Created in COMSOL Multiphysics 6.1

One-Sided Magnet and Plate

Introduction

Permanent magnets with a one-sided flux are used to attach posters and notes to refrigerators and notice boards but can also be found in advanced physics applications like 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 application shows this technique to model a cylindrical one-sided permanent magnet. A special technique to model thin sheets of high permeability material was used to model a thin μ-metal plate next to the magnet. This circumvents the difficulty of volumetric meshing of thin extended structures in 3D.

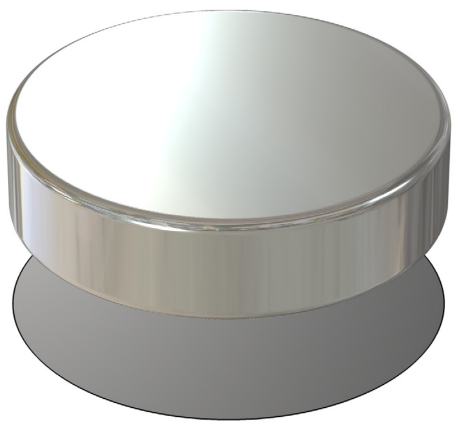


Figure 1: A cylindrical magnet above a μ-metal plate is modeled.

Model Definition

In a current free region, where

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

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

$$\mathbf{H} = -\nabla V_\mathrm{m}$$

This is analogous to the definition of the electric potential for static electric fields.

Using the constitutive relation between the magnetic flux density and magnetic field

$$\mathbf{B} = \mu_0 \mu_{\mathrm{rec}} \mathbf{H} + \mathbf{B}_{\mathrm{r}}$$

where $\mathbf{B}_{\mathrm{r}}$ is the remanent flux density, and together with the equation

$$\nabla \cdot \mathbf{B} = 0$$

you can derive the following equation for V_{m}:

$$-\nabla \cdot (\mu_0 \mu_{\mathrm{rec}} \nabla V_{\mathrm{m}} - \mathbf{B}_{\mathrm{r}}) = 0$$

It can be shown that applying a laterally periodic remanent flux density of

$$\mathbf{B}_{\mathrm{r}} = (\|\mathbf{B}_{\mathrm{r}}\| \sin(kx), 0, \|\mathbf{B}_{\mathrm{r}}\| \cos(kx))$$

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

BOUNDARIES

Along the exterior boundaries, the magnetic field should be tangential to the boundary as the flow lines should form closed loops around the magnet. The natural boundary condition from the equation is

$$\mathbf{n} \cdot (\mu_0 \mu_{\mathrm{rec}} \nabla V_{\mathrm{m}} - \mathbf{B}_{\mathrm{r}}) = \mathbf{n} \cdot \mathbf{B} = 0$$

Thus the magnetic field is made tangential to the boundary by a Neumann condition on the potential. On the interior boundary representing the μ-metal plate, you apply a special boundary condition for thin sheets of highly permeable material. Such plates are often used for the purpose of magnetic shielding.

MAGNETIC SATURATION EFFECT IN THE PLATE

Magnetic saturation effects are important in many applications. In a second step, the instructions show how to include a nonlinear magnetic material with saturation in the plate.

FORCE CALCULATION

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

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

where $\mathbf{n}_1$ is the boundary normal pointing out from the plate and T_2 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

Results and Discussion

Figure 2 shows the calculated magnetic flux density and direction for the version of the one-sided magnet that includes magnetic saturation in the plate. Saturation effects cause a drop in the force on the plate. A comparison also shows that the force is considerably higher for the case with the one-sided magnetization compared to the case with a uniform magnetization of the same amplitude.

