Model created in COMSOL Multiphysics 6.4

Thermal Plasma

Introduction

Low pressure discharges are characterized by the fact that the electron temperature is much higher than the neutral gas temperature. As the gas pressure increases, the number of collisions between the electrons and neutrals increases. At high enough pressures the electron temperature becomes equal to the gas temperature. At this point the plasma is in local thermodynamic equilibrium and a much simpler MHD model can be used to model the plasma.

This model simulates a plasma at medium pressure (1 torr), where the gas temperature cannot be assumed to be constant but the plasma is still not in local thermodynamic equilibrium. In Figure 1 the electron (blue) and gas (black) temperatures are plotted as a function of pressure. At low pressures the two temperatures are decoupled, but as the pressure increases the temperatures tend toward the same limit. There are no axes on the plot since the exact temperature and pressure depend strongly on the gas in question.

Note: This application requires the Plasma Module and AC/DC Module.

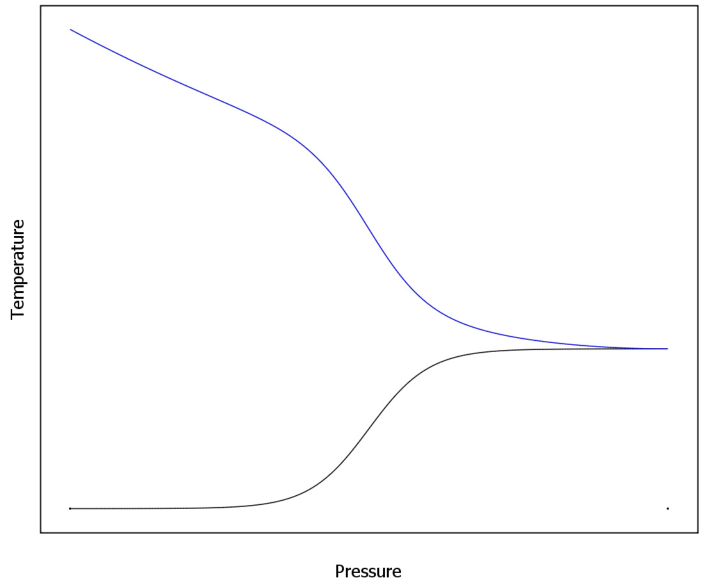

Figure 1: Plot of electron (blue) and gas (black) temperature versus pressure. At higher pressures the two temperatures become equal.

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*)

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

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

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

$$k^f = N_A \gamma \int_0^\infty \varepsilon \sigma(\varepsilon) f(\varepsilon) d\varepsilon$$

where $\gamma = (2q/m_e)^{1/2}$ (SI unit: $C^{1/2}/kg^{1/2}$), 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: $1/(m^2 \cdot s)$). 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

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

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*.

PLASMA CHEMISTRY

Argon is one of the simplest mechanisms to implement at low pressures. The electronically excited states can be lumped into a single species which results in a chemical mechanism consisting of only 3 species and 7 reactions (electron impact cross sections are obtained from Ref. 2):

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon(\text{eV})$
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

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
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 1, elastic collisions with electrons is primarily responsible for heating of the gas. 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 reactor geometry is simply a cylindrical glass tube with a 4-turn coil wrapped around it. Gas flows in from the bottom and exits out of the top. The gas is heated through elastic and inelastic collisions. A fixed power of 700 W is applied to the coil.

