Preliminary Measurements of the Motion of Arcjet Current Channel Using Inductive Magnetic Probes

Magnus A. Haw

AMA Inc., NASA Ames

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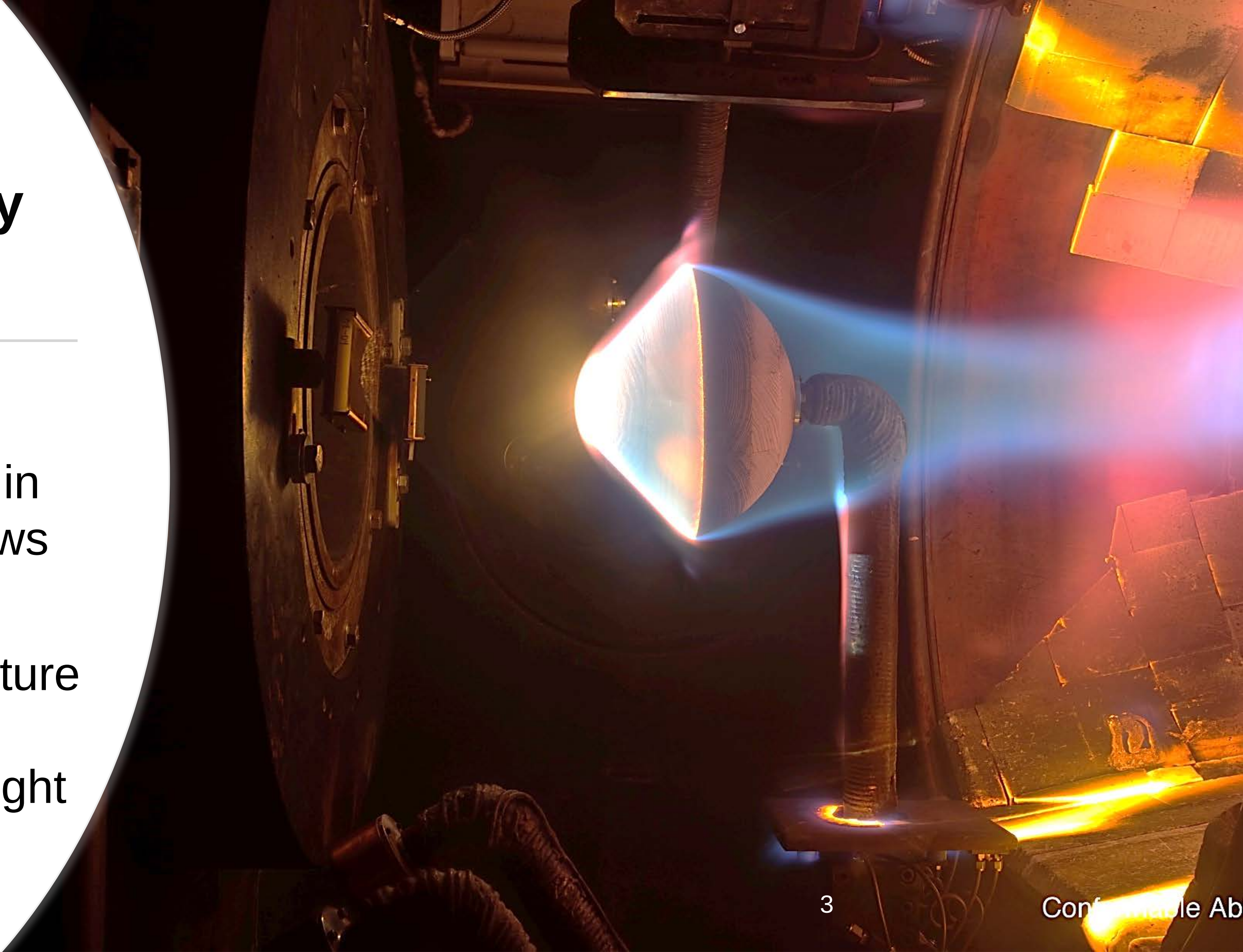
Overview

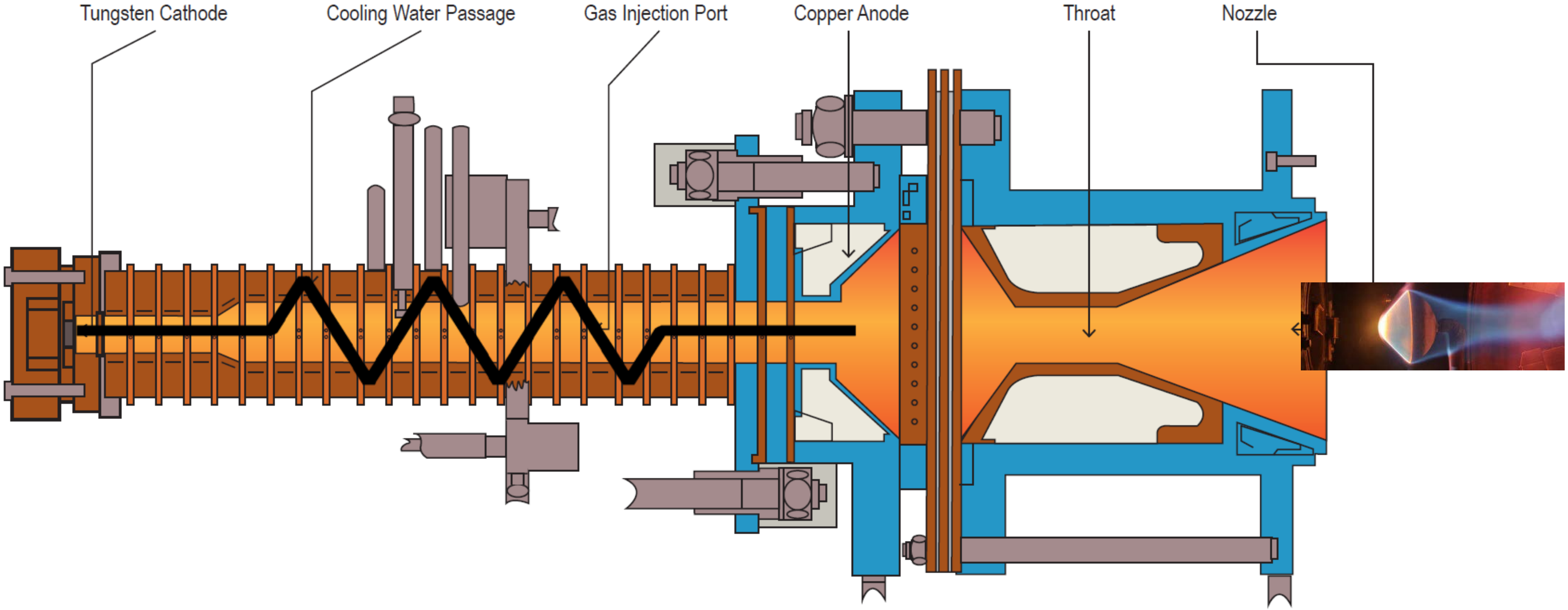
- Background
- Diagnostic design
- Arcjet magnetic measurements
- Future work

NASA Ames Aerodynamic Heating Facility (AHF)

- Arcjet facility for testing materials in high enthalpy flows
- Critical infrastructure for certifying heatshields for flight



