Status Report for COSY Proposal # 213

Measurement of the spin correlation parameter $A_{x,z}$ of the quasi-free $\vec{p}\,\vec{n} \to \{pp\}_s\pi^-$ reaction at ANKE

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Abstract

The measurement of the spin-correlation coefficient $A_{x,z}$ of the $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ reaction for excitation energies of the final diproton less than 3 MeV represents the final part of the pion production programme at ANKE. It aims to resolve the ambiguities in the partial wave analysis of the existing data and the results will be of relevance for Chiral Perturbation Theory. The experiment requires the use of a longitudinally polarised proton beam of 353 MeV energy and a transversally polarised deuterium target at ANKE, equipped with an openable cell, and Silicon Tracking Telescopes (STT).

As a first stage, a preparatory measurement has been carried out to test the feasibility of the experiment and estimate the achievable luminosity. In the current document, we give the status report on the proposal and present the data collected for the first time with the openable cell at ANKE in November 2013. An important result of the beam time was to understand the background conditions when measuring the $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ reaction with an openable cell at 353 MeV, and the optimization of the cell dimensions. The measurement resulted in a more robust estimation of the total beam time required for the main experiment, which is still in a stage of waiting the Siberian snake commissioning at COSY.

The physics case of this proposal was accepted positively by the PAC session 40 and 41, but the final decision was postponed until the installation of the Siberian snake at COSY. The present document contains an update of the proposed plans and an estimation of the beam time required. The preliminary time line of Snake delivery in Jülich is March/April 2014.

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1 Executive summary

In this status report we present the results of the commissioning experiments conducted in November 2013 and mid-January 2014 and formulate the updated time requirements for the main measurement. Since proposals #213 and #219 shared many of the same goals of the commissioning beam times, the latter were carried out in one block and the majority of the results are of relevance for both experiments. Contrary to our plans, the Siberian snake was not installed by the time of the measurement, and the commissioning was conducted with the unpolarised proton beam. The beam was cooled at injection and stacked, thus providing the possibility to study its properties under the conditions of the main experiment.

The beam time pursued the following goals:

- commissioning of the openable storage cell at ANKE and testing its ability to:
  - provide the expected gas density
  - keep the polarisation of the polarised gas
- to study the background conditions with a cell of small diameter,
- to determine the transverse dimensions of the pre-cooled beam at the energy of experiment and to optimise the cell size,
- to define the beam intensity reachable with the openable cell,
- to study the possibility to detect pions with the ANKE STT.

The beam time has shown:

- the openable cell operated at ANKE in a very stable and reliable way,
- density of the deuterium gas from the ANKE ABS with a cell of 11.8 mm diameter (length in the beam direction is 390 mm) reaches 3×10^{13} at/cm^2, which is close to the expected figure,
- only a small polarisation loss of $\sim 5\%$ occurs in a titanium cell and a deuterium polarisation of at least 70% can be achieved,
- the background with the cell is very moderate for a number of processes identified,
- a cell of 11.8 mm diameter can be operated at 353 MeV but this dimension is very close to the limit. A beam intensity of 7×10^9 protons was achieved when passing a pre-cooled stacked beam through the cell,
- the efficient tracking of pions and triggering on them is possible with the presently available STT. Still further improvement of the detector performance is expected.

Still necessary to be done:

- the Siberian snake commissioning (in 2014),
- study of the operation of the snake with the new 2 MeV electron cooler at COSY, especially with respect to preserving the beam polarisation,

- testing of the new STT detectors optimised for pion detection (2014).

The updated time estimates:

The goal of the measurement is to reach a 95% probability level for rejecting a wrong PWA solution [1]. With the parameters listed in Section 5, we consider the following two scenarios:

I. No cooling at flattop is available. The presently achieved target density of 3×10^{13} at/cm^2 and beam intensity of 7×10^9 are assumed. The experiment requires **12 weeks** of beam time.

II. The 2 MeV electron cooler is operated at flattop. The cell size can be decreased down to 10 mm, resulting in a density of $\sim 5 \times 10^{13}$ at/cm^2. The necessary beam time decreases to **7 weeks**.

