Model created in COMSOL Multiphysics 6.4

Cell Membrane Electroporation

Introduction

Electroporation is a technique that employs localized electric fields to generate pores in cell membranes via the rearrangement of the lipid bilayer, improving the cell permeability for ions and pharmaceuticals. High-intensity, nanosecond-short, electric pulses have been shown capable of generating transient nanometric pores onto cell membranes with minimal side effects for the cell. A nanosecond short pulse carries a spectral content in the GHz regime of the frequency domain. Around this frequency, cell membranes are subjected to another concurrent relevant phenomenon called dielectric dispersion, which has been shown to contribute to electroporation efficacy. Both effects are accounted for in this tutorial.

This Cell Membrane Electroporation tutorial model shows the electroporation phenomenon on a standard spherical cell both in the Time Domain and in the Frequency Domain. The model uses an analytical formulation for the electroporation contribution whose parameter values are taken from Ref. 1. In particular, the electroporation effect is accounted for by considering a time-varying conductivity for the membrane:

$$\sigma_{\mathrm{m}}(t) = \sigma_{\mathrm{m0}} + N(t, V_{\mathrm{m}}(t))\sigma_{\mathrm{p}}\pi r_{\mathrm{p}}^2 K \tag{1}$$

where σ_{m0} is the static baseline membrane conductivity, $N(t, V_m(t))$ is the time-dependent and transmembrane voltage-dependent pore density generation, σ_{p} is the pore conductivity, r_{p} is the pore radius, and K is a term proportional to the entrance length and energy barrier of the pore.

On the other hand, the dielectric dispersion is included in this tutorial model by means of a multiple Debye poles dispersion model:

$$\varepsilon_{\mathrm{r}}(f) = \varepsilon_{\infty} + \sum_{m=1}^{N} \frac{\Delta\varepsilon_m}{1 + j2\pi f \tau_{vm}} \tag{2}$$

where $\varepsilon_{\mathrm{r}}(f)$ is the frequency-dependent relative permittivity, ε_{∞} is the relative permittivity at the high frequency limit, $\Delta\varepsilon_m$ is the mth relative permittivity contribution, τ_{vm} is the relaxation time corresponding to the mth relative permittivity contribution, and N is the number of poles. These dispersive material quantities are taken from Ref. 2 and Ref. 3.

Results such as the electric field, transmembrane voltage, pore density, and membrane conductivity are investigated. They are comparable with the results shown in Ref. 4.

Model Definition

Figure 1 shows the geometry of the cell membrane. The model is solved in 2D axisymmetry, and consists of a spherical cell (that is, a thin insulating spherical membrane layer confining a conductive intracellular domain) placed inside a conductive extracellular domain cylinder. The excitation for electroporation is exerted from the top face of the cylinder whilst the bottom face is grounded.

Figure 2 shows the mesh. It is built using a distribution of elements along the membrane's boundaries for a lighter, yet accurate, mesh in the proximity of the thin membrane domain. This saves computational costs without penalizing the accuracy of the simulation.

The implementation requires the Electric Currents interface and the Boundary ODEs and DAEs interface. The former interface models the dielectric dispersion of the materials using a multiple Debye poles dispersion subfeature. This effect is shown in Figure 3 by the red dashed line for the membrane, and by the blue solid/green dotted lines for the extra/intracellular domains. The latter interface allows to incorporate on the cell membrane the electroporation-induced conductivity increase (see the Results and Discussion section for details).

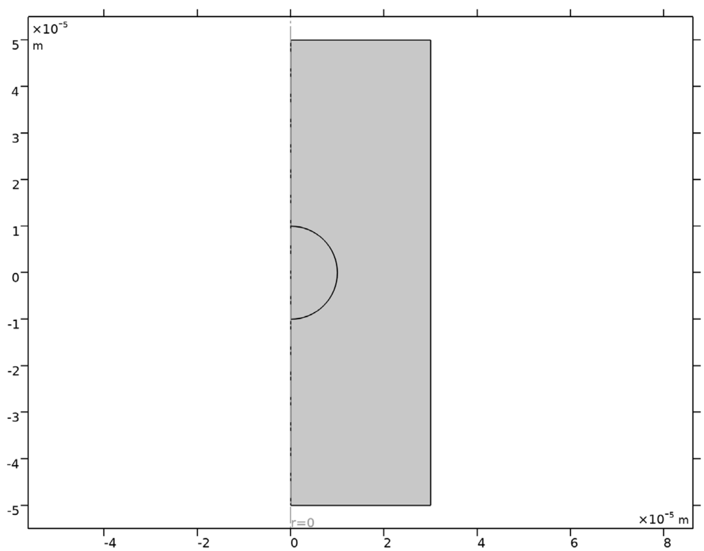


Figure 1: 2D axisymmetric geometry of the spherical cell surrounded by the extracellular domain. The cell membrane domain is not visible given its small thickness.

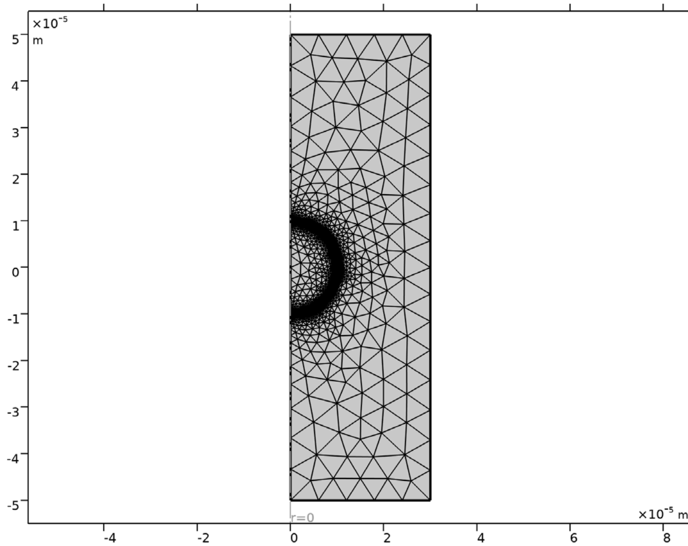


Figure 2: Computational mesh used in this tutorial.

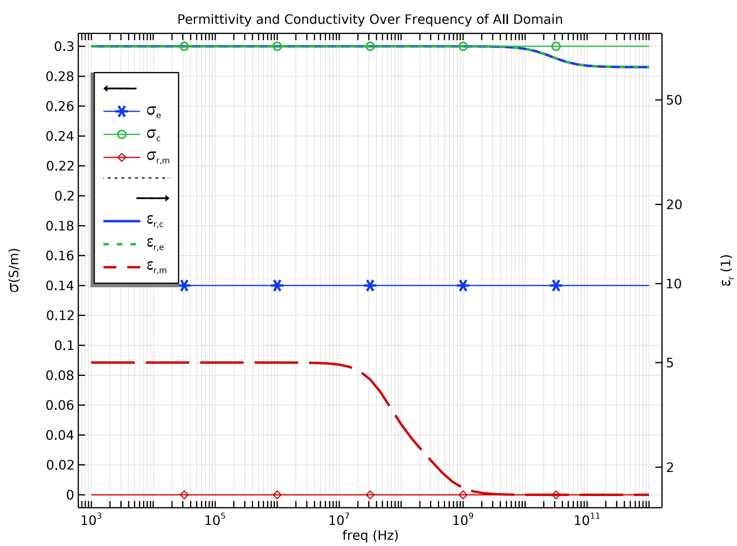


Figure 3: Electrical conductivity (left axis) and relative permittivity (right axis) spectra of all materials used in the model.

Results and Discussion

Two studies are performed in this tutorial: a Small-Signal Analysis, Frequency Domain Perturbation study and a Time Dependent study. Both studies include a first Stationary study step to initialize all variables. Figure 4 and Figure 5 show the frequency response of the system to a 10 V AC perturbation between 1 kHz and 1 THz. Figure 6–Figure 10 show the transient response of the system to a 650 V Gaussian pulse centered at $t = 5$ ns.

Figure 4 shows the 2D axisymmetric electric potential surface plots and streamlines at three different frequencies. At low frequency (1000 kHz, left inset) the membrane behaves like as a DC capacitor and a relatively small excitation signal couples to the inside of the cell. At large frequency (1 GHz, right inset) the membrane behaves like as an AC capacitor and the excitation signal strongly couples to the intracellular domain. The central inset shows an intermediate condition between small and large frequencies.

Figure 5 displays the transmembrane voltage modulus and phase spectra at a point located at the top of the cell.

Figure 6 depicts the same quantities as Figure 4 but for three time instants. It confirms that a nanosecond short pulse reproduces the qualitative behavior of a high-frequency AC excitation (Figure 4, right inset).

Figure 7 shows the transmembrane voltage, the membrane conductivity, and the pore density at a point located at the top of the cell. The increase of the transmembrane voltage due to the charging of the capacitive membrane triggers an exponential increase in the pore density. This translates into a significant increase in the membrane conductivity that in turn creates a conductive path for the potential built onto the external membrane boundary toward the intracellular domain. As a result, the transmembrane potential drops.

