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Polarimetry of pulsed H^-/D^- ion beams: Extended applicability of the Lamb-shift polarimeter

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Until 2023, a polarized H^-/D^- ion source delivered pulsed negative ion beams for stripping injection into the accelerator COSY at Forschungszentrum Jülich. Accurate and efficient measurement of the nuclear spin polarization directly behind the source is essential for precision experiments at COSY. A data acquisition system was developed to enable reliable, automated measurements with improved efficiency and to reduce operator intervention. To achieve that, the applicability of the Lamb-shift polarimeter has been successfully expanded to include pulsed H^- and D^- ion beams. The presented setup is useful and suitable to determine and optimize the polarization of upcoming polarized sources of the COSY type without pre-acceleration.

The 26th international symposium on spin physics (SPIN2025)
21–26 September, 2025
Qingdao (Tsingtao), Shandong Province, China

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1. Introduction

Spin-polarized proton beams are necessary for investigating spin-dependent phenomena in nuclear physics. Precise knowledge of the beams' spin polarization enables the investigation of spin-dependent asymmetries or spin-spin correlations in scattering experiments.
At the Cooler Synchrotron COSY in Jülich, polarized proton beams are provided by a polarized H^-/D^- ion source followed by acceleration and stripping injection into the ring. The beamline is partly illustrated in Fig. 1. Before beamtimes, the standard procedure for the source optimization includes the acceleration with the JULIC cyclotron and polarization measurement with the Low Energy Polarimeter (LEP). The LEP is a nuclear scattering polarimeter and the necessary analyzing powers are reached at 45 MeV H^- energy. Replacing this method by using a Lamb-Shift Polarimeter (LSP) directly behind the source offers several advantages. The LSP does not require a pre-accelerated beam. This means, during polarization measurements and source optimization, the beamline to the cyclotron is not blocked (Fig. 1) and can be used for unpolarized beamtimes in COSY. The LSP spectra are produced in the order of seconds to minutes [1], which enables a significant increase in time efficiency and allows for live-tuning of the source.
This work builds upon our previous results presented at the PSTP in 2022 [2]. A proof of principle measurement was done to show the functionality of the LSP in measuring the nuclear spin polarization of H^-/D^- ion beams. In this work, we focused on developing a more advanced data acquisition setup to improve the reliability and resolution of the measurements.

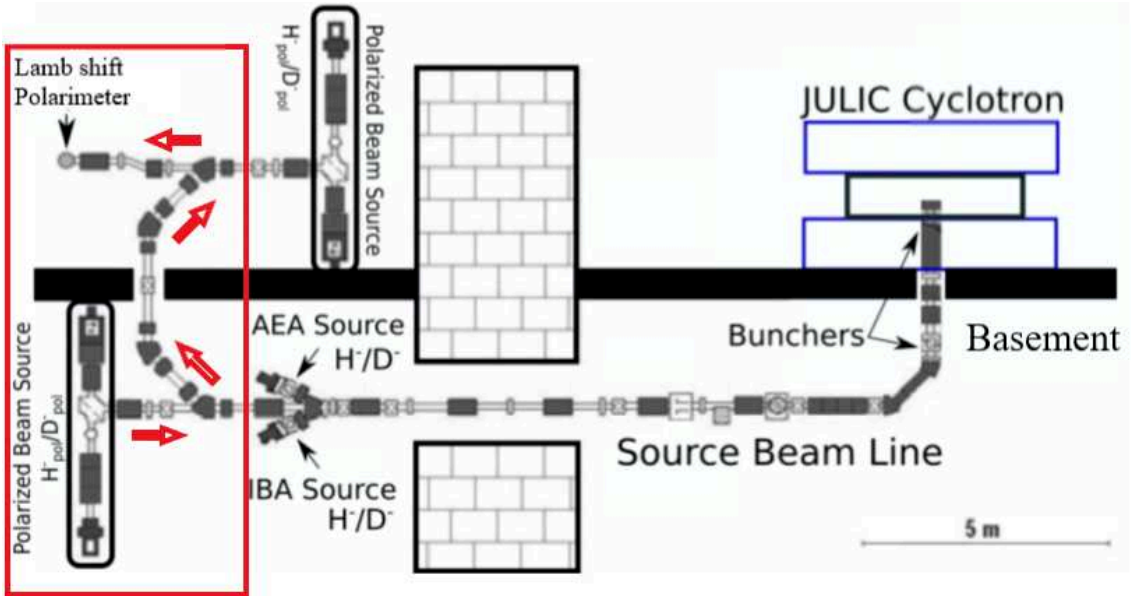


Figure 1: Schematic drawing of the experimental setup [2].

