Final report

Eddy currents analysis in the Muon g-2 experiment

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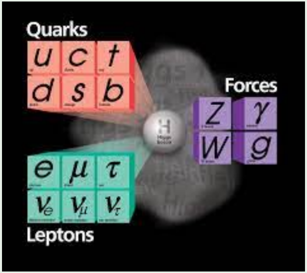
A brief introduction on the Muon g-2 experiment

What g is

- $\vec{\mu}_l = g \frac{e_l}{2m_l} \vec{S}$
- Quantity of interest: $a_l = \frac{g-2}{2}$

What l stands for



Why Muons?

- More massive than electrons
- More long-lived than Tauons

What is the reason why we are really interested in g-factor?

- It is possible to perform a very precise comparison between Theory and Experiments
- It could lead us to New physics beyond the Standard Model

Theory and Experiment: A phenomenological Journey

First Theoretical approach

- Dirac equation Prediction(1928): $a_l = 0$

First experimental discrepancy

- Kusch & Foley(1948): a_e=0.00119(5)

Standard Model Improvements

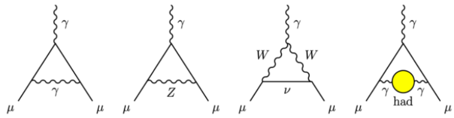


Figure: The lowest Feymann Diagram order for each interaction

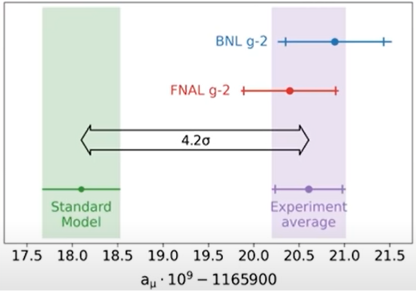
- New approach in the studying of particle physics
- Virtual particles as mediators for interactions
- Possibility to explore further orders beyond Dirac tree level term
- First order correction(Schwinger(1947)): $a_l = \frac{\alpha}{2\pi}$

Question: Is this theory in agreement with the experiments ?

Muon g-2: The state of art

Comparison between latest achievements

	Theoretical prediction	BNL result	RUN 1 result
a_μ^{SM}	$116591810 \times 10^{-11}$	11659208×10^{-10}	$116592061 \times 10^{-11}$
δ_{a_μ}	370 ppb	540 ppb	465 ppb



FNAL Goal

- confirm BNL results
- Increase the statistic
- Achieve a precision of 140 ppb
- Overcome 5σ limit

FNAL Muon g-2 Experiment

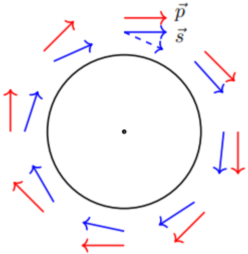


Figure: Anomalous precession frequency

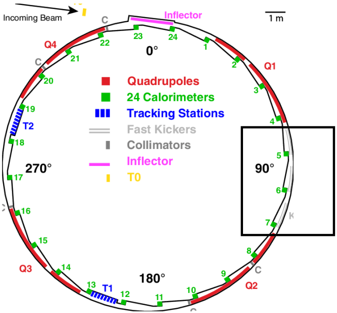
Quantity of interest

- $\vec{\omega}_a$: the difference between momentum and spin angular frequency
- Main goal is to measure $\vec{\omega}_a = \frac{q}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$

My task

- Measure eddy currents contribution on the ω_a fit with Faraday rotation effect
- Reduce the errors on the RUN 1 eddy currents contribution (-27(37) ppb)

Schematic of the Muon g-2 storage ring



- Storage ring is composed by a lot of components and each of them has its role
- In this presentation we are interested in **Fast Kickers**.

