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

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*Work supported by Osram-Sylvania and the NSF

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 LAMPS AND TRAPPING

- **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.**

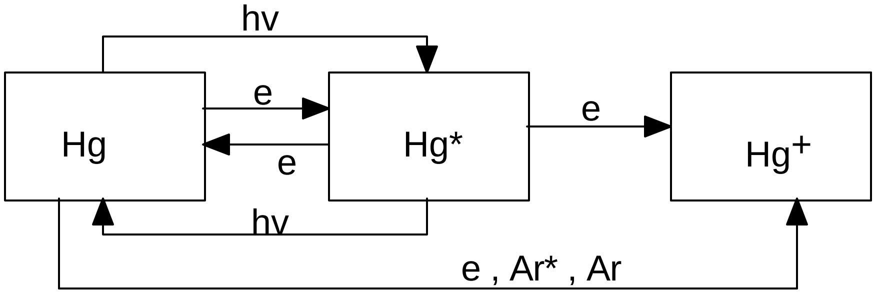
- **Resonance radiation, produced by electron impact excitation of Hg (6^1S_0) to Hg(6^3P_1), can be absorbed and reemitted many times prior to striking the phosphor.**

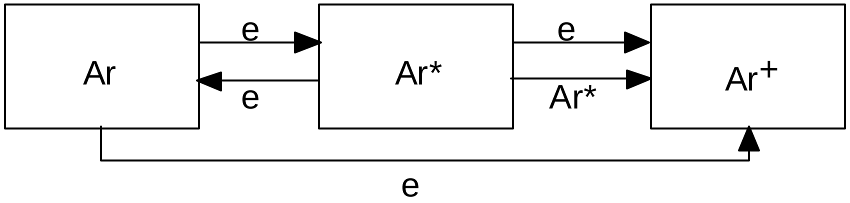
- **The consequence of radiation trapping is to lengthen the effective lifetime of emission as viewed from outside the lamp.**

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

PHYSICAL PROCESSES

- **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.**

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PAST TREATMENT OF RADIATION TRANSPORT

- Characterization of trapping is typically done using Holstein factors

  - $A \rightarrow A \cdot g$,

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

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

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

  where k is the lineshape profile.

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

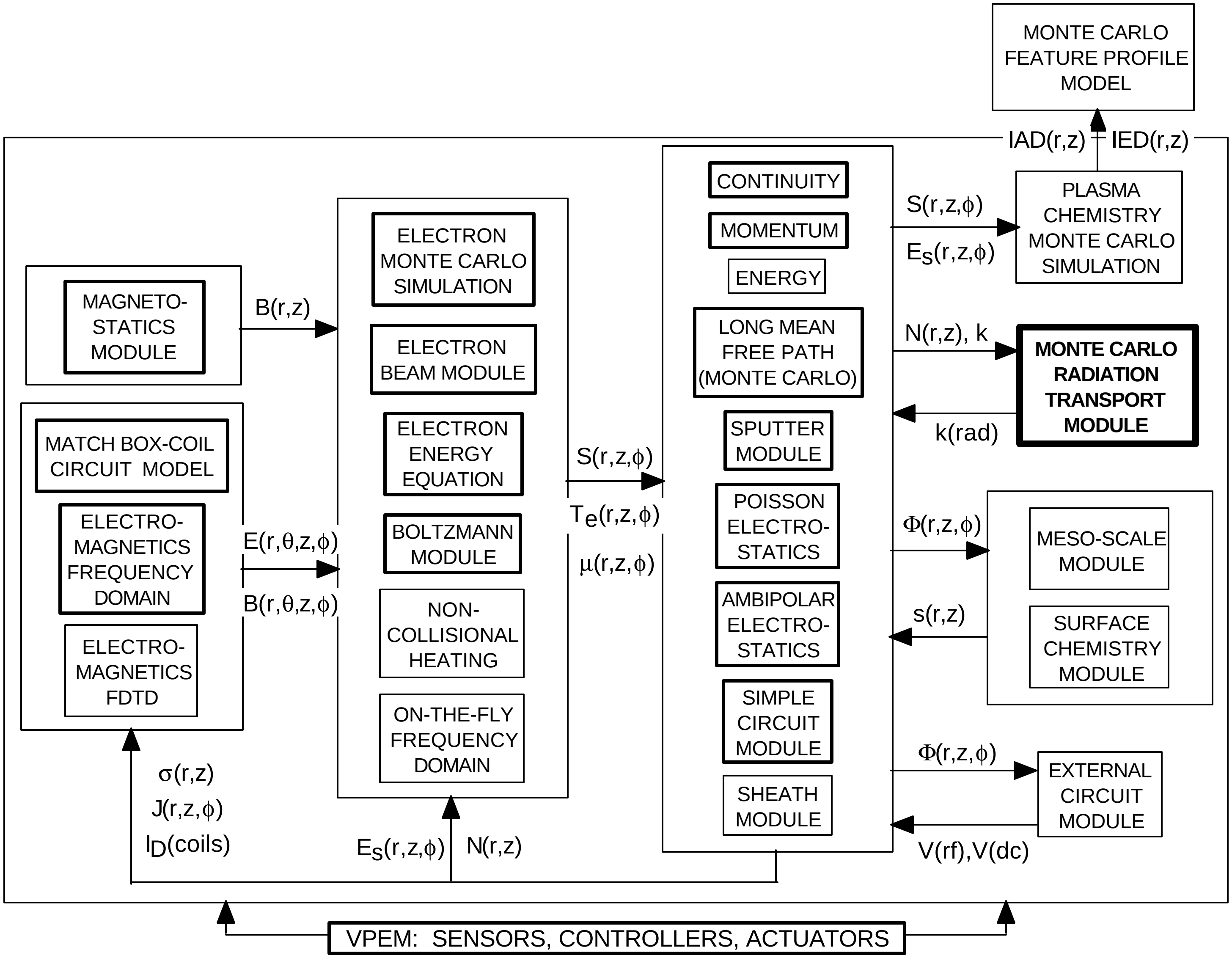
- **We have developed a Monte Carlo resonance radiation transport model for the trapping of the 254 nm radiative transition for mercury.**

