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Hall Thruster Langmuir Probe Analysis, Helmholtz Coil Design, and EMIM-BF4 Electrical Conductivity Testing

Electric Propulsion Research Internship Report – Summer 2020

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Co-op Sierra Lobo, Inc. AFRL/RQRS

Agenda

- Background
- Analysis of Hall Thruster Plasma Properties using Langmuir Probe Data
- Helmholtz Coil Design for EP TEMPEST
- Electrical Conductivity Testing Updates
- Conclusions

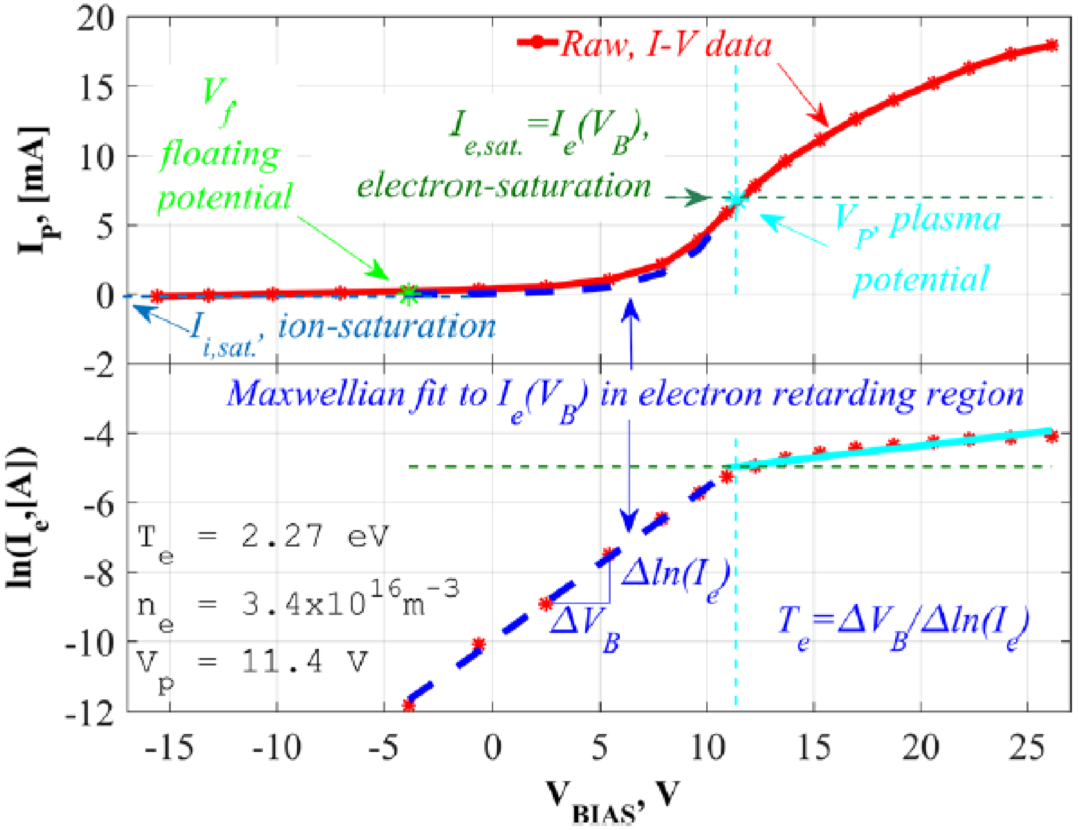
Background

- Education
  - University of Illinois at Urbana-Champaign: Mechanical Engineering (4th Year Undergraduate)
- Undergraduate Experience
  - Undergraduate Research Assistant, UIUC Electric Propulsion Laboratory
  - Project Manager, Hybrid Rocket Engine Project
  - Mechanical Dynamics Lead, Illini Solar Car
- Work Experience
  - Propulsion Engineering Intern, Agile Space Propulsion
  - Mars 2020 Mechanical Engineering Intern, NASA JPL

Hall Thruster Langmuir Probe Analysis

Langmuir Probes

- Langmuir probe is a small electrode immersed within a plasma, measuring the current drawn by the plasma for a range of bias voltages
- Plasma properties mapped by collected Langmuir data across an array of locations within Hall thruster exhaust plume
- I-V Characteristic Curve is created for each collection location
- Plasma properties are derived from identifiable regions on I-V Curve



Lobbia, Robert B. and Beal, Brian E. *Recommended Practice for Use of Langmuir Probes in Electric Propulsion Testing*. The American Institute of Aeronautics and Astronautics, Journal of Propulsion and Power, 2017.

Langmuir Probe Theory Conditions

Langmuir probe theory requires the following conditions to be met:

1. $\frac{T_i}{T_e} \ll 1$
2. Electrons at or near thermal equilibrium (verified by Maxwellian velocity distribution)
3. Collisionless plasma: $K_n = \frac{\lambda}{r_p}$
4. Electrostatic: $\frac{dB}{dt} \approx 0$
5. Nonmagnetized: $\frac{r_{L,e}}{r_p} \gg 1$
6. Quasi-neutral: $n_i \approx n_e$
7. Isotropic and homogenous

- Thin sheath assumption, $A_s = A_p$, valid when thin sheath ratio, $\frac{r_p}{\lambda_D}$, $\gtrsim 50$

