Basic Plasma Diagnostics: Probes and Analyzers

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WHAT IS PLASMA?

Plasma is the fourth state of matter. Plasmas are conductive assemblies of charged particles, neutrals and fields that exhibit collective effects. Plasma is profoundly influenced by the electrical interaction of the ions and electrons, and by the presence of magnetic fields. Plasmas are classified by several parameters that include: amount of ionization, plasma density, plasma temperature, and Debye length (λ), among others. Plasmas are the most common form of matter, comprising more than 99% of the visible universe. When gas particles have enough energy they split into nuclei and electrons and become plasma.

PLASMA DIAGNOSTIC PROBES

A Langmuir probe is a device named after Nobel Prize winning physicist Irving Langmuir which is used to determine the electron temperature, electron density, and plasma potential.

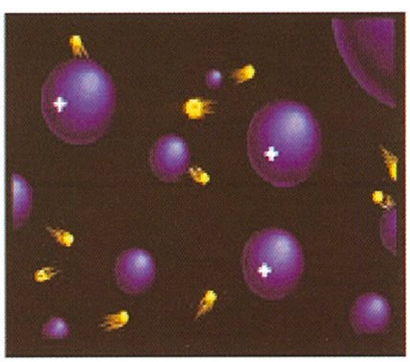

Figure 1: *Picture courtesy of Stephen Haigh, Culham Electromagnetics and Lightning*

It works by inserting one or more electrodes into plasma and observing the current flowing to the probe as a function of the difference between the probe potential and the plasma space potential. This current vs. voltage characteristic is used to determine the basic plasma parameters. Langmuir and collaborators were the first to study phenomena in plasma in the early 1920's while working on the development of vacuum tubes for large currents. It was Langmuir who in 1929 used the term "plasma" for the first time to describe ionized gases.

SINGLE LANGMUIR PROBE

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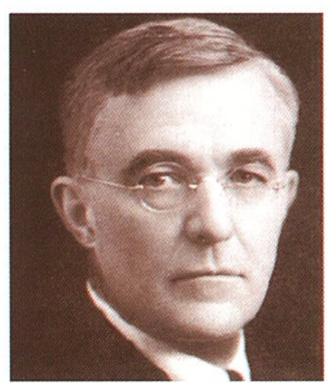

Figure 2: *Irving Langmuir*

difference between the probe potential and the plasma space potential. This current vs. voltage characteristic is used to determine the basic plasma parameters. Most of the data shown in this presentation was taken at Polytechnic University of Puerto Rico Mirror-Cusp (PUPR-MC) plasma machine either as a Mirror or as a Cusp. The probes and analyzers that will be shown below were designed, built and successfully tested in the Fusion Research Laboratory mainly for PUPR-MC plasma machine.

A description of several probes is followed by methods of several authors, among them: A. Wong [3], R Stenzel [2], and E . Leal-Quirós [1].

A design of the Single Langmuir Probe will follow later. Basically, if we consider a small disc inside the plasma, the current collected is given as:

$$I = A\sum_{i=1}^{N} n_i\, q_i\, \bar{v}_i \qquad (1)$$

where A is the total area of the probe, given by $A_{probe} = 2\pi r^2$, r the radius of the disc, $\bar{v}_i$ is the average velocity of the species, given by:

$$\bar{v}_i = \frac{1}{n}\int v\, f_i(\bar{v}_i)\, d\bar{v}_i \qquad (2)$$

In the equilibrium, the velocity distribution is Maxwellian, as is shown in Figure 3.

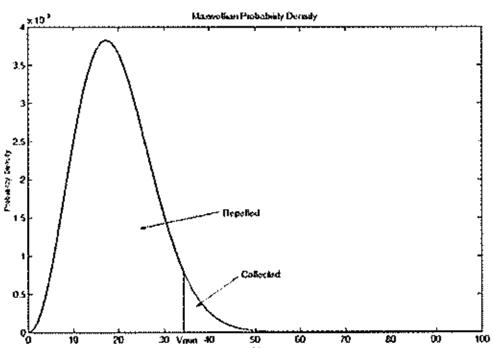

Figure 3: *Electron velocity distribution function. All electrons with energy |eV| greater than* $\frac{1}{2} m_e V_{min}^2$ *are collected.*

The velocity distribution is given by:

$$f_\alpha = n\left(\frac{2\pi k T_\alpha}{m_\alpha}\right)^{\left(-\frac{3}{2}\right)}\left(\frac{-\frac{1}{2} m_\alpha (\bar{v})^2}{k T_\alpha}\right) \qquad (3)$$

where f_α is the equilibrium velocity distribution function or Maxwellian distribution, for the specie α, n is the density of the specie α, kT_α is the temperature for the specie α, and m_α is the mass the specie α.

