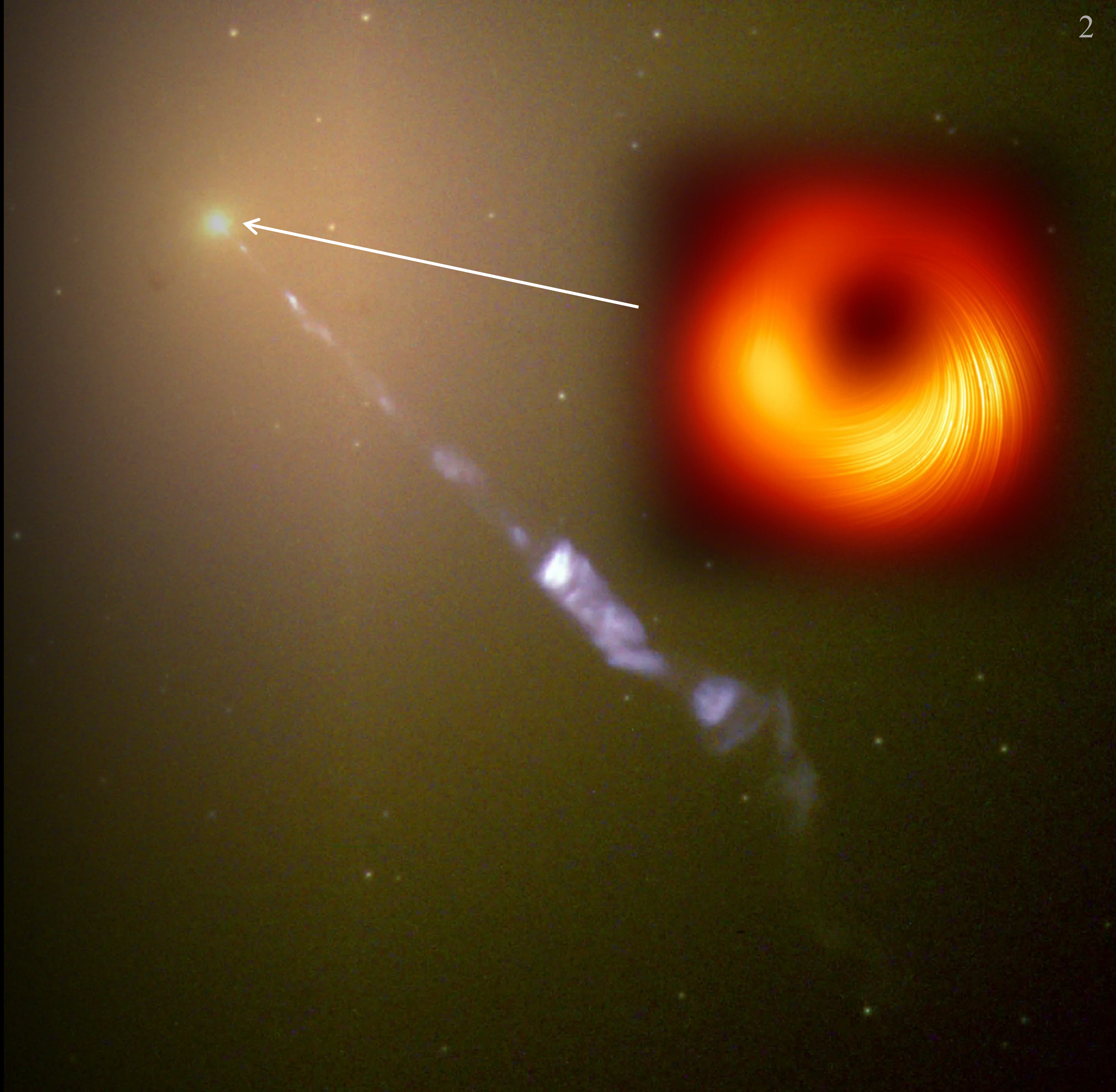
The New Mexico Liquid Sodium $\alpha - \omega$ Dynamo Experiment

