Combined-function magnetic measurement system

Reed Teyber, Erik Wallen, Diego Arbelaez, Soren Prestemon

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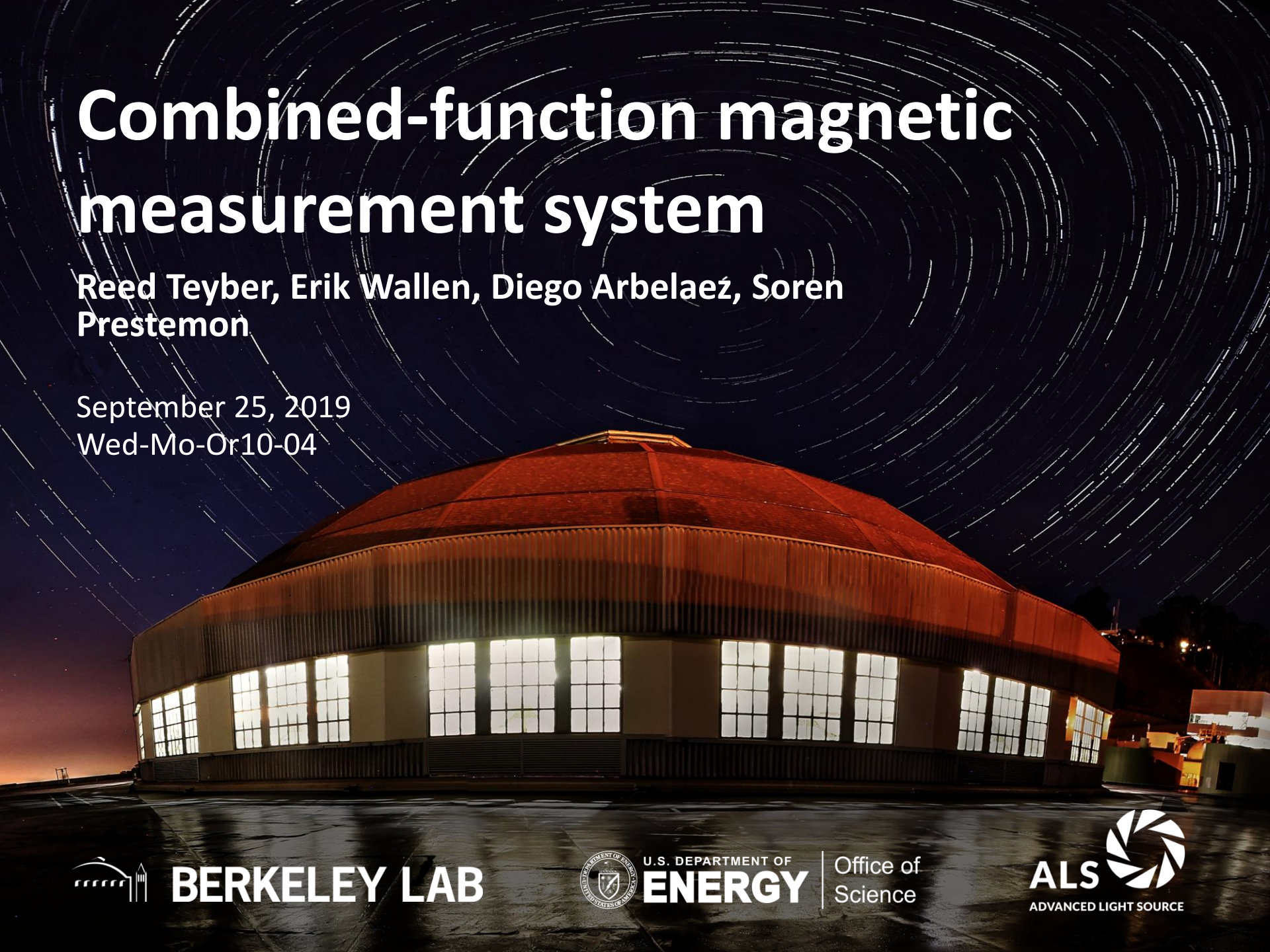


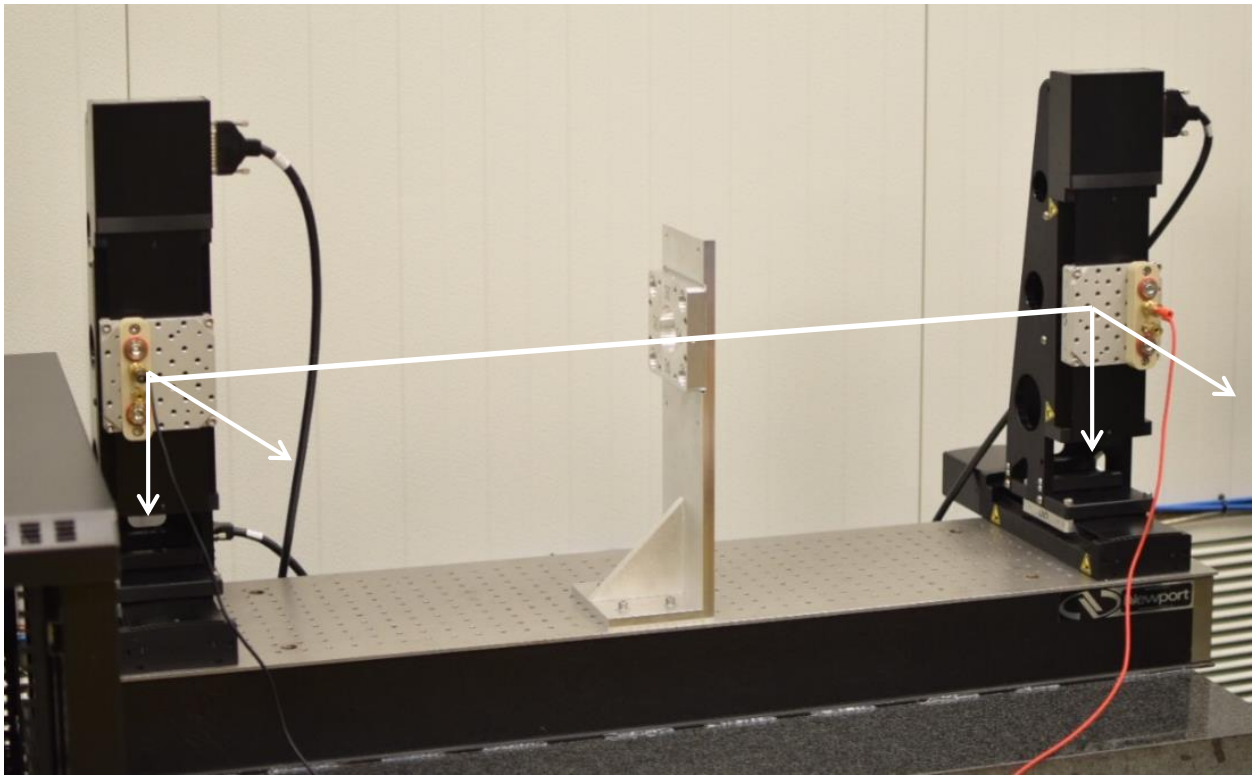
Introduction

- Advanced Light Source Upgrade
  - Measure field harmonics and magnetic axis
  - Many magnets to characterize
  - Automated routines when possible

- Single wire: combined function magnetic measurement system
  - Emulate a rotating coil with a single wire
  - Integrated pulsed wire (or vibrating wire) capabilities

Wire measurement system

- Stretched rotating wire
  - Move wire in circular trajectory to measure field harmonics



