MONTE CARLO SIMULATION OF RADIATION TRAPPING IN ELECTRODELESS LAMPS: COMPLEX GEOMETRIES AND ISOTOPE EFFECTS*

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AGENDA

- Radiation transport in low pressure plasmas
- Overview of the Hybrid Plasma Equipment Model
- Description of the Monte Carlo Radiation Transport Model
- Base case plasma properties
- Multi-level transitions and emission spectra
- Isotope effect studies
- Dependence of trapping factor on
  - Pressure
  - Plasma geometry
- Conclusions

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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.

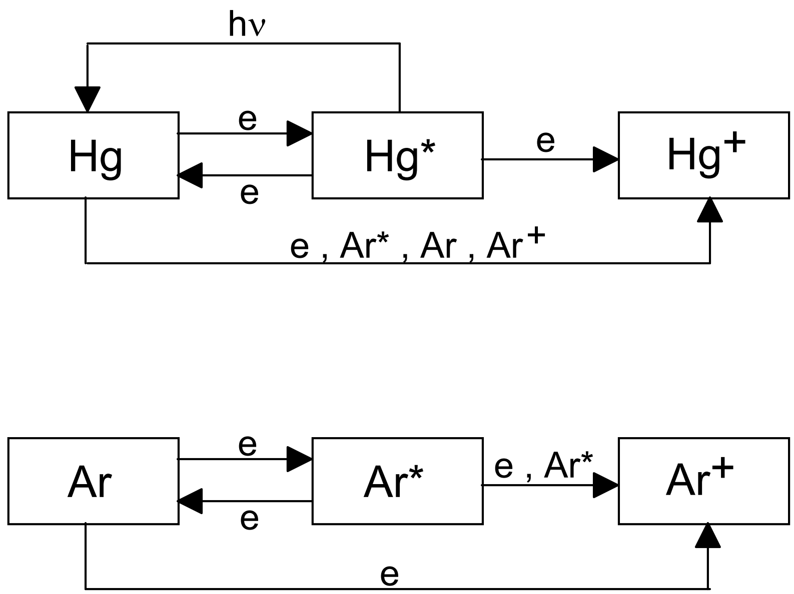
- The consequence of trapping is to lengthen the effective lifetime of emission as viewed from outside the lamp.

- Control of resonance radiation trapping is therefore important to the design of such lamps.

PHYSICAL PROCESSES

- **Detailed level analysis of the radiative transitions as well as isotope effect studies have been performed.**

- **The reaction chemistries for the multi-level and the isotope studies are similar and are shown here:**



- **Ar is a buffer gas, and radiation exciting the phosphor is all due to the mercury transitions.**

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PAST TREATMENT OF RADIATION TRANSPORT

- Characterization of trapping is typically done using Holstein factors

  - $A \rightarrow A.g$,

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

    - $g = 1.115 / \sqrt{\pi k_0 R}$ (impact broadened)

    - $g = 1.60 / k_0 R \sqrt{\pi \ln(k_0 R)}$ (Doppler broadened)

    where k_0 is the absorption coefficient at line center.

- This method fails for more complex geometries, where the propogator 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 propogator functions.**

- **We have developed a Monte Carlo radiation transport model (MCRTM) for the radiative transitions of mercury.**

