Experimental Analysis of kHz Frequencies in a Glow Discharge Tube

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Abstract

This research project involved the use of a Langmuir probe to analyze plasma oscillation behavior in a glow discharge tube as probe voltage and magnetic field strength were varied. The paper consists of brief probe theory and largely deals with data analysis of the various signals observed.

Contents

1 Overview

A glow discharge is a plasma formed by the passage of electric current through a low-pressure gas. It is created by applying a voltage between two electrodes in a glass tube containing the low-pressure gas (in this case, neon). The high voltage accelerates free electrons to speeds sufficient to cause ionization on collision with neutral atoms. If an electrically isolated probe is inserted into the tube then it acts as a wire, collecting particles that bombard its surface. When the conditions are right, the plasma undergoes oscillatory harmonic behavior and this behavior is recorded by a langmuir probe. A magnetic field generator can be used to vary the conditions of the plasma. The confinement of the plasma due to an increase in magnetic field strength changes the plasma conditions and creates new frequencies and modes at which the oscillatory current appears.

2 Probe Theory

A langmuir probe is essentially a metal wire. It is named after Irving Langmuir (1881-1957), an American physicist who was one of the pioneers of the study of the plasma state of matter. The simplest collecting Langmuir probe is a metallic electrode with a well defined geometry (planar, cylindrical or spherical). In this experiment, a planar probe is used with a surface area of approximately 1.5 cm^2 (we called this the paddle probe). When the probe is immersed into the plasma, its surface is bombarded with electrons, ions, and neutrals. The plasma potential is monitored and the plasma parameters are calculated from the voltage-current (IV) characteristic curves. Figure 1 below depicts an ideal IV characteristic composed of three regions- the ion saturation region (A-B), the transition region (B-C), and the electron saturation region (C-D).

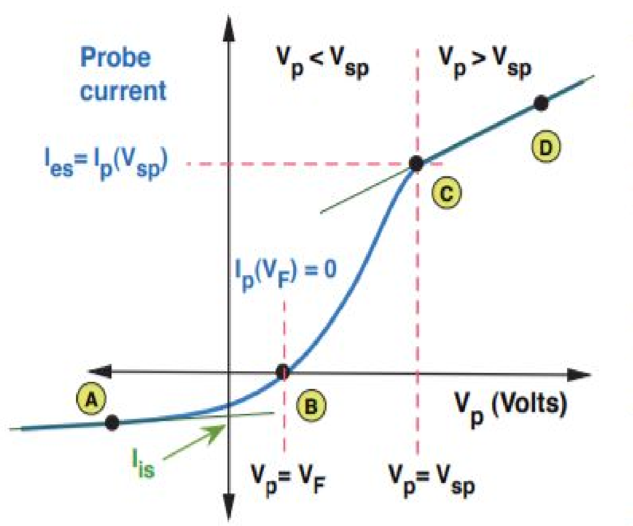


Figure 1: The IV Characteristic

The spatial potential V_{sp} is the electric potential at the point of the plasma where the probe is inserted. For very negative voltages, voltages where the spatial potential is much greater than the plasma potential, electrons are repelled by the probe, while ions are attracted. The drained ion current from the plasma is limited by the electric shielding of the probe and this current is the ion saturation current.

On the other hand, (voltages at the right of point C) where the plasma potential is much greater than the spatial potential, ions are repelled and electrons are the attracted charges. In this case, the electrons are responsible for the electric shielding of the probe and this region of the characteristic is called the electron saturation current.

The potential V_f where the ion saturation current equals zero is denoted the floating potential (point B). This is where the contributions of the ion and electron currents are equal and the net charge is zero. The collection of electrons stops only with the growing negative charge (repulsive to electrons, attractive to ions) reducing the electron current and increasing the ion current so that a balance is reached and zero net current flows to the wire.

