Emitting Probes

J. P. Sheehan\textsuperscript{1}, Yevgeny Raitses\textsuperscript{2}, and Noah Hershkowitz\textsuperscript{3}

1. University of Michigan
2. Princeton Plasma Physics Laboratory
3. University of Wisconsin
Summary of Topics

• Methods for measuring plasma potential
• Emissive sheath theory
• Heating schemes
• Probe construction
• Special case considerations
• Choosing an emissive probe
Why use an emissive probe?

- Measure the electrostatic potential
- Can be used to infer electric fields and particle flows
- Versatile
- Robust
- Proven and established

Start from Langmuir probe I-V trace

- Ions contribute negative current, electrons positive current
- In Maxwellian plasma, electron current exponential below plasma potential
- Above plasma potential current limited only by geometry
Emission current modifies I-V trace below plasma potential

- Electrons can only be emitted when probe biased below plasma potential
- Emission current limited by temperature of probe
  \[ j_{ee,t} = A_G T_w^2 \exp \left( - \frac{e\phi_w}{T_w} \right) \]
- Below plasma potential I-V trace modified by emission, above it stays the same
Separation point technique

- Earliest method, formulated by Langmuir
- Assumes emitted electrons are cold
- Plasma potential is the point where Langmuir I-V and emissive I-V traces separate
- Very time consuming before computer automation
Electron emission reduces the sheath potential and electric field

- In collecting sheath, net positive space-charge
- Emitted electrons reduce net space charge
- Reduce sheath potential
- Reduce electric field at emitter surface
- Increased plasma electron current compensated by emitted electron current
A SCL emitting surface floats $T_{ep}/e$ below the plasma potential

- At large enough emission current, net negative space-charge near surface
- Virtual cathode forms, limiting further reduction of sheath potential
- At Space-Charge Limit (SCL) emissive sheath potential is $T_{ep}/e$
- SCL sheath much smaller potential than collecting sheath

Space-Charge Limited Solution

$$\Phi_w = -\frac{e\Phi_w}{T_{ep}} = 1.02$$
Emissive sheaths require a presheath

- Needed to accelerate ions
- Slightly modified by emitted electrons
- Adds additional $\sim 0.5 – 1.0 \, T_e/e$
- Length scale determined by
  - Charge-exchange collisions
  - Ionization
  - Geometry

Floating point technique

- Plasma potential is floating potential of highly emissive probe
- Error of $\sim 1.5T_{ep}/e$
- Most popular method
- Robust
- Easy to execute

Kinetic effects reduce the electron density near the surface.

Plasma electrons lost to surface

Emitted electron temperature
Emissive sheath potential is reduced by the emitted electron temperature

Kinetic theory predictions were confirmed by experiments

Inflection point technique: developed to reduce space-charge effects

- Take many I-V traces at low emission currents.
Find the inflection point and temperature limited emission current for each I-V trace
Extrapolate inflection point to zero emission current

\[ V_p = -13.73V \]
Fluid theory can provide justification for inflection point technique

\[ T_e = 5eV, \; n_e = 5 \times 10^{16} m^{-3}, \; V_p = 0 \]

Inflection point technique accurate to within $T_{ep}/10e$.

\[
\begin{align*}
\varphi_p &= 0 \text{ V} \\
n_e &= 1 \times 10^9 \text{ cm}^{-3} \\
T_e &= 1 \text{ eV}
\end{align*}
\]

Geometric effects demonstrate limitations to planar theories

- Slope of inflection point vs. emission current dependent on probe diameter
- Smaller probe
  - More accurate measurements
  - Smaller emission current
  - More fragile

Higher curvature allows emitted electrons to quickly disperse
Cylindrical effects further complicate emissive probe floating potential

- Smaller probe radius
  - Ion convergence reduces net space-charge
  - Smaller sheath potential
- Orbital motion effects
  - Preliminary results
  - May increase emitted electron density
  - Increase sheath potential

