Model created in COMSOL Multiphysics 6.4

One-Sided Magnet and Plate

Introduction

One-sided magnets are magnets designed to have both magnetic poles emerging from the same side of the magnet. This results in the magnetic flux being concentrated on one side of the magnet. These kinds of magnets are found in many applications from the common fridge magnet to particle accelerators.

The one-sided flux behavior is obtained by giving the magnet a magnetization that varies in the lateral direction (Ref. 1). As no currents are present, it is possible to model a permanent magnet using a scalar magnetic potential formulation.

This tutorial demonstrates a technique to model a cylindrical one-sided permanent magnet and its influence on a metal plate in close proximity. The plate is modeled using a special technique for thin sheets of high permeability material, which circumvents the difficulty of volumetric meshing of thin structures in 3D.

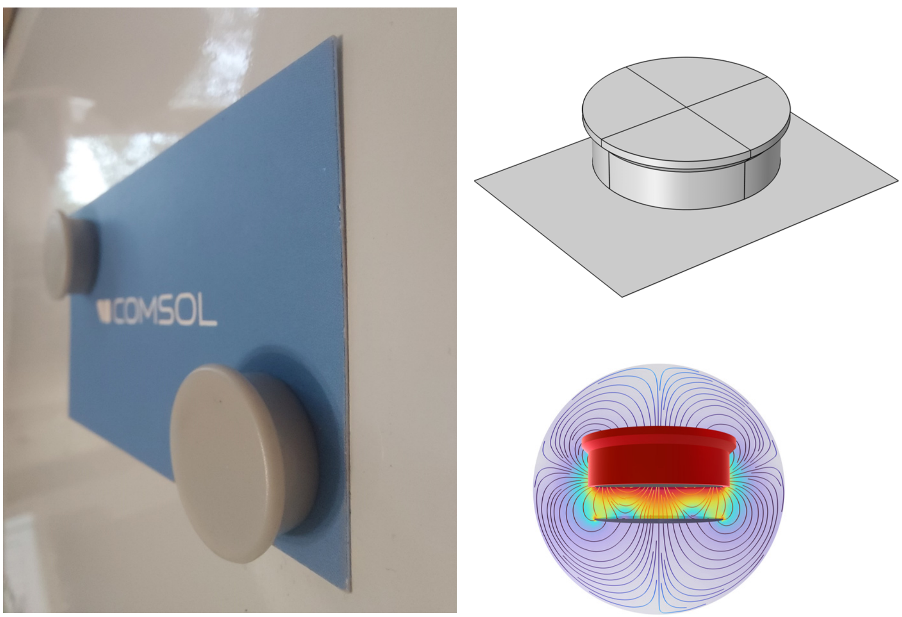


Figure 1: Left, typical use case of a one-sided magnet. Top right, the geometry of the example magnet modeled above a metal plate. Bottom right, a slice of the resultant magnetic flux.

Model Definition

In a current free region, where

$$\nabla \times \mathbf{H} = \mathbf{0} \tag{1}$$

we can define the scalar magnetic potential, V_m, from the relation

$$\mathbf{H} = -\nabla V_m . \tag{2}$$

This is analogous to the definition of the electric potential for static electric fields. We can then use the relation between the magnetic flux density and the magnetic field,

$$\mathbf{B} = \mu_0 \mu_{rec} \mathbf{H} + \mathbf{B}_r , \tag{3}$$

where $\mathbf{B}_r$ is the remanent flux density and μ_{rec} is the recoil permeability. This combines with the relation for magnetic flux conservation,

$$\nabla \cdot \mathbf{B} = 0 , \tag{4}$$

and results in the partial differential equation for the magnetic scalar potential, V_m,

$$-\nabla \cdot (\mu_0 \mu_{rec} \nabla V_m - \mathbf{B}_r) = 0 . \tag{5}$$

ONE-SIDED MAGNET

The characteristic one-sided magnet is formed from a spatially rotating magnetization. Typically, this is a repeating pattern known as a Halbach array. This can be implemented by applying a laterally periodic remanent flux density of

$$\mathbf{B}_r = \begin{bmatrix} \|\mathbf{B}_r\| \sin(kx) \\ 0 \\ \|\mathbf{B}_r\| \cos(kx) \end{bmatrix} \tag{6}$$

resulting in a magnetic flux that only emerges on one side of the magnet.

FORCE CALCULATION

To calculate the force on the plate, we use the surface stress tensor

$$\mathbf{n}_1 T_2 = -\frac{1}{2}(\mathbf{H} \cdot \mathbf{B})\mathbf{n}_1 + (\mathbf{n}_1 \cdot \mathbf{H})\mathbf{B}^T , \tag{7}$$

where $\mathbf{n}_1$ is the boundary normal pointing out from the plate and T_2 is the stress tensor for air. In this model, the $\mathbf{H}$ and $\mathbf{B}$ fields are discontinuous across the plate, which makes it necessary to evaluate the fields on both sides of the plate.

