Using a Microwave Interferometer to Measure Plasma Density

Avital Levi **Mentor: Prof. W. Gekelman. P. Pribyl (UCLA)**

Introduction:

Plasma is the fourth state of matter. It is composed of fully or partially ionized atoms. It can be as tenuous as a gas and as dense as lead. The plasma used in this experiment is a pulsed Helium plasma. Plasma has properties, such as pressure, density, etc. In this plasma the density is not constant everywhere within the plasma device. The density depends on pressure, magnetic field, type of gas, and degree of ionization. (These were 26 mTorr, 94.6 Gauss, Helium, and .005%)

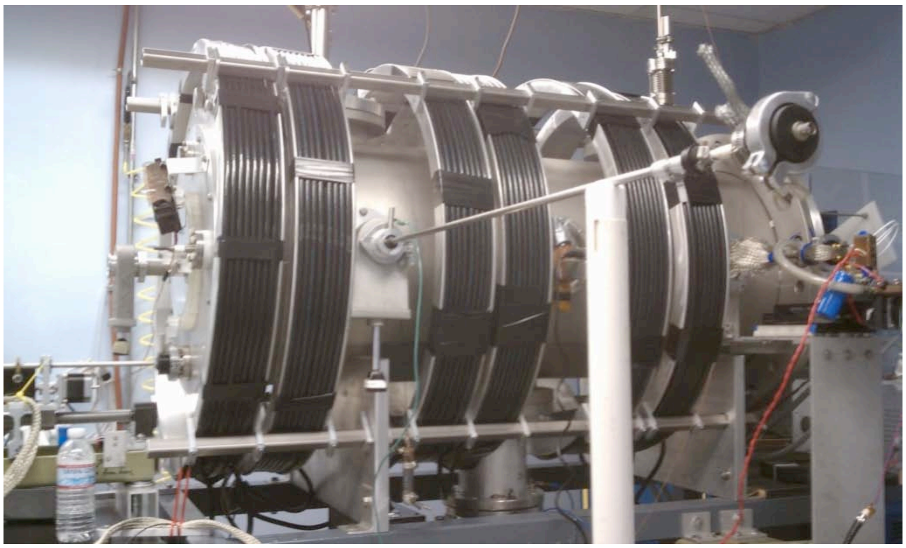

Figure 1. The LAPTAG plasma device and lateral Langmuir probe (LP). There is a radio frequency (RF) source in the back of the device pulsed at 714 kHz. The plasma remains on for 3ms; the black coils create an axial magnetic field which can be varied from 0 to 120 Gauss. The LP is placed 127 cm from the source, it records electron saturation in the center of the chamber.

Here we report on a method used to determine the density of plasma, using a Microwave Interferometer. This stands in contrast to measurement with a Langmuir Probe, a type of electrostatic probe, which is usually just a wire inserted into a plasma which collects current. A Langmuir Probe works by placing it in plasma and measuring the current of electrons to a probe face as the bias applied to that probe is varied.[i] Using the electron saturation current, $I = q_e n_e v_{te} A$, the density may be calculated:

$$(1) \quad n_e = \frac{I}{q_e v_{te} A}$$

Where $q_e \approx 1.6\text{X}10^{-19}$ C; $v_{te} = \sqrt{\frac{kT_e}{m_e}}$ cm/sec, k is Boltzmann's constant, T_e is the electron temperature, and m_e is the electron mass. This may be rewritten as $v_{te} = 4.2X10^7 \sqrt{T_e}$, T_e is measured to be .4 eV[ii], and for helium, $\mu = 4$. Lastly, the probe area A = .43 cm^2 for the probe used.

Measurements of density using a Langmuir Probe are not accurate. First of all the probe theory generally used is for a plasma without a magnetic field. The LAPTAG plasma is magnetized. As the probe is physically inside the plasma it can disturb it thereby affecting the calculated density. Microwave interferometers measure the plasma density without disturbing the plasma. They yield a spatially averaged density, however, while a probe gives a point measurement.

