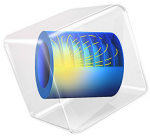

Negative Streamer in Nitrogen

Introduction

Streamers are transient filamentary electric discharges that can develop in a nonconducting background in the presence of an intense electric field. These discharges can attain high electron number density and, consequently, a high concentration of chemical active species that are relevant for numerous applications. Industrial applications include: ozone production, pollution control, and surface processing.

The propagation of streamers is driven by very nonlinear dynamics that involve very steep density gradients and high space-charge density distributed in very thin layers. The charge separation at the front (or head) of the streamer generates intense electric fields that are responsible for sharp ionization fronts propagating into the neutral medium.

In negative (anode directed) streamers, ionizing electrons are accelerated outward by the space-charge (the streamer extends toward the anode). These high energy electrons may have been transported by drift or diffusion, or created by another mechanism that provides preionization ahead of the streamer such as photoionization or ionization from runway electrons. In positive (or cathode directed) streamers the space-charge field in the streamer head accelerates the electrons inward. Consequently, the ionizing electrons must be produced by a preionization mechanism. The preionization of the streamer is a complex subject that is believed to be critical for both negative and positive streamers propagation and is still under intense investigation. This document is an introduction to streamer modeling with focus on basic concepts of streamer propagation. With that in mind it is followed a simplified approach where all preionization is neglected and only negative streamers are discussed.

This example presents a study of a negative streamer in atmospheric pressure nitrogen. The streamer propagates with a constant electric field of 100 kV/cm in front of the streamer. The model here presented is similar to the fluid model used in Ref. 1 and gives similar results. Furthermore, in Ref. 1, results from a fluid and particle-in-cell model are compared to agree very well for fields below 50 kV/cm (at atmospheric pressure).

Model Definition

The model is one dimensional and describes the transient behavior of an initial electron seed in the presence of a strong electric field using fluid-type equations.

The simulation is design with emphasis in the streamer propagation. The streamer develops from an initial small electron density placed near the cathode. Without preionization only a negative streamer develops toward the anode. The initial number density and exact location of the seed are chosen to form a streamer long before it reaches

the anode. The distance between electrodes is 1.15 mm. The cathode (placed on the left) is grounded and at the anode is given a constant electric field of –100 kV/cm. A constant electric field ahead of the streamer allows for an equilibrium in the electron density growth and a constant propagation velocity.

The model solves the electron and ion continuity and momentum equations, in the drift-diffusion approximation, self-consistently coupled with Poisson's equation. The local field approximation is used, which means that transport and source coefficients are assumed to be well parameterized through the reduced electric field (E/N). In the local field approximation the fluid equation for the mean electron energy is not solved, which reduces significantly the complexity of the numerical problem.

The local field approximation is valid in a situation where the rate of electron energy gain from the electric field is locally balanced by the energy loss rate. When this condition is met the electrons are said to be in local equilibrium with the electric field and the electron mean properties can be expressed as a function the reduced electric field.

DOMAIN EQUATIONS

The electron density is computed by solving the drift-diffusion equation for the electron density.

$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot [-n_e(\mu_e \bullet \mathbf{E}) - \mathbf{D}_e \bullet \nabla n_e] = R_e \tag{1}$$

Convection of electrons due to fluid motion is neglected. For more detailed information on electron transport see the section *Theory for the Drift Diffusion Interface* in the *Plasma Module User's Guide*.

When using the local field approximation the electron energy density equation is not solved and the transport and source coefficients are mapped by the reduced electric field. In practice, when using the local field approximation or the local energy approximation, the transport and source coefficients are still given as a function of the mean electron energy. When using the local field approximation however, a function that relates the mean electron energy and the reduced electric field must be provided:

$$\varepsilon = F(E/N)\,. \tag{2}$$

The electron source R_e is defined later. The electron diffusivity and electron mobility are provided as a function of the mean electron energy.