Langmuir Probe Analysis Algorithm

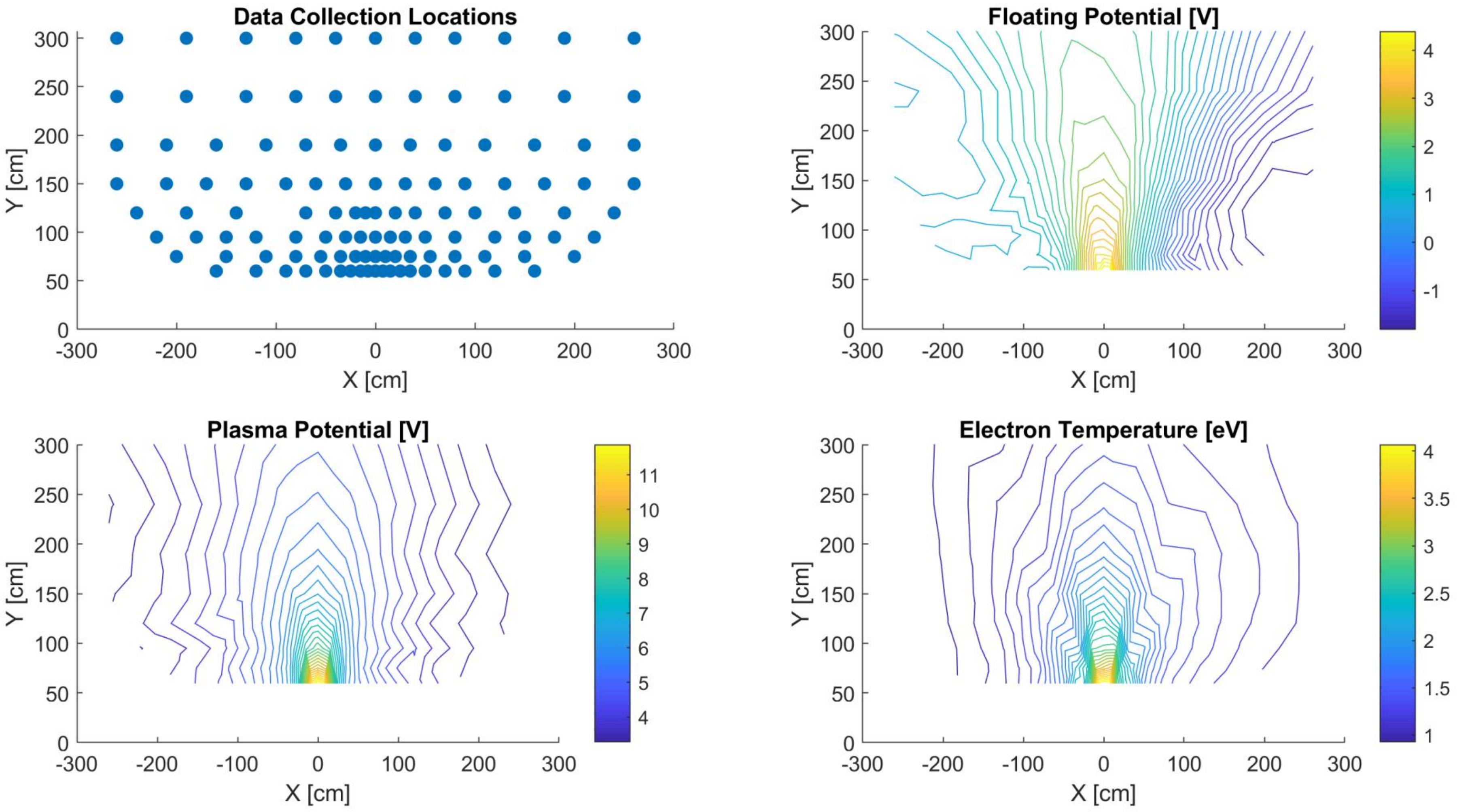
Based upon work described by Lobbia & Beal in *Recommended Practices for Use of Langmuir Probes in Electric Propulsion Testing* (2017)

1. Scan Langmuir probe voltage from large negative to positive voltage. Measure probe bias voltage V_B and probe current I_{probe}.
2. Voltage within ion saturation region where first $I_{probe} = 0\ A$, is the floating potential V_f
3. Create linear fit to I-V characteristic curve below V_f, defined as ion saturation curve, $I_{i,sat}$
4. Compute electron current as $I_e = I_{probe} - I_{i,sat}$
5. If necessary, apply numerical smoothing, then compute first derivative of I_e, $dI_{e,smoothed}/dV_B$. Voltage at maximum value of this derivative is the plasma potential, V_p
6. Create a linear fit to the plot of natural log of I_e vs. V_B. The electron temperature, T_e, is the inverse of this slope, $(\mathrm{d}\, ln\, I_e\, /dV_B)^{-1}$
7. Compute the electron density as $n_e = \left(\frac{I_{e,sat}}{eA_p}\right)\sqrt{\frac{2\pi m_e}{eT_e}}$, where $I_{e,sat} = I_e(V_p)$, $m_e = \text{electron mass}$, $e = electron\ charge$, and $A_p = probe\ area$
8. Compute ion density as $n_i = \frac{-\exp(1/2) I_{i,sat}}{eA_s v_i}$, where ion voltage $v_i = \sqrt{\frac{2eV_d}{m_i}}$, sheath area $A_s = A_p$ under thin sheath assumption, $m_i = ion\ mass$, and $V_d = thruster\ discharge\ voltage$
9. Compute Debye length as $\lambda_d = \sqrt{\frac{\varepsilon_0 T_e}{n_e e}}$, where $\varepsilon_0 = permittivity\ of\ \text{free space}$
10. Compute sheath ratio $\frac{r_p}{\lambda_d}$ to determine applicable sheath expansion correction. Thin sheath assumption valid when $\frac{r_p}{\lambda_d} \gtrsim 50$, where $r_p =\ probe\ radius$

