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

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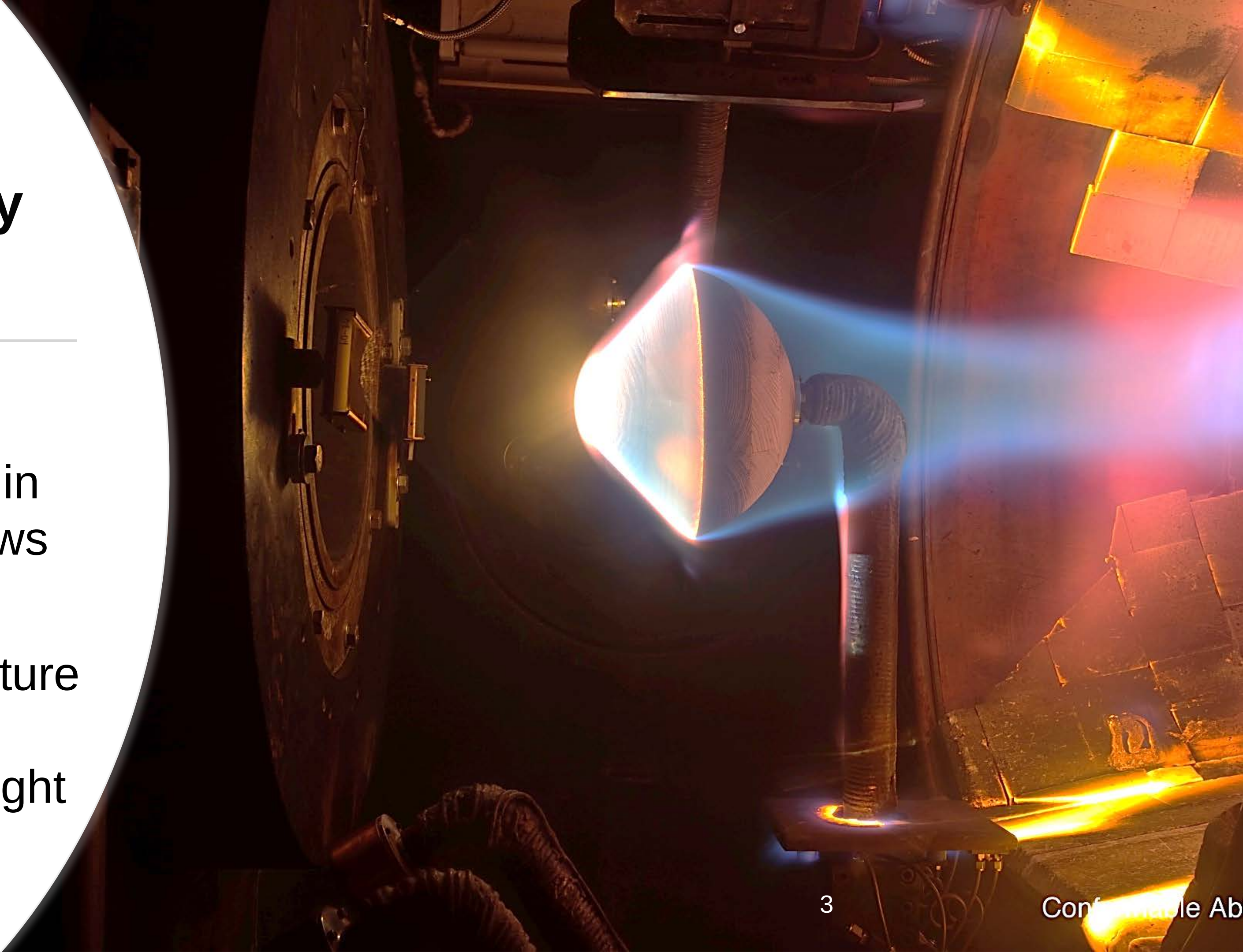
Overview

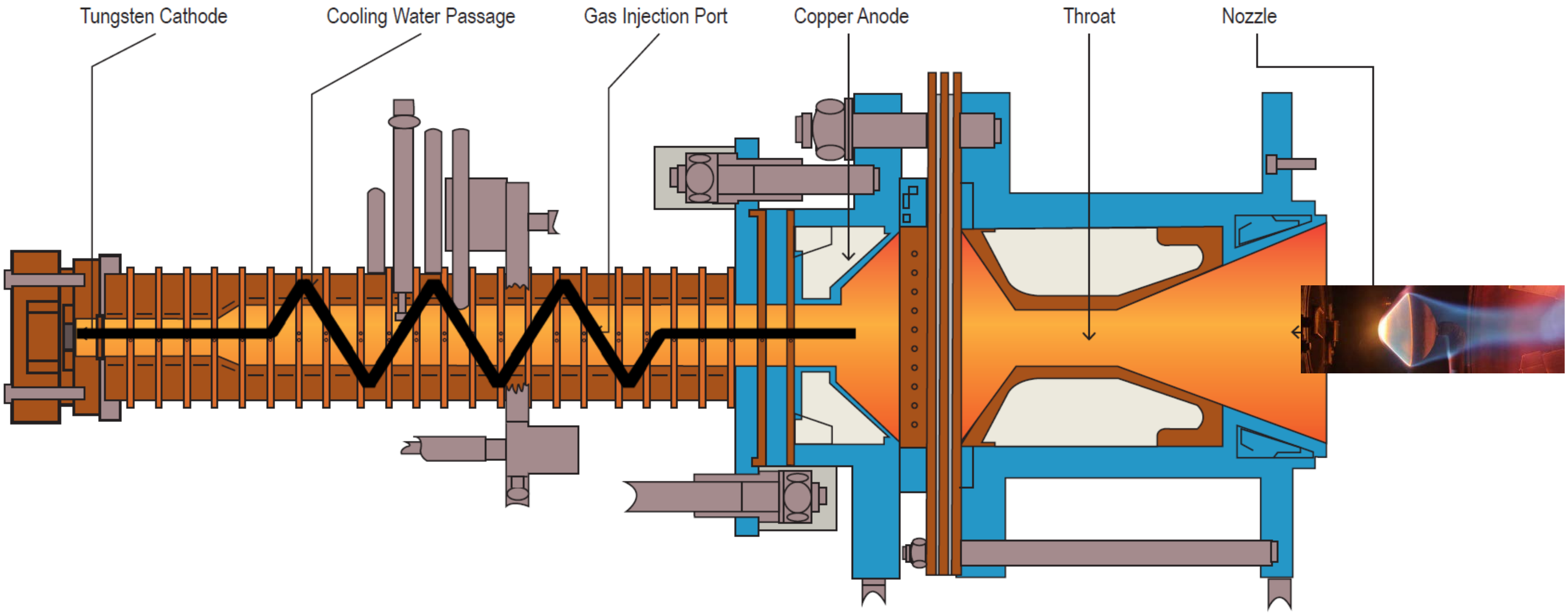
- Background
- Diagnostic design
- Arcjet magnetic measurements
- Future work