The source coefficients in the above equation is determined by the plasma chemistry using rate coefficients. Suppose that there are M reactions that contribute to the growth or decay

of electron density and P inelastic electron-neutral collisions. In general $P \gg M$. In the case of rate coefficients, the electron source term is given by

$$R_e = \sum_{j=1}^{M} x_j k_j N_n n_e \tag{3}$$

where x_j is the mole fraction of the target species for reaction j, k_j is the rate coefficient for reaction j (SI unit: m^3/s), and N_n is the total neutral number density (SI unit: $1/\mathrm{m}^3$). For drift-dominated discharges it is better practice to use Townsend coefficients instead of rate coefficients to define reaction rates. Townsend coefficients provide a better description of what happens in the cathode fall region Ref. 2. When Townsend coefficients are used, the electron source term is given by:

$$R_e = \sum_{j=1}^{M} x_j \alpha_j N_n |\Gamma_e| \tag{4}$$

where α_j is the Townsend coefficient for reaction j (m^2) and Γ_e is the electron flux as defined above ($1/(\mathrm{m}^2 \cdot \mathrm{s})$). Townsend coefficients can increase the stability of the numerical scheme when the electron flux is field driven as is the case with streamers.

For nonelectron species, the following equation is solved for the mass fraction of each species:

$$\rho \frac{\partial}{\partial t}(w_k) + \rho(\mathbf{u} \cdot \nabla) w_k = \nabla \cdot \mathbf{j}_k + R_k \tag{5}$$

For detailed information on the transport of the nonelectron species see the section *Theory for the Heavy Species Transport Interface* in the *Plasma Module User's Guide*.

The electrostatic field is computed using the equation

$$-\nabla \cdot \varepsilon_0 \varepsilon_r \nabla V = \rho \tag{6}$$

The space charge density ρ is automatically computed based on the plasma chemistry specified in the model using the formula

$$\rho = q\left(\sum_{k=1}^{N} Z_k n_k - n_e\right) \tag{7}$$

For detailed information about electrostatics see *Theory for the Electrostatics Interface* in the *Plasma Module User's Guide*.

Boundary Conditions

The present simulation is arranged in a way that the charged particle interaction with the wall is irrelevant to what happen to the streamer propagation. Nevertheless boundary conditions must be given. Electrons are lost to the wall due to random motion within a few mean free paths of the wall resulting in the boundary condition for the electron flux

$$\mathbf{n} \cdot \Gamma_e = \left(\frac{1}{2} v_{e,\,\mathrm{th}} n_e\right). \tag{8}$$

For the heavy species, ions are lost to the wall due to surface reactions and the fact that the electric field is directed toward the wall:

$$\mathbf{n} \cdot \mathbf{j}_k = M_w R_k + M_w c_k Z \mu_k (\mathbf{E} \cdot \mathbf{n})[Z_k \mu_k (\mathbf{E} \cdot \mathbf{n}) > 0] \tag{9}$$

The streamer propagates (from left to right) with a constant electric field ahead of -100 kV/cm. The cathode on the left is grounded,

PLASMA CHEMISTRY

The chemistry of a plasma sustained in nitrogen can be very complex and a detailed study of the main excited states could easily have hundreds of reactions. The main goal of this model is to study the charge particle density profiles in the presence of strong electric fields. With that in mind it is used one single ionization reaction as presented in Table 1 that describes correctly the creation of charged species in a background of nitrogen. In this work it is used the Townsend coefficient as a function of the mean electron energy provided in Ref. 1.

TABLE 1: IONIZATION REACTION.

Reaction	Formula	Type	$\Delta\varepsilon$ (eV)	k_f (m^3/s)
1	e+N=>2e+N+	Ionization	15.5	-

In addition to the volumetric reactions, the following surface reaction is implemented:

TABLE 2: TABLE OF SURFACE REACTION.

Reaction	Formula	Sticking coefficient
1	N+=>N	1

When an ions reach the wall, they are assumed to change back to neutral atoms.

Results and Discussion

The results in this section are for a streamer propagating in a background gas kept at a constant density as obtained by the ideal gas law at atmospheric pressure and at a temperature of 293.15 K. All transport and source coefficients used in this simulation are form Ref. 1. There, the electron mobility and diffusion coefficients, the Townsend coefficient, and the mean electron energy as a function of the reduced electric field are obtain using particle swarm simulations.