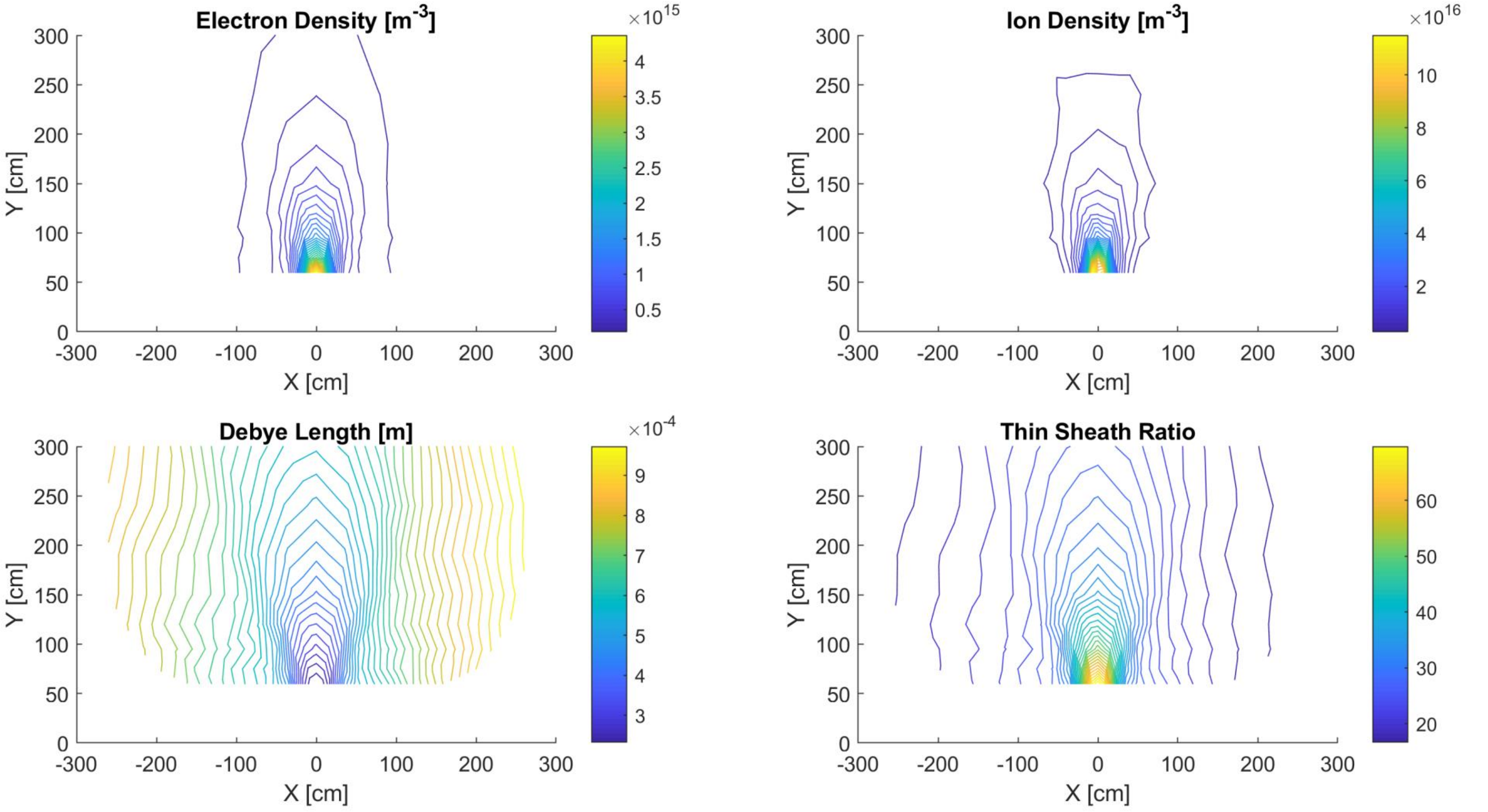
Model Notes

- Testing
  - Data collected on single guarded Langmuir probe with diameter of 9.5 mm
  - 118 collection locations across a 6m x 3m area
  - Bias voltage swept from -20 V through 15 V
  - Hall Thruster operating at:
    - Discharge voltage: 300 V
    - Anode flowrate: 25 sccm (standard cubic centimeters per minute)
- Data Analysis
  - Savitzky-Golay filter applied for smoothing raw data noise

Contour Plots



Contour Plots



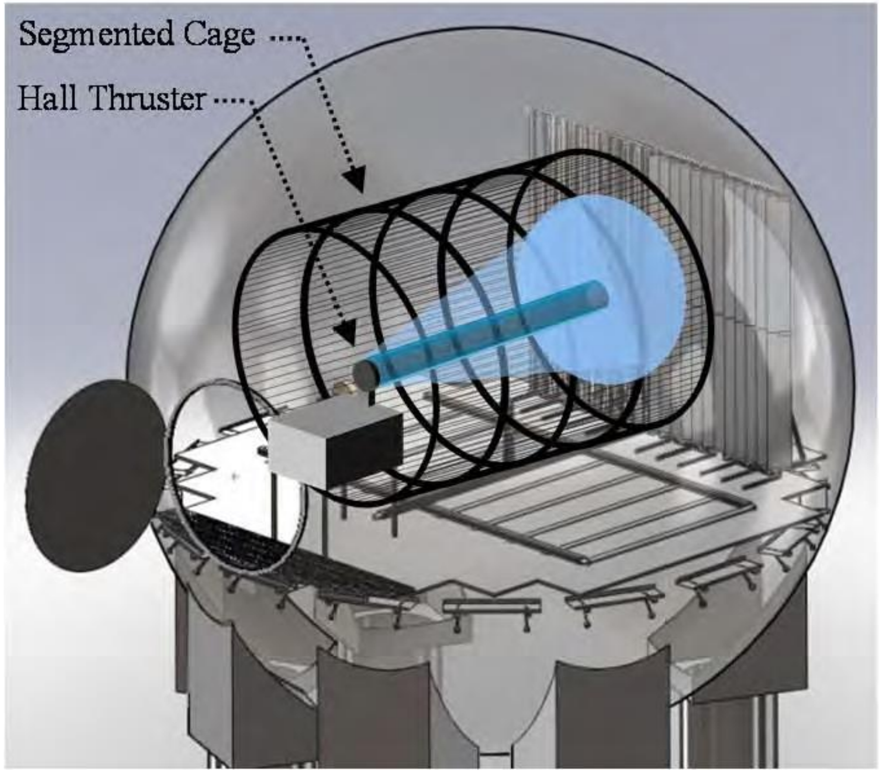
Langmuir Probe Future Work

- Model currently uses preliminary assumptions and relations which can be developed for greater accuracy
- Exhaust plume distribution is asymmetric (best shown by floating potential map), possibly due to numerous external conditions
  - One possible cause of asymmetry is the effect of Earth's magnetic field in vacuum chamber
  - Conducting tests without the effect of Earth's field could fix this issue or rule out Earth's magnetic field as a possible cause

