Model created in COMSOL Multiphysics 6.4

Streamers Initialized From Suspended Metal Particles

Introduction

Suspended metal particles are a well-recognized factor in the degradation of high-voltage insulation systems, as they distort the local electric field and promote premature discharge activity. This model simulates streamer initiation from suspended metallic particles, their propagation under high electric fields, and their eventual merging. The model considers the discharge current flowing into the particles, which are assumed to remain at equal potential, thereby enhancing the local electric field distribution. This field intensification lowers the inception voltage and accelerates streamer growth, demonstrating a strong dependence of discharge dynamics on particle position, size, and concentration. The results provide a detailed framework for evaluating particle-induced breakdown mechanisms, with implications for insulation design, condition monitoring, and reliability assessment of high-voltage equipment.

Model Definition

The model uses the Electric Discharge interface, where the built-in charge transport model is expressed as

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

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.

The suspended metal particles are modeled with the Floating Electrode boundary feature, which automatically takes into account the discharge current flowing into the particles and surface charge accumulation at the surfaces. The boundary conditions are expressed as

$$V = \text{const.}$$

$$\int_{\partial\Omega} \mathbf{D} \cdot \mathbf{n} = -Q_0$$

$$\frac{\partial Q_0}{\partial t} = \int_{\partial\Omega} \mathbf{J}_c \cdot \mathbf{n}$$

where $\mathbf{J}_c$ is the conducting current density.

Results and Discussion

Figure 1 and Figure 2 show the distribution of electric field and electron density, respectively, at different time instants. Figure 3 shows both of them through isosurface plots in color.

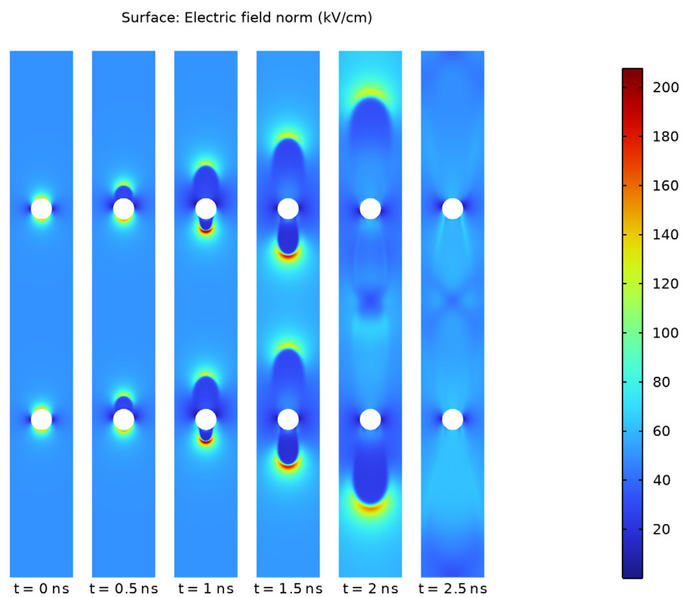


Figure 1: Distribution of electric field.

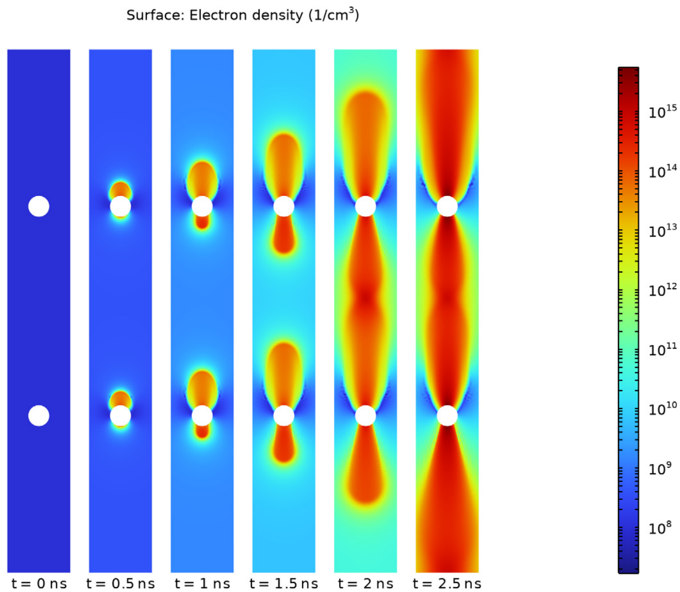


Figure 2: Distribution of electron number density.

