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 LAMPS AND TRAPPING

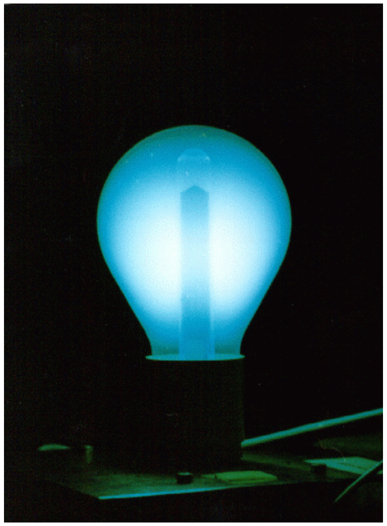
- Electrodeless gas discharges are finding increasing use in the lighting industry due to their increased lifetime.

- Investigations are underway to increase the efficiency of these lamps, now $\cong$ 25%.

- Typical fluorescent lamps consist of Ar/Hg $\approx$ 97/3. Resonance radiation from Hg (6^3P_1) (254 nm) and Hg (6^1P_1) (185 nm) excites phosphors which generate visible light.

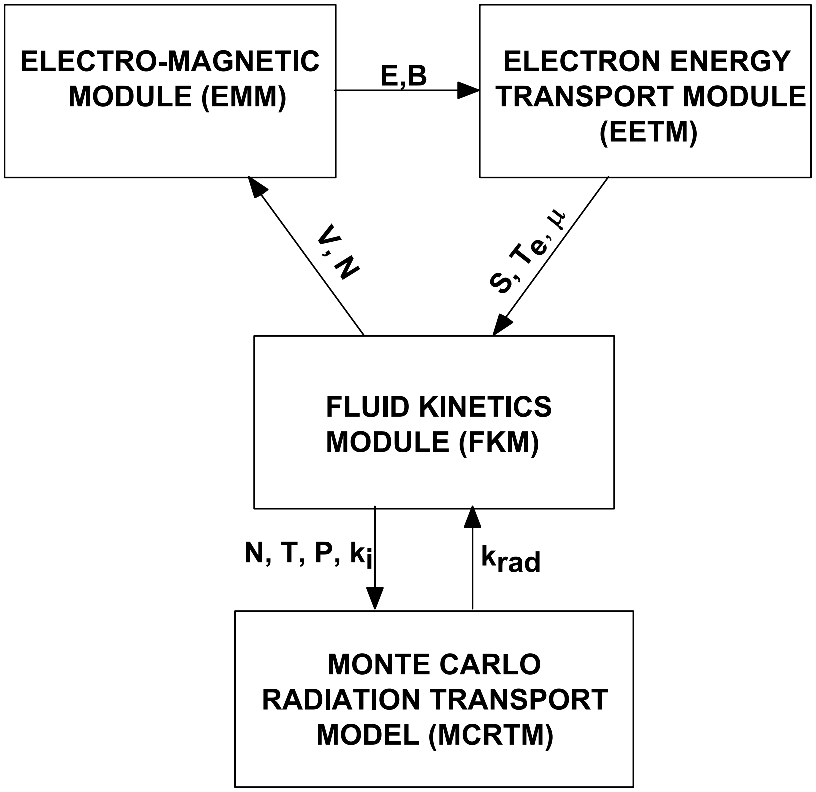
- This resonance radiation can be absorbed and reemitted many times prior to striking the phosphor, increasing the effective lifetime of emission as viewed from outside the lamp.

- 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



ELECTRO-MAGNETIC MODULE (EMM)

ELECTRON ENERGY TRANSPORT MODULE (EETM)

FLUID KINETICS MODULE (FKM)

MONTE CARLO RADIATION TRANSPORT MODEL (MCRTM)

