Created in COMSOL Multiphysics 6.2

In-Plane Microwave Plasma

Introduction

Wave-heated discharges can be very simple, such as when a plane wave is guided into a reactor using a waveguide, or very complicated, such as in the case with ECR (electron cyclotron resonance) reactors. In this simple example, a wave is launched down a waveguide where it intersects a flowing gas at low pressure, resulting in formation of an argon plasma. Microwave plasmas typically have high number density without requiring significant power absorption. The plasma potential is also quite low compared to capacitive or DC discharges. Therefore, microwave plasmas share many of the characteristics of inductive discharges.

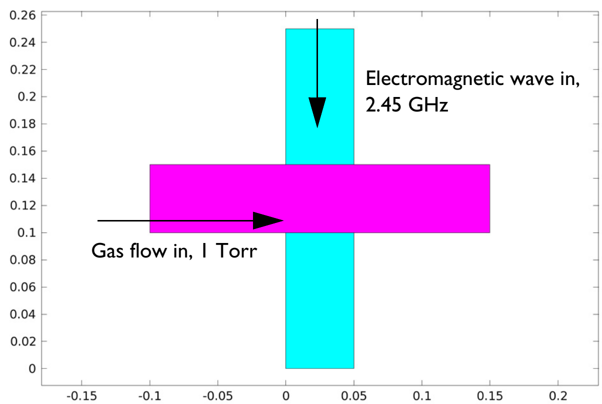

Figure 1: Diagram of geometry modeled. A TE or TM mode wave enters from the top port and intersects the gas flow leading to the formation of a plasma.

Note: The model requires the Plasma Module and RF Module.

Model Definition

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. For detailed information on electron transport, see *Theory for the Drift Diffusion Interface* in the *Plasma Module User's Guide*.

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

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

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:

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

The source coefficients in the above equations are determined by the plasma chemistry using rate coefficients. 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.

For nonelectron species, the following equation is solved for the mass fraction of each species. For detailed information on the transport of the nonelectron species, see *Theory for the Heavy Species Transport 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:

$$-\nabla \cdot \varepsilon_0 \varepsilon_{\mathrm{r}} \nabla V = \rho$$

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 Interface* in the *Plasma Module User's Guide*.

In a microwave reactor the high frequency electric field is computed in the frequency domain using the following equation:

$$\nabla\times(\mu_{\mathrm{r}}^{-1}\nabla\times\mathbf{E}) - k_0^{\ 2}\left(\varepsilon_{\mathrm{r}} - \frac{j\sigma}{\omega\varepsilon_0}\right)\mathbf{E} = 0$$

The relationship between the plasma current density and the electric field becomes more complicated in the presence of a DC magnetic field. The following equation defines this relationship:

$$\sigma^{-1} \bullet \mathbf{J} = \mathbf{E}$$

Here, σ is the plasma conductivity tensor, which is a function of the electron density, collision frequency, and magnetic flux density. Using the definitions:

$$\alpha = \frac{q}{m_e(\nu_e + j\omega)}, \ \beta = n_e q \alpha$$

where q is the electron charge, m_e is the electron mass, n_e is the collision frequency, and ω is the angular frequency of the electromagnetic field. In this example, the inverse of the plasma conductivity is diagonal because there is no external DC magnetic field:

$$\sigma^{-\mathbf{1}} = \begin{bmatrix} \frac{1}{\beta} & 0 & 0 \\ 0 & \frac{1}{\beta} & 0 \\ 0 & 0 & \frac{1}{\beta} \end{bmatrix}$$

The gas flow is modeled assuming a constant velocity in the x direction.

