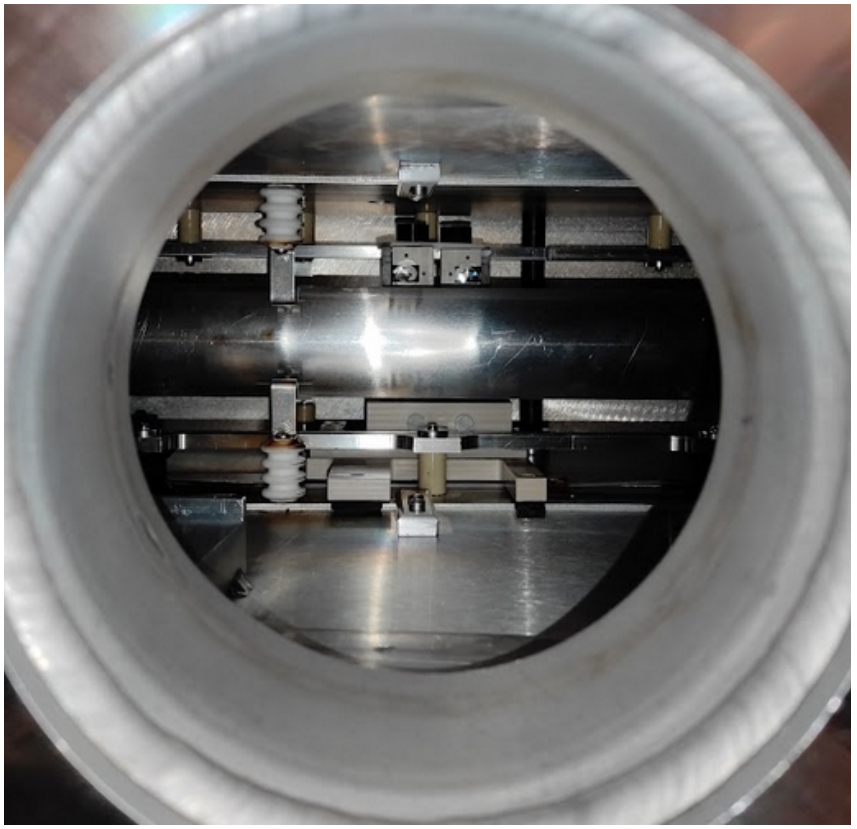


INFN Magnetometer

Collaboration meeting
19 April 2024

P. Girotti
on behalf of the g-2 Italian collaboration

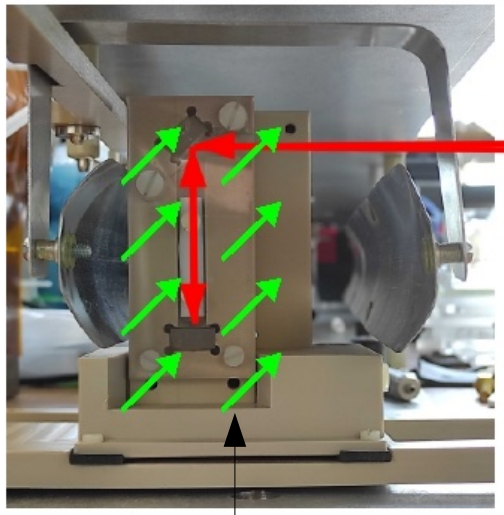
Outline

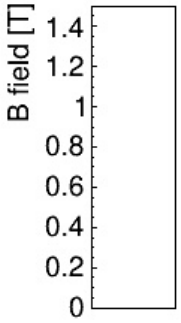
- Magnetometry 101
- Post Run-6 campaigns
- Absolute calibration
- Kick shape measurements
- Kick transient measurements
- Conclusions

INFN Magnetometer

- Goal: measure ~**10^{-7} T** transients with ~**µs** sampling

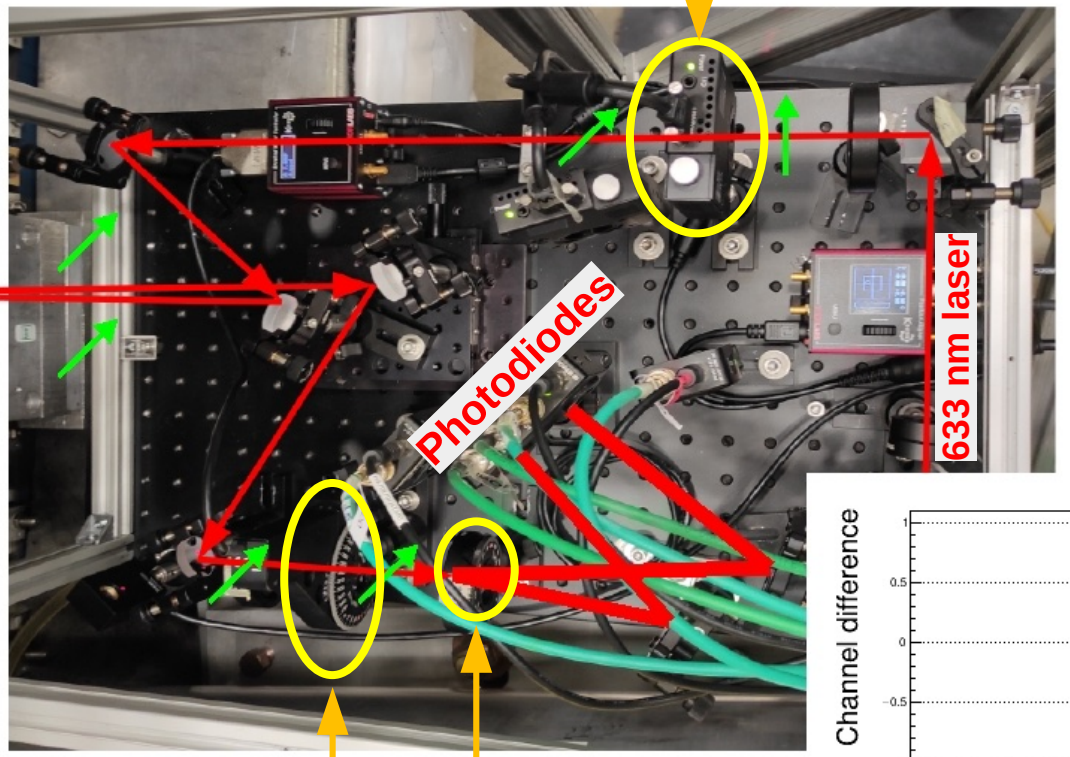
Two periscopes with
32 mm TGG crystals
at magic radius and +17.5 mm





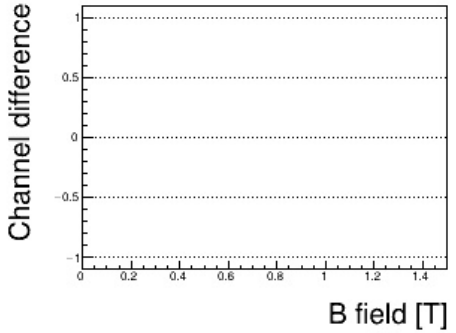
Light polarization angle

Half WavePlate (in)



HWPin: 22.5°

HWPout: 45.0°

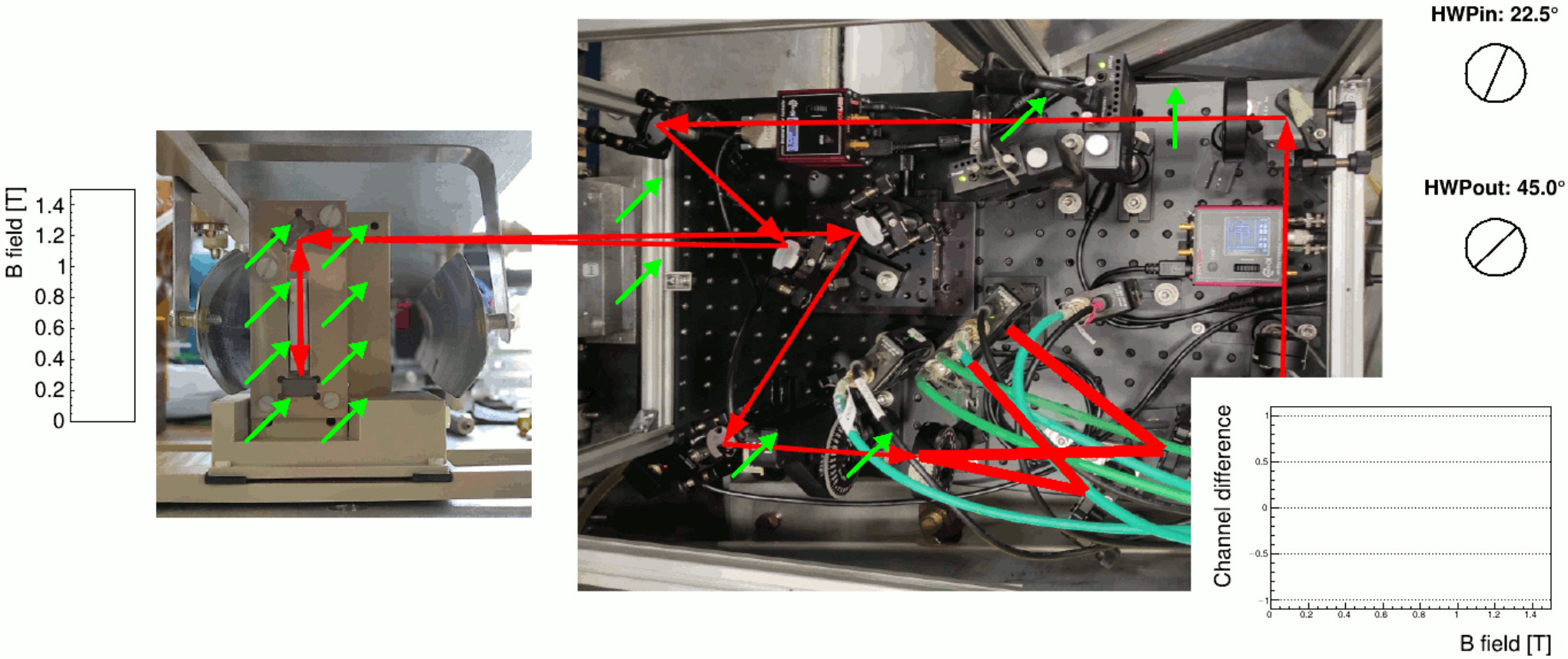


Wollaston cube

Half WavePlate (out)

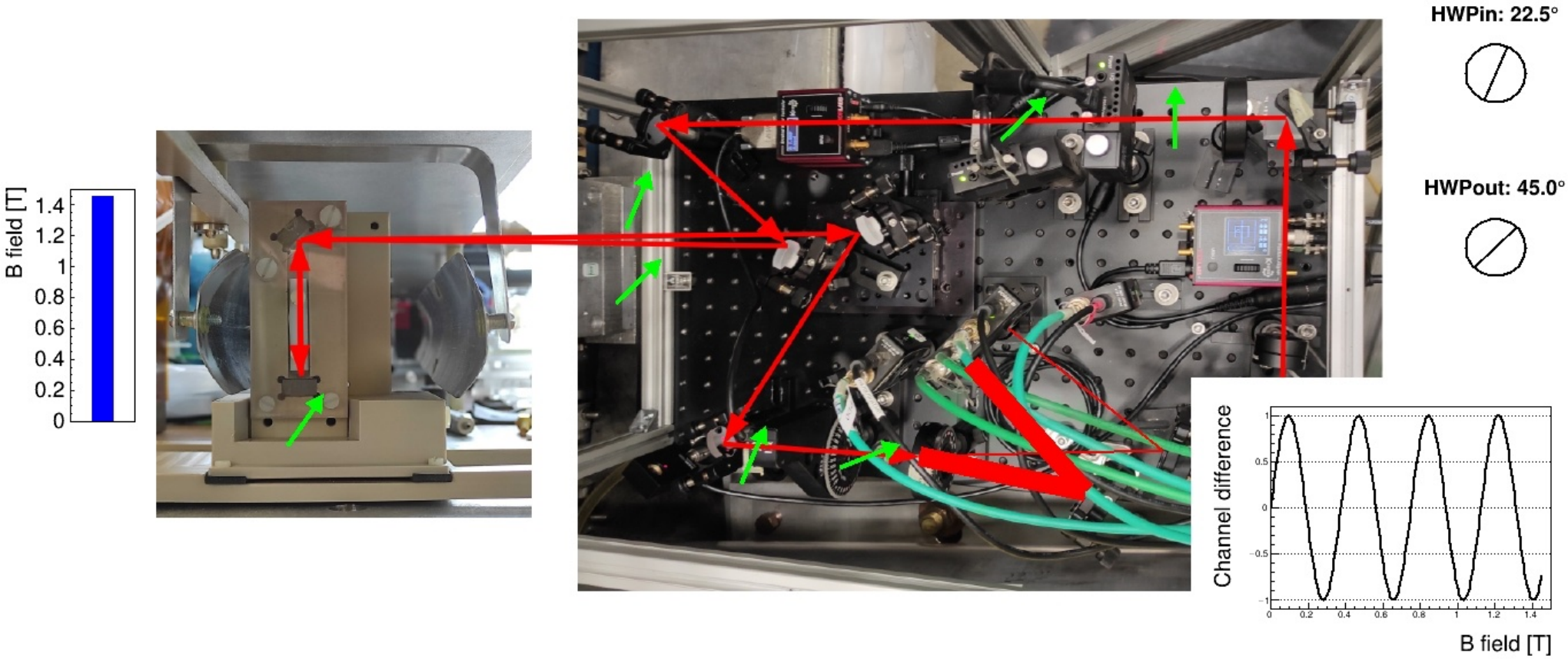
Magnet ramp up

- Faraday rotation due to magnetic field
- Ramp up useful to determine absolute calibration



Magnet ramp up

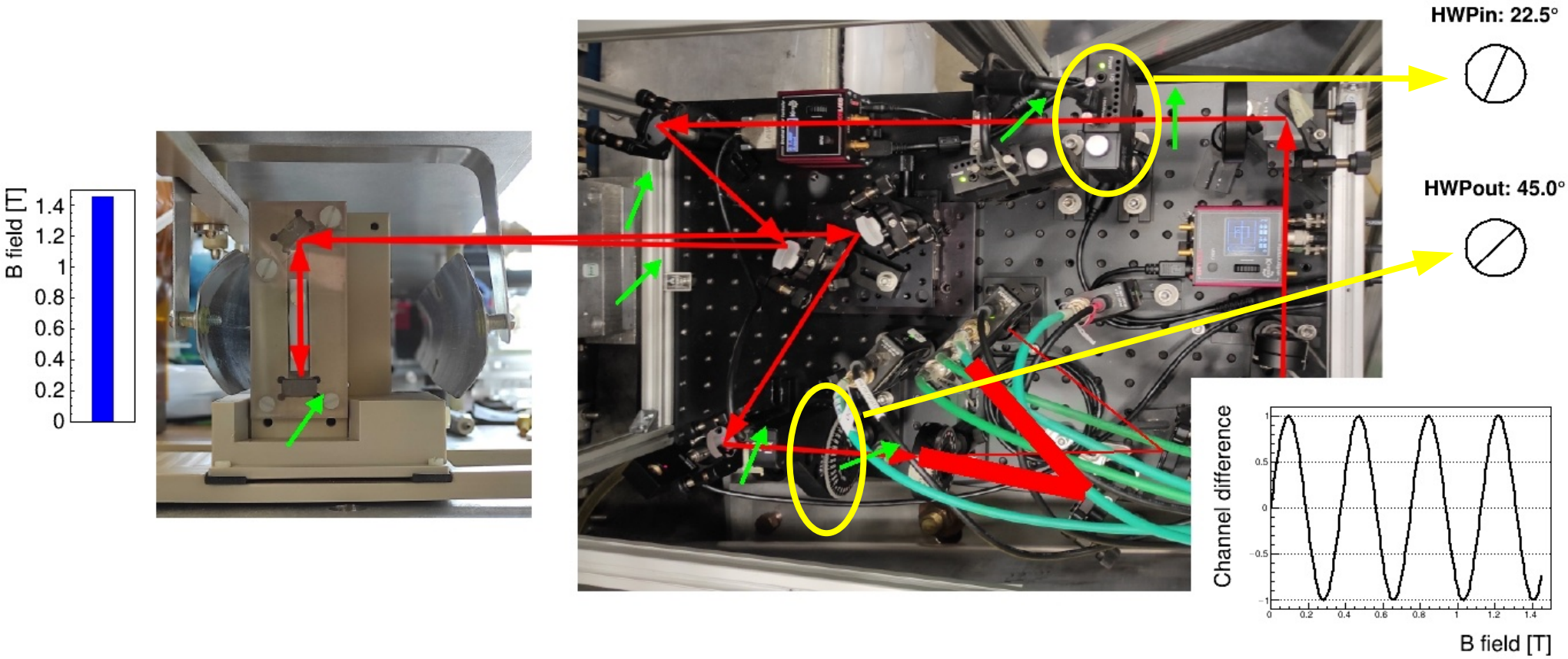
- Faraday rotation due to magnetic field
- Ramp up useful to determine absolute calibration



Equalizing output

- Input HWP to optimize polarization quality
- Output HWP to equalize output at equilibrium

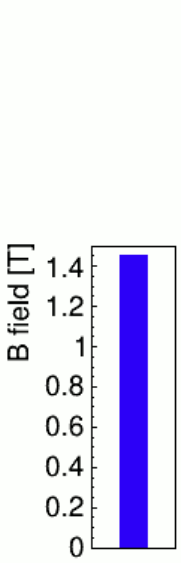
Motorized and remotely operated!

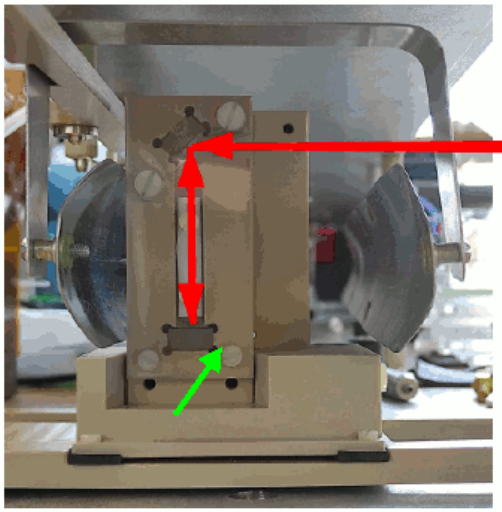


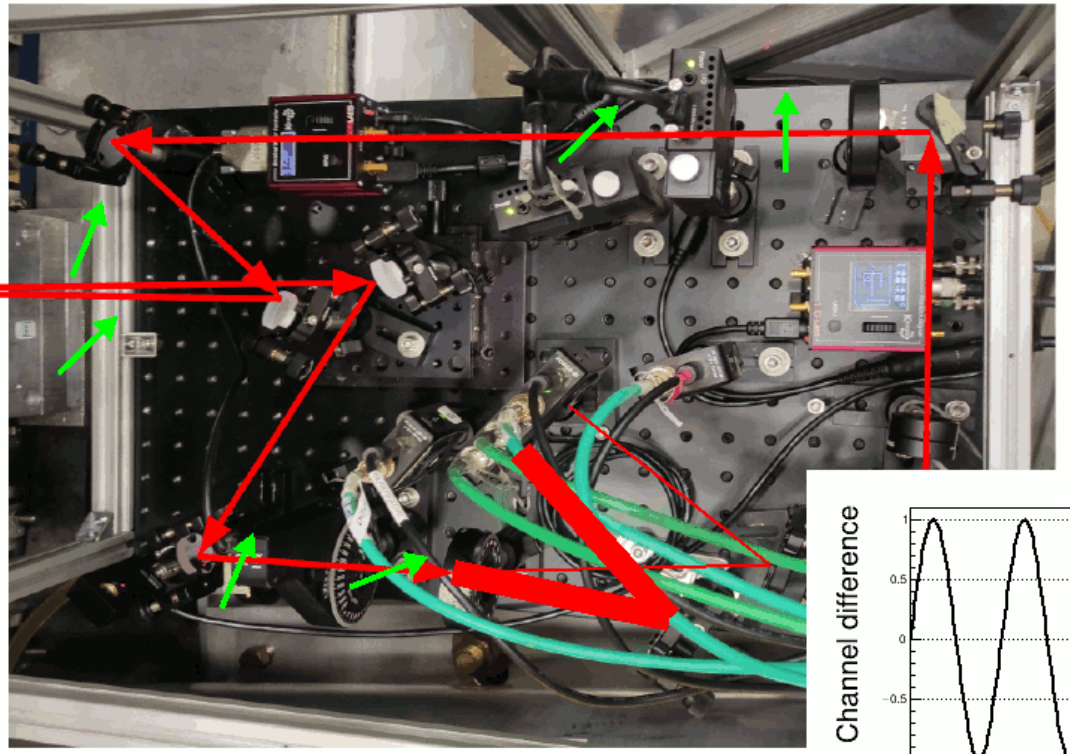
Equalizing output

- Input HWP to optimize polarization quality
- Output HWP to equalize output at equilibrium

Motorized and remotely operated!

