Electrodeless Lamp

Introduction

This model simulates an electrodeless lamp with argon/mercury chemistry. The low excitation threshold for mercury atoms means that even though the mercury is present in small concentrations, its interaction with electrons determines the overall discharge characteristics. here is strong UV emission from the plasma at 185 nm and 253 nm stemming from spontaneous decay of electronically excited mercury atoms. The UV emission can stimulate phosphors coated on the surface of the bulb resulting in visible light. From an electrical point of view, the lamp can be thought of as a transformer, where the coil acts as the primary and the plasma acts as the secondary. If the efficiency of discharge lamps could be increased by 1%, it would result in a saving of 10^9 kWh per year worldwide.

Note: This model requires the Plasma and AC/DC Modules.

Model Definition

A schematic of the geometry used to solve the problem is given in Figure 1. A sinusoidal current is applied to the copper coil (green) which creates a magnetic field in the ferrite core (gray). When the plasma ignites, a magnetic circuit is created between the ferrite core and the plasma. The free electrons in the plasma bulk are accelerated by the electric field. This leads to creation of new electrons through

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ionization which sustains the plasma. In quasi steady-state, the creation of new electrons is balanced by the loss of electrons to the wall.

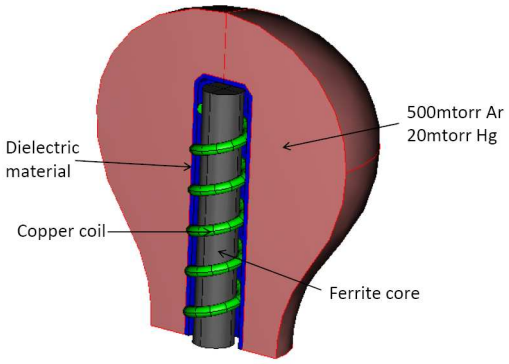

Figure 1: Diagram of electrodeless light source.

The presence of mercury leads to the formation of electronically excited mercury atoms. Certain excited states will emit a photon at a given wavelength with a certain emission frequency. By solving for the number density of each of the excited species, you can determine the amount of energy channeled into creating the excited mercury atoms. You can then calculate the amount of energy emitted from the plasma as photons.

In order to simplify the analysis, the following assumptions are made:

- The model is assumed to be axially symmetric.
- The AC induction currents are solved in the frequency domain.
- The electron energy distribution function (EEDF) is assumed to be Maxwellian.
- Thermal quenching of excited atoms is not considered.
- Energy losses in the ferrite core are not considered.
- A trapping factor is used to specify an effective emission photon frequency for the excited mercury atoms. These trapping factors are based on published data.
- The electronically excited argon species are lumped into a single species.

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PLASMA CHEMISTRY

The chemical mechanism comes from Ref. 1 and consists of 11 species and 96 reactions:

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
1	e+Ar=>e+Ar	Momentum	0
2	e+Ar=>e+Ar*	Excitation	11.56
3	e+Ar=>e+e+Ar^+	Ionization	15.80
4	e+Ar*=>e+Ar	Superelastic	-11.56
5	e+Ar*=>e+e+Ar^+	Ionization	4.24
6	e+Hg=>e+Hg	Momentum	0
7	e+Hg=>e+Hg(63P0)	Excitation	4.66
8	e+Hg=>e+Hg(63P1)	Excitation	4.87
9	e+Hg=>e+Hg(63P2)	Excitation	5.43
10	e+Hg=>e+Hg(61P1)	Excitation	6.70
11	e+Hg=>e+Hg(73S1)	Excitation	7.70
12	e+Hg=>e+Hg(63DJ)	Excitation	8.85
13	e+Hg=>e+e+Hg^+	Ionization	10.44
14	e+Hg(63P0)=>e+Hg(63P0)	Momentum	0
15	e+Hg(63P0)=>e+Hg	Superelastic	-4.66
16	e+Hg(63P0)=>e+Hg(63P1)	Excitation	0.21
17	e+Hg(63P0)=>e+Hg(63P2)	Excitation	0.77
18	e+Hg(63P0)=>e+Hg(61P1)	Excitation	2.04
19	e+Hg(63P0)=>e+Hg(73S1)	Excitation	3.04
20	e+Hg(63P0)=>e+Hg(63DJ)	Excitation	4.18
21	e+Hg(63P0)=>e+e+Hg^+	Ionization	5.78
22	e+Hg(63P1)=>e+Hg(63P1)	Momentum	0
23	e+Hg(63P1)=>e+Hg	Superelastic	-4.87
24	e+Hg(63P1)=>e+Hg(63P0)	Superelastic	-0.21
25	e+Hg(63P1)=>e+Hg(63P2)	Excitation	0.56
26	e+Hg(63P1)=>e+Hg(61P1)	Excitation	1.83
27	e+Hg(63P1)=>e+Hg(73S1)	Excitation	2.83
28	e+Hg(63P1)=>e+Hg(63DJ)	Excitation	3.98

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TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon(\mathrm{eV})$
29	e+Hg(63P1)=>e+e+Hg^+	Ionization	5.57
30	e+Hg(63P2)=>e+Hg(63P2)	Momentum	0
31	e+Hg(63P2)=>e+Hg	Superelastic	-5.43
32	e+Hg(63P2)=>e+Hg(63P0)	Superelastic	-0.77
33	e+Hg(63P2)=>e+Hg(63P1)	Superelastic	-0.56
34	e+Hg(63P2)=>e+Hg(61P1)	Excitation	1.27
35	e+Hg(63P2)=>e+Hg(73S1)	Excitation	2.27
36	e+Hg(63P2)=>e+Hg(63DJ)	Excitation	3.42
37	e+Hg(63P2)=>e+e+Hg^+	Ionization	5.01
38	e+Hg(61P1)=>e+Hg(61P1)	Momentum	0
39	e+Hg(61P1)=>e+Hg	Superelastic	-6.7
40	e+Hg(61P1)=>e+Hg(63P0)	Superelastic	-2.04
41	e+Hg(61P1)=>e+Hg(63P1)	Superelastic	-1.83
42	e+Hg(61P1)=>e+Hg(63P2)	Superelastic	-1.27
43	e+Hg(61P1)=>e+e+Hg^+	Ionization	3.74
44	e+Hg(73S1)=>e+Hg(73S1)	Momentum	0
45	e+Hg(73S1)=>e+Hg	Superelastic	-7.7
46	e+Hg(73S1)=>e+Hg(63P0)	Superelastic	-3.04
47	e+Hg(73S1)=>e+Hg(63P1)	Superelastic	-2.83
48	e+Hg(73S1)=>e+Hg(63P2)	Superelastic	-2.27
49	e+Hg(73S1)=>e+e+Hg^+	Ionization	2.74
50	e+Hg(63DJ)=>e+Hg(63DJ)	Momentum	0
51	e+Hg(63DJ)=>e+Hg	Superelastic	-8.85
52	e+Hg(63DJ)=>e+Hg(63P0)	Superelastic	-4.19
53	e+Hg(63DJ)=>e+Hg(63P1)	Superelastic	-3.98
54	e+Hg(63DJ)=>e+Hg(63P2)	Superelastic	-3.42
55	e+Hg(63DJ)=>e+e+Hg^+	Ionization	1.59
56	Ar*+Ar*=>e+Ar+Ar^+	Penning	0
57	Ar*+Hg=>e+Ar+Hg^+	Penning	0
58	Ar*+Hg(63P0)=>e+Ar+Hg^+	Penning	0
59	Ar*+Hg(63P1)=>e+Ar+Hg^+	Penning	0