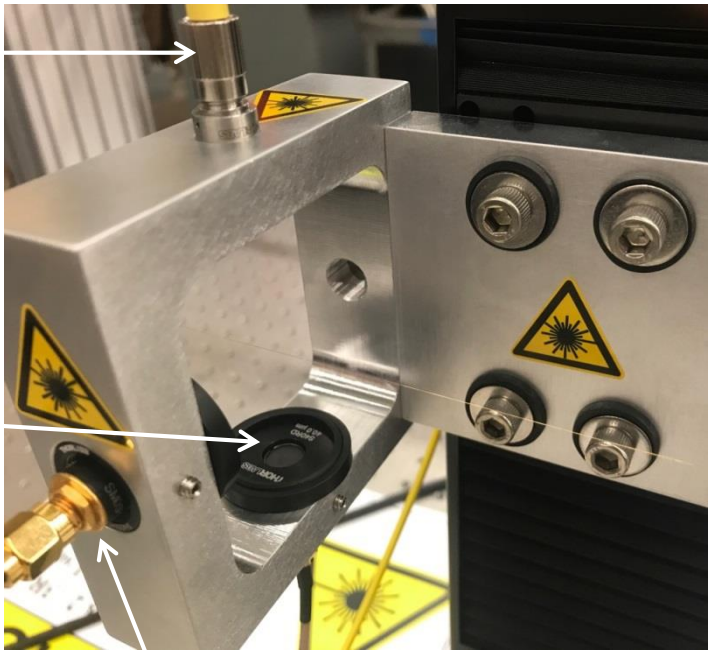
Wire measurement system

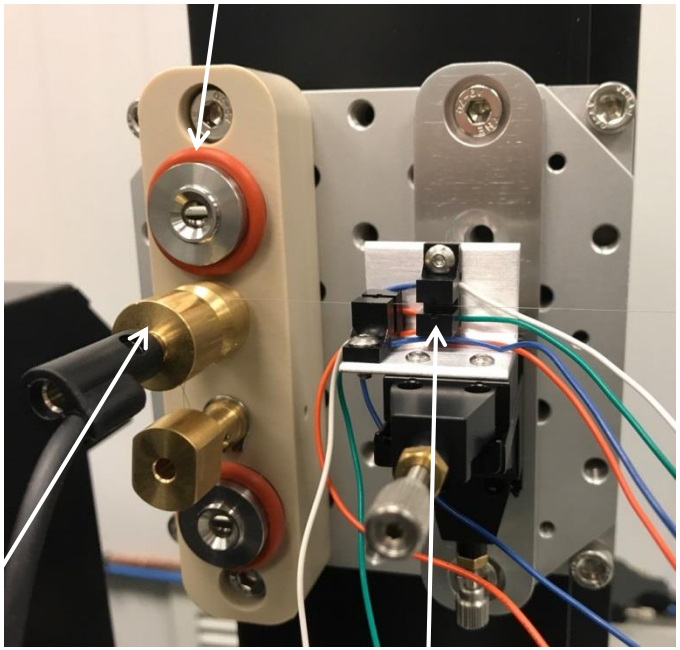
- Pulsed (and vibrating) wire
  - Send current through wire, measure wire displacement

Retroreflector nests

Laser

40 μm Slit





Photodiode

Wire locator

Phototransistor

Magnetic axis

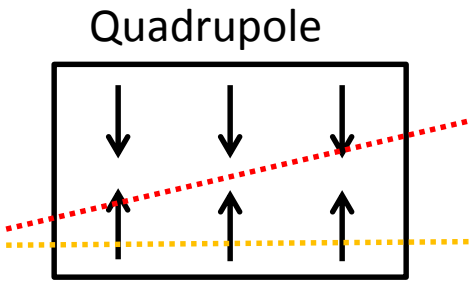
- Pulsed wire
  - Wire displacement, $u(t)$, is proportional to field integral

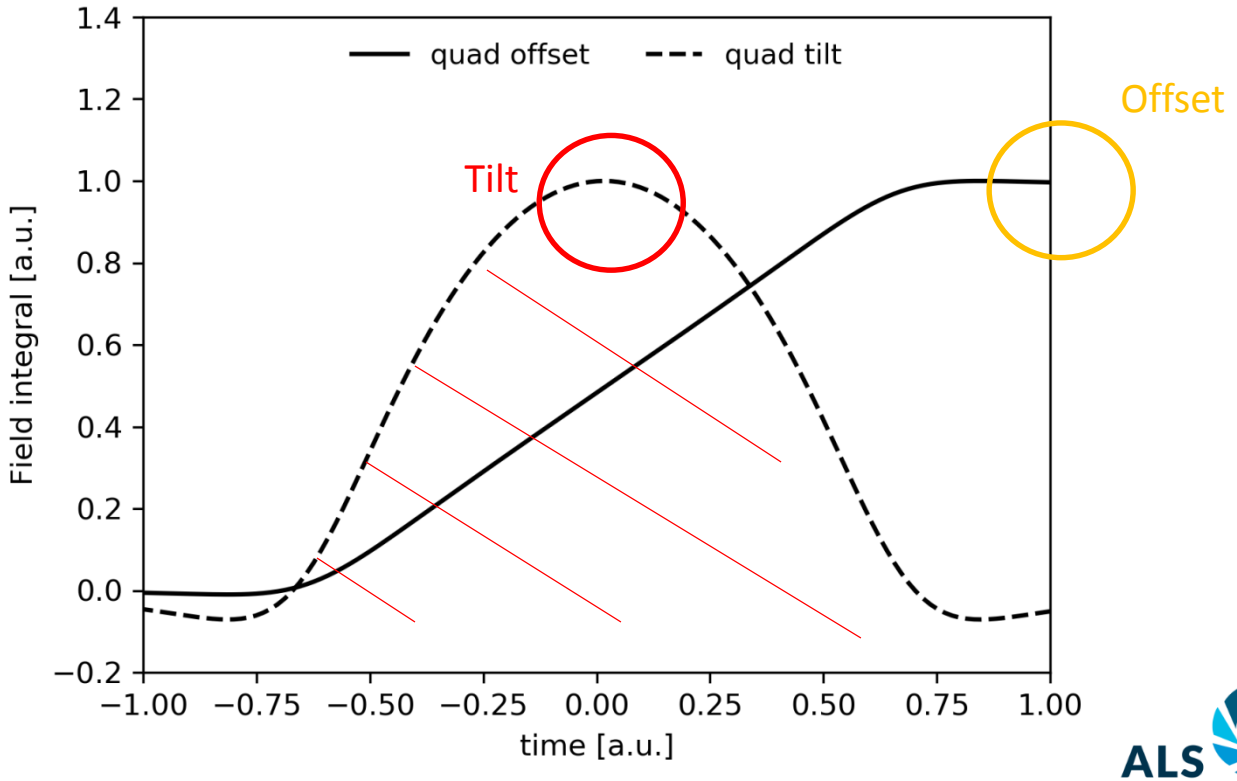
$$\int_0^{c_0 t} B(z)dz = LB(z) = \frac{2T}{Ic_0\delta t}u(t)$$

  - How to accurately *and efficiently* find the magnetic axis?

Magnetic axis

- Pulsed wire simulated response
  - Decouple signal into end value, area under curve
    - Tilt error independent from offset error!





Magnetic axis

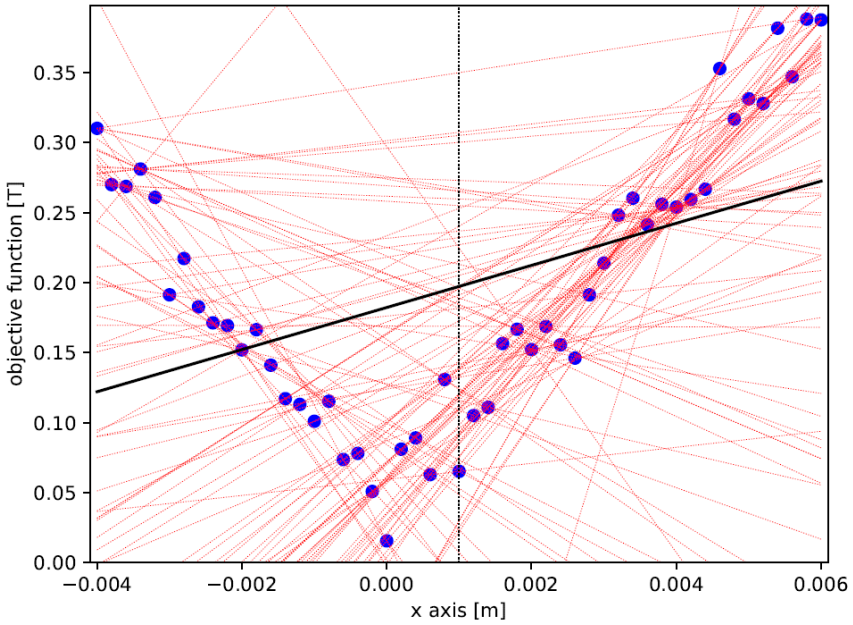
- Decoupled tilt and offset errors
  - Finding magnetic axis -> Four operations of a single variable
    - Minimize end value, then area under curve
    - Repeat in both planes

- Newton-Rhapson iteration
  - Very efficient, few objective function evaluations

$$x_{\text{new}} = -\frac{f(x)}{f'(x)}$$

Magnetic axis

- Hardware-in-loop optimization
  - Derivative challenging with measurement noise
    - Upwinding



