What is a 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 the amount of ionization, the plasma density, the plasma temperature, and the Debye length ($\lambda$) 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 - they become a 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.

It works by inserting one or more electrodes into a plasma and observing the current to the probe as a function of the difference between the probe and the plasma space potential can 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, and it was Langmuir who in 1929 used the term “plasma” for the first time to describe ionized gases.
**Single Langmuir Probe**

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. It works by inserting one or more electrodes into a plasma and observing the current to the probe as a function of the difference between the probe and the plasma space potential can determine the basic plasma parameters. Most of the data that is presented in this presentation was taken at Polytechnic University of Puerto Rico Mirror-Cusp plasma machine PUPR-MC either as a Mirror or as a Cusp. The probes and analyzers that will show below were design, built and successfully tested in the Fusion Research Laboratory mainly for the PUPR-MC machine.

A description of several probes follow the methods of several authors among of them, A. Wong, R. Stenzel, and E. Leal-Quiros among others.

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:

\[
I = A \sum_{i=1}^{N} n_i q_i \overline{v}_i
\]

where \( A \) is the total collecting surface of the probe given by:

\[
A_{probe} = 2(\pi)r^2
\]

\( \overline{v}_i \) is the average velocity of species:

\[
\overline{v}_i = \left( \frac{1}{n} \right) \int v f_i(v) dv
\]

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

![Figure 3: Electron velocity distribution function. All electrons with energy |eV| greater than ½ me \( V^2 \)min are collected.](image)

\[
f_\alpha(v) = n \left( \frac{2\pi kT_\alpha}{m_\alpha} \right)^{-\frac{3}{2}} \exp \left( -\frac{1}{2} \frac{m_\alpha v^2}{kT_\alpha} \right)
\]

\( f_\alpha \) = equilibrium velocity distribution function or Maxwellian distribution, for each specie \( \alpha \).

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 the same \( v_x \) 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:

\[
I(v) = nqA \left[ \int_{-\infty}^{\infty} dv_y \left( \frac{2\pi kT_\alpha}{m_\alpha} \right)^{-\frac{3}{2}} \exp \left( -\frac{1}{2} \frac{m_\alpha v_y^2}{kT_\alpha} \right) \right] \left[ \int_{-\infty}^{\infty} dv_z \left( \frac{2\pi kT_\alpha}{m_\alpha} \right)^{-\frac{3}{2}} \exp \left( -\frac{1}{2} \frac{m_\alpha v_z^2}{kT_\alpha} \right) \right] \left[ \int_{v_{min}}^{\infty} dv_x \left( \frac{2\pi kT_\alpha}{m_\alpha} \right)^{-\frac{3}{2}} \exp \left( -\frac{1}{2} \frac{m_\alpha v_x^2}{kT_\alpha} \right) \right]
\]
Particles with \( v_x \) component of velocity less than \( V_{\text{min}} \) are repelled:

\[
V_{\text{min}} = \sqrt{\frac{2qV}{m_\alpha}}
\]

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

\[
I(V_s) = n_qA \left[ \int_{v_{\text{min}}}^{v} dV_x V_x \left( \frac{2\pi kT_e}{m_e} \right)^{\frac{3}{2}} \exp \left( -\frac{\sqrt{2} m_e V_x^2}{kT_e} \right) \right]
\]

The figure is a typical Langmuir probe characteristic that was taken in PUPR-MC as a Cusp.

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

\[
I(V) = I_{\text{is}} - n_eA \left[ \int_{v_{\text{min}}}^{\infty} dV_x V_x \left( \frac{2\pi kT_e}{m_e} \right)^{\frac{3}{2}} \exp \left( -\frac{\sqrt{2} m_e V_x^2}{kT_e} \right) \right]
\]

Substituting \( \frac{1}{2}m_e v^2 = -eV \), becomes

\[
I(V) = I_{\text{is}} - neA \left( \frac{kT_e}{2\pi m_e} \right)^{\frac{3}{2}} \exp \left( \frac{eV}{kT_e} \right)
\]

Since \( V < 0 \) in region B, equation shows that the electron current increases exponentially until the probe voltage is the same as the plasma space potential:

\[
V = V_p - V_s = 0
\]

**Ion saturation current**, \( I_{\text{is}} \): The ion saturation current is not simply given by an expression similar to \( I_{\text{es}} \). In order to repel all the electrons and observe \( I_{\text{is}} \), \( v_p \) 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 \( \sim kT_e \), which is much larger than their thermal energy \( kT_i \). The ion saturation current is then approximated as:

\[
I_{\text{is}} = neA \left( \frac{2kT_e}{m_i} \right)^{\frac{1}{2}}
\]
**Floating potential**, $V_f$: When $V = V_f$, the ion and electron current are equal and the net probe current is zero.

Combining equations $I(V)$ and $I_{is}$, and letting $I = 0$, we get:

$$V_f = -\frac{kT_e}{e} \ln\left(\frac{m_i}{4\pi m_e}\right)^{1/2}$$

Examples:

$$V_f = -4.34 \frac{kT_e}{e} \quad \text{For Argon}$$

$$V_f = -5.49 \frac{kT_e}{e} \quad \text{For Helium}$$

**The electron temperature**

Measurement of the electron temperature can be obtained from equation $I(v)$. For $I_{is} \ll I$ we have:

$$I(V) \approx -neA \left(\frac{kT_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eV}{kT_e}\right) = I_{es} \exp\left(\frac{eV}{kT_e}\right)$$

$$\frac{d \ln |I|}{dV} = \frac{e}{kT_e}$$

Figure 5: Plasma machine with argon plasma.