MODELING APPROACH

This tutorial will first construct a textbook uniform magnet to evaluate the force imparted on a nearby metal plate. The metal plate is modeled with a simple linear material with a set relative permeability. The second step will introduce the one-sided magnet to demonstrate the difference in forces on the plate in these different scenarios.

Magnetic saturation effect in the Plate

For many applications, it is important to include magnetic saturation effects. In a final step, the instructions show how to model the plate with a nonlinear magnetic material, soft iron in this case, and plot the magnetic saturation across the plate.

Results and Discussion

First, a comparison shows that the force imparted on a highly permeable metal plate is considerably higher for the case with the one-sided magnetization compared to the case with a uniform magnetization of the same magnitude.

Secondly, the modification of the metal plate material to the more realistic soft iron material shows a small reduction in the imparted force from the magnet as the saturation effects in the plate limit the magnetization of the plate. Figure 2 shows the calculated magnetic flux density and direction for the case of the one-sided magnet near the plate with nonlinear magnetic material. The saturation of the plate is visualized using the differential relative permeability.

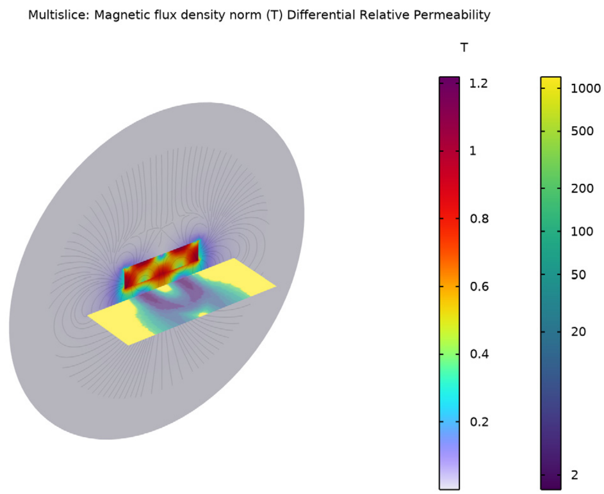


Figure 2: The magnetic flux density and direction is plotted in a cross section of the geometry.The one-sided behavior is apparent, as the flux is negligible on the top of the magnet. The differential relative permeability in the plate is shown on a separate scale. It illustrates that the plate is driven well into magnetic saturation.

Reference

1. H.A. Shute, J.C. Mallinson, D.T. Wilton, and D.J. Mapps, "One-Sided Fluxes in Planar, Cylindrical and Spherical Magnetized Structures," *IEEE Transactions on Magnetics*, vol. 36, no. 2, pp. 440–451, 2000.

Application Library path: `ACDC_Module/Introductory_Magnetostatics/one_sided_magnet`

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 **3D**.

2 In the **Select Physics** tree, select **AC/DC** > **Magnetic Fields, No Currents** > **Magnetic Fields, No Currents (mfnc)**.

3 Click **Add**.

4 Click **Study**.

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

6 Click **Done**.

GEOMETRY 1

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

2 In the **Settings** window for **Geometry**, locate the **Units** section.

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

Sphere 1 (sph1)

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

2 In the **Settings** window for **Sphere**, locate the **Size** section.

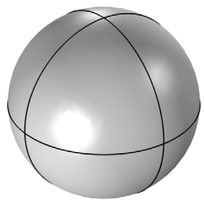
3 In the **Radius** text field, type 40.

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

Layer name	Thickness (mm)
Layer 1	10

5 Locate the **Selections of Resulting Entities** section. Select the **Create layer selections** checkbox.

6 Click **Build Selected**.



Magnet

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

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

3 In the **Radius** text field, type `10`.

4 In the **Height** text field, type `5`.

5 Click **Build Selected**.

6 Click **Highlight Result**.

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

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

9 Click the **Wireframe Rendering** button in the **Graphics** toolbar.

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

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

Work Plane 1 (wp1)

1 In the **Geometry** toolbar, click **Work Plane**.

The plastic cap does not impact the magnetic properties of the simulation but is included for completeness.

2 In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.

3 From the **Plane** list, choose **xz-plane**.

Work Plane 1 (wp1) > Plane Geometry

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

2 In the **Sketch** toolbar, click **Polygon**.

Work Plane 1 (wp1) > Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Width** text field, type 12.

