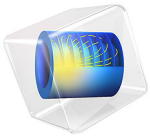

Alpha to Gamma Transition

Introduction

Capacitively coupled RF discharges can operate in two distinct regimes depending on the discharge power. In the low power regime, known as the α regime, the electric field oscillations heats and creates electrons. In the high power regime, known as γ regime, the discharge is sustained primarily by electron avalanche within the plasma sheath. This is initiated by secondary electrons emitted due to ion bombardment of the electrodes.

The two regimes present fundamental differences that can have an important impact in plasma applications. In the following, results are presented for the electron creation and power absorbed by the electrons that illustrate the main features of the two regimes.

The reader can found more information about this subject in Ref. 1 and in the references therein.

Model Definition

The model presented here is based on the one reported in Ref. 1 and simulates an atmospheric pressure argon plasma sustained by a periodic electric excitation at 13.56 MHz. The model is 1-dimensional and describes the space- and time-periodic evolution of several macroscopic properties of the plasma sustained within a 2 mm gap.

The electron mobility and other electron transport properties are automatically computed from the electron impact reactions. For the ions, the mobility is given as a function of the reduced electric field using a lookup table. The ion diffusivity is obtained from the Einstein relation where the ion temperature comes from a local field approximation. It is assumed that the molecular ion has the same mobility as the atomic ion.

ELECTRIC EXCITATION

The driven electrode has a fixed power. This corresponds to the following expression and constraint on the electric potential:

$$V_s = V_a \cos(2\pi f_p t + \alpha) \tag{1}$$

$$P_{rf} = f_p \int_{\partial t} \int_{\partial \Omega} V_s(\mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e + \mathbf{n} \cdot \mathbf{J}_d) dS dt \,. \tag{2}$$

The constraint in Equation 2 is used to compute the RF potential, V_a such that a fixed amount of power is deposited into the plasma.

PLASMA CHEMISTRY

Argon plasmas have one of the simplest reactions schemes. The electronically excited states can be lumped into single states. At atmospheric pressure and low gas temperature three–body reactions are important and lead to the creation of dimers. We use a simplified plasma chemistry similar to the one in Ref. 1 that comprises 9 volumetric reactions involving electrons (electron impact cross-section are obtained from Ref. 2), atomic and molecular ions, and a lumped level representing the argon 4s.

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	e+Ar2+=>Ars+Ar	Excitation	-2.5
7	Ars+Ars =>e+Ar+Ar+	Penning ionization	-
8	Ars => Ar	Spontaneous emission	-
9	2Ar+Ar+=>Ar+Ar2+	3-body Ar2+ creation	-

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

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT	SECONDARY EMISSION COEFFICIENT	MEAN ENERGY OF SECONDARY ELECTRONS (V)
1	Ars=>Ar	1	0	0
3	Ar+=>Ar	0	0.1	5.8
4	Ar2+=>2Ar	0	0.1	5.8

When excited states make contact with the wall, they revert to the ground state argon atom with some probability. The ions use their internal energy to extract one electron from the wall with a probability of 0.1 and a mean energy of 5.8 V. For the ions, the sticking coefficient is zero, meaning that losses to the wall are assumed to be due to migration only.

Results and Discussion

The temporal evolution of the one-dimensional electron density is conveniently represented by extruding the solution into two dimensions. The extra dimension

represents the period fraction. In COMSOL Multiphysics this is accomplished by adding a *Parametric Extrusion 1D* dataset.

Figure 1and Figure 2 present, for the α regime, the spatial distribution of the electron number density and electron temperature (along the horizontal axis) extruded in time for one period of the external excitation along the vertical axis. These results show that this discharge is similar to lower pressure RF capacitively coupled discharges. The electron density is static in time in the discharge center. However, near the wall the electron density evolves in time driven by the applied time–varying electric field. The electron temperature near the wall is also strongly time modulated attaining peak electron temperatures of 3.5 eV. In the plasma bulk the electron temperature is much cooler than near the walls and is much less modulated since the electric field is much less intense than in the sheaths.

Figure 3 shows the power absorbed by the plasma and the averaged electron density as a function of the voltage amplitude. It is possible to identify two regions: (i) a low power region, corresponding to the α regime, where larger voltages amplitudes are needed to increase the power absorbed by the discharge; (ii) and a high power region, corresponding to the γ regime, where high discharge powers are attained for progressively lower voltages amplitudes. The electron density always increases with the applied voltage, however, it increases at a faster rate in the γ regime.

