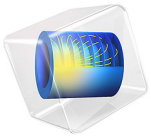

Model created in COMSOL Multiphysics 6.4

Argon Boltzmann Analysis

Introduction

The electron energy distribution function (EEDF) plays an important role in the overall behavior of discharges. Analytic forms of the EEDF exist such as Maxwellian or Druyvesteyn, but in some cases they fail to fit the discharge physics. Factors such as ionization degree (n_e/N_n), mole fraction of excited species, and reduced angular frequency of the electromagnetic field can all influence the shape of the EEDF. This can lead to differences in the magnitude of electron impact rate coefficients which are in turn used in a fluid model to solve for the electron density and mean electron energy. This tutorial model shows how these factors influence the EEDF and the rate coefficients for argon.

Model Definition

This tutorial is based on the results obtained in Ref. 1. The Two-term Boltzmann equation is solved which computes the EEDF rather than assuming a specific form. The Boltzmann equation in the two-term approximation can be written as

$$\frac{\partial}{\partial \varepsilon}\left(Wf - D\frac{\partial f}{\partial \varepsilon}\right) = S$$

where f is the EEDF ($\mathrm{eV}^{-3/2}$) and

$$W = -\gamma\varepsilon^2\sigma_\varepsilon - 3a\left(\frac{n_e}{N_n}\right)A_1 \tag{1}$$

and

$$D = \frac{\gamma}{3}\left(\frac{E}{N_n}\right)^2\left(\frac{\varepsilon}{\sigma_m}\right) + \frac{\gamma k_b T}{q}\varepsilon^2\sigma_\varepsilon + 2a\left(\frac{n_e}{N_n}\right)(A_2 + \varepsilon^{3/2}A_3) \tag{2}$$

For definitions of the quantities in the equations Equation 1 and Equation 2, see the chapter *The Boltzmann Equation, Two-Term Approximation Interface* in the *Plasma Module User's Guide*.

At zero energy, the condition that energy flux is zero must hold:

$$\mathbf{n}\cdot\left(Wf - D\frac{\partial f}{\partial \varepsilon}\right) = 0$$

and as $\varepsilon \to \infty, f \to 0$.

The EEDF is defined by how electrons gain energy from the electric field and lose (or gain) their energy in collisions with the background gas. The electron collisions are characterized by cross sections that need to be provided by the user. In this model, the background gas is argon and the electron impact collisions listed in Table 1 below are considered (electron impact cross sections are obtained from Ref. 2).

TABLE 1: ELECTRON IMPACT COLLISIONS.

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	Excitation	-11.5
4	e+Ar=>2e+Ar+	Ionization	15.8
5	e+Ars=>2e+Ar+	Ionization	4.4

Results and Discussion

In this section it is studied how the EEDF and the ionization rate coefficient are influenced by electron–electron collisions, superelastic collisions, and excitation frequency.

Electron–electron collisions tend to make the shape of the EEDF closer to a Maxwellian distribution function. The influence of these collisions depend mostly on the ionization degree. Figure 1 shows computed EEDFs for several ionization degrees for an electron density of 10^{18} m^{-3} and for a reduced electric field of 10 Td. As the ionization degree increases, the EEDF tends to become more Maxwellian (which would be represented by a linear line on a log scale).

The electron–electron collisions tend to push the electrons at the tail to higher energies, which has an effect on the rate coefficients for electron impact reactions with a high threshold energy. The effect on the ionization rate coefficient can be seen in Figure 2. In the low mean energy range the ionization rate coefficient increases considerable with the ionization degree.

Electrons can collide with neutrals in an excited state and cause them to de-excite to a low energy state. In this type of collisions the electrons can take the energy excess and immediately populate the tail of the EEDF. This effect on the EEDF is presented in Figure 3 for different mole fractions of the excited state of argon. The population of the high energy tail makes the magnitude of the ionization rate coefficients increase in the low energy range as shown in Figure 4.

