



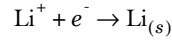
Model created in COMSOL Multiphysics 6.4

# Lithium Plating with Deformation

## Introduction

---

In a lithium metal battery, lithium metal is deposited during charging on the negative electrode according to



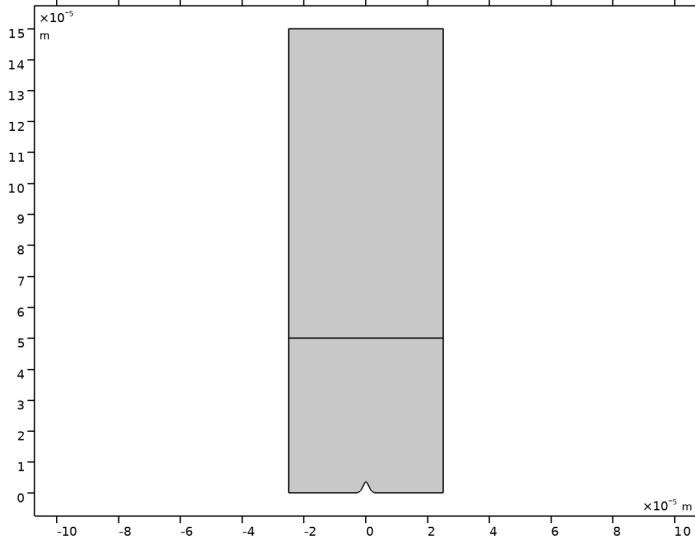
Due to mass transport and ohmic effects in the electrolyte, small initial protrusions on the metal surface will be subjected to accelerated growth during charging, which in the worst case may lead to the formation of dendrites, subsequent internal short circuits, and thermal runaway. This example explores the method of reverse pulse charging for mitigating the formation of dendrites.

The model uses the Lithium-Ion Battery, Deformed Geometry model wizard entry that adds a Lithium-Ion Battery interface along with Deformed Geometry formulation.

## Model Definition

---

Figure 1 shows the model geometry of the lithium-ion battery that consists of two domains (positive porous electrode and separator). The negative lithium metal electrode surface is located at  $y = 0$  mm, with a small protrusion with a height of 40 nm, centered around  $x = 0$ . The materials considered are NMC 622 and  $\text{LiPF}_6$  3:7 EC:EMC for the positive electrode and electrolyte, respectively.



*Figure 1: Model geometry.*

In the first part of the tutorial, a forward current plating model is set up to simulate how a small protrusion of lithium grows during the plating process. A constant electrode current density of 1C is applied on the top boundary of the positive porous electrode, and the resulting growth velocity along the negative lithium electrode surface is used as a boundary condition for the deformed geometry (ALE) time-dependent simulation.

In the second part of the tutorial, a forward and reverse current duty cycle is set up to examine how the protrusion of lithium is attenuated depending on the length of the reverse pulse. The current density for the reverse pulse  $i_{\text{rev}}$  on the top boundary of the positive porous electrode is set to  $-15\text{C}$ . Denoting the forward duty cycle (the relative time spent in forward mode) as  $t_{\text{fwd}}$  (dimensionless) and the overall current density as  $i_{\text{avg}}$ , the forward pulse current density  $i_{\text{fwd}}$  can be calculated as

$$i_{\text{fwd}} = \frac{(i_{\text{avg}} - (1 - t_{\text{fwd}})i_{\text{rev}})}{t_{\text{fwd}}} \quad (1)$$

The total simulated plating time is 0.75 h. The cycle time for a single forward and reverse duty cycle is 180 s. The Load Cycle boundary node is used to set up the switching between the forward and reverse current duty cycles. The applied C rate on the top boundary of the positive porous electrode is appropriately calculated based on the forward and reverse states and respective rates. A parametric sweep is set up in the second part of the tutorial to simulate different lengths of the forward plating duty cycle  $t_{\text{fwd}}$  and examine the lithium electrode surface evolution during the forward and reverse current duty cycle.

This model uses linear elements for all the dependent variables in the Lithium-Ion Battery interface for faster computation times.

## Results and Discussion

Figure 2 shows the lithium electrode surface profile evolution during the forward plating cycle. The initial protrusion grows in size and will result in an uneven surface.