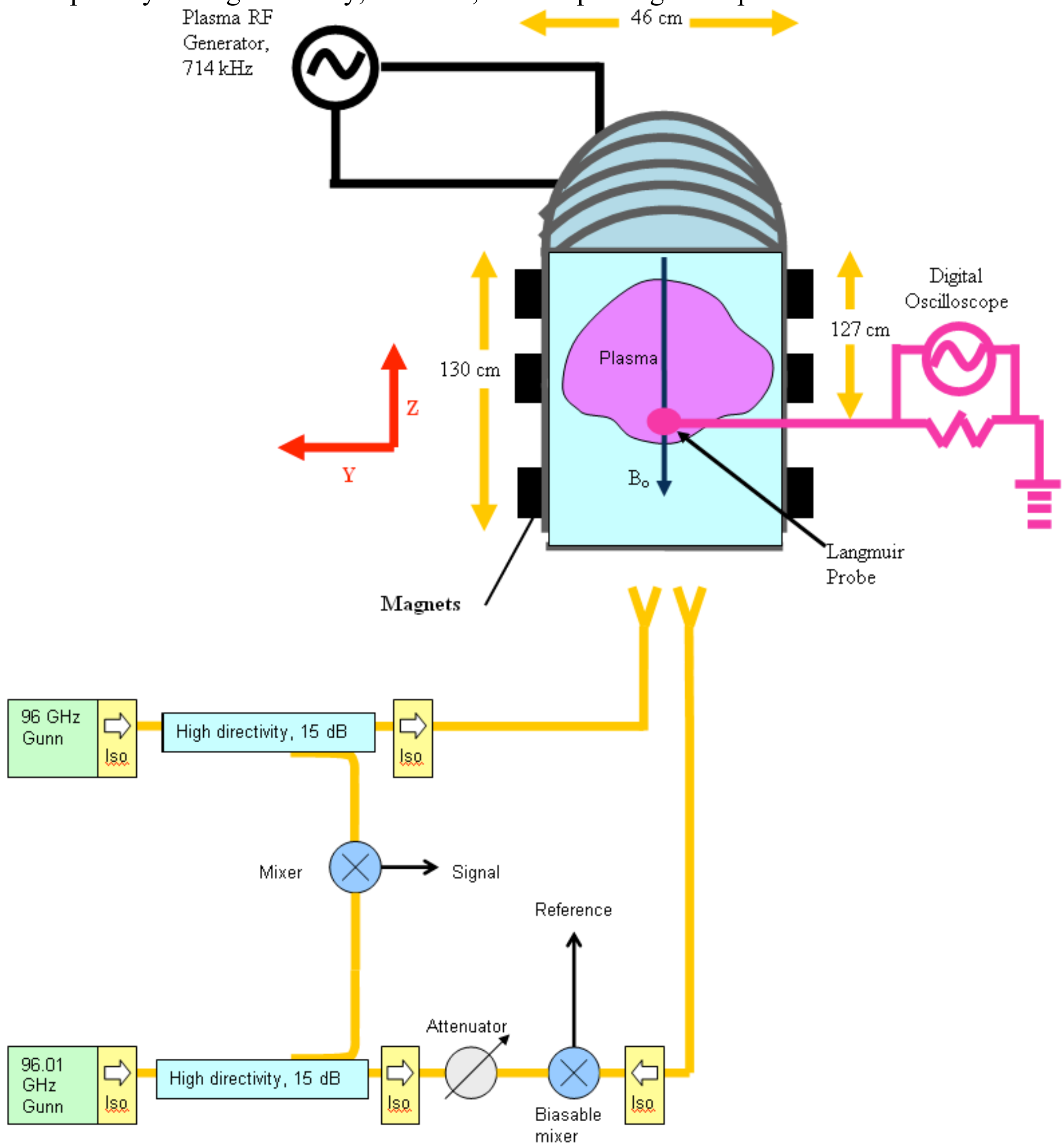

Figure 2. Schematic diagram of the machine and interferometer. The image is looking through the axis of the machine and the waves reflect off the dome. Gunn represents a Gunn diode, which creates an RF; this is the microwave source. "Iso" represents the isolator, which lets the microwaves through in one direction. The Attenuator reduces the amplitude of the signal to be close to the level of the beam that comes back from the plasma. This helps the detector pick out the appropriate signal. The "High Directivity" boxes are directional couplers which tap off a

small part (~3%) of the signal. The B-Field in the chamber (B_o) has a range of 0 to 120 Gauss and is created by wires set up as a solenoid around it. Langmuir Probe is placed 127 cm from the source. The RF generator pulses the plasma. This diagram is not drawn to scale.

Microwave Interferometers split a microwave beam into two paths; one signal goes through a "reference leg" and the other goes through the plasma whose density is to be determined.
A diagram of a simple interferometer is shown in figure 3.

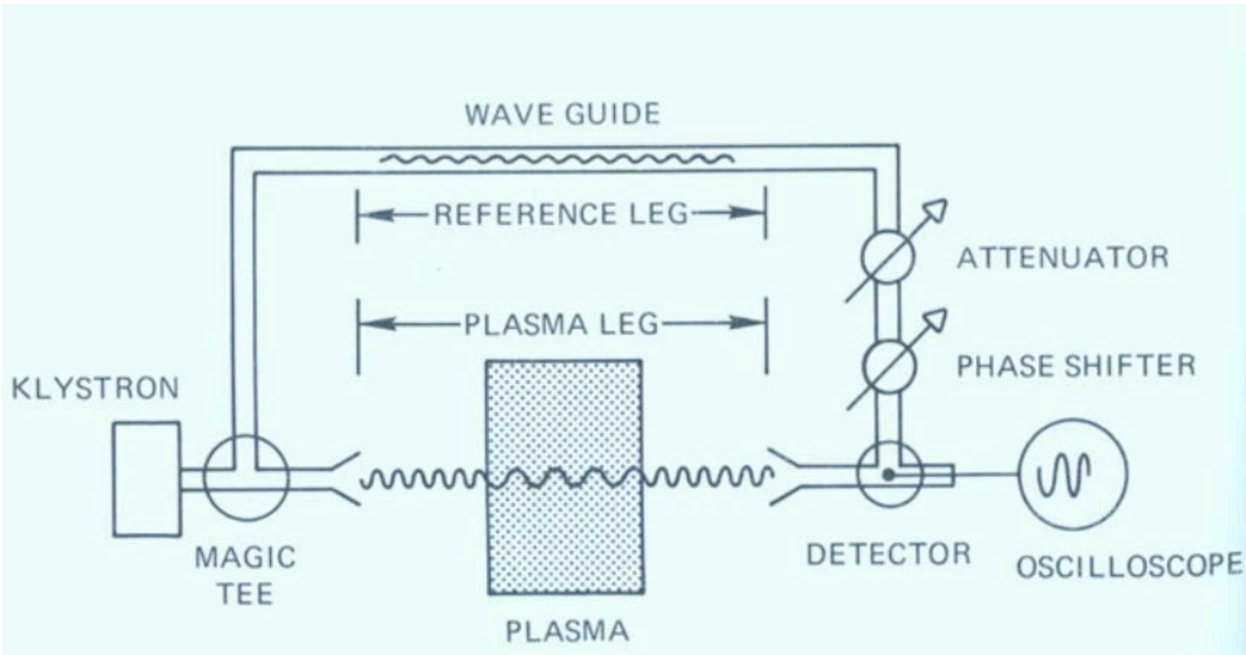

Figure 3. A microwave source (in the figure above it is a Klystron tube; in the LAPTAG experiment it is a Gunn Diode). The microwave beam is split by a magic tee into an object and a reference beam. These are combined in the detector which is a microwave mixer capable of measuring the relative phase between the beams. The LAPTAG interferometer operates at 90 GHz and therefore has a free space wavelength of 3 cm. The interferometer used differs from this in that the reflected signal is detected by a second horn and there is no separate reference leg.

In the LAPTAG machine, one wave is sent out from a horn antenna, propagates through the plasma and reflects off the dome in the back of the machine, and is received by a second antenna. The interferometer can then measure the phase and amplitude of the received signal.[iii] Microwave interferometers may use these to measure the wave shift and attenuation which occurs as the microwave propagates through a plasma.[iv]

Theory behind the operation of a microwave interferometer:

The basic physics behind the operation of an interferometer is that the index of refraction of a plasma, which can be calculated using force, momentum and conservation equations, depends upon the plasma density. The index of refraction affects the wavelength of the signal traveling through the plasma. The effect is that, the phase difference between the reference and plasma leg changes in the presence of a plasma. This phase difference is used to determine average density of the plasma.

To begin, we can use the dispersion relation

$$(2) \quad \tan^2\theta == \frac{\varepsilon_{\parallel}\left(n^2-\varepsilon_R\right)\left(n^2-\varepsilon_L\right)}{\left(n^2-\varepsilon_{\parallel}\right)\left(n^2\varepsilon_T-\varepsilon_R\varepsilon_L\right)}$$

where $\varepsilon_{\parallel} = 1-\Omega_p^2$, $\varepsilon_L = 1-\frac{\Omega_p^2}{(1-\beta_+)(1+\beta_-)}$, $\varepsilon_R = 1-\frac{\Omega_p^2}{(1+\beta_+)(1-\beta_-)}$

and $\varepsilon_T = \frac{\varepsilon_L+\varepsilon_R}{2}$, $\Omega_p^2 = \frac{\omega_{pe}^2}{\omega^2}+\frac{\omega_{pi}^2}{\omega^2}$ and $\beta = \frac{\omega_c}{\omega}$.

Here, θ is the angle relative to the background magnetic field and n is the index of refraction

$$(3) \quad n \equiv \frac{kc}{\omega}$$

where k is the wavenumber and c the speed of light in vacuum.

The frequencies are defined as:

$\omega_{pe} = (4\pi Ne^2/m_e)^2$ is the plasma frequency of the electrons,
$\omega^2_{pe} = Ne^2/m_e\,\epsilon_o$,
ω_{pi} = plasma frequency of the ions,
$\omega_{ce} = eB/m_e$ is the electron cyclotron frequency, and
ω = 90 GHz is the frequency of the microwave times 2π.

