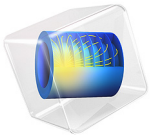

Global Model Coupled with the Two-Term Boltzmann Equation

Introduction

The electron energy distribution function (EEDF) plays an important role in the overall behavior of discharges. In this work, the formation period of an argon plasma with special attention for the EEDF is studied. The plasma is created within a 4 cm gap by a DC source voltage of 1 kV in series with a 100 kΩ resistance at 100 mTorr (compare with the Micro-cathode sustained discharge in Ar example from Ref. 1). A global model in the local field approximation is used to describe the temporal evolution of the plasma species. The rate coefficients for electron impact reactions and electron mobility are obtained from suitable integration of cross sections over the EEDF, and the EEDF is computed from the steady state Boltzmann equation in the two-term approximation (B2T) Ref. 2. The computed EEDF is influenced by how electrons gain energy from the electric field and lose it afterward in collisions with the background gas.

Coupling the B2T with a space dependent model is very computational expensive. Therefore, it is recommended to first explore the influence of the EEDF using a global (volume-averaged) model since it can run simulations in a fraction of the time of a space dependent model while retaining the tendencies of volume-averaged physical quantities.

Model Definition

The model used in this work considers that the spatial distribution of the different quantities in the plasma reactor can be treated as uniform or can be described using an analytic model. Without the spatial derivatives the numerical solution of the equation set becomes considerably simpler and the computation time is reduced. These advantages make a global model a good first approach to study a plasma reactor, especially when complex chemistries are involved or the influence of the EEDF is to be studied. In the following, we make use of the fast computational time to investigate the plasma evolution during the formation period through to steady state.

When using a plasma global model the species densities and the electron temperature are treated as volume-averaged quantities. Detailed information on the global model can be found in the section *Theory for Global Models* in the *Plasma Module User's Guide*. For heavy species the following equation is solved for the mass fraction

$$V\rho\frac{d}{dt}(w_k) = m_f w_{f,k} - m_o w_k + VR_k + \sum_l h_l A_l R_{\text{surf},k,l} M_k - w_k \sum_l h_l A_l M_{f,l}$$

where ρ is the mass density (SI unit: kg/m^3), w_k is the mass fraction, $w_{f,k}$ is the mass fraction in the feed, m_f and m_o are the mass-flow rates of the total feed and outlet, and R_k

is the rate expression (SI unit: kg/(m^3·s)). The fourth term on the right-hand side accounts for surface losses and creation, where A_l is the surface area, h_l is a dimensionless correction term, V is the reactor volume, M_k is the species molar mass (SI unit: kg/mol) and $R_{\text{surf},k,l}$ is the surface rate expression (SI unit: mol/(m^2·s)) at a surface l. The last term is introduced because the species mass balance equations are written in the nonconservative form and it used the mass-continuity equation to replace for the mass density time derivative. In the last term $M_{f,l}$ is the inward mass flux of surface l (SI unit: kg/(m^2·s)). The sum in the last two terms is over all surfaces where there are surface reactions.

To take possible variations of the system total mass or pressure into account, the mass-continuity equation can also be solved

$$V\frac{d\rho}{dt} = m_f - m_o + \sum_l h_l A_l M_{f,l}\,.$$

The electron number density is obtained from electroneutrality

$$n_e = \sum_{k=1}^{N} Z_k n_k$$

and if using the local energy approximation (LEA) the electron energy density n_ε (SI unit: V/ m^3) is computed from

$$V\frac{dn_\varepsilon}{dt} = VR_\varepsilon + \frac{P_{\text{abs}}}{e} + \sum_l \sum_{\text{ions}} h_l A_l R_{\text{surf},k,l} N_a(\varepsilon_e + \varepsilon_i)$$

where R_ε is the electron energy loss due to inelastic and elastic collisions, P_{abs} is the power absorbed by the electrons (SI unit: W), and e is the elementary charge. The last term on the right side accounts for the kinetic energy transported to the surface by electrons and ions. The summation is over all positive ions, ε_e is the mean kinetic energy lost per electron lost, ε_i is the mean kinetic energy lost per ion lost, and N_a is Avogadro's number. If using the local field approximation (LFA) the electron mean energy equation is not solved and the electron mean energy can be: (i) provided as a function of the electric field; or (ii) obtained by solving the Boltzmann equation in the two-term approximation.

