Model created in COMSOL Multiphysics 6.4

Negative Surface Discharge at Gas–Solid Interface

Introduction

Dielectric barrier discharge (DBD) is a type of electrical discharge that occurs between two electrodes separated by an insulating dielectric barrier. This phenomenon is commonly used in various applications, including ozone generation, surface treatment, and plasma medicine. The presence of dielectric materials introduces complexity into the discharge process, affecting the distribution of electric fields and the behavior of charged particles.

This model simulates a negative dielectric barrier discharge under a point-to-plate electrode configuration. Two solid dielectric layers are inserted into the air gap, which influences the discharge dynamics. By applying a negative voltage of 2.5 kV to the cathode electrode, a corona streamer is initiated, propagating through the gap and generating a current pulse. Negative charge carriers accumulate at the gas-solid interface, subsequently altering the electric field distribution. This process ultimately leads to the formation of a stable negative surface discharge.

The simulation results, including discharge current and surface charge distribution at the gas-solid interface, show excellent agreement with experiments published in Ref. 1. This model provides valuable insights into the complex interactions within dielectric barrier discharges, particularly the influence of dielectric materials on the behavior of the discharge and the resulting electrical characteristics.

Model Definition

The Electric Discharge interface is used to simulate the negative surface discharge. The built-in charge transport model is used:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (\mathbf{w}_i n_i - D_i \nabla n_i) = R_i$$

where

$i = \mathrm{e, p, n}$

$z_{\mathrm{e, p, n}} = -1, +1, -1$

$\mathbf{w}_i = z_i \mu_i \mathbf{E}$

$R_\mathrm{e} = \alpha |\mathbf{w}_\mathrm{e}| n_\mathrm{e} - \eta |\mathbf{w}_\mathrm{e}| n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p}$

$R_\mathrm{p} = \alpha |\mathbf{w}_\mathrm{e}| n_\mathrm{e} - \beta_\mathrm{ep} n_\mathrm{e} n_\mathrm{p} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n}$

$R_\mathrm{n} = \eta |\mathbf{w}_\mathrm{e}| n_\mathrm{e} - \beta_\mathrm{pn} n_\mathrm{p} n_\mathrm{n}$

where

- e, p, n denote electrons, positive ions, and negative ions
- n_i is the number density of the charge carrier (SI unit: $1/\mathrm{m}^3$)
- $\mathbf{E}$ is the electric field (SI unit: V/m)
- z_i denotes the carrier charge (SI unit: 1)
- μ_i denotes the carrier mobility (SI unit: $\mathrm{m}^2/(\mathrm{V \cdot s})$)
- $\mathbf{w}_i$ is the drift velocity in the electric field (SI unit: m/s)
- D_i is the diffusion coefficient (SI unit: m^2/s)
- R_i is the reaction rate (SI unit: $1/(\mathrm{m}^3 \cdot \mathrm{s})$)
- α is the ionization coefficient (SI unit: 1/m)
- η is the attachment coefficient (SI unit: 1/m)
- β_ep is the electron–ion recombination coefficient (SI unit: m^3/s)
- β_pn is the ion–ion recombination coefficient (SI unit: m^3/s)

The above transport equations are fully coupled with Poisson's equation through the electric field and the space charge:

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \mathbf{E}) = \rho$$

$$\rho = e \sum_i z_i n_i$$

where e is the elementary charge.

The Gas–Solid interface is modeled with the dedicated *Dielectric Interface, Surface Transport* feature described in the *Electric Discharge Module User's Guide*.

FAST CHARGING

The first study examines the fast surface charging caused by streamer bursts when a high voltage is applied instantaneously. At the negative electrode, surface emission through secondary electron emission is taken into account. To capture the streamer dynamics accurately, a fine mesh around the electrode is required.

SLOW CHARGING

The second study investigates the slow surface charging through glow corona by ramping up the applied voltage. A fixed, low electron density boundary condition is imposed at the electrode surface to represent the seed electrons generated by surface emission. As the discharge is more uniform, a coarser mesh is sufficient.

Results and Discussion

Figure 1 shows the discharge current as a function of time from the first study. There is only one main current pulse due to the charge accumulation effect at the gas–solid interface. Figure 2 shows the radial distribution of the surface charge density at several time instants. The simulated surface charge density is in very good agreement with the experiments published in Ref. 1. Figure 3 plots the corresponding axial electric field at the axis. Note that the electric field is discontinuous due to different material properties.

Figure 4 plots the radial distribution of the surface charge density at several time instants from the second study. The surface charge density approaches a steady state after 1 ms.

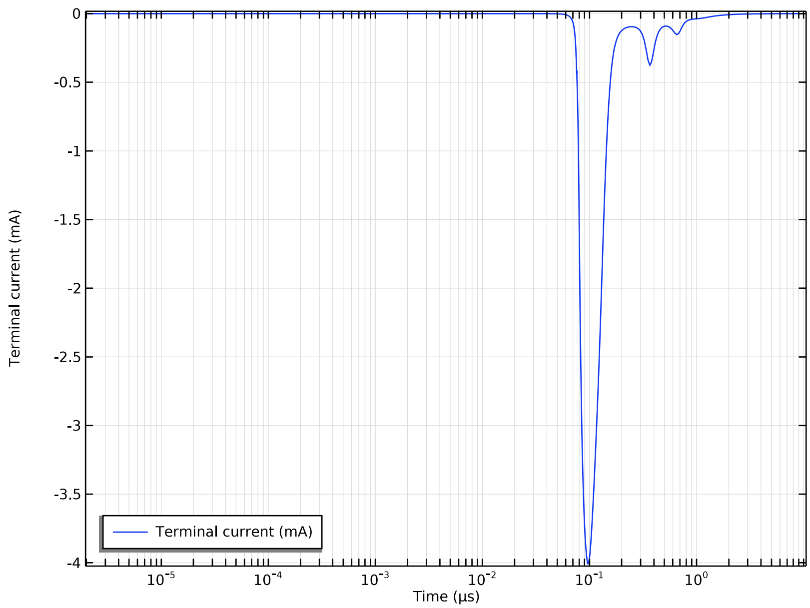


Figure 1: The discharge current as a function of time.