Figure 1 presents the spatial distribution of the electron and ion density for several instants during the streamer simulation. The streamer is initiated by a localized number of electrons near the cathode (left in all figures below). In a first phase there is electron drift and growth in an unperturbed electric field. The first instant in Figure 1 marks the end of this period. A streamer is formed if the amplification of the electron density is enough to generate intense space-charge electric fields and electric shielding before the streamer arrives to the anode. The last three instants of Figure 1 correspond to the streamer phase.

In the streamer phase the maximum electron and ion density reach a constant value and propagate at constant velocity (because the electric field ahead of the streamer is kept constant). The streamer morphology is composed of (i) a region of strong charge separation and strong density gradients (the streamer head), and (ii) a quasi-neutral region with flat profiles (the streamer body) that increases its length with the streamer propagation.

Figure 2, Figure 3, and Figure 4 show the spatial distribution of the electric field, space-charge density, and mean electron energy, respectively, for several instants during the streamer simulation. Note how the quasi-neutral streamer body shields the electric field to very small values causing the electrons to cool down. This makes the electron creation in the body negligible.

On the left there is also a charge separation region. This region is created because the electrons are pulled toward the anode leaving the created ions behind. The ions, being much less mobile than electrons, do not have time to drift in this 0.9 ns simulation. Note also that this charge separation region does not move in time, which is achieved by setting low levels of preionization.

The ionization front moves with a velocity larger than the electron drift velocity

$$v_d = \mu_e |\boldsymbol{E}| \,. \tag{10}$$

determined solely by the electric field in the leading edge of the streamer. The ionization front velocity has also contributions from electron diffusion and creation of new electrons and can be given by the expression Ref. 1

$$v_f = \mu_e|E| + 2\sqrt{D_e\mu_e|E|a}\,. \tag{11}$$

The values of the electron drift velocity and the ionization front propagation are plotted in Ref. 5. Equation 11 is an analytic solution obtained for planar fronts.

There is a general excellent agreement with the results from the model here presented and the ones from the fluid model presented in Ref. 1 when comparing values of peak electron density, ionization level in the body, electron mean energy, streamer propagation velocity, and spatial profiles of different quantities.

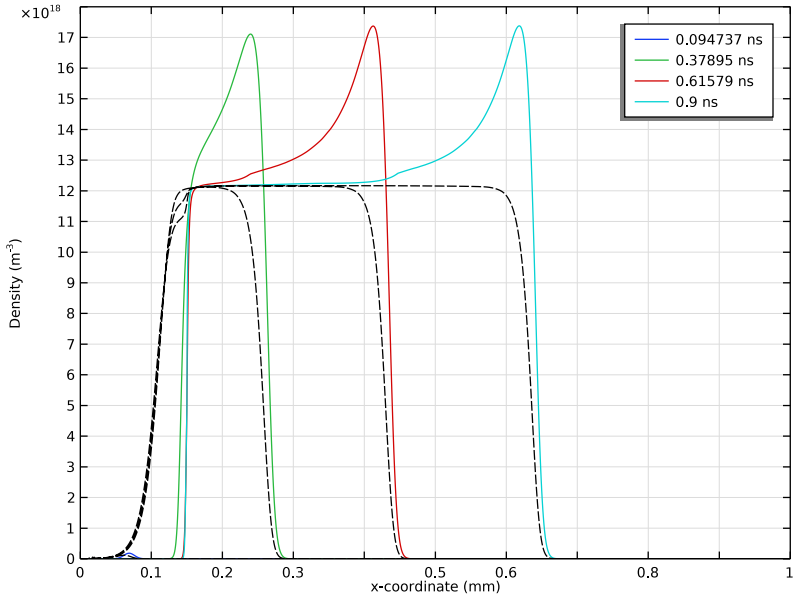

Figure 1: Spatial distribution of the electron (colored solid lines) and ion number density (black dashed lines) for four time instants during the streamer propagation.