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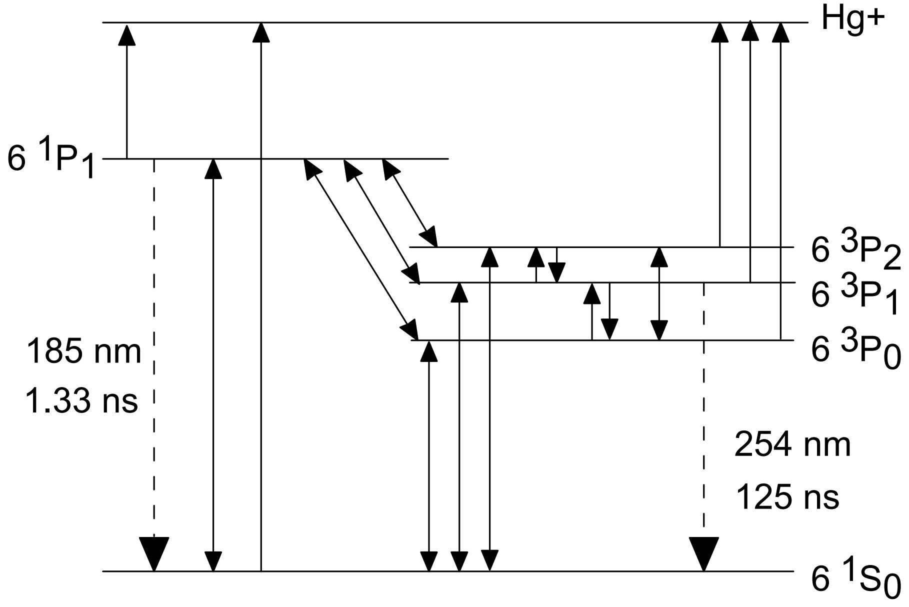
REACTION CHEMISTRY

$Rg + e \rightarrow Rg^* + e$
$Rg + e \rightarrow Rg^+ + 2e$
$Rg^* + e \rightarrow Rg^+ + 2e$
$Rg^* + e \rightarrow Rg + e$
$Hg + e \rightarrow Hg^* + e$
$Hg + e \rightarrow Hg^+ + 2e$
$Hg^* + e \rightarrow Hg + e$
$Rg^* + Rg^* \rightarrow Rg^+ + Rg + e$
$Rg^* + Hg \rightarrow Hg^+ + Rg + e$
$Rg^* + Hg^* \rightarrow Hg^+ + Rg + e$
$Rg^+ + Hg \rightarrow Hg^+ + Rg$
$Rg^+ + Hg^* \rightarrow Hg^+ + Rg$
$Rg^+ + Rg \rightarrow Rg + Rg^+$
$Hg^+ + Hg \rightarrow Hg + Hg^+$
$Hg^* + Hg^* \rightarrow Hg^+ + Hg + e$
$Rg^* \rightarrow Rg + h\nu$
$Hg^* \rightarrow Hg + h\nu$



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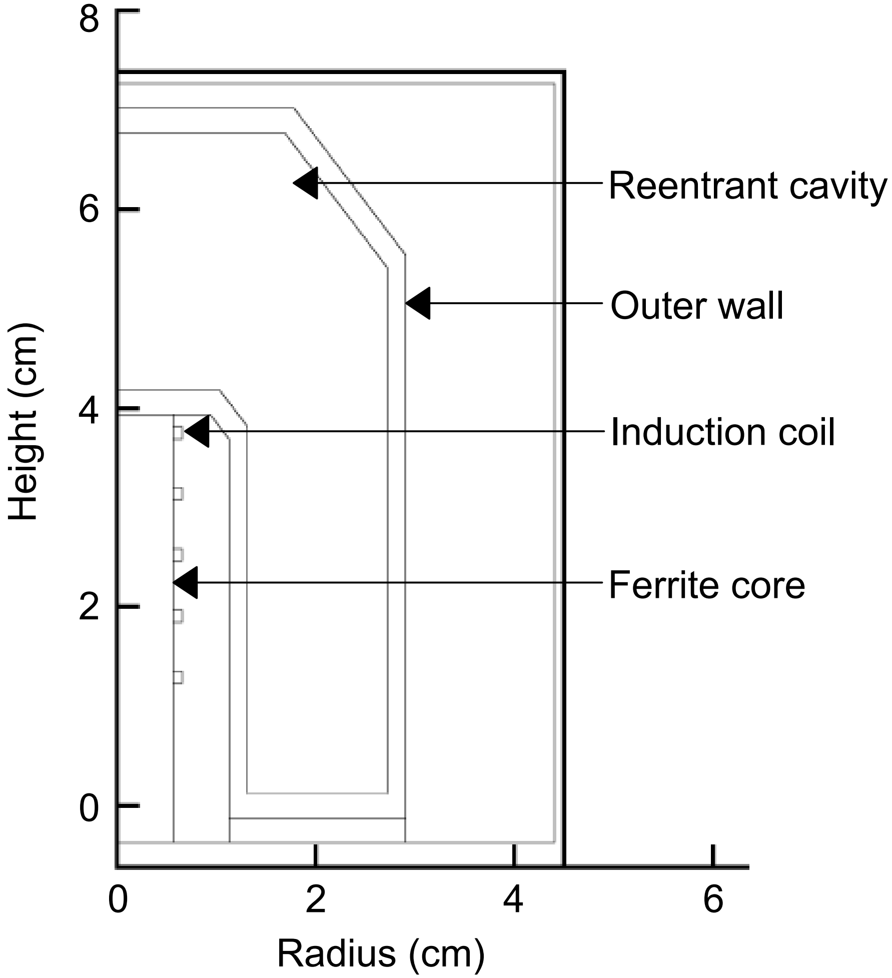
MONTE CARLO RADIATION TRANSPORT MODULE

