Sensing a plasma environment: electron density and ion flux

In effect ‘Plasma diagnostics’

but without suggesting that the plasma is unwell

Nicholas Braithwaite, The Open University, UK
What will we discuss?

• Introduction: A range of plasmas…seeing is believing
• What do you want to measure?
• What can you measure?
  - currents & voltages
  - frequency spectra UV, visible, IR, microwave, RF
• What techniques?
“seeing is believing…”
“seeing is believing…”

...beware of false colour
“seeing is believing…”

13.56 MHz
10 Pa, 50 W
Ar
“seeing is believing…”

13.56 MHz
10 Pa, 50 W
Ar

Side view of a plasma bounded by parallel plate electrodes, showing the dark space in front of the lower electrode - note that the camera is set to view exactly along the lower electrode and does not therefore capture a clear image of the dark space adjacent to the upper electrode.
“seeing is believing…”

13.56 MHz
10 Pa, 50 W
Ar

Side view of a plasma bounded by parallel plate electrodes, showing the dark space in front of the lower electrode - note that the camera is set to view exactly along the lower electrode and does not therefore capture a clear image of the dark space adjacent to the upper electrode.
10 kHz
100 000 Pa, 15 W
He

“seeing is believing…”
“seeing is believing…”
“seeing is believing…”
Pulsed Argon 200 W 3 Pa

“seeing is believing…”

Fig. 3. Spatial distributions of the emission of argon and zinc neutrals and ions when sputtering an aluminium-doped zinc target. The images were obtained after analysing the measured data with Abel inversion. All images were recorded at the same temporal position 150 µs after pulse initiation when the discharge current peaks. The target was sputtered using an argon pressure of 1.33 Pa and an average power of 400 W.

“seeing is believing…”
DC
10 000 Pa, 160 mW
He

“seeing is believing…”
Introduction

RF CCP
Atmospheric Cold-plasma Jet
Magnetron
Micro-Hollow-Cathode
RF atmospheric arc

Electron mean energy /eV 1 - 10
Charge density /m^{-3} 10^{16} - 10^{19} ... 10^{21}

Figure 4. (a) Anode view and (b) cathode view of a discharge generated by the device with semiconducting diamond electrodes, for the case of V = 40 V, I = 0.40 mA. The background gas was helium at a pressure of 30 Pa.
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- What can you measure?
  - currents & voltages
  - frequency spectra UV, visible, IR, microwave, RF
- What techniques?
A semiconductor manufacturing engineer said to me …

“It would be useful to be able to monitor & control electron density, electron energy, ion flux, ion energy”
A semiconductor manufacturing engineer said to me …

“It would be useful to be able to monitor & control electron density, electron energy, ion flux, ion energy”
But as this mass spectrum of an SF6 plasma shows... real plasmas are complicated
What do you want to measure?

composition: atoms, radicals, molecules, dust
concentration: electrons, ± ions, neutral species
temperature/energy: various species
fluxes: various species
electric field…
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<tr>
<td><strong>What do you want to measure?</strong></td>
<td><strong>Gas composition</strong></td>
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<tr>
<td><strong>Density / m⁻³</strong></td>
<td>ion ((n_i))</td>
<td>electron ((n_e))</td>
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<td></td>
<td>neutrals (eg (n^*))</td>
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<td><strong>Energy / eV</strong></td>
<td>ion (&lt;E_i&gt;)</td>
<td>electron (&lt;E_e&gt;)</td>
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<tr>
<td></td>
<td>neutrals (eg (&lt;E_{\text{vib}})&gt;)</td>
<td></td>
</tr>
<tr>
<td><strong>Flux / m⁻² s⁻¹</strong></td>
<td>ion ((\Gamma_i))</td>
<td>electron ((\Gamma_e))</td>
</tr>
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<td></td>
<td>neutrals (eg ((\Gamma^*)))</td>
<td></td>
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<tr>
<td><strong>Potential/V &amp; E field / V m⁻¹</strong></td>
<td>(\Delta \phi)</td>
<td>(\mathbf{E})</td>
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What will we discuss?