The rate coefficients for electron impact reactions can be computed by appropriate averaging of cross sections over an EEDF. The EEDF can be either analytic or can be obtained by solving the steady state Boltzmann equation in the two-term approximation coupled with the equation system (*The Boltzmann Equation, Two-Term Approximation*

Interface in the *Plasma Module User's Guide*). When solving for the EEDF the coupling between the equations is as follows: (i) if the LEA is used, the electron mean energy obtained from the electron mean energy equation is given as input to the Boltzmann solver; (ii) if the LFA is used, the reduced electric field must be given as input to the Boltzmann solver and the electron mean energy comes from averaging over the computed EEDF.

In this work the LFA is used and the B2T is solved. The reduced electric field given as input to the B2T comes from the circuit equation

$$V_p = V_{DC} - RI_p$$

where V_p is the plasma potential, V_{DC} is the applied voltage, and R is the circuit series resistance. The plasma current I_p is computed from

$$I_p = eAn_e(\mu N)\left(\frac{E}{N}\right)$$

where e is the electron charge, A is the plasma cross section area, μN is the reduced electron mobility, E/N is the reduced electric field, and N is the gas density. Solving for E/N one obtains

$$\frac{E}{N} = \frac{V_{dc}}{dN + eRAn_e(\mu N)}$$

where d is the gap distance. One can anticipate that an increase in the plasma density will reduce the electric field in the discharge gap.

PLASMA CHEMISTRY

The plasma chemistry suggested in Ref. 1 is used and presented in Table 1. The chemical mechanism consists of 5 species and 11 reactions.

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
1	e+Ar=>e+Ar	Momentum	0
2	e+Ar=>e+Ars	Excitation	11.5
3	e+Ars=>e+Ar	Excitation	-11.5
4	e+Ar=>2e+Ar+	Ionization	15.8
5	e+Ars=>2e+Ar+	Ionization	4.427
6	2e+Ar+=>Ar+e	Excitation	-15.8

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon(eV)$
7	e+Ar2+=>Ars+e	Excitation	-3
8	2Ar+Ar+=>Ar+Ar2	3-body Ar2+ creation	
9	Ars+2Ar=>3Ar	Quenching	
10	Ars+Ars=>e+Ar2+	Penning ionization	
11	Ar+Ar2+=>2Ar+Ar+	Charge transfer	

The model also includes the surface reactions presented in Table 2.

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT
1	Ar+=>Ar	1
2	Ar2+=>2Ar	1
3	Ars=>Ar	1

The neutral excited species revert to ground state with sticking coefficient equal to one.

Results and Discussion

Figure 1 shows computed and analytic EEDFs for a mean electron energy of 5 eV. These results were obtained with the EEDF Initialization study that only solves for the Boltzmann equation in the two-term approximation without solving for the degrees of freedom from the global model. This approach allows to have a first insight of the EEDF and observe if an analytic EEDF is accurate enough for the modeling expectations. From Figure 1 it is possible to see that above 20 eV the computed EEDF drops much faster than the Maxwellian EEDF. As a consequence the Maxwellian EEDF overpredicts electron impact processes with high energy thresholds like ionization from the ground state. The Druyvesteyn EEDF is in much better agreement with the computed EEDF and it might be good enough for some models.

From Figure 2 to Figure 5, simulation results are presented for the global model coupled with the B2T. Figure 2 shows the temporal evolution of the plasma species and the reduced field in the plasma. In the first instants there is no plasma in the gap and the electric field maintains a constant value until the plasma creation begins. With the plasma creation the current in the gap (which is only plasma conduction current in this model) increases and the voltage decreases as presented in Figure 3. At steady state the plasma is sustained with only 30 V in the gap that corresponds to a field of 3.5 Td.

From Figure 4 it is possible to observe that the temporal evolution of the electron mean energy (obtained by averaging the computed EEDF) follows the same trend as the electric field. The electron mean energy decreases with the electric field and undershoots before reaching the steady state. The same behavior can be inferred from the temporal evolution of the EEDFs presented in Figure 5. Further analyses of the EEDF allows to gain a deeper understating of the plasma physics. In the beginning the electrons have a large population above 15 eV as it is necessary to facilitate the plasma breakdown. After the plasma formation, and due to the decrease of the electric field, the electron population cools down and the EEDF develops a tail with a steeper slope. As time progresses, and with the increase of the argon excited state density, the influence of the superelastic reactions in the EEDF becomes noticeable with the appearance of a bump at the high energy end.