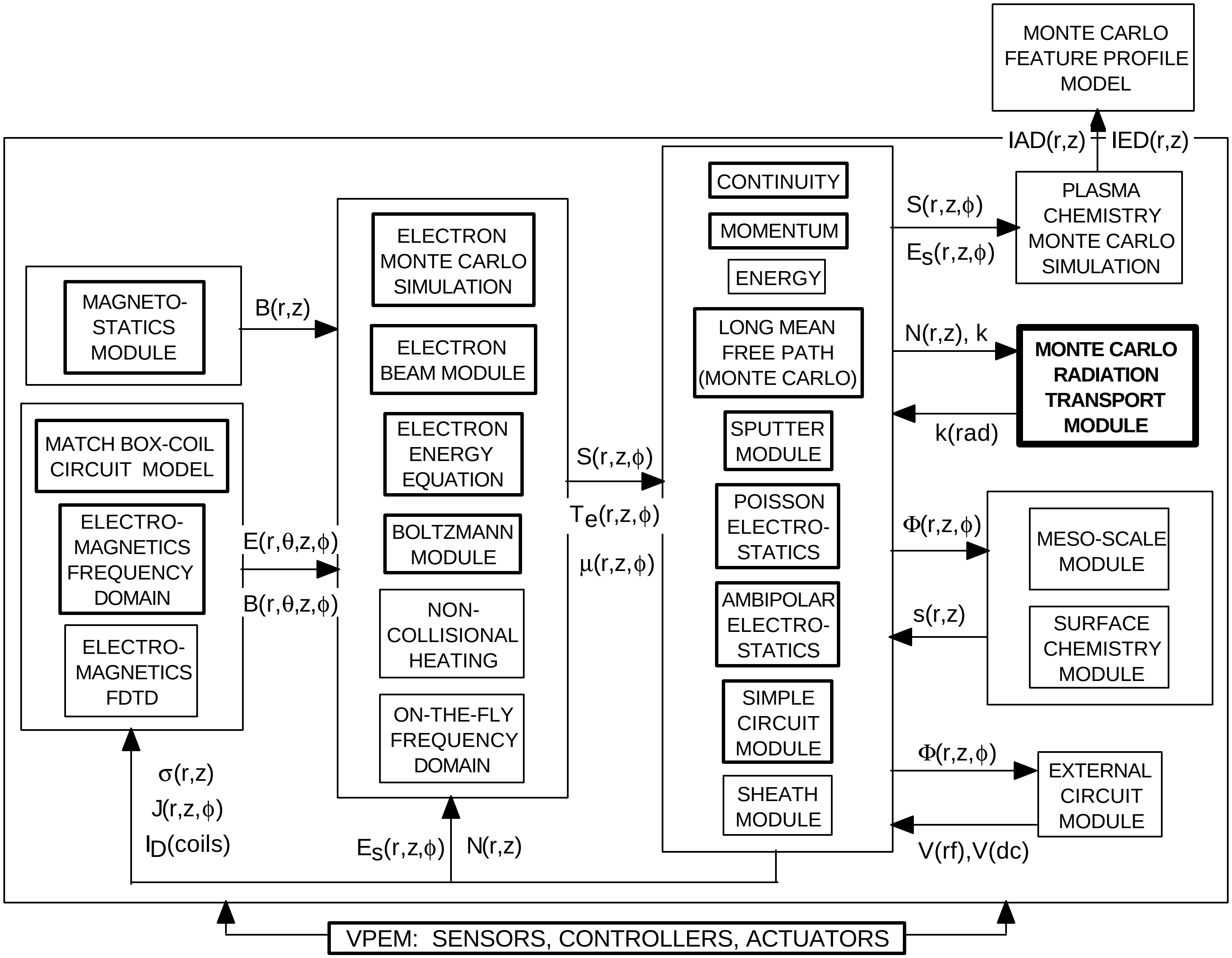
- **This model can be used to study isotope effects as well as multi-level transitions.**

- **The 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 account for evolution of gas densities, temperatures and other plasma parameters.**

- **To address this need, the MCRTM 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 RADIATION TRANSPORT MODEL (MCRTM)

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

- **The absorption/emission lineshape function is a Voigt profile.**

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

- **To avoid statistical errors, we uniformly choose the frequency of photons from a specified bandwidth and assign a weighting which accounts for the lineshape profile.**

- **The null collision method is employed for the photon transport.**

TRAPPING FACTOR AND PFR

- We define the trapping factor as

  $k = \tau_{res} / \tau_{nat}$,

  where τ_{res} is the average residence time of the photon in the plasma, and τ_{nat} is the natural lifetime of the excited state.