10 MW heater geometry



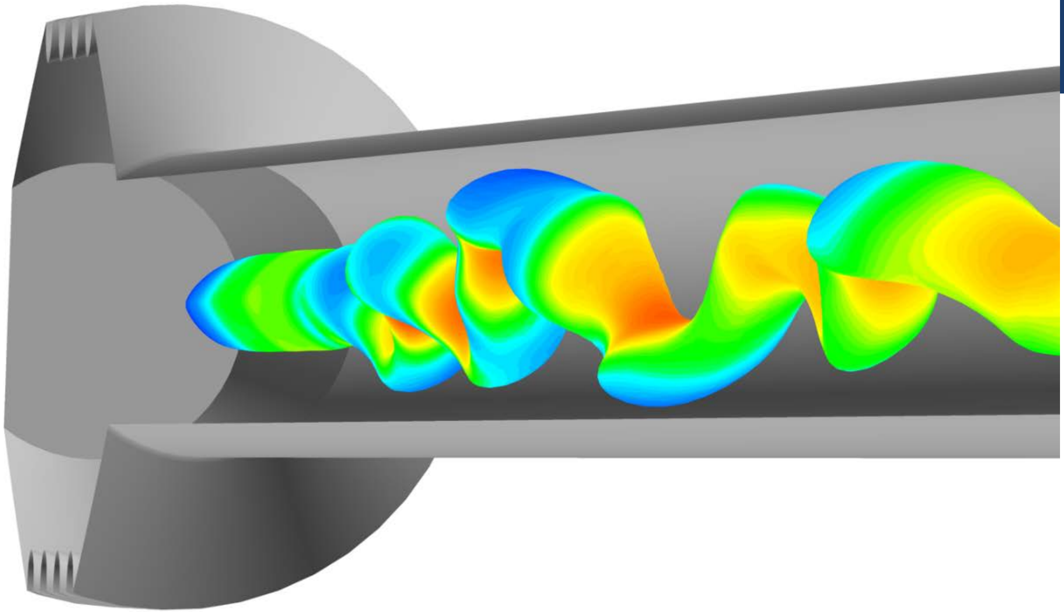
Arcjet Facility Challenges

Flight Condition Matching

- Higher mach number
- Higher enthalpy
- Gas mixture
- Radiative shock heating
- Larger test models

Testing Fidelity

- Facility reproducibility
- Uncertainty quantification
- Diagnostic development



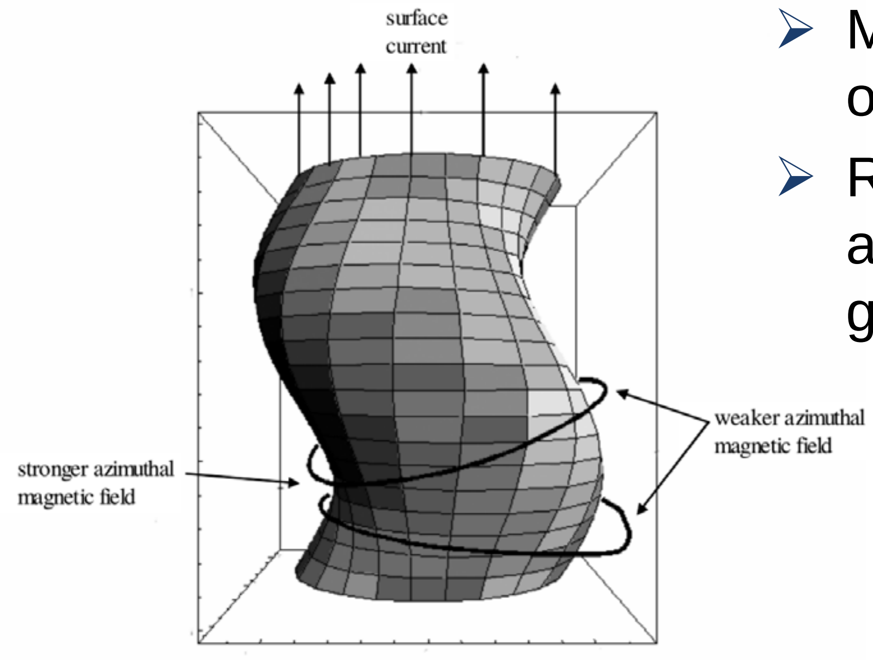
Arcjet Heater Simulator (ARCHeS)

- Compressible flow
- Magnetic fields
- Electric current
- Coupled Thermo
- 3D Radiation

Applications

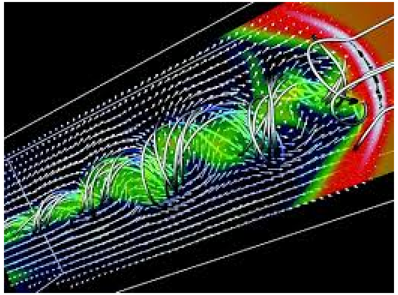
- Physics based inputs for nozzle flow CFD
- Independent verification and validation of existing diagnostics/simulations
- NextGen arcjet design
- Facility maintenance
- Facility reproducibility

Magnetic Kink Instability

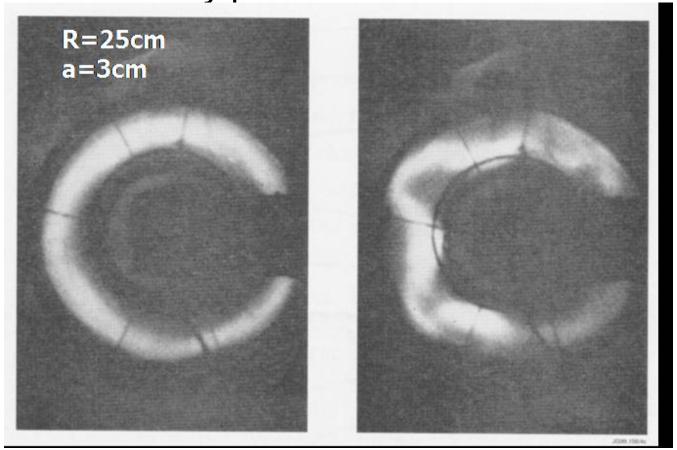


- Magnetic instability of current channels
- Radial perturbations are unstable to growth

Astrophysical jet simulation



Laboratory plasma



Magnetic measurements on AHF constrictor

Questions addressed

- Is the kink instability present in the arcjet heater column?
- If so, what are the parameters of the fluctuations?

