ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPAL024

HIGH PRECISION BEAM PARAMETER STABILIZATION FOR P2 AT MESA

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Abstract

The experiment P2 will measure the weak mixing angle with an all-time high precision via electron-proton scattering. The measured physics asymmetry and its uncertainty has to be corrected by the apparatus' asymmetry, which is generated by helicity correlated fluctuations of the beam parameters position, angle, intensity and energy. In this article will be described how the high precision of 0.1 ppb of the parity violating asymmetry can be provided by the high precision measurements of the parameters position, angle and intensity.

INTRODUCTION

The P2-Experiment aims to measure the weak mixing angle via electron-proton scattering to a relative uncertainty of 0.13% [1]. The measured asymmetry A^{exp} between two helicity states is a sum of the parity violating asymmetry A^{phys} times the polarization p and the apparative asymmetry A^{app}:

$$A^{\text{exp}} = p \cdot A^{\text{phys}} + A^{\text{app}}$$

The uncertainty of A^{app} determines the uncertainty of A^{exp}. This leads to the constraint on the uncertainty of A^{app} not to exceed 0.1 ppb for the scheduled runtime of 10 000 hours of the experiment. We assume ΔA^{app} to arise from the uncertainties of corrections of false asymmetries from helicity correlated fluctuations of beam parameters.

To determine the asymmetry at a certain time parity violating experiments use short term asymmetries (STAs). STAs are calcuated from quadruplets. This is a pattern of helicity states (either positive or negative) of 1 ms length in the following orders: $+--+$ and $-++-$ in a random sequence. Each quadruplet is 4 ms long and 9×10^9 quadruplets will be measured during 10000 hours measuring time. When the uncertainty of the apparative asymmetry shall be maximally

$$\Delta A^{\text{app}} = \frac{\sigma}{\sqrt{9 \times 10^9}} = 0.1\,\text{ppb}$$

[2] the uncertainty of a quadruplet is

$$\sigma = 9.5\,\text{ppm}.$$

On the condition that the error sources are not correlated the root sum square of asymmetry uncertainties from the six parameters Δx, Δy, $\Delta x'$, $\Delta y'$, ΔE and ΔI must not exceed 9.5 ppm for a quadruplet.

For the A4 experiment the existing accelerator MAMI was equipped with a very reliable analog beam stabilisation and provided very good beam quality. During the last three years parts of the beam position monitoring system from MAMI was modified, improved and tested. With the collected data a prediction can be made whether the goal of 9.5 ppm is already fulfilled for certain parameters or if the system has to be improved.

Estimating how a fluctuation of one of the geometric parameters Δx, Δy, $\Delta x'$, $\Delta y'$ contributes to the apparative asymmetry uncertainty, one has to put into account the geometry of the detector and the effects in the hydrogen target as well as the influence of the magnetic field in the solenoid of the detector. The best way to do this estimation is to run Monte Carlo simulations. As long as the work on these simulations is in progress, we consult evaluations made for the A4 experiment [3] solely based on solid angle acceptance, ignoring target effects and details of the solenoidal spectrometer, in order to give a first approach on the expectable asymmetry uncertainties.

MODIFICATIONS ON BEAM MONITORING SYSTEM AT MAMI

For the purpose of testing a new control system for the MESA beam parameters we picked 20 m of beamline at MAMI and installed additional monitors and steerers. The control loops, each with a steerer and a monitor, are arranged as shown in figure 1. The electron beam has an energy of 180 MeV which is close to the P2 beam energy of 155 MeV. The major differences in comparison with the A4 experiment is the switch to a digital system. Also we changed the electronic signal processing to an IQ-Demodulation in order to decrease baseband contributions collected on the signal transfer path. The change to a digital system makes

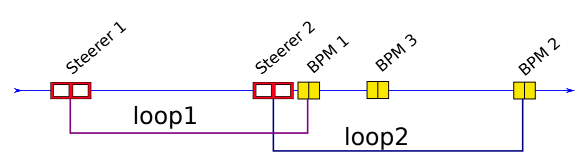

Figure 1: Control system components in the beamline. BPM 3 is used as an unbiased observer.

it possible to control the beam in the classical feedback as well as in feedforward loop to avoid jumps caused by the helicity flips. Its flexibility allows for quick modifications without hall access. For significantly gaining higher accuracy we use fast ADCs and DACs with 14 bits resolution and 125 MHz sampling frequency. The digital control system will be programmed in an FPGA. However, instead of creating a complete new system of ADCs, DACs, CPUs and

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FPGA we decided to choose a commercial board, called "Red Pitaya", that hosts all theses elements.