Figure 8 shows the membrane conductivity along the cell's edge at three time instants. Before 5 ns, the membrane conductivity remains close to a small static value. After 5 ns, the membrane conductivity at the cell's poles increase significantly and remain to high values for a few more nanoseconds.

Figure 9 is similar to Figure 8 but it displays the transmembrane voltage. After 5 ns, the transmembrane voltage at the cell's poles drops due to the locally increased membrane conductivity.

Figure 10 shows the 2D-revolved view of the membrane conductivity at the peak vale of the pulse, remarking that the maximum increase of conductivity occurs at the cell's poles.

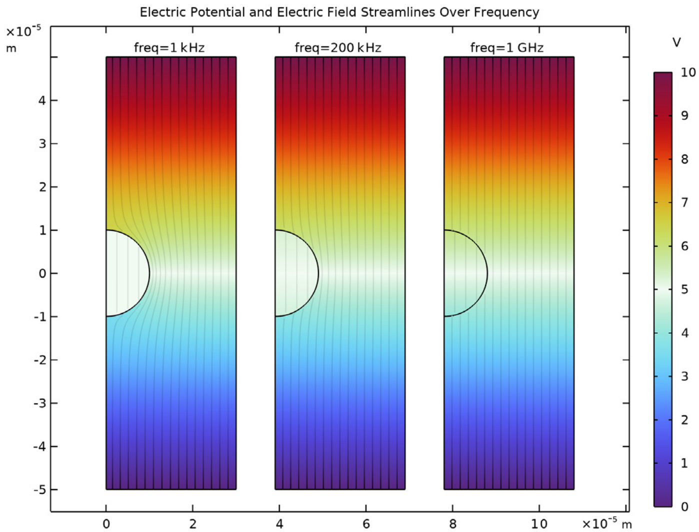


Figure 4: 2D electric potential surface plots and streamlines at different frequencies.

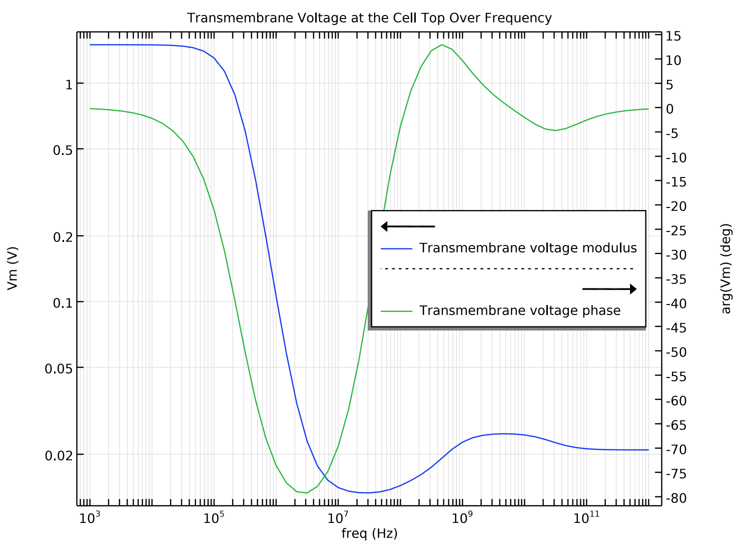


Figure 5: Left axis: transmembrane voltage modulus. Right axis: phase spectra.

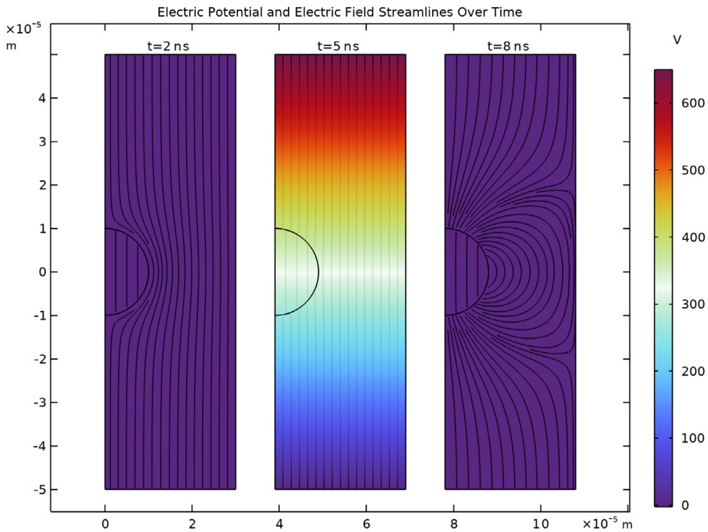


Figure 6: 2D electric field surface plot and streamlines at different time instants.

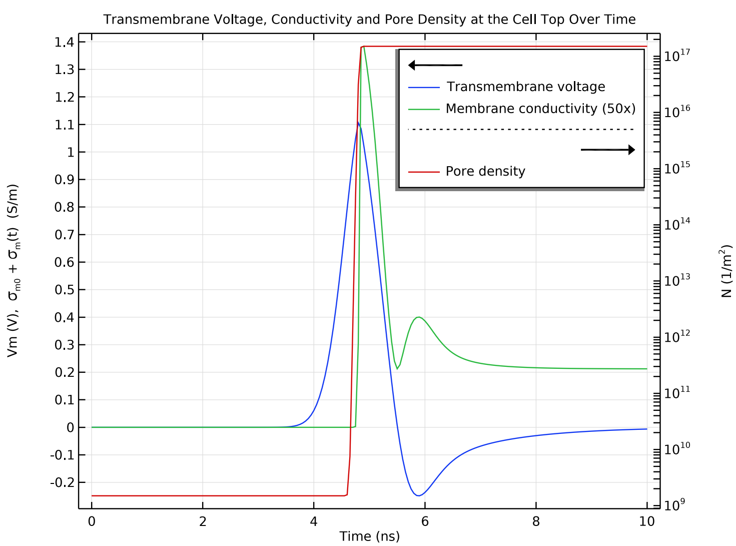


Figure 7: Left axis: transmembrane voltage and membrane conductivity (magnified 50 times for better visualization). Right axis: pore density.

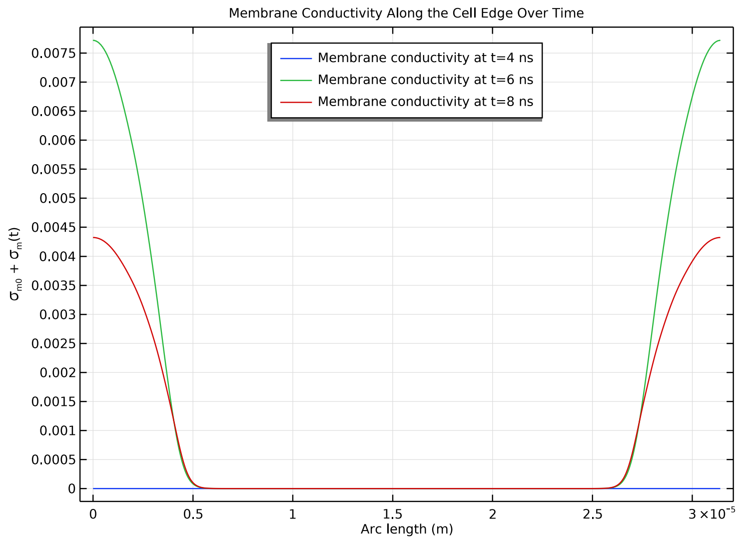


Figure 8: Membrane conductivity profile along the cell's edge at different time instants.

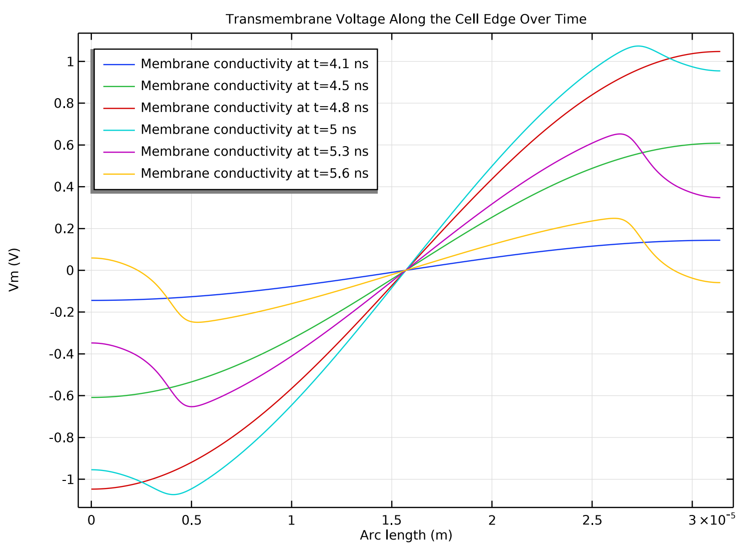


Figure 9: Transmembrane voltage profile along the cell's edge at different time instants.