- Introduction: A range of plasmas…seeing is believing
- What do you want to measure?
- **What can you measure?**
  - currents & voltages
  - frequencies UV, visible, IR microwave, RF
- What techniques do you have?
What can you measure?
What can you measure?

temperature
current
voltages
photons
spectra: mass, energy, wavelength
What techniques do you have?

- (Quadrupole) Mass Analyser
- Langmuir Probe
- Emissive Langmuir Probe
- Retarding Field Analyser
- Ion flux probe
- Microwave interferometry
What techniques do you have?

- Optical emission
- Optical absorption (DLS, FTIR)
- Laser Induced Fluorescence
- Rayleigh scattering
- Thomson scattering
What techniques do you have?

- (Quadrupole) Mass Analyser
- Langmuir Probe
- Emissive Langmuir Probe
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- Microwave interferometry
- RF probe spectroscopy
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<td>Thomson scattering</td>
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### Sensing a Plasma Environment

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<tr>
<th>Potential/V &amp; E field/V m⁻¹</th>
<th>Flux/m².s⁻¹</th>
<th>Energy/eV</th>
<th>Density/m⁻³</th>
<th>Gas composition</th>
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SAQ  What are typical parameters for ‘low temperature plasmas’?

System size
Pressure /Pa
Power density /W m\(^{-2}\)
Plasma source
Electron mean energy /eV
Charge density /m\(^{-3}\)
Gas density /m\(^{-3}\)
**SAQ**  What are typical parameters for ‘low temperature plasmas’?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
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<tr>
<td><strong>System size</strong></td>
<td>100s mm³ ...~100s μm³</td>
</tr>
<tr>
<td><strong>Pressure /Pa</strong></td>
<td>0.3 - 30 ... 10⁵</td>
</tr>
<tr>
<td><strong>Power density /W m⁻²</strong></td>
<td>100 - 10⁴</td>
</tr>
<tr>
<td><strong>Plasma source</strong></td>
<td>CCP, ICP ... DBD, micro</td>
</tr>
<tr>
<td><strong>Electron mean energy /eV</strong></td>
<td>1 - 10</td>
</tr>
<tr>
<td><strong>Charge density /m⁻³</strong></td>
<td>10¹⁶ - 10¹⁹ ... 10²¹</td>
</tr>
<tr>
<td><strong>Gas density /m⁻³</strong></td>
<td>10¹⁹ - 10²¹ ... 10²⁵</td>
</tr>
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Demonstration plasma experiment from *The OpenScience Laboratory*
http://www.opensciencelab.ac.uk
Figure 10.2 Two surfaces linked by a battery – the potential is distributed in order that the current is continuous. It is supposed that the lower surfaces are insulated from the plasma, so current is collected only on the upper surfaces. $I(V)$ is given by Eq. (10.2).
What do you want to measure?

Fluxes onto surfaces

\[ \Gamma = \frac{n \bar{c}}{4} = n \sqrt{\frac{kT_x}{2\pi M_x}} \]
What do you want to measure?

Fluxes onto surfaces

random flux

\[ \Gamma = \frac{n \bar{c}}{4} = n \sqrt{\frac{kT_x}{2\pi M_x}} \]

small or non-absorbing surface
Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K, 1% radicals

Flux $\Gamma$ $1.4 \times 10^{23}$ m$^{-2}$ s$^{-1}$

charges

$10^{16}$ m$^{-3}$, 33 000 K (3 eV)
Fluxes onto surfaces

What do you want to measure?

Flux \( \Gamma \)

- ground state: \( 1.4 \times 10^{23} \, \text{m}^{-2} \, \text{s}^{-1} \)
- excited: \( 1.4 \times 10^{21} \, \text{m}^{-2} \, \text{s}^{-1} \)

Neutrals:
- 6.5 Pa, 50 amu, 300 K, 1% radicals

Charges:
- \( 10^{16} \, \text{m}^{-3} \), 33 000 K (3 eV)
Fluxes onto surfaces

What do you want to measure?