3 Experimental Procedure

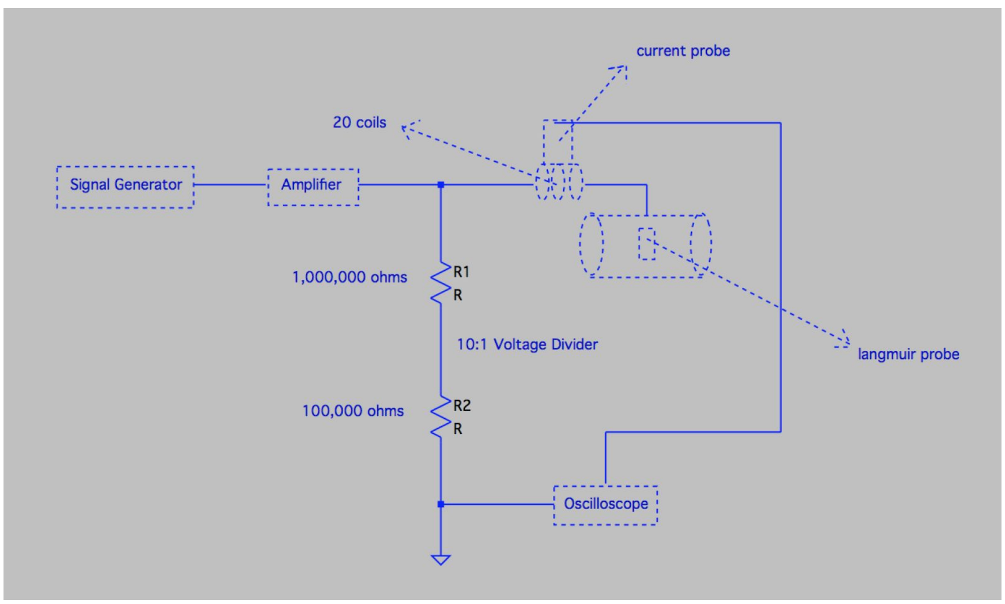


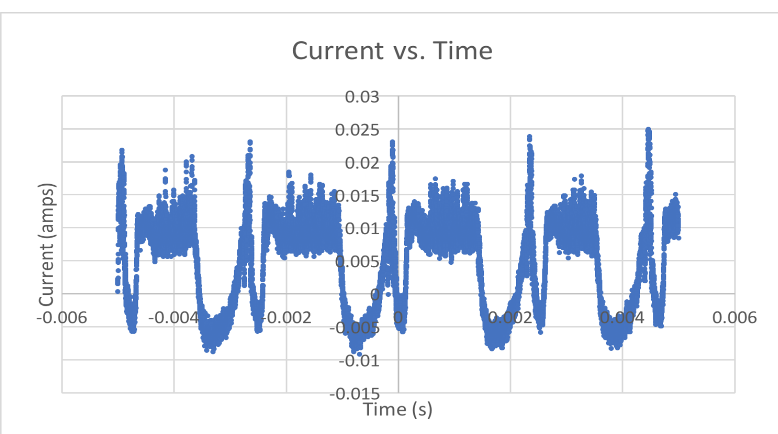
Figure 2: A schematic of the circuit used during the experiment

- Connect all cables and wires as shown in the schematic above.
- Adjust Paddle Probe in the glow discharge tube to sit perpendicular to the magnetic field.
- Turn on neon gas supply.

- Adjust high voltage and switch on the high voltage output until the breakdown occurs (pink glow) in the discharge tube.
- Adjust needle valve to get a flow rate of 2 m^3/s for the gas admitted into the tube.
- Adjust pressure within vessel to 26 mTorr
- Switch on all connected electrical equipment in this respective order:
  - Sweep Generator set to 100 Hz
  - Amplifier
  - Oscilloscope
  - Magnetic Field Generator
- Degauss and zero out current probe on the oscilloscope and then enclose it around the coils shown in the circuit above.
- Allow plasma to stabilize for about 30 minutes.
- Adjust high voltage to 810 V
- Begin sweeping through the magnetic fields at intervals of 0.5 amps (a varying current setting is what varies the magnetic field strength on this magnetic field generator) starting at 0 amps and record plasma oscillations on oscilloscope.
- Repeat sweep for 4 different points of probe voltages (for oscillations to be observed in all 3 regions of the IV characteristic). The IV characteristic can be viewed on the oscilloscope and the designated points along the curve must be set and adjusted on the Bipolar operational device (Amplifier).

4 Varied Magnetic Field Data

During this experiment, two conditions were varied—magnetic field strength and probe voltage. Changes in frequency, amplitude, and other fundamental properties of the oscillation can be observed. It is important to note, however, that the varied B field was dependent on a current setting on a magnetic field generator. Thus, the varied magnetic field strength was a result of the varied current setting. Presented below is a case for which the probe voltage was kept constant at 10v while the B field was varied.



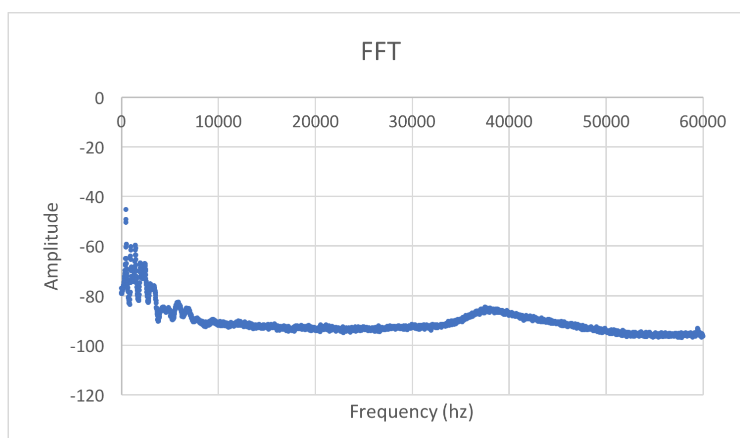


Figure 3: The signal and its accompanying fourier transform at 1.5 amps.

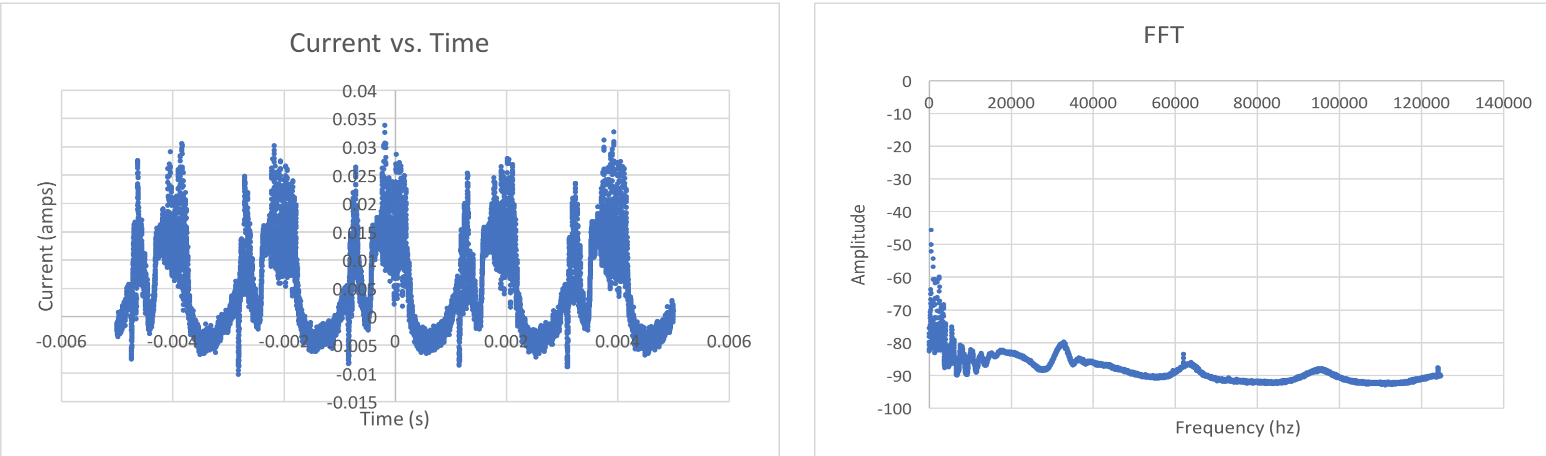


Figure 4: The signal and its accompanying fourier transform at 1.75 amps.

