



Model created in COMSOL Multiphysics 6.4

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.

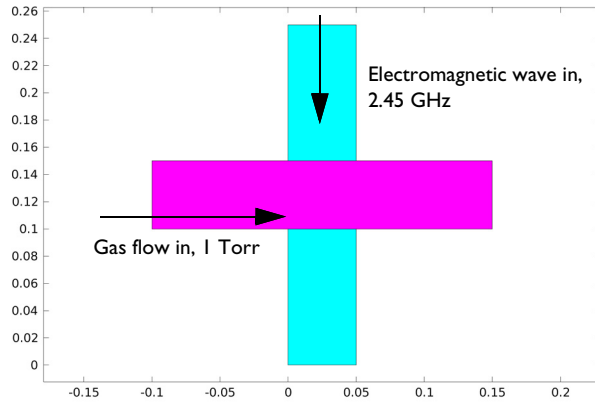


Figure 1: Diagram of geometry modeled. A TE or TM mode wave enters from the top port and intersects the gas flow leading to the formation of a plasma.

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

Model Definition

Electron transport is modeled by solving the continuity equation, the momentum equation under the drift-diffusion approximation, and the mean electron energy equation (for detailed information on electron transport, see *Theory for the Drift Diffusion Interface* in the *Plasma Module User's Guide*)

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

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

The source coefficients in the above equations are determined by the plasma chemistry. The electron rate expression is defined as

$$R_e = N_A \sum_j \nu_{e,j} r_j$$

where $\nu_{e,j}$ is the stoichiometric coefficient, and the reaction rate is defined as

$$r_j = k_j^f \prod_{i \in \text{react}} c_i^{-\nu_{i,j}} + k_j^r \prod_{i \in \text{prod}} c_k^{\nu_{i,j}}$$

where k_j^f is the forward rate constant and k_j^r is the reversed rate constant. Both the Electron Impact Reaction feature and Reaction feature can contribute to the electron rate expression. However, when using the Reaction feature it is important to note that the associated electron energy gain or loss is not included in the source term of the electron mean energy equation.

The rate constants can be computed from electron impact cross-section data

$$k^f = N_A \gamma \int_0^{\infty} \epsilon \sigma(\epsilon) f(\epsilon) d\epsilon$$

where $\gamma = (2q/m_e)^{1/2}$ (SI unit: $\text{C}^{1/2}/\text{kg}^{1/2}$), m_e is the electron mass (SI unit: kg), ϵ is the electron energy (SI unit: V), σ is the electron impact collision cross section (SI unit: m^2), and f is the electron energy distribution function.

When *Townsend coefficients* are used, the reaction rate is defined as

$$r_j = \frac{\alpha_j}{N_n} |\Gamma_e| \prod_{i \neq e \in \text{react}} c_i^{-\nu_{i,j}}$$

where α_j/N_n is the reduced Townsend coefficient for reaction j (SI unit: m^2) and Γ_e is the electron flux as defined above (SI unit: $1/(\text{m}^2 \cdot \text{s})$). Townsend coefficients can increase the stability of the numerical scheme when the electron flux is field driven as is the case with DC discharges.

The total electron energy loss or gained is calculated by summing the collisional energy changes from all reactions defined with the Electron Impact Reaction feature as

$$S_{\text{en}} = -\sum_j r_j \Delta \varepsilon_j F$$

where $\Delta \varepsilon_j$ is the energy loss from reaction j (SI unit: V) and F is the Faraday constant (SI unit: C/mol). For excitation and ionization collisions $\Delta \varepsilon_j$ corresponds to the energy of the excited state being excited/deexcited or ionized, for attachment $\Delta \varepsilon_j$ is set to zero, and for elastic collisions

$$\Delta \varepsilon = 2 \frac{m_e}{m_k} \frac{3}{2} \left[T_e (\text{eV}) - \frac{k_B}{e} T_{\text{gas}} (\text{K}) \right]$$

where m_e and m_k are the electron and heavy species mass in kg, T_e is the electron temperature in eV, and T_{gas} is the gas temperature in K.