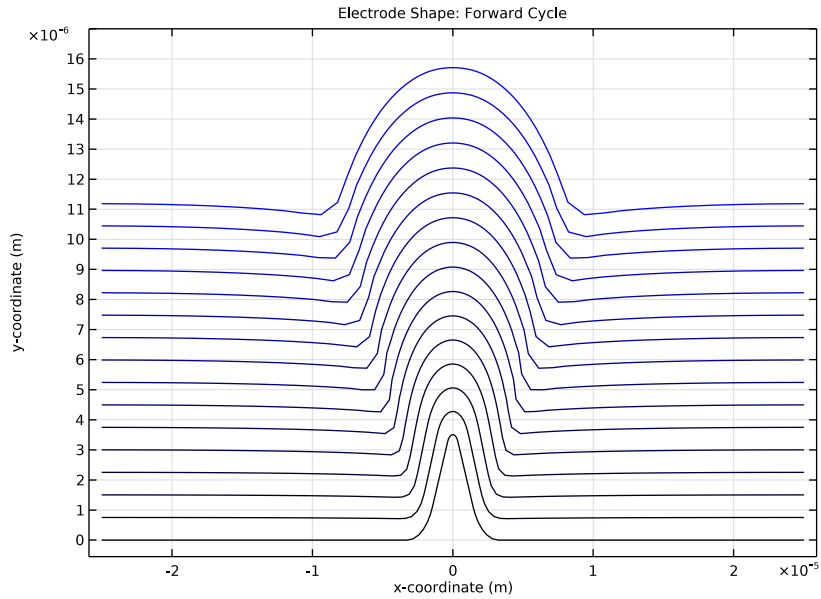


Figure 2: Electrode shape evolution for forward current duty cycle ( $t_{\text{fwd}} = 1$ ).

Figure 3 shows the lithium electrode surface profile evolution during the forward and reverse current duty cycle, for  $t_{\text{fwd}} = 0.9$ . The initial protrusion is now attenuated as the plating proceeds.

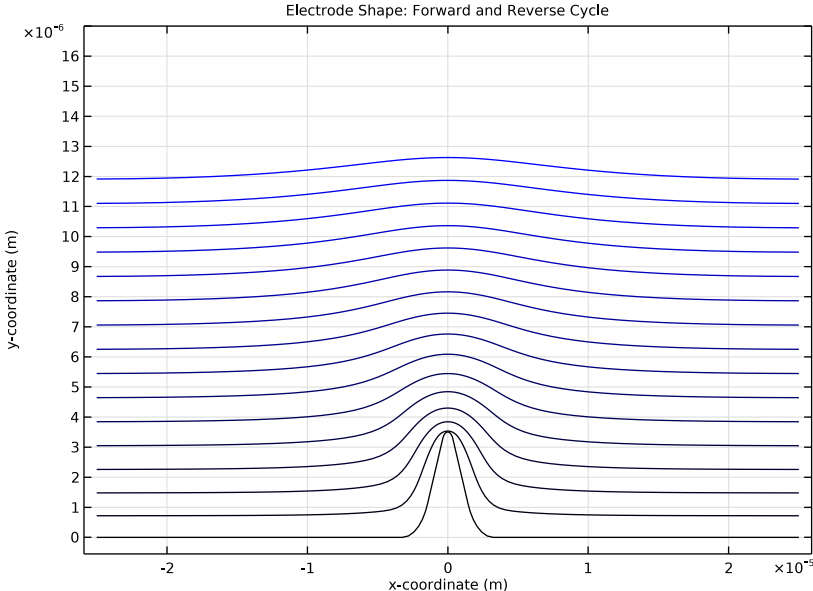


Figure 3: Electrode shape evolution for forward and reverse current duty cycle ( $t_{\text{fwd}} = 0.9$ ).

