Resonant Spiral Coil in 2D Axisymmetry

Introduction

This application presents an axisymmetric model of a self-resonating, 5-turn spiral coil of copper wire with 1 mm square cross section. The wire is equipped with a thin epoxy varnish insulation layer, tightly wound and mounted on a printed circuit board (PCB). The coil is modeled using the **Magnetic and Electric Fields** interface and the **RLC Coil Group** feature that captures the combination of inductive effects from currents flowing in the azimuthal direction and displacement and conduction currents flowing from one turn to another in the meridional direction. In order to efficiently resolve the small skin depth in the copper a **Boundary Layer** mesh is used. The modeling of thin insulation layers effectively becomes intractable in 3D if traditional volumetric meshing has to be employed. In the 3D variant of this model, Resonant Spiral Coil in 3D, it is done by using a special 3D boundary condition in the **Magnetic and Electric Fields** interface. Here the insulation layers are resolved by a mapped, quadrilateral mesh with a single mesh element through the thickness.

The purpose of the application is to investigate the self-resonance of the coil, that is sweeping the frequency through the regime where the coil reactance transitions from being inductive at frequencies below resonance to being capacitive at frequencies above resonance.

Model Definition

The model geometry consists of the spiral-shaped copper inductor with feed lines, the printed circuit board (PCB), and the surrounding air. Figure 1 shows the copper and PCB domains. The axisymmetric cross section used in the model is indicated. The outer diameter of the coil is about 20 mm.

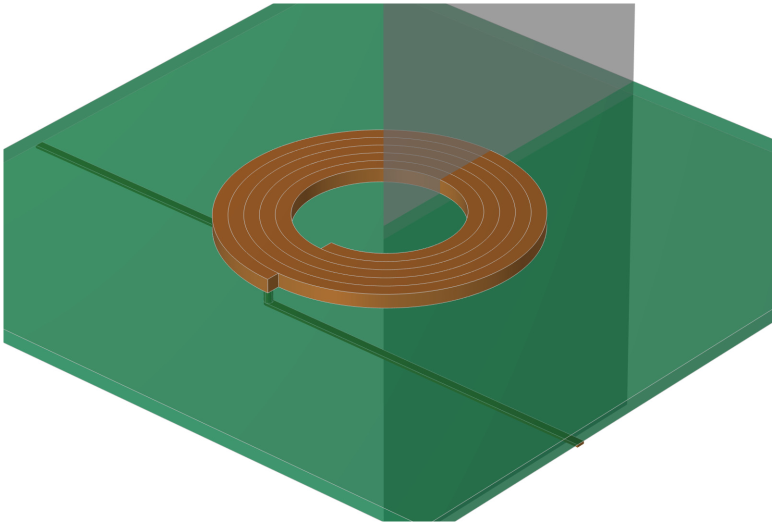


Figure 1: 3D geometry of the spiral coil including the PCB and feed lines on the back side. The feed lines are not included in the axisymmetric model. The axisymmetric cross section used in the model is indicated.

The application uses the Magnetic and Electric Fields interface, taking meridional electric currents and azimuthal magnetically induced currents into account. The formulation solves for the azimuthal component of the magnetic vector potential **A** and the electric potential V. This way the model is inherently gauged. Using the definitions of the electric and magnetic potentials, the system of equations becomes

$$(j\omega\sigma - \omega^2\varepsilon_r\varepsilon_0)\mathbf{A} + \nabla\times(\mu_\mathrm{r}^{-1}\mu_0^{-1}\nabla\times\mathbf{A}) = J_e\mathbf{e}_\varphi$$
$$\mathbf{A} = A_\varphi\mathbf{e}_\varphi$$
$$-\nabla\cdot(-(\sigma + j\omega\varepsilon_r\varepsilon_0)\nabla V) = 0$$
$$V = V(r, z)$$

