Beam Parameter Stabilization at MESA for P2

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P2 @ MESA
P2 Detector

See also:
The P2 Experiment
arXiv:1802.04759
Motivation

- **P2 experiment at MESA**
- Measuring the weak mixing angle
- external beam mode with low energy and high current:
  - 150\(\mu\)A, 155MeV
- longitudinally polarized beam
  - fast helicity flipping \(\sim\)kHz
- parity violation (elastic ep scattering)
  - expected asymmetry \(\sim\)30ppb
- very strong demands on beam quality!
  - intensity, energy, position, angle
Measuring Asymmetry with Electron-Proton-Scattering

electromagnetic + weak

\[ e + e \rightarrow \gamma + e + e \]

\[ p + p \rightarrow Z + p + p \]
Measuring Asymmetry with Electron-Proton-Scattering

- Measured asymmetry determined by the cross section for electron-proton-scattering with polarized electrons:

\[
A^{PV} = \frac{\sigma_{ep}^+ - \sigma_{ep}^-}{\sigma_{ep}^+ + \sigma_{ep}^-}
\]
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\]

\[
\sigma_{ep}^+ \propto |M_\gamma + M_{Z,R}|^2
\]

\[
\sigma_{ep}^- \propto |M_\gamma + M_{Z,L}|^2
\]
Measuring Asymmetry with Electron-Proton-Scattering

- Measured asymmetry determined by the cross section for electron-proton-scattering with polarized electrons:

\[ A^{PV} = \frac{\sigma^+_{ep} - \sigma^-_{ep}}{\sigma^+_{ep} + \sigma^-_{ep}} \]

\[ \sigma^+_{ep} \propto |M_\gamma + M_{Z,R}|^2 \]

\[ \sigma^-_{ep} \propto |M_\gamma + M_{Z,L}|^2 \]

\[ M_\gamma \propto \frac{1}{Q^2} \]

\[ M_Z \propto \frac{1}{m^2_Z} \]
Measuring Asymmetry with Electron-Proton-Scattering

- Measured asymmetry determined by the cross section for electron-proton-scattering with polarized electrons:

\[ A^{PV} = \frac{\sigma_{ep}^+ - \sigma_{ep}^-}{\sigma_{ep}^+ + \sigma_{ep}^-} \]

\[ \sigma_{ep}^+ \propto |M_\gamma + M_{Z,R}|^2 \]

\[ \sigma_{ep}^- \propto |M_\gamma + M_{Z,L}|^2 \]

\[ M_\gamma \propto \frac{1}{Q^2} \]

\[ M_Z \propto \frac{1}{m_Z^2} \]

- Expected asymmetry determined by spin polarization and apparative asymmetry.

\[ A^{exp} = P \cdot \langle A^{PV} \rangle_L, \delta \theta_f + A^{app} \]
P2 Beam Quality Requirements

Uncertainty of weak mixing angle

max. 0.1 ppb from beam systematics assumed!

See also arXiv:1802.04759
Measuring Asymmetry in 4ms

- STA: short term asymmetry
- Measured in a 4ms pattern of spin states of 1ms length: +--+, or -+++-
- In 10kh measuring time are $9 \times 10^9$ STAs.

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

$$\sigma = \Delta A^{\text{app}}(STA) \overset{!}{=} 9.5 \text{ ppm}$$
Approach for Stable and Accurate Beam

- **Digital Control System (FPGA)**
  - Further Pros: highly flexible, quickly replaceable
- **IQ-Demodulation**
- **Differential Signal Transfer**
- **Feedback and Feedforward Control**
  - "Feedforward": pre-adaption to upcoming beam shift from helicity switch
- **High Sensitivity Beam Position Monitors**
Stabilization Principle and Setup of Hardware
Arrangement of Steerers and BPMs in Hall B (RTM3)@MAMI

RTM3

10 m

180MeV

XY-Monitor with Intensity Monitor
Steerer
Dipol
Stabilization Principle and Hardware

- **Red Pitaya**
  - FPGA
  - CPU
  - 14bit DACs (125MHz)
  - ADCs
  - Power Amps
  - Steerer
  - BPM
  - XYMO-Electronics
  - e⁻

- **XYMO-Steerer**
  - Master connection

- **XYMO-Beam Position Monitor (BPM)**
Stabilization Principle and Hardware

Fast Steerer

- Red Pitaya
  - FPGA
  - CPU
  - 14bit 125MHz
  - DAC DAC
  - ADC ADC

- Power Amps
  - Steerer
  - BPM

- XYMO-Electronics
  - master

Diagram showing the components and connections of the stabilizer system.
Stabilization Principle and Hardware

Fast Steerer

BPM

- 2 Resonating Cavities
- 2.45 GHz resonance frequency

Red Pitaya

FPGA

CPU

14bit
125MHz

Power Amps

X

Y

Steerer

BPM

X

Y

XYMO-Electronics

master
Successful Stabilization Tests

- using RedPitaya internal PID blocks (used only PI)!