Finally, the influence of a high frequency oscillating field on the EEDF and the ionization rate coefficients is studied by applying different excitation frequencies at a constant mean electron energy. The results are plotted in Figure 5 and Figure 6.

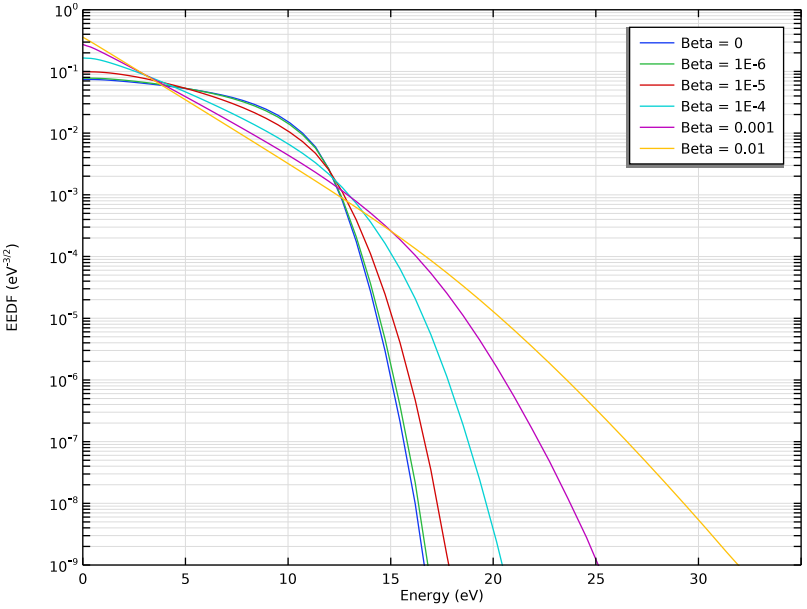

Figure 1: EEDF for 10 Td and for different ionization degrees.

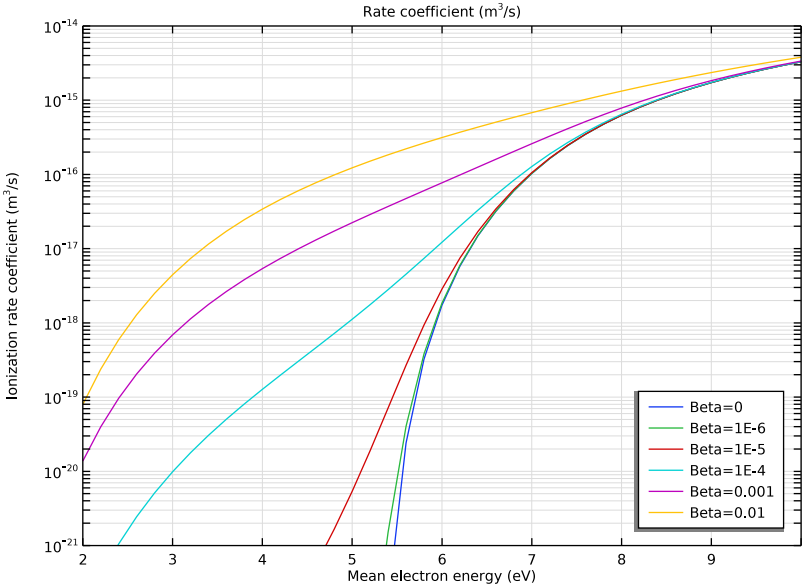

Figure 2: Ionization rate coefficient as a function of the mean electron energy for different ionization degrees.