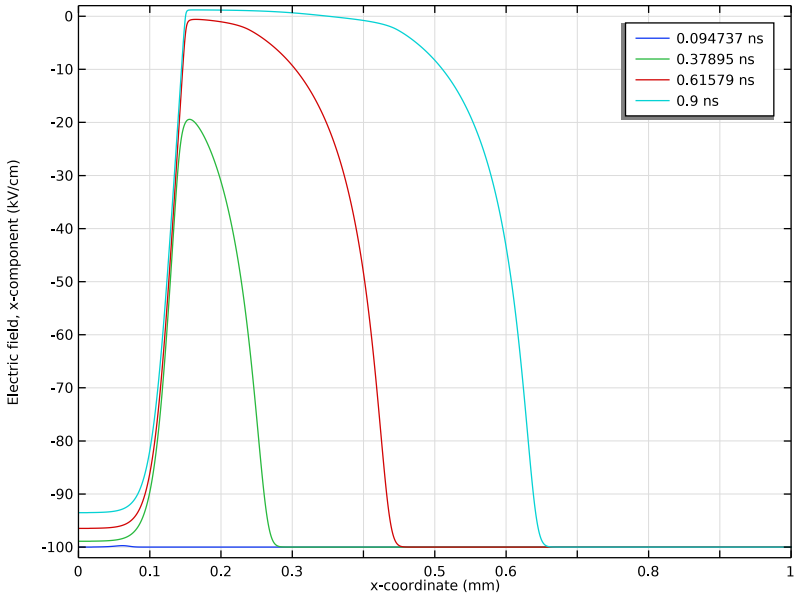

Figure 2: Electric field spatial distribution for four time instants during the streamer propagation.

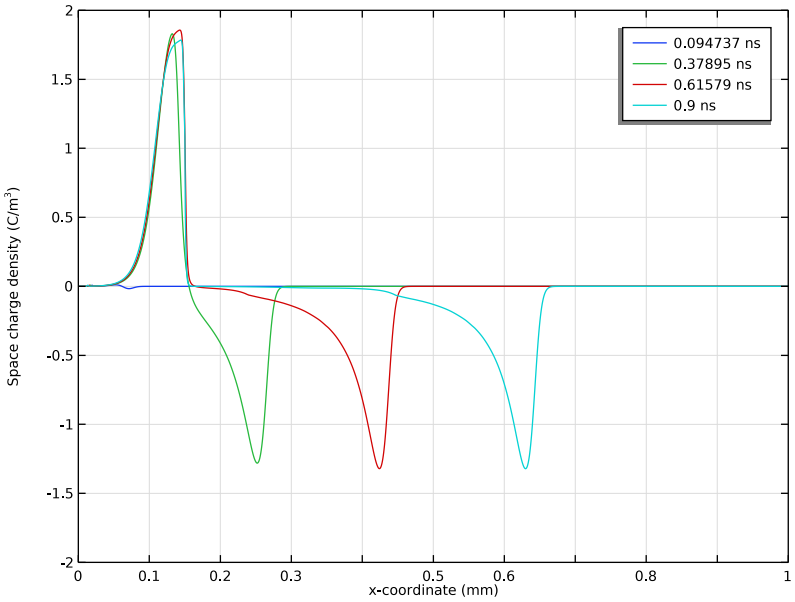

Figure 3: Space charge density for four time instants during the streamer propagation.