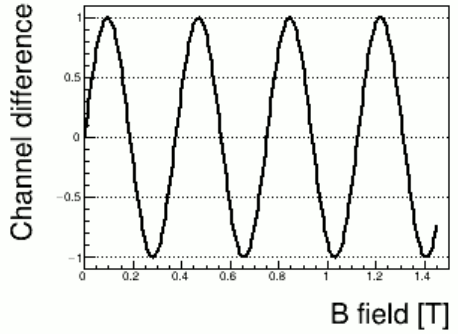






HWPin: 22.5°

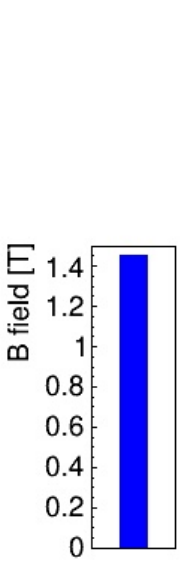
HWPout: 45.0°

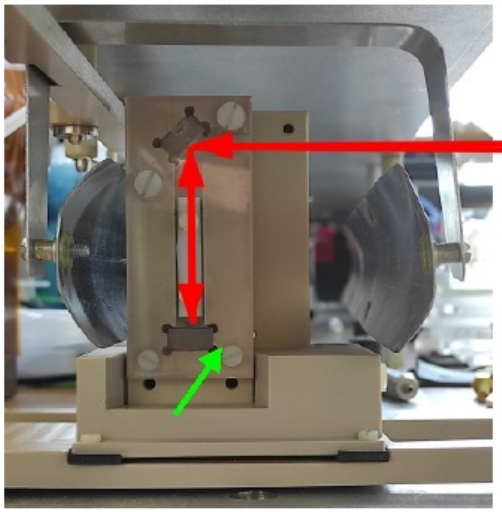


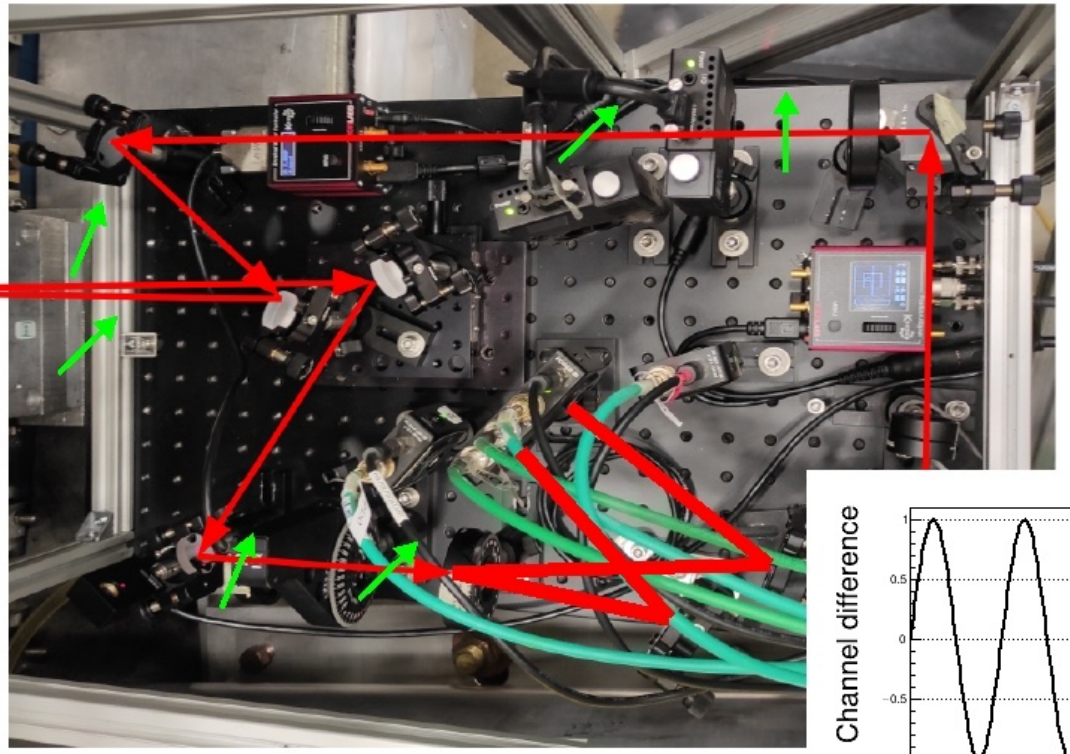
Equalizing output

- Input HWP to optimize polarization quality
- Output HWP to equalize output at equilibrium

Motorized and remotely operated!

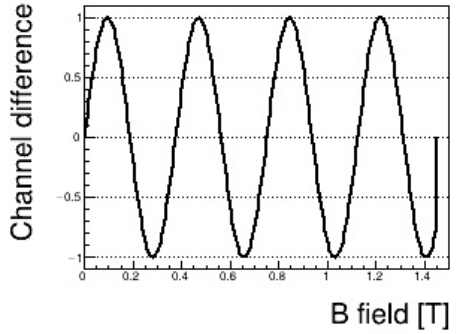






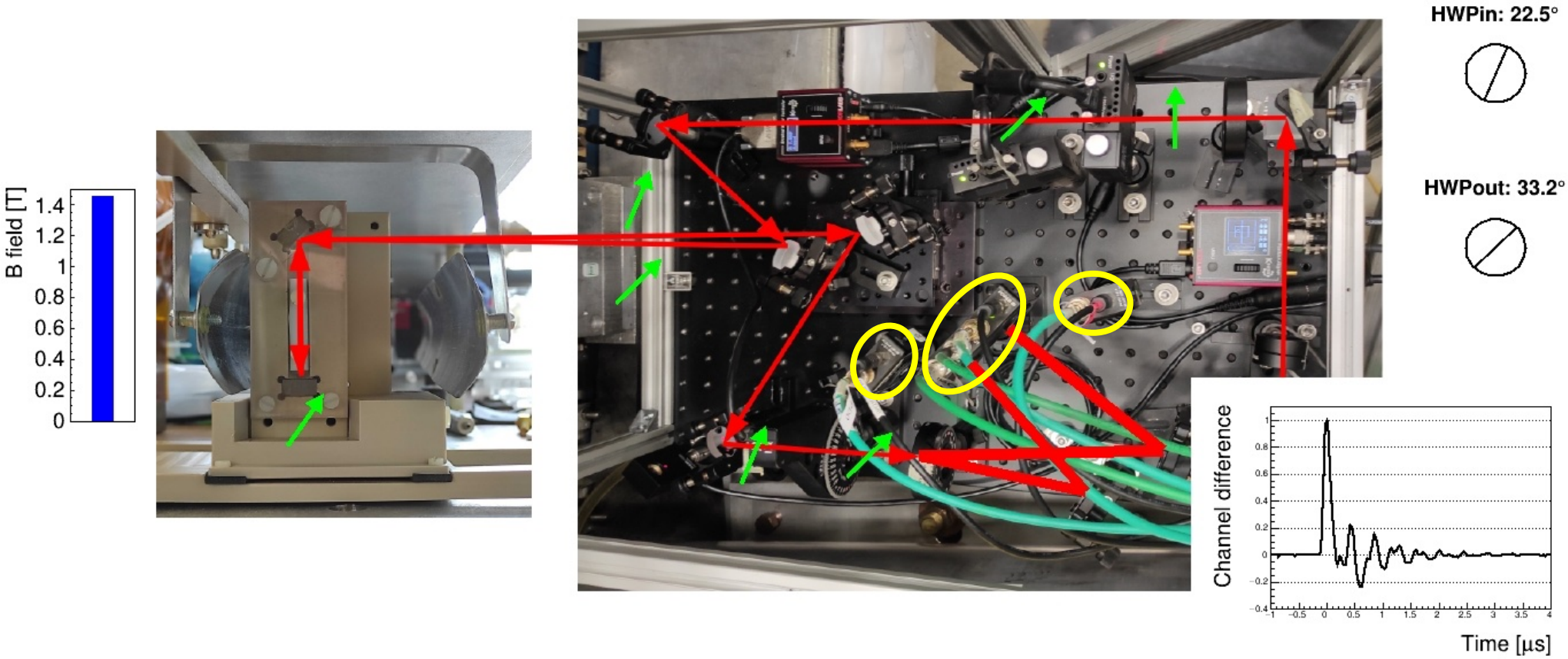
HWPin: 22.5°

HWPout: 33.3°

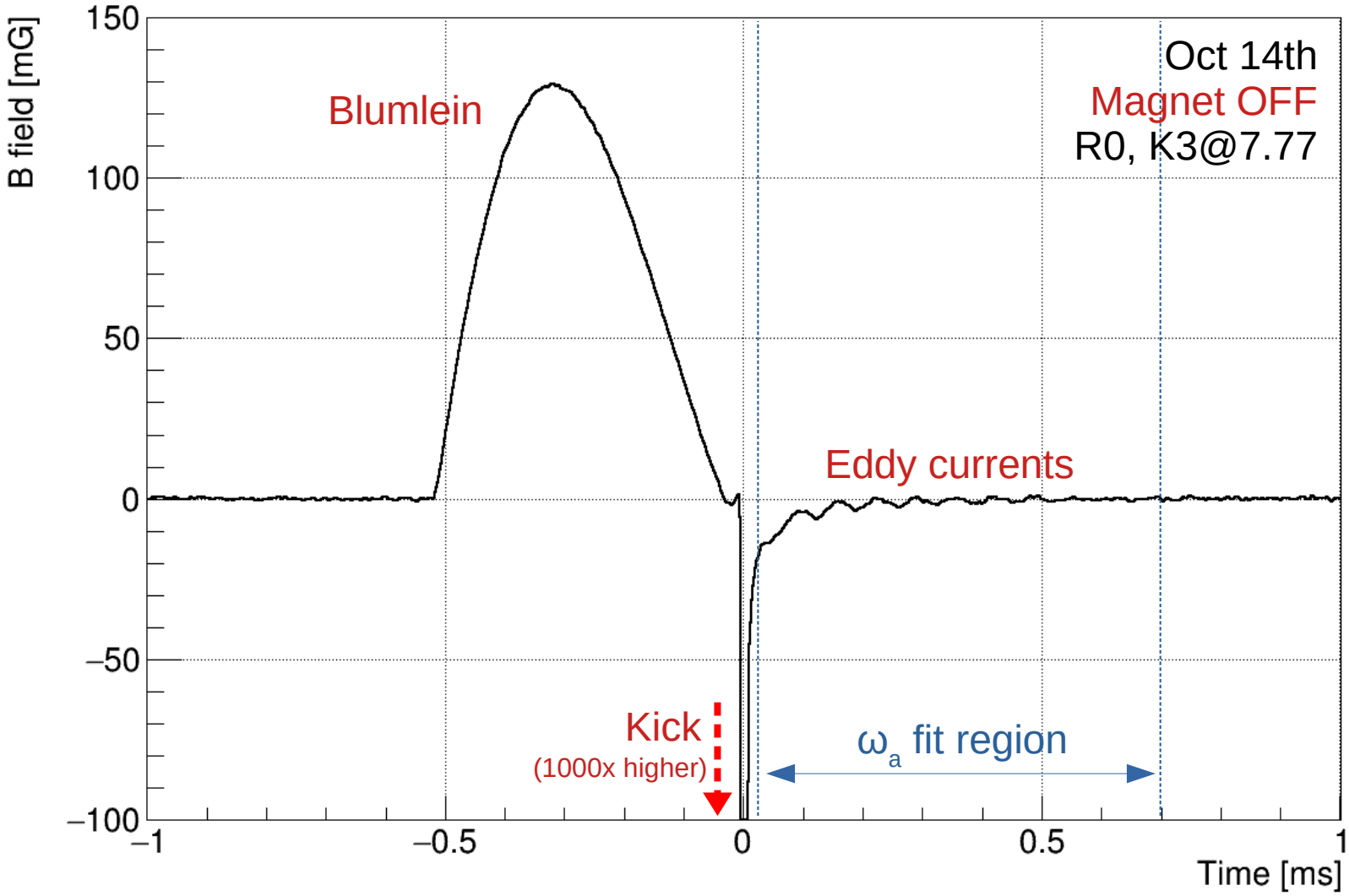


Kick measurement

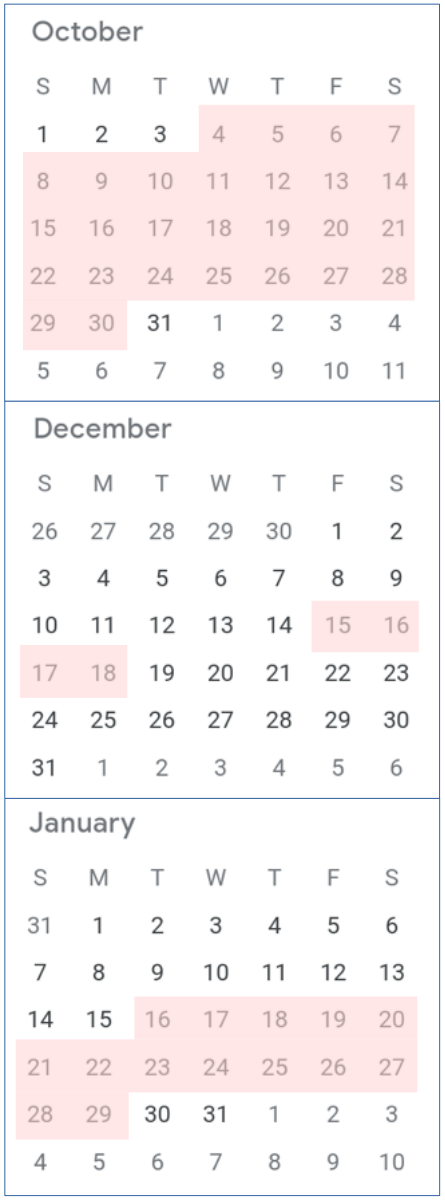
- Two separate fast diodes for kick measurements (300 Mhz)
- Two balanced slow diodes for transient measurement (2 Mhz)



Transient anatomy



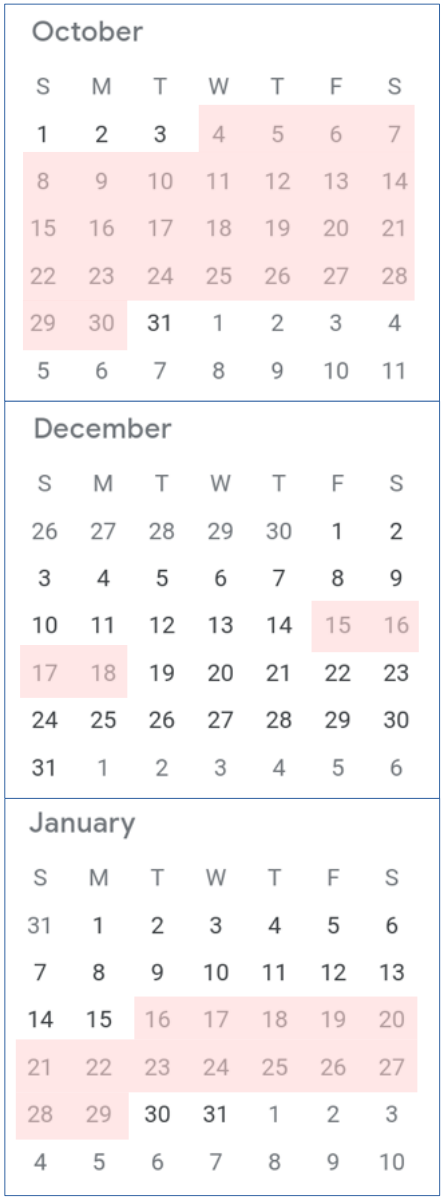
Post Run-6 campaigns



October 2023:

- 550+ hours of acquisition
- Many configurations tested here:
  - Nominal and offset radii
  - Free-standing and clamped bridge
  - Various magnet and kicker setpoints
  - Fast kick shape measurements
  - Vibration measurements (new quadrant photodiode)

Post Run-6 campaigns



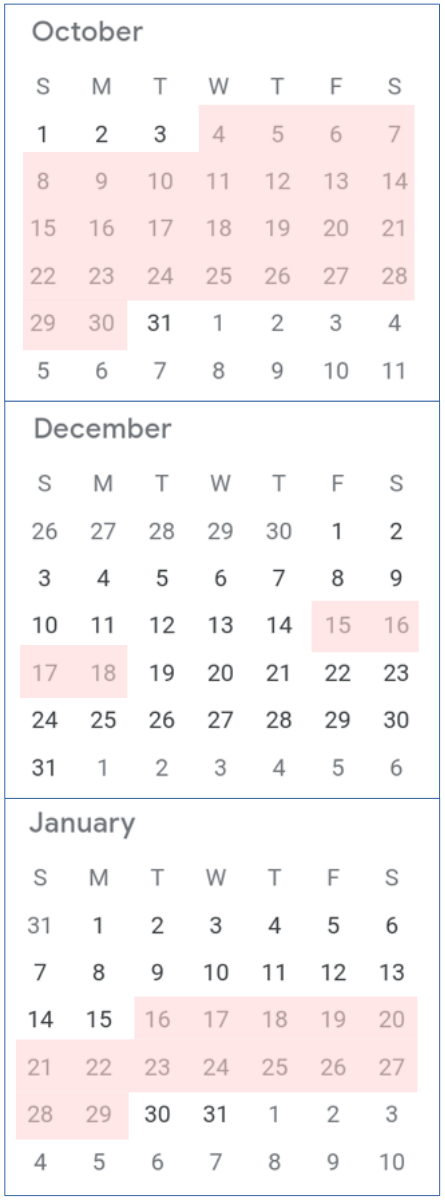
October 2023:

- 550+ hours of acquisition
- Many configurations tested here:
  - Nominal and offset radii
  - Free-standing and clamped bridge
  - Various magnet and kicker setpoints
  - Fast kick shape measurements
  - Vibration measurements (new quadrant photodiode)

December 2023:

- HWPout symmetry test
- Full 16-kicks supercycle measurement

Post Run-6 campaigns



October 2023:
- 550+ hours of acquisition
- Many configurations tested here:
  - Nominal and offset radii
  - Free-standing and clamped bridge
  - Various magnet and kicker setpoints
  - Fast kick shape measurements
  - Vibration measurements (new quadrant photodiode)

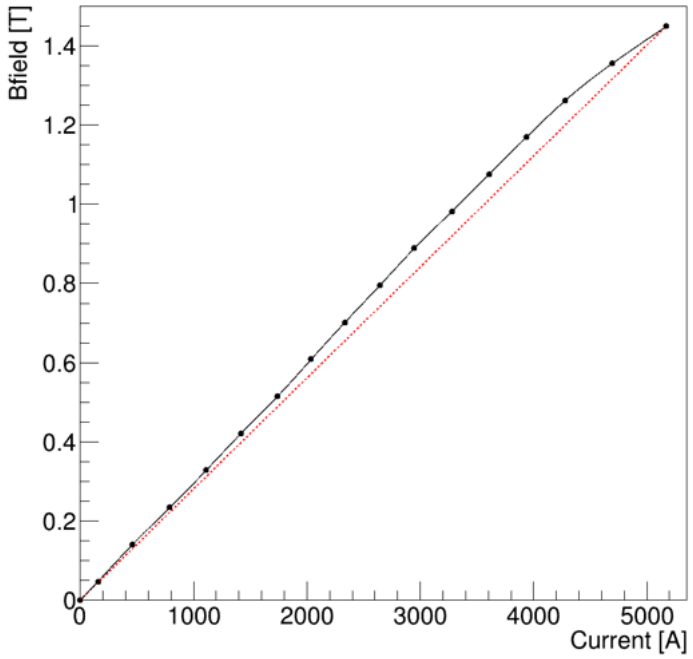
December 2023:
- HWPout symmetry test
- Full 16-kicks supercycle measurement

January 2024:
- 230+ hours of eddy currents measurements
- Measurement at various magnet setpoints
- Vibration suppression studies with Quarter WavePlate
- Best campaign for transient determination at R0

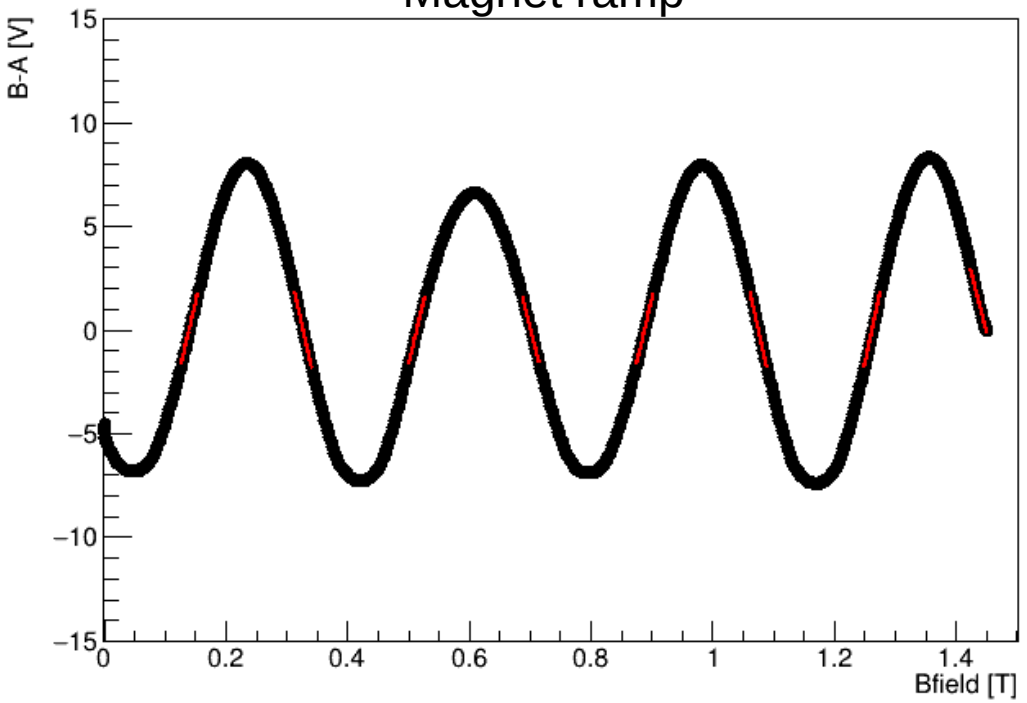
Absolute calibration

- Magnet ramps to determine **mV/mG** sensitivity
  - Magnet non-linearity (mG/A) determined too
- Total light output (sum of diodes) to normalize for laser fluctuations
- Blumlein amplitude to normalize different HWP settings and alignments