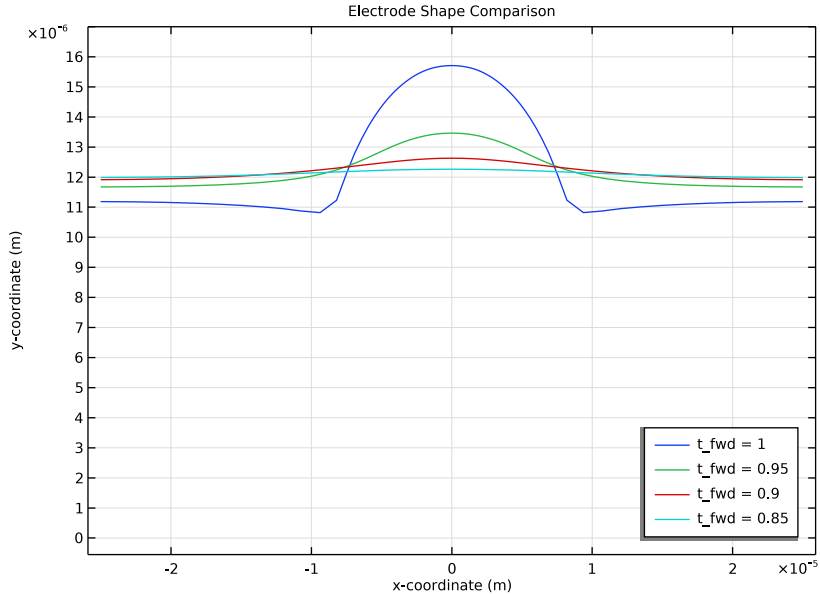


Figure 4: Comparison of final electrode surface profiles for different values of  $t_{\text{fwd}}$ .

Finally, Figure 4 shows a comparison of the lithium electrode surface profiles at the last time step for different values of the forward plating duty cycle  $t_{\text{fwd}}$ .

---

**Application Library path:** Battery\_Design\_Module/Lithium-Ion\_Batteries, \_Aging\_and\_Abuse/li\_plating\_with\_deformation

---


### *Modeling Instructions*

This tutorial consists of two parts. In the first part you will set up a forward current plating model to simulate how a small protrusion of lithium grows during the plating process.




In the second part you will set up a forward and reverse current duty cycle, and examine how the protrusion of lithium is attenuated depending on the length of the reverse pulse.

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

## NEW

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


## MODEL WIZARD

- 1 In the **Model Wizard** window, click  **2D**.
- 2 In the **Select Physics** tree, select **Electrochemistry > Batteries > Lithium-Ion Battery, Deformed Geometry**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces > Time Dependent with Initialization**.
- 6 Click  **Done**.

## GLOBAL DEFINITIONS

### *Parameters I*


Load the model parameters from a text file.

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters I**.
- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 Click  **Load from File**.
- 4 Browse to the model's Application Libraries folder and double-click the file `li_plating_with_deformation_parameters.txt`.

## GEOMETRY I

Set up the geometry that consists of two domains (positive porous electrode and separator). The negative lithium electrode surface is located at  $y = 0$  mm, with a small protrusion with a height of 40 mm, centered at  $x = 0$ .


### *Polygon I (pol1)*

- 1 In the **Geometry** toolbar, click  **Polygon**.
- 2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.
- 3 In the table, enter the following settings:

<b>x (m)</b>	<b>y (m)</b>
0	H_prot
-W_prot/2	0
-W_cell/2	0


<b>x (m)</b>	<b>y (m)</b>
-W_cell/2	H_sep
W_cell/2	H_sep
W_cell/2	0
W_prot/2	0

#### *Rectangle 1 (r1)*




- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
- 3 In the **Width** text field, type W\_cell.
- 4 In the **Height** text field, type H\_pos.
- 5 Locate the **Position** section. In the **x** text field, type -W\_cell/2.
- 6 In the **y** text field, type H\_sep.

#### *Fillet 1 (fil1)*

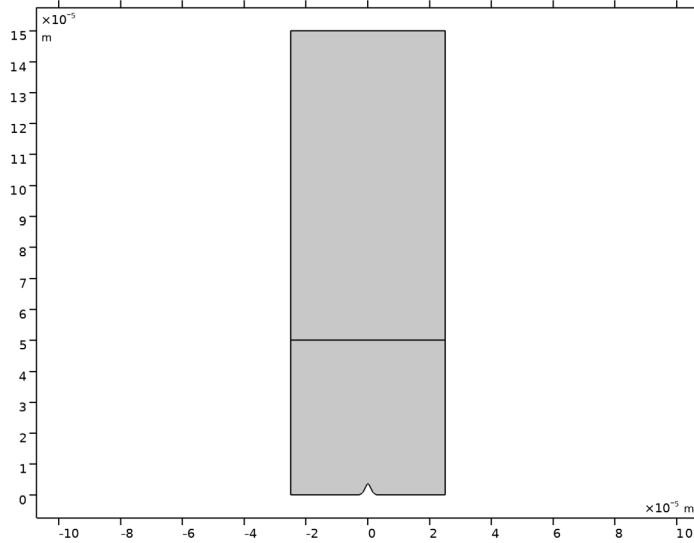
Round the corners by adding fillets.