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TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon(eV)$
60	Ar*+Hg(63P2)=>e+Ar+Hg^+	Penning	0
61	Ar*+Hg(61P1)=>e+Ar+Hg^+	Penning	0
62	Ar*+Hg(73S1)=>e+Ar+Hg^+	Penning	0
63	Ar*+Hg(63DJ)=>e+Ar+Hg^+	Penning	0
64	Hg(63P2)+Hg(63P2)=>e+Hg+Hg^+	Penning	0
65	Hg(63P2)+Hg(63P1)=>e+Hg+Hg^+	Penning	0
66	Hg(63P2)+Hg(73S1)=>e+Hg+Hg^+	Penning	0
67	Hg(63P2)+Hg(63DJ)=>e+Hg+Hg^+	Penning	0
68	Hg(61P1)+Hg(63P0)=>e+Hg+Hg^+	Penning	0
69	Hg(61P1)+Hg(63P1)=>e+Hg+Hg^+	Penning	0
70	Hg(61P1)+Hg(63P2)=>e+Hg+Hg^+	Penning	0
71	Hg(61P1)+Hg(61P1)=>e+Hg+Hg^+	Penning	0
72	Hg(61P1)+Hg(73S1)=>e+Hg+Hg^+	Penning	0
73	Hg(61P1)+Hg(63DJ)=>e+Hg+Hg^+	Penning	0
74	Hg(73S1)+Hg(63P0)=>e+Hg+Hg^+	Penning	0
75	Hg(73S1)+Hg(63P1)=>e+Hg+Hg^+	Penning	0
76	Hg(73S1)+Hg(63P2)=>e+Hg+Hg^+	Penning	0
77	Hg(73S1)+Hg(61P1)=>e+Hg+Hg^+	Penning	0
78	Hg(73S1)+Hg(73S1)=>e+Hg+Hg^+	Penning	0
79	Hg(73S1)+Hg(63DJ)=>e+Hg+Hg^+	Penning	0
80	Hg(63DJ)+Hg(63P0)=>e+Hg+Hg^+	Penning	0
81	Hg(63DJ)+Hg(63P1)=>e+Hg+Hg^+	Penning	0
82	Hg(63DJ)+Hg(63P2)=>e+Hg+Hg^+	Penning	0
83	Hg(63DJ)+Hg(61P1)=>e+Hg+Hg^+	Penning	0
84	Hg(63DJ)+Hg(73S1)=>e+Hg+Hg^+	Penning	0
85	Hg(63DJ)+Hg(63DJ)=>e+Hg+Hg^+	Penning	0
86	Ar^++Hg=>Hg^++Ar	Charge exchange	0
87	Ar^++Ar=>Ar+Ar^+	Charge exchange	0
88	Hg^++Hg=>Hg+Hg^+	Charge exchange	0
89	Hg(63P1)=>Hg	253nm	0
90	Hg(61P1)=>Hg	185nm	0

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
91	Hg(73S1)=>Hg(63P0)	405nm	0
92	Hg(73S1)=>Hg(63P1)	436nm	0
93	Hg(73S1)=>Hg(63P2)	546nm	0
94	Hg(63DJ)=>Hg(63P0)	297nm	0
95	Hg(63DJ)=>Hg(63P1)	-	0
96	Hg(63DJ)=>Hg(63P2)	365nm	0

The following surface reactions are considered:

TABLE 2: SURFACE REACTIONS.

REACTION	FORMULA
1	Ars=>Ar
2	Ar+=>Ar
3	Hg1=>Hg
4	Hg2=>Hg
5	Hg3=>Hg
6	Hg4=>Hg
7	Hg5=>Hg
8	Hg6=>Hg
9	Hg+=>Hg

DOMAIN EQUATIONS

The electron density and mean electron energy are computed by solving a pair of drift-diffusion equations for the electron density and mean electron energy. Convection of electrons due to fluid motion is neglected. For detailed information on electron transport see Theory for the Drift Diffusion User Interface in the *Plasma Module User's Guide*.

$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot [-n_e(\boldsymbol{\mu}_e \bullet \mathbf{E}) - \mathbf{D}_e \bullet \nabla n_e] = R_e$$

$$\frac{\partial}{\partial t}(n_\varepsilon) + \nabla \cdot [-n_\varepsilon(\boldsymbol{\mu}_\varepsilon \bullet \mathbf{E}) - \mathbf{D}_\varepsilon \bullet \nabla n_\varepsilon] + \mathbf{E} \cdot \boldsymbol{\Gamma}_e = R_\varepsilon$$

The electron source R_e and the energy loss due to inelastic collisions R_ε are defined later. The electron diffusivity, energy mobility, and energy diffusivity are computed from the electron mobility using:

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$$\mathbf{D}_e = \boldsymbol{\mu}_e T_e, \boldsymbol{\mu}_\varepsilon = \left(\frac{5}{3}\right)\boldsymbol{\mu}_e, \mathbf{D}_\varepsilon = \boldsymbol{\mu}_\varepsilon T_e$$

The source coefficients in the above equations are determined by the plasma chemistry using rate coefficients. Suppose that there are M reactions that contribute to the growth or decay of electron density and P inelastic electron-neutral collisions. In general $P >> M$. In the case of rate coefficients, the electron source term is given by:

$$R_e = \sum_{j=1}^{M} x_j k_j N_n n_e$$

where x_j is the mole fraction of the target species for reaction j, k_j is the rate coefficient for reaction j (SI unit: m^3/s), and N_n is the total neutral number density (SI unit: $1/\mathrm{m}^3$). The electron energy loss is obtained by summing the collisional energy loss over all reactions:

$$R_\varepsilon = \sum_{j=1}^{P} x_j k_j N_n n_e \Delta\varepsilon_j$$

where $\Delta\varepsilon_j$ is the energy loss from reaction j (SI unit: V). The rate coefficients can be computed from cross section data by the following integral:

$$k_k = \gamma \int_0^\infty \varepsilon \sigma_k(\varepsilon) f(\varepsilon) d\varepsilon$$

where $\gamma = (2q/m_e)^{1/2}$ (SI unit: $\mathrm{C}^{1/2}/\mathrm{kg}^{1/2}$), m_e is the electron mass (SI unit: kg), ε is energy (SI unit: V), σ_k is the collision cross section (SI unit: m^2), and f is the electron energy distribution function. In this case a Maxwellian EEDF is assumed.