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2. Experimental Setup

2.1 Polarized Ion Source

The experimental setup is based on the polarized ion source and Lamb-shift polarimeter described in Ref. [2]. Further details about the used source and the physics of the LSP can be found in [3–5] and [1, 6, 7]. Mainly the data acquisition was modified and tested.
The polarized source produces a pulsed, nuclear polarized H^- or D^- ion beam with an energy of 2 keV and a repetition rate of 0.5 Hz.

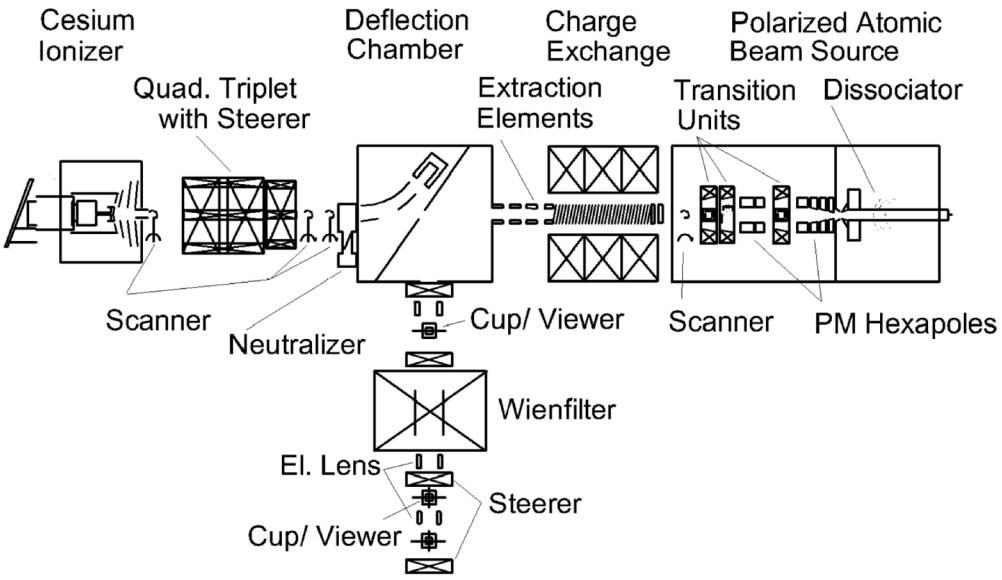


Figure 2: The COSY source [8].

The working principle of the source is based on a colliding beam setup. Polarized H^-/D^- ions are produced by the following charge exchange reaction [5]

$$Cs + \vec{H} \rightarrow Cs^+ + \vec{H}^-, \tag{1}$$

between a neutral cesium beam with a nuclear polarized atomic hydrogen beam inside a solenoid providing a longitudinal magnetic field. After electric extraction and mass selection with a Wien filter, the ions are directed towards the LSP by several magnetic and electrostatic deflectors. As visible in Fig. 1, the beam transport from the basement to the ground floor to the LSP (red arrows) requires several electrostatic deflection and magnetic focusing elements. Overall, the beam is rotated by 360° over a distance of about 6 meters. The pulsed setup, in combination with huge intensity losses, makes precise and reliable nuclear spin polarization measurements very challenging. Therefore, a more advanced version of the LSP data acquisition system was installed and tested, as described in the following section.

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2.2 Remote controlled Lamb-shift Polarimeter

The Lamb-shift polarimeter is able to detect the relative occupation numbers of the possible nuclear spin states of metastable hydrogen atoms. As illustrated in Fig. 3, its main components are:

- Cesium cell: The LSP is sensitive to distinguish between nuclear spin states of metastable hydrogen ($2S_{1/2}$). Therefore, the incoming ions undergo a charge exchange reaction with Cs vapor to produce metastable atoms in the 2S state while preserving the initial nuclear spin polarization.

- Spin filter: The spin filter allows for selective transmission of a single hyperfine state while the remaining three are quenched into the ground state. Under specific conditions – a static electric field, perpendicular to the beam direction, a radio frequency field of approximately $f = 1.60975$ GHz and a ramped longitudinal external magnetic field – two resonances can be produced. At each resonance, one of the two substates with different nuclear spin projections is populated.

- Quenching chamber: While the magnetic field in the spin filter is ramped, a static electric field in the quenching chamber couples the remaining metastable atoms to the ground state. The emitted Lyman-α photons are detected with a photomultiplier. At the two resonances, the peak heights and volumes correspond to the occupation number of the respective states with nuclear spin up or down. By comparing the peak intensities, the nuclear spin polarization of the beam can be determined.