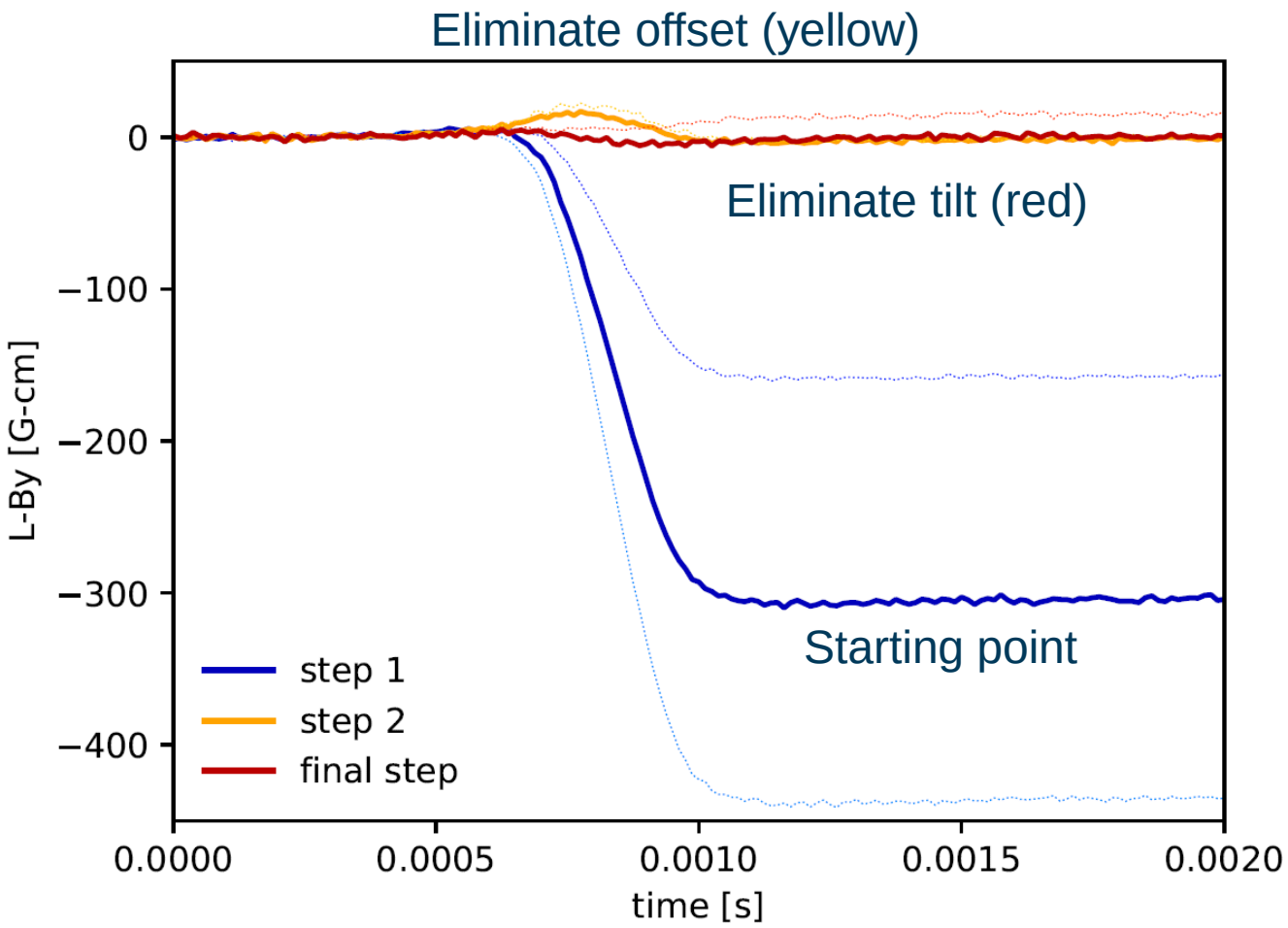
$$f'(x)^{+} = \frac{f(x+\Delta x) - f(x)}{\Delta x}$$

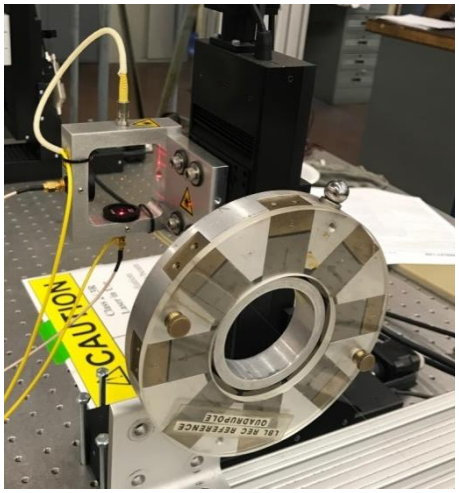
$$f'(x)^{-} = \frac{f(x) - f(x-\Delta x)}{\Delta x}$$

$$f'(x) = max(|f'(x)^{+}|, |f'(x)^{-}|)$$

(Simulated values)

Results





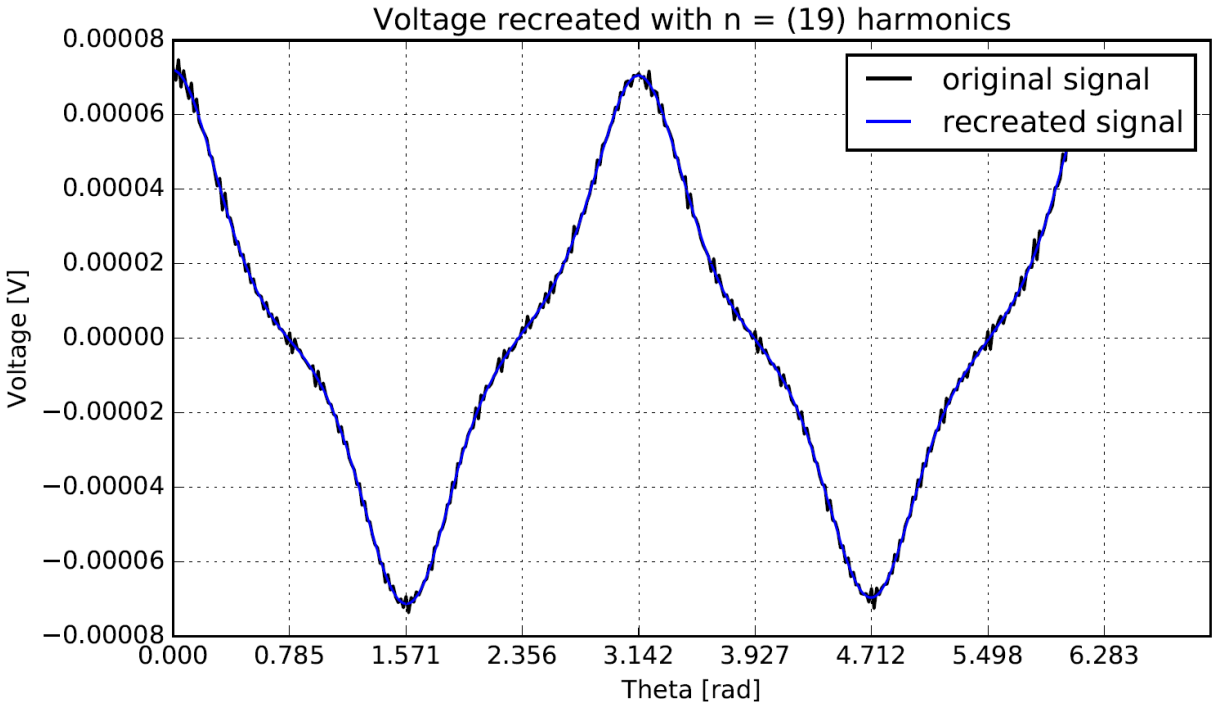
(Measured values)