In the equations, **A** denotes the magnetic vector potential, V the electric scalar potential, J_e the externally generated or prescribed azimuthal current density vector, σ the electrical conductivity, ε_0 the permittivity in vacuum, ε_r the relative permittivity, μ_0 the permeability in vacuum, μ_r the relative permeability, r the radial coordinate and z the axial coordinate. The first equation is Maxwell–Ampère's law for azimuthal currents only as indicated by the second equation. The third equation is the equation of continuity for meridional currents, stating the meridional conservation of charge. The magnetic vector potential and the electric scalar potential are decoupled everywhere save on the boundaries of the domain selection for the **RLC Coil Group** feature where additional equations and state variables impose a, turn to turn, current balance between the flow of meridional currents represented by the scalar electric potential and the flow of azimuthal currents represented by the magnetic vector potential. The externally generated azimuthal current density, J_e is formally zero everywhere though the current balancing is introduced by a similar term not shown in the equations above. The current balancing can be seen as being performed in an azimuthal, turn to turn average sense.

The application uses a 5 mV **Voltage** excitation of he **RLC Coil Group** feature. The feed impedance Z is then obtained from the resulting coil current.

Results

Figure 2 shows the current density (logarithm), the magnetic flux density norm and the electric potential distribution in the coil at the resonance frequency. The skin and proximity effects are pronounced with the current flow concentrated to the edges of the turns.

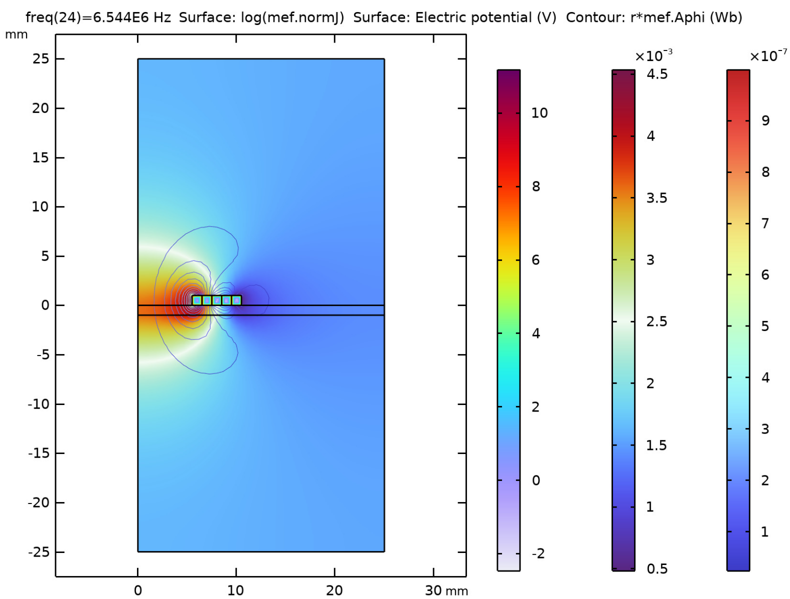


Figure 2: Current density (logarithm), magnetic flux density norm and electric potential distribution in the resonating coil exhibiting pronounced skin and proximity effects.

Figure 3 displays the feed impedance of the coil where the reactance transitions from being inductive at frequencies below resonance to being capacitive at frequencies above resonance.

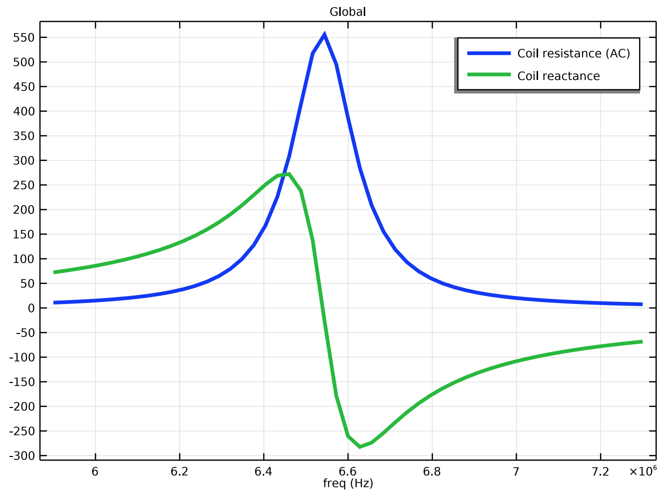


Figure 3: The feed impedance (resistance and reactance) is shown. Note the transition from inductive (positive) to capacitive (negative) reactance at the resonance frequency.