- **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



MONTE CARLO FEATURE PROFILE MODEL

IAD(r,z) IED(r,z)

MAGNETO-STATICS MODULE

B(r,z)

MATCH BOX-COIL CIRCUIT MODEL

ELECTRO-MAGNETICS FREQUENCY DOMAIN

ELECTRO-MAGNETICS FDTD

$E(r,\theta,z,\phi)$

$B(r,\theta,z,\phi)$

ELECTRON MONTE CARLO SIMULATION

ELECTRON BEAM MODULE

ELECTRON ENERGY EQUATION

BOLTZMANN MODULE

NON-COLLISIONAL HEATING

ON-THE-FLY FREQUENCY DOMAIN

$S(r,z,\phi)$

$T_e(r,z,\phi)$

$\mu(r,z,\phi)$

CONTINUITY

MOMENTUM

ENERGY

LONG MEAN FREE PATH (MONTE CARLO)

SPUTTER MODULE

POISSON ELECTRO-STATICS

AMBIPOLAR ELECTRO-STATICS

SIMPLE CIRCUIT MODULE

SHEATH MODULE

$S(r,z,\phi)$

$E_S(r,z,\phi)$

PLASMA CHEMISTRY MONTE CARLO SIMULATION

N(r,z), k

MONTE CARLO RADIATION TRANSPORT MODULE

k(rad)

$\Phi(r,z,\phi)$

s(r,z)

MESO-SCALE MODULE

SURFACE CHEMISTRY MODULE

$\Phi(r,z,\phi)$

EXTERNAL CIRCUIT MODULE

V(rf),V(dc)

$\sigma(r,z)$

$J(r,z,\phi)$

I_D(coils)

$E_S(r,z,\phi)$ N(r,z)

VPEM: SENSORS, CONTROLLERS, ACTUATORS

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 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.**

TRAPPING FACTOR AND PFR

- We define the trapping factor as

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

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 $\nu \pm \Delta\nu$.