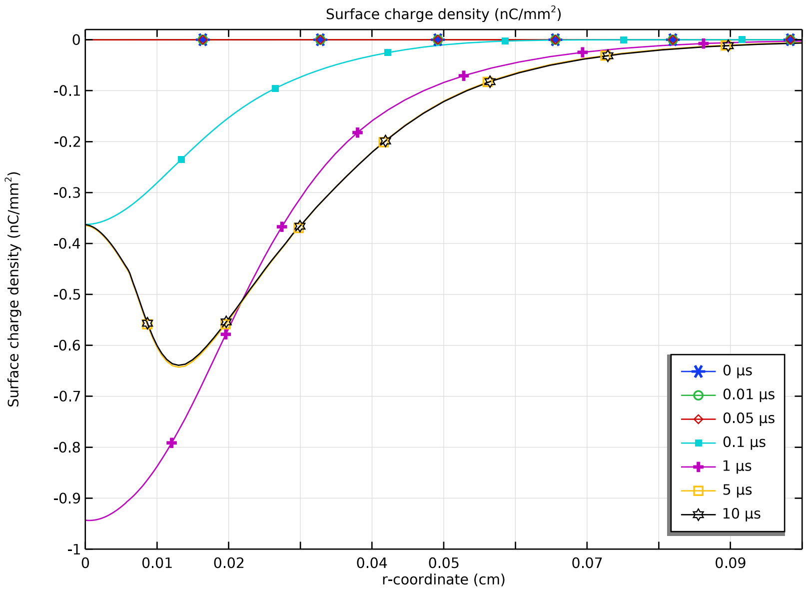


Figure 2: The radial distributions surface charge density at several time instants of the first study.

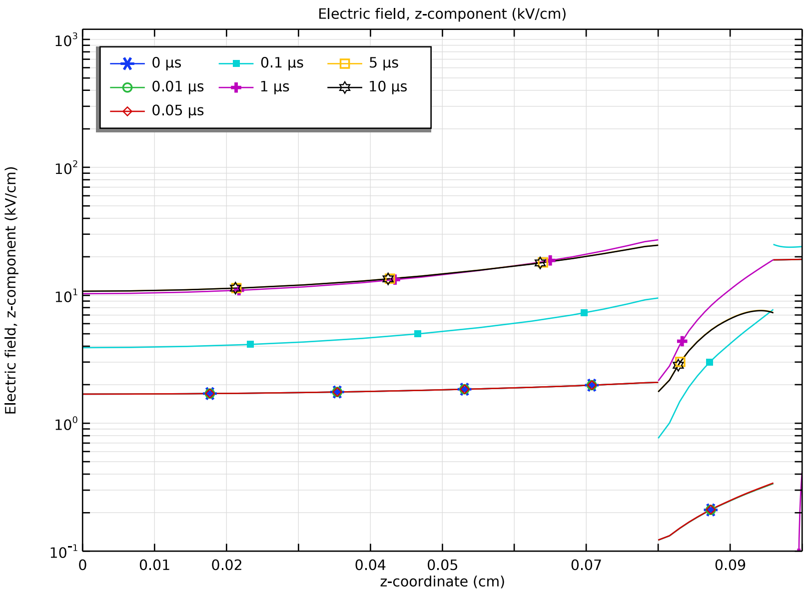


Figure 3: The axial electric field at several time instants.

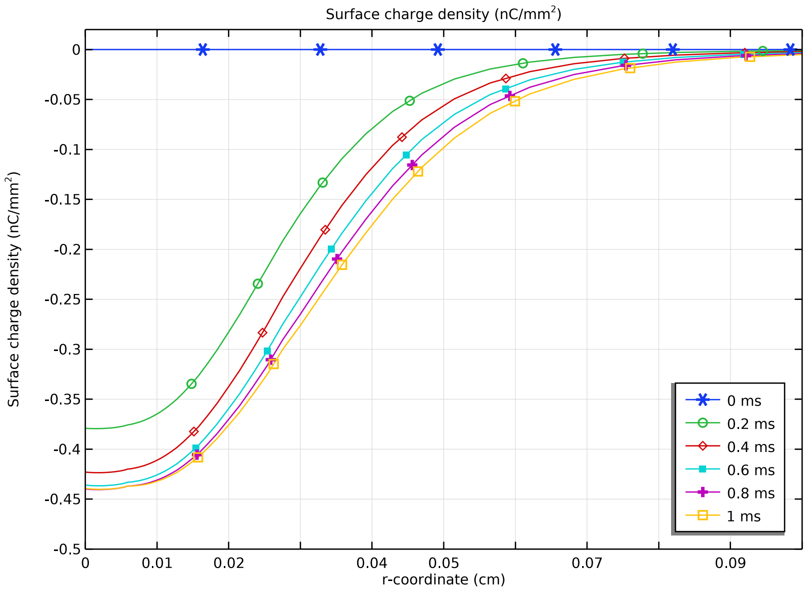


Figure 4: The radial distributions surface charge density at several time instants of the second study.