Application Library path: `ACDC_Module/Tutorials,_Coils/resonant_spiral_coil_2daxi`

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>Electromagnetic Fields>Vector Formulations>Magnetic and Electric Fields (mef)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Frequency Domain**.

6 Click **Done**.

Define all the required parameters.

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
`frq`	`6e6[Hz]`	6E6 Hz	
`delta`	`sqrt(2/(mu0_const*2*pi*frq* 5.98e7[S/m]))`	2.657E-5 m	
`gap`	`1e-7[m]`	1E-7 m	

GEOMETRY 1

The following instructions explain how to build the model geometry.

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 Select the **Scale values when changing units** check box.

4 From the **Length unit** list, choose **mm**.

Rectangle 1 (r1)

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

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

3 From the **Base** list, choose **Center**.

4 In the **r** text field, type `6`.

5 In the **z** text field, type `0.5`.

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

Layer name	Thickness (mm)
`Layer 1`	`gap+eps`

7 Select the **Layers to the left** check box.

8 Select the **Layers to the right** check box.

9 Select the **Layers on top** check box.

10 Click **Build Selected**.

Rectangle 2 (r2)

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

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

3 From the **Base** list, choose **Center**.

4 In the **r** text field, type `7`.

5 In the **z** text field, type `0.5`.

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

Layer name	Thickness (mm)
`Layer 1`	`gap+eps`

7 Select the **Layers to the left** check box.

8 Select the **Layers to the right** check box.

9 Select the **Layers on top** check box.

10 Click **Build Selected**.

Rectangle 3 (r3)

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

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

3 From the **Base** list, choose **Center**.

4 In the **r** text field, type `8`.

5 In the **z** text field, type `0.5`.

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

Layer name	Thickness (mm)
`Layer 1`	`gap+eps`

7 Select the **Layers to the left** check box.

8 Select the **Layers to the right** check box.

9 Select the **Layers on top** check box.

10 Click **Build Selected**.

Rectangle 4 (r4)

1 In the **Geometry** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, locate the **Position** section.
3 From the **Base** list, choose **Center**.
4 In the **r** text field, type `9`.
5 In the **z** text field, type `0.5`.
6 Locate the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (mm)
Layer 1	gap+eps

7 Select the **Layers to the left** check box.
8 Select the **Layers to the right** check box.
9 Select the **Layers on top** check box.

Rectangle 5 (r5)

1 In the **Geometry** toolbar, click **Rectangle**.
2 In the **Settings** window for **Rectangle**, locate the **Position** section.
3 From the **Base** list, choose **Center**.
4 In the **r** text field, type `10`.
5 In the **z** text field, type `0.5`.
6 Locate the **Layers** section. In the table, enter the following settings:

Layer name	Thickness (mm)
Layer 1	gap+eps

7 Select the **Layers to the left** check box.
8 Select the **Layers to the right** check box.
9 Select the **Layers on top** check box.
10 Click **Build Selected**.

Rectangle 6 (r6)

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 `25`.
4 Locate the **Position** section. In the **z** text field, type `-1`.

5 Click **Build Selected**.

Rectangle 7 (r7)

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 `25`.

4 In the **Height** text field, type `50`.

5 Locate the **Position** section. In the **z** text field, type `-25`.

6 Click **Build Selected**.

7 In the **Model Builder** window, collapse the **Geometry 1** node.

DEFINITIONS

Copper

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

2 Right-click **Definitions** and choose **Selections>Explicit**.

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

4 Locate the **Input Entities** section. Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `8, 17, 26, 35, 44` in the **Selection** text field.

6 Click **OK**.

Layer Corner Boundaries

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Layer Corner Boundaries` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `4, 6, 10, 12, 13, 15, 19, 21, 22, 24, 28, 30, 31, 33, 37, 39, 40, 42, 46, 48` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Explicit**, locate the **Output Entities** section.

