Model created in COMSOL Multiphysics 6.4

Electrostatic Discharge

Introduction

Electrostatic discharge (ESD) occurs when there is a sudden flow of electricity between two objects with different electrical potentials. This often happens when a charged object, like a human hand, comes into contact with a conductive material, such as metal. The process begins with the accumulation of static charge on the human body, typically due to frictional contact with various materials—like walking across a carpet or rubbing against certain fabrics. The human body can store this static electricity, leading to a significant voltage build-up.

As the charged hand approaches the metal object, the electric field between the two intensifies. Once the hand is close enough, the electric field becomes strong enough to ionize the air molecules between them, creating a conductive path. This allows the accumulated charge to rapidly discharge from the hand to the metal, resulting in a brief, high-current pulse—an ESD event. This discharge equalizes the potential difference between the hand and the metal, often producing a visible spark and potentially damaging sensitive electronic components.

To simulate this complex phenomenon, the model connects the Electrical Discharge interface with the Electrical Circuit interface. The Electrical Discharge interface is used to simulate the ionization and discharge process between the hand and the metal. Meanwhile, the Electrical Circuit interface represents the human body, modeling how it stores and releases the static charge. Together, these interfaces allow for a detailed simulation of how ESD current is generated and how it interacts with electrical circuits.

Model Definition

FIELD–CIRCUIT MODEL

The human body is represented by a typical RLC circuit as shown in Figure 1. In this model, it is assumed that human body is charged to 8 kV and has a resistance, inductance, and capacitance of 300 Ω, 1.5 μH, and 150 pF, respectively. The Electrical Circuit interface is employed to model this circuit. The node names (0, 1, 2, 3) are also labeled in Figure 1. To integrate the circuit with the physical discharge model, the External U vs. I feature is used to establish the connection between the circuit and the discharge simulation.

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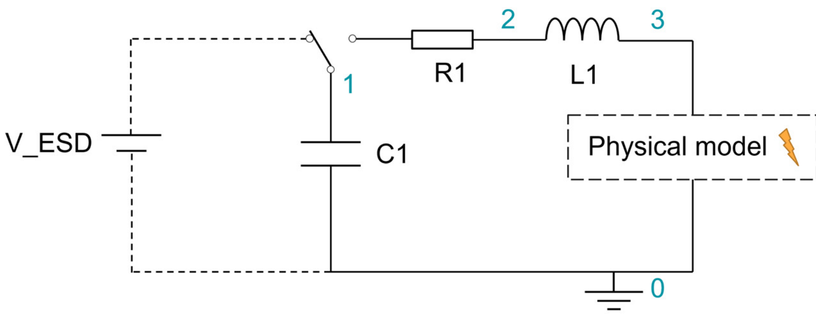


Figure 1: The Field–Circuit Model.

CHARGE TRANSPORT MODEL

The spark discharge between human finger and metal is modeled using the built-in charge transport model in the Electric Discharge interface.

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

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:

$$\nabla \cdot (\varepsilon_\mathrm{r} \varepsilon_0 \mathbf{E}) = \rho$$

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

where e is the elementary charge.

Results and Discussion

Figure 2 plots the electric current density for several instants during the ESD simulation. Figure 3 compares the ESD current with and without the discharge gap.

