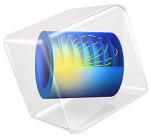


Model created in COMSOL Multiphysics 6.4

Shape Optimization of Coils

Introduction

This model demonstrates how to design a coil geometry using gradient-based shape optimization. The objective is to achieve a uniform magnetic field along the coil axis and a field minimum near the axis ends. The model assumes azimuthal symmetry, but one can use the optimization result as inspiration for a 3D design.

Model Definition

The model is set up with six inner coils and one coil at each end with the opposite current direction. The current in the two outermost coils at each end is also optimized to mimic the effect of having coils with partial turns. The result of the shape optimization is shown in Figure 2, while the initial geometry for this model is shown in Figure 1.

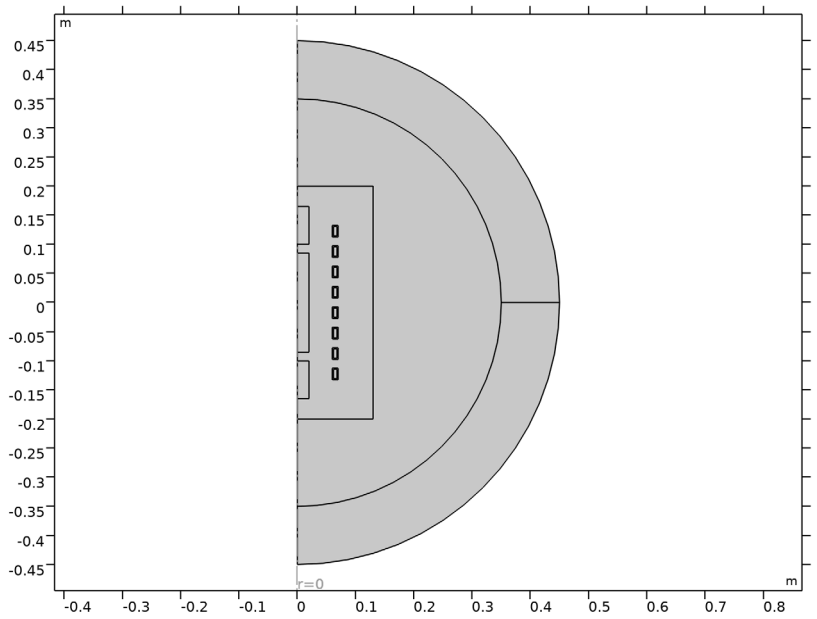


Figure 1: The initial geometry.

The **Transformation** and **Free Shape Domain** features are used to allow the coils to move in the radial direction. There are 8 control variables for the coil positions and one for the current in the outer coils. The IPOPT optimization can solve such problems fast.

The objective function, φ, consists of two terms:

$$\varphi = \varphi_1 + \varphi_2$$

$$\varphi_1 = \int_{\Omega_{\text{inner}}} (|\mathbf{B}| - \mathbf{B}_{\text{avg}})^2 d\Omega / \int_{\Omega_{\text{inner}}} d\Omega$$

$$\mathbf{B}_{\text{avg}} = \int_{\Omega_{\text{inner}}} |\mathbf{B}| d\Omega / \int_{\Omega_{\text{inner}}} d\Omega$$

$$\varphi_2 = \int_{\Omega_{\text{outer}}} |\mathbf{B}| d\Omega / \int_{\Omega_{\text{outer}}} d\Omega$$

The setup of the first objective function is simplified by the use of the **Standard Deviation** feature.

Results and Discussion

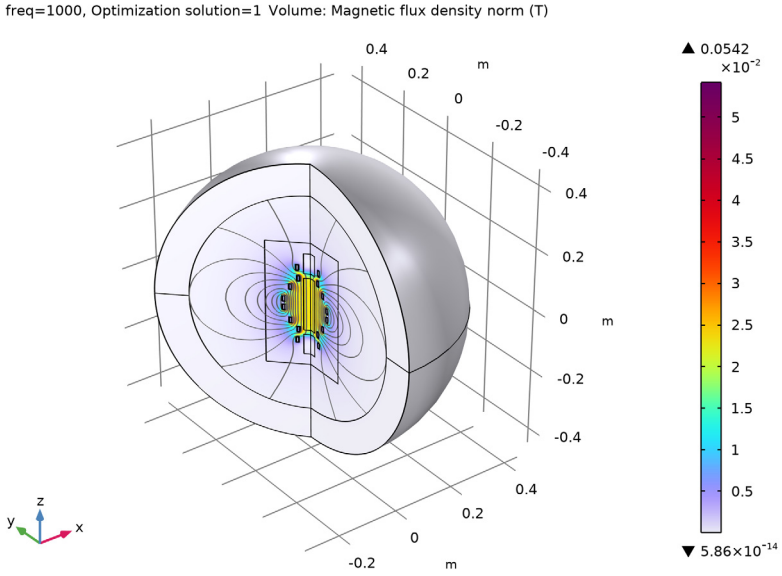


Figure 2: The optimized geometry.