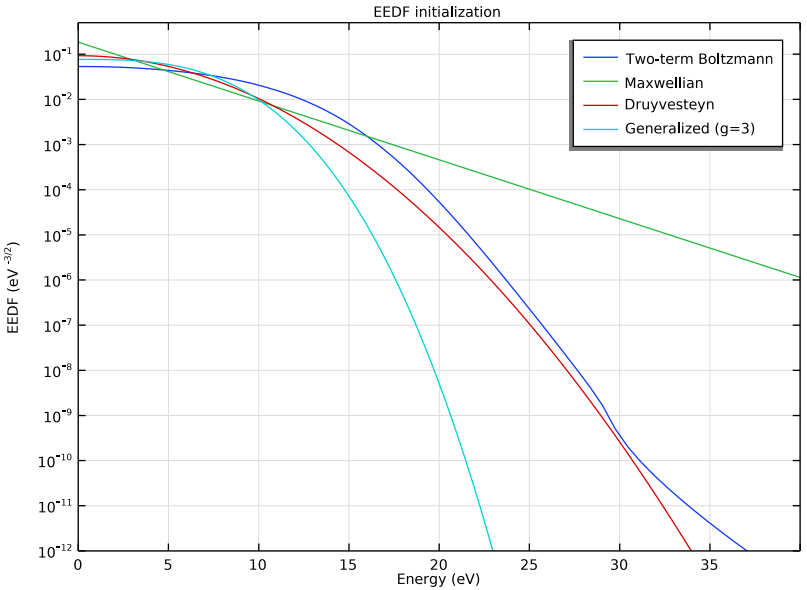

Figure 1: Computed and analytic EEDFs for a mean electron energy of 5 eV.

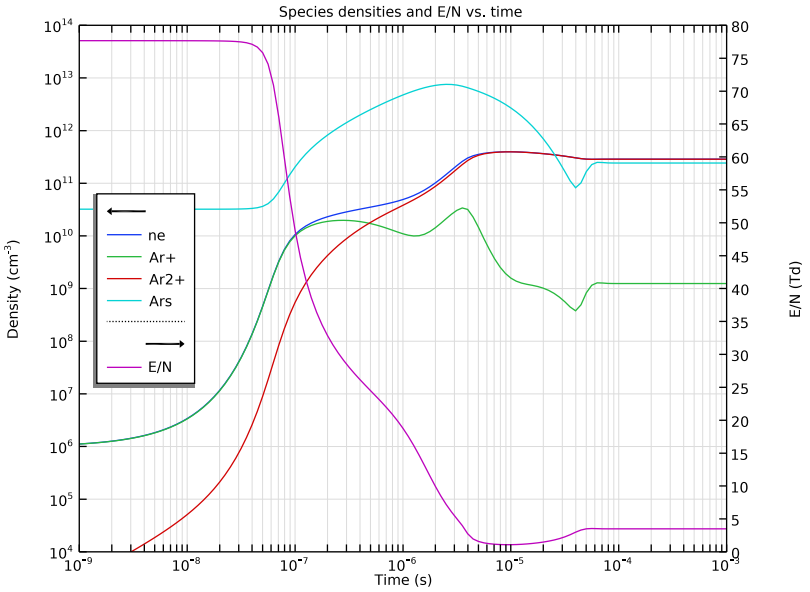

Figure 2: Temporal evolution of the plasma species and the reduced electric field.