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



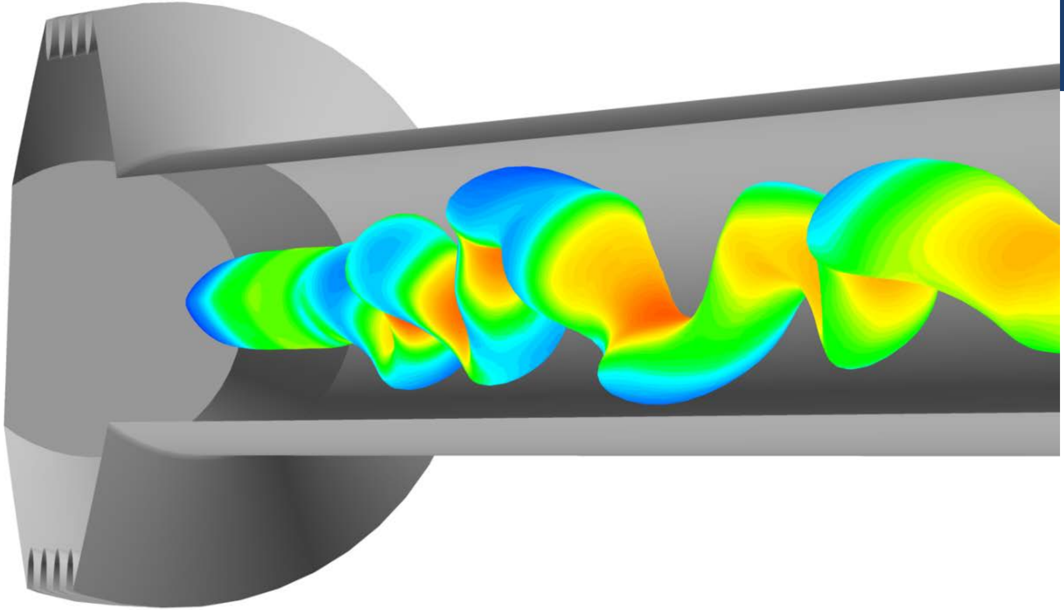
Arcjet Facility Challenges

Flight Condition Matching

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

Testing Fidelity

- Facility reproducibility
- Uncertainty quantification
- Diagnostic development



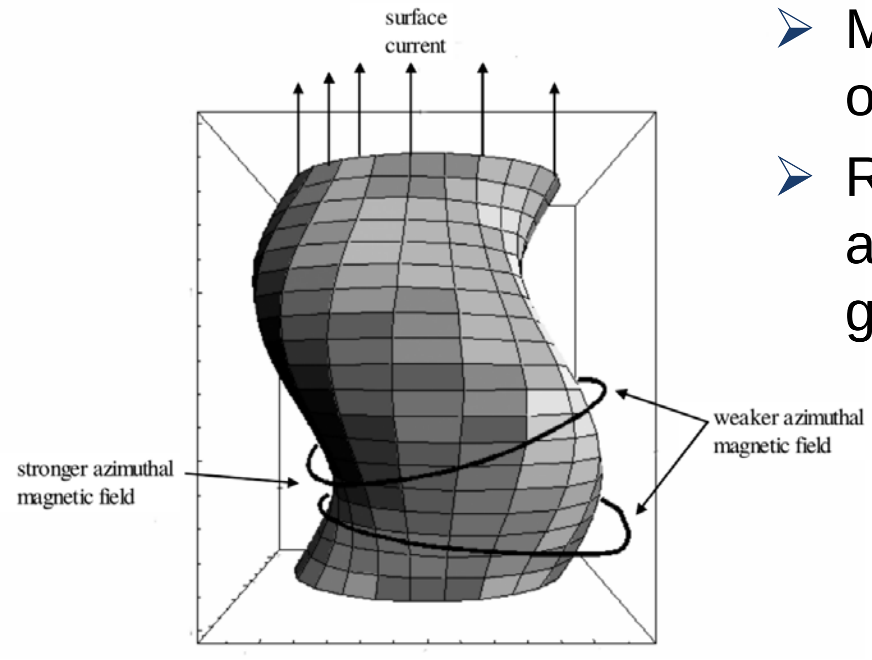
Arcjet Heater Simulator (ARCHeS)

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

Applications

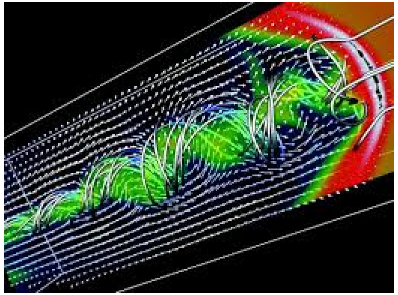
- Physics based inputs for nozzle flow CFD
- Independent verification and validation of existing diagnostics/simulations
- NextGen arcjet design
- Facility maintenance
- Facility reproducibility

Magnetic Kink Instability

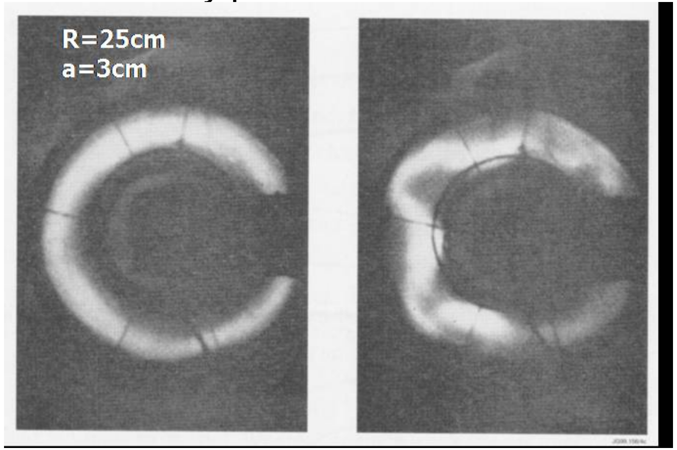


- Magnetic instability of current channels
- Radial perturbations are unstable to growth