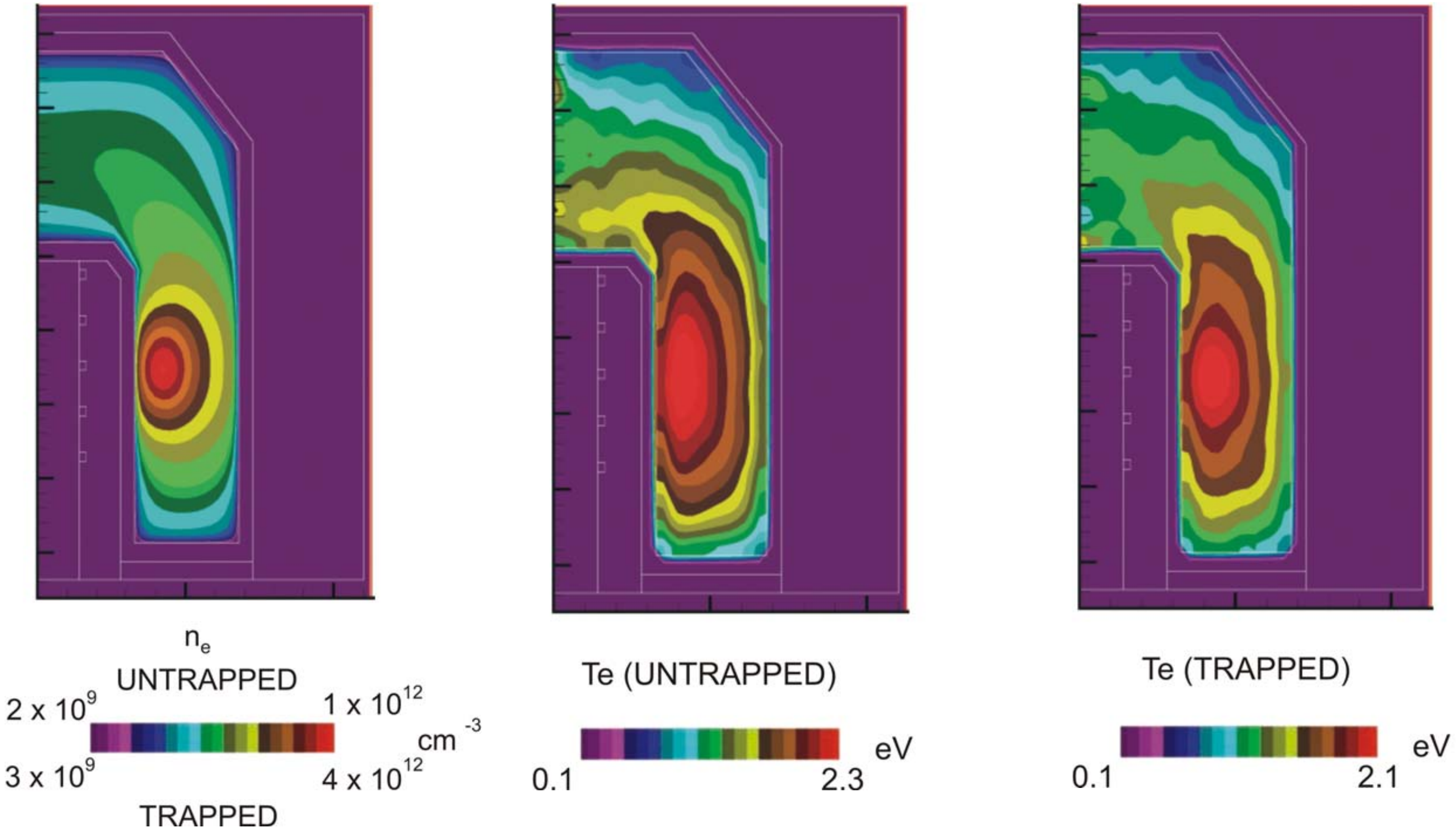
- **Monte Carlo photon pseudo-particles are launched from locations proportional to Hg^* density.**
- **Trajectories are tracked accouting for absorption/emission based on Voight profile.**
- **Null cross section techniques account for variations in absorber and perturber densities, collision frequency 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**