4 In the **Height** text field, type 2.

5 Locate the **Position** section. In the **yw** text field, type 5.

6 Click **Build Selected**.

Work Plane 1 (wp1) > Chamfer 1 (cha1)

1 In the **Work Plane** toolbar, click **Chamfer**.

2 On the object **r1**, select Point 2 only.

3 In the **Settings** window for **Chamfer**, locate the **Distance** section.

4 In the **Distance from vertex** text field, type 1.

5 Click **Build Selected**.

Work Plane 1 (wp1) > Rectangle 2 (r2)

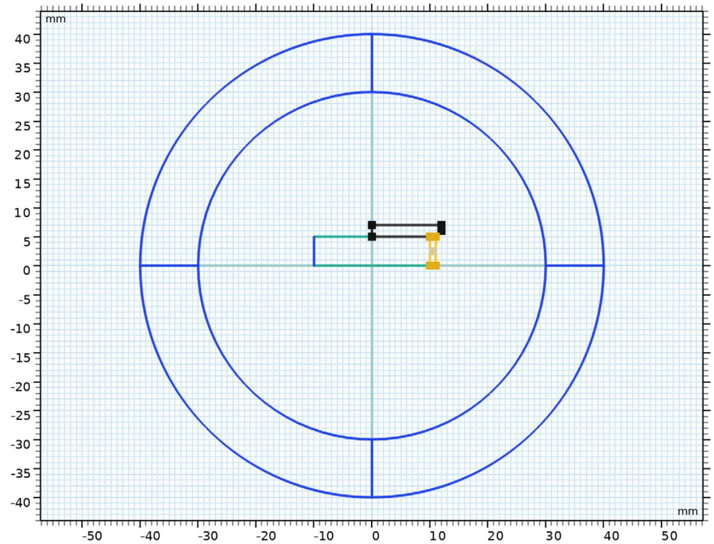
1 In the **Work Plane** toolbar, click **Rectangle**.

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

3 In the **Height** text field, type 5.

4 Locate the **Position** section. In the **xw** text field, type 10.

5 Click **Build Selected**.



The axis-symmetric representation can now be revolved around the z-axis.

Cap

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** right-click **Work Plane 1 (wp1)** and choose **Revolve**.

2 In the **Settings** window for **Revolve**, type `Cap` in the **Label** text field.

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

4 Locate the **Revolution Angles** section. Clear the **Keep original faces** checkbox.

5 Click **Build All Objects**.

Plate

1 In the **Geometry** toolbar, click **Work Plane**.

2 In the **Settings** window for **Work Plane**, type `Plate` in the **Label** text field.

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

4 Locate the **Plane Definition** section. In the **z-coordinate** text field, type `-3`.

5 Click **Go to Plane Geometry**.

Plate (wp2) > Rectangle 1 (r1)

1 In the **Work Plane** toolbar, click **Rectangle**.

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

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

4 Locate the **Size and Shape** section. In the **Width** text field, type 40.

5 In the **Height** text field, type 30.

Sphere 1 (sph1)

In the **Model Builder** window, under **Component 1 (comp1)** > **Geometry 1** right-click **Sphere 1 (sph1)** and choose **Enable**.

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**.

Next, the selections will be defined. These will be used later on when assigning domain features or building the mesh for instance.

Air

1 In the **Model Builder** window, right-click **Geometry 1** and choose **Selections** > **Complement Selection**.

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

3 Click **Add**.

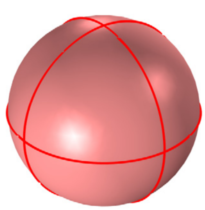
4 In the **Add** dialog, in the **Selections to invert** list, choose **Layer 1 (Sphere 1)**, **Core (Sphere 1)**, **Magnet**, and **Cap**.

5 Click **OK**.

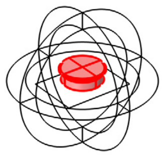
6 In the **Settings** window for **Complement Selection**, type Air in the **Label** text field.

7 Click **Build Selected**.

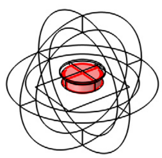
8 Locate the **Input Entities** section. In the **Selections to invert** list box, select **Layer 1 (Sphere 1)**.



9 In the **Selections to invert** list box, select **Cap**.



10 In the **Selections to invert** list box, select **Magnet**.



11 In the **Selections to invert** list, choose **Layer 1 (Sphere 1)** and **Core (Sphere 1)**.

12 Click **Delete**.

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.