Consider a small plane disc probe inside the plenums and in the y-z plane. A particle will give rise to a current only if it has a v_x component of velocity. Thus, the current to the probe does not depend on v_y or v_z . The current to the probe from each species is a function of

$$I(v) = nqA.\left[\int_{-\infty}^{\infty} dv_y \left(\frac{2pkT_a}{m_a}\right)^{-\frac{1}{2}} \exp\left(\frac{-\frac{1}{2} m_a v_y^2}{kT_a}\right)\right]$$
$$\left[\int_{-\infty}^{\infty} dv_z \left(\frac{2pkT_a}{m_a}\right)^{-\frac{1}{2}} \exp\left(\frac{-\frac{1}{2} m_a v_z^2}{kT_a}\right)\right]$$
$$\left[\int_{V_{min}}^{\infty} d\bar{v}_x \bar{v}_x \left(\frac{2pkT_a}{m_a}\right)^{-\frac{1}{2}} \exp\left(\frac{-\frac{1}{2} m_a v_x^2}{kT_a}\right)\right] \qquad (4)$$

Particles with v_x component of velocity less than V_{min} are repelled, with V_{min} given by

$$V_{min} = \sqrt{\frac{2qV}{m_\alpha}} \qquad (5)$$

Integrals over v_y and v_z give a unit so the current of each species is:

$$I(\bar{v}_x) = nqA \left[\int_{V_{min}}^{\infty} d\bar{v}_x \bar{v}_x \left(\frac{2\pi k T_\alpha}{m_\alpha}\right)^{-\frac{1}{2}} exp\left(\frac{-\frac{1}{2} m_\alpha (\bar{v}_x)^2}{k T_\alpha}\right)\right] \qquad (6)$$

Figure 4 is a typical Langmuir probe characteristic that was taken in PUPR-MC plasma machine as a Cusp.

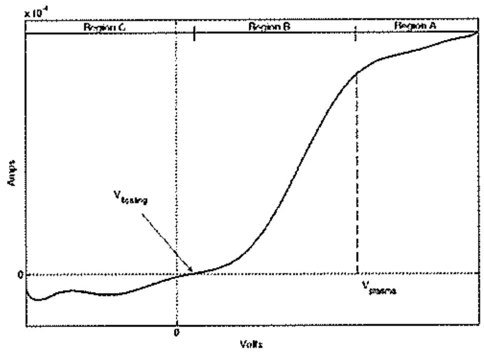

Figure 4: *Typical Single Langmuir probe I-V Characteristic Acquired at PUPR-MC Plasma Machine*

ELECTRON SATURATION CURRENT, I_{es}

All electrons with v_x component toward the probe are collected until the electron saturation current is obtained as

$$I_{es} = -n_e A \int_{V_{min}}^{\infty} d\,\bar{v}_x\, \bar{v}_x \left(\frac{2\pi k T_\alpha}{m_\alpha}\right)^{-\frac{1}{2}} exp\left(\frac{-\frac{1}{2} m_\alpha \left(\bar{v}_x\right)^2}{k T_\alpha}\right) \tag{7}$$

$$I_{es} = n_e A \sqrt{\frac{kT_e}{2\pi m_e}} \tag{8}$$

Hence, the electron density is obtained by

$$n_e = \frac{-I_{es}}{eA\sqrt{\frac{kT_e}{2\pi m_e}}} \tag{9}$$

Similarly, in region B and C where $V_p < V_s$ and electrons are repelled, the total current is:

$$I_{es} = I_{is} - n_e A \left[\int_{V_{min}}^{\infty} d\,\bar{v}_x \bar{v}_x \left(\frac{2\pi k T_e}{m_e}\right)^{-\frac{1}{2}} exp\left(\frac{-\frac{1}{2} m_e \left(\bar{v}_x\right)^2}{kT_e}\right)\right] \tag{10}$$