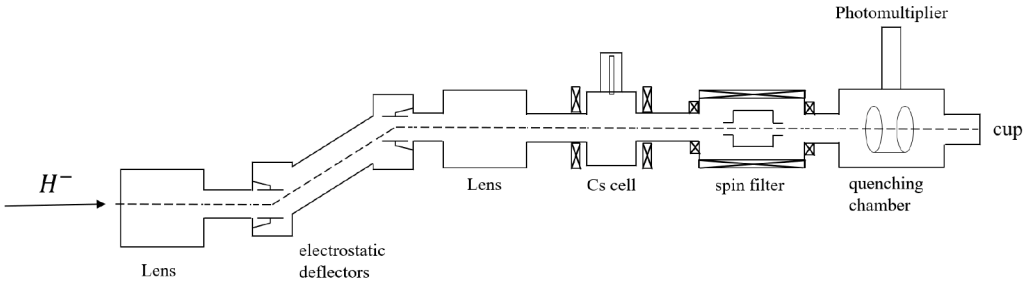


Figure 3: Lamb-shift polarimeter at COSY, showing a schematic overview of the main components.

The data acquisition is based on a Python-controlled loop. The power supplies used to set the magnetic field in the spin filter as well as the oscilloscope that records the photomultiplier and cup signals is synchronized with the trigger of the pulsed source. In addition to ramping the field and recording the signals for each pulse, the software repeats this procedure over multiple sweeps and averages the detected spectra. This is essential to improve the statistical quality of the data.
As an example listed in table 1, a typical spectrum is recorded using 20 sweeps with 40 magnetic-field steps. Considering a repetition rate of 0.5 Hz, this measurement takes around 26 minutes.

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Observable	value and unit	Observable type
spinfilter magnetic field	ADC converted current in SF coils	beam observable
PMT signal	~ mV	beam observable
H^- Cup signal	~ mV	beam observable
cesium cell temperature	~ 160 °C	LSP parameter
spin filter E-fields	± ~ 200 V	LSP parameter
Cavity output power	~ mW	LSP parameter
Voltage quenching lens	700 V	LSP parameter
PMT high voltage	3 kV	LSP parameter
Vacuum pressure	~ 10^{-7} mbar	LSP parameter
measured samples PMT	1 – 2000	software & analysis
number of averages	~ 20	software & analysis
number of B-field steps	~ 40	software & analysis

Table 1: Measurement variables grouped into three categories. They are distinguished by physical information, parameters required for reproducability and software-related parameters.

3. Results

To provide suitable conditions for testing the data acquisition itself, an optimal Cs-cell temperature is required. In particular, the production efficiency of metastable atoms from H^- ions is a subject of investigation in this study. The cesium density experienced by the incoming ions depends on the cesium temperature. Therefore, the amount of produced metastable atoms is measured as a function of the temperature of the cell. The results of the temperature scan (Fig. 4, left side) show a linear increase in the number of metastable atoms for increasing temperature. Contrary to expectations, there is no indication of a maximum within the scanned temperature range. The production efficiency may be optimized for temperatures above 200 °C, which could not be measured due to the limited temperature resistance of the O-rings used.

After setting the reasonable operating point for the cesium cell to around 180 °C, spectra with H^- ions were recorded. The right side of Fig. 4 shows an obtained spectrum where the x-axis corresponds to the magnetic field in the spin filter and the y-axis shows the photomultiplier signal. This spectrum evolved measuring with positive polarization settings of the source. The data acquisition was set to sweep 30 times through 50 B-field steps. Considering the source frequency of $f = 0.5$ Hz, this measurement takes 50 minutes to complete. The analysis resulted in an average beam polarization of $P_z = 0.35 \pm 0.03$. The goodness of fit of the gaussian fitted peaks resulted in χ^2 values of approximately 1, indicating an adequate model. However, the uncertainty of the measurement is dominated by the sweep-by-sweep fluctuations. The general background decrease originates from a systematic disturbance of the PMT gain by the magnetic field of the spinfilter and appeared in each measurement. The SEM (standard error of the mean) as a function of sweeps,