MATERIALS

Air (mat1)

1. In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
2. From the **Selection** list, choose **Air**.

ADD MATERIAL

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

2 In the tree, select **Built-in** > **Acrylic plastic**.

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

MATERIALS

Acrylic plastic (mat2)

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

2 From the **Selection** list, choose **Cap**.

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

Property	**Variable**	**Value**	**Unit**	**Property group**
Coefficient of thermal expansion	alpha_iso ; alphaii = alpha_iso, alphaij = 0	1	1/K	Basic

ADD MATERIAL

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

2 In the tree, select **AC/DC** > **Hard Magnetic Materials** > **Sintered NdFeB Grades (Chinese Standard)** > **N28TH (Sintered NdFeB)**.

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

MATERIALS

N28TH (Sintered NdFeB) (mat3)

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

2 From the **Selection** list, choose **Magnet**.

ADD MATERIAL FROM LIBRARY

In the **Home** toolbar, click **Windows** and choose **Add Material from Library**.

ADD MATERIAL

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

2 In the tree, select **AC/DC** > **Soft Iron (Without Losses)**.

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

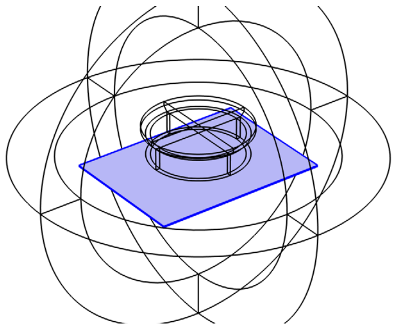
MATERIALS

Soft Iron (Without Losses) (mat4)

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

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

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



This soft iron material has a magnetization response that is dependent on the applied magnetic field represented by the B-H curve in the material parameters. Under weak magnetic fields, it behaves in a linear fashion with an effective relative permeability of approximately 1200. However, under stronger fields, the magnetization begins to saturate.

4 Click to expand the **Material Properties** section. In the **Material properties** tree, select **Basic Properties** > **Relative Permeability**.

5 Click **Add to Material**.

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

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1200	1	Basic

This relative permeability value is chosen to be comparable to the nonlinear material used later in the tutorial.

DEFINITIONS

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 **Layer 1 (Sphere 1)**.

4 Locate the **Geometry** section. From the **Type** list, choose **Spherical**.

Modeling Instructions — Two-Sided Magnet, Linear Plate Material

For the first study, set up the physics for the magnet and the plate. Start with a uniform magnetization across the magnet to model a simple two-sided magnet.

MAGNETIC FIELDS, NO CURRENTS (MFNC)

Two-sided Magnet

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

2 In the **Settings** window for **Magnet**, type `Two-sided Magnet` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Magnet**.

4 Locate the **Magnet** section. From the **Direction method** list, choose **User defined**.

5 Specify the **e** vector as

0	X
0	Y
1	Z

Linear Shielding Alloy

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

2 In the **Settings** window for **Magnetic Shielding**, type `Linear Shielding Alloy` in the **Label** text field.

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

4 Locate the **Magnetic Shielding** section. In the d_s text field, type `0.5[mm]`.

So far the magnetic potential is not constrained anywhere and the solution can only be computed up to a constant. Add a zero magnetic scalar potential to a point on the surface of the air domain to get a reference point enabling the numerical solver to produce a unique solution.

Zero Magnetic Scalar Potential 1

1 In the **Physics** toolbar, click **Points** and choose **Zero Magnetic Scalar Potential**.

2 Select Point 1 only.

Force Calculation 1

1 In the **Physics** toolbar, click **Domains** and choose **Force Calculation**.
2 In the **Settings** window for **Force Calculation**, locate the **Domain Selection** section.
3 From the **Selection** list, choose **Magnet**.
4 Locate the **Force Calculation** section. In the **Force name** text field, type `magnet`.

Boundary Force Calculation 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Boundary Force Calculation**.
2 In the **Settings** window for **Boundary Force Calculation**, locate the **Boundary Selection** section.
3 From the **Selection** list, choose **Plate**.
4 Locate the **Force Calculation** section. In the **Force name** text field, type `plate`.

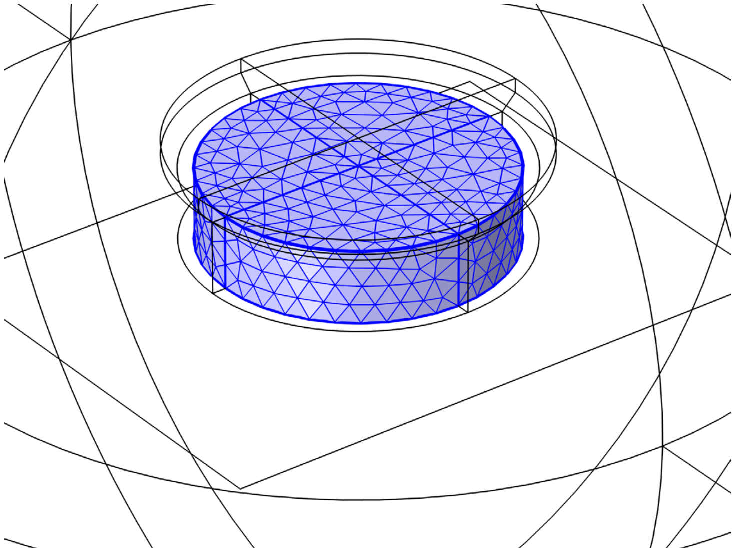
MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Edit Physics-Induced Sequence**.

