Commissioning and First Data Analysis of the Mainz Radius Experiment

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20/07/2023

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The Mainz Radius Experiment
MREX

The Mainz Radius Experiment is an experimental campaign at the nuclear physics institute of Mainz, with the aim of investigating the properties of nuclear matter with imbalance in the number of protons and neutrons.

Objective

Determination of the neutron spacial density for ^{208}Pb nucleus, through the elastic electron scattering. From an accurate determination of the neutron spacial distribution, the *Neutron Skin Thickness* of ^{208}Pb is measured.

The results of the experiment will be valuable to constrain the Equation of State (EOS) of nuclear matter. It has also implications for the structure of neutron star.

$^{208}_{82}\mathrm{Pb}$
Lead
Da 207.977

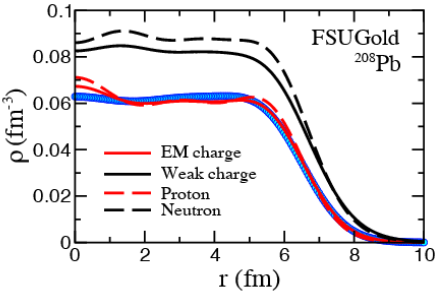
MREX and Neutron Skin Thickness

Definition

The neutron skin thickness is defined as the difference between rms radius of neutron and proton spacial distributions:

$$\delta r_{np} = \sqrt{< r_n^2 >} - \sqrt{< r_p^2 >}, \tag{1}$$

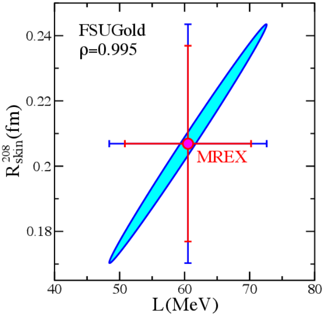
In neutron rich nuclei, the spacial distribution of neutrons in more extended than proton spacial distribution. Theoretical models link the Neutron skin thickness of heavy nuclei, such as ^{208}Pb, with the **slope of the symmetry energy L**.

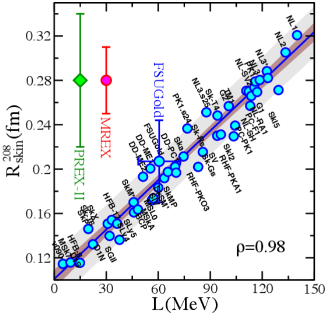


Symmetry Energy

The symmetry energy $S(\rho)$ is the key component of the equation of state which controls the neutron skin thickness. $S(\rho)$ quantifies the change in energy related to the neutron-proton asymmetry.

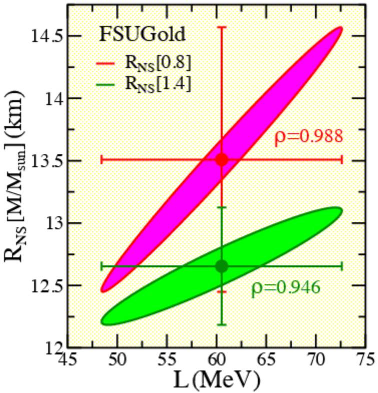
$$
\begin{aligned}
\epsilon(\rho,\alpha) &= \epsilon_{SNM}(\rho) + \alpha^2 S(\rho) + O(\alpha^4) \\
\epsilon(\rho) &= J + L \cdot \left(\frac{\rho-\rho_0}{3\rho_0}\right) + \dots
\end{aligned}
\tag{2}
$$





Neutron Skin and Neutron Star Radius

The slope of the symmetry energy is related to both the **neutron skin** of lead and **neutron star radius**. The radius of the neutron star is determined from Tolman-Oppenheimer-Volkoff (TOV) equation. Giving the pressure P_c at the center of the star, the radius R can be determined. But for neutron star, the pressure at the center is strongly related to the **pressure of pure neutron matter**, in large part determined by L.