Diagnostics

- Inductive magnetic probes

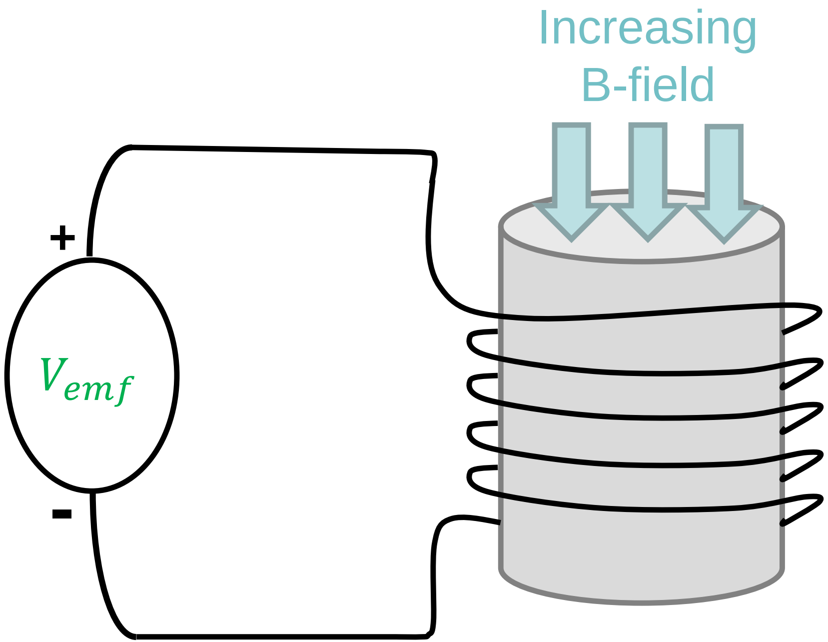
Relevance

- Electrode wear patterns
- Facility reproducibility
- Gas mixing

Diagnostic Design

Design of multiple probe iterations
and optical link circuit

Inductive magnetic probes



Voltage proportional to time derivative of B

$$V_{emf} = -N\,A\frac{\partial B}{\partial t}$$

Pros

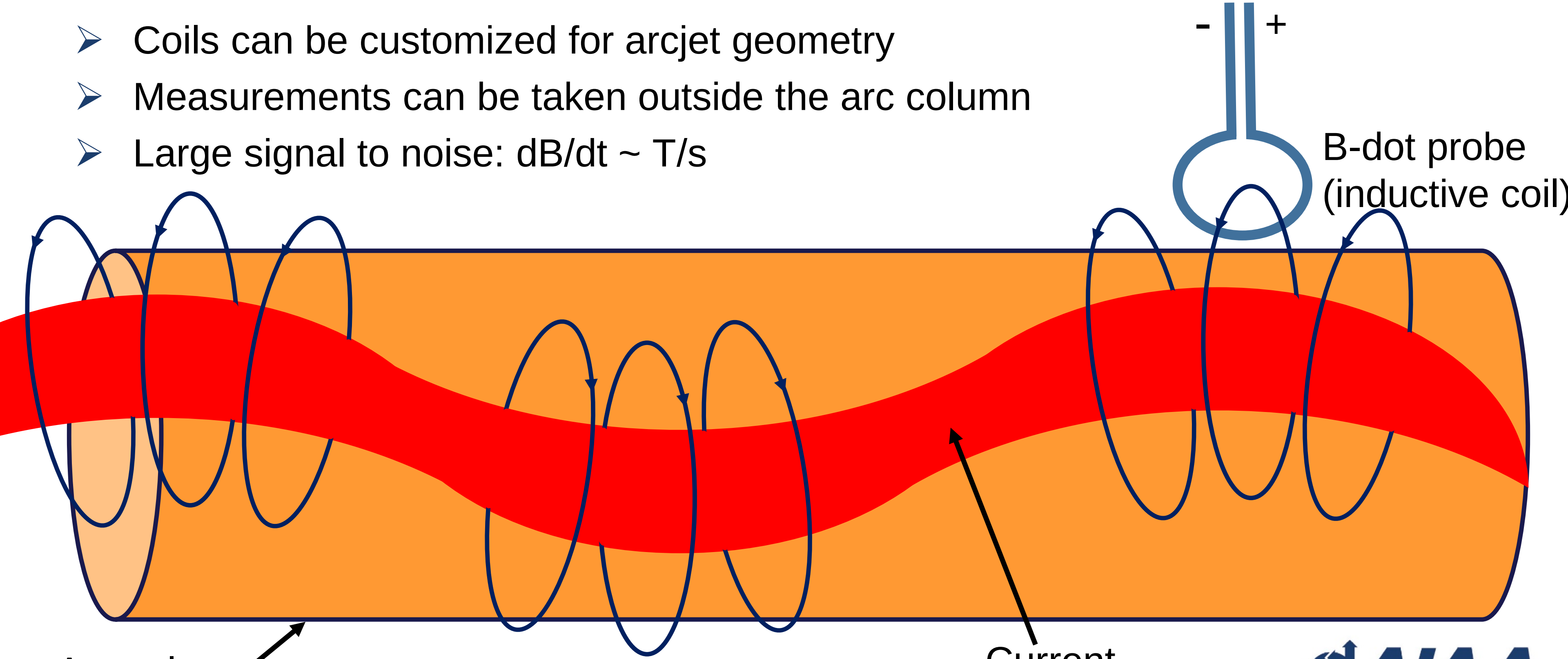
1. Sensitive to fast changes in B-field
2. Design is simple and easily modified

Cons

1. Measurement is not absolute
2. Integration errors limit measurement time to short intervals (< 50 ms)

Measuring arcjet kink instability

- Coils can be customized for arcjet geometry
- Measurements can be taken outside the arc column
- Large signal to noise: dB/dt ~ T/s