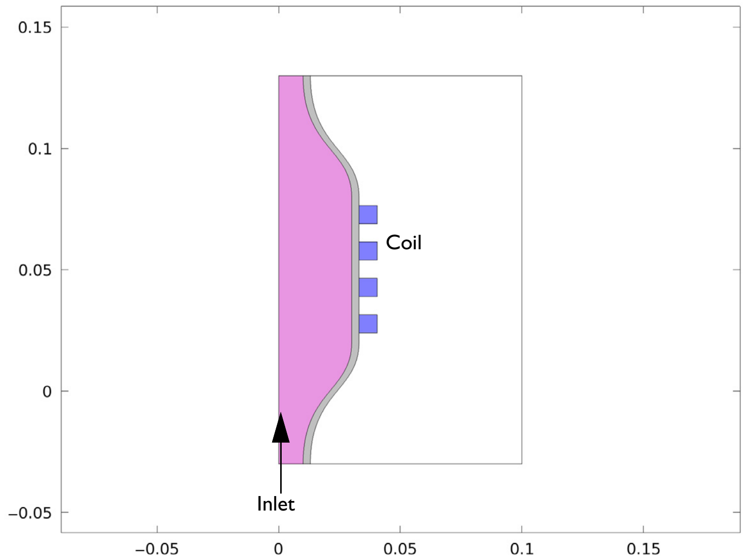

Figure 2: Schematic of the ICP reactor. Flow enters from the base and leaves out the top.

STRATEGY TO SETUP A MODEL WITH INLETS AND OUTLETS

In this model, an inlet or argon is added in the system. There is also an outlet responsible to fix the system pressure. After setting the **Inlet** and **Outlet** features in the **Laminar Flow** interface the following reasoning should be used to set up the **Inlet** and **Outflow** subfeatures of the species in the **Plasma** interface:

- If a species is set **From mass constraint** it does not need any **Inlet** and **Outflow** subfeature since its mass fraction is computed so that the mass in the system is conserved. There are no dependent variables being solved for the mass constraint species and as such does not need the boundary conditions set by the subfeatures.
- If the feed into the system contains another species (the present model does not have) one of these species should be set as mass constraint and the other should use an **Inlet** subfeature that specifies the appropriate proportion. Consider as an example of a feed of Ar/O2 at 60/40 mole fraction. If Ar is set as mass constrain than O2 should have an **Inlet** subfeature with a mole fraction of 0.4.

- If the species in created inside the reactor (as are Ar+ and Ars) no **Inlet** subfeature should be added.
- If the species flows out of the system (as are Ar+ and Ars) an **Outflow** subfeature should be added.

Results

Results of the different quantities computed in this model are presented below. The electron density reaches high values while the electron temperature is kept very low meaning that electron losses by transport are small. The gas temperature in the system peaks to 1300 K showing that there is a considerable amount of energy transferred from the electrons to the heavy species that is not lost in transport. More that 90% of the heating of the gas is caused by electron impact elastic collisions defined in reaction 1.

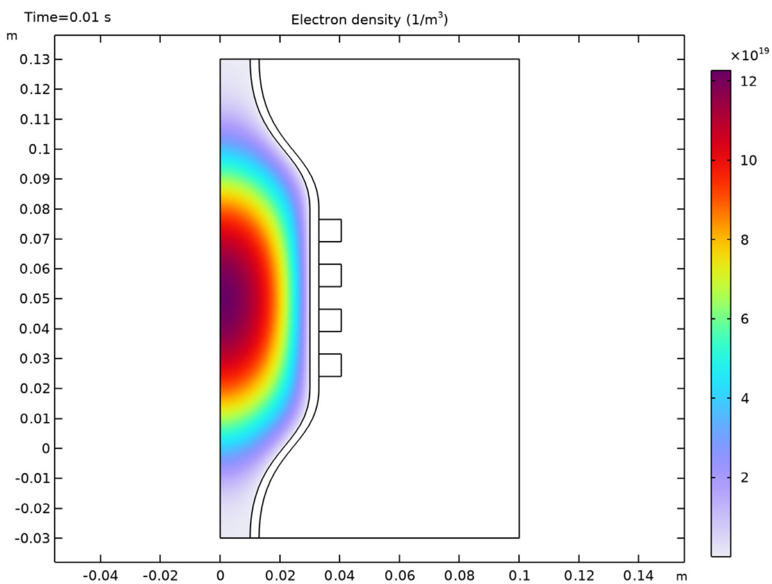

Figure 3: Electron density inside the column.