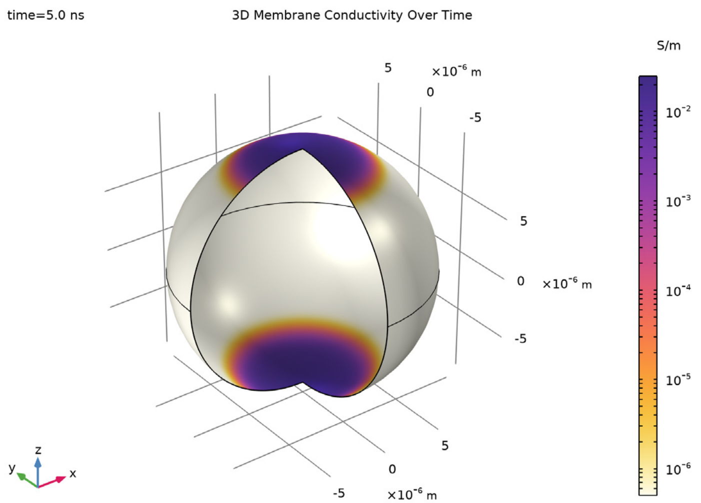


Figure 10: 2D-revolved view of the membrane conductivity at the peak value of the pulse.

References

1. G. Pucihar, D. Miklavcic, and T. Kotnik, “A Time-Dependent Numerical Model of Transmembrane Voltage Inducement and Electroporation of Irregularly Shaped Cells,” in *IEEE Transactions on Biomedical Engineering*, vol. 56, no. 5, pp. 1491–1501, 2009.

2. R. Büchner, G.T. Hefter, and P.M. May, “Dielectric Relaxation of Aqueous NaCl Solutions,” *J. Phys. Chem. A*, vol. 103, no. 1, pp. 1–9, 1999.

3. B. Klösgen, C. Reichle, S. Kohlsmann, and K.D. Kramer, “Dielectric Spectroscopy as a Sensor of Membrane Headgroup Mobility and Hydration,” *J. Biophys.*, vol. 71, no. 6, pp. 3251–3260, 1996.

4. E. Salimi, *Nanosecond Pulse Electroporation of Biological Cells: The Effect of Membrane Dielectric Relaxation,* master’s thesis, Dept. Electrical and Computer Eng., Univ. Manitoba, Winnipeg, 2011.

The parameter values of this tutorial model were taken from Ref. 1 with the permission of the authors’ research group (Laboratory of Biocybernetics, Department of Biomedical Engineering, Faculty of Electrical Engineering, University of Ljubljana, Slovenia), as well as from Ref. 2 and Ref. 3. The results of the present model are in agreement with those shown in Ref. 4.

Application Library path: ACDC_Module/Devices,_Resistive/cell_membrane_electroporation

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 **AC/DC** > **Electric Fields and Currents** > **Electric Currents (ec)**.
3 Click **Add**.
4 In the **Select Physics** tree, select **Mathematics** > **ODE and DAE Interfaces** > **Boundary ODEs and DAEs (bode)**.
5 Click **Add**.
6 Click **Study**.
7 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces** > **Electric Currents** > **Small-Signal Analysis, Frequency Domain**.
8 Click **Done**.

First, define the geometric and physical parameters of the model.

GLOBAL DEFINITIONS

Geometric Parameters

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
2 In the **Settings** window for **Parameters**, type Geometric Parameters in the **Label** text field.

3 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
r_cell	10[um]	1E-5 m	Radius of the cell
t_m	5[nm]	5E-9 m	Thickness of the cell membrane
r_p	0.8[nm]	8E-10 m	Pore radius
h_dom	100[um]	1E-4 m	Height of the extracellular domain
r_dom	3*r_cell	3E-5 m	Radius of the extracellular domain

Physical Parameters

1 In the **Home** toolbar, click Pi **Parameters** and choose **Add** > **Parameters**.

2 In the **Settings** window for **Parameters**, type `Physical Parameters` in the **Label** text field.

3 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
Vep	170[mV]	0.17 V	Characteristic voltage of electroporation
sigma_p	0.16[S/m]	0.16 S/m	Electrical conductivity inside the pore
N0	1.5e9[m^-2]	1.5E9 1/m²	Equilibrium pore density
n	0.15	0.15	Relative entrance length of pores
q	2.46	2.46	Pore creation rate
alpha	1e9[m^-2/s]	1E9 1/(m²·s)	Pore creation rate density
w0	2.65	2.65	Pore energy barrier
sigma_m	5e-7[S/m]	5E-7 S/m	Electrical conductivity of the membrane (static value)
Ginf_m	13.9e-12[F/m]/epsilon0_const	1.5699	Relative electrical permittivity at high frequency of the membrane
Gvm1_m	2.3e-11[F/m]/epsilon0_const	2.5976	First relative electrical permittivity contribution of the membrane

Name	Expression	Value	Description
Gvm2_m	7.4e-12[F/m]/epsilon0_const	0.83576	Second relative electrical permittivity contribution of the membrane
tauvm1_m	3e-9[s]	3E-9 s	First relaxation time of the membrane
tauvm2_m	4.6e-10[s]	4.6E-10 s	Second relaxation time of the membrane
sigma_e	0.14[S/m]	0.14 S/m	Electrical conductivity of the extracellular domain
sigma_i	0.3[S/m]	0.3 S/m	Electrical conductivity of the intracellular domain
Ginf_f	5.9e-10[F/m]/epsilon0_const	66.635	Relative electrical permittivity at high frequency of cellular domains
Gvm1_f	1.18e-10[F/m]/epsilon0_const	13.327	Relative electrical permittivity contribution of cellular domains
tauvm1_f	6.2e-12[s]	6.2E-12 s	Relaxation time of the cellular domains

Study Parameters

1 In the **Home** toolbar, click **Pi** **Parameters** and choose **Add** > **Parameters**.

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

3 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
V_fd	10[V]	10 V	Amplitude of the frequency domain perturbation
V_td	650[V]	650 V	Amplitude of the time dependent pulse
t_end	10[ns]	1E-8 s	Duration of the time dependent study

Build the geometry following these steps.

GEOMETRY 1

Cell

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

2 Right-click **Geometry 1** and choose **Circle**.

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

4 In the **Radius** text field, type `r_cell`.

5 In the **Sector angle** text field, type `180`.

6 Locate the **Rotation Angle** section. In the **Rotation** text field, type `-90`.

7 In the **Label** text field, type `Cell`.

8 Click to expand the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (m)
`Layer 1`	`t_m`

Cellular Domains

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

2 In the **Settings** window for **Rectangle**, type `Cellular Domains` in the **Label** text field.

3 Locate the **Size and Shape** section. In the **Width** text field, type `r_dom`.

4 In the **Height** text field, type `h_dom`.

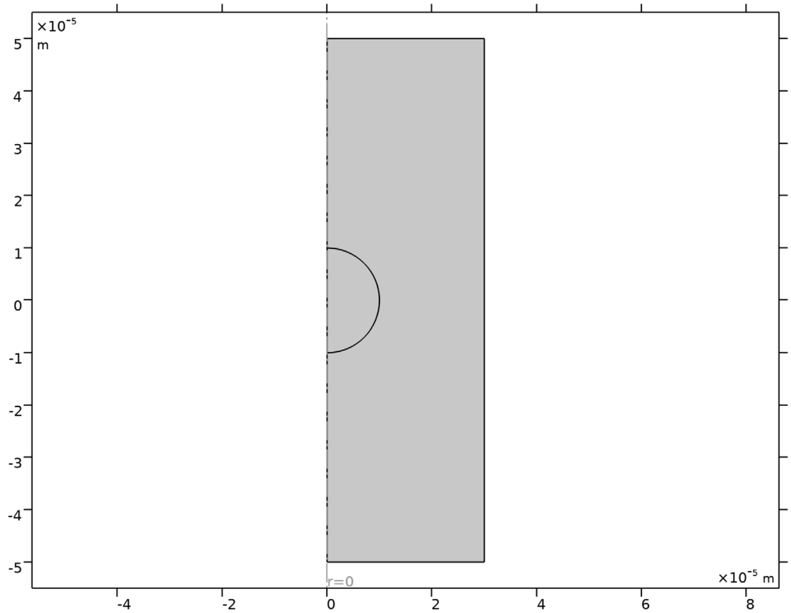
5 Locate the **Position** section. In the **z** text field, type `-h_dom/2`.

Form Union (fin)

1 In the **Model Builder** window, click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, click **Build Selected**.

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



Define useful selections under the Geometry node.

Membrane

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 In the **Settings** window for **Explicit Selection**, type `Membrane` in the **Label** text field.

3 On the object **fin**, select Domains 2 and 4 only.

Intracellular Domain

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 3 only.

3 In the **Settings** window for **Explicit Selection**, type `Intracellular Domain` in the **Label** text field.

4 Click **Build Selected**.

Extracellular Domain

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.

2 On the object **fin**, select Domain 1 only.

3 In the **Settings** window for **Explicit Selection**, type `Extracellular Domain` in the **Label** text field.

Intra/Extracellular Domains

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 On the object **fin**, select Domains 1 and 3 only.
3 In the **Settings** window for **Explicit Selection**, type `Intra/Extracellular Domains` in the **Label** text field.

