold of 500 keV) for $d\vec{p}$ and $\vec{p}d$ reactions is 21.5 % and 6.8 %, respectively.

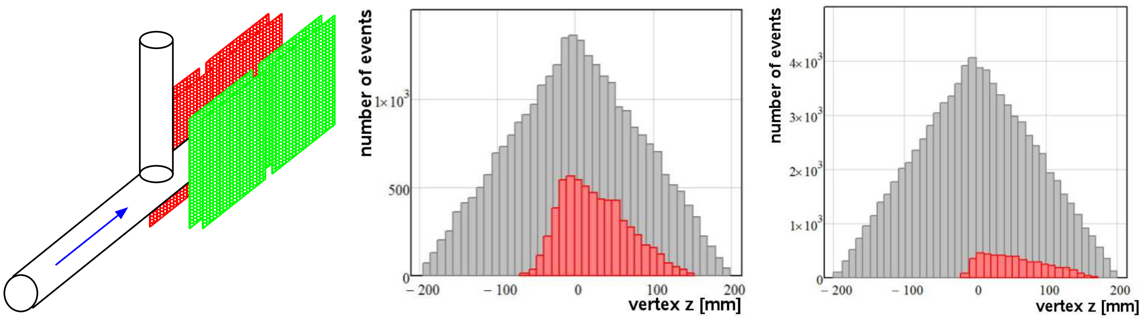

Figure 8: **Left**: Detection scheme for the filtering experiments. Detectors are located downstream of the cell feeding tube. **Centre**: Event distribution as a function of the vertex z coordinate for generated and reconstructed $d\vec{p}$ events at $T_\mathrm{d} = 98.6\,\mathrm{MeV}$. **Right**: Event distribution as a function of the vertex z coordinate for generated and reconstructed $\vec{p}d$ events at $T_\mathrm{p} = 49.3\,\mathrm{MeV}$.

The PAX detector is based on two layers of double–sided silicon–strip sensors of large area ($97 \times 97\ \mathrm{mm}^2$) and standard thickness of $300\,\mu\mathrm{m}$. Eventually, the number of silicon layers can be increased to three to provide redundancy of the obtained track information. A pitch of 0.76 mm provides the required vertex resolution of about 1 mm, while minimising the number of channels to be read out [22].

The read–out electronics is based on a scheme that has been developed for the ANKE spectrometer. The in–vacuum board carries the read–out chips with 11 MeV linear range, and a time resolution of better than 1 ns, sufficient to provide a fast signal for triggering. The interface card outside the vacuum provides power supplies, control signals, trigger pattern threshold and calibration pulse amplitudes to the front–end chips. The vertex read–out module developed at Jülich comprises a sequencer together with a 12 bit ADC with 10 MHz sampling; it allows common–mode correction for hardware zero–suppression to reduce the output flow to 0.1 MByte/s with less than 50 μs dead–time. A programmable trigger and a pre-scaler modules have been developed to provide a flexible trigger logic.

5 Polarimetry of Beam and Target

As it has been mentioned in Sec. 2 it is hardly possible to use elastic *pp* scattering due to negligibly small analysing powers at these energies. Therefore, after spin–filtering process is complete, the beam polarisation will be measured with the elastic $\vec{p}d$ scattering at $T_\mathrm{p} = 49.3\,\mathrm{MeV}$, where precise analysing power data are available [23]. In order to avoid contributions from other spin observables an unpolarised D_2 gas will be injected into the cell. As shown in Ref. [3] elastic deuterons can be cleanly selected. A complication, which could arise because the cell target is no more point–like, is overcome by the triggering on coincidences from two tracks coming from left and right sides.

The target density can be either obtained from the observed deceleration of the stored beam when the electron cooling is switched off, as shown in Refs. [25, 26], or it can be inferred from the measured rates in the detectors using the quite well established elastic proton–proton [6] or measured proton–deuteron differential cross sections [24].