PLASMA CHEMISTRY

The chemical mechanism for the plasma consists of only 3 species and 7 reactions (electron impact cross section are obtained from Ref. 2):

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
1	e+Ar=>e+Ar	Elastic	0
2	e+Ar=>e+Ars	Excitation	11.5
3	e+Ars=>e+Ar	Superelastic	-11.5
4	e+Ar=>2e+Ar+	Ionization	15.8
5	e+Ars=>2e+Ar+	Ionization	4.24
6	Ars+Ars=>e+Ar+Ar+	Penning ionization	-
7	Ars+Ar=>Ar+Ar	Metastable quenching	-

Stepwise ionization (reaction 5) can play an important role in sustaining low pressure argon discharges. Excited argon atoms are consumed via superelastic collisions with electrons, quenching with neutral argon atoms, ionization or Penning ionization where two metastable argon atoms react to form a neutral argon atom, an argon ion and an electron. Reaction number 7 is responsible for heating of the gas. The 11.5 eV of energy which was consumed in creating the electronically excited argon atom is returns to the gas as thermal energy when the excited metastable quenches. In addition to volumetric reactions, the following surface reactions are implemented:

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT
1	Ars=>Ar	1
2	Ar+=>Ar	1

When a metastable argon atom makes contact with the wall, it reverts to the ground state argon atom with some probability (the sticking coefficient).

ELECTRICAL EXCITATION

The plasma is sustained through absorption of electromagnetic waves. The Port boundary condition is used to excite the plasma. A total absorbed power of 30 W is fed into the port.

In a second study, the electrical excitation is changed to the TM mode, where the electric field has only an in-plane component. The total absorbed power is the same as the TE mode case.

Results and Discussion

The electron density is plotted in Figure 2 and peaks slightly downstream of the crossing point. The electron density is also slightly asymmetric in the y-plane due to the fact that the electromagnetic waves are absorbed asymmetrically. The electron “temperature” is plotted in Figure 3. The electron temperature is relatively low everywhere, in part due to the high operating pressure (1 Torr). The electron “temperature” peaks directly underneath the waveguide where the wave is absorbed. The norm of the electric field can be seen in Figure 5. The electric field is high inside the waveguide and there are no losses. Once the wave is exposed to the plasma, the energy is absorbed by the electrons, raising the electron temperature enough to generate new electrons through ionization. The ionization rate is high enough to sustain the plasma. The contour of the critical plasma density is also plotted in Figure 5. The electromagnetic wave cannot penetrate into regions exceeding the critical plasma density. Since the electron “temperature” is relatively low, one would expect the plasma potential to be low. The plasma potential is plotted in Figure 4 and is only around 10 volts.

In the TE mode, electrons do not experience any change in the high-frequency electric field during the microwave time scale. This means that the phase coherence between the electrons and electromagnetic waves is only destroyed through collisions with the background gas. The loss of phase coherence between the electrons and high-frequency fields is what results in energy gain for the electrons. Therefore, the momentum collision frequency is simply given by:

$$\nu_m = \nu_e$$

where ν_e is the collision frequency between the electrons and neutrals.

When switching to the TM mode, the electron density, electron “temperature” and plasma potential are quite similar to the TE mode case. This can be seen in Figure 7, Figure 8 and Figure 9. The electric field is very different however, Figure 9. The electric field cannot penetrate past the contour of critical electron density, and has its greatest magnitude in this location. The power deposition, Figure 10 is also highly localized to the contour of critical electron density. The TM mode causes in-plane motion of the electrons on the microwave time scale, so in regions where the high-frequency electric field is significant (the contour where the electron density is equal to the critical density), the time-averaged electric field experienced by the electrons may be nonzero. This destroys the phase coherence between the electrons and the fields, causing the electrons to gain energy. This is an example of a nonlocal kinetic effect, which is difficult to approximate with a fluid model. However, since this effect is similar to collisions with a background gas, the nonlocal effects can be approximated by adding an effective collision frequency to the momentum collision frequency:

$$\nu_m = \upsilon_e + \nu_{\mathrm{eff}}$$

where ν_{eff} is the effective collision frequency to account for nonlocal effects. In this example, since the Doppler broadening parameter is set to 20, this corresponds to an effective collision frequency of:

$$\nu_{\mathrm{eff}} = \frac{\omega}{20}$$

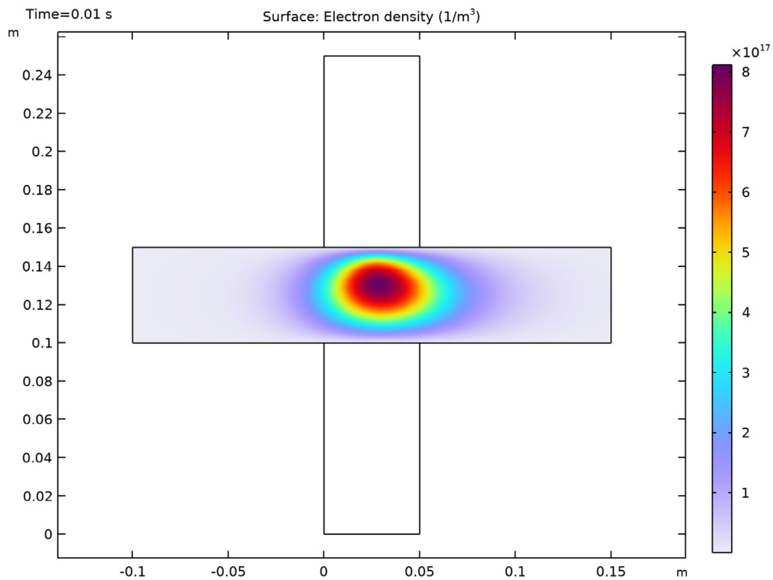

Figure 2: Plot of the electron density.

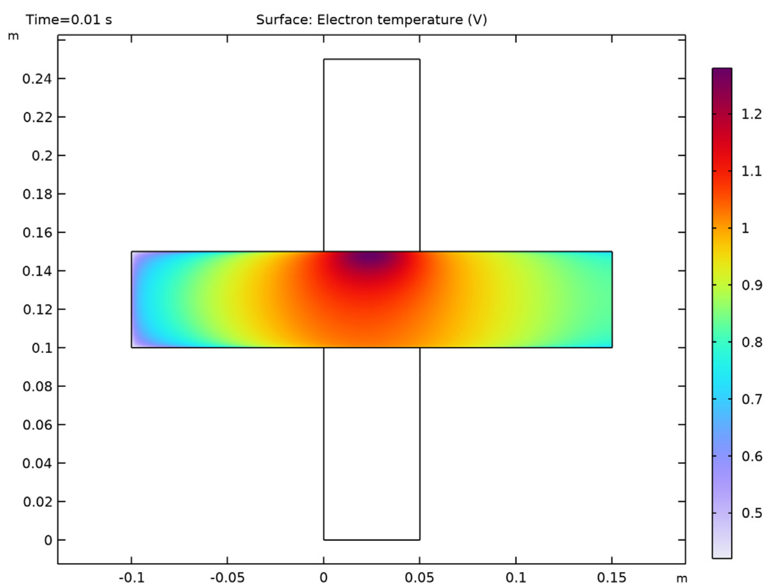

Figure 3: Plot of the electron temperature in the reactor.

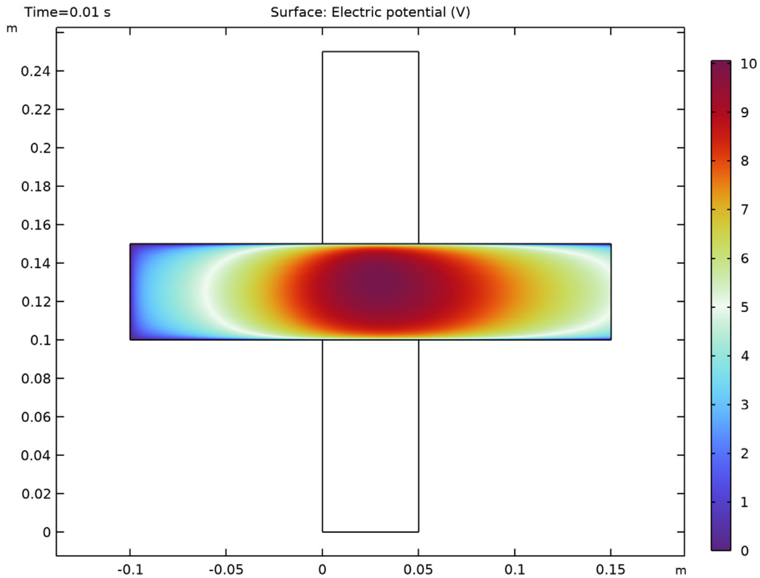

Figure 4: Plot of the plasma potential in the reactor.