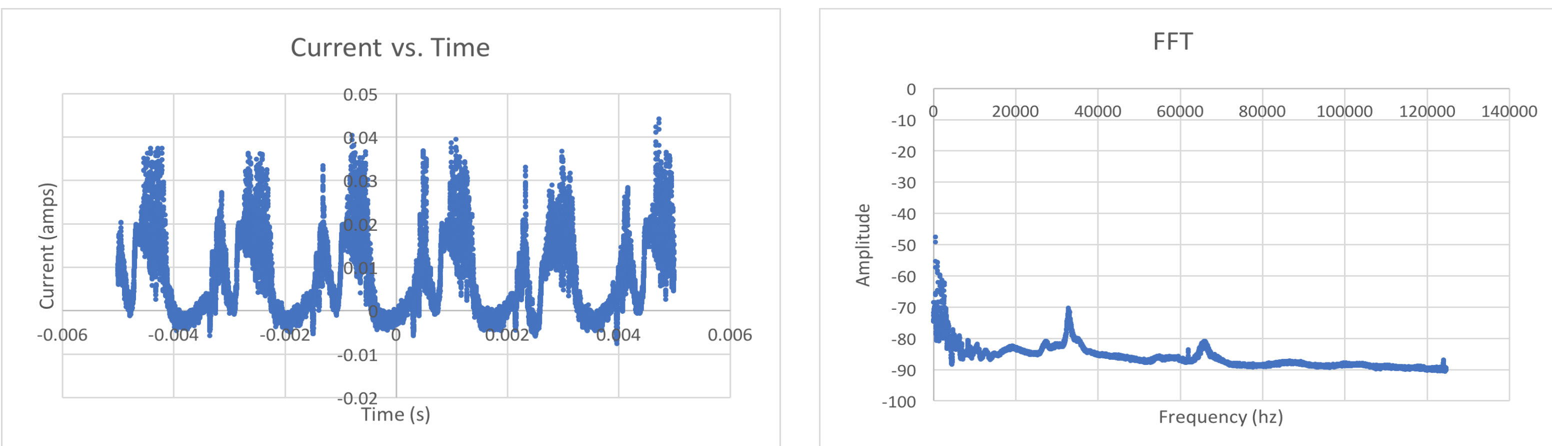


Figure 5: The signal and its accompanying fourier transform at 2 amps.

The current oscillation at a constant probe voltage of 10v appears first at 1.5 amps (Figure 3). The signal is purely periodic. It is composed of two parts—a narrow triangle shaped peak immediately followed by a somewhat distorted square wave. Important to notice are the surges at the amplitude of the square wave (Figure 3a shows this). The fourier transform has multiple narrow, low amplitude peaks in the 0-8 khz range and there is a broad peak at 30 khz. It appears, the surges are responsible for this higher frequency signal.

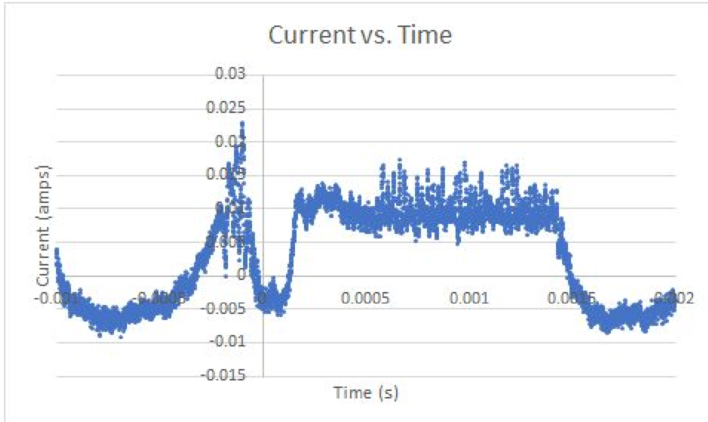


Figure 3a: A magnified, improved resolution of the signal where the surges are more apparent.

Following this oscillation through to an amp setting of 1.75 amps (Figure 4), we see on the fourier transform that the lower frequency signals have become more narrow and two new high modes have appeared. There are now broad peaks at 65 kHz and 90 kHz. Analyzing the altered signal at a magnified scale (Figure 4a) reveals that the overall frequency of the signal has increased and the surges at the amplitudes of the signal are more apparent, more narrow and are of greater amplitudes.

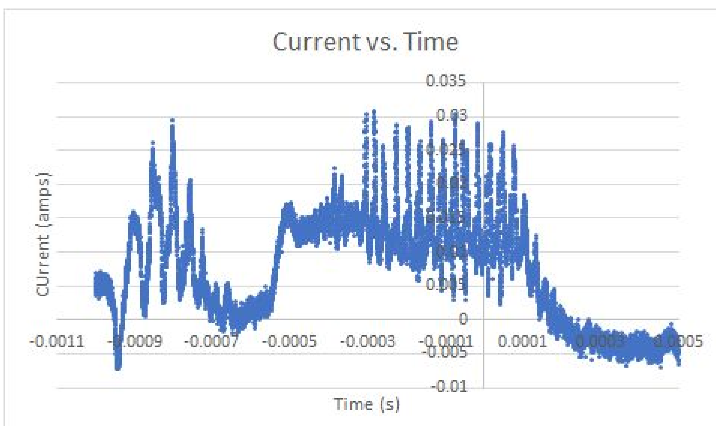


Figure 4a: A magnified plot of the signal at 1.75 amps.