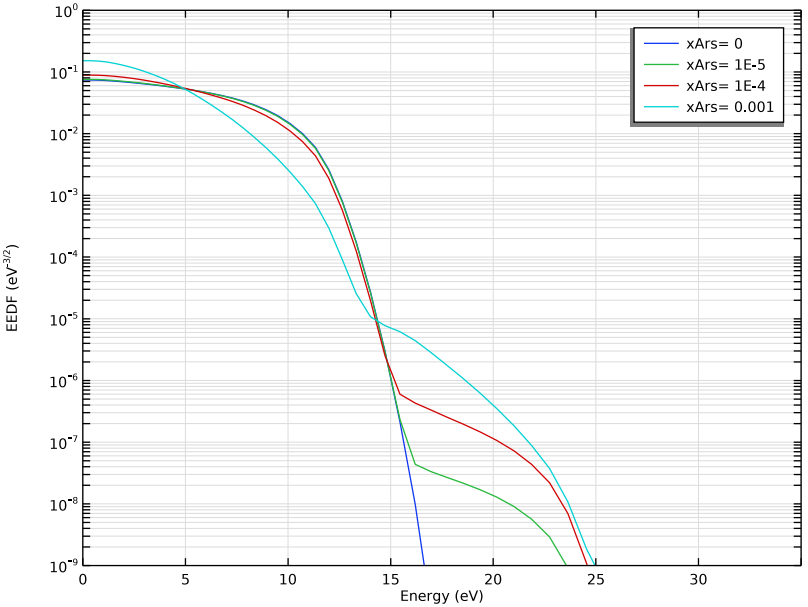

Figure 3: EEDF for 10 Td and for different mole fractions of the argon excited state.

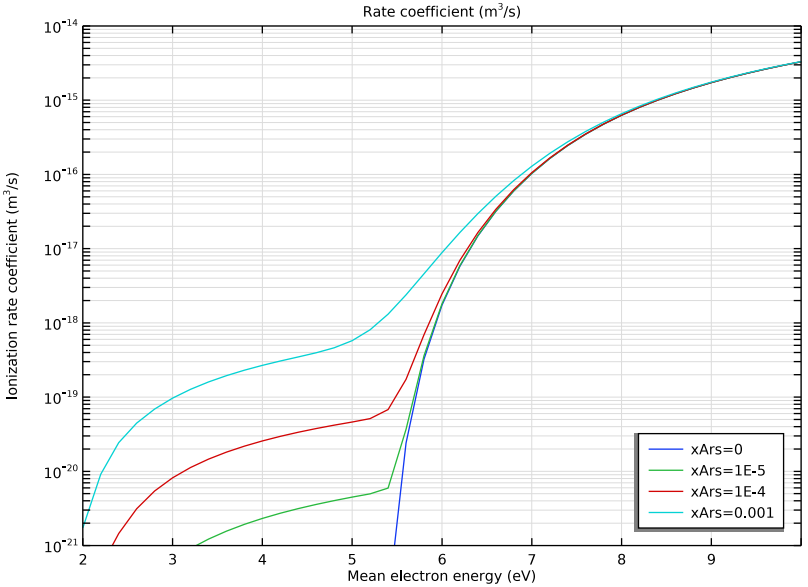

Figure 4: Ionization rate coefficient as a function of the mean electron energy for different mole fractions of the argon excited state.

