Created in COMSOL Multiphysics 6.0

Transient Negative Mobility and Negative Differential Conductivity Effects in Xenon

Introduction

This model simulates two interesting effects that can be explained by solving the Boltzmann equation in the two-term approximation: (i) the Negative Differential Conductivity (NDC) in gases that occurs when the electron drift velocity decreases with the increase of the electric field; and (ii) the Transient Negative Mobility (TNM) that occurs when the temporal variation of the Electron Energy Distribution Function (EEDF) is much faster than the variation of the electron number density and the electron mobility becomes negative during the relaxation of the EEDF. The model results here presented agree well with the results from Ref. 1.

Model Definition

The theory and formulation used in this tutorial is based on Ref. 2. In Ref. 2 only a approximated version of the stationary Boltzmann equation is solved. Here, to study the TNM effect the time derivative of the electron energy distribution function is introduced in the same way as in Ref. 1.

The time dependent Boltzmann equation in the two-term approximation can be written as

$$\frac{\sqrt{\varepsilon}}{N}\frac{\partial F_0}{\partial t}+\frac{\partial}{\partial \varepsilon}\left(WF_0-D\frac{\partial F_0}{\partial \varepsilon}\right) = S$$

where F_0 is the normalized 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:

$$\mathbf{n}\cdot\left(WF_0-D\frac{\partial F_0}{\partial \varepsilon}\right) = 0$$

and as $\varepsilon \rightarrow \infty$, $F_0 \rightarrow 0$.

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 xenon and the electron impact collisions cross-sections are obtained from Ref. 3.

Results and Discussion

To study the NDC it is used the stationary Boltzmann equation in the two-term approximation. The simulations are done at 1 atm and cover a range of reduced electric fields between 0.1 and 10 Td, and ionization degrees between 0 and 10^{-5}. The results are presented in Figure 1to Figure 4. The electron drift velocity is presented in Figure 4 as a function of the reduced electric field. Without electron-electron collisions the drift velocity is a monotonic increasing function of the electric field. However, introducing electron-electron collisions a negative slope on the drift velocity appears indicating the presence of NDC.

To study the TNM it is used the time dependent Boltzmann equation in the two-term approximation. The simulations are done at 10 atm and solve the temporal relaxation of the EEDF to 0.01 Td starting from a stationary solution at 2.2 Td. Figure 5 to Figure 7 show simulation results related to the TNM. Figure 7 shows the electron drift velocity as a function of time. After switching the electric field to 0.01 Td there is a fast drop (~3 ns) in the drift velocity followed by long relaxation period of the order of 100 ns. For the case with electron-electron collisions (ionization degree of 10^{-7}) the drift velocity is allays positive and reaches a steady just after 100 ns. Without electron-electron collisions the drift velocity passes by a region of negative values clearly showing the TNM effect and a steady state is still not reached at 200 ns.

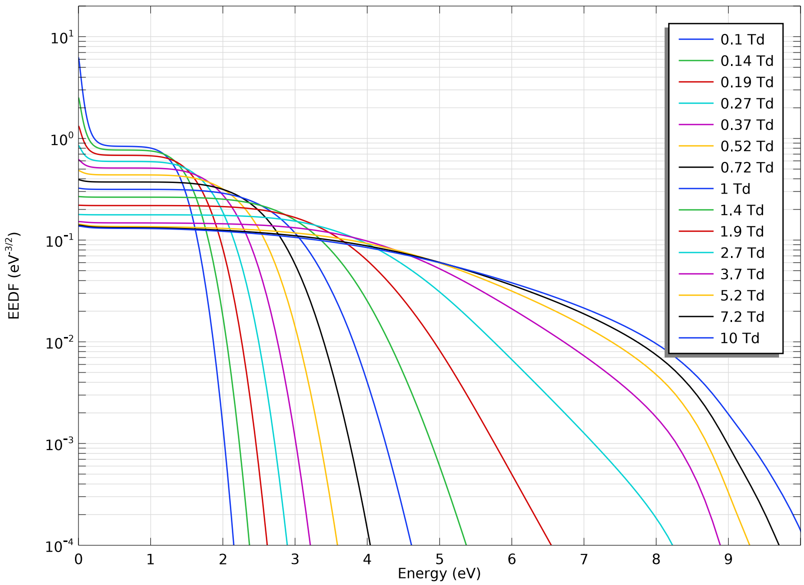

Figure 1: EEDFs for the stationary case for β*=0, 1 atm, and for several reduced electric fields between 0.1 and 10 Td. Compare with figure 2 of* Ref. 1.