Finally, at 2 amps (Figure 5) it appears that the 90 kHz oscillation has disappeared but the amplitudes of the 30 kHz and 65 kHz on the FFT are more narrow and of a greater amplitude. Additionally, the surges at the amplitudes have lost sharpness and are of less amplitude as can be seen in Figure 5a below.

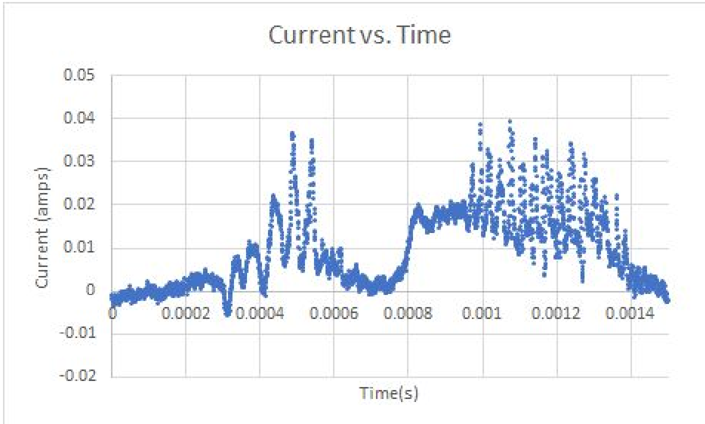
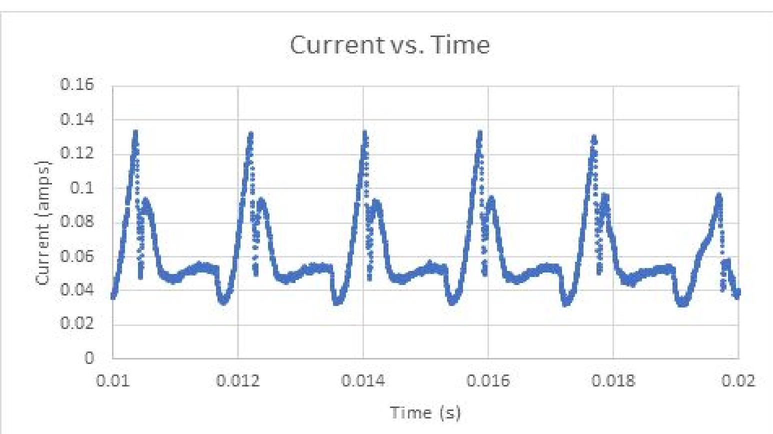


Figure 5a: A magnified plot of the current signal at 2 amps.

5 Varied Probe Voltage Data

Now, presented below is the data for the other case in which the B field was kept at a constant 0.5 amps while the probe voltage was varied. Again, this is just one case for which the probe voltage was varied. The other cases all include other amp settings (1-3 amps) where the probe voltage was varied between -5v and -20v. The purpose of these varying probe voltages is as mentioned before—to sweep the probe through the IV characteristic's 3 major parts: ion saturation current, the transition region and the electron saturation current. Accordingly, -20v puts us on the ion saturation current part of the characteristic and the -5v puts us in the electron saturation part of the current while the voltages between keep us in the transition region. The purpose of this, of course, is to observe how the oscillation changes behaviour in different parts of the characteristic.



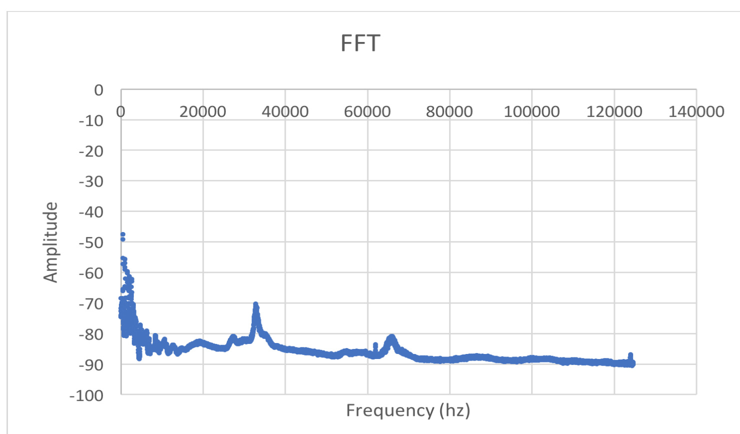


Figure 6: The signal and its accompanying fourier transform at -5v.

