# 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.

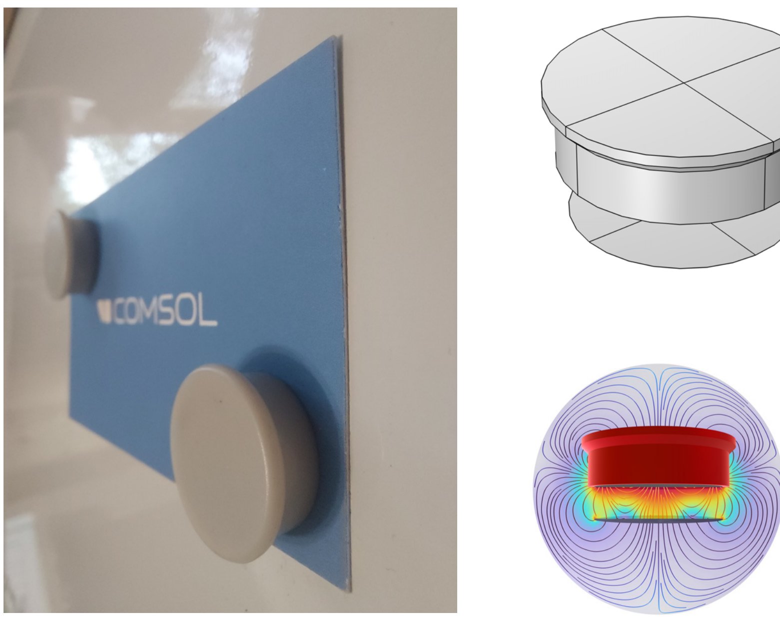



*Figure 1: Left, typical use case of a one-sided magnet. Top right, the geometry of the example magnet modeled above a metal plate. Bottom right, a slice of the resultant magnetic flux.*

## *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 $\mu_{rec}$ 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.

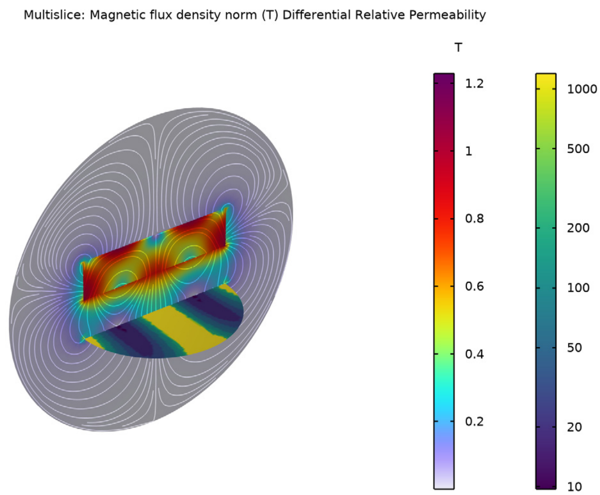



*Figure 2: The magnetic flux density and direction is plotted in a cross section of the geometry.The one-sided behavior is apparent, as the flux is negligible on the top of the magnet. The differential relative permeability in the plate is shown on a separate scale. It illustrates that the plate is driven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

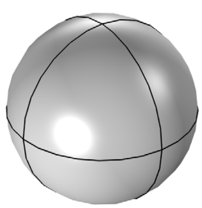
1 In the **Model Wizard** window, click **3D**.
2 In the **Select Physics** tree, select **AC/DC>Magnetic Fields, No Currents>Magnetic Fields, No Currents (mfnc)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Stationary**.
6 Click **Done**.

## 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 20.
4 Click **Build Selected**.



The magnet and the plate are circularly symmetric so the cross-sections can be drawn in 2D and then later revolved into the full 3D structure.

### *Work Plane 1 (wp1)*

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

  This drawing consists of the rectangle that will become the magnet, the plastic cap over the magnet and the line segment is the plate experiencing the magnetic field. Note: 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*

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

### *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 10.

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

5 Click **Build Selected**.

### *Work Plane 1 (wp1)>Line Segment 1 (ls1)*

1 In the **Work Plane** toolbar, click **More Primitives** and choose **Line Segment**.

2 In the **Settings** window for **Line Segment**, locate the **Starting Point** section.

3 From the **Specify** list, choose **Coordinates**.

4 In the **yw** text field, type -5.

5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.