- Fluxes to the surface
  - Neutrals: 1.4 x 10^{23} m^{-2} s^{-1}
  - Excited charges: 1.4 x 10^{21} m^{-2} s^{-1}
  - Neutrals: 2 x 10^{19} m^{-2} s^{-1}

Parameters:
- Pressure: 6.5 Pa
- Atomic Mass: 50 amu
- Temperature: 300 K
- Radical concentration: 1%

Additional information:
- Radical density: 10^{16} m^{-3}
- Temperature: 33 000 K
- Energy: 3 eV
SAQ  Electrical discharges through gases are used in the dry etching and deposition of thin films.

(a) Identify the role of electrons in these two applications.
SAQ Electrical discharges through gases are used in the dry etching and deposition of thin films.

(a) Identify the role of electrons in these two applications.

Electron-molecule collisions produce active species that combine with surface atoms to produce volatile products (etching) or to extend the surface (deposition)
SAQ  Electrical discharges through gases are used in the dry *etching and deposition* of thin films.

(b) Explain how the uniformity of either process can be monitored in real-time.
SAQ  Electrical discharges through gases are used in the dry etching and deposition of thin films.

(b) Explain how the uniformity of either process can be monitored in real-time.

Monitor the electron density at various points in space in the region where active species are produced or ...

What do you want to measure?
SAQ  Electrical discharges through gases are used in the dry etching and deposition of thin films.

(c) Suggest how both processes could be speeded up.
SAQ  Electrical discharges through gases are used in the dry etching and deposition of thin films.

(c) Suggest how both processes could be speeded up.

Increase the density and/or energy of electrons to increase the production rate.
SAQ  Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

(a) Identify the role of ions in this application.
SAQ  Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

(a) Identify the role of ions in this application.

*Sputtering.*
SAQ  Electrical discharges through gases are used to deposit thin films by sputtering material from a target onto a substrate.

(b) Suggest how the process could be speeded up.
SAQ  Electrical discharges through gases are used to deposit thin films by *sputtering* material from a target onto a substrate.

(b) Suggest how the process could be speeded up.

*Increase ion flux and/or ion energy.*
Fluxes onto surfaces

neutrals

6.5 Pa, 50 amu, 300 K
Fluxes onto surfaces

**neutrals**

6.5 Pa, 50 amu, 300 K, 1% radicals

ground state  excited

What can you measure?

What can you measure?
Fluxes onto surfaces

**neutrals**

- 6.5 Pa, 50 amu, 300 K, 1% radicals

**charges**

- $10^{16} \text{ m}^{-3}$, 33 000 K (3 eV)

**ground state**

**excited**

What can you measure?
Fluxes onto surfaces

- **neutrals**
  - 6.5 Pa, 50 amu, 300 K, 1% radicals
  - Particle flux:
    - Ground state: $1.4 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$
    - Excited: $1.4 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$

- **charges**
  - $10^{16} \text{ m}^{-3}$, 33 000 K (3 eV)
  - $2 \times 10^{19} \text{ m}^{-2} \text{ s}^{-1}$

**What can you measure?**
- Ground state excited particles
- Neutrals
- Charges
Fluxes onto surfaces

6.5 Pa, 50 amu, 300 K, 1% radicals

Ground state

Neutral flux: $1.4 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$

Excited flux: $1.4 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$

Electron flux: $2 \times 10^{19} \text{ m}^{-2} \text{ s}^{-1}$

What can you measure?

Particle flux

- Neutrals: $1.4 \times 10^{23} \text{ m}^{-2} \text{ s}^{-1}$
- Ground state: $0.025 \text{ eV}$
- Excited: $10 \text{ eV}$
- Charges: $2 \times 10^{19} \text{ m}^{-2} \text{ s}^{-1}$
- Electron: $700 \text{ eV}$

$10^{16} \text{ m}^{-3}$, $33000 \text{ K}$ (3 eV)
Fluxes onto surfaces

6.5 Pa, 50 amu, 300 K, 1% radicals

1.4 × 10^23 m^−2 s^−1 2 × 10^19 m^−2 s^−1

ground state
excited

charges

10^{16} m^−3, 33 000 K (3 eV)

What can you measure?