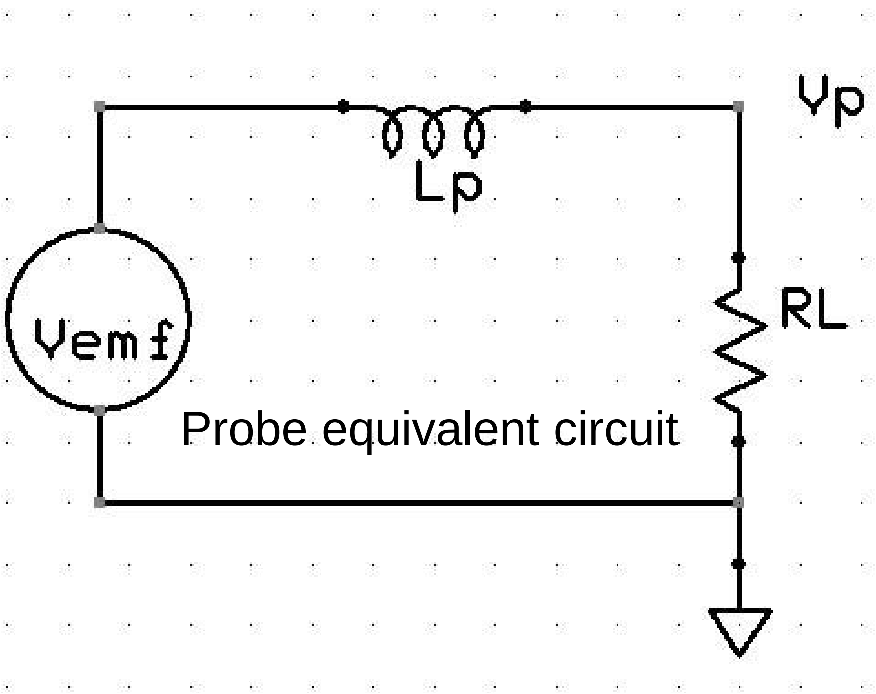
Optimizing Inductive Probes

Probe self-attenuation: $\frac{1}{\sqrt{1+(\omega L_p/R_L)^2}}$

For a typical coil with $L_p = N^2 L_0$,
the optimal number of turns is,

$$N_{best} = \sqrt{\frac{R_L}{\omega L_0}}$$

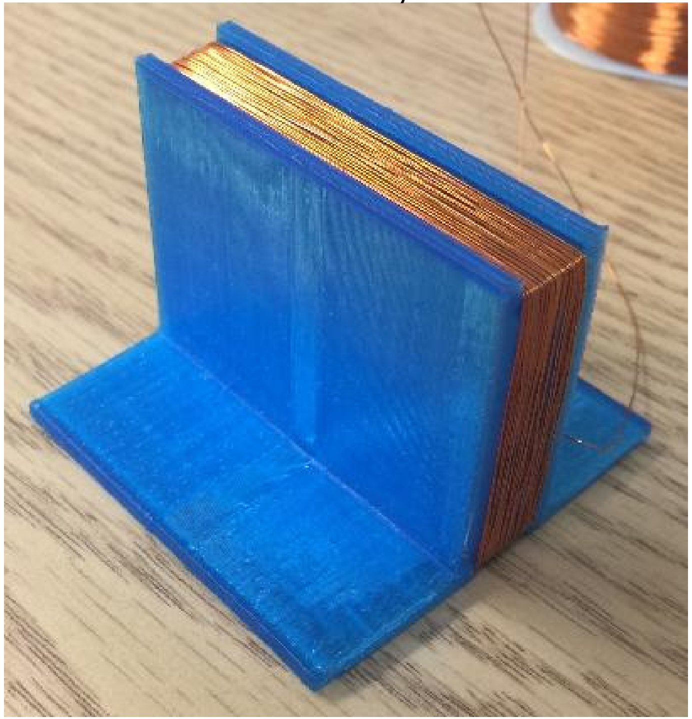
So N ~ [50, 300] for the arcjet context



Probe equivalent circuit

3D Printed Mounts for Fast Prototyping

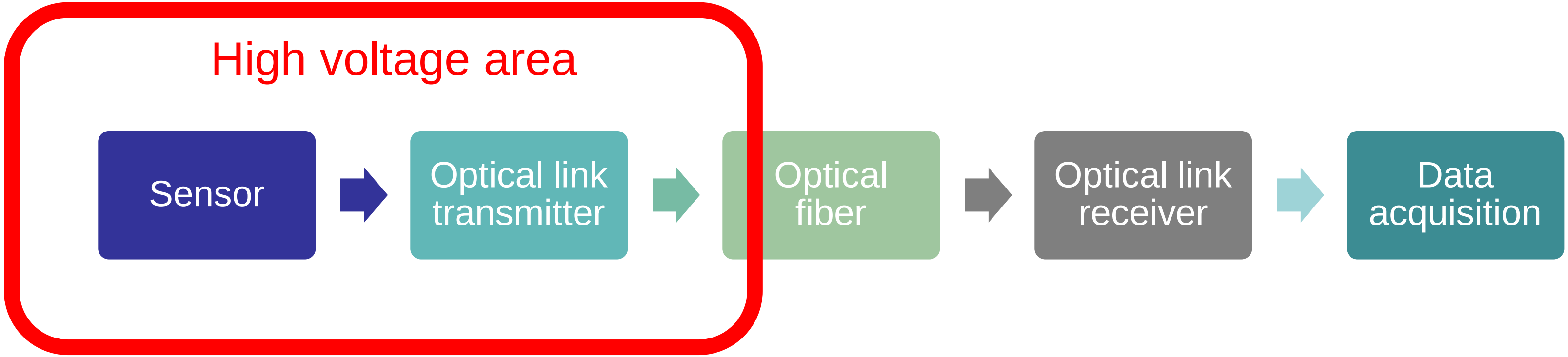
6 x 4.2 x 1 cm, N = 50



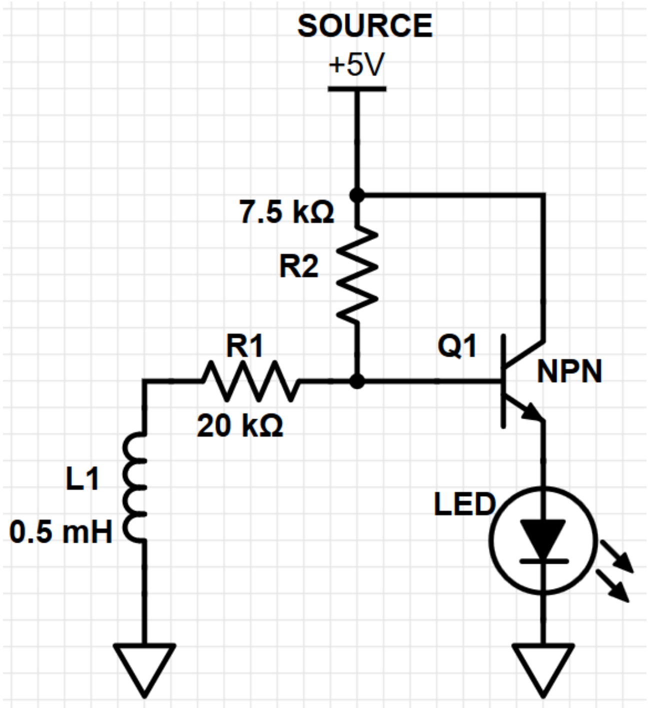
4.2 x 2.4 x 0.8 cm, N = 100

Optical Link

- Provides electrical isolation (safety req.)
- Reduces electrical noise/pickup from long cables

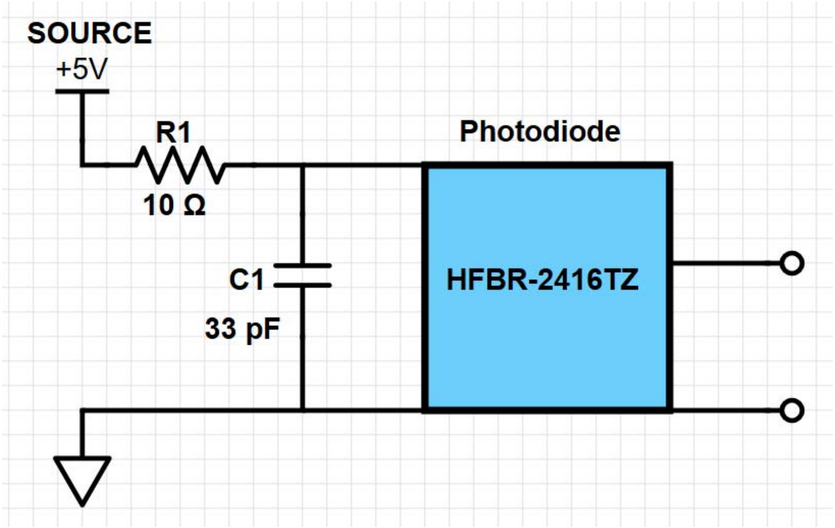


Optical Link Transmitter



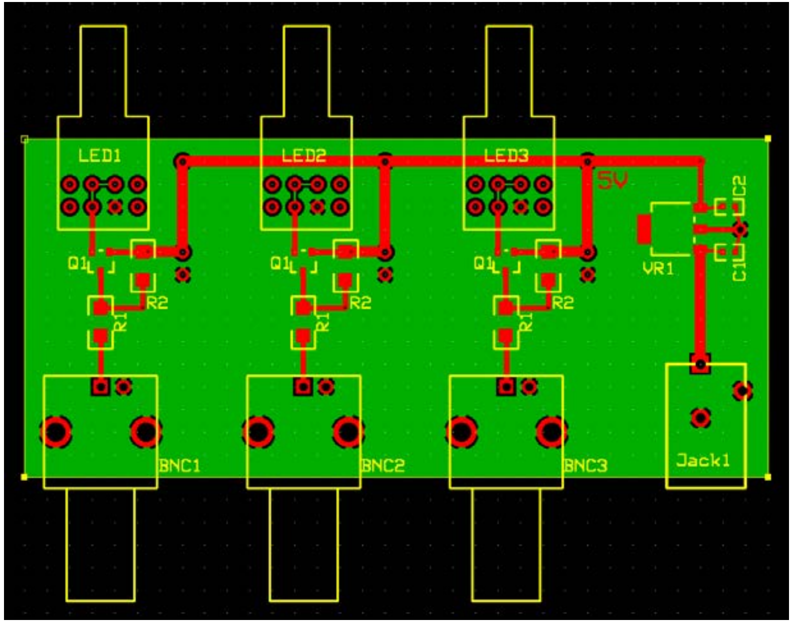
- Current amplifier circuit feeding high power IR LED (820 nm)
- Robust linear circuit
- Transistor amplification varies, careful calibration required