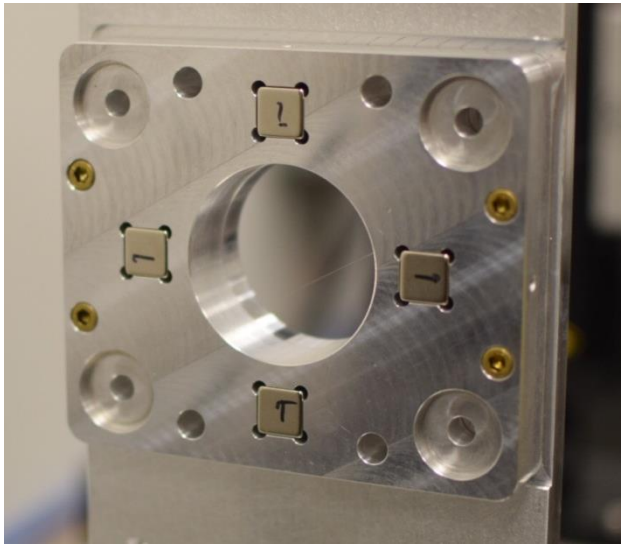
Combined functionality

- Stretched wire on circular trajectory
  - Measure coefficients a_n, b_n
  - Find x, y offset errors in single step
- Pulsed wire
  - Minimize tilt in horizontal and vertical planes
- Repeat until converged

Field harmonics

- Fourier transformation of measured voltage
  - Process into Fourier field coefficients

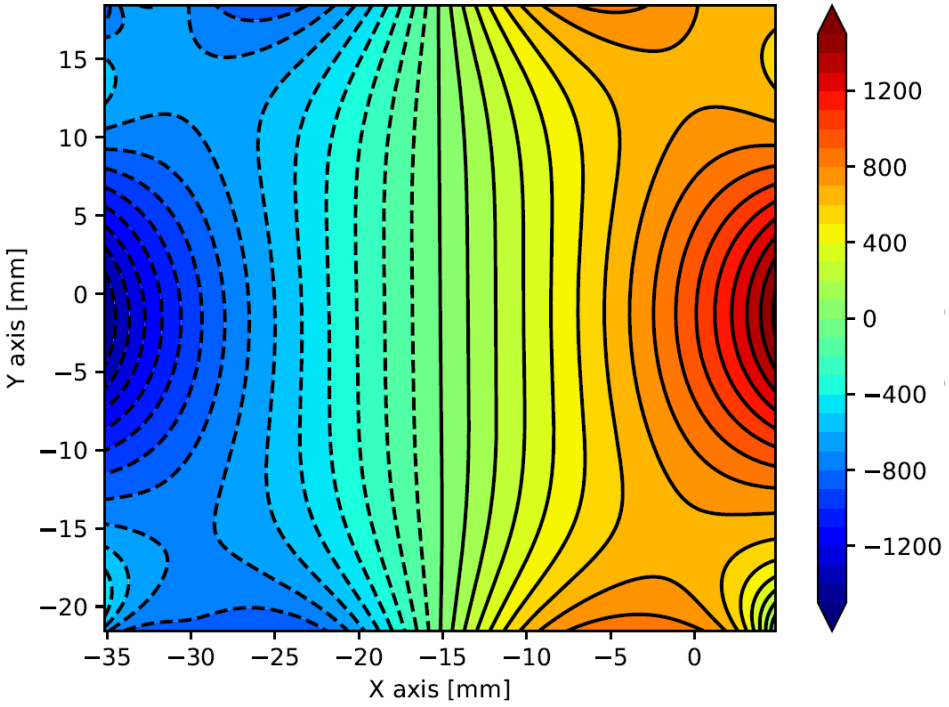




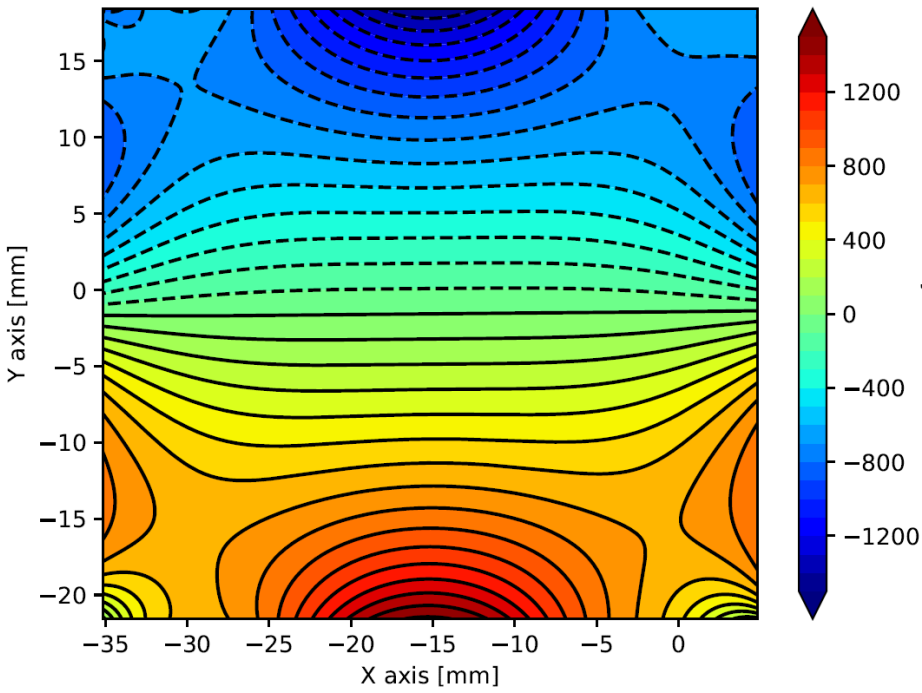
$$LB_y + iLB_x = \sum_{n=1}^{\infty} \left(b_n + ia_n\right)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$

Field harmonics

X fields



Y fields



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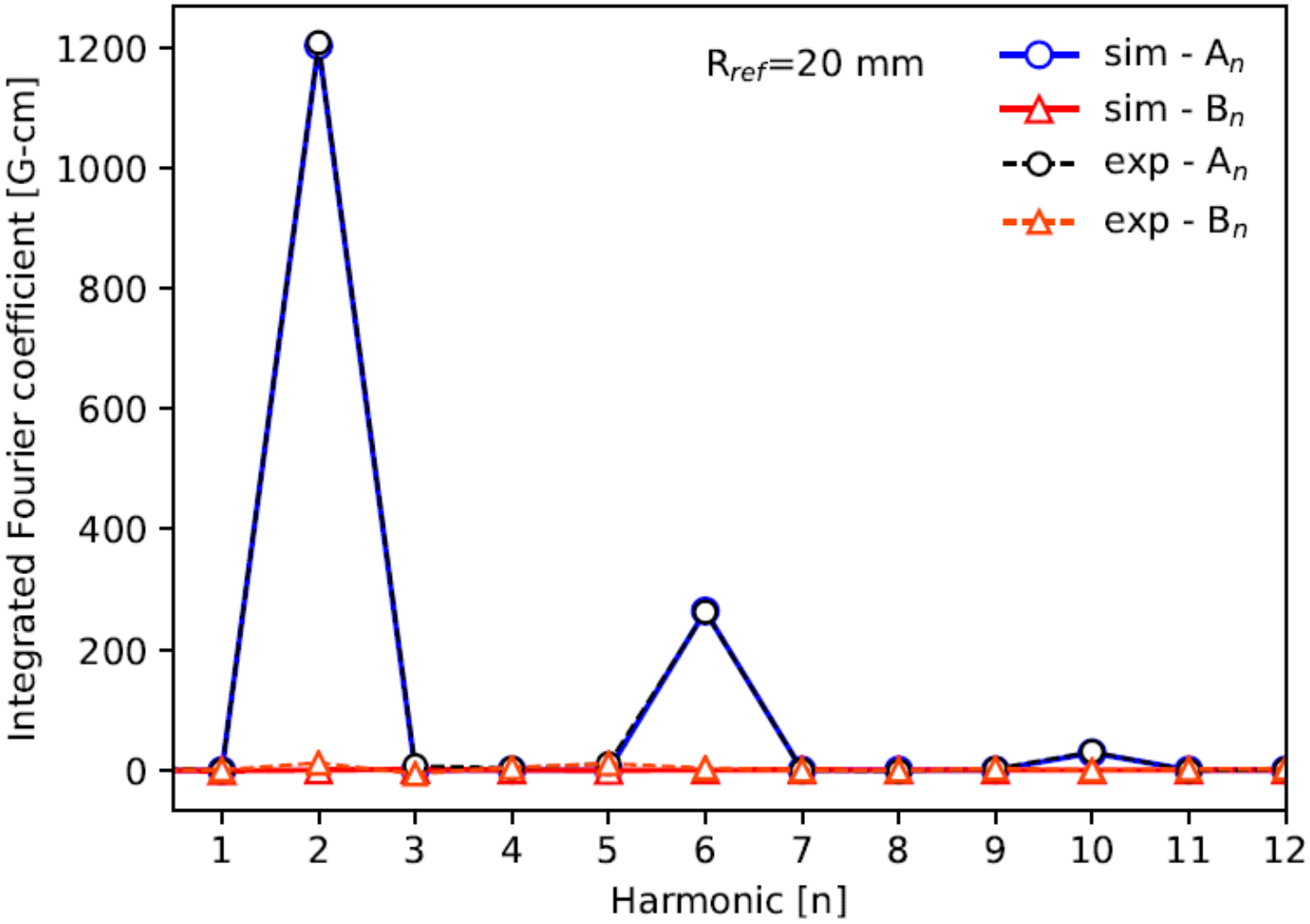
Conclusion

- Axis finding routine
  - Routine converges to axis with four, single-variate steps
  - Upwinding scheme stabilizes efficient update algorithm
  - Stretched rotating wire integration for rapid offset minimization
- Explore vibrating wire instead of pulsed wire
- Extend methodology to sextupole fiducialization

Questions?