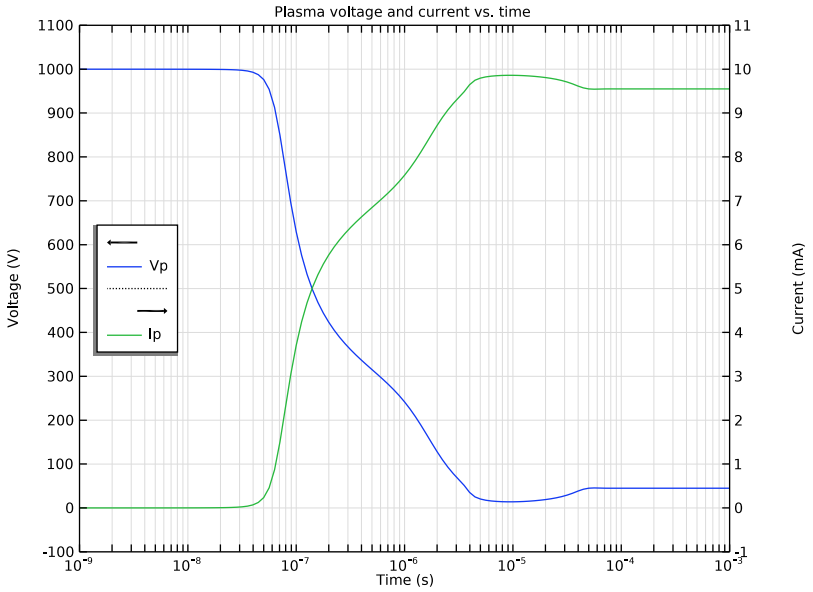

Figure 3: Temporal evolution of the plasma voltage and current.

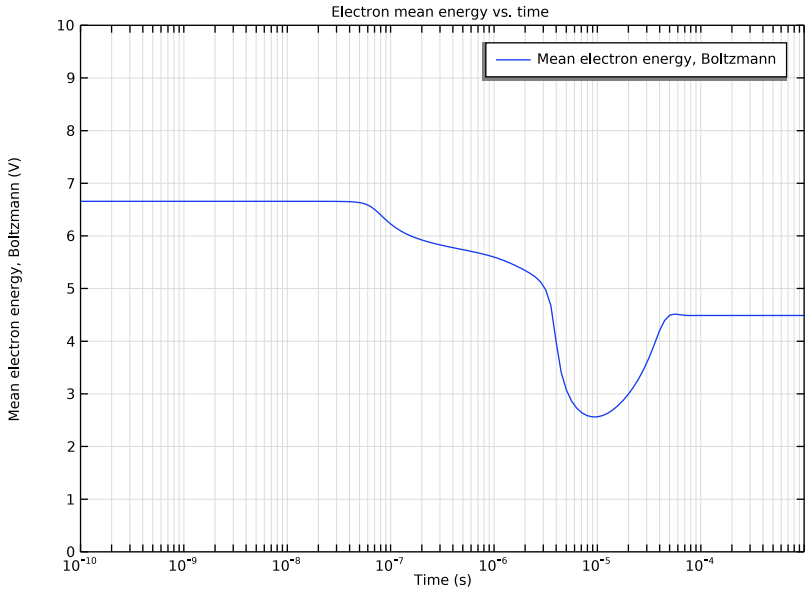

Figure 4: Temporal evolution of the mean electron energy.

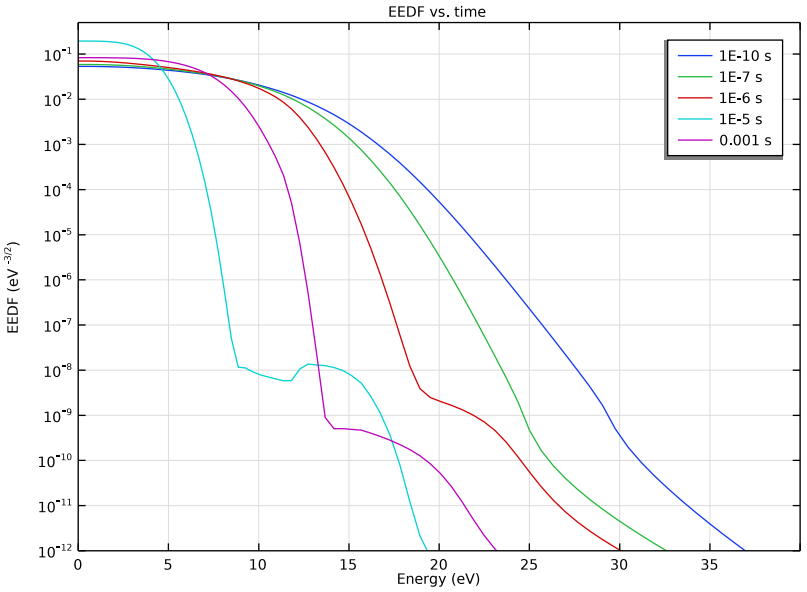

Figure 5: Computed EEDF at several instants of the simulation.

