Magnetometry for the Muon g-2 Experiment

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Abstract

The Muon g-2 Experiment at Fermilab aims to measure the muon anomalous magnetic moment with a precision of 140 parts per billion (ppb). The collaboration has published the latest measurement based on the first three Runs (collected from 2018 to 2020) in August 2023 with a precision of 200 ppb. The experiment accumulated three more years of data, from 2020 to 2023, which are currently being analyzed. This additional statistics is sufficient to achieve and possibly exceed the goal of 100 ppb of final statistical uncertainty. As the statistical error gets reduced, increasing attention is dedicated to the study of the systematic uncertainties. Among them, one source is a magnetic transient generated by the fast kickers. In order to center the muon orbit into its final position in the storage ring, a 120 ns magnetic pulse of ~240 G is issued by three kickers right after injection. This induces eddy currents in the kicker aluminum structure that last for several microseconds. To measure the 10 mG magnetic perturbations generated by the eddy currents, the INFN team developed a laser magnetometer based on the Faraday effect. This poster describes the technical principles, the operations, and the data analysis of this very sensitive device.

Introduction

The Muon g − 2 experiment (E989), based at Fermilab, has measured with an accuracy of 200 ppb the muon magnetic anomaly a_μ, thus testing with high precision the Standard Model of Particle Physics. The measurement of the muon anomaly using a storage ring relies on the spin precession and cyclotron motion of a charged particle orbiting in a uniform magnetic field. For a particle with momentum and spin vectors in a plane perpendicular to *B*, a classical calculation of the difference of these frequencies yields

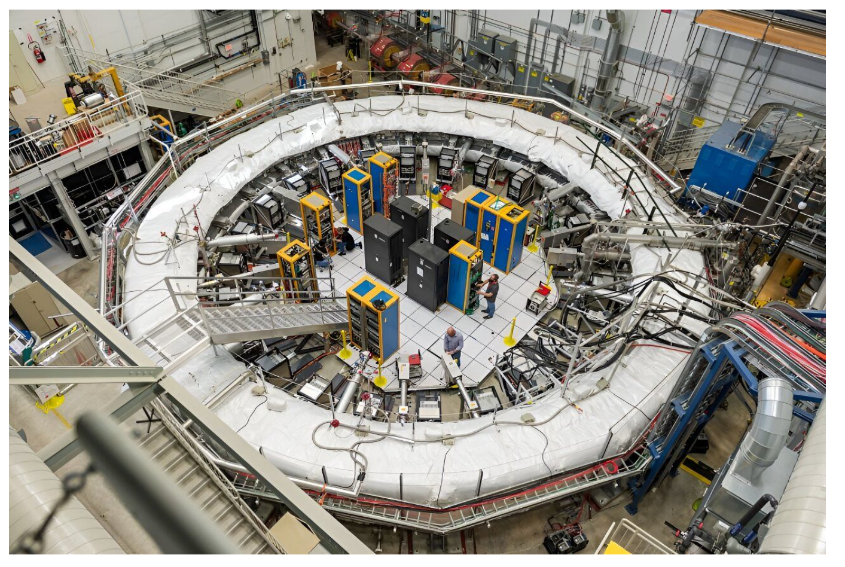
$$\omega_a = \omega_s - \omega_c = g\frac{e}{2m}B - \frac{e}{m}B = a_\mu\frac{e}{m}B$$

so that

$$a_\mu = \frac{\omega_a}{B}\frac{m}{e}$$

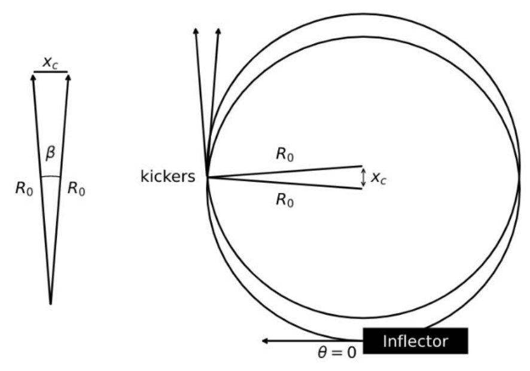
Thus the experiment relies on a precise measurement of the precession frequency ω_a and of the magnetic field *B* to extract a_μ.