The target polarisation has to be permanently monitored during filtering, and for this purpose the Breit–Rabi polarimeter (BRP) analyses a fraction of the atomic beam that is extracted from the cell. However, the BRP has to be calibrated for both hydrogen and deuterium targets beforehand. In the case of hydrogen this task can be accomplished by measuring the target polarisation simultaneously with the BRP and the silicon detection system in reversed kinematics – $d\vec{p}$ elastic scattering at $T_\mathrm{d} = 98.6\,\mathrm{MeV}$. In order to commission the deuterium target yet another separate experiment is necessary. For this purpose the BRP has to be calibrated with $p\vec{d}$ scattering at $T_\mathrm{p} = 135\,\mathrm{MeV}$, where the differential cross section and analysing powers A_y^d are known [27].

The detector system needed to observe $\vec{p}d$, $p\vec{d}$ and $d\vec{p}$ scattering is the same as described in Sec. 4.5.

6 Acceptance and Event Rate Estimate

The detection system arrangement shown in Fig. 8 is optimal to provide most effective detection of $d\vec{p}$ at $T_\mathrm{d} = 98.6\,\mathrm{MeV}$ and $\vec{p}d$ at $T_\mathrm{p} = 49.3\,\mathrm{MeV}$ processes without the necessity of breaking vacuum and repositioning of the detectors. The acceptances for $d\vec{p}$ and $\vec{p}d$ scattering in this geometry is 21.5 % and 6.8 %, respectively. The same arrangement provides 8.9 % acceptance for $p\vec{d}$ reaction at $T_\mathrm{p} = 135\,\mathrm{MeV}$.

With target thickness of $5 \cdot 10^{13}\,\mathrm{cm}^{-2}$ the rates given in Tab. 1 can be expected. For $\vec{p}d$ scattering the beam intensity after spin–filtering for four beam lifetimes is assumed. In $d\vec{p}$

Table 1: Rate estimate for $d\vec{p}$, $p\vec{d}$ and $\vec{p}d$ elastic scattering.

Process	$d\vec{p}$	$p\vec{d}$	$\vec{p}d$
Beam energy (MeV)	98.6	135	49.3
Beam intensity (particles/spill)	10^{10}	10^{10}	10^{9}
Luminosity ($cm^{-2}s^{-1}$)	$2.5 \cdot 10^{29}$	$3.8 \cdot 10^{29}$	$2.5 \cdot 10^{28}$
Input trigger rate (s^{-1})	6000	2400	185
Time to reach $\Delta P/P = 1\%$ (h)	0.2[1]	0.02[1]	8.5[1,2]

[1] pure measurement time; [2] after filtering for four beam lifetimes, $P = 2\%$ is assumed.

and $p\vec{d}$ experiments we aim at 1% accuracy in the target polarisation determination, while in $\vec{p}d$ the beam polarisation of $P \sim 2\%$ has to be determined with at least 10% relative error. The last line in the table gives the time needed to reach this accuracy.

As one can see, the $\vec{p}d$ experiment is especially time demanding: the total measurement time of a single point of the build–up time evolution (with the target in a single spin state) including spin–filtering for four beam lifetimes itself takes

$$(6\,\text{h filtering} \; + \; 0.5\,\text{h measurement cycle}) \cdot \frac{8.5\,\text{h total measurement time}}{0.5\,\text{h measurement cycle}} = 111\,\text{h} = 5\,\text{days},$$

while to take the spin–filtering phenomenon under control one has to evaluate the time evolution of the beam polarisation build–up for both spin orientations of the target. Therefore, at least four measurement points are necessary. In addition to that, for points with shorter filtering times smaller polarisation values are reached, thus more time is required to determine the polarisation value with good precision.

7 Timing of Activities

We suggest to organise the implementation of the experimental setup required for the measurements at COSY proposed here in a number of consecutive phases. This approach ensures that the regular COSY is not adversely affected. An outline of this sequence of phases is given below, a detailed description follows in the subsequent sections.

1. Commissioning of the low–β section.
2. Spin–filtering measurements with transverse polarisation at $T_p \approx 50$ MeV.
3. Commissioning of the complete experimental setup including detection system for AD (see Ref. [22]).
4. Implementation and commissioning of the injection beam line solenoids. Studies of the longitudinally polarised beam at COSY.
5. Implementation and commissioning of the AD Siberian snake.