Francisco Pedroza, Jiahe Si, Art Colgate

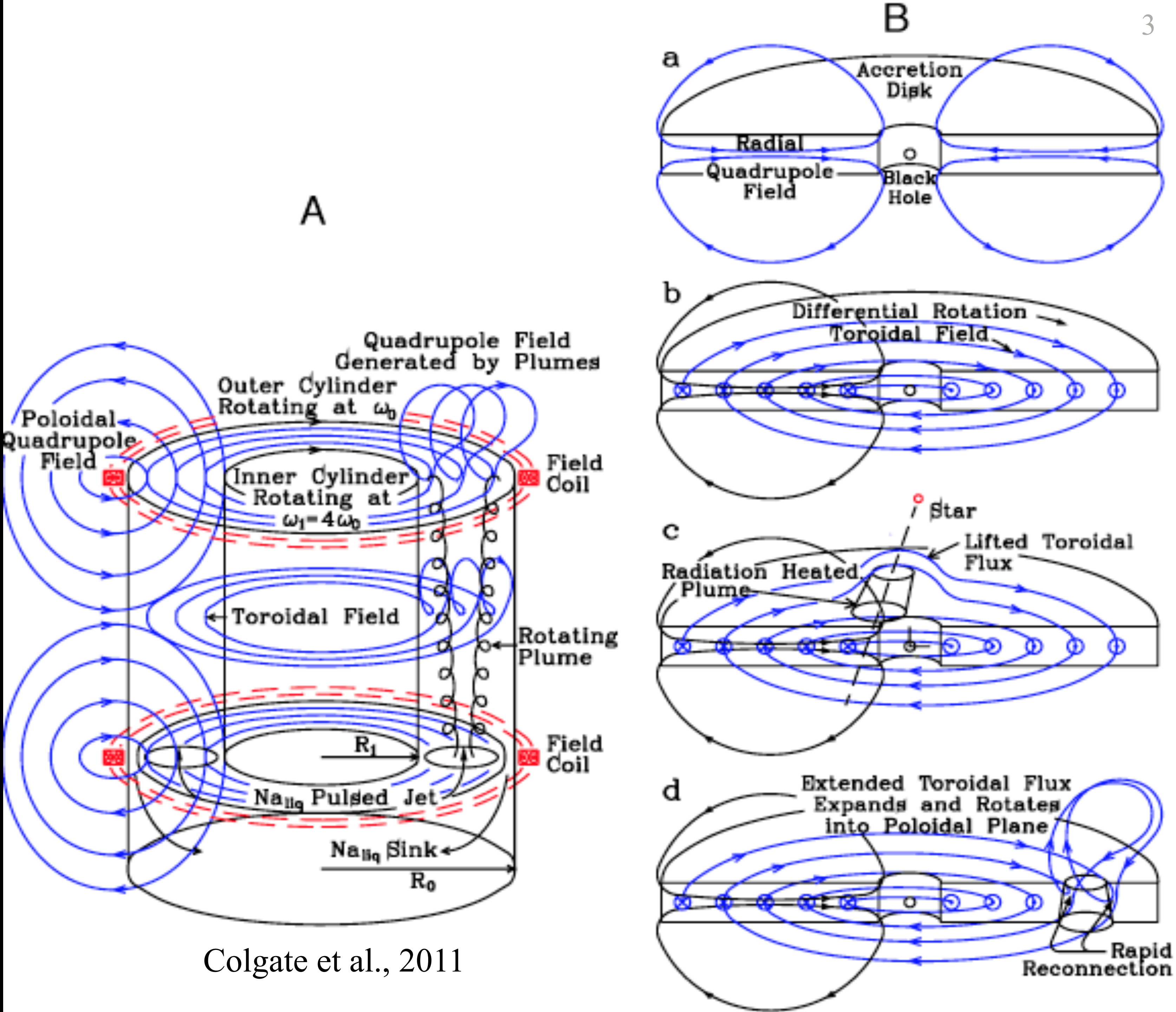
What is a Dynamo?

- The conversion of mechanical energy to electromagnetic energy
- The most popular dynamo: automobile alternator
  - Mechanically driven rotor generates AC current within stator (Faraday's Law)
- A bigger example: Earth
  - Large spatial B-field generated from complex fluid motions within the planet's core
- Galactic Accretion Disk Dynamos?
  - Plasma disk around SMBH
  - Keplerian flow profile $\Omega(r) \propto r^{-3/2}$
    - i.e. differential rotation
  - How can B-fields be generated and amplified in this MHD scenario?



Our Galactic Dynamo Model

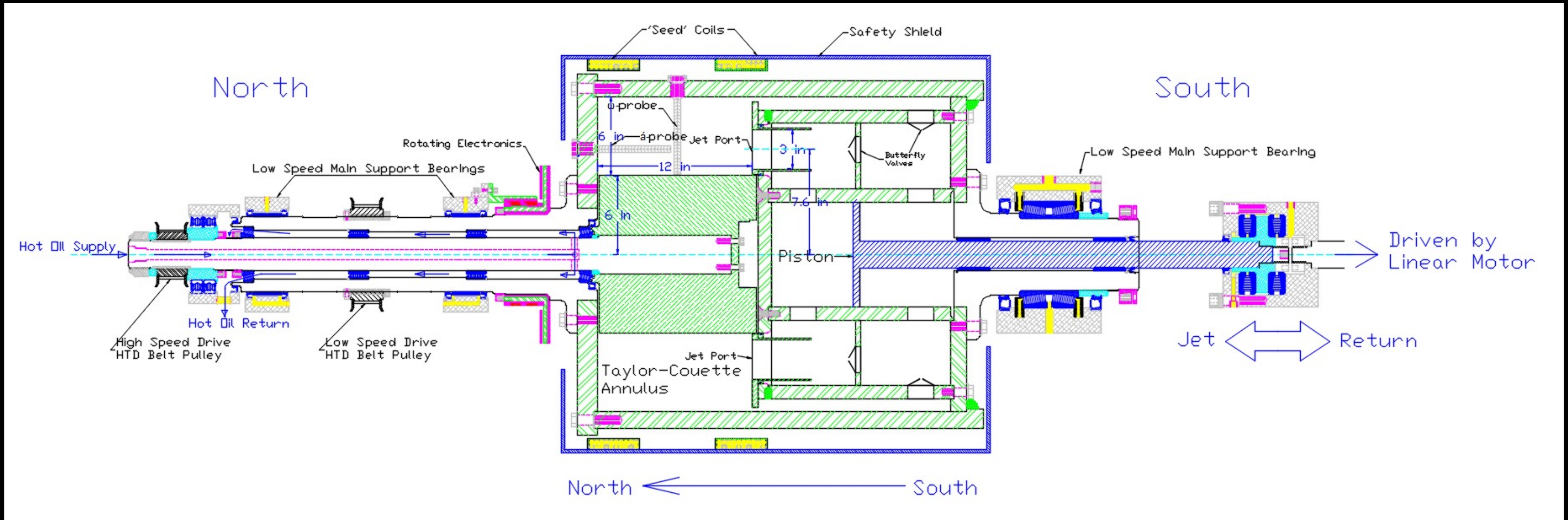
- A conversion of mechanical energy to magnetic energy *through the stretching and twisting of B-field lines.*
- ”Star-disk” collision
- $\alpha - \omega$ Dynamo process
  - ω-effect: amplification of a seed magnetic field through differential rotation
  - α-effect: conversion of the toroidal field to the poloidal field
  - A positive feedback loop
- $\omega_{gain} = B_{\phi}/B_{r,seed}$