The experiment uses 3.1 GeV/c polarized muons produced by the Fermilab Muon Campus. Muons are injected into a 7.112 m radius storage ring. Two key components of the storage ring are kicker magnets, that direct the injected muons onto the central orbit of the storage ring, and electrostatic quadrupoles that provide vertical focusing of the stored beam. The two fast switching storage ring elements introduce transient corrections to the magnetic field that have to be taken into proper account in order to reach the desired precision in the final result.



The Kicker System

The Fermilab accelerator complex produces a polarized muon beam that enters the storage ring vacuum (SRV) through a superconducting inflector magnet that is aligned to the tangent of the ring. The inflector's interior aperture is displaced 77 mm from the central radius of the storage region. The muons are then moved into the nominal orbit by a series of three 1.27-m-long non-ferric aluminum kicker electromagnets that are placed at an azimuthal distance of π/2 with respect to the injection point. The magnets are pulsed with a ~ 4 kA current for a duration of ~ 120 ns, corresponding to the beam longitudinal width, to reduce the ring magnetic field. The result of the localized perturbation moves muons onto stable orbits that facilitate a measurement of a_μ. The use of non-ferric materials was explicitly selected to not affect the a_μ measurement, which is sensitive to magnetic field sources.



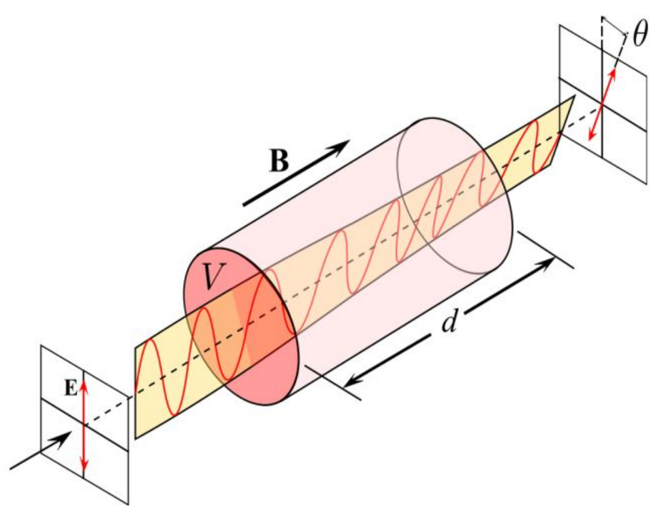
The Magnetometer

Even if the strength of the kicker field alone is well known, its very fast rise and fall times induce eddy currents in all nearby metal, which in turn create additional magnetic fields whose strengths are difficult to predict. These fields can last on a time scale of tens of μs, thus persisting into the fit window of ω_a. Measuring such transient fields is difficult both because of their small amplitude and fast decay which requires a precision of ~ mG in the field amplitude and an apparatus response of ~ μs.

The measurement principle

The plane of polarization of linear light incident on a piece of glass rotated when a strong magnetic field was applied in the propagation direction. The relation between the angle of rotation of the polarization and the magnetic field in a transparent material is: $\theta = VBd$ where:

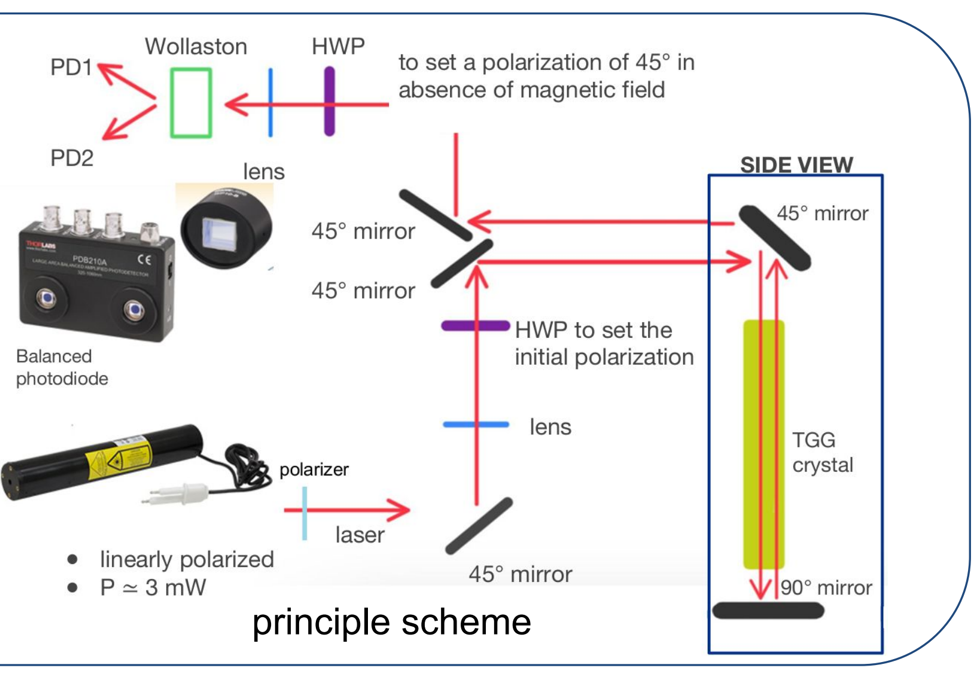
- θ is the angle of rotation in radians (in our case δθ ~ 17 μrad)
- B is the magnetic field in the direction of the light propagation (in teslas)
- d is the length of medium traversed (in meters) where the light and magnetic field interact
- V is the Verdet constant for the material (empirical constant in units of radians per tesla per meter)