For heavy 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:

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

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:

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

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:

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

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:

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

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	$\Delta\epsilon(\text{eV})$
1	$e+\text{Ar} \Rightarrow e+\text{Ar}$	Elastic	0
2	$e+\text{Ar} \Rightarrow e+\text{Ar}_s$	Excitation	11.5
3	$e+\text{Ar}_s \Rightarrow e+\text{Ar}$	Superelastic	-11.5
4	$e+\text{Ar} \Rightarrow 2e+\text{Ar}^+$	Ionization	15.8
5	$e+\text{Ar}_s \Rightarrow 2e+\text{Ar}^+$	Ionization	4.24
6	$\text{Ar}_s+\text{Ar}_s \Rightarrow e+\text{Ar}+\text{Ar}^+$	Penning ionization	-
7	$\text{Ar}_s+\text{Ar} \Rightarrow \text{Ar}+\text{Ar}$	Metastable quenching	-

In addition to volumetric reactions, the following surface reactions are implemented:

TABLE 2: TABLE OF SURFACE REACTIONS.

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

ELECTRICAL EXCITATION

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:

$$\nu_m = \nu_e + \nu_{\text{eff}}$$

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:

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

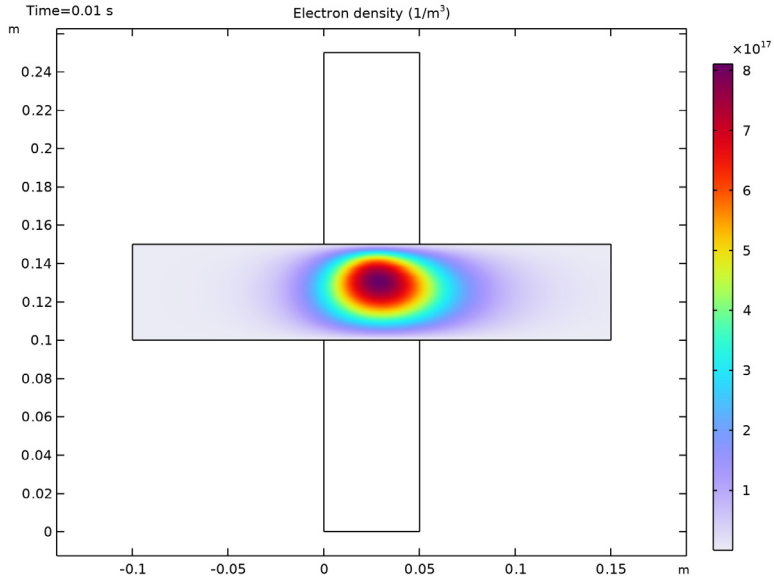


Figure 2: Plot of the electron density.

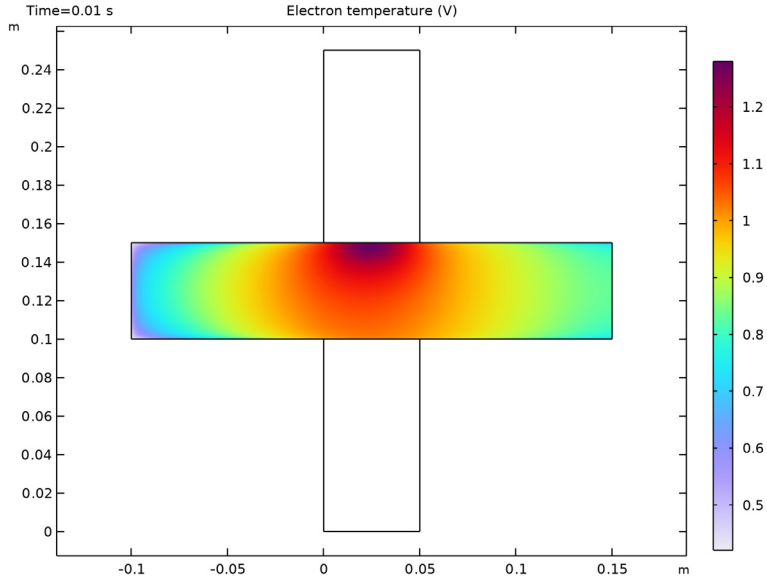


Figure 3: Plot of the electron temperature in the reactor.