Optical Link Receiver



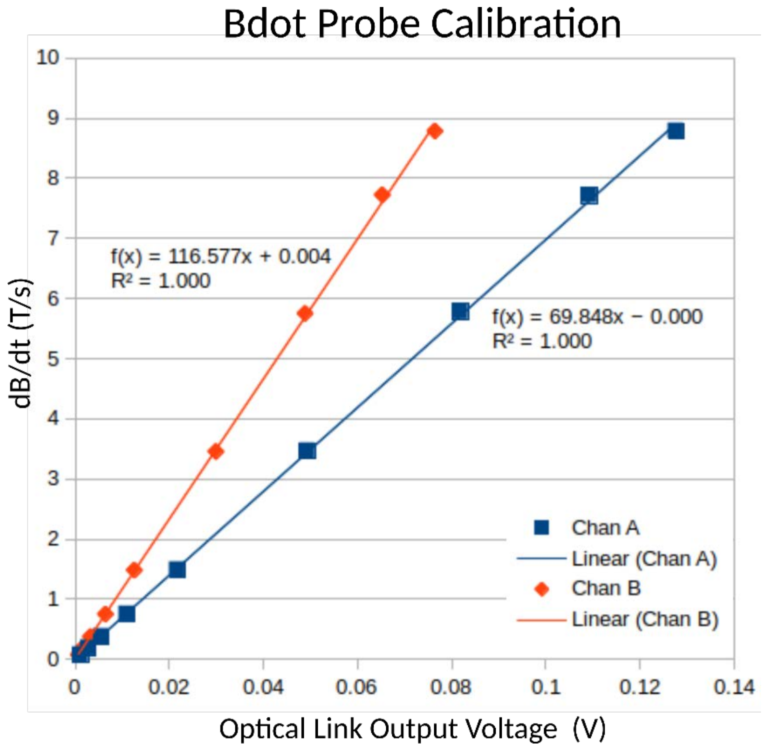
- Reverse biased IR photodiode (820 nm)
- Matched pair with transmitter, sensitive up to 125 MHz

Optical Link Specs



Optical Link Specifications	
Linear range [V]	(-3.17, 1.8)
Frequency range [MHz]	(0, 10)
Transmission range [km]	2.7
Dimensions [mm]	100x85x20
Cost/channel	$50

Calibration of Sensors + Optical Links



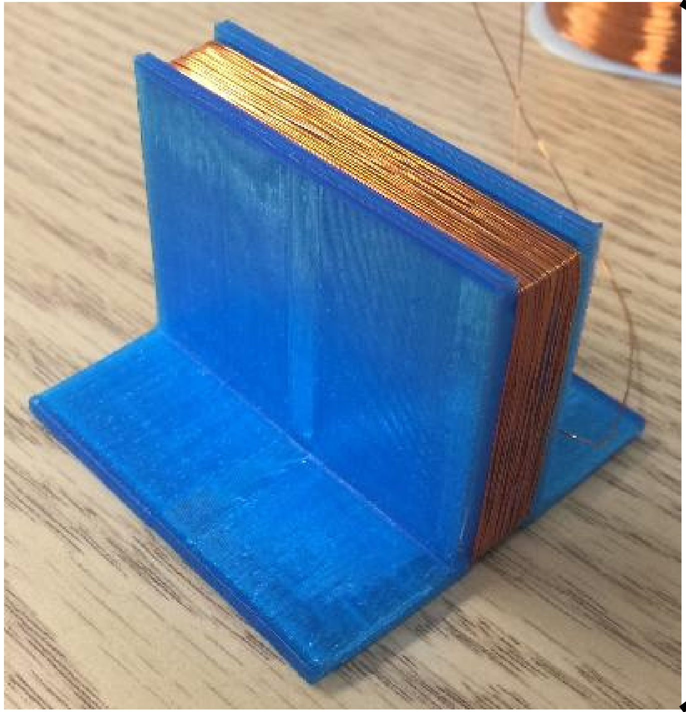
- Helmholtz coils are used for calibration of the sensor + optical link system.
- Coils are calibrated with a specific optical link channel

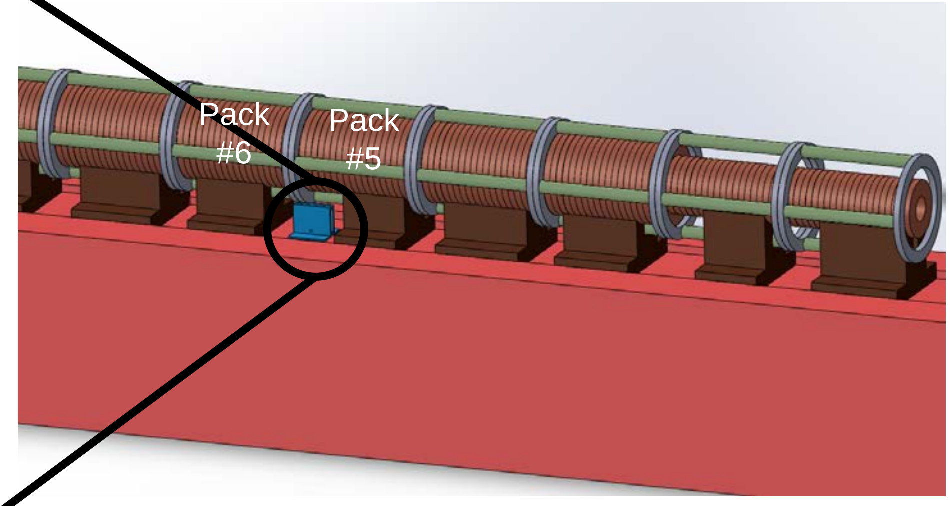
Helmholtz coils

Magnetic Measurements on AHF

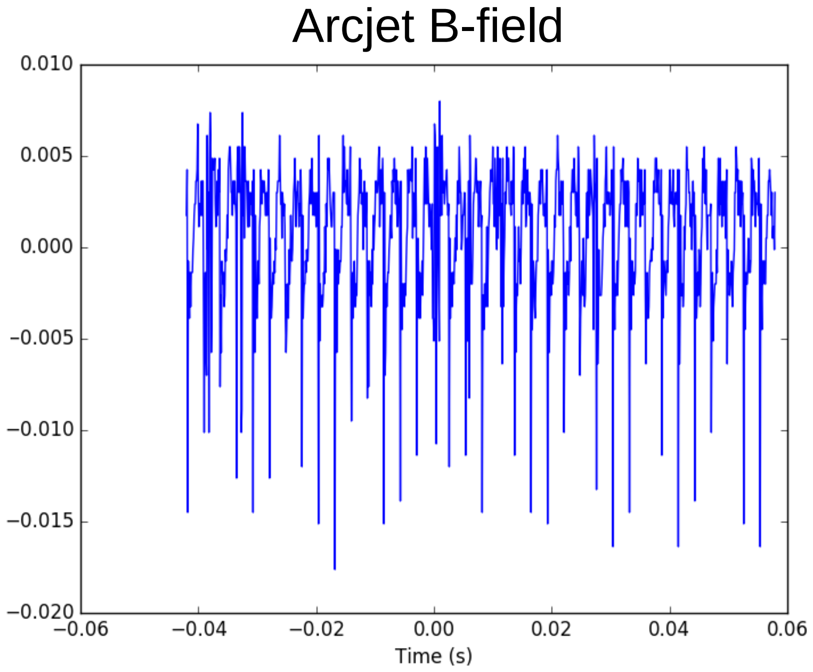
Single and differential measurements of AHF magnetic field