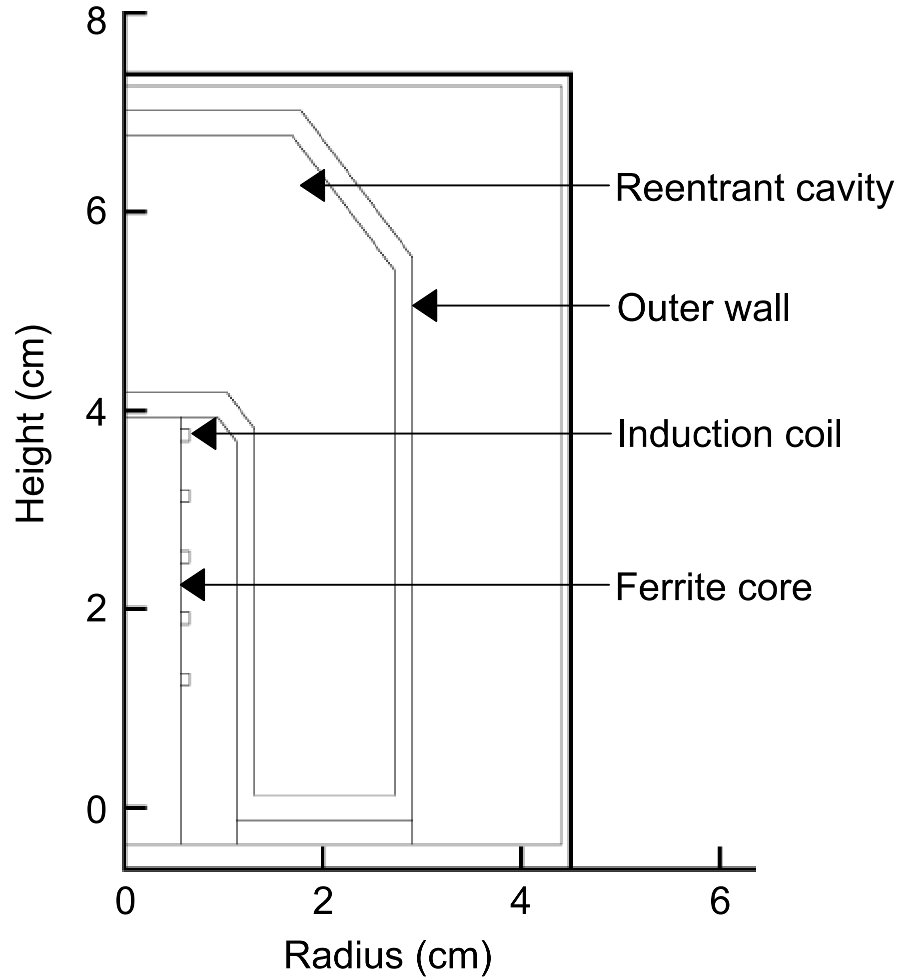
- After each absorbing collision at photon frequency ν, the partial frequency redistribution is incorporated by randomly choosing a new frequency within a range $\nu \pm \Delta\nu$.

- 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 simulation results with those found by Lister.

- The results agreed well for $\Delta\nu \approx \alpha \, \Delta\nu_d$, where α ranged from 1.5 to 2.0.

BASE CASE CONDITIONS

- **Diameter – 9 cm**
- **Height – 8 cm**
- **Depth – 5 cm**
- **Initial pressure – 500 mTorr**
- **Initial temperature – 400 K**
- **Operating power – 50 W**
- **Operating frequency – 2.65 Mhz**
- **Initial Ar mole fraction ≅ 0.98**
- **Initial Hg mole fraction (ground state) ≅ 0.02**
- **For the isotope study, the initial concentrations ≅ 95 : 5**



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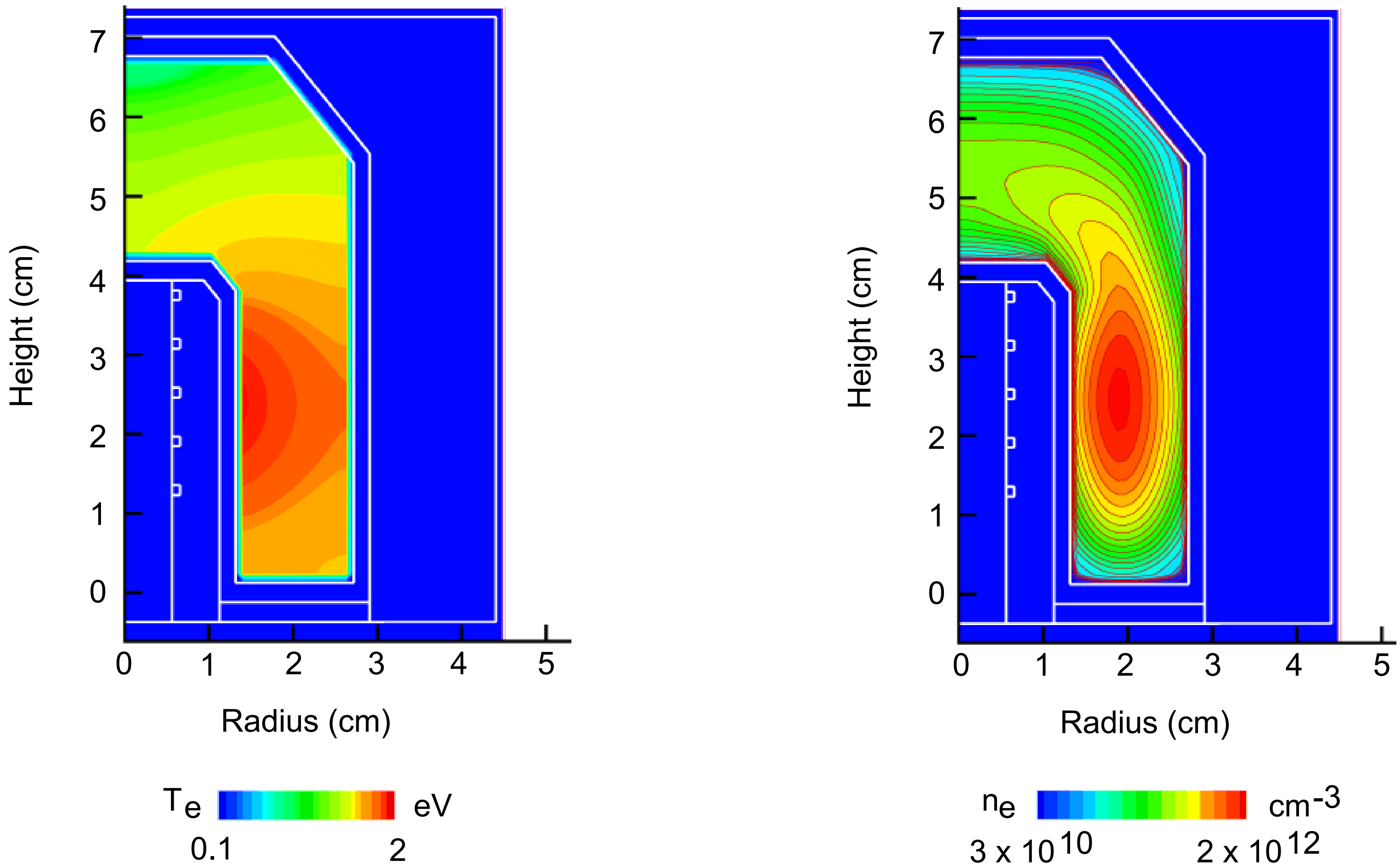
ELECTRON TEMPERATURE AND DENSITY