- 1 In the **Geometry** toolbar, click  **Fillet**.
- 2 On the object **poll**, select Point 1 only.
- 3 In the **Settings** window for **Fillet**, locate the **Radius** section.
- 4 In the **Radius** text field, type H\_prot/10.

#### *Fillet 2 (fil2)*


- 1 In the **Geometry** toolbar, click  **Fillet**.
- 2 On the object **fill**, select Points 3 and 6 only.
- 3 In the **Settings** window for **Fillet**, locate the **Radius** section.
- 4 In the **Radius** text field, type W\_prot/2.
- 5 In the **Geometry** toolbar, click  **Build All**.
- 6 Click the  **Zoom Extents** button in the **Graphics** toolbar.

**7** In the **Model Builder** window, click **Geometry 1**.



#### **ADD MATERIAL**

The model has a lithium metal negative electrode, a NMC 622 positive electrode, and a LiPF6 3:7 EC:EMC electrolyte. Import the materials from the Battery material library.

- 1** In the **Materials** toolbar, click  **Add Material** to open the **Add Material** window.
- 2** Go to the **Add Material** window.
- 3** In the tree, select **Battery > Electrolytes > LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery)**.
- 4** Click the **Add to Component** button in the window toolbar.

#### **ADD MATERIAL**

- 1** Go to the **Add Material** window.
- 2** In the tree, select **Battery > Electrodes > NMC 622, LiNi0.6Mn0.2Co0.2O2 (Positive, Li-ion Battery)**.
- 3** Click the **Add to Component** button in the window toolbar.

#### **ADD MATERIAL**

- 1** Go to the **Add Material** window.
- 2** In the tree, select **Battery > Electrodes > Lithium Metal, Li (Negative, Li-ion Battery)**.
- 3** Click the **Add to Component** button in the window toolbar.

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

## MATERIALS

*NMC 622, LiNi0.6Mn0.2Co0.2O2 (Positive, Li-ion Battery) (mat2)*

1 In the **Model Builder** window, click **NMC 622, LiNi0.6Mn0.2Co0.2O2 (Positive, Li-ion Battery) (mat2)**.

2 Select Domain 2 only.

*Lithium Metal, Li (Negative, Li-ion Battery) (mat3)*

1 In the **Model Builder** window, click **Lithium Metal, Li (Negative, Li-ion Battery) (mat3)**.

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

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

Use a box selection to select all the (lower) boundaries pertaining to the lithium electrode surface, including the protrusion.

4 Select Boundaries 2, 6–8, and 11–13 only.

5 Click  **Create Selection**.

By creating a selection in this way you can conveniently select the same set of boundaries again later on.

6 In the **Create Selection** dialog, type Lithium Electrode Surface in the **Selection name** text field.

7 Click **OK**.

## LITHIUM-ION BATTERY (LIION)

Now start setting up the forward cycle lithium-ion battery model.

*Porous Electrode 1*

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

2 Select Domain 2 only.

3 In the **Settings** window for **Porous Electrode**, locate the **Electrolyte Properties** section.

4 From the **Electrolyte material** list, choose **LiPF6 in 3:7 EC:EMC (Liquid, Li-ion Battery) (mat1)**.

5 Locate the **Electrode Properties** section. In the  $\sigma_s$  text field, type sigmas\_pos.


6 Locate the **Porous Matrix Properties** section. In the  $\epsilon_s$  text field, type eps\_s\_pos.

*Particle Intercalation 1*


1 In the **Model Builder** window, click **Particle Intercalation 1**.

- 2 In the **Settings** window for **Particle Intercalation**, locate the **Particle Transport Properties** section.
- 3 In the  $r_p$  text field, type `rp_pos`.

#### *Electrode Surface I*

- 1 In the **Physics** toolbar, click  **Boundaries** and choose **Electrode Surface**.
- 2 In the **Settings** window for **Electrode Surface**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Lithium Electrode Surface**.

Use a **Dissolving-Depositing Species** to define the growth velocity of the lithium electrode surface.

- 4 Click to expand the **Dissolving-Depositing Species** section. Click  **Add**.
- 5 In the table, enter the following settings:

Species	Density (kg/m <sup>3</sup> )	Molar mass (kg/mol)
Li	rho_Li	M_Li

- 6 Clear the **Solve for surface concentration variables** checkbox.