6 In the **xw** text field, type 10.

7 In the **yw** text field, type -5.

### *Plastic cap*

Click **Build Selected**.

### *Work Plane 1 (wp1)>Plane Geometry*

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

### *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 **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 **r2**, 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 3 (r3)*

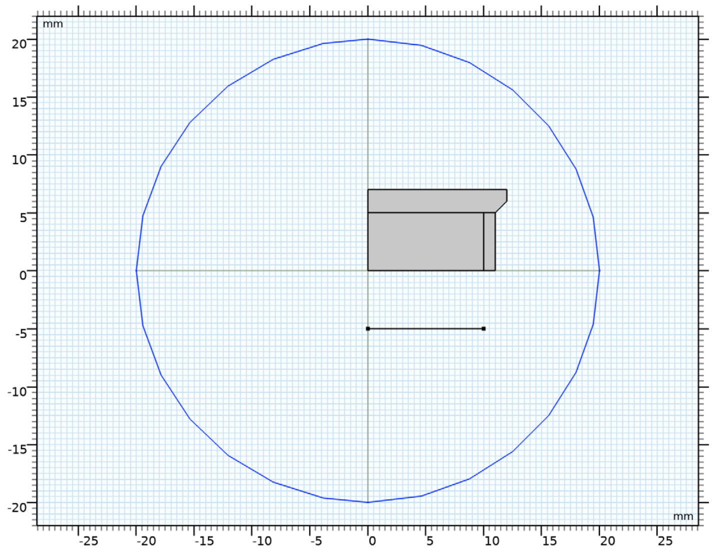
1 In the **Work Plane** toolbar, click **Rectangle**.

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.

*Revolve 1 (rev1)*

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**, locate the **Revolution Angles** section.

3 Clear the **Keep original faces** check box.

4 Click **Build All Objects**.

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

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

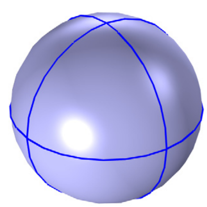
### DEFINITIONS

*Air*

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

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

3 Select Domain 1 only.

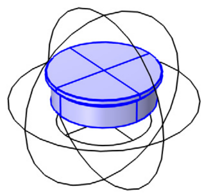


*Cap*

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

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

3 Select Domains 2 and 3 only.

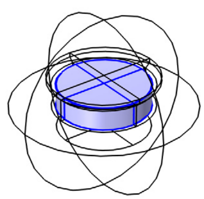


*Magnet*

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

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

3 Select Domain 4 only.



*Plate*

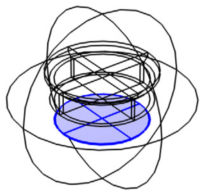
1 In the **Definitions** toolbar, click **Explicit**.

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

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

4 In the **Label** text field, type `Plate`.

**5** Select Boundaries 17, 18, 33, and 38 only.



### 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.

### 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 **Add to Component** 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** |
|---|---|---|---|---|
| Relative permeability | mur_iso ; murii = mur_iso, murij = 0 | 1 | 1 | 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 **Add to Component** in the window toolbar.

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

### 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**.

#### *Linear Shielding Alloy*

**1** In the **Model Builder** window, right-click **Materials** and choose **Blank Material**.

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

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

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

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

**6** Click **Add to Material**.

**7** 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.

## *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)

*Magnet 1*

1. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Magnetic Fields, No Currents (mfnc)** and choose **Magnet**.
2. In the **Settings** window for **Magnet**, locate the **Domain Selection** section.
3. 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 |

*Magnetic Shielding 1*

1. In the **Physics** toolbar, click **Boundaries** and choose **Magnetic Shielding**.
2. In the **Settings** window for **Magnetic Shielding**, locate the **Boundary Selection** section.
3. 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.

For a more accurate result, the mesh can be modified to have more detail near the objects of interest, in this case that is the magnet and the plate.