ELECTRON DENSITY AND TEMPERATURE

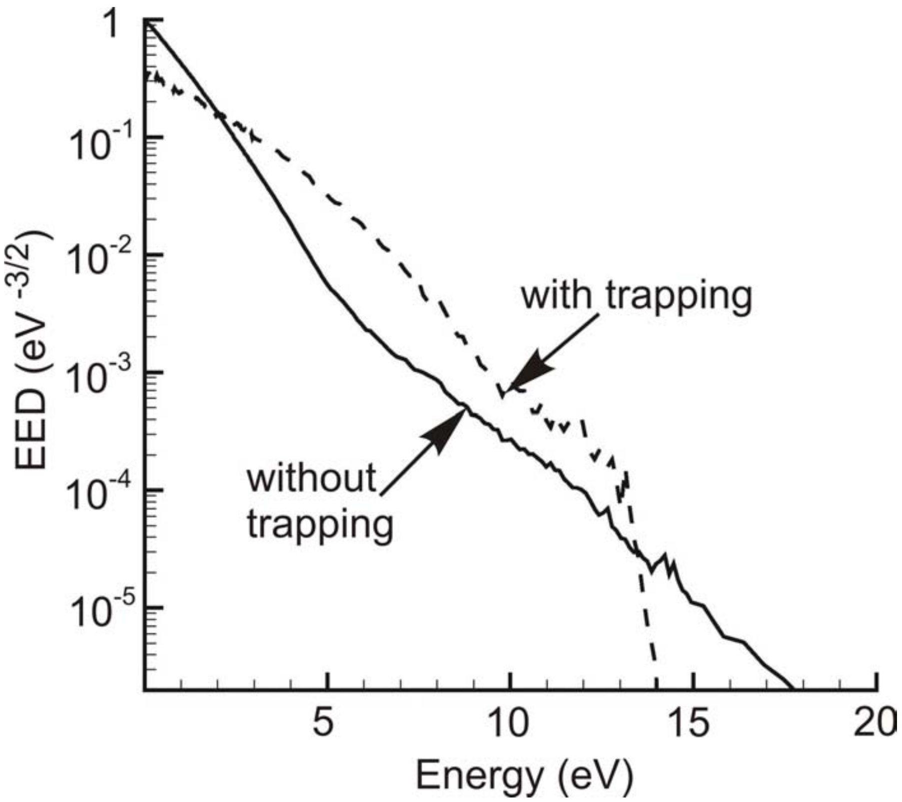


- **The electron density goes up with trapping due to more ionization processes, while the temperature becomes more localized due to a reduced skin depth.**

EFFECT OF RADIATION TRAPPING

- **Radiation trapping leads to an increased lifetime for the [Hg*] atoms.**

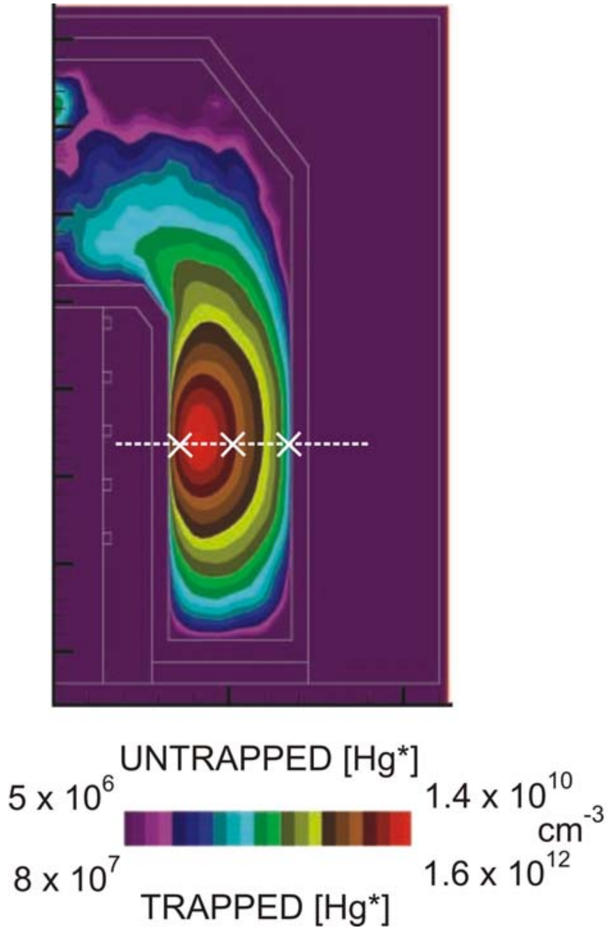
- **There are more super-elastic collisions and hence most lower energy electrons gain an additional amount of energy (≅ 5 eV).**