Membrane Boundary Intra

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, locate the **Entities to Select** section.
3 From the **Geometric entity level** list, choose **Boundary**.
4 In the **Label** text field, type `Membrane Boundary Intra`.
5 On the object **fin**, select Boundaries 12 and 13 only.

Membrane Boundary Extra

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, locate the **Entities to Select** section.
3 From the **Geometric entity level** list, choose **Boundary**.
4 In the **Label** text field, type `Membrane Boundary Extra`.
5 On the object **fin**, select Boundaries 11 and 14 only.

Terminal Boundary

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, locate the **Entities to Select** section.
3 From the **Geometric entity level** list, choose **Boundary**.
4 On the object **fin**, select Boundary 8 only.
5 In the **Label** text field, type `Terminal Boundary`.

Ground Boundary

1 In the **Geometry** toolbar, click **Selections** and choose **Explicit Selection**.
2 In the **Settings** window for **Explicit Selection**, locate the **Entities to Select** section.
3 From the **Geometric entity level** list, choose **Boundary**.
4 In the **Label** text field, type `Ground Boundary`.
5 On the object **fin**, select Boundary 2 only.

Set up two general extrusions to map the potential between membrane boundaries; use them to define the membrane potential difference.

DEFINITIONS

Mapping from Intracellular to Extracellular

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

2 Right-click **Definitions** and choose **Nonlocal Couplings** > **General Extrusion**.

3 In the **Settings** window for **General Extrusion**, type `Mapping from Intracellular to Extracellular` in the **Label** text field.

4 In the **Operator name** text field, type `in2out`.

5 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

6 From the **Selection** list, choose **Membrane Boundary Intra**.

7 Locate the **Destination Map** section. In the **r-expression** text field, type `r/sqrt(r^2+z^2)*(r_cell-t_m)`.

8 In the **z-expression** text field, type `z/sqrt(r^2+z^2)*(r_cell-t_m)`.

9 Locate the **Source** section. Select the **Use source map** checkbox.

Mapping from Extracellular to Intracellular

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **General Extrusion**.

2 In the **Settings** window for **General Extrusion**, type `Mapping from Extracellular to Intracellular` in the **Label** text field.

3 In the **Operator name** text field, type `out2in`.

4 Locate the **Source Selection** section. From the **Geometric entity level** list, choose **Boundary**.

5 From the **Selection** list, choose **Membrane Boundary Extra**.

6 Locate the **Destination Map** section. In the **r-expression** text field, type `r/sqrt(r^2+z^2)*r_cell`.

7 In the **z-expression** text field, type `z/sqrt(r^2+z^2)*r_cell`.

8 Locate the **Source** section. Select the **Use source map** checkbox.

Transmembrane Potential

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

2 In the **Settings** window for **Variables**, type `Transmembrane Potential` in the **Label** text field.

3 Locate the **Geometric Entity Selection** section. From the **Geometric entity level** list, choose **Boundary**.

4 From the **Selection** list, choose **Membrane Boundary Intra**.

5 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
Vm	out2in(V)-V	V	

Membrane Variables

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

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

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

4 From the **Selection** list, choose **Membrane**.

5 In the **Label** text field, type `Membrane Variables`.

6 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
vm	in2out(Vm)*F_const/R_const/minput.T		Dimensionless transmembrane voltage
K	((exp(vm)-1)/(exp(vm)*(w0*exp(w0-n*vm)-n*vm)/(eps+w0-n*vm) -(w0*exp(w0+n*vm)+n*vm)/(w0+n*vm)))		Electroporation parameter related to wo and n
sigma_m_t	in2out(N)*sigma_p*pi*r_p^2*K		Time-dependent membrane conductivity

Gaussian Pulse

1 In the **Definitions** toolbar, click f(x) **More Functions** and choose **Gaussian Pulse**.

2 In the **Settings** window for **Gaussian Pulse**, type `Gaussian Pulse` in the **Label** text field.

3 Locate the **Parameters** section. In the **Location** text field, type `t_end/2`.

4 In the **Standard deviation** text field, type `t_end/25`.

5 From the **Normalization** list, choose **Peak value**.

6 In the **Peak value** text field, type `V_td`.

Use the following settings for the Electric Current interface and the Boundary ODE interface.

ELECTRIC CURRENTS (EC)

Current Conservation - Membrane

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Electric Currents (ec)** click **Current Conservation in Solids 1**.
2 In the **Settings** window for **Current Conservation in Solids**, type `Current Conservation - Membrane` in the **Label** text field.
3 Locate the **Constitutive Relation D-E** section. From the **Dielectric model** list, choose **Dispersion**.

Dispersion 1

1 In the **Model Builder** window, click **Dispersion 1**.
2 In the **Settings** window for **Dispersion**, locate the **Dispersion Model** section.
3 From the **Material model** list, choose **Multipole Debye**.
4 From the **Material property** list, choose **From material**.
5 In the N text field, type `2`.

Current Conservation - Intra/Extracellular

1 In the **Physics** toolbar, click **Domains** and choose **Current Conservation in Solids**.
2 In the **Settings** window for **Current Conservation in Solids**, type `Current Conservation - Intra/Extracellular` in the **Label** text field.
3 Locate the **Constitutive Relation D-E** section. From the **Dielectric model** list, choose **Dispersion**.
4 Locate the **Domain Selection** section. From the **Selection** list, choose **Intra/ Extracellular Domains**.

Dispersion 1

1 In the **Model Builder** window, click **Dispersion 1**.
2 In the **Settings** window for **Dispersion**, locate the **Dispersion Model** section.
3 From the **Material model** list, choose **Multipole Debye**.
4 From the **Material property** list, choose **From material**.
5 In the N text field, type `1`.

Ground 1

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

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

3 From the **Selection** list, choose **Ground Boundary**.

Terminal for Small-Signal Analysis, Frequency Domain

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

2 In the **Settings** window for **Boundary Terminal**, type `Terminal for Small-Signal Analysis, Frequency Domain` in the **Label** text field.

3 Locate the **Terminal** section. From the **Terminal type** list, choose **Voltage**.

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

Harmonic Perturbation 1

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

2 In the **Settings** window for **Harmonic Perturbation**, locate the **Terminal** section.

3 In the V_0 text field, type `V_fd`.

Terminal for Stationary Before Time Dependent

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

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

3 From the **Selection** list, choose **Terminal Boundary**.

4 Locate the **Terminal** section. From the **Terminal type** list, choose **Voltage**.

5 In the V_0 text field, type `1e-9`.

6 In the **Label** text field, type `Terminal for Stationary Before Time Dependent`.

Terminal for Time Dependent

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

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

3 Locate the **Boundary Selection** section. From the **Selection** list, choose **Terminal Boundary**.

4 Locate the **Terminal** section. From the **Terminal type** list, choose **Voltage**.

5 In the V_0 text field, type `gp1(t)`.

BOUNDARY ODES AND DAES (BODE)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Boundary ODEs and DAEs (bode)**.

2 In the **Settings** window for **Boundary ODEs and DAEs**, locate the **Boundary Selection** section.

3 From the **Selection** list, choose **Membrane Boundary Intra**.

4 Locate the **Units** section. Click **Define Dependent Variable Unit**.

5 In the **Dependent variable quantity** table, enter the following settings:

Dependent variable quantity	Unit
Custom unit	1/m^2

6 In the **Source term quantity** table, enter the following settings:

Source term quantity	Unit
Custom unit	1/m^2/s

7 Click to expand the **Dependent Variables** section. In the **Field name (1/m²)** text field, type N.

8 In the **Dependent variables (1/m²)** table, enter the following settings:

N

Distributed ODE 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Boundary ODEs and DAEs (bode)** click **Distributed ODE 1**.

2 In the **Settings** window for **Distributed ODE**, locate the **Source Term** section.

3 In the *f* text field, type alpha*exp((Vm/Vep)^2)*(1-N/N0*exp(-q*(Vm/Vep)^2)).

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* text field, type N0.

Add one blank material per domain and link the corresponding dielectric dispersion properties.