Colgate et al., 2011

The Experiment

- Coaxial Drums
  - Establish a Taylor-Couette (TC) flow
  - $R_{in} = 15.25\ cm = 6\ in$ / $R_{out} = 2 \cdot R_{in}$ / $L_{TC} = 2 \cdot R_{in}$
  - $f_{in} = [0,70]\ Hz = [0,4200]\ RPM$ / $f_{out} = 1/4 \cdot f_{in}$
- Helmholtz Coils
  - Dipole or Quadrupole B-field configuration
  - Can toggle B-field polarity and strength
- Jet Pump Assembly
  - Piston powered by linear air motor
  - 2 or 4 plumes generated within TC annulus
  - Plume velocity and frequency easily adjusted
- DAQ System and Sensors
  - LabView control and DAQ – Stationary & Rotating Boards sampling at 2000 Hz.
  - A multitude of sensors…



Coaxial Drums

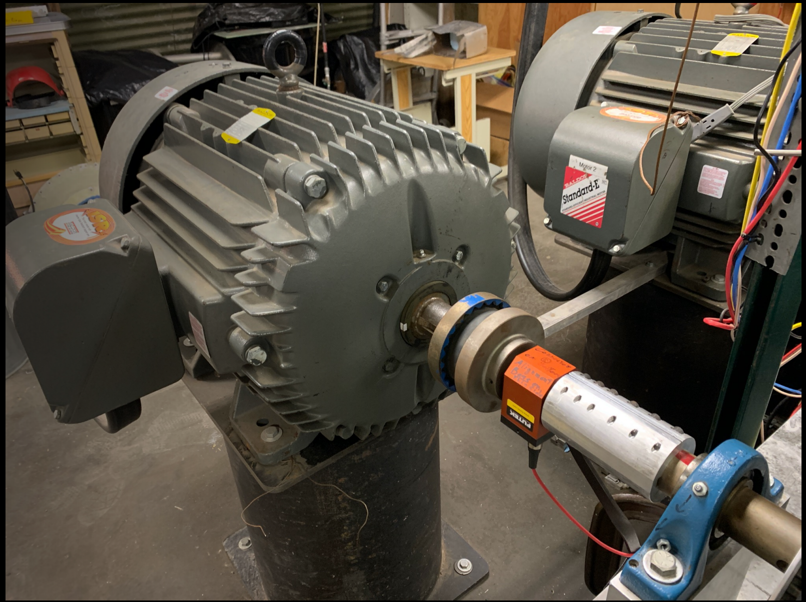
- The Drums
  - Each drum driven by 100 HP electric motor, controlled via Variable Frequency Drives (VFDs)
  - Scientific strain-gauge torque meters mounted on each motor-shaft
  - Tungsten-carbide mechanical seal separates hot oil supply and sodium
- The Taylor-Couette annulus
  - Responsible for establishing the ω-effect
  - 15.25 cm (6 in.) wide / 30.5 cm (12 in.) long
  - We can quantify the TC flow with Reynolds numbers
    - If $f_{in} = 70$ Hz and $f_{out} = 17.5$ Hz,

$$Re_{\omega} = \frac{2\pi(f_{in} - f_{out})(R_{out} - R_{in})^2}{\nu} = 1.09 \times 10^7$$

$$Rm_{\omega} = \frac{2\pi(f_{in} - f_{out})(R_{out} - R_{in})^2}{\eta} = 102$$

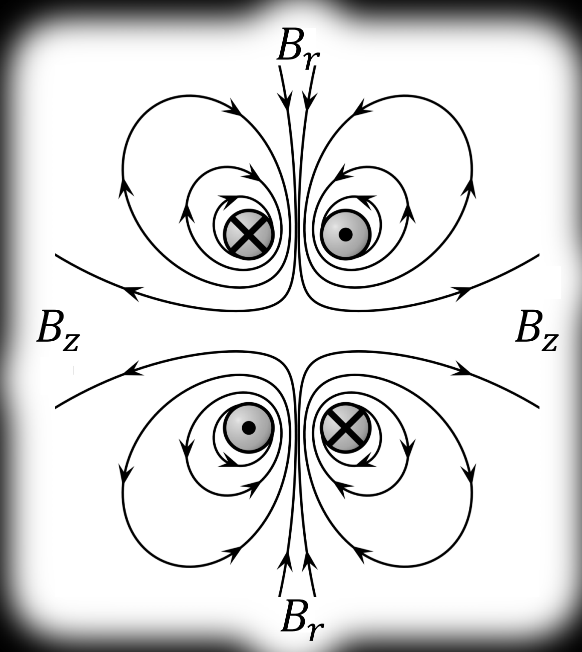
- For liquid sodium at ~110°C (230°F),

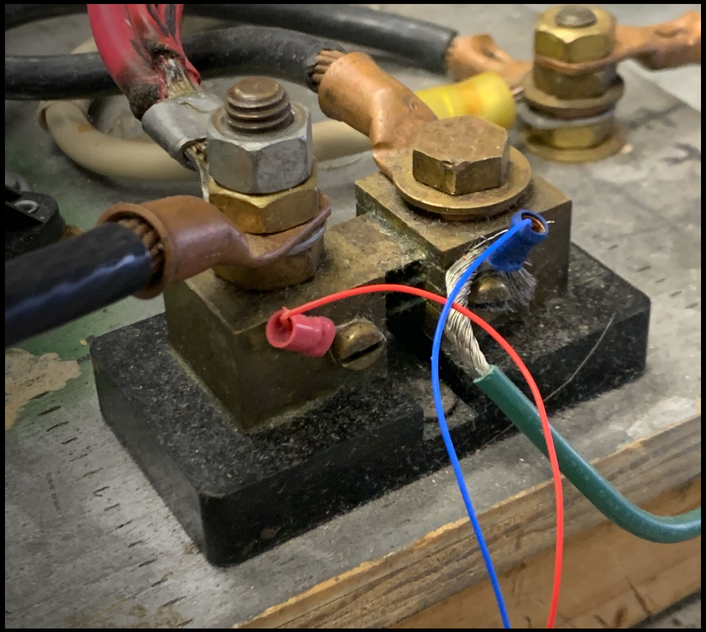
$\nu \cong 7\times10^{-3}\ cm^2/s$ and $\eta \cong 750\ cm^2/s$