Figure 2 shows the optimized design. The first and second objectives are reduced by around 90% and 50%, respectively. The strength of the magnetic field on the axis is illustrated in Figure 3.

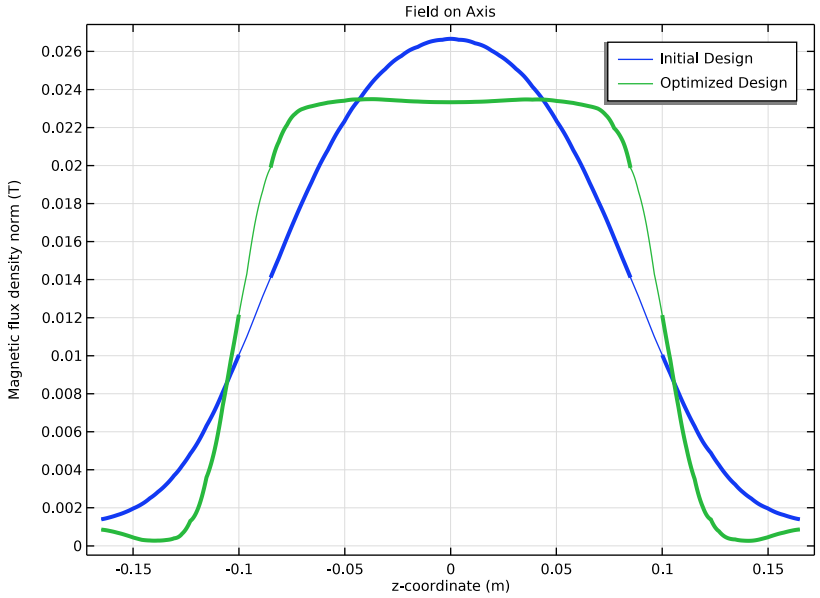


Figure 3: The optimization increases the magnetic field in the middle domain and decreases it in the outer domains.

Notes About the COMSOL Implementation

This model can be constructed in a way that exploits symmetry in the *xy*-plane, leading to a reduction in the computational time.

Application Library path: `ACDC_Module/Electromagnetics_and_Optimization/coil_shape_optimization`

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** > **Magnetic Fields (mf)**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

GEOMETRY 1

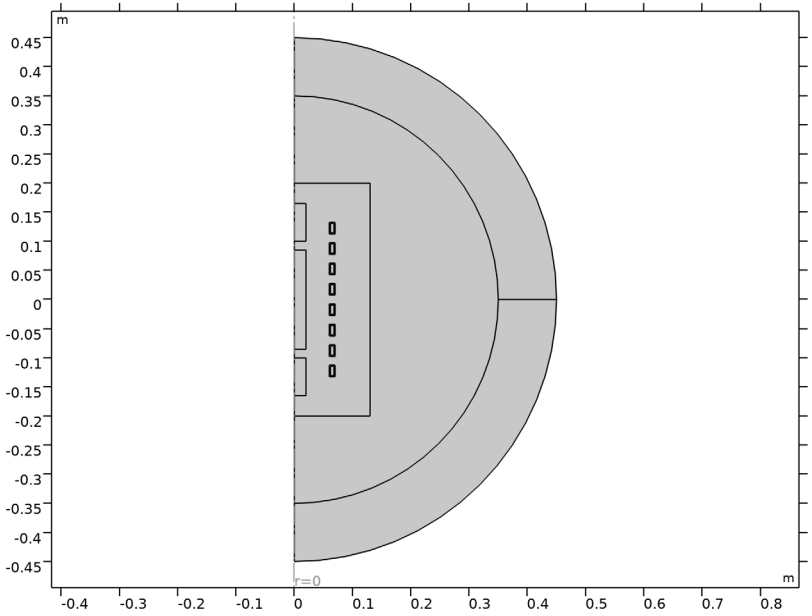
1 In the **Model Builder** window, expand the **Component 1 (comp1)** > **Geometry 1** node.