The factor ω_{pi} is small that the second term in $\Omega_p{}^2 = \omega^2_{pe}/\,\omega^2 + \omega^2_{pi}/\,\omega^2$ may be neglected, making $\Omega_p{}^2 = \omega^2_{pe}/\,\omega^2$.

Consider propagation along or across the magnetic field, where $\theta = 0, \frac{\pi}{2}$. Then the dispersion relation is satisfied when

$$n^2 = 1-\Omega_p^2 = 1-\left(\frac{\omega_{pe}^2}{\omega^2}+\frac{\omega_{pi}^2}{\omega^2}\right)$$
$$(4) \quad k^2c^2 = \omega^2-(\omega_{pe}^2+\omega_{pi}^2) \cong \omega^2-\omega_{pe}^2$$

Note that the difference between equation 4 and that for a lightwave ($\frac{\omega}{k}=c$) is the plasma frequency term, which depends upon the density ($f_{pe} = \frac{\omega_{pe}}{2\pi} = 8.98\times10^3\sqrt{N}$ $\quad$ N = $\frac{\text{\# electrons}}{\text{cm}^3}$).

Since the index of refraction of the plasma is directly related to the density, and the phase of the beam going through the “plasma leg” is affected by the index of refraction, the phase difference between the signals can be used to determine the density.

The phase detector works by subtracting the phase difference between the two waves. This is displayed as a voltage. The attenuator and phase shifter are adjusted to make the signals equal in amplitude and out of phase by 180°, this makes the detector output zero in the absence of plasma. To calibrate the interferometer, data is collected while aiming it at a reflective surface and varying its distance to the surface. This is done on a bench top, not using the plasma. This data is shown in figure 4. This graph indicates that a 2π phase shift corresponds to 2 Volts; this ratio is used to change the interferometer voltage into phase angle.

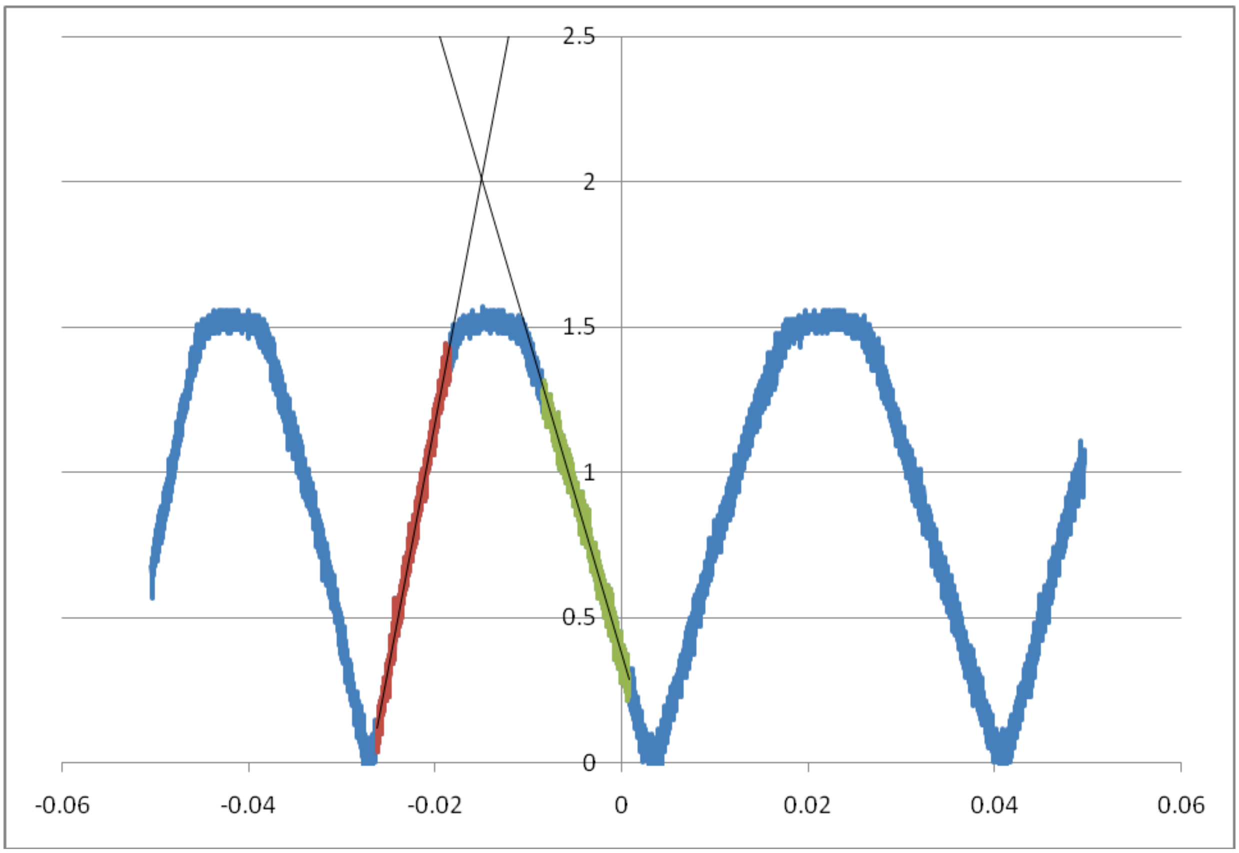

Figure 4. Interferometer calibration data. The interferometer is aimed at a moving reflective surface and the fringes are displayed. The flattened peaks are caused by inaccurate instrumentation, so linear trendlines are used to determine the voltage corresponding to two fringes. Here a fringe is 2 Volts and corresponds to π phase shift.

When the plasma is turned on, the index of refraction causes the signal which travels through the plasma to have an increased wavelength, causing a change in the phase of the signal which will be compared to the signal which traveled through the “reference leg.” As the density of the plasma increases when the plasma is switched on, throughout the volume of the chamber, the detector output fluctuates between zero and two times the maximum amplitude every time the phase shift changes by 180°. These are called fringe shifts. The obtained density is a spatially averaged density found from the number of fringe shifts, where one interferometer fringe is 2 Volts and corresponds to π phase shift.

According to theory the phase shift (Δφ) equals $\frac{L}{2c\omega}\omega_{pe}^2$, where L is twice the length of the plasma within the chamber. Using $\omega^2_{pe} = ne^2/m_e\epsilon_o$, density may be calculated as

$$n = \frac{2c\omega\Delta\varphi}{L}\left(\varepsilon_0 \frac{m_e}{e^2}\right) \quad (5)$$

Scans were taken of variable pressure, background magnetic field, and RF supply voltage. These varied from 15 to 45 mTorr, 33 to 94.6 Gauss, and 120 to 320 Volts, respectively. Electron saturation at a fixed location in the chamber was also recorded. Ion saturation may be obtained from electron saturation by

$$i_{sat} = \sqrt{\frac{kT_e}{m_I}}\, e_{sat}A, \quad (6)$$

where A is the area of the probe, .43 cm^2.