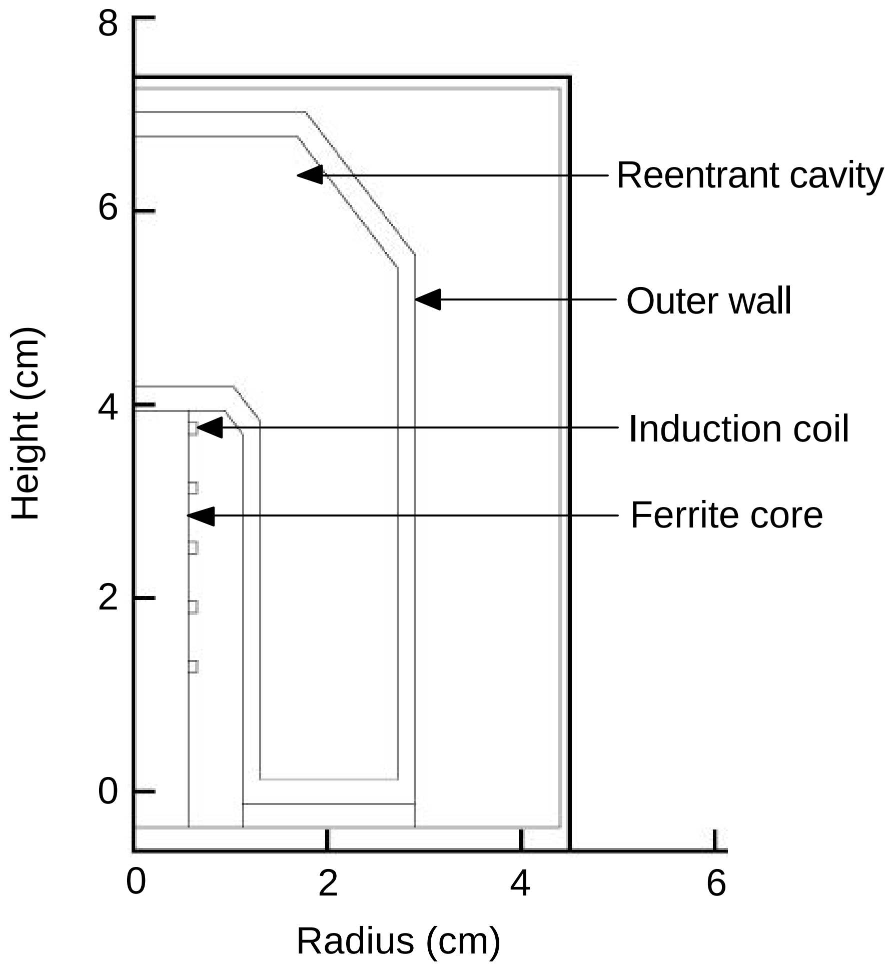
- The value of $\Delta\nu$ was found by simulating trapping in a cylindrical discharge with a uniform density of Ar and Hg atoms, and comparing the results with those found by Lister.

- The results agreed well for $\Delta\nu \approx \alpha\,\Delta\nu_d$, where α ranged from 1.75 to 2.0.

BASE CASE CONDITIONS

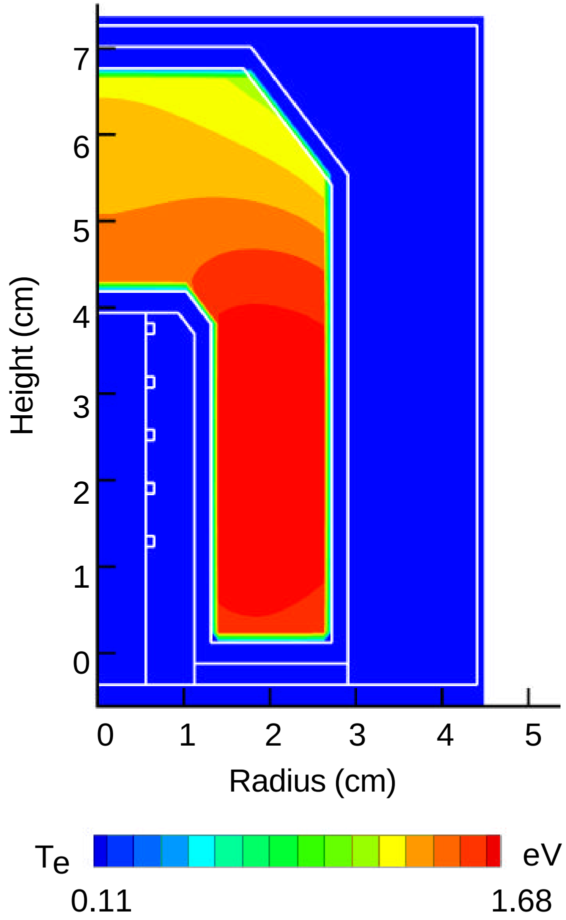
- **Diameter – 9 cm**
- **Depth – 5 cm**
- **Height – 8 cm**
- **Initial pressure – 250 mTorr**
- **Initial temperature – 400 K**
- **Operating power – 50 W**
- **Operating frequency – 2.65 Mhz**
- **Initial Ar mole fraction- 0.98**
- **Initial Hg mole fraction – 0.02**
- **Only 254 nm resonance line has been studied.**