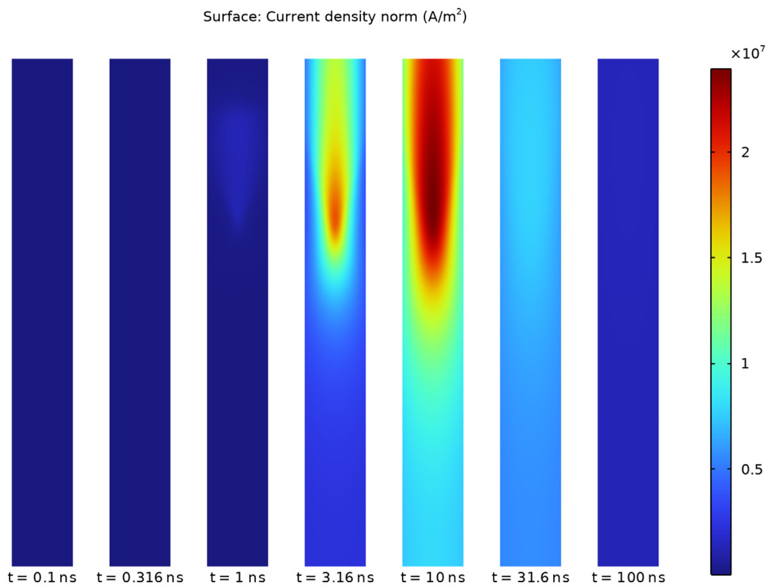


Figure 2: Electric current density distribution in the discharge gap.

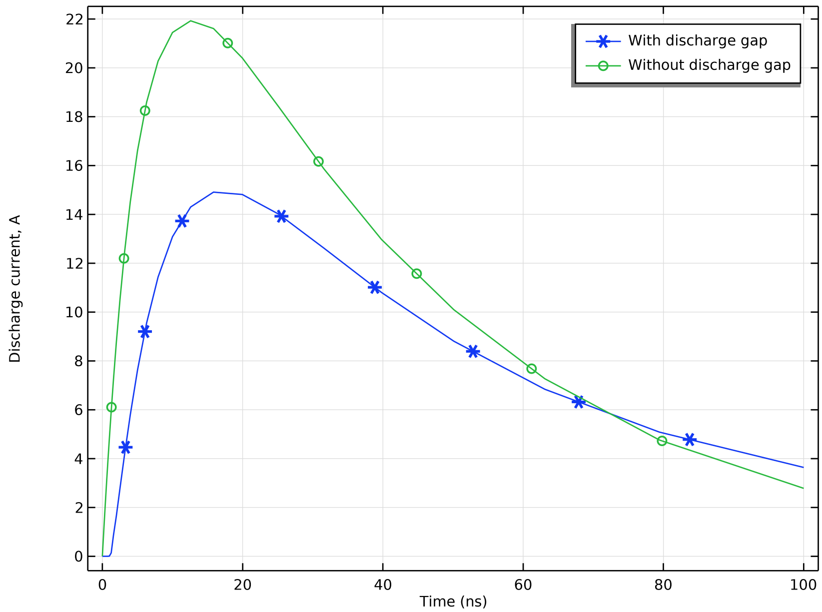


Figure 3: Simulated ESD current.

Application Library path: `Electric_Discharge_Module/Electrostatic_Discharges/esd`

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**.

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 **mm**.

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
V_ESD	8[kV]	8000 V	
C1	150[pF]	1.5E-10 F	
R1	300[Ω]	300 Ω	
L1	1.5[uH]	1.5E-6 H	

GEOMETRY 1

Rectangle 1 (r1)

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

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

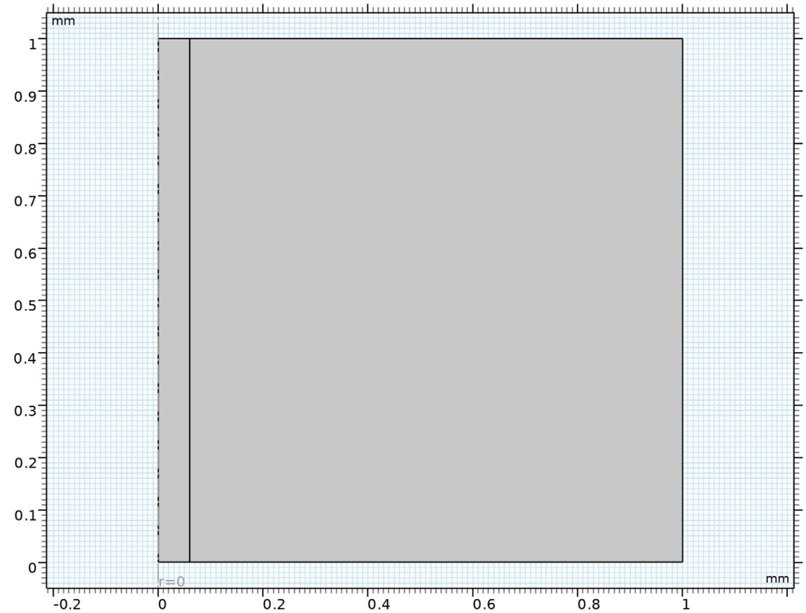
3 Select the **Layers to the left** checkbox.