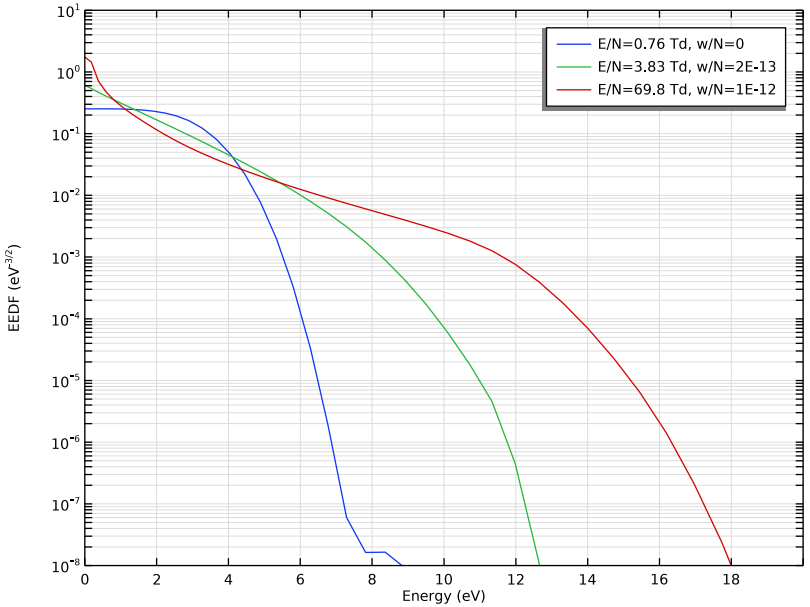

Figure 5: EEDF for oscillating electric fields with different amplitudes and different reduced frequencies. All EEDFs have the same mean electron energy of 2.15 eV.

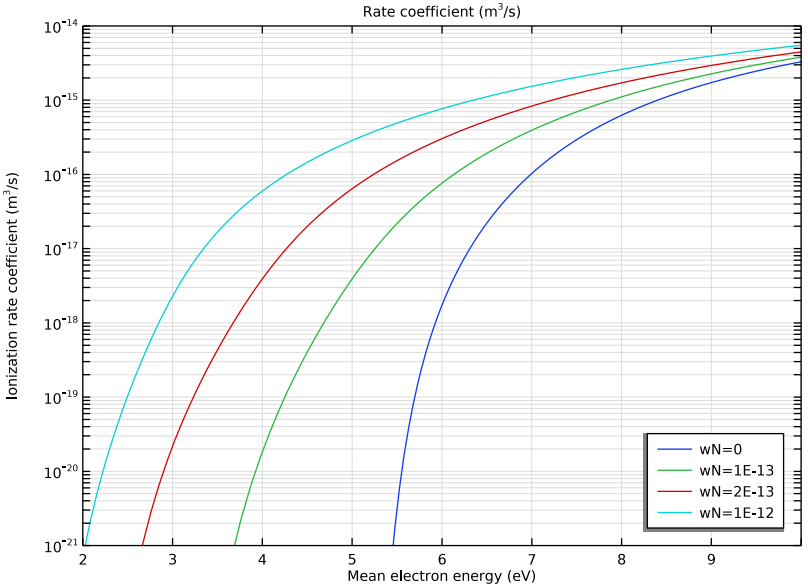

Figure 6: Ionization rate coefficient as a function of the mean electron energy for different reduced frequencies.

References

1. 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.

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

Application Library path: `Plasma_Module/Two-Term_Boltzmann_Equation/boltzmann_argon`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, Select the **Boltzmann Equation, Two-Term Approximation (be)** interface and the **Reduced Electric Fields** study.

2 click **0D**.

3 In the **Select Physics** tree, select **Plasma** > **Boltzmann Equation, Two-Term Approximation (be)**.

4 Click **Add**.

5 Click **Study**.

6 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Reduced Electric Fields**.

7 Click **Done**.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

Select to solve the Boltzmann equation in the two-term approximation.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Boltzmann Equation, Two-Term Approximation (be)**.

2 In the **Settings** window for **Boltzmann Equation, Two-Term Approximation**, locate the **Electron Energy Distribution Function Settings** section.

3 From the **Electron energy distribution function** list, choose **Boltzmann equation, two-term approximation (linear)**.

4 Select the **Electron–electron collisions** checkbox.

Define parameters for the ionization degree, argon excited state mole fraction, and reduced oscillating 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
Beta	0	0	Ionization degree
xAr	0	0	Ar mole fraction
wN	0	0	Reduced frequency

Import a cross section set for argon.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

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**.

In the first two studies the effect of the electron-electron collisions on the eedf and the ionization rate coefficient are analyzed.

In the first study, compute the eedf for a constant reduced electric field for several ionization degrees.

In the second study, use the parametric sweep feature to compute the rate coefficients over a wide range of mean electron energies for different degrees of ionization.