Data:

Data was analyzed to determine how conditions such as fill gas pressure and magnetic field affect the plasma density.

Figures 5a through 5d are density versus time plots at varying pressures with background magnetic field at 94.6 Gauss and RF equal to 320 Volts. The solid lines are densities as calculated through the interferometer; the dashed lines are those calculated with the Langmuir Probe (LP). The LP is at a fixed location 127 cm away from the source and collects electrons in the center of the chamber. The measurements are made 0.010 seconds, after the RF source is turned off.

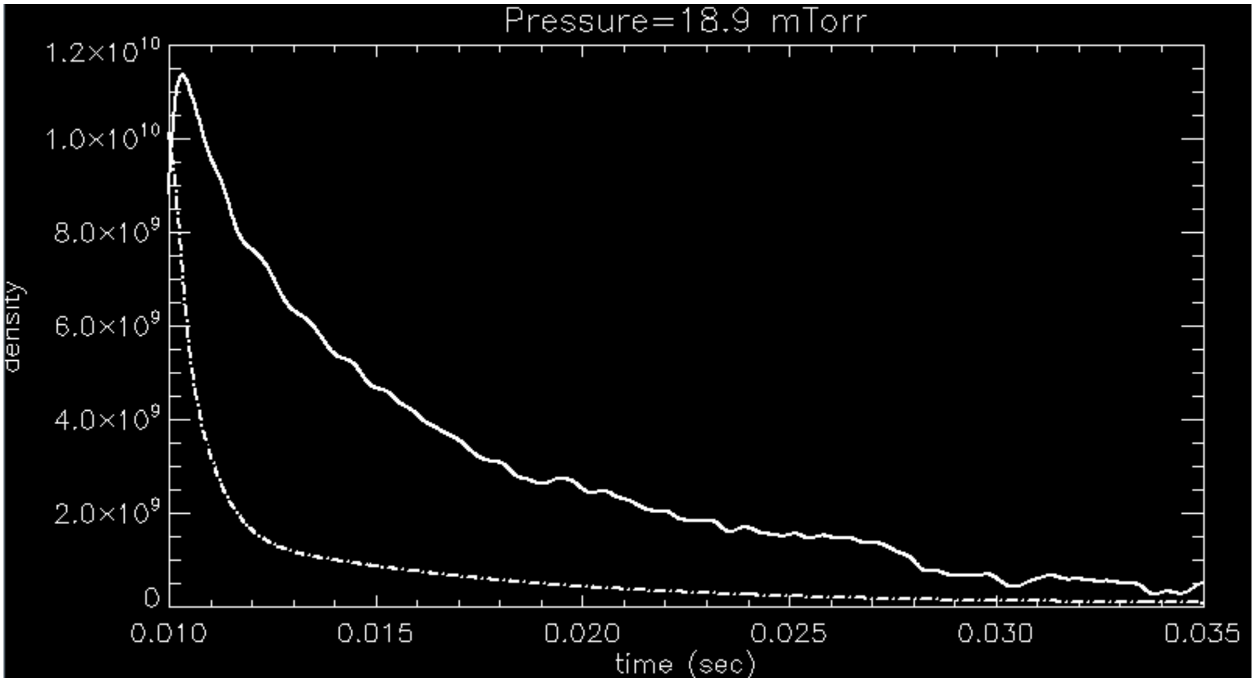

Figure 5a. Measured plasma density at 18.9 mTorr. The interferometer density is 4 times larger than the LP density at .012 seconds.

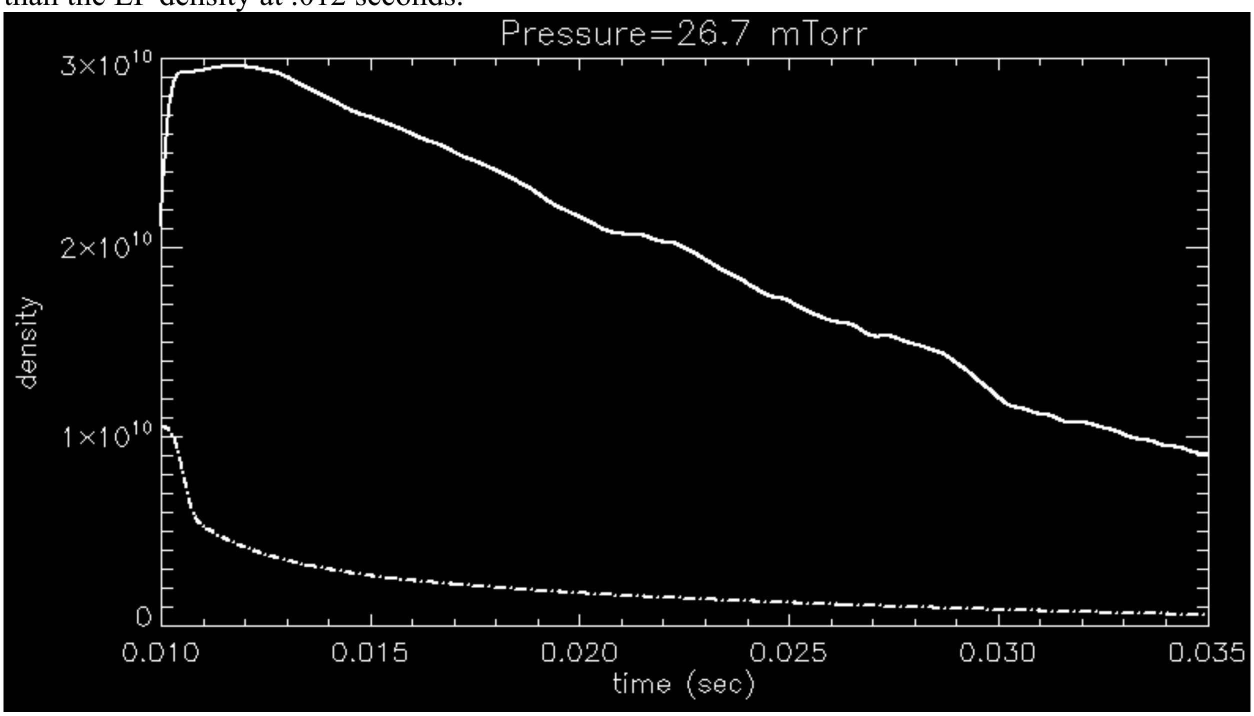

Figure 5b. Measured plasma density at 26.7 mTorr. The interferometer density is 6 times larger than the LP density at .012 seconds.