Substituting $\frac{1}{2} m_e V_{min}^2$ by $-eV$, equation 7 then becomes

$$I_{es} = I_{is} - n_e A \int_{V_{min}}^{\infty} d\,\bar{v}_x\, \bar{v}_x \left(\frac{2\pi k T_e}{m_e}\right)^{-\frac{1}{2}} exp\left(\frac{eV}{kT_e}\right) \tag{11}$$

Since $V<0$ in region B, equation 11 shows that the electron current increases exponentially until the probe voltage is the same as the **plasma space potential**,

$$V = V_p - V_s \tag{12}$$

ION SATURATION CURRENT, I_{is}

The ion saturation current is not simply given by an expression similar to I_{es}. In order to repel all the electrons and observe I_{is}, V_p must be negative and have a magnitude near $\frac{kT_e}{e}$. The sheath criterion requires that ions arriving at the periphery of the probe sheath be accelerated toward the probe with an energy ; kT_e , which is basically their thermal energy kT_i. The ion saturation current is then approximated as

$$I_{is} = neA\sqrt{\frac{2kT_e}{m_i}} \tag{13}$$

FLOATING POTENTIAL, V_f

When $V = V_f$, the ion and electron current are equal and the net probe current is zero. Combining equations $I(\bar{v}_x)$ and I_{is}, and letting $I(\bar{v}_x) = 0$,

$$V_f = -\frac{kT_e}{e}\sqrt{ln\left(\frac{m_e}{4\pi m_i}\right)} \tag{14}$$

Examples:

$V_f = -4.34\frac{kT_e}{e}$ for argon

$V_f = -5.39\frac{kT_e}{e}$ for helium

The Electron Temperature

Measurement of the electron temperature can be obtained from equation $I\left(\overline{v}_x\right)$. For $I_{is} = I$ we have

$$I(\overline{v}_x) \approx -neA\sqrt{\frac{kT_e}{2\pi m_e}}\;exp\frac{eV}{kT_e}$$

$$I(\overline{v}_x) = I_{es}\;exp\frac{eV}{kT_e} \qquad (15)$$

Hence,

$$\frac{d\ln|I|}{dV} = \frac{e}{kT_e} \qquad (16)$$

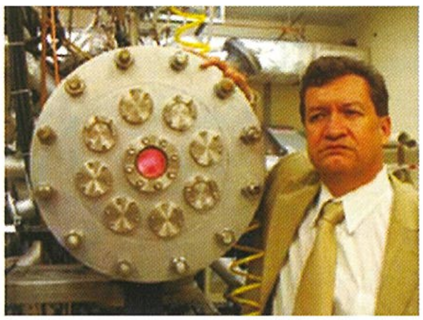

Figure 5: *Dr. Edbertho Leal-Quirós with PUPR-MC Plasma Machine*

The electron temperature is the voltage difference for a change in *ln(I)* of one, i.e., kT_e ; $1.47\,eV$. 1 eV $= 11{,}600^o$ K .

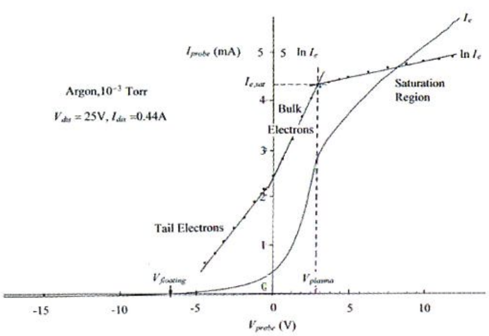

Figure 6: *Single Langmuir Probe plot taken at UCLA by Dr. R. Stenzel.*

Measurement of the Electron Distribution Function, $f_e\left(v_x\right)$.