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

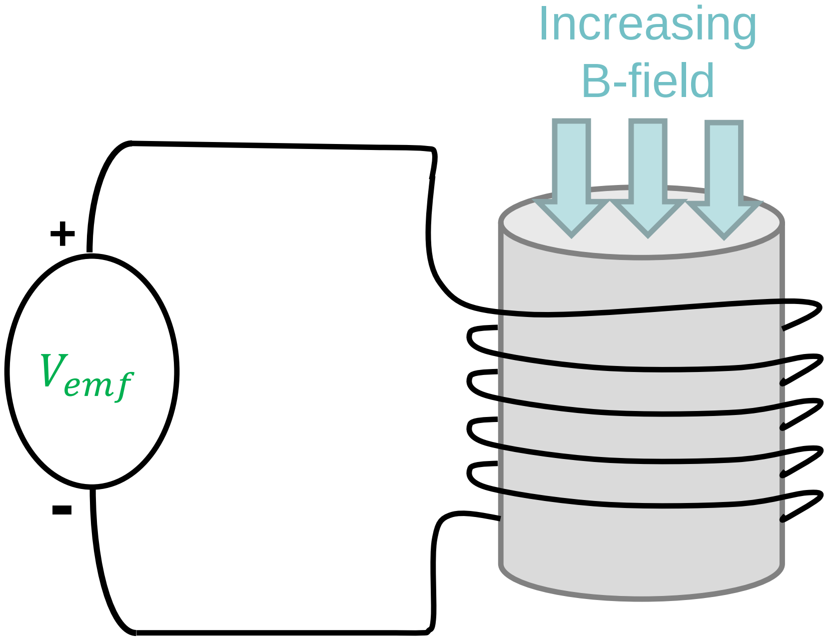
Relevance

- 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

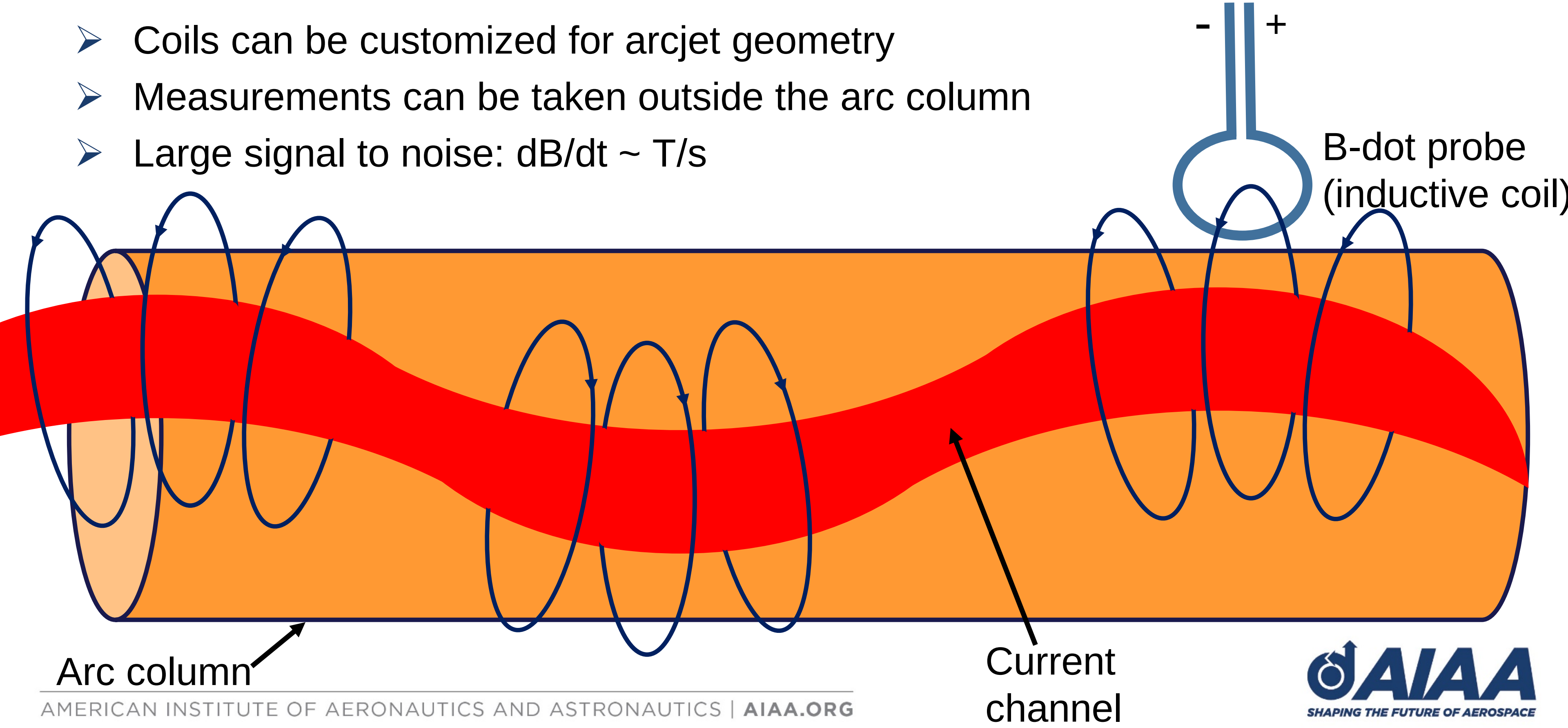
1. Sensitive to fast changes in B-field
2. Design is simple and easily modified