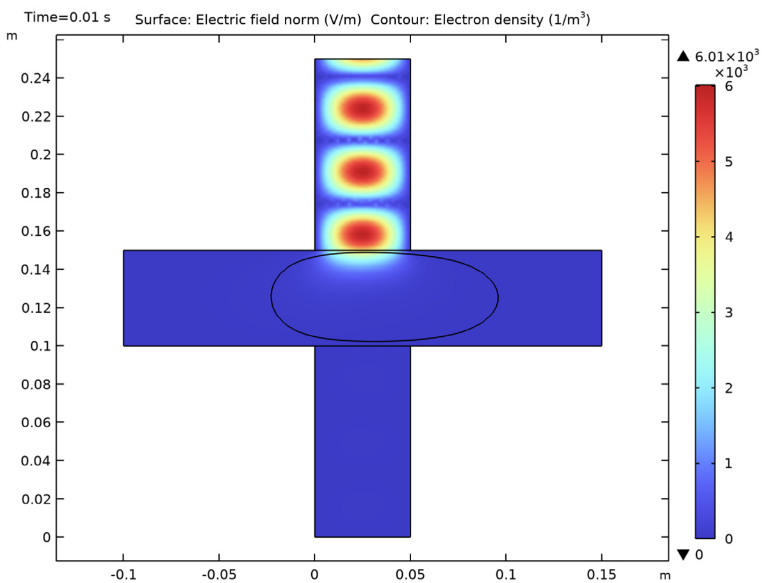

Figure 5: Plot of the electric field norm. The white contour represents the critical plasma

density, where the electron density is equal to 7.6E16[1/m^3].

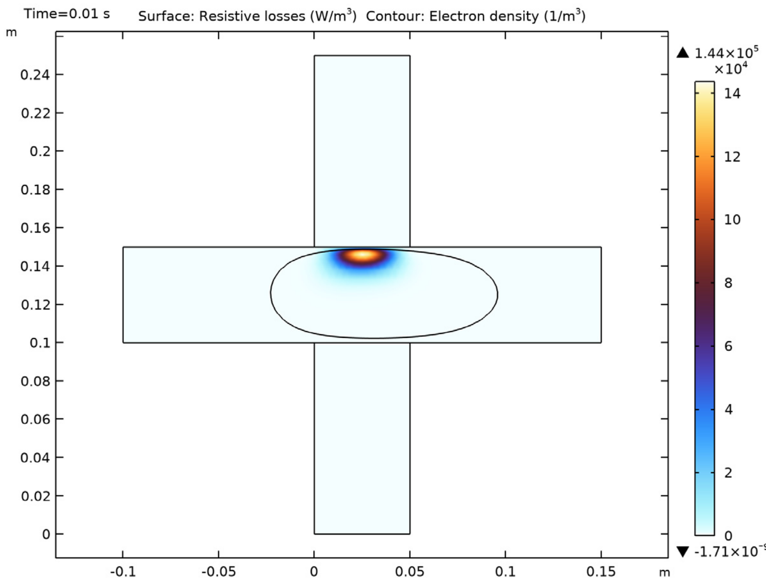

Figure 6: Plot of the power deposition into the plasma. The white contour represents the critical plasma density, where the electron density is equal to 7.6E16 1/m^3.