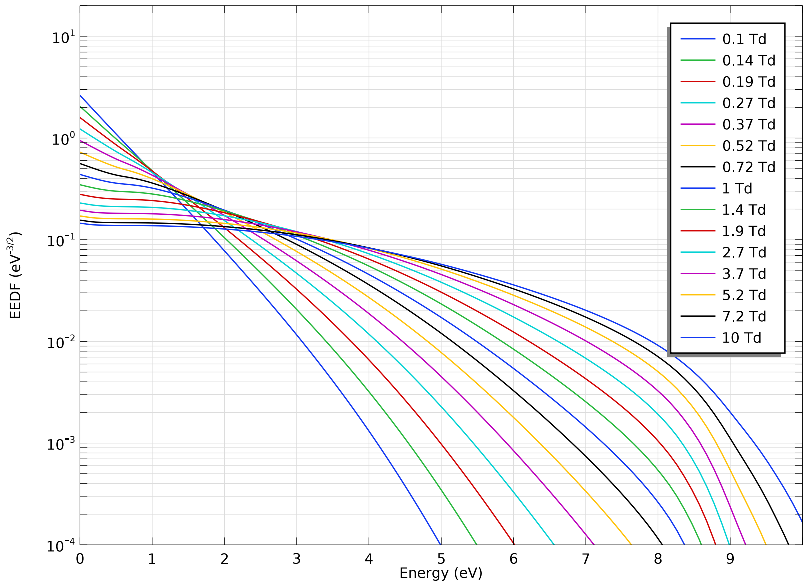

Figure 2: EEDFs for the stationary case for $\beta=10^{-6}$*, 1 atm, and for several reduced electric fields between 0.1 and 10 Td. Compare with figure 2 of* Ref. 1.

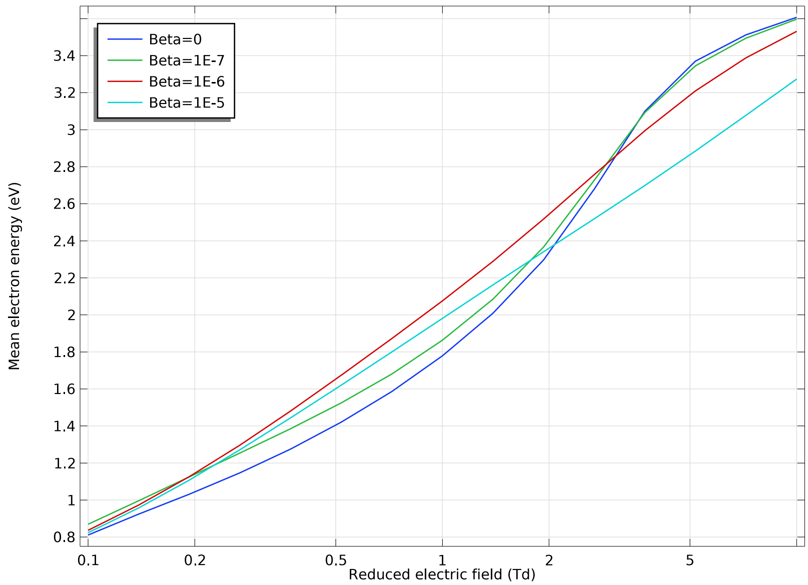

Figure 3: Mean electron energy as a function of the reduced electric field for several ionization degrees at 1 atm. Compare with figure 2 of Ref. 1.