Free Tetrahedral 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Mesh 1** click **Free Tetrahedral 1**.
2 In the **Settings** window for **Free Tetrahedral**, locate the **Domain Selection** section.
3 From the **Selection** list, choose **Magnet**.

4 Click **Build Selected**.

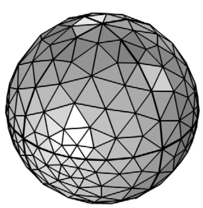


5 In the **Model Builder** window, click **Mesh 1**.

6 In the **Settings** window for **Mesh**, locate the **Sequence Type** section.

7 From the list, choose **Physics-controlled mesh**.

8 Click **Build All**.



TWO-SIDED MAGNET - LINEAR

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

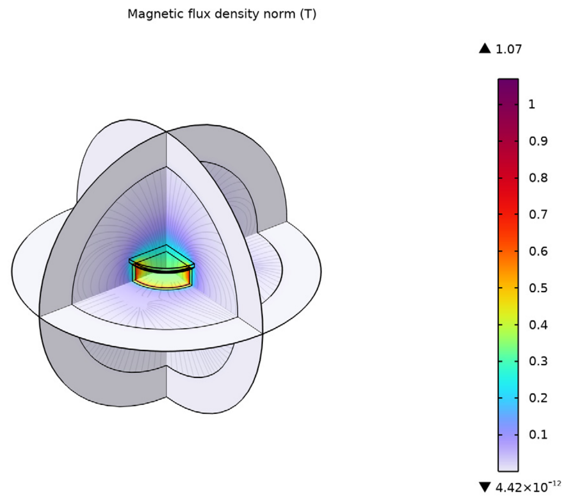
2 In the **Settings** window for **Study**, type `Two-sided Magnet - Linear` in the **Label** text field.

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

RESULTS

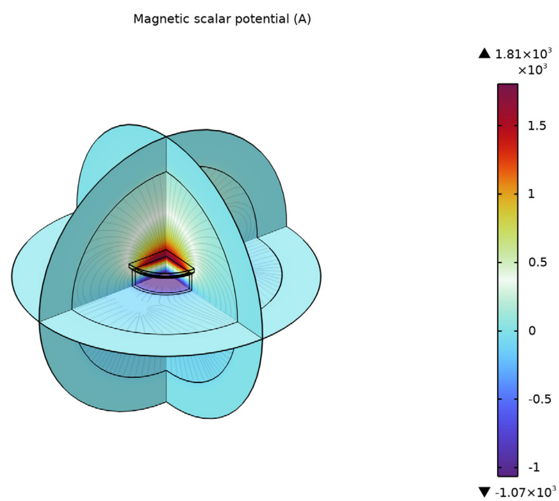
Magnetic Flux Density (mfnc)

In the **Magnetic Flux Density (mfnc)** toolbar, click **Plot**.



Magnetic Scalar Potential (mfnc)

In the **Model Builder** window, click **Magnetic Scalar Potential (mfnc)**.



The default plot displays the magnetic flux density with the corresponding field lines in three planes and the magnetic scalar potential. Alter the default plots to display the magnetic flux on the plate.

Two-sided Magnet - Linear

1 In the **Model Builder** window, under **Results** click **Magnetic Flux Density (mfnc)**.

2 In the **Settings** window for **3D Plot Group**, type `Two-sided Magnet - Linear` in the **Label** text field.

Multislice 1

1 In the **Model Builder** window, expand the **Two-sided Magnet - Linear** node, then click **Multislice 1**.

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

3 Find the **z-planes** subsection. Clear the **Coordinates** text field.

4 Find the **x-planes** subsection. Clear the **Coordinates** text field.

Streamline Multislice 1

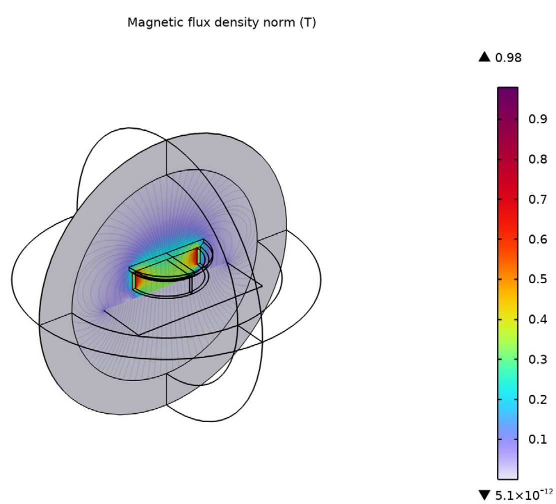
1 In the **Model Builder** window, click **Streamline Multislice 1**.