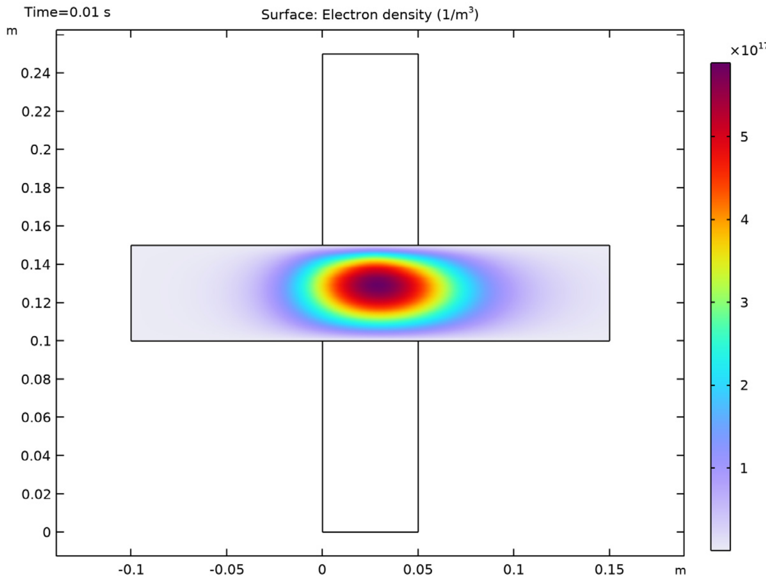

Figure 7: Electron density for the TM mode case.

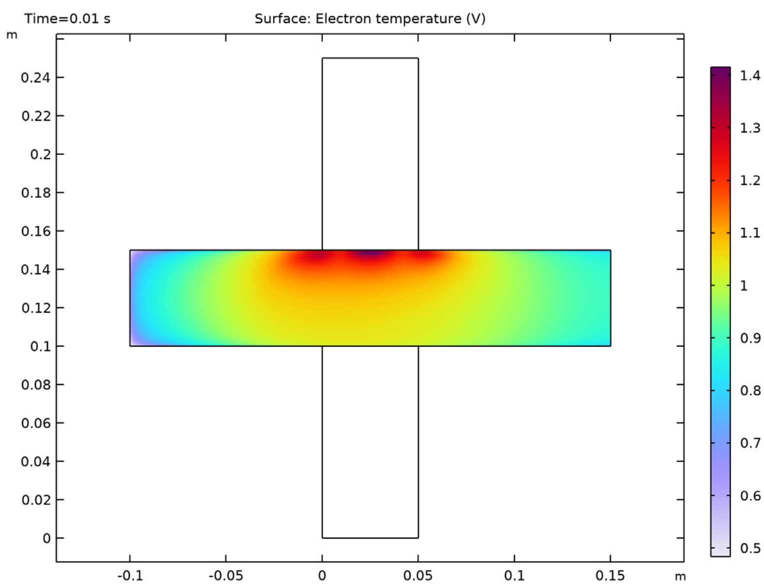

Figure 8: Plot of the electron temperature for the TM mode case.

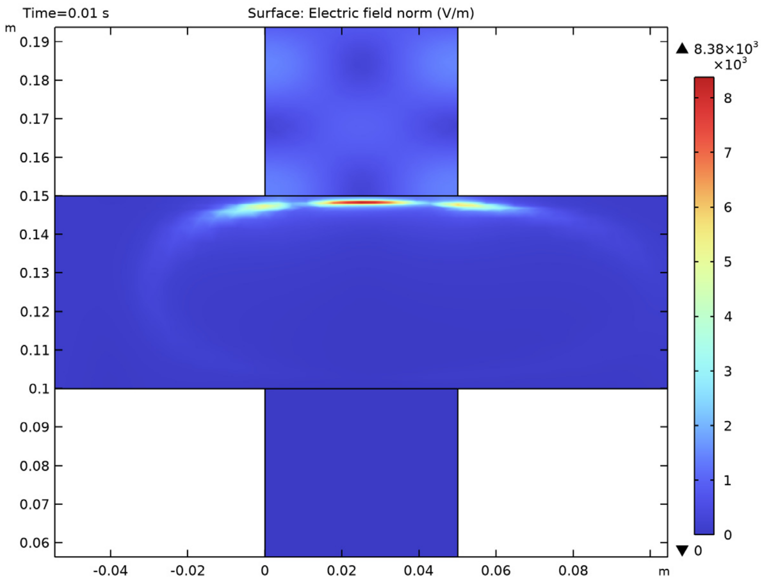

Figure 9: Close up of the high frequency electric field norm for the TM mode case.