~500 W m^−2
~2000 W m^−2
~2000 W m^−2

Particle flux

0.025 eV
10 eV
700 eV

Energy flux

What can you measure?
Electrical models for plasma boundaries

What can you measure?
Electrical models for plasma boundaries

What can you measure?

From A von Keudell’s lecture
This is how ions approach a sheath...
This is how ions approach a sheath...
Electrical models for plasma boundaries

Boltzmann relation

\[ n_e(x) = n_s \exp \left( \frac{e\phi(x)}{kT_e} \right). \]

For the cold ions, the low pressure continuity and momentum equations,

\[ n_i(x)u(x) = n_s u_s \]
\[ \frac{1}{2}Mu(x)^2 + e\phi(x) = \frac{1}{2}Mu_s^2, \]

where \( u_s \) is the positive ion fluid speed at the plasma/sheath transition,

positive ion density as a function of the potential,

\[ n_i(x) = n_s \left( 1 - \frac{2e\phi(x)}{Mu_s^2} \right)^{-1/2}. \]
Electrical models for plasma boundaries

The net space-charge in the sheath is therefore

\[
\rho = en_s \left[ \left( 1 - \frac{2e\phi}{Mu_s^2} \right)^{-1/2} - \exp \left( \frac{e\phi}{kT_e} \right) \right]
\]  

(3.29)

Differentiating Eq. (3.29) with respect to \( \phi \) leads to a requirement that

\[
\frac{d\rho}{d\phi} < 0.
\]

Expanding this for small \( \phi \) the development of positive space-charge requires that

\[
\frac{e^2n_s}{Mu_s} \left( 1 - \frac{3e\phi}{Mu_s} \ldots \right) < \frac{e^2n_s}{kT_e} \left( 1 + \frac{e\phi}{kT_e} \ldots \right)
\]

and for \( \phi < 0 \) this inequality is satisfied if at the boundary the ion speed is such that

\[
u_s = \left( \frac{kT_e}{M} \right)^{1/2} = u_B = c_s
\]

Bohm speed
Electrical models for plasma boundaries
What can you measure?

Electrical models for plasma boundaries

[Diagram showing a probe and a reference with labeled components]

$V$ $I$
Electrical models for plasma boundaries

What can you measure?
Electrical models for plasma boundaries

What can you measure?
What can you measure?

Electrical models for plasma boundaries

\[ I = -j_{\text{ref}} A_{\text{ref}} = eA_{\text{ref}} \left\{ n_{s,\text{ref}} \frac{c_e}{4} \exp\left(\frac{e(V_{\text{ref}} - V_p)}{kT_e}\right) - n_{s,\text{ref}} c_s \right\} \]
What can you measure?

Electrical models for plasma boundaries

\[ I = j_{\text{probe}} A_{\text{probe}} = eA_{\text{probe}} \left\{ -n_{s,\text{probe}} \frac{c_e}{4} \exp(e(V_{\text{probe}} - V_p) / kT_e) + n_{s,\text{probe}} c_s \right\} \]
Electrical models for plasma boundaries

\[ I = eA_{\text{probe}} \left\{ -n_{s,\text{probe}} \frac{c_e}{4} \exp\left( e(V_{\text{probe}} - V_p) / kT_e \right) + n_{s,\text{probe}} c_s \right\} \]

\[ I = eA_{\text{ref}} \left\{ n_{s,\text{ref}} \frac{c_e}{4} \exp\left( e(V_{\text{ref}} - V_p) / kT_e \right) - n_{s,\text{ref}} c_s \right\} \]
If $A_{\text{ref}} = A_{\text{probe}}$

\[ I = I_o(n_i, kT, A_{\text{ref}}) \tanh \left( \frac{eV_{\text{applied}}}{kT} \right) \]

"Double probe"
Nitrogen, inductively coupled plasma, 250 W

Double And Triple Langmuir Probes Measurements In Inductively Coupled Nitrogen Plasma, Naz et al. 2011
Prog. Electromagnetics Research 114 113-128  DOI: 10.2528 PIER10110309
What can you measure?