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

3 Find the **z-planes** subsection. Clear the **Coordinates** text field.

4 Find the **x-planes** subsection. Clear the **Coordinates** text field.

5 In the **Two-sided Magnet - Linear** toolbar, click **Plot**.



Surface 1

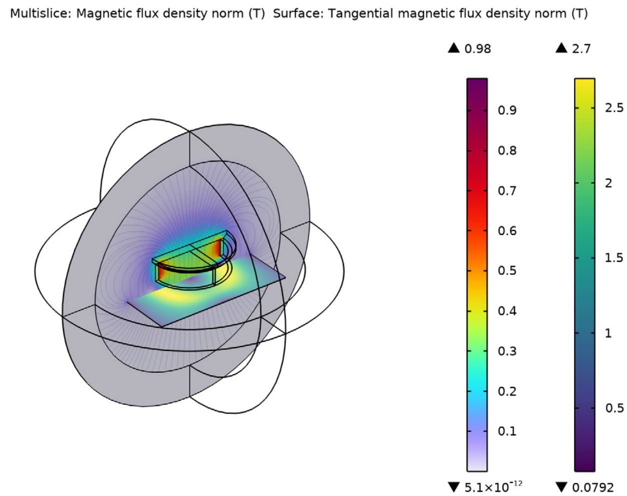
1 In the **Model Builder** window, right-click **Two-sided Magnet - Linear** and choose **Surface**.

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

3 In the **Expression** text field, type `mfnc.normtB`.

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

5 In the **Two-sided Magnet - Linear** toolbar, click **Plot**.



Now evaluate the force on the plate and the magnet.

Resulting Forces

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

2 In the **Settings** window for **Evaluation Group**, type `Resulting Forces` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **None**.

4 Locate the **Transformation** section. Select the **Transpose** checkbox.

Global Evaluation 1

1 Right-click **Resulting Forces** and choose **Global Evaluation**.

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

3 From the **Dataset** list, choose **Two-sided Magnet - Linear/Solution 1 (sol1)**.

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

Expression	Unit	Description
mfnc.Forcez_plate	N	Two-sided Magnet - Linear, Total Force on plate
mfnc.Forcez_magnet	N	Two-sided Magnet - Linear, Total Force on magnet

5 In the **Resulting Forces** toolbar, click **=** **Evaluate**.

The force calculation on the plate for a two-sided magnet yields a result of 9.9 to 10.4 N. The next section implements a Halbach array in the magnet, turning it into a one-sided magnet.

Modeling Instructions — One-Sided Magnet, Linear Plate Material

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
k	pi/10[mm]	314.16 1/m	Wave number in x direction

MAGNETIC FIELDS, NO CURRENTS (MFNC)

One-sided Magnet

1 In the **Model Builder** window, right-click **Two-sided Magnet** and choose **Duplicate**.

2 In the **Settings** window for **Magnet**, type `One-sided Magnet` in the **Label** text field.

3 Locate the **Magnet** section. Specify the **e** vector as

sin(k*x)	x
0	y
cos(k*x)	z

The specified magnetization will result in a magnetic flux that only emerges from the lower side of the magnet.

Add a new study for the one-sided magnet. This way you can keep the results of the previous two-sided magnet simulation.

TWO-SIDED MAGNET - LINEAR

Step 1: Stationary

1 In the **Model Builder** window, under **Two-sided Magnet - Linear** click **Step 1: Stationary**.
2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.
3 Select the **Modify model configuration for study step** checkbox.
4 In the tree, select **Component 1 (comp1)** > **Magnetic Fields, No Currents (mfnc)** > **One-sided Magnet**.
5 Right-click and choose **Disable**.

ADD STUDY

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 **General Studies** > **Stationary**.
4 Click the **Add Study** button in the window toolbar.
5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

ONE-SIDED MAGNET - LINEAR

1 In the **Settings** window for **Study**, type `One-sided Magnet - Linear` in the **Label** text field.
2 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.
3 In the **Study** toolbar, click **Compute**.