2 Right-click **Geometry 1** and choose **Insert Sequence**.

3 Browse to the model's Application Libraries folder and double-click the file `coil_shape_optimization_geom_sequence.mph`.

4 In the **Geometry** toolbar, click **Build All**.

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



The geometry should now look like that in Figure 1.

GLOBAL DEFINITIONS

Geometry Parameters

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

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

Parameters 2

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

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
f0	1[kHz]	1000 Hz	Frequency
lastTurns	0.5	0.5	Outer loop current factor
dmax	3[cm]	0.03 m	Maximum coil translation

ADD MATERIAL

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 **Built-in** > **Air**.

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

5 In the tree, select **Built-in** > **Copper**.

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

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

MATERIALS

Copper (mat2)

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

2 From the **Selection** list, choose **Objects to Mirror**.

MAGNETIC FIELDS (MF)

Domain Coil 1

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

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

3 From the **Selection** list, choose **Inner Coils**.

4 Locate the **Coil** section. Select the **Coil group** checkbox.

5 In the I_{coil} text field, type `1[kA]`.

Domain Coil 2

1 Right-click **Domain Coil 1** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Outer Coils 2**.

4 Locate the **Coil** section. In the I_{coil} text field, type `1[kA]*lastTurns`.

In a 2D axisymmetric model, specifying a coil with a fraction of the total current is a way to represent a coil with partial turns. Similarly, specifying a current with the opposite sign represents a coil that is wound in the opposite direction.

Domain Coil 3

1 Right-click **Domain Coil 2** and choose **Duplicate**.

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

3 From the **Selection** list, choose **Outer Coils**.

4 Locate the **Coil** section. In the I_{coil} text field, type `-1[kA]*lastTurns`.

MESH 1

Mapped 1

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

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

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

4 From the **Selection** list, choose **Infinite Domains**.

Distribution 1

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

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

3 From the **Selection** list, choose **Infinite Domain Boundaries**.

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 **Domain**.

4 From the **Selection** list, choose **Deforming Domain**.

5 Locate the **Element Size** section. From the **Predefined** list, choose **Extremely fine**.

Size 2

1 In the **Model Builder** window, right-click **Free Triangular 1** and choose **Size**.

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

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

4 From the **Selection** list, choose **Whole Axis**.

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

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

7 Select the **Maximum element size** checkbox. In the associated text field, type `0.004`.

8 Click  **Build All**.

COMPONENT 1 (COMP1)

Free Shape Domain 1

1 In the **Physics** toolbar, click **Optimization** and choose **Shape Optimization**.

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

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

Transformation 1

1 In the **Shape Optimization** toolbar, click **Transformation**.

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

3 From the **Selection** list, choose **Objects to Mirror**.

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

	Lock	Lower bound (m)	Upper bound (m)
R		`-dmax`	`dmax`
Z		`-coilSpace/4`	`coilSpace/4`

5 Locate the **Scaling** section. From the **Scaling type** list, choose **No scaling**.

DEFINITIONS

Standard Deviation 1 (std1)

1 In the **Definitions** toolbar, click **Physics Utilities** and choose **Standard Deviation**.

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

3 From the **Selection** list, choose **Rectangle 4**.

4 Click **Replace Expression** in the upper-right corner of the **Standard Deviation** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Fields** > **Magnetic** > **comp1.mf.normB - Magnetic flux density norm - T**.

5 Locate the **Quadrature Settings** section. Select the **Compute integral in revolved geometry** checkbox.

Average outer magnetic field

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

2 In the **Settings** window for **Domain Probe**, type `Average outer magnetic field` in the **Label** text field.

3 In the **Variable name** text field, type `Bouter`.

4 Locate the **Source Selection** section. From the **Selection** list, choose **Outer Objective Domain**.

5 Locate the **Expression** section. In the **Expression** text field, type `mf.normB`.

Infinite Element Domain 1 (ie1)

1 In the **Definitions** toolbar, click **Infinite Element Domain**.

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

3 From the **Selection** list, choose **Infinite Domains**.

STUDY 1

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 `f0`.

General Optimization

1 In the **Study** toolbar, click **Optimization** and choose **General Optimization**.

2 In the **Settings** window for **General Optimization**, locate the **Optimization Solver** section.

3 From the **Method** list, choose **GCMMA**.

4 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **comp1.std1 - Standard deviation**.

5 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **comp1.Bouter - Average outer magnetic field - T**.