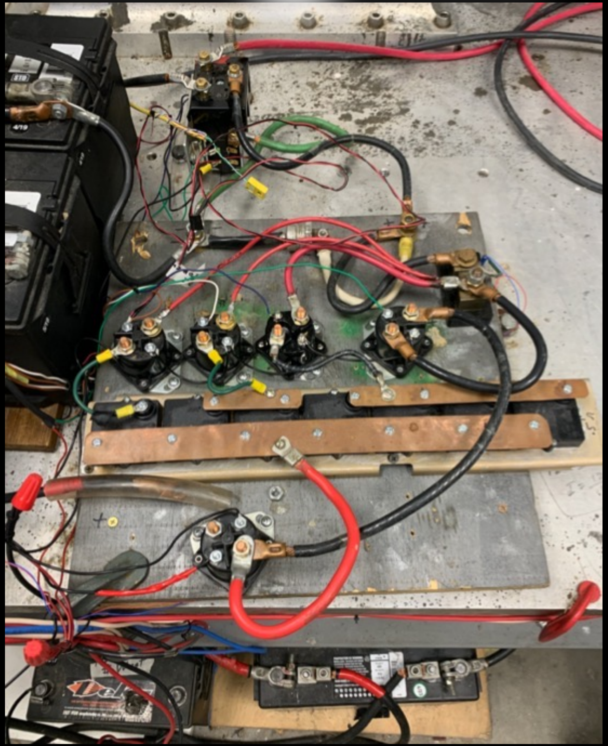


(Anti)-Helmholtz Coils

- The Coils
  - ‘Helmholtz’ = Dipole B-field
  - ‘Anti-Helmholtz’ = Quadrupole B-field
  - Provides a ‘seed’ field to the TC flow
  - Can toggle B-field topology, polarity, and strength
  - Produces quadrupole (radial in/out) or dipole ($\pm\hat{z}$) seed B-field
  - Four 12 VDC batteries in parallel (1000 Ah)
  - Four current settings using resistors (0.5 Ω) in parallel
    - Option 1: ~23 A
    - Option 2: ~42 A
    - Option 3: ~70 A
    - Option 4: ~210 A (‘direct short’)
  - New coils made with Kapton-coated #2 AWG mag wire
  - 20 turns each in a 2×10 layout
    - Combined resistance: ~0.05 Ω







Jet Assembly

- Piston powered by linear air motor
  - Driving pressure: 0 – 200 psi
  - Position (hence velocity) tracked by linear encoder
  - Maximum stroke of ~10 cm (4 in)
  - Relays control the duration and frequency of the piston
  - Recent observation: 40 psi yields $U_{piston} \sim 2.35\ m/s$ at $f_{jet} \sim 5.5$ Hz for 4 seconds
- Sodium Plumes
  - 2 or 4 plumes can be generated (requires minimal mechanical alteration)
  - Liquid sodium is incompressible
    - $U_{piston} \sim U_{jet}$ (for 4 plumes)
  - Complex 3D process; can quantify using Re and Rm
    - Plume twisting:

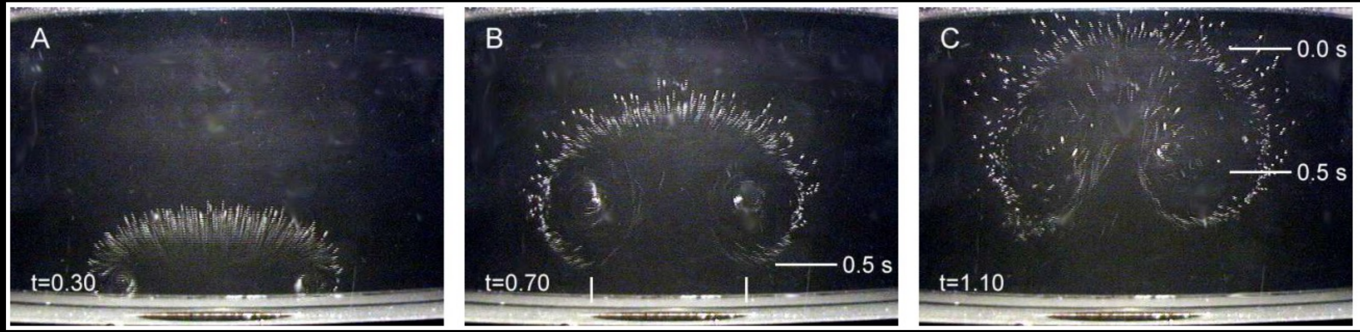
$$Re_{\alpha,twist} = \frac{L_{TC}(f_{in} + f_{out})\left(D_{port} + \frac{L_{TC}}{2\pi}\right)}{4\nu}$$