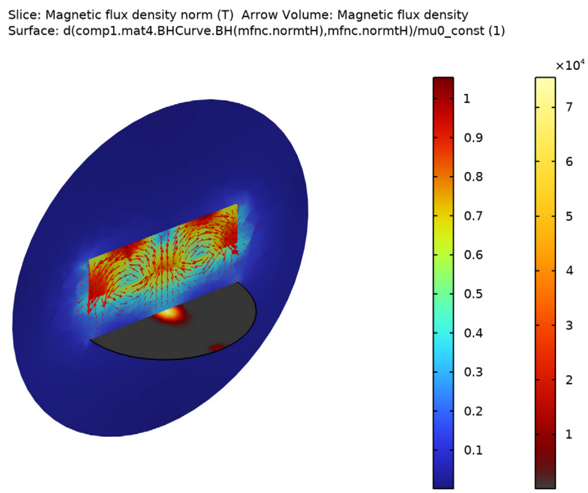


Figure 2: The magnetic flux density and direction is plotted in a cross section of the geometry.The one-sided behavior is apparent, as the flux does not emerge on the top of the magnet. The differential relative permeability in the plate is shown on a separate scale illustrating that it is driven well into 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**.

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

GEOMETRY 1

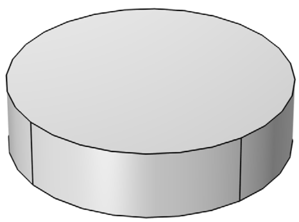
1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.

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

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

Cylinder 1 (cyl1)

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. In the **Geometry** toolbar, click **Build All**.
6. Click the **Zoom Extents** button in the **Graphics** toolbar.



Work Plane 1 (wp1)

1. In the **Geometry** toolbar, click **Work Plane**.
2. In the **Settings** window for **Work Plane**, locate the **Plane Definition** section.
3. In the **z-coordinate** text field, type `-5`.

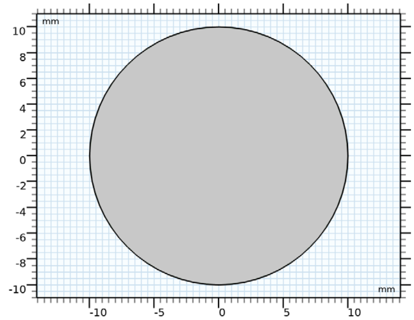
Work Plane 1 (wp1)>Plane Geometry

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

Work Plane 1 (wp1)>Circle 1 (c1)

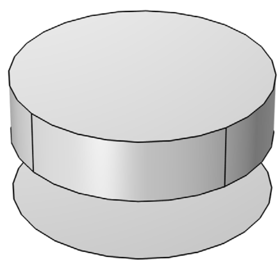
1. In the **Work Plane** toolbar, click **Circle**.
2. In the **Settings** window for **Circle**, locate the **Size and Shape** section.
3. In the **Radius** text field, type `10`.
4. In the **Work Plane** toolbar, click **Build All**.

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



6 In the **Model Builder** window, right-click **Geometry 1** and choose **Build All**.

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



Sphere 1 (sph1)

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

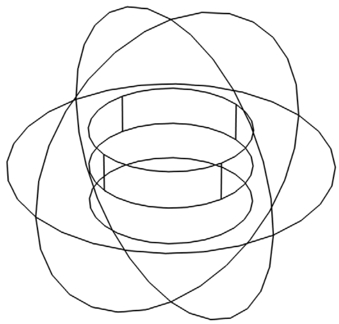
2 In the **Settings** window for **Sphere**, locate the **Size** section.

3 In the **Radius** text field, type `20`.

4 Click **Build All Objects**.

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

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



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

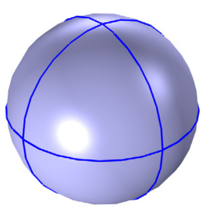
DEFINITIONS

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.

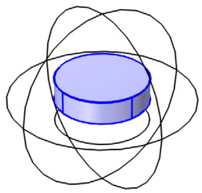


Magnet

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

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

3 Select Domain 2 only.



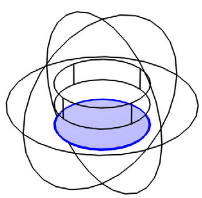
Plate

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

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

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

4 Select Boundary 5 only.



MATERIALS

Air

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

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

3 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Air**.