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



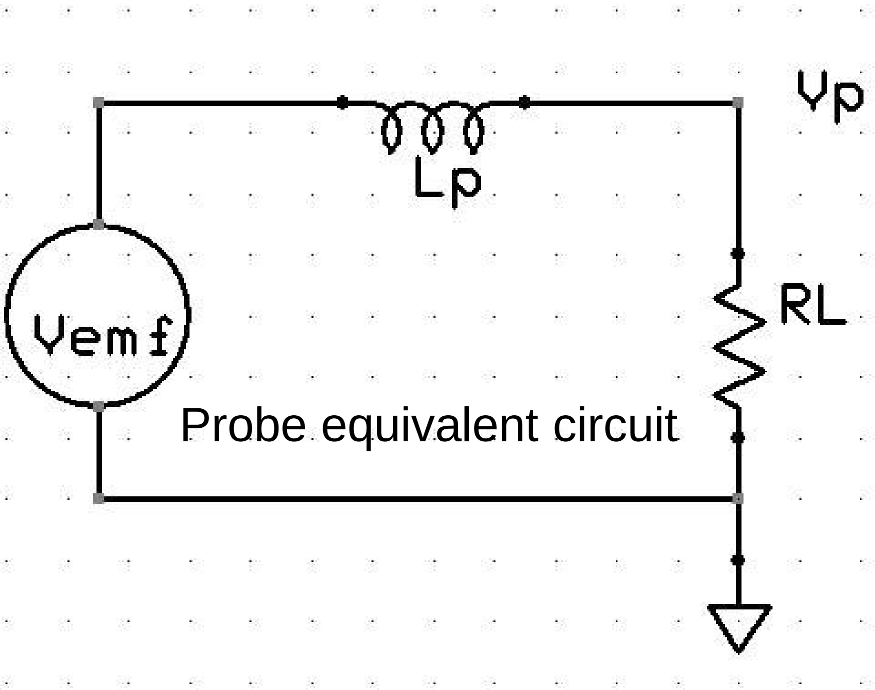
Optimizing Inductive Probes

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,

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

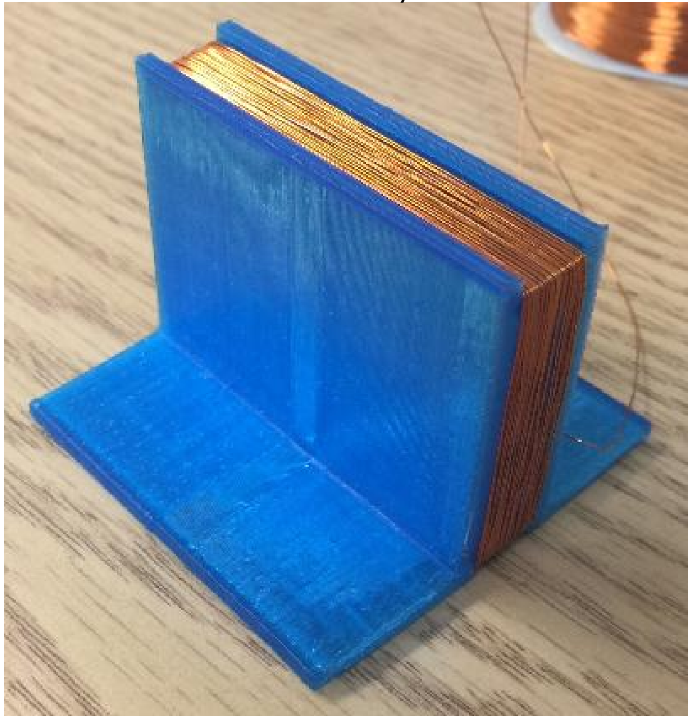
So N ~ [50, 300] for the arcjet context



Probe equivalent circuit

3D Printed Mounts for Fast Prototyping

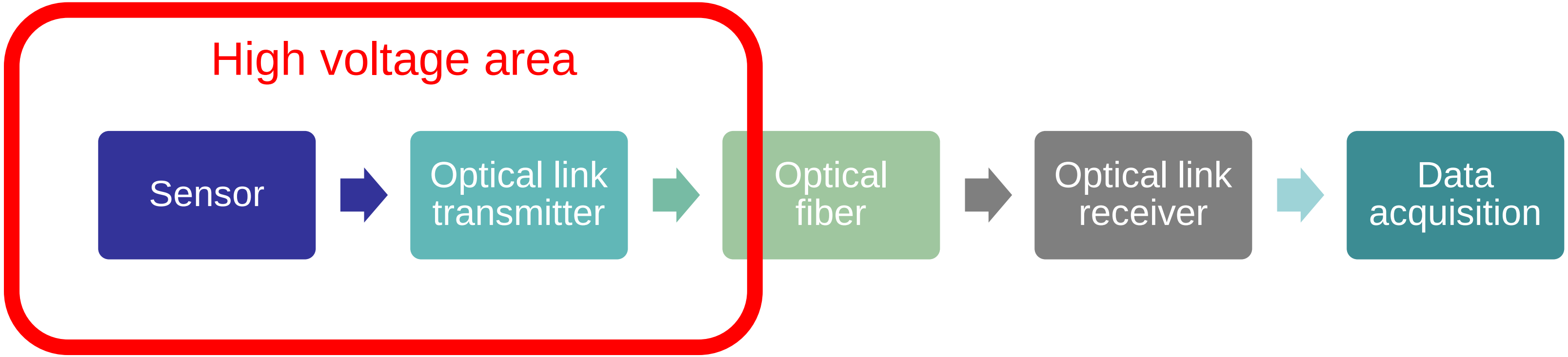
6 x 4.2 x 1 cm, N = 50



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



High voltage area

Sensor

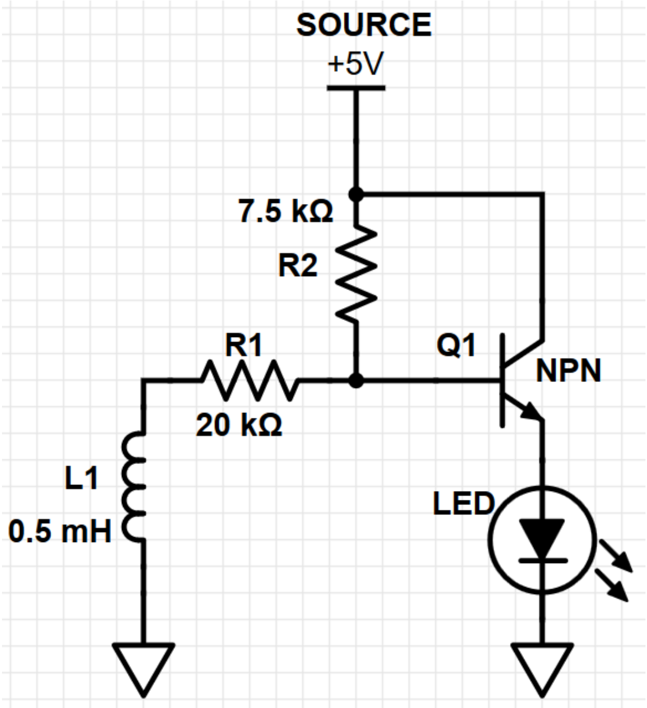
Optical link transmitter

Optical fiber

Optical link receiver

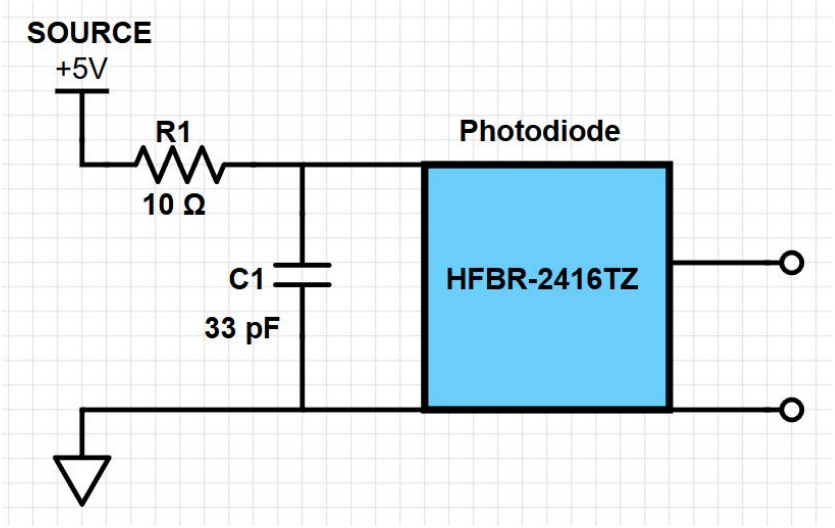
Data acquisition

Optical Link Transmitter



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

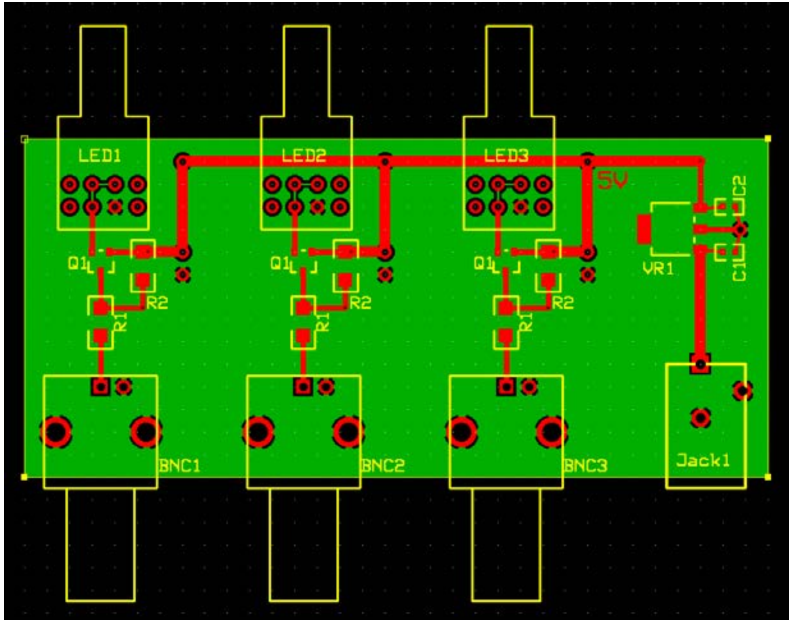
Optical Link Receiver



- Reverse biased IR photodiode (820 nm)