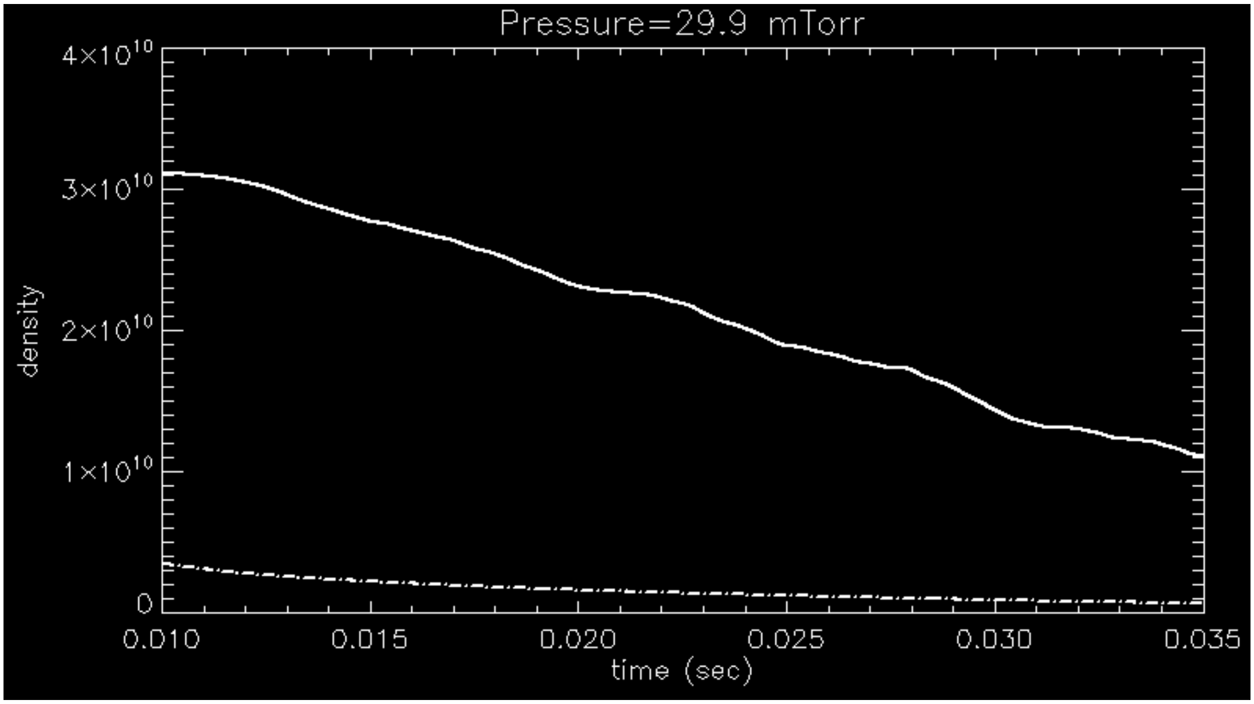

Figure 5c. Measured plasma density at 29.9 mTorr. The interferometer density is 10 times larger than the LP density at .012 seconds.

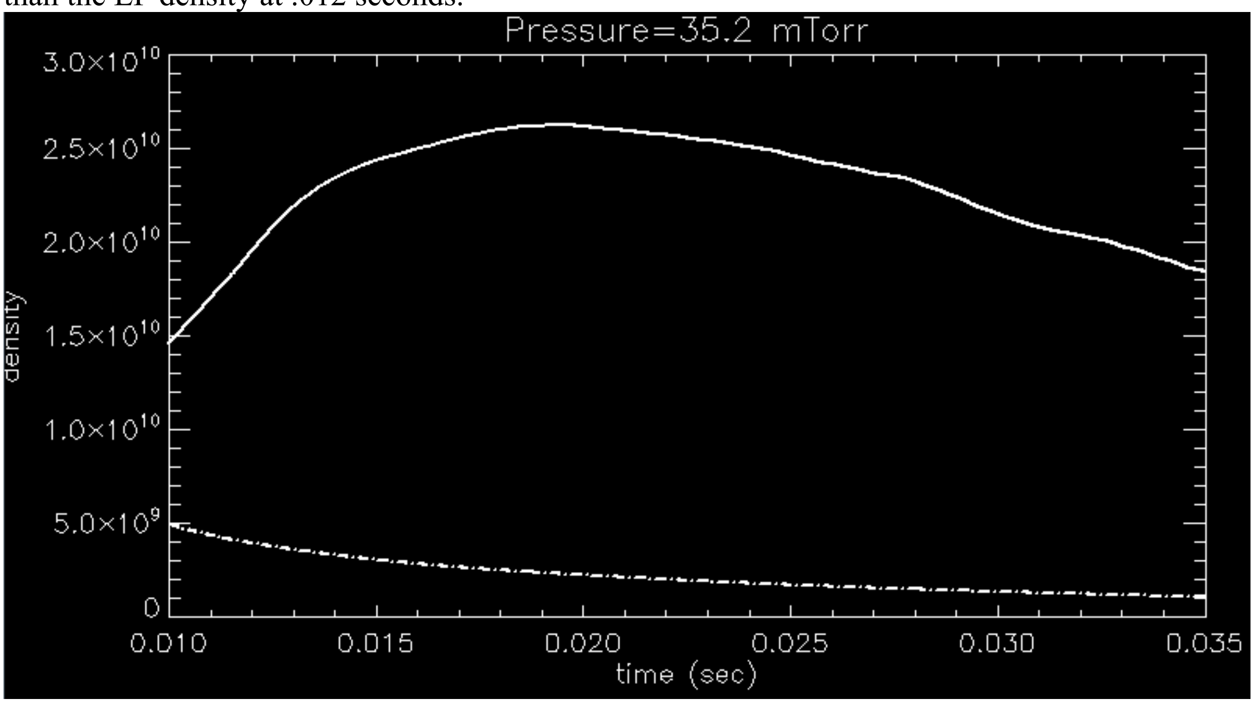

Figure 5d. Measured plasma density at 35.2 mTorr. The shape of the density as calculated by the interferometer is more bell-shaped compared to the densities at other pressures and is lower in magnitude. This shows that the density-pressure relationship loses its linearity at high pressures.