MATERIALS

Cell Membrane

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

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

3 From the **Selection** list, choose **Membrane**.

4 In the **Label** text field, type `Cell Membrane`.

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

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	`sigma_m+sigma_m_t`	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`Ginf_m+Gvm1_m+Gvm2_m`	1	Basic
Relaxation times	{tauvm1, tauvm2}	`{tauvm1_m, tauvm2_m}`	s	Multipole Debye
Relative permittivity contributions	{Gvm1, Gvm2}	`{Gvm1_m, Gvm2_m}`	1	Multipole Debye

Intracellular Domain

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

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

3 From the **Selection** list, choose **Intracellular Domain**.

4 In the **Label** text field, type `Intracellular Domain`.

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

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	`sigma_i`	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`Ginf_f+Gvm1_f`	1	Basic

Property	Variable	Value	Unit	Property group
Relaxation times	tauvm	`tauvm1_f`	s	Multipole Debye
Relative permittivity contributions	Gvm	`Gvm1_f`	1	Multipole Debye

Extracellular Domain

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

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

3 From the **Selection** list, choose **Extracellular Domain**.

4 In the **Label** text field, type `Extracellular Domain`.

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

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	`sigma_e`	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	`Ginf_f+ Gvm1_f`	1	Basic
Relaxation times	tauvm	`tauvm1_f`	s	Multipole Debye
Relative permittivity contributions	Gvm	`Gvm1_f`	1	Multipole Debye

Cell Membrane (mat1)

1 In the **Model Builder** window, click **Cell Membrane (mat1)**.

2 In the **Settings** window for **Material**, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Reference temperature	Tref	`minput.T`	K	Multipole Debye

Intracellular Domain (mat2)

1 In the **Model Builder** window, click **Intracellular Domain (mat2)**.
2 In the **Settings** window for **Material**, locate the **Material Contents** section.
3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Reference temperature	Tref	`minput.T`	K	Multipole Debye

Extracellular Domain (mat3)

1 In the **Model Builder** window, click **Extracellular Domain (mat3)**.
2 In the **Settings** window for **Material**, locate the **Material Contents** section.
3 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Reference temperature	Tref	`minput.T`	K	Multipole Debye

Build the computational mesh.

MESH 1

Edge 1

1 In the **Mesh** toolbar, click **More Generators** and choose **Edge**.
2 Select Boundaries 11–14 only.

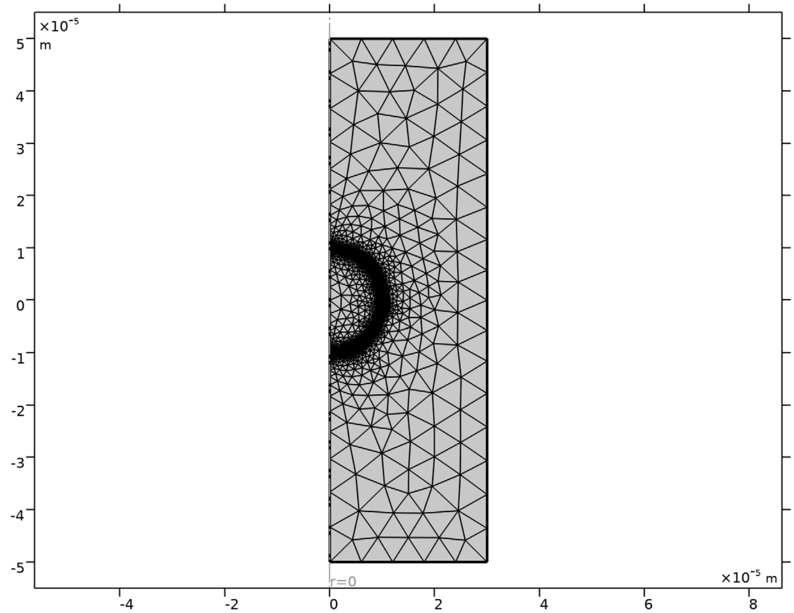
Distribution 1

1 Right-click **Edge 1** and choose **Distribution**.
2 In the **Settings** window for **Distribution**, locate the **Distribution** section.
3 In the **Number of elements** text field, type `200`.
4 Select the **Equidistant** checkbox.

Free Triangular 1

1 In the **Mesh** toolbar, click **Free Triangular**.
2 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

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



Finally, add two studies with the following settings and then compute.

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.

Step 1: Stationary

1 In the **Model Builder** window, under **Study 1** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, 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 Currents (ec)** > **Terminal for Stationary Before Time Dependent** and **Component 1 (comp1)** > **Electric Currents (ec)** > **Terminal for Time Dependent**.

5 Click **Disable**.

Step 2: Frequency-Domain Perturbation

1 In the **Model Builder** window, click **Step 2: Frequency-Domain Perturbation**.

2 In the **Settings** window for **Frequency-Domain Perturbation**, locate the **Study Settings** section.

3 In the **Frequencies** text field, type `10^{range(log10(1.e3),1/6,log10(1.0e12))}`.

4 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.

5 In the tree, select **Component 1 (comp1)** > **Electric Currents (ec)** > **Terminal for Stationary Before Time Dependent** and **Component 1 (comp1)** > **Electric Currents (ec)** > **Terminal for Time Dependent**.

6 Click **Disable**.

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

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** > **Stationary**.

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

STUDY 2

Step 1: Stationary

1 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.

2 Select the **Modify model configuration for study step** checkbox.

3 In the tree, select **Component 1 (comp1)** > **Electric Currents (ec)** > **Terminal for Time Dependent**.

4 Click **Disable**.

Step 2: Time Dependent

1 In the **Study** toolbar, click **Time Dependent**.

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

3 In the **Output times** text field, type `range(0,t_end/200,t_end)`.

Solution 3 (sol3)

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

2 In the **Model Builder** window, expand the **Solution 3 (sol3)** node.

3 In the **Model Builder** window, under **Study 2** > **Solver Configurations** > **Solution 3 (sol3)** click **Time-Dependent Solver 1**.

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

5 From the **Steps taken by solver** list, choose **Intermediate**.

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

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

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

Cut Point 2D 1

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

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

3 In the **Settings** window for **Cut Point 2D**, locate the **Point Data** section.

4 In the **r** text field, type `0`.

5 In the **z** text field, type `r_cell-t_m/2`.

Revolution 2D 1

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

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

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

4 Click to expand the **Revolution Layers** section. In the **Start angle** text field, type `-90`.

5 In the **Revolution angle** text field, type `270`.

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 From the **Selection** list, choose **Membrane**.

Permittivity and Conductivity Spectra

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

2 In the **Settings** window for **1D Plot Group**, type `Permittivity and Conductivity Spectra` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Permittivity and Conductivity Over Frequency of All Domain`.

5 Click to collapse the **Title** section. Locate the **Plot Settings** section. Select the **x-axis label** checkbox.

6 Select the **y-axis label** checkbox.

7 Select the **Two y-axes** checkbox.

8 In the **x-axis label** text field, type `freq (Hz)`.

9 In the **y-axis label** text field, type `\sigma (S/m)`.

10 Select the **Secondary y-axis label** checkbox. In the associated text field, type `\varepsilon<SUB>r</SUB> (1)`.

Point Graph 1

1 Right-click **Permittivity and Conductivity Spectra** and choose **Point Graph**.

2 Select Points 5 and 6 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `ec.cucns2.epsilonPrimRR`.

5 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** checkbox.

6 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

7 Find the **Line style** subsection. From the **Line** list, choose **Cycle**.

8 Click to expand the **Legends** section. Select the **Show legends** checkbox.

9 From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
`\varepsilon <SUB>r,c</SUB>`
`\varepsilon <SUB>r,e</SUB>`

Point Graph 2

1 In the **Model Builder** window, right-click **Permittivity and Conductivity Spectra** and choose **Point Graph**.

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

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

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `ec.cucns1.epsilonPrimRR`.

5 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** checkbox.

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

7 From the **Width** list, choose **2**.

8 Locate the **Legends** section. Select the **Show legends** checkbox.

9 From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
\varepsilon _{r,m}

11 In the **Permittivity and Conductivity Spectra** toolbar, click **Plot**.

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

Point Graph 3

1 Right-click **Permittivity and Conductivity Spectra** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **Selection** section.

3 Click to select the **Activate Selection** toggle button.

4 Select Points 1 and 4 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `ec.sigmaRR`.

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

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

8 Set the **Number** value to **5**.

9 From the **Color** list, choose **Cycle (reset)**.

10 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

11 Select the **Show legends** checkbox.

12 In the table, enter the following settings:

Legends
\sigma _e
\sigma _c

Point Graph 4

1 Right-click **Permittivity and Conductivity Spectra** and choose **Point Graph**.

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

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

4 Locate the **y-Axis Data** section. In the **Expression** text field, type ec.sigmaRR.

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**.