7 From the **Output entities** list, choose **Adjacent boundaries**.

Layer Side Boundaries

1 In the **Definitions** toolbar, click **Explicit**.

2 In the **Settings** window for **Explicit**, type `Layer Side Boundaries` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `5, 7, 9, 11, 14, 16, 18, 20, 23, 25, 27, 29, 32, 34, 36, 38, 41, 43, 45, 47` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Explicit**, locate the **Output Entities** section.

7 From the **Output entities** list, choose **Adjacent boundaries**.

Varnish

1 In the **Definitions** toolbar, click **Explicit**.

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

3 Locate the **Input Entities** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `4-7, 9-16, 18-25, 27-34, 36-43, 45-48` in the **Selection** text field.

5 Click **OK**.

Difference 1

1 In the **Definitions** toolbar, click **Difference**.

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

3 From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Under **Selections to add**, click + **Add**.

5 In the **Add** dialog box, select **Layer Side Boundaries** in the **Selections to add** list.

6 Click **OK**.

7 In the **Settings** window for **Difference**, locate the **Input Entities** section.

8 Under **Selections to subtract**, click + **Add**.

9 In the **Add** dialog box, select **Layer Corner Boundaries** in the **Selections to subtract** list.

10 Click **OK**.

ADD MATERIAL

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

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

3 In the tree, select **Built-in>Air**.

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **AC/DC>FR4 (Circuit Board)**.

6 Click **Add to Component** in the window toolbar.

7 In the tree, select **AC/DC>Copper**.

8 Click **Add to Component** in the window toolbar.

9 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

FR4 (Circuit Board) (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **FR4 (Circuit Board) (mat2)**.

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

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

4 Select Domains 2, 4–7, 9–16, 18–25, 27–34, 36–43, and 45–48 only.

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

Property	Variable	Value	Unit	Property group
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	`0[S/m]`	S/m	Basic

Copper (mat3)

1 In the **Model Builder** window, click **Copper (mat3)**.

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

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

4 In the **Model Builder** window, collapse the **Component 1 (comp1)>Materials** node.

MAGNETIC AND ELECTRIC FIELDS (MEF)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic and Electric Fields (mef)**.

2 In the **Settings** window for **Magnetic and Electric Fields**, click to expand the **Discretization** section.

3 From the **Magnetic vector potential** list, choose **Linear**.

4 From the **Electric potential** list, choose **Linear**.

Magnetic Insulation 1

In the **Model Builder** window, under **Component 1 (comp1)>Magnetic and Electric Fields (mef)** click **Magnetic Insulation 1**.

Electric Insulation 1

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

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

3 From the **Selection** list, choose **All boundaries**.

Ampère's Law 1

1 In the **Physics** toolbar, click **Domains** and choose **Ampère's Law**.

2 In the **Settings** window for **Ampère's Law**, locate the **Domain Selection** section.

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

RLC Coil Group 1

1 In the **Physics** toolbar, click **Domains** and choose **RLC Coil Group**.

2 In the **Settings** window for **RLC Coil Group**, locate the **Domain Selection** section.

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

4 Locate the **RLC Coil Group** section. From the **Coil excitation** list, choose **Voltage**.

5 In the V_{coil} text field, type `5[mV]`.

6 Locate the **Geometry** section. From the **Domain ordering** list, choose **Manual**.

7 In the **Domain list** text field, type `44 35 26 17 8`.

8 In the **Model Builder** window, collapse the **Magnetic and Electric Fields (mef)** node.

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 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 Click the **Custom** button.

4 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `1`.

5 In the **Minimum element size** text field, type `0.3`.

6 In the **Maximum element growth rate** text field, type `1.5`.

7 In the **Curvature factor** text field, type `0.6`.

8 Click **Build Selected**.

Size 1

1 In the **Model Builder** window, right-click **Mesh 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 From the **Selection** list, choose **Copper**.

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

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

7 Select the **Maximum element size** check box. In the associated text field, type 1.

8 Click **Build Selected**.

Edge 1

1 In the **Mesh** toolbar, click **More Generators** and choose **Edge**.

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

3 From the **Selection** list, choose **Layer Corner Boundaries**.

Distribution 1

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

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

3 From the **Selection** list, choose **Layer Corner Boundaries**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type 1.