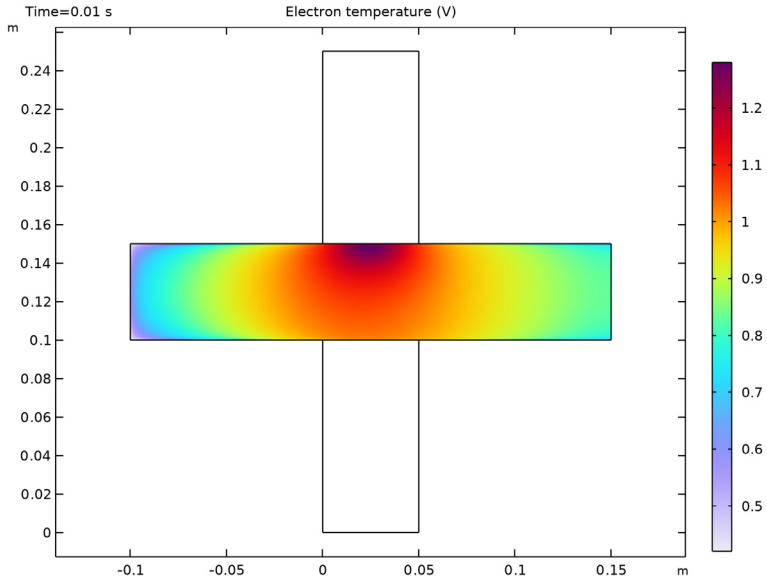


Figure 4: Plot of the plasma potential in the reactor.\

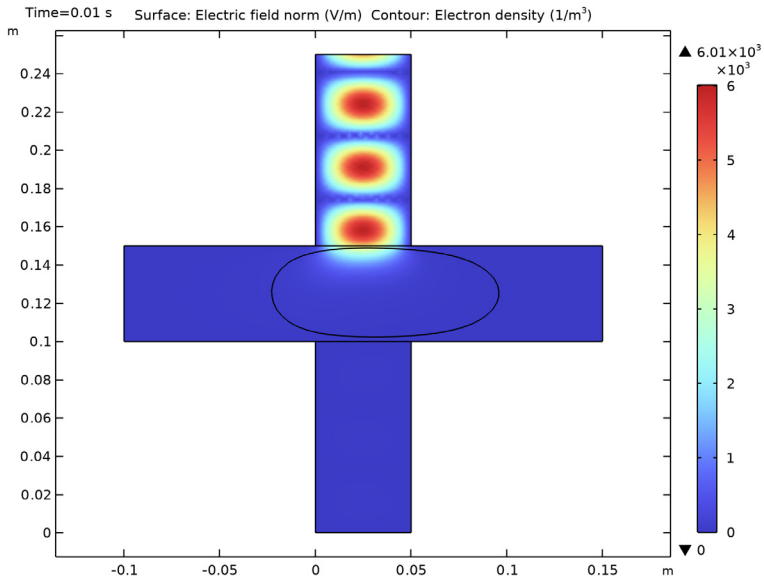


Figure 5: Plot of the electric field norm. The white contour represents the critical plasma

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

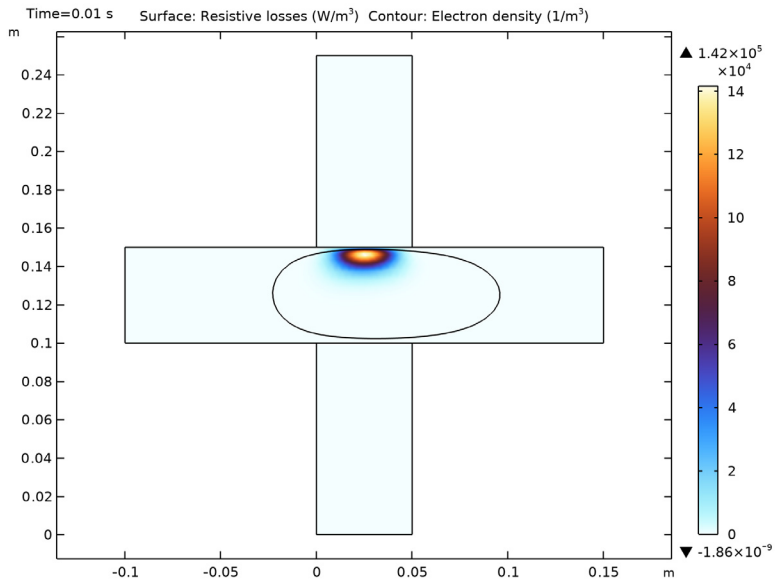


Figure 6: Plot of the power deposition into the plasma. The white contour represents the critical plasma density, where the electron density is equal to $7.6E16$ $1/m^3$.