The electron temperature is the voltage difference for a change in $\ln(I)$ of one, i.e., $kT_e \approx 1.47$ eV. 1 eV = 11,600°K

**Figure 6:** Figure was taken at UCLA by Dr. R. Stenzel.

**Measurement of the electron distribution function**, $f_e(vx)$. The electron current to a plane probe could be written in a more general expression as:

$$I = nqA \int V_e f(V_e) dV_e = \frac{nqA}{m_e} \int f(qV) d(qV)$$

If we measure $f(vx)$ as a function of plasma position, we can obtain the phase space distribution $f(vx,x)$. A design of a Single Langmuir Probe and the electronic circuit are shown in the next figure.

**Figure 7:** Single Langmuir probe electronic circuit and diagram.
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).

$$I_i = I_{ix} - I_{iex} \exp \left( \frac{e(V_f + V_e - V_i)}{kT_e} \right)$$

Using the definition of the floating potential with $I(V)$:

$$I_{iex} \exp \left( \frac{e(V_f - V_e)}{kT_e} \right) = I_{ix}$$
Hence $I_1$ becomes, and in the same manner we get:

$$I_1 = I_{1is} \left[1 - \exp\left(\frac{eV_1}{kT_e}\right)\right]$$

$$I_2 = I_{2is} \left[1 - \exp\left(\frac{eV^2}{kT_e}\right)\right]$$

If the probe areas are equal, then implies:

$$I_{1is} = I_{2is} = I_{is}$$

Zero net probe circuit current led to the definition:

$$I = I_1 = -I_2$$

Combining this equations $I_1, I_2, I_{is}$ and $I$ yields:

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

Where the double probe potential is defined by:

$$\psi \equiv V_1 - V_2$$

Differentiating previous equation with respect to $\psi$ at $\psi = c$ yields:

$$\left(\frac{dI}{d\psi}\right)_{\psi=0} = -I_{is} \sec h^2 \left(\frac{e\psi}{2kT_e}\right) \left(\frac{e}{2kT_e}\right)$$

Therefore, the electron temperature is related to the slope of the double probe characteristic by:

$$\left(\frac{dI}{d\psi}\right)_{\psi=0} = -I_{is} \left(\frac{e}{2kT_e}\right)$$

or

$$kT_e = \frac{-I_{is}e}{2 \tan \theta}$$

The double probe can collect a maximum current equal to the ion saturation current, the double probe does not disturb the plasma as much as the single probe with is non-floating anode connection.

**Figure 12:** Characteristic of $I$ vs $V$ obtained for two different plasma with the double probe.

**Figure 13:** Double Langmuir probe electronic circuit and diagram.
Double Probe

Figure 14: Current vs Voltage characteristic with the double probe in PUPR-MC machine in Polythecnic university of Puerto Rico.

Emissive Probe

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 that of the Single Langmuir Probe.

Figure 15: Photo of the emissive probe producing the emission of electrons in order to sheath ions around it.

Figure 16: I vs. V. Emissive Probe Characteristic for filament currents.

Figure 17: Emissive Probe diagram and electric circuit.

Figure 18: Characteristic of emissive probe in the PUPR-MC machine in Polythecnic university of Puerto Rico.
**Ion Energy Analyzer**

While a simple plane probe yields information about the electron density and temperature, an ion energy analyzer with additional electrodes to eliminate the electron contribution 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:

\[
I(\phi) = eA \int_{v_{\text{min}}}^{v_{\text{max}}} vF(v)dv = \frac{eA}{m} \int_{v_{\text{min}}}^{v_{\text{max}}} F(v)d\left(\frac{mv^2}{2}\right) = \frac{eA}{m} \int_{v_{\text{min}}}^{v_{\text{max}}} F(v)dE
\]

Where

\[
v_{\text{min}} = \left(\frac{2e\phi}{m}\right)^{1/2} \quad E = \frac{1}{2} mv^2
\]

Differentiating with respect to \(\phi\), we get 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 \(F\):

\[
F(v) = -\frac{m}{e^2 A} \frac{dI}{d\phi}
\]

**Ion Temperature:** If \(F(v)\) is a Maxwellian function, then

\[
I(\phi) = (\text{const.}) \exp\left(-\frac{e\phi}{kT_i}\right)
\]

or \(\ln(I)(\phi) = (\text{const.}) - \left(\frac{e\phi}{kT_i}\right)\)

or \(kT_i = \text{const.} - \frac{e\phi}{\ln(I)} \Rightarrow kT_i = -\frac{e}{\tan \theta}\)

**Space Plasma potential:** The analyzer also measures the space plasma potential (i.e. the potential at which all ions are collected). Experimentally this potential is given by the value of the potential at which:

\[
\frac{dI(\phi)}{d\phi} = 0
\]

\[
n = \frac{I_o}{eA} \frac{kT_i}{2\pi m_i}
\]

In the following figures, a design, the electronic circuit, typical characteristics and distributions functions are shown. All have been taken in the PUPR-MC machine in Polythecnic university of Puerto Rico device, in the Fusion Research Laboratory at UM-C.

**Figure 19:** Emissive Probe diagram and electric circuit.
Figure 20: Ion Energy Analyzer, electronic schematic diagram.