Reference

1. T. Tran and others, “Numerical modelling of negative discharges in air with experimental validation,” *J. Phys. D: Appl. Phys.*, vol. 44, no. 1, p. 15203, 2010.

Application Library path: `Electric_Discharge_Module/Dielectric_Barrier_Discharges/negative_surface_discharge`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1 In the **Model Wizard** window, click **2D Axisymmetric**.

2 In the **Select Physics** tree, select **Electric Discharge** > **Electric Discharge (edis)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Time Dependent with Initialization**.

6 Click **Done**.

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
V0	-2.5[kV]	-2500 V	Applied voltage
Rcurv	25[um]	2.5E-5 m	Radius of curvature
a	1/Rcurv/2*1[cm]	200	Parabola parameter in cm
d_air	500[um]	5E-4 m	Air gap
d_glass	800[um]	8E-4 m	Thickness of the glass layer
d_BSO	160[um]	1.6E-4 m	Thickness of the BSO layer
gap	d_air+d_BSO+d_glass	0.00146 m	Electrode gap

GEOMETRY 1

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 **cm**.

Rectangle 1 (r1)

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

2 In the **Settings** window for **Rectangle**, click to expand the **Layers** section.

3 In the table, enter the following settings:

Layer name	Thickness (cm)
`Layer 1`	`d_glass`
`Layer 2`	`d_BSO`

Rectangle 2 (r2)

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 `0.03`.

4 Locate the **Layers** section. Clear the **Layers on bottom** checkbox.

5 Select the **Layers to the left** checkbox.

6 In the table, enter the following settings:

Layer name	Thickness (cm)
`Layer 1`	`60[um]`

7 Click **Build Selected**.

Parametric Curve 1 (pc1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Parametric Curve**.

2 In the **Settings** window for **Parametric Curve**, locate the **Parameter** section.

3 In the **Maximum** text field, type `0.2`.

4 Locate the **Expressions** section. In the **r** text field, type `s`.

5 In the **z** text field, type `a*(s)^2*1[cm]+gap`.

6 Click **Build Selected**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 On the object **pc1**, select Point 2 only.

3 In the **Settings** window for **Line Segment**, locate the **Endpoint** section.

4 Click to select the **Activate Selection** toggle button for **End vertex**.

5 On the object **r1**, select Point 4 only.

6 Click **Build Selected**.

Line Segment 2 (ls2)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 On the object **ls1**, select Point 2 only.

3 In the **Settings** window for **Line Segment**, locate the **Endpoint** section.

4 Click to select the **Activate Selection** toggle button for **End vertex**.

5 On the object **pc1**, select Point 1 only.

6 Click to clear the **Activate Selection** toggle button for **End vertex**.

7 Click **Build Selected**.

Convert to Solid 1 (csol1)

1 In the **Geometry** toolbar, click **Conversions** and choose **Convert to Solid**.

2 Select the objects **ls1**, **ls2**, and **pc1** only.

3 In the **Settings** window for **Convert to Solid**, click **Build Selected**.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the objects **r1** and **r2** only.

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

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **csol1** only.

Parametric Curve 2 (pc2)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** right-click **Parametric Curve 1 (pc1)** and choose **Duplicate**.

2 In the **Settings** window for **Parametric Curve**, locate the **Parameter** section.

3 In the **Maximum** text field, type `60[um]`.

4 Locate the **Expressions** section. In the **z** text field, type `a*(s)^2*1[cm]/1.2+gap-10[um]`.

Parametric Curve 3 (pc3)

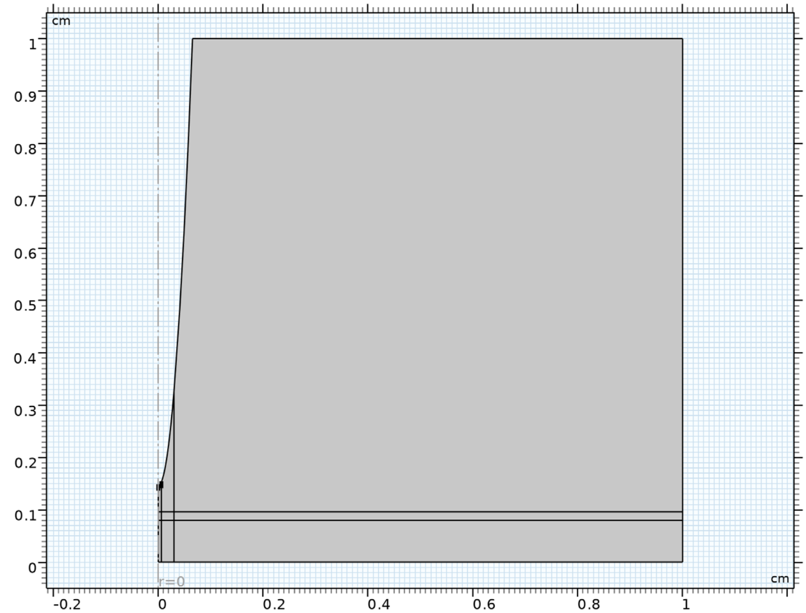
1 Right-click **Parametric Curve 2 (pc2)** and choose **Duplicate**.