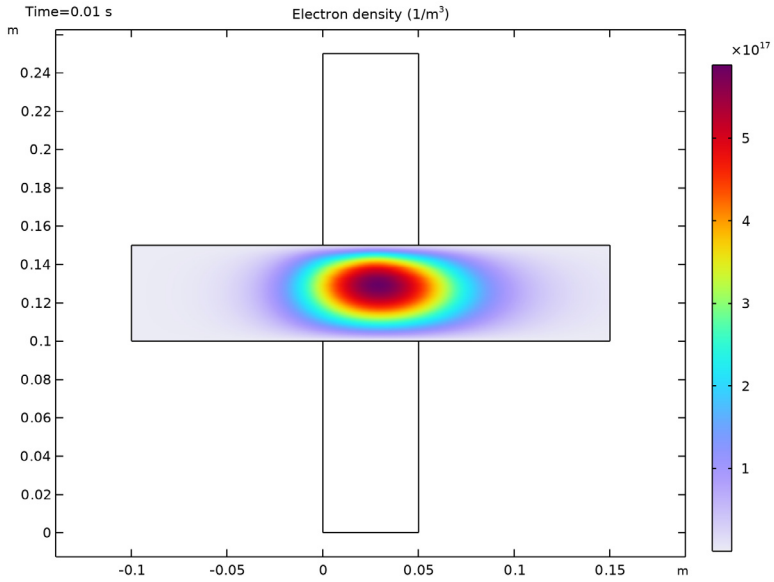


Figure 7: Electron density for the TM mode case.

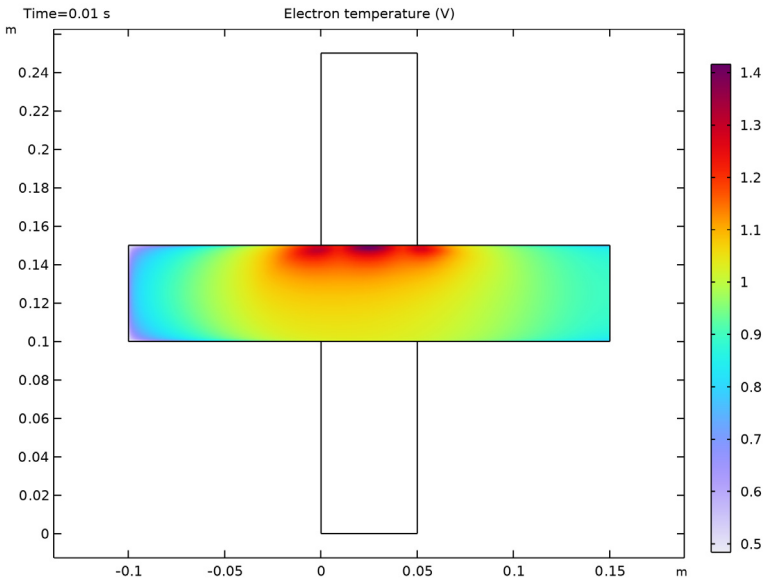


Figure 8: Plot of the electron temperature for the TM mode case.