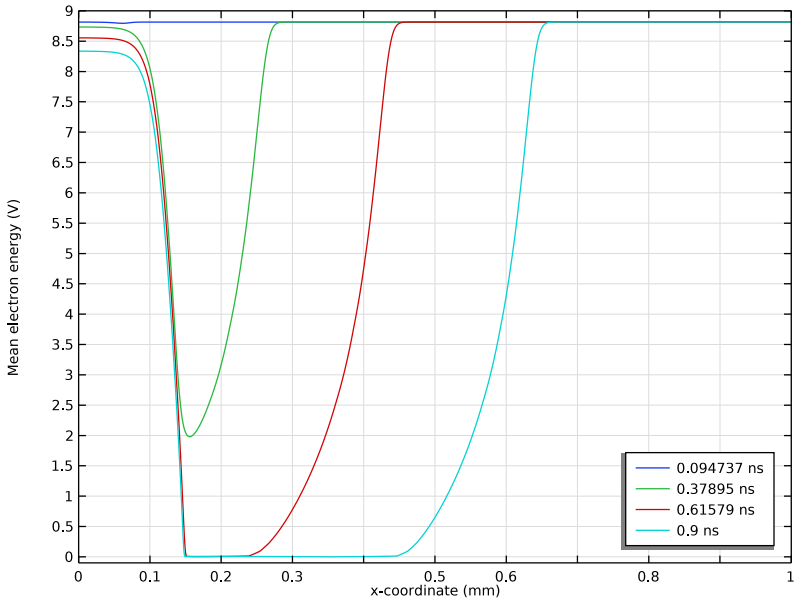

Figure 4: Mean electron energy for four time instants during the streamer propagation.

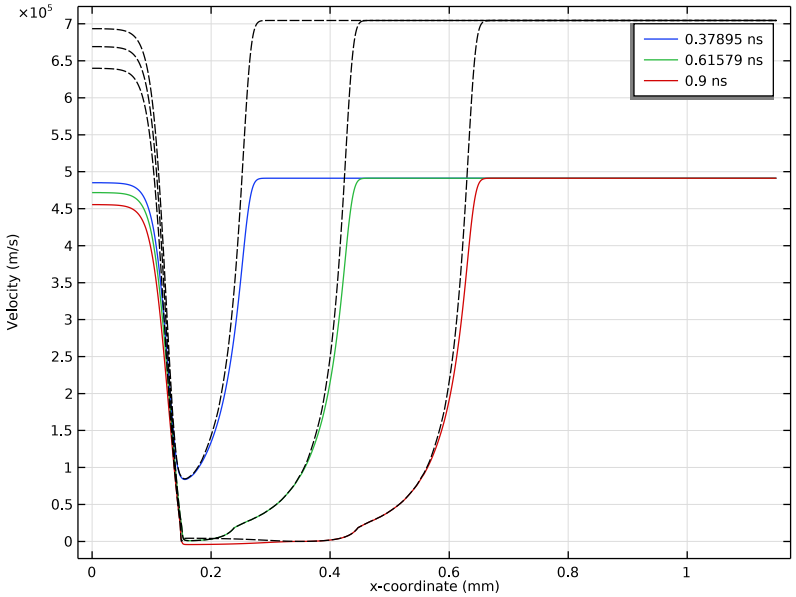

Figure 5: Electron drift velocity (colored solid lines) and velocity computed using Equation 11 *(black dashed lines) for three time instants during the streamer propagation.*

References

1. C. Li, W.J.M. Brok, U. Ebert, and J.J.A.M. van der Mullen, "Deviations from the local field approximation in negative streamer heads," *J. Appl. Phys.*, vol. 101, pp. 123305–1–11, 2007.

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

Application Library path: `Plasma_Module/Direct_Current_Discharges/streamer_1d`

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 **1D**.

2 In the **Select Physics** tree, select **Plasma>Plasma (plas)**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

GEOMETRY 1

Follow the steps below to create the model geometry: a simple 1D geometry consisting of a grounded electrode on the left (cathode) and a boundary condition to fix a constant electric field on the right (anode).

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

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

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

Interval 1 (i1)

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

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

3 In the table, enter the following settings:

Coordinates (mm)
0
1.15

Interval 2 (i2)

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Interval**.

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

3 In the table, enter the following settings:

Coordinates (mm)
1.15
1.151

4 Click **Build All Objects**.

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
ne0	ne0max*exp(-((x-x0)/sigma)^2)+ ne0min	1/m³	
ne0min	1e-15[m^-3]	1/m³	
ne0max	5e16[m^-3]	1/m³	
x0	0.02e-3[m]	m	
sigma	0.01e-4[m]	m	

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
Efield	-100[kV/cm]	-1E7 V/m	

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

5 In the **Show More Options** dialog box, in the tree, select the check box for the node **Physics>Stabilization**.

6 Click **OK**.

PLASMA (PLAS)

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

2 In the **Settings** window for **Plasma**, click to expand the **Stabilization** section.

3 Clear the **Source stabilization** check box.

4 Clear the **Reaction source stabilization** check box.

5 Locate the **Plasma Properties** section. Select the **Use reduced electron transport properties** check box.

This model uses the local field approximation to parameterize in space source and transport coefficients.