2 In the **Settings** window for **Parametric Curve**, locate the **Expressions** section.

3 In the **z** text field, type `a*(s)^2*1[cm]/1.5+gap-60[um]`.

4 Click **Build All Objects**.

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



ELECTRIC DISCHARGE (EDIS)

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

2 In the **Show More Options** dialog, select **Physics** > **Stabilization** in the tree.

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

4 Click **OK**.

5 In the **Model Builder** window, under **Component 1 (comp1)** click **Electric Discharge (edis)**.

6 In the **Settings** window for **Electric Discharge**, click to expand the **Consistent Stabilization** section.

7 Clear the **Streamline diffusion** checkbox.

8 Click to expand the **Inconsistent Stabilization** section. Select the **Isotropic diffusion** checkbox.

9 In the δ_{id} text field, type `0.15`.

10 Locate the **Physical Model** section. Select the **Solid** checkbox.

Solid 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Discharge (edis)** click **Solid 1**.

2 Select Domains 1, 2, 6, 7, 9, and 10 only.

3 In the **Settings** window for **Solid**, locate the **Model Formulation** section.

4 From the **Material model** list, choose **Insulator**.

Gas 1

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

2 In the **Settings** window for **Gas**, locate the **Transport Properties** section.

3 Find the **Diffusion** subsection. From the **Diffusion coefficient** list, choose **User defined**.

4 In the D_e text field, type `0.18`.

5 In the D_p text field, type `0.01`.

6 In the D_n text field, type `0.01`.

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 text field, type `1E5[1/cm^3]`.

4 In the n_p text field, type `1E5[1/cm^3]`.

5 In the n_n text field, type `1E5[1/cm^3]`.

Dielectric Interface, Bulk Transport 1

1 In the **Model Builder** window, click **Dielectric Interface, Bulk Transport 1**.

2 In the **Settings** window for **Dielectric Interface, Bulk Transport**, locate the **Charge Transport** section.

3 From the **Boundary condition for positive ions** list, choose **No flux**.

Gas 1

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

Electrode 1

1 In the **Physics** toolbar, click **Attributes** and choose **Electrode**.

2 Select Boundaries 29–31 only.

3 In the **Settings** window for **Electrode**, locate the **Terminal** section.

4 In the V_0 text field, type `V0`.

5 Locate the **Charge Transport** section. From the **Boundary condition for electrons** list, choose **Surface emission**.

6 From the **Boundary condition for negative ions** list, choose **Number density**.

7 In the $n_{0,n}$ text field, type 1E5[1/cm^3].

8 Locate the **Surface Emission** section. Find the **Surface emission mechanisms** subsection. Select the **Secondary electron emission** checkbox.

Solid 1

In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Discharge (edis)** click **Solid 1**.

Electrode 1

1 In the **Physics** toolbar, click **Attributes** and choose **Electrode**.

2 Select Boundaries 2, 10, and 18 only.

ADD MATERIAL

1 In the **Materials** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Electric Discharge** > **Gases** > **Air** > **Air [Kang et al. 2003]**.

4 Right-click and choose **Add to Component 1 (comp1)**.

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

MATERIALS

BSO

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

2 In the **Settings** window for **Material**, type BSO in the **Label** text field.

3 Select Domains 2, 7, and 10 only.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	56	1	Basic

Glass

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

2 Select Domains 1, 6, and 9 only.

3 In the **Settings** window for **Material**, type Glass in the **Label** text field.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	3	1	Basic

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

3 From the list, choose **User-controlled mesh**.

Mapped 1

1 In the **Mesh** toolbar, click **Mapped**.

2 Drag and drop below **Size**.

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

4 From the **Geometric entity level** list, choose **Domain**.

5 Select Domains 4 and 5 only.

Distribution 1

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

2 Select Boundaries 27–29 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 150.

6 In the **Element ratio** text field, type 10.

Distribution 2

1 In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 7 and 15 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 150.

6 In the **Element ratio** text field, type 2.

7 Select the **Reverse direction** checkbox.

Distribution 3

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

2 Select Boundaries 8 and 16 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type `15`.

6 In the **Element ratio** text field, type `10`.

7 Select the **Reverse direction** checkbox.

Size 1

1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Domain**.

4 Select Domains 3 and 8 only.

5 Locate the **Element Size** section. Click the **Custom** button.

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

7 Select the **Maximum element size** checkbox. In the associated text field, type `1/1000`.

8 Select the **Maximum element growth rate** checkbox. In the associated text field, type `1.1`.

Size 2

1 Right-click **Free Triangular 1** and choose **Size**.

2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

3 From the **Geometric entity level** list, choose **Boundary**.

4 Select Boundary 5 only.

5 Locate the **Element Size** section. Click the **Custom** button.

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

7 Select the **Maximum element size** checkbox. In the associated text field, type `1[um]`.

Distribution 1

1 Right-click **Free Triangular 1** and choose **Distribution**.

2 Select Boundary 6 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 50.

6 In the **Element ratio** text field, type 5.

7 Click **Build Selected**.

Boundary Layers 1

In the **Mesh** toolbar, click **Boundary Layers**.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog, type 30 31 in the **Selection** text field.