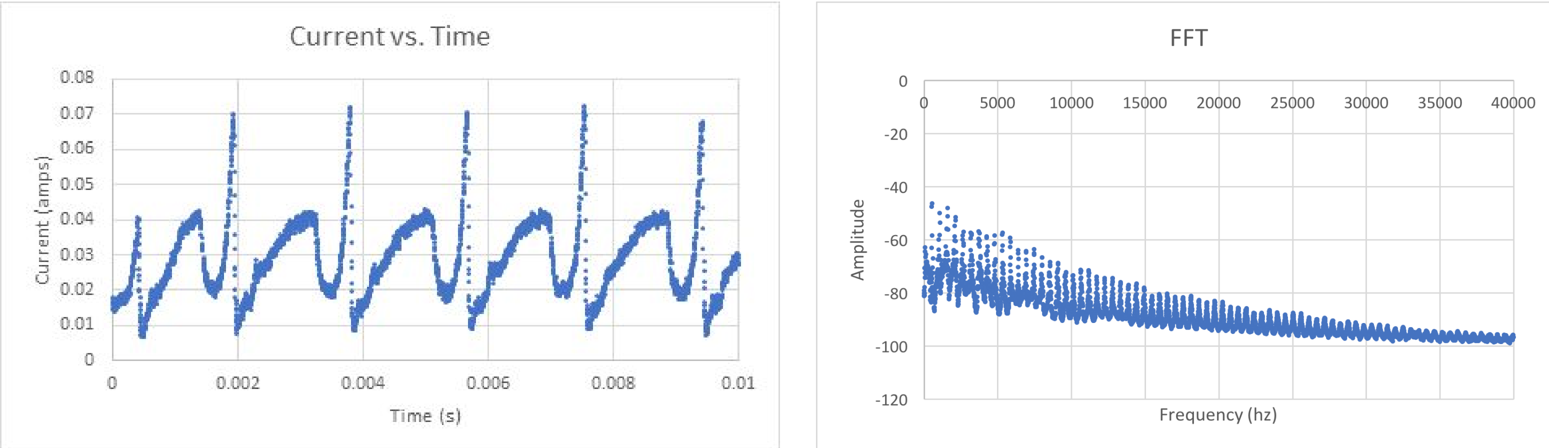


Figure 7: The signal and its accompanying fourier transform at -10v.

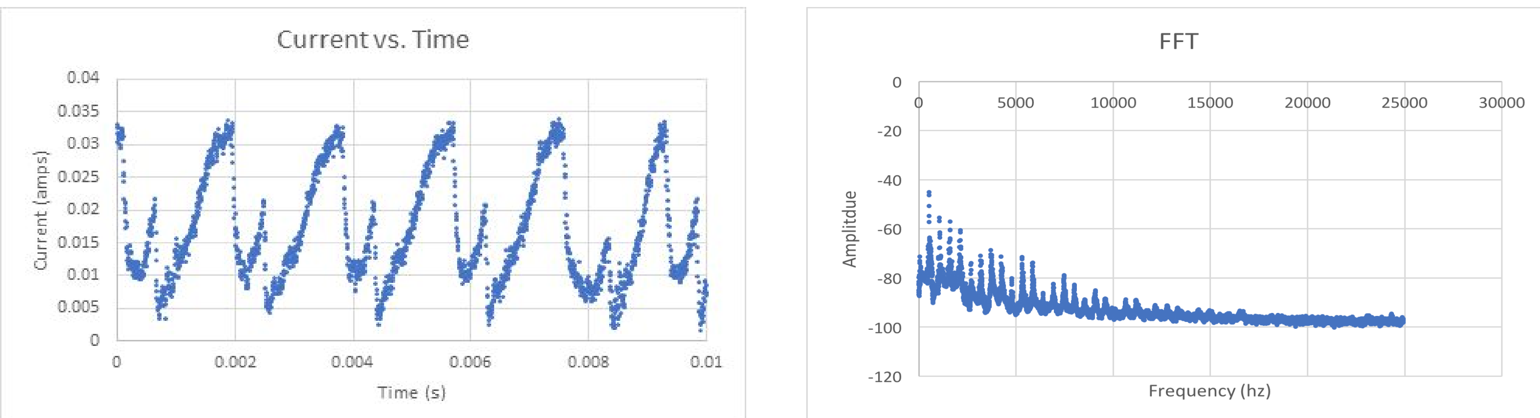


Figure 8: The signal and its accompanying fourier transform at -15v.

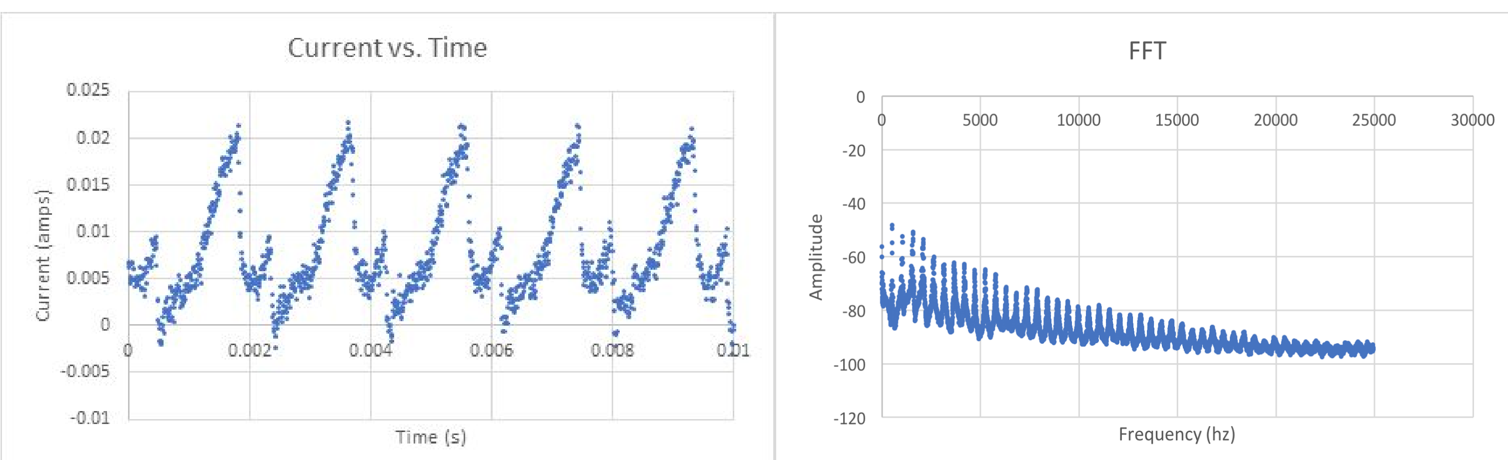


Figure 9: The signal and its accompanying fourier transform at -20v.