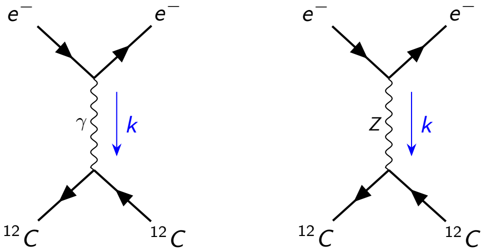
Parity Violating Asymmetry

Measurement of the Neutron Spacial Distribution of Lead

The determination of the neutron spacial distribution relies on the electron nucleus elastic scattering experiment, planned at the future MESA accelerator, in Mainz. The neutron spacial distribution is measured via the parity violating scattering, where longitudinal polarized electrons scatter from a fixed lead target. The key quantity is the asymmetry in the cross-section due to the different polarization state of the beam,

$$A_{pv} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{3}$$

The asymmetry is due to the interference between two Feynmann diagrams.

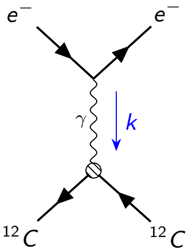


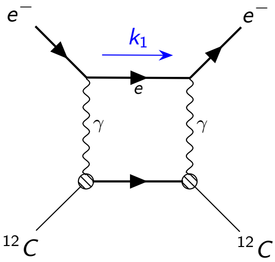
Transverse Asymmetry

Argomento principale della tesi: misura dell'asimmetria trasversa, fondo sistematico di A_{pv} da determinare. Introduzione alla fisica del processo
The transverse asymmetry is defined as the ratio between the sum and the difference of the elastic cross section for the two different polarized electrons:

$$A_{transverse} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

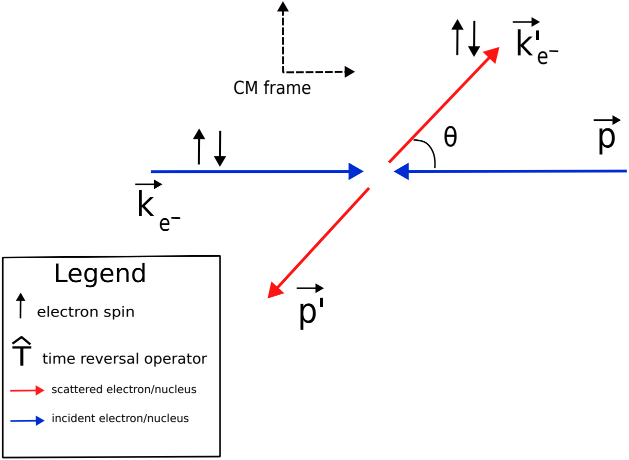
Before moving on to the experimental details, we identify the kinematics of the experiment. For the beam normal single spin asymmetry, the electrons are polarized in the normal plane identified by the $\frac{\vec{k'} \wedge \vec{k}}{|\vec{k}||\vec{k'}|}$





Description of the Process

The transverse asymmetry arises considering the time reversal operator. The time reversal operator reverses all the momenta and the spin direction.



Scattering Process

The incident beam is made by 570 MeV electrons, that are polarized along the transverse axes (↑ and ↓). The physical quantity to measure is the asymmetry between the number of scattered electrons, due to the change of the polarity:

$$asym = \frac{N_+ - N_-}{N_+ + N_-} (\text{expected} \sim +/\text{- } 20 \text{ ppm, Q} = 0{,}2\,\text{GeVc}^{-1}) \quad (4)$$

The prediction for the transverse asymmetry is given by the formula below:

$$A_n \simeq C_0 \log \frac{Q^2}{m_e^2 c^2} \frac{F_{Compton}(Q^2)}{F_{ch}(Q^2)} \quad (5)$$

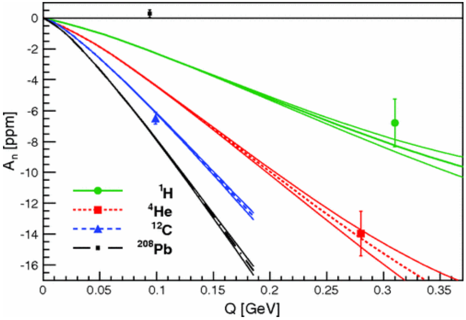


Figure: Asymmetry versus transferred momentum for selected nuclei.