5 Click **Build Selected**.

Edge 2

1 In the **Mesh** toolbar, click **More Generators** and choose **Edge**.

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

3 From the **Selection** list, choose **Difference 1**.

Distribution 1

1 Right-click **Edge 2** and choose **Distribution**.

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

3 From the **Selection** list, choose **Difference 1**.

4 Locate the **Distribution** section. In the **Number of elements** text field, type 1000.

5 Click **Build Selected**.

Mapped 1

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

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

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

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

5 Click to expand the **Reduce Element Skewness** section. Click to expand the **Control Entities** section. Click **Build Selected**.

Free Triangular 1

1 In the **Model Builder** window, click **Free Triangular 1**.

2 In the **Settings** window for **Free Triangular**, click to expand the **Scale Geometry** section.

3 Click to expand the **Control Entities** section. Click to expand the **Tessellation** section. Click **Build Selected**.

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

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** check box.

Step 1: Frequency Domain

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

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

3 In the **Frequencies** text field, type `range(5900000,28000,7300000)`.

DEFINITIONS

Global Variable Probe 1 (var1)

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, locate the **Expression** section.

3 In the **Expression** text field, type `mef.RCoil_1`.

Global Variable Probe 2 (var2)

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, locate the **Expression** section.

3 In the **Expression** text field, type `mef.XCoil_1`.

4 In the **Table and plot unit** field, type `[Omega]`.

5 In the **Model Builder** window, collapse the **Definitions** node.

STUDY 1

In the **Home** toolbar, click **Compute**.

RESULTS

Study 1/Solution 1 (3) (sol1)

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

2 Right-click **Results>Datasets** and choose **Solution**.

3 Drag and drop **Study 1/Solution 1 (3) (sol1)** below **Study 1/Solution 1 (3) (sol1)**.

Selection

1 Right-click **Study 1/Solution 1 (3) (sol1)** 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 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `24, 31, 38, 45, 52, 59, 66, 73, 80, 87, 94, 101` in the **Selection** text field.

6 Click **OK**.

Study 1/Solution 1 (4) (sol1)

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

Selection

1 Right-click **Study 1/Solution 1 (4) (sol1)** 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 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `8, 17, 26, 35, 44` in the **Selection** text field.

6 Click **OK**.

Study 1/Solution 1 (5) (sol1)

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

Selection

1 Right-click **Study 1/Solution 1 (5) (sol1)** 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 2 only.

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 1/Solution 1 (3) (sol1)**.

4 Click to expand the **Revolution Layers** section.

Revolution 2D 2

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 1/Solution 1 (4) (sol1)**.

4 Locate the **Revolution Layers** section. In the **Start angle** text field, type -90.

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

6 Click to expand the **Advanced** section. Click **Plot**.

Revolution 2D 1

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

2 In the **Settings** window for **Revolution 2D**, click **Plot**.

Revolution 2D 3

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 1/Solution 1 (5) (sol1)**.

4 Locate the **Revolution Layers** section. In the **Start angle** text field, type -90.

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

6 Click **Plot**.

Revolution 2D 4

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

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

3 In the **Start angle** text field, type -90.

4 In the **Revolution angle** text field, type 270.

5 Click **Plot**.

6 In the **Model Builder** window, collapse the **Results>Datasets** node.

J, B and V

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

2 In the **Settings** window for **2D Plot Group**, type `J, B and V` in the **Label** text field.

3 Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **6.544E6**.

Surface 1

1 Right-click **J, B and V** and choose **Surface**.

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

3 In the **Expression** text field, type `log(mef.normJ)`.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Prism** in the tree.

6 Click **OK**.

7 In the **Settings** window for **Surface**, click to expand the **Inherit Style** section.

Selection 1

1 Right-click **Surface 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `8, 17, 26, 35, 44` in the **Selection** text field.

5 Click **OK**.

Surface 2

1 In the **Model Builder** window, right-click **J, B and V** and choose **Surface**.

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

3 Click **Change Color Table**.

4 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.