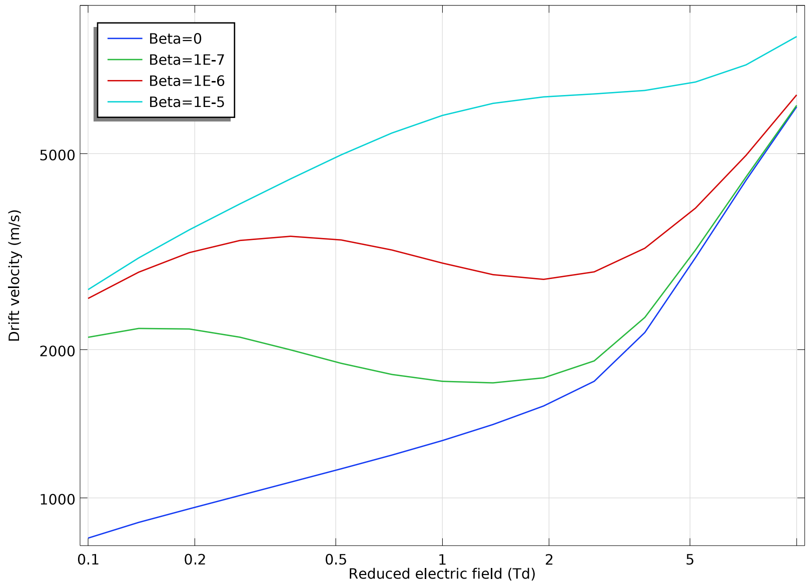

Figure 4: Electron drift velocity as a function of the reduced electric field for several ionization degrees at 1 atm. Compare with figure 4 of Ref. 1.

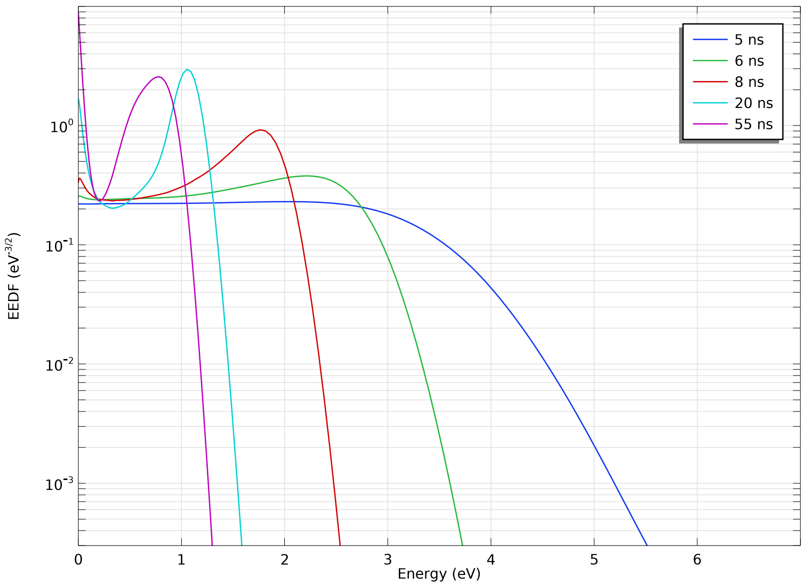

Figure 5: EEDFs for several time instants during the relaxation from 2.2 to 0.01 Td at 10 atm and β=0. Compare with figure 8 of Ref. 1.