5 Click **OK**.

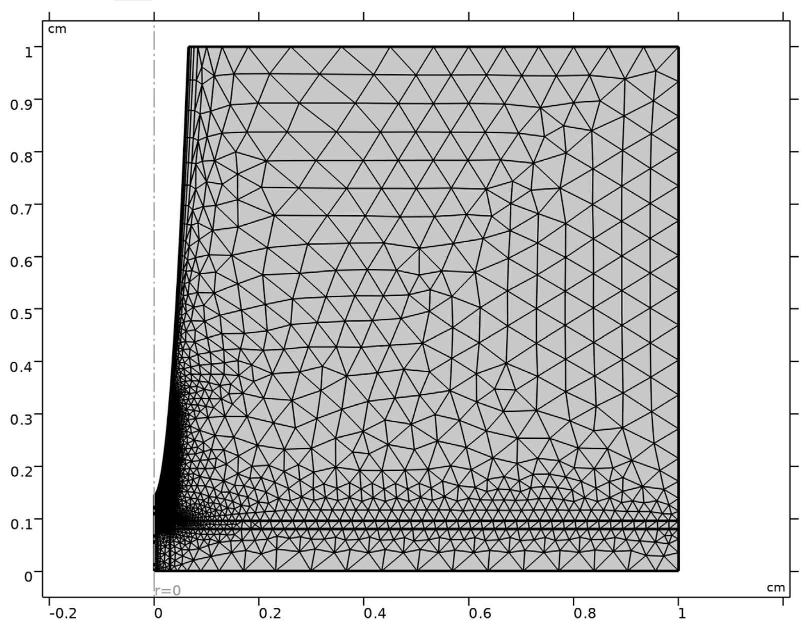
6 In the **Settings** window for **Boundary Layer Properties**, locate the **Layers** section.

7 In the **Number of layers** text field, type 4.

8 In the **Stretching factor** text field, type 1.5.

9 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

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



11 In the **Model Builder** window, collapse the **Mesh 1** node.

DEFINITIONS

Global Variable Probe 1 (var1)

1. In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.
2. Right-click **Definitions** and choose **Probes** > **Global Variable Probe**.
3. In the **Settings** window for **Global Variable Probe**, type `i0` in the **Variable name** text field.
4. Locate the **Expression** section. In the **Expression** text field, type `edis.I0_0`.
5. From the **Table and plot unit** list, choose **mA**.

STUDY 1

Step 2: Time Dependent

1. In the **Model Builder** window, under **Study 1** click **Step 2: Time Dependent**.
2. In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.
3. From the **Time unit** list, choose **µs**.
4. In the **Output times** text field, type `range(0,0.01,0.2) range(1,2,5) 10`.
5. Click to expand the **Results While Solving** section. In the **Model Builder** window, click **Study 1**.
6. In the **Settings** window for **Study**, locate the **Study Settings** section.
7. Clear the **Generate default plots** checkbox.

Solution 1 (sol1)

1. In the **Study** toolbar, click  **Show Default Solver**.
2. In the **Model Builder** window, expand the **Solution 1 (sol1)** node.
3. In the **Model Builder** window, expand the **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** node.
4. In the **Model Builder** window, under **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** click **Segregated 1**.
5. In the **Settings** window for **Segregated**, locate the **General** section.
6. From the **Stabilization and acceleration** list, choose **Anderson acceleration**.
7. In the **Model Builder** window, under **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** > **Segregated 1** click **Segregated Step 1**.
8. In the **Settings** window for **Segregated Step**, click to expand the **Method and Termination** section.

9 From the **Termination technique** list, choose **Tolerance**.

10 In the **Model Builder** window, under **Study 1** > **Solver Configurations** > **Solution 1 (sol1)** > **Time-Dependent Solver 1** > **Segregated 1** click **Segregated Step 2**.

11 In the **Settings** window for **Segregated Step**, locate the **Method and Termination** section.

12 From the **Termination technique** list, choose **Tolerance**.

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

RESULTS

Discharge Current

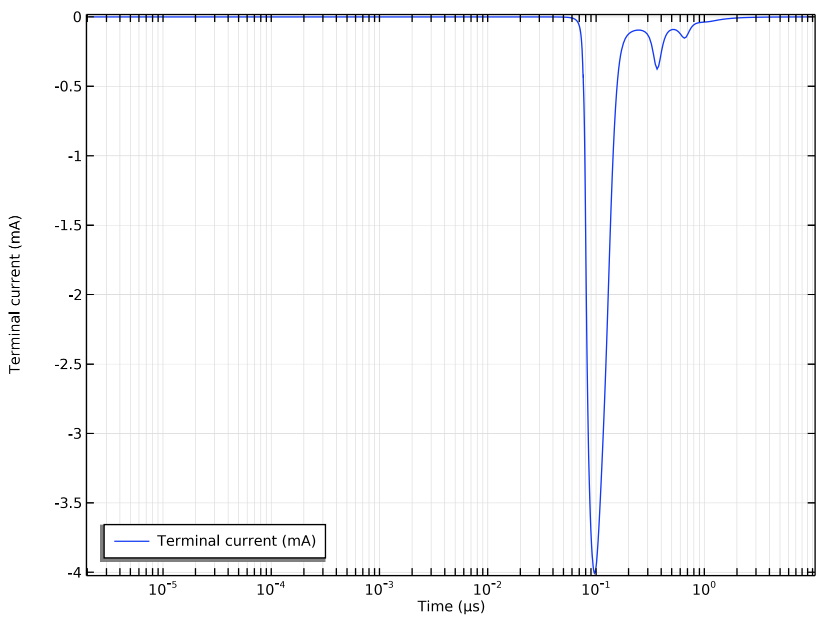
1 In the **Model Builder** window, under **Results** click **Probe Plot Group 1**.