For non-electron species, the following equation is solved for the mass fraction of each species. For detailed information on the transport of the non-electron species see Theory for the Heavy Species Transport User Interface in the *Plasma Module User's Guide*.

$$\rho \frac{\partial}{\partial t}(w_k) + \rho(\mathbf{u} \cdot \nabla) w_k = \nabla \cdot \mathbf{j}_k + R_k$$

The electrostatic field is computed using the following equation:

$$-\nabla \cdot \varepsilon_0 \varepsilon_r \nabla V = \rho$$

The space charge density ρ is automatically computed based on the plasma chemistry specified in the model using the formula:

$$\rho = q\left(\sum_{k=1}^{N} Z_k n_k - n_e\right)$$

For detailed information about electrostatics see Theory for the Electrostatics User Interface in the *Plasma Module User's Guide*.

For a nonmagnetized and nonpolarized plasma, the induction currents are computed in the frequency domain using the following equation:

$$(j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1}\nabla \times \mathbf{A}) = \mathbf{J}^e \quad (1)$$

The plasma conductivity needs to be specified as a material property, usually from the cold plasma approximation:

$$\sigma = \frac{n_e q^2}{m_e(\nu_e + j\omega)} \quad (2)$$

where n_e is the electron density, q is the electron charge, m_e is the electron mass, ν_e is the collision frequency and ω is the angular frequency.

ELECTRICAL EXCITATION

The lamp is operated by a fixed power of 80 watts. This means that the total power dissipation in the system is 80 W. Some of the power is lost in the coil and the ferrite but the bulk of the power is channeled into the plasma.

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Results and Discussion

The results are presented below.

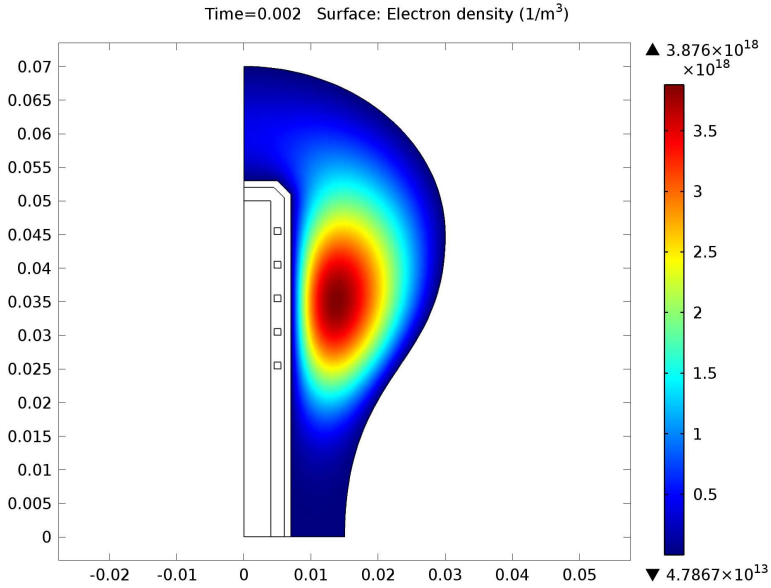

Figure 2: Surface plot of electron density inside the column.

The electron density is plotted in Figure 2. The electron density is high, as one would expect in an inductively coupled plasma. The peak value of the electron density at the driving frequency used in the model results in a peak plasma conductivity of around 180 S/m. The high value for the electron density and low excitation and ionization threshold for mercury results in a very low electron "temperature" which is plotted in Figure 3. The peak electron temperature is only 1.27 eV, which through Boltzmann's relation results in a low plasma potential. The plasma potential is plotted in Figure 4 and only peaks at 8 V.

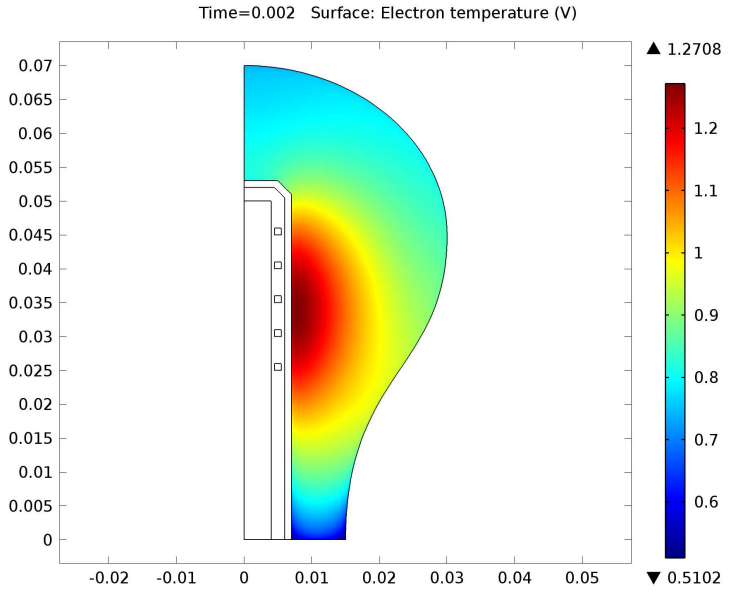

Figure 3: Plot of the electron "temperature".

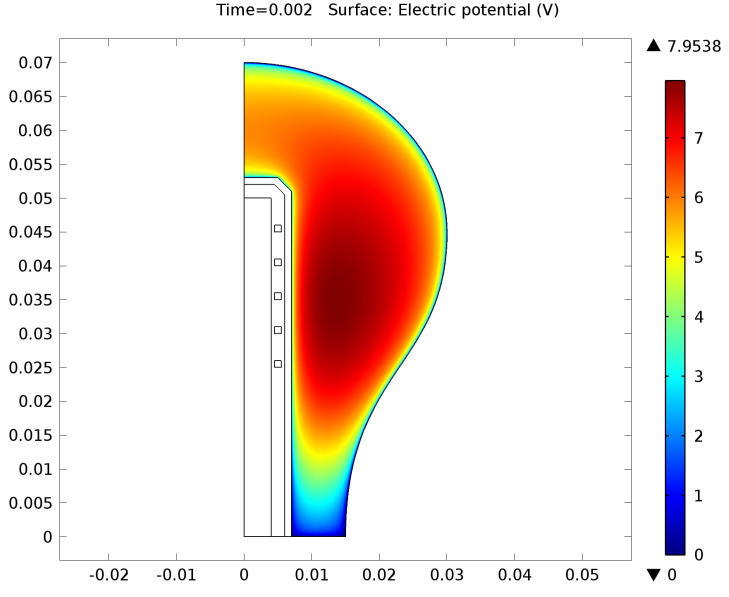

Figure 4: Plot of plasma potential.