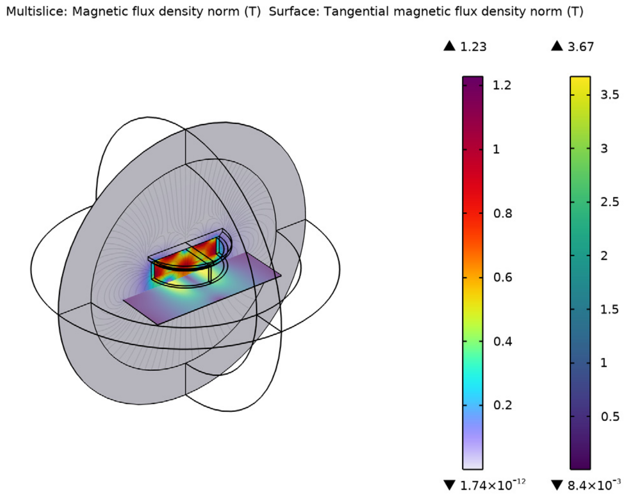
Reuse the modified plot to display the data from the new study.

RESULTS

One-sided Magnet - Linear

1 In the **Model Builder** window, right-click **Two-sided Magnet - Linear** and choose **Duplicate**.
2 In the **Settings** window for **3D Plot Group**, type `One-sided Magnet - Linear` in the **Label** text field.
3 In the **One-sided Magnet - Linear** toolbar, click **Plot**.
4 Locate the **Data** section. From the **Dataset** list, choose **One-sided Magnet - Linear/Solution 2 (sol2)**.

5 In the **One-sided Magnet - Linear** toolbar, click **Plot**.



Global Evaluation 2

1 In the **Model Builder** window, right-click **Resulting Forces** and choose **Global Evaluation**.

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

3 From the **Dataset** list, choose **One-sided Magnet - Linear/Solution 2 (sol2)**.

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

Expression	Unit	Description
mfnc.Forcez_plate	N	One-sided Magnet - Linear, Total Force on plate
mfnc.Forcez_magnet	N	One-sided Magnet - Linear, Total Force on magnet

5 In the **Resulting Forces** toolbar, click **Evaluate**.

The result should be 17.3 N. The one-sidedness of the magnet increases the force by approximately a factor 1.7.

This concludes the part of the application using a linear shielding alloy. The remaining instructions show how to use a nonlinear shielding alloy.

MAGNETIC FIELDS, NO CURRENTS (MFNC)

Nonlinear Shielding Alloy

1 In the **Model Builder** window, right-click **Linear Shielding Alloy** and choose **Duplicate**.
2 In the **Settings** window for **Magnetic Shielding**, type `Nonlinear Shielding Alloy` in the **Label** text field.
3 Locate the **Magnetic Shielding** section. From the **Magnetization model** list, choose **B-H curve**.

Create a new study to store the new set of results produced using the nonlinear plate material.

ADD STUDY

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 **General Studies** > **Stationary**.
4 Click the **Add Study** button in the window toolbar.
5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

ONE-SIDED MAGNET - NONLINEAR

1 In the **Settings** window for **Study**, type `One-sided Magnet - Nonlinear` in the **Label** text field.
2 Locate the **Study Settings** section. Clear the **Generate default plots** checkbox.
3 In the **Study** toolbar, click **Compute**.

ONE-SIDED MAGNET - LINEAR

Step 1: Stationary

1 In the **Model Builder** window, under **One-sided Magnet - Linear** click **Step 1: Stationary**.
2 In the **Settings** window for **Stationary**, locate the **Physics and Variables Selection** section.
3 Select the **Modify model configuration for study step** checkbox.
4 In the tree, select **Component 1 (comp1)** > **Magnetic Fields, No Currents (mfnc)** > **Nonlinear Shielding Alloy**.
5 Right-click and choose **Disable**.

TWO-SIDED MAGNET - LINEAR

1 In the **Model Builder** window, under **Two-sided Magnet - Linear** click **Step 1: Stationary**.

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

3 In the tree, select **Component 1 (comp1)** > **Magnetic Fields, No Currents (mfnc)** > **Nonlinear Shielding Alloy**.

4 Right-click and choose **Disable**.

RESULTS

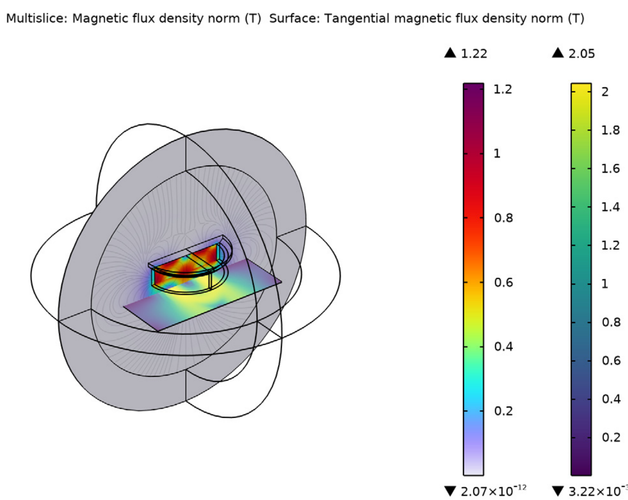
One-sided Magnet - Nonlinear

1 In the **Model Builder** window, right-click **Two-sided Magnet - Linear** and choose **Duplicate**.

2 In the **Settings** window for **3D Plot Group**, type `One-sided Magnet - Nonlinear` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **One-sided Magnet - Nonlinear/ Solution 3 (sol3)**.