4 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

Linear mu-metal

1 Right-click **Materials** and choose **Blank Material**.

2 In the **Settings** window for **Material**, type `Linear mu-metal` 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 Locate 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	4e4	1	Basic

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>Hard Magnetic Materials>Sintered NdFeB Grades (Chinese Standard)>N28TH (Sintered NdFeB)**.

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

5 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 Click **Paste Selection**.

3 In the **Paste Selection** dialog box, type 2 in the **Selection** text field.

4 Click **OK**.

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 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type 2 in the **Selection** text field.

5 Click **OK**.

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

7 From the **Direction method** list, choose **User defined**.

8 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.

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**.

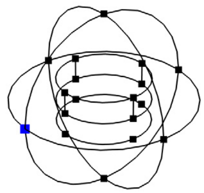
4 Locate the **Magnetic Shielding** section. In the d_s text field, type `0.5[mm]`.

So far the magnetic potential is not constrained anywhere and the solution can only be computed up to a constant. Add a condition to fix a specific value on a point.

Zero Magnetic Scalar Potential 1

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

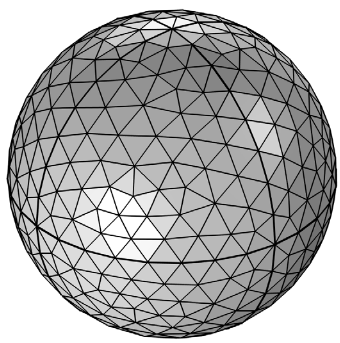
2 Select Point 1 only.



MESH 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Build All**.

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



The default mesh is sufficient for the time being. We will refine it later.

STUDY 1

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

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

3 Clear the **Generate default plots** check box.

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

RESULTS

3D Plot Group 1

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

Slice 1

1 Right-click **3D Plot Group 1** and choose **Slice**.

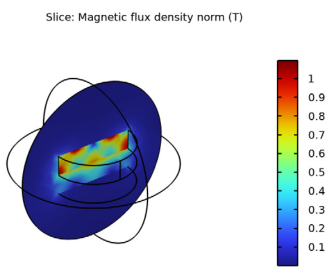
2 In the **Settings** window for **Slice**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields, No Currents>Magnetic>mfnc.normB - Magnetic flux density norm - T**.

3 Locate the **Plane Data** section. From the **Plane** list, choose **zx-planes**.

4 In the **Planes** text field, type 1.

5 In the **3D Plot Group 1** toolbar, click **Plot**.

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



Arrow Volume 1

1 In the **Model Builder** window, right-click **3D Plot Group 1** and choose **Arrow Volume**.

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

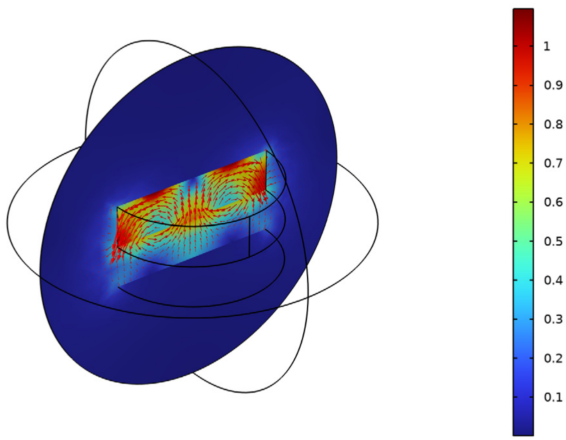
3 Find the **x grid points** subsection. In the **Points** text field, type 50.

4 Find the **y grid points** subsection. In the **Points** text field, type 1.

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

6 In the **3D Plot Group 1** toolbar, click **Plot**.

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



The arrow plot shows the magnetic flux density and the surface plot shows its norm.

Having plotted the magnetic flux density, proceed to visualize the magnetic field on the plate.

