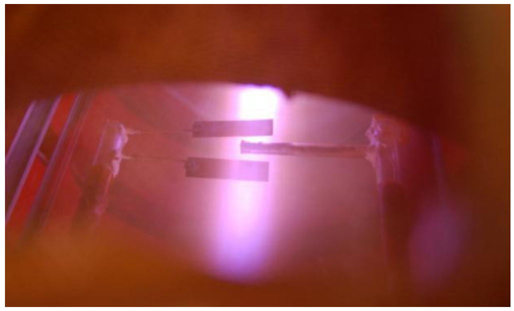

Figure 1: Langmuir probe between antenna in an Argon plasma

The Beating Waves Experiment: Detecting the Backward Branch
Julia Ling
Advisor: Professor Choueiri, EPPDyL
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I spent this summer working in the Electric Propulsion and Plasma Dynamics Lab (EPPDyL) on the Beating Waves Experiment (BWX) with a graduate student, Ben Jorns. BWX is a concept for a more efficient plasma heating technique that could be used in electrothermal plasma propulsion. Previous numerical and theoretical modeling by former graduate student Slava Spektor and Professor Edgar Choueiri suggested that plasma could be heated more efficiently with beating electrostatic waves than with a single frequency of electrostatic wave. [1] Whereas a single frequency electrostatic wave can only accelerate charged particles already above a certain energy threshold, beating waves can accelerate a much broader range of charged particles because many particles whose energies are below the single-wave threshold can be coherently accelerated above the threshold into regime where acceleration becomes chaotic. The most efficient heating occurs in this chaotic regime. [1] Slava was able to experimentally verify the superior heating of beating electrostatic waves over single electrostatic waves in his plasma. [4] However, he was not able to demonstrate 300% heating as was reported for single electrostatic waves in other plasmas, perhaps because his waves were poorly coupled to the plasma. [3]

In order for the heating to be optimal, the wave launched by the antenna must be able to couple with the plasma. When the antenna has an alternating voltage applied to it, it launches electrostatic waves in the radial direction that propagate at the given frequency but with two separate wave numbers. One of the waves launched at a given frequency corresponds to the "forward branch" and has a positive group velocity, whereas the other wave is part of the "backward branch" and has a negative group velocity. [4] Slava was not able to observe the backward branch of the waves, and subsequent analysis by Ben suggested that perhaps this branch was evanescent in the parameter space that Slava was operating in. Furthermore, the method that Slava used to detect waves was not suitable for detecting two separate waves. One of our main goals for this summer, therefore, was to detect the backward branch of the waves and determine which magnetic fields and radio-ionization fractions optimized this detection. A less evanescent backward branch wave in the plasma corresponds to better wave-plasma coupling, and therefore more efficient heating.

The first challenge that we faced was setting up the experimental apparatus. Although future plans include building a new experimental set-up, for the purpose of this proof-of-concept experiment, a previously built experimental set-up was used. I built new diagnostics to be used for our experiment, including a radio-frequency compensated Langmuir probe that used inductors to help damp out noise from our 13.56 M Hz radio-frequency plasma source. Furthermore, I repaired the wave-launching antenna, which had fallen apart partially because of its delicate construction. In order to install the Langmuir probe and antenna in the experiment, the vacuum chamber had to be opened up. However, upon closing it up again, we found that there were too many leaks to allow us to pump down to the necessary vacuum for operation. It took us no small amount of effort to track down the leaks and repair them, but finally, we succeeded and were able to pump down to less than 1 mTorr.

Using our Langmuir probe, we were able to take electron temperature and density measurements which agreed well with previous measurements taken on this experimental set-up. These measurements yielded values of 3 eV and 10^{11} atoms per cubic centimeter respectively. These measurements helped to verify that our Langmuir probe was in working order.

The next step was trying to detect waves. While we were able to detect waves with our Langmuir probe with relative ease, determining their wave number values soon revealed itself to be more difficult. Our first attempts at measuring the wave number relied on launching a wave with the antenna at the center of the plasma and then recording the current through the Langmuir probe at various distances and measuring the phase differences between the Langmuir probe signal when it was positioned at varying radial distances from the center of the plasma. However, this method was extremely time consuming and ineffective for detecting both wave branches, so we borrowed an idea from Goree. [2] Instead of looking at the signal from the Langmuir probe itself, we started using the product of the Langmuir probe signal $sin(kx - wt)$ and the antenna signal $sin(wt)$.

$$\begin{aligned} &\sin(kx - wt) * \sin(wt) \\ &= \sin(wt)\sin(kx)\cos(wt)(1 - \cos(2wt))\cos(kx) \\ &= -\cos(kx) + \cos(wt)\cos(kx - wt) \\ &= -0.5[\cos kx + \cos(kx - 2wt)] \end{aligned}$$

Therefore, the product of the Langmuir probe signal and the antenna signal can be decomposed into a time-dependent and a time-independent term! Averaging over the time-dependence, only the time-independent term will be left, giving a value for k. Using this property of the product of the two signals, we were able to take data much more quickly and with higher spatial resolution by sweeping the Langmuir probe around its axis to different radial points as the antenna was launching waves. I wrote a MATLAB program that could then pick out the data points from when the Langmuir probe was at equally spaced radial distances from the antenna and multiply the Langmuir probe signal at those points with the antenna signal at those points. We could then take the fast Fourier transform of this multiplied signal to find the wave number value of the backward branch. Unfortunately, because the wavelength of the forward branch was longer than the wavelength of the backward branch and on the order of the plasma radius, we were not able to measure the wavenumber of the forward branch.

We were able to use this method to take data for the backward branch at two different plasma source power strengths and three different magnetic field strengths. Ben Jorns could then compare the data we took with numerical modeling values for k to confirm that we observed the backward branch of the launched waves.

Over the course of the summer, we were not only able to get our experimental set-up up and running, but we were also able to observe the backward branch of the electrostatic waves that our antenna launched using a new data analysis technique. Future plans include taking data at even more magnetic field strengths and plasma source power levels, observing heating using both beating and single-frequency waves at these varied parameters, and then using the lessons we learned with this experimental set-up to help design an even better set-up to continue the work on BWX.

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I pledge my honor that this is my own work in accordance with University regulations.

References

[1] E.Y. Choueiri, R. Spektor, "Coherent Ion Acceleration using Two Electrostatic Waves," AIAA-2000-3759.

[2] J. Goree, M. Ono, and K.L. Wong, "Observation of the backward electrostatic ion-cyclotron wave," Phys. Fluids 28, 2845 (1985).

[3] F. Skiff, F. Anderegg, and M.Q. Tran, "Stochastic particle acceleration in an electrostatic wave," Phys. Rev. Lett. 58, 1430 - 1433 (1987).

[4] R. Spektor, E.Y. Choueiri, "Excitation and propagation of Electrostatic Ion Cyclotron waves in rf-sustained plasmas of interest to propulsion research," AIAA-2004-4095.