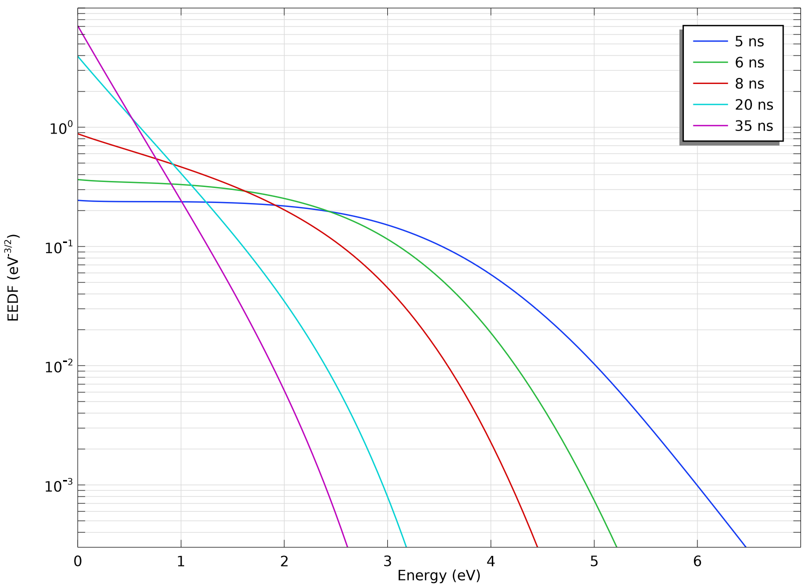

Figure 6: EEDFs for several time instants during the relaxation from 2.2 to 0.01 Td at 10 atm and β*=10*$^{-7}$. *Compare with figure 8 of* Ref. 1.

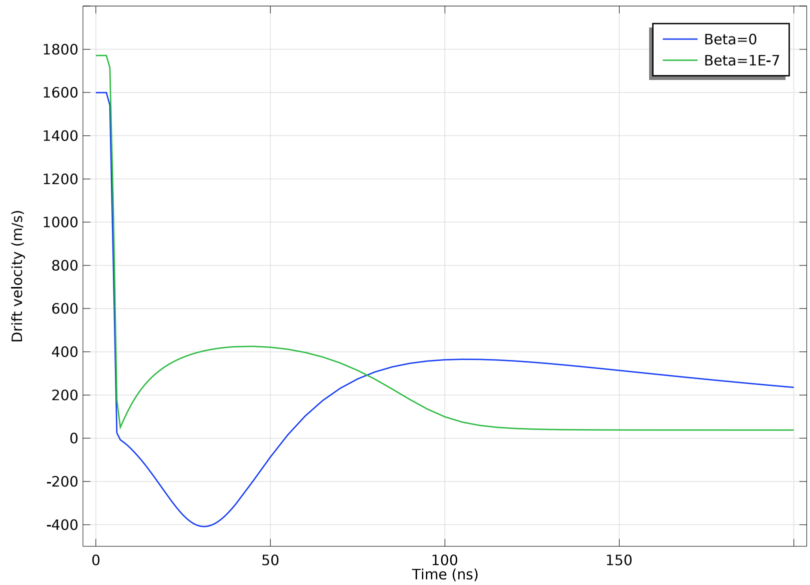

Figure 7: Temporal evolution of the electron drift velocity at 10 atm for β*=0 and* 10^{-7}*. Compare with figure 7 of* Ref. 1.

References

1. Z. Donko and N. Dyatko, "First-Principles Particle Simulation and Boltzmann Equation of Negative Differential Conductivity and Transient Negative Effects in Xenon", *Eur.Phys. J. D* vol. 70, pp. 135–146, 2016.

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. M. Hayashi (2003) database, www.lxcat.net, retrieved 2021.

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

Modeling Instructions

Select a 0D space dimension to have access to the Boltzmann Equation, Two-Term Aproximation interface.

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **0D**.

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

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

Select to include electron-electron collision, add more elements, refine the region at 0 eV, and set the maximum energy to 30 eV.

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** check box.

5 In the N text field, type 300.

6 In the R text field, type 30.

7 In the ε_{max} text field, type 30.

Import electron impact cross sections for Xenon.

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 `Xe_xsecs.txt`.

5 Click **Import**.

Set some parameters to be used in the model. Some of the parameters are only relevant for the time dependent study.

Add a rectangle function that will work as a switch to be used in the time dependent model.