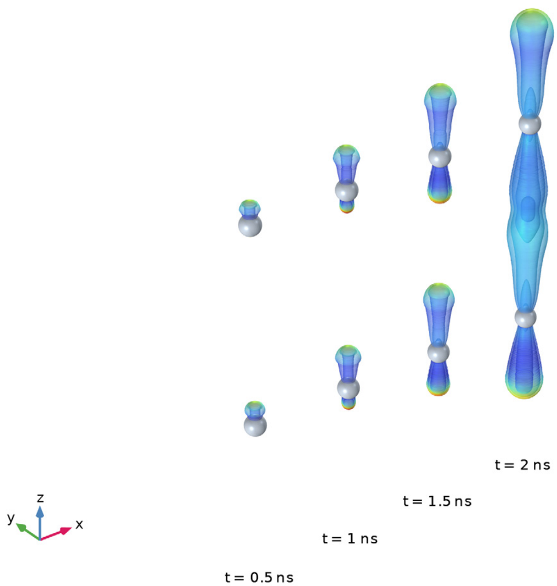


Figure 3: 3D plots where the isosurface plots are for electron density and the color indicates the electric field strength.

Application Library path: `Electric_Discharge_Module/Streamer_Discharges/streamer_from_metal_particles`

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 **cm**.

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`	`50[kV]`	50000 V	`Applied voltage`

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 In the table, enter the following settings:

Layer name	Thickness (cm)
`Layer 1`	`0.06`

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

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

Circle 1 (c1)

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

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type `0.02`.

4 Locate the **Position** section. In the **z** text field, type `0.3`.

Circle 2 (c2)

1 Right-click **Circle 1 (c1)** and choose **Duplicate**.

2 In the **Settings** window for **Circle**, locate the **Position** section.

3 In the **z** text field, type 0.7.

Difference 1 (dif1)

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

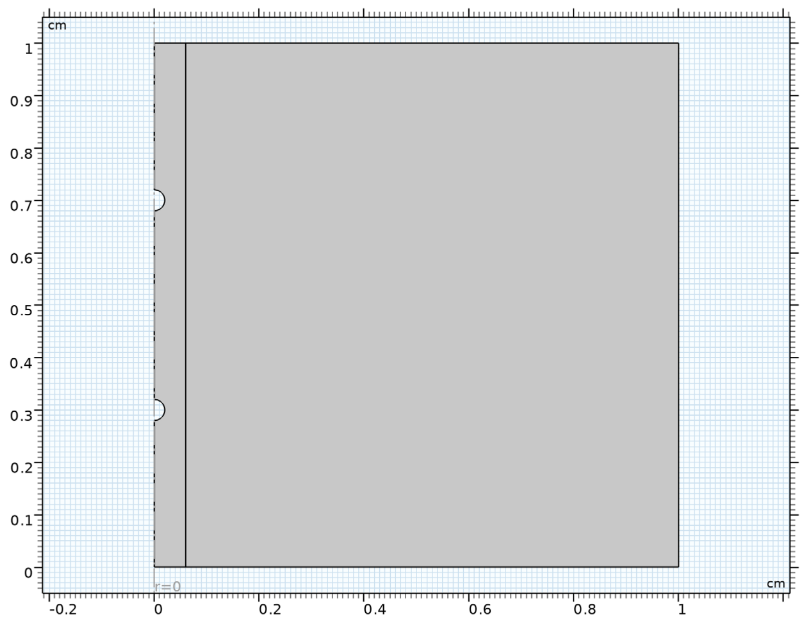
2 Select the object **r1** only.

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 objects **c1** and **c2** only.

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 [Morrow and Lowke, 1997]**.

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 7 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 5 and 8 only.

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

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

Gas 1

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

Floating Electrode 1

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

2 Select Boundaries 10 and 11 only.

Gas 1

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

Floating Electrode 2

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

2 Select Boundaries 12 and 13 only.

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 `1e8[1/cm^3]`.

4 In the n_n text field, type `1e8[1/cm^3]`.

5 In the n_p text field, type `2e8[1/cm^3]`.

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**.

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 **Boundary**.

4 Select Boundaries 1, 3, 4, and 10–13 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 `1/2000`.

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 **Domain**.