## MESH 1

*Free Tetrahedral 1*

1 In the **Mesh** toolbar, click **Free Tetrahedral**.

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

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

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

*Size 1*

1 Right-click **Free Tetrahedral 1** and choose **Size**.

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

3 From the **Predefined** list, choose **Extremely fine**.

4 In the **Model Builder** window, right-click **Mesh 1** and choose **Size**.

*Size 1*

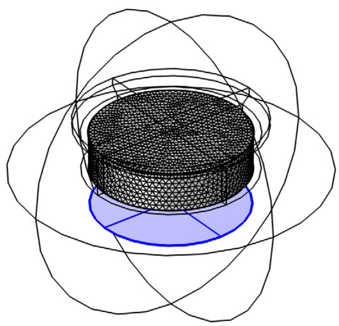
1 In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.

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

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

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

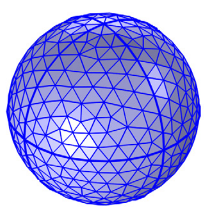
**5** Click **Build Selected**.



*Free Tetrahedral 2*

**1** In the **Mesh** toolbar, click **Free Tetrahedral**.

**2** In the **Settings** window for **Free Tetrahedral**, click **Build All**.



### TWO-SIDED MAGNET - LINEAR

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

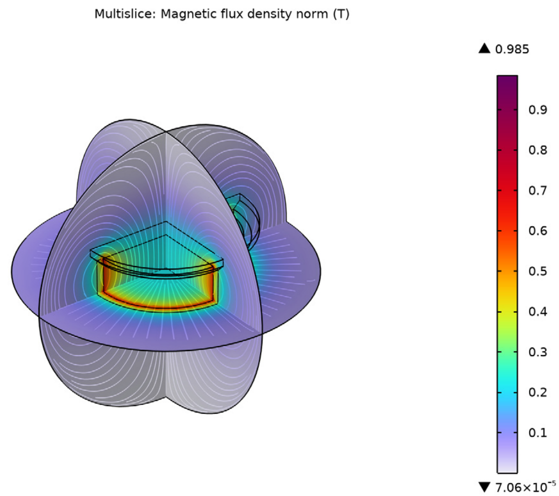
**2** In the **Settings** window for **Study**, type `Two-sided Magnet - Linear` in the **Label** text field.

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

## RESULTS

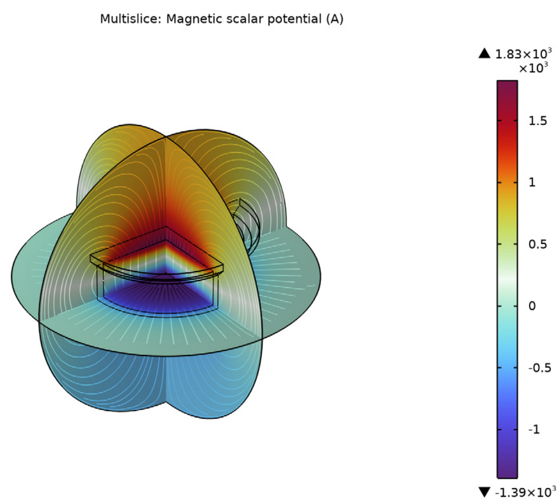
### *Magnetic Flux Density Norm (mfnc)*

In the **Magnetic Flux Density Norm (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 Norm (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*

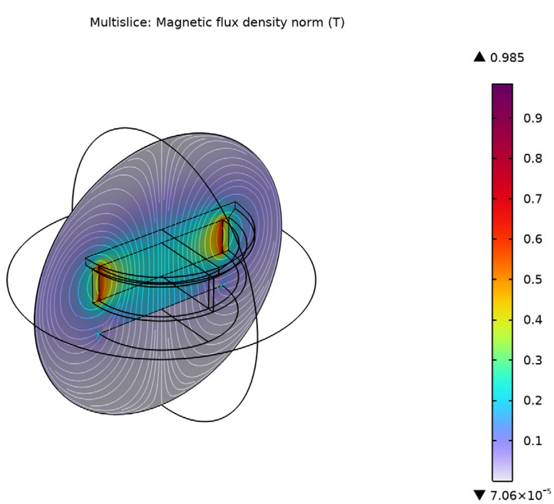
1 In the **Model Builder** window, click **Streamline Multislice 1**.