The electron current to a plane probe could be written in a more general expression as

$$I_{es} = nqA\int_{V_{min}}^{\infty} \overline{v}_x\, f\left(\overline{v}_x\right) d\,\overline{v}_x \qquad (17)$$

$$I_{es} = \frac{nqA}{m_e}\int_{V_{min}}^{\infty} f\left(qV\right) d\left(qV\right) \qquad (18)$$

If we measure $f\left(\overline{v}_x\right)$ as a function of plasma position, we can obtain the phase space distribution $f\left(\overline{v}_x, x\right)$. A design of a Single Langmuir probe and the electronic circuit are shown in Figure 7. The characteristic I-V plot from a Single Langmuir probe measurement is shown in Figure 8, while the electron distribution function obtained from that measurement is shown in Figure 9. Also, a picture showing plasma with two probes inside is shown in Figure 10.

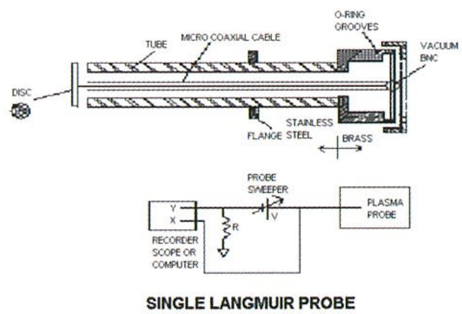

Figure 7: *Single Langmuir Probe Electronic Circuit and Diagram*

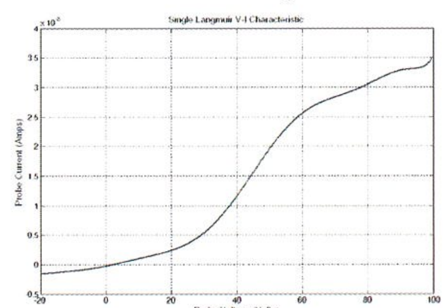

Figure 8: *Single Langmuir I-V Characteristic Acquired at PUPR-MC Plasma Machine*

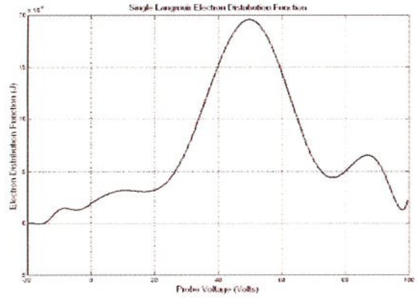

Figure 9: *Single Langmuir Electron Distribution Function Acquired at PUPR-MC*

Figure 10: *Picture of Plasma with analyzers inside at PUPR-MC.*

Summarizing, the Single Langmuir probe is used for plasma diagnostics obtaining from it parameters such as: plasma potential, plasma electron density and temperature, and the electron distribution function by extracting information from the V-I characteristic of this analyzer. Figure 11 shows a V-I characteristic, identifying the most important regions and points.

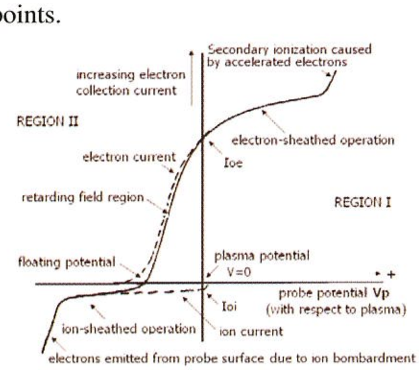

Figure 11: *Complete Single Langmuir Probe Current Vs Voltage Characteristic*

DOUBLE LANGMUIR PROBE

A Double probe consists of two electrodes of equal surface area separated by a small distance and immersed in the plasma. A design of a Double Langmuir probe and an electronic circuit used for taking the characteristic curves, are shown in the following figures. One probe draws current I_1 while the other draws current I_2. To find the electron temperature of the plasma, we consider quantitatively the current to the probe for various potential differences between the probes. Since the probes are floating at V_f of the plasma, i. e., the double probe circuit has no plasma ground (anode) connection, the total current in the probe circuit must be zero. The net current drawn from one of the collectors of a Double probe may be written as

$$I_1 = I_{1is} - I_{1es} exp\left(\frac{e\left(V_1 + V_f - Vs\right)}{kT_e}\right). \tag{19}$$

Using the definition of the floating potential,

$$I_{es} exp\left(\frac{e\left(V_f - Vs\right)}{kT_e}\right) = I_{is} \tag{20}$$

Hence, I_1 and I_2 become

$$I_1 = I_{1is}\, exp\left(\frac{eV_1}{kT_e}\right)$$
$$I_2 = I_{2is}\, exp\left(\frac{eV_2}{kT_e}\right). \tag{21}$$

If the area of both collectors is the same, then $I_{1is} = I_{2is} = I_{2is}$.