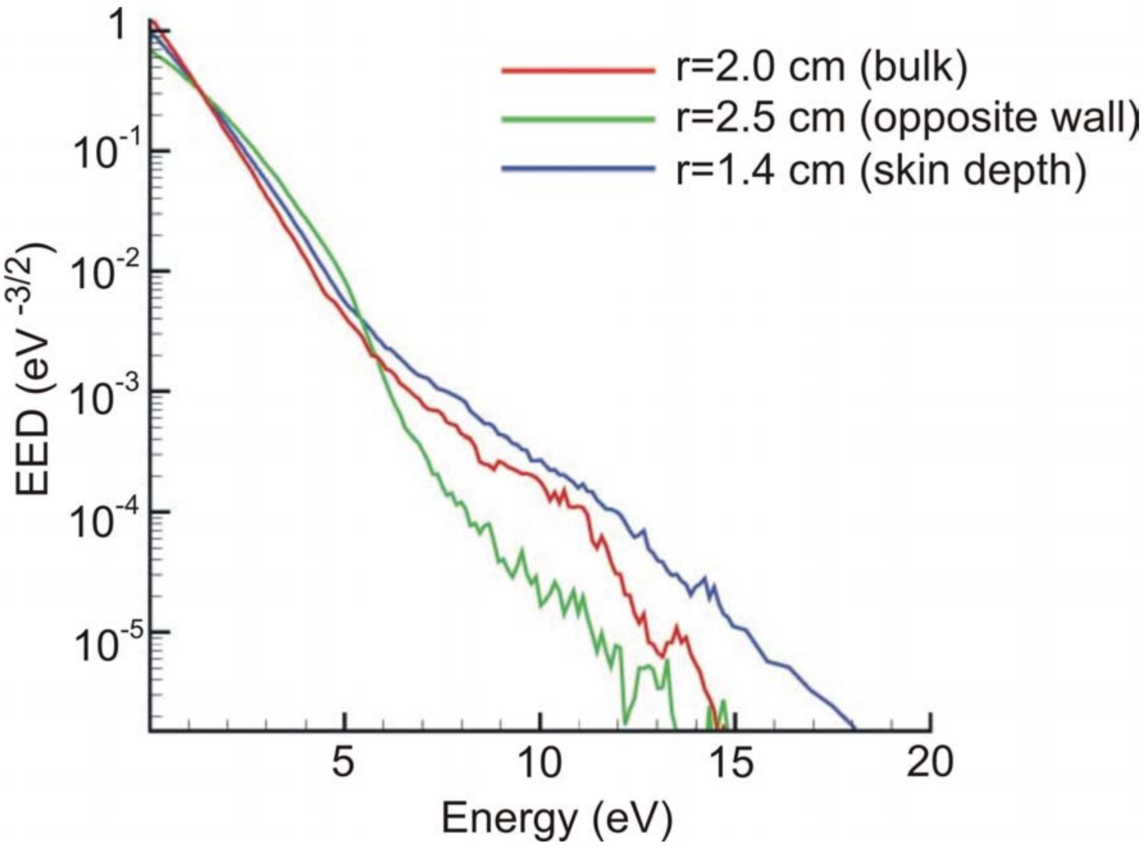


- **This leads to a "bulge" in the lower energies in the EED, which is smoothed out by other inelastic collisions.**