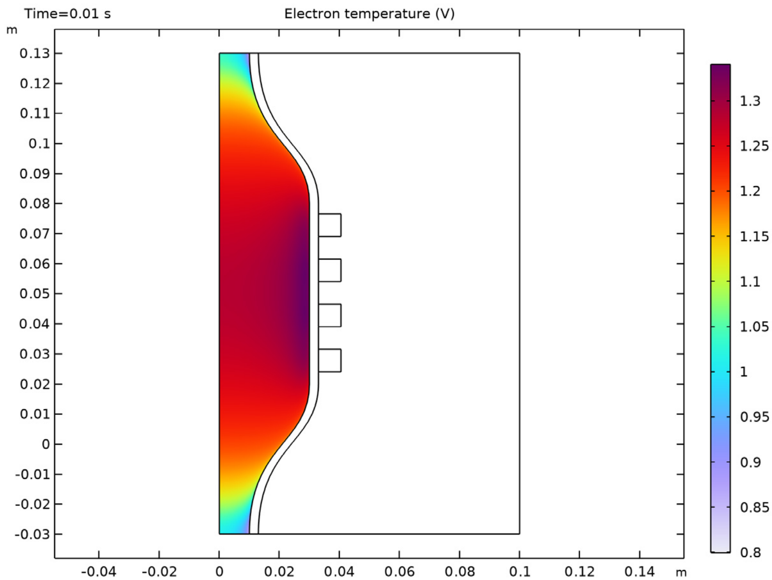

Figure 4: Electron temperature inside the plasma source.

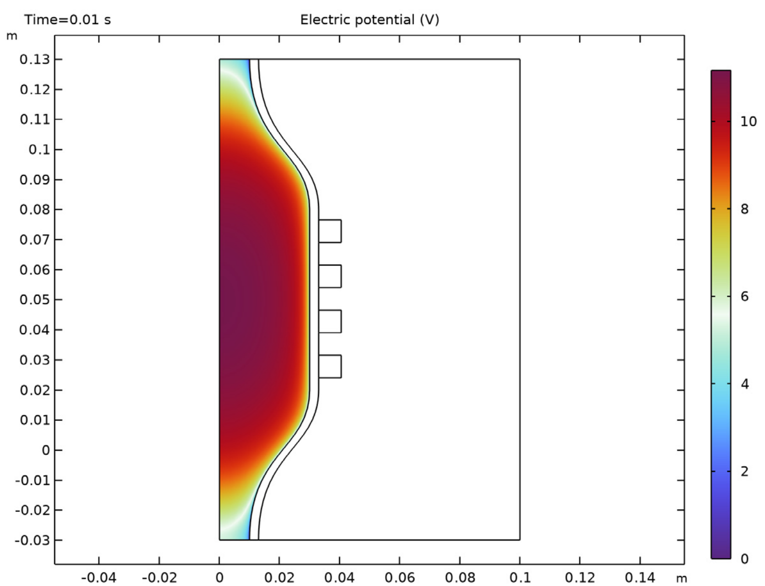

Figure 5: Plasma potential inside the plasma source.

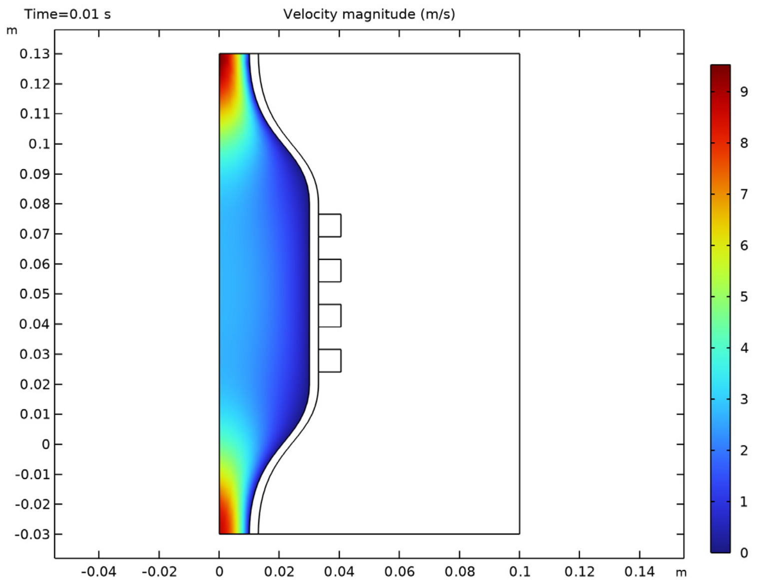

Figure 6: Velocity field inside the plasma source.