Boltzmann Model 1

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

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

3 In the n_e text field, type `1E18[1/m^3]`.

4 In the β text field, type `Beta`.

5 Locate the **Results** section. Find the **Generate the following default plots** subsection. Clear the **Rate coefficients** checkbox.

6 Clear the **Transport properties** checkbox.

7 Clear the **Mean electron energy** checkbox.

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 ε_0 text field, type `5[V]`.

4 In the E/N_0 text field, type `10[Td]`.

EEDF E-E

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

2 In the **Settings** window for **Study**, type `eedf e-e` in the **Label** text field.

Step 1: Reduced Electric Fields

1 In the **Model Builder** window, under **eedf e-e** click **Step 1: Reduced Electric Fields**.

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

3 In the **Reduced electric fields** text field, type `10[Td]`.

4 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

5 Click + **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Beta (Ionization degree)	`0 1e-6 1e-5 1e-4 1e-3 1e-2`	

7 From the **Run continuation for** list, choose **Last parameter**.

8 In the **Study** toolbar, click = **Compute**.

RESULTS

EEDF e-e

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

2 Locate the **Axis** section. Select the **Manual axis limits** checkbox.

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

4 In the **x maximum** text field, type `35`.

5 In the **y minimum** text field, type `1e-9`.

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

Line Graph 1

1 In the **Model Builder** window, expand the **EEDF e-e** node, then click **Line Graph 1**.

2 In the **Settings** window for **Line Graph**, click to expand the **Legends** section.

3 From the **Legends** list, choose **Evaluated**.

4 In the **Legend** text field, type `Beta = eval(Beta)`.

5 In the **EEDF e-e** toolbar, click **Plot**.

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** > **Mean Energies**.

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

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

STUDY 2

Step 1: Mean Energies

1 In the **Settings** window for **Mean Energies**, locate the **Study Settings** section.

2 Click **Range**.

3 In the **Range** dialog, type `2` in the **Start** text field.

4 In the **Step** text field, type `0.2`.

5 In the **Stop** text field, type `10`.

6 Click **Replace**.

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

8 In the **Settings** window for **Study**, type `Rion e-e` in the **Label** text field.

9 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

10 Clear the **Generate convergence plots** checkbox.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Beta (Ionization degree)	`0 1e-6 1e-5 1e-4 1e-3 1e-2`	

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

RESULTS

Ionization vs. electron mean energy e-e

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

2 In the **Settings** window for **1D Plot Group**, type `Ionization vs. electron mean energy e-e` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Rion e-e/ Parametric Solutions 1 (sol3)**.

4 Locate the **Plot Settings** section.

5 Select the **x-axis label** checkbox. In the associated text field, type `Mean electron energy (eV)`.

6 Select the **y-axis label** checkbox. In the associated text field, type `Ionization rate coefficient (m<sup>3</sup>/s)`.

7 Locate the **Axis** section. Select the **Manual axis limits** checkbox.

8 In the **x minimum** text field, type `2`.

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

10 In the **y minimum** text field, type `1e-21`.

11 In the **y maximum** text field, type `1e-14`.

12 Select the **y-axis log scale** checkbox.

13 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

Global 1

1 Right-click **Ionization vs. electron mean energy e-e** 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
`be.k_4`	`m^3/s`	`Rate coefficient`

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

5 Find the **Include** subsection. Clear the **Description** checkbox.

6 In the **Ionization vs. electron mean energy e-e** toolbar, click **Plot**.

In the following, the effects of the Ars state mole fraction in the eedf are studied. Do not include electron-electron collisions and set the model fraction of xArs.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Boltzmann Equation, Two-Term Approximation (be)**.

2 In the **Settings** window for **Boltzmann Equation, Two-Term Approximation**, locate the **Electron Energy Distribution Function Settings** section.

3 Clear the **Electron–electron collisions** checkbox.

Boltzmann Model 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Boltzmann Equation, Two-Term Approximation (be)** click **Boltzmann Model 1**.