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

3 Locate the **Axis** section. Select the **x-axis log scale** checkbox.

4 Locate the **Legend** section. From the **Position** list, choose **Lower left**.

5 In the **Discharge Current** toolbar, click **Plot**.



Surface Charge Density

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

2. In the **Settings** window for **1D Plot Group**, type `Surface Charge Density` in the **Label** text field.
3. Locate the **Data** section. From the **Time selection** list, choose **From list**.
4. In the **Times (μs)** list, choose **0**, **0.01**, **0.05**, **0.1**, **1**, **5**, and **10**.
5. Locate the **Axis** section. Select the **Manual axis limits** checkbox.
6. In the **x minimum** text field, type `0`.
7. In the **x maximum** text field, type `0.1`.
8. In the **y maximum** text field, type `0.02`.

Line Graph 1

Right-click **Surface Charge Density** and choose **Line Graph**.

Surface Charge Density

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

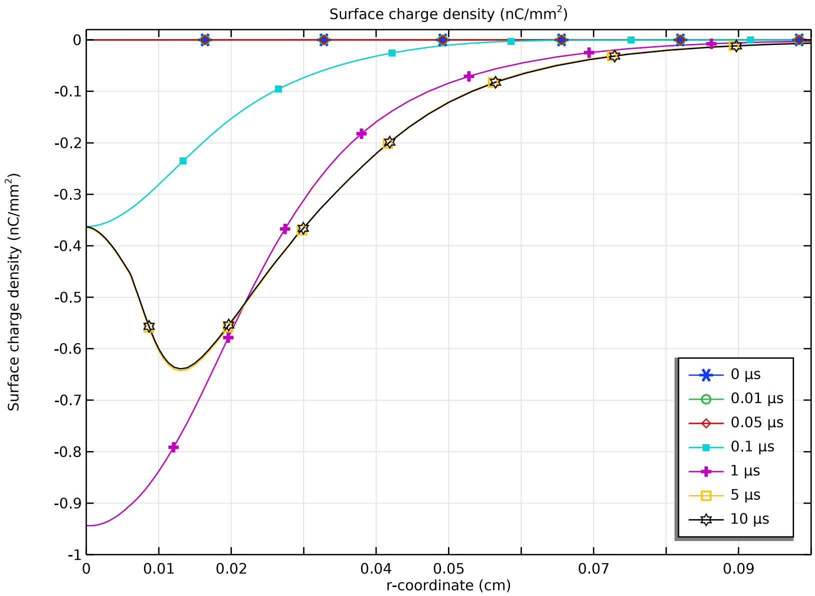
Line Graph 1

1. In the **Model Builder** window, 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 `edis.rhos`.
4. In the **Unit** field, type `nC/mm^2`.
5. Locate the **Selection** section. Click to select the **Activate Selection** toggle button.
6. Click the **Zoom Box** button in the **Graphics** toolbar.
7. Select Boundaries 6, 14, and 22 only.
8. Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
9. In the **Expression** text field, type `r`.
10. Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.
11. From the **Positioning** list, choose **Interpolated**.
12. In the **Number** text field, type `60`.
13. Click to expand the **Legends** section. Select the **Show legends** checkbox.

Surface Charge Density

1. In the **Model Builder** window, click **Surface Charge Density**.

2 In the **Surface Charge Density** toolbar, click **Plot**.



Axial Electric Field

1 Right-click **Surface Charge Density** and choose **Duplicate**.

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

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

4 In the **Number of columns** text field, type `3`.

Line Graph 1

1 In the **Model Builder** window, expand the **Axial 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 `edis.Ez`.

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

5 Locate the **Selection** section. Click to select the **Activate Selection** toggle button.

6 Click **Clear Selection**.

7 Select Boundaries 1, 3, 5, 7, and 8 only.

8 Locate the **x-Axis Data** section. In the **Expression** text field, type `z`.

9 Locate the **Coloring and Style** section. Find the **Line markers** subsection. In the **Number** text field, type `8`.

Axial Electric Field

1 In the **Model Builder** window, click **Axial Electric Field**.

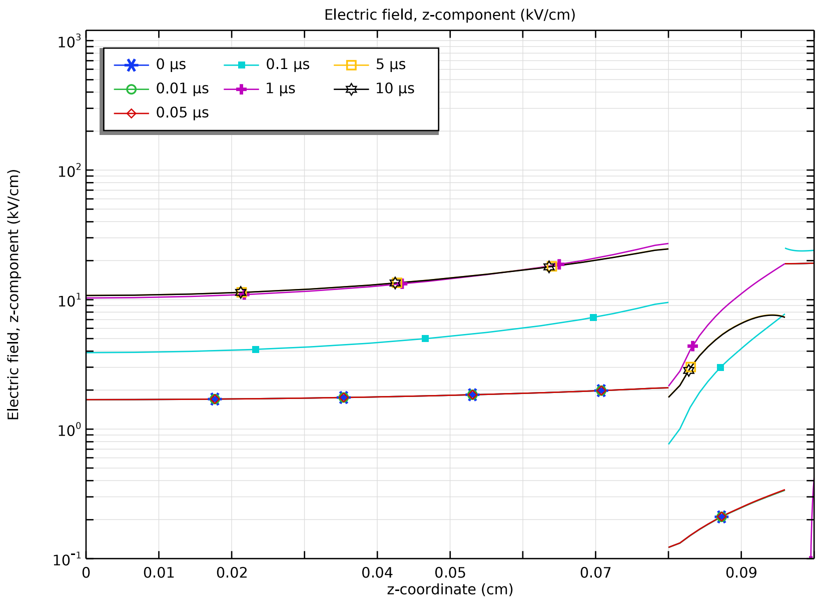
2 In the **Settings** window for **1D Plot Group**, locate the **Axis** section.