2 Commissioning of the ANKE polarised internal gas target

In this section results of the commissioning of the ANKE polarised internal gas target are summarized. Due to the common effort of the ANKE collaboration in preparation for the double polarised experiments #213 and #219 the contents of the Sec. 2.1 and Sec. 3 in proposals presented to the PAC42 is identical.

2.1 ANKE openable/closable storage cell

One of the main goals in the commissioning run was to bring a new openable/closable storage cell into operation. The ANKE storage cell was built in the ZEA of the Forschungszentrum Jülich. As illustrated in Fig. 1, it is made up of two tubes welded to the rectangular block of material with an opening/closing mechanism. The long tube (storage tube), which is welded to the rigid block of material with a hall, is cut into two halves along its length. The second tube (injection tube) is connected to the same metallic block of material inside which the injection and storage volume are connected. The storage cell is 390 mm long and has an inner diameter 11.8 mm. The feeding tube is 130 mm long and has an inner diameter of 11.8 mm. Each half of the storage cell can be moved up and down using precision piezoelectric drives. Each individual drive provides a precision in positioning of the order of < 1 μm [2]. All cell parts are covered by a 30 μm PTFE [3] coating designed to minimize recombination effects [6].

During the machining and cutting of the storage cells, special attention was paid to retaining the coplanarity of the halves. If there were a gap between the two halves of the cell of the order of 50 μm then a significant fraction of the target thickness (up to 20%) in the beam-target interaction region could be lost. The stainless steel storage cell, used during commissioning run, was very tight and no visible gap between two halves was observed before and after the beam time.

The expected target thickness distribution has been calculated as a function of the coordinate for the storage cell of this dimension and later measured in the laboratory using Baratron [5] and none-cut cell. The results of the measurements are compared to the calculations in Fig. 2, where it is seen that the agreement is very good. The integrated target thicknesses from the calculations and measurements in the laboratory are in a good agreement.

The first storage cell shown in Fig. 3 had an inner diameter of 11.8 mm and was produced from stainless steel (wall thickness 100 μm) covered with Teflon. During the test

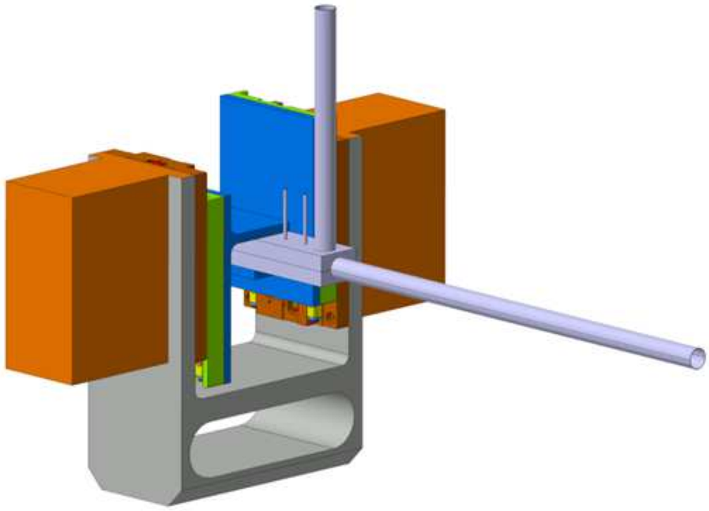


Figure 1: The principle of the ANKE cell construction. It consist of two tubes, one injection tube to introduce the ABS gas and the storage tube that keeps the polarised gas in the interaction region. Both tubes are welded to the rigid metallic block to preserve the coplanarity in the system. The storage tube and block are cut into two halves along the long side. The halves can be moved up and down using piezoelectric motors (green parts) which are connected using special support (blue parts) to the each half of the block. The yellow parts in the picture are protection for the STTs which, in the final version, can be parked behind them during injection.