6 Locate the **Control Variables and Parameters** section. Click **Add**.

Initialize the study to generate a plot for use while solving.

7 In the table, enter the following settings:

Parameter	Initial value	Scale	Lower bound	Upper bound	Unit
lastTurns (Outer loop current factor)	0.5	1	0	1	

8 Click to expand the **Solver Settings** section. Find the **Objective settings** subsection. From the **Objective scaling** list, choose **Initial solution based**.

9 Click to expand the **Output** section. From the **Keep solutions** list, choose **First and last**.

10 From the **Probes** list, choose **None**.

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

12 In the **Settings** window for **Study**, type `Shape Optimization` in the **Label** text field.

13 In the **Study** toolbar, click **Get Initial Value**.

RESULTS

Shape Optimization

The plot shows the displacement. Add an **Annotation** feature to also show the value of the `lastTurns` parameter.

Annotation 1

1 In the **Model Builder** window, right-click **Shape Optimization** and choose **Annotation**.

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

3 In the **Text** text field, type `eval(lastTurns)`.

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

5 From the **Background color** list, choose **Gray**.

SHAPE OPTIMIZATION

General Optimization

1 In the **Model Builder** window, under **Shape Optimization** click **General Optimization**.

2 In the **Settings** window for **General Optimization**, locate the **Output** section.

3 Select the **Plot** checkbox.

4 In the table, enter the following settings:

Plot group	Plot window
Shape Optimization	Graphics

Enable move limits to reduce the risk of inverted elements.

Solver Configurations

In the **Model Builder** window, expand the **Shape Optimization** > **Solver Configurations** node.

Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Shape Optimization** > **Solver Configurations** > **Solution 1 (sol1)** node, then click **Optimization Solver 1**.

2 In the **Settings** window for **Optimization Solver**, locate the **Optimization Solver** section.

3 Select the **Move limits** checkbox.

4 Select the **Maximum number of outer iterations** checkbox. In the associated text field, type `50`.

5 Click **Run**.

RESULTS

Magnetic Flux Density, Revolved Geometry (mf)

1 In the **Magnetic Flux Density, Revolved Geometry (mf)** toolbar, click **Plot**.

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

Field on Axis

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

2 In the **Settings** window for **1D Plot Group**, type `Field on Axis` in the **Label** text field.

3 Locate the **Data** section. From the **Optimization solution** list, choose **First**.

4 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Line Graph 1

1 Right-click **Field on Axis** and choose **Line Graph**.

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

3 From the **Selection** list, choose **Whole Axis**.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

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

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

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

8 In the table, enter the following settings:

Legends
`Initial Design`

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 **Shape Optimization/Solution 1 (sol1)**.

4 From the **Optimization solution** list, choose **Last**.

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

Legends
Optimized Design

Line Graph 3

1 In the **Model Builder** window, right-click **Field on Axis** and choose **Line Graph**.

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

3 From the **Selection** list, choose **Inner Axis**.

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Expression**.

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

6 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Cycle (reset)**.

7 From the **Width** list, choose **3**.

Line Graph 4

1 Right-click **Line Graph 3** and choose **Duplicate**.

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

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

4 From the **Optimization solution** list, choose **Last**.

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

Line Graph 3, Line Graph 4

1 In the **Model Builder** window, under **Results** > **Field on Axis**, Ctrl-click to select **Line Graph 3** and **Line Graph 4**.

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

Line Graph 5

1 In the **Settings** window for **Line Graph**, locate the **Selection** section.

2 From the **Selection** list, choose **Outer Axis**.

Line Graph 6

1 In the **Model Builder** window, click **Line Graph 6**.

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

3 From the **Selection** list, choose **Outer Axis**.

4 In the **Field on Axis** toolbar, click **Plot**.

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

Compute the value of the objective functions before and after optimization.

Evaluation Group 1

In the **Results** toolbar, click **Evaluation Group**.

Global Evaluation 1

1. Right-click **Evaluation Group 1** and choose **Global Evaluation**.
2. In the **Settings** window for **Global Evaluation**, click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **std1 - Standard deviation - T**.
3. Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Definitions** > **Bouter - Average outer magnetic field - T**.
4. In the **Evaluation Group 1** toolbar, click **Evaluate**.

Compute the value of the corners, so that one can construct an interpolation function for 3D verification.

Point Displacements

1. In the **Results** toolbar, click **Evaluation Group**.
2. In the **Settings** window for **Evaluation Group**, type `Point Displacements` in the **Label** text field.
3. Locate the **Data** section. From the **Optimization solution** list, choose **Last**.