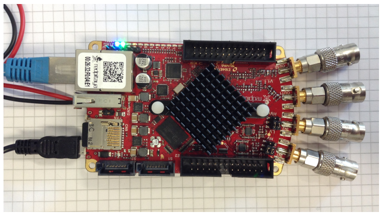

Figure 2: Red Pitaya.

RESULTS FOR ACCURACY

For the P2 experiment a significantly lower data rate than 125 MHz is sufficient, for example of the order of few times the helicity flip rate. Due to the excessive supply of samples compared to the helicity flip rate of 1 kHz we use the method of averaging over N samples, which improves the effective resolution. The data rate is then so-called decimated by the factor of N. A decimation of 8192 at a sampling rate of 125 MHz gives a data rate of about 15.2 kHz. This procedure will reduce the error of the measured value by a factor of $\sqrt{8192}$ assuming that the noise is white noise.

The following results comprise contributions from different sources to the overall noise budget. Beam position values refer to the BPM 2 in Fig. 1. Its sensitivity is 640 mV mm^{-1} at 10 µA beam current. For 150µA beam current the sensitivity increases to 9.6 Vmm^{-1}.

ADC Effective Resolution

The effective resolution of the data acquisition system is determined by the effective number of bits (ENOB) of the ADCs. The used ADCs have 11.5 ENOB and 2.5 bits of noise. This noise is caused by variation of voltage supply, clock jitter, and the quantization error. This noise is not further reducable. To measure this limit, all other components are detached from the ADCs. Tab. 1 shows the effective resolution of the data acquisition in bits. The beam width in µV is the measured value with the ADCs and the last column is the false contribution to a measured beam width in nm caused by the ADC noise if measured at 150 µA with BPM 2.

Table 1: Maximal Possible Resolution for a Decimation of 8192 in Number of Bits and µV. W stands for signal width.

bits	**W/µV**	**W/nm @150 µA**
0.42	40.8	4.3

Signal Width with Beam off

Table 2 shows the signal width of a measurement with beam off. This contains the overall noise of the data acquistion system. The last column tells what the noise would contribute to a false width of the beam if measured with BPM 2 at 150 µA. Noise sources are electronic components such as mixers, amplifiers, splitters, and connections. Noise collected on the transfer path is partially cancelled because signals are differentially transfered.

Table 2: Signal Width without Beam for Decimation of 8192

bits	**W/µV**	**W/nm @150 µA**
0.97	59.8	6.2

Signal Width with Beam on

Table 3 shows results for the width of a stabilized 5 µA beam measured with BPM 3 in Fig. 1 as well as the extrapolated beam width after 10 kh beam time. For this measurement a standard PID controller on the FPGA was employed. One can see that the beam width is 10 000 times wider than the noise contribution from electronics which makes them neglectible.

Table 3: Signal Width and Beam Width of a Stabilized 5 µA Beam

bits	**W/mV @5 µA**	**W/µm**	**W/nm @10 kh**
3.15	6.25	54.3	0.29

Beam Current

Also the beam current was measured with the new DAQ system. An STA can be calculated straight from the beam current. Table 4 shows the beam current fluctuations at 10 µA beam current as well as the resulting and extrapolated STA for 150 µA (col. 3) and after 10 kh measuring time (col. 4). This extrapolation is based on the evaluation of beam current data from the A4 experiment. The beam current stability still has to be improved for the P2 experiment.

Table 4: Width and Extrapolated STA of the Beam Current

W/mV @10µA	**W/nA**	**ΔSTA/ppm @150µA**	**ΔSTA/ppb @10kh**
6.0	5.9	28	0.29

Beam Energy

So far we did not take energy measurements with our data acquisition system. So we have to make an estimation of the impact of energy fluctuations on the apparative asymmetry. The result is shown in Tab. 5. for the two different beam energies used for A4 and P2. The last column gives the range of parity violationl asymmetry for A4 and P2 and the middle column shows that at A4@MAMI for a fluctuation of 1 eV the apparative asymmetry is at about 0.04 % but for

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P2 the apparative asymmetry would be 23 % of the measured asymmetry, which is not acceptable. The beam energy stability has to improve at MESA compared to MAMI and the energy measurement spread after 10 kh shall not exceed 15 meV. That corresponds to a precision of 1500 eV for a single quadruplet measurement. It seams feasible to measure this uncertainty with a 180 ° arc with a longitudinal dispersion of 10 mm/10^{-3}. The alternative of measuring the transversal dispersion of 3 mm/10^{-3} with a 90 ° arc is also possible. 0.3 nm precision in 10 000 h are required. This is already achievable, as can be seen in Tab. 4.