7 Set the **Number** value to **5**.

8 Locate the **Legends** section. Select the **Show legends** checkbox.

9 From the **Legends** list, choose **Manual**.

10 In the table, enter the following settings:

Legends
\sigma _{m0}

11 In the **Permittivity and Conductivity Spectra** toolbar, click **Plot**.

12 Click the **x-Axis Log Scale** button in the **Graphics** toolbar.

Permittivity and Conductivity Spectra

1 In the **Model Builder** window, click **Permittivity and Conductivity Spectra**.

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

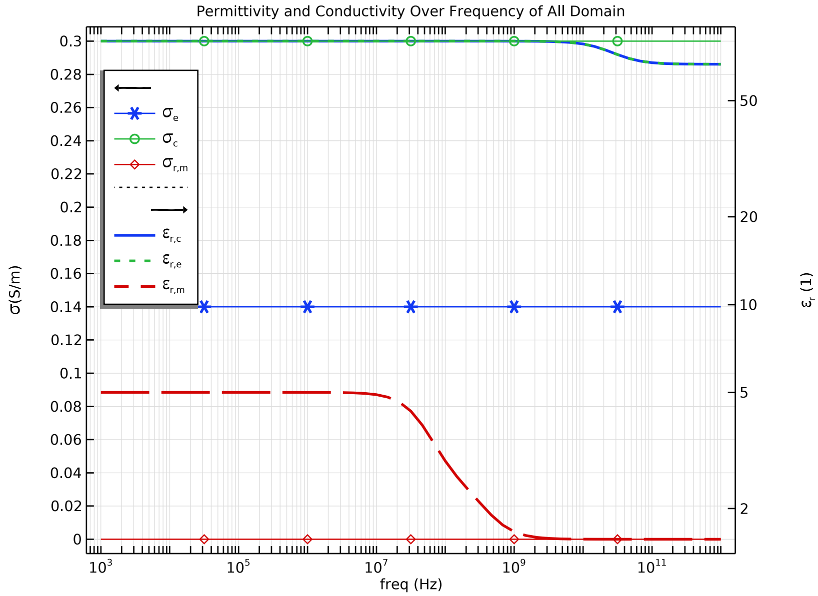
3 From the **Position** list, choose **Manual**.

4 In the **y-position** text field, type 0.9.

5 In the **x-position** text field, type 0.

6 In the **Permittivity and Conductivity Spectra** toolbar, click **Plot**.

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



Electric Potential (Frequency Domain)

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

2 In the **Settings** window for **2D Plot Group**, type `Electric Potential (Frequency Domain)` in the **Label** text field.

3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Electric Potential and Electric Field Streamlines Over Frequency`.

5 Clear the **Parameter indicator** text field.

6 Locate the **Color Legend** section. Select the **Show units** checkbox.

7 Click to expand the **Plot Array** section. From the **Array type** list, choose **Linear**.

Surface 1

1 Right-click **Electric Potential (Frequency Domain)** and choose **Surface**.

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

3 From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

4 From the **Parameter value (freq (Hz))** list, choose **1000**.

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

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

Streamline 1

1 In the **Model Builder** window, right-click **Electric Potential (Frequency Domain)** and choose **Streamline**.

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

3 In the **r-component** text field, type `ec.ER`.

4 In the **z-component** text field, type `ec.EZ`.

5 Locate the **Data** section. From the **Dataset** list, choose **Study 1/Solution 1 (sol1)**.

6 From the **Parameter value (freq (Hz))** list, choose **1000**.

7 Locate the **Streamline Positioning** section. From the **Positioning** list, choose **Uniform density**.

8 In the **Density level** text field, type `7.77`.

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

10 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

11 Clear the **Color** checkbox.

Color Expression 1

1 Right-click **Streamline 1** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Coloring and Style** section.

3 Clear the **Color legend** checkbox.

4 From the **Color table** list, choose **DipoleDark**.

Filter 1

1 In the **Model Builder** window, right-click **Streamline 1** and choose **Filter**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `!isScalingSystemDomain`.

Surface 2

1 In the **Model Builder** window, under **Results** > **Electric Potential (Frequency Domain)** right-click **Surface 1** and choose **Duplicate**.

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

3 From the **Parameter value (freq (Hz))** list, choose **2.1544E5**.

4 Locate the **Plot Array** section. In the **Index** text field, type `1`.

5 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

Streamline 2

1 In the **Model Builder** window, under **Results** > **Electric Potential (Frequency Domain)** right-click **Streamline 1** and choose **Duplicate**.

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

3 From the **Parameter value (freq (Hz))** list, choose **2.1544E5**.

4 Locate the **Plot Array** section. In the **Index** text field, type `1`.

Surface 3

1 In the **Model Builder** window, under **Results** > **Electric Potential (Frequency Domain)** right-click **Surface 2** and choose **Duplicate**.

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

3 From the **Parameter value (freq (Hz))** list, choose **1E9**.

4 Locate the **Plot Array** section. In the **Index** text field, type `2`.

Streamline 3

1 In the **Model Builder** window, under **Results** > **Electric Potential (Frequency Domain)** right-click **Streamline 2** and choose **Duplicate**.

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

3 From the **Parameter value (freq (Hz))** list, choose **1E9**.

4 Locate the **Plot Array** section. In the **Index** text field, type `2`.

Annotation 1

In the **Model Builder** window, right-click **Electric Potential (Frequency Domain)** and choose **Annotation**.

Electric Potential (Frequency Domain)

In the **Model Builder** window, collapse the **Electric Potential (Frequency Domain)** node.

Annotation 1

1 In the **Model Builder** window, expand the **Electric Potential (Frequency Domain)** node, then click **Annotation 1**.

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

3 In the **Text** text field, type `freq=1 kHz`.

4 Locate the **Position** section. In the **r** text field, type `1.45*r_cell`.

5 In the **z** text field, type `5.2e-5`.

6 Locate the **Coloring and Style** section. From the **Anchor point** list, choose **Center**.

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

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

9 In the **Electric Potential (Frequency Domain)** toolbar, click **Plot**.

Annotation 2

1 Right-click **Results** > **Electric Potential (Frequency Domain)** > **Annotation 1** and choose **Duplicate**.

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

3 In the **Index** text field, type `1`.

4 Locate the **Annotation** section. In the **Text** text field, type `freq=200 kHz`.

Annotation 3

1 Right-click **Annotation 2** and choose **Duplicate**.

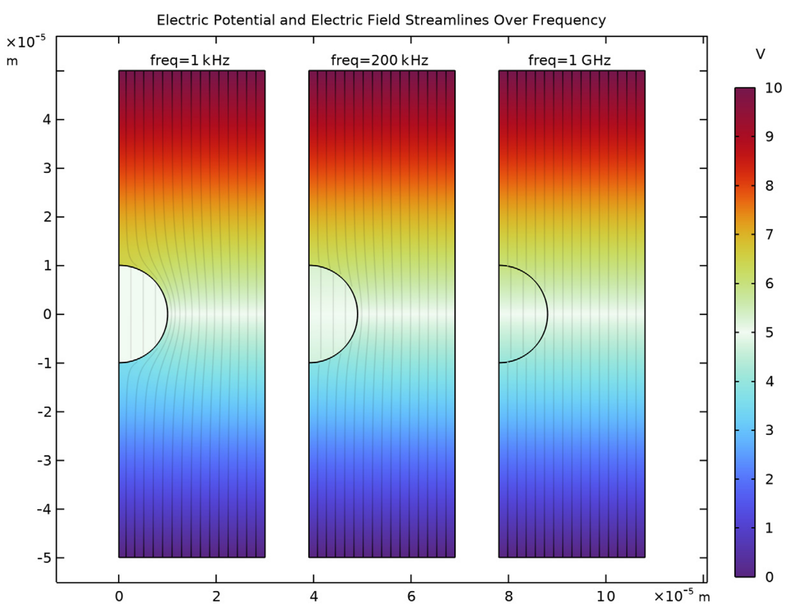
2 In the **Settings** window for **Annotation**, locate the **Plot Array** section.