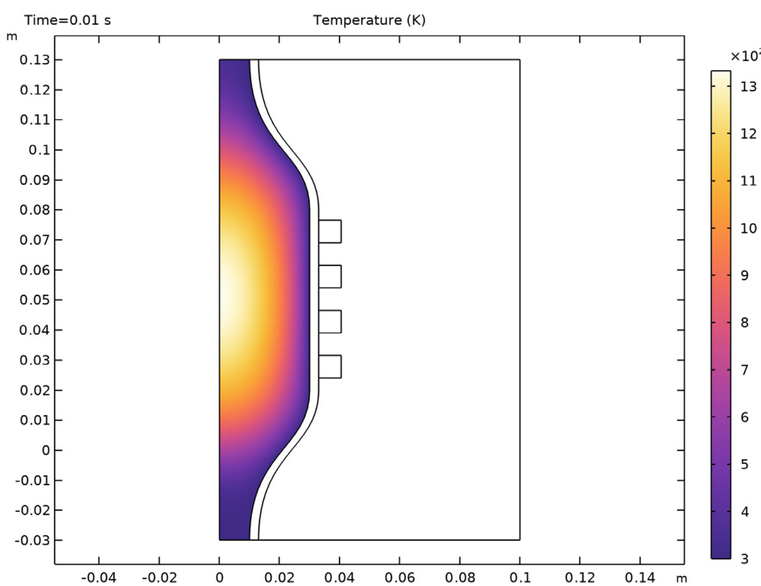

Figure 7: Temperature inside the plasma source.

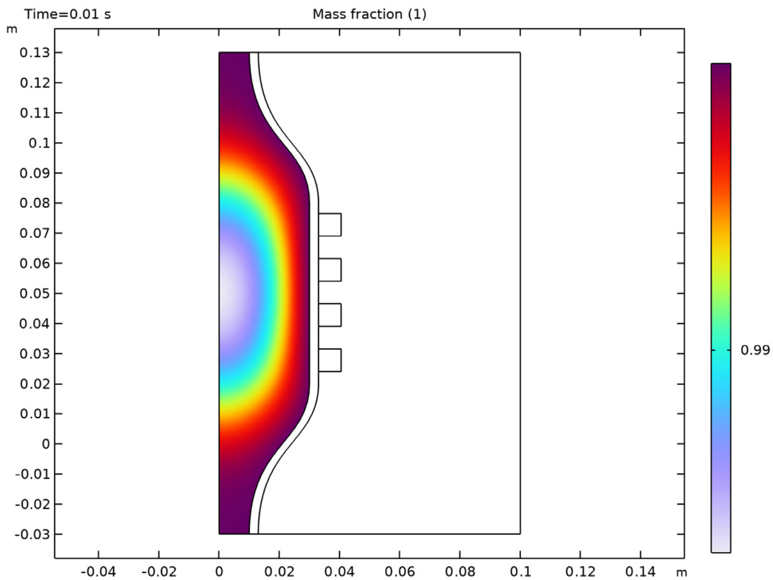

Figure 8: Mass fraction of ground state argon.