Table 5: Estimated Apparative Asymmetries from Helicity Correlated Beam Energy Fluctuations for P2 at MESA

E_{beam} / MeV	A^{app} / ppb/eV	A^{PV} / ppb
855	2.0	≈ 5000
155	6.8	≈ 30

Expected Asymmetry Uncertainties for P2 from Beam Position

Table 6 summarizes the expected STAs from the parameters discussed above. The beam position stability of 0.11 ppb still outreaches the requirement of 0.1 ppb. Improvements are expected with a new beam position monitor design and by dint of increasing the BPMs sensitivity with increasing the beam current up to 150 µA as well as increasing the decimation factor.

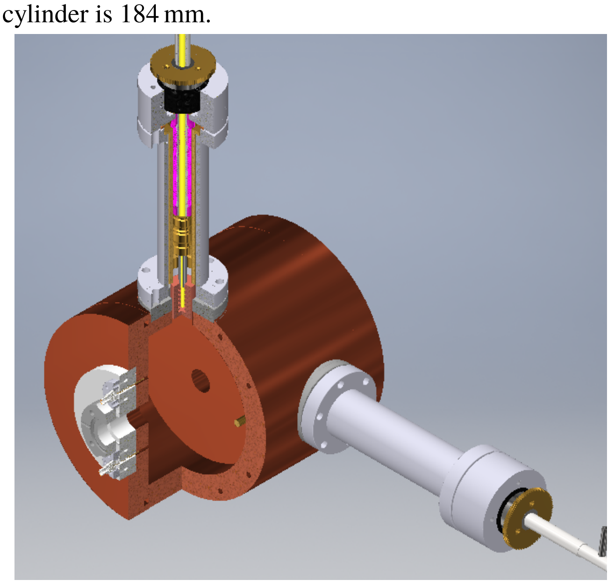
Table 6: Uncertainties of the Asymmetry Projected from A4 to P2 for the Data with a Decimation of 8192

	Width/nm	**ΔSTA/ppb per quadr.**	**ΔSTA/ppb @10 kh**
eff. resolution	4.3	0.83	8.7×10^{-6}
electronics	6.2	1.2	1.3×10^{-5}
stabilized beam	5.4×10^{4}	1.0×10^{4}	0.11

BPM CAVITY DESIGN

For the P2 experiment new beam position monitors (BPMs) have to be designed because of the different bunch frequency 1.3 GHz compared to MAMI and stronger demands on precision. We decided in favor of cavity monitors because they are noninvasive and provide a strong signal due to their amplifying character. To meet a compromise between signal strength and acceptable geometric dimensions we decided on a cavity with a resonance frequency at 2.6 GHz, the first harmonic of 1.3 GHz. This measure leads to only three percent signal loss due to the short bunches in MESA. Our control loop has a low-pass at about 100 kHz which comes from the steerers amplifier. The BPMs bandwidth should be placed above 100 kHz to shift the positive amplitude response with more than 180 degree phase shift to higher frequencies, where amplification is safely below 1. 250 kHz is a good compromise between high signal and high bandwidth and means a loaded Q-Factor of 10 400. Simulations revealed a (unloaded) Q-Factor of more than 20 000. A design of a cavity is shown in Fig. 3. It embraces two cavities, one for displacement in x and one for y direction. The electric field of the standing wave of the TM_{110}- mode inside the cavity is sensed with a pair of antennas for each direction. The two resulting signals for one direction will be subtracted from each other, which cancels out symmetrical modes such as TM_{0x0}-modes and doubles the outcome. The unwanted perpendicular TM_{110}-modes are suppressed with pins that protrude into the cavities on an axis 90 degrees rotated to the antenna axis. Tuning pistons are attached to the BPM to allow for adjustment of the resonance frequency by changing the cavity volume. Also it allows for remotely detuning the resonance frequency in order to lower the signal if high beam displacements are expected. This protects sensitive electronic components in the signal transfer path. All connections are of Conflat Standard because the cavity has to be bakeable to provide an environment for ultra-high vacuum.

Figure 3: Copper cavity design. The outer diameter of the cylinder is 184 mm.



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