Helmholtz Coil

Helmholtz Coil Theory

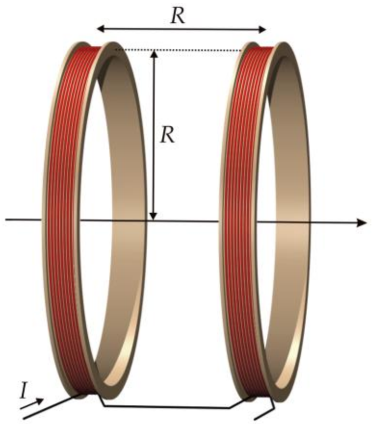
- Helmholtz coils will be used to create a region of uniform magnetic field to cancel out the effect of Earth's magnetic field on plume exhaust
  - Investigating whether Earth's magnetic field is responsible for asymmetric distribution of plasma shown in Langmuir data analysis
- EP TEMPEST investigates vacuum chamber interactions on Hall thruster plasma plumes to replicate accurate space environments
- AFRL SPace Environmental Facility (SPEF) vacuum chamber houses EP TEMPEST and will host this Helmholtz Coil around the outside of the chamber walls

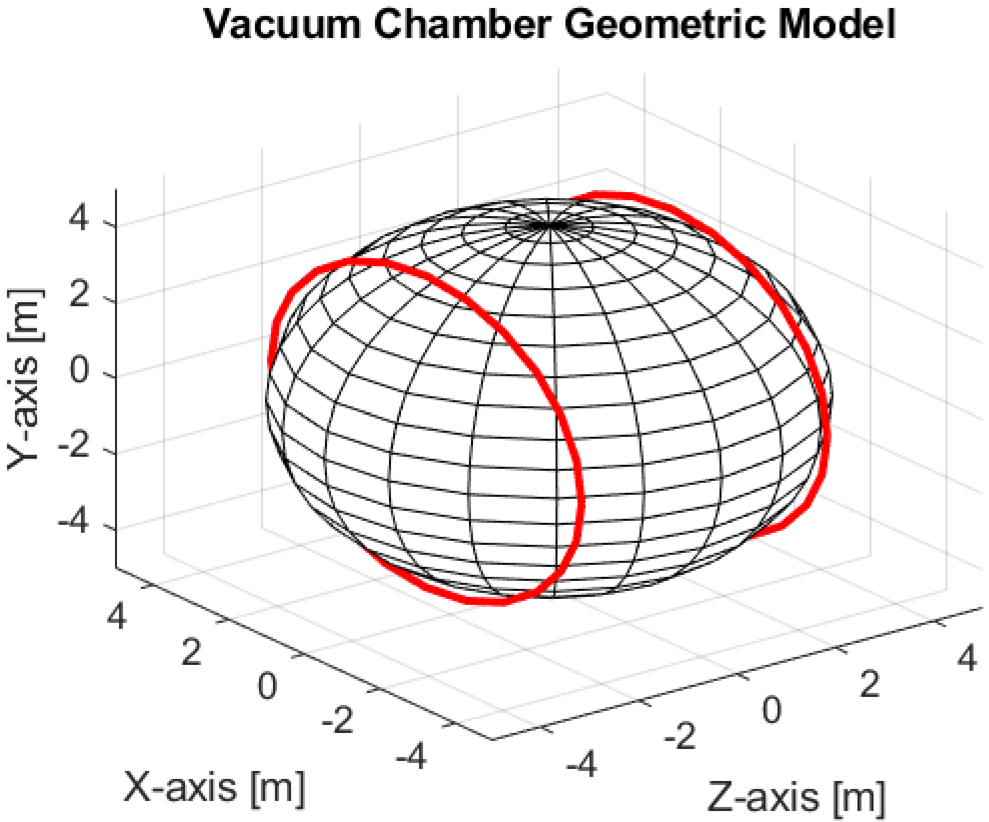


Brown, Daniel L. *Electric Propulsion Test & Evaluation Methodologies for Plasma in the Environments of Space and Testing (EP TEMPEST) – Program Review*. AFRL/RQRS, AFOSR T&E Annual Program Review, 2015.

Helmholtz Coil Design

- Two electromagnetic coils on the same axis
  - Magnetic field vector points along this axis
- Distance of one coil radius between each coil
- Design parameters:
  - Vacuum chamber spherical radius: 4.57 m (15 ft)
  - Coil radius: 4.12 m
  - Coil position: 2.06 m off chamber center
- SPEF walls made of stainless steel and have negligible effect on magnetic field





Earth’s Magnetic Field at AFRL Edwards AFB

- Earth’s magnetic field strength at surface commonly ranges from 25-65 μT
- During coil assembly, coil central axis will be rotated to align with direction of Earth’s field
- Earth’s magnetic field data collected from NOAA’s Magnetic Field Calculator for testing location at AFRL