- **Peak electron temperature (≈ 2 eV) surrounds the reentrant coil resulting in a peak electron density in an annulus around the antenna.**



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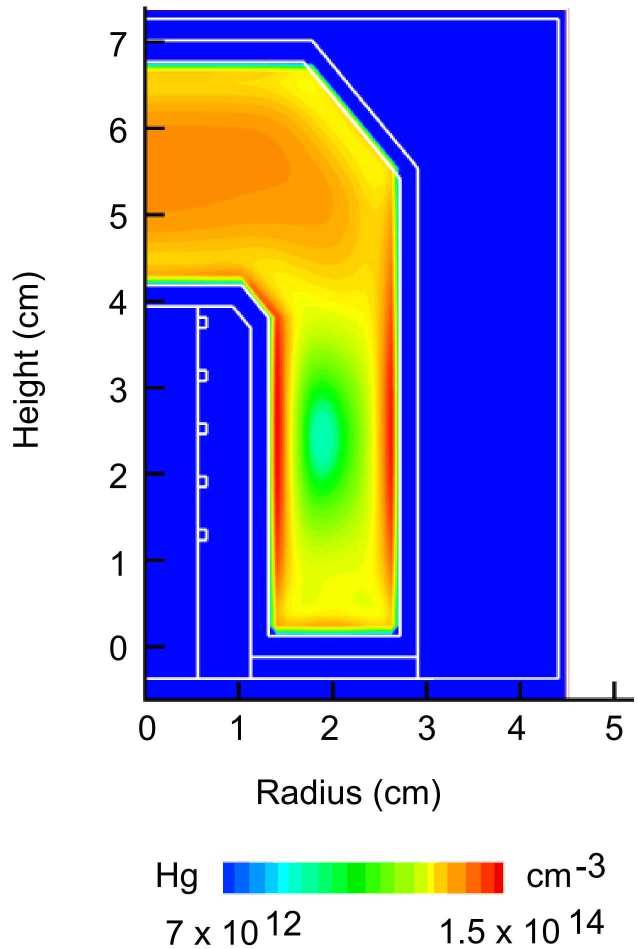
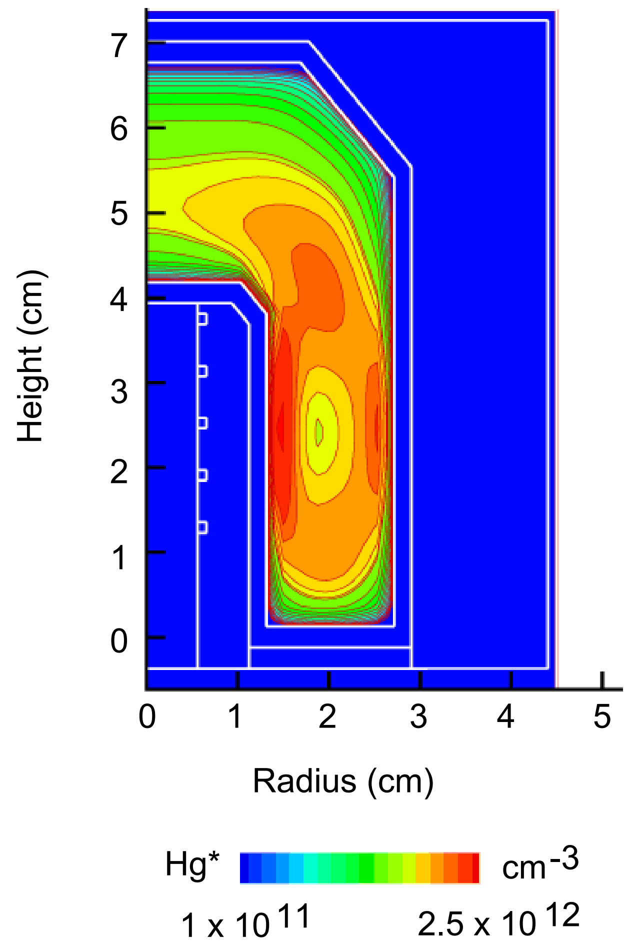
Hg GROUND AND EXCITED STATE DENSITIES