2 In the **Settings** window for **Boltzmann Model**, locate the **Mole Fraction Settings** section.

3 From the **Mole constrained species** list, choose **Ar**.

4 In the table, enter the following settings:

Species	Mole fraction (1)
Ars	xArs

As before two studies are made. The first study, parameterizes over the Ars mole fraction and serves to analyze the effects of superelastic reactions on the eedf.

The second study, parameterizes over the Ars mole fraction over a wide range of mean electron energies and serves to analyze the effects of superelastic reactions on the ionization rate coefficient.

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** > **Reduced Electric Fields**.

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

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

STUDY 3

Step 1: Reduced Electric Fields

1 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

2 In the **Reduced electric fields** text field, type `10[Td]`.

3 From the **Reuse solution from previous step** list, choose **No**.

4 Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

5 Click **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
xArs (Ars mole fraction)	`0 1e-5 1e-4 1e-3`	

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

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

9 Clear the **Generate convergence plots** checkbox.

10 Clear the **Generate default plots** checkbox.

11 In the **Label** text field, type `eedf xArs`.

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

RESULTS

EEDF xArs

1 In the **Model Builder** window, right-click **EEDF e-e** and choose **Duplicate**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **eedf xArs/Solution 10 (sol10)**.

Line Graph 1

1 In the **Model Builder** window, expand the **EEDF xArs** node, then click **Line Graph 1**.

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

3 From the **Legends** list, choose **Evaluated**.

4 In the **Legend** text field, type `xArs= eval(xArs)`.

5 In the **EEDF xArs** toolbar, click **Plot**.

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** > **Mean Energies**.

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

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

STUDY 4

Step 1: Mean Energies

1 In the **Settings** window for **Mean Energies**, locate the **Study Settings** section.

2 Click **Range**.

3 In the **Range** dialog, type `2` in the **Start** text field.

4 In the **Step** text field, type `0.2`.

5 In the **Stop** text field, type `10`.

6 Click **Replace**.

7 In the **Model Builder** window, click **Study 4**.

8 In the **Settings** window for **Study**, type `Rion xArs` in the **Label** text field.

9 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

10 Clear the **Generate convergence plots** checkbox.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
xArs (Ars mole fraction)	`0 1e-5 1e-4 1e-3`	

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

RESULTS

Ionization vs. electron mean energy xArs

1 In the **Model Builder** window, right-click **Ionization vs. electron mean energy e-e** and choose **Duplicate**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Rion xArs/ Parametric Solutions 2 (sol12)**.

Global 1

1 In the **Model Builder** window, expand the **Ionization vs. electron mean energy xArs** node, then click **Global 1**.

2 In the **Settings** window for **Global**, locate the **Legends** section.

3 From the **Legends** list, choose **Automatic**.

4 Find the **Include** subsection. Clear the **Description** checkbox.

5 In the **Ionization vs. electron mean energy xArs** toolbar, click **Plot**.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Boltzmann Equation, Two-Term Approximation (be)**.

2 In the **Settings** window for **Boltzmann Equation, Two-Term Approximation**, locate the **Electron Energy Distribution Function Settings** section.

3 Select the **Oscillating field** checkbox.

4 In the ω/N text field, type `wN`.

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** > **Reduced Electric Fields**.

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

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

STUDY 5

Step 1: Reduced Electric Fields

In the following 3 EEDFs, all with the same mean electron energy of 2.15 eV, are computed for different reduced fields and reduced oscillating frequencies.