Magnet non-linearity

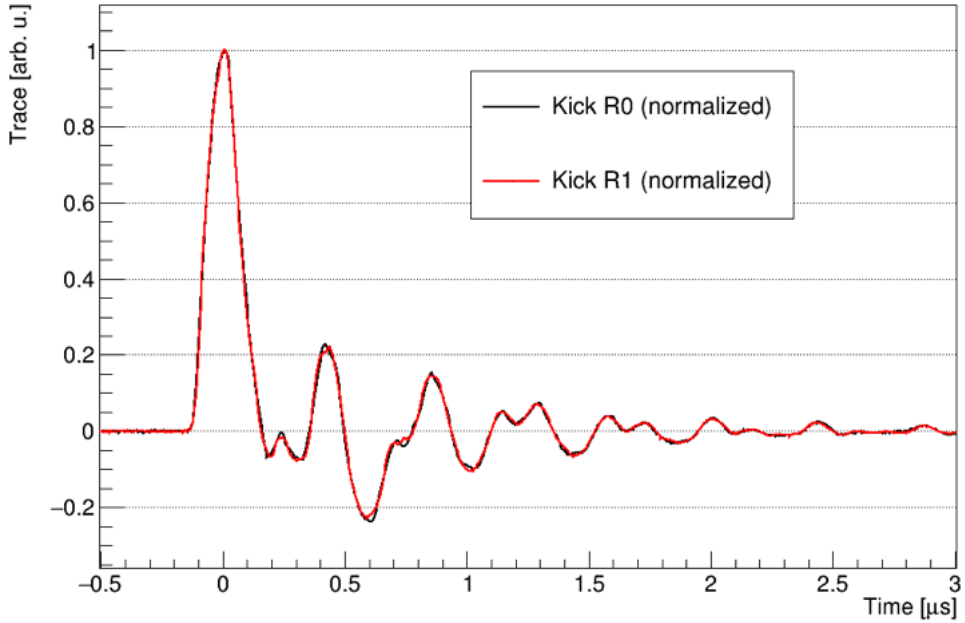


Magnet ramp

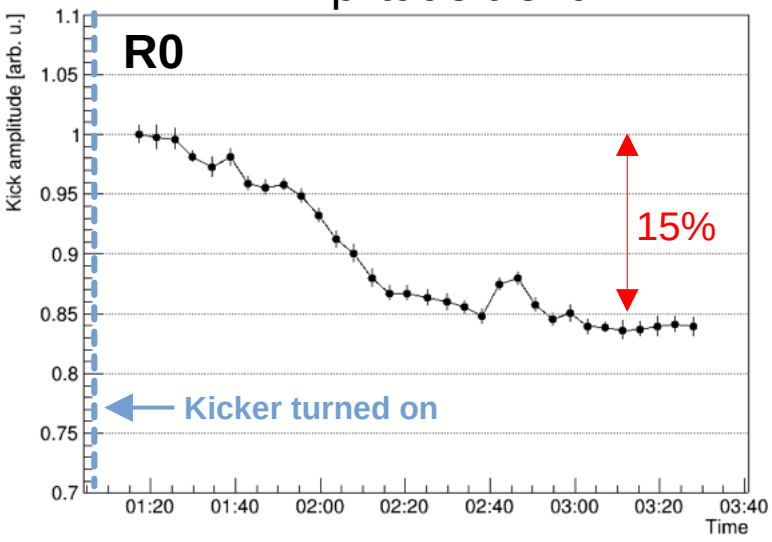


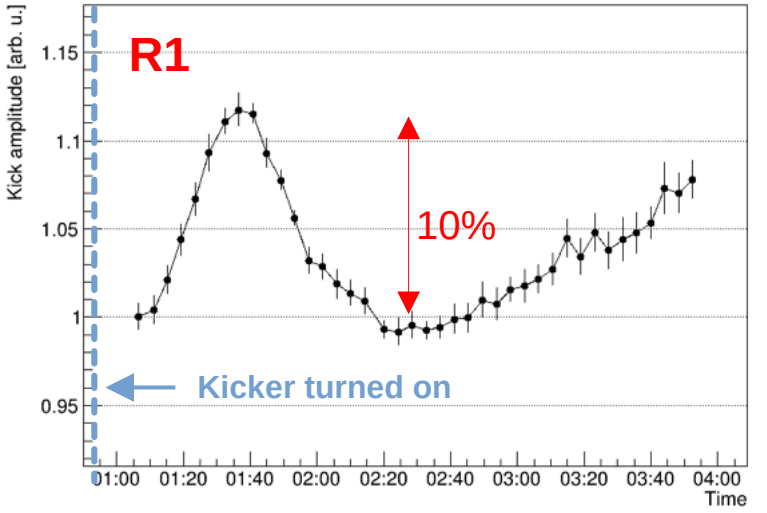
Kick shape

- R0 and R1 with magnet ON measured in Oct 8-9
- Measurement done in AC-coupling mode – no light output normalization :(
  - Can’t distinguish between kick warmup effects vs laser fluctuation
- Proposed acquisition with DC-coupling for this week but MC-1 is now in shutdown mode
- Kick **shape** is very consistent between R0 & R1



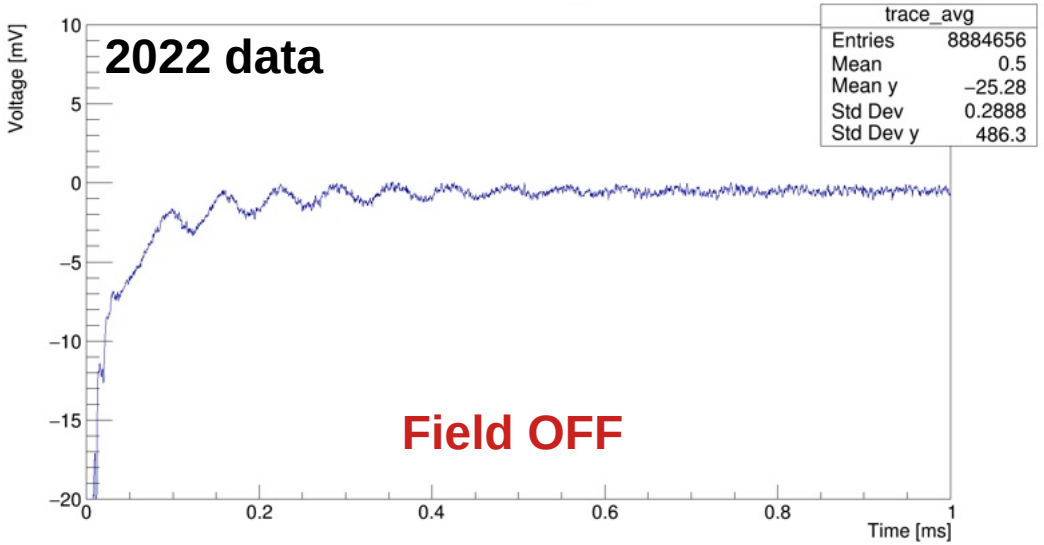
Amplitude trend

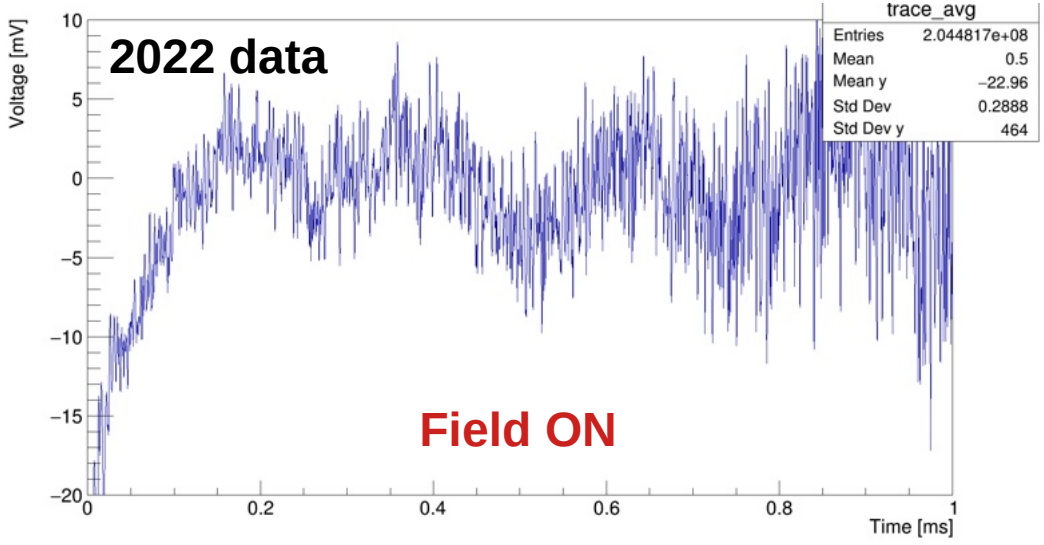




Eddy currents

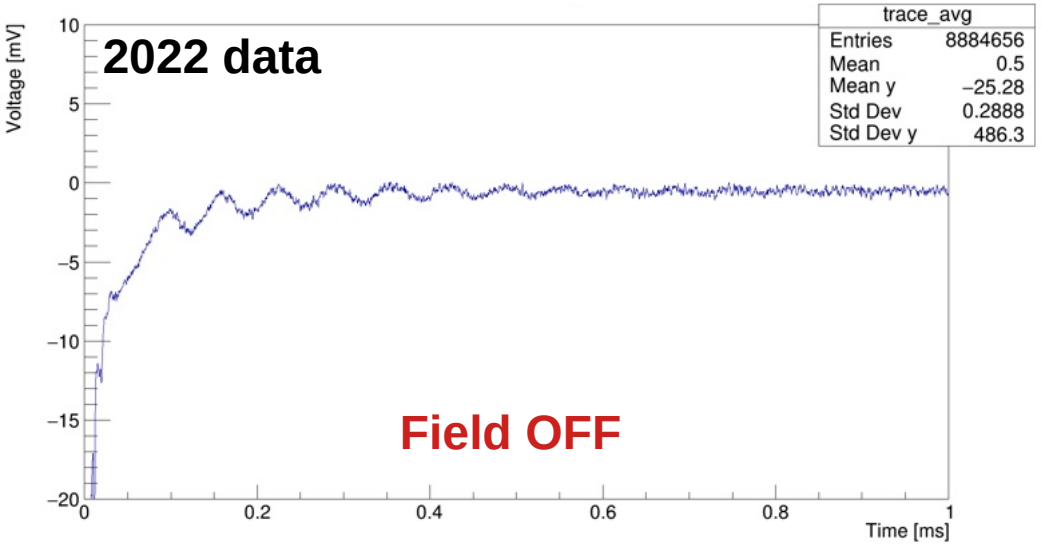
- Oscillations with magnet **ON** are a puzzle since long time

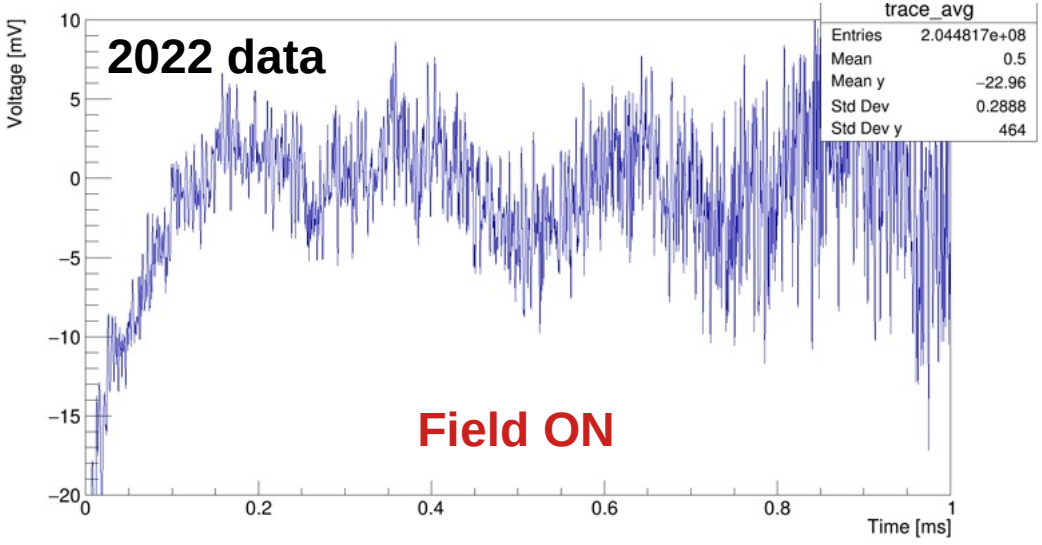


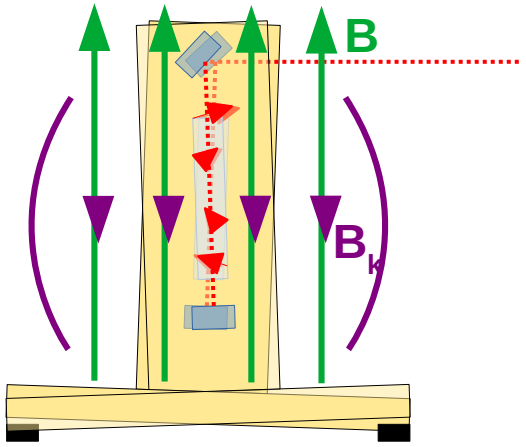


Eddy currents

- Oscillations with magnet **ON** are a puzzle since long time

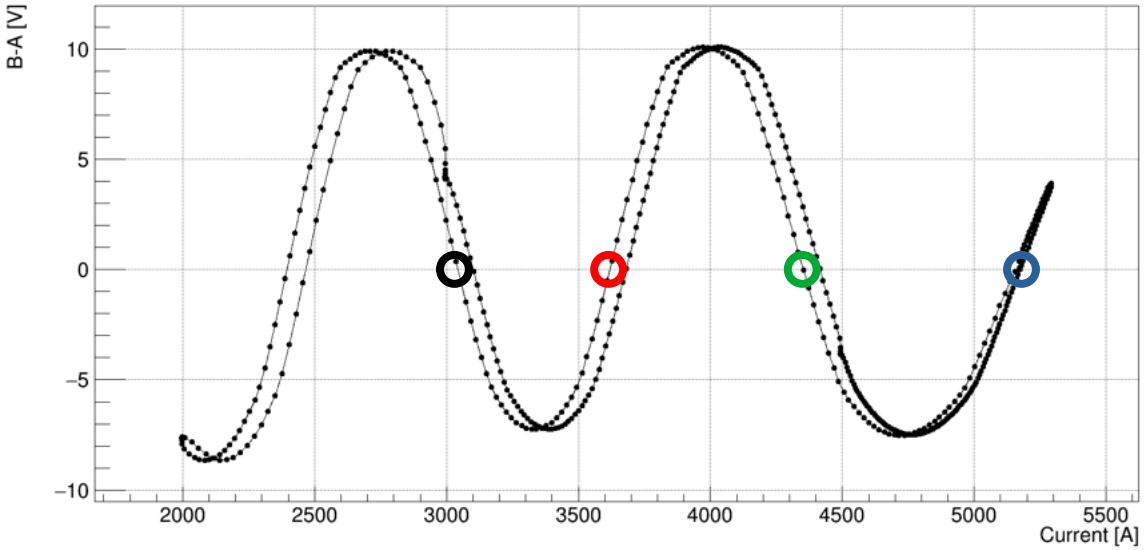






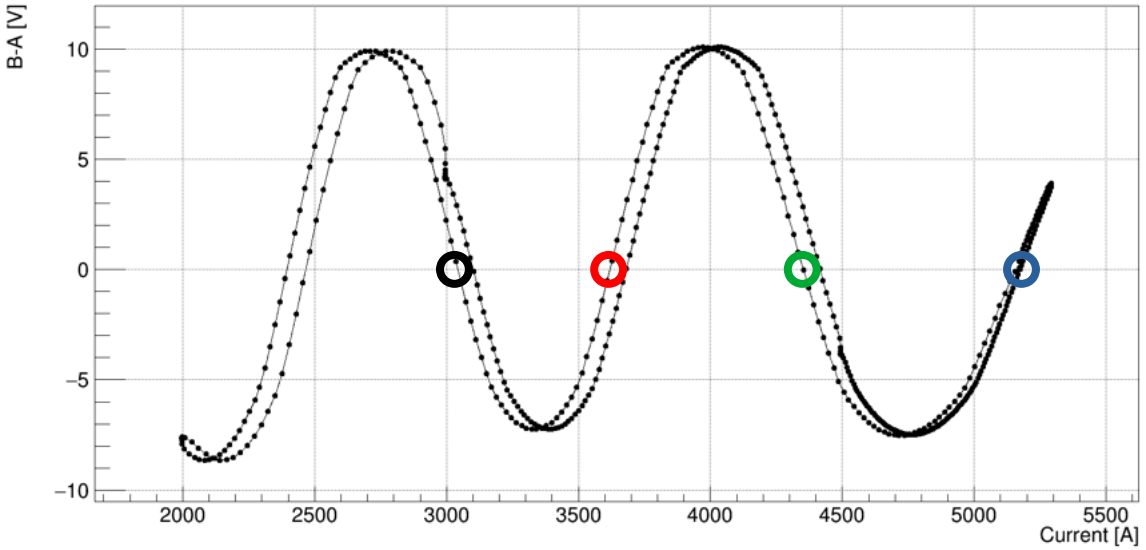
- Kick-induced periscope vibration is a *possible* explanation
- Signal oscillation produced by angle of crystal vs B field
  - Right order of magnitude for ~10 µm oscillations
- January campaign focused on solving this puzzle
- Magnet scan, Quarter WavePlate studies

Magnet scan



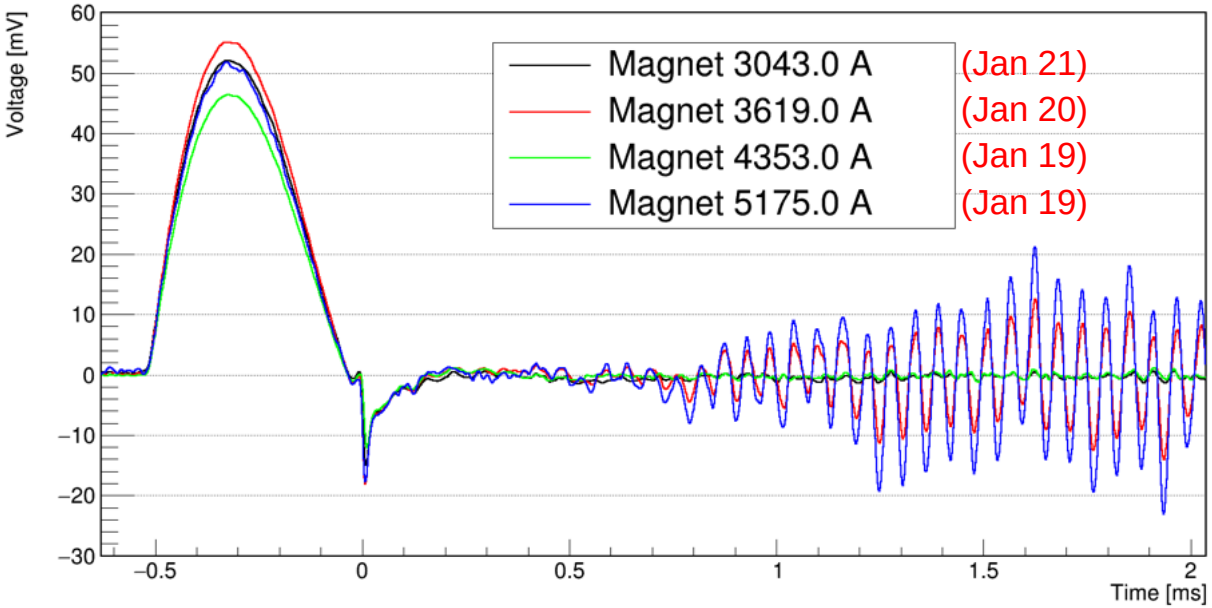
- Magnet strength values corresponding to the nodes of descending ramp measurements
- [3043, 3619, 4353, 5173] A
- Faraday rotation angles: [2.5π, 3π, 3.5π, 4π]

Magnet scan



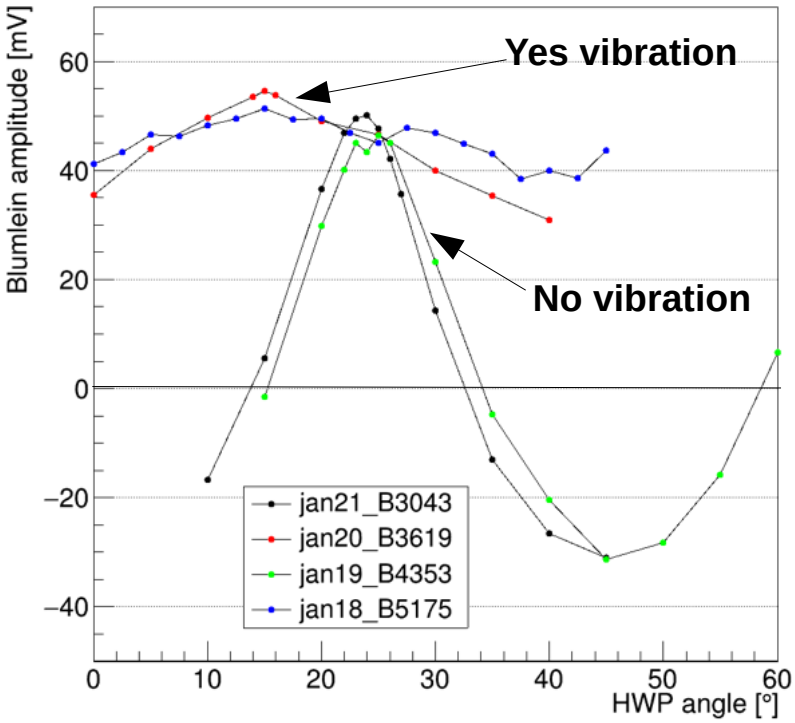
- Magnet strength values corresponding to the nodes of descending ramp measurements
- [3043, 3619, 4353, 5173] A
- Faraday rotation angles: [2.5π, 3π, 3.5π, 4π]

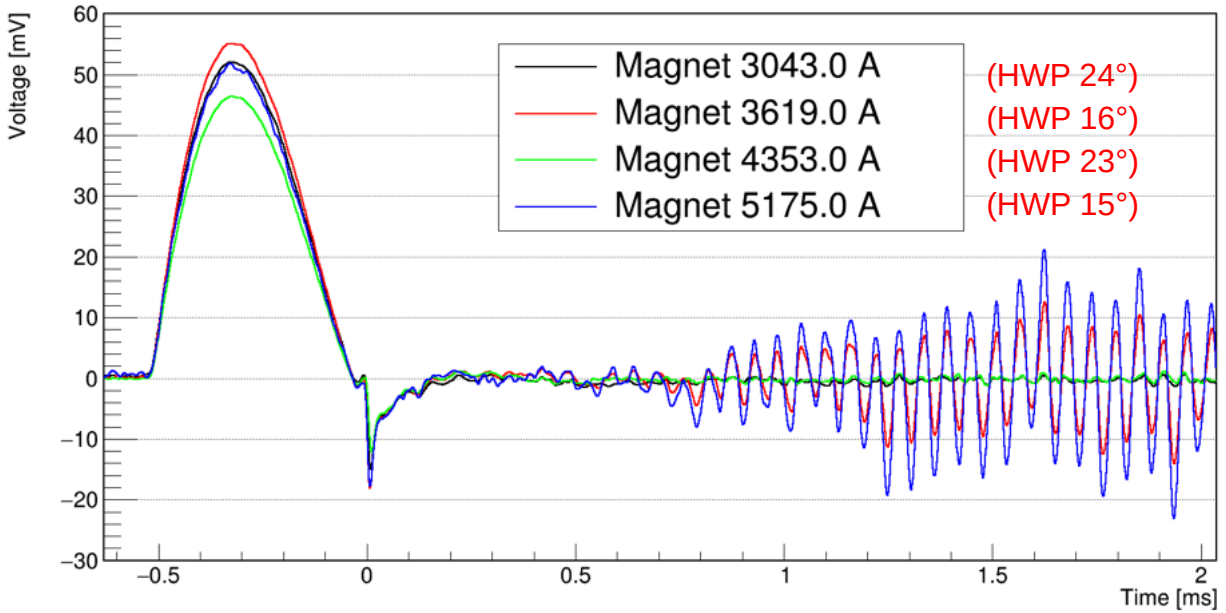
- Vibrations suppressed for the nodes with negative slope! (2.5π, 3.5π)
- This is very surprising
- Physical reason not understood yet