In general, the prerequisites for the spin–filtering measurements are as follows: excellent vacuum conditions in the COSY ring; large acceptance angle at the target in the low–β insertion; long beam lifetime due to both the target and residual gas; dense stable target delivering highly polarised hydrogen and deuterium; reliable and survivable detection system suited for the measurement of polarisation observables.

7.1 Phases of the Experimental Program

- **Phase 1: Commissioning of Low–β Section.**
  In phase 1, four quadrupole magnets are installed in the straight section of COSY to

provide the required small β–function to operate the PIT. The lattice calculations have been already reported in Sec. 4.2. To satisfy the requirements from the calculations, quadrupoles of the former CELSIUS ring in Uppsala are available to be installed at COSY. The foreseen complete setup of phase 1 is depicted in Fig. 9.

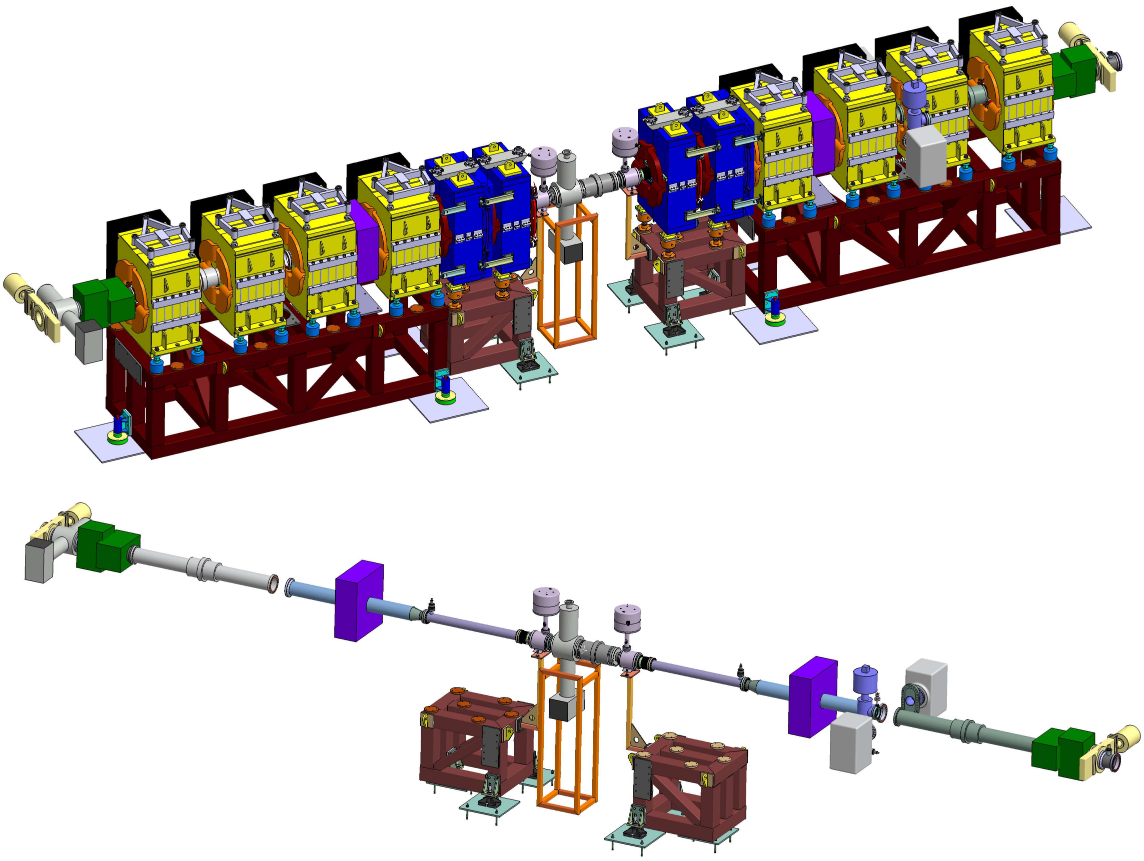

Figure 9: The low–β insertion (upper panel) consisting of the four new magnets (blue ones), a beam position monitor (in the middle), together with the new vacuum system (lower panel).

Together with the quadrupole magnets, a set of four steerer magnets (2×horizontal and 2×vertical) and a Beam Position Monitor (BPM) are installed to control the machine orbit in the low–β insertion. Because of spatial restrictions the steerer windings have to be mounted on the yokes of the existing COSY quadrupole magnets.