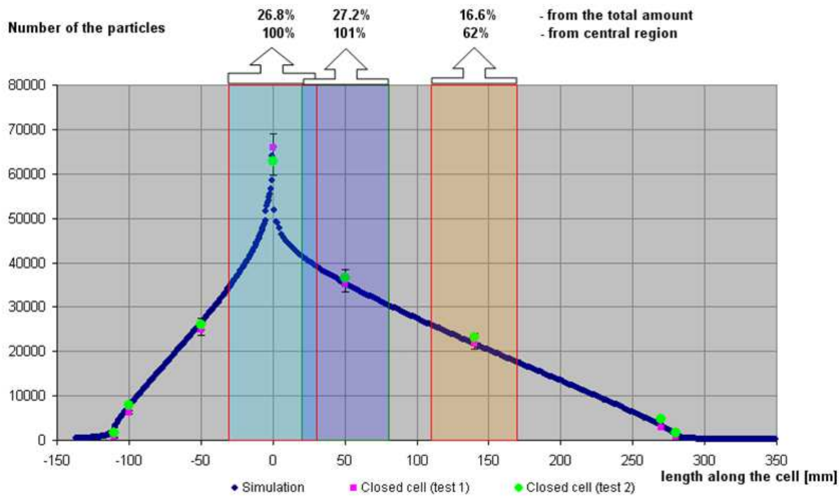


Figure 2: Target thickness in the storage cell as a function of coordinate along the beam direction. The calculations (blue symbols) are compared to the measurements (magenta and green symbols) for the 12 mm storage cell.

run with this stainless steel cell the target thickness was measured at different energies using the Schottky method [4]. Thicknesses of about 3×10^{13} cm^{-2} were obtained for hydrogen and deuterium. The measured value of the target thickness for the hydrogen is in good agreement with the expected thickness.

Figure 3: Photograph of the opened ANKE storage cell mounted on a flange in the laboratory. Also shown are the Piezoelectric drivers for opening/closing the tube, the STT installation, the plastic tubes for the Baratron to control the pressure, and the unpolarised gas supply system (UGSS).

Since the target polarisation with the stainless steel cell was low, a second cell prototype was built from Titanium (inner diameter 11.6 mm, wall thickness 200 μm, feeding tube inner diameter 10 mm) and covered with 30 μm PTFE. Due to mechanical imperfections, the target thickness for the Titanium cell was lower then for the stainless steel cell. Using the Schottky method a value of $\approx 1.8 \times 10^{13}$ cm^{-2} for hydrogen target was found.

3 Target polarisation with the openable storage cell

The first approach to the cell construction was through the use of stainless steel for the walls. This type of cell was tested in the November 2013 beam time and the results of these tests are presented in Sections 3.1–3.3. The low value of the polarisation achieved in the steel cell required a change in the construction material. A new cell with titanium walls was tested with the COSY beam in mid-January 2014 and the excellent results obtained are described in Section 3.4.

The target polarisation was studied with nuclear reactions that were accessible under the conditions of the two experiments being commissioned (proposals #213 and #219). Both pp elastic scattering and the $pp \to d\pi^+$ reaction were used for this purpose with the hydrogen gas target. The polarisation of the $\vec{\mathrm{D}}$ target was defined with the use of $pd \to pd$ elastic scattering and the quasi-free $pp \to d\pi^+$ reaction. The necessary analysing powers in these reactions are available from the literature.

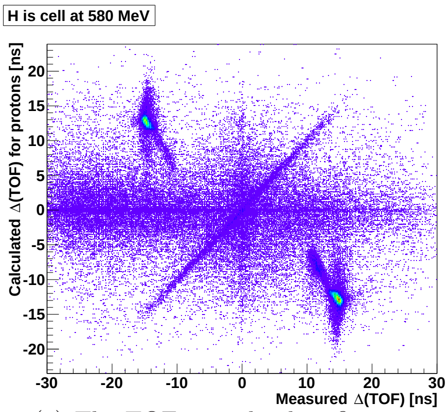
Elastic scattering reactions were recorded with the STT, which covered only about a 5 cm long region of the cell (the cell length is 39 cm). The (quasi)-free $pp \to d\pi^+$ process, with both final particles detected in the ANKE forward (Fd) or Positive (Pd) detectors, allowed estimates to be made of the average gas polarisation over the whole cell, as well as the study of the distribution of the polarisation along the cell. Neither the $T_p = 1.66$ nor 0.353 GeV beam energy is suitable for a polarimetry study on the basis of the $pp \to d\pi^+$ process, for which the optimal is ≈ 580 MeV. Thus, dedicated runs were undertaken at this energy with both $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ targets.

