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Langmuir Probes in a Microwave Generated Plasma

Wesley Rawlins, Ajay Singh Ph.D.

Abstract

In this work, we considered a microwave generated plasma, in a toroidal device. In this set up, we tend to meet the conditions for several known plasma instabilities. Not all the gas in the chamber was ionized. Using a Langmuir probe we were able to determine the population temperature and the plasma density in the chamber. The existence of a plasma was determined by measuring the strength of reflected microwaves. We varied the fill pressure in the chamber, as well as the strength of an externally imposed magnetic field. From this, we determined that the plasma temperature decreased with an increased fill pressure. Plasma density however, appears largely unaffected by the fill pressure. Imposing any external magnetic field causes the temperature to drop, though beyond this, the field strength does not appear to influence the temperature. For certain magnetic field strengths tested, the plasma density increased. Further work needs to be done on how temperature and density vary with distance from the chamber wall.

Introduction

Plasma is one of the most prevalent states of matter in the universe. However, because of the ionized nature of plasma, it must be modeled both with fluid dynamics and electromagnetism. There are a few methods of working with this. The first is known as magnetohydrodynamics (mhd), which treats the electrons and ions as behaving identically. There is also the two fluid model, which treats the ions and electrons as two, interacting fluids. These are discussed by L. C. Steinhaur and A. Ishia [1].

A plasma in a pure toroidal field lacks mhd equilibrium. There are several sources of free energy in the form of gradients in plasma density, temperature, magnetic field etc. This free energy manifests itself in fluctuations of equilibrium quantities like density, temperature and potential. Generally speaking, conditions for several plasma instabilities (namely Drift wave, Rayleigh Taylor, Simon-Hoh etc.) are met at the same time and hence these devices offer easily accessible plasmas to study the same. The nature of these fluctuations depends on the source used to create plasma as the source defines strength of the gradients.

There are a number of different set ups for running experiments on plasma, including the Tokamak design as well as the plasma focus. One method of creating plasma is bombarding a gas with radiation, often microwaves, to ionize the gas. This has been used on several different gases, including hydrogen and helium [2]. One feature of this is that the plasmas can be much cooler than other methods for ionizing. This allows for the use of some diagnostic tools, including Langmuir probes.

Method

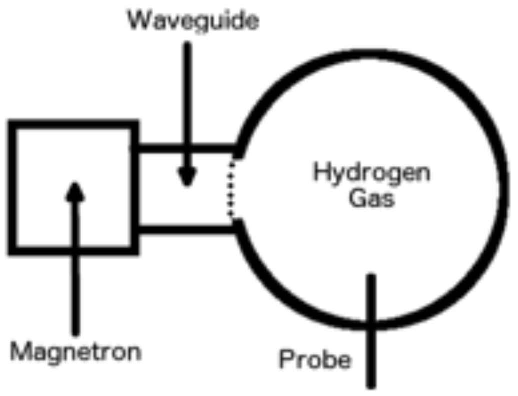

Figure 1. Cross section of the set up.

The STOR-1M tokamak device, which was obtain on loan from University of Saskatchewan, has been modified to operate as a current-less toroidal device. The plasma is created by using a microwave source at 2.45 GHz available from the commercially available magnetrons from kitchen microwave ovens. The present work describes measurements of the basic plasma properties using Langmuir probes. We have measured the temperature and density of the plasma at different combinations of magnetic field and fill pressure. Here we consider the general characteristics of plasma in terms of temperature and density profiles at about 0.9 milliseconds after the plasma was created. Here we will focus on the data taken by a probe close to where the plasma was generated and then consider some of the future work that needs to be done to better understand plasmas of this nature.

Our initial set up involves a toroidal vacuum chamber, with electromagnets around the outside. The result is an imposed magnetic field perpendicular to the cross section of the torus. We specifically considered the magnetic fields of 0, 13, 20, and 45 gauss.

We would then let hydrogen gas into the chamber. As it is not a perfect vacuum, we would maintain a slow flow of gas into the chamber to create an equilibrium pressure that we wanted. In this exploration, we considered pressures ranging from 20 millitorr to 34 millitorr.

In order to generate the plasma, we attached the magnetron, and a wave guide to a window into the chamber, as seen in figure 1. This allowed us to bombard the gas with microwaves, and generate the plasma.

Since a plasma consists of electrons and protons free to move, it responds to external electric and magnetic fields. Measuring the temperatures and plasma densities of the system can be done through what is referred to as a Langmuir probe. The probe, which is a metal tip, is inserted into the plasma, and we apply a time varying voltage to it. As we vary the voltage, we measure the current from the plasma, which gives a characteristic current-voltage curve of the plasma. This I-V curve can be used to determine various properties of the plasma.