#### *Electrode Reaction I*

- 1 In the **Model Builder** window, click **Electrode Reaction I**.
- 2 In the **Settings** window for **Electrode Reaction**, locate the **Stoichiometric Coefficients** section.
- 3 In the **Stoichiometric coefficients for dissolving-depositing species:** table, enter the following settings:

Species	Stoichiometric coefficient (I)
Li	1

- 4 In the **Model Builder** window, click **Lithium-Ion Battery (liion)**.
- 5 In the **Settings** window for **Lithium-Ion Battery**, locate the **Cell Settings** section.
- 6 Select the **Define cell state of charge (SOC) and initial charge inventory** checkbox.

#### *SOC and Initial Charge Distribution I*

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Lithium-Ion Battery (liion)** click **SOC and Initial Charge Distribution I**.
- 2 In the **Settings** window for **SOC and Initial Charge Distribution**, locate the **Cell Type** section.
- 3 From the list, choose **Half cell**.

4 Locate the **Initial Cell Charge Distribution** section. In the  $SOC_0$  text field, type 0.

#### *Positive Electrode Domain Selection 1*

1 In the **Model Builder** window, click **Positive Electrode Domain Selection 1**.

2 Select Domain 2 only.

#### *Load Cycle: Forward Only*

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

2 In the **Settings** window for **Load Cycle**, type Load Cycle: Forward Only in the **Label** text field.

3 Select Boundary 5 only.

4 Locate the **Load Type** section. From the list, choose **Galvanostatic**.

5 Locate the **Continuation Conditions** section. Select the **Use elapsed time only** checkbox.

#### *C Rate 1*

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

2 In the **Settings** window for **C Rate**, locate the **C-Rate Multiple** section.

3 In the  $C_{set}$  text field, type  $C_{rate\_avg}$ .

## **GLOBAL DEFINITIONS**

#### *Default Model Inputs*

1 In the **Model Builder** window, under **Global Definitions** click **Default Model Inputs**.

2 In the **Settings** window for **Default Model Inputs**, locate the **Browse Model Inputs** section.

3 In the tree, select **General > Temperature (K) - minput.T**.

4 Find the **Expression for remaining selection** subsection. In the **Temperature** text field, type T.

## **DEFORMED GEOMETRY**

Select the separator domain as the **Deforming Domain**.

#### *Deforming Domain 1*

1 In the **Model Builder** window, expand the **Deformed Geometry** node, then click **Deforming Domain 1**.

2 Select Domain 1 only.

## MULTIPHYSICS

### *Nondeforming Boundary 1 (ndbdg1)*

Set zero normal displacement at the vertical nondeforming boundaries.

- 1 In the **Model Builder** window, expand the **Multiphysics** node, then click **Nondeforming Boundary 1 (ndbdg1)**.
- 2 In the **Settings** window for **Nondeforming Boundary**, locate the **Nondeforming Boundary** section.
- 3 From the **Boundary condition** list, choose **Zero normal displacement**.

## LITHIUM-ION BATTERY (LIION)


Set linear elements for all the dependent variables in the **Lithium-Ion Battery** interface to speed up computation time.

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Lithium-Ion Battery (liion)**.
- 2 In the **Settings** window for **Lithium-Ion Battery**, click to expand the **Discretization** section.
- 3 From the **Electrolyte potential** list, choose **Linear**.
- 4 From the **Electrolyte salt concentration** list, choose **Linear**.
- 5 From the **Electric potential** list, choose **Linear**.

## MESH 1

Modify the mesh as follows to get more mesh elements along the lithium electrode surface.


### *Free Triangular 1*

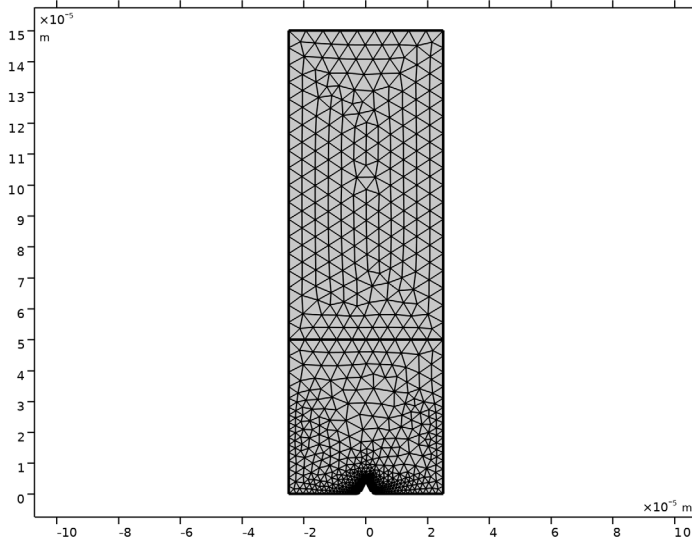
In the **Mesh** toolbar, click  **Free Triangular**.