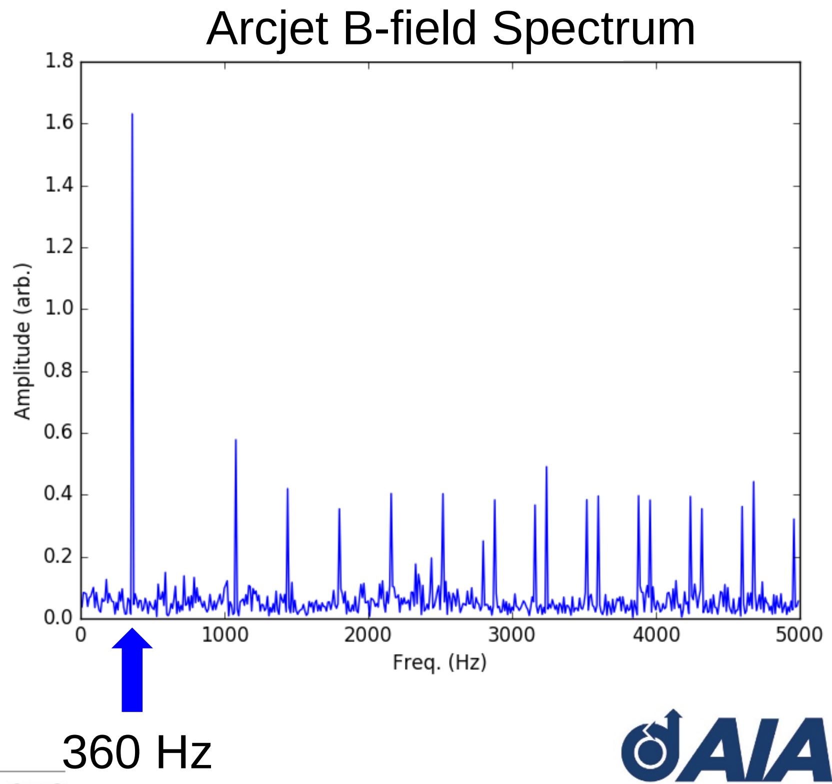
Single Coil Measurements





Single Coil Measurements

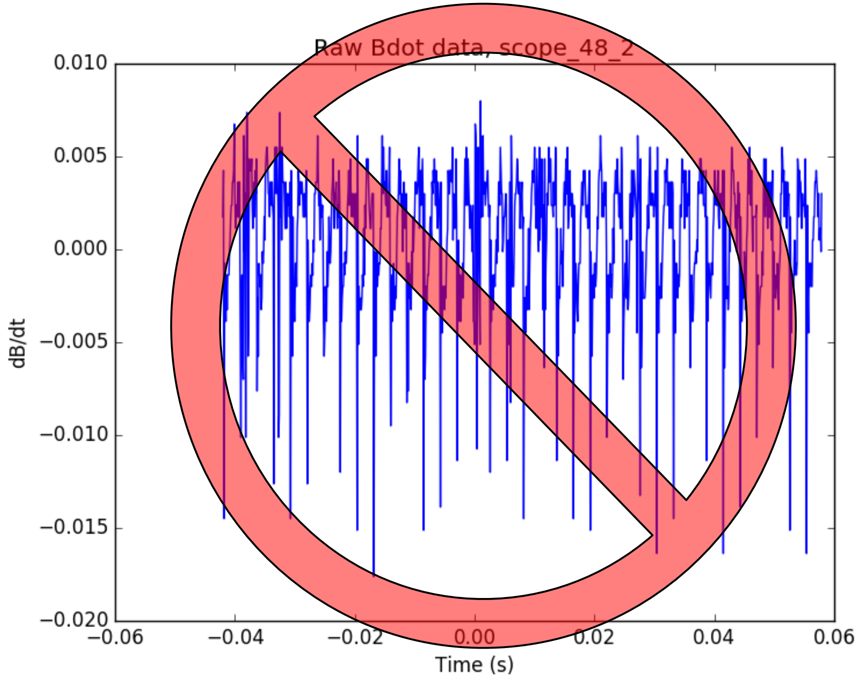




SHAPING THE FUTURE OF AEROSPACE

Single Coil Measurements

- Power supply oscillates at +- 8 Amps @360 Hz
- These oscillations obscure any signal from motion of the current channel
- The contribution from the power supply must be subtracted out to measure the current channel motion



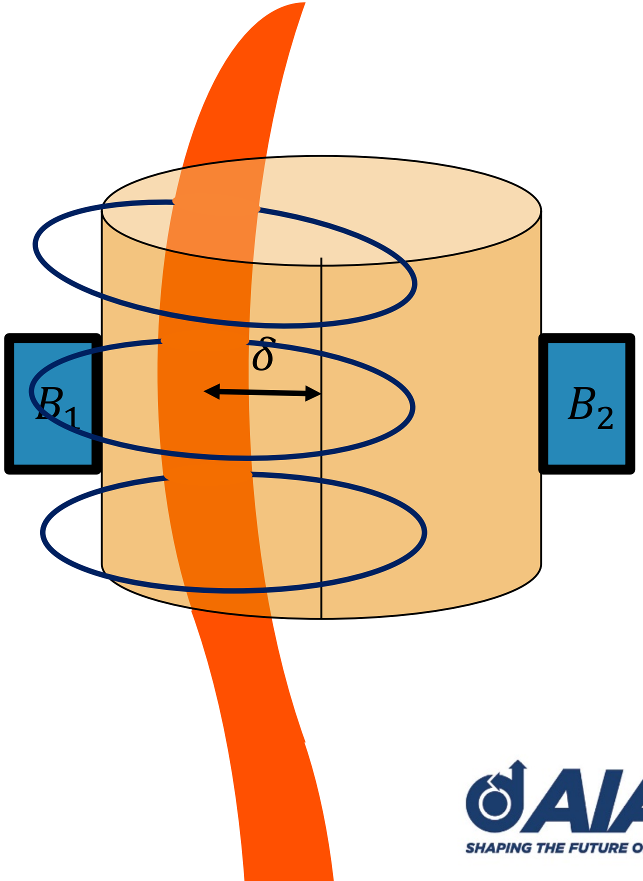
Differential dB/dt Measurements

$$B_1 = \frac{\mu_0(I_0+\partial I)}{2\pi(R-\delta)} + \partial B$$

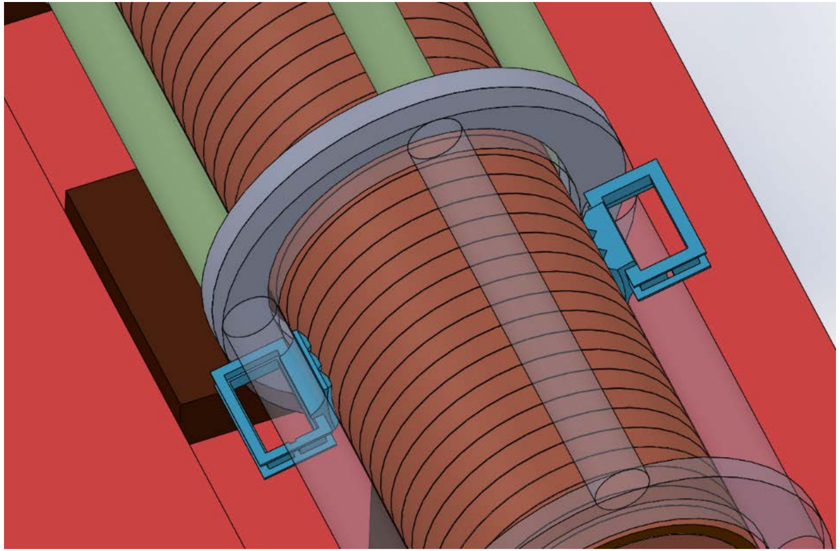
$$B_2 = \frac{\mu_0(I_0+\partial I)}{2\pi(R+\delta)} + \partial B$$