During the last beam-time, several measurements were performed at Mainz Mikrotron MAMI. The last data acquisition campaign had the following goals:

- Test the new **data acquisition system**, developed for the new setup with a low rate signals ($\simeq 1\,\mathrm{MHz}$).
- Measure the **transverse asymmetry** A_n of ^{12}C.
- Measure the expected **rates** on ^{208}Pb target, in anticipation of the future measurement of A_n for lead.
- Long term goal: acquire more knowledge on the **systematic effects** that the transverse asymmetry has on the measurement of the Parity-violating asymmetry.

Structure of the event

The Data are divided in a series of events (80 ms), that correspond to 4 sequential sub-event. For each sub-event there is a precise polarization of the Beam. For each sub-event all the scattering electrons are counted.uring .

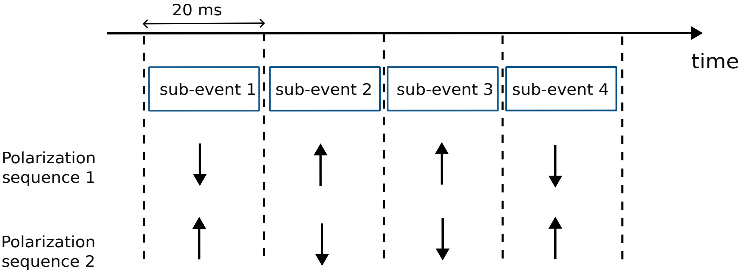


Figure: Event sequence: all the particle

MAMI Electron Accelerator

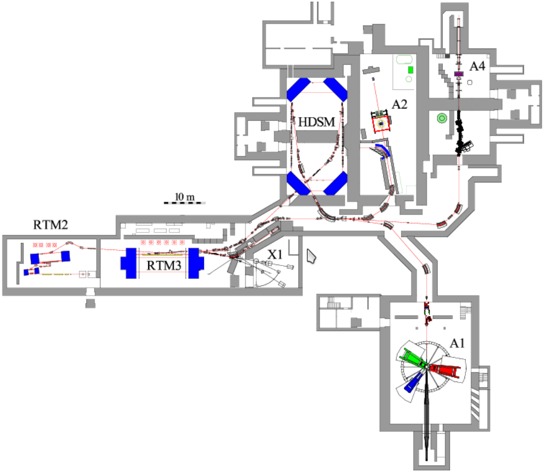
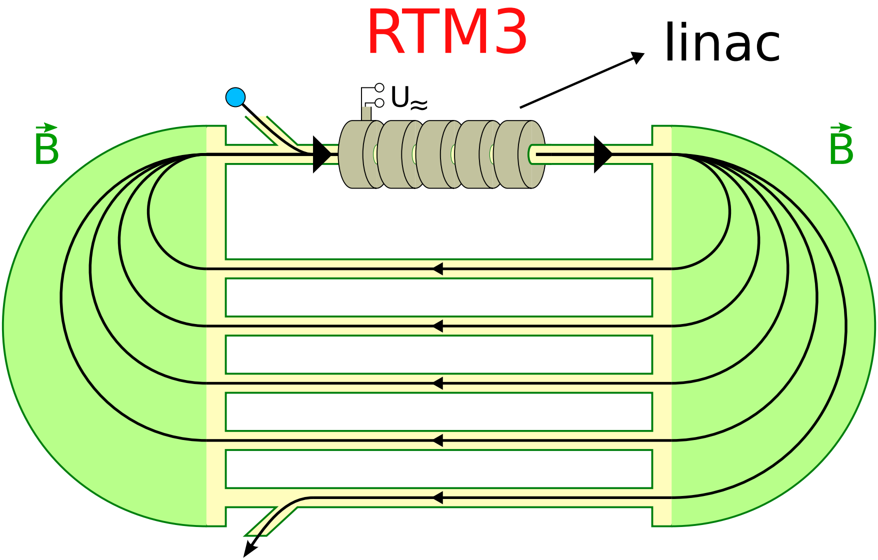