The different mechanisms for electron heating and electron creation for both the α and γ regimes are shown in Figure 4 through Figure 7. Figure 4 and Figure 5 show the power absorbed by the electrons. Figure 6 and Figure 7 show the electron production rate. The white line marks a region of constant charge density that roughly corresponds to the plasma-sheath transition. In the α regime a great part of the absorbed power and most of electron creation is localized along the plasma-sheath transition with the peak values occurring during the sheath expansion. In the γ regime the majority of the absorbed power and ionization occur at the sheath maximum expansion.

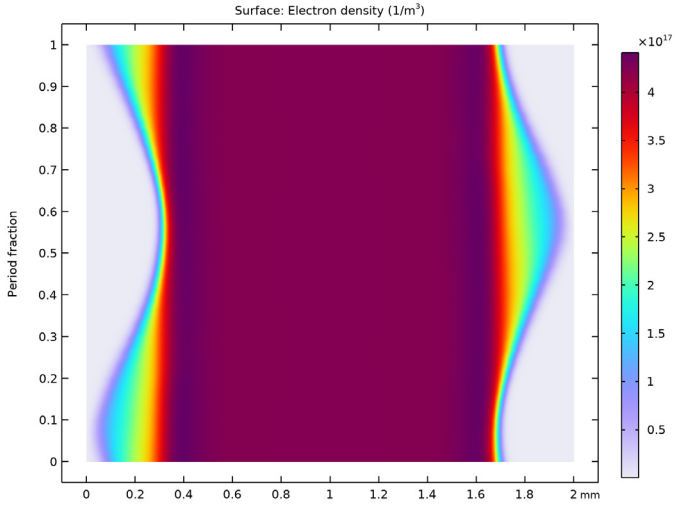

Figure 1: Electron number density spatial and time evolution in the α regime (100 W).

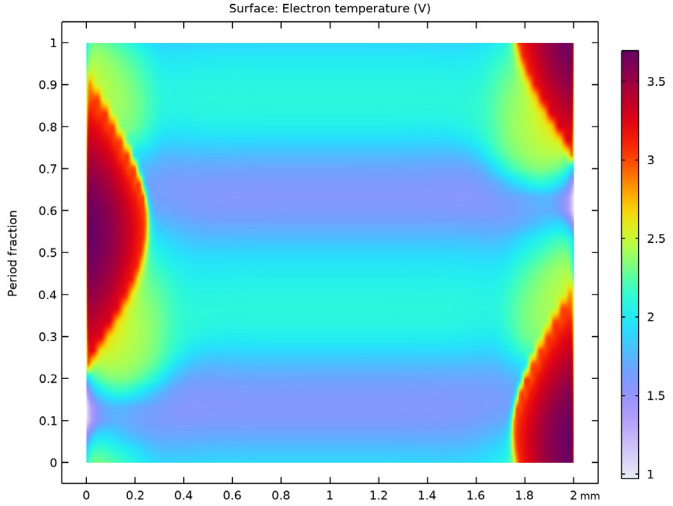

Figure 2: Electron temperature spatial and time evolution in the α regime (100 W).