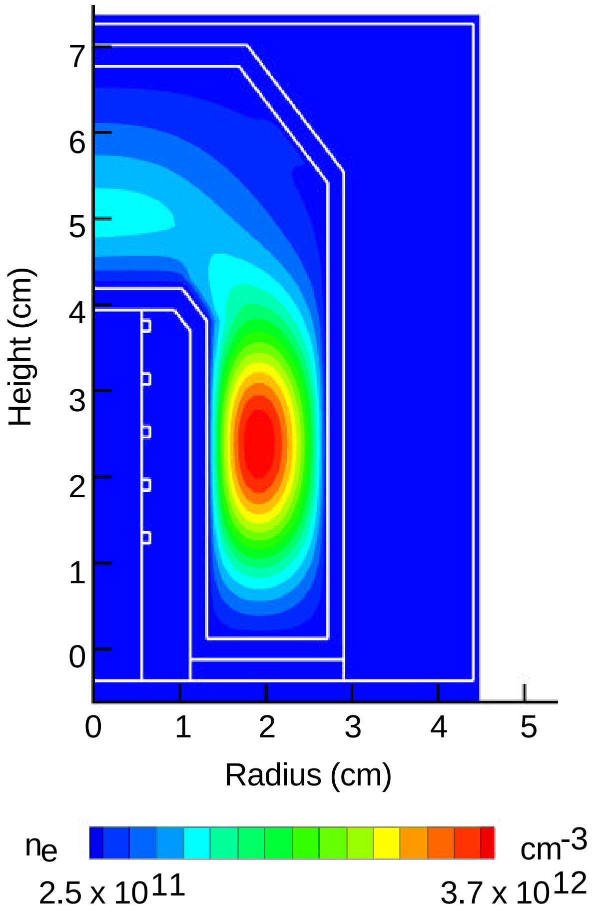
- **The trapping factor for these conditions is »40**



ELECTRON DENSITY AND TEMPERATURE

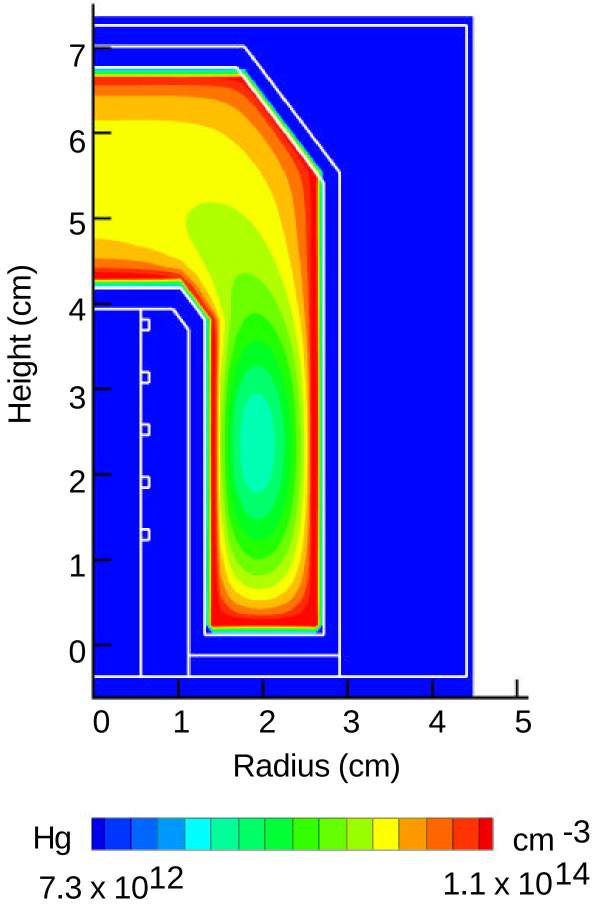
- **Peak electron temperature (» 2 eV) surrounds the reentrant coil resulting in a peak plasma density in an annulus around the antenna.**