To measure a Faraday rotation due to a small magnetic field, a material with a high Verdet constant is required, as well as a precise measurement of the initial and final polarization of the light source (in our case a Crystal made of Terbium Gallium Garnet (TGG), with a Verdet constant of V = 131 rad T^{-1} m^{-1}).

With a final laser of I_0 intensity and polarization of 45°, then the vertically I_y and horizontally I_x polarized beams exiting a beam splitter will have the same intensity of $I_0/2$ (Malus's Law). In these conditions, $I_x - I_y = 0$, i.e., the difference between output voltages of the two photodiodes that intercept the two beams (see the figure on the right), V_{diff}, will be, ideally, equal to zero.

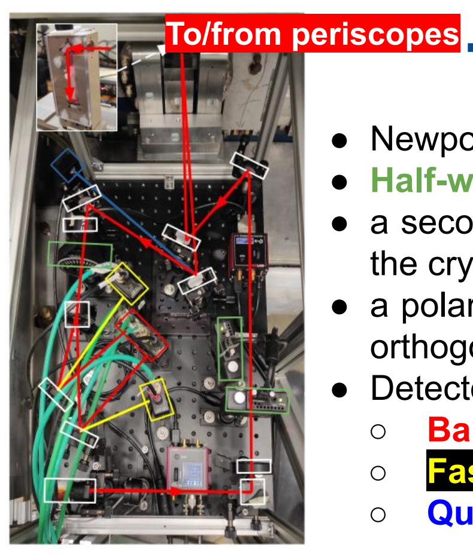
In the presence of an additional vertical magnetic field *B* in the Verdet crystal region $I_x \neq I_y$, and V_{diff} will no longer be zero.



principle scheme

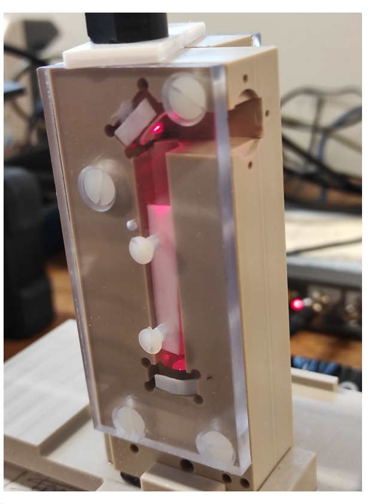
The Breadboard

The laser, the optics and the photodiodes is mounted on a breadboard located inside the ring but outside the vacuum area, far from region with a strong dipole field.



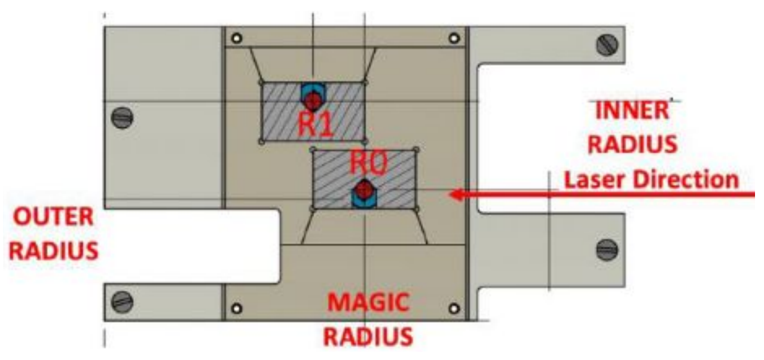
- Newport diode laser (635 nm)
- **Half-wave** plate (HWP) to set the initial polarization angle (remotely controlled)
- a second **half-wave** plate (remotely controlled) to rotate the polarization of the light exiting the crystal: (in absence of a varying magnetic field, a 45° polarized laser beam)
- a polarizing beam splitter (Wollaston prism) to separates the incoming laser beam into two orthogonally-polarized beams
- Detectors:
  - **Balanced photodiode** for eddy currents measurements
  - **Fast photodiodes** for kick shape measurements
  - **Quadrant photodiode** for mechanical vibration measurements