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

4 In the **y maximum** text field, type `1200`.

5 Click the **y-Axis Log Scale** button in the **Graphics** toolbar.

6 In the **Axial Electric Field** toolbar, click **Plot**.



Mirror 2D 1

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

2 Right-click **Results** > **Datasets** and choose **More 2D Datasets** > **Mirror 2D**.

Electron Density

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

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

3 Locate the **Plot Settings** section. Clear the **Plot dataset edges** checkbox.

Surface 1

1 Right-click **Electron Density** and choose **Surface**.

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

3 In the **Expression** text field, type `edis.n_e`.

4 In the **Unit** field, type `1/cm^3`.

5 Locate the **Coloring and Style** section. From the **Color table** list, choose **Prism**.

Electron Density

1 In the **Model Builder** window, click **Electron Density**.

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

3 From the **Dataset** list, choose **Mirror 2D 1**.

4 Locate the **Plot Settings** section. From the **View** list, choose **New view**.

5 In the **Electron Density** toolbar, click **Plot**.

6 Click **Go to Source**.

Axis

1 In the **Model Builder** window, expand the **View 2D 2** node, then click **Axis**.

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

3 In the **x minimum** text field, type `-0.06`.

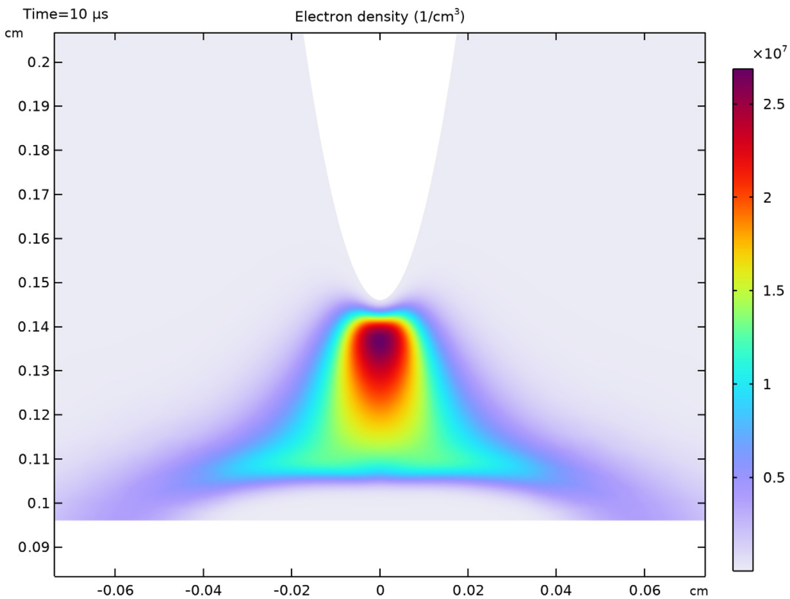
4 In the **x maximum** text field, type `0.06`.

5 In the **y minimum** text field, type `0.09`.

6 In the **y maximum** text field, type `0.2`.

Electron Density

In the **Model Builder** window, under **Results** click **Electron Density**.



Next, use a different boundary condition to model the slow charging.

ELECTRIC DISCHARGE (EDIS)

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Electric Discharge (edis)** and choose **Copy**.

ELECTRIC DISCHARGE 2 (EDIS2)

1. In the **Model Builder** window, right-click **Component 1 (comp1)** and choose **Paste Electric Discharge**.
2. In the **Messages from Paste** dialog, click **OK**.

GLOBAL DEFINITIONS

Ramp 1 (rm1)

1. In the **Home** toolbar, click f(X) **Functions** and choose **Global** > **Ramp**.
2. In the **Settings** window for **Ramp**, locate the **Parameters** section.
3. Select the **Cutoff** checkbox.

Electric Discharge 2 (edis2)

In the **Model Builder** window, expand the **Component 1 (comp1)** > **Electric Discharge 2 (edis2)** node.

Electrode 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Electric Discharge 2 (edis2)** > **Gas 1** node, then click **Electrode 1**.
2 In the **Settings** window for **Electrode**, locate the **Terminal** section.
3 In the V_0 text field, type `V0*rm1(t/10[us])`.
4 Locate the **Charge Transport** section. From the **Boundary condition for electrons** list, choose **Number density**.
5 In the $n_{0,e}$ text field, type `1E5[1/cm^3]`.

Dielectric Interface, Bulk Transport 1

1 In the **Model Builder** window, click **Dielectric Interface, Bulk Transport 1**.
2 In the **Settings** window for **Dielectric Interface, Bulk Transport**, locate the **Charge Transport** section.
3 From the **Boundary condition for positive ions** list, choose **No diffusive flux**.

Definitions

Global Variable Probe 2 (var2)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Definitions** right-click **Global Variable Probe 1 (i0)** and choose **Duplicate**.
2 In the **Settings** window for **Global Variable Probe**, type `i02` in the **Variable name** text field.
3 Locate the **Expression** section. In the **Expression** text field, type `edis2.I0_0`.
4 Click to expand the **Table and Window Settings** section. Click + **Add Table**.
5 Click + **Add Plot Window**.