**Typical Ion Analyzer probe I-V characteristics**

Figure 21: I (A) Vs Vret. Ion energy analyzer characteristic for a Mirror at 3 kW.

Figure 22: I (mA) vs Vret (Volts). Characteristic different ECRH powers. Multigried Ion Energy Analyzer for a Cusp

Figure 23: F(qV) vs Vret. Ion Energy Analyzer distribution function for Cusp at 2, 2.5 and 3 kW
NEW ANALYZERS AND PROBES

**Figure 24:** Electron Energy analyzer diagram and electric circuit.

**Figure 25:** Electron Energy Analyzer Schematic Diagram.

**Figure 26:** Magnetic probe analyzer diagram and electric circuit.

**Figure 27:** Photo of magnetic probe at the Polytechnic University of Puerto Rico.
Microwave Interferometer

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

$$\Delta \phi = \int_0^L (K_{\text{vacuum}} - K_{\text{plasma}}) \, dx$$

where $L$ is the path length of the plasma.

$$K_{\text{vacuum}} = \frac{\omega}{c}$$

is the free space wave number of the electromagnetic waves. $K_{\text{plasma}}$ is the wave number of the wave propagation in the plasma, which is given by the dispersion relation:

$$K_{\text{plasma}} = \left( \frac{\omega^2 - \omega_{pe}^2}{c^2} \right)^{1/2}$$

Here $\omega$ is the wave frequency,

$$\omega_{pe} = \left( \frac{4\pi ne^2}{m} \right)^{1/2}$$

is the electron plasma frequency, and $c$ is the speed of the light.

If the plasma density is uniform over the distance, we obtain this equation for the phase shift:

$$\Delta \phi = \frac{\omega}{c} \left[ 1 - \left( \frac{\omega_{pe}^2}{\omega^2} \right)^{1/2} \right] L$$

When $\omega_{pe} \ll \omega$ (note this restriction), we obtain:

$$\Delta \phi = \frac{\omega}{c} \left[ \frac{1}{2} \frac{\omega_{pe}^2}{\omega^2} \right] L$$

Figure 28: Microwave Interferometer Diagram

Figure 29: Detected amplitude of microwave signal in vacuum and with the dielectric (plasma) in order to evaluate the phase shift using the 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 surface treatment
- 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 avoid disturb the plasma. The most of the probes need to be very small and they are extremely delicate. In the evolution of the plasma diagnostic with probes, we have made contribution with several new analyzers and probes, for example the author have designed built and test the VEA (Variable Energy Analyzer, the HEA (Hyperbolic Energy Analyzer), The µ-Analyzer (Magnetic Moment Analyzer) and the PADE (Pitch Angle Detector or Double Energy Analyzer).

References;

Abstract
Various novel analyzers and probes were designed, built and successfully tested in the Cusp-Mirror machine in the Fusion Research Laboratory at University of Missouri-Columbia. We will discuss four of them: The Variable Energy Analyzer (VEA), the Magnetic Dipole Moment Meter (The \(\mu\)-Meter), The Double Energy Analyzer (DEA), and the Hyperbolic Energy Analyzer (HEA). The main advantage of these analyzers is that they are very small (about 7-mm diameter) and they are made of materials that resist high temperature, high plasma flux and they are shielded for RF signals. All of them have a probe driver in such way that they can move back and forward inside the machine. For that reason is possible map the plasma inside almost all points inside the device.

THE VARIABLE ENERGY ANALYZER (VEA)

INTRODUCTION
The Variable Energy Analyzer (VEA) was first described by Leal-Quirós in 19811. The VEA is an electrostatic multi-grid (ion or electron) energy analyzer in which the geometry can be changed externally with a micrometer control. This new type of diagnostic probe is an improvement over conventional ion energy analyzers because the resolution of ion spectra is improved by a factor of two, and the sensitivity is improved by a factor of two. As an example, the ion energy analyzer developed by Taylor 2 was able to measure ion temperatures as low as 0.3 eV. A prototype VEA built and tested by Leal-Quirós was able to measure ion temperatures as low as 0.125 eV. Geometric parameters such as the separation distance between the grids, the aperture diameter, the transparency of the grids, and the space
charge all influence the characteristic curve of the diagnostic probe (collector current vs. the retarding potential on the discriminator grid).

**THEORETICAL DISCUSSION**

A simple plane Langmuir probe yields information on the electron density and temperature. An ion energy analyzer, using additional electrodes to eliminate the electron contribution, is required to measure the ion temperature. After the electrons have been screened out by the retarding potential of the discriminator grid ($f$), the ion current $I(f)$ reaching the plate collector (of area $A$), is given by:

$$I(f) = eA \int_{V_{\text{min}}}^{\infty} VF(v)dv \quad (1)$$

where:

$$V_{\text{min}} = \left( \frac{2e\phi}{M} \right)^2$$

and

$$E = \frac{1}{2} Mv^2$$

Differentiating equation (1) with respect to $f$, we get an expression for the velocity distribution function $F(v)$ in terms of the first derivative of the current-voltage characteristic, ($I(f)$ vs. $f$),

$$F(v) = -\frac{M}{e^2A} \frac{dI}{d\phi} \quad (2)$$

In order to calculate the ion temperature, assuming that $F(v)$ is approximately Maxwellian, we can manipulate equation (1):

$$I(\phi) = (\text{const.}) \exp \left( -\frac{e\phi}{kT_i} \right)$$

where:

$$kT_i = -\frac{d}{d\phi} \ln (I(\phi))$$

The plasma potential can be deduced from the characteristic curve of the VEA. This potential is related to the point where all of the ions are collected. Experimentally, the potential is given by the value at which:

$$\frac{dI(\phi)}{d\phi}$$

becomes zero.