References

1. S. Pancheshnyi, B. Eismann, G.J.M. Hagelaar, and L.C. Pitchford, Computer code ZDPlasKin, http://www.zdplaskin.laplace.univ-tlse.fr (University of Toulouse, LAPLACE, CNRS-UPS-INP, Toulouse, France, 2008).

2. G.J.M. Hagelaar and L.C. Pitchford, "Solving the Boltzmann Equation to Obtain Electron Transport Coefficients and Rate Coefficients for Fluid Models", *Plasma Sources Science and Technology*, vol. 14, pp. 722–733, 2005.

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

Application Library path: `Plasma_Module/Global_Modeling/boltzmann_global_model_argon`

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 (plas)** interface and the **EEDF Initialization** study.
2. click **2D Axisymmetric**.
3. In the **Select Physics** tree, select **Plasma>Plasma (plas)**.
4. Click **Add**.
5. Click **Study**.
6. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> EEDF Initialization**.
7. Click **Done**.

GEOMETRY 1

Create a geometry to define the plasma volume and contact surfaces.

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 `rad`.
4. In the **Height** text field, type `gap`.

Add some parameters to define the geometry, background gas temperature, and circuit components.

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
rad	0.4[cm]	0.004 m	
gap	0.4[cm]	0.004 m	
Res	1e5[ohm]	1E5 Ω	
Tg	300[K]	300 K	
P0	100[torr]	13332 Pa	
Vdc	1000[V]	1000 V	

Add some variables to define the diffusion length, the reduced electric field in the plasma, and the plasma current and voltage.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.

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

3 In the table, enter the following settings:

Name	Expression	Unit	Description
Ldiff	((pi/gap)^2+(2.405/rad)^2)^-0.5	m	
Ip	e_const*Area*plas.ne*plas.EN*plas.muN		
Vp	Vdc-Res*Ip		
EN	Vdc/(gap+Res*e_const*Area*plas.ne*nojac(plas.muN)/plas.Nn)/plas.Nn		
Area	pi*rad^2	m^2	

Choose to solve a global model in the local field approximation coupled with the electron Boltzmann equation in the two-term approximation.

PLASMA (PLAS)

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

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

3 From the **Diffusion model** list, choose **Global**.

4 Locate the **Plasma Properties** section. From the **Mean electron energy** list, choose **Local field approximation**.

5 Locate the **Electron Energy Distribution Function Settings** section. From the **Electron energy distribution function** list, choose **Boltzmann equation, two-term approximation (linear)**.

6 In the ε_{max} text field, type `50[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 `Ar++e+e=>Ar+e`.

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

5 In the $\Delta\varepsilon$ text field, type `-15.8`.

6 Locate the **Reaction Parameters** section. In the k^f text field, type `8.75e-27[cm^6/s]*(plas.Te/1[V])^-4.5*N_A_const*N_A_const`.

Electron Impact Reaction 7

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 `Ar2++e=>Ars+Ar`.

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

5 In the $\Delta\varepsilon$ text field, type `-3`.

6 Locate the **Reaction Parameters** section. In the k^f text field, type `8.5e-7[cm^3/s]*(plas.Te*11600[K/V]/300[K])^-0.67*N_A_const`.

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

4 Locate the **Reaction Parameters** section. In the k^{f} text field, type `2.25e-31[cm^6/s]*(Tg/300[K])^-0.4*N_A_const*N_A_const`.

9: Ar++Ar+Ar=>Ar2++Ar

1 Right-click **8: Ar++Ar+Ar=>Ar2++Ar** and choose **Duplicate**.

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

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

4 Locate the **Reaction Parameters** section. In the k^{f} text field, type `1.4e-32[cm^6/s]*N_A_const*N_A_const`.

10: Ars+Ar+Ar=>Ar+Ar+Ar

1 Right-click **9: Ars+Ar+Ar=>Ar+Ar+Ar** and choose **Duplicate**.

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

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

4 Locate the **Reaction Parameters** section. In the k^{f} text field, type `6e-10[cm^3/s]*N_A_const`.

11: Ars+Ars=>Ar2++e

1 Right-click **10: Ars+Ars=>Ar2++e** and choose **Duplicate**.

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

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

4 Locate the **Reaction Parameters** section. In the k^{f} text field, type `6.06e-6[K*cm^3/s]/Tg*exp(-15130[K]/Tg)*N_A_const`.