The entire low–β section is made bakeable and is coated with NEG material. Fast shutters will be used to seal the section off from the rest of the ring in case of emergency.

After all the needed hardware is installed, it is absolutely necessary to demonstrate, that COSY still operates, and its performance did not suffer from the modifications made. This includes several things to be carefuly studied:

– Beam optics has to be developed. The beam has to stay on the geometrical axis of the beam pipe with precision of 0.2 mm.

– First point requires that the BPM, which deliveres beam position in PAX section, is calibrated versus steerer magnets.

- Machine acceptance has to be measured using *e.g.* existing COSY scrapers. It should not be smaller than the value measured before the ring modifications (see Sec. 3.1).
- As it has already been mentioned excellent vacuum conditions in the COSY ring have to be provided ($< 10^{-9}$ mbar H_2)
- As a consequence of the unchanged ring acceptance the beam lifetime must at least not be affected by the installation. An improvement can even be expected when increasing the pumping speed. Thus, a value of $\tau \approx 6000$ s or more is expected.

Since the new quadrupole magnets are currently being installed, we estimate that two weeks of dedicated machine development time would be sufficient to commission the installation and to prove that the machine acceptance remained the same. The machine could then be ready at the end of 2009 for the new tasks involved in the measurements proposed here.

- **Phase 2: Spin–filtering Measurements with Transverse Polarisation at $T_p =$ 50 MeV.**
  During phase 2 the target chamber equipped with the holding field and compensation coils will replace the BPM in the centre of the low–β insertion. The collimators installed to protect the detection system are made openable in order to allow for the unrestricted acceptance at injection, when the magnets of the low–β insertion are not in use. In addition, the Atomic Beam Source (ABS), and the Breit-Rabi polarimeter (BRP) will be installed together with the detection system (see Fig. 8). Contrary to later experiments at COSY the storage cell does not have to be opened (see Fig. 4, right). Preceding storage cell and detector installation the acceptance angle at the target has to be measured with a scraper system installed in the target chamber.

  Once installed the vacuum system has to be commissioned under gas load, the NEG pumps have to be activated, the cycle for the ABS gas flow has to be organised, mechanics of the collimator opening has to be thoroughly tested.

  After phase 2, the necessary requirements for the first polarisation build–up studies at COSY are fulfilled. The setup available at this point is shown in Fig. 3. The measurements will be carried out using transversely polarised beam produced by spin–filtering using a transversely polarised hydrogen target. The presence of the BRP is essential, since, once calibrated with $d\vec{p}$ scattering, the polarimeter will permanently provide a measurement of the target polarisation.

  The measurement sequence is composed of the following stages:

  1. **Machine acceptance studies.**
     Determination of the acceptance angle at the target is first possible when the target chamber is installed. It is important to determine the machine acceptance with electron cooled beam exactly in the place of the forthcoming measurements. The technique we have established for this purpose is described in Ref. [28]. It uses a small movable frame to scrape the beam. $\theta_{\rm acc}$ needs to be precisely measured because it plays a crucial role in the interpretation of the observed polarisation build–up. After this measurement is completed, a fixed storage cell will replace the scraper system. The beam life time with the cell target has to be then measured. For this stage we ask for two weeks of beam time.
  2. **Measurement of the hydrogen target polarisation.**
     Once the COSY beam is brought through the cell, the detection system can be

put in. These first measurements with detectors installed will address the determination of the target polarisations when hydrogen is injected into the storage cell, while a deuteron beam is circulated in the COSY ring at 98.6 MeV beam energy. During these measurements the signal from the Breit–Rabi polarimeter is calibrated, and the polarimeter will later on be able to monitor hydrogen target polarisation.

3. **Measurement of the deuterium target polarisation.**
A dedicated measurement is necessary to be able to determine the deuterium target polarisation in future. For this purpose the BRP has to be calibrated with $p\vec{d}$ scattering at $T_p = 135\,\mathrm{MeV}$. This is of high importance for the planned measurements at the AD because $\overline{p}\vec{d}$ analysing powers are unknown. The two stages needed to measure target cell polarisation and to calibrate the BRP require two weeks of beam time.