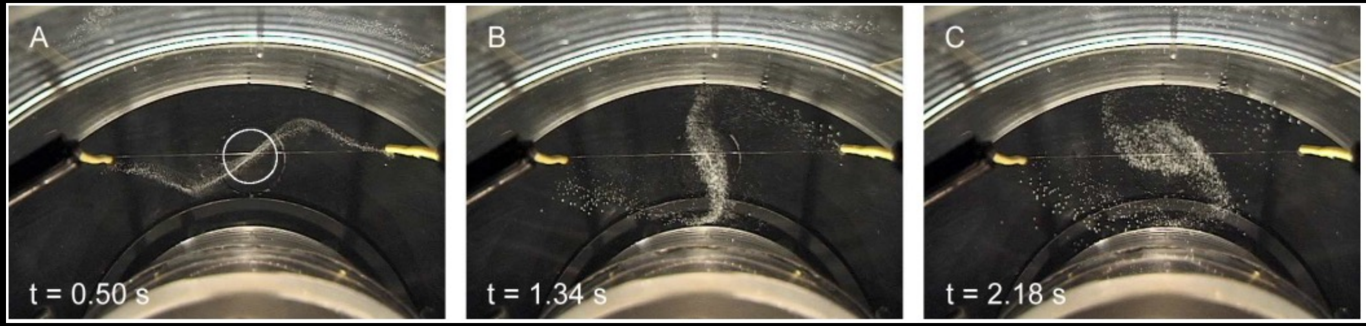
$$Rm_{\alpha,twist} = \frac{L_{TC}(f_{in} + f_{out})\left(D_{port} + \frac{L_{TC}}{2\pi}\right)}{4\eta}$$

    - Plume expansion:

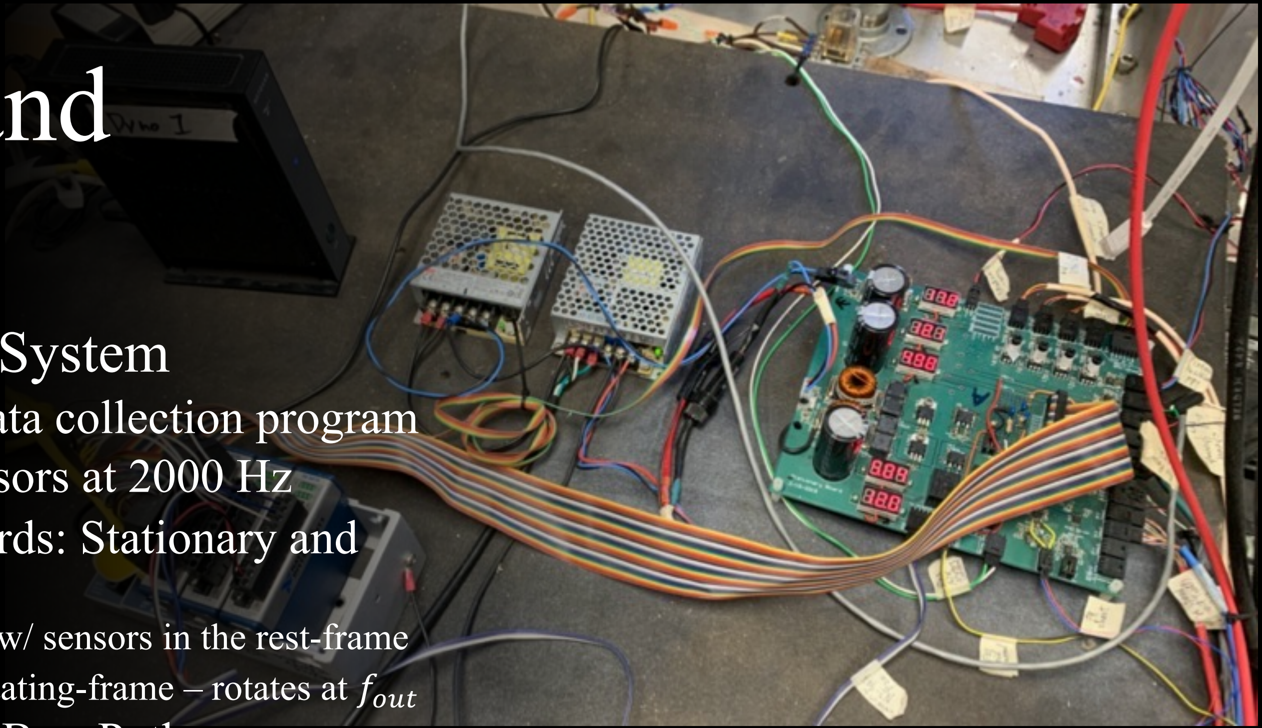
$$Re_{\alpha,expand} = \frac{U_{jet}\left(D_{port} + \frac{L_{TC}}{2\pi}\right)}{\nu}$$

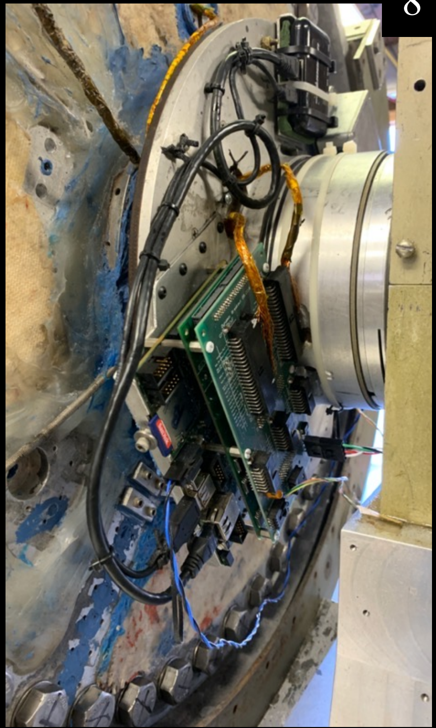
$$Rm_{\alpha,expand} = \frac{U_{jet}\left(D_{port} + \frac{L_{TC}}{2\pi}\right)}{\eta}$$