HWP scans

- 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]
- Physical reason not yet understood

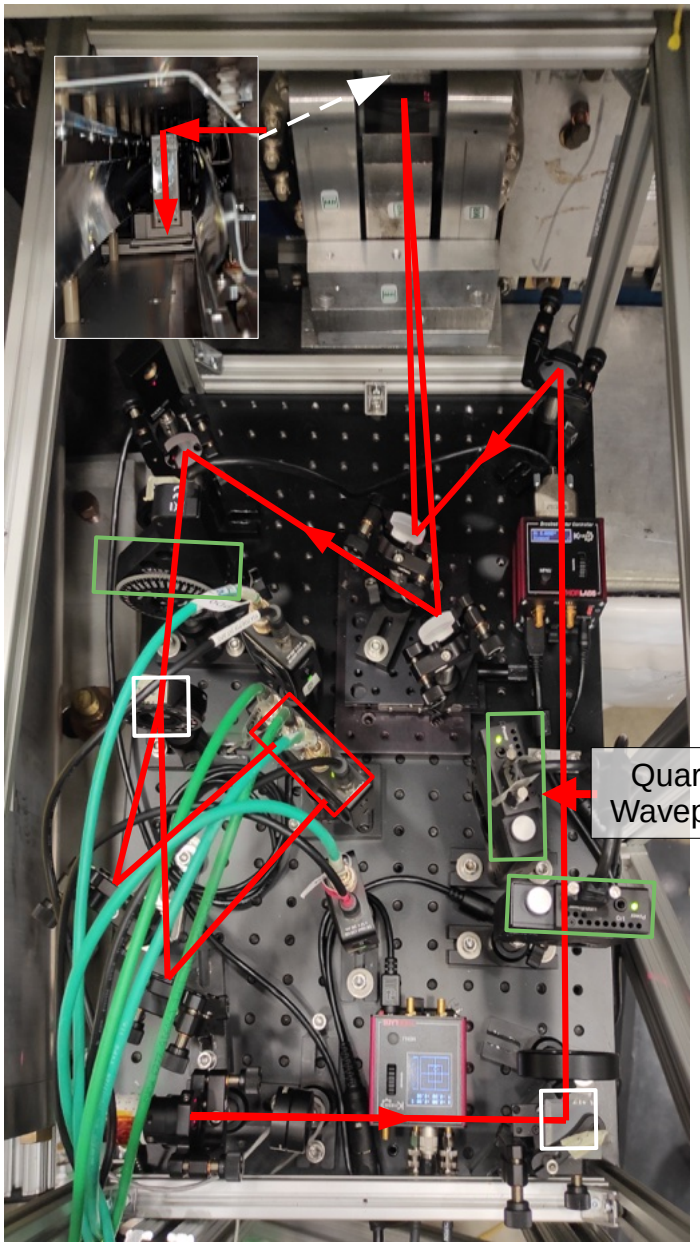




Quarter WavePlate

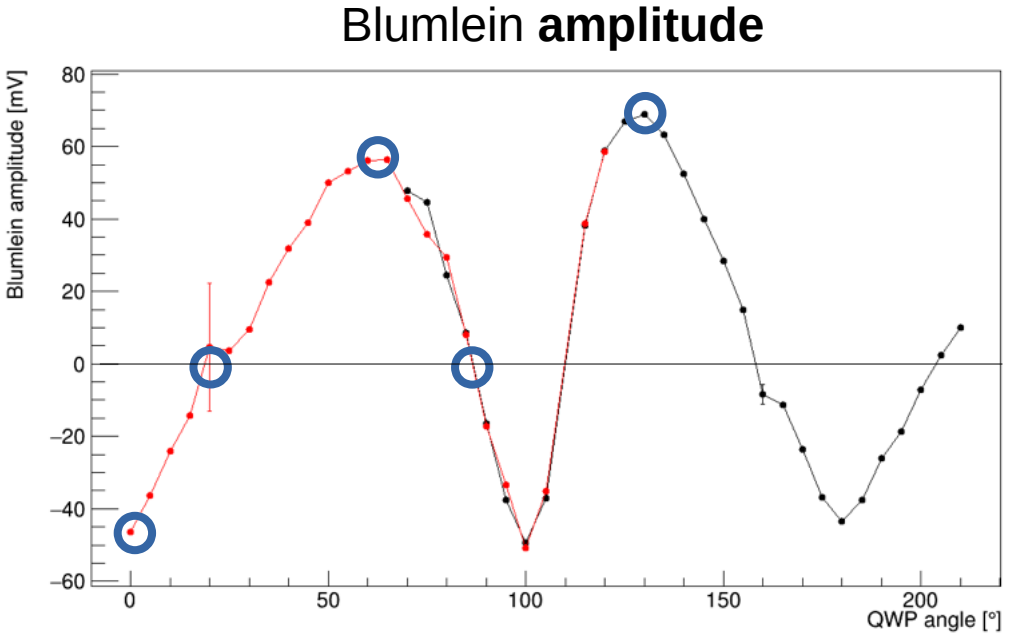
- Quarter WavePlate inserted on Jan 23rd
  - Last 6 days of acquisition
  - 100% remote, eventually proven to be the best quality data
- 45° incident linearly polarized light becomes circularly polarized

  - No Faraday effect
- Goal is to measure effects not depending on the kicker magnetic field
- First, QWP scan to determine working setpoints



QWPscan

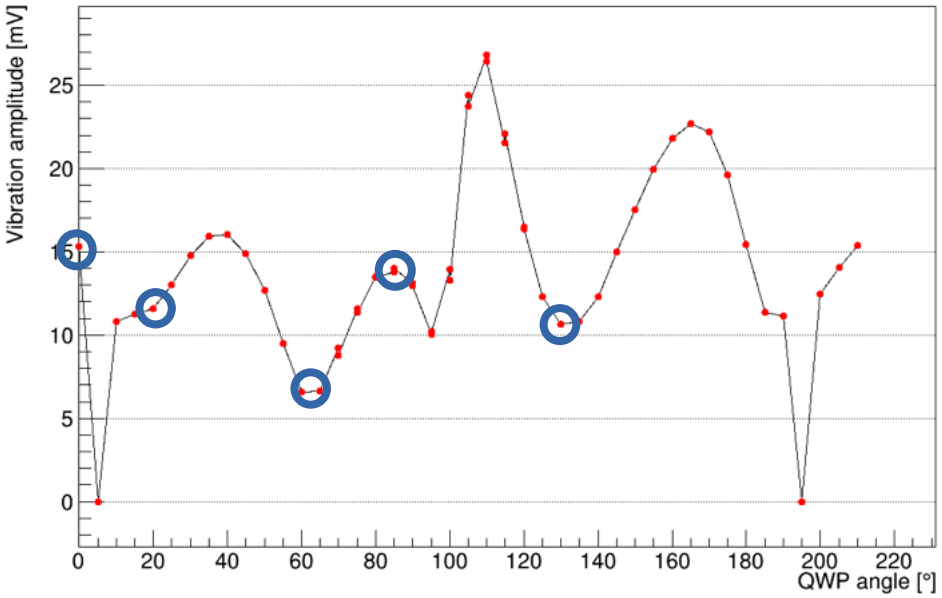
- Some QWP values manage to zero the blumlein amplitude → perfect circular polarization



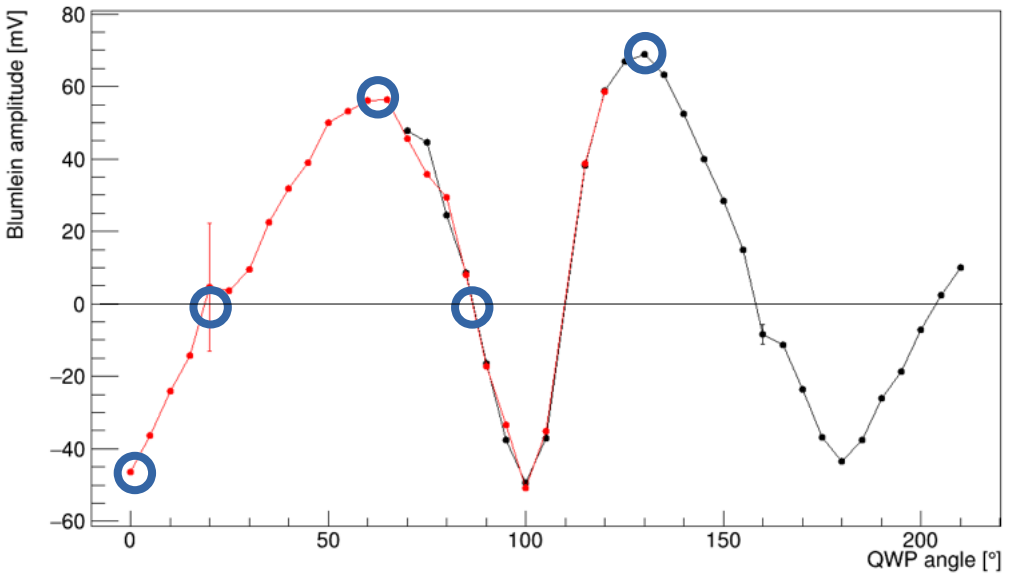
QWPscan

- Some QWP values manage to zero the blumlein amplitude → perfect circular polarization
- Some values enhance or decrease measured vibrations
- But never truly suppressed as for 2.5π, 3.5π Faraday nodes

Trace **vibration**



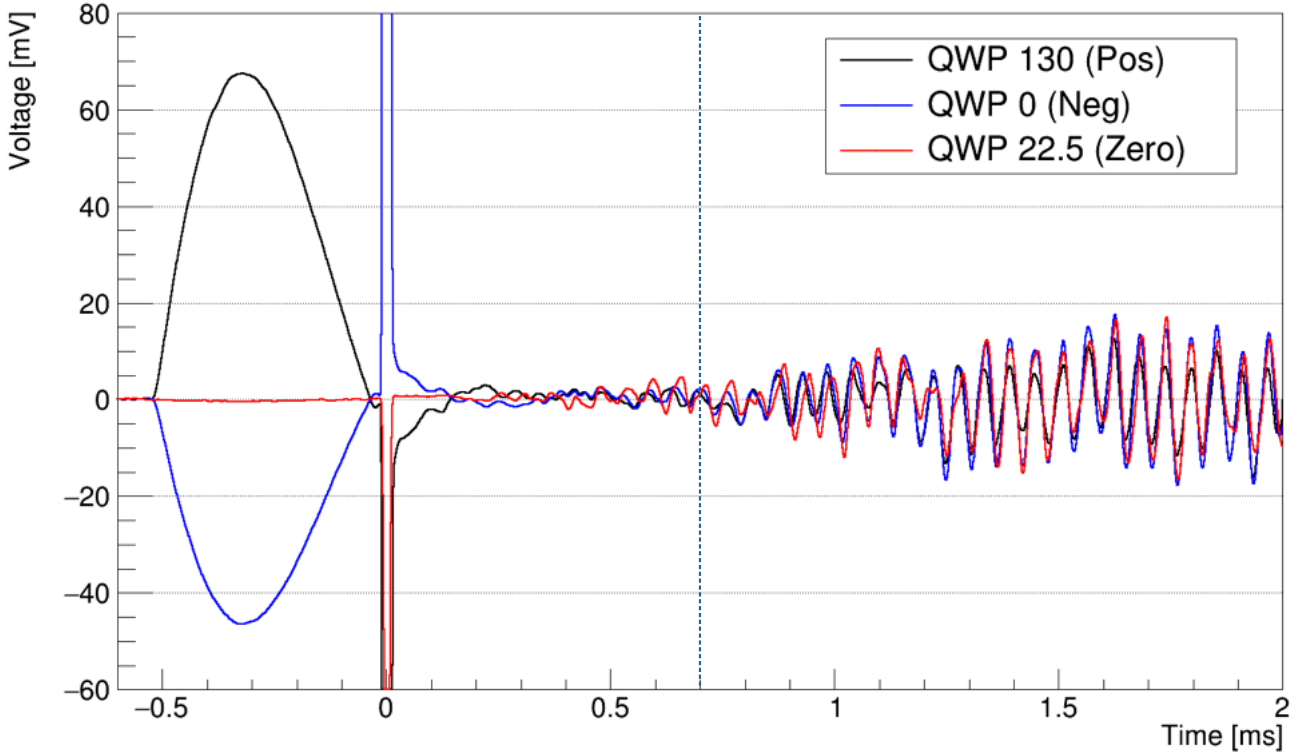
Blumlein **amplitude**



- QWP values chosen for long eddy currents measurements:
- 62°, 130° → blumlein maximized
- 22.5°, 85° → blumlein minimized
- 0° → blumlein negative

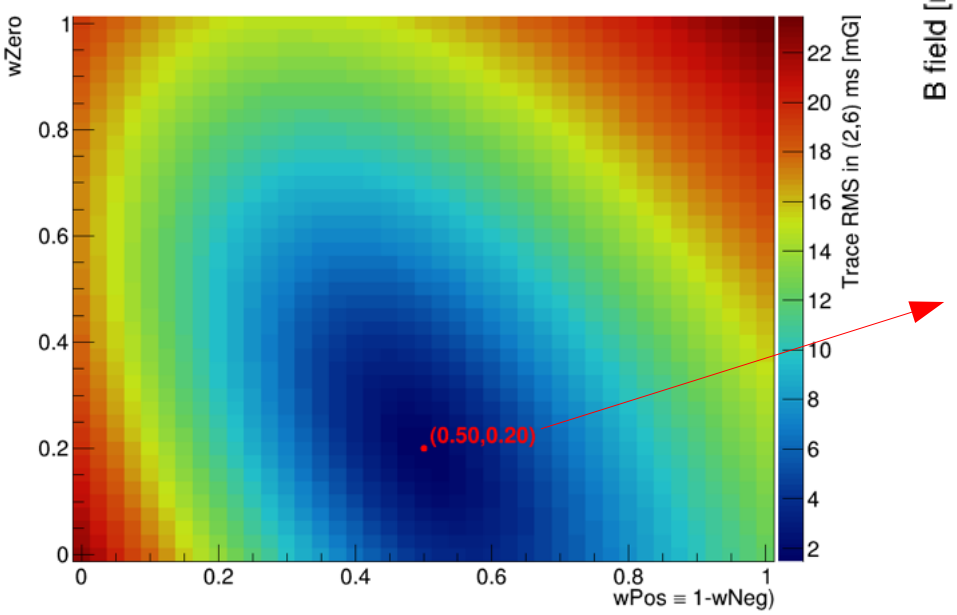
Vibration subtraction

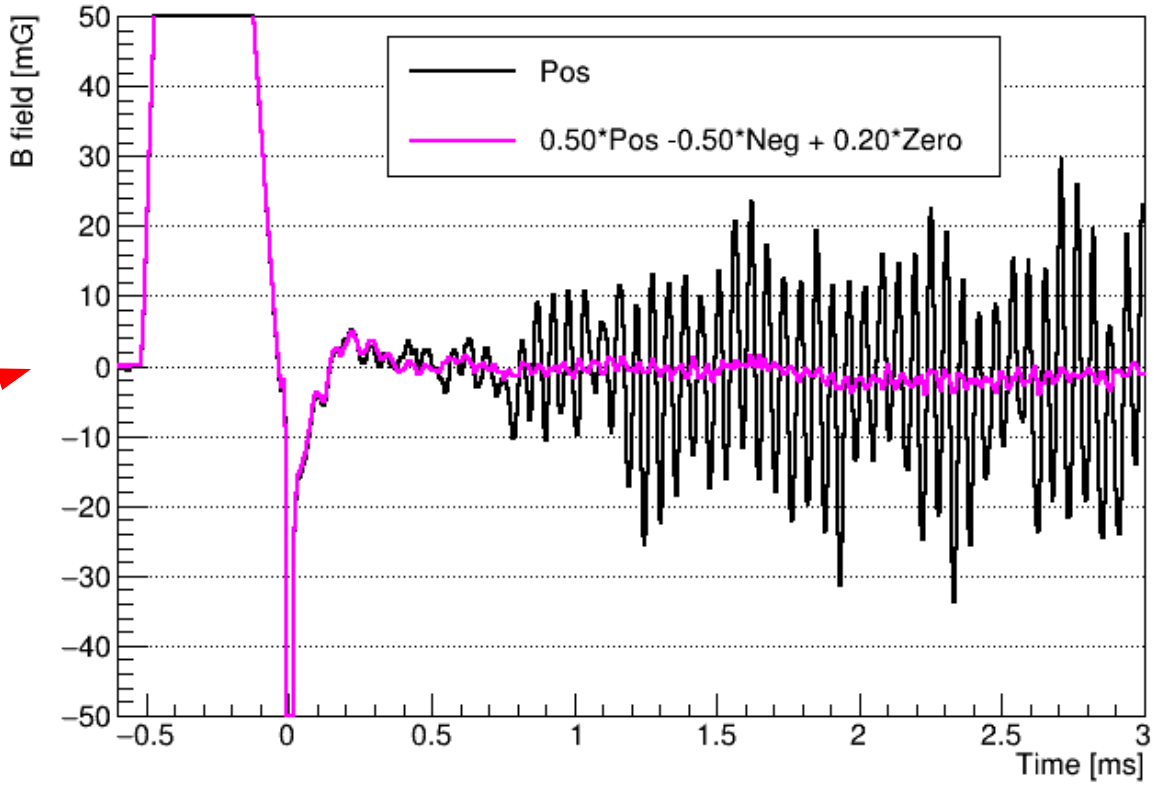
- Three significant acquisitions
- QWP 22.5°: zero blumlein and transient → oscillations are not field **transients**
- Sign, phase, amplitude of oscillation in the three cases is very similar – but not exactly equal. Can we cancel them out?



Minimization scan

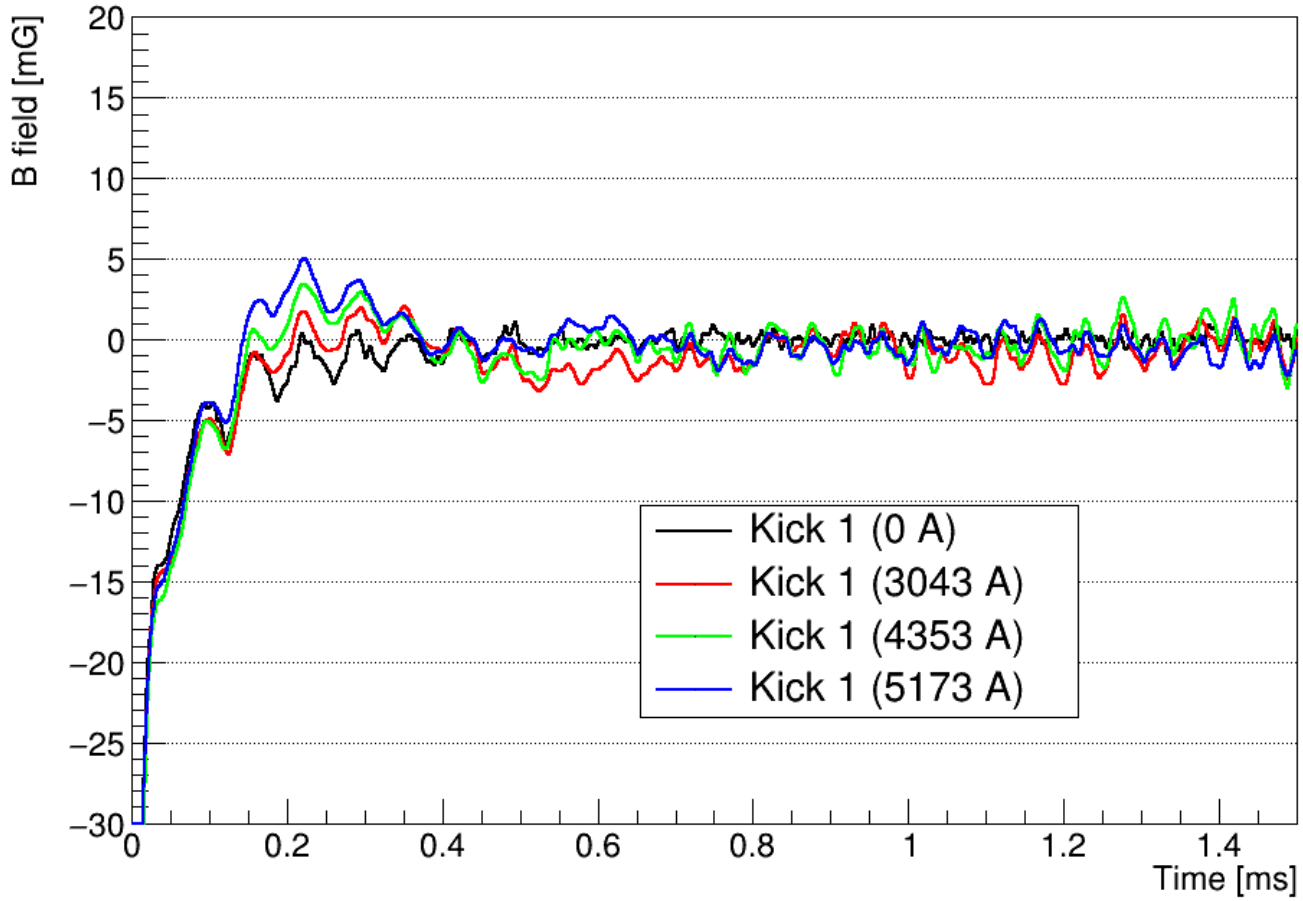
- Finding the best combination of P, N, Z with a minimization scan
- wPos*Pos + wNeg*Neg + wZero*Zero
- Vibration quantified as trace RMS in [2,6] ms range
- Success!