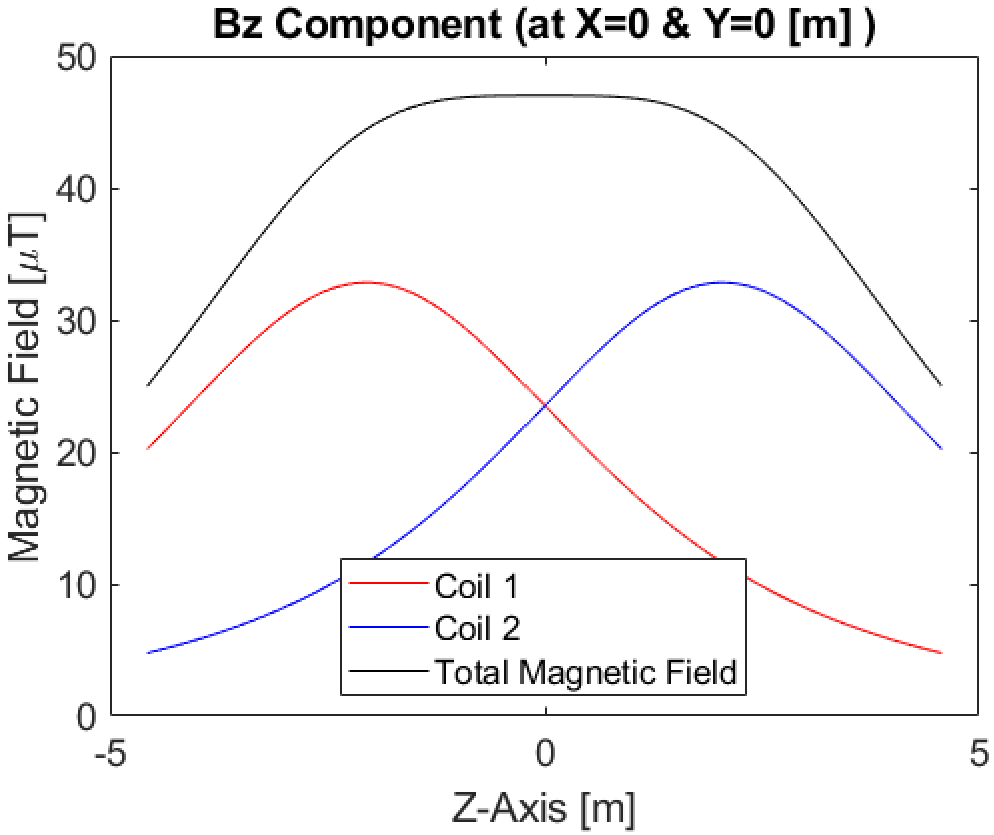
Magnetic Field

Model Used:	WMM-2020
Latitude:	34.926890° N
Longitude:	117.697023° W
Elevation:	0.0 km Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2020-08-12	11.8537°	59.7293°	23,777.9 nT	23,270.8 nT	4,884.3 nT	40,738.9 nT	47,170.3 nT
Change/year	-0.0887°/yr	-0.0027°/yr	-47.6 nT/yr	-39.0 nT/yr	-45.8 nT/yr	-85.8 nT/yr	-98.1 nT/yr
Uncertainty	0.35°	0.21°	128 nT	131 nT	94 nT	157 nT	145 nT

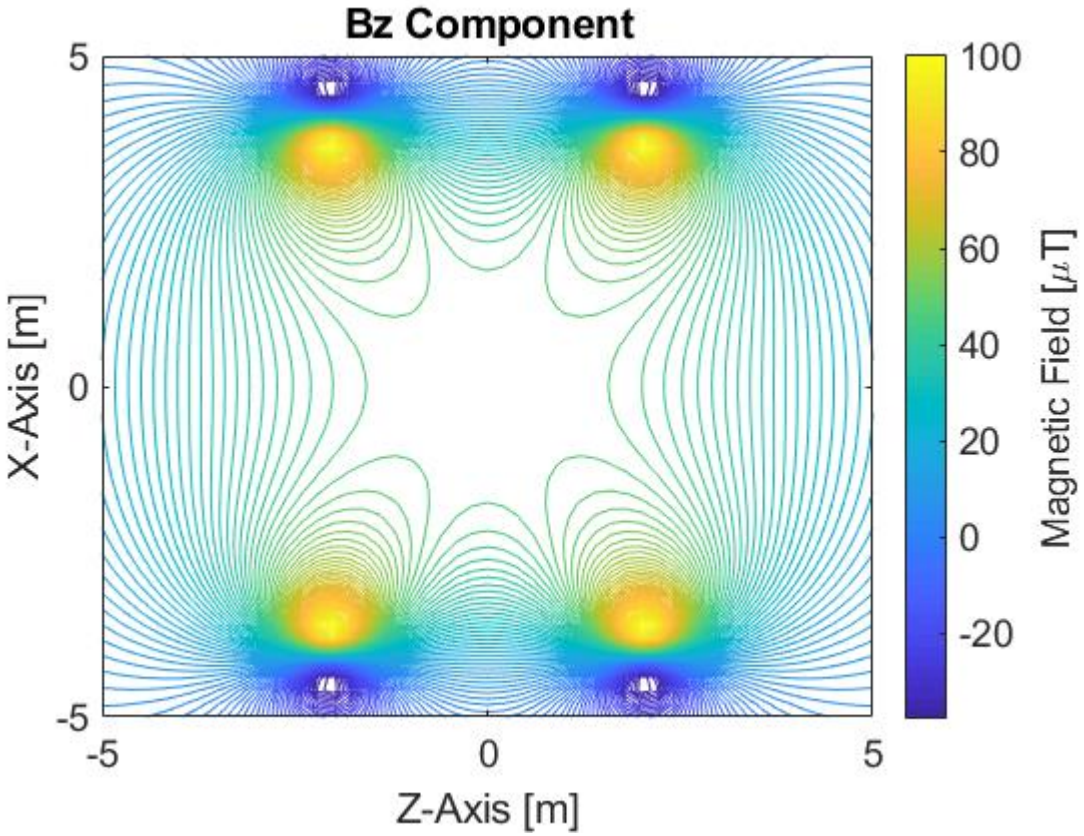
1-Dimensional Model

- Magnetic field calculations based on simplified Biot-Savart Law
  - $B = \frac{\mu_0 I_n R^2}{2(R^2+Z^2)^{3/2}}$
- I_n represents the wire current-turn product
  - Product of current and number of turns of wire in each coil
  - Given Earth's magnetic field with coil of this size, $I_n \approx 214\ \mathrm{A}$
  - Ex.: 12 AWG at 17.8 A and 12 turns