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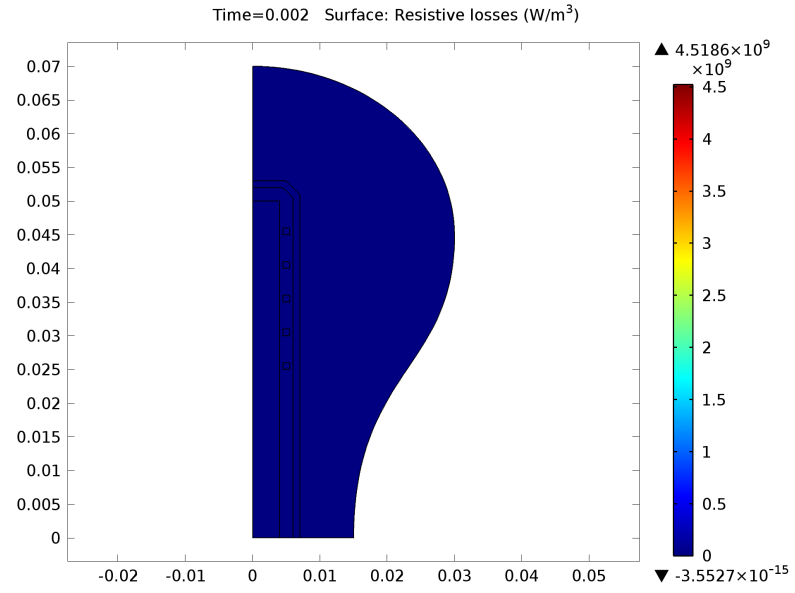

Figure 5: Plot of the resistive losses.

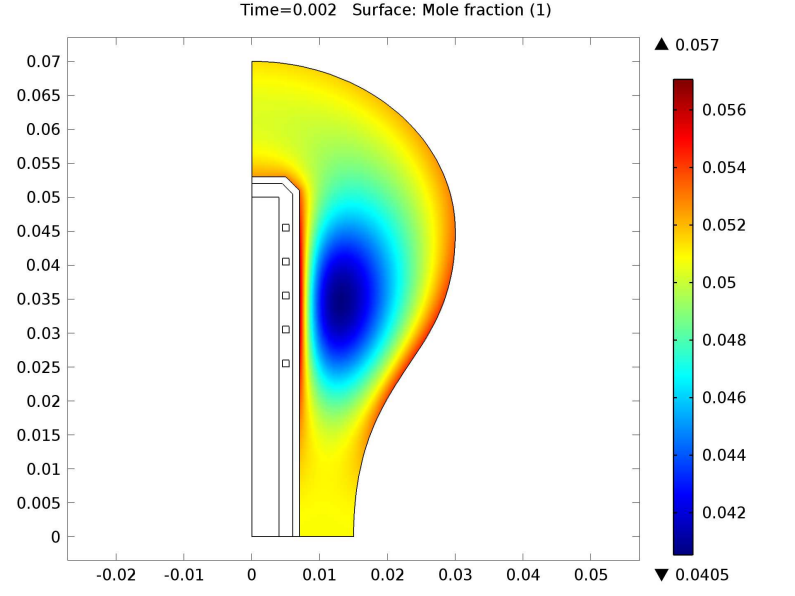

Figure 6: Plot of the mole fraction of ground state mercury.

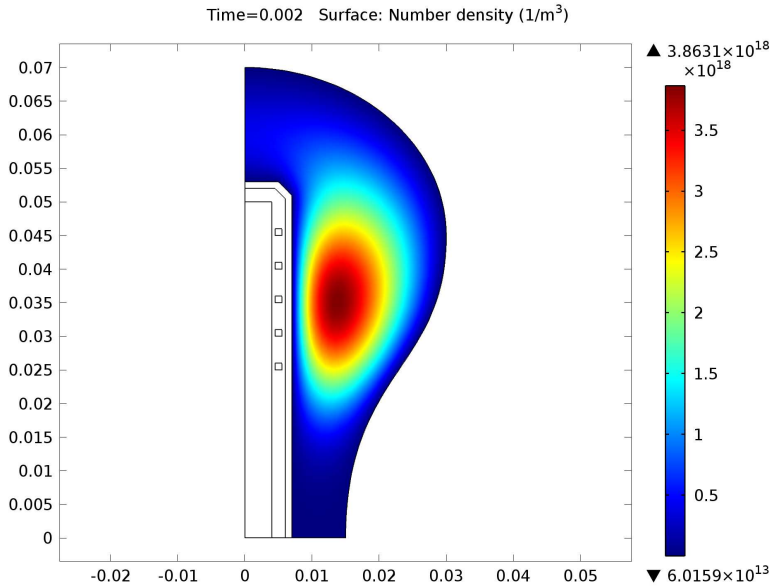

Figure 7: Plot of the number density of mercury ions.

The resistive losses in the plasma are plotted in Figure 5. The plasma skin depth is a few centimeters so there is no real shielding of the azimuthal electric field. The mole fraction of the ground state mercury is plotted in Figure 6. The mole fraction is low in the core of the plasma and higher on the walls. This is because the electrons consume the ground state mercury in the plasma core, converting it to electronically excited states. The electronically excited mercury atoms diffuse to the walls of the lamp where they de-excite back to the ground state. This continuous consumption of ground state mercury in the plasma bulk and release on the walls results in large gradients in mole fraction within the bulb.

There are two ion species present in the plasma, argon, and mercury. Despite the fact that the number density of ground state argon is 25 times higher than mercury, the density of mercury ions is several hundred times greater than the density of argon ions. This is because the ionization energy for mercury is only 10.44 eV compared to 15.7 eV for argon. Direct ionization of mercury is preferable to argon because the tail of the electron energy distribution function drops dramatically at higher electron energies. Additionally, any argon ions which encounter a ground state or electronically excited mercury atom will donate their charge because it is energetically favorable.