Even when the effects introduced by the grids, secondary electrons, and space charge are neglected, the measurement of the distribution function would be in error unless the analyzer is: infinite in extent or particle flow, one dimensional, and aligned parallel to the retarding field. The error arises because the apertures, in the electrodes of the analyzer, block some particles that have sufficient energy or momentum to be collected. The analyzer has two separate components which are placed in separate boxes that are linked together by an axis which acts like a transmission line. The first component is located in the vacuum chamber and has direct contact with the plasma. This component contains the three electrodes (Grid 1, Grid 2 and the collector), their associated insulators, the other electrical connections, and the rail mechanism to move G2 and the collector back and forth.
THE DOUBLE ENERGY ANALYZER (DEA)

Introduction

The double energy analyzer is a new analyzer formed by two directional energy analyzers perpendicular to each other. One goal of this analyzer was to study the axial and radial loses of plasma, in Mirrors and in Cusps. The configuration of the DEA is such that one directional energy analyzer allows the measurement of the charged particles, for example, in the direction parallel to the magnetic field. The second analyzer then, measures the velocity of the particles in the direction perpendicular to the magnetic field, (if the correct orientation of the analyzer with the magnetic field is made). Because directional energy analyzers are in the same small case, very close to each other, this allows the measurement of both average velocities $\mathbf{V}_{II}$ and $\mathbf{V}^\perp$, at almost exactly the same point. When the double energy analyzer is inside a magnetized plasma, so that the parallel analyzer is aligned with the magnetic field and the other analyzer is perpendicular to the magnetic field, then the pitch angle $\alpha$ for particles with perpendicular average velocity $\mathbf{V}^\perp$, and parallel average velocity $\mathbf{V}_{II}$ could be measured instantaneously.

THEORETICAL CONSIDERATIONS

The pitch angle, the adiabatic invariant, the loss cone and the trapping mechanism should be defined using Stacey and Chamberlain approach, the pitch angle $\alpha$ is defined as:

$$\frac{V^\perp(I)}{V_{II}(I)} = \sqrt{\frac{W_{II}(I)}{W_{II}(I)}}$$
\[ \tan \alpha (I) = \]
A relationship between the total kinetic energy of the particle \( W \), the local magnetic field \( B \), the pitch angle \( \alpha \), and the dipole moment \( \mu \) is:

\[
\mu = \frac{W \sin^2 \alpha}{B} = \text{const.}
\]

\[
W = \frac{1}{2} m \left( v_{\parallel}^2 + v_{\perp}^2 \right) = \text{const.}
\]

At a given point (I1) on the trajectory, the field and angle of pitch are \( B_1 \) and \( \alpha_1 \) respectively. Then the particle will be magnetically reflected when the field seen by the particle increases to the value:

\[
B_m = \frac{B_1}{\sin \alpha_1^2}
\]

Where \( B_m \) defines a mirror point. At this point all the kinetic energy has been transformed into the gyration of the particle.

DEA DESIGN
The Double Energy Analyzer formed by two directional energy analyzers, independent each other, but in the same case. The directional Energy Analyzers are mutually perpendicular.

Figure 32: The directional energy analyzer design

Figure 33: Double perpendicular analyzer design

THE DIRECTIONAL ENERGY ANALYZER
The directional energy analyzer is a two grid component analyzer of retarding field design with the characteristic property that the first components selects only ions (or electrons) with velocity paraxial to the analyzer to be detected, which means that it is possible to measure only ion (or electron) velocity in one direction. That direction should be parallel \( V|| \) (in one case), and perpendicular to the magnetic field \( V^\perp \) (in the other case). The directional energy analyzer follows the Stenzel criteria in order to detect in the collector plate only the charged particles (electrons or ions, depending on the mode of operation of the analyzer) whose velocity is perpendicular to the collector in the analyzer. This measurement is possible because the first component is a micro-channel plate facing the plasma. Additionally, the analyzers follow also Leal Criteria. For ions, the first grid is electronically floating i.e. reflects most electrons, collects most thermal ions, and passes
beam ions moving along the direction of the micro-channels.

**EXPERIMENTAL SET UP**

For ions, each one of the directional energy analyzers will be set up to permit determination of ion current vs retarding potential characteristics. The DEA detector can be mounted on a probe driver, so that it is possible to move the analyzer backward and forward inside the machine. The actual electronic circuit used for the measurements is shown in the next slide.