The current oscillation at a constant B field setting of 0.5 amps appears first at -5v (Figure 6) and it is clearly periodic. In this case, the signal is made up of two distinct parts - an initial, sharp triangular signal followed by a curve resembling a sinusoidal. The fourier transform has several peaks in the 0 - 1.5 kHz range, as well as a few stray peaks at 33 kHz and 65 kHz.

Now, at a probe voltage setting of -10v (Figure 7), once again a periodic signal appears that is different than the one at the preceding voltage setting of -5v. Specifically, the signal has a more sinusoidal characteristic and has a smaller amplitude. The fourier transform has many peaks throughout the 0 - 40 kHz range, but has its largest peaks at smaller frequencies.

Next, at a probe voltage setting of -15v (Figure 8), a more interesting periodic signal is observed—one that appears to have a sinusoidal characteristic followed by a triangular section. The fourier transform has its main peaks in the 0 - 1 kHz range.

Finally, at a probe voltage setting of -20v (Figure 9), the signal seems to be similar to that of the -15v, in terms of the signal's shape. The fourier transform displays peaks throughout the 0 - 25 kHz range, with the major ones appearing at lower frequencies. One very important observation to be noted from the fourier transforms for 10v, 15v, and 20v, are the presence of delta functions. The plots have high harmonic content, so it's not a nice, linear wave.

6 Results

The data presented above was just a specific example of the trends and patterns seen when either the probe voltage or the magnetic field strength was varied while the other remained constant. These final results provide a more holistic understanding of the deviations in the oscillation frequencies as one of the two variables was changed.

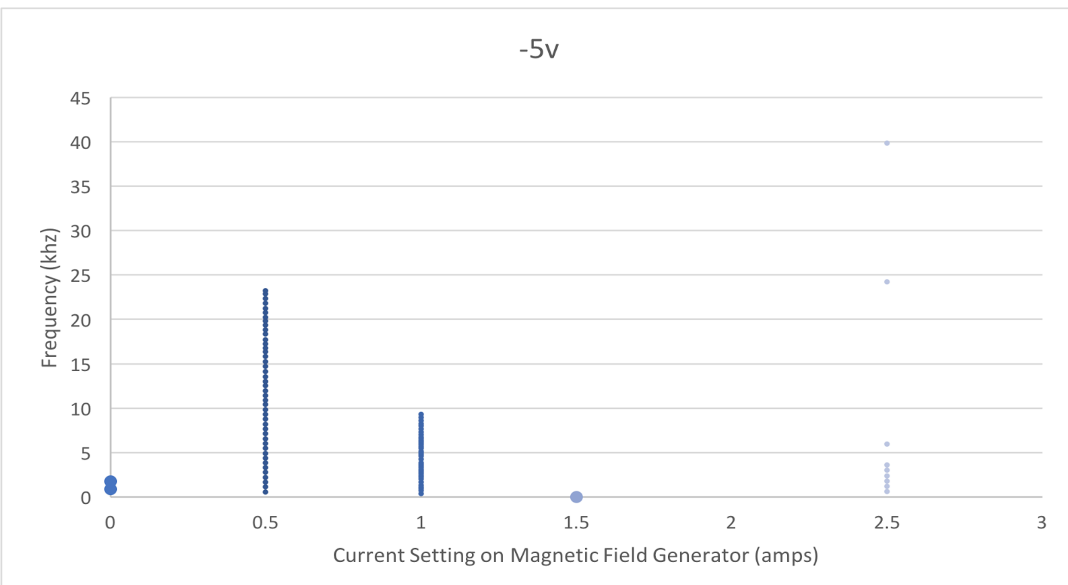


Figure 10: The results graph for varying B field values at a probe voltage of -5v.

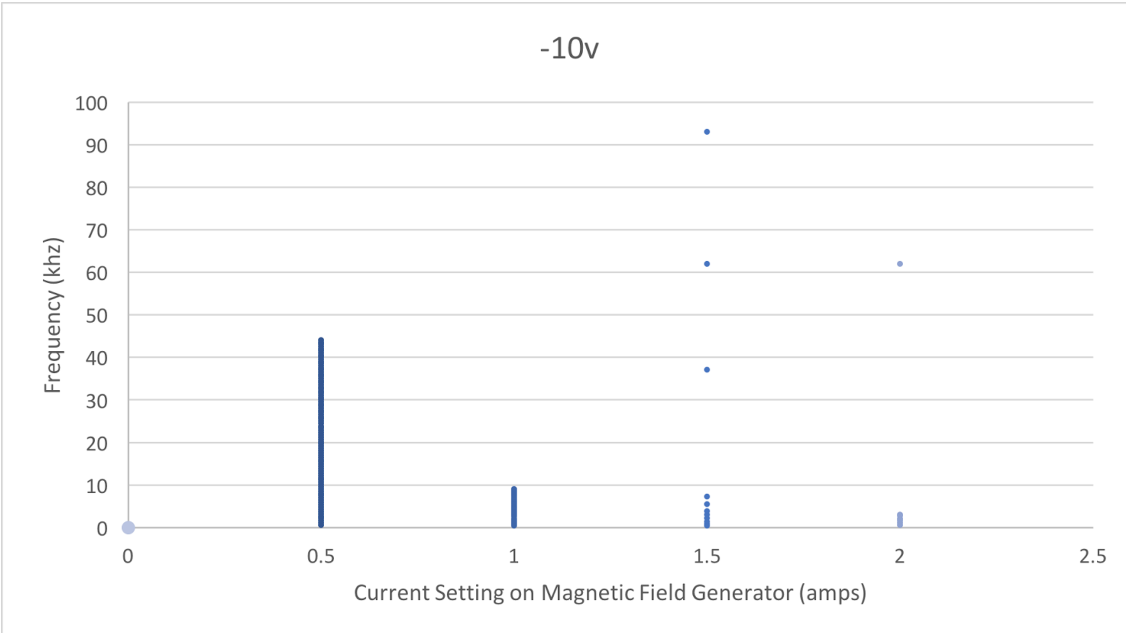


Figure 11: The results graph for varying B field values at a probe voltage of -10v.