Zero net probe current leads to the definition:

$$I \equiv I_1 = -I_2 \tag{22}$$

Combining equations 20, 21, and 22 yields

$$\frac{I - I_{is}}{-I - I_{is}} = exp\left(\frac{e\Psi}{kT_e}\right) \tag{23}$$

where ψ is the double probe potential, defined by

$$\Psi = V_1 - V_2 \qquad (24)$$

Differentiating 23 with respect to ψ at ψ=0 yields

$$\left[\frac{dI}{d\Psi}\right]_{\Psi=0} = -I_{is}\left(\frac{e}{2kT_e}\right) \qquad (25)$$

which yields

$$kT_e = \frac{-I_{is}e}{2tan\theta} \qquad (26)$$

The Double probe can collect a maximum current equal to the ion saturation current. It does not disturb the plasma as much as the Single probe with its non-floating anode potential. Figure 12 shows a typical Double probe I-V characteristic. Figure 13 shows a schematic of the Double Langmuir probe and its electronic circuit.

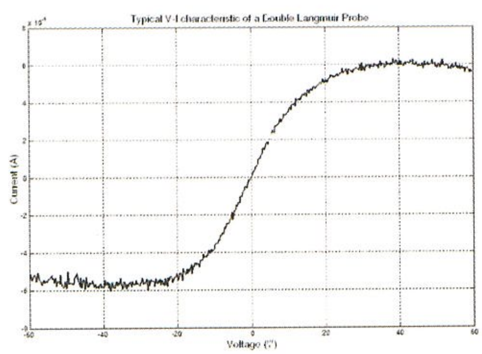

Figure 12: *Typical Double Langmuir Probe Current Vs Voltage Characteristic Acquired at PUPR-MC Plasma Machine*

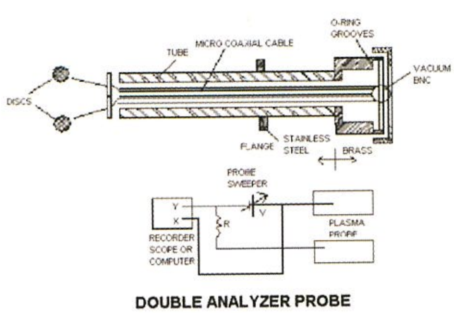

Figure 13: *Double Langmuir Probe Electronic Circuit and Diagram*

EMISSIVE PROBE

The emissive probe consists of a current loop inserted into the plasma. The current *I* heats the probe producing an emission of electrons to the plasma, and therefore neutralizing the sheath of ions around it. The advantage of this method is that we can measure the plasma potential very accurately. As we increase the emission current, more electrons are emitted to the plasma, neutralizing the sheath of ions and therefore decreasing the effect of the sheath. When the probe is emitting, one electron is leaving the probe is the same to one ion coming to it. So, the emissive probe indicates a falsely large ion current. The theory of the Emissive Probe is the same as that of the Single Langmuir probe.

Figure 14: *Picture of the Emissive Probe Producing Electron Emission*

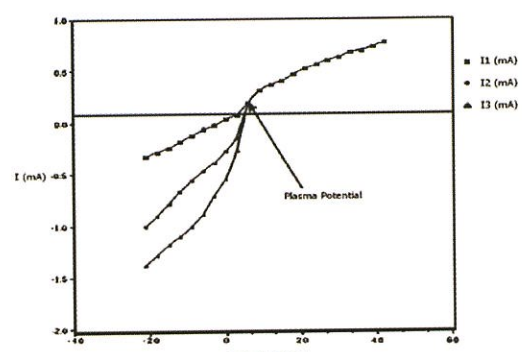

Figure 15: *I vs. V. Emissive Probe Characteristic for Filament Currents*

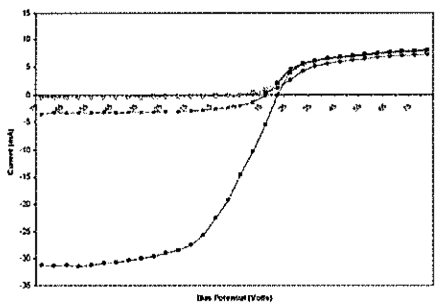

Figure 16: *I vs. V. Emissive Probe Characteristic Acquired at PUPR-MC Plasma Machine*