3 In the **Index** text field, type `2`.

4 Locate the **Annotation** section. In the **Text** text field, type `freq=1 GHz`.

5 In the **Electric Potential (Frequency Domain)** toolbar, click **Plot**.

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



Transmembrane Voltage Spectra

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

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

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

4 In the **Label** text field, type `Transmembrane Voltage Spectra`.

5 Locate the **Title** section. From the **Title type** list, choose **Manual**.

6 In the **Title** text area, type `Transmembrane Voltage at the Cell Top Over Frequency`.

7 Locate the **Plot Settings** section. Select the **Two y-axes** checkbox.

8 Select the **x-axis label** checkbox.

9 Select the **y-axis label** checkbox.

10 Select the **Secondary y-axis label** checkbox.

11 In the **x-axis label** text field, type `freq (Hz)`.

12 In the **y-axis label** text field, type `Vm (V)`.

13 In the **Secondary y-axis label** text field, type `arg(Vm) (deg)`.

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

15 Select the **y-axis log scale** checkbox.

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

Point Graph 1

1 Right-click **Transmembrane Voltage Spectra** and choose **Point Graph**.

2 In the **Settings** window for **Point Graph**, locate the **Selection** section.

3 Click to select the **Activate Selection** toggle button.

4 Select Point 5 only.

5 Locate the **y-Axis Data** section. In the **Expression** text field, type `Vm`.

6 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

Legends
`Transmembrane voltage modulus`

8 Select the **Show legends** checkbox.

Point Graph 2

1 In the **Model Builder** window, right-click **Transmembrane Voltage Spectra** and choose **Point Graph**.

2 Select Point 5 only.

3 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

4 In the **Expression** text field, type `arg(Vm)`.

5 In the **Unit** field, type `deg`.

6 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

7 In the table, enter the following settings:

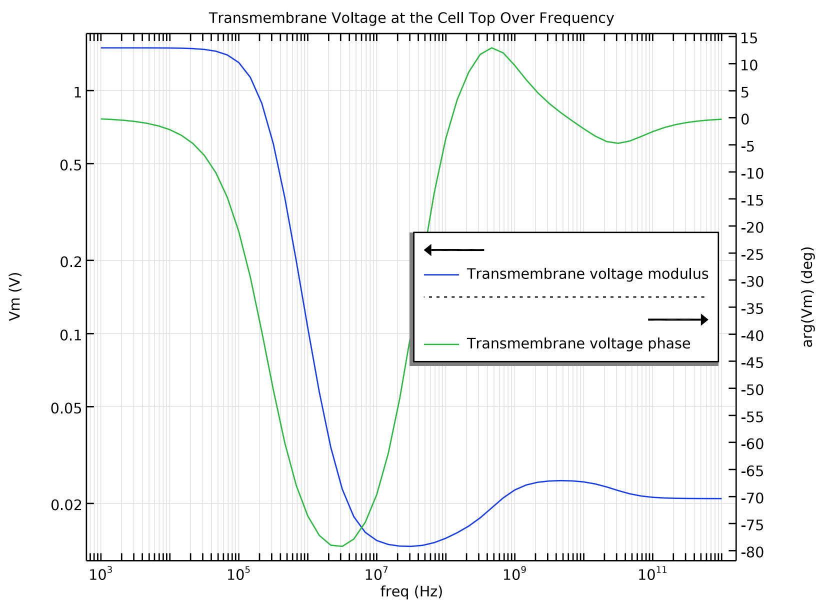
Legends
Transmembrane voltage phase

8 Select the **Show legends** checkbox.

9 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** checkbox.

10 In the **Transmembrane Voltage Spectra** toolbar, click **Plot**.

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



Electric Potential (Time Dependent)

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

2 In the **Settings** window for **2D Plot Group**, type `Electric Potential (Time Dependent)` in the **Label** text field.

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Electric Potential and Electric Field Streamlines Over Time`.

5 Clear the **Parameter indicator** text field.

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

7 Locate the **Color Legend** section. Select the **Show units** checkbox.

8 Locate the **Plot Array** section. From the **Array type** list, choose **Linear**.

Surface 1

1 Right-click **Electric Potential (Time Dependent)** and choose **Surface**.

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

3 Select the **Manual indexing** checkbox.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **Dipole**.

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

6 From the **Time (s)** list, choose **2E-9**.

7 In the **Electric Potential (Time Dependent)** toolbar, click  **Plot**.

Streamline 1

1 In the **Model Builder** window, right-click **Electric Potential (Time Dependent)** and choose **Streamline**.

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

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

4 From the **Time (s)** list, choose **2E-9**.

5 Locate the **Expression** section. In the **r-component** text field, type `ec.ER`.

6 In the **z-component** text field, type `ec.EZ`.

7 Locate the **Streamline Positioning** section. From the **Positioning** list, choose **Uniform density**.

8 In the **Density level** text field, type `7.77`.

9 Click to collapse the **Inherit Style** section. Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

10 Clear the **Color** checkbox.

11 Locate the **Plot Array** section. Select the **Manual indexing** checkbox.

Color Expression 1

1 Right-click **Streamline 1** and choose **Color Expression**.

2 In the **Settings** window for **Color Expression**, locate the **Coloring and Style** section.

3 Clear the **Color legend** checkbox.

4 From the **Color table** list, choose **DipoleDark**.

Filter 1

1 In the **Model Builder** window, right-click **Streamline 1** and choose **Filter**.

2 In the **Settings** window for **Filter**, locate the **Element Selection** section.

3 In the **Logical expression for inclusion** text field, type `!isScalingSystemDomain`.

4 In the **Electric Potential (Time Dependent)** toolbar, click **Plot**.

Surface 2

1 In the **Model Builder** window, under **Results** > **Electric Potential (Time Dependent)** right-click **Surface 1** and choose **Duplicate**.

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

3 From the **Time (s)** list, choose **5E-9**.

4 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

5 Locate the **Plot Array** section. In the **Index** text field, type `1`.

Streamline 2

1 In the **Model Builder** window, under **Results** > **Electric Potential (Time Dependent)** right-click **Streamline 1** and choose **Duplicate**.

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

3 From the **Time (s)** list, choose **5E-9**.

4 Locate the **Plot Array** section. In the **Index** text field, type `1`.

Surface 3

1 In the **Model Builder** window, under **Results** > **Electric Potential (Time Dependent)** right-click **Surface 1** and choose **Duplicate**.

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

3 From the **Time (s)** list, choose **8E-9**.

4 Locate the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.

5 Locate the **Plot Array** section. In the **Index** text field, type `2`.

Streamline 3

1 In the **Model Builder** window, under **Results** > **Electric Potential (Time Dependent)** right-click **Streamline 1** and choose **Duplicate**.

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

3 From the **Time (s)** list, choose **8E-9**.

4 Locate the **Plot Array** section. In the **Index** text field, type `2`.

Annotation 1, Annotation 2, Annotation 3

1 In the **Model Builder** window, under **Results** > **Electric Potential (Frequency Domain)**, Ctrl-click to select **Annotation 1**, **Annotation 2**, and **Annotation 3**.

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

Electric Potential (Time Dependent)

In the **Model Builder** window, under **Results** right-click **Electric Potential (Time Dependent)** and choose **Paste Multiple Items**.

Annotation 1

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

2 In the **Text** text field, type `t=2 ns`.

Annotation 2

1 In the **Model Builder** window, click **Annotation 2**.

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

3 In the **Text** text field, type `t=5 ns`.

Annotation 3

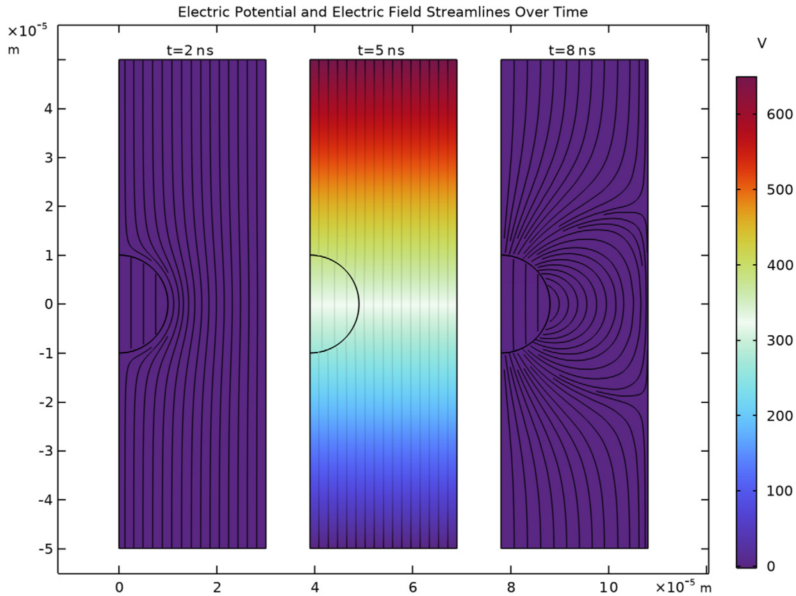
1 In the **Model Builder** window, click **Annotation 3**.

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

3 In the **Text** text field, type `t=8 ns`.

4 In the **Electric Potential (Time Dependent)** toolbar, click **Plot**.

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



Voltage, Conductivity and Pore Density

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

2 In the **Settings** window for **1D Plot Group**, type Voltage, Conductivity and Pore Density in the **Label** text field.

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

4 Locate the **Title** section. From the **Title type** list, choose **Manual**.

5 In the **Title** text area, type Transmembrane Voltage, Conductivity and Pore Density at the Cell Top Over Time.

6 Locate the **Plot Settings** section. Select the **x-axis label** checkbox.

7 Select the **y-axis label** checkbox.

8 Select the **Two y-axes** checkbox.

9 Select the **Secondary y-axis label** checkbox.

10 In the **x-axis label** text field, type Time (ns).

11 In the **y-axis label** text field, type Vm (V), \sigma _{m0} + \sigma _m(t) (S/m).

12 In the **Secondary y-axis label** text field, type N (1/m²).

13 Locate the **Axis** section. Select the **Secondary y-axis log scale** checkbox.

Point Graph 1

1. Right-click **Voltage, Conductivity and Pore Density** and choose **Point Graph**.
2. Select Point 5 only.
3. In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `Vm`.
5. Locate the **x-Axis Data** section. From the **Unit** list, choose **ns**.
6. Locate the **Legends** section. Select the **Show legends** checkbox.
7. From the **Legends** list, choose **Manual**.
8. In the table, enter the following settings:

Legends
`Transmembrane voltage`

Point Graph 2

1. In the **Model Builder** window, right-click **Voltage, Conductivity and Pore Density** and choose **Point Graph**.
2. Select Point 5 only.
3. In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `50*(sigma_m+sigma_m_t)`.
5. Locate the **x-Axis Data** section. From the **Unit** list, choose **ns**.
6. Locate the **Legends** section. Select the **Show legends** checkbox.
7. From the **Legends** list, choose **Manual**.
8. In the table, enter the following settings:

Legends
`Membrane conductivity (50x)`

Point Graph 3

1. Right-click **Voltage, Conductivity and Pore Density** and choose **Point Graph**.
2. Select Point 5 only.
3. In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.
4. In the **Expression** text field, type `N`.
5. Locate the **x-Axis Data** section. From the **Unit** list, choose **ns**.