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What can you measure?

ion saturation → electron retardation → electron saturation

$I$/mA

$V$/V

floating potential
($I = 0$)

$A_{\text{ref}} / A_{\text{probe}}$
What can you measure?

- Ion saturation
- Electron retardation
- Electron saturation

$I$/mA vs $V$/V graph with
- $I$ in mA ranging from $10^{-15}$ to $10^4$
- $V$ in V ranging from $-15$ to $15$

Floating potential
Plasma potential
(Sudden change in behaviour)

$A_{\text{ref}} / A_{\text{probe}}$
What can you measure?

If $A_{\text{ref}} \gg A_{\text{probe}}$

**Single 'Langmuir' probe**

\[
I = I_i(V_{\text{applied}}) - I_o(n_e, kT, A_{\text{probe}}) \exp(eV_{\text{applied}} / kT)
\]
In practice, what can you measure?
In practice

What can you measure?

$I$/mA

d$I$/d$V$/mA $V^{-1}$

real probe, real plasma

d$I$/d$V$

$I$/mA

$V$/V

$V$/V
SAQ  Identify
(a) Plasma potential $V_p$
(b) Floating potential $V_f$
(c) Where to measure $n_e$

From Plasma Sources Science & Technology
Special issue: 80 yrs of ‘Plasma’

A Langmuir probe system for high power RF-driven negative ion sources on high potential

P McNeely$^{1,3}$, SV Dudin$^2$, S Christ-Koch$^3$, U Fantz$^1$ and NNBI Team$^1$

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$^2$V.N. Karazin Kharkov National University, 4 Svobody Sq., Kharkov-61007, Ukraine
What can you measure?

Figure 10.7 Schematics of a cylindrical (or spherical) probe. (a) Sheath development around a biased probe – the potential indicated is referenced to the plasma ($\phi_p$); (b) example ion trajectories ($\phi < \phi_p$); (c) example electron trajectories in electron saturation ($\phi > \phi_p$). The lighter regions represent net space charge: positive if $\phi_p < 0$ and negative if $\phi > \phi_p$. 
What can you measure?

**Orbital Motion Limited electron collection**

will be conserved, so that for an electron that is accelerated to just graze the probe at the surface,

\[
\frac{1}{2} m v^2 = \frac{1}{2} m v_e^2 - e (V_e - \phi_v).
\]

At the same time angular momentum must be conserved, so that for a particle that is going to graze the probe,

\[
m v h_{\text{graze}} = m v_e r_e.
\]

These two expressions can be combined to give the impact parameter for grazing incidence as a function of the initial speed:

\[
h_{\text{graze}} = r_e \left(1 + \frac{2e (V_e - \phi_v)}{mv^2}\right)^{1/2}.
\]

(10.9)
What can you measure?

Orbital Motion Limited
electron collection

d\!I_e = 2e \!I \times r_c \left( 1 + \frac{2e(V_c - \Phi_p)}{mv^2} \right)^{1/2} \nu \!d\nu.

f_{s-cyl} = \frac{\!dn}{\!du} = n_0 \left( \frac{m}{2\pi kT_e} \right) 2\pi \nu \exp \left( -\frac{mv^2}{2kT_e} \right).

I_e = e 2\pi r_c l \frac{n_0 \bar{u}}{4} 2\sqrt{\frac{1 + e(V_c - \Phi_p)/kT_e}{\pi}};
What can you measure?

Orbital Motion Limited
electron collection

\[ dI_e = 2e l \times r_c \left( 1 + \frac{2e(V_c - \phi_p)}{mv^2} \right)^{1/2} \nu \, dn. \]

\[ f_{s-cyl} = \frac{dn}{dv} = n_0 \left( \frac{m}{2\pi kT_e} \right) 2\pi \nu \exp \left( -\frac{mv^2}{2kT_e} \right) \]

\[ I_e = e 2\pi r_c l \frac{n_0 \bar{v}}{4} 2^{\sqrt[3]{1 + e(V_c - \phi_p)/kT_e}} \]

\[ I^2 \propto V \]
Orbital Motion Limited collection doesn’t work so well for ions...