Appendices

Appendix: validation



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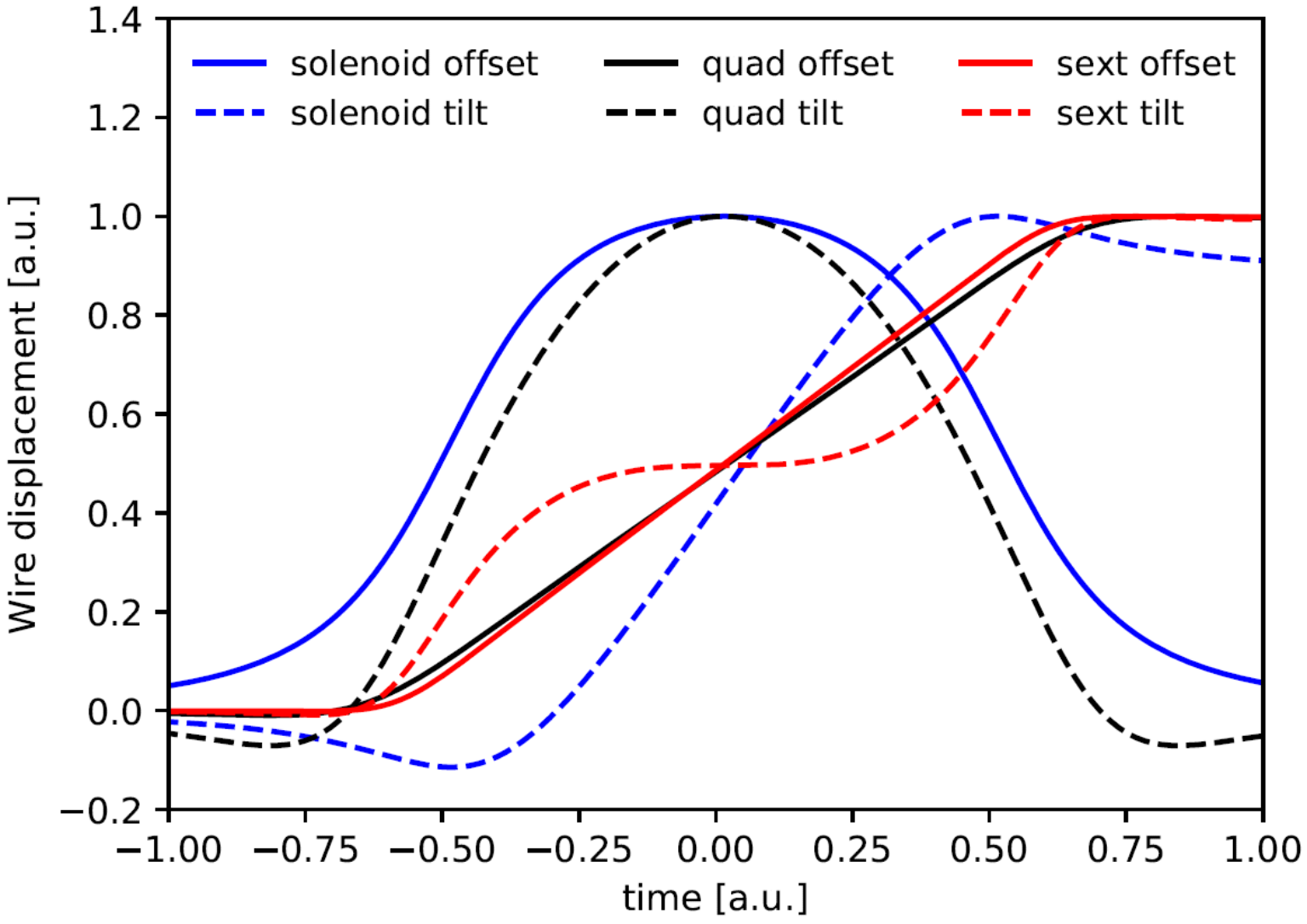
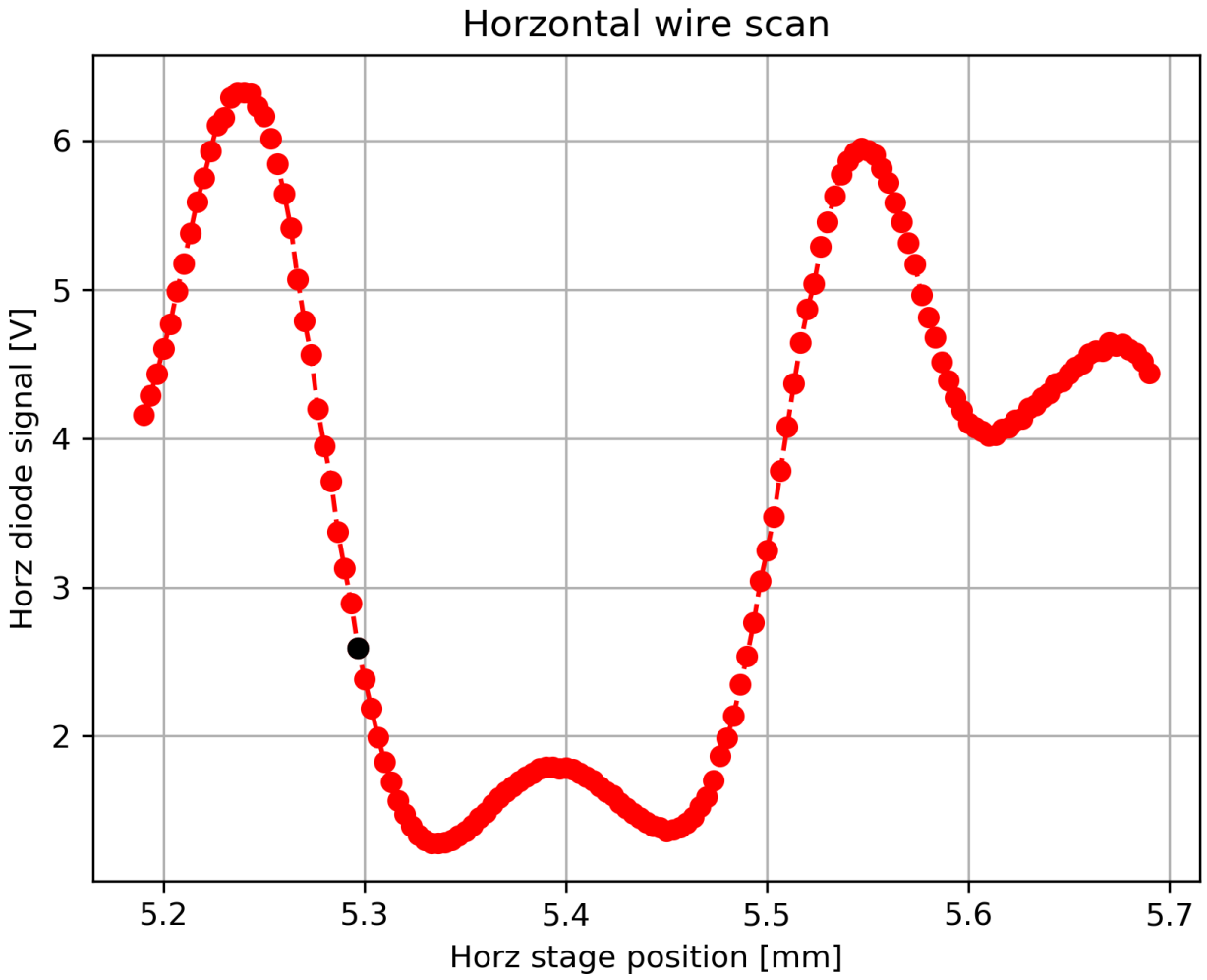
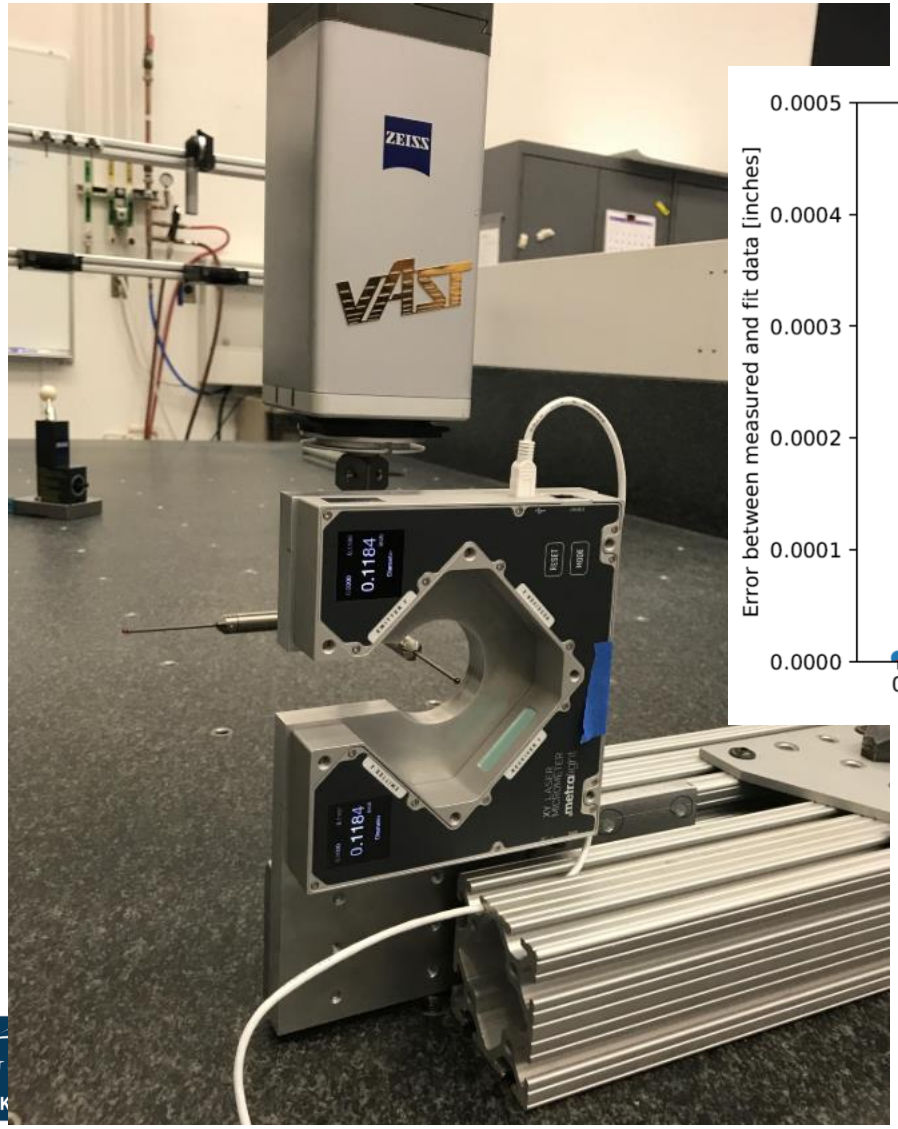
Appendix: magnet errors