### *Size 1*

- 1 Right-click **Free Triangular 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
- 3 From the **Geometric entity level** list, choose **Boundary**.
- 4 From the **Selection** list, choose **Lithium Electrode Surface**.
- 5 Locate the **Element Size** section. Click the **Custom** button.
- 6 Locate the **Element Size Parameters** section.
- 7 Select the **Maximum element growth rate** checkbox. In the associated text field, type 1.1.

## Size

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Mesh 1** click **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 From the **Predefined** list, choose **Finer**.
- 4 Click  **Build All**.




## STUDY: FORWARD CYCLE

The forward cycle problem is now ready for solving. Update the time unit and output times before solving.

- 1 In the **Model Builder** window, click **Study 1**.
- 2 In the **Settings** window for **Study**, type Study: Forward Cycle in the **Label** text field.


### Step 2: Time Dependent

- 1 In the **Model Builder** window, expand the **Study: Forward Cycle** node, then 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 **h**.
- 4 In the **Output times** text field, type range(0,0.05/C\_rate\_avg,0.75/C\_rate\_avg).
- 5 In the **Study** toolbar, click  **Compute**.

## RESULTS

Create a line plot for the shape of the lithium electrode surface at different times during the forward cycle (Figure 2) as follows:

### *Electrode Shape: Forward Cycle*

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Electrode Shape: Forward Cycle** in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

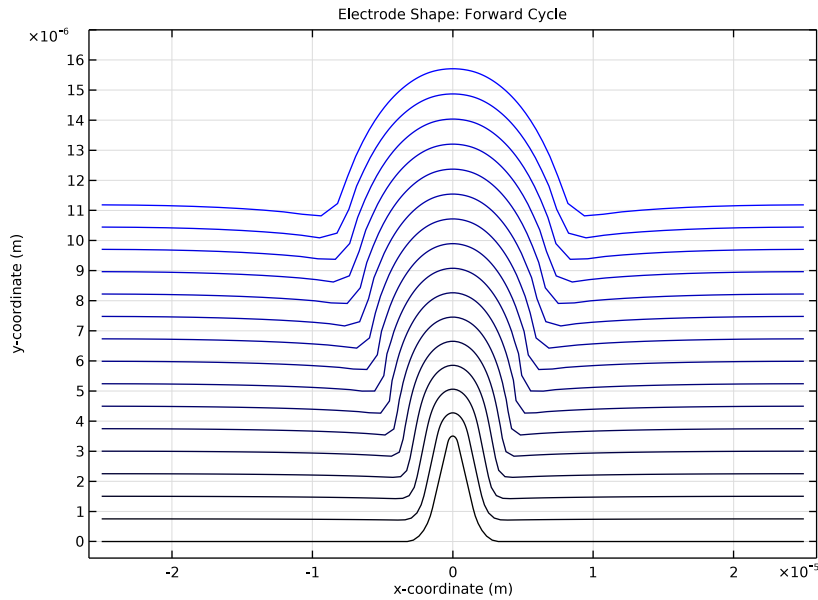
### *Line Graph 1*

- 1 Right-click **Electrode Shape: Forward Cycle** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 From the **Selection** list, choose **Lithium Electrode Surface**.
- 4 Locate the **y-Axis Data** section. In the **Expression** text field, type **y**.
- 5 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.
- 6 In the **Expression** text field, type **x**.
- 7 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Gradient**.
- 8 From the **Top color** list, choose **Blue**.

### *Electrode Shape: Forward Cycle*

- 1 In the **Model Builder** window, click **Electrode Shape: Forward Cycle**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Axis** section.
- 3 Select the **Manual axis limits** checkbox.
- 4 In the **y minimum** text field, type  $-5.5e-7$ .
- 5 In the **y maximum** text field, type  $1.7e-5$ .

6 In the **Electrode Shape: Forward Cycle** toolbar, click  **Plot**.



### LITHIUM-ION BATTERY (LIION)

You have now completed the first part of this tutorial where the applied current included only the forward current duty cycle. We will now set up the second part of the tutorial where the applied current includes both the forward and reverse current duty cycles.