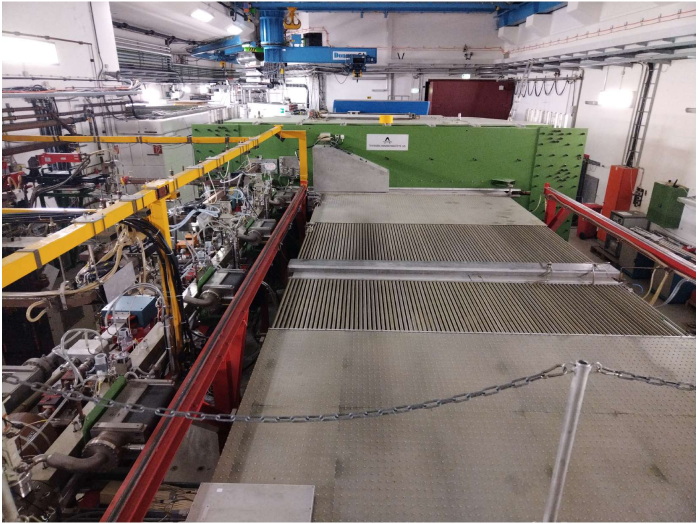
Figure: Scheme of MAMI accelerator. RTM2 is the first acceleration stage, where the electrons are extracted from the source. RTM3 corresponds to the final acceleration stage of the experiment (570 MeV), A1 is the experiment hall where the experiment described is the thesis is set up.

Race Track Microtron Scheme



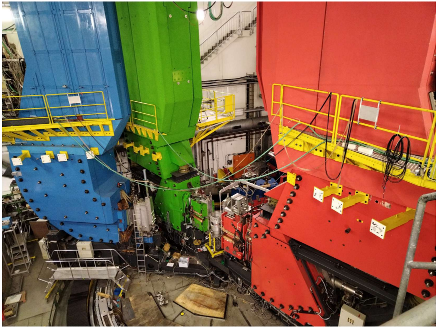
RTM3

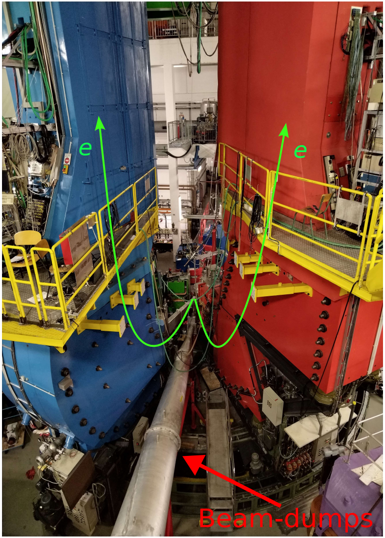
Race Track Microtron 3 of MAMI



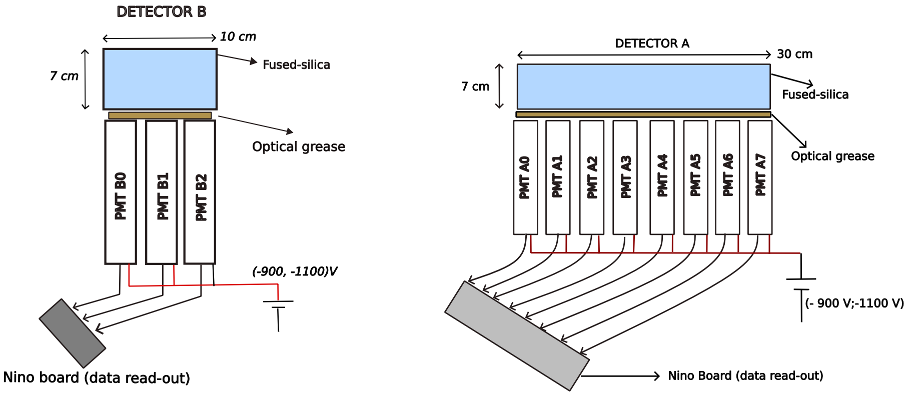
A1 Experimental Hall
MAMI Electron Accelerator

In MAMI A1, three large spectrometers are positioned on a rail track around the scattering chamber. For the experiment, only the red and blue spectrometers were used.