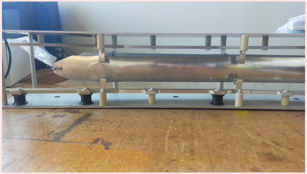
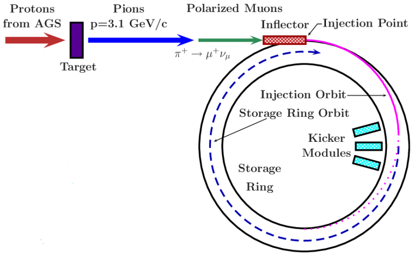


Figure: Kicker in MC-1 mezzanine

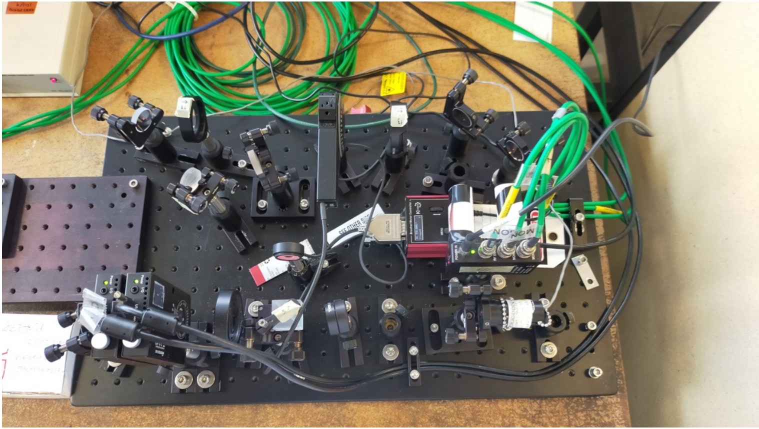
Kickers role and the reason why we are interested in them

The issue in a nutshell

- We need a system of kickers in order to place the muons in the correct orbit.
- This is achieved thanks to a $\sim$ 4 kA current along aluminium plates lasting only 120 ns
- However this produces eddy currents hence a small spurious magnetic field.
- The goal of the project is to measure magnetic field due to eddy currents.



Eddy currents effect is measured with a Magnetometer

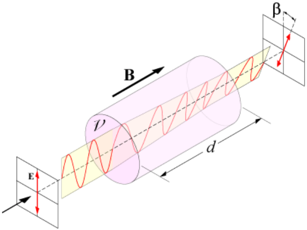


The Faraday effect

We set this breadboard in order to measure magnetic field inside a crystal.

Faraday effect equation:

$$\theta = BVd$$



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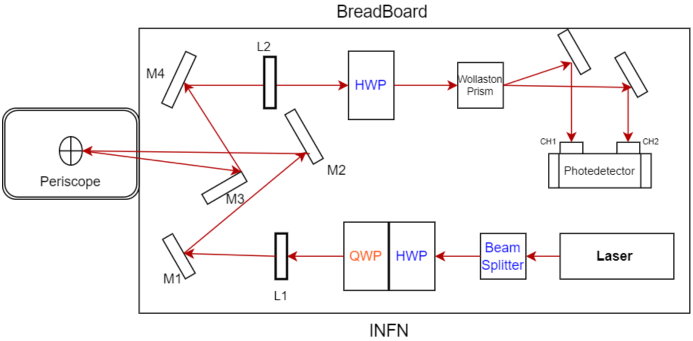
where

- θ is the angle between in and out polarization
- B is the magnetic field inside the crystal
- V is the Verdet constant
- d is the distance travelled by laser beam

We choose d such that for B $= 1.45$ T (field in the ring), $\theta = 2\pi n$ in order to avoid a further rotation. We set n=4.

Measuring Magnetic field: Breadboard in a nutshell

The principle of the measurement is to send a laser light through a Verdet crystal made of Terbium Gallium Garnet(TGG) in order to study Faraday rotation.



Lensed and Unlensed Periscopes

Two different periscopes: We want analyze both in order to make a comparison.

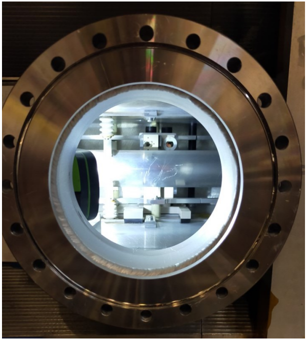


Figure: Periscope mounted in the ring

A brief description of the components

- Plastic Bridge: to reduce vibrations effect due to kicks
- Unlensed Periscope
- Lensed periscope: to avoid symmetry axis distortion between laser beam and crystal during kicks
- Teflon Bar: to give stability
- Kapton tape: to fix trolley line

Into the ring: Preparation for acquisition

After testing the breadboard,we move it in the ring

Figure: Breadboard in the ring

Preliminary steps:

- Mount periscopes and the Breadboard
- Laser alignment
- Turn on magnetic field at 1.45 T
- Turn on the kicker 3 at 42 kV
- HWP & QWP scan in order to find the best angle

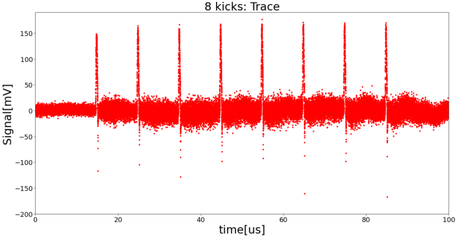
The goal of the project

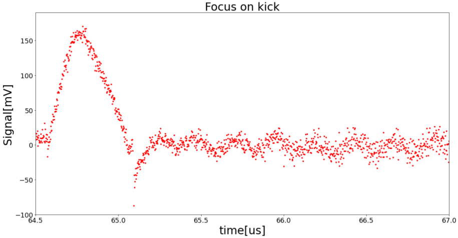
Experimental setup

- Two 8 kicks' groups separated by 300 ms
- Kicks separated by 10 ms
- One kick for each muons bunch

Analysis

- Average over very long Data acquisitions
- Rebinning by 10
- Exponential fit at the end of each kick



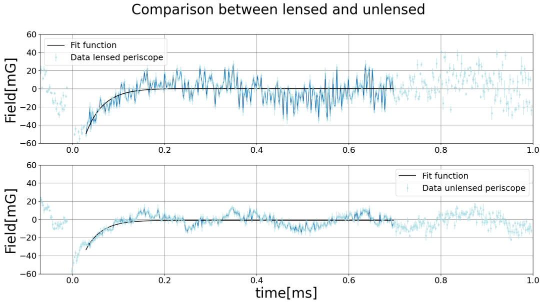


First attempt: Fitting data

- Signal/noise for Unlensed periscope : ~ 27
- Signal/noise for Lensed periscope : ~ 7

Fit function and interval

- Analysis strategy similar to Run-1
- Fit function: $a + B_{EC} \cdot e^{-\frac{(t-0.03)}{\tau}}$
- Fit interval: between $30\mu s$ and $700\mu s$ after the kick (like ω_a fit)



Correction required

- Remove baseline oscillation in order to get same baseline for each kick
- Remove mechanical oscillation

First correction: Remove the baseline oscillation

What we noticed

- Baseline is not the same for each kick
- It needs to be adjusted before doing average and comparing kicks

What we did

- Remove points from signal regions (kicks)
- Sinusoidal fit over the 100ms-trace
- Subtract point by point the oscillation ($\sim$ 20 Hz) from original data

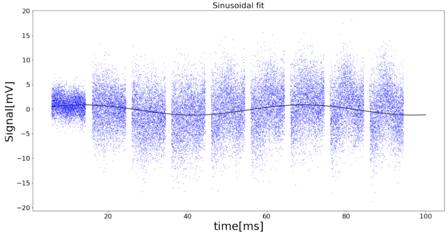


Figure: Unlensed periscope

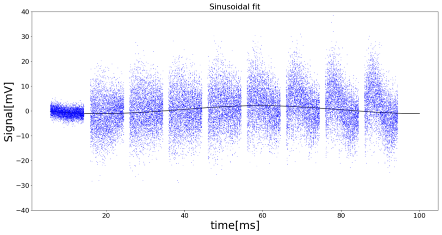


Figure: Lensed periscope

Second correction: Remove mechanical vibrations

What we noticed

- After each kick we see oscillations
- More visible thanks to FFT of exponential fit residuals
- These are due to mechanical vibrations of the periscope

What we did

- Sinusoidal fit between 0.1 and 1 ms after each kick
- Fit function describes mechanical oscillation for each kick ($\sim$ 4.5 kHz)
- Subtract point by point the oscillation from each kick

