Diagnostic tools for multi-dimensional plasmas

DOE-OFS Plasma Science Center

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Outline of the talk

- Introduction to Sandia
  - What we’ve done, what we are doing, where we are going
- Plasma density and temperature diagnostics
  - Laser-collision induced fluorescence (LCIF)
- Electric field diagnostics
  - Laser-induced fluorescence-dip (LIF-Dip)
- Surface diagnostics
  - Picosecond sum frequency generation ps-SFG
- Future directions and concluding thoughts
  - Where can connections be made?
Low temperature plasma studies at Sandia

- Sandia has rich history in LTP
  - Broad range of customers

- Long-term investment by DOE
  - Responsive to broad range of needs

- Past
  - Sematech, Applied Materials
  - DOE-BES
  - Various internal customers

- Present
  - WFO (NASA and others)
  - Internal customers
  - DOE-OFS PLSC

- Future
  - Maintain open door and stay responsive
Time-resolved, two dimensional electron density and temperature measurements

- Laser-collision induced fluorescence (LCIF)
  - Pump population to an intermediate state
  - Plasma electrons redistribute portion of population
  - Monitor fluorescence from neighboring states

Degree of redistribution depends on $n_e$, $T_e$
A "good" model is required to predict transfer between levels

- Employ a collisional-radiative model (CRM):

\[
\frac{dN_j}{dt} = \left[ \sum_{i \neq j} K_{ij}^e N_i - \sum_{i \neq j} K_{ji}^e N_j \right] n_e + \left[ \sum_{i > j} A_{ij} N_i - \sum_{i < j} A_{ji} N_j \right] + \sum_k \left[ \sum_{i \neq j} K_{ikj}^a N_i - \sum_{i \neq j} K_{jki}^a N_j \right] N_k
\]

- Temperature dependence is introduced via collisional rates \( K_{ij}^e \)

\[
K_{ij}^e = \langle \sigma_{ij} v_e \rangle = \left( \frac{m_e}{2\pi k T_e} \right)^{\frac{3}{2}} \int_0^\infty \sigma_{ij}(v) \exp\left( -\frac{m_e v^2}{2k_B T_e} \right) 4\pi v^2 dv
\]

Key transitions in Helium

Computed and measured excitation rates in Helium

Success is dependant on knowledge of rates

Density and temperature dependent trends derived from CMR results

- Computed temporal evolution of LCIF
  - Focus on key transitions

**Normalized time dependent LCIF trends**

![Normalized time dependent LCIF trends diagram]

**Time integrated, ratio trends**

![Time integrated, ratio trends diagram]

Key transitions

These transitions have yielded best signals
Demonstration of LCIF technique: Time modulated plasma

- **Proof of principle:** Examine time evolution of transient plasma
  - Afterglow of RF modulated plasma,
  - Pulse bias generated to planar electrode

### Setup

- RF coil
- Image area
- Double floating probes

### Data

<table>
<thead>
<tr>
<th>Time (μs)</th>
<th>n_e (LCIF)</th>
<th>kT_e (LCIF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^1</td>
<td>5 eV</td>
</tr>
<tr>
<td>10</td>
<td>10^1</td>
<td>5 eV</td>
</tr>
<tr>
<td>20</td>
<td>10^1</td>
<td>5 eV</td>
</tr>
<tr>
<td>30</td>
<td>10^1</td>
<td>5 eV</td>
</tr>
<tr>
<td>40</td>
<td>10^1</td>
<td>5 eV</td>
</tr>
</tbody>
</table>

### Analysis

- Captures decay of the plasma
  - Fast kT_e, slower n_e, very slow metastable
- Reasonable agreement between LCIF and probe
  - Probe problematic, uncertainties in rates

Proof of principle demonstrated
Demonstration of LCIF technique: Static structure of a sheath

- Examine spatial structure around biased electrode
  - Representative LCIF data used for analysis

**Key transitions**

Temperature measurements become tricky in the sheath....

![Graphs showing electron density and temperature](image-url)
Demonstration of LCIF technique: Formation of ion sheath

- Proof of principle: Two-dimensional maps of electron density
  - 50 $\mu$s after positive pulse applied to electrode
  - 20 ns snapshots of LCIF, 30 ns steps

Decent temporal and spatial resolution demonstrated
Current plasmas of interest

- We are looking at various plasma systems
  - Plasma double layers and anode glows
  - Expanding and flowing plasmas
  - ECR and magnetized plasmas (B. Weatherford & J. Foster, U. Mich)

What other systems can this technique be applied to?
Time-resolved, two dimensional electric fields