**Figure 34:** Set up of the detection circuit for each of the two components of the DEA Cusp.

**Figure 35:** Variation of the paral. & perp. nTi along the axis in the Cusp configuration.

**Figure 36:** Variation of the paral. & perp. nTi along the axis in the Mirror configuration.

**Figure 37:** Variation of the paral. Current Density along the axis proportional to the plasma.

**Figure 38:** Variation of the perp. Current Density along the axis proportional to the plasma flux.
Figure 39: Pitch angle with DEA

DOUBLE ENERGY ANALYZER RESULTS

The parallel densities and the temperatures have about the same order of magnitude. But the density in the parallel direction to the axis is $2.2 \times 10^{13}$ (cm$^{-3}$) in the Mirror, and only $5.6 \times 10^{11}$ (cm$^{-3}$) in the Cusp. The axial losses are also larger in Mirror. The current density $J$ is defined as: $J = env$ (Amp/cm$^2$) where $e$, is the electron charge, $n$ is the plasma density and $v$ is the average velocity. One of the more interesting results from these experiments is that the plasma is better confined in the Cusp than in the Mirror.

\[
\frac{J(Mirror)}{J(Cusp)} \approx 50
\]

Is approximately equal to 50. This fact can be noticed by making a comparison between the results at the same ZL (approximately 71 cm) from the center, for both machines approximately equal to 50.

CONCLUSIONS

Although the goal of the DEA was to measure ion densities and temperatures mutually perpendicular simultaneously at the same point, information about the physics of the losses of the particles from the Mirror and from the Cusp has been measured directly. The DEA is a powerful tool that helps measure the trapping and losses of plasma particles in the Cusp and Mirror Machine. This helps us understand magnetic confinement in general. One important conclusion is that Cusp confines the plasma better in the axial direction than the Mirror. The axial losses in the Mirror are approximately fifty times more than in the Cusp, for the same external parameters of the machine. It is our hope that eventually we will be able to use this diagnostic for a direct measurement of local pitch angle.

THE MAGNETIC MOMENT ANALYZER ($\mu$-Analyzer)

INTRODUCTION

The $\mu$-Analyzer consists of a Directional Energy Analyzer and a Magnetic Hall in the same detector case. The Directional Energy Analyzer measures the ion temperature in the perpendicular direction to the magnetic field. On the other side, the hall probe measures the magnetic field. The $\mu$-Analyzer is a miniature analyzer to avoid plasma perturbation. This allows the measurement of the ion temperature and the local magnetic field at the same point at the same time, therefore $\mu$, the first adiabatic invariant is found.

THEORETICAL CONSIDERATIONS

The first adiabatic invariant $\mu$ is defined as:

\[
\mu = \frac{W_{\perp}(I)}{B(I)} \mathbf{n}
\]
where:

$$\hat{n}_B = \frac{\vec{B}}{B}$$

unit vector parallel to the magnetic field B and

$$W_\perp = \frac{1}{2} m v_\perp^2$$

References:

SURFACE TREATMENT OF DIAMOND POWDER WITH SODIUM CHLORIDE AND SODIUM FLUORIDE, TO ENHANCE HYDROGEN STORAGE FOR USE IN FUEL CELLS.

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Background
Today, fossil fuel is the main source of energy in the world. A person uses in a regular day at least 7 gallons of gasoline. Population is growing fast: 6 billion (present). There are 678 million cars in the world. The level of CO2 keeps growing. Statistics prove that with the present consumption there is at least enough fuel for 18 years.

Intervention
Alternative energy resources: Wind and solar, where only solar can be used for transportation purposes, but solar systems are not practical.
Fuel cell:
An electrochemical energy conversion that uses hydrogen and oxygen to produce electricity in the process, this is mostly like a battery that instead of using electricity to recharge uses hydrogen.

Figure 40: Solar Car (MU)
**Comparative Tables**

![Power Generating Systems Efficiency Comparison](image)

**Figure 41**

**Implications**

In order to improve fuel cells technology is necessary to found a way to make this less expensive and secure.

![Actual high pressure tanks](image)

**Figure 43**

**Purpose**

To develop a better way to efficiently and safely store hydrogen:

![Diamond Powder & NaCl](image)

**Figure 44**

**Fuel Cell**

**Advantage:**
- Works without pollution when run on pure hydrogen.
- Higher thermodynamic efficiency.
- Does not require tuning.

**Disadvantage:**
- Difficult to manufacture and store.
- Gaseous hydrogen storage tanks are large and heavy.

Requires relatively pure fuel, free of specific contaminants.
- Hydrogen is hard to produce.
**Objectives**
Understand the importance of alternate methods of hydrogen storage in strong hydrocarbon compounds such as artificial diamond.

Perform surface treatment on the diamond surface with a chlorine compound and a fluoride compound with plasma.

Place the diamond powder pellets into the heat transfer chamber for hydrogen absorption at 650°C.

Compare the treated samples with untreated samples after reactor analysis for increase in mass percentage of hydrogen absorbed.

**Materials**
99% pure diamond powder

Sodium fluoride (NaF) and Sodium Chlorine (NaCl)

Plasma Machine

High-pressure hydrogen tank

Glass beakers, plastic beakers

Electronic balance

Distilled water

Vacuum filter

Vacuum oven

High pressure cylindrical press

Conduction machine (stainless steel bell jar)
**Findings**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Hydrogen (ppm)</th>
<th>Chlorine (ppm)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>450°C</td>
<td>16389</td>
<td>291</td>
<td>1 to 1</td>
</tr>
<tr>
<td></td>
<td>17330</td>
<td>351</td>
<td>1 to 0.5</td>
</tr>
<tr>
<td></td>
<td>16730</td>
<td>232</td>
<td>1 to 1.5</td>
</tr>
<tr>
<td>Withd. surface treatment</td>
<td>17536</td>
<td>7304</td>
<td>1 to 1</td>
</tr>
<tr>
<td>650°C</td>
<td>16478</td>
<td>298</td>
<td>1 to 1</td>
</tr>
<tr>
<td></td>
<td>14197</td>
<td>365</td>
<td>1 to 0.5</td>
</tr>
<tr>
<td></td>
<td>13947</td>
<td>036</td>
<td>1 to 1.5</td>
</tr>
<tr>
<td>Withd. surface treatment</td>
<td>20376</td>
<td>7102</td>
<td>1 to 1</td>
</tr>
<tr>
<td>Control sample at 650°C</td>
<td>18264</td>
<td>129</td>
<td>1 to 0</td>
</tr>
</tbody>
</table>