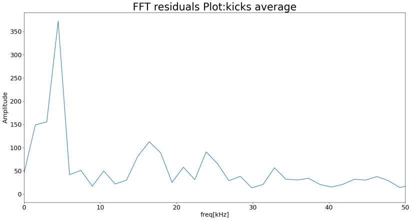


Figure: FFT example plot

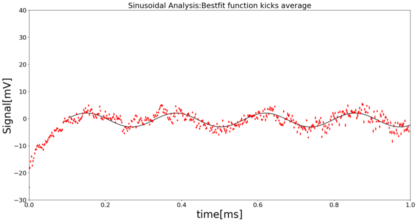


Figure: Unlensed periscope example plot

Second attempt: fitting Data

Repeat same steps as the first attempt

Fit function: $a + B_{EC} \cdot e^{-\frac{(t-0.03)}{\tau}}$

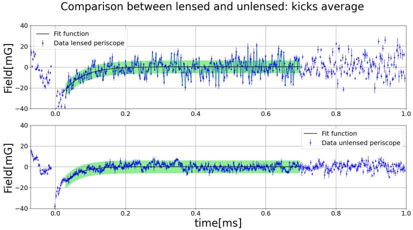


Figure: kicks' average

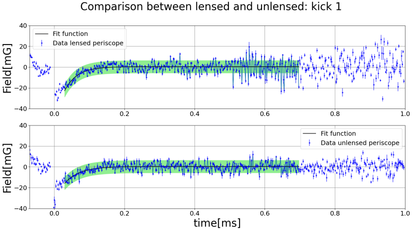
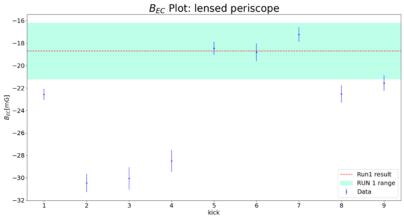
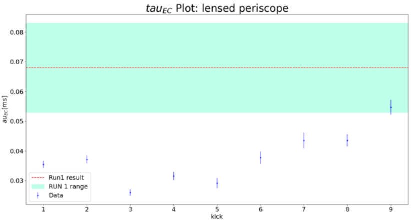


Figure: First kick

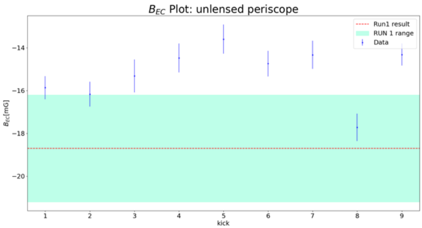
- The green shaded band represents the associated uncertainty in RUN1 (~ 6 mG)
- Great consistency!

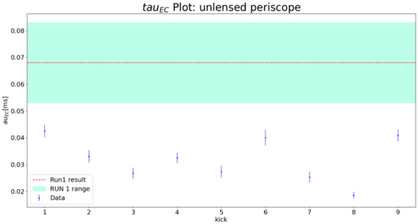
Lensed periscope





Unlensed periscope

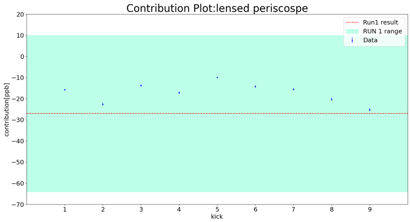


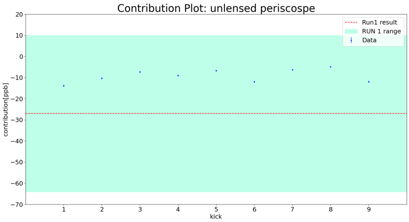


Contribution to omega A

Contribution Calculus

- We want to consider the contribution of eddy currents upon the ω_a fit.
- Function: $\frac{\Delta\omega_a}{\omega_a} \simeq \frac{B_{EC}}{B_{tot}} \times 8.5\% \times 0.94 \times \left(\frac{\tau_k}{\tau_k+\gamma\tau_\mu}\right)^2$
- We have not yet estimate systematic uncertainties





What's next?