- Laser-induced fluorescence-dip spectroscopy (LIF-dip)
  - Pump population into intermediate state
  - Redistribute portion of this population to Rydberg state with probe laser
  - Monitor fluorescence from intermediate state

Rydberg levels offer varying sensitivity to electric fields.
Typical 2D LCIF-dip experimental arrangement

- Firing of lasers synched to rf phase.
  - 13 MHz rf, 20 Hz lasers
  - Time resolved rf voltages
- Gate ICCD after firing of the lasers
  - 2D snapshot of LIF
  - Accumulate for ~ 100's of laser shots
- Repeat as probe laser is incrementally stepped
  - Typically 30 discrete steps
- Post process to determine electric fields
  - Plot LIF vs. wavelength for each pixel
  - Assign electric field, create 2D map
Scenario: Metal-dielectric interface

- Test case:
  - We know that the electric fields will be non-uniform

How will electric field distribution influence energy deposited into the plasma?
Structured boundaries introduce non-uniformities

- 2D measurements demonstrate technique
  - Electric fields impacted by boundaries
- Analysis above both surfaces
  - Sheath potentials are not equal
  - Potential drop across dielectric
- Compare measured electric fields to models
  - Validate predictions

Comparison to model

Analysis of electric fields

Measured distribution of electric fields

<table>
<thead>
<tr>
<th>Surface</th>
<th>$kT_e$(eV)</th>
<th>$\lambda_e$(mm)</th>
<th>$\phi_m$(mm)</th>
<th>$n_i$(ion/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>2</td>
<td>0.12</td>
<td>3.3</td>
<td>$1.6\times10^{16}$</td>
</tr>
<tr>
<td>Insulator</td>
<td>2</td>
<td>0.12</td>
<td>3.1</td>
<td>$1.9\times10^{15}$</td>
</tr>
</tbody>
</table>

400 mTorr Argon; 320 V$_{pp}$ @ 13.56 MHz; 1.5 mm Teflon ($\kappa$ ~ 2.1)

\[ V = -\int E \cdot dl \]

Time resolved studies provide more insight

- Single "snapshot" is indicative - at risk of missing whole picture
  - Time resolved measurements yield more complete picture

- Phase-resolved measurements
  - Phase-locked LIF-Dip
  - Phase resolved optical emission (PROES)

Capture transient phenomena with time resolved measurements
Incorporate additional diagnostics to help complete the picture

- Lower fields mean less energy deposited into the plasma above the dielectric
  - Less excitation, less ionization

- Gradients in potential across the sheath are maintained by a horizontal component of the electric field
  - Influence angular distribution of ions hitting surface

Electrode topology impacts plasma and surface interactions
Scenario: Different conductors

- Less obvious - both are conductors
  - No induced voltage across either one

Is there any noticeable difference introduced by the dissimilar metals?
Different metals do influence discharge structure….

Under certain circumstances

- At a pressure of 100 mTorr, very little difference is observed

- At a pressure of 400 mTorr, there is a difference

The choice of metal and choice of operating conditions influences the plasma

320 V_{pp} @ 13.56 MHz
Secondary electrons become more important in plasma heating at higher pressures

- Species hitting the surface can liberate electrons (Secondary emission $\gamma$)
- Electrons accelerated by sheath into the plasma
- Cascading collisions arise if mean-free path ($\lambda$) is short compared to sheath thickness

\[
\frac{n_{\gamma}}{n_0} \approx \gamma e^{\frac{\Delta x}{\lambda}}
\]

Fraction of $\gamma$ electrons

Estimated $\gamma$ contribution

Measured charge densities

Plasma is coupled to emission from the surface, surface is coupled to the plasma......
Scenario: Electric fields around a charged "dust grain"

- Initially funded through BES - Dusty plasmas
  - "Invested" in electric field diagnostics
- Thrust II area of interest

"Far" - Langmuir probe

"Near" - Dusty plasma

Structure is symmetric in bulk plasma, independent of neutral density

Field profiles around the probe are symmetric, and extend ~ 1 mm from probe

Sheath structure changes with bias
  • Higher fields, slightly thicker sheath

Sheath structure is independent of pressure
  • Not dependent on collisions??
Interaction between the probe and plasma extends beyond the sheath

- Unexpected changes in excitation observed around the probe:
  \[ \text{Difference} \equiv \frac{LIF_{\text{Bias}} - LIF_{\text{Float}}}{LIF_{\text{Float}}} \]

- Differences extend beyond measured sheath
  - Sheath thickness \( \sim 1 \text{ mm} \)
  - Change extends > 5 mm

- Differences are not symmetric
  - Dependent on location w.r.t. powered electrode?

- What is the source of the loss?