Study 1/Solution 1 (sol1)

In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1/ Solution 1 (sol1)**.

Selection

1 In the **Results** toolbar, click **Attributes** and choose **Selection**.

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

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

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

Surface 1

1 In the **Model Builder** window, right-click **3D Plot Group 1** and choose **Surface**.

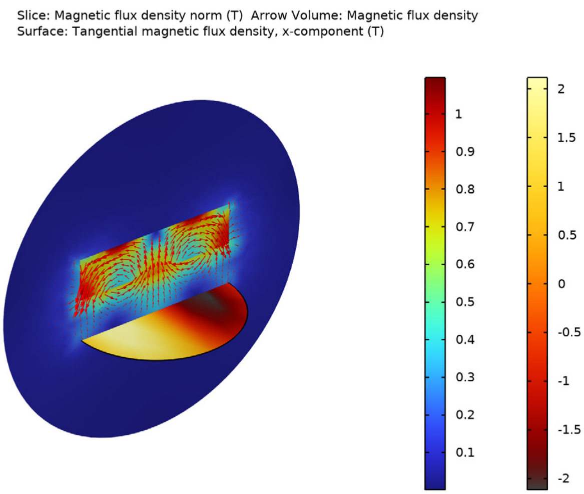
2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields, No Currents>Magnetic>Tangential magnetic flux density - T>mfnc.tBx - Tangential magnetic flux density, x-component**.

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

4 In the **Color Table** dialog box, select **Thermal>GrayBody** in the tree.

5 Click **OK**.

6 In the **3D Plot Group 1** toolbar, click **Plot**.



To evaluate the force on the plate, integrate the surface stress tensor. Since the plate is modeled by a boundary, the integral must be carried on the two sides of the plates only.

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 **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	

Here, `mfnc.unTmz` is the z-component of the Maxwell upward magnetic surface stress tensor, whereas `mfnc.dnTmz` is the downward equivalent.

5 Click **Evaluate**.

TABLE

1 Go to the **Table** window.

The result should be 3.5 N. As a comparison, setting `k` to `0` and solving the model again gives the result 0.9 to 1.2 N. The one-sidedness of the magnet increases the force by approximately a factor 3.

This concludes the part of the application using a linear mu-metal. The remaining instructions show how to use a nonlinear mu-metal.

Modeling Instructions — Nonlinear Mu-Metal

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 **Nonlinear Magnetic>Nickel Steel>Nickel Steel Mumetal 77% Ni**.

4 Right-click and choose **Add to Component 1 (comp1)**.

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

MATERIALS

Nickel Steel Mumetal 77% Ni (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**.

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**.

   Since the chosen B-H curve is rather steep from a numerical viewpoint, the model may become unstable. The strong nonlinearity in the plate may lead to an abrupt spatial variation of the differential permeability, that is, the ratio dB/dH. For models such as this, it is therefore good practice to switch to linear elements. Switching to linear elements will reduce the model's ability to resolve the field shape though, you can compensate for this by refining the mesh.
4. In the **Model Builder** window, click **Magnetic Fields, No Currents (mfnc)**.
5. In the **Settings** window for **Magnetic Fields, No Currents**, click to expand the **Discretization** section.
6. From the **Magnetic scalar potential** list, choose **Linear**.

MESH 1

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.
2. In the **Settings** window for **Mesh**, locate the **Sequence Type** section.
3. From the list, choose **User-controlled mesh**.

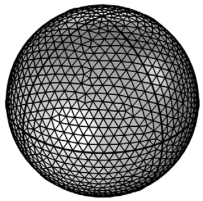
Size

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

Size 1

1. In the **Model Builder** window, right-click **Free Tetrahedral 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 **Plate**.
5. Locate the **Element Size** section. From the **Predefined** list, choose **Extremely fine**.
6. Click **Build All**.

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



The mesh should be refined close to the plate. Let us investigate the mesh by creating a plot.