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**.

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 In the n_0 text field, type `1e6[1/cm^3]`.

Species: Ar2+

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

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

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

4 In the n_0 text field, type `1E1[1/cm^3]`.

Define surface losses for ions and argon excited state.

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 **All boundaries**.

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

5 From the **Specify reaction using** list, choose **Sticking coefficient and diffusion**.

6 Locate the **Reaction Parameters** section. In the Λ_{eff} text field, type `Ldiff`.

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+=>Ar+Ar`.

3: Ar2+=>Ar+Ar

1 Right-click **2: Ar2+=>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 `Ars=>Ar`.

Set the gas temperature, the gas pressure, the reduced electric field for the EEDF, and the mean electron energy for the EEDF initialization.

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 In the T text field, type `Tg`.

4 In the p_0 text field, type `P0`.

5 Locate the **EEDF Inputs** section. In the E/N text field, type `EN`.

6 In the ε_0 text field, type `5[V]`.

Compute the EEDF without solving for the other plasma degrees of freedom. This is a good first step to gain knowledge about the EEDF for the present conditions. The EEDF will also be used as an initial EEDF for the time dependent plasma model.

STUDY 1

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

Compare the computed EEDF with analytic EEDFs.

RESULTS

EEDF initialization

1 In the **Settings** window for **1D Plot Group**, type `EEDF initialization` in the **Label** text field.

2 Locate the **Plot Settings** section. In the **x-axis label** text field, type `Energy (eV)`.

3 In the **y-axis label** text field, type `EEDF (eV <sup>-3/2</sup>)`.

4 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

5 Locate the **Axis** section. Select the **Manual axis limits** check box.

6 In the **x minimum** text field, type `0`.

7 In the **x maximum** text field, type `40`.

8 In the **y minimum** text field, type `1e-12`.

9 In the **y maximum** text field, type `0.5`.

10 In the **EEDF initialization** toolbar, click **Plot**.

Add a study to solve for the global model equations coupled with the Boltzmann equation.

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 **General Studies> Time Dependent**.

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: Time Dependent

1 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

2 Click **Range**.

3 In the **Range** dialog box, choose **Logarithmic** from the **Entry method** list.

4 In the **Start** text field, type `1e-10`.

5 In the **Stop** text field, type `0.001`.

6 In the **Steps per decade** text field, type `20`.

7 Click **Replace**.

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

9 Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

11 From the **Study** list, choose **Study 1, EEDF Initialization**.

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

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

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

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

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

4 From the **Steps taken by solver** list, choose **Strict**.

5 Click **Compute**.

RESULTS

Prepare a plot to show the temporal evolution of the species densities and the reduced electric field.

Species densities and E/N vs. time

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

2 In the **Settings** window for **1D Plot Group**, type `Species densities and E/N vs. time` in the **Label** text field.

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

4 Locate the **Title** section. From the **Title type** list, choose **Label**.

Global 1

1 Right-click **Species densities and E/N vs. time** 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
`plas.ne`	`1/cm^3`	`ne`
`plas.n_wAr_1p`	`1/cm^3`	`Ar+`
`plas.n_wAr2_1p`	`1/cm^3`	`Ar2+`
`plas.n_wArs`	`1/cm^3`	`Ars`

Global 2

1 In the **Model Builder** window, right-click **Species densities and E/N vs. time** 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
`EN`	`Td`	`E/N`

Species densities and E/N vs. time

1 In the **Model Builder** window, click **Species densities and E/N vs. time**.

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

3 Select the **Two y-axes** check box.

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

5 Select the **y-axis label** check box. In the associated text field, type `Density (cm<sup>-3</sup>)`.

6 Locate the **Axis** section. Select the **Manual axis limits** check box.

7 In the **x minimum** text field, type `1e-9`.

8 In the **x maximum** text field, type `1e-3`.

9 In the **y minimum** text field, type `1e4`.

10 In the **y maximum** text field, type `1e14`.

11 In the **Secondary y minimum** text field, type `0`.

12 In the **Secondary y maximum** text field, type `80`.

13 Select the **x-axis log scale** check box.

14 Select the **y-axis log scale** check box.

15 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

16 In the **Species densities and E/N vs. time** toolbar, click **Plot**.

Plot the temporal evolution of the plasma voltage and current.