A further improvements in Data analysis considering:

- A more complex fit function
- Study of the systematic uncertainties

Improvements in Hardware

- New Breadboard system is being tested in laboratory

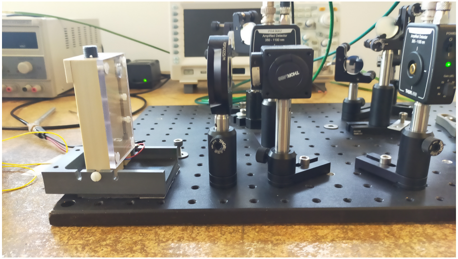


Figure: New periscope project

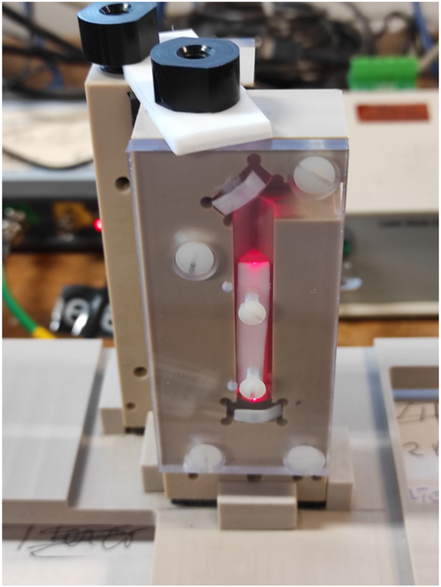
Conclusion

- I would like to extend my sincere thanks to Hogan Nguyen, Marco Incagli, Paolo Girotti, Anna Driutti and Antonio Gioiosa for their assistance at every stage of the research project.

Thank you for your attention

Backup slides

Periscope



Measuring Magnetic field: Breadboard in a nutshell

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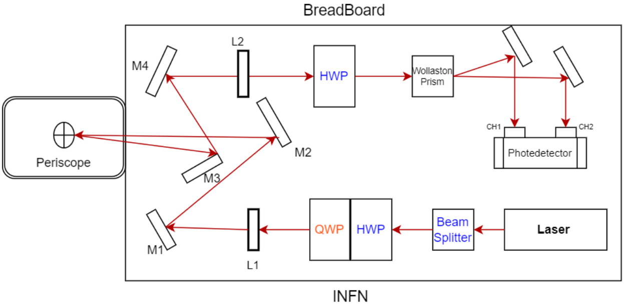


- Beam splitter is used to improve laser beam signal
- First HWP is used to set the angle maximizing the signal.
- QWP is used to study noise.
- Polarized laser light hits the crystal and changes its polarization.
- Wollaston prism splits laser light in two beams with a defined angles.
- Photodetector collects signals and gives first beam, second beam and the difference output intensities.

Preliminary test

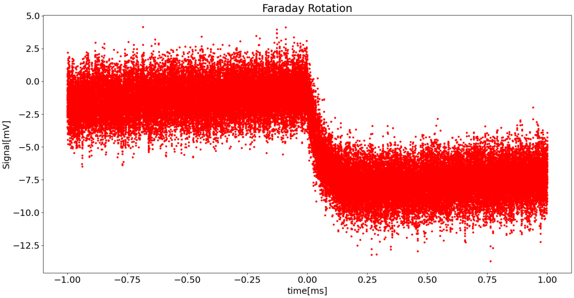
Real experiment

- 8 bunches, one every 10 ms
- 300 ms pause
- other 8 bunches, one every 10 ms

Laboratory test

- We simulated kicker magnetic field using a coil and setting the following parameters:

WF	Ampl	Period	P.Width
Pulse	1 Vpp	10 ms	1 ms



- A-B channel[mV] vs time[ms]
- $B = 0 \implies$ signal~ 0
- $B \neq 0 \implies$ Light polarization changes $\implies$ signal $\neq 0$

Steps required before starting Acquisition

Different types of frameworks

Mezzanine test	Ring no field	Ring with field
Magnetic field simulated by a coil	Kicker set at ~42 kV (as in RUN 2-3) and Magnetic field off	Kicker set at ~ 42 kV (as in RUN 2-3) and Magnetic field on

Steps required

Laser alignment	HWP scan	QWP scan
Setting mirrors in order to get a correct trajectory of the laser beam	Setting the initial HWP angle that maximize signal	Setting the QWP angle that maximize signal

Mezzanine test:HWP scan & QWP scan

- Studying the difference between up and down signals during Faraday rotation in order to get the best angles

HWP scan

- Remove QWP polarizer
- Scan over the initial HWP angles
- Find angle that maximize signal and signal over noise
- Repeat a more carefully survey around a peak
- Choose best angle: in our case 28.5°!