\[ I^2 \propto V \]
SAQ Some say that Orbital Motion Limited collection doesn’t work so well for ions…why not?
Single (Langmuir) probe

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\textsuperscript{2}V.N. Karazin Kharkov National University, 4 Svobody Sq., Kharkov-61007, Ukraine
$V < V_p$

\[
\frac{d^2 I_e}{dV^2} = -\frac{1}{4} e^2 A \left( \frac{2}{m} \right)^{1/2} (-e) \varepsilon^{-1/2} f_\varepsilon(\varepsilon_{\text{min}}) \\
= \frac{1}{4} e^3 A \left( \frac{2}{m} \right)^{1/2} \left[ \frac{f_\varepsilon(\varepsilon_{\text{min}})}{\varepsilon_{\text{min}}^{1/2}} \right],
\]
\[
\frac{d^2 I_e}{dV^2} = -\frac{1}{4} e^2 A \left(\frac{2}{m}\right)^{1/2} (-e)\epsilon_{\text{min}}^{-1/2} f_{\epsilon}(\epsilon_{\text{min}})
\]

\[
= \frac{1}{4} e^3 A \left(\frac{2}{m}\right)^{1/2} \left[\frac{f_{\epsilon}(\epsilon_{\text{min}})}{\epsilon_{\text{min}}^{1/2}}\right],
\]
\[ \frac{d^2 I_e}{dV^2} = -\frac{1}{4} e^2 A \left( \frac{2}{m} \right)^{1/2} (-e) \varepsilon_{\text{min}}^{-1/2} f_\varepsilon(\varepsilon_{\text{min}}) \]

\[ = \frac{1}{4} e^3 A \left( \frac{2}{m} \right)^{1/2} \left[ \frac{f_\varepsilon(\varepsilon_{\text{min}})}{\varepsilon_{\text{min}}^{1/2}} \right], \]
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But what effect do the following have?

- collisions
- geometry - planar/cylindrical/hemispherical
- RF potentials in the plasma
- secondary emission and reflection from surfaces
- non-thermal electrons
- magnetic fields
- negative ions

Precise models for $I(V)$...book by Swift & Schwar and reviews by Chen...Chabert & B.
Figure 2.4 Elastic and inelastic cross-sections in argon – schematic. Broken lines indicate useful approximations.
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Resonances in plasma-sheath systems

What can you measure?
Resonances in plasma-sheath systems

What can you measure?

\[ \omega_{pe} = \frac{1}{\sqrt{L_p C_p}} \]
Resonances in plasma-sheath systems

What can you measure?

Figure 10.19 A spherical probe coupling a coaxial cable to a large volume of plasma.
Resonances in plasma-sheath systems

Figure 10.19 A spherical probe coupling a coaxial cable to a large volume of plasma.
Resonances in plasma-sheath systems
Figure 10.18 Various types of microwave probes in cross-section: (a) hairpin resonator (the hairpin is supported in a plane slightly behind that of the loop, from which it is DC-isolated); (b) multipole resonator; (c) transmission cut-off; (d) surface waveguide.
Electromagnetic modes in plasmas

E-M waves are guided along interfaces:
- vacuum/dielectric
- dielectric/dielectric
- dielectric/conductor

What can you measure?
Electromagnetic waves in *unmagnetized*, collisionless, unbounded plasma

\[ v = \frac{c}{\lambda} \]
Electromagnetic waves in *unmagnetized*, collisionless, unbounded plasma

\[ \varepsilon_{\text{eff}}(\omega) = 1 - \frac{\omega_p^2}{\omega^2}. \]

\[ k = \frac{n \omega}{c} = \frac{\sqrt{\varepsilon_{\text{eff}}} \omega}{c}. \]

What do you want to measure?

refractive index

\[ \omega = \sqrt{\omega_p^2 + k^2 c^2}, \]
**SAQ** Suggest a microwave ‘cut-off’ experiment for measuring $n_e$

**SAQ** Suggest a microwave interferometer experiment for measuring $n_e$
Electromagnetic waves in *unmagnetized*, collisionless, plasma around a cylinder

What can you measure?
What can you measure?

\[ \omega \]

\[ \omega_{\text{pe}} \]

- fast wave
- slow wave

\[ k \]
Transmission line interferometer

What can you measure?