-50dB @50Hz, -50 dB @100Hz, -20dB @1000Hz
(A4/MAMI: -40dB@50Hz)
Planned Setup Beam Control in MESA

P2 Beamline Instrumentation
- fast steerer
- slow steerer
- XYMO (cavity BPM)
- PIMO (phase, intensity)
- luminescence screen
- vacuum valve
- vacuum pump
- vacuum gauge

Diagram of the MESA setup with various components and measurements.
Planned Setup Beam Control in MESA
Asymmetry Uncertainties Results

Expected Asymmetry Uncertainties after 10kh measuring time at 150μA

- Position and current based on signal widths measured in Tests at MAMI
- Scaled to 150μA in 10kh and averaged over 8192 samples of 8ns.
- Energy asymmetry is estimated from A4 data. 0.1 ppb feasible but not yet demonstrated. Relative energy width of $10^{-5}$ needed.
Thank you for your attention
Backup
Cavity Design
Cavity Design

- 2 Pillboxes in one
- TM110-mode
- 2,6GHz resonance frequency
- 250kHz bandwidth
- Electric coupling
- Remote tuning/detuning
- Water cooled
Polarized Beam: Short Term Asymmetry

Beam Current Measurement:
- Stabilization off
- maximize asymmetry with half wave plate
- Helicity flip:
  +--- -++- (8ms)

Asymmetry

\[
A = \frac{I_{up} - I_{down}}{I_{up} + I_{down}}
\]

How do you avoid effects from drifts?!
DAQ with “RedPitayas”

- FPGA+CPU (Xilinx Zynq 7010 SoC)
- 2 fast DACs, 14 Bit / 125MSa/s
- 2 fast ADCs, 14 Bit / 125MSa/s
- GPIO connector w/digital pins (trigger, clock, ...)
- Ethernet, USB
- Linux on dual core ARM (Cortex A9)
- open source (firmware/software)
- ~250 €/pc.
DAQ with “RedPitayas”

RunControl

PC

daccord_server

DAQcore

Run

Trigger

Raspberry Pi

daccord_server

DAQcore

Trigger

Spartan6

Clock

I2C

FPGA

Data Acquisition

Red Pitaya

daccord_server

DAQcore

acquire

FPGA

ADC

Sata in

Clock

ADC

Sata out

Red Pitaya

Sata out

Sata in

Red Pitaya

Sata out

Sata in

Red Pitaya

Sata out

Sata in
loop 1
7840mm

loop 2
8000mm
Tuning and Detuning

- Moving the Piston changes the resonance frequency
- Piston can drive 12 mm
- Motor makes 7000 steps
TM110-mode

- Node at the axis of the cavity
- Linear close to the cavity axis
- Perpendicular mode suppressed with mode dividers
Field Magnitude along antenna axis (without antennas)

Maxima at ± 33 mm

Linear close to the axis
Remote Tuning und Detuning

- To save sensitive electronics in case of high displacements
- Possible maximal damping: -30 to -36 dB depending on piston position at 2.6GHz
Double Differences

- Check for beam loss between two beam current monitors
- Yet no data, example for A4:
  - The double difference:
    \[ dd = sta_1 - sta_2 \]
  is strictly around zero if no beam was lost.

- The width indicates the resolution of the monitors:
  \[ \sigma(dd) = \sigma(pimo_{13})^2 + \sigma(pimo_{27})^2 \]

- Tests with our setup in December
Measurements of Transfer Functions

- automatic measurement
- RedPitaya as signal generator + digitizer
- With beam at MAMI or without beam at test stand (MESA halls)
- characterization of components of control loop
- open loop → predict closed loop behavior

Transfer function Example

**Amplitude**

Transfer Function Toellner TOE7610-20 (Amplitude)

**Phase**

Transfer Function Toellner TOE7610-20 (Phase in radian)
Resolution of XYMOs:
2.2V/mm
LSB 1.28µm with HV-jumper
→ not less than 60 nm with lv-jumper

Principle of Beam Monitoring
IQ-Demodulation

- XYMO-Signal: MAMI 2.45GHz carrier
- After 2.44 GHz mixing: 10MHz carrier
- Two branches demodulated with 90° shifted 10MHz.

→ signal amplitude = \( A = \sqrt{I^2 + Q^2} \)

No nasty phase tuning needed any more because signal is always reconstructable with \( I \) and \( Q \).
IQ-Demodulation

- Measurement of $I$ and $Q$ of the 1000 Hz Peak at different phase tunes result in a circle.
- Circle is not evenly circular.
- Electronics are still susceptible to DC Offsets, errors in gain matching of $I$ and $Q$.
- Digital IQ-Demodulation maybe better?! Offline tests after beamtime with Signal on 10MHz.
Digital Feedforward – (@Test Stand)

- helicity flip → beam position “jump”
- measure “jump” → push current into coils during flip!
  - feedback takes care of residual helicity correlation
  - 300 mA/µs possible
    - uses only 50% of amplifier output swing
    - other 50% swing available for feedback
- adjust feedback loop gain during flip? digital system → no problem!
Polarized Beam: Short Term Asymmetry

Beam Current Measurement:

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- maximize asymmetry with half wave plate

- Helicity flip:
  - +++- +++- (8ms)