4 Select Domain 1 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 `1/100`.

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

Boundary Layers 1

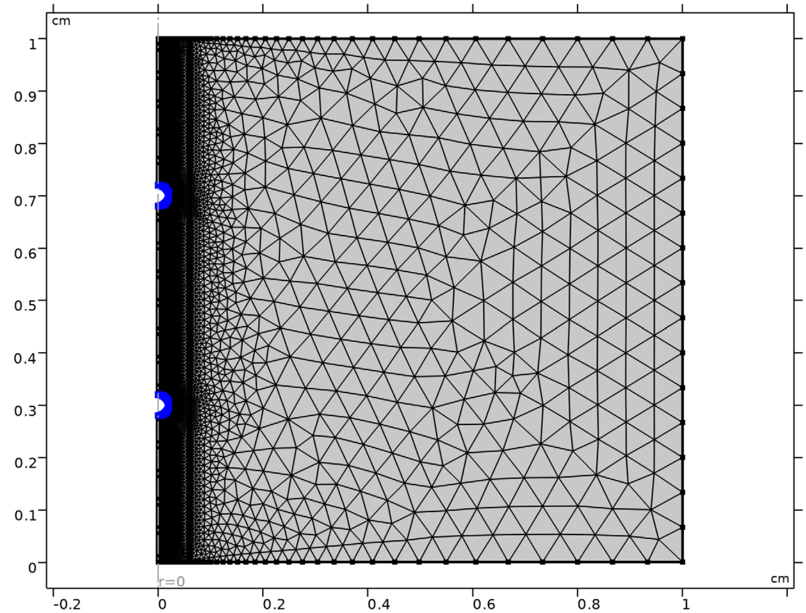
In the **Mesh** toolbar, click **Boundary Layers**.

Boundary Layer Properties

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

2 Select Boundaries 10–13 only.

3 In the **Settings** window for **Boundary Layer Properties**, click **Build All**.



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 **ns**.

4 In the **Output times** text field, type `range(0,0.5,2.5)`.

Next, include time steps effect on the consistent stabilization to increase numerical accuracy and stability.

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 Select the **Include time steps effect on stabilization time scale** checkbox.

STUDY 1

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node, then click **Time-Dependent Solver 1**.

3 In the **Settings** window for **Time-Dependent Solver**, click to expand the **Time Stepping** section.

4 From the **Maximum step constraint** list, choose **Constant**.

5 In the **Maximum step** text field, type `0.005`.

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

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

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

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

RESULTS

Mirror 2D 1

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

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

Electric Fields

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

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

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

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

Surface 1

1 Right-click **Electric Fields** and choose **Surface**.

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

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

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

Solution Array 1

Right-click **Surface 1** and choose **Solution Array**.

Annotation 1

1 In the **Model Builder** window, right-click **Electric Fields** 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.

5 From the **Anchor point** list, choose **Upper middle**.

Solution Array 1

Right-click **Annotation 1** and choose **Solution Array**.

Annotation 1

Click to expand the **Plot Array** section. Select the **Manual indexing** checkbox.

Electric Fields

1 In the **Model Builder** window, click **Electric Fields**.

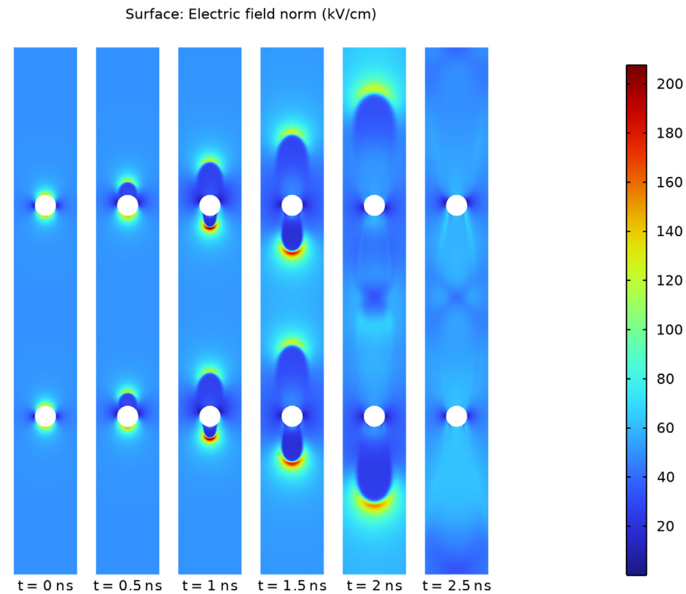
2 In the **Settings** window for **2D Plot Group**, click to expand the **Title** section.