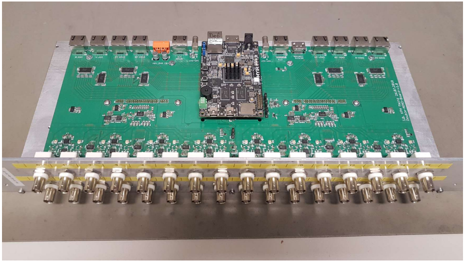


Detectors


DETECTOR B
10 cm
7 cm
Fused-silica
Optical grease
PMT B0
PMT B1
PMT B2
(-900, -1100)V
Nino board (data read-out)
DETECTOR A
30 cm
7 cm
Fused-silica
Optical grease
PMT A0
PMT A1
PMT A2
PMT A3
PMT A4
PMT A5
PMT A6
PMT A7
(- 900 V;-1100 V)
Nino Board (data read-out)

The NINO board is the DAQ system that counts the input signals coming from the Cherenkov detectors.

- 32 input channels.
- Attenuation circuit for each input channel.
- Common current Threshold for 4 adjacent channels.



False Asymmetries

The counts of the pmts can be slightly different due to the variation of the position of the beam on the target, the variations of the incident angles, the uncertain associated with the energy and the current of the beam. All this quantity can influence the asymmetry measured by the pmts, considering also that the expected asymmetry is in the order of ten part per million, and small asymmetry introduced by fluctuations of the beam parameters are not negligible:

$$Asym = A_{physical} \cdot P + \delta_I + A_x \delta x + A_y \delta y + A_{\theta_x} \delta \theta_x + A_{\theta_y} \delta \theta_y + A_E \delta E \tag{6}$$

MAMI Beam Monitors

At MAMI the beam parameters, as **X,Y** transverse positions, **Energy** and **Current** are measured by resonant cavities.

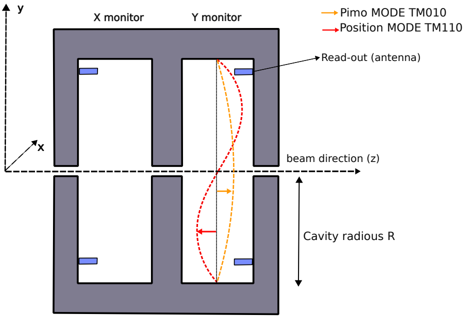
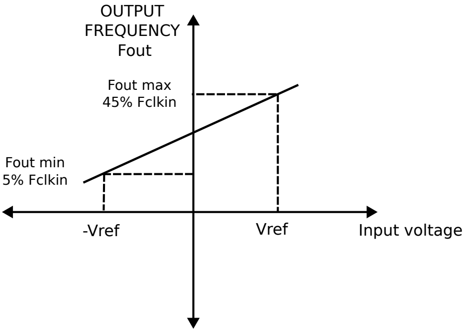


Figure: Scheme of the resonant cavity in MAMI, with the different electromagnetic modes excited by the beam passage.

The beam monitors are read-out with the voltage-to-frequency converters **VFC** devices, which produces an output signal whose frequency is proportional to the amplitude of the beam monitor signals.