To save time and effort during the commissioning, both experiments were conducted with the same ANKE D2 magnet deflection angle of $\alpha = 8.44°$, which is optimal for the experiment at 1.66 GeV. For the 353 MeV experiment, this meant the use of the 0.55 Tl magnetic field of the ANKE D2 magnet, instead of the 0.70 Tl foreseen for the main experiment at $\alpha = 10.6°$. However, the field value at 580 MeV and 8.44° is 0.75 Tl, so that the polarimetry results obtained at this energy fit the commissioning goals of the experiment at 353 MeV.

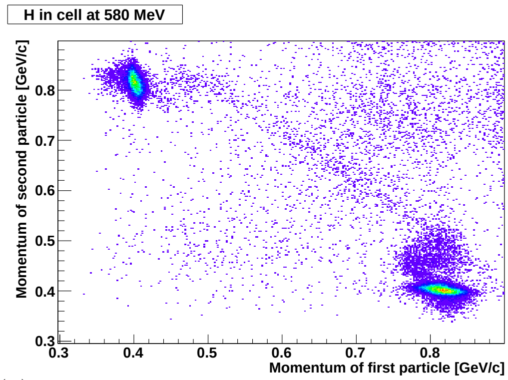
To accomplish the polarisation study with the cell, one had to ensure a high value of polarisation of the gas in the ABS jet. The measurements with the Lamb Shift polarimeter could not provide the absolute values of the polarisation. Thus, a separate measurement of the jet polarisation with nuclear reactions was done, with the cell removed from the target chamber.

We present below the results of this series of measurements.

3.1 Polarimetry with the steel cell at 580 MeV



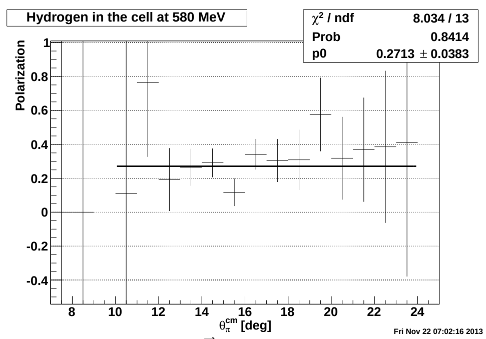
(a) The TOF particle identification



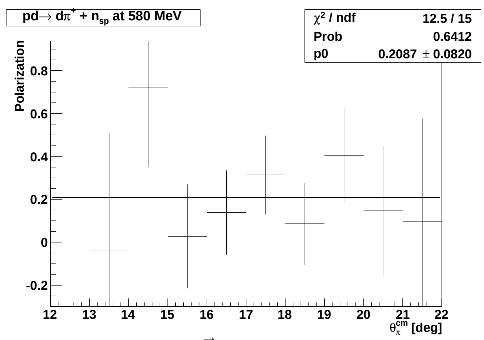
(b) Momentum correlation of two tracks in the Forward detector

Figure 4: $pp \to d\pi^+$ reaction identification at 580 MeV

This measurement was performed early in the beam time, before the STT had been installed. Thus, the only polarimetry reaction employed was the (quasi)-free $pp \to d\pi^+$. The ejectile deuteron from this process was detected in the Fd, while the pion hit either the Fd or Pd. The $d\pi^+$ pairs were clearly identified through the time-of-flight (TOF) difference of the two particles and the process was then selected kinematically. In Fig. 4(a)