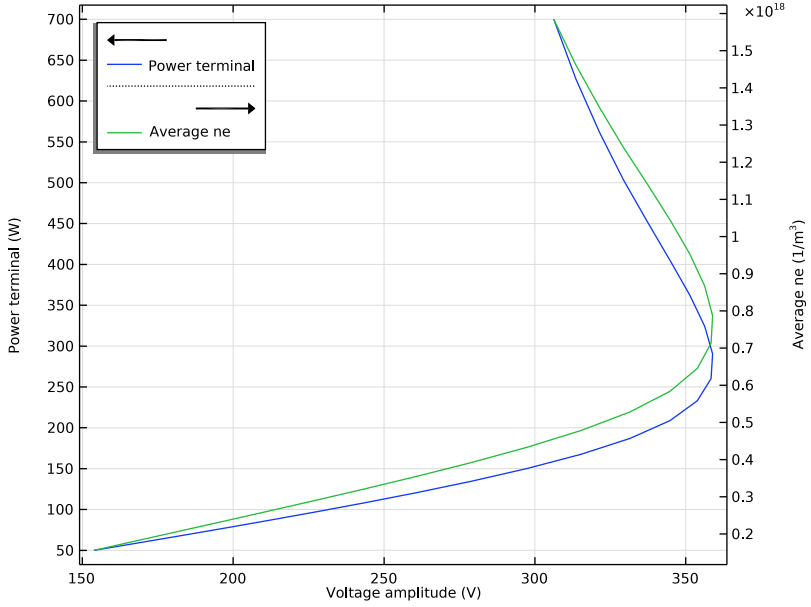

Figure 3: Power absorbed by the plasma and average electron density as a function of the source voltage amplitude.

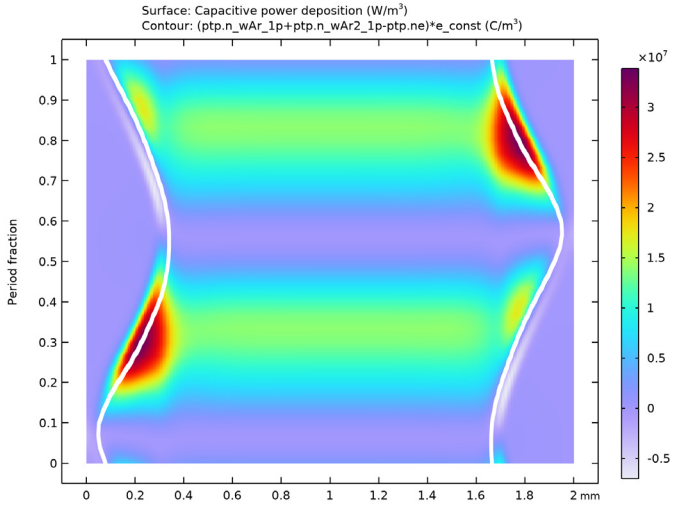

Figure 4: Power absorbed by the electrons in the α regime (100 W). The white line is a counter of constant charge density (0.01 C/m^3) that roughly represents the boundary between plasma and sheath.

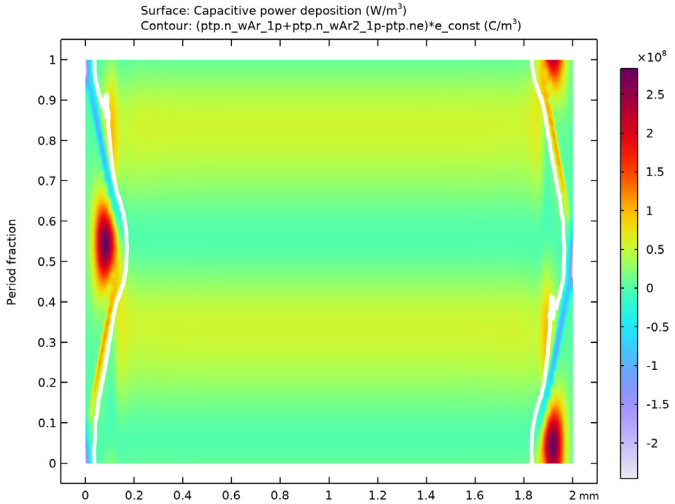

Figure 5: Power absorbed by the electrons in the γ regime (630 W). The white line is a counter of constant charge density (0.01 C/m^3) that roughly represents the boundary between plasma and sheath.

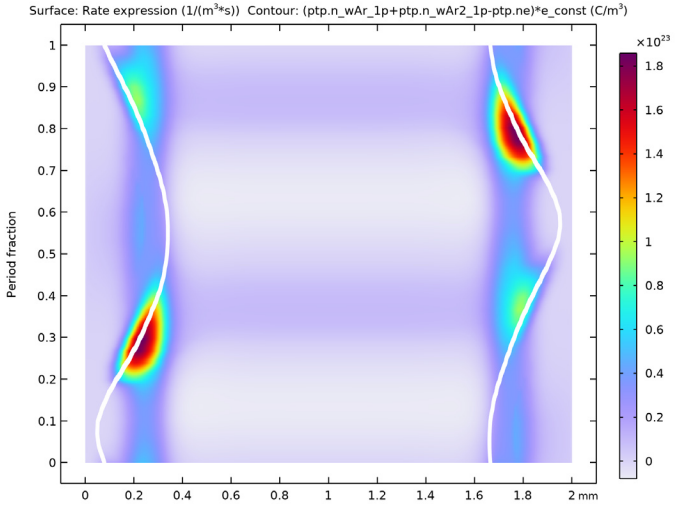

Figure 6: Electron creation rate in the α regime (100 W). The white line is a counter of constant charge density (0.01 C/m³) that roughly represents the boundary between plasma and sheath.