The presence of this “small particle” impacts “large region”

Relative changes in 1s\(_4\) LIF
Ion dynamics depend on properties of the grain

- **Above the sheath**
  - $V_{\text{Probe}} < V_{\text{Local}}$
  - Some "bending"
  - Depletion of space charge by the probe

- **At the sheath edge**
  - Big $q/m$ grain
  - $V_{\text{Probe}} \sim V_{\text{Local}}$
  - Hard to detect focusing

- **In the sheath**
  - Small $q/m$ grain
  - $V_{\text{Probe}} > V_{\text{Local}}$
  - Ions repelled from probe

Floating Probe: $V_{\text{Probe}} \sim 5$ V

200 mTorr, 25 Watts
SNL is implementing cw laser diagnostics for ion velocity measurements

- Developing and implementing cw-laser based diagnostic for measuring ion velocities
  - K. Frederickson
- Our “deliverable” for FY10

This is going to be a challenge…
Future directions: Ultrafast laser diagnostics to probe plasma-surface interface

- “Holy Grail” of LTP
  - Synergistic effects
  - Peer into mechanisms
- Diagnostics are “challenging”
  - LTP community actively engaged
- (Ultra) fast spectroscopy offers access to surface/interface
  - Intense photon flux to drive non-linear processes
  - Faster than molecular and electronic relaxation timescales

**Sum-frequency generation**

\[
|0> \quad \omega_{IR} \quad \omega_{Vis} \quad |v> \quad \omega_{SFG} \\
|1> \quad \omega_{IR} \quad \omega_{Vis} \quad |v> \quad \omega_{SFG}
\]

**Time-resolved pump-probe**

\[
\Delta t \quad \omega_{pump} \quad \omega_{Probe}
\]
Future directions: Sum frequency generation

“Sum-frequency generation (SFH)
- Second order, non-linear Raman technique
- $I_{SFG} \sim |\chi^{(2)} E_{Vis} E_{IR}|^2$

Powerful diagnostic for surface studies
- Sensitive to chemical composition
- Molecular orientation
- Broad range of pressures

Has been implemented in our lab
- Darcy Farrow

Conversation is underway with Task III PI's to identify paths towards implementation
Future directions: Time-resolved pump-probe spectroscopy

- Time-resolved pump-probe spectroscopy
  - Femtosecond laser pulses, temporally delayed

- Probe electronic structure of various materials
  - Relaxation times depend on electronic structure of material

- Potential PLSC applications
  - Poisoned catalysts
  - Metal hydrides, nitrides, oxide.
  - Film thickness

### Concept

\[ \Delta t \quad \omega_{\text{pump}} \quad \omega_{\text{Probe}} \]

### Setup

Bench-top setup looking for the right mission...

### Results

- Samples provided by S. G. Walton, NRL

- Untreated
- Plasma treated

Guiding data

Concluding remarks

- Emphasis placed on more recent experiments performed mostly by EVB
  - More powerful, "unique capabilities" at our disposal
  - "Tip of the iceberg"

- It is our goal to capitalize on the unique opportunities offered to us through funding of PLSC
  - Great chance to open the doors and invite community in…..

There are many opportunities to host members of the PLSC (Professors, post-docs and students …)

Is there interest from members of the PLSC at large to pursue these opportunities?

Thank you!
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Appendix: Microwave diagnostics

- Large array of microwave hardware and expertise accessible for plasma characterization
  - (P. Miller and G. Hebner)
Appendix: Probes

- Specialization in probes and probe arrays for characterizing plasma
  - P. Miller, G. Hebner, E. Barnat

**Ion Flow**

**"B-dot"**

**Hairpin resonator**
Appendix: Multi-frequency rf plasmas

WFO with Applied Materials - High frequency and multi frequency scaling studies

300 mm chamber

Frequency scaling

Dual frequency

Electromagnetic effects

Radial current density

Radial sheath voltage

WFO with Applied Materials - High frequency and multi frequency scaling studies

300 mm chamber

Frequency scaling

Dual frequency

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Radial current density

Radial sheath voltage
Appendix: Magnetized rf plasmas

- WFO with Applied Materials - Model validation and predictive development

Modified GEC ref cell | I & V trends | Electric fields
---|---|---

**I & V trends**

- [Graphs showing I & V trends with magnetic field variations]

**Electric fields**

- [Graphs showing electric field distributions with and without magnetic field]

**Modified GEC ref cell**

- Diagram of the modified GEC reference cell with dimensions and magnetic field orientations.

**Magnetized Hydrogen plasma**

- Diagram showing excitation profiles at different heights and magnetic field strengths.

[Images of experimental setups and data visualizations related to magnetized plasmas]