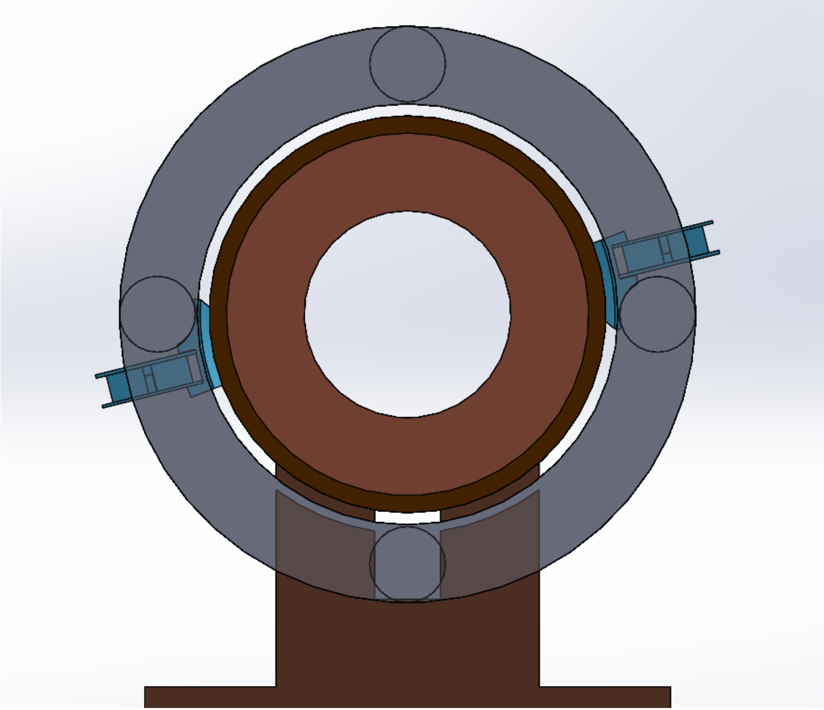
$$\Delta B = B_1 - B_2$$

- Direct measurement of motion
- Subtracts out common noise
- Subtracts out power supply fluctuations



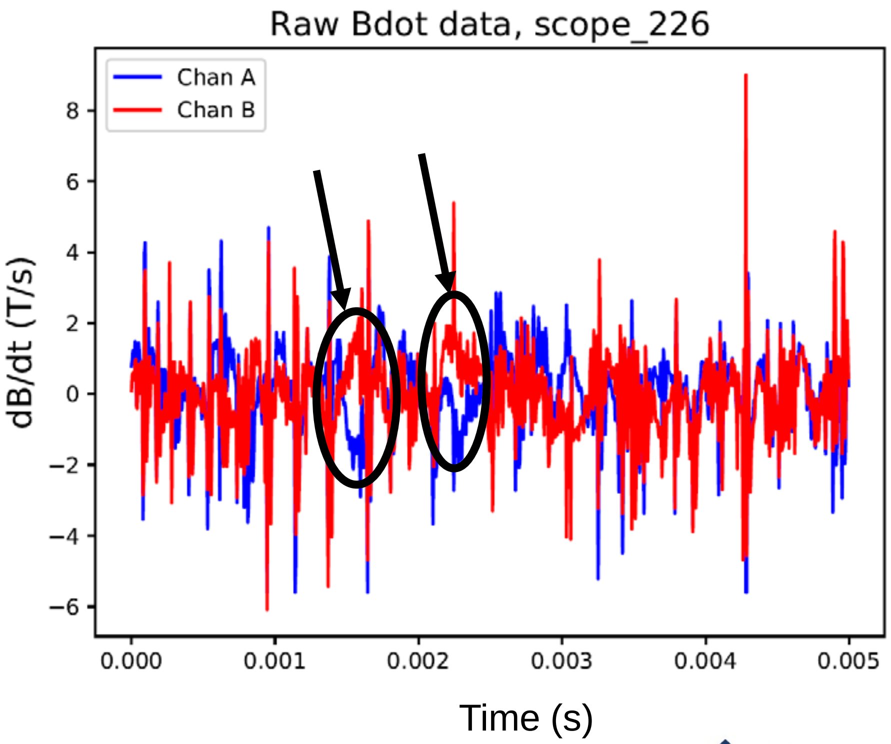
Probe Placement for Differential Measurements



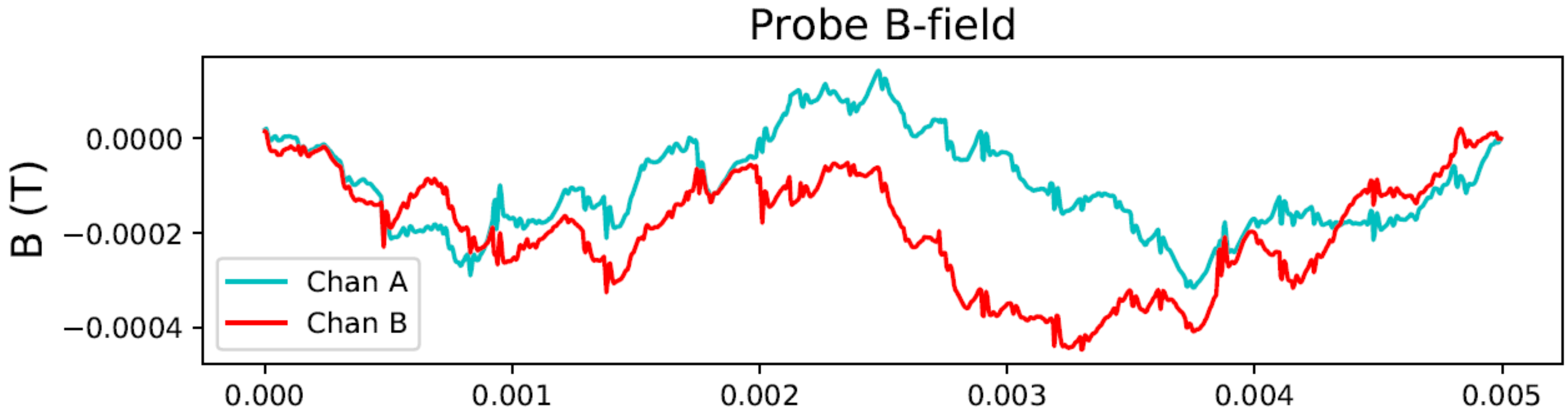


Raw probe data

- 5 ms dB/dt data taken at 1 MHz sampling rate
- Calibration of channels is sufficiently accurate to subtract out noise
- Differential signal observed

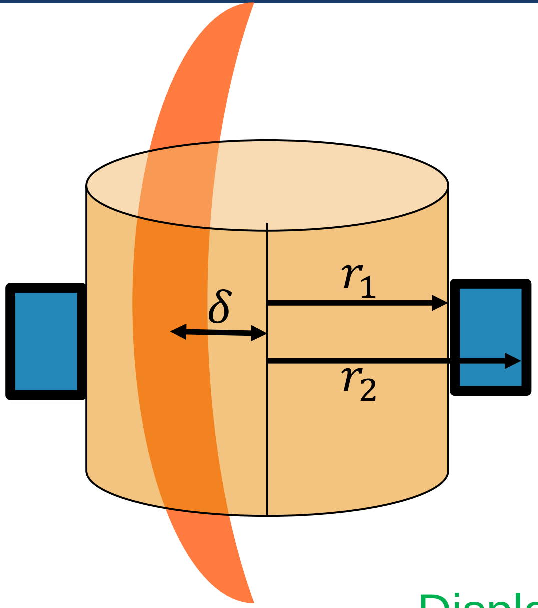


Differential Magnetic field



- Integration of Bdot measurements over 5 ms
- ΔB present at low and high frequencies