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

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

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

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



Electron Density

1 Right-click **Electric Fields** and choose **Duplicate**.

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

Surface 1

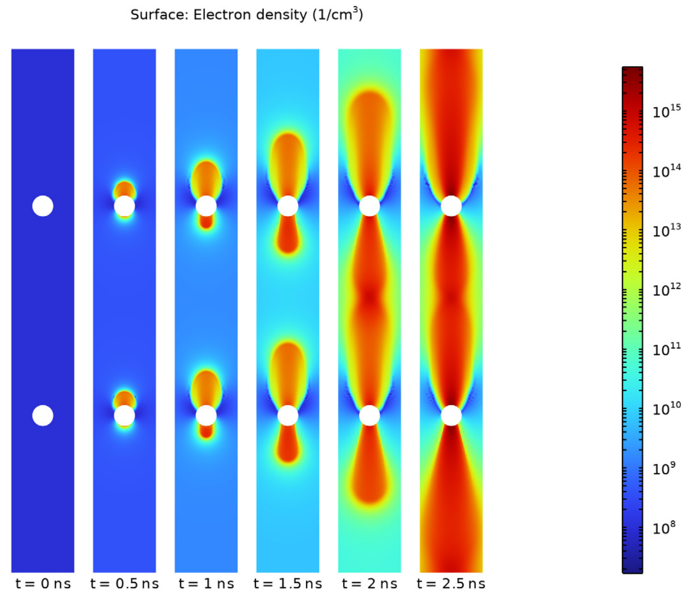
1 In the **Model Builder** window, expand the **Electron Density** node, then click **Surface 1**.

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 **Scale** list, choose **Logarithmic**.



Revolution 2D 1

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

Isosurface 1

1 In the **Results** toolbar, click **More Datasets** and choose **Isosurface**.

2 In the **Settings** window for **Isosurface**, 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 **Levels** section. From the **Entry method** list, choose **Levels**.

6 In the **Levels** text field, type `10^{range(log10(1.0e13),1/2,log10(1.0e15))}`.

Revolution 2D 2

In the **Model Builder** window, under **Results** > **Datasets** right-click **Revolution 2D 1** and choose **Duplicate**.

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 **Boundary**.

4 Select Boundaries 10–13 only.

3D Plot Group 3

1 In the **Results** toolbar, click **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, locate the **Plot Settings** section.

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

4 Locate the **Color Legend** section. Clear the **Show legends** checkbox.

Surface 1

1 Right-click **3D Plot Group 3** and choose **Surface**.

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

3 From the **Dataset** list, choose **Revolution 2D 2**.

4 Locate the **Expression** section. In the **Expression** text field, type `1`.

5 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.

6 From the **Color** list, choose **Custom**.

7 On Windows, click the colored bar underneath, or — if you are running the cross-platform desktop — the **Color** button.

8 Click **Define custom colors**.

9 Set the RGB values to 189, 201, and 216, respectively.

10 Click **Add to custom colors**.

11 Click **Show color palette only** or **OK** on the cross-platform desktop.

Solution Array 1

1 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 **From list**.

4 In the **Times (ns)** list, choose **0.5**, **1**, **1.5**, and **2**.

Surface 2

1 In the **Model Builder** window, right-click **3D Plot Group 3** and choose **Surface**.

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

3 From the **Dataset** list, choose **Isosurface 1**.

4 Locate the **Expression** section. In the **Expression** text field, type `edis.normE`.

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

Solution Array 1

1 Right-click **Surface 2** and choose **Solution Array**.

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

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

4 In the **Times (ns)** list, choose **0.5**, **1**, **1.5**, and **2**.

Transparency 1

1 In the **Model Builder** window, right-click **Surface 2** and choose **Transparency**.

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

3 Find the **Fresnel transmittance** subsection. Set the **Fresnel transmittance** value to **0.5**.

Surface 1

1 In the **Model Builder** window, under **Results** > **3D Plot Group 3** click **Surface 1**.

2 In the **Settings** window for **Surface**, click to expand the **Plot Array** section.

3 Select the **Manual indexing** checkbox.

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

3D Plot Group 3

1 In the **Model Builder** window, click **3D Plot Group 3**.

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

3 From the **Displacement** list, choose **Absolute**.

4 In the **Cell displacement** text field, type `0.2`.

5 In the **3D Plot Group 3** toolbar, click **Plot**.

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

Annotation 1

1 Right-click **3D Plot Group 3** 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.

5 From the **Anchor point** list, choose **Upper middle**.

Solution Array 1

1 Right-click **Annotation 1** and choose **Solution Array**.

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

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

4 In the **Times (ns)** list, choose **0.5**, **1**, **1.5**, and **2**.

Annotation 1

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

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

3 Select the **Manual indexing** checkbox.

3D Plot Group 3

1 Click the **Go to Default View** button in the **Graphics** toolbar.

2 In the **Model Builder** window, click **3D Plot Group 3**.

3 In the **3D Plot Group 3** toolbar, click **Plot**.