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
Tgas	300[K]	300 K	Gas temperature
P0	1[atm]	1.0133E5 Pa	Gas pressure
Ngas	P0/(k_B_const*Tgas)	2.4463E25 1/m³	Gas density
Beta	1e-7	1E-7	Ionization degree
ne	Beta*Ngas+eps	2.4463E18 1/m³	Electron density

DEFINITIONS (COMP1)

Rectangle 1 (rect1)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>Rectangle**.

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

3 In the **Lower limit** text field, type `-5`.

4 In the **Upper limit** text field, type `5`.

5 Click to expand the **Smoothing** section. In the **Size of transition zone** text field, type `3`.

Set the gas temperature, electron density, and ionization degree.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

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 **Boltzmann Settings** section.

3 In the T_g text field, type `Tgas`.

4 In the n_e text field, type `ne`.

5 In the β text field, type `Beta`.

6 Locate the **Results** section. Find the **Generate the following default plots** subsection. Clear the **Mean electron energy** check box.

7 Clear the **Transport properties** check box.

8 Clear the **Rate coefficients** check box.

9 Select the **Mean electron energy** check box.

10 From the **Plot as a function of** list, choose **Reduced electric field**.

Prepare a study to solve for a reduce field from 0.1 to 10 Td and for several ionization degrees.

STATIONARY

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

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

Step 1: Reduced Electric Fields

1 In the **Model Builder** window, under **Stationary** 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^{range(log10(0.1),1/7, log10(10))}[Td]`.

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-7 1e-6 1e-5	

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

RESULTS

EEDF (be)

Make plots to show the effect of the electric field and the ionization degree in the EEDFs, electron mean energy, and electron drift velocity.

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

2 From the **Parameter selection (Beta)** list, choose **From list**.

3 In the **Parameter values (Beta)** list, select **0**.

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

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

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

7 In the **y minimum** text field, type `1e-4`.

8 In the **y maximum** text field, type `20`.

9 In the **EEDF (be)** toolbar, click **Plot**.

Line Graph 1

1 In the **Model Builder** window, expand the **EEDF (be)** 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 `eval(be.EN, Td, 2) Td`.

EEDF, Beta=0

1 In the **Model Builder** window, under **Results** click **EEDF (be)**.

2 In the **Settings** window for **1D Plot Group**, type `EEDF, Beta=0` in the **Label** text field.

EEDF, Beta=1e-6

1 Right-click **EEDF, Beta=0** and choose **Duplicate**.

2 In the **Settings** window for **1D Plot Group**, type `EEDF, Beta=1e-6` in the **Label** text field.

3 Locate the **Data** section. In the **Parameter values (Beta)** list, select **1E-6**.

4 In the **EEDF, Beta=1e-6** toolbar, click **Plot**.

Mean Electron Energy (be)

1 In the **Model Builder** window, click **Mean Electron Energy (be)**.

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

3 Select the **Manual axis limits** check box.

4 In the **y minimum** text field, type `0.5`.

5 In the **y maximum** text field, type `4`.

6 Locate the **Legend** section. Select the **Show legends** check box.

Global 1

1 In the **Model Builder** window, expand the **Mean Electron Energy (be)** node, then click **Global 1**.

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

3 Find the **Include** subsection. Clear the **Description** check box.

Mean Electron Energy (be)

1 In the **Model Builder** window, click **Mean Electron Energy (be)**.

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

3 From the **Position** list, choose **Upper left**.

4 Locate the **Axis** section. Select the **x-axis log scale** check box.

5 In the **Model Builder** window, collapse the **Mean Electron Energy (be)** node.

EEDF, Beta=0

In the **Model Builder** window, collapse the **Results>EEDF, Beta=0** node.

EEDF, Beta=0, EEDF, Beta=1e-6, Mean Electron Energy (be)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **EEDF, Beta=0**, **Mean Electron Energy (be)**, and **EEDF, Beta=1e-6**.

2 Right-click and choose **Group**.

Stationary

In the **Settings** window for **Group**, type `Stationary` in the **Label** text field.