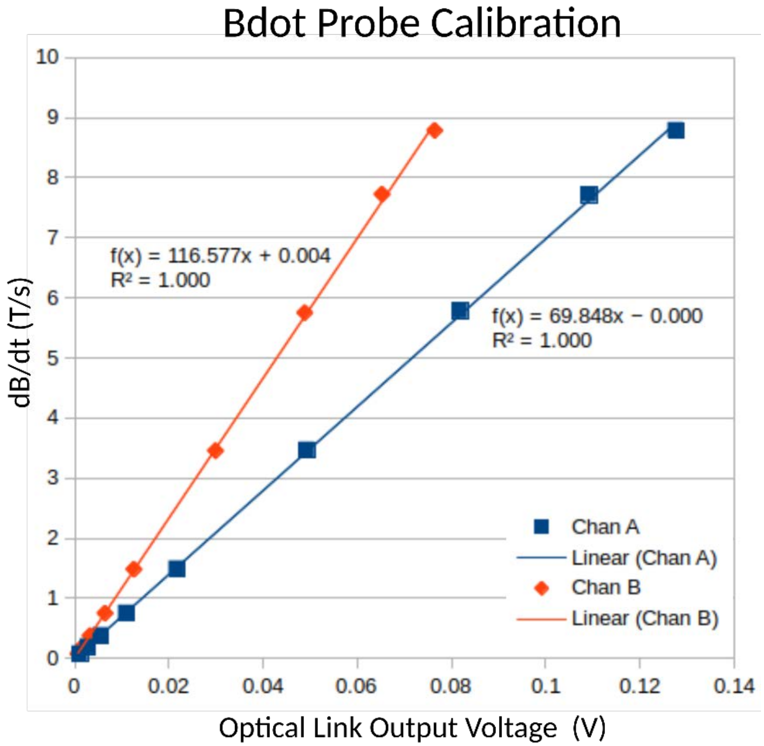
- Matched pair with transmitter, sensitive up to 125 MHz

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



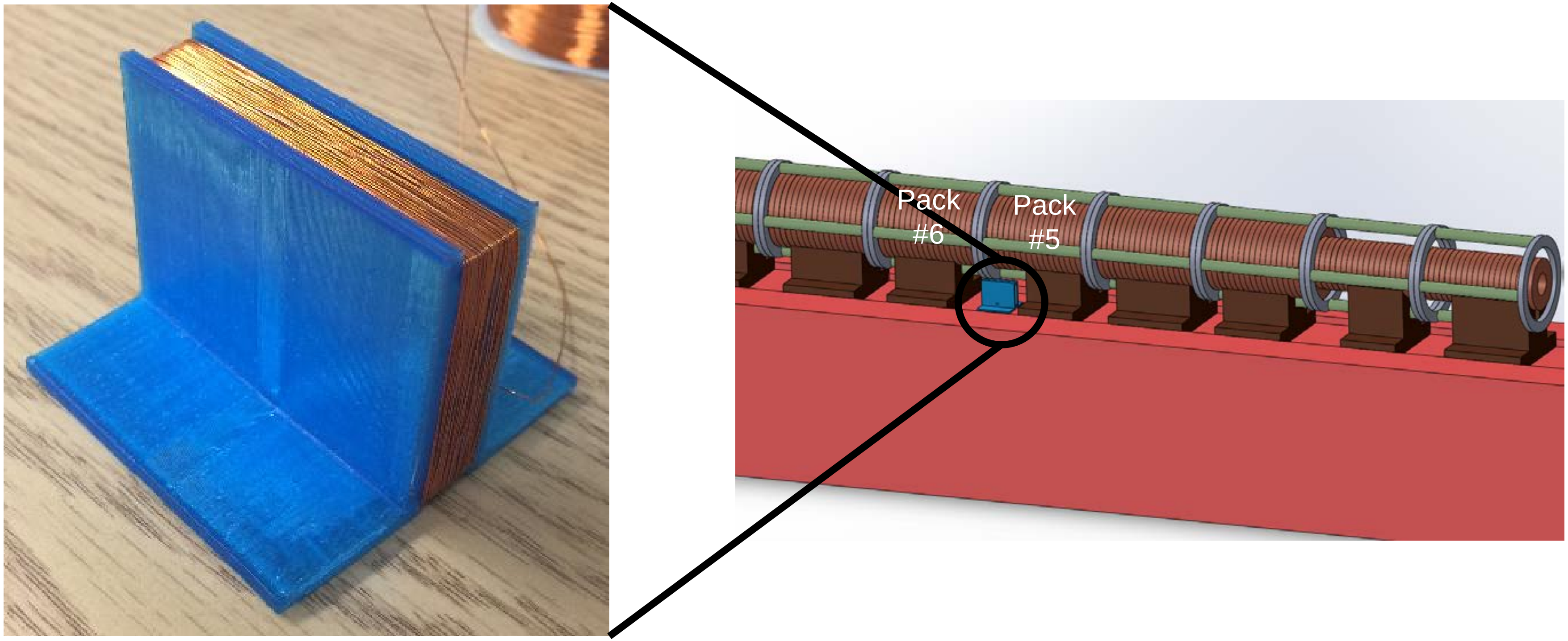
- ➢ Helmholtz coils are used for calibration of the sensor + optical link system.
- ➢ Coils are calibrated with a specific optical link channel