**Results with Fluorine Treatment**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Rate of Diamond and half</th>
<th>Temp/Start of Treatment</th>
<th>Hydrogen ppm</th>
<th>% Hydrogen after weight</th>
<th>Fluoride ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5L</td>
<td>1 to 1</td>
<td>650°C</td>
<td>12928</td>
<td>1.5628</td>
<td>7003</td>
</tr>
<tr>
<td>2L</td>
<td>1 to 0.5</td>
<td>650°C</td>
<td>13669</td>
<td>1.3629</td>
<td>4886</td>
</tr>
<tr>
<td>3L</td>
<td>1 to 0.35</td>
<td>650°C</td>
<td>11752</td>
<td>1.1752</td>
<td>1433</td>
</tr>
<tr>
<td>4L</td>
<td>1 to 1</td>
<td>650°C</td>
<td>22329</td>
<td>2.2329</td>
<td>1149</td>
</tr>
<tr>
<td>5L</td>
<td>1 to 0.35</td>
<td>650°C</td>
<td>20271</td>
<td>2.0271</td>
<td>5127</td>
</tr>
<tr>
<td>6L</td>
<td>1 to 0.5</td>
<td>650°C</td>
<td>18876</td>
<td>1.8876</td>
<td>1288</td>
</tr>
<tr>
<td>7L</td>
<td>Control Sample without NaCl</td>
<td>650°C</td>
<td>17820</td>
<td>1.7820</td>
<td>257</td>
</tr>
</tbody>
</table>
Results

This demonstrates that the presence of chlorine compounds for hydrogen storage without necessarily utilizing plasma, produces tremendous results by attracting more H2 molecules to the surface of the nanodiamond structure.

This is tremendous progress in fuel cell research. The best results were produced by a 1 to 1 ratio of diamond powder and sodium chloride without plasma treatment with a 2.0376% mass of hydrogen.

Surface treatment of diamond powder utilizing Sodium Fluoride is a vital step towards the practical usage and commercialization of fuel cell systems.

The surface treatment at high temperatures, such as 650°C, increases the percentage of hydrogen storage in a sample of diamond powder.

The comparison of the data of treated specimens vs. control samples of untreated samples displays that treating the surface of the diamond powder with an electronegative element such as fluoride activates the surface of the material allowing for the more loose bonds to be made between the hydrogen molecules and the surface of the diamond powder.

The highest amount was the 1 to 1 ratio at 650°C with 2.2229% mass percentage of hydrogen.

This is a significant increase in hydrogen storage.

Conclusion

In conclusion, in plasma surface treatment of diamond powder utilizing chlorine compounds in plasma reactions at high temperatures, does not increase the amount of hydrogen that can be stored when comparing with samples mixed with chlorine without plasma treatment.
IDENTIFICATION OF ELECTRON CYCLOTRON RESONANCE HEATING (ECR) SURFACES IN THE UPPR-PLASMA DEVICE OPERATING IN THE CUSP AND MIRROR MODE.

David Leal Escalante and Franklyn Colmenares Ochoa, Mechanical Engineering, PUPR
Mentors: Dr. Angel Gonzalez and Dr. Edbertho Leal
NASA Puerto Rico Space Grant Consortium PR-LSAMP

What's Plasma
Fourth state of matter.

Influenced by the electrical interaction of the ions and electrons and by the presence of magnetic fields.

Plasma is the most abundant form of matter in the universe (99%).

Plasma applications
- Fusion confinement.
- Surface treatment.
- Waste disposal.
- Propulsion systems.

Methodology
Rotary pumps.

Power supply of coils.
Microwave generator.

Resonance frequency
In order to produce plasma with microwave power, it is necessary to have a resonance frequency between the magnetron frequency of the high power microwave source and the cyclotron frequency.

This cyclotron frequency is a result of the circular movement of the electrons in the external magnetic field formed utilizing two large Helmholtz Coils.

The effect of both these frequencies in the chamber ionizes the gas and creates plasma.

The heating source is a variable high power microwave generator from 50 watts to 5,000 watts at a frequency of 2.45 GHz.

Figure 46: Electron and Ion path

Investigation
The goal of this research project is to identify the adequate magnetic field surfaces at the PUPR-Plasma machine that have a magnitude value in which resonance will be present when the plasma machine is operating in the Mirror Mode and in the Cusp Mode.

Utilizing a Hall Probe 2100 Gauss meter, several Magnetic Field Measurements are taken by varying the probe location in longitudinal and radial coordinates.

After the data is collected utilizing a variation of the electrical current generated by the power supply in the Helmholtz Coils, a comparison can be made of the results experimentally obtained with data from a Matlab calculation of the field vector coordinates utilizing the magnetic flux in the volume between the Helmholtz coils utilizing the equation.
**Measuring the magnetic field**

Connect the Gaussmeter 2100 and Insert the magnetic hall probe into the chamber.

