CONSEQUENCES OF RADIATION TRAPPING ON 
ELECTRON ENERGY DISTRIBUTIONS IN LOW 
PRESSURE INDUCTIVELY COUPLED 
Hg/Ar DISCHARGES*

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AGENDA

- Radiation transport in low pressure plasmas
- Overview of the Hybrid Plasma Equipment Model
- The Monte Carlo Radiation Transport Model
- Effect of radiation trapping on EEDFs
- Variation of EEDF with
  - Power
  - Frequency
  - Radiative lifetime
- Conclusions
Electrodeless gas discharges are finding increasing use in the lighting industry 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) and Hg (6^1P_1) (185 nm) excites phosphors which generate visible light.

This resonance radiation can be absorbed and reemitted many times prior to striking the phosphor, increasing the effective lifetime of emission as viewed from outside the lamp.

We have modeled this mechanism using a Monte Carlo radiation transport model linked to a hybrid plasma equipment model, to realistically simulate the discharge.
HYBRID PLASMA EQUIPMENT MODEL

- A modular simulator addressing low temperature, low pressure plasmas.
- EMM: electromagnetic fields and magneto-static fields
- EETM: electron temperature, electron impact sources, and transport coefficients
- FKM: densities, momenta, and temperatures of charged and neutral plasma species; and electrostatic potentials
Rg + e → Rg* + e
Rg + e → Rg^+ + 2e
Rg* + e → Rg^+ + 2e
Rg* + e → Rg + e
Hg + e → Hg* + e
Hg + e → Hg^+ + 2e
Hg* + e → Hg + e
Rg* + Rg* → Rg^+ + Rg + e
Rg* + Hg → Hg^+ + Rg + e
Rg* + Hg* → Hg^+ + Rg + e
Rg^+ + Hg → Hg^+ + Rg
Rg^+ + Hg* → Hg^+ + Rg
Rg^+ + Rg → Rg + Rg^+
Hg^+ + Hg → Hg + Hg^+
Hg* + Hg* → Hg^+ + Hg + e
Rg* → Rg + hv
Hg* → Hg + hv
• Monte Carlo photon pseudo-particles are launched from locations proportional to Hg$^*$ density.

• Trajectories are tracked accounting for absorption/emission based on Voight profile.

• Null cross section techniques account for variations in absorber and perturber densities, collision frequency and gas temperature.

• Partial frequency redistribution of emitted photons.

• Isotope shifts and fine structure splitting.

• Effective lifetimes (residence times) of photons in plasma and exit spectra are calculated.

• Rate constant of radiative reaction decreased by the trapping factor (ratio of effective to natural photon lifetime for given transition).
BASE CASE CONDITIONS

- Diameter – 9 cm
- Height – 8 cm
- Initial pressure – 500 mTorr
- Initial temperature – 375 K
- Power – 50 W
- Frequency – 10 Mhz
- Initial Ar mole fraction ≅ 0.97
- Initial Hg mole fraction (ground state) ≅ 0.03
The electron density goes up with trapping due to more ionization processes, while the temperature becomes more localized due to a reduced skin depth.
Radiation trapping leads to an increased lifetime for the \([\text{Hg}^*]\) atoms.

There are more super-elastic collisions and hence most lower energy electrons gain an additional amount of energy \((\approx 5 \text{ eV})\).

This leads to a “bulge” in the lower energies in the EED, which is smoothed out by other inelastic collisions.

However, since the total power deposited is a constant, higher rate of dissipation at low energies produces a decrease in the EED at higher energies.
• The EED in the skin depth has a longer tail due to more stochastic heating.

• Diffusion cooling near sheath of the opposite wall depletes high energy electrons.
• The EEDs shown here are for an untrapped lifetime of 125 ns ($6^3P_1 \rightarrow 6^1S_0$ transition).

• As the power increases, we have more electrons in the plasma:

\[ n_e = 2.1 \times 10^{11} \text{ cm}^{-3} \text{ (50 W)} \]
\[ = 1.8 \times 10^{12} \text{ cm}^{-3} \text{ (100 W)} \]

• This increased electron density leads to more Maxwellian EEDs (both trapped and untrapped) for deposition of 100 W.

• The two-temperature distribution seen at 50 W is not seen at 100 W.
VARIATION WITH POWER DEPOSITED (10 ns LIFETIME)

- The EEDs shown here are for a fictitious transition having the same energy difference as the $6^3P_1 \rightarrow 6^1S_0$ transition, but with a vacuum lifetime of 10 ns.

- The increased power deposition in the plasma leads to a doubling of electron heating in the skin depth.

- $n_e = 1.6 \times 10^{11} \text{ cm}^{-3} (50 \text{ W})$
  $= 2.1 \times 10^{11} \text{ cm}^{-3} (100 \text{ W})$

- This heating leads to a tail in the untrapped EED with increase in power.

- In the case of 10 ns radiative lifetime, we see that the electric field acceleration dominates the EED, while in the 125 ns case, e-e collisions determine the EED at high powers.
With increase in frequency, the untrapped distributions do not change.

However, the trapped EEDs are significantly different in the three cases, with lower frequencies showing a longer tail in the distribution.
- There is more stochastic heating in the trapped EED at skin depth.

- At low frequencies, this heating offsets the reduction in the tail due to trapping.
SUMMARY

• A Monte Carlo Resonance Radiation Transport Model has been interfaced with a plasma equipment model to model the effects of radiation trapping on EEDs.

• Radiation trapping is seen to affect the bulk as well as the tail of the EED due to enhancement of super-elastic collisions.

• The EED becomes more Maxwellian with increase in power at high radiative lifetimes. At lower lifetimes, stochastic heating dominates the tail of the EED.

• Increased skin depth electron heating at lower frequencies for trapped distributions significantly changes the tail of the EED.