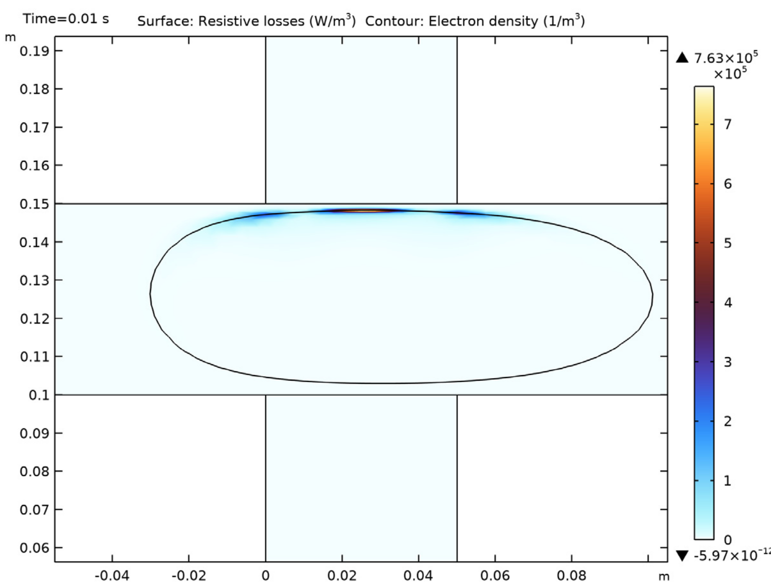

Figure 10: Close up of the power deposition into the plasma for the TM mode case.

References

1. M.A. Lieberman and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, John Wiley & Sons, 2005.

2. Phelps database, www.lxcat.net, retrieved 2017.

Application Library path: `Plasma_Module/Wave-Heated_Discharges/inplane_microwave_plasma`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **Plasma>Microwave Plasma**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Multiphysics>Frequency-Transient**.

6 Click **Done**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	**Expression**	**Value**	**Description**
P0	30[W]	30 W	Absorbed power

GEOMETRY 1

Rectangle 1 (r1)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `0.05`.

4 In the **Height** text field, type `0.1`.

5 Click **Build All Objects**.

Rectangle 2 (r2)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `0.25`.

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

5 Locate the **Position** section. In the **x** text field, type `-0.1`.

6 In the **y** text field, type `0.1`.

Rectangle 3 (r3)

1 In the **Geometry** toolbar, click **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type `0.05`.

4 In the **Height** text field, type `0.1`.

5 Locate the **Position** section. In the **y** text field, type `0.15`.

6 Click **Build All Objects**.

7 Click the **Zoom Extents** button in the **Graphics** toolbar.

DEFINITIONS

Walls

1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 Select Boundaries 1–3, 6, 8, 11, and 13 only.

5 In the **Label** text field, type `Walls`.

PLASMA (PLAS)

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Plasma (plas)**.
2. In the **Settings** window for **Plasma**, locate the **Domain Selection** section.
3. Click **Clear Selection**.
4. Select Domain 1 only.

Cross Section Import 1

1. In the **Physics** toolbar, click **Global** and choose **Cross Section Import**.
2. In the **Settings** window for **Cross Section Import**, locate the **Cross Section Import** section.
3. Click **Browse**.
4. Browse to the model's Application Libraries folder and double-click the file `Ar_xsecs.txt`.
5. Click **Import**.

Reaction 1

1. In the **Physics** toolbar, click **Domains** and choose **Reaction**.
2. In the **Settings** window for **Reaction**, locate the **Reaction Formula** section.
3. In the **Formula** text field, type `Ars+Ars=>e+Ar+Ar+`.
4. Locate the **Reaction Parameters** section. In the k^{f} text field, type `3.734E8`.

Reaction 2

1. In the **Physics** toolbar, click **Domains** and choose **Reaction**.
2. In the **Settings** window for **Reaction**, locate the **Reaction Formula** section.
3. In the **Formula** text field, type `Ars+Ar=>Ar+Ar`.
4. Locate the **Reaction Parameters** section. In the k^{f} text field, type `1807`.

Species: Ar

1. In the **Model Builder** window, click **Species: Ar**.
2. In the **Settings** window for **Species**, locate the **Species Formula** section.
3. Select the **From mass constraint** check box.