Helmholtz coils

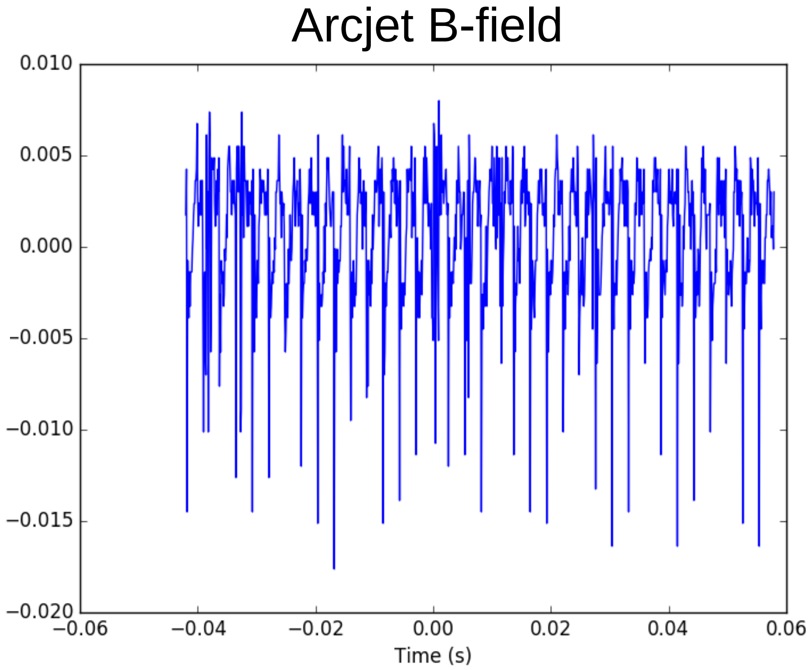
Magnetic Measurements on AHF

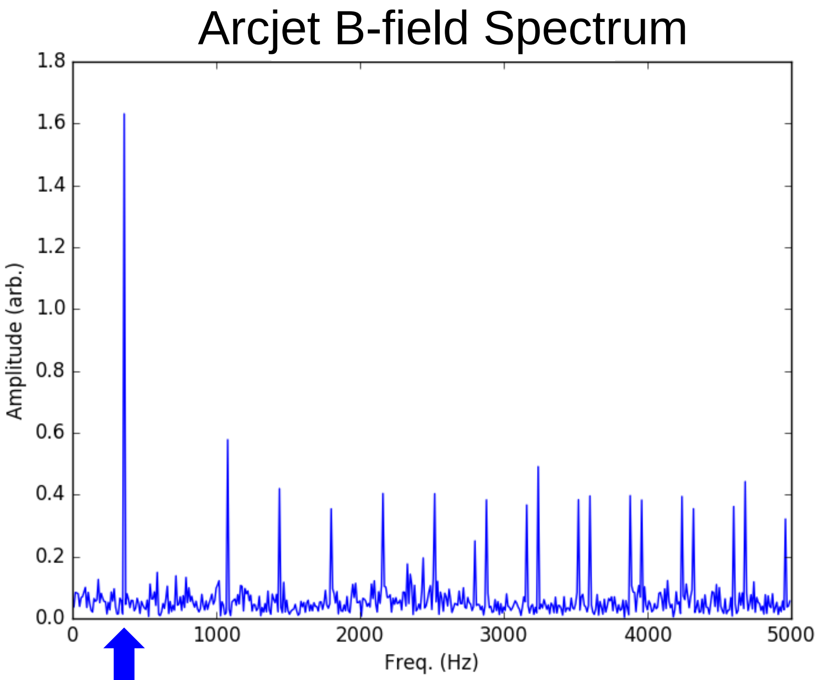
Single and differential measurements of AHF magnetic field