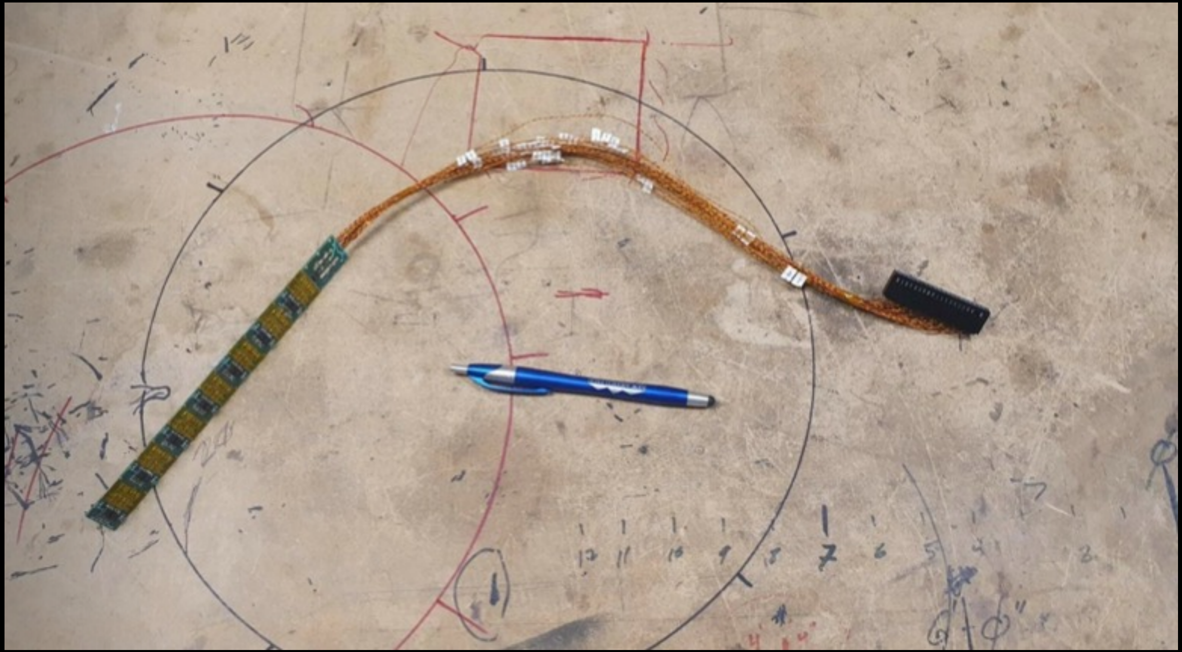


DAQ System and Sensors





- Data Acquisition (DAQ) System
  - A LabView control and data collection program
  - Records data from all sensors at 2000 Hz
  - Two main electronics boards: Stationary and Rotating
    - Stationary: communicates w/ sensors in the rest-frame
    - Rotating: sensors in the rotating-frame – rotates at f_{out}
  - Analysis done in MATLAB or Python
- The Sensor Suite
  - Stationary:
    - Tachometer (6), torque (2), shunt (1), air pressure (1), linear encoder (1), oil temp. (4), board voltage inputs (4)
  - Our "Eyes Inside"
    - 2 symmetric airfoil-shaped aluminum housings for electronics boards populated with Hall-Effect sensors (namely the α and ω-probe)
  - Rotating:
    - Hall-Effect sensitive to (B_r, B_ϕ, B_z) (42) (21/probe), sodium temp (4) (2/probe), outside 'skin' temp. (2), liquid pressure (9), 'skin' Hall-Effect (6), board voltage inputs (4)