- **Cataphoresis and gas heating produce a maximum Hg density near the walls, which results in the maximum of Hg* density occurring towards and near the inner wall.**





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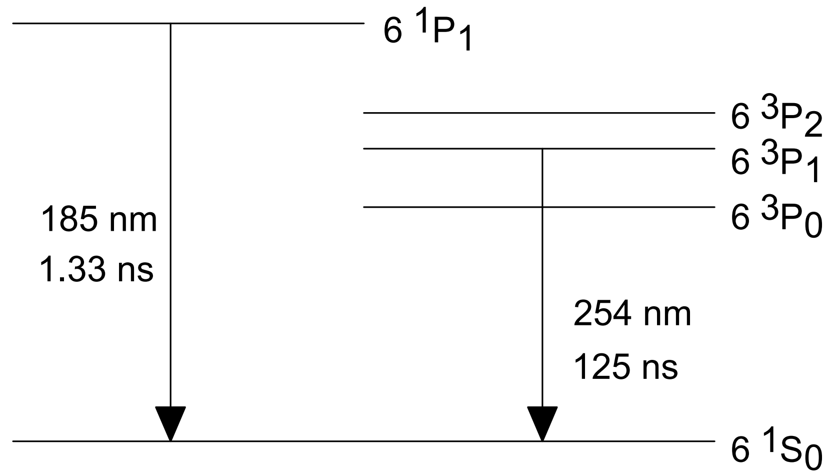
MULTI-LEVEL TRANSITIONS

- A study was made of the Hg (6^1P_1) $\rightarrow$ Hg (6^1S_0) transition at 185 nm as well as the Hg (6^3P_1) $\rightarrow$ Hg (6^1S_0) transition at 254 nm.

- The states Hg 6^1S_0, 6^3P_0, 6^3P_1, 6^3P_2, 6^1P_1, 6^3D_J, and 7^3S_1 were treated as separate species.

- As a result of different vacuum lifetimes, the photons are absorbed and reemitted many more times for the 185 nm transition before they leave the plasma, and the trapping factor goes up by as much as two orders of magnitude.



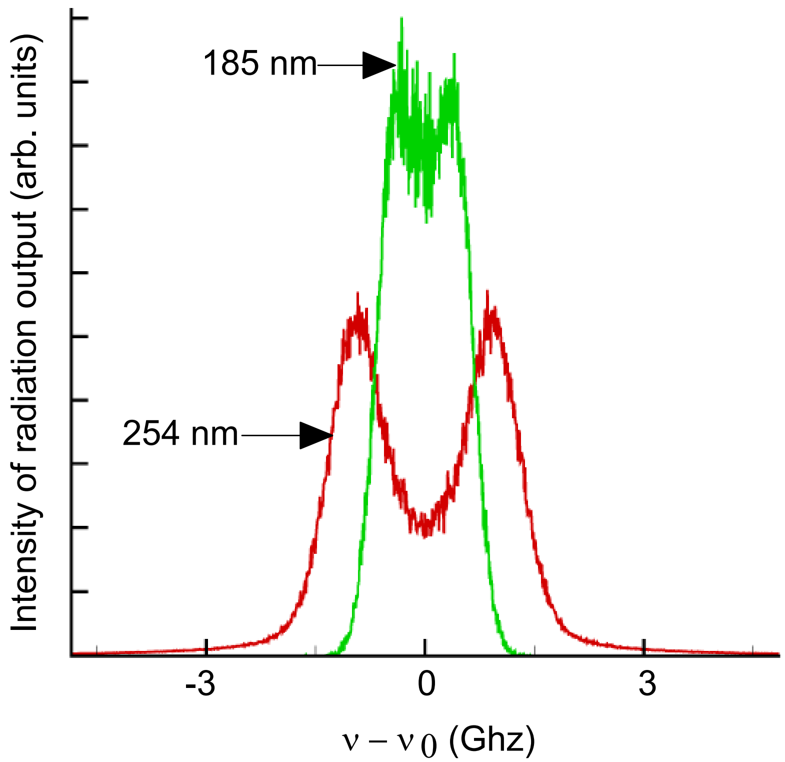
- This result agrees well with the Holstein formulation for a Doppler-broadened line in cylindrical geometry.