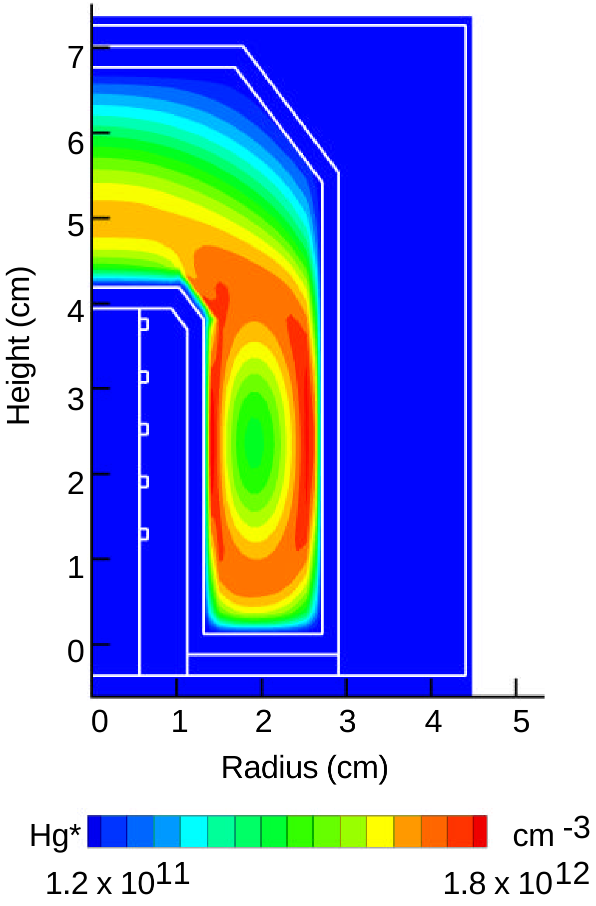




Hg GROUND AND EXCITED STATE DENSITIES

- **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.**



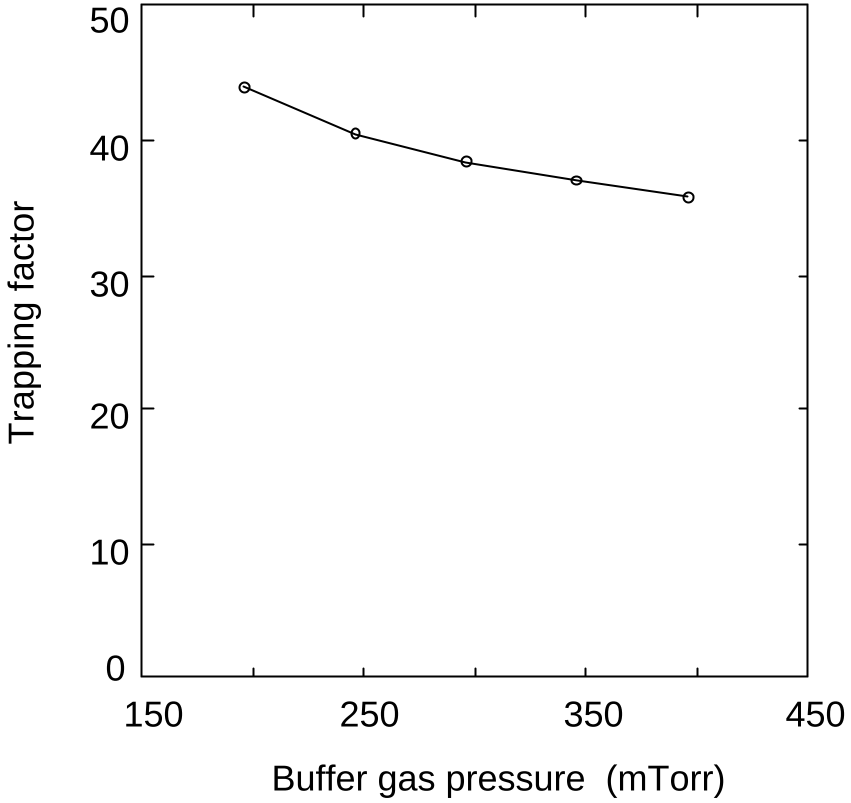


DEPENDENCE ON Ar PRESSURE

- **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.**

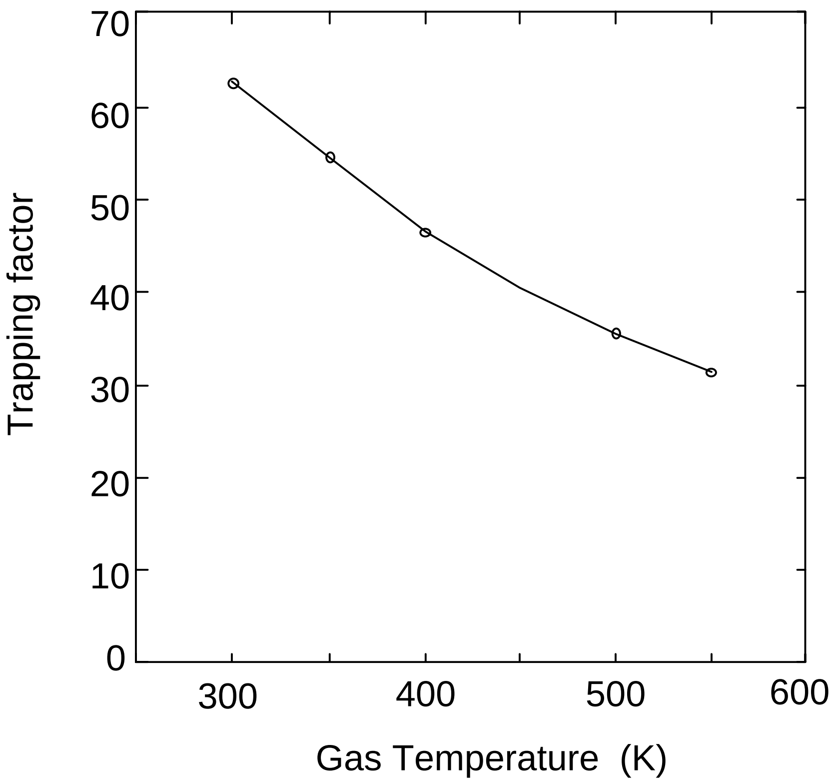