#### *Load Cycle: Forward and Reverse*

- 1 In the **Model Builder** window, right-click **Load Cycle: Forward Only** and choose **Duplicate**.
- 2 In the **Settings** window for **Load Cycle**, type Load Cycle: Forward and Reverse in the **Label** text field.


#### *C Rate I*

- 1 In the **Model Builder** window, expand the **Load Cycle: Forward and Reverse** node, then click **C Rate I**.
- 2 In the **Settings** window for **C Rate**, locate the **C-Rate Multiple** section.
- 3 In the  $C_{\text{set}}$  text field, type  $C_{\text{rate\_fwd}}$ .
- 4 Locate the **Continuation Conditions** section. Select the **Elapsed time** checkbox.
- 5 In the  $t_{\text{max}}$  text field, type  $t_{\text{fwd}}*T_{\text{cycle}}$ .

### Load Cycle: Forward and Reverse



In the **Model Builder** window, click **Load Cycle: Forward and Reverse**.

#### C Rate 2

- 1 In the **Physics** toolbar, click  **Attributes** and choose **C Rate**.
- 2 In the **Settings** window for **C Rate**, locate the **C-Rate Multiple** section.
- 3 In the  $C_{set}$  text field, type  $C\_rate\_rev$ .
- 4 Locate the **Continuation Conditions** section. Select the **Elapsed time** checkbox.
- 5 In the  $t_{max}$  text field, type  $t\_rev * T\_cycle$ .

#### ADD STUDY


The forward and reverse cycle model is now ready for solving. Use a **Parametric Sweep** to simulate different lengths of the forward plating duty cycle.

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

#### STUDY: FORWARD AND REVERSE CYCLE

- 1 In the **Model Builder** window, click **Study 2**.
- 2 In the **Settings** window for **Study**, type Study: Forward and Reverse Cycle in the **Label** text field.


#### Parametric Sweep

- 1 In the **Study** toolbar, click  **Parametric Sweep**.
- 2 In the **Settings** window for **Parametric Sweep**, locate the **Study Settings** section.
- 3 Click **+ Add**.
- 4 In the table, enter the following settings:


Parameter name	Parameter value list	Parameter unit
$t\_fwd$ (Forward current duty cycle)	0.95 0.9 0.85	

#### Step 1: Current Distribution Initialization

Also, disable **Load Cycle: Forward Only** node in this study.

- 1 In the **Model Builder** window, click **Step 1: Current Distribution Initialization**.
- 2 In the **Settings** window for **Current Distribution 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) > Lithium-Ion Battery (liion) > Load Cycle: Forward Only**.
- 5 Click  **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 **Study Settings** section.
- 3 From the **Time unit** list, choose **h**.
- 4 In the **Output times** text field, type  $\text{range}(0, 0.05/C\_rate\_avg, 0.75/C\_rate\_avg)$ .
- 5 Locate the **Physics and Variables Selection** section. Select the **Modify model configuration for study step** checkbox.
- 6 In the tree, select **Component 1 (comp1) > Lithium-Ion Battery (liion) > Load Cycle: Forward Only**.
- 7 Click  **Disable**.
- 8 Click to expand the **Study Extensions** section. Select the **Automatic remeshing** checkbox.

**STUDY: FORWARD CYCLE**


Before solving the forward and reverse cycle study, disable appropriate nodes in the forward cycle study for completeness.

*Step 1: Current Distribution Initialization*

- 1 In the **Model Builder** window, under **Study: Forward Cycle** click **Step 1: Current Distribution Initialization**.
- 2 In the **Settings** window for **Current Distribution 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) > Lithium-Ion Battery (liion) > Load Cycle: Forward and Reverse**.
- 5 Click  **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 Select the **Modify model configuration for study step** checkbox.
- 4 In the tree, select **Component 1 (comp1) > Lithium-Ion Battery (liion) > Load Cycle: Forward and Reverse**.
- 5 Click  **Disable**.

#### **STUDY: FORWARD AND REVERSE CYCLE**

Finally, solve the forward and reverse cycle model.

- 1 In the **Model Builder** window, click **Study: Forward and Reverse Cycle**.
- 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**.