- **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.**

VARIATION WITH SPATIAL POSITION





- **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.**

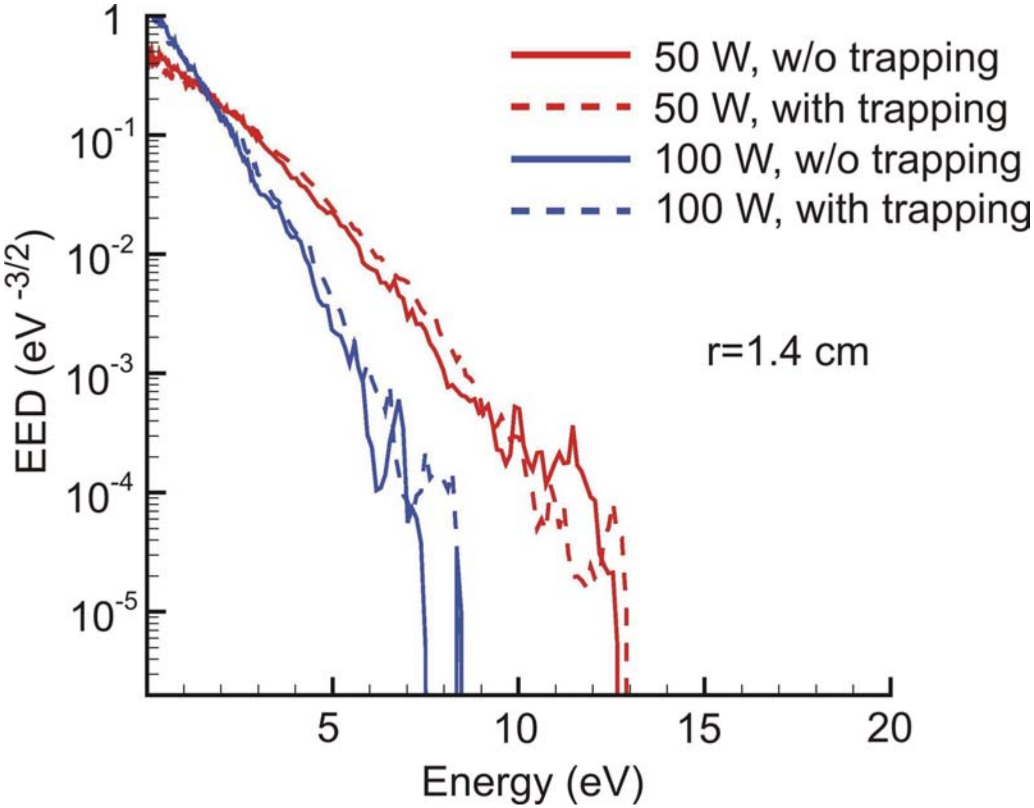
VARIATION WITH POWER DEPOSITED

- **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 x 10^{11} cm^{-3} (50 W)

=1.8 x 10^{12} cm^{-3} (100 W)



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

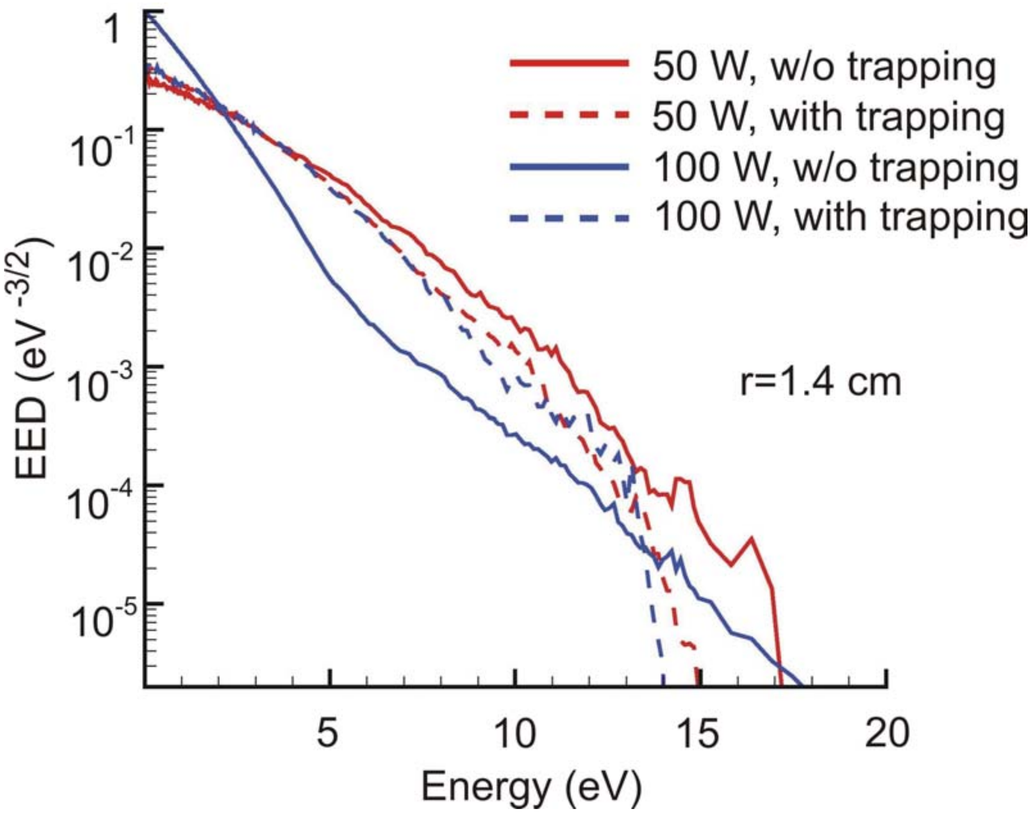
- **The two-temperature distribution seen at 50 W is not seen at 100 W.**