6 Locate the **y-Axis** section. Select the **Plot on secondary y-axis** checkbox.

7 Locate the **Legends** section. From the **Legends** list, choose **Manual**.

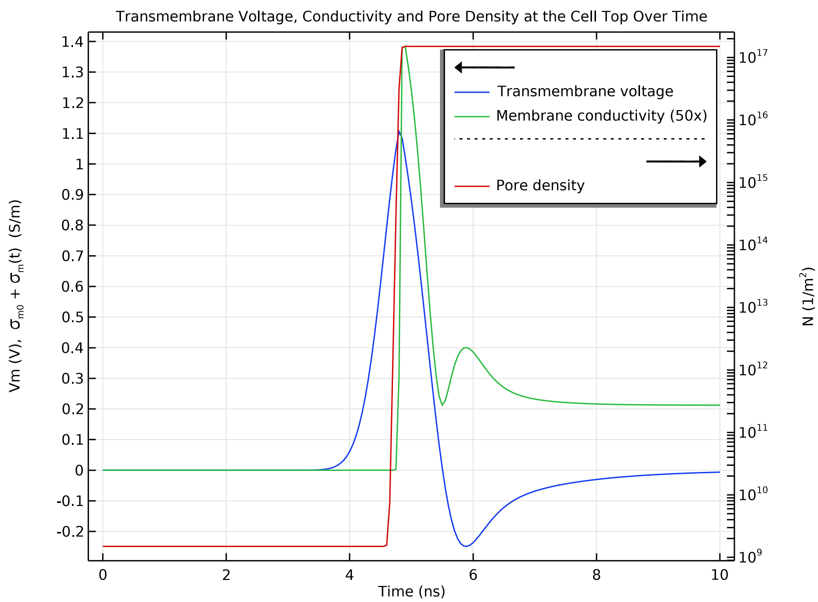
8 In the table, enter the following settings:

Legends
`Pore density`

9 Select the **Show legends** checkbox.

10 In the **Voltage, Conductivity and Pore Density** toolbar, click **Plot**.

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



Membrane Conductivity Profile

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

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

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Membrane Conductivity Along the Cell Edge Over Time`.

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

6 From the **Time selection** list, choose **Manual**.

7 In the **Time indices (1-201)** text field, type 81 121 161.

8 Locate the **Plot Settings** section. Select the **x-axis label** checkbox.

9 Select the **y-axis label** checkbox.

10 In the **x-axis label** text field, type Arc length (m).

11 In the **y-axis label** text field, type \sigma _{m0} + \sigma _m (t).

12 Locate the **Legend** section. From the **Position** list, choose **Upper middle**.

Line Graph 1

1 Right-click **Membrane Conductivity Profile** and choose **Line Graph**.

2 Select Boundaries 12 and 13 only.

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

4 In the **Expression** text field, type sigma_m+sigma_m_t.

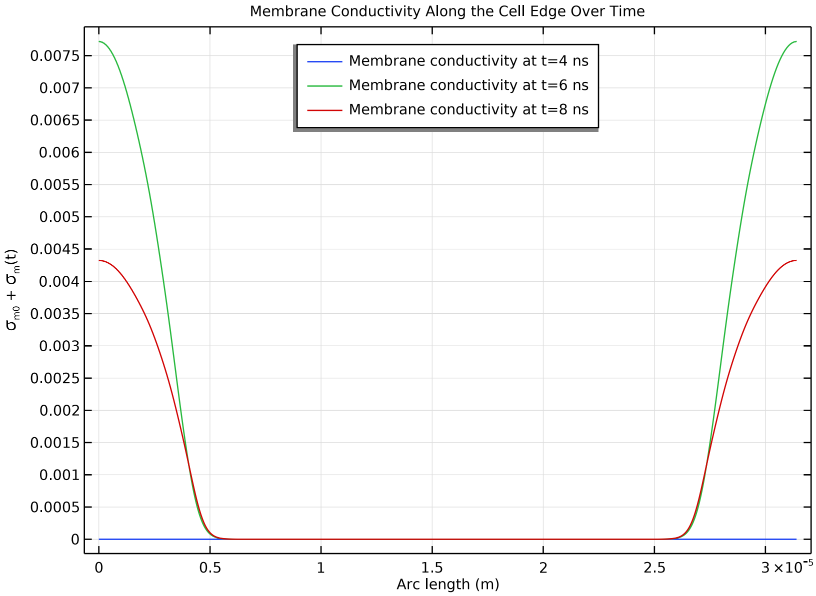
5 Click to expand the **Legends** section. Select the **Show legends** checkbox.

6 From the **Legends** list, choose **Evaluated**.

7 In the **Legend** text field, type Membrane conductivity at t=eval(t,ns,2) ns.

8 In the **Membrane Conductivity Profile** toolbar, click **Plot**.

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



Transmembrane Voltage Profile

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

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

3 Locate the **Title** section. From the **Title type** list, choose **Manual**.

4 In the **Title** text area, type `Transmembrane Voltage Along the Cell Edge Over Time`.

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

6 From the **Time selection** list, choose **Manual**.

7 In the **Time indices (1-201)** text field, type `84 91 96 100 107 112`.

8 Locate the **Plot Settings** section. Select the **x-axis label** checkbox.

9 Select the **y-axis label** checkbox.

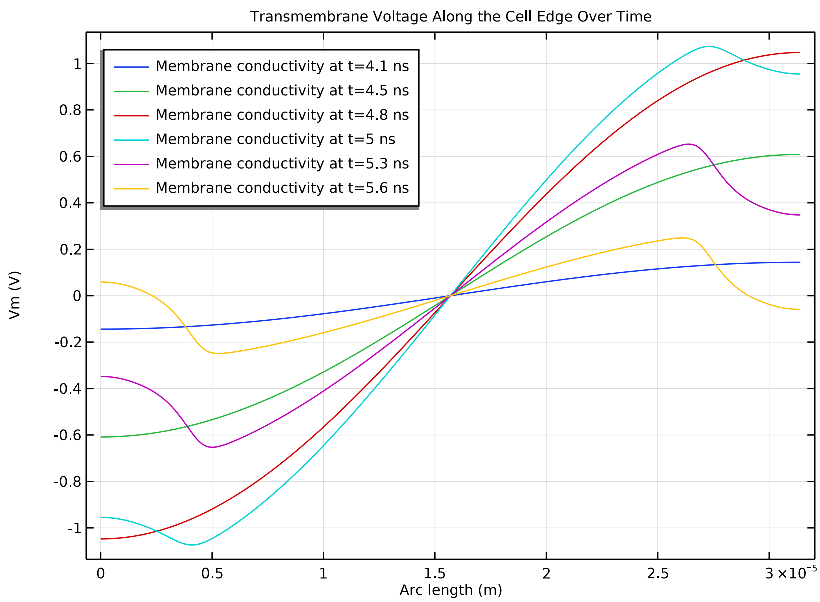
10 In the **x-axis label** text field, type `Arc length (m)`.

11 In the **y-axis label** text field, type `Vm (V)`.

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

Line Graph 1

1 Right-click **Transmembrane Voltage Profile** and choose **Line Graph**.
2 Select Boundaries 12 and 13 only.
3 In the **Settings** window for **Line Graph**, locate the **y-Axis Data** section.
4 In the **Expression** text field, type `Vm`.
5 Locate the **Legends** section. Select the **Show legends** checkbox.
6 From the **Legends** list, choose **Evaluated**.
7 In the **Legend** text field, type `Membrane conductivity at t=eval(t,ns,2) ns`.
8 In the **Transmembrane Voltage Profile** toolbar, click **Plot**.
9 Click the **Zoom Extents** button in the **Graphics** toolbar.



3D Membrane Conductivity

1 In the **Results** toolbar, click **3D Plot Group**.
2 In the **Settings** window for **3D Plot Group**, type `3D Membrane Conductivity` in the **Label** text field.
3 Click to expand the **Title** section. From the **Title type** list, choose **Manual**.
4 In the **Title** text area, type `3D Membrane Conductivity Over Time`.
5 In the **Parameter indicator** text field, type `time=5.0 ns`.

6 Locate the **Data** section. From the **Time (s)** list, choose **5E-9**.

7 Locate the **Color Legend** section. Select the **Show units** checkbox.

Volume 1

1 Right-click **3D Membrane Conductivity** and choose **Volume**.

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

3 In the **Expression** text field, type `sigma_m+sigma_m_t`.

4 Locate the **Coloring and Style** section. From the **Color table** list, choose **HeatCameraLight**.

5 From the **Color table transformation** list, choose **Reverse**.

6 From the **Scale** list, choose **Logarithmic**.

7 In the **3D Membrane Conductivity** toolbar, click **Plot**.

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

9 Click the **Collapse All** button in the **Model Builder** toolbar.