1D Plot Group 3

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

Global 1

1 Right-click **1D Plot Group 3** 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
Vp	V	Vp

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
Ip	mA	Ip

Plasma voltage and current vs. time

1 In the **Model Builder** window, under **Results** click **1D Plot Group 3**.

2 In the **Settings** window for **1D Plot Group**, type `Plasma voltage and current vs. time` in the **Label** text field.

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

4 Locate the **Title** section. From the **Title type** list, choose **Label**.

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

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

7 Select the **y-axis label** check box. In the associated text field, type `Voltage (V)`.

8 Select the **Secondary y-axis label** check box. In the associated text field, type `Current (mA)`.

9 Locate the **Axis** section. Select the **Manual axis limits** check box.

10 In the **x minimum** text field, type `1e-9`.

11 In the **x maximum** text field, type `1e-3`.

12 In the **y minimum** text field, type `-100`.

13 In the **y maximum** text field, type `1100`.

14 In the **Secondary y minimum** text field, type `-1`.

15 In the **Secondary y maximum** text field, type `11`.

16 Select the **x-axis log scale** check box.

17 Locate the **Legend** section. From the **Position** list, choose **Middle left**.

18 In the **Plasma voltage and current vs. time** toolbar, click **Plot**.

Plot the temporal evolution of the electron mean energy.

Electron mean energy vs. time

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

2 In the **Settings** window for **1D Plot Group**, type `Electron mean energy vs. time` in the **Label** text field.

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

4 Locate the **Title** section. From the **Title type** list, choose **Label**.

5 Locate the **Axis** section. Select the **Manual axis limits** check box.

6 In the **x minimum** text field, type `1e-10`.

7 In the **x maximum** text field, type `1e-3`.

8 In the **y minimum** text field, type `0`.

9 In the **y maximum** text field, type `10`.

10 Select the **x-axis log scale** check box.

Global 1

1 Right-click **Electron mean energy vs. time** 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
plas.ebarB	V	Mean electron energy, Boltzmann

4 In the **Electron mean energy vs. time** toolbar, click **Plot**.

Create a new dataset to plot the EEDF at several time instants.

Study 2/Solution 2 (4) (sol2)

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Results>Datasets>Study 2/Solution 2 (sol2)** and choose **Duplicate**.

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

4 From the **Component** list, choose **Extra Dimension from Plasma (plas_eedf_xdim)**.

Plot the EEDF at several time instants.

EEDF vs. time

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

2 In the **Settings** window for **1D Plot Group**, type `EEDF vs. time` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2/Solution 2 (4) (sol2)**.

4 Locate the **Title** section. From the **Title type** list, choose **Label**.

5 Locate the **Data** section. From the **Time selection** list, choose **From list**.

6 In the **Times (s)** list, choose **1E-10**, **1E-7**, **1E-6**, **1E-5**, and **0.001**.

7 Locate the **Plot Settings** section.

8 Select the **x-axis label** check box. In the associated text field, type `Energy (eV)`.

9 Select the **y-axis label** check box. In the associated text field, type `EEDF (eV <sup>-3/2</sup>)`.

10 Locate the **Axis** section. Select the **Manual axis limits** check box.

11 In the **x minimum** text field, type `0`.

12 In the **x maximum** text field, type `40`.

13 In the **y minimum** text field, type `1e-12`.

14 In the **y maximum** text field, type `0.5`.

15 Select the **y-axis log scale** check box.

Line Graph 1

1 Right-click **EEDF vs. time** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

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

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.fcap`.

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

6 In the **Expression** text field, type `plas.xeedf`.

7 Click to expand the **Legends** section. Select the **Show legends** check box.

8 In the **EEDF vs. time** toolbar, click  **Plot**.