4 In the **One-sided Magnet - Nonlinear** toolbar, click **Plot**.



Global Evaluation 3

1 In the **Model Builder** window, right-click **Resulting Forces** and choose **Global Evaluation**.

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

3 From the **Dataset** list, choose **One-sided Magnet - Nonlinear/Solution 3 (sol3)**.

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

Expression	Unit	Description
mfnc.Forcez_plate	N	One-sided Magnet - Nonlinear, Total Force on plate
mfnc.Forcez_magnet	N	One-sided Magnet - Nonlinear, Total Force on magnet

5 In the **Resulting Forces** toolbar, click **Evaluate**.

Resulting Forces

1 In the **Model Builder** window, click **Resulting Forces**.

2 In the **Settings** window for **Evaluation Group**, locate the **Transformation** section.

3 Clear the **Transpose** checkbox.

4 In the **Resulting Forces** toolbar, click **Evaluate**.

Table 1

In the **Resulting Forces** toolbar, click **Copy to Table**.

Resulting Forces

1 In the **Model Builder** window, under **Results** click **Resulting Forces**.

2 Select the **Transpose** checkbox.

3 In the **Resulting Forces** toolbar, click **Evaluate**.

The result should be around 13.4 N. The nonlinear permeability results in a lower field strength in the plate as the material is brought into saturation in localized areas. You can visualize the saturation by plotting the differential permeability (the ratio dB/dH). Add this to a plot overlaying the "Surface: Tangential magnetic flux density" plot.

Differential Relative Permeability

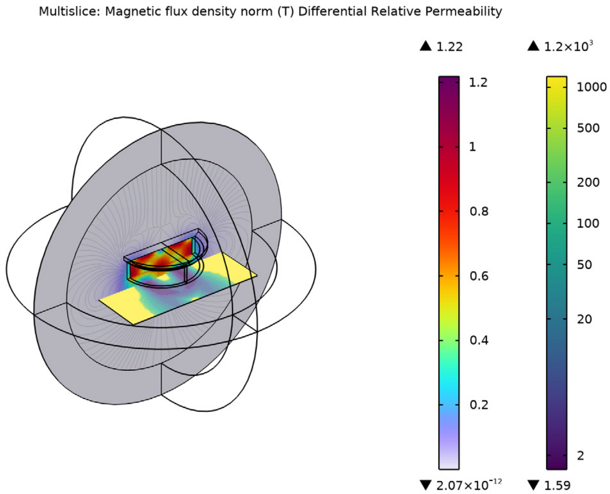
1 In the **Model Builder** window, expand the **One-sided Magnet - Nonlinear** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, type `Differential Relative Permeability` in the **Label** text field.

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

4 Locate the **Expression** section. In the **Expression** text field, type `d(comp1.mat4.BHCurve.BH(mfnc.ms2.normtHshield), mfnc.ms2.normtHshield)/mu0_const`.

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



Here, `comp1.mat4.BHCurve.BHCurve1()` refers to the nonlinear magnetic curve for material 4. Since the operator `d(y,x)` performs the derivative of y with respect to x, the plot shows the differential relative permeability. The maximum value of this differential corresponds to a linear relative permeability of the material of 1200. Where the value of this differential is reduced, the more magnetically saturated the plate material is at that point approaching complete saturation at a value of 1. You can see that the highly saturated regions of the plate correspond to the regions that had the highest tangential magnetic flux density.

Notice that the force calculated using the nonlinear material, `13.4 N`, is still close to the linear approximation of `17.3 N`. This is because the reluctance is dominated by the air gap between the magnet and the plate. Performing the simulation with the plate closer to the magnet will yield a greater force for both the linear and nonlinear cases as well have a larger discrepancy between the two values. This is left as an exercise for the user.

One-sided Magnet - Nonlinear

1 In the **Model Builder** window, click **One-sided Magnet - Nonlinear**.

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

3 Clear the **Show maximum and minimum values** checkbox.

4 Select the **Show units** checkbox.

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

6 In the **One-sided Magnet - Nonlinear** toolbar, click **Plot**.