(a) $\vec{\mathrm{H}}$ in the cell

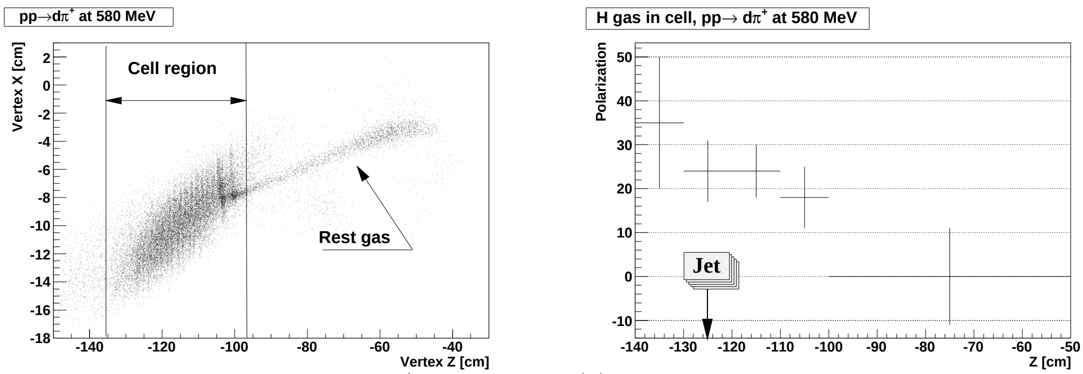


(b) $\vec{\mathrm{D}}$ in the cell

Figure 5: Target polarisations measured with the stainless steel cell at 580 MeV

the measured TOF difference of the two particles is compared to the one estimated under the assumption that the two charged particles each have the proton mass. The $d\pi^+$ pairs are located in the two bright spots in the figure. The correlation of the momenta of the two particles detected in Fd is shown in Fig. 4(b), where the $pp \to d\pi^+$ events also group into two regions at $\sim (0.4, 0.8)$ GeV/c. The analysing power in this process is available from the SAID data base [7] and reaches 0.2 in the angular range of our experiment, $\theta_\pi^{cm} = (12 - 24)^\circ$. The results of polarisation determination with $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ targets are shown in Fig. 5. The values of $Q(\vec{\mathrm{H}}) = 27 \pm 4\%$ and $Q(\vec{\mathrm{D}}) = 21 \pm 8\%$ are close to those obtained with a cell of stainless steel [6].

The measurement of the time-of-flight difference allows the possibility to reconstruct the longitudinal coordinate Z of the reaction vertex. In the case of the hydrogen target, the kinematical constraints improve the accuracy of this coordinate down to $\sigma_Z = 5$ cm (Fig. 6(a)), so that one can study the distribution of the polarisation along the cell, as shown in Fig. 6(b). One can see that, within our limited statistics, no substantial change of the polarisation is observed within the cell $Z = (-136, -97)$ cm, with a possible reduction in the region outside of the cell.



(a) Vertex reconstructed for $pp \to d\pi^+$ events

(b) Polarisation as function of the longitudinal coordinate

Figure 6: Measurement with $\vec{\mathrm{H}}$ with the stainless steel cell at 580 MeV

3.2 Polarimetry with the steel cell at 1.66 GeV

Both the cross section and analysing power of the $pp \to d\pi^+$ reaction in the angular range of the ANKE acceptance are too low at this energy and the polarisation could only be measured reliably with pp elastic scattering. The two final protons from the latter were recorded in coincidence in the Fd and STT. The recoil proton in STT could be identified through the energy loss and the process was selected by the kinematics.

The pp elastic scattering analysing power was measured during the ANKE beam time in March 2013 [8] at 1.6 GeV in the angular range of interest of $\theta_p^{cm} = (15 - 25)^\circ$, and only a small change of 4% is expected for A_y between the 1.6 and 1.66 GeV beam energies.

A polarisation of 19±3% was obtained, which is consistent with the results at 580 MeV. At this beam energy only the $\vec{\mathrm{H}}$ target polarisation is of interest.

3.3 Polarimetry with the ABS jet

A special feature of this measurement is the low target density in the jet, amounting to $\sim 10^{11}$at/cm^2. One consequence of this was that the count rate was too low for the $pp \to d\pi^+$ reaction even at 580 MeV to collect reasonable statistics within the time available. Furthermore, the jet density was comparable to that of the rest gas in the vacuum chamber. It was therefore necessary to select the jet region directly, using the tracks reconstructed in STT. With this aim in mind, after the cell removal, the STT was moved to a position close to the jet and the polarisation of the $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ jets was defined by pp and pd elastic scattering, respectively.

