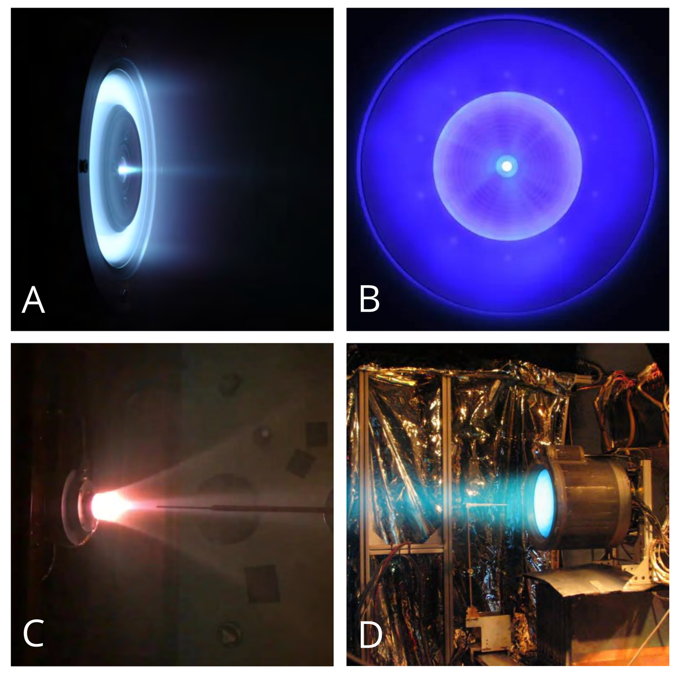
Experimental Study of Helicon Mode Transition Scaling Laws

STUDENT: Landon Bevier
PI: Justin Little

Electric Propulsion and RF Plasmas

- Electric Propulsion (EP) devices are a high specific impulse alternative to chemical propulsion for in-space applications.
- Several different EP device configurations generate thrust by exciting a propellant into a plasma then accelerating and exhausting it using electromagnetic forces.
- Radio Frequency (RF) driven plasmas are an efficient source of high density plasma and have applications in Ion thrusters, staged EP devices such as VASIMR, or standalone as electrothermal devices.



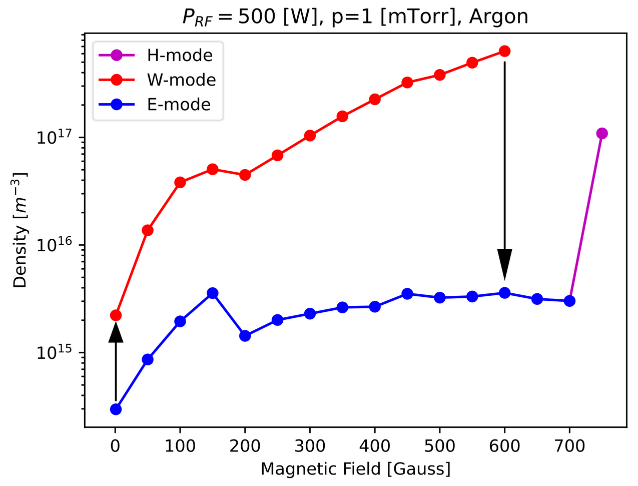
(A) ACME Hall Thruster. (B) HiPeR-PIT (Pulsed Inductive Thruster). (C) SPACE Lab ECR Thruster. (D) T6 Ion Engine (Credit: ESA)

Helicon Mode Transition Model

RF energy from an antenna can be coupled into a plasma via 3 distinct modes [1]:

- Capacitive (E-mode)
- Inductive (H-mode)
- Wave or Helicon (W-mode)