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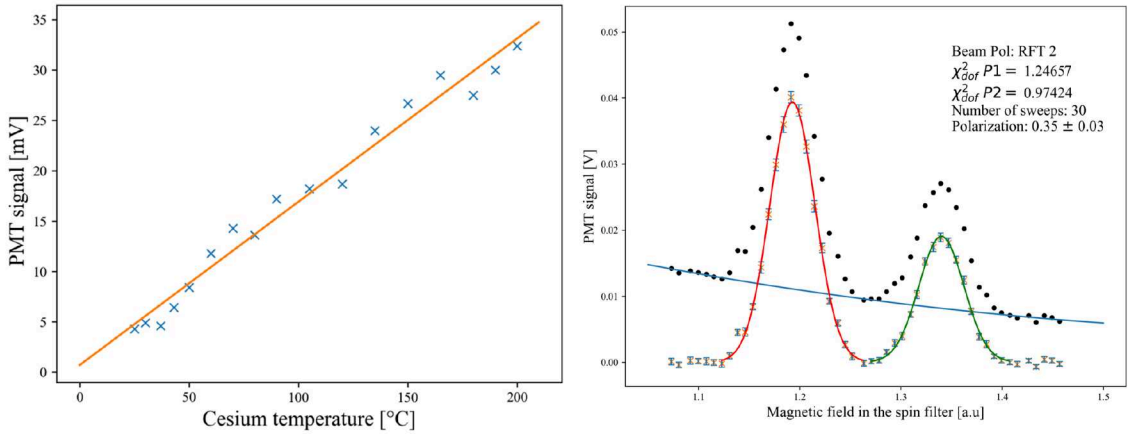


Figure 4: Left side: Cesium temperature scan. The figure illustrates the temperature dependence of the production of metastable atoms. Right side: Analyzed Lyman-α spectrum. The black dots show the average values of the PMT signal after all sweeps. After subtraction of the background, fitted by the blue line, the red and green lines indicate the gaussian fits for the respective relative occupation numbers of the different nuclear spin states.

shown on the left of Fig. 5 was obtained by dividing the standard deviation of the polarization values P_i by the square root of the number of sweeps. The SEM decreases and shows an expected behavior for statistical independent measurements.

For D^- ions, varying the spin filter B-field selects atoms with three different nuclear spin pro-

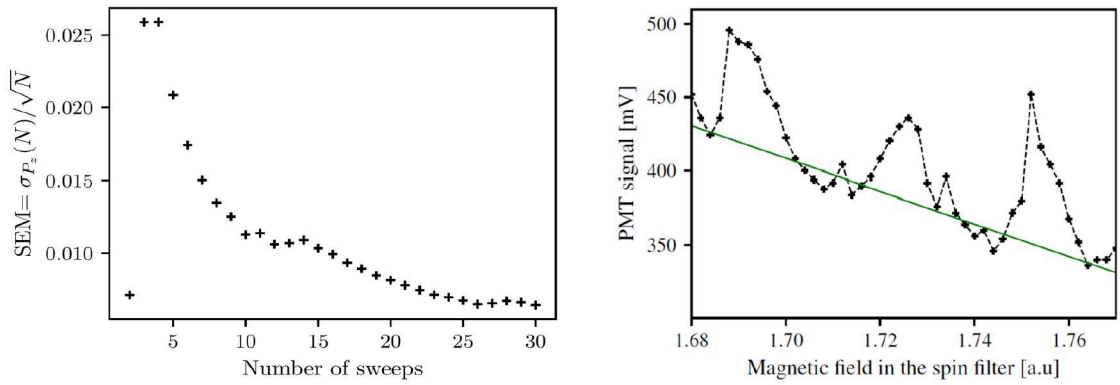


Figure 5: Left side: Evolution of the Standard Error of the mean Polarization $\langle P_z \rangle = \frac{1}{N}\sum_{i=1}^{N} P_i$ as a function of sweeps N ($SEM(N) = \frac{\sigma_{P_z}(N)}{\sqrt{N}}$). Right side: Lyman-$\alpha$ spectrum for incident D^- ions. The source intensity decreased over time leading to this background shape.

jections, as visible on the right side of Fig. 5. Since the incident beam is unpolarized, the peak heights should be equal. It is apparent that the background decreases significantly with increasing magnetic field. The spinfilter settings do not permit sufficiently large amounts of residual ions to pass through for focusing effects to be a plausible explanation. Further analysis revealed that the ion source trigger occasionally failed, increasingly often over the duration of the measurement. This

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source instability resulted in a decrease of the average PMT signal intensity, which manifests as the observed background trend. To avoid such effects, the sequence of data acquisition is crucial: rather than averaging at a fixed magnetic field, successive full sweeps over the B-field range provide a more stable and reliable measurement.

4. Summary

A remote-controlled Lamb-shift polarimeter was successfully operated with pulsed polarized H^- and D^- ion beams at COSY. Reliable polarization measurements were achieved without pre-acceleration, allowing for efficient source optimization as well as live plotting and analysis of the data. The precision was determined from sweep-by-sweep spectral analysis, and the statistical uncertainty was quantified using the standard error of the mean. The presented setup is well suited for the polarization measurements of current and future polarized ion sources of the COSY type.

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