Beating Waves Experiment II (BWX II)

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In the summer of 2013 I worked at Princeton's EPPDyL research lab with Professor Edgar Choueiri and graduate students Matthew Feldman and Patrick Vail. My efforts were directed towards upgrading the BWX II, which is an experiment designed to test the efficiency of plasma heating processes that may be applicable to future plasma propulsion systems. The specific motivation behind BWX II is to compare the efficiency of radio-frequency heating of plasmas using beating electrostatic (BEW) waves as opposed to using a single electrostatic waves (SEW). Unlike SEW heating, which is a resonant process that targets ions with velocities close to the phase velocity of the SEW, BEW heating is a non-resonant process that targets a broader population of ions in plasma. This BEW heating phenomena has been predicted to be more efficient than SEW heating at high wave energy levels [1], but this has yet to be experimentally verified because of limitations on the available wave power that can be introduced into the plasma.

Testing the hypothesis of BEW superiority by making upgrades to the experiment such that high power waves could be produced was my original intent for my research this summer. However, the experiment's vacuum chamber developed a crack before I was able to take any data. We sent the vacuum chamber in for maintenance, but the repair company ended up destroying the vacuum chamber during a routine heating procedure (the crack broadened, resulting in catastrophic failure). By the end of my summer at

EPPDyL, we had ordered a new and improved vacuum chamber, but it had not arrived at the lab yet. As a result of these unanticipated complications, this paper is more of a summary of collective projects than a presentation of empirical results.

When I arrived at the lab last summer, my first project was to upgrade the optical components of the Laser-Induced Fluorescence (LIF) system used in BWX II. Briefly, LIF systems are used to acquire ion temperature data from a plasma by taking advantage of Doppler shifting. A laser is tuned to match the excitation state of the ions it is measuring (Argon in our case). The excited ion emits a photon of a known wavelength in its own rest frame, and is then Doppler shifted in comparison to the lab frame. Measuring light intensity as a function of wavelength, a Maxwellian distribution is found, centered on the rest frame's emitted photon wavelength. By correcting for the Doppler shift, the velocity of the ions can readily be obtained, and temperature can be calculated from the standard deviation of the Maxwellian distribution. In this experiment, however, ion velocity is not isotropic since we create an axial magnetic field from a several sets of coiled wires that enclose the vacuum chamber. Thus, taking LIF data measurements from different angles with respect to the magnetic field gives different ion temperature measurements. This, however, is to our benefit, since we can see in which direction relative to the magnetic field the BEW heat ions and how quickly the ions transfer their energy from the perpendicular to the parallel direction via collisions.

My work with the optics component of the LIF system was to set up the system such that it could easily take both parallel and perpendicular ion temperature measurements. Beforehand, the system of mirrors and lenses had to be meticulously aligned with the collection optics for either perpendicular or parallel temperature measurements before each time the plasma was introduced into the system. By adding a mobile interrupting mirror and a second table of mirrors, I was able to circumvent the problem of aligning the collection optics for a particular temperature reading.

Another project I worked on was to write MATLAB code to output electron temperature and density given the I-V curve of a double Langmuir probe. Since this experiment was using RF energy to generate the plasma, cutting through the electromagnetic noise was an obvious concern when reading data from a typical single Langmuir probe. One common solution to this problem is to include a noise-cancelling circuit on the backend of a single Langmuir probe to cancel the RF noise, but such a noise-cancelling circuit would have to be fairly complicated in this experiment since it would have to cancel the RF contributions from both the helicon plasma-generating antenna and the beating wave frequencies from the wave-launching antenna. Our solution was to use a double Langmuir probe, which measures the current as a function of voltage across two small Langmuir probe tips.

Around the time I completed this double Langmuir probe analysis code, Pat and I discovered the small spider crack in the vacuum vessel. After we learned that the crack had wrecked the vessel upon heating, we took it upon ourselves to modify the vessel design. After consulting with Mike Souza, a glassblower in the physics department, we came to the conclusion that we needed thinner walls to prevent stress concentrations due to thermal gradients from cracking the glass. We also decided to use quartz instead of the Pyrex we were using before. Quartz is a much stronger glass than Pyrex, which should prevent cracks from forming as easily. Additionally, Mr. Souza noted that Pyrex has a significant amount of sodium in it, which would cause the resistivity of the glass to rise with temperature. Thus, at high temperature we might observe arcing within the plasma. I created a CAD mockup of the new design in the program Creo, which Pat and I took to a glassmaking company to get manufactured.