5 Click **OK**.

Contour 1

1 Right-click **J, B and V** and choose **Contour**.

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

3 In the **Expression** text field, type `r*mef.Aphi`.

4 Locate the **Coloring and Style** section. From the **Contour type** list, choose **Tube**.

5 Select the **Radius scale factor** check box. In the associated text field, type `0.025`.

6 Click to expand the **Quality** section.

Color Expression 1

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

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

3 In the **Expression** text field, type `mef.normB`.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>RainbowLight** in the tree.

6 Click **OK**.

Selection 1

1 In the **Model Builder** window, right-click **Contour 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `1-3` in the **Selection** text field.

5 Click **OK**.

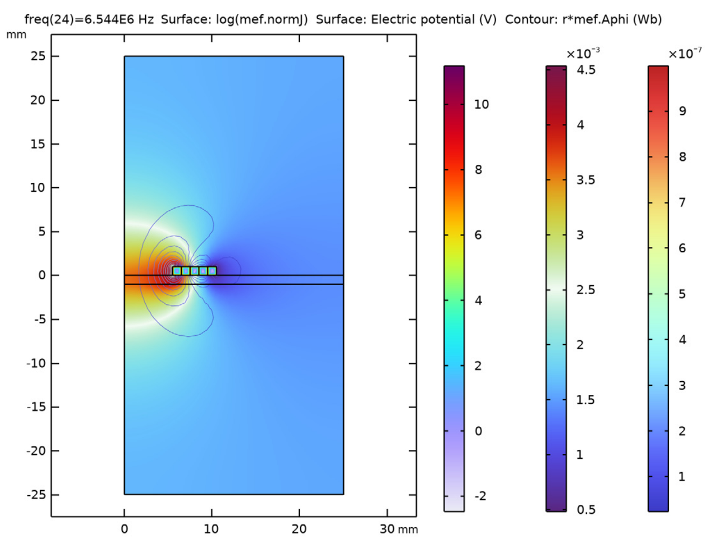
J, B and V

1 In the **Model Builder** window, under **Results** click **J, B and V**.

2 In the **J, B and V** toolbar, click **Plot**.

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

The first Surface shows the norm of the Current density. The second Surface shows the Electric potential.



4 In the **Model Builder** window, collapse the **J, B and V** node.

J, B and V, 3D

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.

2 In the **Settings** window for **3D Plot Group**, type `J, B and V, 3D` in the **Label** text field.

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

Surface 1

1 Right-click **J, B and V, 3D** and choose **Surface**.

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

3 In the **Expression** text field, type `log(mef.normJ)`.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Prism** in the tree.

6 Click **OK**.

Surface 2

1 In the **Model Builder** window, right-click **J, B and V, 3D** and choose **Surface**.

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

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

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>Dipole** in the tree.

6 Click **OK**.

Transparency 1

Right-click **Surface 2** and choose **Transparency**.

Arrow Volume 1

1 In the **Model Builder** window, right-click **J, B and V, 3D** and choose **Arrow Volume**.

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

3 From the **Dataset** list, choose **Revolution 2D 4**.

4 Locate the **Arrow Positioning** section. Find the **x grid points** subsection. In the **Points** text field, type `50`.