The measurement at 1.66 GeV with the $\vec{\mathrm{H}}$ jet was done in a similar way to the cell. It resulted in a jet polarisation of $59 \pm 2\%$. Although significantly higher than that found with the cell, this value is lower than that expected from the laboratory ABS tests (91%). The reasons for this reduction have still to be discovered.

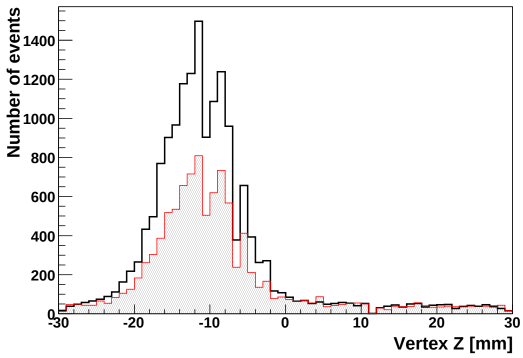


Figure 7: Vertex Z coordinate reconstructed from the STT measurements with ABS jet at 580 MeV. The counts for ABS polarisation-up are shown by the thick line, and for polarisation-down by the filled histogram.

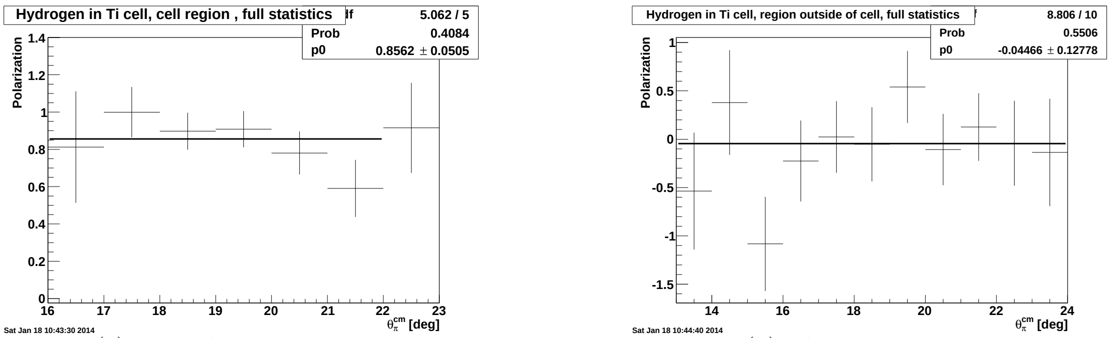
At 580 MeV, the polarisations of both the $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ jets have been measured. The pp elastic scattering analysing power is well described at this energy by the SAID phase shift analysis. Figure 7 shows the distribution of the longitudinal vertex coordinate Z reconstructed from the STT data. One can clearly see the jet peak surrounded by the unpolarised rest gas background. In the other measurements with the jet the distributions were very similar. The measured polarisation of the jet was $85 \pm 4\%$.

The analysing powers in $pd \to pd$ elastic scattering were measured at energies close to 580 MeV at Argonne and ANKE [9, 10]. Although the nominal tensor polarisation of the $\vec{\mathrm{D}}$ jet for the modes chosen was equal to 1, it introduced only a $\sim 10\%$ correction to the estimated vector polarisation of the jet. In this measurement, the recoil deuteron was stopped in the second layer of he STT and thus could be clearly identified by its energy loss. The resulting deuterium polarisation was $80 \pm 5\%$.

3.4 Measurement with the titanium cell

The measurement was conducted for both $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ targets with the 580 MeV proton beam, using the $pp \to d\pi^+$ reaction for the polarimetry in the same way as described in section 3.1. The results obtained with the hydrogen target are shown separately in Fig. 8 for events originating in the cell region (a) and for the rest gas in the target chamber (b). The value of the polarisation in the cell is $Q = 86 \pm 5\%$, which is only 5% lower than the highest jet polarisation observed in the laboratory tests. As expected, the rest-gas polarisation is very low, which supports the correctness of the analysis.