The next project I tackled was to build a new antenna for launching the beating RF waves. The new antenna is a square Helmholtz design, meaning that there are two rectangular coils placed lengthwise along the cylindrical vacuum chamber. Testing the new antenna's performance against the old strap antenna was not possible since the experiment was incapable of generating a plasma, but by comparing the antennas' respective complex impedances we can make some preliminary judgments which suggest that the square Helmholtz design radiates energy more effectively than the strap antenna. Observe that resistance of the square antenna is less than that of the strap antenna (Figures A and C). This means that less power is lost to heat, allowing for RF energy to potentially couple to waves in the plasma more effectively. Additionally, note that the reactance of the square antenna is greater than that of the strap antenna (Figures A and D), which suggests that the square antenna produces stronger magnetic fields. For these two reasons, the square Helmholtz antenna appears to be a promising design.

That being said, these data do not indicate how well the electrostatic waves will couple to the plasma, thus we cannot definitively predict how effective the new antenna is at heating. However, the square Helmholtz design has been shown experimentally to be particularly efficient at ion heating by a series of experiments conducted at West Virginia University [2, 3]. Thus, it can be said with a fair amount of confidence that the square Helmholtz antenna is a better choice than the strap antenna for this experiment.

A)

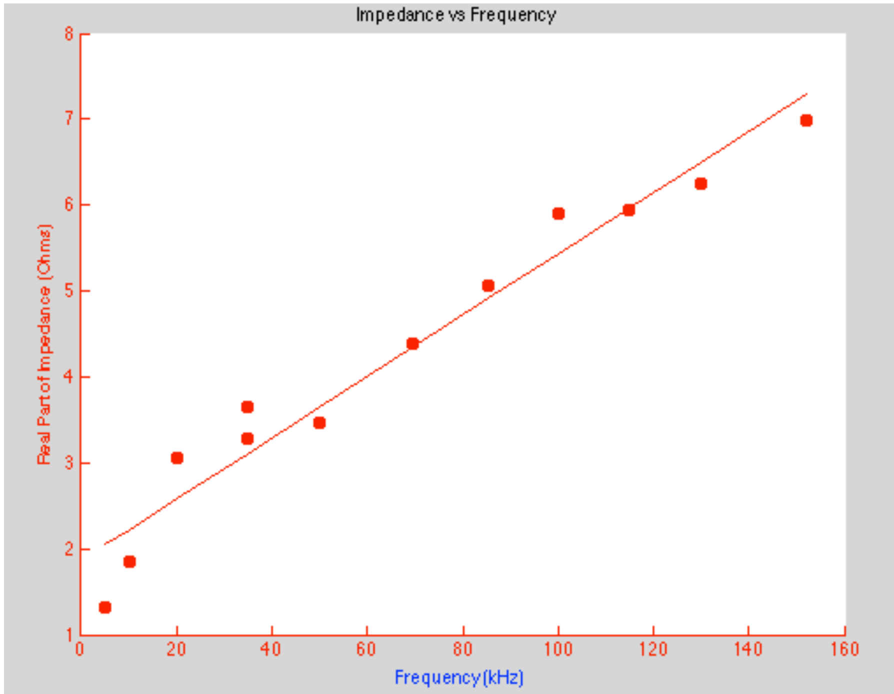

Figure A: Square Helmholtz Design; Re{Impedance} Slope = 0.03567 Ohms/kHz

B)

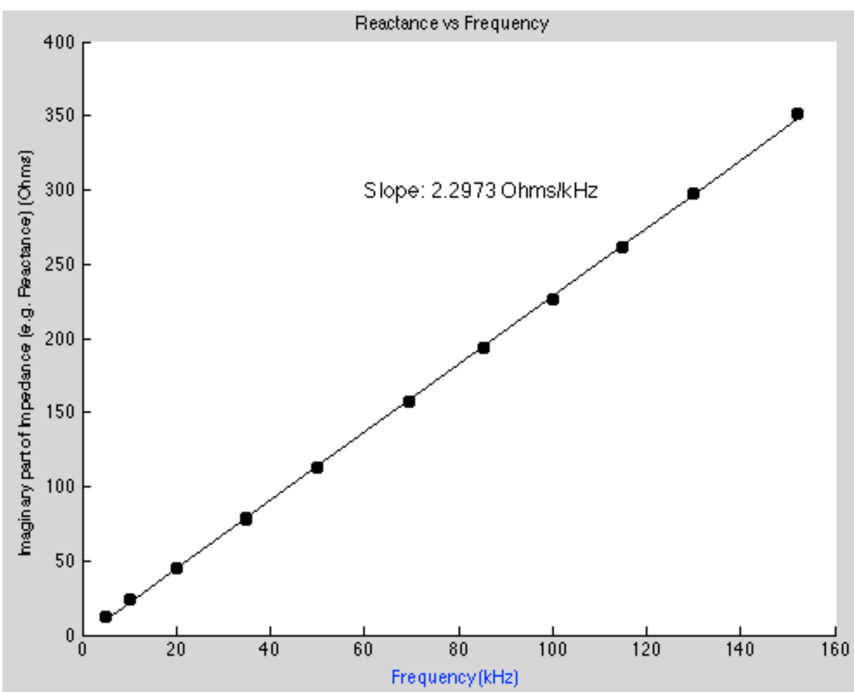

Figure B: Square Helmholtz Design; Reactance Slope = 2.2973 Ohms/kHz

C)