General Scheme of the Experiment

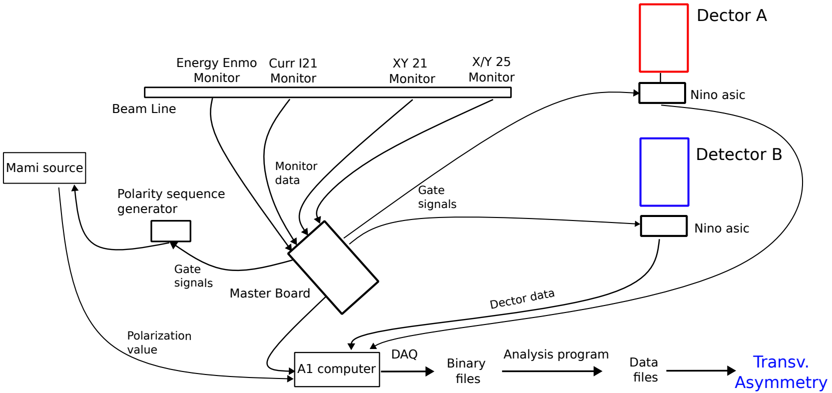


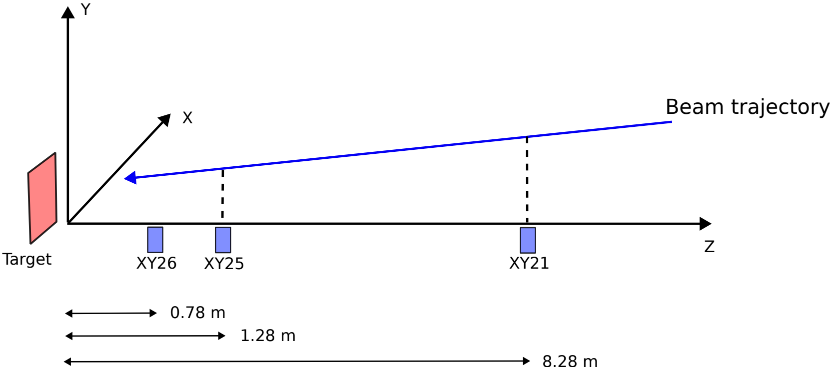
Figure: Scheme of the experiment.

Detector Tests

Calibration of the Beam Parameters

Beam Position

Computing the beam spot (X,Y) coordinates on the target



The beam is assumed following a straight path given by $x, y = m \cdot z + q_{x,y}$, the (X, Y) coordinates are given by $q_{x,y}$

Beam Energy and Beam Current

Auto-Calibration procedure

Analysis on Carbon Target

Model For Fitting the Data

The final model that describes the asymmetry takes care of the possible false asymmetries, assuming a **linear dependence** on the beam parameters.

$$A_{tot} = A_{physical} \cdot P + \delta_I + A_x \delta x + A_y \delta y + A_{\theta_x} \delta\theta_x + A_{\theta_y} \delta\theta_y + A_E \delta E \tag{7}$$

Each δq is computed as the mean difference between up and down polarized sub-events:

$$\delta q = \frac{q_{\uparrow,0} + q_{\uparrow,1}}{2} - \frac{q_{\downarrow,0} + q_{\downarrow,1}}{2} \tag{8}$$

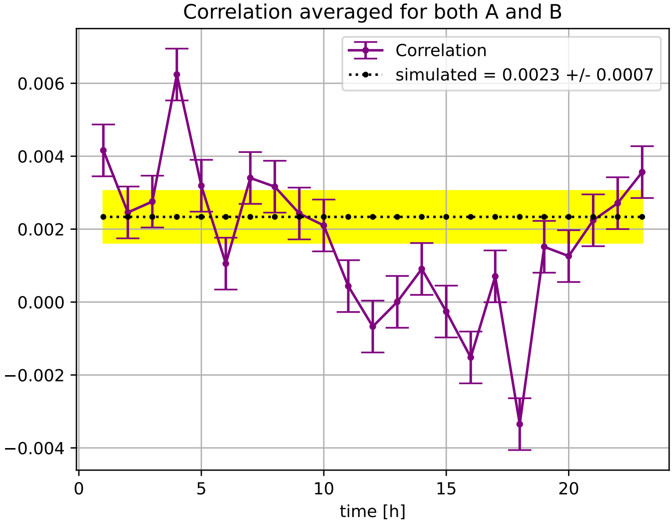
The current asymmetry is defined differently. Because the scattering rate is proportional to the beam current, the model contains the current asymmetry directly:

$$\delta I = \frac{I_\uparrow - I_\downarrow}{I_\uparrow + I_\downarrow} \tag{9}$$

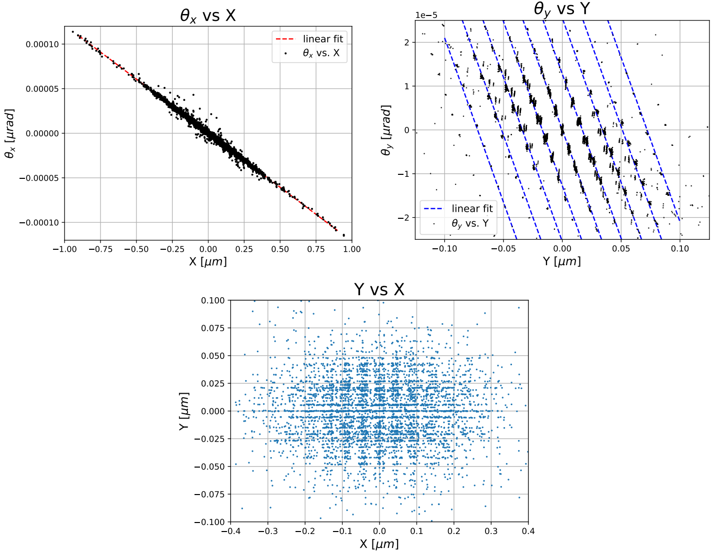
Data Selection

Polarization Loss

During the experiment, a relevant part of the data was affected by a loss of polarization of the beam:



Beam Parameters Correlation



Variance of the Asymmetry Data

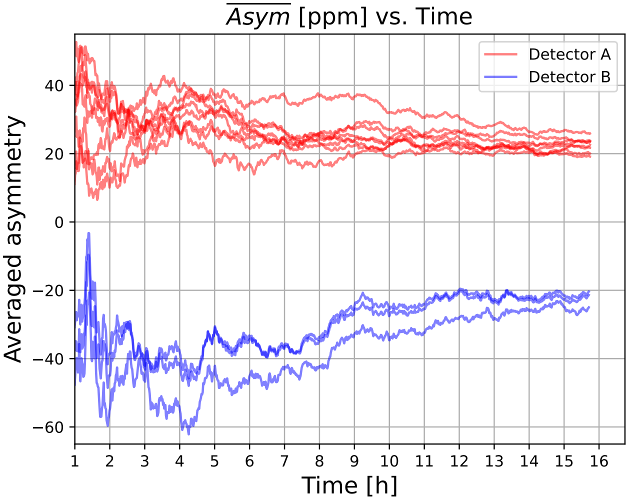
The statistical error of the measured asymmetries is now computed:

$$Var[A_{asym}] = Var[\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}] \simeq \frac{Var[N_\uparrow - N_\downarrow]}{(N_\uparrow + N_\downarrow)^2}$$

$$\frac{2Var[N]}{4N^2} = \frac{1}{2N} \qquad \sigma = \frac{1}{\sqrt{2N}}$$

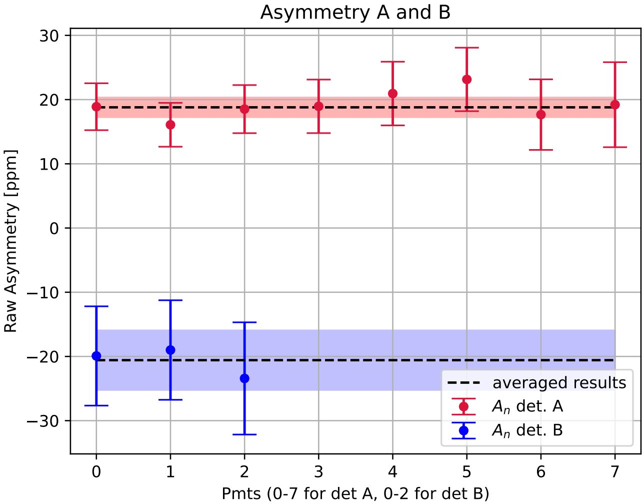
Where it is supposed that the PMTs counts are normal distributed, with μ equal to σ^2.
The rms associated to the sample mean decreases as the $\sqrt{N_{measure}}$.
Considering $5 \cdot 10^5$ events and $\mu = 40000$ counts per PMT (similar to what was measured for detector A) we obtain an error of $\simeq 5ppm$.

Here a plot about the trend of the asymmetry as the data increases. The band is the error computed as showed in the previous slide, centered around the values of $+20ppm$ for detector A and $-20ppm$ for detector B.



Visualization of the Data

Final asymmetry result for each PMTs:



Results

To combining the result of each PMTs, the formula used is:

$$\hat{A} = \frac{\Sigma_i A_i \frac{1}{w_i}}{\frac{1}{w_i}} \qquad w_i = \frac{1}{\sigma_i^2}$$

the final value of the BNSSA is:

$$A_A = (23.1 \pm 1.7)\, ppm \qquad A_B = (-21 \pm 5)\, ppm \tag{10}$$

Reversing the sign of the asymmetry for Det. B we notice that the two measurement are consistent within $1\,\sigma$.

Rates on Lead