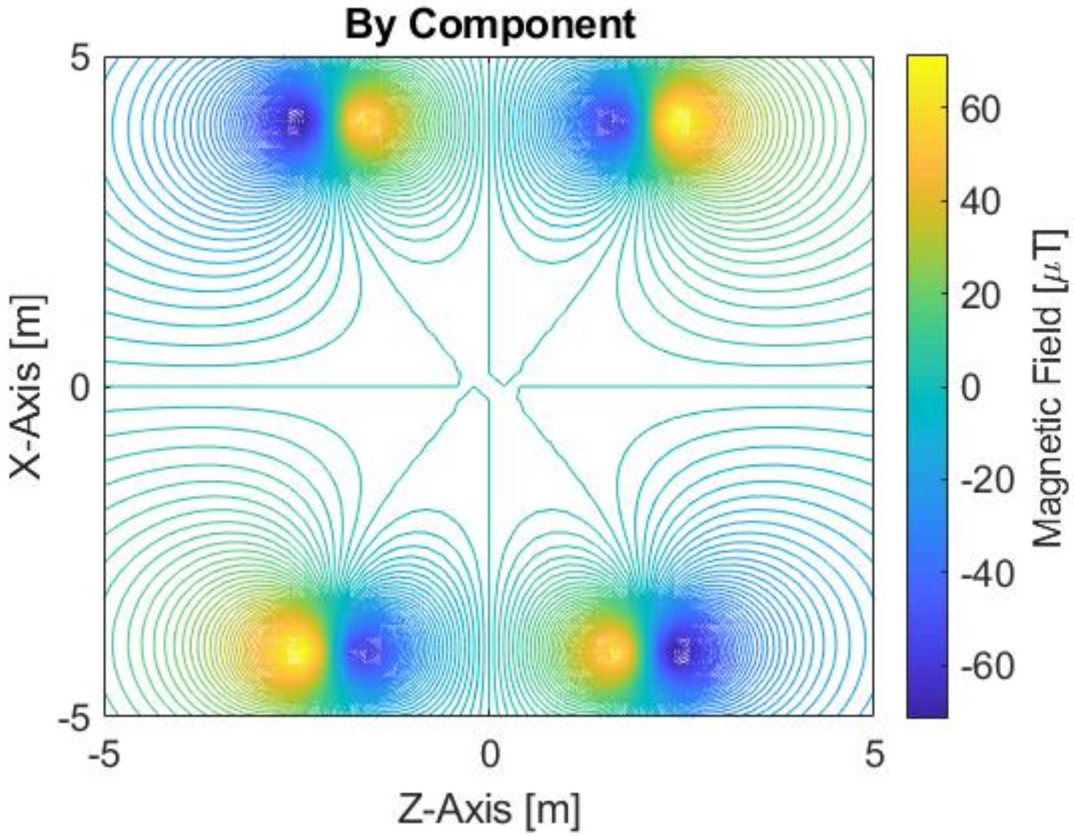
2-Dimensional Model

- Long-form Biot-Savart Law
  - $dB = \frac{\mu_0 I_n dL}{4\pi r^2}$
  - dL is integrated over length of coil
  - r is a vector from dL to mapped location
- Z-axis component through coil center
  - $dB_z = \frac{\mu_0 I_n (dL_x Y - dL_y X)}{4\pi r^3}$