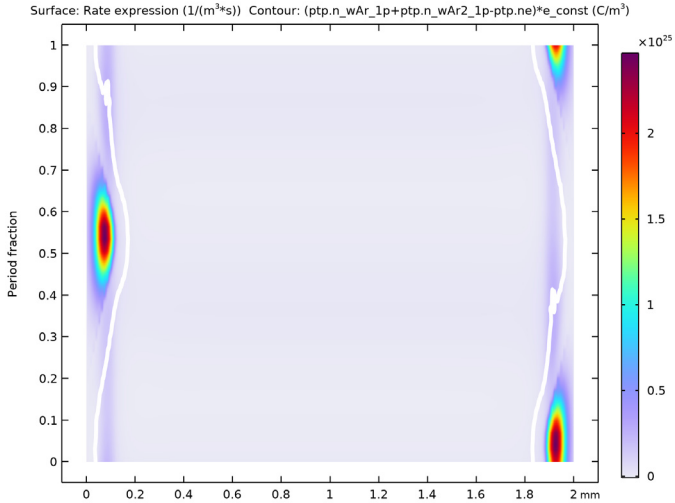

Figure 7: Electron creation rate in the γ regime (630 W). The white line is a counter of constant charge density (0.01 C/m³) that roughly represents the boundary between plasma and sheath.

References

1. N Balcon, G.J.M. Hagelaar, and J.P. Boeuf, "Numerical model of an argon atmospheric pressure RF discharge", *IEEE Trans. Plasma Sci.*, vol. 36, p. 2782 (6pp), 2008.

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

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

Application Library path: `Plasma_Module/Capacitively_Coupled_Plasmas/alpha_to_gamma_transition`

Modeling Instructions

In the following are the instructions to create a 1D model of a RF capacitively coupled plasma that is used to demonstrate the α to γ transition in an argon discharge. The transition is represented in the form of absorbed power as a function of applied voltage. To obtain such plot, a **Time Periodic** study is performed where power is swept from 50 to 700 W. After that study, two **Time Periodic to Time Dependent** studies are performed to convert the periodic steady-state solutions from two different powers (from the first study) to the time domain. The conversion to the time domain is necessary in order to create surface plots representing the spatial and time variation of different quantities.

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

NEW

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

MODEL WIZARD

1. In the **Model Wizard** window, Select the **Plasma, Time Periodic (ptp)** interface and the **Time Periodic** study to compute the periodic steady state solution of the plasma.
2. click **1D**.
3. In the **Select Physics** tree, select **Plasma>Plasma, Time Periodic (ptp)**.
4. Click **Add**.
5. Click **Study**.

6 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> Time Periodic**.

7 Click **Done**.

GEOMETRY 1

Create the 2 mm gap where the plasma is sustained.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

3 From the **Length unit** list, choose **mm**.

Interval 1 (i1)

1 In the **Model Builder** window, expand the **Geometry 1** node.

2 Right-click **Component 1 (comp1)>Geometry 1** and choose **Interval**.

3 In the **Settings** window for **Interval**, locate the **Interval** section.

4 In the table, enter the following settings:

Coordinates (mm)
0
2

Add some parameters for the power and excitation frequency.

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
f0	13.56[MHz]	1.356E7 Hz	
Prf	1[W]	1 W	

Add a nonlocal average coupling to compute the average electron density in postprocessing.

DEFINITIONS (COMP1)

Average 1 (aveop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Average**.

2 In the **Settings** window for **Average**, locate the **Source Selection** section.

3 From the **Selection** list, choose **All domains**.

Set the area perpendicular to the solved dimension and set the period and the number of elements in the extra dimension.

PLASMA, TIME PERIODIC (PTP)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Plasma, Time Periodic (ptp)**.