If the probe is biased positive with respect to the plasma, it will collect electrons. At sufficiently large positive bias all electrons near the probe are collected. Further increase in the probe bias does not result in an increase in the current. As the probe is made negative only electrons with energies higher than the probe bias get collected and the probe collects ion current. The current collected consists of both ion and electron current in this region of the probe I-V characteristics. There is a bias at which electron current equals the ions current and net current collected by the probe is zero. This is called floating potential of the probe.

Further increase of negative bias results in collection of all ions from the plasma and the current saturates at what is called the ion saturation current of the probe. The ions collect around the probe, creating what is known as the Debye Sheath [3] that shields the plasma from applied probe potential.

$$I = exp[a_1 tanh(\frac{V + a_2}{a_3})] + a_4 \qquad (1)$$

In order to determine the plasma temperature, we use the method described by A. A. Azooz [4]. We take the voltage and current, and fit eq 1 to the data. These properties allow us to determine the electron energy distribution. We then use eq 2 to determine the electron temperature.

$$T_e = \frac{2}{3} \int E f(E) dE \qquad (2)$$

where E is the energy and f(E) is the electron energy distribution function. The energy and temperature are in electron-volts.
Once we have the temperature, we can calculate the electron density, using eq 3.

$$n_e = \frac{I}{A^*e^*u^*exp(-.5)} \qquad (3)$$

where I is the saturation current from the data, A is the surface area of the probe, e is the elementary charge, and u is the Bohm velocity, as determined by eq 4 (where m is the mass of the ions).

$$u = \sqrt{\frac{eT}{m}} \qquad (4)$$

Our probe was a cylinder of length 3.5 millimeters and radius 0.5 millimeters.

It is important to note that since we are starting with a neutral hydrogen gas, the electron density is approximately equal to the ion density in this plasma.

We specifically consider data around .9 milliseconds after plasma creation, as the plasma lasts for about half a second, and this allows enough time for the plasma to settle into an equilibrium, especially if there is an imposed magnetic field, but not long enough that it begins to degrade. We know the life span of the plasma based on the reflected microwaves. Before a plasma is created, the gas is somewhat “transparent” in that the microwaves are either absorbed, or pass through the gas. However, as the gas becomes ionized, the plasma becomes “opaque” in that the majority of the microwaves are reflected. This measurement was actually what was used to trigger the data collection. An example of this is in figure 2, where we see that initially, there is a significant amount of reflected microwave radiation, indicating the presence of plasma. However, as time goes on, and as the plasma degrades, more microwaves are allowed to pass through the gas.

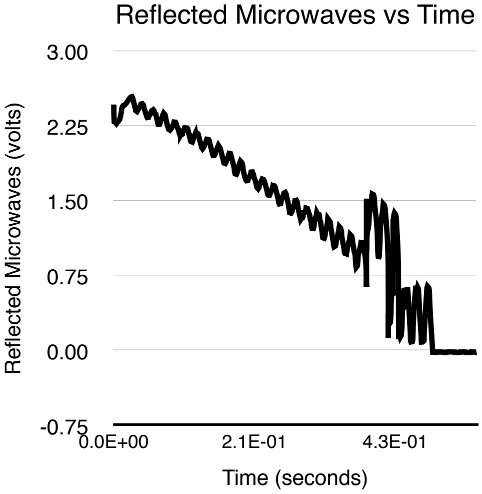

Figure 2. Reflected microwave signal for one data run.

Error considerations

From one data run to another, even if we are using the same properties, there is some variation. The error intrinsic to this fluctuation is quite a bit larger than error associated with our diagnostics themselves.

As such, the way we determined the error associated with each set of data is by doing a T test, to determine a confidence interval, for each of the data points. The confidence intervals tended to be reasonably small for the temperature measurements.

The values for density tend to have larger confidence intervals, than the values for temperature. This is largely due to the fact that the ion saturation current used to calculate it, is sometimes difficult to determine from the data. However, the conclusions are statistically significant.

Results

1. Varied Pressures

As we see from figure 3, when we vary the pressure, in general, the temperature decreases. This is specifically for data taken at 10mm from the chamber wall. Over the full range, it decreased about .4 eV. If we considered adjacent data sets (e.g. 20 mTorr, and 22 mTorr), the uncertainty is large enough, that they could be the same population. However, if we consider 20 mTorr and 34 mTorr, the temperature populations are statistically different. This holds true for magnetic fields from 0 Gauss to 20 gauss. However, when we consider the different pressures at 45 gauss, there is not a clear trend.

If we consider the density, what we find is that in general, the density is fairly consistent, across different pressures. However, this isn’t the case when we consider densities with a magnetic field of 45 Gauss. The densities drop far enough to be statistically significant as we increase the pressure.