The polarisation of the deuterium target was $61 \pm 10\%$. This value is consistent with the one obtained from the deuterium target commissioning run in 2012 $Q = 72 \pm 1\%$ [11]. Based on the small polarisation loss observed with the hydrogen target, one can reasonably assume a polarisation value of 70% for the count rate estimations.



(a) The cell region selected (b) The rest-gas region

Figure 8: $\vec{\mathrm{H}}$ target polarisations measured with the titanium cell at 580 MeV

4 Cell size and background considerations

The size of the beam at 353 MeV was studied with the Ionization Profile Monitor (IPM). The beam dimensions at ANKE were calculated from this measurement using the values of the beta functions and dispersions at the IPM and ANKE locations. The resulting time dependence of the beam size is shown in Fig. 9. One can see that a cell diameter of 11.8 mm corresponds to $\pm(2-2.5)\sigma$ of the beam vertical dimension. This information was also confirmed by the direct beam profile measurement at ANKE with the STT telescope.

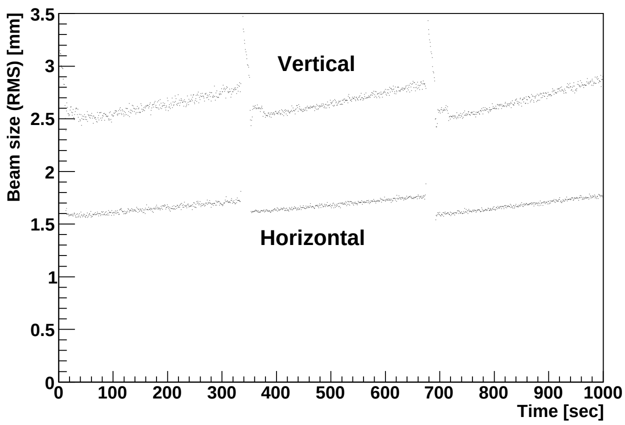


Figure 9: The beam size at ANKE measured with the IPM as a function of time. The upper graph corresponds to the vertical beam dimension, the lower one to the horizontal.

Figure 10 shows the beam current (BCT) and the rates in the ANKE forward detector with the cell closed and filled with gas. Although the decrease of the BCT within the cycle is rather slow, the observed growth of the forward rates limits the useful cycle length due to the worsening of the background conditions. For this reason, rather short cycles of 180 seconds were used. Additionally, the beam intensity had to be limited to 7×10^9 protons due to the beam instability occurring at higher intensity with the cell closed.

These considerations lead to the conclusion that a cell size of 11.8 mm is very close to the minimum possible at this beam energy. The use of the 2 MeV electron cooler at the flattop can drastically change this picture. According to the preliminary discussion with

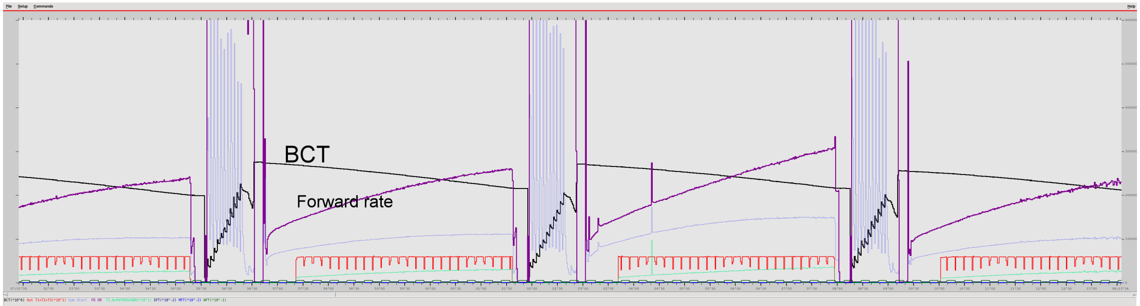


Figure 10: Rates measured at ANKE. The thick black line is the BCT; the rising magenta line shows the Forward detector rates.

the COSY crew [12], there are possibilities to use the cooler together with the Siberian snake. The solenoidal field of the cooler can then be compensated by the snake to preserve the beam polarisation. We suppose that the size of the cooled beam can be small enough to use a 10 mm cell, but this must be investigated after the snake installation. Further decrease of the cell diameter is less effective, due to the limitations connected with the feeding tube conductivity.