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.**

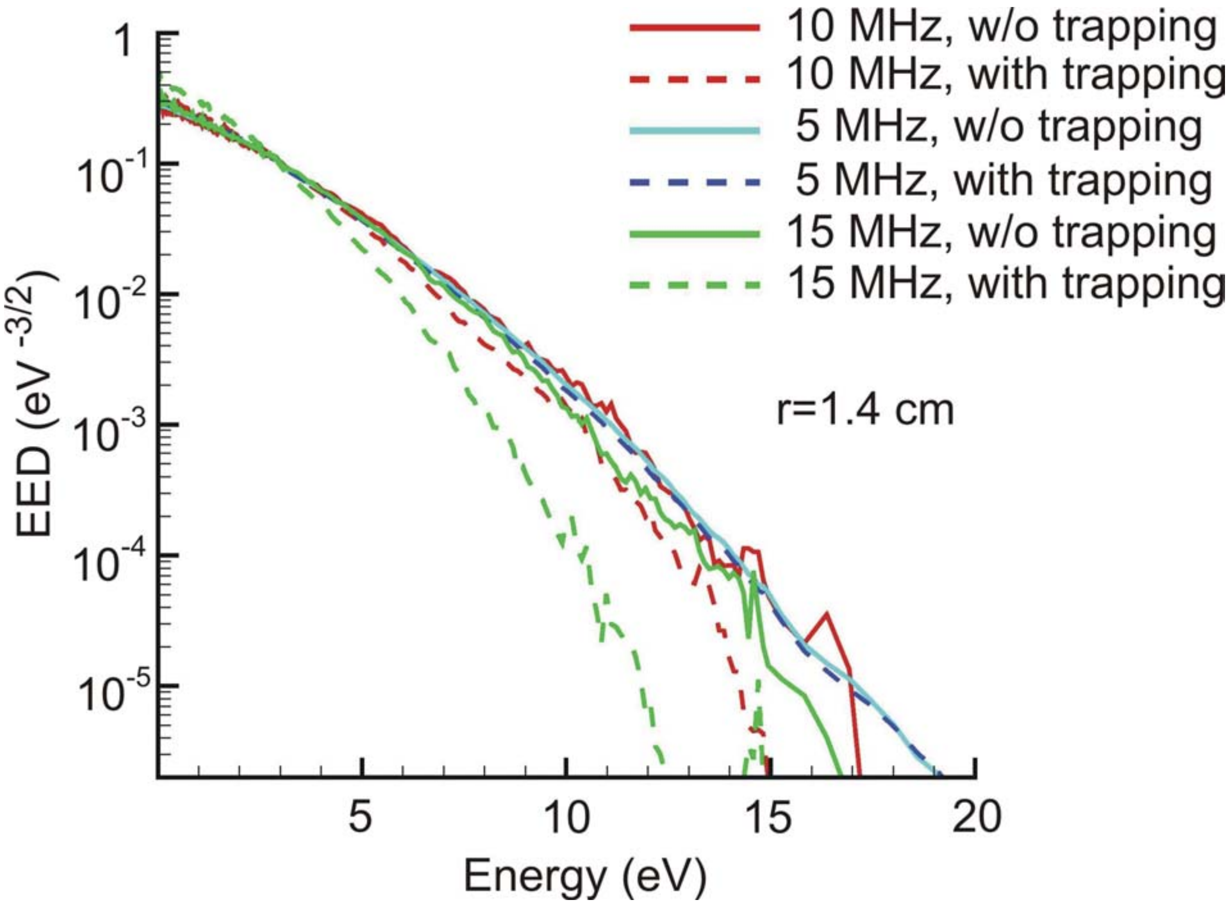
- **n_e=1.6 x 10^{11} cm^{-3} (50 W)**
  =2.1 x 10^{11} cm^{-3} (100 W)