2 In the **Settings** window for **Plasma, Time Periodic**, locate the **Cross-Section Area** section.

3 In the A text field, type `80[cm^2]`.

4 Locate the **Extra Dimension Settings** section. In the P_{xd} text field, type `1/f0`.

5 In the N text field, type `30`.

Set the temperature and use the default pressure of 1 atm for the background gas. The electron mobility and other transport parameters are by default to automatically computed from the set of electron impact reactions.

Plasma Model 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Plasma, Time Periodic (ptp)** click **Plasma Model 1**.

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

3 In the T text field, type `300[K]`.

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 `1E15[1/m^3]`.

4 In the ε_0 text field, type `2[V]`.

Import cross section data for argon.

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**.

Add other reactions to complete the plasma chemistry.

Electron Impact Reaction 6

1 In the **Physics** toolbar, click **Domains** and choose **Electron Impact Reaction**.

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

3 In the **Formula** text field, type `e+Ar2+=>Ars+Ar`.

4 Locate the **Collision Type** section. From the **Collision type** list, choose **Excitation**.

5 In the $\Delta\varepsilon$ text field, type `-2.5[V]`.

6 Locate the **Reaction Parameters** section. In the k^f text field, type `7e-13[m^3/s]*N_A_const*(300/(ptp.Te*11600))^0.5`.

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 `1.2e-15[m^3/s]*N_A_const`.

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`.

4 Locate the **Reaction Parameters** section. In the k^f text field, type `5e5`.

Reaction 3

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 `Ar+Ar+Ar+=>Ar2++Ar`.

4 Locate the **Reaction Parameters** section. In the k^f text field, type `2.5e-43[m^6/s]*N_A_const^2`.

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.

4 Locate the **General Parameters** section. From the **Preset species data** list, choose **Ar**.

Species: Ars

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

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

3 From the **Preset species data** list, choose **Ar**.

The electric fields generated will be rather high in the sheath, so use the local field approximation for the ion temperature, and a lookup table for the ion mobility.

Species: Ar+

1 In the **Model Builder** window, click **Species: Ar+**.

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

3 From the **Preset species data** list, choose **Ar**.

4 Locate the **Mobility and Diffusivity Expressions** section. From the **Specification** list, choose **Specify mobility, compute diffusivity**.

5 From the **Ion temperature** list, choose **Use local field approximation**.

6 Locate the **Mobility Specification** section. From the **Specify using** list, choose **Argon ion in argon**.

The mobility of the molecular ion is assumed equal to the atomic ion for simplicity.

Species: Ar2+

1 In the **Model Builder** window, click **Species: Ar2+**.

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

3 Select the **Initial value from electroneutrality constraint** check box.

4 Locate the **General Parameters** section. In the M_{w} text field, type `0.08[kg/mol]`.

5 Locate the **Mobility and Diffusivity Expressions** section. From the **Specification** list, choose **Specify mobility, compute diffusivity**.

6 From the **Ion temperature** list, choose **Use local field approximation**.

7 Locate the **Mobility Specification** section. From the **Specify using** list, choose **Argon ion in argon**.

Define surface losses for ions and argon excited state. For the ions, set the **Forward sticking coefficient** to zero to assume that ion losses are due to migration only, and set the **Secondary emission coefficient** to 0.1 to match the work that it is being followed.

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 `Ar+=>Ar`.

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

5 Locate the **Reaction Parameters** section. In the γ_f text field, type `0`.

6 Locate the **Secondary Emission Parameters** section. In the γ_i text field, type `0.1`.

2: Ar+=>Ar

1 Right-click **1: Ar+=>Ar** and choose **Duplicate**.

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

3 In the **Formula** text field, type `Ar2+=>2Ar`.

3: Ar2+=>2Ar

1 Right-click **2: Ar2+=>2Ar** and choose **Duplicate**.

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 **Secondary Emission Parameters** section. In the γ_i text field, type `0`.

5 In the ε_i text field, type `0`.

6 Locate the **Reaction Parameters** section. In the γ_f text field, type `1`.

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 **All boundaries**.

Define the electric excitation of the discharge. Set a ground and a RF power source on the boundaries.

Ground 1

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

2 Select Boundary 2 only.

The most stable way of driving the electrode is to use a fixed power. Use the previously defined parameter Prf to set the **RF power**. The exact values for the power sweep are set later in the study.