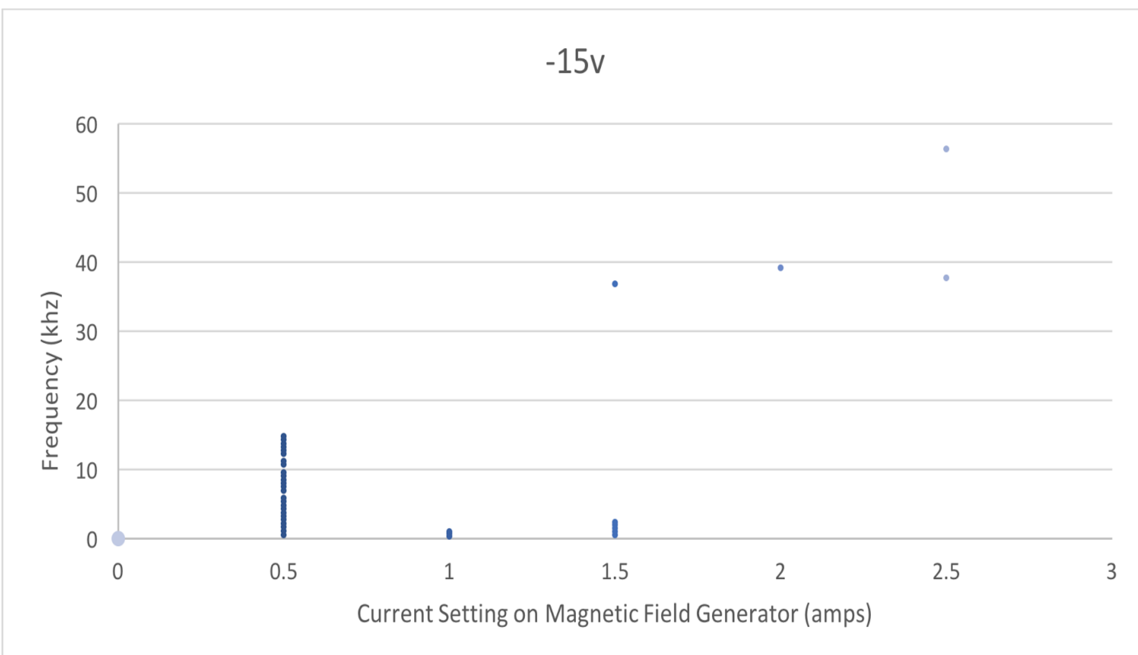


Figure 12: The results graph for varying B field values at a probe voltage of -15v.

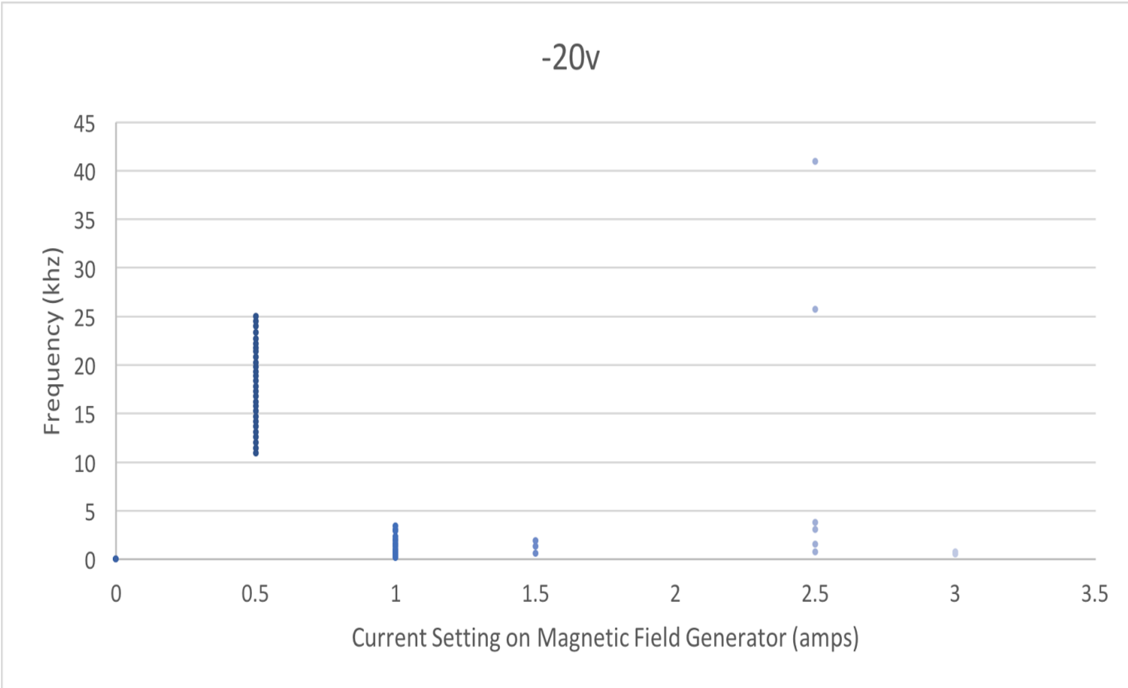


Figure 13: The results graph for varying B field values at a probe voltage of -20v.

7 Analysis

Beginning at a probe voltage of -5v (Figure 10), the 0.5 amp setting has the largest amount of varying frequencies—with most of them occurring between 0 and 25 kHz. The 1.0 amp setting seems to follow the same trend of frequencies except the the maximum frequency is 10 kHz. Moving up to higher amp settings, the oscillation is lost and then achieved again at 2.5 amps where there is again a consistent, low frequency trend, however, peaking at a small value than it did at 1 amp. This time around the oscillation only peaks at about 5 kHz. Most important to note is the emerging of new higher frequency modes at this amp setting. One can be seen at around 25 kHz and the other at 40 kHz. As the current setting is increased to 3 amps, the oscillation is lost.