Periscopes



We used two TGG crystals hold in position between the kicker plates by a mechanical structure made in PEEK (Polyether ether ketone) called *periscopes* placed between kicker plates (the laser light enters the Storage Ring area through a glass flange).

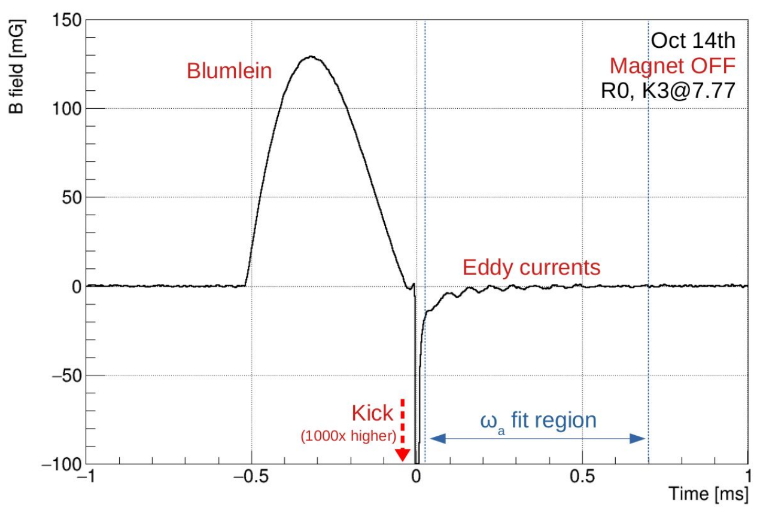
Each periscope's axis needs to be positioned along the direction of the magnetic field to be measured: the vertical direction (in our case the crystals have a length of d = 32 mm).



- R0 (magic radius)
- R1 = R0 + 17.5 mm

Measuring the kick

The kicker signal shows, on top of the main kick, a large bump due to the Blumlein and the residual transient field extending into the muon precession measurement region.

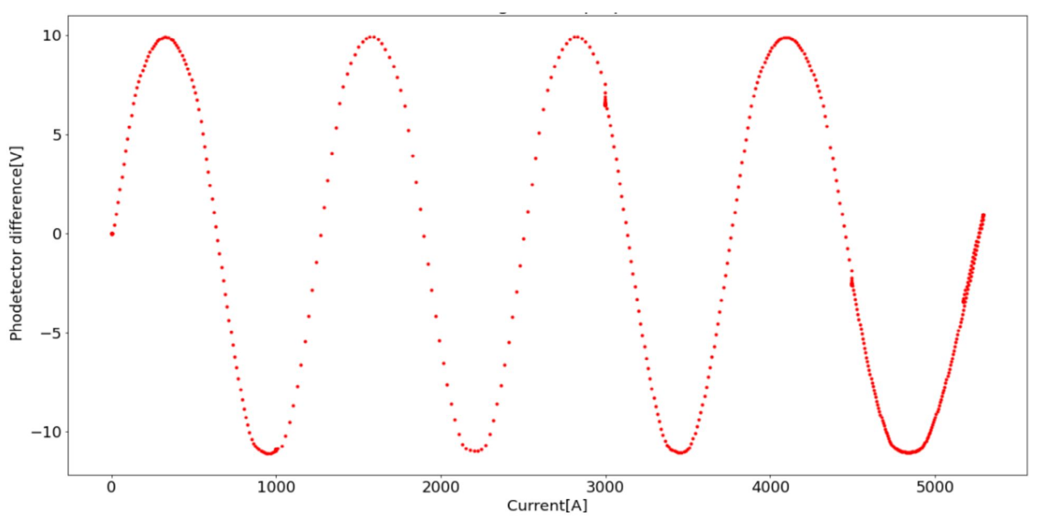


Photodiode calibration

It is important to properly calibrate the detector, before data acquisitions, in order to obtain the proportionality constant between Volts and Tesla, or between mVolts and mGauss.