QWP scan

- Set HWP best angle
- Repeat same steps as HWP scan
- Choose best angle: 36.5°

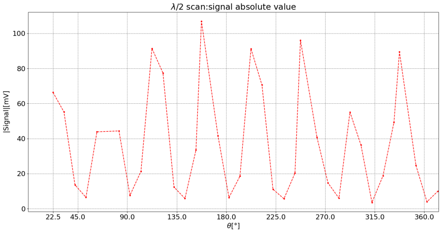
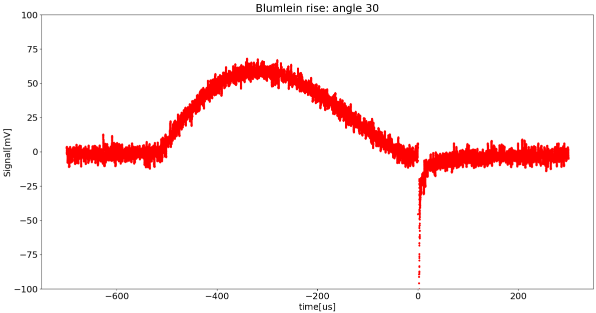


Figure: $\lambda/2$ scan: Absolute value[mV] vs angle[°]

Amplitude: analysis method

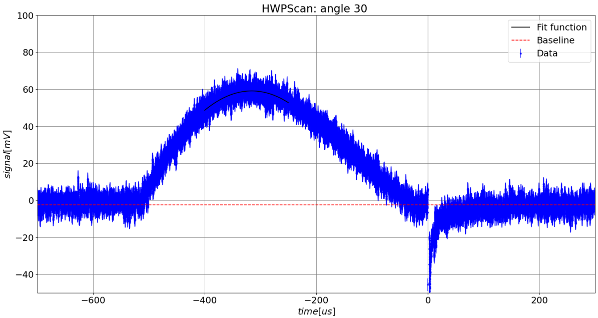


- Different waveform compared to mezzanine
- New analysis method required for Wave Plates scan

Method used to get peak and baseline for each angle:

- Baseline: taking first 10% and last 20%: average and std
- Peak: Parabolic fit around the peak (30-45%) in order to get it
- Amplitude : Difference between the peak and the baseline

HWP & QWP scan

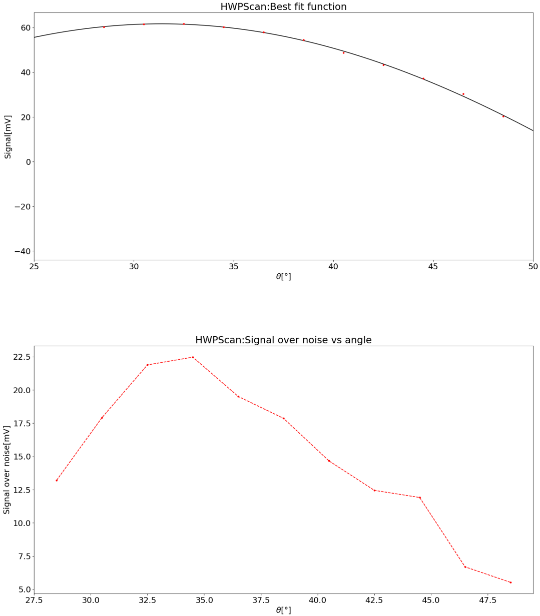


- Data Plot
- baseline
- Fit function for peaks

Angle analysis to get best value

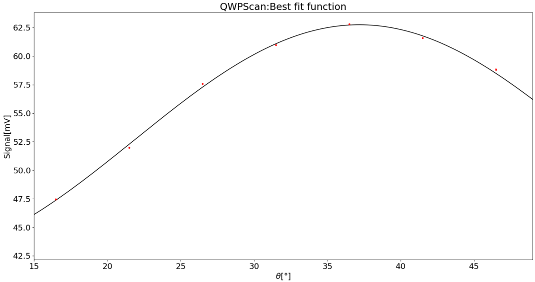
- Sinusoidal Fit between angles and amplitudes
- Plot Signal over noise vs angle
- Choosing best angles both for HWP and QWP