8 In the **Mesh** toolbar, click **Plot**.

RESULTS

Mesh 1

1 In the **Settings** window for **Mesh**, locate the **Level** section.

2 From the **Level** list, choose **All**.

3 Locate the **Coloring and Style** section. From the **Element color** list, choose **Size**.

4 Click **Change Color Table**.

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

6 Click **OK**.

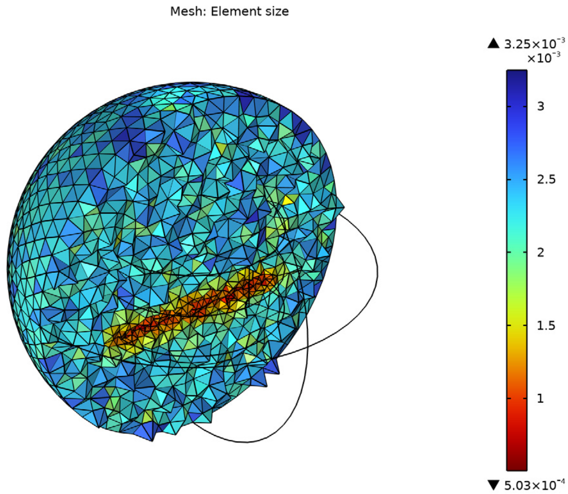
7 In the **Settings** window for **Mesh**, click to expand the **Element Filter** section.

8 Select the **Enable filter** check box.

9 In the **Expression** text field, type `y>0`.

10 In the **Mesh Plot 2** toolbar, click **Plot**.

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



Next, compute the solution. For nonlinear models, the default tolerance of 0.001 may be insufficient, leading to a solution that is not fully converged. Adjust it to improve accuracy.

STUDY 1

Solver Configurations

In the **Model Builder** window, expand the **Study 1>Solver Configurations** node.

Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Study 1>Solver Configurations>Solution 1 (sol1)** node.
2 In the **Settings** window for **Stationary Solver**, locate the **General** section.
3 In the **Relative tolerance** text field, type `1e-4`.
4 In the **Model Builder** window, expand the **Study 1>Solver Configurations> Solution 1 (sol1)>Stationary Solver 1** node, then click **Fully Coupled 1**.
5 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.
6 In the **Maximum number of iterations** text field, type `100`.
7 Click **Compute**.

RESULTS

3D Plot Group 1

The nonlinear permeability results in a lower field strength in the plate. To study how far the material is brought into saturation, you can plot the differential permeability (the ratio dB/dH).

Surface 1

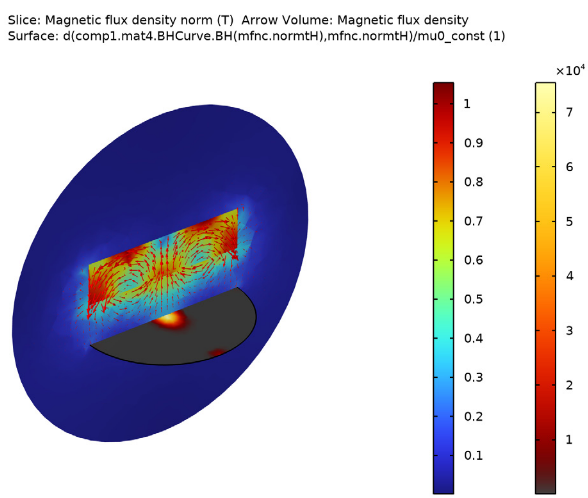
1 In the **Model Builder** window, click **Surface 1**.

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

3 In the **Expression** text field, type `d(comp1.mat4.BHCurve.BH(mfnc.normtH), mfnc.normtH)/mu0_const`.

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, we are plotting the differential relative permeability. A value close to 1 indicates that the material is saturated.

4 In the **3D Plot Group 1** toolbar, click **Plot**.



5 In the **Results** toolbar, click **Evaluate** and choose **Evaluate All**.

TABLE

1 Go to the **Table** window.

The result should be around 2.2 N.