Point Evaluation 1

1. Right-click **Point Displacements** and choose **Point Evaluation**.
2. In the **Settings** window for **Point Evaluation**, locate the **Selection** section.
3. From the **Selection** list, choose **Lower left point**.
4. Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
`r`	`m`	`r-coordinate`
`z`	`m`	`z-coordinate`

5. In the **Point Displacements** toolbar, click **Evaluate**.

Geometry Modeling Instructions

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

NEW

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

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **2D Axisymmetric**.

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
R1	45[cm]	0.45 m	Domain radius
infR	10[cm]	0.1 m	Infinite domain radius
coilWidth	1[cm]	0.01 m	Coil width
coilHeight	2[cm]	0.02 m	Coil height
R2	6[cm]	0.06 m	Coil inner radius
nCoil	3	3	Number of coils
coilSpace	1.5[cm]	0.015 m	Coil spacing
objHeight	33[cm]	0.33 m	Objective domain height
objR	2[cm]	0.02 m	Objective domain radius
objOuter	6.5[cm]	0.065 m	Outer objective domain
objSpace	1.5[cm]	0.015 m	Objective domain spacing
deformR	13[cm]	0.13 m	Deforming domain width
deformHeight	40[cm]	0.4 m	Deforming domain height
tTube	2[mm]	0.002 m	Tube thickness
objInner	objHeight-2*objSpace-2*objOuter	0.17 m	Inner objective domain

GEOMETRY 1

Circle 1 (c1)

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

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

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

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

5 In the **Radius** text field, type `R1`.

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

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

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

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 `coilWidth`.

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

5 Locate the **Position** section. In the **r** text field, type `R2`.

6 In the **z** text field, type `-coilSpace*(nCoil+0.5)-(nCoil+1)*coilHeight`.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Rectangle 2 (r2)

1 Right-click **Rectangle 1 (r1)** and choose **Duplicate**.

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

3 In the **Width** text field, type `coilWidth-2*tTube`.

4 In the **Height** text field, type `coilHeight-2*tTube`.

5 Locate the **Position** section. In the **r** text field, type `R2+tTube`.

6 In the **z** text field, type `-coilSpace*(nCoil+0.5)-(nCoil+1)*coilHeight+tTube`.

Difference 1 (dif1)

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

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

3 From the **Objects to add** list, choose **Rectangle 1**.

4 From the **Objects to subtract** list, choose **Rectangle 2**.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

6 Click **Build Selected**.

Lower left point

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

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

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

4 In the **Label** text field, type `Lower left point`.

5 Locate the **Size and Shape** section. In the **Outer radius** text field, type `coilWidth/100`.

6 Locate the **Disk Center** section. In the **r** text field, type `R2`.

7 In the **z** text field, type `-coilSpace*(nCoil+0.5)-(nCoil+1)*coilHeight`.

Copy 1 (copy1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Copy**.

2 In the **Settings** window for **Copy**, locate the **Input** section.

3 From the **Input objects** list, choose **Difference 1**.

4 Locate the **Displacement** section. In the **z** text field, type `coilSpace+coilHeight`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Inner Coils

1 Right-click **Copy 1 (copy1)** and choose **Duplicate**.

2 In the **Settings** window for **Copy**, type `Inner Coils` in the **Label** text field.

3 Locate the **Input** section. Click to select the **Activate Selection** toggle button for **Input objects**.

4 From the **Input objects** list, choose **Copy 1**.

5 Click **Build Selected**.

Array 1 (arr1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

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

3 From the **Input objects** list, choose **Inner Coils**.

4 Locate the **Size** section. In the **z size** text field, type `nCoil-1`.

5 Locate the **Displacement** section. In the **z** text field, type `coilHeight+coilSpace`.

Objects to Mirror

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

2 In the **Settings** window for **Union Selection**, type `Objects to Mirror` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Object**.

4 Locate the **Input Entities** section. Click **Add**.

5 In the **Add** dialog, in the **Selections to add** list, choose **Difference 1**, **Copy 1**, and **Inner Coils**.

6 Click **OK**.

Mirror 1 (mir1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Mirror**.