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

5 In the table, enter the following settings:

Layer name	Thickness (mm)
Layer 1	0.06

6 Click **Build All Objects**.



ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

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

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

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

ELECTRIC DISCHARGE (EDIS)

Gas 1

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

Electrode 1

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

2 Select Boundaries 2 and 5 only.

Gas 1

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

Electrode 2

1. In the **Physics** toolbar, click **Attributes** and choose **Electrode**.
2. Select Boundaries 3 and 6 only.
3. In the **Settings** window for **Electrode**, locate the **Terminal** section.
4. In the V_0 text field, type `V_ESD`.

Electrode 3

1. Right-click **Electrode 2** and choose **Duplicate**.
2. In the **Settings** window for **Electrode**, locate the **Terminal** section.
3. From the **Terminal type** list, choose **Circuit**.

ADD PHYSICS

1. In the **Home** toolbar, click **Windows** and choose **Add Physics**.
2. Go to the **Add Physics** window.
3. In the tree, select **AC/DC** > **Electrical Circuit (cir)**.
4. Click the **Add to Component 1** button in the window toolbar.

ELECTRICAL CIRCUIT (CIR)

Capacitor 1 (C1)

1. In the **Electrical Circuit** toolbar, click **Capacitor**.
2. In the **Settings** window for **Capacitor**, locate the **Node Connections** section.
3. In the table, enter the following settings:

Label	Node names
n	0

4. Locate the **Device Parameters** section. In the C text field, type `C1`.
5. In the U_{C0} text field, type `V_ESD`.

Resistor 1 (R1)

1. In the **Electrical Circuit** toolbar, click **Resistor**.
2. In the **Settings** window for **Resistor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	1
n	2

4 In the **Model Builder** window, click **Resistor 1 (R1)**.

5 Locate the **Device Parameters** section. In the R text field, type `R1`.

Inductor 1 (L1)

1 In the **Electrical Circuit** toolbar, click **Inductor**.

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

3 In the L text field, type `L1`.

4 Locate the **Node Connections** section. In the table, enter the following settings:

Label	Node names
p	2
n	3

5 In the **Model Builder** window, right-click **Electrical Circuit (cir)** and choose **Copy**.

ELECTRICAL CIRCUIT 2 (CIR2)

1 In the **Model Builder** window, right-click **Component 1 (comp1)** and choose **Paste Electrical Circuit**.

2 In the **Messages from Paste** dialog, click **OK**.

ELECTRICAL CIRCUIT (CIR)

External U vs. I 1 (UvsI1)

1 In the **Electrical Circuit** toolbar, click **External U vs. I**.

2 In the **Settings** window for **External U vs. I**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
p	3
n	0

4 Locate the **External Device** section. From the I list, choose **Terminal current (edis/gas1/ece3)**.

ELECTRICAL CIRCUIT 2 (CIR2)

Inductor 1 (L1)

1 In the **Model Builder** window, expand the **Electrical Circuit 2 (cir2)** node, then click **Inductor 1 (L1)**.

2 In the **Settings** window for **Inductor**, locate the **Node Connections** section.

3 In the table, enter the following settings:

Label	Node names
n	0

DEFINITIONS

Variables 1

1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Definitions** node.