The balanced photodiode signal V_{diff} is $\propto I_x - I_y = 2I_0\cdot(\delta\theta + O(\delta^2\theta))$ (small angle approximation).

The calibration constant is obtained by varying the main magnet current in a controlled way and measuring the difference between the two polarizations with the magnetometer. The value of V_{diff} as the current is increased from 0 A to the maximum value of 5170 A. By fitting the points around $V_{diff} = 0$ with a straight line, and knowing that 5170 A correspond to 1.45 T, it is possible to determine the conversion constant ***c [mV /mG]***.



Difference between the two polarization components as a function of the solenoid current.

Eddy currents studies

Motivation

To quantify the impact of kicker transient field on the ω_a determination needs consider it proportional to the effective *B* field (time-dependent):

$$\tilde{N}(t) = N_0 \cdot e^{(-t/\tau)} \cdot \left(1 + A \cdot \cos\left(\boxed{a_\mu \cdot \frac{Q\cdot e}{m_\mu} \cdot \int_{30\mu s}^{t} B(t')dt'} + \phi_0\right)\right)$$

$\omega_a(t)$

It means that the measured *B* field must be corrected adding the estimated kicker eddy field to get the actual *B* field sensed by the muons,

$$B(t') = \boxed{1.4513\,T} + B_{transient}(t')$$

main field

fit or spline reconstruction

At the end the impact of the transient field in the K_3 kicker region can be estimated by

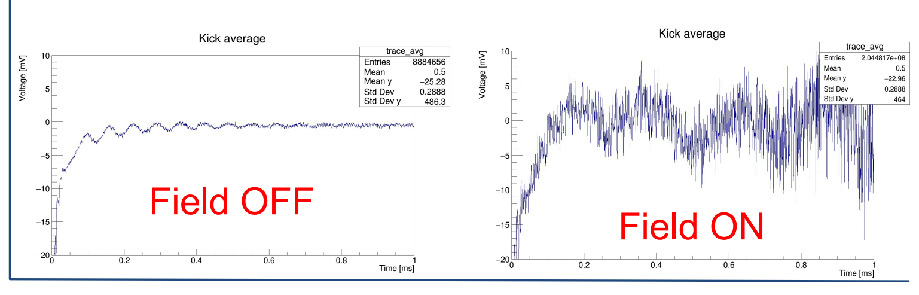
$$B_k = \frac{\omega_{a,fit}\,(main + transient) - \omega_a\,(main)}{\omega_a\,(main)}$$

$$\longrightarrow \quad a_\mu \propto \frac{f_{clock}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle\omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

Oscillations

with magnet ON are observed with our configuration. Kick-induced periscope vibration is a possible explanation and a signal oscillation produced by angle of crystal vs B field is a order of magnitude for ~10 μm oscillations.

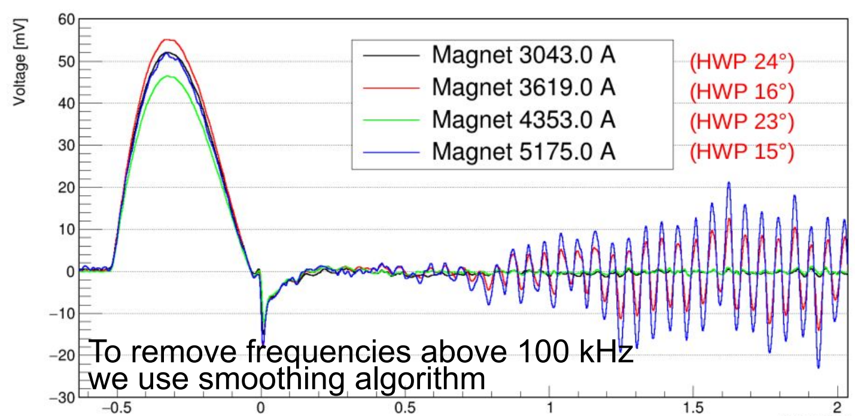
Last campaign of acquisition has been focused on solving this puzzle: a new magnet scan and a Quarter Wave Plate studies have been performed.