Metal Contact 1

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

2 Select Boundary 1 only.

3 In the **Settings** window for **Metal Contact**, locate the **Terminal** section.

4 From the **Source** list, choose **RF**.

5 Locate the **RF Source** section. In the P_{rf} text field, type `Prf`.

6 In the f_p text field, type `f0`.

MESH 1

Edge 1

In the **Mesh** toolbar, click **Edge**.

Distribution 1

1 Right-click **Edge 1** and choose **Distribution**.

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

3 From the **Distribution type** list, choose **Predefined**.

4 In the **Number of elements** text field, type `150`.

5 In the **Element ratio** text field, type `10`.

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

7 Click **Build All**.

STUDY 1

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

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

3 Clear the **Generate default plots** check box.

4 Clear the **Generate convergence plots** check box.

Set a power sweep to observe the alpha to gamma transition in a plot of power as a function of applied voltage.

Step 1: Time Periodic

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Periodic**.

2 In the **Settings** window for **Time Periodic**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** check box.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Prf		W

6 Click **Range**.

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

8 In the **Start** text field, type `log10(50)`.

9 In the **Stop** text field, type `log10(700)`.

10 In the **Number of values** text field, type 25.

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

12 Click **Add**.

13 In the **Study** toolbar, click **Get Initial Value**.

Create a plot of power and average electron density as a function of the voltage amplitude.

RESULTS

Power and ne vs. applied voltage

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

2 In the **Settings** window for **1D Plot Group**, type `Power and ne vs. applied voltage` in the **Label** text field.

Global 1

1 Right-click **Power and ne vs. applied voltage** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`ptp.mct1.PowerT`	W	`Power terminal`

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

5 In the **Expression** text field, type `ptp.mct1.Va_per`.

Global 2

1 Right-click **Global 1** and choose **Duplicate**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
aveop1(ptp.neav)	1/m^3	Average ne

Power and ne vs. applied voltage

1 In the **Model Builder** window, click **Power and ne vs. applied voltage**.

2 In the **Settings** window for **1D Plot Group**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section. Select the **Two y-axes** check box.

5 In the table, select the **Plot on secondary y-axis** check box for **Global 2**.

6 Locate the **Legend** section. From the **Position** list, choose **Upper left**.

STUDY 1

Solver Configurations

In the **Model Builder** window, expand the **Study 1>Solver Configurations** node.

Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)** node.

Choose to observe the results of the plot previously created while solving.

2 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)>Stationary Solver 1** node, then click **Fully Coupled 1**.

3 In the **Settings** window for **Fully Coupled**, click to expand the **Results While Solving** section.

4 Select the **Plot** check box.

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

RESULTS

Power and ne vs. applied voltage

So far, we have computed the periodic steady state solution only. In order to see the time-dependent behavior of the plasma, we need to convert the solution to the time domain. To do this, use the **Time Periodic to Time Dependent** study.

Add two **Time Periodic to Time Dependent** studies to represent the temporal evolution for two different powers.

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 Physics Interfaces>Time Periodic to Time Dependent**.

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

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> Time Periodic to Time Dependent**.

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

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

STUDY 2

1 In the **Model Builder** window, click **Study 2**.

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

3 Clear the **Generate default plots** check box.

4 Clear the **Generate convergence plots** check box.

The final output time should correspond to 1 RF cycle. The number of output times should typically be around 100. When computing the time periodic solution, only 30 points were used in the (hidden) time axis. When converting to the time domain, COMSOL will use linear interpolation of the solution between these points.

Step 1: Time Periodic to Time Dependent

1 In the **Model Builder** window, under **Study 2** click **Step 1: Time Periodic to Time Dependent**.

2 In the **Settings** window for **Time Periodic to Time Dependent**, locate the **Study Settings** section.

3 Click **Range**.

4 In the **Range** dialog box, type `(1/f0)/101` in the **Step** text field.

5 In the **Stop** text field, type `1/f0`.

6 Click **Replace**.

7 In the **Settings** window for **Time Periodic to Time Dependent**, click to expand the **Values of Dependent Variables** section.