Magnet strength

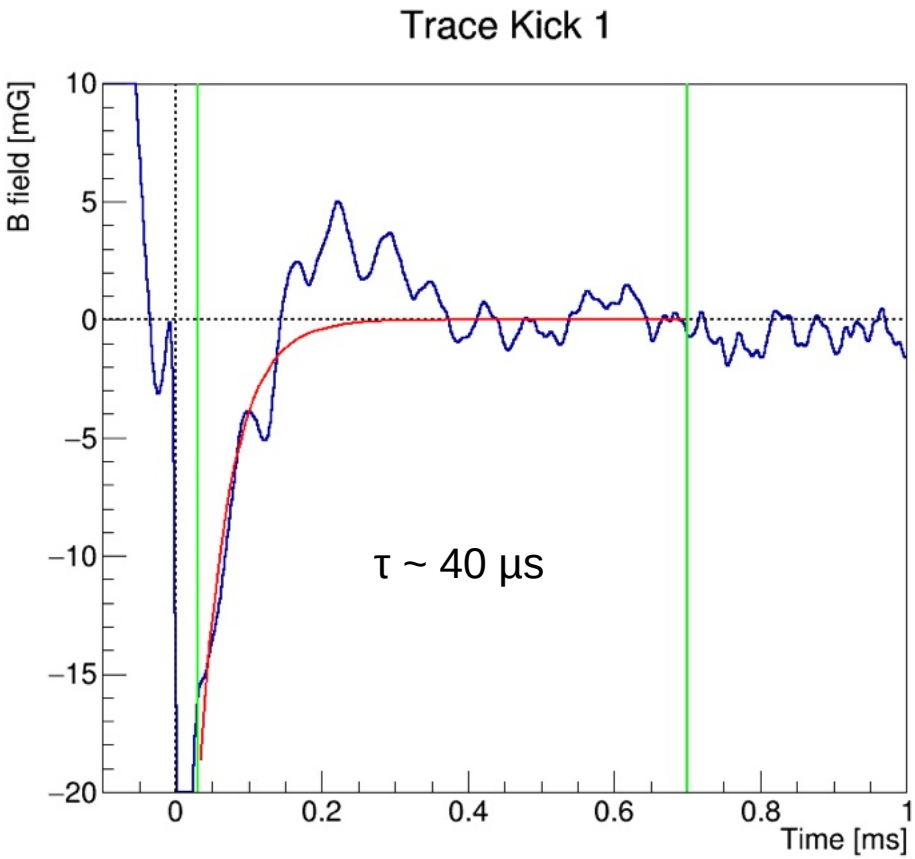
- Back to magnet strength comparison → with calibration and no vibrations
- Full current (blue) treated with vibration subtraction with QWP
- “Overshoot” at ~0.2 ms correlated with magnet current

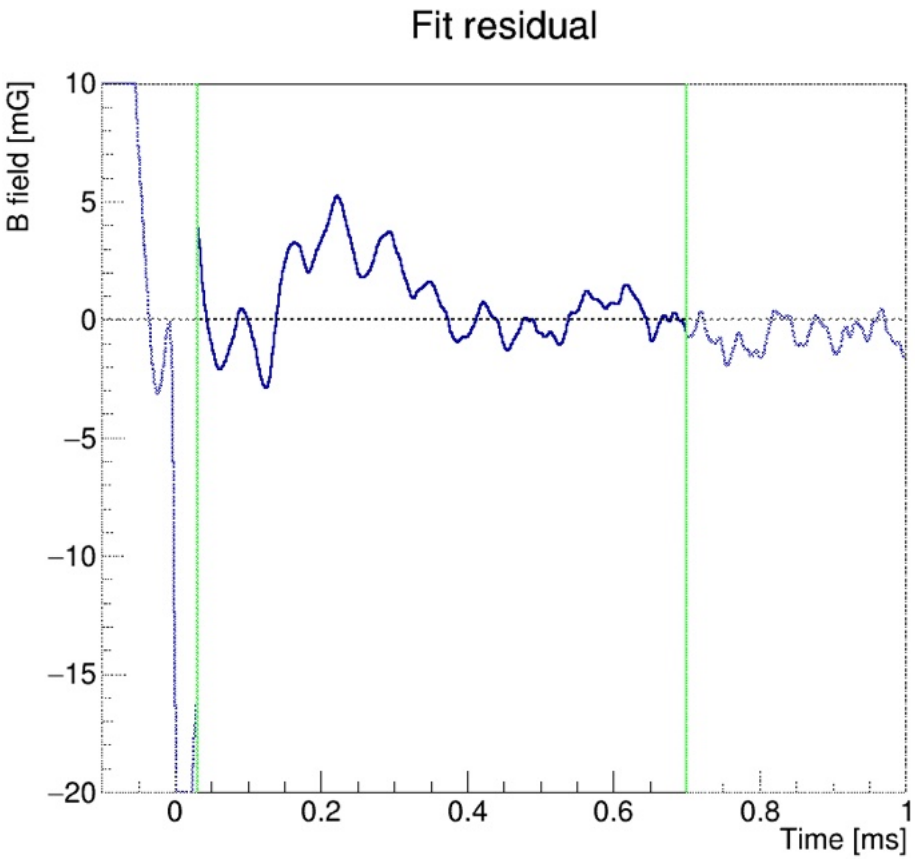


Oct 14
Jan 21
Jan 19
Jan 25-28

Fit functions

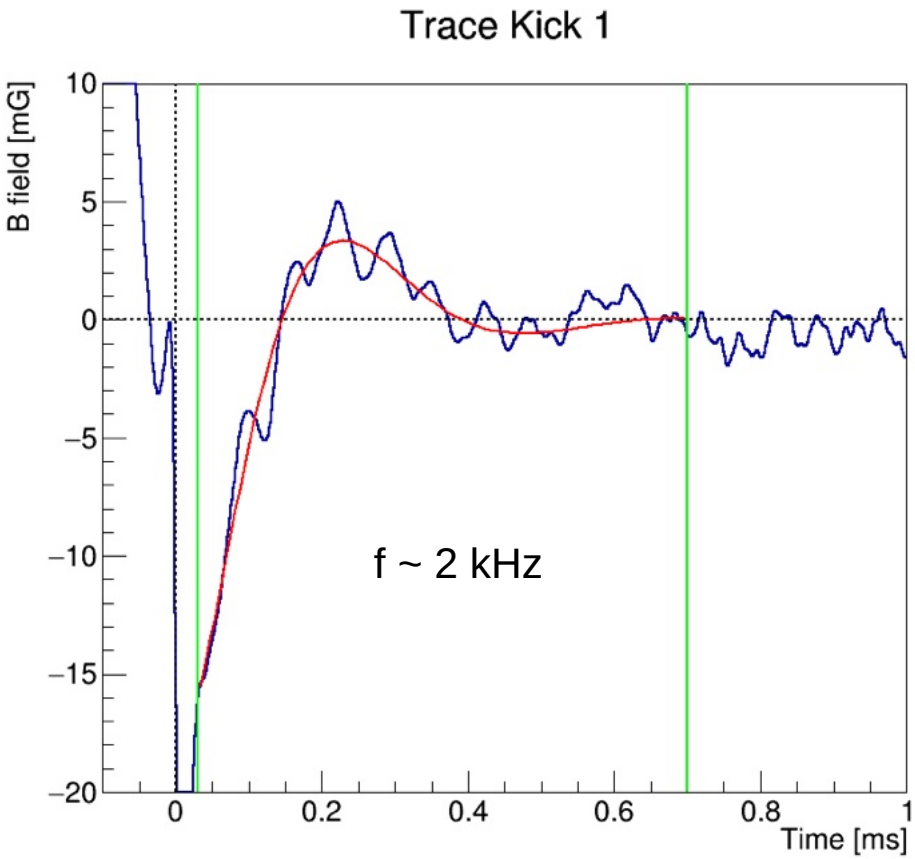
B(t) = $b - Ae^{-t/\tau}$

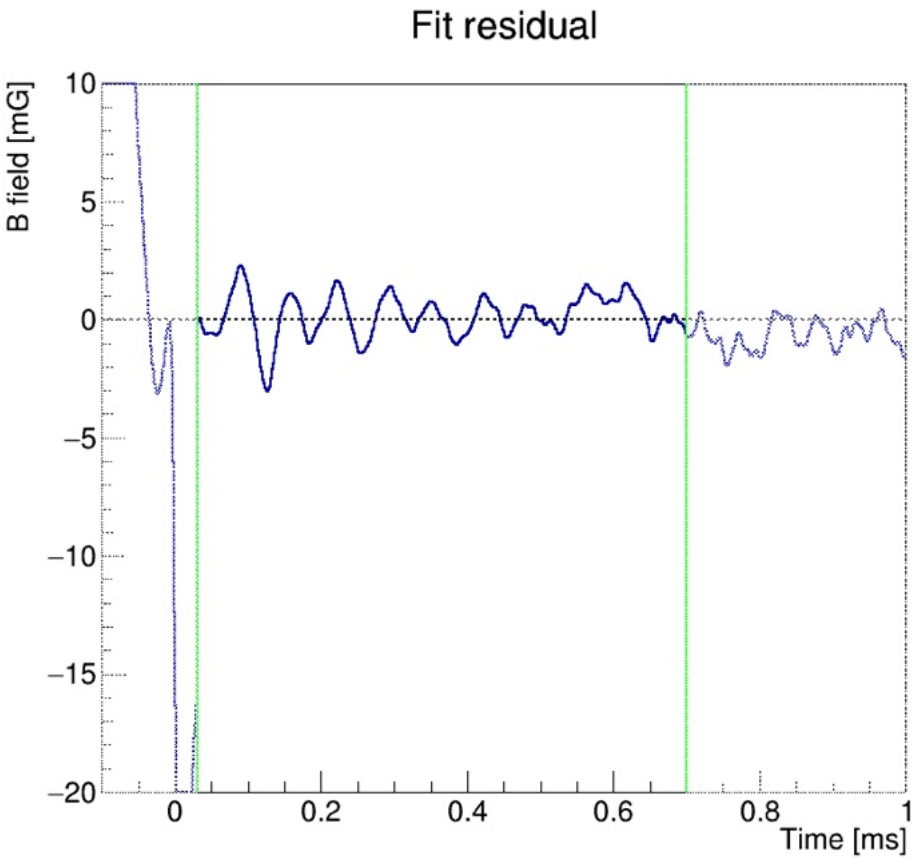




Fit functions

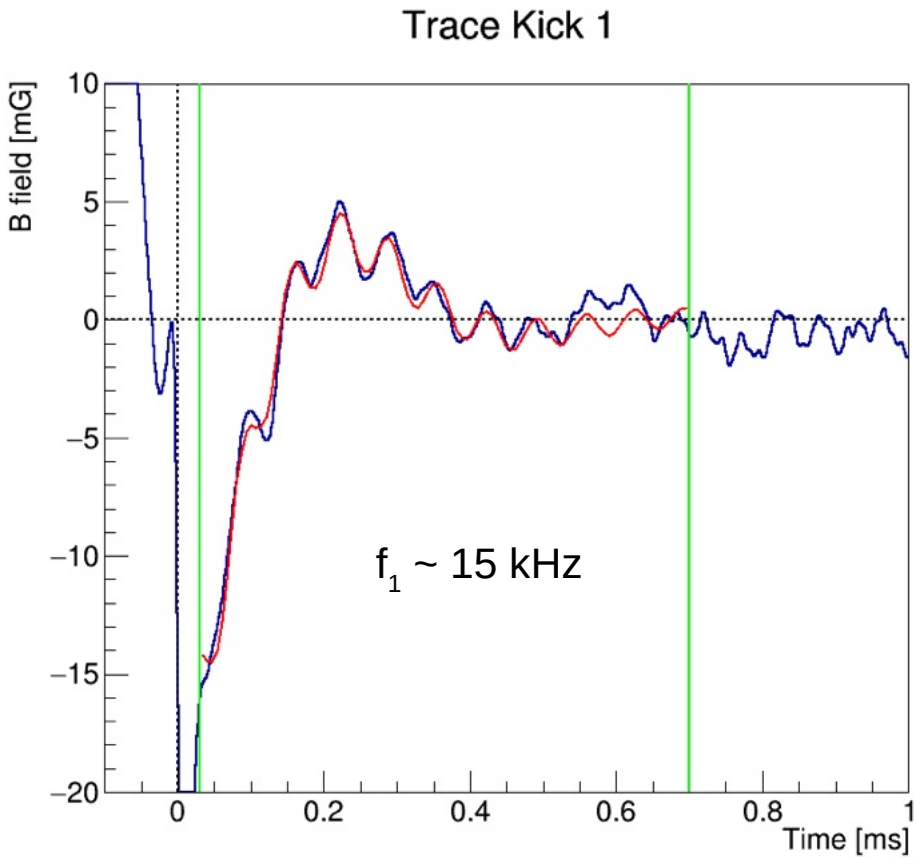
B(t) = $b - Ae^{-t/\tau}\sin(ft + \phi)$

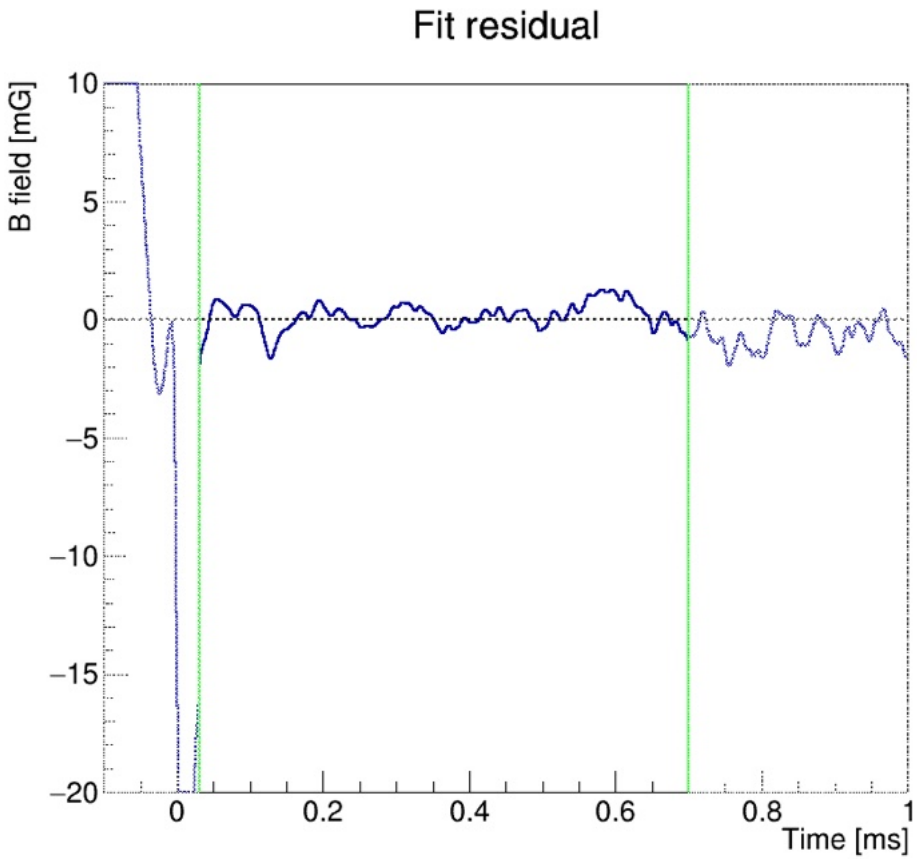




Fit functions

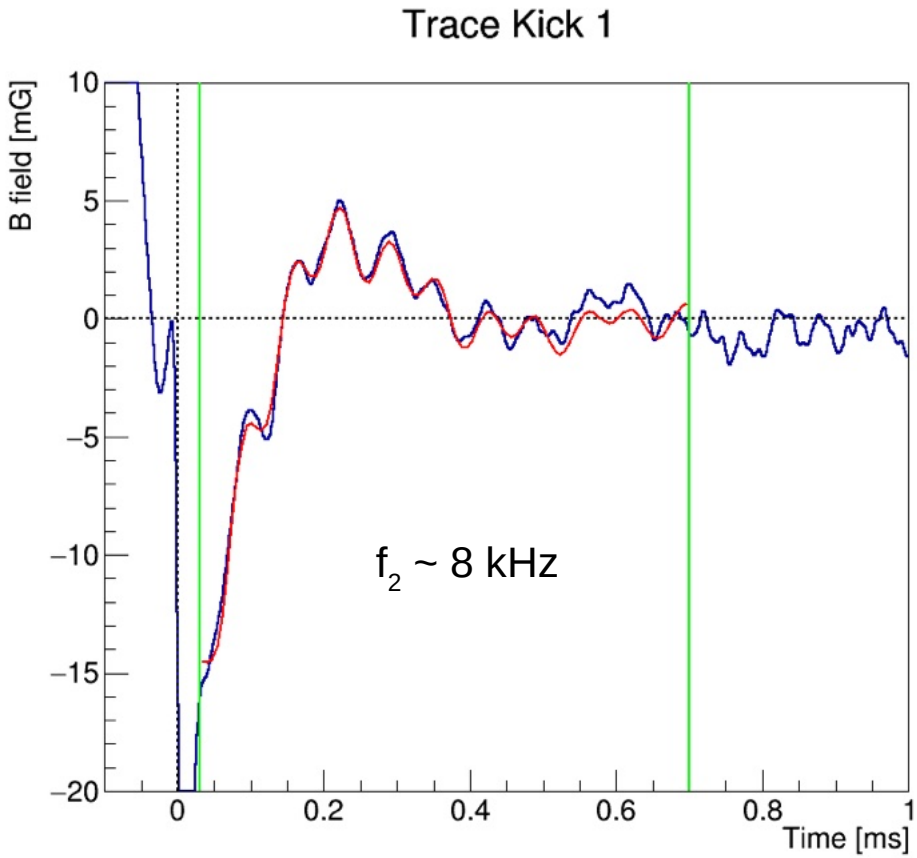
B(t) = $b - Ae^{-t/\tau}\sin(ft+\phi) + A_1 e^{-t/\tau_1}\sin(f_1 t+\phi_1)$

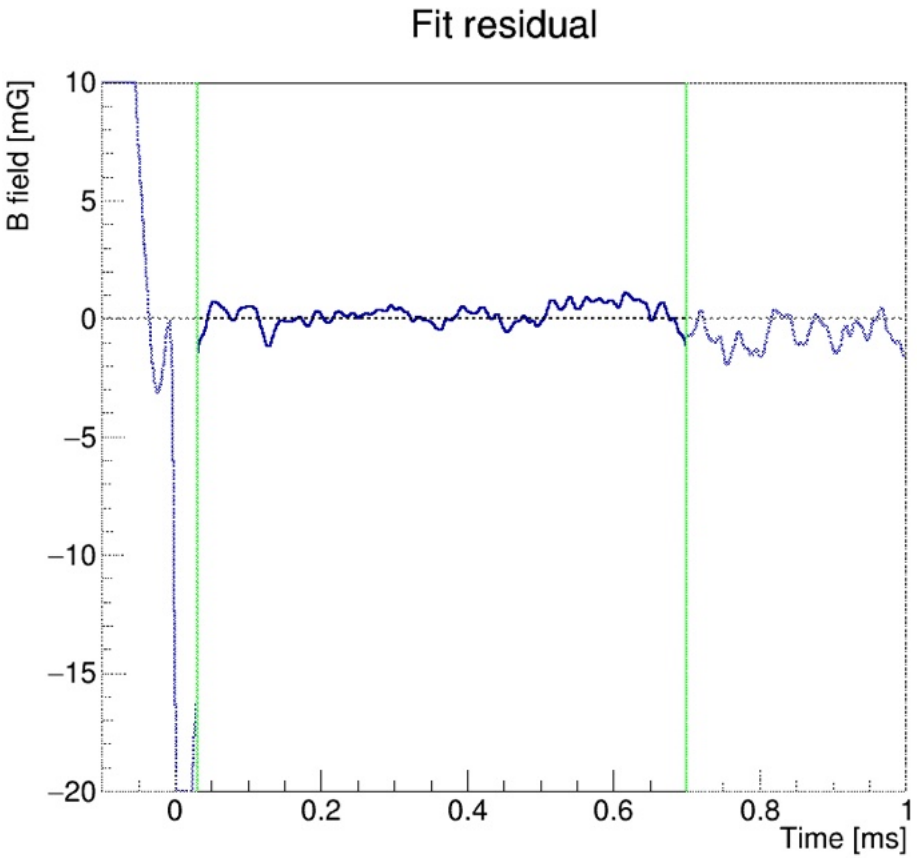




Fit functions

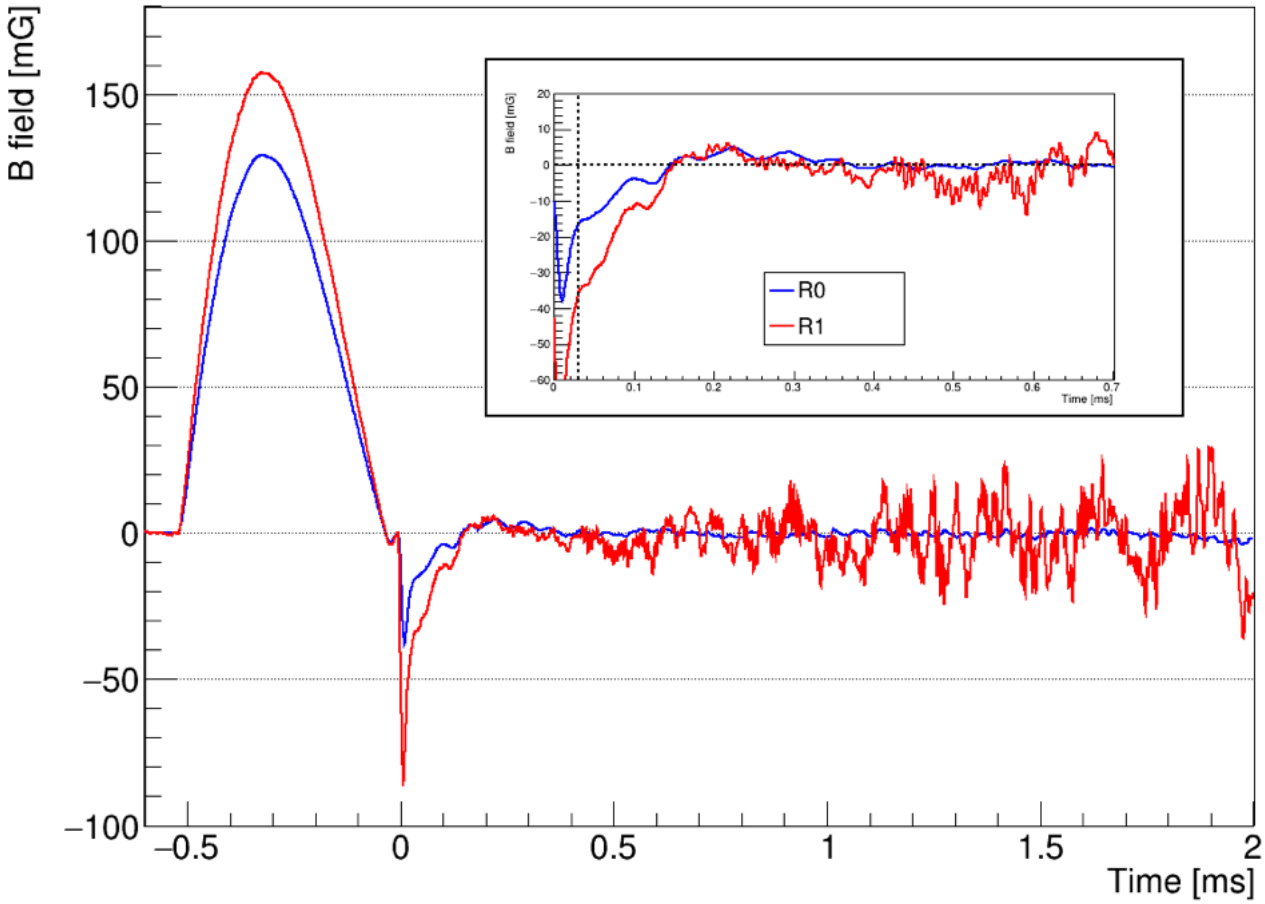
B(t) = $b - Ae^{-t/\tau}\sin(ft+\phi) + A_1 e^{-t/\tau_1}\sin(f_1 t+\phi_1) + A_2\sin(f_2 t+\phi_2)$