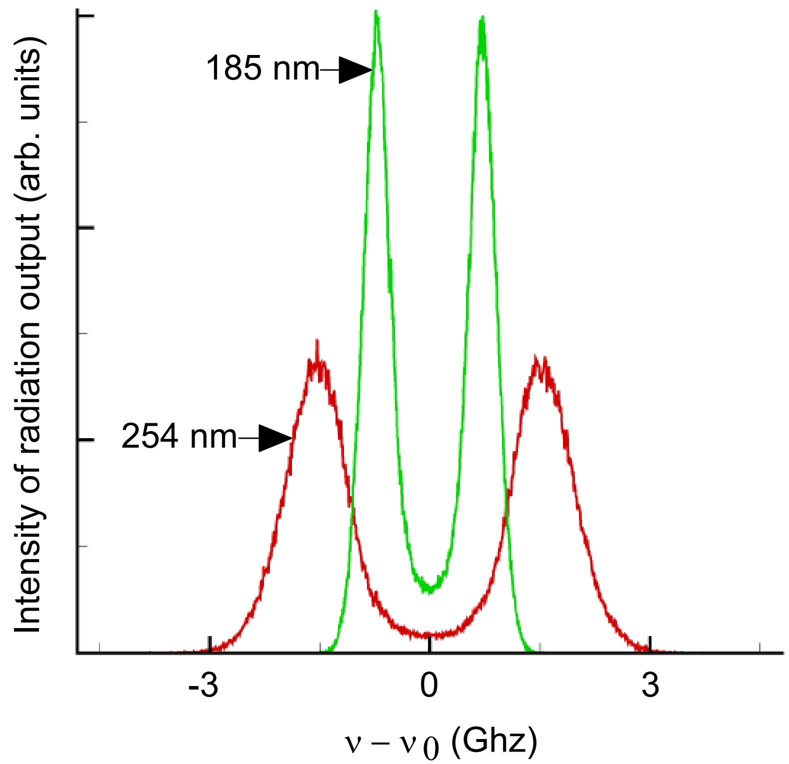
- $g \approx 1/k\sqrt{\ln(k)}$, where $k=\sigma N$, so for the same number density, the trapping factor scales inversely with vacuum lifetime.

EMISSION SPECTRA FOR MULTI-LEVEL STUDIES

- **The UV profile is line reversed near the center frequency, because most of the photons that escape are in the wings of the profile.**

- **An increase in ground state absorbers due to an increase in cold spot temperaure affects the 185 nm transition more than the 254 nm transition.**