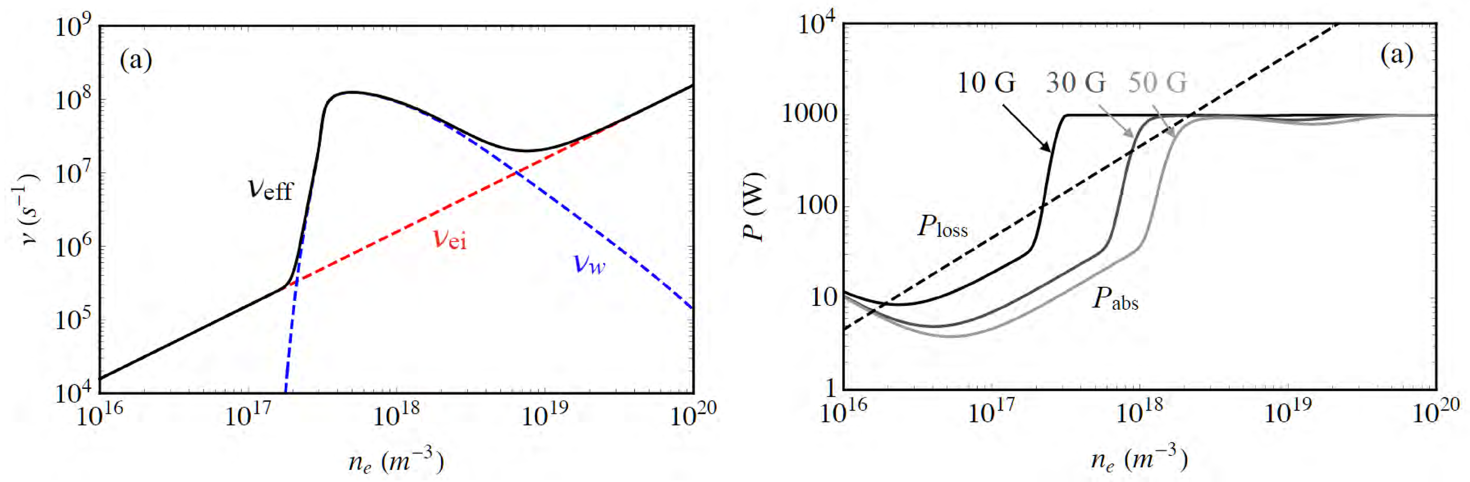
The helicon mode is desirable for most EP applications due to its higher coupling efficiency giving rise to higher densities.



A model for the general scaling of when the W-to-E mode transitions occur has been derived [2] using power balance and the dispersion relation for an m=0 helicon wave absorbed by Landau damping:

$$B^* = \alpha n_e T_{eV}^{1/2}$$

Where B^* is the external magnetic field strength, n_e and T_{eV} are the electron density and temperature respectively, and α is a constant calculated from the plasma radius and physical constants.



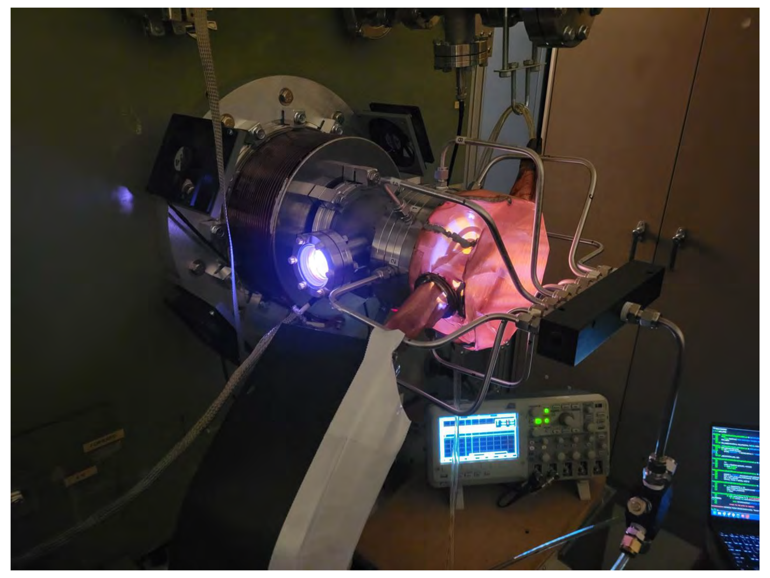
(Left) Effective wave-particle collision frequency given by the sum of Landau damping and electron-ion collisions. (Right) B-field dependance of absorbed wave power. [2]

Experimental Setup

A helicon plasma source has been constructed for this experiment and is mounted to the end-wall of a cylindrical vacuum vessel.