Magnet scan

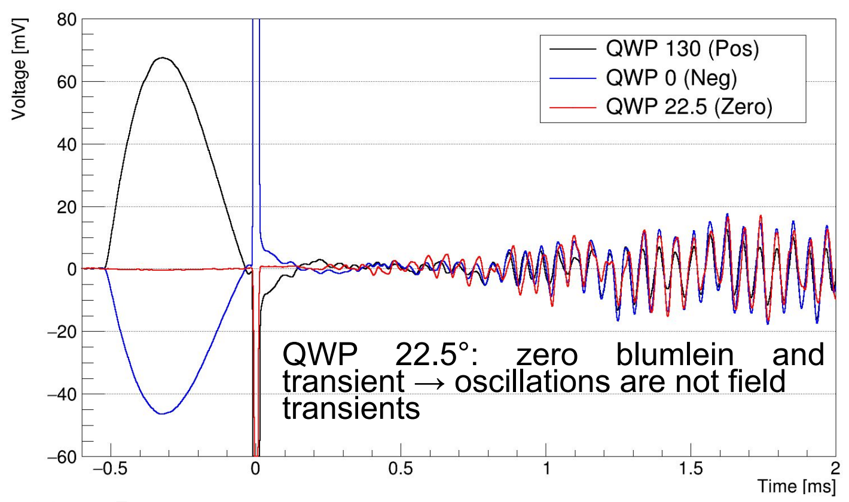
Magnet strength values corresponding to the nodes of descending ramp measurements [3043, 3619, 4353, 5173] A. The relative Faraday rotation angles are: [2.5π, 3π, 3.5π, 4π]

HWP optimization scan performed at each magnet setpoint. HWP angle chosen to maximize blumlein amplitude (or SNR). Very different behavior between the various setpoints [2.5π, 3π, 3.5π, 4π].

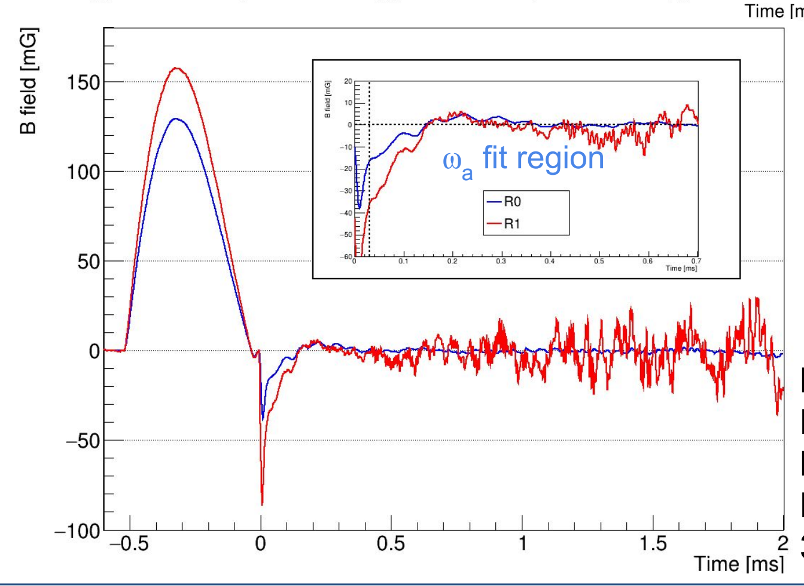


To remove frequencies above 100 kHz we use smoothing algorithm

Vibrations suppressed for the nodes with negative slope! (2.5π, 3.5π).



QWP 22.5°: zero blumlein and transient → oscillations are not field transients



Quarter Wave Plate (QWP) inserted for last study. 45° incident linearly polarized light becomes circularly polarized for some QWP values. It means no Faraday effect (zero blumlein amplitude). Goal is to measure effects not depending on the kicker magnetic field. Finding the best combination of Pos, Neg, Zero with a minimization QWP scan:

$$weigth_{Pos}{*}Pos + weigth_{Neg}{*}Neg + weigth_{Zero}{*}Zero$$

$$\downarrow$$

$$0.5{*}Pos - 0.5{*}Neg + 0.2{*}Zero$$

$$\downarrow$$

Full current treated with vibration subtraction with QWP

(Vibration quantified as trace RMS in [2,6] ms range)

Radial dependence

R_0 is at magic radius, R_1 is + 17.5 mm
Blumlein amplitude higher at R_1 → +22%
Eddy currents transient higher at R_1 → ~2x up to 30 μs

Conclusions

In 2023/2024 we performed very successful magnetometer campaigns. We made many periscope improvements but them didn't remove oscillations. Magnet scan plus QWP studies are now shining light on this puzzle → successful vibration cancellation. Both kick and transient data show higher effects at outer radius (+22% kick, +90% transient at +17.5 mm). Analysis is toward completion. Rest to estimate the B_k term and the systematics uncertainties.

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