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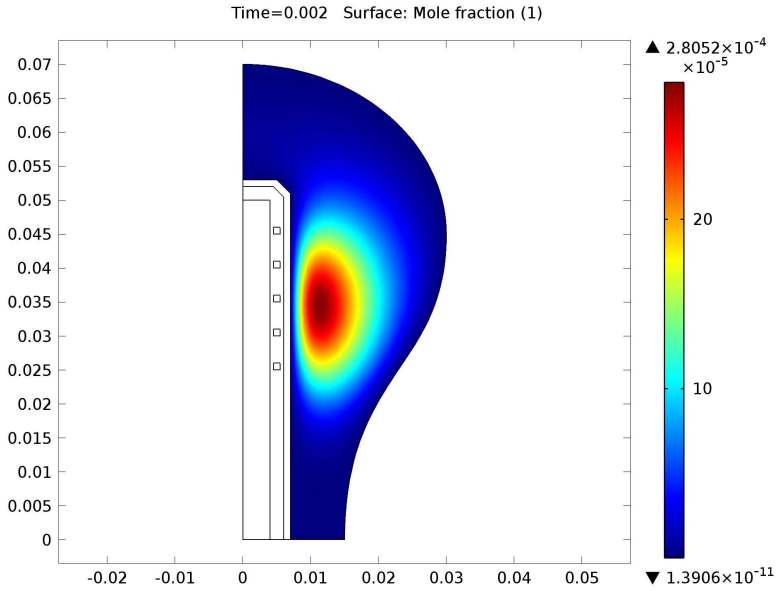

Figure 8: Plot of the mole fraction of Hg(63P1). Spontaneous decay of this species is responsible for the generation of 253nm radiation.

The mole fraction of Hg(63P1) is plotted in Figure 8. These atoms will spontaneously emit photos at a frequency factor of $8 \cdot 10^6$ s^{-1}. On the way to the walls of the lamp, the photons will continuously excite mercury atoms and then be released when spontaneous decay occurs. This resonant absorption and re-absorption of the photons means that the frequency factor appears to be much lower than it actually is. Since a self consistent model of the radiation imprisonment of the photons is computationally impractical, a trapping factor is used to approximate this effect. A trapping factor of 10 is used for the Hg(63P1) atoms which means that the frequency factor is lowered by a factor of 10. In Figure 9 the mole fraction of Hg(61P1) is plotted. A trapping factor of 1000 is used for the spontaneous decay back to ground state mercury.

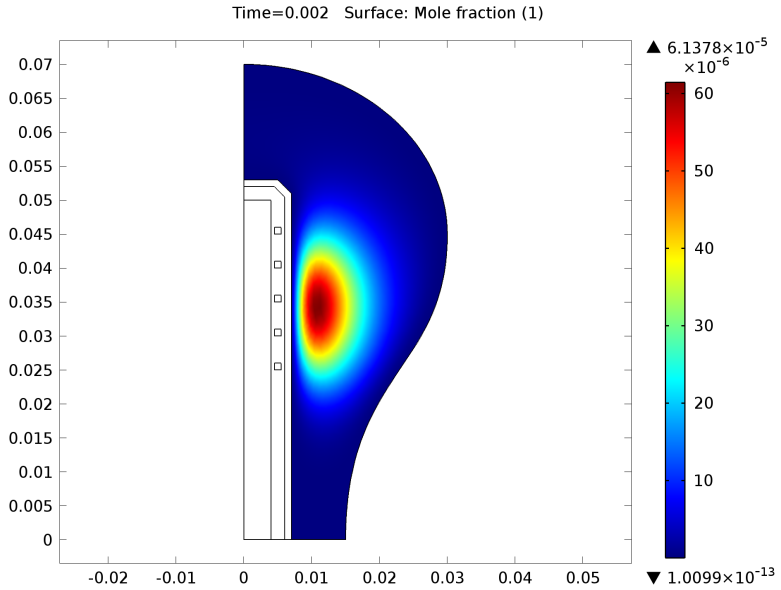

Figure 9: Plot of the mole fraction of Hg(61P1). Spontaneous decay of this species is responsible for the generation of 185nm radiation.

Reference

1. K. Rajaraman, *Radiation Transport in Low Pressure Plasmas: Lighting and Semiconductor Etching Plasmas*, Ph.D. thesis, 2005.

Model Library path: `Plasma_Module/Inductively_Coupled_Plasmas/electrodeless_lamp`

Modeling Instructions

MODEL WIZARD

1 Go to the **Model Wizard** window.

2 Click the **2D axisymmetric** button.

3 Click **Next**.

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4 In the **Add physics** tree, select **Plasma>Inductively Coupled Plasma (icp)**.

5 Click **Next**.

6 Find the **Studies** subsection. In the tree, select **Preset Studies>Frequency-Transient**.

7 Click **Finish**.

GEOMETRY 1

Bézier Polygon 1

1 In the **Model Builder** window, under **Model 1** right-click **Geometry 1** and choose **Bézier Polygon**.

2 In the **Bézier Polygon** settings window, locate the **Polygon Segments** section.

3 Find the **Added segments** subsection. Click the **Add Linear** button.

4 Find the **Control points** subsection. In row **2**, set **r** to `0.015`.

5 Find the **Added segments** subsection. Click the **Add Cubic** button.

6 Find the **Control points** subsection. In row **2**, set **z** to `0.025`.

7 In row **3**, set **r** to `0.03`.

8 In row **3**, set **z** to `0.025`.

9 In row **4**, set **r** to `0.03`.

10 In row **4**, set **z** to `0.045`.

11 Find the **Added segments** subsection. Click the **Add Quadratic** button.

12 Find the **Control points** subsection. In row **3**, set **r** to `0`.

13 In row **2**, set **z** to `0.07`.

14 In row **3**, set **z** to `0.07`.

15 Find the **Added segments** subsection. Click the **Add Linear** button.

16 Find the **Control points** subsection. In row **2**, set **z** to `0`.

17 Find the **Added segments** subsection. Click the **Add Linear** button.

18 Click the **Build All** button.

Rectangle 1

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Rectangle**.

2 In the **Rectangle** settings window, locate the **Size** section.

3 In the **Width** edit field, type `0.004`.

4 In the **Height** edit field, type `0.05`.

Rectangle 2

1 Right-click **Geometry 1** and choose **Rectangle**.

2 In the **Rectangle** settings window, locate the **Size** section.

3 In the **Width** edit field, type `0.006`.

4 In the **Height** edit field, type `0.052`.

Rectangle 3

1 Right-click **Geometry 1** and choose **Rectangle**.

2 In the **Rectangle** settings window, locate the **Size** section.

3 In the **Width** edit field, type `0.007`.

4 In the **Height** edit field, type `0.053`.

Chamfer 1

1 Right-click **Geometry 1** and choose **Chamfer**.

2 Click the **Zoom In** button on the Graphics toolbar.

3 On the object **r2**, select Point 3 only.

4 In the **Chamfer** settings window, locate the **Distance** section.

5 In the **Distance from vertex** edit field, type `1.5e-3`.

6 Click the **Build All** button.

Chamfer 2

1 Right-click **Geometry 1** and choose **Chamfer**.

2 On the object **r3**, select Point 3 only.

3 In the **Chamfer** settings window, locate the **Distance** section.

4 In the **Distance from vertex** edit field, type `2e-3`.

5 Click the **Build All** button.

Square 1

1 Right-click **Geometry 1** and choose **Square**.

2 In the **Square** settings window, locate the **Size** section.

3 In the **Side length** edit field, type `0.001`.

4 Locate the **Position** section. In the **r** edit field, type `0.0045`.

5 In the **z** edit field, type `0.025`.

6 Click the **Build All** button.

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Array 1

1 Right-click **Geometry 1** and choose **Transforms>Array**.

2 Select the object **sq1** only.

3 In the **Array** settings window, locate the **Size** section.

4 From the **Array type** list, choose **Linear**.

5 In the **Size** edit field, type `5`.

6 Locate the **Displacement** section. In the **z** edit field, type `5e-3`.

7 Click the **Build All** button.

8 Click the **Zoom Extents** button on the Graphics toolbar.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Model 1** right-click **Definitions** and choose **Variables**.