Study 1, Fast Charging

1 In the **Model Builder** window, click **Study 1**.
2 In the **Settings** window for **Study**, type `Study 1, Fast Charging` in the **Label** text field.

Disable the second Electric Discharge interface in model such that the Study 1 can still be solved. Note that disabling in solver is not enough since the second interface overrides the common model input that is used by the material.

Step 1: Electrostatics Initialization

1 In the **Model Builder** window, under **Study 1, Fast Charging** click **Step 1: Electrostatics Initialization**.
2 In the **Settings** window for **Electrostatics Initialization**, locate the **Physics and Variables Selection** section.
3 Select the **Modify model configuration for study step** checkbox.
4 In the tree, select **Component 1 (comp1)** > **Electric Discharge 2 (edis2)**.
5 Right-click and choose **Disable in Model**.

Step 2: Time Dependent

1 In the **Model Builder** window, click **Step 2: Time Dependent**.
2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.
3 Select the **Modify model configuration for study step** checkbox.
4 In the tree, select **Component 1 (comp1)** > **Electric Discharge 2 (edis2)**.
5 Right-click and choose **Disable in Model**.
6 Locate the **Results While Solving** section. From the **Probes** list, choose **Manual**.
7 In the **Probes** list box, select **Global Variable Probe 2 (i02)**.
8 Under **Probes**, click **Delete**.

ADD STUDY

1 In the **Home** toolbar, click **Windows** and choose **Add Study**.
2 Go to the **Add Study** window.
3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Time Dependent with Initialization**.
4 Click the **Add Study** button in the window toolbar.

STUDY 2

Step 1: Electrostatics Initialization

1 In the **Settings** window for **Electrostatics Initialization**, locate the **Physics and Variables Selection** section.
2 In the **Solve for** column of the table, under **Component 1 (comp1)**, clear the checkbox for **Electric Discharge (edis)**.

Step 2: Time Dependent

1 In the **Model Builder** window, click **Step 2: Time Dependent**.
2 In the **Settings** window for **Time Dependent**, locate the **Physics and Variables Selection** section.
3 In the **Solve for** column of the table, under **Component 1 (comp1)**, clear the checkbox for **Electric Discharge (edis)**.
4 Locate the **Study Settings** section. From the **Time unit** list, choose **ms**.
5 In the **Output times** text field, type `range(0,0.2,1)`.
6 Locate the **Results While Solving** section. From the **Probes** list, choose **Manual**.
7 In the **Probes** list box, select **Global Variable Probe 1 (i0)**.
8 Under **Probes**, click **Delete**.

The second study does not require a fine mesh. Add a coarse mesh for it.

MESH 1

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

MESH 2

In the **Model Builder** window, expand the **Mesh 2** node.

Distribution 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Meshes** > **Mesh 2** > **Mapped 1** node, then click **Distribution 1**.
2 In the **Settings** window for **Distribution**, locate the **Distribution** section.
3 In the **Number of elements** text field, type `30`.

Distribution 2

1 In the **Model Builder** window, click **Distribution 2**.
2 In the **Settings** window for **Distribution**, locate the **Distribution** section.
3 In the **Number of elements** text field, type `30`.

Size 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Meshes** > **Mesh 2** > **Free Triangular 1** node, then click **Size 1**.
2 In the **Settings** window for **Size**, locate the **Element Size Parameters** section.
3 In the **Maximum element size** text field, type `1/100`.

Size 2

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Meshes** > **Mesh 2** > **Boundary Layers 1** node, then click **Component 1 (comp1)** > **Meshes** > **Mesh 2** > **Free Triangular 1** > **Size 2**.

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

3 In the **Maximum element size** text field, type `5[um]`.

Boundary Layer Properties

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Meshes** > **Mesh 2** > **Boundary Layers 1** right-click **Boundary Layer Properties** and choose **Build All**.

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

STUDY 2

Step 1: Electrostatics Initialization

1 In the **Model Builder** window, under **Study 2** click **Step 1: Electrostatics Initialization**.

2 In the **Settings** window for **Electrostatics Initialization**, click to expand the **Mesh Selection** section.

3 In the table, enter the following settings:

Component	Mesh
Component 1	Mesh 2

Step 2: Time Dependent

1 In the **Model Builder** window, click **Step 2: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, click to expand the **Mesh Selection** section.

3 In the table, enter the following settings:

Component	Mesh
Component 1	Mesh 2

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

5 In the **Settings** window for **Study**, type `Study 1, Slow Charging` in the **Label** text field.

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

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

RESULTS

Surface Charge Density 1

In the **Model Builder** window, right-click **Surface Charge Density** and choose **Duplicate**.

Discharge Current, Slow Charging

In the **Settings** window for **1D Plot Group**, type `Discharge Current, Slow Charging` in the **Label** text field.

Surface Charge Density, Slow Charging

1 In the **Model Builder** window, under **Results** click **Surface Charge Density 1**.
2 In the **Settings** window for **1D Plot Group**, type `Surface Charge Density, Slow Charging` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Study 1, Slow Charging/ Solution 3 (sol3)**.
4 Locate the **Axis** section. In the **y minimum** text field, type `-0.5`.

Line Graph 1

1 In the **Model Builder** window, expand the **Surface Charge Density, Slow Charging** 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 `edis2.rhos`.

4 In the **Surface Charge Density, Slow Charging** toolbar, click **Plot**.