DEPENDENCE ON GAS TEMPERATURE

- **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.**

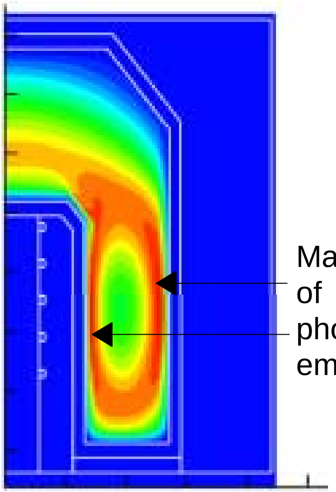


DEPENDENCE ON PLASMA GEOMETRY

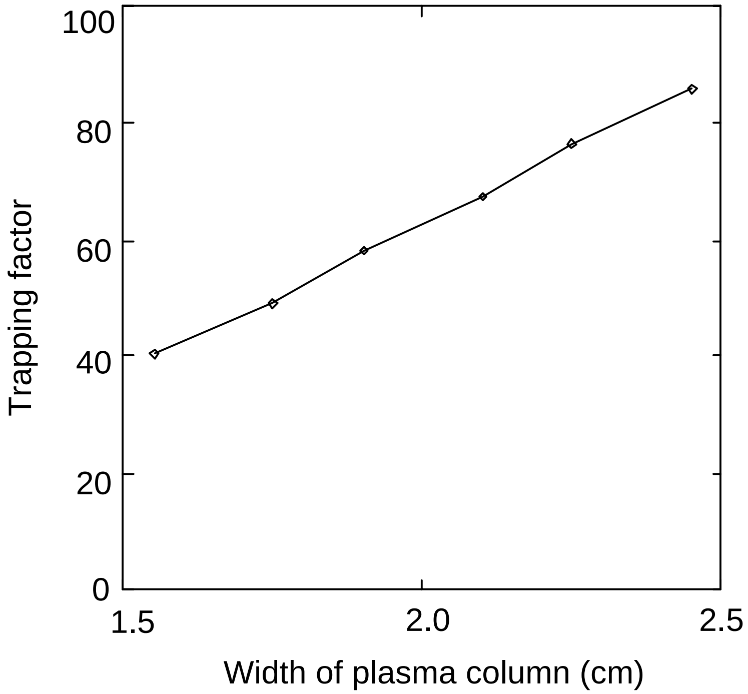
- **The plasma volume was increased by increasing the outer radius of the lamp and other parameters are constant.**