2 In the **Variables** settings window, locate the **Variables** section.

3 In the table, enter the following settings:

NAME	EXPRESSION	DESCRIPTION
Tinit	350[K]	Gas temperature
pinit	101325*(500E-3/760)[Pa]	Initial pressure
lamp_power	80[W]	Lamp power
tf1	10	Trapping factor
tf2	1000	Trapping factor

Explicit 1

1 In the **Model Builder** window, right-click **Definitions** and choose **Selections>Explicit**.

2 Select Domains 5–9 only.

3 In the **Explicit** settings window, locate the **Output Entities** section.

4 From the **Output entities** list, choose **Adjacent boundaries**.

5 Right-click **Model 1>Definitions>Explicit 1** and choose **Properties**.

6 In the **Explicit** settings window, locate the **Node Properties** section.

7 In the **Name** edit field, type `Coil boundaries`.

Explicit 2

1 In the **Model Builder** window, right-click **Definitions** and choose **Selections>Explicit**.

2 Select Domains 5–9 only.

3 Right-click **Model 1>Definitions>Explicit 2** and choose **Properties**.

4 In the **Explicit** settings window, locate the **Node Properties** section.

5 In the **Name** edit field, type `Coil domains`.

Explicit 3

1 In the **Model Builder** window, right-click **Definitions** and choose **Selections>Explicit**.

2 In the **Explicit** settings window, locate the **Input Entities** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundaries 8, 27, and 35–38 only.

5 Right-click **Model 1>Definitions>Explicit 3** and choose **Properties**.

6 In the **Explicit** settings window, locate the **Node Properties** section.

7 In the **Name** edit field, type `Boundary layers`.

Explicit 4

1 In the **Model Builder** window, right-click **Definitions** and choose **Selections>Explicit**.

2 Select Domain 4 only.

3 Right-click **Model 1>Definitions>Explicit 4** and choose **Properties**.

4 In the **Explicit** settings window, locate the **Node Properties** section.

5 In the **Name** edit field, type `Discharge`.

INDUCTIVELY COUPLED PLASMA

Cross Section Import 1

1 In the **Model Builder** window, under **Model 1** right-click **Inductively Coupled Plasma** and choose the domain condition **Heavy Species Transport>Cross Section Import**.

2 In the **Cross Section Import** settings window, locate the **Cross Section Import** section.

3 Click the **Browse** button.

4 Browse to the model's Model Library folder and double-click the file `Ar_xsecs.txt`.

Cross Section Import 2

1 In the **Model Builder** window, right-click **Inductively Coupled Plasma** and choose the domain setting **Heavy Species Transport>Cross Section Import**.

2 In the **Cross Section Import** settings window, locate the **Cross Section Import** section.

3 Click the **Browse** button.

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4 Browse to the model's Model Library folder and double-click the file `Hg_xsecs.txt`.

Reaction 1

1 Right-click **Inductively Coupled Plasma** and choose the domain setting **Heavy Species Transport>Reaction**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Ars=>Ar++Ar+e`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*1.00E-15`.

Reaction 2

1 Right-click **Inductively Coupled Plasma** and choose the domain setting **Heavy Species Transport>Reaction**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg=>Hg++Ar+e`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*9E-16`.

58: Ars+Hg=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>Reaction 2** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg1=>Hg++Ar+e`.

59: Ars+Hg1=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>58: Ars+Hg=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg2=>Hg++Ar+e`.

60: Ars+Hg2=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>59: Ars+Hg1=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg3=>Hg++Ar+e`.

61: Ars+Hg3=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>60: Ars+Hg2=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg4=>Hg++Ar+e`.

62: Ars+Hg4=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>61: Ars+Hg3=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg5=>Hg++Ar+e`.

63: Ars+Hg5=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>62: Ars+Hg4=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars+Hg6=>Hg++Ar+e`.

64: Ars+Hg6=>Hg++Ar+e

1 Right-click **Model 1>Inductively Coupled Plasma>63: Ars+Hg5=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg3+Hg3=>Hg++Hg+e`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*3.50E-16`.

65: Hg3+Hg3=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>64: Ars+Hg6=>Hg++Ar+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg3+Hg4=>Hg++Hg+e`.

66: Hg3+Hg4=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>65: Hg3+Hg3=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg3+Hg5=>Hg++Hg+e`.

67: Hg3+Hg5=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>66: Hg3+Hg4=>Hg++Hg+e** and choose **Duplicate**.

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2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg3+Hg6=>Hg++Hg+e`.

68: Hg3+Hg6=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>67: Hg3+Hg5=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg1=>Hg++Hg+e`.

69: Hg4+Hg1=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>68: Hg3+Hg6=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg2=>Hg++Hg+e`.

70: Hg4+Hg2=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>69: Hg4+Hg1=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg3=>Hg++Hg+e`.

71: Hg4+Hg3=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>70: Hg4+Hg2=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg4=>Hg++Hg+e`.

72: Hg4+Hg4=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>71: Hg4+Hg3=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg5=>Hg++Hg+e`.

73: Hg4+Hg5=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>72: Hg4+Hg4=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4+Hg6=>Hg++Hg+e`.

74: Hg4+Hg6=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>73: Hg4+Hg5=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg1=>Hg++Hg+e`.

75: Hg5+Hg1=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>74: Hg4+Hg6=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg2=>Hg++Hg+e`.

76: Hg5+Hg2=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>75: Hg5+Hg1=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg3=>Hg++Hg+e`.

77: Hg5+Hg3=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>76: Hg5+Hg2=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg4=>Hg++Hg+e`.

78: Hg5+Hg4=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>77: Hg5+Hg3=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg5=>Hg++Hg+e`.

79: Hg5+Hg5=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>78: Hg5+Hg4=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5+Hg6=>Hg++Hg+e`.

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80: Hg5+Hg6=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>79: Hg5+Hg5=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg1=>Hg++Hg+e`.

81: Hg6+Hg1=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>80: Hg5+Hg6=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg2=>Hg++Hg+e`.

82: Hg6+Hg2=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>81: Hg6+Hg1=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg3=>Hg++Hg+e`.