6 From the **Mean electron energy** list, choose **Local field approximation**.

Electron Impact Reaction 1

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

Add an ionization reaction.

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

3 In the **Formula** text field, type `e+N=>2e+N+`.

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

5 In the Δε text field, type `15.6`.

Import the ionization Townsend coefficient.

6 Locate the **Collision** section. From the **Specify reaction using** list, choose **Use lookup table**.

7 Locate the **Reaction Parameters** section. From the **Rate constant form** list, choose **Townsend coefficient**.

8 Find the **Townsend coefficient data** subsection. Click **Load from File**.

9 Browse to the model's Application Libraries folder and double-click the file `alphaN2.txt`.

Species: N

When solving any type of reacting flow problem one species must always be chosen to fulfill the mass constraint. This should be taken as the species with the largest mass fraction.

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

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 **N2**.

Species: N+

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

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

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

4 Locate the **General Parameters** section. From the **Preset species data** list, choose **N2**.

Surface Reaction 1

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

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

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

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

5 In the list, select **3**.

6 Click **Remove from Selection**.

7 Select Boundaries 1 and 2 only.

Plasma Model 1

Import the tables of the electron mobility and diffusivity, and the mean electron energy as a function of the reduced electric field.

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 From the **Electron transport properties** list, choose **Use lookup tables**.

4 Find the **Reduced electron mobility** subsection. Click **Load from File**.

5 Browse to the model's Application Libraries folder and double-click the file `muN2.txt`.

6 Find the **Reduced electron diffusivity** subsection. Click **Load from File**.

7 Browse to the model's Application Libraries folder and double-click the file `DN2.txt`.

8 Locate the **Mean Electron Energy Specification** section. From the **Specify using** list, choose **Use lookup table**.

9 Find the **Mean electron energy** subsection. Click **Load from File**.

10 Browse to the model's Application Libraries folder and double-click the file `EN_to_NrgN2.txt`.

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 `ne0`.

Wall 1

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

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

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

Ground 1

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

2 Select Boundary 1 only.

Electric Displacement Field 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Electric Displacement Field**.

2 In the **Settings** window for **Electric Displacement Field**, locate the **Electric Displacement Field** section.

3 Specify the $\mathbf{D}_0$ vector as

`Efield*epsilon0_const`	x

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

Charge Conservation 1

1 In the **Physics** toolbar, click **Domains** and choose **Charge Conservation**.

2 In the **Settings** window for **Charge Conservation**, locate the **Domain Selection** section.

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

4 In the list, select **1**.

5 Click **Remove from Selection**.

6 Select Domain 2 only.

7 Locate the **Constitutive Relation D-E** section. From the ε_r list, choose **User defined**. In the associated text field, type `10`.

MESH 1

Edge 1

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

Distribution 1

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

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

3 In the list, select **2**.

4 Click **Remove from Selection**.

5 Select Domain 1 only.

6 Locate the **Distribution** section. In the **Number of elements** text field, type `2000`.

Edge 2

In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Edge 1** and choose **Duplicate**.

Distribution 1

1 In the **Model Builder** window, expand the **Edge 2** node, then click **Distribution 1**.

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

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

4 In the list, select **1**.

5 Click **Remove from Selection**.

6 Select Domain 2 only.

7 Locate the **Distribution** section. In the **Number of elements** text field, type `10`.

8 Click **Build All**.

STUDY 1

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

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

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

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** 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 `range(0,0.9/19,0.9)`.

5 Click to expand the **Results While Solving** section. Select the **Plot** check box.

6 From the **Update at** list, choose **Time steps taken by solver**.

Get the initial values to prepare a plot to show the electron and ion densities while the solver runs.