- **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 ($g \sim R \ln(R)$).**

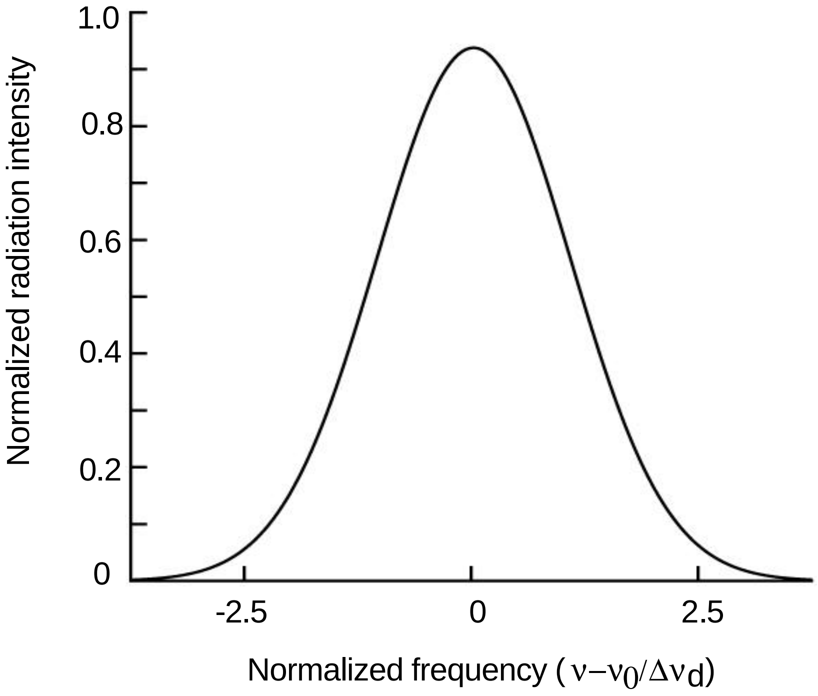


Majority of photon emitters

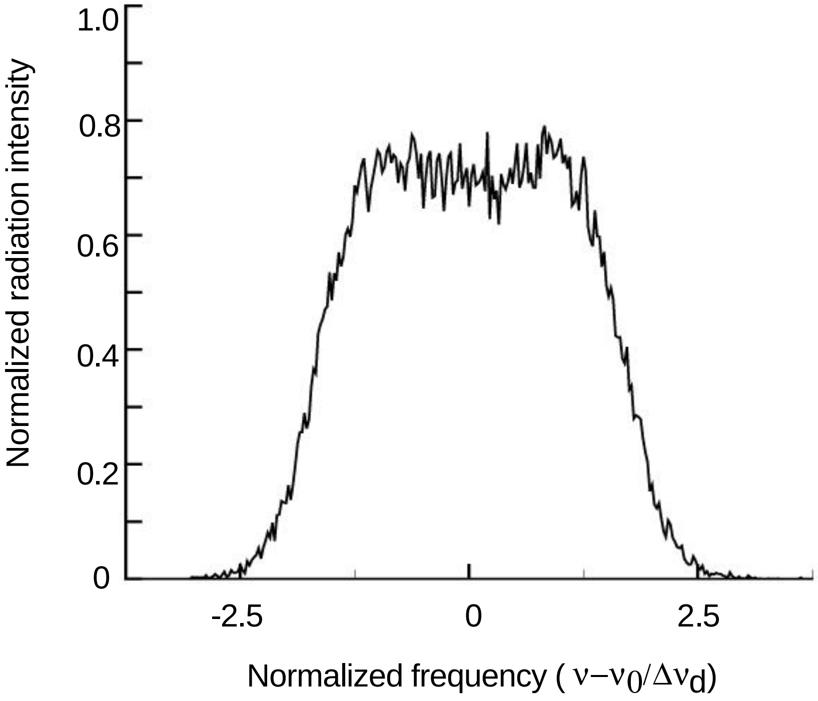


EMISSION SPECTRA

- **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.**