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

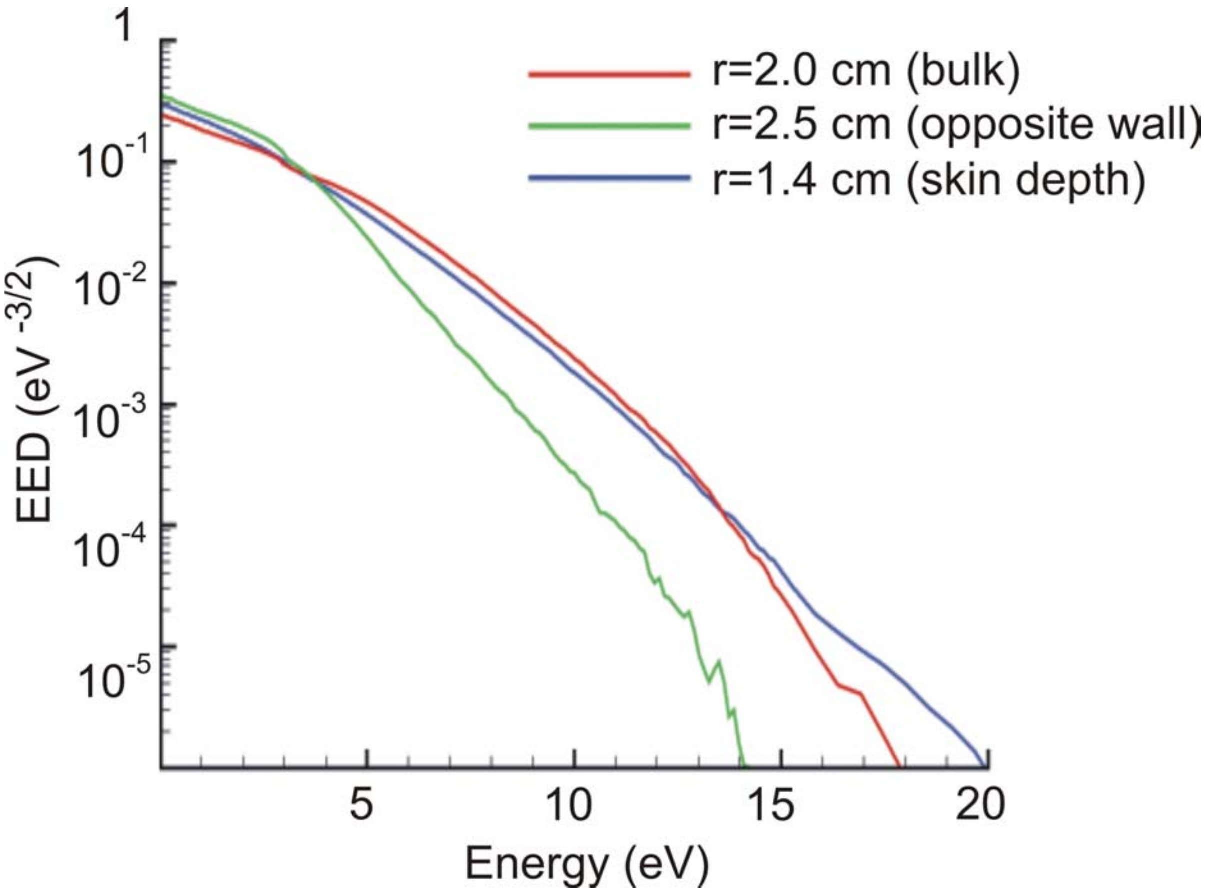
- **In the case of 10 ns radiative lifetime, we see that the electric field acceleration dominates the EED, while in the 125 ns case, e-e collisions determine the EED at high powers.**

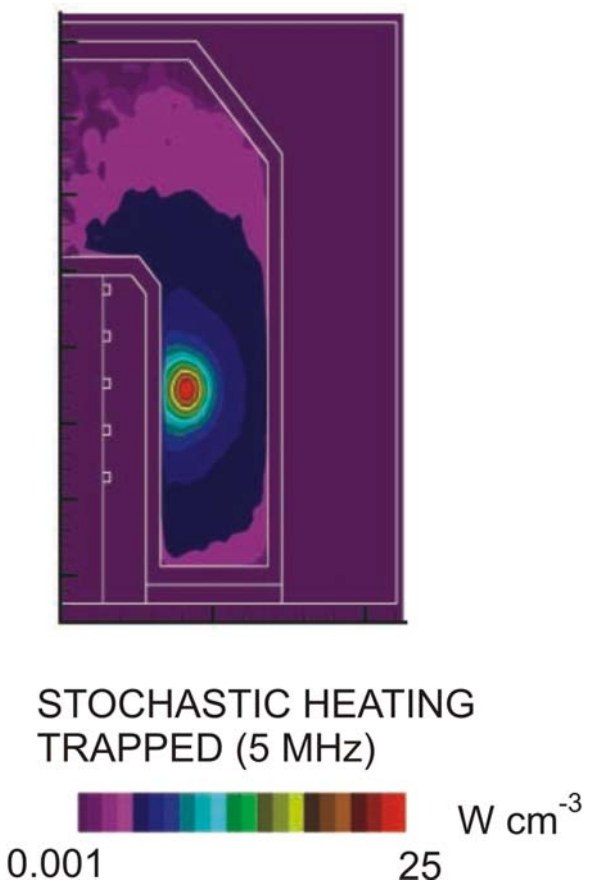
EFFECT OF ICP FREQUENCY



- **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.**

EFFECT OF ICP FREQUENCY (contd.)





- 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.