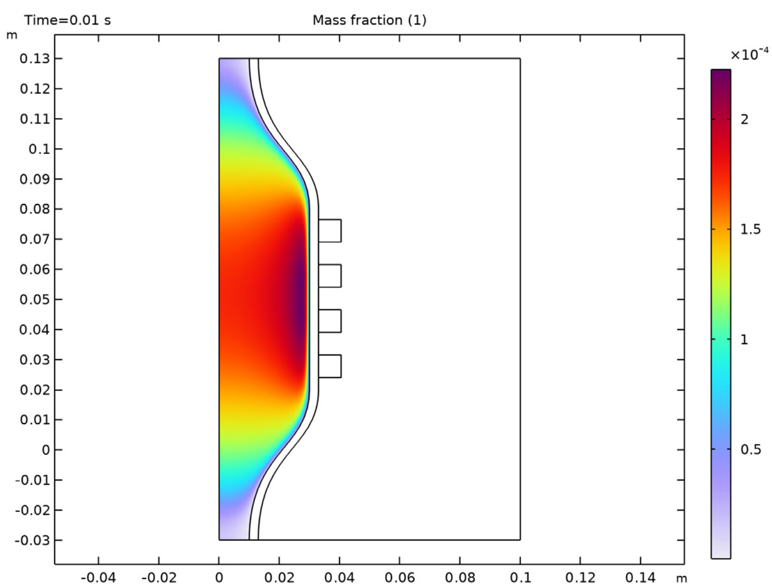

Figure 9: Mass fraction of electronically excited argon atoms.

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/Inductively_Coupled_Plasmas/thermal_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 Axisymmetric**.

2 In the **Select Physics** tree, select **Plasma** > **Nonisothermal Plasma Flow** > **Inductively Coupled Plasma**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

GEOMETRY 1

1 Click the **Show More Options** button in the **Model Builder** toolbar.

2 In the **Show More Options** dialog, in the tree, select the checkbox for the node **Physics** > **Advanced Physics Options**.

3 In the tree, select the checkbox for the node **Physics** > **Stabilization**.

4 Click **OK**.

Import 1 (imp1)

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

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

3 Click **Browse**.

4 Browse to the model's Application Libraries folder and double-click the file `thermal_plasma.mphbin`.

5 Click **Import**.

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	1[torr]	133.32 Pa	Initial and outlet pressure

DEFINITIONS

Plasma

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

2 Select Domain 1 only.

3 In the **Settings** window for **Explicit**, type `Plasma` in the **Label** text field.

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 9, 10, 34, and 35 only.

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

Outlet

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 Boundary 4 only.

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

Coil 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 12, 13, 15–17, 19, 21, 22, 24–26, and 28–32 only.

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

Start by importing the cross sections for argon and by activating the convection and thermodynamic property evaluation.

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 From the **Selection** list, choose **Plasma**.

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**.

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

7 In the **Settings** window for **Plasma**, locate the **Plasma Properties** section.

8 Select the **Use reduced electron transport properties** checkbox.

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`.

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**.

Surface Reaction 1

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

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

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

4 Locate the **Reaction Formula** section. In the **Formula** text field, type `Ar+=>Ar`.

Surface Reaction 2

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

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

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

4 Locate the **Reaction Formula** section. In the **Formula** text field, type `Ars=>Ar`.

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**.

Outflow 1

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

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

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

4 Locate the **Ions** section. Select the **Include ions** 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 **From mass constraint** checkbox.

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 In the x_0 text field, type `1E-4`.

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

5 Click to expand the **Species Thermodynamic Parameters** section. In the Δh text field, type `11.5`.

The thermodynamic properties for the electronically excited argon atoms can be the same as for the ground state species plus the threshold energy for the electron impact reaction. In this case this corresponds to an energy of 11.5eV. This is added in the text field **Additional enthalpy contribution**.

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.

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

5 Locate the **Species Thermodynamic Parameters** section. In the Δh text field, type `15.8`.

The thermodynamic properties for the argon ions can be the same as for the ground state species plus the threshold energy for ionization. In this case this corresponds to an energy of 15.8eV. This is added in the text field **Additional enthalpy contribution**.

You can set the gas temperature and pressure in the plasma model to the computed gas pressure and temperature from other physics interfaces. The velocity field is also set to the velocity field computed from the **Laminar Flow** interface.

Plasma Model 1

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

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

3 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 `1E15`.

4 In the ε_0 text field, type `3`.

MAGNETIC FIELDS (MF)

In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic Fields (mf)**.

Domain Coil 1

1 In the **Physics** toolbar, click **Domains** and choose **Domain Coil**.

2 Select Domains 4–7 only.

3 In the **Settings** window for **Domain Coil**, locate the **Coil** section.

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

5 Select the **Coil group** checkbox.

6 In the P_{coil} text field, type `700[W]`.

LAMINAR FLOW (SPF)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Laminar Flow (spf)**.

2 In the **Settings** window for **Laminar Flow**, click to expand the **Consistent Stabilization** section.

3 Find the **Navier–Stokes equations** subsection. Clear the **Crosswind diffusion** checkbox.

Define the pressure reference level to be 1 torr.