Although the single particle rates are dominated by the background originating in the beam interaction with the cell material, the background level for reactions with several particles detected is quite low. This has been observed for the (quasi)-free $pp \to d\pi^+$ reaction as well as in elastic pp and pd scattering used for the polarimetry, as described in Section 3. Especially effective is the background suppression when one of the ejectiles is detected in the STT since it then becomes possible to reconstruct the interaction vertex. Reconstruction of the vertex is important because most of the background is produced in the entrance part of the cell, which does not fall within the STT acceptance for any reaction of interest. The analysis of the background conditions for the $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ process is in progress and the results will be presented at the PAC session.

The ability to detect charged pions in the STT has been studied with the π^+ ejectiles from the $pp \to d\pi^+$ reaction. Pions with kinetic energies of $15 - 70$ MeV deposit $250 - 350$ keV in the 300μm thick layer of the STT. The threshold value of the deposited energy necessary for triggering was found to be 170 keV. Thus, even with the current setup, it is possible to detect effectively pions in the energy range of interest. The new generation of the STT detectors being constructed are designed for operation with a 100 keV threshold.

5 Estimation of the beam time required

The main objective of the measurement of $A_{x,z}$ in the $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ process is to resolve the ambiguity in the partial wave analysis of the existing data [1]. Predictions for $A_{x,z}$ obtained for the three possible solutions are shown in Fig. 11 together with the $A_{x,z}$ histograms “reconstructed” in the simulation with the corresponding prediction used as input. The goal of the beam time is to provide data sufficient to reject the wrong solutions with a 95% probability. The probability is calculated from the χ^2 constructed for the $A_{x,z}$ histogram and the predictions for each solution.

We used the following assumptions in the simulation:

- the beam intensity of 7×10^9 protons,
- the target density of 3×10^{13} at/cm^2 (cell size of 11.8 mm),

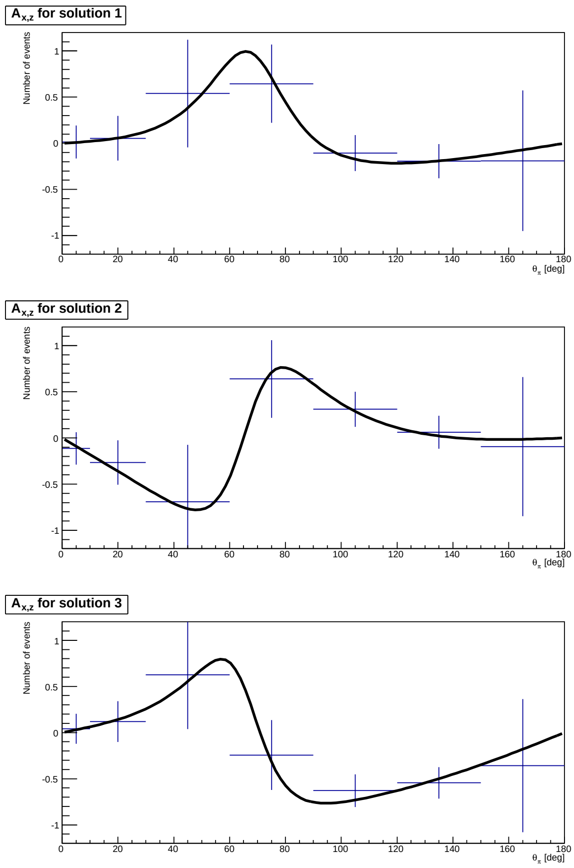


Figure 11: Predictions for $A_{x,z}$ in $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ made for the three PWA solutions (the curves). The error bars are the $A_{x,z}$ values "reconstructed" in the simulation.

- the beam and target polarisations of 70%.

Under these conditions we reach the desired level of distinction between the solutions after **12 weeks** of measurement. If beam cooling is available at the flattop, the cell size can be reduced to 10 mm, which brings the necessary time down to **7 weeks**.

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