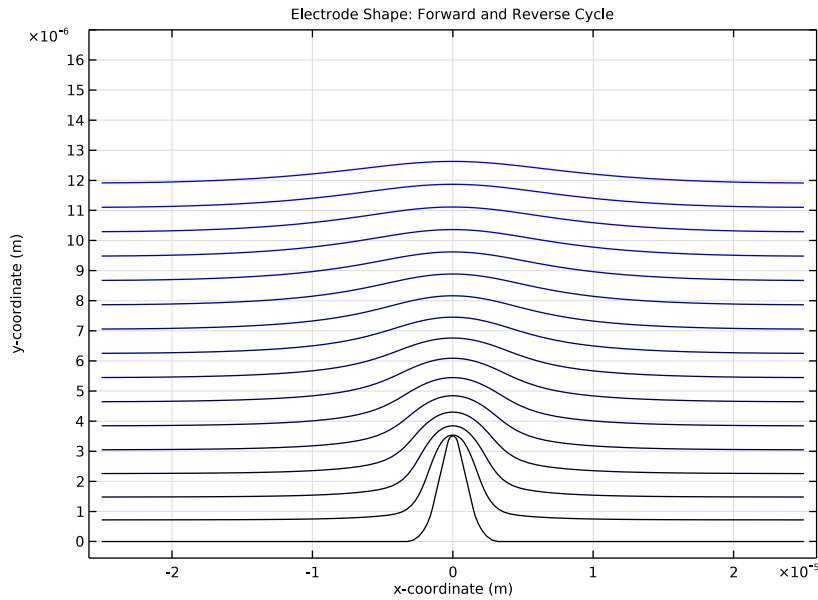
#### **RESULTS**

As before, create a line plot for the shape of the lithium electrode surface at different times during the forward and reverse cycle (Figure 3).

*Electrode Shape: Forward and Reverse Cycle*


- 1 In the **Model Builder** window, right-click **Electrode Shape: Forward Cycle** and choose **Duplicate**.
- 2 In the **Settings** window for **ID Plot Group**, type **Electrode Shape: Forward and Reverse Cycle** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **Study: Forward and Reverse Cycle/ Parametric Solutions 1 (sol6)**.
- 4 From the **Parameter selection (t\_fwd)** list, choose **From list**.
- 5 In the **Parameter values (t\_fwd)** list box, select **0.9**.
- 6 From the **Time selection** list, choose **Interpolated**.
- 7 In the **Times (h)** text field, type range (0, 0.05, 0.75).

**8** In the **Electrode Shape: Forward and Reverse Cycle** toolbar, click  **Plot**.



#### *Electrode Shape Comparison*

Finally, create a line plot for the shape of the lithium electrode surface at the last time step for different values of the forward plating duty cycle (Figure 4).

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type **Electrode Shape Comparison** in the **Label** text field.
- 3 Locate the **Data** section. From the **Dataset** list, choose **None**.
- 4 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

#### *Line Graph 1*

- 1 Right-click **Electrode Shape Comparison** and choose **Line Graph**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study: Forward Cycle/Solution 1 (sol1)**.
- 4 From the **Time selection** list, choose **Last**.
- 5 Locate the **Selection** section. From the **Selection** list, choose **Lithium Electrode Surface**.
- 6 Locate the **y-Axis Data** section. In the **Expression** text field, type **y**.
- 7 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

- 8 In the **Expression** text field, type  $x$ .
- 9 Click to expand the **Legends** section. Select the **Show legends** checkbox.
- 10 From the **Legends** list, choose **Evaluated**.
- 11 In the **Legend** text field, type  $t\_fwd = 1$ .

#### *Line Graph 2*

- 1 Right-click **Line Graph 1** and choose **Duplicate**.
- 2 In the **Settings** window for **Line Graph**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study: Forward and Reverse Cycle/ Parametric Solutions 1 (sol6)**.
- 4 From the **Time selection** list, choose **Last**.
- 5 Locate the **Legends** section. In the **Legend** text field, type  $t\_fwd = eval(t\_fwd)$ .

#### *Electrode Shape Comparison*

- 1 In the **Model Builder** window, click **Electrode Shape Comparison**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Axis** section.
- 3 Select the **Manual axis limits** checkbox.
- 4 In the **y minimum** text field, type  $-5.5e-7$ .
- 5 In the **y maximum** text field, type  $1.7e-5$ .
- 6 Locate the **Legend** section. From the **Position** list, choose **Lower right**.

7 In the **Electrode Shape Comparison** toolbar, click  **Plot**.