Species: Ar+

1. In the **Model Builder** window, click **Species: Ar+**.
2. In the **Settings** window for **Species**, locate the **Species Formula** section.
3. Select the **Initial value from electroneutrality constraint** check box.

Surface Reaction 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Surface Reaction**.

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

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

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

Surface Reaction 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Surface Reaction**.

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

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

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

5 In the **Model Builder** window, click **Plasma (plas)**.

6 In the **Settings** window for **Plasma**, locate the **Transport Settings** section.

7 Find the **Include** subsection. Select the **Convection** check box.

8 Locate the **Plasma Properties** section. Select the **Use reduced electron transport properties** check box.

Plasma Model 1

1 In the **Model Builder** window, click **Plasma Model 1**.

2 In the **Settings** window for **Plasma Model**, locate the **Model Inputs** section.

3 Specify the **u** vector as

10	x
0	y

4 In the T text field, type `350`.

5 In the p_A text field, type `1[torr]`.

6 Locate the **Electron Density and Energy** section. In the $\mu_e N_n$ text field, type `4E24`.

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

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

Wall 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

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

3 From the **Selection** list, choose **Walls**.

Ground 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Ground**.

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

3 From the **Selection** list, choose **Walls**.

Electron Outlet 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Electron Outlet**.

2 Select Boundary 14 only.

Species: Ars

In the **Model Builder** window, click **Species: Ars**.

Outflow 1

1 In the **Physics** toolbar, click **Attributes** and choose **Outflow**.

2 In the **Settings** window for **Outflow**, locate the **Boundary Selection** section.

3 Click **Clear Selection**.

4 Select Boundary 14 only.

Species: Ar+

In the **Model Builder** window, under **Component 1 (comp1)>Plasma (plas)** click **Species: Ar+**.

Outflow 1

1 In the **Physics** toolbar, click **Attributes** and choose **Outflow**.

2 In the **Settings** window for **Outflow**, locate the **Boundary Selection** section.

3 Click **Clear Selection**.

4 Select Boundary 14 only.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.

3 From the **Electric field components solved for** list, choose **Out-of-plane vector**.

Port 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Port**.

2 Select Boundary 9 only.

3 In the **Settings** window for **Port**, locate the **Port Properties** section.

4 From the **Type of port** list, choose **Rectangular**.

5 Select the **Enable active port feedback** check box.

6 In the P_{dep} text field, type `P0`.

MATERIALS

Material 1 (mat1)

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 Select Domains 2 and 3 only.

3 In the **Settings** window for **Material**, locate the **Material Contents** section.

4 In the table, enter the following settings:

Property	**Variable**	**Value**	**Unit**	**Property group**
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	5	1	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

MESH 1

Boundary Layers 1

1 In the **Mesh** toolbar, click **Boundary Layers**.

2 In the **Settings** window for **Boundary Layers**, locate the **Domain Selection** section.

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

4 Select Domain 1 only.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.

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

3 From the **Selection** list, choose **Walls**.

Free Triangular 1

In the **Mesh** toolbar, click **Free Triangular**.