An RF compensated Langmuir probe provided temperature and density measurements at the magnetic field throat.

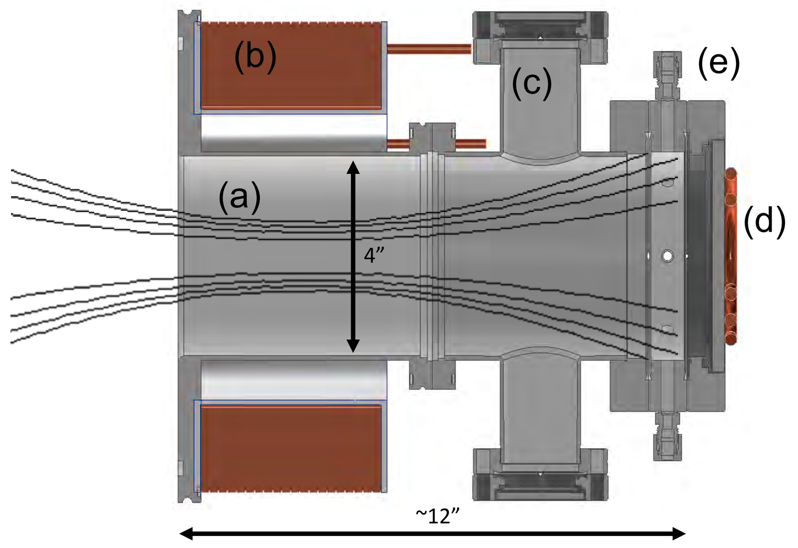
A linear array of inductive magnetic field probes (B-dot probes) was used to directly measure the azimuthal component of the helicon waves. This probe was inserted axially such that the first probe was located near one of the gas injection ports.



Operating conditions:

- Gasses: Argon and Nitrous Oxide
- Power: 500-1000 W
- Backfill Pressure: 1 mTorr

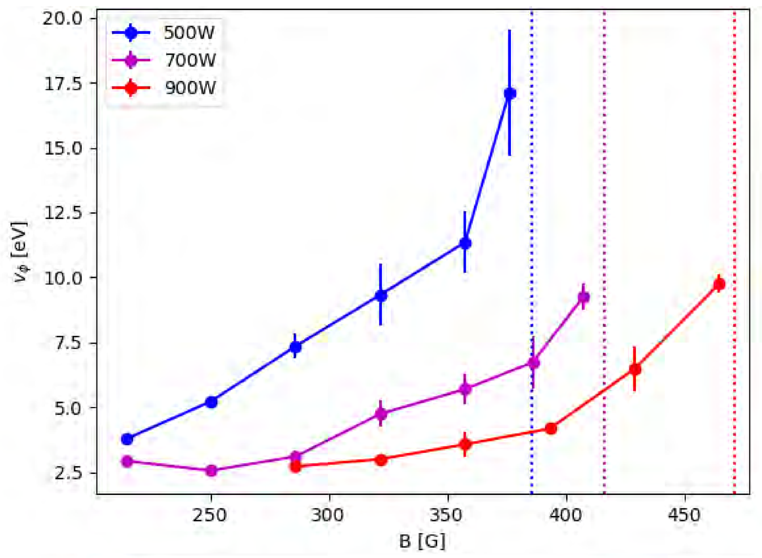
a) Magnetic field (magnetic simulation overlay)
b) 220-turn electromagnet
c) Diagnostic access ports (future work)
d) 2-turn spiral antenna mounted to a glass vacuum window
e) Radial gas injection ports (8 total)