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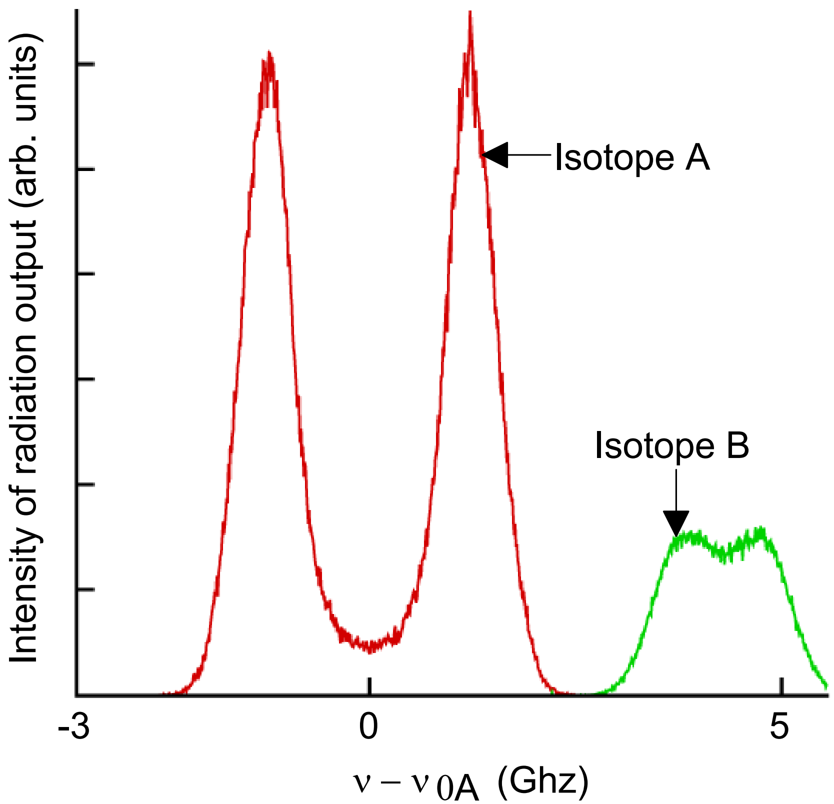
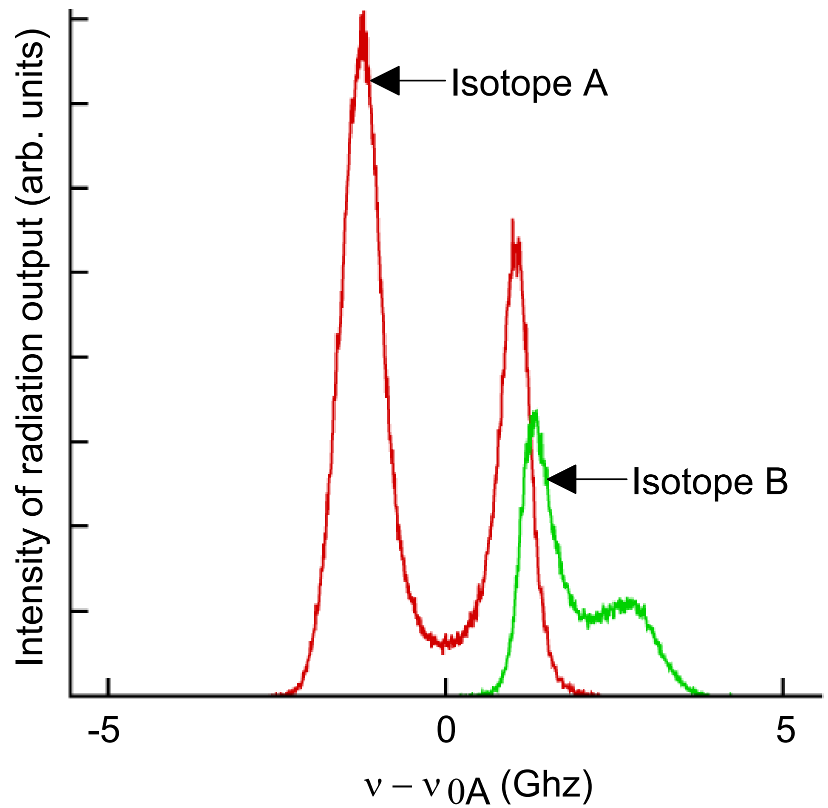
EMISSION SPECTRA FOR ISOTOPE STUDIES

- **At sufficiently large inter-isotope spacing, only self-trapping is seen.**
- **As the line centers converge, the photons can "spill" easily between isotopes, creating asymmetry in the shoulders of the UV profile.**





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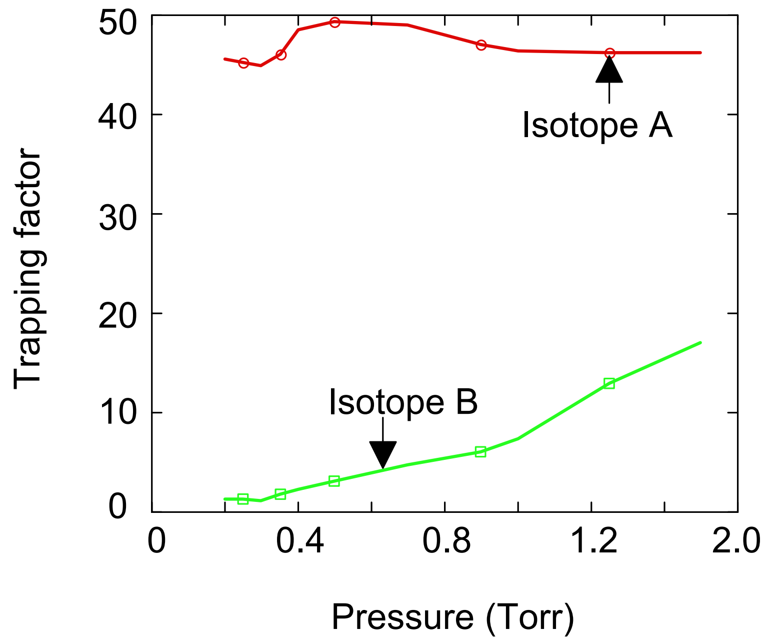
EFFECT OF PRESSURE ON TRAPPING FACTOR