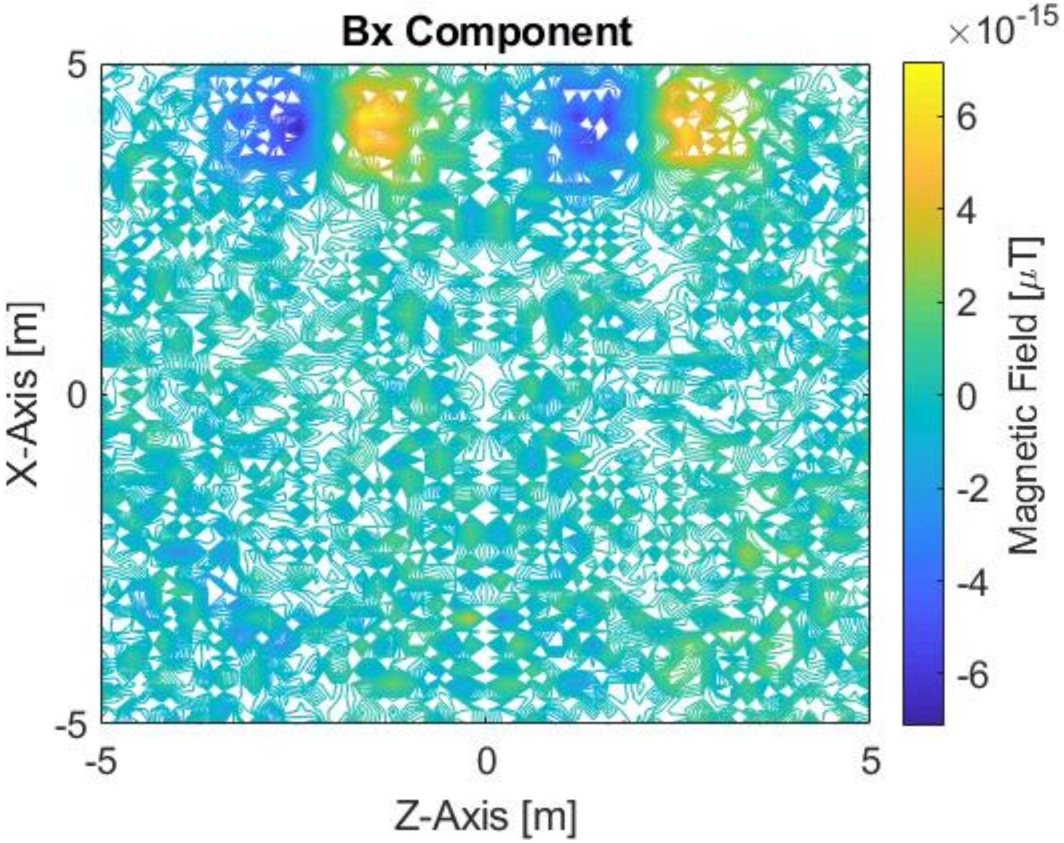
2-Dimensional Model

- Y-axis vertical component
  - $dB_y = \frac{\mu_0 I_n (dL_x Z)}{4\pi r^3}$



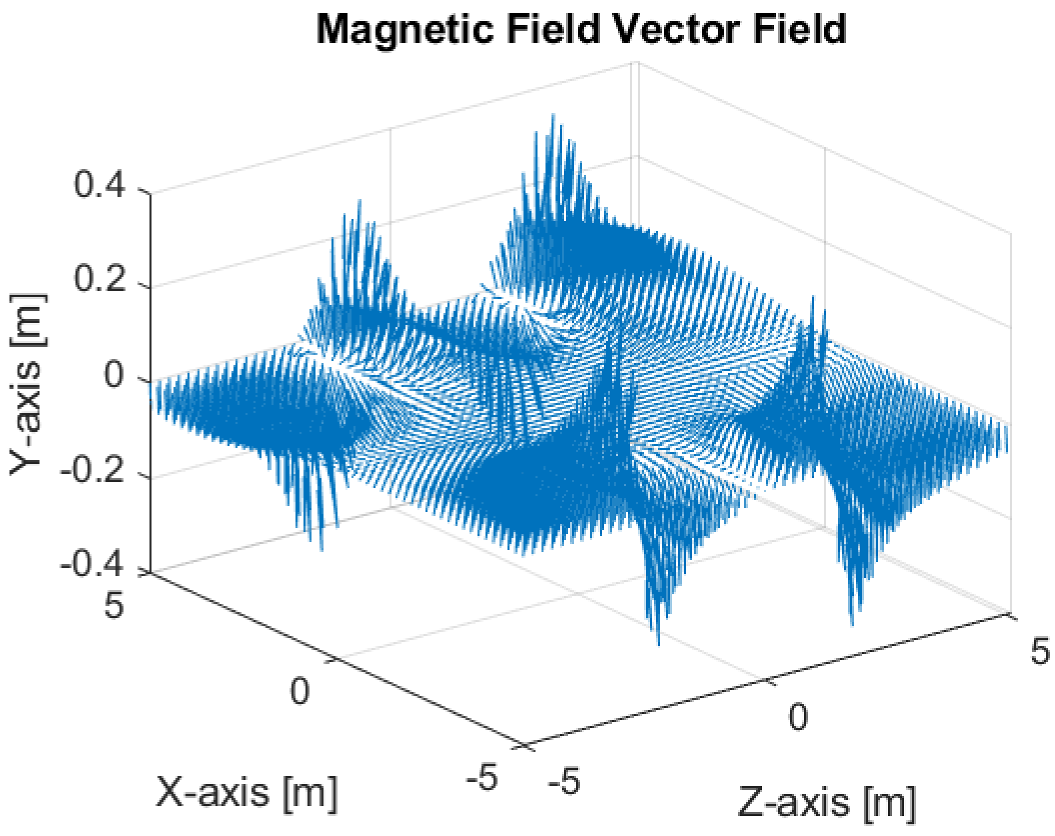
2-Dimensional Model

- X-axis component perpendicular to coil center axis
  - $dB_x = \frac{\mu_0 I_n (dL_y Z)}{4\pi r^3}$



Magnetic Field Vector Field

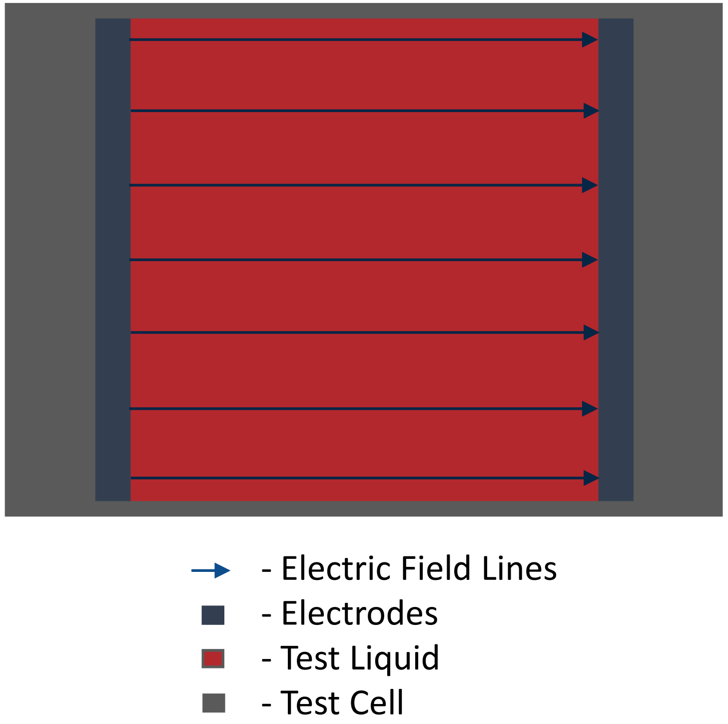
- Wide region of uniform magnetic field in center of vacuum chamber along positive Z-axis
- Coil center axis will be rotated to match direction of Earth’s magnetic field vector at EP TEMPEST testing location upon assembly