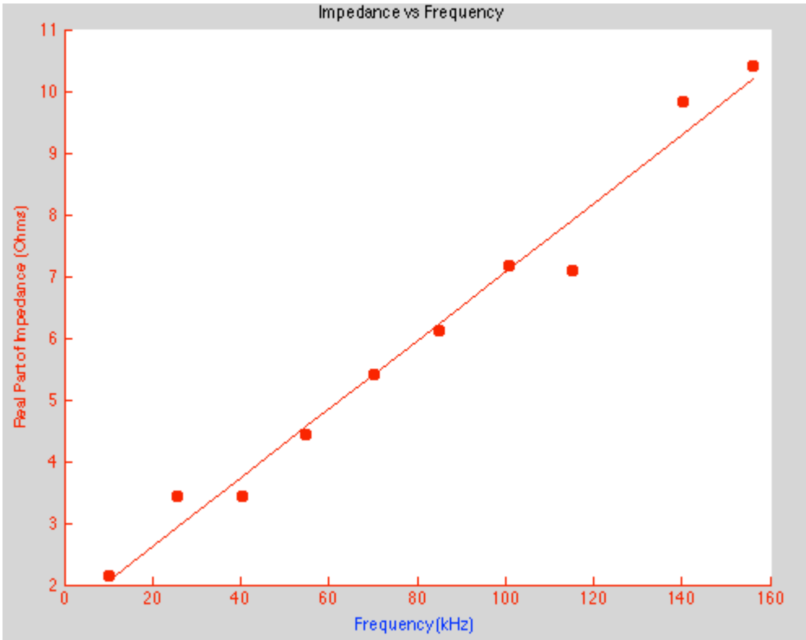

Figure C: Old Strap Antenna Design; Re{Impedance} Slope = 0.05564 Ohms/kHz

D)

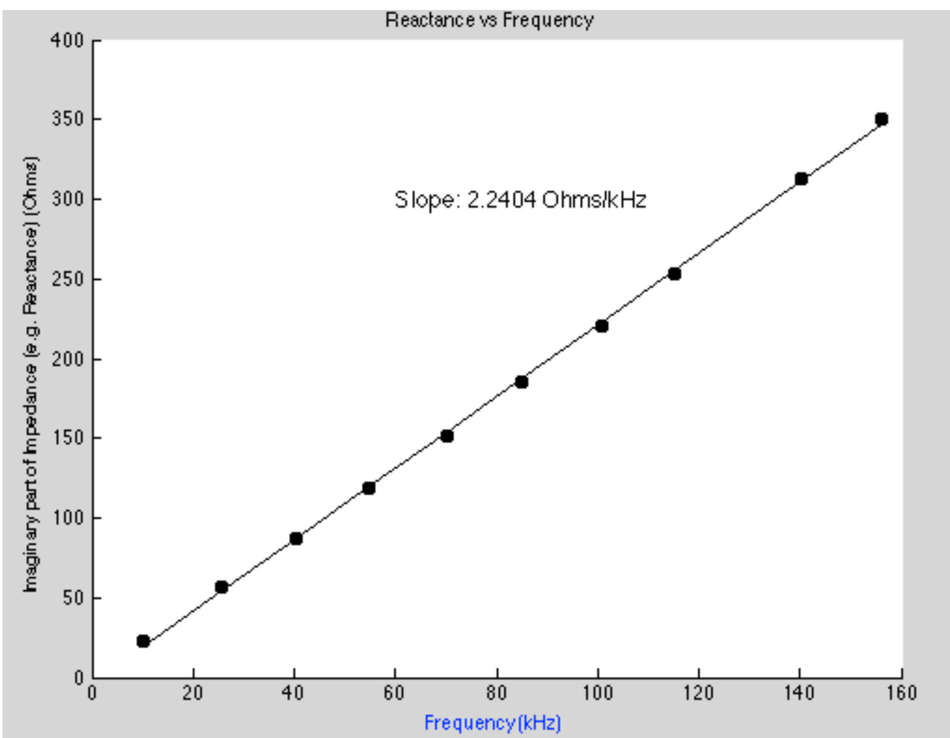

Figure D: Old Strap Antenna Design; Reactance slope = 2.2404 Ohms/kHz

Acknowledgements

Although it was a bit of a disappointment to not experimentally verify much this summer, I definitely gained a significant amount of practical experience in machining, learned much about wave propagation in plasmas, and had a great experience overall. I am very grateful for this opportunity this summer, and consider myself lucky to have worked with a host of fantastic people. Specifically, I'd like to thank Matthew Feldman and Pat Vail for their unwavering support, Bob Sorenson for his patience and expertise, and Professor Choueiri for presenting me with this opportunity.

References

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