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**.

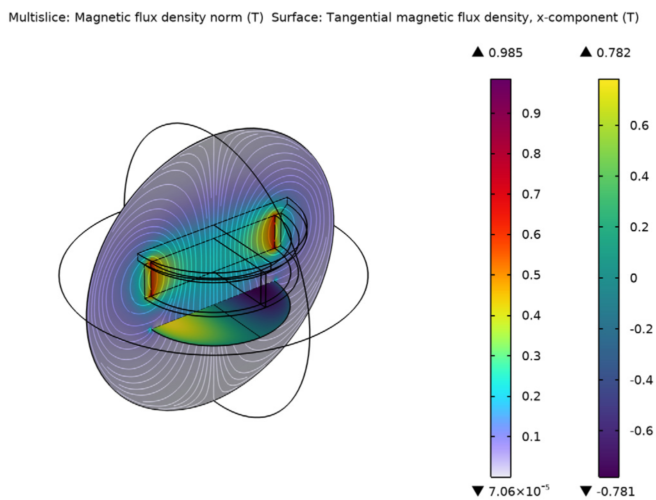
2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields, No Currents>Magnetic>Tangential magnetic flux density - T>mfnc.tBx - Tangential magnetic flux density, x-component**.

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

4 In the **Color Table** dialog box, select **Linear>Viridis** in the tree.

5 Click **OK**.

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




To evaluate the force on the plate, you can integrate the surface stress tensor as shown in Equation 7. Since the plate is modeled using a boundary, the integral must be evaluated on both sides of the plate.

All surfaces have an *up* and a *down* side. The physics interface defines variables for the surface stress tensor on the up and downside of the boundaries, for example, `mfnc.unTmz` and `mfnc.dnTmz` for the $z$-component of the magnetic surface stress tensor. To integrate the stress tensor on both sides of the plate it is sufficient to integrate the sum of the two quantities on the boundary.

### *Surface Integration 1*

**1** In the **Results** toolbar, click 8.85 e-12 **More Derived Values** and choose **Integration>Surface Integration**.

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

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

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

| Expression | Unit | Description |
|---|---|---|
| mfnc.unTmz+mfnc.dnTmz | N | |

**5** Click **Evaluate**.

The force calculation on the plate for a two-sided magnet yields a result of 0.9 to 1.2 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)

### *Magnet 2*

**1** In the **Model Builder** window, under **Component 1 (comp1)>Magnetic Fields, No Currents (mfnc)** right-click **Magnet 1** and choose **Duplicate**.

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

3 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.

## 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 **Add Study** 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 **Model Builder** window, click **Study 2**.

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

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

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

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

## RESULTS

### *One-sided Magnet - Linear*

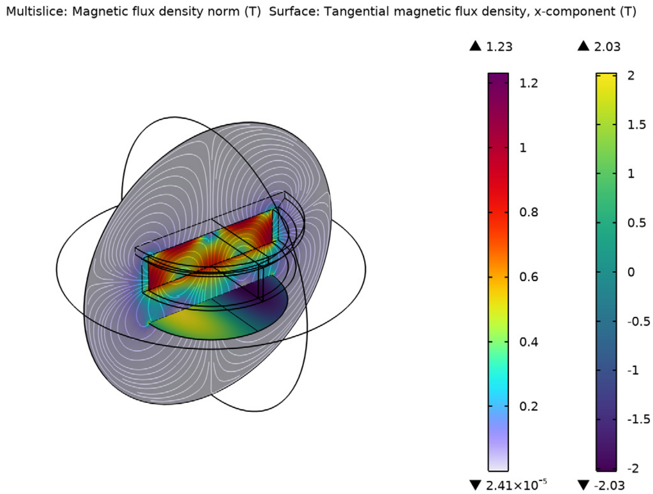
1 In the **Model Builder** window, right-click **Two-sided Magnet - Linear** and choose **Duplicate**.

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**.