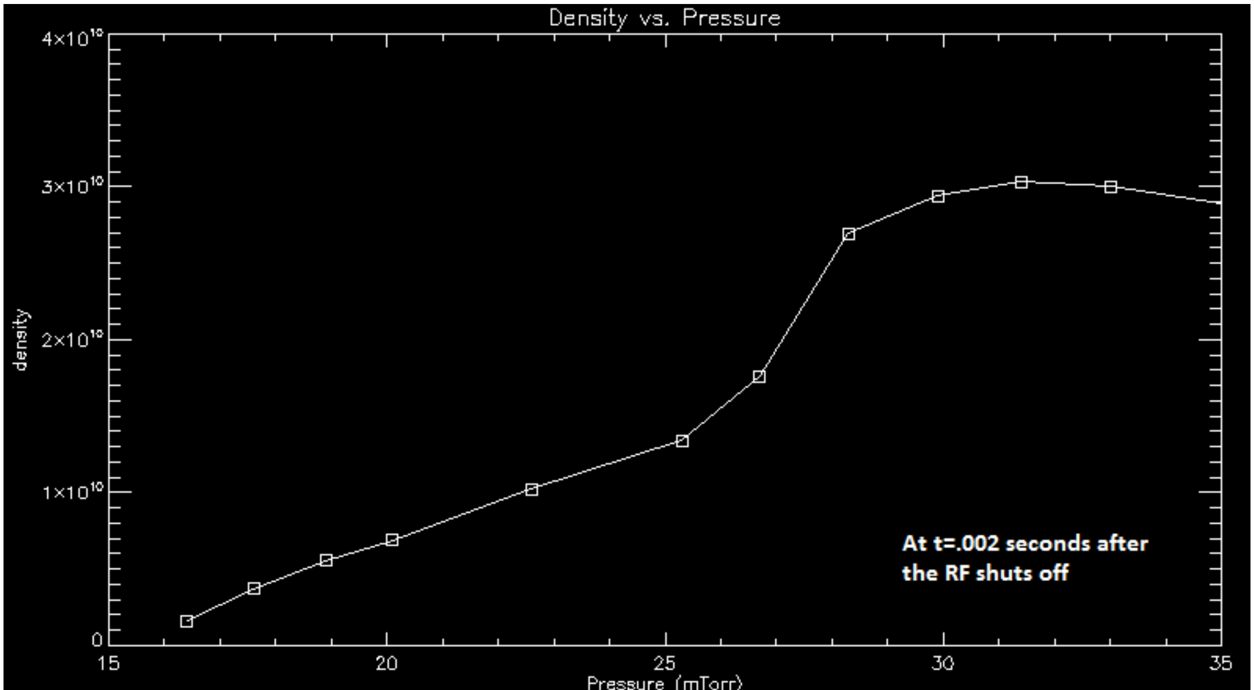

Figure 6. The above plot is density (cm^{-3}) versus pressure (mTorr), at t = .002 seconds after the RF turns off; with a background b-field at 94.6 G and RF at 320 V. The relationship is fairly linear until the chamber is at a higher pressure. This is because at higher pressure the fast electrons in the plasma source lose more of their energy to non-ionizing collisions.

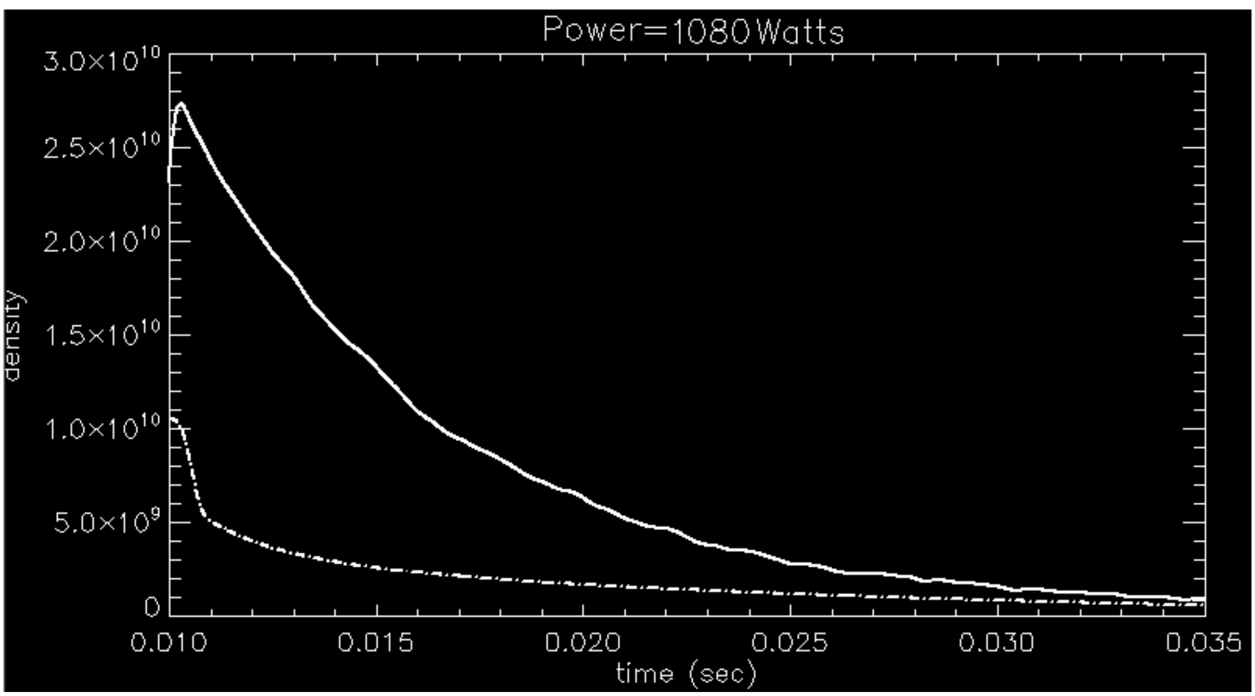

Figure 7. Density versus time with 1080 Watts of power. The RF is at 300 V, background magnetic field at 94.6 Gauss, and pressure equal to 26.7 mTorr. The solid lines are densities as calculated through the interferometer; the dashed lines are those calculated with the Langmuir Probe (LP). The LP is at a fixed location 127 cm away from the source and collects electrons in

the center of the chamber. The measurements are made 0.010 seconds, after the RF source is turned off. The interferometer density is 5 times larger than the LP density at .012 seconds.

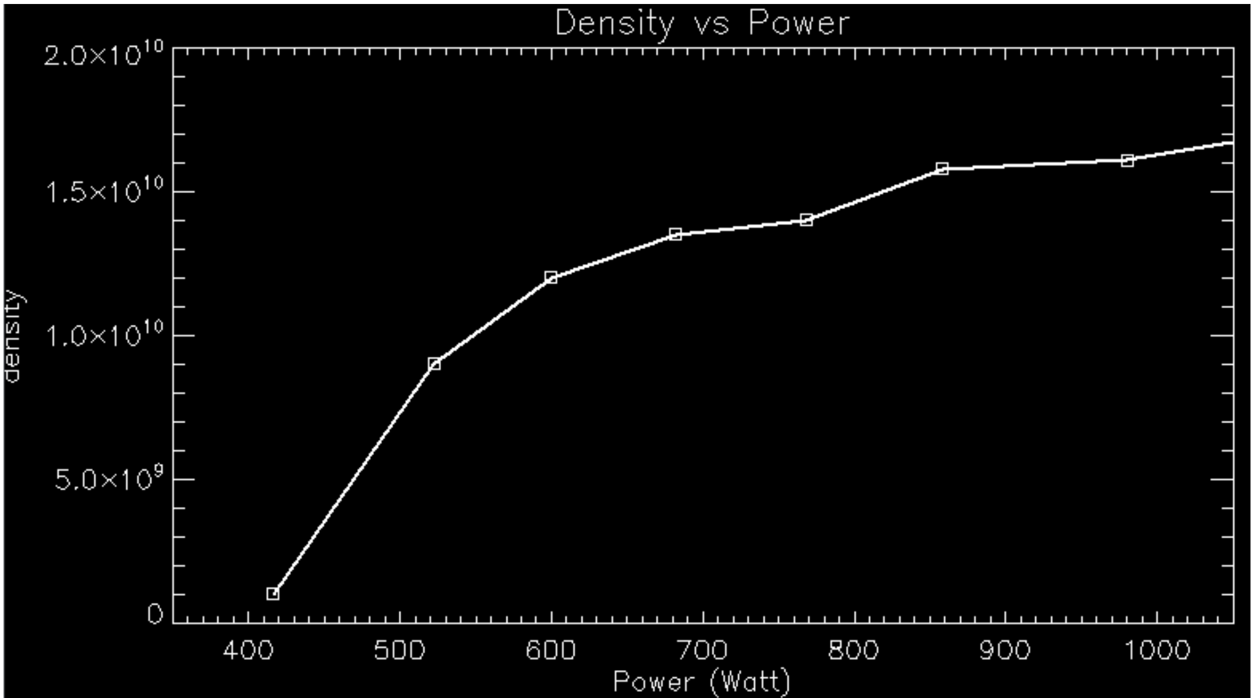

Figure 8. The above plot is density (cm^{-3}) versus power (Watt), at t = .002 seconds after the RF turns off; with a background b-field at 94.6 G and pressure at 26.7 mTorr. The relationship is fairly linear except at low power. This is because the power is too low to ionize the atoms.