Next, at a probe voltage of -10v (Figure 11) we observe something similar. Starting at 0.5 amps we see the same type of oscillation as we did in -5v but here the oscillation frequencies peak at about 45 kHz instead of 25 kHz. As the current setting on the B-field generator is increased to 1 amp, we observe exactly what we did in the plot for -5v. The oscillation peak falls to 10 kHz. When the current setting continues to be increased to 1.5 amps, we see something particularly distinct from what was seen at -5v. Rather than having virtually no oscillation at 1.5 amps, we retain the same oscillation we saw at 1 amp with a lower peak frequency but we also see the emerging of new modes: frequencies of 37, 62 and 93 kHz. This emergence occurred in the -5v plot as well yet it was at 2.5 amps instead of 1.5 amps and the new modes were of relatively lower frequencies. At 2 amps, the 37 kHz and 93 kHz frequencies are lost and finally the full current oscillation vanishes at a current setting of 2.5 amps on the magnetic field generator.

Now, at a probe voltage of -15v (Figure 12) we notice some key differences. Beginning with the 0.5 amps setting, we notice a different type of phenomenon with the spacing of the points, which in this case is more unequal than in the previous two cases. Also, the oscillation frequencies peak at a lower value of 15 kHz, instead of 45 kHz, which was seen at a probe voltage of -10v. Moving on to a B-field setting of 1 amp, we see fewer points compared to the previous case with the oscillation peak at 2 kHz. Next, at 1.5 amps we notice the appearance of a higher frequency mode at 37 kHz, very similar to the one seen at -10v, and a much lower oscillation peak frequency value compared to the one noticed at a probe voltage of -10v. Now looking at the 2 amp setting, only one point is seen at a frequency of 39 kHz and can also be considered the previous mode reaching a higher frequency. At 2.5 amps, we notice the higher frequency mode dropping back to what it was roughly at 1.5 amps, while a new mode appears at 48 kHz.

Finally, at a probe voltage of -20v (Figure 13), starting at 0.5 amps, we do not notice any points with frequencies from 0 to 11 kHz, but only from 11 kHz to 26 kHz. This is different than the previous cases, since they showed a natural increasing trend from 0 kHz. Moving onto 1 amp, we see a peak frequency at around 4 kHz, slightly higher than the one noticed at the same amp setting for -15v. Next at 1.5 amps, no high frequency modes are discerned, which differs from the previous case. The peak frequency at this amp setting occurred at 2 kHz. As the current is increased to 2 amps, the oscillation is lost. Finally, at 2.5 amps, one peak frequency is observed at around 41 kHz, which also happens to be a higher frequency mode. Finally, the oscillation is surprisingly lost at 3 amps just as it was at all 3 previous probe voltage settings.

8 Oscillation Analysis

This part of the paper will be brief, investigating possible sources of the oscillations. After analyzing the results, there are some common trends seen throughout all of the oscillations. There are lower frequency oscillations that range between 0 and 40 kHz in addition to higher frequencies at higher amp settings that range between 60 and 100 kHz. Since we're dealing with plasma, the first oscillation values to look at are the electron and ion gyro-frequencies.

Nomenclature:

e = electron charge

B = induction of magnetic field

m_i = ion mass

m_e = electron mass

Ω_i = ion gyrofrequency

Ω_e = electron gyrofrequency

ω_{LH} = lower hybrid frequency

ω_{Pe} = electron Langmuir frequency

ω_{Pi} = ion plasma frequency

n_e = number density of electrons

n_i = number density of ions

z = charge state

m_p = proton mass

Electron gyrofrequency

$$\Omega_e \equiv \frac{eB}{m_e} = 1.76 \times 10^{11} B \left(s^{-1}\right)$$

Ion gyrofrequency

$$\Omega_i \equiv \frac{eB}{m_i} = 0.96 \times 10^{8} \frac{zB}{(m_i/m_p)} \left(s^{-1}\right)$$

The magnetic field strength was roughly 5 G/A. Oscillations were observed between 0.5 amps and 2.5 amps (on the current setting of the magnetic field generator) so solving for both gyro-frequencies with a lower and higher estimate gives us a range within which these oscillations could have occurred. However, it is apparent right after looking at the variables and relations for the equations of the gyro frequencies that the order of magnitude of these values are too large to explain the sources of our oscillations (even for the lower end estimates). Thus, we turn to electron and ion plasma frequencies as the source of our oscillations.

Electron plasma frequency

$$\omega_{Pe} \equiv \left(\frac{n_e e^2}{\epsilon_0 m_e}\right)^{\frac{1}{2}} = 5.64 \times 10^{1} \sqrt{n_e} \left(s^{-1}\right)$$

Ion plasma frequency

$$\omega_{Pi} \equiv \left(\frac{n_i z^2 e^2}{\epsilon_0 m_i}\right)^{\frac{1}{2}} = 1.32 \frac{z\sqrt{n_i}}{(m_i/m_p)^{\frac{1}{2}}} \left(s^{-1}\right)$$

These calculations yield numbers that are too low. Finally, we must attribute the oscillatory behaviour observed in the experiment to ion acoustic waves. By cancellation, there really is not much else that can be responsible for oscillations in this frequency range.

9 Acknowledgements

This summer was such a great learning opportunity and we would like to thank several people for making it possible. Firstly, we would like to thank Dr. Cohen for his guidance throughout the summer project and his patience with us as we delved into an unfamiliar study. Secondly, thank you to Charles Swanson for his help with the fundamental theory involved as well as lab technique. Finally, thank you to all the other interns and PPPL for allowing us to have an amazing summer.