4 Locate the **Physical Model** section. In the p_{ref} text field, type `p0`.

5 Locate the **Domain Selection** section. Click **Clear Selection**.

6 Select Domain 1 only.

7 Click to expand the **Equation** section. From the **Equation form** list, choose **Stationary**.

Inlet 1

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

2 Select Boundary 2 only.

3 In the **Settings** window for **Inlet**, locate the **Boundary Condition** section.

4 From the list, choose **Mass flow**.

5 Locate the **Mass Flow** section. From the **Mass flow type** list, choose **Standard flow rate (SCCM)**.

6 In the Q_{sccm} text field, type `100*tanh(1E5*t[1/s])`.

Outlet 1

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

2 Select Boundary 4 only.

HEAT TRANSFER IN FLUIDS (HT)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Heat Transfer in Fluids (ht)**.

2 In the **Settings** window for **Heat Transfer in Fluids**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Select Domain 1 only.

Initial Values 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Heat Transfer in Fluids (ht)** click **Initial Values 1**.

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

3 In the T text field, type `300`.

Temperature 1

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

2 Select Boundaries 2, 9, 10, 34, and 35 only.

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

4 In the T_0 text field, type `300`.

Outflow 1

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

2 Select Boundary 4 only.

MATERIALS

Dielectric

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

2 Select Domain 2 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 permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	4.5	1	Basic

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

Air

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

2 Select Domain 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 permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

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

Copper coil

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

2 Select Domains 4–7 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
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	6E7	S/m	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

5 In the **Label** text field, type `Copper coil`.

A boundary layer mesh is used on the reactor walls so that the region of space charge separation between the ions and electrons can be resolved.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

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

Edge 1

1 In the **Mesh** toolbar, click  **More Generators** and choose **Edge**.

2 Select Boundary 2 only.

Size 1

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

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

3 From the **Predefined** list, choose **Extremely fine**.

4 Click to expand the **Element Size Parameters** section. Locate the **Element Size** section. Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** checkbox. In the associated text field, type `0.001`.

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.
2 In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
3 From the **Geometric entity level** list, choose **Domain**.
4 Select Domain 1 only.

Size 1

1 Right-click **Free Triangular 1** and choose **Size**.
2 In the **Settings** window for **Size**, locate the **Element Size** section.
3 From the **Predefined** list, choose **Extra fine**.

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**.
4 Locate the **Layers** section. In the **Number of layers** text field, type `5`.
5 In the **Stretching factor** text field, type `1.5`.

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.
2 In the **Settings** window for **Mapped**, locate the **Domain Selection** section.
3 From the **Geometric entity level** list, choose **Domain**.
4 Select Domains 4–7 only.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.
2 In the **Settings** window for **Distribution**, locate the **Boundary Selection** section.
3 From the **Selection** list, choose **Coil Walls**.
4 Locate the **Distribution** section. From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type `35`.

6 In the **Element ratio** text field, type `8`.

7 From the **Growth rate** list, choose **Exponential**.

8 Select the **Symmetric distribution** checkbox.

Free Triangular 2

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

2 In the **Settings** window for **Free Triangular**, 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, 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 `21`.

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 `13.56E6`.

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

RESULTS

Electron Density (plas)

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

Argon Mass Fraction

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

2 In the **Settings** window for **2D Plot Group**, type `Argon Mass Fraction` in the **Label** text field.

Surface 1

1 Right-click **Argon Mass Fraction** and choose **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)** > **Plasma** > **Mass fractions** > **plas.wAr - Mass fraction - 1**.

3 In the **Argon Mass Fraction** toolbar, click **Plot**.

Excited Argon Mass Fraction

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

2 In the **Settings** window for **2D Plot Group**, type `Excited Argon Mass Fraction` in the **Label** text field.

Surface 1

1 Right-click **Excited Argon Mass Fraction** and choose **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)** > **Plasma** > **Mass fractions** > **plas.wArs - Mass fraction - 1**.

3 In the **Excited Argon Mass Fraction** toolbar, click **Plot**.