83: Hg6+Hg3=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>82: Hg6+Hg2=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg4=>Hg++Hg+e`.

84: Hg6+Hg4=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>83: Hg6+Hg3=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg5=>Hg++Hg+e`.

85: Hg6+Hg5=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>84: Hg6+Hg4=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6+Hg6=>Hg++Hg+e`.

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86: Hg6+Hg6=>Hg++Hg+e

1 Right-click **Model 1>Inductively Coupled Plasma>85: Hg6+Hg5=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ar++Hg=>Hg++Ar`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*1.50E-17`.

87: Ar++Hg=>Hg++Ar

1 Right-click **Model 1>Inductively Coupled Plasma>86: Hg6+Hg6=>Hg++Hg+e** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ar++Ar=>Ar++Ar`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*4.60E-16`.

88: Ar++Ar=>Ar++Ar

1 Right-click **Model 1>Inductively Coupled Plasma>87: Ar++Hg=>Hg++Ar** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg++Hg=>Hg+Hg+`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `N_A_const*1.00E-15`.

89: Hg++Hg=>Hg+Hg+

1 Right-click **Model 1>Inductively Coupled Plasma>88: Ar++Ar=>Ar++Ar** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg2=>Hg`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `8.00E6/tf1`.

90: Hg2=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>89: Hg++Hg=>Hg+Hg+** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4=>Hg`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `7.50E8/tf2`.

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91: Hg4=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>90: Hg2=>Hg** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5=>Hg1`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `2.20E7`.

92: Hg5=>Hg1

1 Right-click **Model 1>Inductively Coupled Plasma>91: Hg4=>Hg** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5=>Hg2`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `6.60E7`.

93: Hg5=>Hg2

1 Right-click **Model 1>Inductively Coupled Plasma>92: Hg5=>Hg1** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5=>Hg3`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `2.00E7`.

94: Hg5=>Hg3

1 Right-click **Model 1>Inductively Coupled Plasma>93: Hg5=>Hg2** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6=>Hg1`.

95: Hg6=>Hg1

1 Right-click **Model 1>Inductively Coupled Plasma>94: Hg5=>Hg3** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6=>Hg2`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `6.00E7`.

96: Hg6=>Hg2

1 Right-click **Model 1>Inductively Coupled Plasma>95: Hg6=>Hg1** and choose **Duplicate**.

2 In the **Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6=>Hg3`.

4 Locate the **Kinetics Expressions** section. In the k^{f} edit field, type `5.00E7`.

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Surface Reaction 1

1 In the **Model Builder** window, right-click **Inductively Coupled Plasma** and choose the boundary condition **Heavy Species Transport>Surface Reaction**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ars=>Ar`.

4 Locate the **Boundary Selection** section. From the **Selection** list, choose **Boundary layers**.

2: Ars=>Ar

1 Right-click **Model 1>Inductively Coupled Plasma>Surface Reaction 1** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Ar+=>Ar`.

3: Ar+=>Ar

1 Right-click **Model 1>Inductively Coupled Plasma>2: Ars=>Ar** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg1=>Hg`.

4: Hg1=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>3: Ar+=>Ar** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg2=>Hg`.

5: Hg2=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>4: Hg1=>Hg** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg3=>Hg`.

6: Hg3=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>5: Hg2=>Hg** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg4=>Hg`.

7: Hg4=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>6: Hg3=>Hg** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg5=>Hg`.

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8: Hg5=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>7: Hg4=>Hg** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg6=>Hg`.

9: Hg6=>Hg

1 Right-click **Model 1>Inductively Coupled Plasma>8: Hg5=>Hg** and choose **Duplicate**.

2 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.

3 In the **Formula** edit field, type `Hg+=>Hg`.

Species: Hg

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `0.05`.

Species: Hg1

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg1**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `2E-6`.

Species: Hg2

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg2**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `1E-6`.

Species: Hg3

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg3**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `5E-6`.

Species: Hg4

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg4**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `1E-6`.

Species: Hg5

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg5**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `5E-6`.

Species: Hg6

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg6**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 In the x_0 edit field, type `1E-6`.

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Species: Ar

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Ar**.

2 In the **Species** settings window, locate the **Species Formula** section.

3 Select the **From mass constraint** check box.

Species: Ar+

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Ar+**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the n_0 edit field, type `1E16`.

Species: Hg+

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Hg+**.

2 In the **Species** settings window, locate the **General Parameters** section.

3 In the M_w edit field, type `0.2006`.

4 In the σ edit field, type `2.969[angstrom]`.

5 In the ε/k_b edit field, type `750`.

6 Locate the **Species Formula** section. Select the **Initial value from electroneutrality constraint** check box.

Plasma Model 1

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Plasma Model 1**.

2 In the **Plasma Model** settings window, locate the **Electron Density and Energy** section.

3 In the μ_e edit field, type `4E24[1/(m*V*s)]/icp.Nn`.

4 Locate the **Model Inputs** section. In the T edit field, type `Tinit`.

5 In the p_A edit field, type `pinit`.

Ampère's Law 1

1 In the **Model Builder** window, right-click **Inductively Coupled Plasma** and choose the domain setting **Magnetic Fields>Ampère's Law**.

2 Select Domains 1–3 and 5–9 only.

Ground 1

1 Right-click **Inductively Coupled Plasma** and choose the boundary condition **Electrostatics>Ground**.

2 In the **Ground** settings window, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Boundary layers**.

Wall 1

1 Right-click **Inductively Coupled Plasma** and choose the boundary condition **Drift Diffusion>Wall**.

2 In the **Wall** settings window, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Boundary layers**.

Initial Values 1

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Initial Values 1**.

2 In the **Initial Values** settings window, locate the **Initial Values** section.

3 In the $n_{e,0}$ edit field, type `1E17`.

4 In the ε_0 edit field, type `2`.

5 Click the **Zoom Box** button on the Graphics toolbar.

Coil Group Domain 1

1 In the **Model Builder** window, right-click **Inductively Coupled Plasma** and choose the domain setting **Magnetic Fields>Coil Group Domain**.