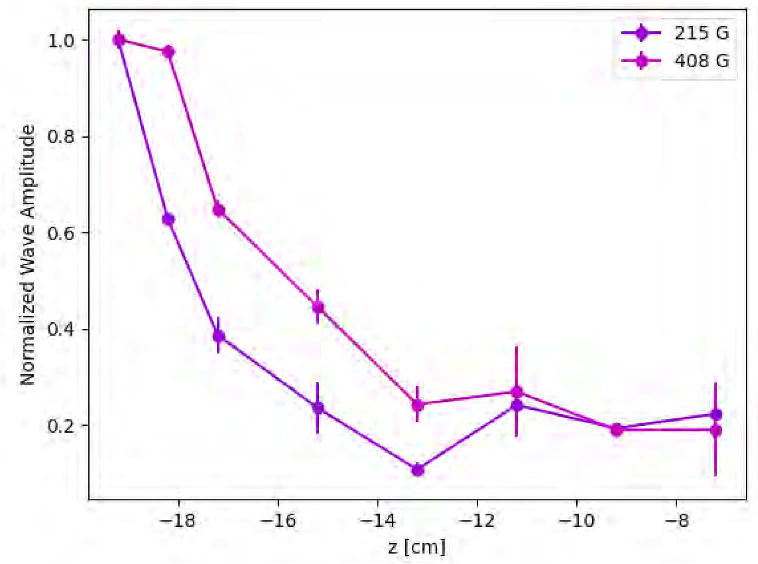


Direct Wave Measurements

By directly measuring the characteristics of the helicon wave using B-dot probes [3] we are able to validate the assumptions used in the mode transition model.

- Landau damping is a kinetic effect where electrons with velocities near the wave's phase velocity are absorbed.
- We can see in the plot to the right that the phase velocity of the helicon wave exponentially increases as we approach B^* which leads to a condition where the W-mode can no longer sustain the plasma from a power balance perspective. (Note that phase velocity has been converted to an equivalent electron beam energy)
- The lower plot shows how the helicon waves are absorbed along the axis of the device. The antenna is at z = -21cm and we can see that the wave undergoes exponential decay, characteristic of Landau damping.
- Furthermore, the stronger decay is observed for lower field strengths, consistent with theory.