Size

1 In the **Model Builder** window, click **Size**.

2 In the **Settings** window for **Size**, locate the **Element Size** section.

3 From the **Calibrate for** list, choose **Plasma**.

4 From the **Predefined** list, choose **Fine**.

5 Click **Build All**.

STUDY 1

Step 1: Frequency-Transient

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

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

3 In the **Output times** text field, type `0`.

4 Click **Range**.

5 In the **Range** dialog box, choose **Number of values** from the **Entry method** list.

6 In the **Start** text field, type `-8`.

7 In the **Stop** text field, type `-2`.

8 In the **Number of values** text field, type `31`.

9 From the **Function to apply to all values** list, choose **exp10(x)** – **Exponential function (base 10)**.

10 Click **Add**.

11 In the **Settings** window for **Frequency-Transient**, locate the **Study Settings** section.

12 In the **Frequency** text field, type `2.45[GHz]`.

13 In the **Home** toolbar, click **Compute**.

RESULTS

Contour 1

1 In the **Model Builder** window, right-click **Electric Field (emw)** and choose **Contour**.

2 In the **Settings** window for **Contour**, locate the **Levels** section.

3 From the **Entry method** list, choose **Levels**.

4 In the **Levels** text field, type `7.6E16`.

5 Locate the **Coloring and Style** section. Clear the **Color legend** check box.

6 From the **Coloring** list, choose **Uniform**.

7 From the **Color** list, choose **Black**.

8 In the **Electric Field (emw)** toolbar, click **Plot**.

Resistive Heating

1 Right-click **Electric Field (emw)** and choose **Duplicate**.

2 Right-click **Electric Field (emw) 1** and choose **Rename**.

3 In the **Rename 2D Plot Group** dialog box, type `Resistive Heating` in the **New label** text field.

4 Click **OK**.

Surface

1 In the **Model Builder** window, expand the **Resistive Heating** node, then click **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Electromagnetic Waves, Frequency Domain>Heating and losses>emw.Qrh - Resistive losses - W/m³**.

3 Locate the **Coloring and Style** section. Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Thermal>ThermalWave** in the tree.

5 Click **OK**.

6 In the **Resistive Heating** toolbar, click **Plot**.

Now change to the in-plane electric field, which makes the problem much more difficult to solve. This is because all the power will be absorbed on the contour of critical electron density. Setting a **Doppler broadening parameter** of 20 smooths out the region over which power is deposited to help with convergence.

MULTIPHYSICS

Plasma Conductivity Coupling 1 (pcc1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Multiphysics** click **Plasma Conductivity Coupling 1 (pcc1)**.

2 In the **Settings** window for **Plasma Conductivity Coupling**, locate the **Compute Tensor Plasma Conductivity** section.

3 Select the **Compute tensor plasma conductivity** check box.

4 In the δ text field, type `20`.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Components** section.

3 From the **Electric field components solved for** list, choose **In-plane vector**.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Multiphysics>Frequency-Transient**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency-Transient

1 In the **Settings** window for **Frequency-Transient**, locate the **Study Settings** section.

2 In the **Output times** text field, type `0`.

3 Click **Range**.

4 In the **Range** dialog box, choose **Number of values** from the **Entry method** list.

5 In the **Start** text field, type `-8`.

6 In the **Stop** text field, type `-2`.

7 In the **Number of values** text field, type `31`.

8 From the **Function to apply to all values** list, choose **exp10(x) – Exponential function (base 10)**.

9 Click **Add**.

10 In the **Settings** window for **Frequency-Transient**, locate the **Study Settings** section.

11 In the **Frequency** text field, type `2.45[GHz]`.

12 In the **Home** toolbar, click **Compute**.

RESULTS

Electric Field (emw) 1

1 In the **Model Builder** window, click **Electric Field (emw) 1**.

2 In the **Electric Field (emw) 1** toolbar, click **Plot**.

3 Click the **Zoom In** button in the **Graphics** toolbar.

Resistive Heating 1

1 In the **Model Builder** window, right-click **Resistive Heating** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.

4 In the **Resistive Heating 1** toolbar, click **Plot**.

Port Power

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Port Power` in the **Label** text field.

Global 1

1 Right-click **Port Power** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Electromagnetic Waves, Frequency Domain>Global>emw.port1.Pin - Port input power - W/ m**.

3 In the **Port Power** toolbar, click **Plot**.

4 Click to expand the **Legends** section. From the **Legends** list, choose **Manual**.

5 In the table, enter the following settings:

Legends
`TE Mode`

6 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

Port Power

1 In the **Model Builder** window, click **Port Power**.

2 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.

3 From the **Position** list, choose **Upper left**.

Global 2

1 In the **Model Builder** window, under **Results>Port Power** right-click **Global 1** and choose **Duplicate**.
2 In the **Settings** window for **Global**, locate the **Data** section.
3 From the **Dataset** list, choose **Study 2/Solution 2 (sol2)**.
4 Locate the **Legends** section. In the table, enter the following settings:

Legends
`TM Mode`

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.
6 In the **Port Power** toolbar, click **Plot**.