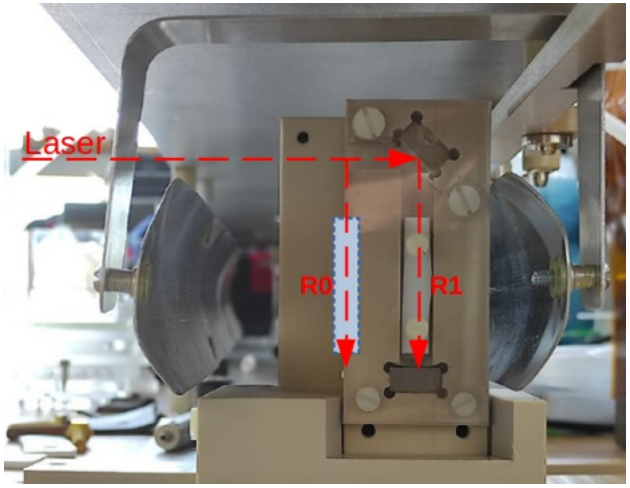




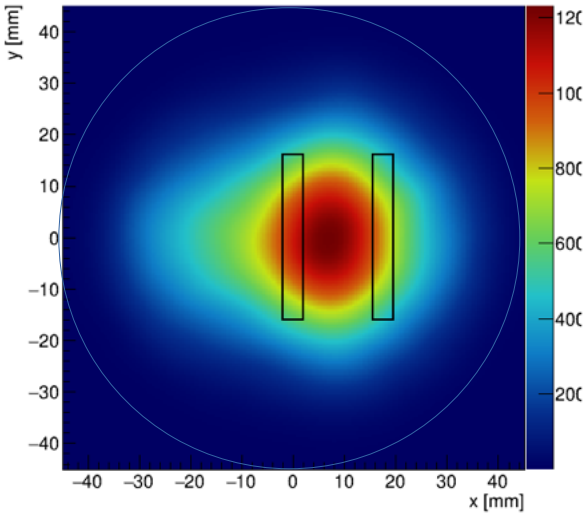
Radial dependence

- R0 is at magic radius, R1 is +17.5 mm
- Blumlein amplitude higher at R1 → +22%
- Eddy currents transient higher at R1 → ~2x @30 μs





Beam distribution Run3b

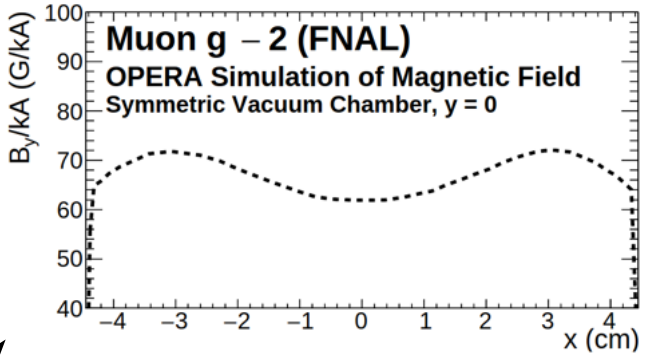


Radial dependence

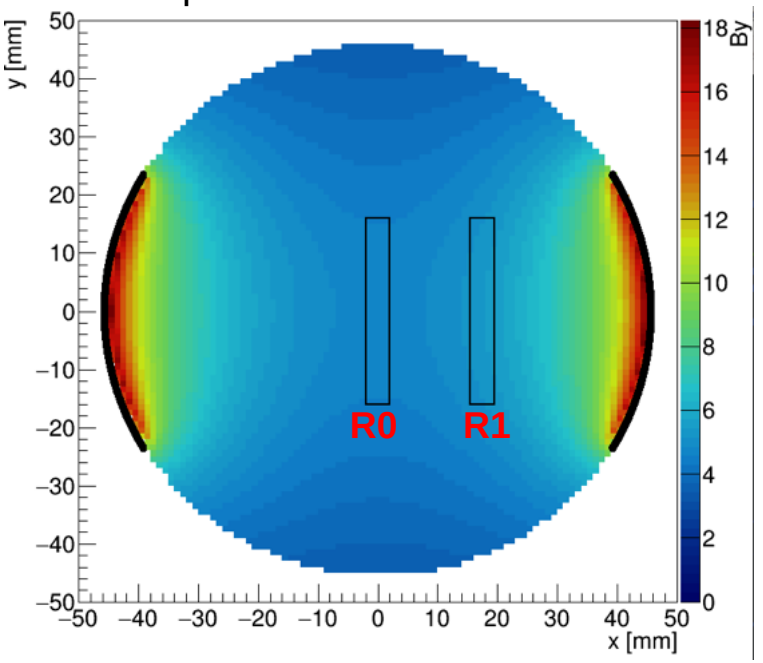
- Kick radial dependence:
- From magnetometer magnet ramp calibrations and slow diodes
  - Blumlein ratio R1/R0 ~ 1.22 ±0.06*
- From magnetometer kick measurements
  - Kick ratio R1/R0 ~ 1.27 ±0.20*
- From the kicker paper: https://arxiv.org/pdf/2104.07805.pdf
  - Kick ratio R1/R0 ~ 1.08
- Simple Biot-Savart simulation (thin wires)
  - Kick ratio R1/R0 ~ 1.13

*Errors are conservative, NOT FINAL

OPERA simulation (Kicker paper)



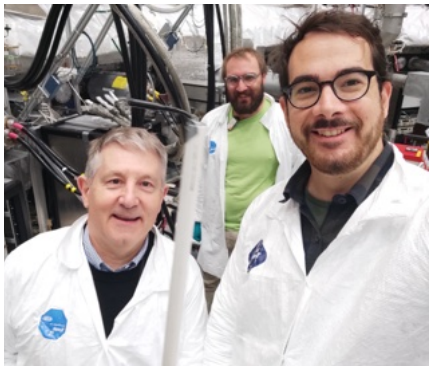
Simple Biot-Savart simulation

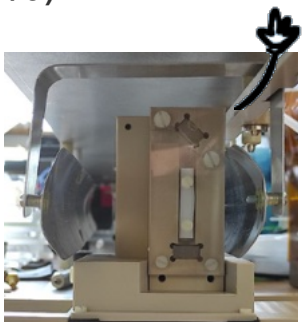


Conclusions

Interested? More details in:
Dec 2023: DocDB 29814
Feb 2024: DocDB 30020
Apr 2024: DocDB 30161

- Overall, very successful 2023/2024 magnetometer campaigns with many fully-remote shifts
- Many periscope improvements but didn't remove oscillations
- Magnet scan + 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)
- Only missing item is an accurate kick amplitude absolute determination (drift-limited to ±15%)
- Analysis toward completion, TODOs:
  - Bk term estimation
  - Systematics uncertainties



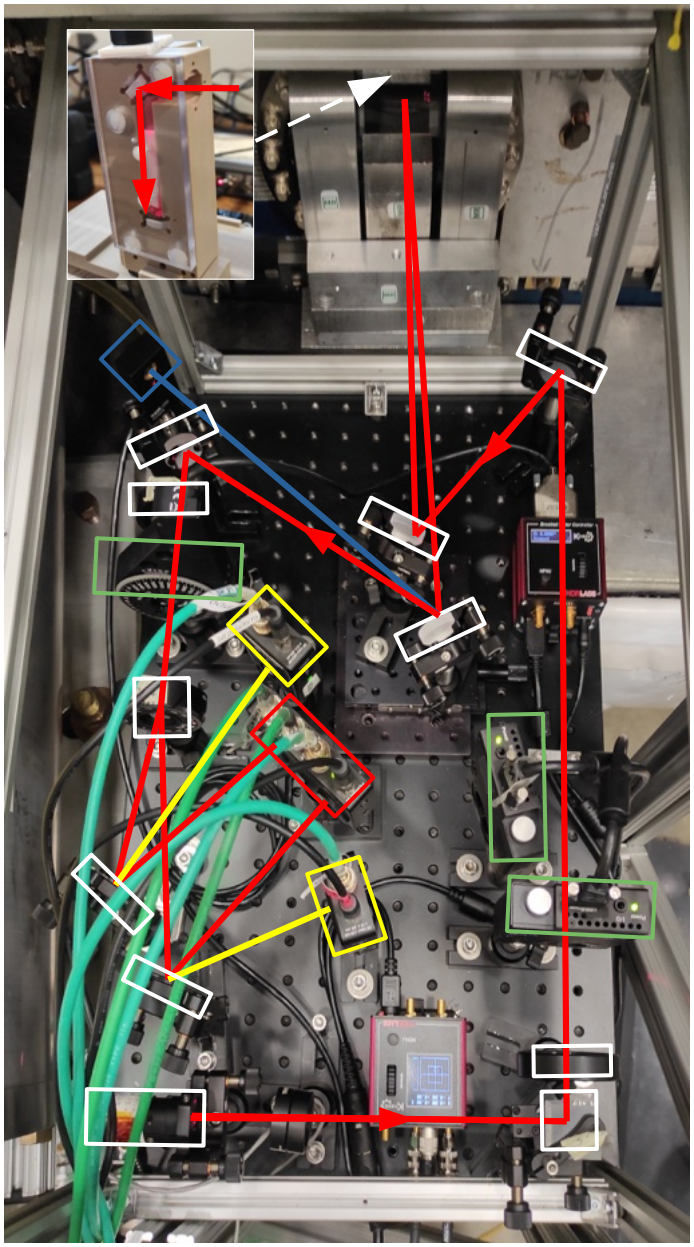


Thank you for your attention!

Backup slides

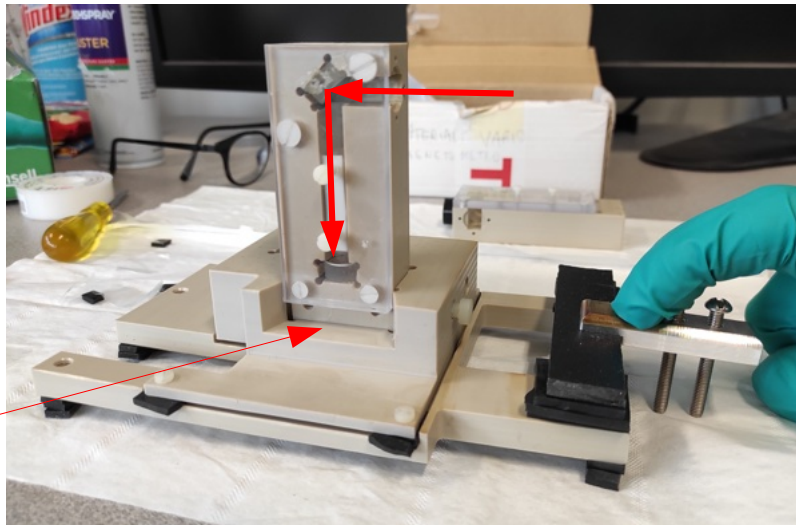
Hardware

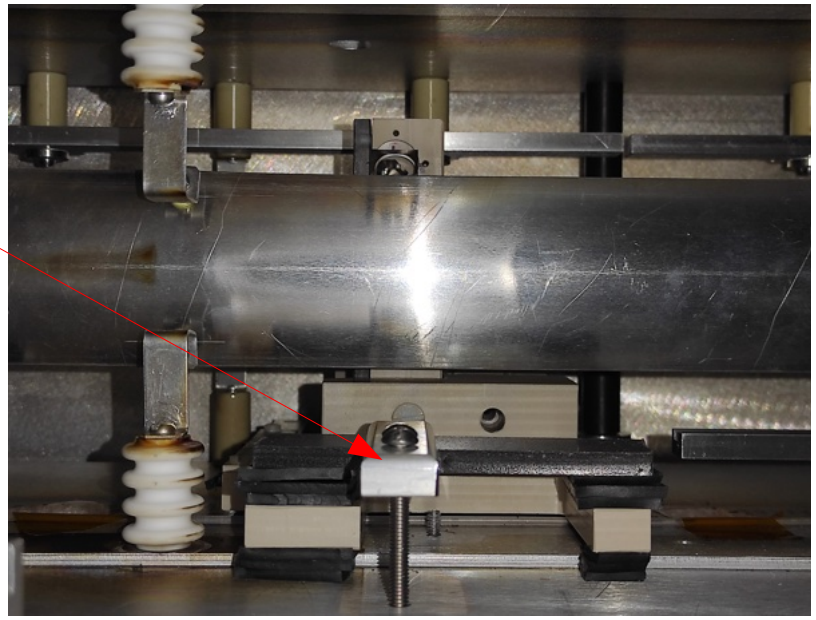
- Newport diode laser (635 nm)
- Two TGG crystals encapsulated in periscopes placed between kicker plates
- Halfwave plates for input polarization and output equalization (remotely controlled)
- Detectors:
  - Balanced photodiode for eddy currents measurements
  - Fast photodiodes for kick shape measurements
  - Quadrant photodiode for mechanical vibration measurements
- Fully remote-controlled DAQ laptop, digitizer, and delay generator

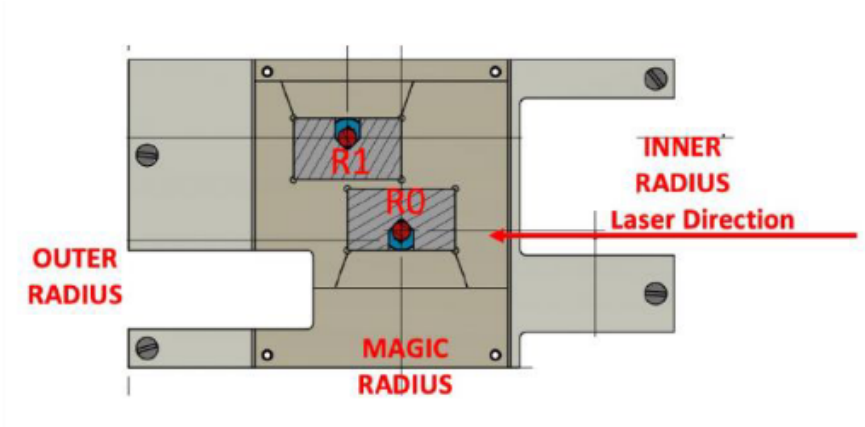


Periscopes

- Two periscopes
  - R0 (magic radius)
  - R1 = R0 + 15 mm
- New bridge design wrt 2022 with added rigidity
- Kicker cage clamp repurposed to hold the bridge since Oct 17