5 Find the **y grid points** subsection. From the **Entry method** list, choose **Coordinates**.

6 In the **Coordinates** text field, type `1e-4`.

7 Find the **z grid points** subsection. In the **Points** text field, type `50`.

8 Locate the **Coloring and Style** section. From the **Arrow type** list, choose **Cone**.

9 From the **Arrow length** list, choose **Logarithmic**.

10 In the **Range quotient** text field, type `1000`.

11 From the **Arrow base** list, choose **Center**.

Color Expression 1

1 Right-click **Arrow Volume 1** and choose **Color Expression**.

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

3 In the **Expression** text field, type `mef.normB`.

4 Locate the **Coloring and Style** section. Click **Change Color Table**.

5 In the **Color Table** dialog box, select **Rainbow>PrismDark** in the tree.

6 Click **OK**.

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

8 Clear the **Color legend** check box.

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

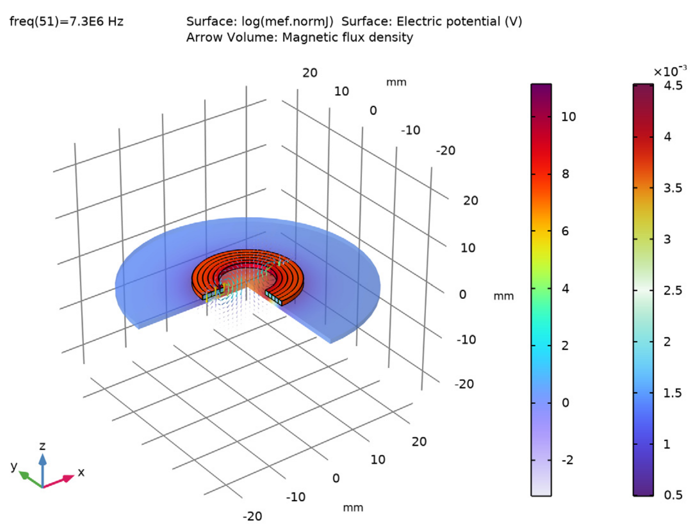
J, B and V, 3D

1 In the **Model Builder** window, under **Results** click **J, B and V, 3D**.

2 In the **J, B and V, 3D** toolbar, click **Plot**.

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

The first Surface shows the norm of the Current density. The second Surface shows the Electric potential. The Arrow Volume shows the Magnetic flux density.



4 In the **Model Builder** window, collapse the **J, B and V, 3D** node.

|nJ|

1 In the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

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

3 Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **6.544E6**.

Line 1

1 Right-click **|nJ|** and choose **Line**.

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

3 In the **Expression** text field, type `abs(V_lm[A/m])/(2*pi*r)`.

4 In the **Unit** field, type `A/mm^2`.

5 Locate the **Coloring and Style** section. From the **Line type** list, choose **Tube**.

6 Select the **Radius scale factor** check box. In the associated text field, type `0.05`.

7 Click **Change Color Table**.

8 In the **Color Table** dialog box, select **Rainbow>RainbowLightClassic** in the tree.

9 Click **OK**.

Selection 1

1 Right-click **Line 1** and choose **Selection**.

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

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `24, 38, 45, 59, 66, 80, 87, 101` in the **Selection** text field.

5 Click **OK**.

Filter 1

1 In the **Model Builder** window, right-click **Line 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 `(s>0.01)&&(s<0.99)`.

|nJ|

1 In the **Model Builder** window, under **Results** click **|nJ|**.

2 In the **|nJ|** toolbar, click **Plot**.

3 In the **Model Builder** window, collapse the **|nJ|** node.

|nJ|, 3D

1 In the **Home** toolbar, click **Add Plot Group** and choose **3D Plot Group**.
2 In the **Settings** window for **3D Plot Group**, type `|nJ|, 3D` in the **Label** text field.
3 Locate the **Data** section. From the **Parameter value (freq (Hz))** list, choose **6.544E6**.

Surface 1

1 Right-click **|nJ|, 3D** and choose **Surface**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `abs(V_lm[A/m])/(2*pi*r)`.
4 In the **Unit** field, type `A/mm^2`.
5 Locate the **Coloring and Style** section. Click **Change Color Table**.
6 In the **Color Table** dialog box, select **Rainbow>RainbowLightClassic** in the tree.
7 Click **OK**.

Filter 1

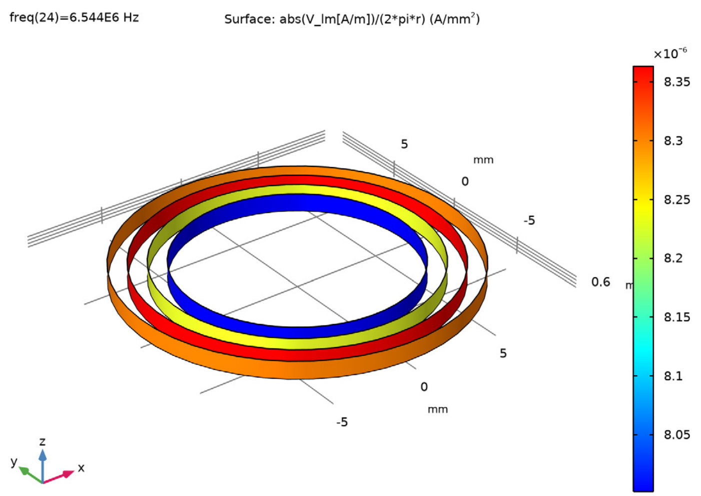
1 Right-click **Surface 1** and choose **Filter**.
2 In the **Settings** window for **Filter**, locate the **Element Selection** section.
3 In the **Logical expression for inclusion** text field, type `(s>0.01)&&(s<0.99)`.