$\omega$ vs $k$

$\omega_{pe}$
Hairpin resonator

\[ \omega \]

\[ \omega_{pe} \]

\[ L = 25 \text{ mm} \]

\[ \nu_{vac} = \frac{c}{4L} \]

\[ \nu_{plasma} = \frac{c / \sqrt{\varepsilon}}{4L} = \frac{c / \sqrt{1 - \frac{\omega_p^2}{\omega^2}}}{4L} \]

Techniques
Hairpin resonator

 Offset absorption

 $f_r$ /GHz

ICP Argon
Plasma transmission probe

Figure 10. Comparison between the measured transmitted coefficient spectrum (50 W) and the calculated one ($n_e \approx 2 \times 10^{10} \text{ cm}^{-3}$) at 40 mTorr in argon.

S Diuc, J-P Booth¹, G A Curley, C S Corr, J Jolly and J Guillou
Plasma absorption probe

Vacuum Seal

Dielectric Tube

Antenna

Coaxial Cable

Network Analyzer

PLASMA

Coaxial Cable

$P_{\text{in}}$

$P_{\text{ref}}$

$2b$

$2a$

$d$

$z=0$

$z$

$L$

$d$
Plasma absorption probe/Multipole Resonance Probe

FIG. 3. Comparison of experiment (left) and simulation (right) with increasing thickness $d$ of the surrounding dielectric (top down).

Scharwitz et al. 
Plasma absorption probe/Multipole Resonance Probe

**Figure 5.** Schematic of the MRP. Two metallic hemispheres are mounted on a multilayer printed circuit board (tapered balun), that also serves as a holder for the hemispheres. The holder also serves as a balancing unit for an unbalanced signal from the NWA.

**Figure 11.** Absorption spectra taken with the MRP obtained in a dielectric deposition process.
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<th>Techniques</th>
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SAQ  How will the presence of negative ions affect the measurement of electron density with a hairpin resonator?
SAQ What is required for a satisfactory measurement of charged particle density?
Retarding Field Analyzer

Retarding Field Analyzer

\[ I_+ = A e \int_{v_{\text{min}}}^{v_{\text{max}}} v f(v) \, dv \quad v_{\text{min}} = \sqrt{2e\phi/M} \]

\[ \frac{dI}{d\phi} \propto f(v) \frac{f(\sqrt{2e\phi/M})}{f(\sqrt{2e\phi/M})} \]

**Figure 3.** Ion velocity distributions for a range of pressures. N.B. The horizontal axis is kinetic energy ($\frac{1}{2}Mv^2/\phi$).

Retarding Field Analyzer

Figure 1. The experimental reactor with the RFEA mounted remote (independently biased) electrode.

Figure 2. Cross section of the RFEA.

C.Hayden et al.

Plasma Sources Sci. Technol. 18 (2009) 025018
Figure 14. Ar IED plots as a function of frequency: (a) capacitively coupled; at a fixed bias of 37.5 V_{pk} at 300 W and pressure of 0.2 Pa.
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What will we discuss?

• Introduction: A range of plasmas…seeing is believing
• What do you want to measure?
• What can you measure?
  - currents & voltages
  - frequency spectra UV, visible, IR, microwave, RF
• What techniques?
Appendix (slides not used in 2013 presentation)
Self bias in RF driven plasma sheaths