Technical Aspects

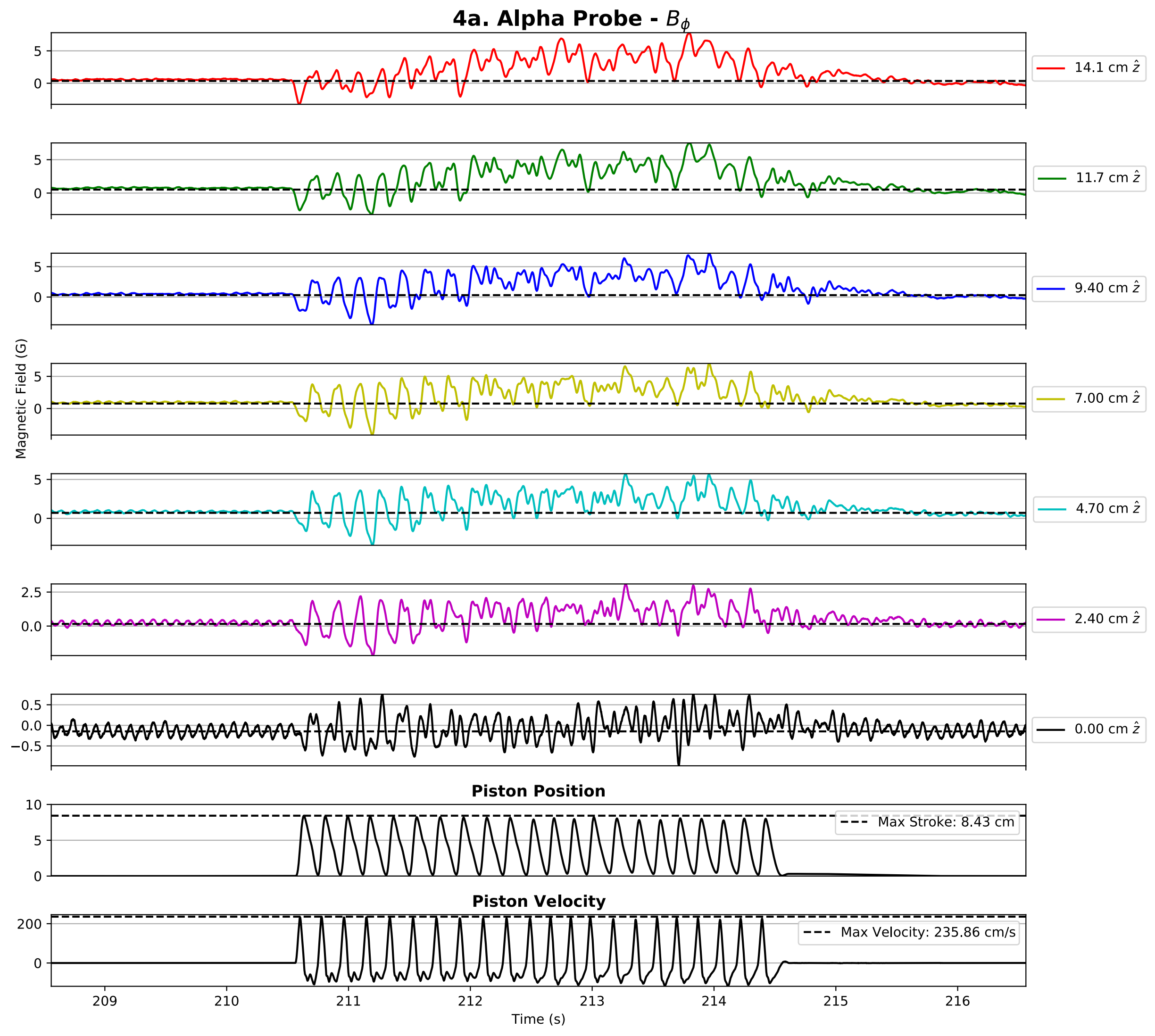
- Sodium (Na)
  - A fairly easily element to work with…
  - Temperature well-maintained at a ”low” 110°C (230°F)
    - Auto-combustion of liquid sodium in air occurs when T_{Na_l}~120°C (248°F)
    - Liquid sodium ‘freezes’ at T_{Na_l}~100°C (212°F)
    - As temperature increases, Re increases and Rm decreases
  - A good solvent – Denatured alcohol
  - For storage – Mineral oil and/or Argon
  - For handling – Argon
- Centripetal Forces
  - Steel safety shield for heating and mechanical failure
  - Al alloy 5083-H3 (high tensile strength~300 MPa)
  - Outer drum has a 3.2 cm (1.25 in.) thickness
  - Expected g-force ~ 375 at R_{out} with $f_{out} = 17.5$ Hz
  - 138 kg (305 lbs) of liquid Na with an outward pressure of 827 kPa (120 psi) at $f_{in} = 4 \cdot f_{out} = 70$ Hz
  - ‘Galactic jake brake’ for outer cylinder

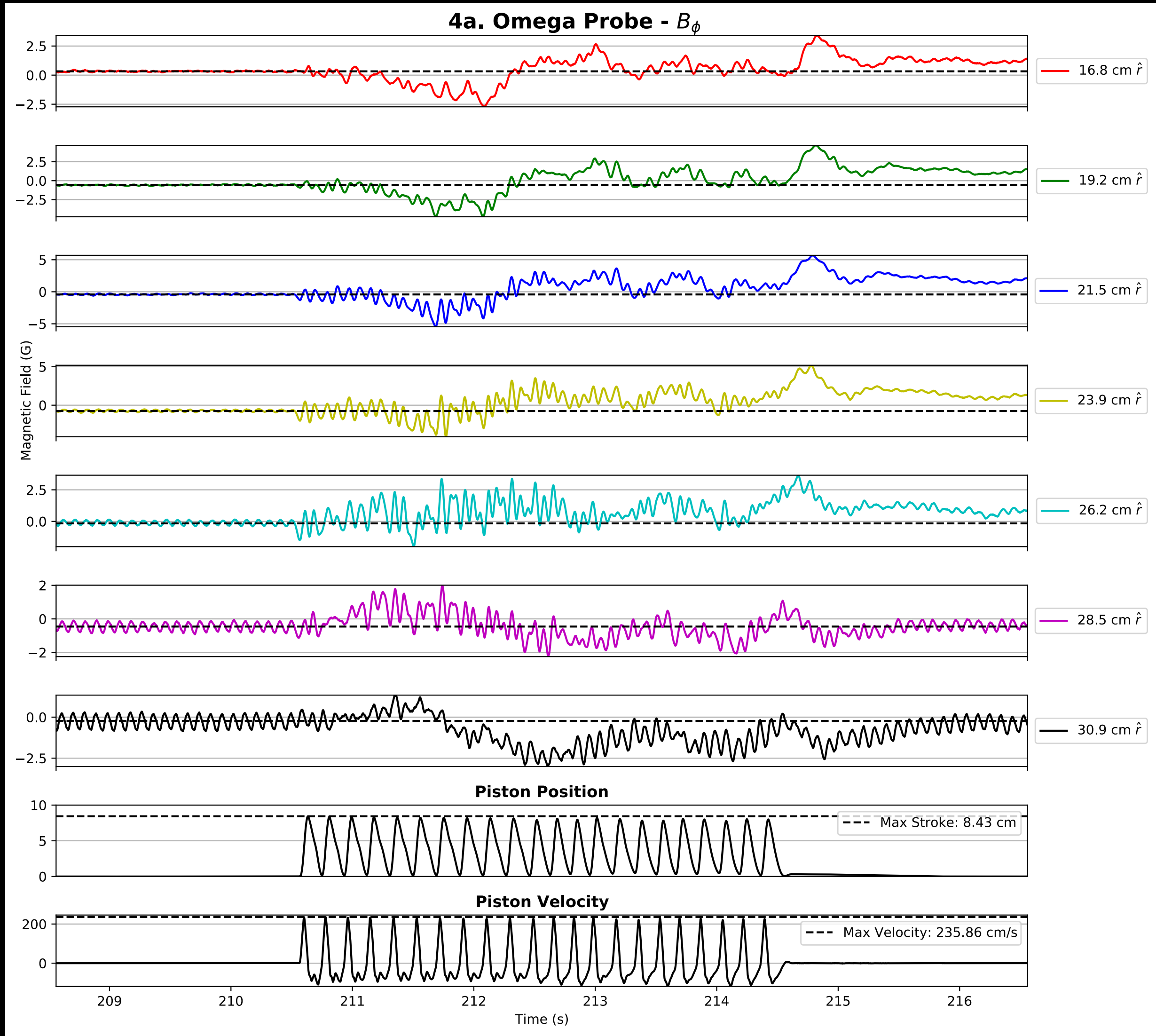
Property	Sodium (Na)
Melting Point	97.8°C
Boiling Point	883°C
Density	0.927 g/cm^3 (l)
Kinematic Viscosity (ν)	7×10^{-7} m^2/s ($\sim110°C$)
Magnetic Diffusivity (η)	0.075 m^2/s ($\sim110°C$)
Electrical Conductivity	$\sim10^7$ S/m ($\sim110°C$)