Single Coil Measurements



Single Coil Measurements



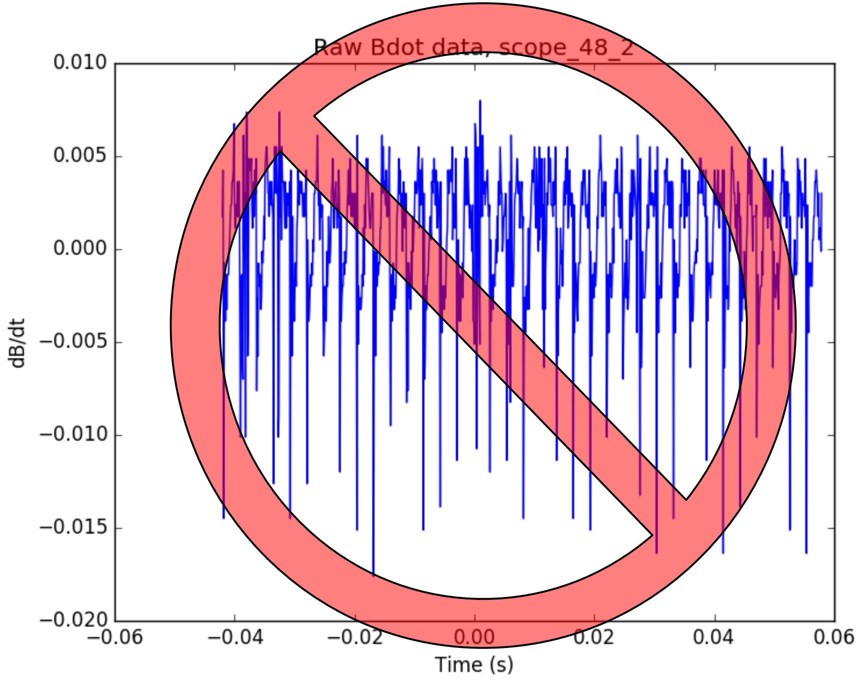


360 Hz

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



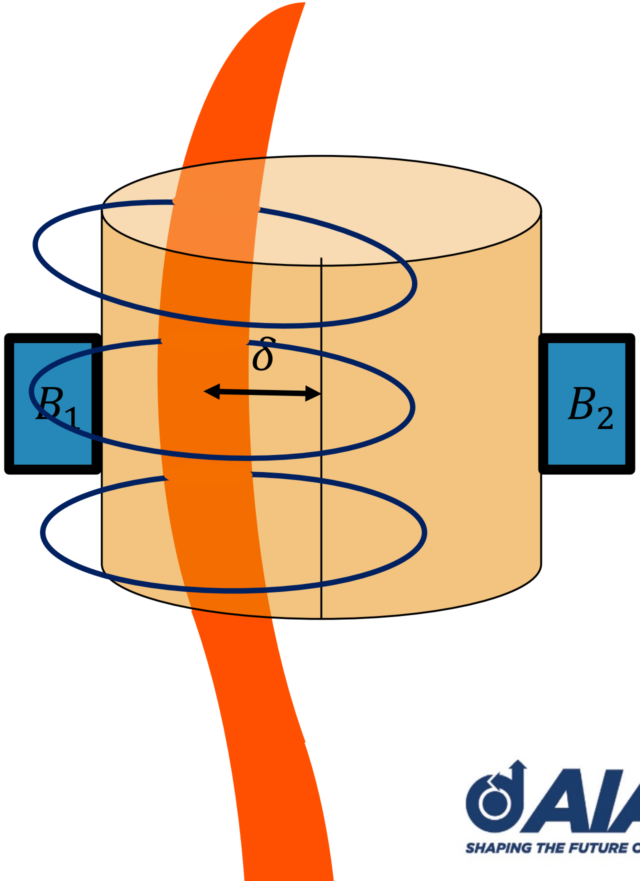
Differential dB/dt Measurements

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

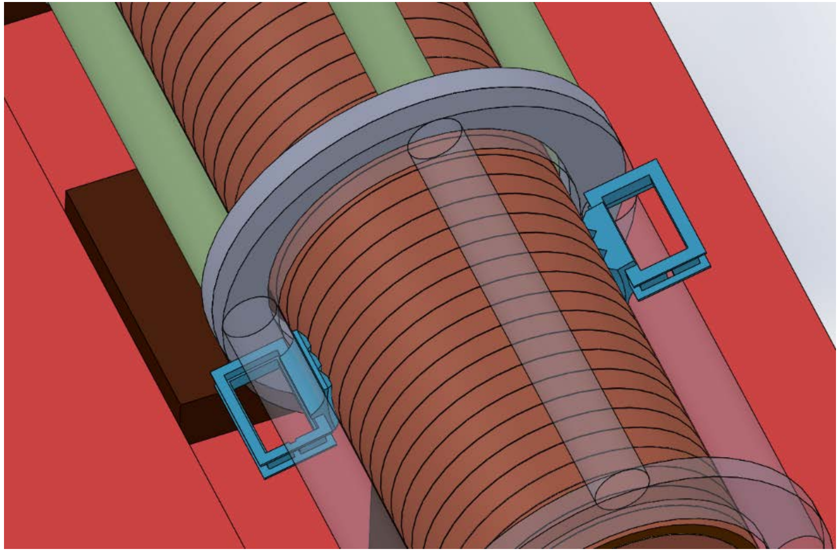
$$B_2 = \frac{\mu_0(I_0+\partial I)}{2\pi(R+\delta)} + \partial B$$

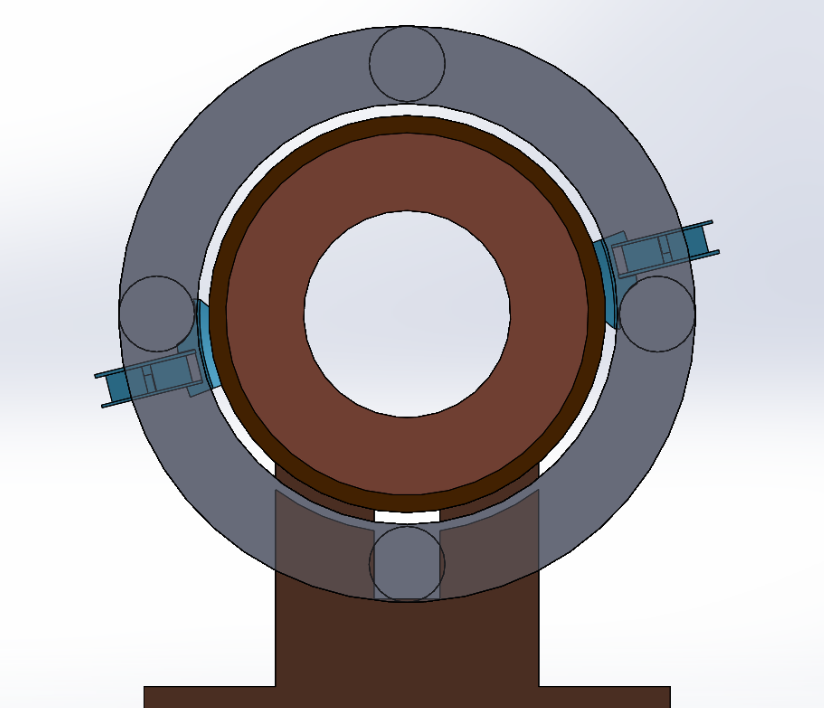
$$\Delta B = B_1 - B_2$$

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



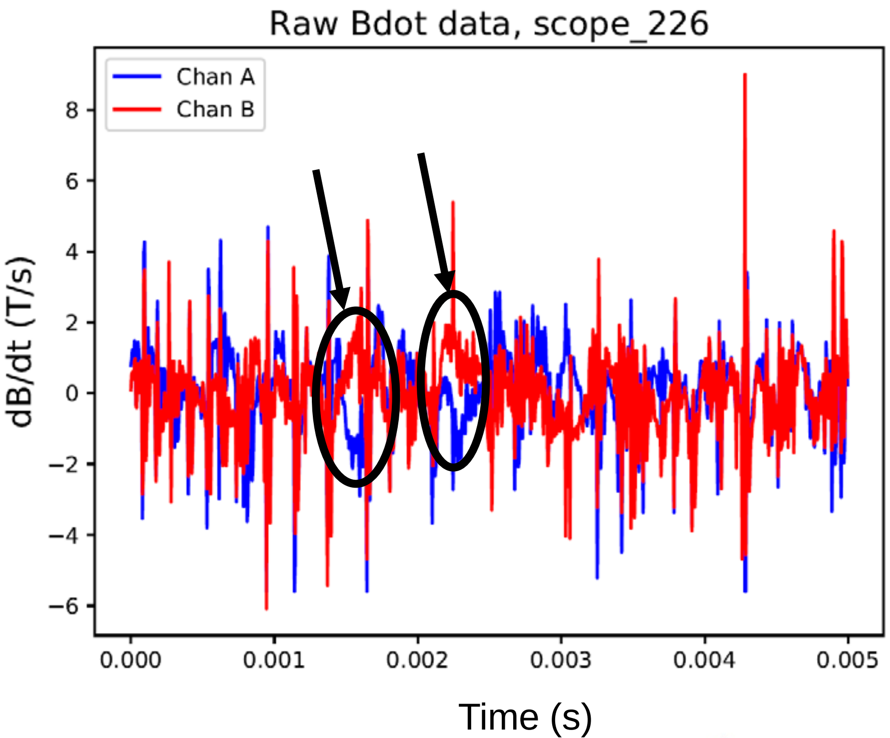
Probe Placement for Differential Measurements