4. **Spin–filtering.**
The spin–filtering measurement itself consists of two separate parts. During the first part, the COSY beam will slowly gain polarisation while interacting with the polarised hydrogen gas in the storage cell. In the second part, which is devoted to the measurement of the final beam polarisation, unpolarised deuterium gas will be injected into the storage cell providing sufficient target density for the measurement. We ask for four weeks of beam time to accomplish this task.

It is anticipated that in total eight weeks of beam time are sufficient to accomplish phase 2.

- **Phase 3: Commissioning of the experimental setup for AD.**
The installation of the complete detection system, consisting of 36 detectors, is foreseen to take place in the summer shutdown 2011. The experimental setup is to be commissioned before it is implemented at the AD ring of CERN. It is anticipated that four weeks are sufficient to complete this task.

- **Phase 4: Implementation and commissioning of the IBL solenoids. Spin–filtering with longitudinally polarised beam at COSY.**
In order to determine σ_2, the COSY beam has to be made longitudinally polarised at the position of the PAX target. Therefore, in the straight section opposite the PIT, a solenoidal Siberian snake consisting of the e-Cooler and the WASA solenoid has to be operated. COSY has never been operated with longitudinally polarised beam. In order to test that this works, we suggest to inject longitudinally polarised beam. Since the target polarisation is known from the BRP, the asymmetry $P_\mathrm{z} \cdot Q_\mathrm{z} \cdot A_\mathrm{zz}$ in $\vec{p}\vec{p}$ elastic scattering measures the beam polarisation. A measurement of the polarisation lifetime will be possible as well. Therefore, two new solenoids have to be installed in the Injection Beam Line (IBL) of COSY in order to match the spin direction of the proton beam at injection to the stable spin direction of COSY at this point. A careful machine study has to be carried out before final conclusions can be drawn.

We anticipate that such a snake could be ready for tests at the end of 2011. With a Siberian snake, polarisation build–up studies with longitudinally polarised target shall be carried out in 2012. As at this time the complete PAX setup will likely be installed at AD, the ABS and the STT detection system of ANKE will be used to conclude the longitudinal case. We anticipate that this phase requires about five weeks of beam time.

- **Phase 5: Implementation and commissioning of the AD Siberian snake.** A Siberian snake for the AD ring has to be commissioned prior to the installation at the AD [22]. The only place at the COSY ring where the snake can be installed is the PAX place in the straight section. By the time of installation the target is already installed at the AD. Similar to the measurement of phase 4 the ABS and detection system of ANKE, this time installed at the original ANKE position, will serve the measurement of the beam polarisation using $P_{\mathrm{z}} \cdot Q_{\mathrm{y}} \cdot A_{\mathrm{xz}}$ observable. We anticipate that this phase requires about three weeks of beam time to measure the beam polarisation and the polarisation lifetime.

7.2 Anticipated time plan

Below we give an approximate timetable for the activities outlined in the present proposal.

Phase	Time	Beam time required	Description
1	Shutdown 2009		Installation of four magnets for the low–β insertion.
	Fall 2009	2 weeks	Commissioning of the low–β section and machine acceptance measurement.
2	Shutdown 2010		Installation of the target chamber, ABS, BRP and a detection system for spin–filtering.
	2010	2 weeks	Measurement of the acceptance angle at the target position.
	2010	2 weeks	Measurement of the target polarisation in $d\vec{p}$ and $\vec{p}d$.
	2010	4 weeks	Spin–filtering at COSY with transverse beam polarisation.
3	Shutdown 2011		Installation of the complete AD detector.
	2011	4 weeks	Commissioning of the installed equipment.
4	Shutdown 2012		Implementation of the two additional solenoids in the injection beam line, ANKE ABS and detectors.
	2012	1 week	Commissioning of the Siberian snake.
	2012	4 weeks	Spin–filtering at COSY with longitudinal beam polarisation.
5	Shutdown 2013		Implementation of the AD Siberian snake.
	2013	3 weeks	Commissioning of the AD Siberian snake.

In total 22 weeks of beam time are needed to complete the experimental program at COSY. We now ask for two weeks of beam time in 2009 for commissioning of the low–β section and measuring the machine acceptance.

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