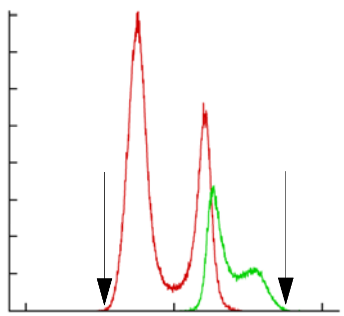
- **The pressure was increased keeping ground state densities and cold spot temperature constant, leading to a broadening of the line profiles.**

- **At first, the trapping factor goes up as the lineshapes begin to overlap.**



- **When pressure is increased further, the trapping factor for an isotope goes up or down depending on whether its self-trapping decreases slower or faster than the other isotope.**

- **This is because the photon escape paths are now limited to the wings of the combined profile.**



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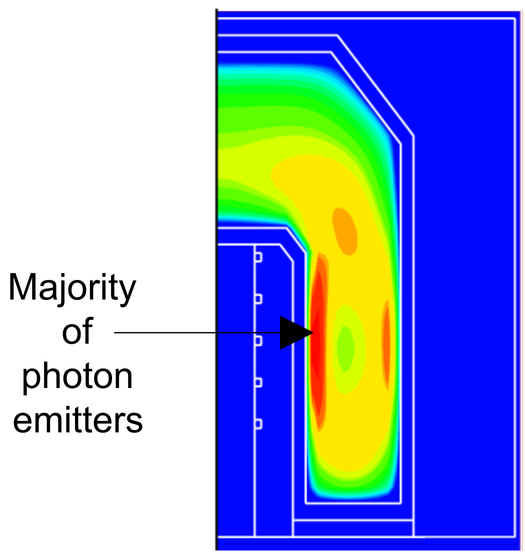
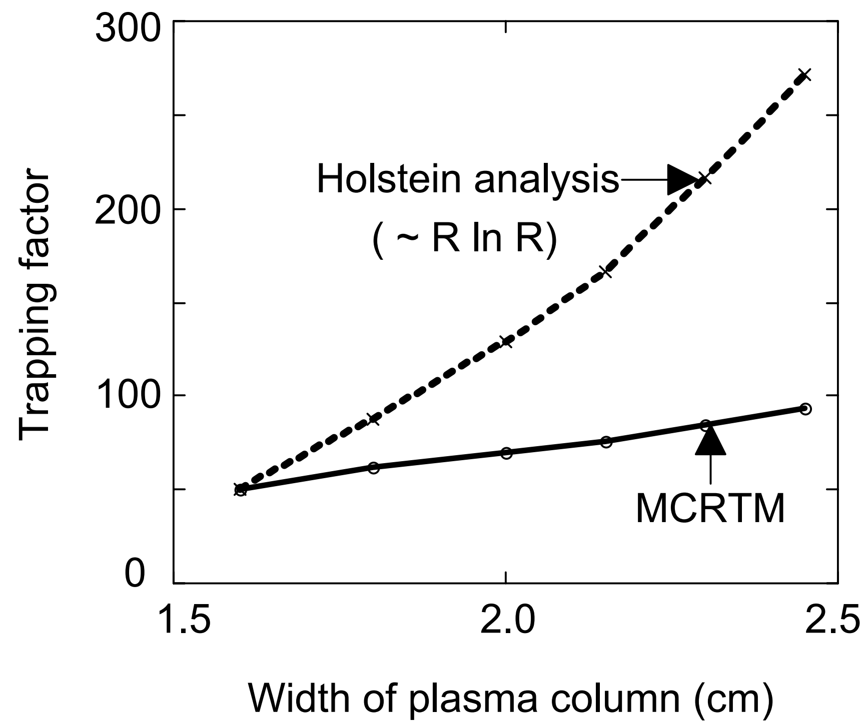
DEPENDENCE ON PLASMA GEOMETRY

- **The plasma volume was increased keeping other parameters constant.**

- **As the radius increases, the photons have to traverse a larger column of length of Hg before escaping the plasma.**

- **The average column length is much less than R, the radius of the discharge, which explains the difference of the MCRTM results from the Holstein result.**





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CONCLUSIONS

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

- It is seen that for similar number densities, the radiation trapping factor scales inversely with the vacuum radiative lifetime.

- The effect of pressure was investigated on isotopes which were optically thick. The trend of the trapping factor depends on the relative rate of fall-off of self-trapping for each isotope.

- Finally, we see that cataphoresis causes a non-uniform distribution of radiative absorbers and emitters, and scaling laws which apply to simpler density profiles are not valid in these lamps.