Preliminary Results

- Solid Body + Jet (August 2023)

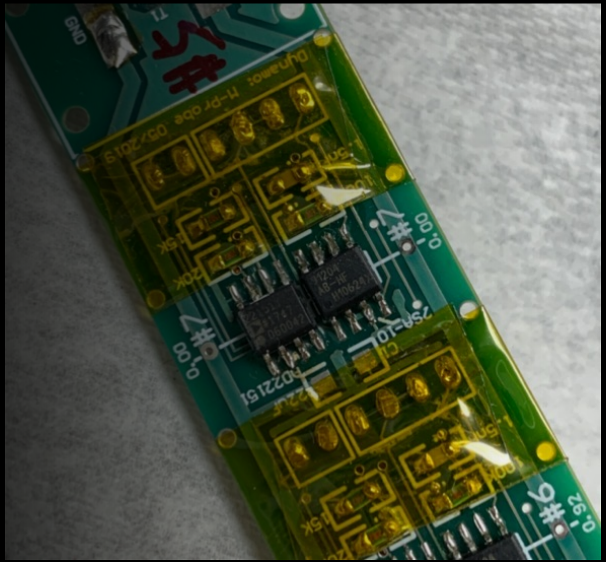
$$f_{in} = f_{out} = 10.5\text{ Hz}, f_{jet} \sim 5.5\text{ Hz}, f_{sample} = 2000\text{ Hz}$$
$$Rm_{\omega} = 0, Rm_{\alpha,twist} = 2.67, Rm_{\alpha,expand} = 3.92$$

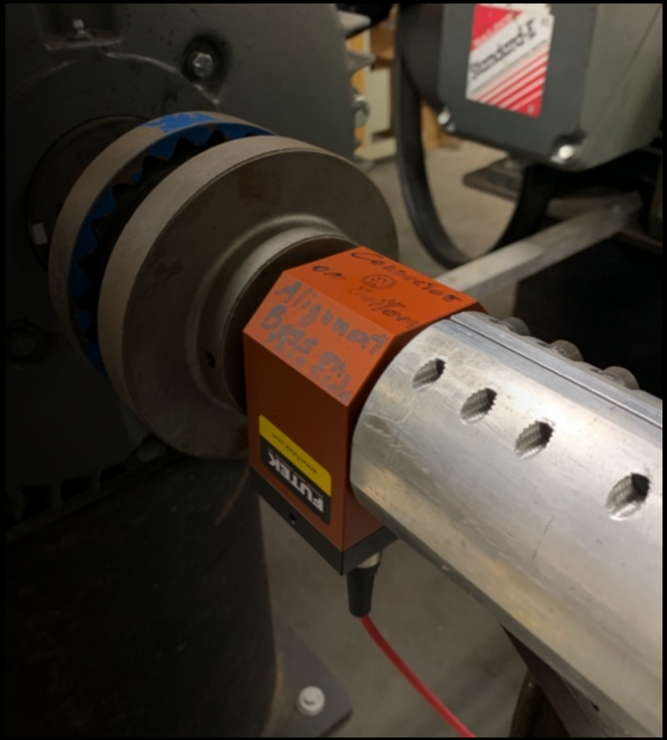




Our Experimental Realm

- ω-effect
  - Differential rotation at varied f_{in}/f_{out}
  - Quadrupole seed field (radial in/out)
  - No jet influence
- $\alpha - \omega$ dynamo
  - Differential rotation at varied f_{in}/f_{out}
  - Quadrupole seed field (radial in/out)
  - Active jet motor at f_{jet}
- Possibly the MRI
  - Differential rotation at varied f_{in}/f_{out}
  - Dipole seed field ($\pm\hat{z}$)
  - Increase strength of seed B-field ($\lesssim$3000 G)
  - No jet influence – change port plate with 0 ports





Acknowledgements

- Government funding through NSF
- Funding from the Department of Energy through Los Alamos National Labs
- Funding from the state of New Mexico through New Mexico Tech
- Private donors
- Stirling Colgate – Designer of the experiment
- Howard Beckley – Former NMT PhD student who presented the experiment's fluid dynamics
- Jiahe Si – Current Principle Investigator and developer of the DAQ system
- Art Colgate – Current Project Manager and industrial engineer
- Many former faculty, graduate, and undergraduate students (~30)

For more, visit http://kestrel.nmt.edu/~dynamo/