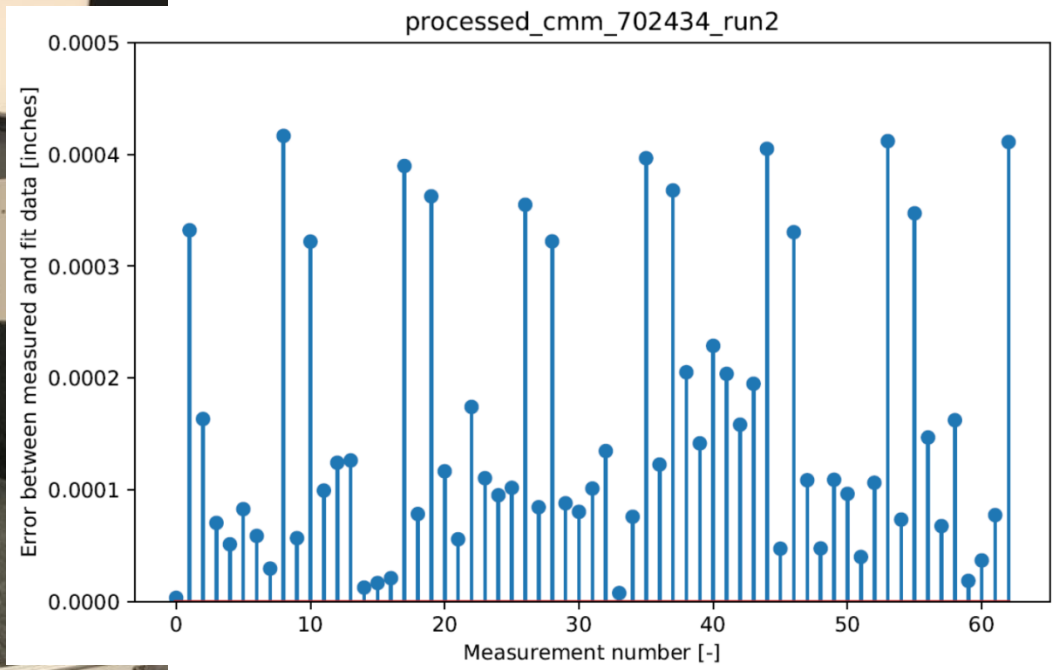


Appendix: laser scan

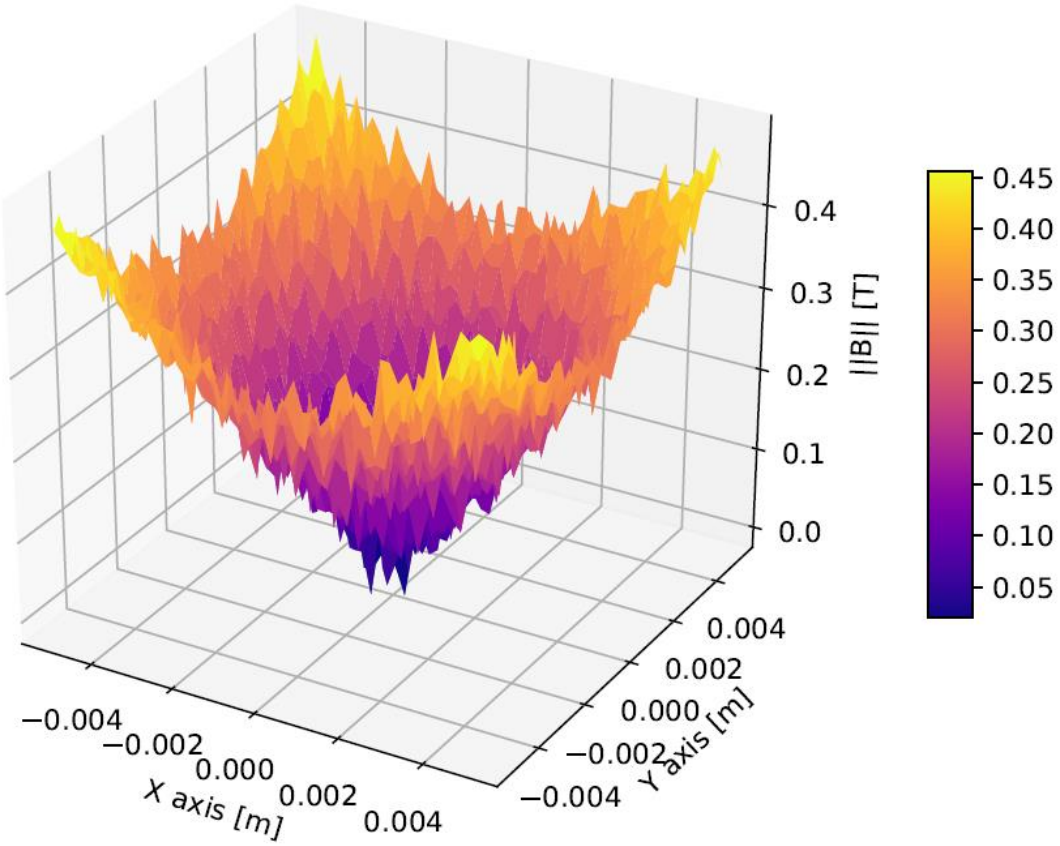


Appendix: laser micrometers





Appendix: noisy optimization