Summary of techniques

• Separation point: where collecting I-V and emitting I-V intersect
• Floating point: floating potential at space-charge limit
• Inflection point: in the limit of zero emission for low emission currents
Emissive probe techniques were compared in Hall thruster plume
Floating potential of highly emissive probe $\sim 2T_e/e$ below plasma potential

AC Joule Heating

- Resistive heating
- Typical probe resistance: \( \sim 3\Omega \)
- Half-wave rectified heating current
- Period must be shorter than cooling time (10s of ms)
- Data collected during nonheating half-cycle
- Inflection point and floating point may shift due to cooling

DC Joule Heating

- Heating current: 100s of mA to 1s of A
  - Depends on probe thickness
- Added circuit elements can reduce noise
- Data taken while probe is heated
  - Must account for heating potential
- Large shunt resistor (10s – 100s of MΩ) for accurate measurements
Laser Heating

- \( \text{CO}_2 \text{ laser (10 – 20 W)} \)
- Probe can be made of non-ductile material
- Infrequently used

Emissive filament shape

**Hairpin**

- 0.0025 cm diam tungsten wire
- 0.3 cm diam thinwall stainless tubing
- Spotweld
- Ceramic insulator
- 0.05 cm diam nickel support rods


**Linear**

- 1 mil tungsten 2.5 mm long
- Stainless steel wire 0.035 cm
- Ceramic tube
- 2-hole ceramic tubing 0.32 cm diameter
- Glass tubing 0.64 cm diameter
- To external connections


**Loop-Free**

- Molybdenum wire
- Ceramic tube
- Probe tip

Low work function materials are necessary for high emission

- Thoriated tungsten wire is typical
  - 2% doped
  - $10^3 - 10^4$ more emissive than undoped
- Loop-free
  - Graphite
  - LaB$_6$
- For oxygen plasmas
  - Rhenium
  - Iridium

Connecting electrical leads

**Mechanical**

![Mechanical Connection Diagram]


**Braid**

![Braid Connection Diagram]

Connecting electrical leads (cont.)

**Spot Weld**

- 0.0025 cm diam tungsten wire
- 0.3 cm diam thinwall stainless tubing
- Spotweld
- Ceramic insulator
- 0.05 cm diam nickel support rods


**Electrolytic Etching**

- Thoria coated
- 0.010" tungsten
- Alumina
- 0.047"
- 0.012"

Probe shaft may perturb plasma

- Dual bore alumina tube
- Telescoping probe
- Electrical shielding for temporal resolution
- SEE in high energy density plasmas
- Segmented conductive probe shaft
  - Tungsten or graphite
  - Greatly reduces plasma perturbations


Magnetic Fields

• Changes effective probe area
  – Orient probe perpendicular to magnetic field
• Deformation of Joule heated probe
  – Avoidable with laser heating
• Anisotropic EVDF
Temperature, density gradients

- Hall thrusters, for instance
- Temperature and density decrease away from thruster
- \( V_p - V_f \approx T_e \)
- \( \lambda_d / r_p \)
- Errors in electric field measurements

Sheaths

- Langmuir probes cannot be used in sheaths
- Floating potential method more difficult as density decreases
- Inflection point method preferred
- Direction of slope can identify sheath edge

Radio frequency plasmas

• Time averaged floating potential ambiguous
• Derivative of I-V trace reveals time averaged potential oscillations
• Mostly insensitive to emission current as long as $I_{e0} \sim 1 - 10 I_{c0}$


Temporal Resolution

• Probe acts as RC circuit
  – $C_0$: stray capacitance
  – $R_0$: sheath resistance
  – $R_M$: measurement resistor
• High speed op amp greatly improves response time ($< 1 \mu s$)
• Laser heated probes have faster response times
• Time resolved rf potentials

\[ \tau_M = \frac{C_0 R_0 R_M}{R_0 + R_M} \]