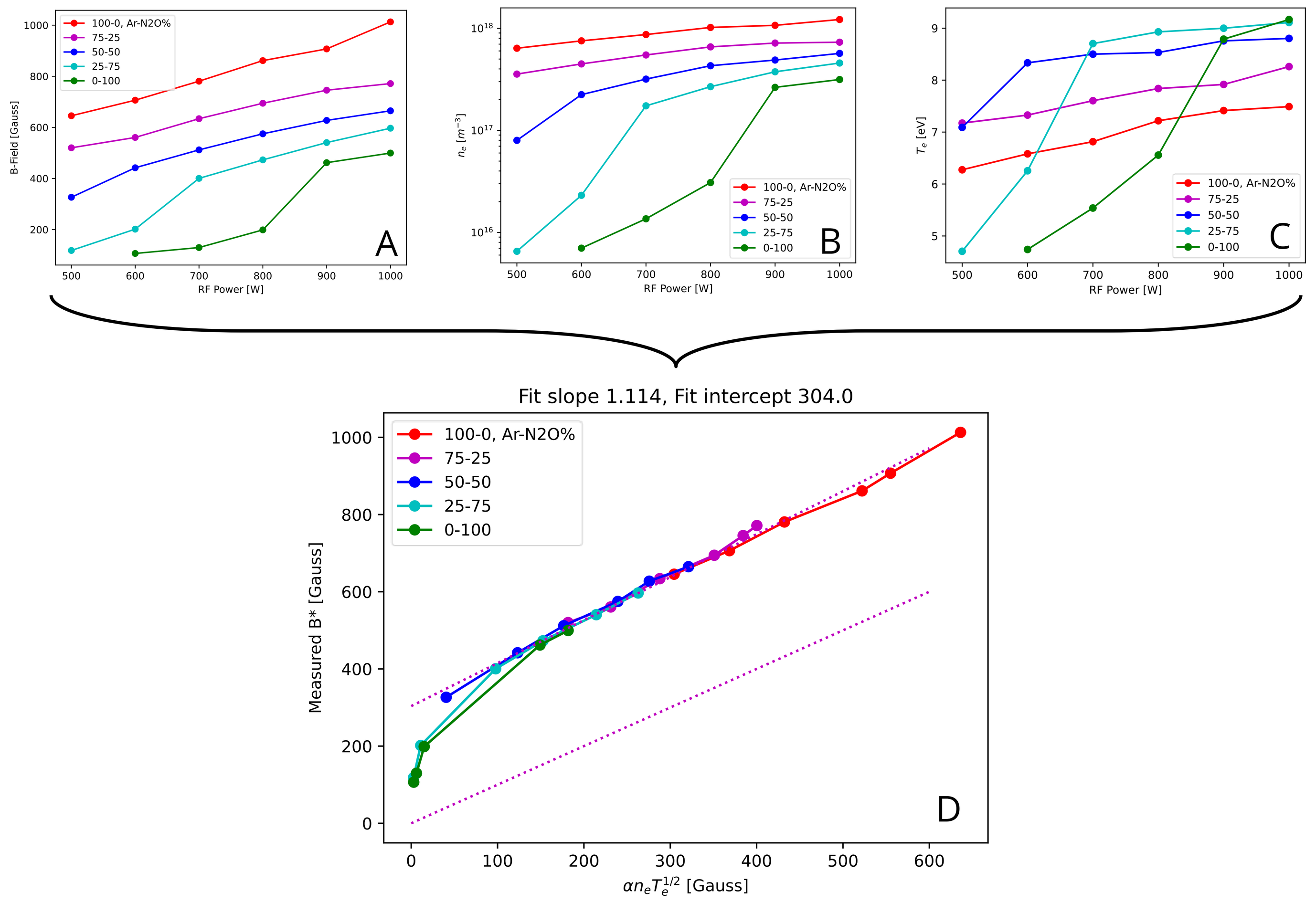




Mode Transition Scaling

By varying the RF power supplied as well as the propellant composition we were able to observe the mode transition at 29 distinct test conditions. Electron temperature and density were measured using a Langmuir probe to validate the transition field strength scaling given in the model.

A. The transition field strengths found by slowly ramping magnetic field until transition occurs.
B. Density measurement calculated from ion current in Langmuir probe I-V curve [4]
C. Temperature measurement from exponential fit of probe I-V curve [5]
D. Strong correlation is observed between the measured transition and the model predicted transition.



These results demonstrate the accuracy of the model and with the direct wave measurements create a strong argument in favor of Landau damping as the primary absorption mechanism for m=0 helicon waves.

Future Work & References

- Exploration of vertical shift in transition field strength as compared to model predicted value.
- Installation of laser absorption spectroscopy system for studying plasma chemistry effects due to molecular propellants.
- Study of high frequency oscillations observed in B-dot probe data (possible breathing mode)

References:
[1] Chabert, P., & Braithwaite, N. (2011). *Physics of Radio-Frequency Plasmas*.
[2] Little, J. M. (2019, September 15). Low-Field Mode Transitions in a Spiral-Antenna Helicon Thruster. *IEPC-2019-848*.
[3] Polzin, K. A., Hill, C. S., Turchi, P. J., Burton, R. L., Messer, S., Lovberg, R. H., & Hallock, A. K. (2017). Recommended practice for use of inductive magnetic field probes in electric propulsion testing. *Journal of Propulsion and Power, 33(3),* 659–667.
[4] Chen, F. F. (2003). Langmuir Probe Diagnostics. In *IEEE-ICOPS meeting*.
[5] Lobbia, R. B., & Beal, B. E. (2017). Recommended practice for use of langmuir probes in electric propulsion testing. *Journal of Propulsion and Power*, *33*(3), 566–581.

WILLIAM E. BOEING
DEPARTMENT OF AERONAUTICS & ASTRONAUTICS

S·P·A·C·E LABORATORY