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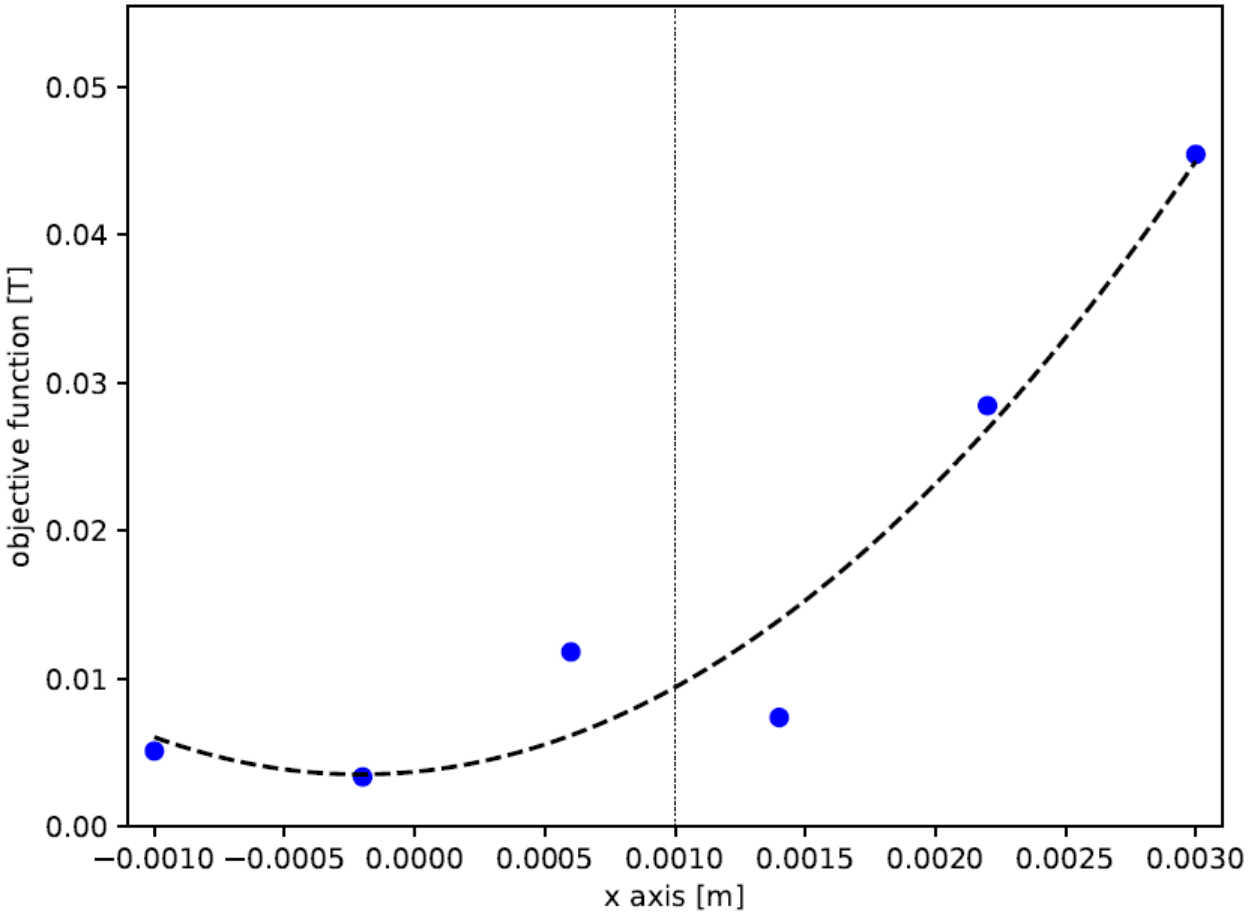

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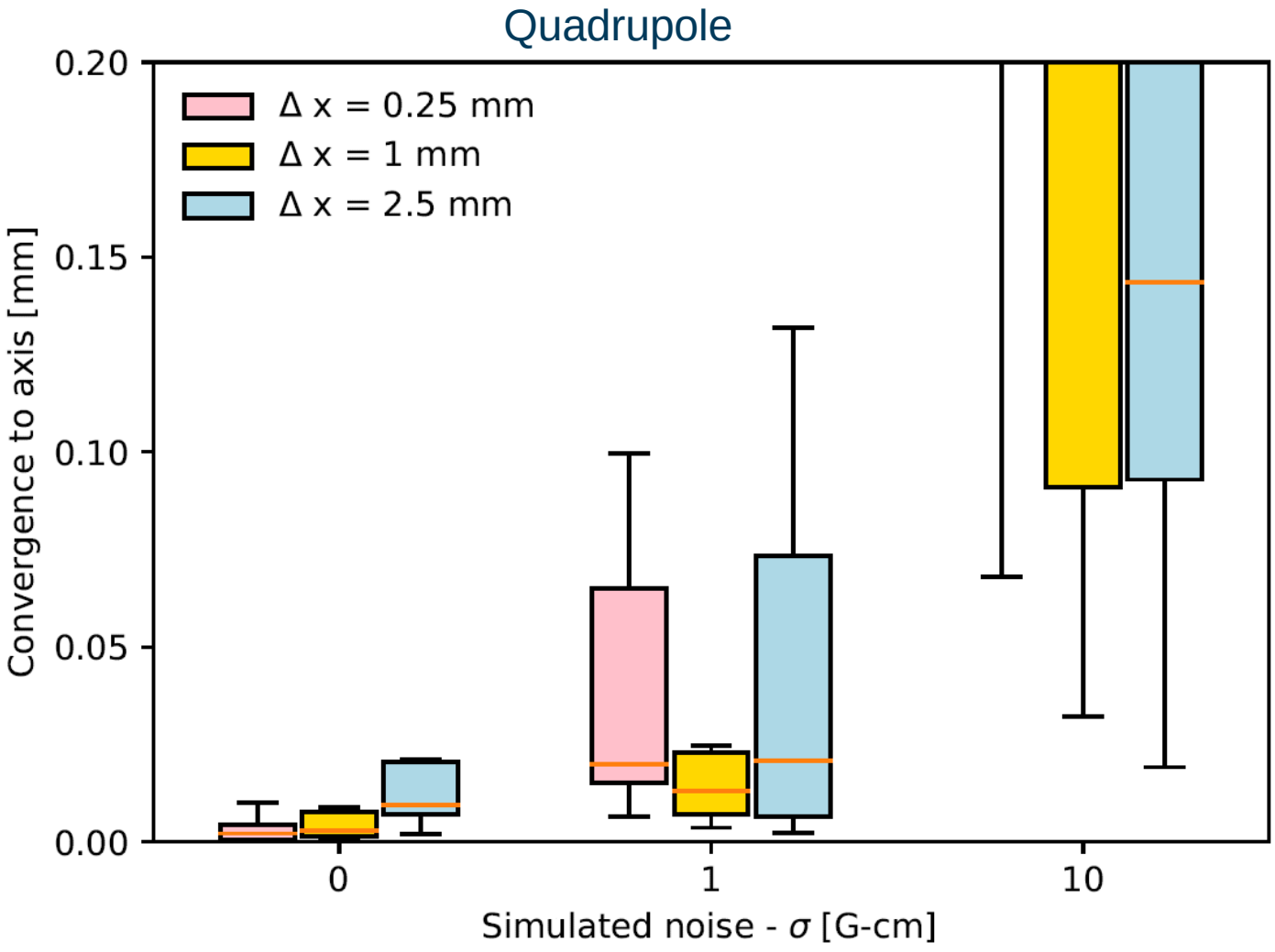