|nJ|, 3D

1 In the **Model Builder** window, collapse the **Results>|nJ|, 3D** node.
2 In the **Model Builder** window, click **|nJ|, 3D**.
3 In the **|nJ|, 3D** toolbar, click **Plot**.

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

The Arrow Volume shows the Magnetic flux density.



Coil Current

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** check box. In the associated text field, type `freq (Hz)`.

5 Clear the **x-axis label** check box.

Global 1

1 Right-click **Coil Current** and choose **Global**.

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

3 In the table, enter the following settings:

Expression	Unit	Description
`abs(mef.ICoil_1)`	A	

Coil Current

In the **Model Builder** window, collapse the **Coil Current** node.

Feed Impedance

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

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

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** check box. In the associated text field, type `freq (Hz)`.

5 Clear the **x-axis label** check box.

Global 1

1 Right-click **Feed Impedance** and choose **Global**.

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

3 In the table, enter the following settings:

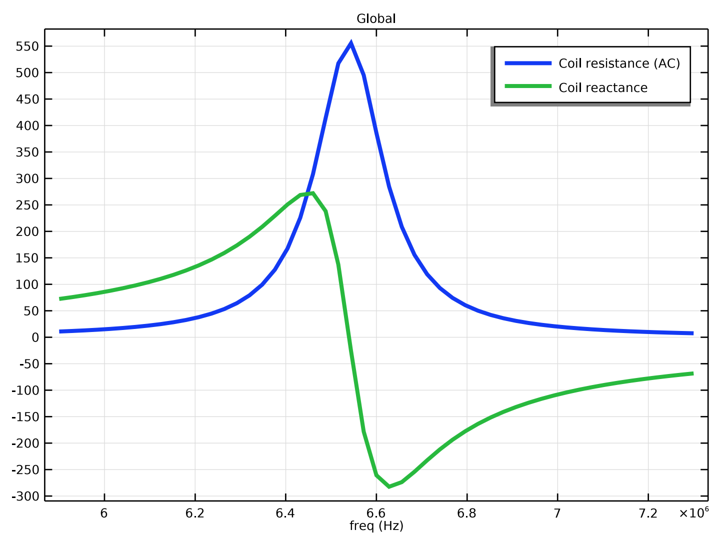
Expression	Unit	Description
`mef.RCoil_1`	Ω	`Coil resistance (AC)`
`mef.XCoil_1`	Ω	`Coil reactance`

4 Click to expand the **Coloring and Style** section. From the **Width** list, choose **3**.

Feed Impedance

1 In the **Model Builder** window, click **Feed Impedance**.

2 In the **Feed Impedance** toolbar, click **Plot**.



3 In the **Model Builder** window, collapse the **Feed Impedance** node.

Probe Plot Group 1

1 In the **Model Builder** window, click **Probe Plot Group 1**.
2 Drag and drop below **Feed Impedance**.
3 In the **Settings** window for **1D Plot Group**, locate the **Legend** section.
4 Clear the **Show legends** check box.

Probe Table Graph 1

1 In the **Model Builder** window, expand the **Probe Plot Group 1** node, then click **Probe Table Graph 1**.
2 In the **Settings** window for **Table Graph**, locate the **Coloring and Style** section.
3 Find the **Line markers** subsection. From the **Marker** list, choose **Cycle**.
4 From the **Positioning** list, choose **In data points**.

RESULTS

Probe Plot Group 1

In the **Model Builder** window, collapse the **Results>Probe Plot Group 1** node.