8 Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

9 From the **Method** list, choose **Solution**.

10 From the **Study** list, choose **Study 1, Time Periodic**.

11 From the **Parameter value (Prf (W))** list, choose **From list**.

12 In the **Parameter value (Prf (W))** list, select **107.96 W**.

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

STUDY 3

1 In the **Model Builder** window, click **Study 3**.

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

3 Clear the **Generate default plots** check box.

4 Clear the **Generate convergence plots** check box.

Step 1: Time Periodic to Time Dependent

1 In the **Model Builder** window, under **Study 3** click **Step 1: Time Periodic to Time Dependent**.

2 In the **Settings** window for **Time Periodic to Time Dependent**, locate the **Study Settings** section.

3 Click **Range**.

4 In the **Range** dialog box, type `(1/f0)/101` in the **Step** text field.

5 In the **Stop** text field, type `1/f0`.

6 Click **Replace**.

7 In the **Settings** window for **Time Periodic to Time Dependent**, locate the **Values of Dependent Variables** section.

8 Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

9 From the **Method** list, choose **Solution**.

10 From the **Study** list, choose **Study 1, Time Periodic**.

11 From the **Parameter value (Prf (W))** list, choose **From list**.

12 In the **Parameter value (Prf (W))** list, select **627.11 W**.

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

Next, create parametric extrusion datasets to later represent space and time evolution of different variables in a 2D surface plot.

RESULTS

Parametric Extrusion 1D 1

1 In the **Results** toolbar, click  **More Datasets** and choose **Parametric Extrusion 1D**.

2 In the **Settings** window for **Parametric Extrusion 1D**, locate the **Data** section.

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

4 Locate the **Settings** section. In the **Level scale factor** text field, type `f0`.

Parametric Extrusion 1D 2

1 Right-click **Parametric Extrusion 1D 1** and choose **Duplicate**.

2 In the **Settings** window for **Parametric Extrusion 1D**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3/Solution 3 (sol3)**.

Create plots for the electron density and temperature in the alpha regime.

Electron density, alpha regime

1 In the **Results** toolbar, click  **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Electron density, alpha regime` in the **Label** text field.

3 Locate the **Plot Settings** section.

4 Select the **y-axis label** check box. In the associated text field, type `Period fraction`.

Surface 1

1 Right-click **Electron density, alpha regime** and choose **Surface**.

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

3 In the **Expression** text field, type `ptp.ne`.

4 In the **Electron density, alpha regime** toolbar, click  **Plot**.

Electron temperature, alpha regime

1 In the **Model Builder** window, right-click **Electron density, alpha regime** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Electron temperature, alpha regime` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Electron temperature, alpha regime** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `ptp.Te`.

4 In the **Electron temperature, alpha regime** toolbar, click **Plot**.

Create plots for the power absorbed by electrons and the ionization rate for the alpha and gamma regimes. Add contour lines of the charge density that roughly represent the plasma sheath boundary.

Power absorbed by electrons, alpha regime

1 In the **Model Builder** window, right-click **Electron temperature, alpha regime** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Power absorbed by electrons, alpha regime` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Power absorbed by electrons, alpha regime** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `ptp.Pcap`.

Contour 1

1 In the **Model Builder** window, right-click **Power absorbed by electrons, alpha regime** and choose **Contour**.

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

3 In the **Expression** text field, type `(ptp.n_wAr_1p+ptp.n_wAr2_1p-ptp.ne)*e_const`.

4 Locate the **Levels** section. From the **Entry method** list, choose **Levels**.

5 In the **Levels** text field, type `1e-2`.

6 Locate the **Coloring and Style** section. From the **Contour type** list, choose **Tube**.

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

8 From the **Color** list, choose **White**.

9 Clear the **Color legend** check box.

10 In the **Power absorbed by electrons, alpha regime** toolbar, click **Plot**.

Power absorbed by electrons, gamma regime

1 Right-click **Power absorbed by electrons, alpha regime** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Power absorbed by electrons, gamma regime` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Parametric Extrusion 1D 2**.

4 In the **Power absorbed by electrons, gamma regime** toolbar, click **Plot**.

Electron source, alpha regime

1 Right-click **Power absorbed by electrons, alpha regime** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Electron source, alpha regime` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Electron source, alpha regime** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `ptp.Re`.

4 In the **Electron source, alpha regime** toolbar, click **Plot**.

Electron source, gamma regime

1 In the **Model Builder** window, right-click **Electron source, alpha regime** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Electron source, gamma regime` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Parametric Extrusion 1D 2**.

4 In the **Electron source, gamma regime** toolbar, click **Plot**.