ION ENERGY ANALYZER

While a simple plane probe yields information about the electron density and temperature, an Ion Energy Analyzer (IEA) has additional electrodes to eliminate the electron contribution to the probe current. This is required to measure the ion temperature. After the discriminator grid has screened out the electrons, the ion current reaching the plate collector of area A is given by

$$I(\phi) = eA\int_{V_{min}}^{\infty} vF(v)dv$$

$$I(\phi) = \frac{eA}{m}\int_{V_{min}}^{\infty} F(v)d\left(\frac{mv^2}{2}\right)$$

$$I(\phi) = \frac{eA}{m}\int_{e^{\phi}}^{\infty} F(v)dE \qquad (27)$$

where $V_{min} = \sqrt{\frac{2e^{\phi}}{m}}$ and $E = \frac{1}{2}mv^2$. Differentiating with respect to ϕ, an expression for the velocity distribution function $F(v)$ or $G(\phi)$ in terms of the first derivative of the current–voltage characteristic $I(\phi)$ vs F is obtained as

$$F(v) = -\frac{m}{e^2A}\frac{dI}{d\phi} \qquad (28)$$

Figure 17 shows a schematic of the IEA used at the PUPR-MC plasma machine at Polytechnic University of Puerto Rico device, and at the Fusion Research Laboratory at University of Missouri–Columbia (UMC).

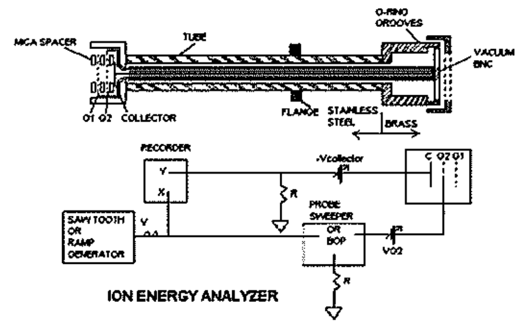

Figure 17: *Ion Energy Analyzer Schematics*

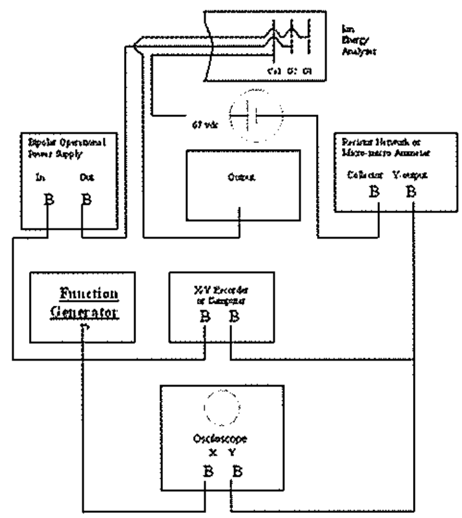

Figure 18: *Ion Energy Analyzer Measurement Circuit Schematics*

Ion Temperature

If $F(v)$ is a Maxwellian function, then according to equation 1 and with K a constant expression:

$$I(\phi) = Kexp\left(\frac{e^{\phi}}{kT_i}\right)$$

$$\ln I(\phi) = ln(K) - \frac{e^{\phi}}{kT_i} \Rightarrow$$

$$kT_i = ln(K) - \frac{e^{\phi}}{lnI(\phi)} \qquad (29)$$

or

$$kT_i = -\frac{e^{\phi}}{tan\theta} \qquad (30)$$

where θ is the slope of the plot $\ln I(\phi)$ vs. ϕ (It should be a straight line).