2 In the **Settings** window for **Mirror**, locate the **Input** section.

3 From the **Input objects** list, choose **Objects to Mirror**.

4 Select the **Keep input objects** checkbox.

5 Locate the **Normal Vector to Line of Reflection** section. In the **r** text field, type `0`.

6 In the **z** text field, type `1`.

Outer Objective Domain

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

2 In the **Settings** window for **Rectangle**, type `Outer Objective Domain` in the **Label** text field.

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

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

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

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

7 Click **Build Selected**.

Outer Axis

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

2 In the **Settings** window for **Box Selection**, type `Outer Axis` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Box Limits** section. In the **r maximum** text field, type `objR*0.1`.

5 In the **z minimum** text field, type `-objHeight/2-objOuter*0.01`.

6 In the **z maximum** text field, type `-objHeight/2+objOuter*1.01`.

7 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.

Mirror 2 (mir2)

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** right-click **Mirror 1 (mir1)** and choose **Duplicate**.

2 In the **Settings** window for **Mirror**, locate the **Input** section.

3 Click to select the **Activate Selection** toggle button for **Input objects**.

4 From the **Input objects** list, choose **Outer Objective Domain**.

Rectangle 4 (r4)

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 `objR`.

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

5 Locate the **Position** section. From the **Base** list, choose **Center**.

6 In the **r** text field, type `objR/2`.

7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

Rectangle 5 (r5)

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 `deformR`.

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

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

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.

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**.

Deforming Domain

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

2 In the **Settings** window for **Difference Selection**, type `Deforming Domain` in the **Label** text field.

3 Locate the **Input Entities** section. Click the **Add** button for **Selections to add**.

4 In the **Add** dialog, select **Rectangle 5** in the **Selections to add** list.

5 Click **OK**.

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

7 Click the **Add** button for **Selections to subtract**.

8 In the **Add** dialog, in the **Selections to subtract** list, choose **Rectangle 1**, **Outer Objective Domain**, and **Rectangle 4**.

9 Click **OK**.

Infinite Domain Boundaries

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

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

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

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

5 Locate the **Size and Shape** section. In the **Outer radius** text field, type `R1*0.99`.

6 In the **Inner radius** text field, type `R1*0.98`.

Infinite Domains

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

2 In the **Settings** window for **Adjacent Selection**, type `Infinite Domains` in the **Label** text field.

3 Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.

4 Locate the **Output Entities** section. From the **Geometric entity level** list, choose **Adjacent domains**.

5 Locate the **Input Entities** section. Click **Add**.

6 In the **Add** dialog, select **Infinite Domain Boundaries** in the **Input selections** list.

7 Click **OK**.

Coil Cavities

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

2 In the **Settings** window for **Box Selection**, type `Coil Cavities` in the **Label** text field.

3 Locate the **Box Limits** section. In the **r minimum** text field, type `R2+tTube*0.5`.

4 In the **r maximum** text field, type `R2+coilWidth-0.5*tTube`.

5 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.

Outer Coils

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

2 In the **Settings** window for **Difference Selection**, type `Outer Coils` in the **Label** text field.

3 Locate the **Input Entities** section. Click the **Add** button for **Selections to add**.

4 In the **Add** dialog, select **Difference 1** in the **Selections to add** list.

5 Click **OK**.

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

7 Click the **Add** button for **Selections to subtract**.

8 In the **Add** dialog, select **Copy 1** in the **Selections to subtract** list.

9 Click **OK**.

Outer Coils 2

1 Right-click **Outer Coils** and choose **Duplicate**.

2 In the **Settings** window for **Difference Selection**, type `Outer Coils 2` in the **Label** text field.

3 Locate the **Input Entities** section. Click **Build Preceding State**.

4 In the **Selections to subtract** list box, select **Copy 1**.

5 Click the **Delete** button for **Selections to subtract**.

6 Click the **Add** button for **Selections to subtract**.

7 In the **Add** dialog, in the **Selections to subtract** list, choose **Inner Coils** and **Outer Coils**.

8 Click **OK**.

Inner Axis

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

2 In the **Settings** window for **Box Selection**, type `Inner Axis` in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Box Limits** section. In the **r maximum** text field, type `objR*0.1`.

5 In the **z minimum** text field, type `-objInner/1.99`.

6 In the **z maximum** text field, type `objInner/1.99`.

7 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.

Whole Axis

1 Right-click **Inner Axis** and choose **Duplicate**.

2 In the **Settings** window for **Box Selection**, type `Whole Axis` in the **Label** text field.

3 Locate the **Box Limits** section. In the **z minimum** text field, type `-objHeight/1.99`.

4 In the **z maximum** text field, type `objHeight/1.99`.

5 Click **Build Selected**.

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

The model geometry is now complete.