Inferring Current Channel Position



Coil B-field

$$\bar{B} = \frac{1}{r_2 - r_1}\int_{r_1}^{r_2} \frac{\mu_0 I}{2\pi r}\, dr = \frac{\mu_0 I}{2\pi(r_2 - r_1)} \ln\left(\frac{r_2}{r_1}\right)$$

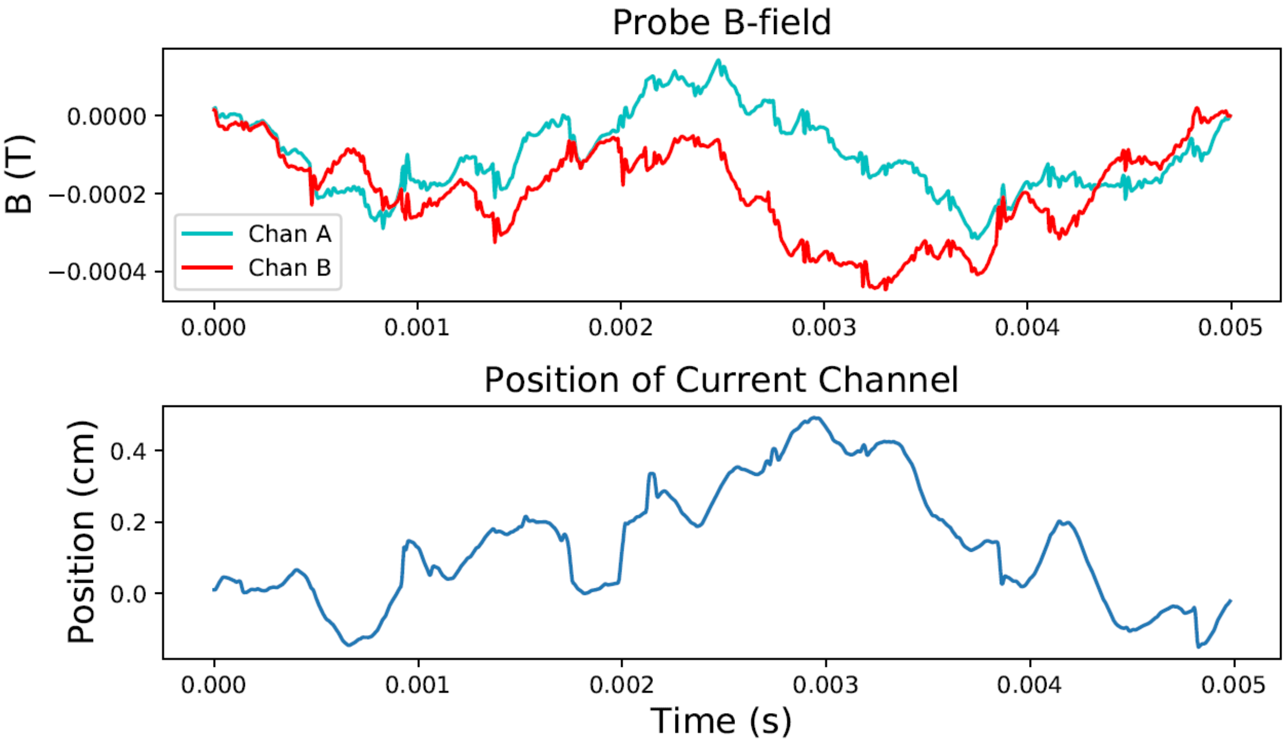
Differential B-field

$$\Delta\bar{B} = \bar{B}_b - \bar{B}_a = \frac{\mu_0 I}{2\pi(r_2 - r_1)}\left[\ln\left(\frac{r_2 - \delta}{r_1 - \delta}\right) - \ln\left(\frac{r_2 + \delta}{r_1 + \delta}\right)\right]$$

Displacement from axis

$$\delta = \frac{\sqrt{4 r_1 r_2 \chi^2 + (r_2 - r_1)^2(\chi + 2)^2} - (r_2 - r_1)(\chi + 2)}{2\chi}, \quad \text{where} \quad \chi = \exp\left(\frac{2\pi \Delta B (r_2 - r_1)}{\mu_0 I}\right) - 1$$

Current Channel Position



- 4mm displacements observed at ~700 Hz
- 2mm displacements observed at ~2 kHz
- δ ~ 13% of heater radius

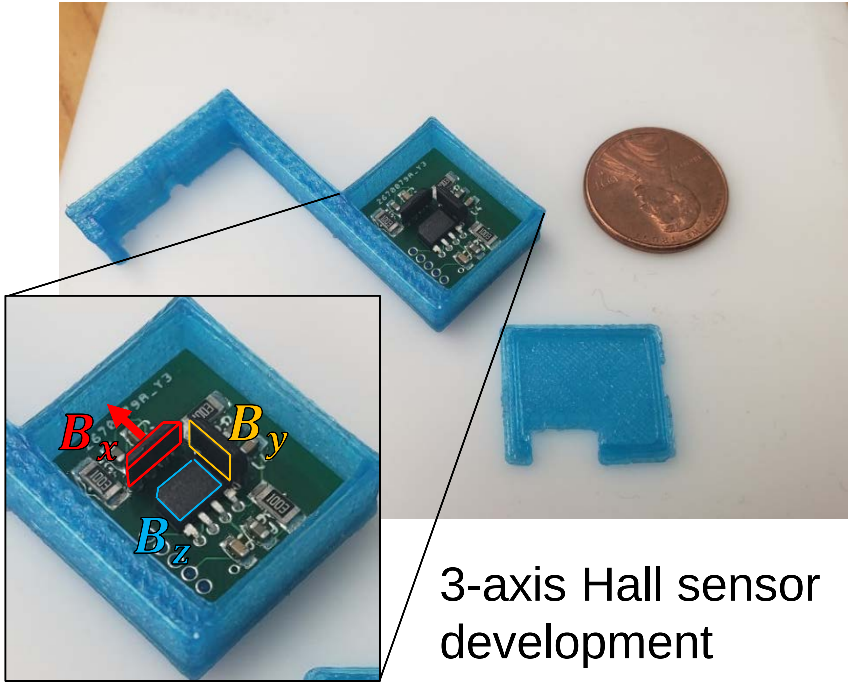
Discussion

- Current channel corresponds to enthalpy profile (path of least Ω)
- Motion of current channel implies equivalent motion of enthalpy profile

Affects interpretation of

- Time averaged heat flux measurements
- Time averaged spectral measurements
- Inferred spatial enthalpy profile

Future Work



3-axis Hall sensor development

Questions addressed:

- Does the current attach at one location on a given electrode?
- Does this attachment point rotate and with what frequency?
- Does the current detach?

Diagnostics

- Bdot sensors
- Hall sensors

Relevance

- Electrode wear/damage
- Higher power electrode development

Summary

- ARCHeS simulations predicted kink instability
- Magnetic sensors were developed to measure this phenomenon
- Measurements indicate ~4mm displacements at kHz freq

Acknowledgements

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- ARCHeS team
- Arcjet team
- Shock tube team
- TSF branch

Any Questions?

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