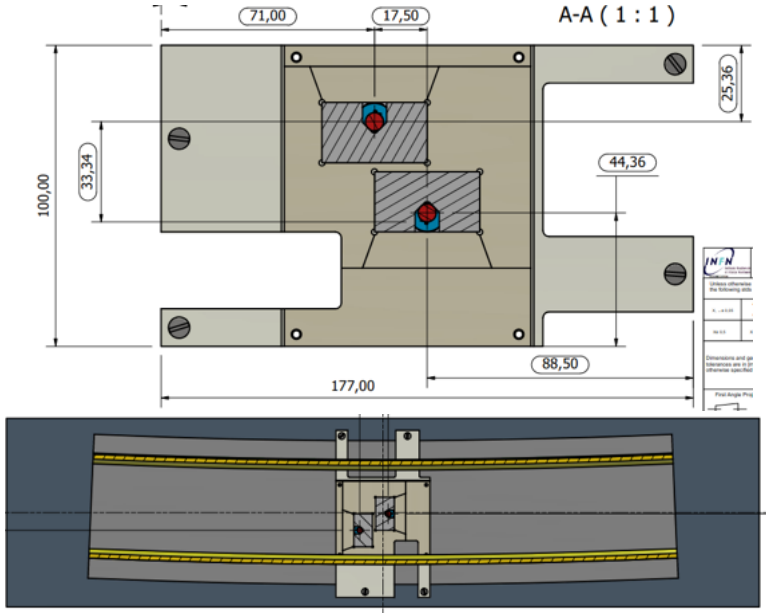


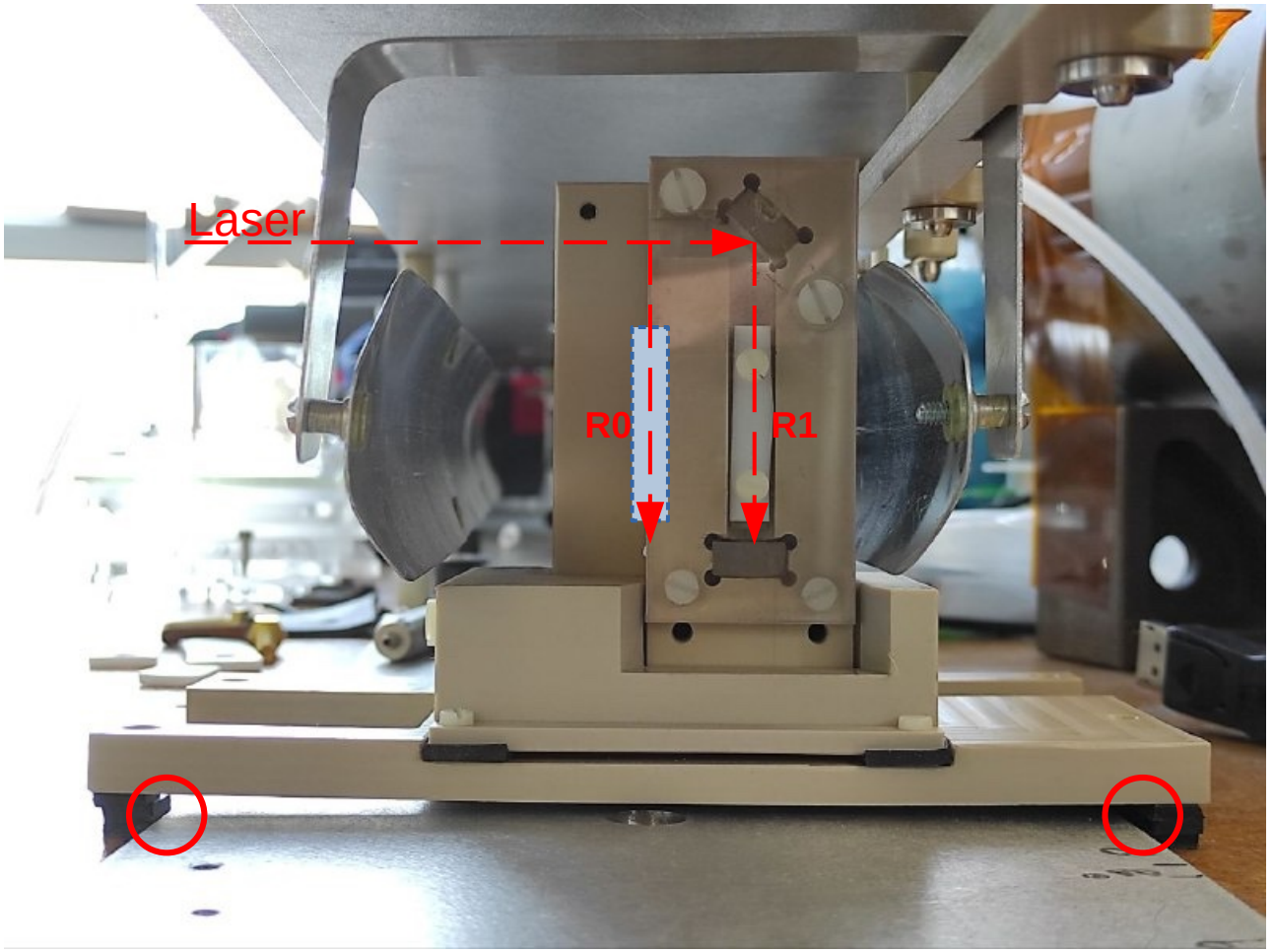




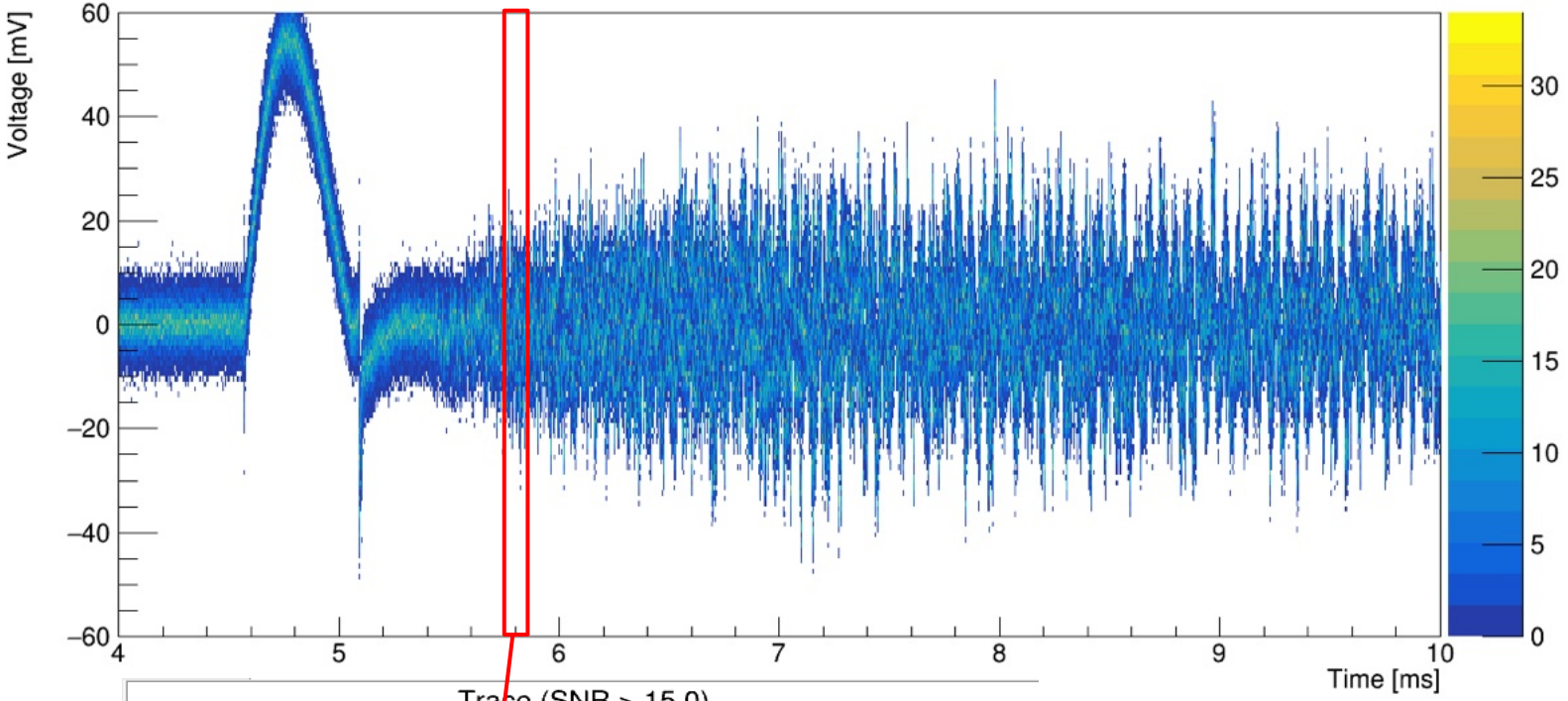
Periscope positioning

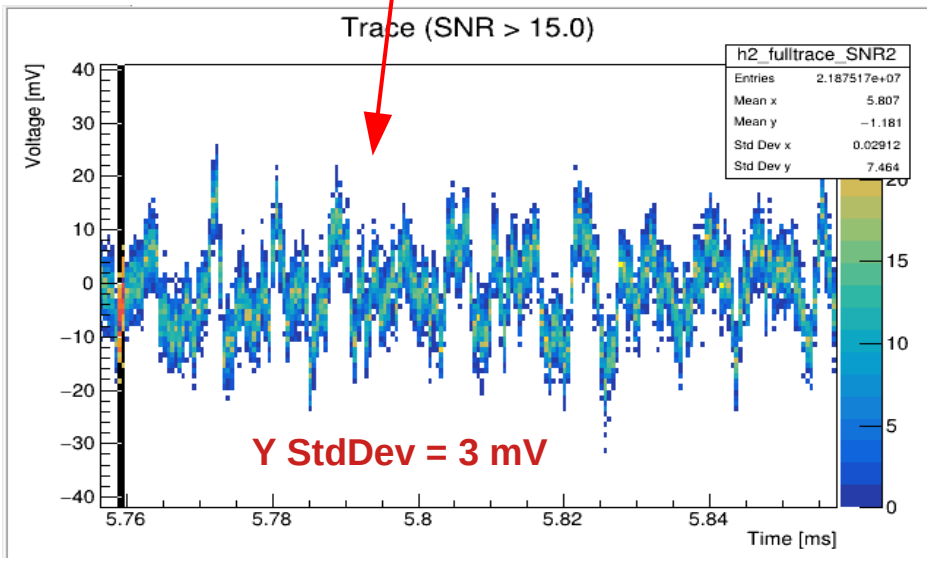
- R0 and R1 positioning determined with kicker mock-up at MC-1
- Bridge positioning has few millimeters of play
- R0 = 0 ± 2 mm
- R1 = +17.5 ± 2 mm





Oscillations



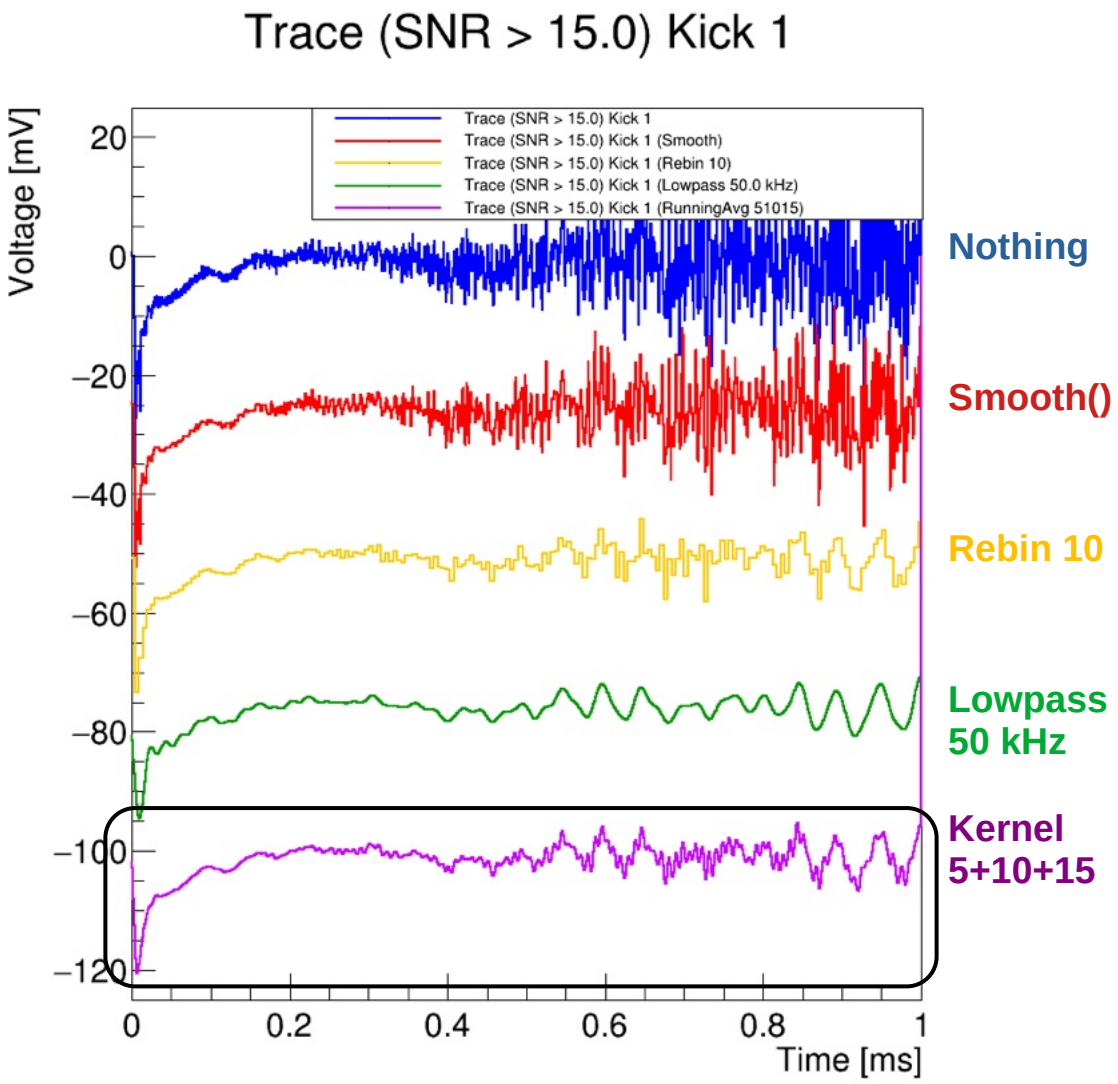


Oct27-29
1st kick
SNR > 15

- Observed vibrations not due to statistical noise
- Except for the first 1 ms of the first kick, all high-frequency oscillations are perfectly identical between consecutive kicks

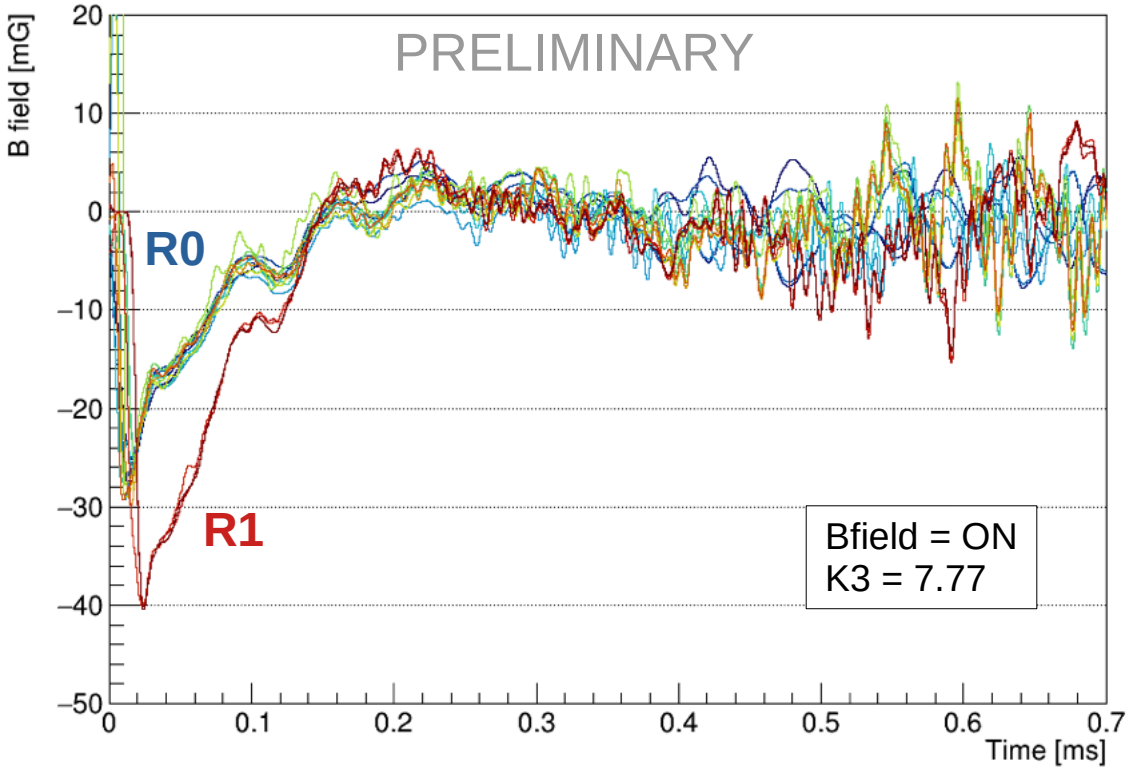
Smoothing

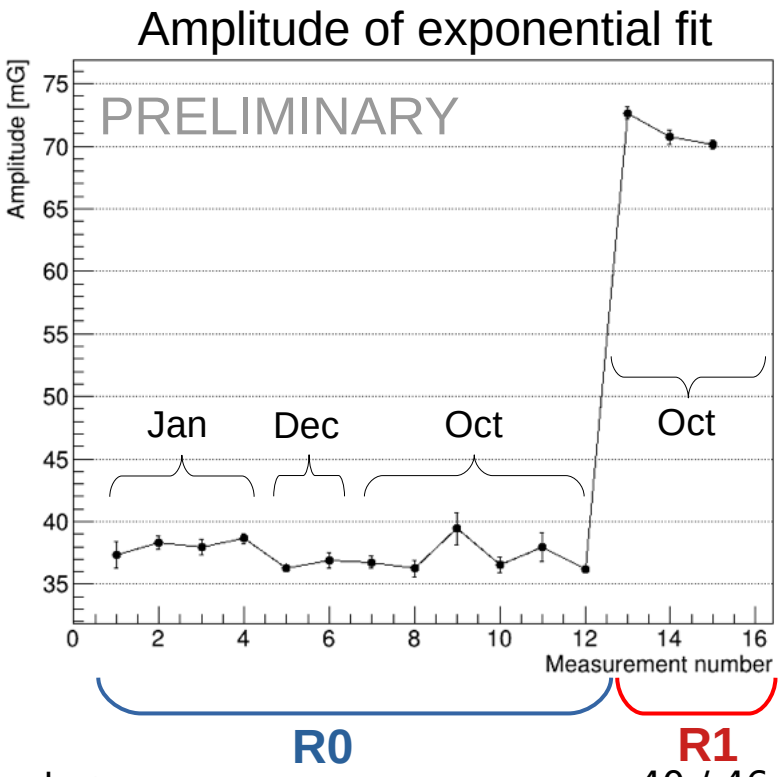
- Given the high-frequency oscillations, some smoothing operations have been studied
- Running Average with triangular kernel is a good compromise in removing high frequencies withouth altering eddy currents shape



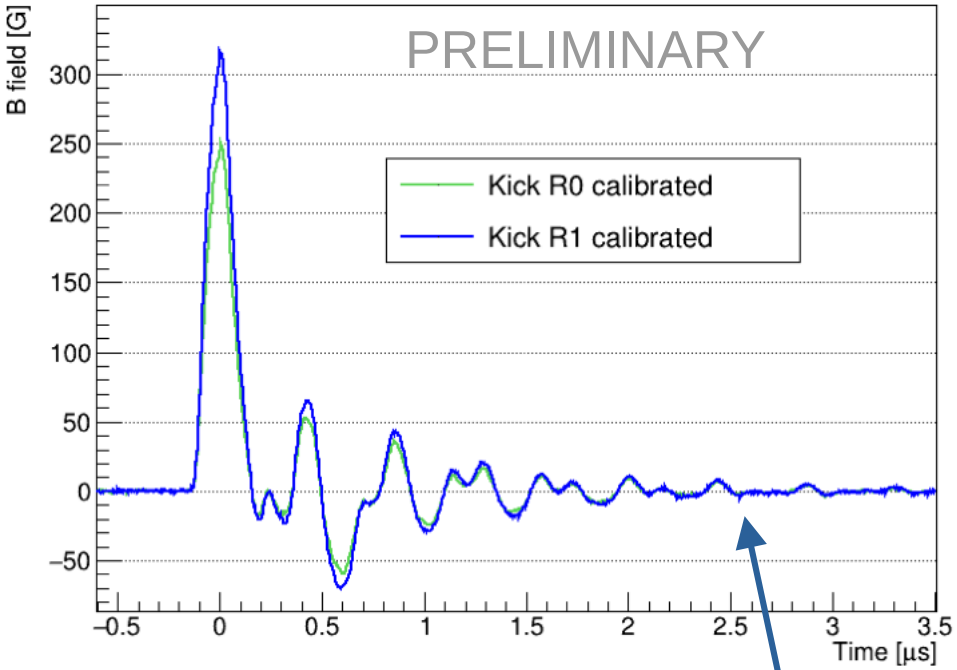
R0 vs R1 (Eddy)

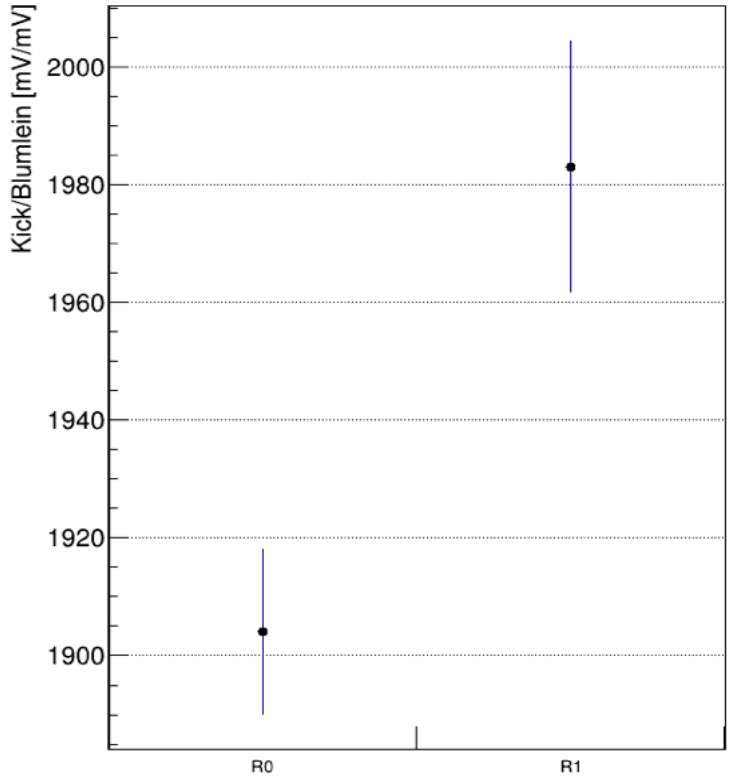
- Blumlein used for relative calibration.
- R0 measurements spanning Oct, Dec, and Jan campaigns
- Relative calibration gives excellent consistency
- R1 transient is +90% wrt R0

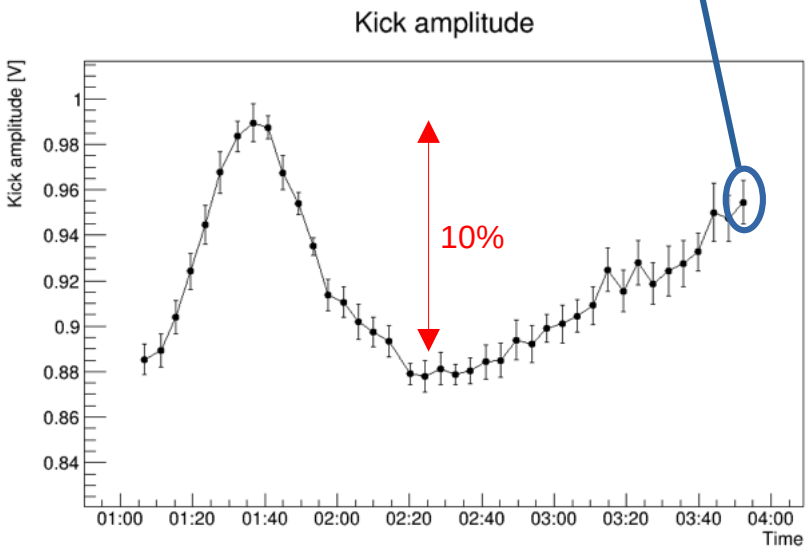




R0 vs R1

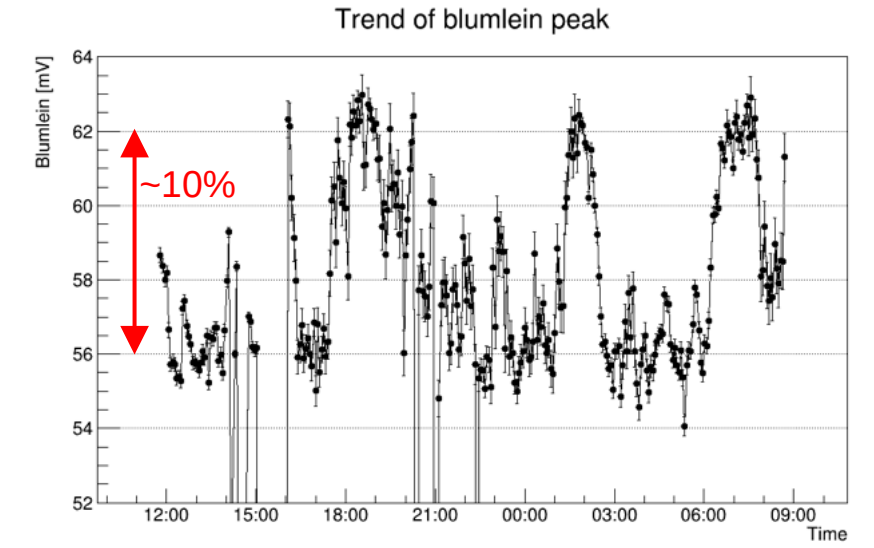


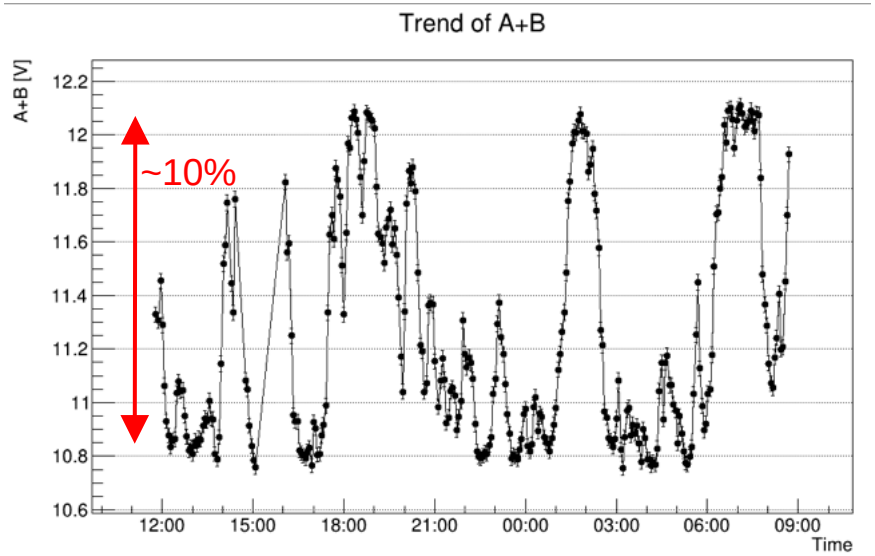


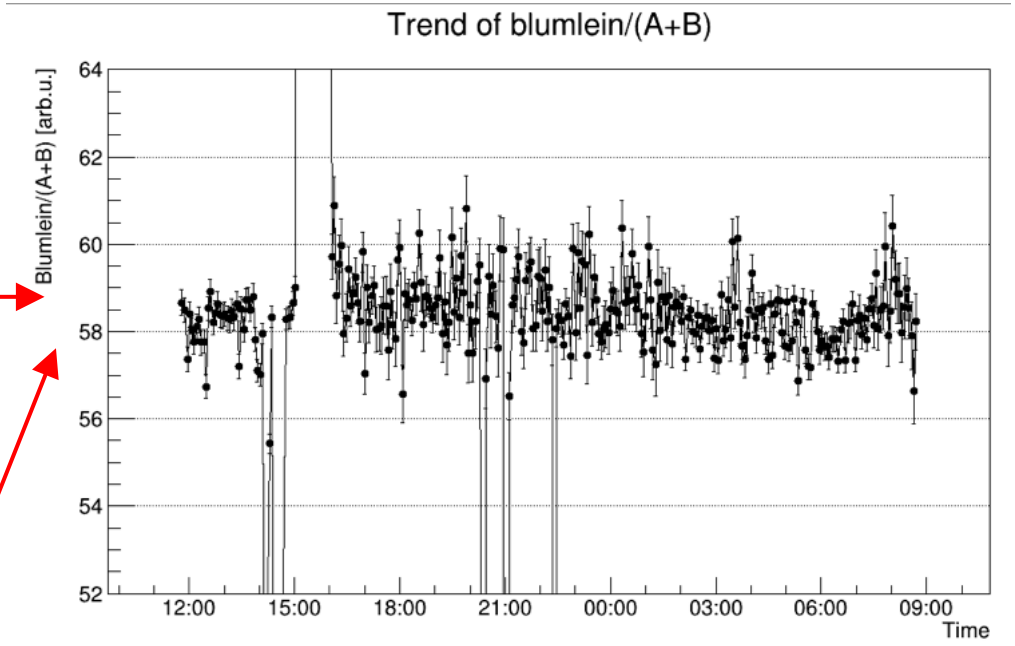


- Absolute calibration from with blumlein
- R0: 243 G (±10%)
- R1: 308 G (±15%)
- R1/R0 ~1.27
- Note: need to correct for $\cos^2$ nonlinearity