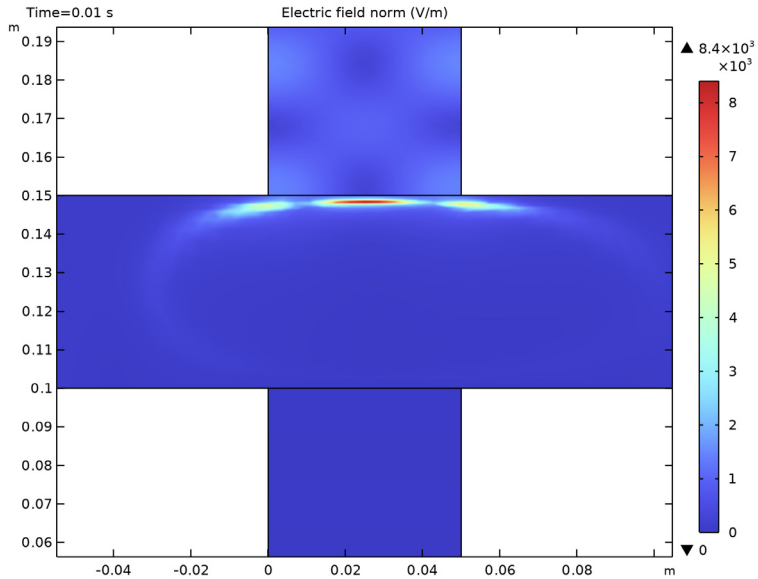


Figure 9: Close up of the high frequency electric field norm for the TM mode case.

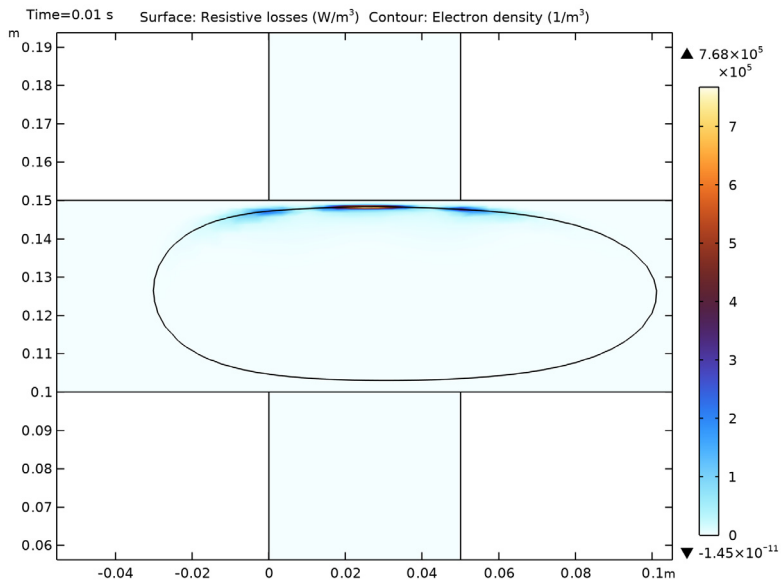


Figure 10: Close up of the power deposition into the plasma for the TM mode case.

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 I




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 $\text{Ar} + \text{Ar} \Rightarrow \text{e} + \text{Ar} + \text{Ar} +$.
- 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 $\text{Ar} + \text{Ar} \Rightarrow \text{Ar} + \text{Ar}$.
- 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** checkbox.


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** checkbox.

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 $\text{Ar} \text{ s} \Rightarrow \text{Ar}$.
- 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 $\text{Ar} \text{ +} \Rightarrow \text{Ar}$.
- 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 Select the **Convection** checkbox.
- 8 Locate the **Plasma Properties** section. Select the **Use reduced electron transport properties** checkbox.

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.


Outflow 1

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Outflow**.
- 2 Select Boundary 14 only.
- 3 In the **Settings** window for **Outflow**, locate the **Ions** section.
- 4 Select the **Include ions** checkbox.

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** checkbox.
- 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	epsilon _{r_iso} ; epsilon _{r_ii} = epsilon _{r_iso} , epsilon _{r_ij} = 0	5	l	Basic
Relative permeability	mu _{r_iso} ; mu _{r_ii} = mu _{r_iso} , mu _{r_ij} = 0	1	l	Basic
Electric conductivity	sigma _{iso} ; sigma _{ii} = sigma _{iso} , sigma _{ij} = 0	0	S/m	Basic

MESH I

Boundary Layers I

- 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 I

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 I

Step 1: Frequency–Transient

- 1 In the **Model Builder** window, under **Study I** 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, 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 **Study** 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** checkbox.
- 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) I** and choose **Rename**.

- 3 In the **Rename 2D Plot Group** dialog, type **Resistive Heating** in the **New label** text field.
- 4 Click **OK**.

Surface 1

- 1 In the **Model Builder** window, expand the **Resistive Heating** node, then click **Surface 1**.
- 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. From the **Color table** list, choose **ThermalWave**.
- 4 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** checkbox.
- 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 the **Add Study** button 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, 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 **Study** 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 **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID 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 **ID 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**.