Turn on the power supply.

Readings are taken in the longitudinal direction by varying the distance from the center of the chamber to the outside every 2 cm. The same procedure is followed in the radial direction of the machine.

**Magnetic Field Equations**

Magnetic Flux in the volume between a Helmholtz Coil pair:

\[
B_x = \mu_0 \frac{\sqrt{P \lambda}}{r_1 \rho} G
\]

\( \mu \) = Permeability

\( \lambda \) = flux linkage
\[ \rho = \text{Resistivity} \]
\[ P = \text{Power} \]
\[ r = \text{radius} \]
\[ G = \text{Unit less geometry factor} \]

**Magnetic Field Results**

Due to many variables and data measurements necessary to establish the correct parameters needed to obtain the magnetic resonance frequency experimentally, high precision is needed in the control of the Hall Probe.

Repeating measurements at each location would allow for mean values to be obtained, in such way that a comparison between the experimental results and the theoretical values can be performed.

By increasing the current in the coils, the magnetic field magnitude also increased at each location.

By using the Hall probe it was found that the resonance field can be greater than 875 Gauss, which is the minimum field amount necessary for plasma formation in both modes.

Utilizing Matlab software, a precise graph can be made of each mode of the machine, both in CUSP and in MIRROR mode, similar to the figures below. By understanding the shape and intensity of the magnetic field formed, the magnetic confinement of the plasma can be obtained.
In conclusion, we can determine that the resonance field can be greater than 875 Gauss, which is the minimum field amount necessary for plasma formation in both modes.

Obtaining the optimum magnetic field in the machine is crucial to creating useful plasmas.

Utilizing the mathematical equations, the ideal cyclotron frequency can be obtained, allowing for the formation of higher density plasmas useful for surface treatment of materials, energy analysis, and fusion research.

Future Work

More in depth experimentation is necessary with the Hall Probe in order to gather more data at each point, allowing for a more precise mean value of field magnitude at each point that can be graphed.
The University of Missouri-Columbia Research Reactor Center (MURR) is the center of a world class, totally unique environment for the research, development, and production in major advances in nuclear medicine. MURR, as a multifunctional research reactor, differs significantly from such a power reactor. While a power reactor, such as Callaway, needs a source of electricity to cool the reactor core, MURR's pool is capable of absorbing all the heat from the reactor core without the aid of forced convection. The reactor operates at a five or ten megawatt power level; samples are placed in three strategically positioned canisters situated in the flux trap zone of the nuclear reactor core, to be later exposed to high temperature treatments. The core walls can reach temperatures up to 305 degrees Fahrenheit, so a cooling system must exist in order to stabilize the reactor’s core. The cooling system consists of three vertical cylinders 4 meters long which are encased inside one bigger cylinder, inside every cylinder there is one canister, where the samples are placed. Pool water at a high mass flow rate must be pumped inside and around the cylinders to cool and stabilize the reactor core.
What is Fluent?

- Fluent is the world's largest provider of computational fluid dynamics (CFD) software. The software is used for simulation, visualization, and analysis of fluid flow, heat and mass transfer, and chemical reactions. It is a vital part of the computer-aided engineering (CAE) process for companies around the world, and is deployed in nearly every manufacturing industry.

- GAMBIT is Fluent’s Pre-processor, GAMBIT has a single interface for geometry creation and meshing that brings together all of Fluent's preprocessing technologies in one environment.

- GAMBIT can import geometry from virtually any CAD/CAE software in Parasolid, ACIS, STEP or IGES format. Native CATIA V4 import and Pro/E Integration is also available. Tolerant modeling and healing capabilities are automatically providing connected solid geometry during import.

- Intelligent Meshing- Different CFD problems require different mesh types, and GAMBIT provides you with all of the options necessary. GAMBIT's meshing toolkit lets you decompose geometries for structure meshing or perform automated meshing with control over clustering.

Objectives:

- Pre-Processing- Design the University of Missouri Research Reactor (MURR) cooling system using Fluent’s Computational Fluid Dynamics (CFD) pre-processor, Gambit, while working with up to scale measurements
• **Processing**: Export design to Fluent CFD software, and set boundary conditions, materials, define equations, etc. to visually project the pool water and cylinders physical and thermophysical behaviors as heat is being inputted from the core

• **Post-Processing**: Analyze results, charts and diagrams.

**Purpose:**

To model the MURR using Fluent Computational Fluid Dynamics (CFD) software, to visually project the pool water flow and heat transfer in the flux trap to enable possible improved positioning of the irradiation samples, our focus is on being able to create a model of MURR, and understand the effects of geometry in the flux trap for the pool water flow to the furthest extent possible.

**Methodology:**

1. Run the Pre-Processor, Gambit.

2. Create three circles that define their outer diameters, whose centers describe a triangle, so each center must have a 60 degree angle difference with each other.

3. Repeat step two with three more circles which describes their inner diameters

4. Create a larger fourth circle that defines its inner diameter, which should tightly encase all three circles.

5. Repeat step four with another larger circle which describes its outer diameter.

6. The center of the drawing must be the center of the three connected circles, so create a 30 degree line coming out of each of the smaller circles center; each line should point towards the center of the three connected cylinders. The point where all the three lines intersect is the center of the three circles.