Drift Velocity

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Stationary/Parametric Solutions 1 (sol2)**.

Global 1

1 Right-click **Drift Velocity** 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.w`	`m/s`	`Drift velocity`

4 In the **Drift Velocity** toolbar, click **Plot**.

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

6 In the **Expression** text field, type `be.EN`.

7 From the **Unit** list, choose **Td**.

8 Locate the **Legends** section. Find the **Include** subsection. Clear the **Description** check box.

9 In the **Drift Velocity** toolbar, click **Plot**.

Drift Velocity

1 In the **Model Builder** window, click **Drift Velocity**.

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 **Axis** section. Select the **y-axis log scale** check box.

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

6 Select the **Manual axis limits** check box.

7 In the **y minimum** text field, type `800`.

8 In the **y maximum** text field, type `10000`.

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

Add two Reduced Electric Fields studies and two Time Dependent studies.

The Reduced Electric Fields studies are used to provide initial conditions for the time dependent studies.

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 **Add Study** in the window toolbar.

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

6 In the **Select Study** tree, select **General Studies>Time Dependent**.

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

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

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

INITIAL CONDITIONS FOR TIME DEPENDENT, 2.2[TD], BETA=0

In the **Settings** window for **Study**, type `Initial conditions for time dependent, 2.2[Td], Beta=0` in the **Label** text field.

Step 1: Reduced Electric Fields

1 In the **Model Builder** window, under **Initial conditions for time dependent, 2.2[Td], Beta=0** 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 `2.2[Td]`.

The next simulations are to be done at 10 atm.

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	10[atm]	1.0133E6 Pa	Gas pressure
Beta	0	0	Ionization degree

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION (BE)

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 **Results** section.

3 Find the **Generate the following default plots** subsection. Clear the **Mean electron energy** check box.

INITIAL CONDITIONS FOR TIME DEPENDENT, 2.2[TD], BETA=0

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

RESULTS

EEDF, Beta=0, 2.2 Td

1 In the **Settings** window for **1D Plot Group**, type `EEDF, Beta=0, 2.2 Td` in the **Label** text field.

2 In the **EEDF, Beta=0, 2.2 Td** toolbar, click **Plot**.

INITIAL CONDITIONS FOR TIME DEPENDENT, 2.2[TD], BETA=1E-7

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

2 In the **Settings** window for **Study**, type `Initial conditions for time dependent, 2.2[Td], Beta=1e-7` in the **Label** text field.

Step 1: Reduced Electric Fields

1 In the **Model Builder** window, under **Initial conditions for time dependent, 2.2[Td], Beta=1e-7** 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 `2.2[Td]`.

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	1e-7	1E-7	Ionization degree

INITIAL CONDITIONS FOR TIME DEPENDENT, 2.2[TD], BETA=1E-7

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

RESULTS

EEDF, Beta=1e-7, 2.2[Td]

1 In the **Model Builder** window, under **Results** click **EEDF, Beta=0, 2.2 Td**.

2 In the **Settings** window for **1D Plot Group**, type `EEDF, Beta=1e-7, 2.2[Td]` in the **Label** text field.

3 In the **EEDF, Beta=1e-7, 2.2[Td]** toolbar, click **Plot**.

EEDF (be), EEDF, Beta=1e-7, 2.2[Td]

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **EEDF, Beta=1e-7, 2.2[Td]** and **EEDF (be)**.

2 Right-click and choose **Group**.

Initial conditions

1 In the **Settings** window for **Group**, type `Initial conditions` in the **Label** text field.

Select to solve for a time dependent EEDF.

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 From the **Temporal behavior** list, choose **Time dependent EEDF**.

Set the pressure and the reduce electric field. In the first nanoseconds the reduced electric field is 2.2 Td and it drops to 0.01 Td in about 3 ns.

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 **Boltzmann Settings** section.