Appendix: stretched rotating wire

- Fourier transformation of measured voltage waveform

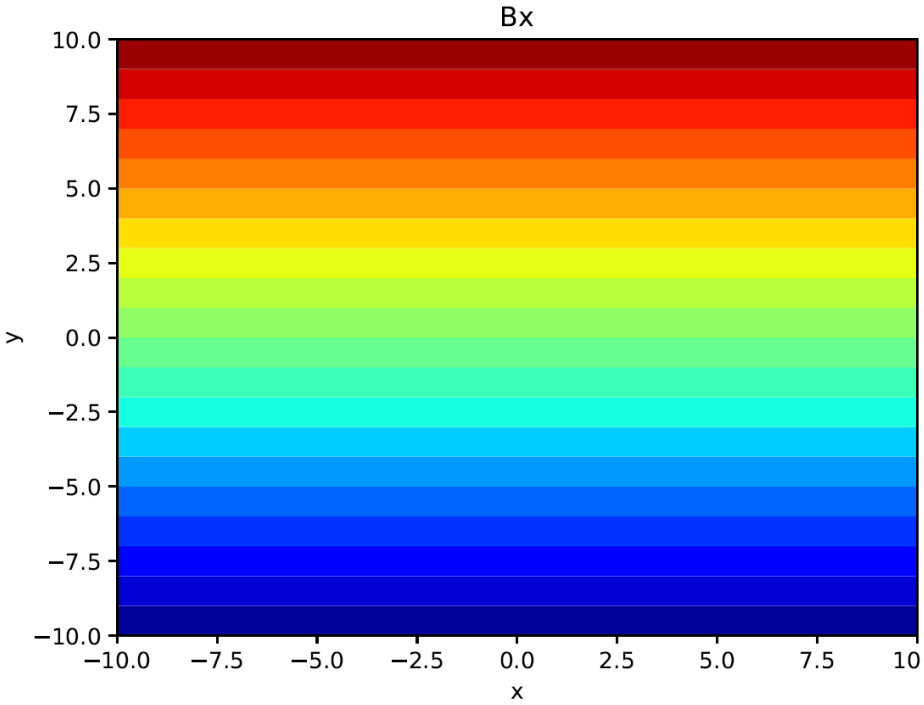
$$V(\theta) = p_0 + \sum_{n=1}^{\infty} \left(p_n \cos(n\theta) + q_n \sin(n\theta) \right)$$

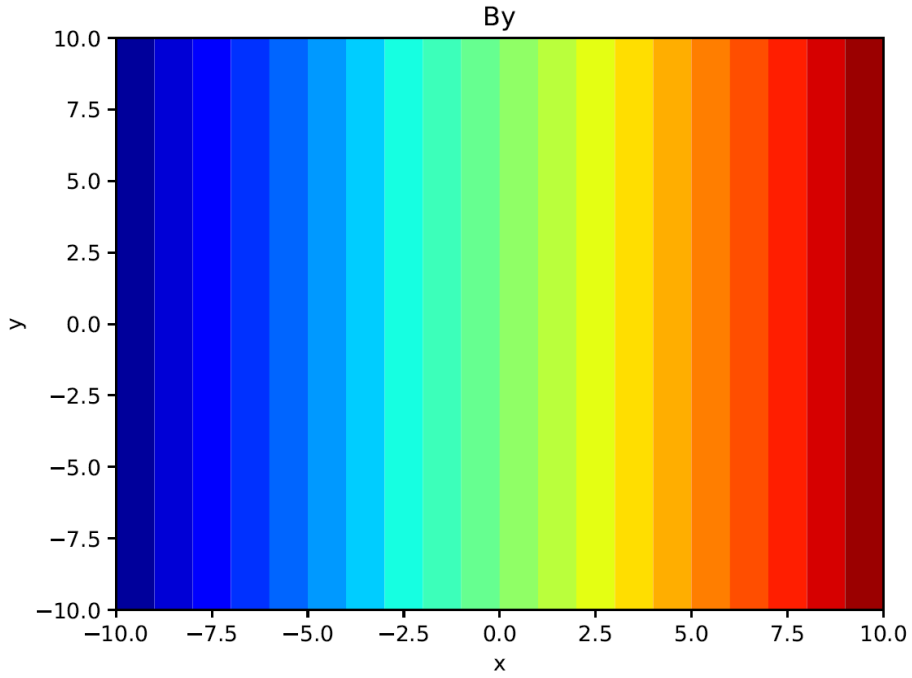
- Relate measured voltages to Field harmonics

$$a_n = \frac{p_n}{LR_{ref}\left(\frac{R_o}{R_{ref}}\right)^n \frac{d\theta}{dt}}$$

$$b_n = \frac{q_n}{LR_{ref}\left(\frac{R_o}{R_{ref}}\right)^n \frac{d\theta}{dt}}$$

Appendix: quadrupole





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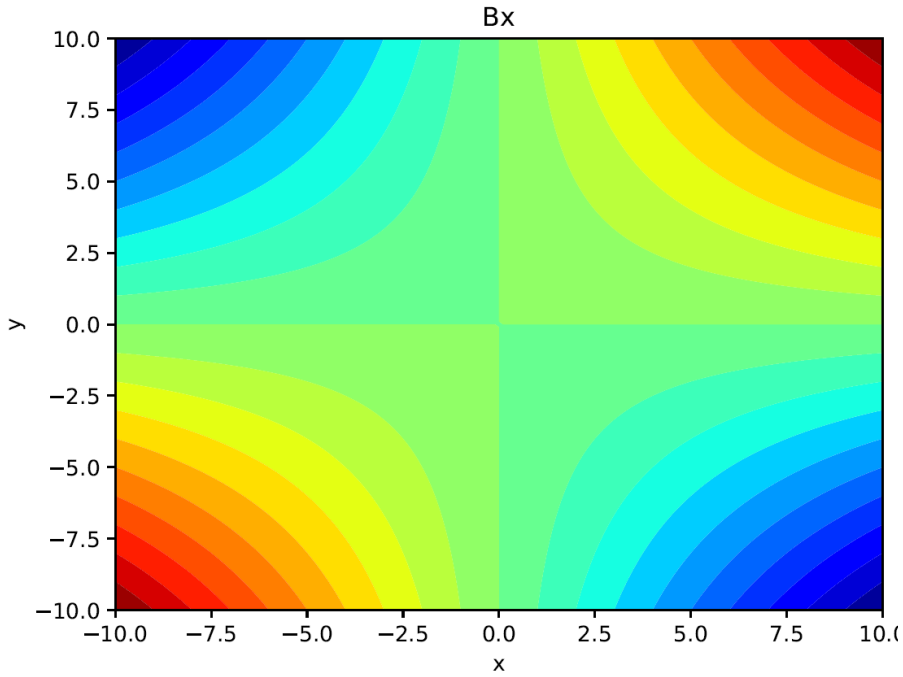
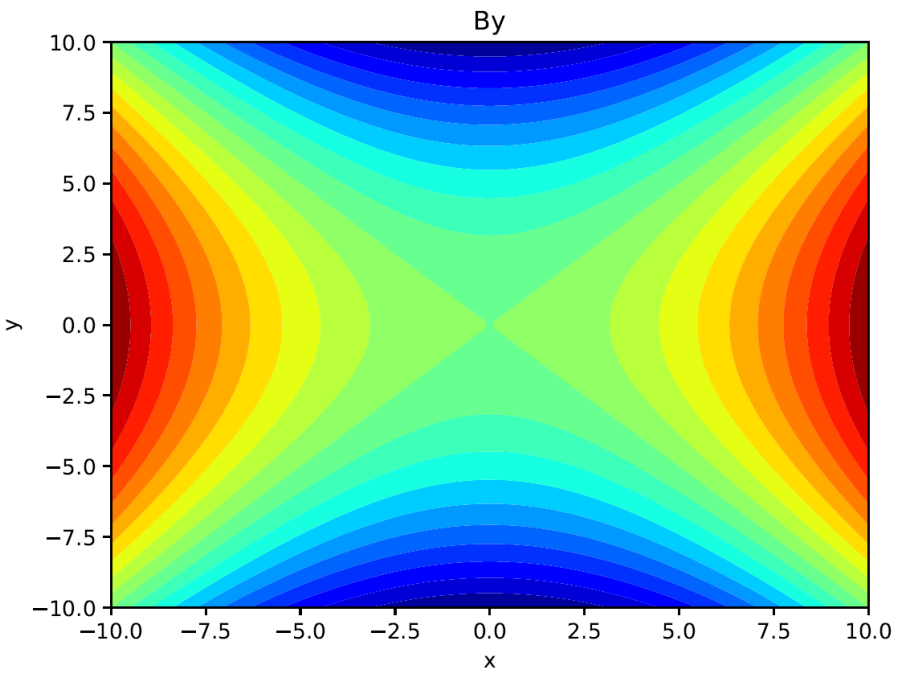
Appendix: sextupole





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