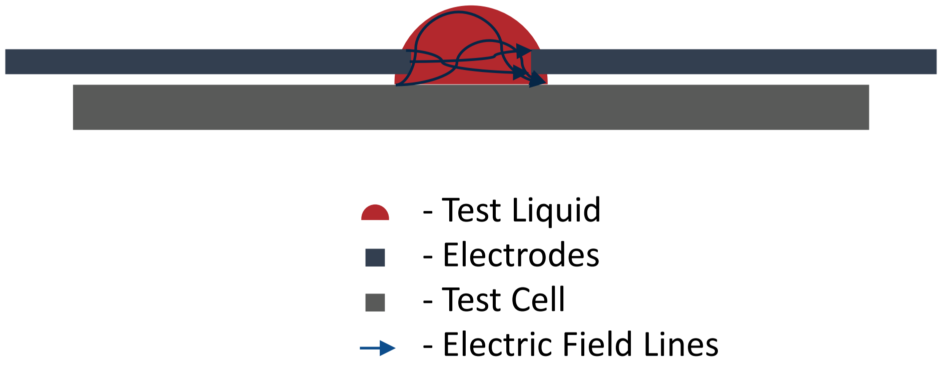


Electrical Conductivity Testing

Previous Work

- Previous testing developed by 2019 EP intern, Louis Alexander Blaya
- EMIM-BF4 – ionic liquid propellant used in electrosprays
- Testing used a combination of parallel electrodes and droplet test cells
  - Parallel electrode test cell allowed for determination of geometric constant, c, used in determining electrical conductivity on droplet test cell
- Parallel electrode test cell requires a large amount of propellant and adds complexity to testing process for extensive testing



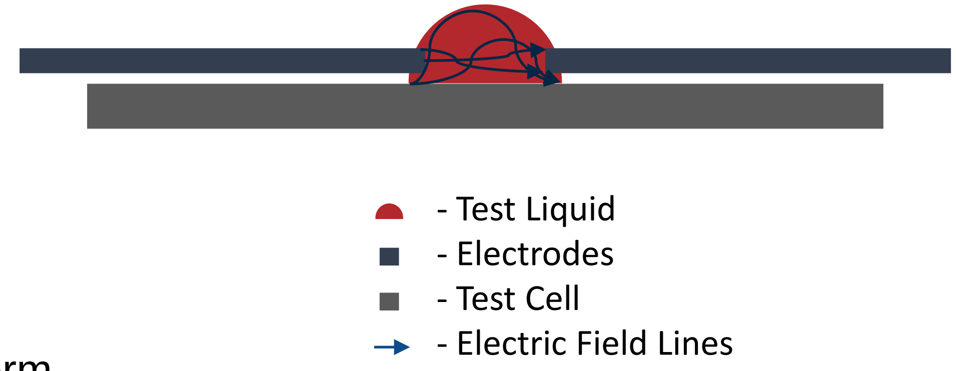


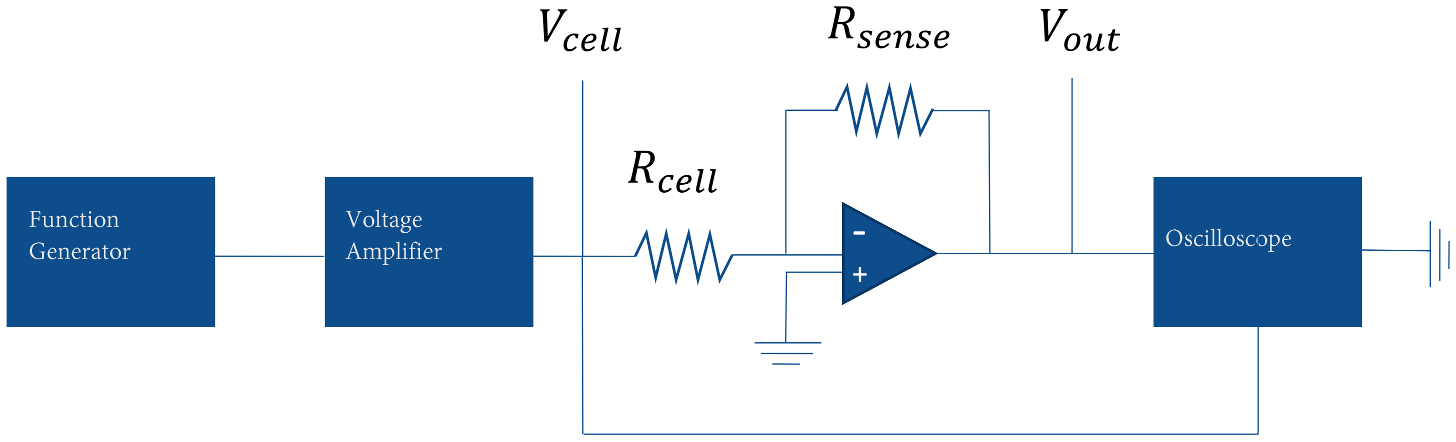
Testing Update Goals

- Make tests easier to repeat on a larger scale
  - Use only droplet test cell
  - Add transimpedance amplifier to simplify current measurements
- Test more independent variables
  - Pressure
    - Reach vacuum pressure
  - Temperature
  - Frequency
  - Voltage
  - Electrode Material
    - Tungsten
    - Iridium
    - Copper
    - Titanium
    - Molybdenum
    - Platinum

Droplet Test Cell

- $I_{cell} = \frac{V_{out}}{R_{sense}}$
- $R_{cell} = \frac{V_{cell}}{I_{cell}}$
- Conductivity: $\sigma = \frac{c}{R_{cell}}$
  - C is geometric constant
  - Derive C from previous data or leave final result as σ/c term





Conclusion

- Hall Thruster Plasma Properties
  - Created model to analyze plasma properties of Hall thruster exhaust plume using data collected by Langmuir probes
  - Model shows plasma exhaust unevenly distributed
- Helmholtz Coil Design
  - Helmholtz Coil designed and modeled to cancel out the effects of Earth's magnetic field on thruster exhaust plume distribution
- Electrical Conductivity Tests
  - Updated testing scheme to be easier to repeat tests on a larger scale
  - Test more independent variables
- Helmholtz coil design and propellant electrical conductivity tests will be implemented once COVID-19 social distancing requirements are lifted

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- I’d also like to thank others at AFRL, outside of HEEP, for weekly tech talks

References

- Lobbia, Robert B. and Beal, Brian E. *Recommended Practice for Use of Langmuir Probes in Electric Propulsion Testing*. The American Institute of Aeronautics and Astronautics, Journal of Propulsion and Power, 2017.
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Questions?