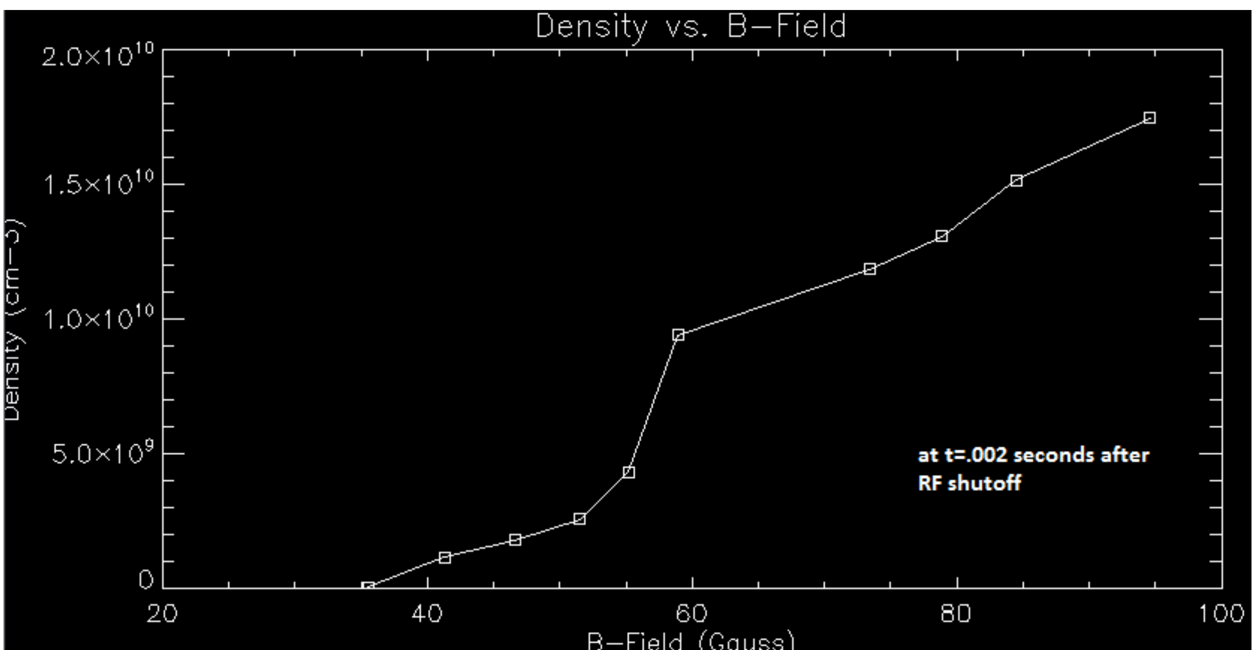

Figure 9. The above plot is density (cm^{-3}) versus background magnetic field (Gauss), at t = .002 seconds after the RF turns off; with RF at 320 Volts and pressure at 26.7 mTorr. The relationship

is linear except for the data at 58.9 Gauss; since the data is quite linear except at this point, this may be a result of some outside interaction with the interferometer.

The length L used in determining these densities, 300 cm, is an approximated length; L is properly determined by calculating $\int_0^L n(z)dz$, the area under the graph of the density along the z-axis (along the b-field), and dividing by the average density of the plasma. A plot of this data is shown in figure 10. After computing the data, a length of 126.99 cm is obtained; this is multiplied by 2 to get the length of plasma that the signal travels through, 254.0 cm.

3.55575 * 10^12/(2.8 * 10^10)

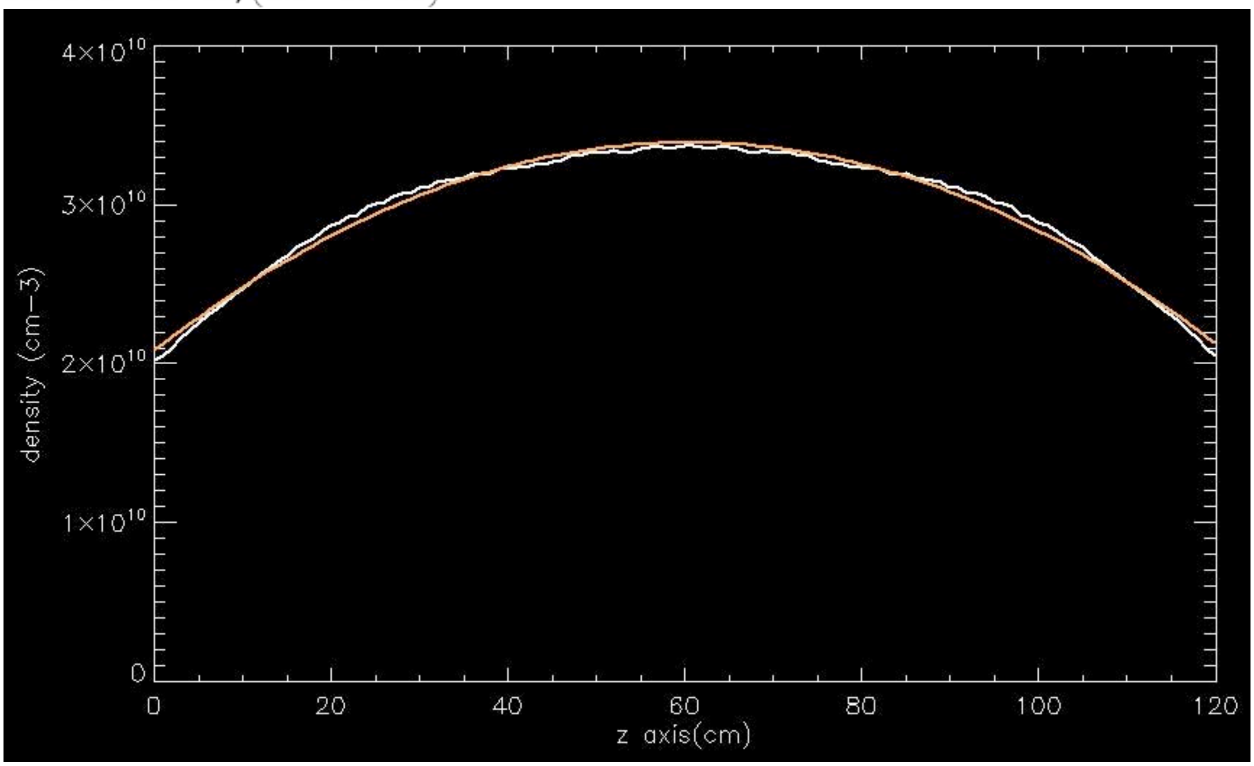

Figure 10. The white line is the density along z-axis, the orange is a best fit line of the density curve. This data was taken with pressure at 26.0 mTorr, B-field at 94.8 Gauss, and RF was at 310 V. The best fit line is $f(x) = ax^2 + bx + c$, with a=2.08258X10^10, b= 4.32616X10^8, and c= -3.57323X10^6.