7. Mark the intersection as a vertex point, connect the center of the circle which is at a 90 degree or 270 degree angle (Varies with chosen position of circles), with the marked intersection. Measure the length of the line, and shift the entire drawing that exact length in the y direction. The new center should be the center of the three circles.
8. Create a line from the center of the drawing to the desired length of the four cylinders in the positive z direction.

9. Sweep the faces of the circles using the line from step eight. This should convert the four circles to four solid cylinders.

10. Subtract the outer diameter of each cylinder to its smaller diameter, to create four hollow cylinders.

11. Repeat steps 2 and 9 for three smaller circles, which represent the three solid canisters.

12. Move the canisters to desired position in the positive z direction.

13. Specify the walls, inflows and outflows of the created figure.

14. Mesh entire figure, and export the mesh.

15. Close Gambit, and open Fluent CFD software.

16. Import mesh, and set scale, materials, and boundary conditions.

17. Iterate, and display desired grids, tables and animations.

18. Analyze results.

**Diagrams and Grids:**
**Conclusions:**

The geometry of the MURR flux trap was successfully modeled using GAMBIT, in addition water velocity, temperature, pressure and turbulence have also been successfully computed using FLUENT. The results show regions of high turbulence, strain and velocity in the flux trap. For Future work it will be useful to obtain functional data so these computer results can be verified, also the model that we have constructed should be improved to include all details of the reactor, and finally, the model should be further used to optimize the flow geometry and canister placement of the reactor.
STORING HYDROGEN, BY ENHANCING DIAMOND POWDER PROPERTIES WITH CALCIUM FLUORIDE AND POTASSIUM FLUORIDE FOR USE IN FUEL CELLS.

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University of Missouri-Columbia  
Ls-MoAMP summer research internship  
Nuclear Science Engineering Institute Department  
Mentor : Mark A. Prelas Ph.D.  
Advisors : Tusher Ghosh Ph.D.,  
Alexis Sotomayor and Angel Veles.

Objectives

Develop a safe and economical way to store hydrogen.

Observe if the calcium fluoride or potassium fluoride helped in the hydrogen storage on the surface of the diamond powder.

Understand hydrogen properties and how it can be used as a fuel for fuel cells.

Achieve at least a 2% weight mass of hydrogen in diamond powder.

Hydrogen as a fuel?

Eliminate the economic dependence on oil.

Eliminate the pollution caused by fossil fuels.

Can be produce anywhere that you have electricity and water.

Figure 50: Power Production
**Why Hydrogen?**

**Properties:**

It’s the most plentiful element in the universe.

It’s the simplest of all elements.

Weight less and generate more power than hydrocarbon-based fuels. (nearly 3 times.)

![Image of Hydrogen atom](image1.png)

**Intervention**

Since hydrogen can easily provide energy; a technology called *Fuel Cells* has been developed. Fuel cells compared to combustion engines; has a higher thermodynamic efficiency.

![Image of Fuel Cell Car](image2.png)

Figure 52: Fuel Cell Car

Figure 53: Power Generating System Efficiency Comparison

**Fuel Cell technology**

- **Fuel** $H_2$ (Hydrogen)
- **O$_2$** (Oxygen) from air
- **Heat (850°C)** Water + Air Cracked
- **Flue Fuel Recirculates**
- **Gas Diffusion Electrode (Anode)  + Catalyst**
- **Flow Field Plate**
- **Gas Diffusion Electrode (Cathode) + Catalyst**
- **Air + Water Vapor**
- **Electric Circuit** (46% – Cell Efficiency)

![Diagram of Fuel Cell](image3.png)
Hydrogen manufacturing

How to extract it?
H2O (electrolysis)

How to store it?
Gaseous (high pressure tanks)
Liquid (cryogenic temperatures)
Carbon compounds (diamond powder)

How to release it?
Still in development (heat)

Why Diamond Powder?

- Extreme hardness.
- High electrical resistance.
- High thermal conductivity.
- Large surface area.
- Easy to handle and to manufacture.

Why CaF₂ and KF?

In previous experiments, sodium fluoride mixed with nanodiamond powder was investigated. The results verified that more hydrogen was stored. Following these same goals, calcium and potassium fluoride were use in order to increase the fluorine density in diamond powder and to see if the hydrogen storage properties would be improved.

Methodology

The ratios

Plasma machine
Filtering and drying

Pellet making

Conduction machine

Prompt Gamma Neutron Activation Analysis

**Results**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Sample ID</th>
<th>Concentration of H (ppm)</th>
<th>% of Hydrogen per weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1A</td>
<td>37541</td>
<td>3.75</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>38546</td>
<td>3.96</td>
</tr>
<tr>
<td></td>
<td>1C</td>
<td>38107</td>
<td>3.81</td>
</tr>
<tr>
<td></td>
<td>1D</td>
<td>26372</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td>2D</td>
<td>7823</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>2E</td>
<td>7851</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>2F</td>
<td>7271</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>2G</td>
<td>6494</td>
<td>0.56</td>
</tr>
</tbody>
</table>

**Conclusion**

In this investigation it has been shown that an increase in fluorine density does lead to an increase in hydrogen storage capability.

It was demonstrated that 3.81% of hydrogen by mass percentage was stored by using the potassium fluoride compound as a fluorine impurity source. This work demonstrates that the presence of fluorine compounds
produces a significant increase in hydrogen storage in nanodiamond powders.

It is believed that this improvement of hydrogen storage capability is due to the weak attraction forces of the hydrogen to the fluorine bonded to the diamond surface.

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