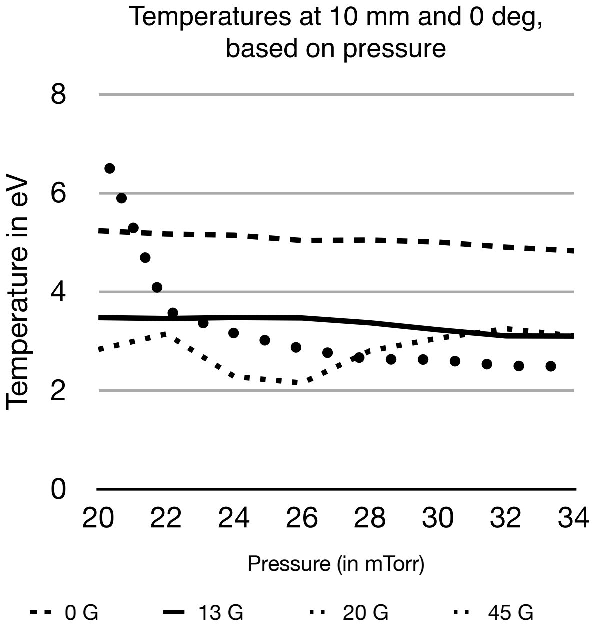

Figure 3. Temperatures based on pressure, for different magnetic fields.

2. Varied External Magnetic Fields

If we consider different magnetic fields, the first observation that can be made is that the presence of any externally imposed magnetic field significantly reduces the temperature (~2eV). Beyond this, there doesn't appear to be a consistent pattern, as for some pressures, the temperature continues to go down with magnetic field, and for others, it remains fairly similar. Densities increase as we impose a magnetic field, but then drop off with a magnetic field of 45 Gauss, as seen in figure 4.

3. Probe distance from the chamber wall

What we found was that as the probe was inserted deeper into the plasma, the temperatures largely were consistent. However, the density increased. This profile was done specifically with a 20 Gauss external magnetic field.

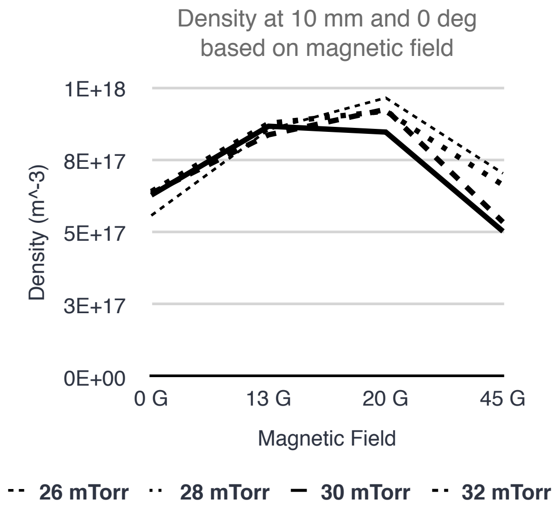

Figure 4. Densities based on Magnetic field. Some pressures excluded for clarity. Others follow the same observed pattern.

4. Anomalies

One of the most significant anomalies is the population of temperatures where there is 20 mTorr of pressure, and 20 Gauss of magnetic field. What we see here is that, while the temperatures close to the chamber wall are comparable to other pressures, as we get closer to the center of the chamber, the temperatures increase dramatically.

At 20 mm depth, with 20 Gauss magnetic field, and 22 mTorr of pressure, as well as 24 mTorr of pressure, we also see a significant increase in the density.

Discussion

We had expected the temperature of the plasma to decrease as we increase the pressure of the gas. The idea behind this is that we are putting an equivalent amount of energy into the gas via the microwaves, but the higher pressure means that there are more particles to absorb the energy. However, this would imply that the plasma density would have increased some, as more particles would have been ionized.

It is unclear why the temperature decreases with the externally imposed magnetic field. Taking this measurement at multiple depths, as well as a different location around the torus might indicate where the energy was going. Similar investigation would be needed to explore the density behavior that was observed.

Plasma tends to flow parallel to the magnetic field, and not perpendicular. So we would expect the plasma to spread laterally. This would cause us to predict lower densities deeper in the chamber. As this was not what was observed, more exploration needs to be done.

Future work

One of the important extensions of the work would be to consider the plasma at different depths and locations in the torus. As mentioned, we only considered varied depths with a 20 gauss external magnetic field, and so more work needs to be done to understand this behavior. Understanding how the various properties affect this diffusion will give us greater insight.

It would also be useful to use a triple Langmuir probe to examine some of the same phenomena. The triple probe technique uses a different method of determining temperatures, and can thus be used to confirm the observed results. The triple probe measurements also have the advantage of determining the temperature at the point in time, rather than an average over some time period. This would give us an opportunity to consider how temperature evolves over time.

The anomalies mentioned are of interest, because it is unclear as to whether or not these are a by-product of the technique, or if these are the actual properties of the plasma. As such, there needs to be further exploration to determine what is that cause of these different values to occur.

Sources

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