Conclusions:

Plasma density depends on pressure, magnetic field, type of gas, and degree of ionization. In the determination of the LAPTAG plasma density, scans were taken with variable pressure, background magnetic field, and RF voltage. Analysis of these scans indicate generally linear relationships between these parameters and the density of the plasma – as pressure, B-field, and power increase, the density of the plasma increases as well.

The linear relationship between density and chamber pressure ends at high pressures, almost at 30 mTorr. This is because at higher pressure the fast electrons in the plasma source lose more of their energy to non ionizing collisions. Similarly, the relationship between density and power is non-linear until about 30 Watts; this is because below 30 Watts, the power is too low to ionize the Helium atoms.

Scans were also taken with a Langmuir Probe; the densities calculated with the LP are 4 to 10 times lower than those from the interferometer. This may be because the positive bias on the probe leads to electrons building up around it, making other electrons not as attracted to the LP which leads to a lower density.

<u>Plasma Chamber Design:</u>

In addition to the work with the interferometer, a chamber was designed for the UCLA plasma physics lab 180E. The chamber is 160 cm long and 51 cm in diameter, has 33 circular ports and three rectangular ports, has a pump located beneath it, and has nine coils around it to create the axial magnetic field. Figures 11 through 13 are different views of the chamber.

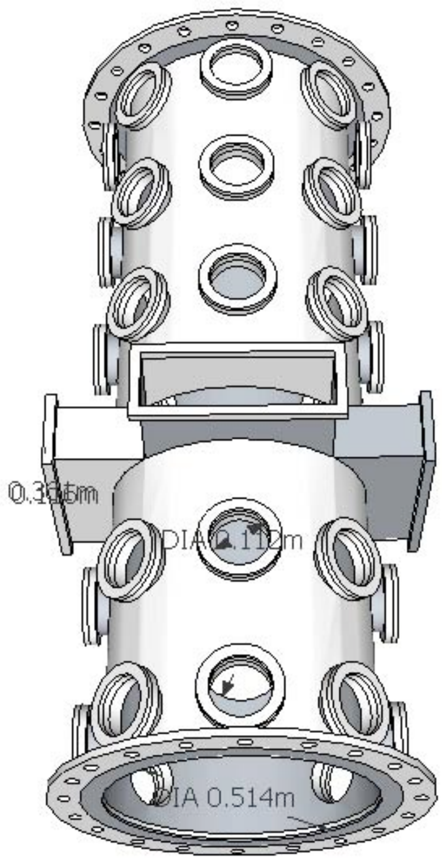

Figure 11. Top view.

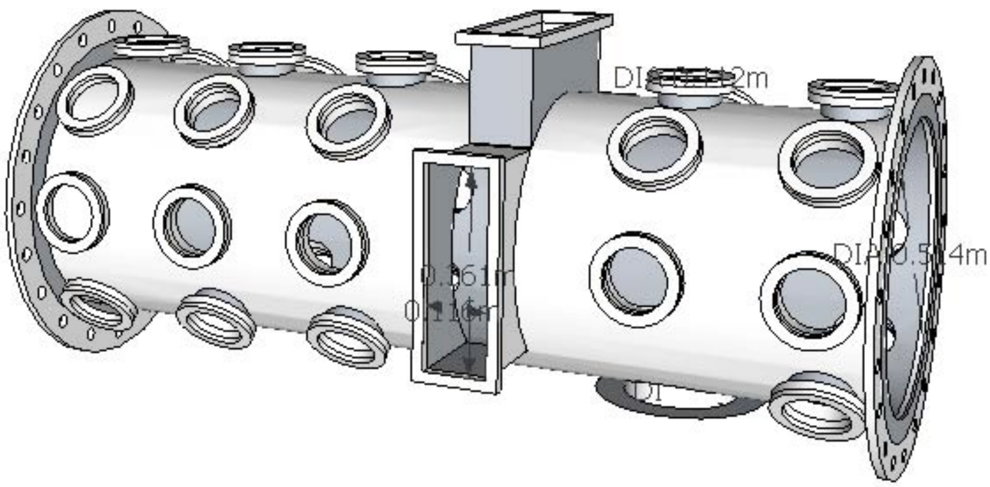

Figure 12. Side view.

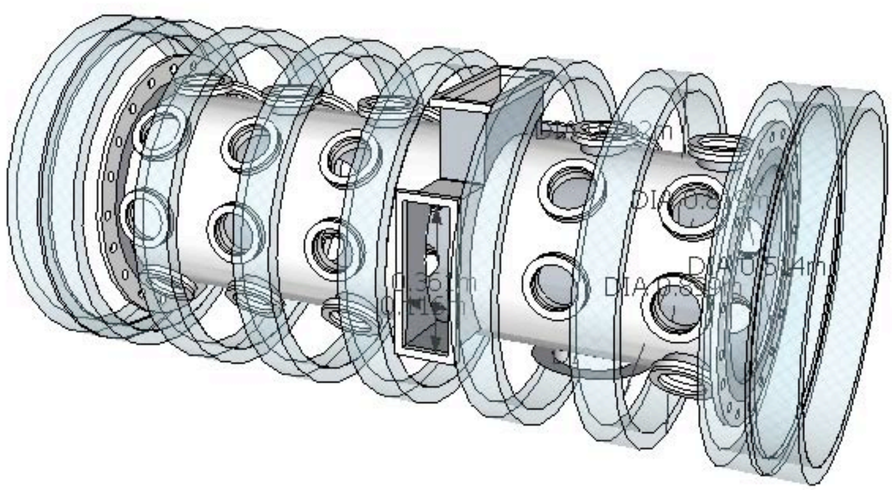

Figure 13. Side view with magnets.

[i] F.F. Chen, Plasma Diagnostic Techniques, Academic Press, New York, 1965, p. 114.
[ii] Personal communication, P. Pribyl, from a separate measurement.
[iii] C.B. Wharton, Plasma Diagnostic Techniques, Academic Press, New York, 1965, p. 500-501.
[iv] C.B. Wharton and A.L. Gardner, Microwave Circuits and Horns for Plasma Measurements, U.S. Patent 2,971,153 (1959).