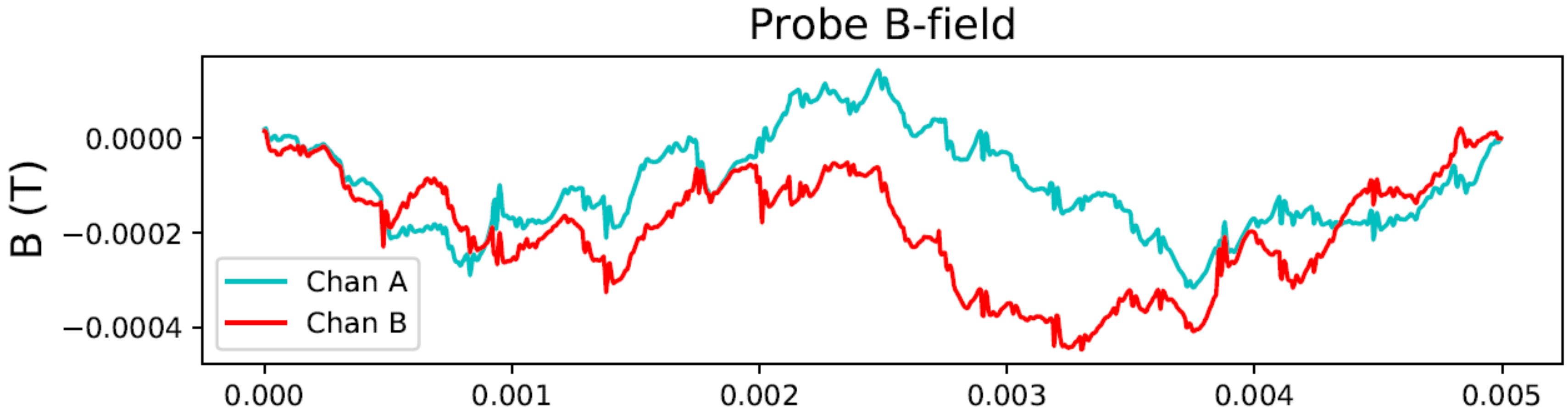


Raw probe data

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

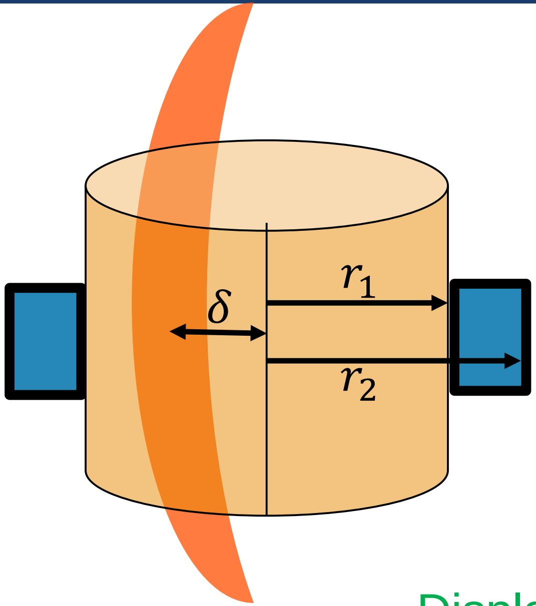


Differential Magnetic field



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

Inferring Current Channel Position



Coil B-field

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

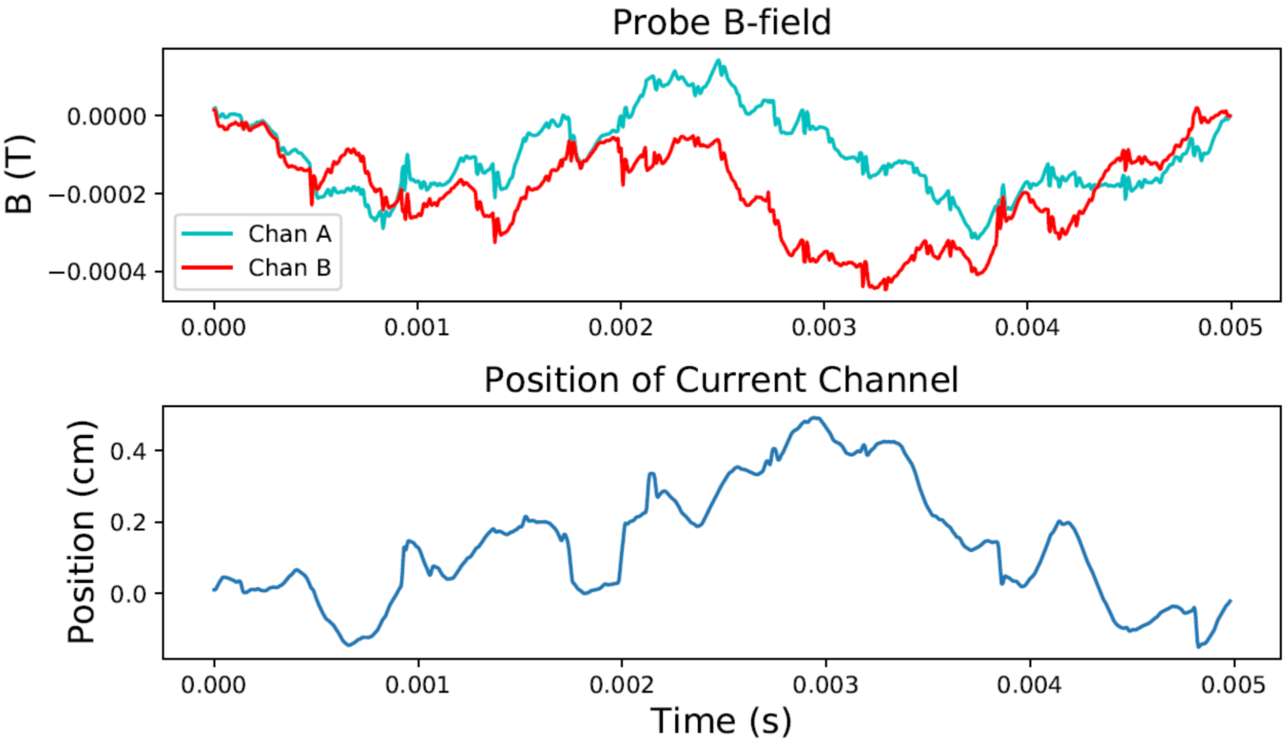
Differential B-field

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

Displacement from axis

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

Current Channel Position



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

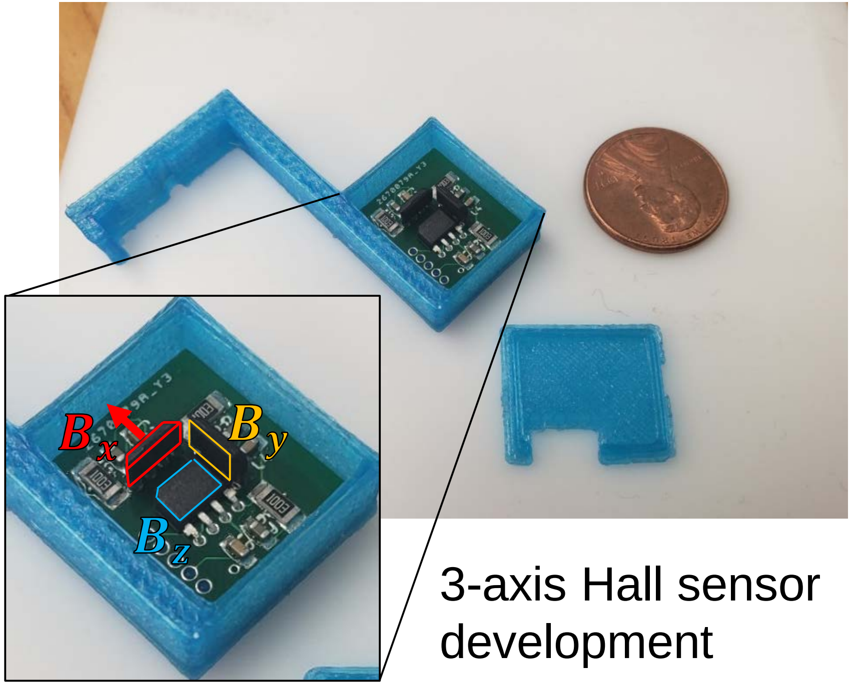
Discussion

- 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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- Nagi N. Mansour
- ARCHeS team
- Arcjet team
- Shock tube team
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Any Questions?

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