1. RF applied voltage
2. No dc current

\[ I = eA \left\{ -n_s \frac{c_e}{4} \exp \left[ e \left( \bar{V}_s \cos(\omega_{RF}t) - \bar{V}_s \right) / kT_e \right] + n_s c_s \right\} \]

\[ \langle I \rangle = 0 \]

\[ \Rightarrow \frac{e\bar{V}_s}{kT} = \ln \left( \sqrt{\frac{2\pi m}{M}} - \ln I_0 \left( \frac{e\bar{V}_s}{kT} \right) \right) \]
Self bias in RF driven plasma sheaths

\[ I = eA \left\{ -n_s \frac{c_e}{4} \exp[\frac{e\widetilde{V}_s}{kT} \cos(\omega_{RF} t) - \widetilde{V}_s] / kT_e \right\} + n_s c_s \}

\[ \langle I \rangle = 0 \]

\[ \Rightarrow \frac{e\widetilde{V}_s}{kT} = \ln \sqrt{\frac{2\pi m}{M}} - \ln I_0 \left( \frac{e\widetilde{V}_s}{kT} \right) \]

modified Bessel function
Self bias in RF driven plasma sheaths

What can you measure?
Self bias in RF driven plasma sheaths
Self bias in RF driven plasma sheaths

\[ C \frac{dV_0}{dt} = \left[ \Gamma_+ - \Gamma_0 \exp \left( \frac{eV_0}{kT} \right) I_0 \left( \frac{eV_{RF}}{kT} \right) \right] eA \]

\[ = 1 \]
Electromagnetism in plasmas

Maxwell

\[ \text{div } \mathbf{D} = \rho \]
\[ \text{div } \mathbf{B} = 0 \]
\[ \text{curl } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \text{curl } \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \]

\[ \mathbf{D} = \varepsilon \varepsilon_0 \mathbf{E} \]
\[ \mathbf{B} = \mu \mu_0 \mathbf{H} \]

= 1
Define a complex dielectric function for a plasma

\[ \text{curl } \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \]

\[ \mathbf{J}_f = \sigma \mathbf{E} \]

\[ \text{curl } \mathbf{H} = \sigma \mathbf{E} + \varepsilon \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}. \]

\[ \text{curl } \mathbf{H} = \sigma \mathbf{E} - i \omega \varepsilon \varepsilon_0 \mathbf{E}. \]

\[ \text{curl } \mathbf{H} = -i \omega \varepsilon_{\text{eff}}(\omega) \varepsilon_0 \mathbf{E}, \]

where \( \varepsilon_{\text{eff}}(\omega) = \varepsilon - \sigma / i \omega \varepsilon_0 \)

\[ \mathbf{E}, \mathbf{H} \sim \exp(-i\omega t) \]
Dielectric function (permittivity) for an insulator

Dielectric model: Motion of a bound electron in an E-M field

\[ m \frac{d^2 \mathbf{r}(t)}{dt^2} + a \mathbf{r}(t) + b \frac{d\mathbf{r}(t)}{dt} = -e \mathbf{E}_0 \exp[-i\omega t] \]

\[ [-m\omega^2 + a - i\omega b] \mathbf{r}_0 = -e \mathbf{E}_0 \]

\[ \mathbf{r}_0 = -\frac{e\mathbf{E}_0}{m} \frac{1}{(\omega^2_n - \omega^2) - i\omega\gamma} \]

resonances

losses
Polarization:

\[ P(t) = n_e (-e) r(t) \]

\[ = -n_e e r_0 \exp[-i\omega t] \]

\[ = \frac{n_e e^2}{m} \frac{1}{\omega_n^2 - \omega^2 - i\omega\gamma} E_0 \exp[-i\omega t] \]

\[ = \omega_p^2 \frac{1}{\omega_n^2 - \omega^2 - i\omega\gamma} \epsilon_0 E_0 \exp[-i\omega t]. \]

Dielectric function:

\[ \epsilon(\omega) = 1 + \omega_p^2 \frac{1}{\omega_n^2 - \omega^2 - i\omega\gamma}. \]
Dielectric function (permittivity) for a plasma

Dielectric model: free electron in an E-M field

\[ \varepsilon(\omega) = 1 + \omega_p^2 \frac{1}{(\omega_n^2 - \omega^2) - i\omega\gamma}. \]

= 0 for free electron

\[ \varepsilon_{\text{eff}}(\omega) = 1 - \frac{\omega_p^2}{\omega^2}. \]

= 0 for low collisionless

\[ \omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}. \]
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