1 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

2 In the **Reduced electric fields** text field, type `0.76[Td]`.

3 In the **Model Builder** window, click **Study 5**.

4 In the **Settings** window for **Study**, type `0.76Td w/N=0` in the **Label** text field.

5 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

6 Clear the **Generate convergence plots** checkbox.

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

ADD STUDY

1 In the **Study** 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** > **Reduced Electric Fields**.

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

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

3.83TD W/N=2E-13

1 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

2 In the **Reduced electric fields** text field, type `3.83[Td]`.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

4 Click **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
wN (Reduced frequency)	2e-13	

6 In the **Model Builder** window, click **Study 6**.

7 In the **Settings** window for **Study**, type `3.83Td w/N=2e-13` in the **Label** text field.

8 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

9 Clear the **Generate convergence plots** checkbox.

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

ADD STUDY

1 In the **Study** 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** > **Reduced Electric Fields**.

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

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

69.8TD W/N=1E-12

1 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

2 In the **Reduced electric fields** text field, type `69.8[Td]`.

3 Locate the **Study Extensions** section. Select the **Auxiliary sweep** checkbox.

4 Click + **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
wN (Reduced frequency)	`1e-12`	

6 In the **Model Builder** window, click **Study 7**.

7 In the **Settings** window for **Study**, type `69.8Td w/N=1e-12` in the **Label** text field.

8 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

9 Clear the **Generate convergence plots** checkbox.

10 In the **Study** toolbar, click = **Compute**.

RESULTS

EEDF w/N

1 In the **Model Builder** window, right-click **EEDF e-e** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **0.76Td w/N=0/Solution 17 (sol17)**.

4 Locate the **Axis** section. In the **x maximum** text field, type `20`.

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

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

7 In the **Label** text field, type `EEDF w/N`.

Line Graph 1

1 In the **Model Builder** window, expand the **EEDF e-e 1** node, then click **Results** > **EEDF w/N** > **Line Graph 1**.

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

3 From the **Legends** list, choose **Evaluated**.

4 In the **Legend** text field, type `E/N=eval(be.EN,Td,3) Td, w/N=eval(wN)`.

5 In the **EEDF w/N** toolbar, click **Plot**.

Line Graph 2

1 Right-click **Results** > **EEDF w/N** > **Line Graph 1** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **3.83Td w/N=2e-13/Solution 18 (sol18)**.

Line Graph 3

1 Right-click **Line Graph 2** and choose **Duplicate**.

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

3 From the **Dataset** list, choose **69.8Td w/N=1e-12/Solution 19 (sol19)**.

4 In the **EEDF w/N** toolbar, click **Plot**.

The last study parameterizes over the reduced oscillating frequency over a wide range of reduced electric fields.

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** > **Reduced Electric Fields**.

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

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

STUDY 8

Step 1: Reduced Electric Fields

1 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

2 Click **Range**.

3 In the **Range** dialog, type `10` in the **Start** text field.

4 In the **Step** text field, type `5`.

5 In the **Stop** text field, type `2500`.

6 Click **Replace**.

7 In the **Settings** window for **Reduced Electric Fields**, locate the **Study Settings** section.

8 In the **Reduced electric fields** text field, type `range(10,2,2500)[Td]`.

9 From the **Reuse solution from previous step** list, choose **Yes**.

10 In the **Model Builder** window, click **Study 8**.

11 In the **Settings** window for **Study**, type `Rion w/N` in the **Label** text field.

12 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.

13 Clear the **Generate convergence plots** checkbox.

Parametric Sweep

1 In the **Study** toolbar, click **Parametric Sweep**.

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

3 Click **Add**.

4 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
wN (Reduced frequency)	`0 1e-13 2e-13 1e-12`	

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

RESULTS

Ionization vs. electron mean energy w/N

1 In the **Model Builder** window, right-click **Ionization vs. electron mean energy xArs** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `Ionization vs. electron mean energy w/N` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Rion w/N/ Parametric Solutions 3 (sol21)**.

Global 1

1 In the **Model Builder** window, expand the **Ionization vs. electron mean energy w/N** node, then click **Global 1**.

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

3 From the **Parameter** list, choose **Expression**.

4 In the **Expression** text field, type `be.ebar`.

5 Locate the **Legends** section. From the **Legends** list, choose **Automatic**.

6 Find the **Include** subsection. Clear the **Description** checkbox.

7 In the **Ionization vs. electron mean energy w/N** toolbar, click **Plot**.