Slow-Sweep

- Measure current vs time at many probe biases
- Transpose to determine I-V trace vs time
- Allows time resolved inflection point method
- Easy, inexpensive to execute
- Same temporal resolution as floating probe
- Only for regular, period oscillations
High Energy Density

• High heat flux can melt probe
• For I-V trace, electron saturation current can contribute to Joule heating
• Self emissive probe uses plasma for heating
• Fast (1 m/s) actuator removes probe before it melts

High Pressure ($\gtrsim 1$ Torr)

- Electrons accelerating to/from probe can cause additional ionization
- Measurements have not yet be attempted in atmospheric pressure plasma

Vacuum potential measurements

- Emissive probes can make vacuum potential measurements
- Useful for plasma/vacuum interface
- Circuit forces probe potential to draw set current
- Graph shows measurements between capacitive plates
Probes vs. Optics

- Stark broadening
  - Measures electric field (> 30 V/cm)
  - Resolution of 0.1 mm
  - Limited by ion electric microscopic fields

- Probes
  - No minimum electric field
  - Resolution of 1 mm

## Recommendations: Density

<table>
<thead>
<tr>
<th>( n_e \text{ (cm}^{-3} )</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_e \leq 10^5 )</td>
<td>Vacuum current bias</td>
</tr>
<tr>
<td>Inflection point in the limit of zero emission</td>
<td></td>
</tr>
<tr>
<td>( 10^5 \leq n_e \leq 10^{12} )</td>
<td>Inflection point in the limit of zero emission</td>
</tr>
<tr>
<td>Floating point in the limit of large emission</td>
<td></td>
</tr>
<tr>
<td>( 10^{12} &lt; n_e \leq \frac{1.8 \times 10^{14}}{\sqrt{T_e}} )</td>
<td>Secondary electron emissive probe</td>
</tr>
<tr>
<td>Floating point with self-emissive probe</td>
<td></td>
</tr>
<tr>
<td>( n_e &gt; \frac{1.8 \times 10^{14}}{\sqrt{T_e}} )</td>
<td>Optical techniques</td>
</tr>
</tbody>
</table>

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### Recommendation: System

<table>
<thead>
<tr>
<th>Plasma system</th>
<th>Heating method</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>Joule heating</td>
<td>Vacuum current bias</td>
</tr>
<tr>
<td>Highly magnetized plasma</td>
<td>Laser heating</td>
<td>Inflection point</td>
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<tr>
<td></td>
<td></td>
<td>Floating point</td>
</tr>
<tr>
<td>Radio frequency</td>
<td></td>
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<tr>
<td>Double plasma device or beams</td>
<td>Joule heating</td>
<td>Inflection point</td>
</tr>
<tr>
<td>Non-neutral</td>
<td></td>
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<tr>
<td>Fusion plasma: bulk</td>
<td></td>
<td>Optical techniques</td>
</tr>
<tr>
<td>Fusion plasma: edge</td>
<td>Laser heating</td>
<td>Floating point</td>
</tr>
<tr>
<td></td>
<td>Self-emission</td>
<td></td>
</tr>
</tbody>
</table>

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Recommendation: Applications

<table>
<thead>
<tr>
<th>Applications</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state potential</td>
<td>Inflection point in the limit of zero emission</td>
</tr>
<tr>
<td>Potential in a sheath</td>
<td></td>
</tr>
<tr>
<td>Real time monitoring</td>
<td>Floating point in the limit of large emission</td>
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<tr>
<td>Spatial scans</td>
<td></td>
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<td>Temporal development Fluctuations</td>
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</tbody>
</table>
Conclusions

• Very useful tool for plasma potential measurements
  – Robust for a wide variety of plasmas
  – Good range for many low temperature plasma experiments

• Don’t ignore the uncertainties of each technique
  – Electron temperature
  – Parameter gradients
  – Geometry
Acknowledgments

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