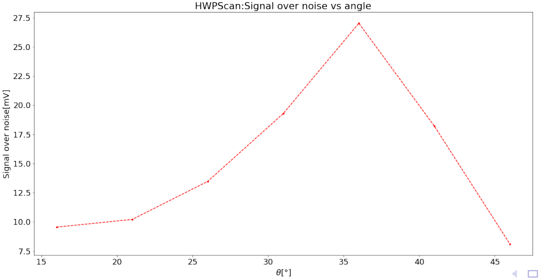
HWP:Angles vs signal Plots and Fits



- Starting from the results of mezzanine analysis
- Analysis around the peak
- Best angle choosen: 31.5°

QWP:Angles vs signal Plots and Fits





- Starting from the results of mezzanine analysis
- Analysis around the peak
- Best angle chosen: 36.5°

A long acquisition: Looking for Eddy currents

Collected about 30k wave forms and perform an average over Data

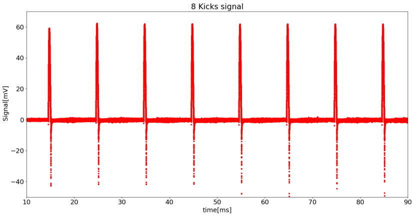


Figure: 8 Kicks:signal[mV] vs angle[°]

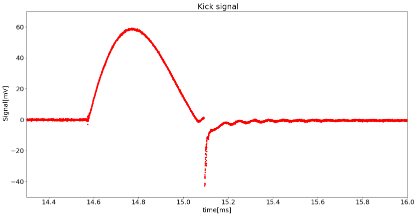


Figure: Focus on the first kick

We are able to see Blumlein rise and fall

We saw a new detail

Zooming on the end of the fall...

Got eddy currents!

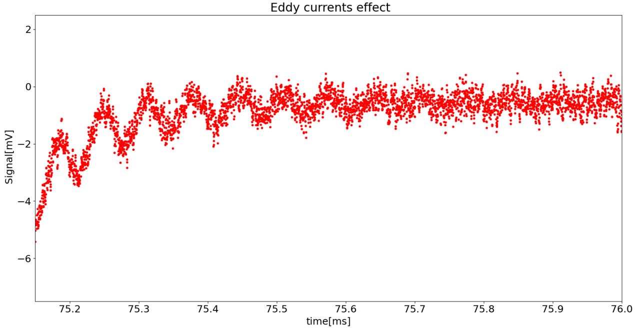


Figure: Eddy Currents effect at the end of kick

Magnet on and final steps

- **Repeat same steps as magnetic field off framework**
- **Study calibration between angles and magnetic field ramp up**

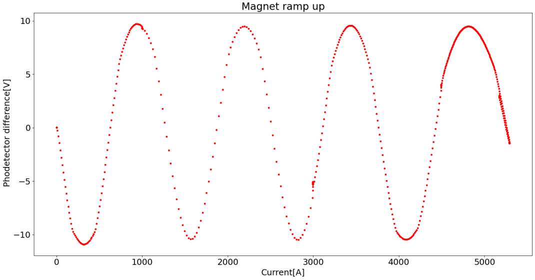


Figure: Signal[V] vs current[A]

- **This is another way to see Faraday effect!**

Description

- Current increases with time
- Magnetic field increases with current
- Light polarization inside crystal changes
- Relationship between Magnetic field (I) and angle

Linear fit: magnet ramp up

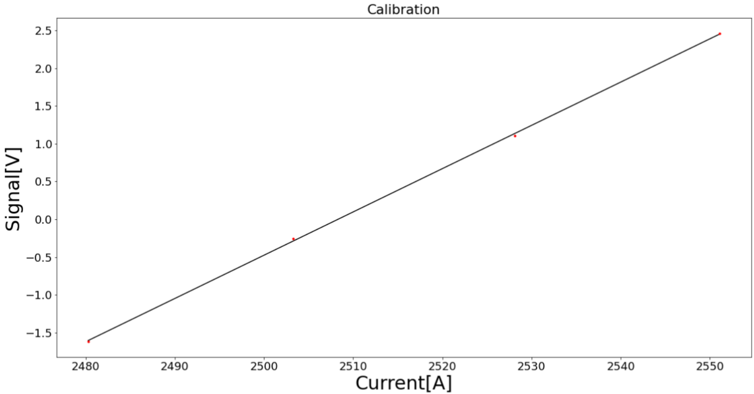


Figure: Calibration

Amplified calibration:
calibration in Ampere = 0.057315(9) mV/mA
calibration in Gauss == 0.57253(9) mV/mG