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

RESULTS

Charged Species

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

2 Right-click **Results** and choose **1D Plot Group**.

3 In the **Settings** window for **1D Plot Group**, type `Charged Species` in the **Label** text field.

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

5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Plot Settings** section.

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

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

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

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

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

12 In the **y maximum** text field, type `1.8e19`.

Electrons

1 Right-click **Charged Species** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, type `Electrons` in the **Label** text field.

3 Select Domain 1 only.

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

5 In the **Expression** text field, type `x`.

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

Ions

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

2 In the **Settings** window for **Line Graph**, type `Ions` in the **Label** text field.

3 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.n_wN_1p`.

4 Click to expand the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

5 From the **Color** list, choose **Black**.

6 Locate the **Legends** section. Clear the **Show legends** check box.

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

Charged Species

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

2 From the **Time selection** list, choose **From list**.

3 In the **Times (ns)** list, choose **0.094737**, **0.37895**, **0.61579**, and **0.9**.

4 In the **Charged Species** toolbar, click **Plot**.

Mean electron energy

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

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

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

4 In the **Times (ns)** list, choose **0.094737**, **0.37895**, **0.61579**, and **0.9**.

5 Locate the **Title** section. From the **Title type** list, choose **None**.

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

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

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

9 In the **y minimum** text field, type `-0.1`.

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

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

Line Graph 1

1 Right-click **Mean electron energy** and choose **Line Graph**.

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

3 In the **Expression** text field, type `plas.ebar`.

4 Select Domain 1 only.

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

6 In the **Expression** text field, type `x`.

7 Locate the **Legends** section. Select the **Show legends** check box.

8 In the **Mean electron energy** toolbar, click **Plot**.

Space charge

1 In the **Model Builder** window, right-click **Mean electron energy** and choose **Duplicate**.

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

3 Locate the **Axis** section. In the **y minimum** text field, type `-2`.

4 In the **y maximum** text field, type `2`.

5 Locate the **Legend** section. From the **Position** list, choose **Upper right**.

Line Graph 1

1 In the **Model Builder** window, expand the **Space charge** node, then click **Line Graph 1**.

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

3 In the **Expression** text field, type `plas.scharge`.

4 In the **Space charge** toolbar, click **Plot**.

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 `Velocity` in the **Label** text field.

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

4 In the **Times (ns)** list, choose **0.37895**, **0.61579**, and **0.9**.

5 Locate the **Title** section. From the **Title type** list, choose **None**.

6 Locate the **Plot Settings** section.

7 Select the **y-axis label** check box. In the associated text field, type `Velocity (m/s)`.

Drift velocity

1 Right-click **Velocity** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, type `Drift velocity` in the **Label** text field.

3 Select Domain 1 only.

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

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

6 In the **Expression** text field, type `x`.

7 Locate the **Legends** section. Select the **Show legends** check box.

Analytic

1 In the **Model Builder** window, right-click **Velocity** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, type `Analytic` in the **Label** text field.

3 Select Domain 1 only.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.muexx*abs(plas.Ex)+2*sqrt(plas.Dexx*plas.muexx*abs(plas.Ex)*plas.alpha_1*plas.Nn)`.

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

6 In the **Expression** text field, type `x`.

7 Locate the **Coloring and Style** section. Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

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

Velocity

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

2 In the **Velocity** toolbar, click **Plot**.

Electric field

1 In the **Model Builder** window, right-click **Mean electron energy** and choose **Duplicate**.

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

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

4 In the **x maximum** text field, type `1`.

5 In the **y minimum** text field, type `-102`.

6 In the **y maximum** text field, type `2`.

7 Locate the **Legend** section. From the **Position** list, choose **Upper right**.

Line Graph 1

1 In the **Model Builder** window, expand the **Electric field** node, then click **Line Graph 1**.

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

3 In the **Expression** text field, type `plas.Ex`.

4 In the **Unit** field, type `kV/cm`.

5 In the **Electric field** toolbar, click **Plot**.