2 Right-click **Definitions** and choose **Variables**.

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

4 In the table, enter the following settings:

Name	Expression	Unit	Description
N0	(1e6+1e10*exp(-((z/(1[mm])-0.5)/0.027)^2-(r/(1[mm])/0.021)^2))[cm^-3]	1/m³	Initial number density

ELECTRIC DISCHARGE (EDIS)

Gas 1

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

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

3 From the **Charge carriers** list, choose **Electrons and positive ions**.

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 N0.

4 In the n_p text field, type N0.

STUDY 1

Step 1: Electrostatics Initialization

1 In the **Model Builder** window, under **Study 1** 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 (edis)** > **Gas 1** > **Electrode 3**.

5 Right-click and choose **Disable**.

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 **Electrical Circuit 2 (cir2)**.

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 **General Studies** > **Time Dependent**.

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

STUDY 1

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

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

3 In the **Output times** text field, type `0 10^{range(log10(0.001),1/10, log10(100))}`.

STUDY 2

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2** 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 10^{range(log10(0.001),1/10, log10(100))}`.

MESH 1

Mapped 1

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

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

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

4 Select Domain 1 only.

Distribution 1

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

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

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

4 Select Boundaries 2 and 3 only.

5 In the **Number of elements** text field, type `20`.

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

7 Select the **Reverse direction** checkbox.

Distribution 2

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

2 Select Boundaries 1 and 4 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 `400`.

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

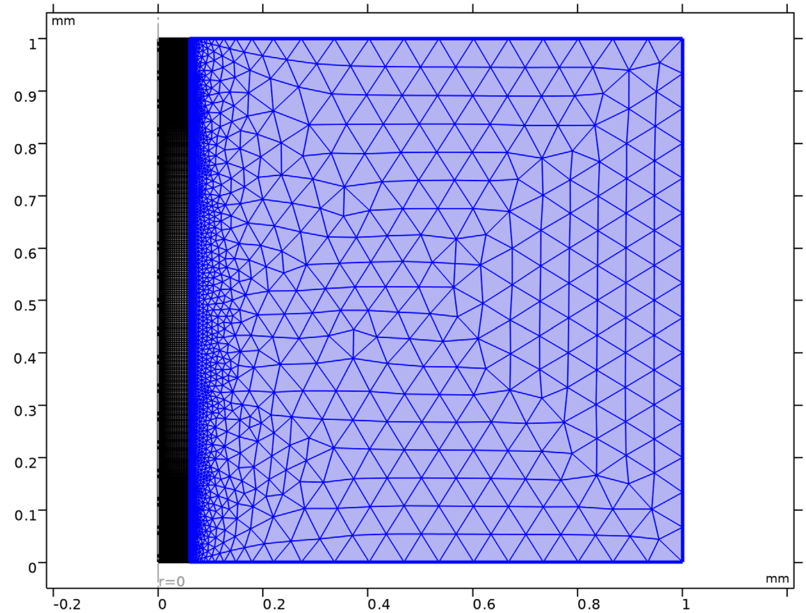
7 Select the **Symmetric distribution** checkbox.

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

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.

2 In the **Settings** window for **Free Triangular**, 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** checkbox.

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

STUDY 2

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 2** click **Step 1: 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 checkboxes for **Electric Discharge (edis)** and **Electrical Circuit (cir)**.

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

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

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

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

RESULTS

1D Plot Group 1

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

Global 1

1 Right-click **1D Plot Group 1** 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
`cir.R1.i`	`A`	`With discharge gap`