2 Select Domains 5–9 only.

3 In the **Coil Group Domain** settings window, locate the **Coil Group Domain** section.

4 From the **Coil excitation** list, choose **Power**.

5 In the P_{coil} edit field, type `lamp_power`.

Species: Ar

1 In the **Model Builder** window, under **Model 1>Inductively Coupled Plasma** click **Species: Ar**.

2 In the **Species** settings window, locate the **Species Formula** section.

3 Select the **From mass constraint** check box.

4 Click the **Zoom Extents** button on the Graphics toolbar.

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MATERIALS

Material 1

1 In the **Model Builder** window, under **Model 1** right-click **Materials** and choose **Material**.

2 Select Domains 5–9 only.

3 In the **Material** settings window, locate the **Material Contents** section.

4 In the table, enter the following settings:

Property	Name	Value
Electric conductivity	sigma	6e7
Relative permittivity	epsilonr	1
Relative permeability	mur	1

5 Right-click **Model 1>Materials>Material 1** and choose **Rename**.

6 Go to the **Rename Material** dialog box and type `Coils` in the **New name** edit field.

7 Click **OK**.

Material 2

1 Right-click **Materials** and choose **Material**.

2 Select Domain 1 only.

3 In the **Material** settings window, locate the **Material Contents** section.

4 In the table, enter the following settings:

Property	Name	Value
Electric conductivity	sigma	0
Relative permittivity	epsilonr	1
Relative permeability	mur	1e3

5 Right-click **Model 1>Materials>Material 2** and choose **Rename**.

6 Go to the **Rename Material** dialog box and type `Ferrite` in the **New name** edit field.

7 Click **OK**.

Material 3

1 Right-click **Materials** and choose **Material**.

2 Select Domain 2 only.

3 In the **Material** settings window, locate the **Material Contents** section.

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4 In the table, enter the following settings:

Property	Name	Value
Electric conductivity	sigma	0
Relative permittivity	epsilonr	1
Relative permeability	mur	1

5 Right-click **Model 1>Materials>Material 3** and choose **Rename**.

6 Go to the **Rename Material** dialog box and type `Air` in the **New name** edit field.

7 Click **OK**.

Material 4

1 Right-click **Materials** and choose **Material**.

2 Select Domain 3 only.

3 In the **Material** settings window, locate the **Material Contents** section.

4 In the table, enter the following settings:

Property	Name	Value
Electric conductivity	sigma	0
Relative permittivity	epsilonr	4.2
Relative permeability	mur	1

5 Right-click **Model 1>Materials>Material 4** and choose **Rename**.

6 Go to the **Rename Material** dialog box and type `Dielectric` in the **New name** edit field.

7 Click **OK**.

MESH 1

1 In the **Mesh** settings window, locate the **Mesh Settings** section.

2 From the **Element size** list, choose **Extra fine**.

Edge 1

1 Right-click **Model 1>Mesh 1** and choose **Edge**.

2 In the **Edge** settings window, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Coil boundaries**.

Distribution 1

1 Right-click **Model 1>Mesh 1>Edge 1** and choose **Distribution**.

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2 In the **Distribution** settings window, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Coil boundaries**.

4 Locate the **Distribution** section. From the **Distribution properties** list, choose **Predefined distribution type**.

5 In the **Number of elements** edit field, type `30`.

6 In the **Element ratio** edit field, type `6`.

7 From the **Distribution method** list, choose **Geometric sequence**.

8 Select the **Symmetric distribution** check box.

Mapped 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Mapped**.

2 In the **Mapped** settings window, locate the **Domain Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 From the **Selection** list, choose **Coil domains**.

Edge 2

1 Right-click **Mesh 1** and choose **More Operations>Edge**.

2 Select Boundaries 8, 27, and 35 only.

Size 1

1 Right-click **Model 1>Mesh 1>Edge 2** and choose **Size**.

2 In the **Size** settings window, locate the **Element Size** section.

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

5 In the associated edit field, type `5e-4`.

Edge 3

1 In the **Model Builder** window, right-click **Mesh 1** and choose **More Operations>Edge**.

2 Select Boundaries 36–38 only.

Size 1

1 Right-click **Model 1>Mesh 1>Edge 3** and choose **Size**.

2 In the **Size** settings window, locate the **Element Size** section.

3 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

5 In the associated edit field, type `1e-3`.

Boundary Layers 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Boundary Layers**.

2 Select Domain 4 only.

3 In the **Boundary Layers** settings window, locate the **Domain Selection** section.

4 From the **Geometric entity level** list, choose **Domain**.

5 Click to expand the **Corner Settings** section.

Boundary Layer Properties

1 In the **Model Builder** window, under **Model 1>Mesh 1>Boundary Layers 1** click **Boundary Layer Properties**.

2 In the **Boundary Layer Properties** settings window, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Boundary layers**.

4 Locate the **Boundary Layer Properties** section. In the **Boundary layer stretching factor** edit field, type `1.1`.

5 In the **Thickness adjustment factor** edit field, type `1`.

6 From the **Thickness of first layer** list, choose **Manual**.

7 In the **Thickness** edit field, type `2E-5`.

Free Triangular 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Free Triangular**.

2 In the **Settings** window, click **Build All**.

STUDY 1

Step 1: Frequency-Transient

1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Frequency-Transient**.

2 In the **Frequency-Transient** settings window, locate the **Study Settings** section.

3 In the **Frequency** edit field, type `2[MHz]`.

4 In the **Times** edit field, type `0`.

5 Click the **Range** button.

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6 Go to the **Range** dialog box.

7 From the **Entry method** list, choose **Number of values**.

8 In the **Start** edit field, type `-8`.

9 In the **Stop** edit field, type `log10(2e-3)`.

10 In the **Number of values** edit field, type `3`.

11 From the **Function to apply to all values** list, choose **exp10**.

12 Click the **Add** button.

13 In the **Model Builder** window, right-click **Study 1** and choose **Compute**.

RESULTS

2D Plot Group 4

1 In the **Model Builder** window, right-click **Results** and choose **2D Plot Group**.

2 Right-click **2D Plot Group 4** and choose **Surface**.

3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Inductively Coupled Plasma (Magnetic Fields)>Heating and losses>Resistive losses (icp.Qrh)**.

4 Click the **Plot** button.

2D Plot Group 5

1 In the **Model Builder** window, right-click **Results** and choose **2D Plot Group**.

2 Right-click **2D Plot Group 5** and choose **Surface**.

3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Inductively Coupled Plasma (Heavy Species Transport)>Mole fractions>Mole fraction (icp.x_wHg)**.

4 Click the **Plot** button.

2D Plot Group 6

1 In the **Model Builder** window, right-click **Results** and choose **2D Plot Group**.

2 Right-click **2D Plot Group 6** and choose **Surface**.

3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Inductively Coupled Plasma (Heavy Species Transport)>Number densities>Number density (icp.n_wHg_1p)**.

4 Click the **Plot** button.

2D Plot Group 7

1 In the **Model Builder** window, right-click **Results** and choose **2D Plot Group**.

2 Right-click **2D Plot Group 7** and choose **Surface**.

3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Inductively Coupled Plasma (Heavy Species Transport)>Mole fractions>Mole fraction (icp.x_wHg2)**.

4 Click the **Plot** button.

2D Plot Group 8

1 In the **Model Builder** window, right-click **Results** and choose **2D Plot Group**.

2 Right-click **2D Plot Group 8** and choose **Surface**.

3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Inductively Coupled Plasma (Heavy Species Transport)>Mole fractions>Mole fraction (icp.x_wHg4)**.

4 Click the **Plot** button.

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