A MONTE CARLO SIMULATION OF RADIATION TRAPPING IN ELECTRODELESS GAS DISCHARGES HAVING COMPLEX GEOMETRIES*

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AGENDA

- Radiation transport in low pressure plasmas
- Overview of the Hybrid Plasma Equipment Model
- Description of Monte Carlo Transport model
- Base case plasma properties
- Dependence of radiation trapping factor on
  - Plasma geometry
  - Pressure
  - Gas temperature
- Emission spectra
- Conclusion
• Electrodeless gas discharges are finding increasing use in lighting applications due to their increased lifetime.

• Investigations are underway to increase the efficiency of these lamps, now ≈ 25%

• Typical fluorescent lamps consist of Ar/Hg ≈ 97/3. Resonance radiation from Hg(6^3P_1) (254 nm) excites phosphors which generate visible light.

• Resonance radiation, produced by electron impact excitation of Hg (6^1S_0) to Hg(6^3P_1), can be absorbed and reemitted many times prior to striking the phosphor.

• The consequence of radiation trapping is to lengthen the effective lifetime of emission as viewed from outside the lamp.

• Control of resonance radiation trapping is therefore important to the design of such lamps.
• The excited Hg and Ar levels have been treated as a single state.

• Ar is a buffer gas. Radiation exciting the phosphor is essentially all due to the mercury transition.
Characterization of trapping is typically done using Holstein factors:

\[ A \rightarrow A \cdot g, \]

where \( A \) is the Einstein A-coefficient and \( g \) is a geometry-dependent factor. For a cylinder,

\[ g = 1.115 \sqrt{\pi k_p R} \] (impact broadened)

\[ g = 1.60 \frac{k_0 R}{\sqrt{\pi \ln(k_0 R)}} \] (doppler broadened)

where \( k \) is the lineshape profile.

This method fails for more complex geometries, where the propagator cannot be easily evaluated.
MONTE CARLO METHODS FOR RADIATION TRANSPORT

• Monte Carlo methods are desirable for complex geometries where it is not easy to evaluate propagator functions.

• We have developed a Monte Carlo resonance radiation transport model for the trapping of the 254 nm radiative transition for mercury.

• This model incorporates the effects of Partial Frequency Redistribution (PFR) and quenching of excitation, using a Voigt profile for emission and absorption.

• However, one needs a self-consistent plasma model to “drive” the kinetics and to account for evolution of gas densities, temperatures and other plasma parameters.

• To address this need, the Monte Carlo resonance radiation transport model is interfaced with the Hybrid Plasma Equipment Model (HPEM) to realistically model the gas discharge.
SCHEMATIC OF THE HYBRID PLASMA EQUIPMENT MODEL

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Monte Carlo method is used to follow trajectories of photons from initial emission to escape from plasma.

The absorption/emission profile used is a Voigt profile.

MC photons are generated in proportion to the excited atom density at each point in the plasma.

The initial frequency of each photon is not directly sampled from the lineshape profile. Instead, to avoid statistical errors, we choose the frequency uniformly from a chosen bandwidth, and assign to this particle a weighting which accounts for the lineshape profile.

The null collision method is employed for the photon transport.
We define the trapping factor as

\[ k = \frac{\tau_{\text{res}}}{\tau_{\text{nat}}} \]

where \( \tau_{\text{res}} \) is the average residence time of the photon in the plasma, and \( \tau_{\text{nat}} \) is the natural lifetime of the excited state.

After each absorbing collision at photon frequency \( \nu \), the partial frequency redistribution is incorporated by randomly choosing a new frequency within a range \( \nu \pm \Delta \nu \).

The value of \( \Delta \nu \) was found by simulating trapping in a cylindrical discharge with a uniform density of Ar and Hg atoms, and comparing the results with those found by Lister.

The results agreed well for \( \Delta \nu \approx \alpha \Delta \nu_d \), where \( \alpha \) ranged from 1.75 to 2.0.
• Diameter – 9 cm
• Depth – 5 cm
• Height – 8 cm
• Initial pressure – 250 mTorr
• Initial temperature – 400 K
• Operating power – 50 W
• Operating frequency – 2.65 Mhz
• Initial Ar mole fraction – 0.98
• Initial Hg mole fraction – 0.02
• Only 254 nm resonance line has been studied.

• The trapping factor for these conditions is \( \approx 40 \)
• Peak electron temperature ($\approx 2$ eV) surrounds the reentrant coil resulting in a peak plasma density in an annulus around the antenna.

![Plasma density and temperature distribution](image)

- Electron temperature ($Te$) range: 0.11 eV to 1.68 eV
- Electron density ($ne$) range: $2.5 \times 10^{11}$ cm$^{-3}$ to $3.7 \times 10^{12}$ cm$^{-3}$
Cataphoresis and gas heating produce a maximum Hg density near the walls, which results in the maximum of the Hg* density occurring in the top “dome” and near the walls.
• The fill buffer gas pressure was increased while keeping other parameters (e.g. Hg density) constant.

• The increase in Ar – Hg* collision frequency produces a broader redistribution of re-emission allowing the photons to move into the wings of the lineshape profile.

• Owing to a longer mean free path in the wings, the photons can escape the plasma more easily, reducing the trapping factor.
• The initial background gas temperature was varied keeping initial ground state number densities and other parameters constant.

• As the temperature is increased, the number of collisions that the gas atoms undergo increases, and this allows for a higher redistribution.

• Moreover, the increase in temperature affects the Voigt profile via the Doppler broadening. Therefore, the trapping factor decreases.
DEPENDENCE ON PLASMA GEOMETRY

- The plasma volume was increased by increasing the outer radius of the lamp and other parameters are constant.

- As the radius increases, the photon has to traverse a larger column of length of Hg before escaping the plasma.

- This average column length is less than \( R \), the radius of the discharge, which explains the difference of our results from Holstein factors (\( g \sim R \ln(R) \)).

![Diagram showing the majority of photon emitters in a plasma column](image)

<table>
<thead>
<tr>
<th>Width of plasma column (cm)</th>
<th>Trapping factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>2.5</td>
<td>100</td>
</tr>
</tbody>
</table>
Due to radiation trapping, line reversal is observed in the UV emission spectra near the center frequency because the photons that leave the plasma are mainly in the wings.

- No trapping

- With trapping (base case)
• Emission spectra were also obtained while increasing mole fraction of Hg and the radius of the plasma column. Increased trapping led to greater line reversal.

- Mole fraction of Hg=4%
- Radius=4.5 cm
SUMMARY AND FUTURE WORK

• A self-consistent Monte Carlo radiation transport model has been developed which, in conjunction with a plasma model, can be used to realistically model resonance radiation transport in a gas discharge, for complex geometries.

• Studies have been carried out on the Hg (6^3P\textsubscript{1}) → Hg (6^1S\textsubscript{0}) transition under different geometries and gas pressures.

• The future work that has to be carried out includes
  • Study of the other resonance radiation levels
  • Inclusion of isotope effects
  • Detailed analysis of all transitions involved by treating each excited state level separately.