Plasma Potential

The analyzer is also useful to measure the plasma potential that is the potential at which ions are collected. The plasma potential occurs when

$$\frac{dI(\phi)}{d\phi} = 0. \qquad (31)$$

Then, by measuring the value of the voltage for which the analyzer current is flat, the plasma potential can be obtained.

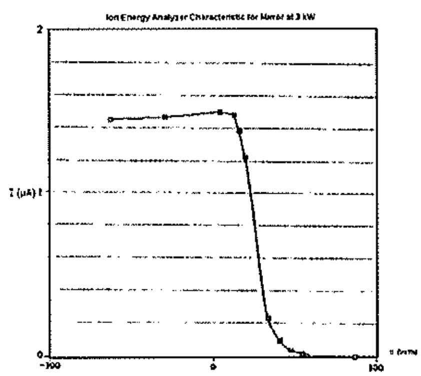

Figure 19: *I-V Characteristic of the IEA*

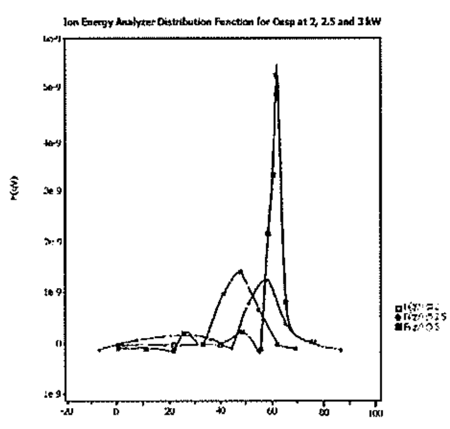

Figure 20: $F(qV)$ vs V_{ret}. *IEA Distribution Function for Cusp at 2, 2.5 and 3 kW*

NEW ANALYZERS AND PROBES

Microwave Interferometer

The plasma acts like a dielectric medium to electromagnetic radiation. A wave propagating through the plasma suffers a change in phase

$$\Delta\phi = \int_0^L \left(k_{vacuum} - k_{plasma}\right) dx \qquad (32)$$

where L is the path length of the plasma, $k_{vacuum} = \frac{\omega}{c}$ is the free space wave number, k_{plasma} is the plasma wave number, and ϕ is the phase of the wave propagating through the medium. The plasma wave number is given by the relationship

$$k_{plasma} = \frac{\sqrt{\omega^2 - \omega_{pe}^2}}{c} \qquad (33)$$

where $\omega_{pe} = \sqrt{\frac{4\pi ne^2}{m}}$ is the electron plasma frequency and c is the speed of light. If the plasma density is uniform over the propagation path, the phase shift is obtained by

$$\Delta\phi = \frac{\omega}{c}\left(1 - \sqrt{\left(\frac{\omega_{pe}^2}{\omega^2}\right)}\right)L, \qquad (34)$$