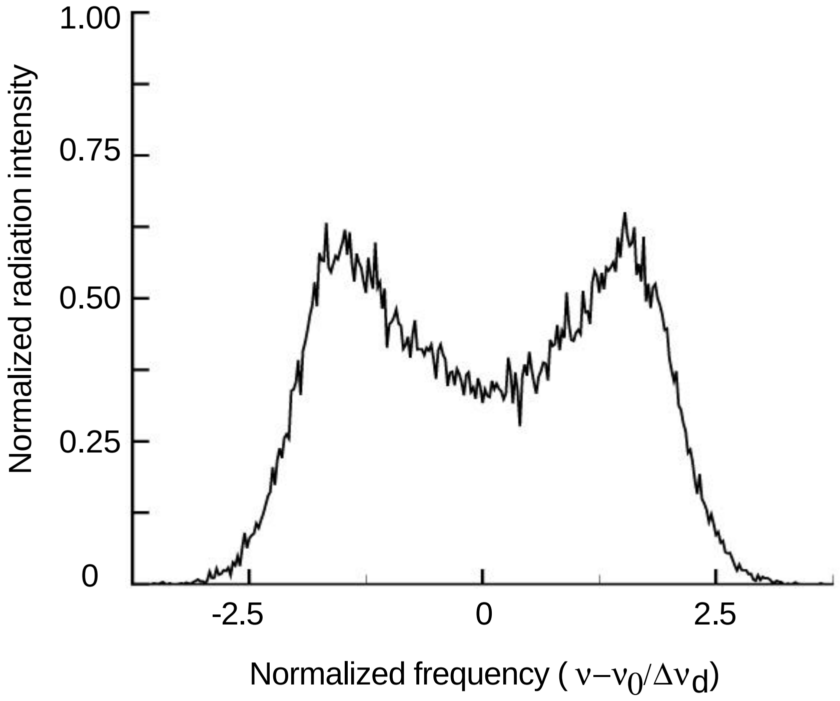
- **No trapping**



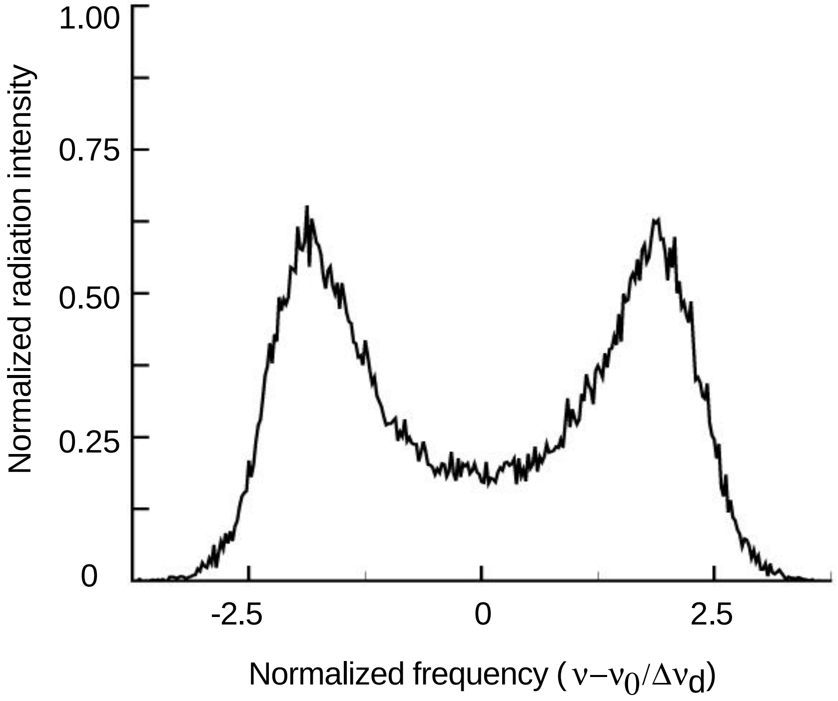
- **With trapping (base case)**

EMISSION SPECTRA (contd.)

- **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_1) ® Hg (6^1S_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.**