Light output



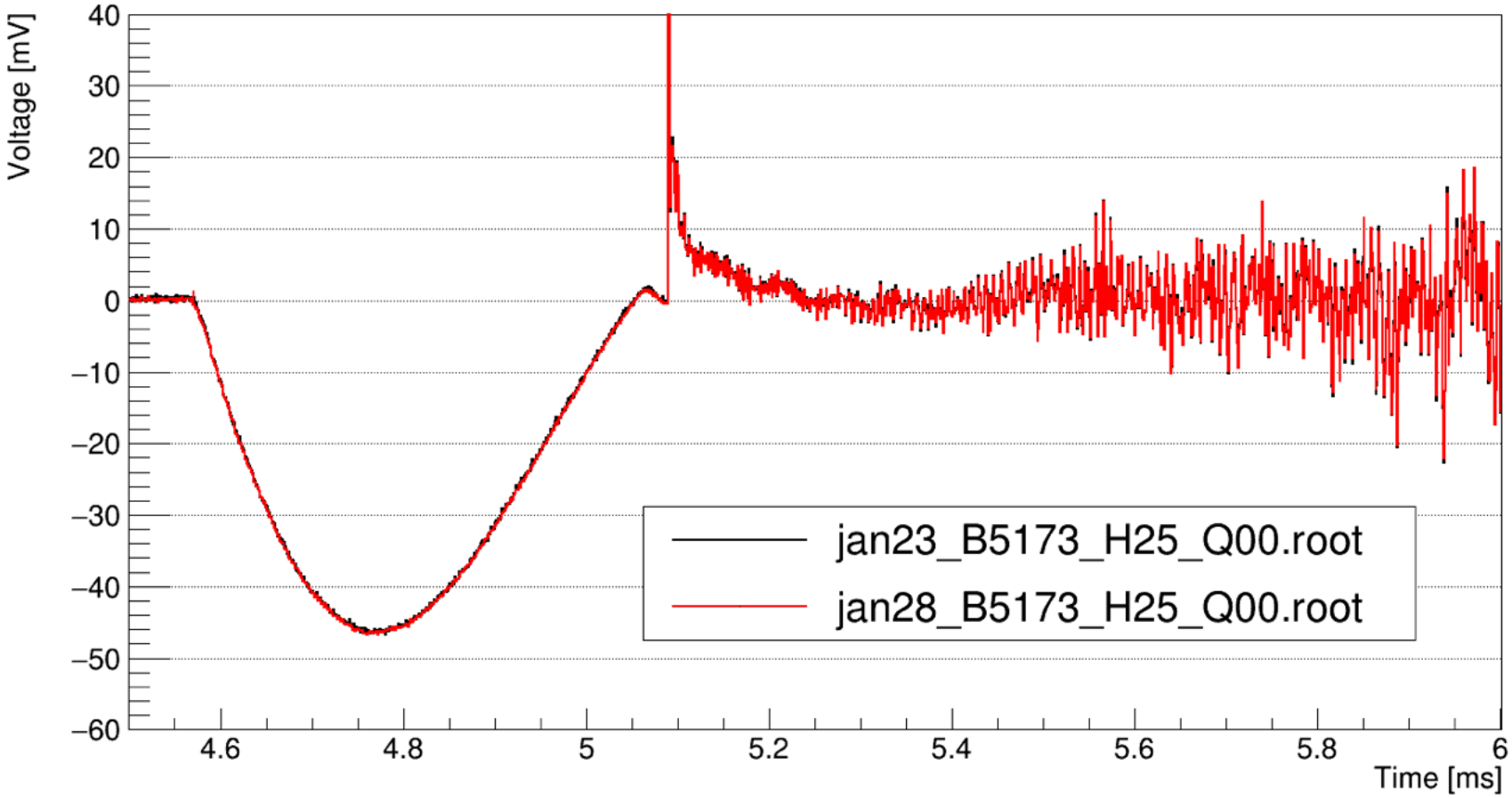




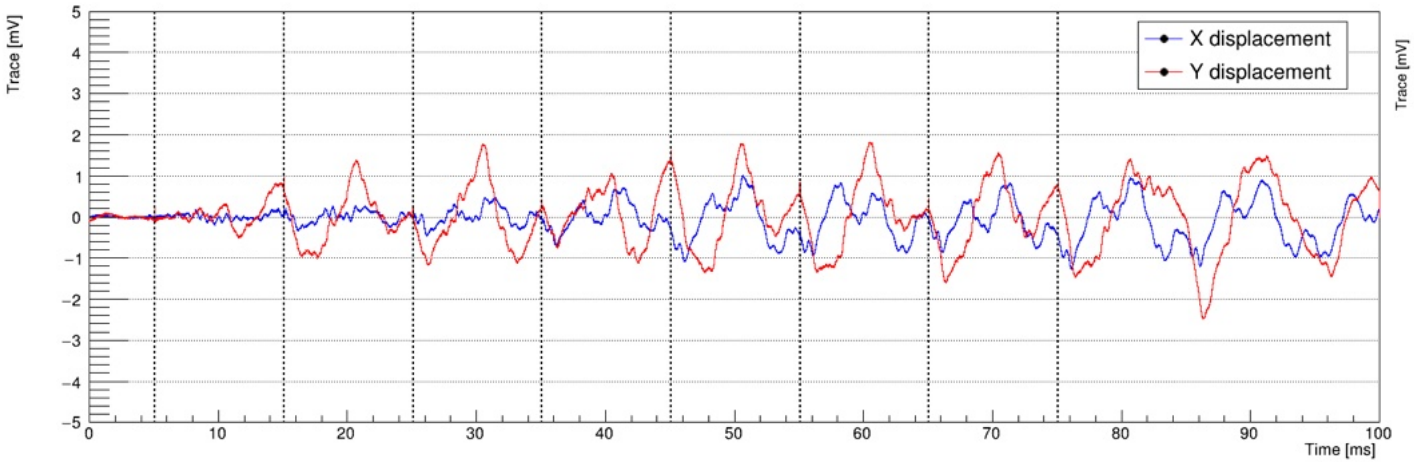
- Blumlein amplitude strongly correlates with sum of diodes (A+B)
- Much more stable after normalization
- A+B used to normalize between ramp and eddy currents too

January stability

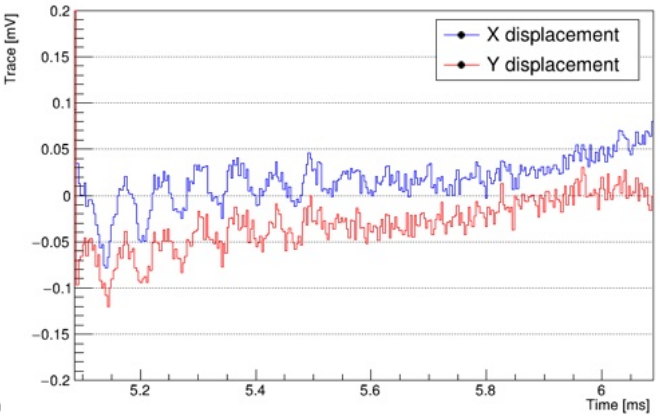
- QWP 0° acquired two times, 5 days apart
- Traces are remarkably similar

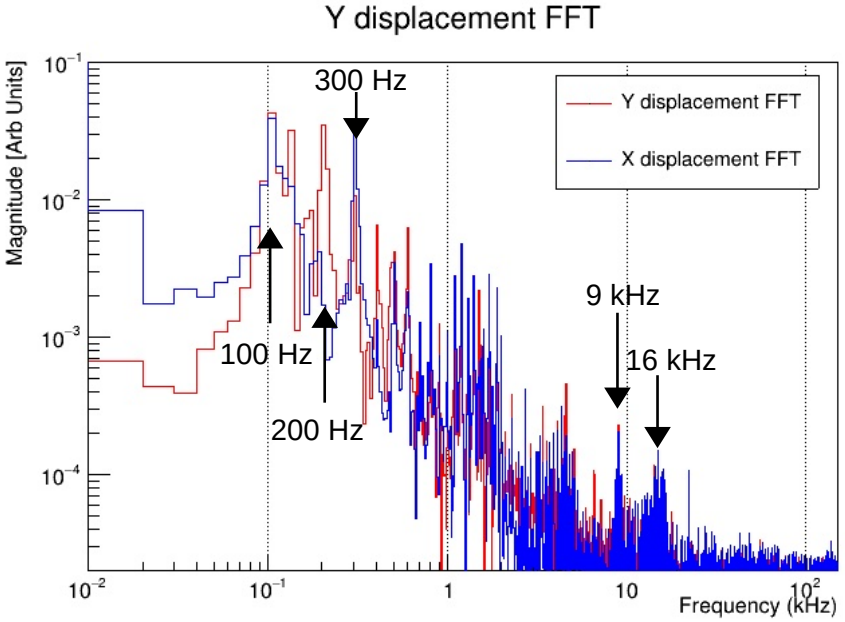


Vibration analysis

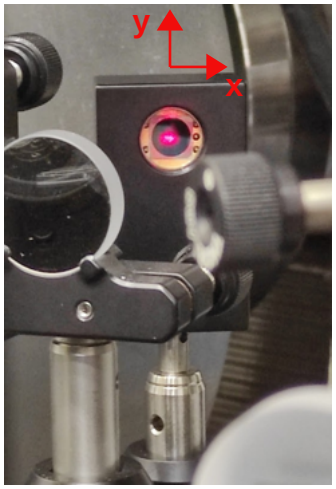


1st kick zoomed





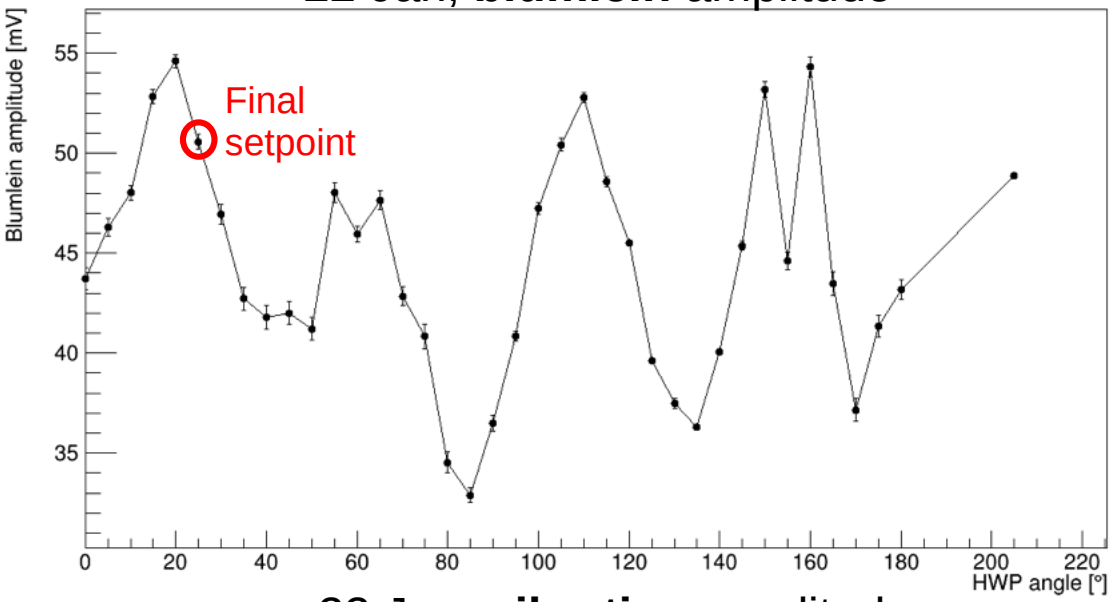
- Quadrant photodiode measures x,y oscillations of the laser beam after exiting the periscopes
- Low frequencies (100, 200, 300 Hz) evident and correlated with kicks
- 17 kHz visible too in the first 1 ms after the first kick



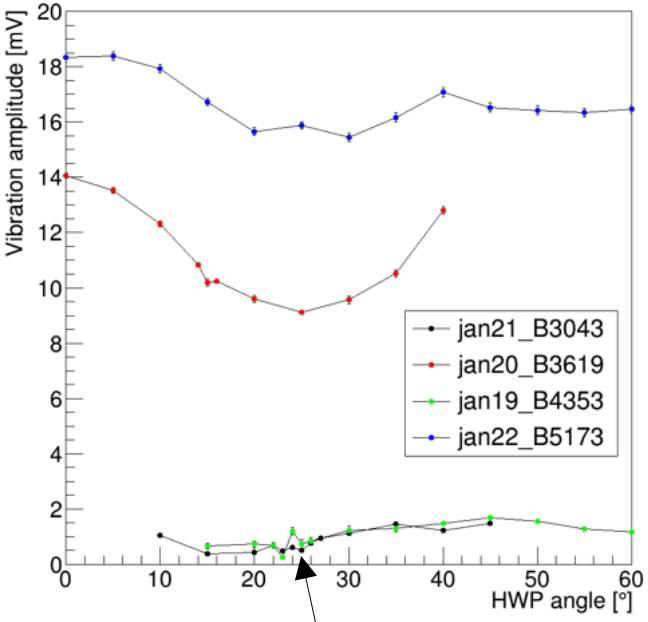
HWP scans

- Blumlein always [35-55] mV
- Vibration never suppressed

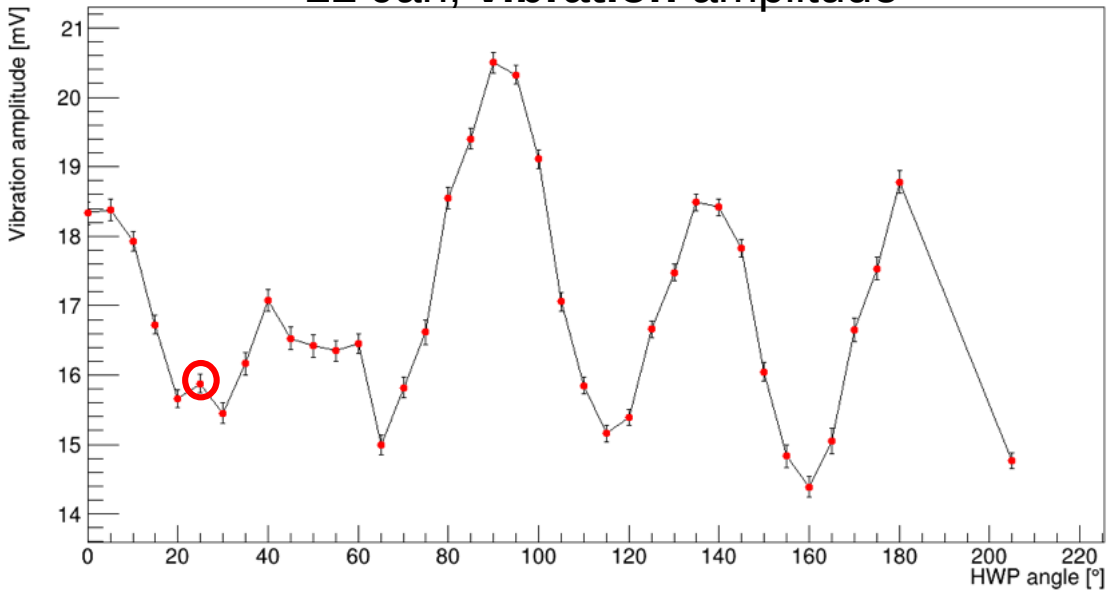
22 Jan, **blumlein** amplitude



- Vibration suppressed only for 2.5π and 3.5π Faraday angles

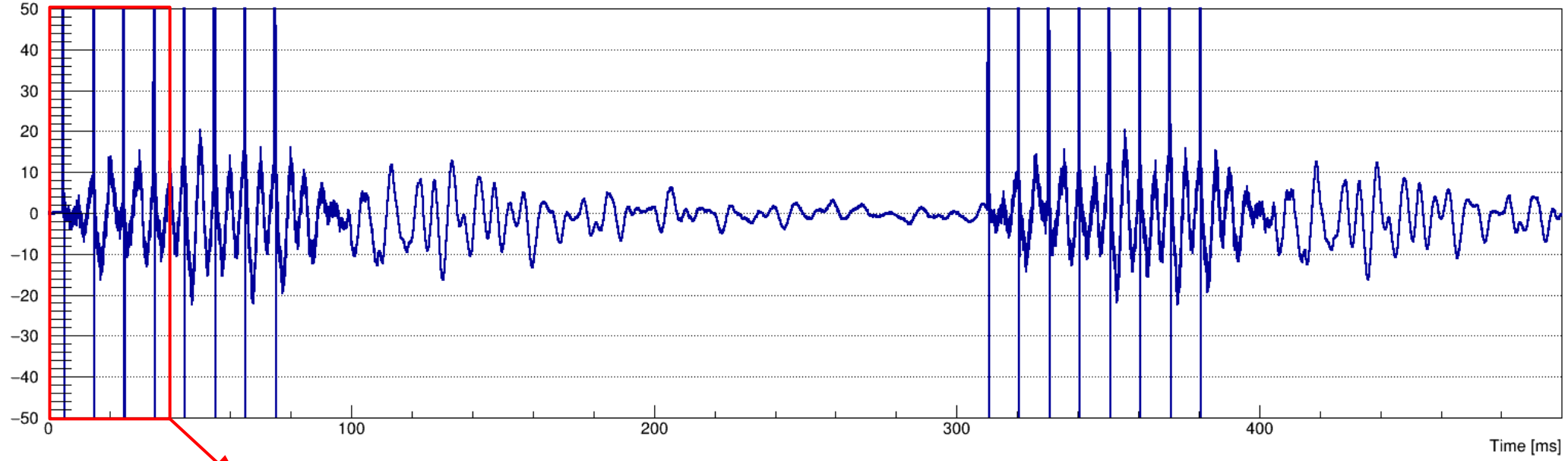


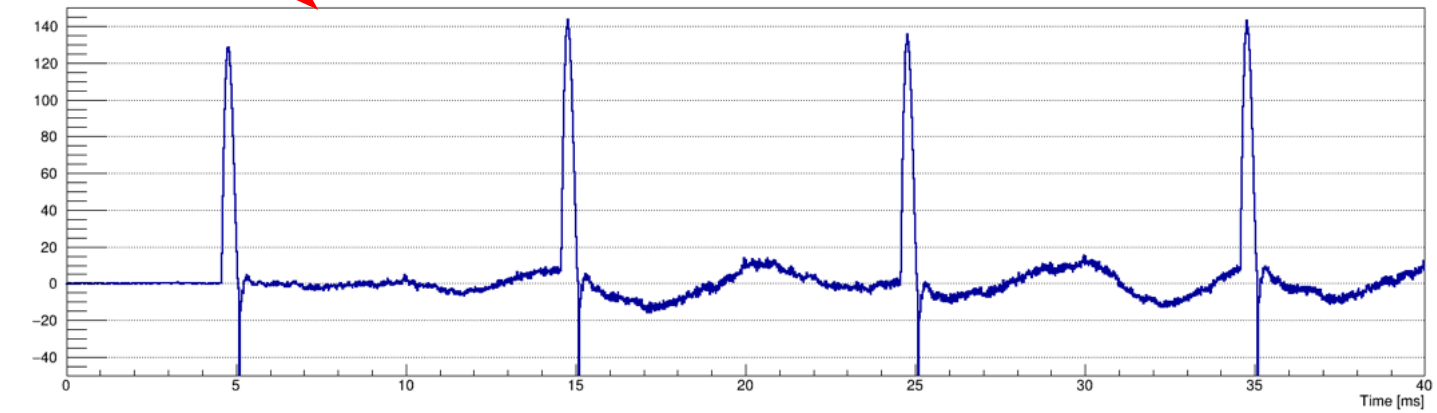
22 Jan, **vibration** amplitude



Full trace

- Combination successfully reduces ~20 kHz vibrations
- Slow drifts (> 10 ms) remain





- Baseline-removal techniques could be tested to analyze kicks 2-8 (and 9-16)