and for $\omega_{pe} = \omega$

$$\Delta\phi = \frac{1}{2}\frac{\omega_{pe}^2}{\omega c}L \qquad (35)$$

Then

$$\Delta\phi = \frac{2\pi ne^2}{m\omega c} \Rightarrow \qquad (36)$$

$$n = \frac{m\omega c\Delta\phi}{2\pi e^2} \qquad (37)$$

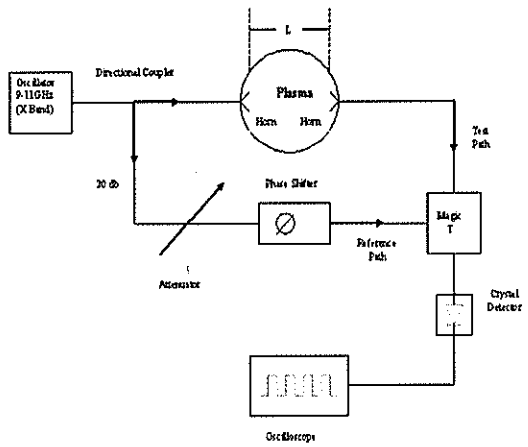

Figure 21: Microwave Interferometer Diagram

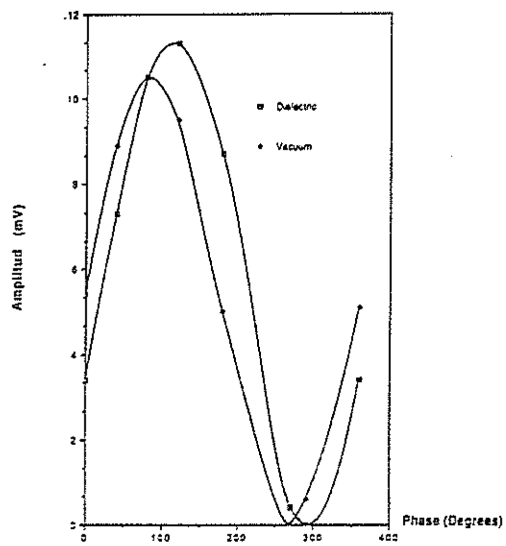

Figure 22: *Amplitude vs. Phase Shift Using µ?Wave Interferometer*

APPLICATIONS

PLASMA DIAGNOSTICS

- Ion and Neutral Beam Diagnostics
- Spectroscopy (Mass, Photon) and Imaging
- Probe Measurements to Determine Density and Temperature
- Scattering for Remote Sensing of Density and Perturbations
- Laser-Induced Fluorescence to Determine Distribution Functions
- Laser Transmission Diagnostics (E.g., Interferometry, Polarimetry)
- Charged-Particle Spectrometers to Determine Distribution Functions
- Magnetic Field Measurements
- Electric Field Measurements
- Neutral Particle Analysis
- Diagnostics at One Atmosphere Pressure

INDUSTRIAL PLASMA

- Plasma SurfaceT
- Plasma Etching
- Plasma Thin Film Deposition (E.g., Synthetic Diamond Film and High-Temperature Superconducting Film)
- Ion Interaction with Solids
- Synthesis of Materials (E.g., arc Furnaces in Steel Fabrication)
- Destructive Plasma Chemistry (E.g., Toxic Waste Treatment)
- Destruction of Chemical Warfare Agents
- Thermal Plasmas
- Isotope Enrichment
- Electrical Breakdown, Switchgear, and Corona
- Plasma Lighting Devices
- Meat Pasteurization
- Water Treatment Systems
- Electron Scrubbing of Flue Gases in Coal or Solid Waste Burning
- Ion Beams for Fine Mirror Polishing
- Plasma Surface Cleaning
- Electron Beam-Driven Electrostatic Fuel and Paint Injectors

- Sterilization of Medical Instruments
- Synthetic Diamond Films for Thin-Panel Television Systems
- Plasma Chemistry (Produce Active Species to Etch, Coat, Clean and Otherwise Modify Materials)
- Low–Energy Electron-Molecule Interactions
- Low–Pressure Discharge Plasmas
- Production of Fullerenes
- Plasma Polymerization
- Heavy Ion Extraction from Mixed-Mass Gas Flows
- Deterioration of Insulating Gases (E.g., High Voltage Switches)
- One-Atmosphere Glow Discharge Plasma Reactor for Surface Treatment of Fabrics (Enables Improved Wettability, Wickability, Printability of Polymer Fabrics and Wool)
- Laser Ablation Plasmas; Precision Laser Drilling
- Plasma Cutting, Drilling, Welding, Hardening
- Ceramic Powders from Plasma Synthesis
- Impulsive Surface Heating by Ion Beams
- Metal Recovery, Primary Extraction, Scrap Melting
- Waste Handling in Pulp, Paper, and Cement Industries
- Laser Ablation Plasmas
- DC to AC Radiation Generation by Rapid Plasma Creation
- Infrared to Soft X-Ray Tunable Free-Electron Laser (FEL)
- Optoelectronic Microwave and Millimeter Wave Switching
- Plasma Source Ion Implantation (PSII)

CONCLUSIONS

The diagnostics of plasma is very complex and is very difficult, mainly because we want to avoid disturbing the plasma. Most of the probes need to be very small and they are extremely delicate. In the evolution of the plasma diagnostics with probes, we have made a contribution with several new analyzers and probes, for example the authors have designed, built, and tested the VEA (Variable Energy Analyzer), the HEA (Hyperbolic Energy Analyzer), The ì-Analyzer (Magnetic Moment Analyzer) and the PADE (Pitch Angle Detector or Double Energy Analyzer).

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