*Surface Integration 1*

1. In the **Model Builder** window, under **Results>Derived Values** click **Surface Integration 1**.
2. In the **Settings** window for **Surface Integration**, locate the **Data** section.
3. From the **Dataset** list, choose **One-sided Magnet - Linear/Solution 2 (sol2)**.
4. Click **Evaluate**.

### TABLE 1

1. Go to the **Table 1** window.

   The result should be 4 N. The one-sidedness of the magnet increases the force by approximately a factor 4.

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

## *Modeling Instructions — One-sided Magnet, Nonlinear Plate Material*

### 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 **AC/DC>Soft Iron (Without Losses)**.

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

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

## MATERIALS

*Soft Iron (Without Losses) (mat5)*

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. Next, modify the physics model to use the B-H curve of the material.

## MAGNETIC FIELDS, NO CURRENTS (MFNC)

*Magnetic Shielding 1*

1 In the **Model Builder** window, under **Component 1 (comp1)>Magnetic Fields, No Currents (mfnc)** click **Magnetic Shielding 1**.

2 In the **Settings** window for **Magnetic Shielding**, locate the **Magnetic Shielding** section.

3 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 **Add Study** 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 **Model Builder** window, click **Study 3**.

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

3 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

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

## RESULTS

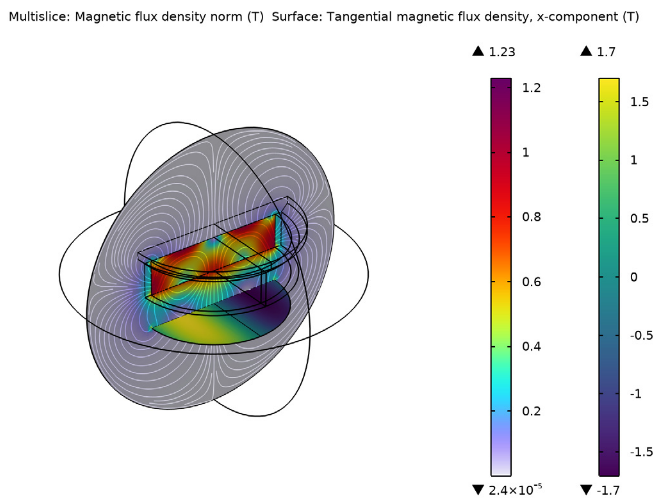
### *One-sided Magnet - Nonlinear*

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**.




### *Surface Integration 1*

1 In the **Model Builder** window, under **Results>Derived Values** click **Surface Integration 1**.

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

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

4 Click **Evaluate**.

#### TABLE 1

1 Go to the **Table 1** window.

   The result should be around 3.8 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.

#### RESULTS

*Differential Relative Permeability*

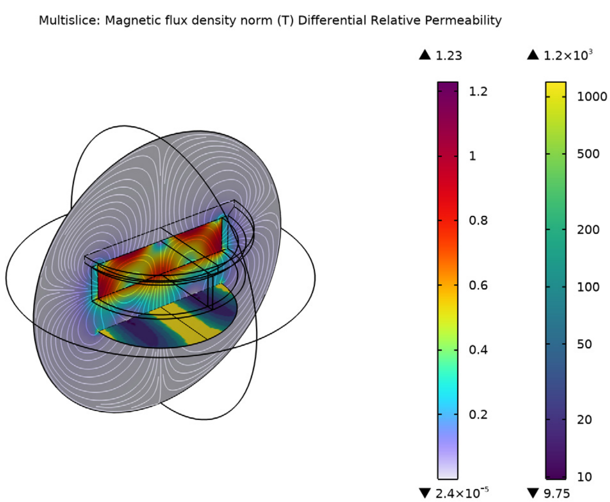
1 In the **Model Builder** window, expand the **One-sided Magnet - Nonlinear** node, then click **Surface 1**.

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.mat5.BHCurve.BH(mfnc.normtH),mfnc.normtH)/mu0_const`.

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




   Here, `comp1.mat5.BHCurve.BHCurve1()` refers to the nonlinear magnetic curve for material 5. 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, `3.8 N`, is still close to the linear approximation of `4 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. Note: to perform the linear plate material simulation again, the soft iron material needs to be disabled and the magnetic shielding magnetization model must be set back to relative permeability.