3 In the p_A text field, type `P0`.

4 In the *E/N* text field, type `rect1(t/1[ns])*(2.2-0.01)[Td]+0.01[Td]`.

TIME DEPENDENT, BETA=0

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

2 In the **Settings** window for **Study**, type `Time dependent, Beta=0` in the **Label** text field.

Make a careful selection of the output times to obtain a good description of the fast transient phase. Solve and make a plot of the EEDFs for several time instants.

Step 1: Time Dependent

1 In the **Model Builder** window, under **Time dependent, Beta=0** click **Step 1: Time Dependent**.

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

3 From the **Time unit** list, choose **ns**.

4 In the **Output times** text field, type `0  range(1,1,40) range(45,5,200)`.

5 Click to expand the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

7 From the **Study** list, choose **Initial conditions for time dependent, 2.2[Td], Beta=0, Reduced Electric Fields**.

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

TIME DEPENDENT, BETA=0

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

RESULTS

EEDF Time Dependent, Beta=0

1 In the **Settings** window for **1D Plot Group**, type `EEDF Time Dependent, Beta=0` in the **Label** text field.

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

3 In the **Times (ns)** list, choose **5**, **6**, **8**, **20**, and **55**.

4 In the **EEDF Time Dependent, Beta=0** toolbar, click **Plot**.

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 `7`.

8 In the **y minimum** text field, type `3e-4`.

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

10 In the **EEDF Time Dependent, Beta=0** toolbar, click **Plot**.

Change the ionization degree to 1e-7 and repeat.

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`	`1e-7`	1E-7	`Ionization degree`

STUDY 5

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 5** click **Step 1: Time Dependent**.

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

3 From the **Time unit** list, choose **ns**.

4 In the **Output times** text field, type `0 range(1,1,40) range(45,5,200)`.

5 Locate the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

6 From the **Study** list, choose **Initial conditions for time dependent, 2.2[Td], Beta=1e-7, Reduced Electric Fields**.

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

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

9 In the **Settings** window for **Study**, type `Time dependent, Beta=1e-7` in the **Label** text field.

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

RESULTS

EEDF Time Dependent, Beta=1e-7

1 In the **Settings** window for **1D Plot Group**, type `EEDF Time Dependent, Beta=1e-7` in the **Label** text field.

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

3 In the **Times (ns)** list, choose **5**, **6**, **8**, **20**, and **35**.

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

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

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

7 In the **y minimum** text field, type `3e-4`.

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

9 In the **EEDF Time Dependent, Beta=1e-7** toolbar, click **Plot**.

EEDF Time Dependent, Beta=0, EEDF Time Dependent, Beta=1e-7

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **EEDF Time Dependent, Beta=0** and **EEDF Time Dependent, Beta=1e-7**.

2 Right-click and choose **Group**.

Time Dependent

In the **Settings** window for **Group**, type `Time Dependent` in the **Label** text field.

Time Dependent Drift velocity

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

Create a plot to show the temporal evolution of the electron drift velocity.

2 In the **Settings** window for **1D Plot Group**, type `Time Dependent Drift velocity` in the **Label** text field.

Global 1

1 Right-click **Time Dependent Drift velocity** and choose **Global**.

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

3 From the **Dataset** list, choose **Time dependent, Beta=0/Solution 9 (sol9)**.

4 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
be.w	m/s	Drift velocity

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

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

7 In the **Time Dependent Drift velocity** toolbar, click **Plot**.

Global 2

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

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

3 From the **Dataset** list, choose **Time dependent, Beta=1e-7/Solution 10 (sol10)**.

4 In the **Time Dependent Drift velocity** toolbar, click **Plot**.

Time Dependent Drift velocity

1 In the **Model Builder** window, click **Time Dependent Drift velocity**.
2 In the **Settings** window for **1D Plot Group**, locate the **Title** section.
3 From the **Title type** list, choose **None**.
4 Locate the **Axis** section. Select the **Manual axis limits** check box.
5 In the **y minimum** text field, type `-500`.
6 In the **y maximum** text field, type `2000`.
7 In the **Time Dependent Drift velocity** toolbar, click **Plot**.