4 Click to expand the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

5 From the **Positioning** list, choose **Interpolated**.

Global 2

1 In the **Model Builder** window, right-click **1D Plot Group 1** and choose **Global**.

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

3 From the **Dataset** list, choose **Study 2/Solution 3 (sol3)**.

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

Expression	Unit	Description
`cir2.R1.i`	`A`	`Without discharge gap`

5 Locate the **Coloring and Style** section. Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.

6 From the **Positioning** list, choose **Interpolated**.

1D Plot Group 1

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

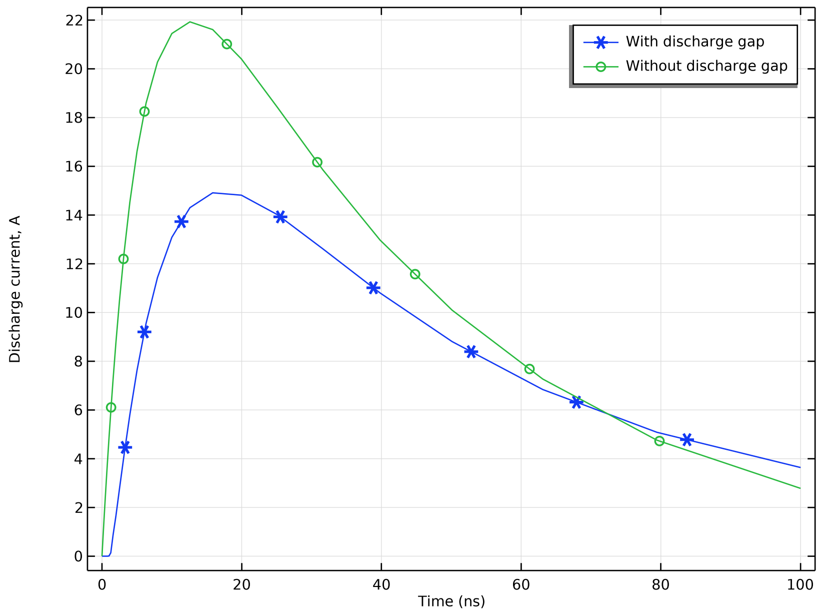
2 In the **Settings** window for **1D Plot Group**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

4 Locate the **Plot Settings** section.

5 Select the **y-axis label** checkbox. In the associated text field, type `Discharge current, A`.

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



2D Plot Group 2

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

Surface 1

Right-click **2D Plot Group 2** and choose **Surface**.

Mirror 2D 1

In the **Results** toolbar, click **More Datasets** and choose **Mirror 2D**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

4 Select Domain 1 only.

Surface 1

1 In the **Model Builder** window, under **Results** > **2D Plot Group 2** click **Surface 1**.

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

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

2D Plot Group 2

1 In the **Model Builder** window, click **2D Plot Group 2**.

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. Clear the **Plot dataset edges** checkbox.

Solution Array 1

1 In the **Model Builder** window, right-click **Surface 1** and choose **Solution Array**.

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

3 From the **Time selection** list, choose **Interpolated**.

4 In the **Times (ns)** text field, type `10^{range(log10(0.1),1/2,log10(100))}`.

2D Plot Group 2

1 Click the **Show Grid** button in the **Graphics** toolbar.

2 In the **Model Builder** window, under **Results** click **2D Plot Group 2**.

3 In the **Settings** window for **2D Plot Group**, click to expand the **Title** section.

4 From the **Title type** list, choose **Custom**.

5 Find the **Solution** subsection. Clear the **Solution** checkbox.

Annotation 1

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

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

3 In the **Text** text field, type `t = eval(t,ns,3) ns`.

4 Locate the **Coloring and Style** section. Clear the **Show point** checkbox.

Solution Array 1

In the **Model Builder** window, under **Results** > **2D Plot Group 2** > **Surface 1** right-click **Solution Array 1** and choose **Copy**.

Solution Array 1

In the **Model Builder** window, right-click **Annotation 1** and choose **Paste Solution Array**.

Annotation 1

1 In the **Settings** window for **Annotation**, click to expand the **Plot Array** section.

2 Select the **Manual indexing** checkbox.

3 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Upper middle**.

Current Density

1 In the **Model Builder** window, under **Results** click **2D Plot Group 2**.

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

3 Click to expand the **Plot Array** section. In the **Relative padding** text field, type `0.6`.

4 In the **Current Density** toolbar, click **Plot**.

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