Created in COMSOL Multiphysics 6.2

Iron Sphere in a Magnetic Field — 13.56 MHz

Introduction

This tutorial is part of a series on modeling an iron sphere in a background magnetic field within the Introduction to Electromagnetics tutorial group. This tutorial focuses the case of an magnetically permeable iron sphere in a spatially uniform magnetic field where the magnetic field sinusoidally varies in time at a frequency of 13.56 MHz. At this frequency, the skin depth of the iron used in the model is ~ 0.65 μm, which is negligible compared to the size of the sphere. In this scenario, we only need to consider surface effects and can model the sphere as an empty shell with an Impedance Boundary Condition.

Model Definition

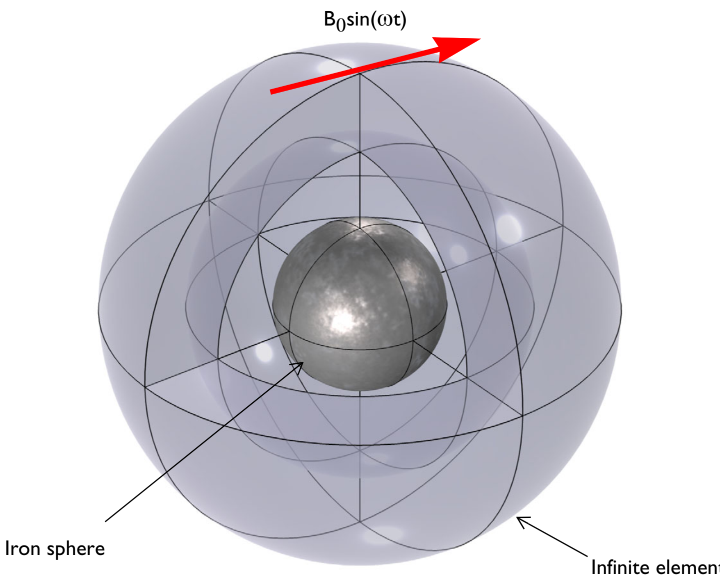


Figure 1: A magnetically permeable iron sphere in a spatially uniform background magnetic field that sinusoidally varies in time with angular frequency, ω. The sphere at the center is surrounded by air and enclosed in a region of Infinite Elements.

Each model in this tutorial series uses the same basic structure illustrated in Figure 1. It consists of a 0.25 mm diameter iron sphere, with a relative permeability of, $\mu_r = 4000$, placed in a spatially uniform background magnetic field of strength $B_0 = 1$ mT. In this case, that magnetic field oscillates at a frequency of 13.56 MHz. Due to the negligible skin depth of iron at this frequency, the sphere volume is removed from the Magnetic Fields physics selection and the associated mesh. This saves on computational power. However, when implemented in this manner, the volume of the sphere is still available to other physics if the user wishes to implement another physics interface (such as Heat Transfer) to model the iron sphere center.

Results and Discussion

The results for this model are shown in Figure 2. This distortion of the background magnetic field is visible along with the distribution of the induced current density across the surface of the iron sphere.

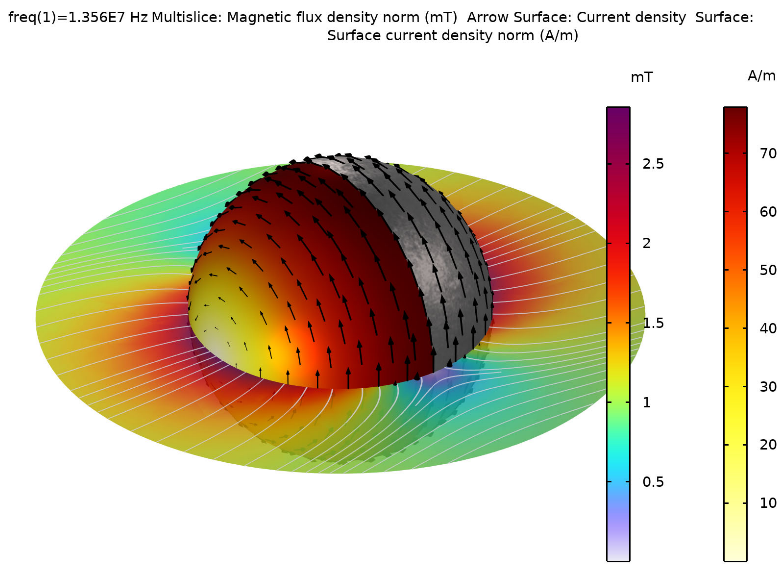


Figure 2: The induced currents on the surface of the iron sphere and the magnetic field in the surrounding space.

Application Library path: `ACDC_Module/Introductory_Electromagnetics/iron_sphere_bfield_04_13mhz`

Modeling Instructions

This tutorial will demonstrate the physics of an iron sphere in a spatially uniform magnetic field sinusoidally varying at 13.56 MHz. The instructions on the following pages will help you to build, configure, solve, and analyze the model. If anything seems out of order, please retrace your steps. The finalized model — available in the model's Application Libraries folder — can help you out. You can compare it directly to your current model by means of the **Compare** option in the **Developer** toolbar.

ROOT

The geometry, materials, and selections have been prepared in the *Introduction* tutorial (chapter 1). They have been saved in the file `iron_sphere_bfield_00_introduction.mph`. You can start by opening this file and saving it under a new name.

Hint: if you are new to COMSOL Multiphysics, it is worthwhile to check out the Introduction tutorial first.

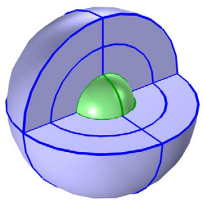
1 From the **File** menu, choose **Open**.
2 Browse to the model's Application Libraries folder and double-click the file `iron_sphere_bfield_00_introduction.mph`.
3 From the **File** menu, choose **Save As**.
4 Browse to a suitable folder and type the filename `iron_sphere_bfield_04_13mhz.mph`.

MAGNETIC FIELDS (MF)

As the skin depth is negligible in this model, we are only considering surface effects. This means the volume of the iron sphere can be removed from the physics selection to save on computational cost.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic Fields (mf)**.
2 In the **Settings** window for **Magnetic Fields**, locate the **Domain Selection** section.
3 In the list, select **9**.
4 Right-click **Component 1 (comp1)>Magnetic Fields (mf)** and choose **Plot**.

5 Click the Zoom to Selection button in the **Graphics** toolbar.



Note: In the introduction modeling steps, the nearest upper quarter sphere was hidden to improve visibility in the result plots. This allows the visibility of the mesh layers of the Infinite Element Domain and the Analysis Domain.

6 Click **Remove from Selection**.

7 Select Domains 1–8 and 10–17 only.

The surface of the sphere is then modeled using an impedance boundary.

Impedance Boundary Condition 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Impedance Boundary Condition**.

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

3 From the **Selection** list, choose **Iron Sphere Surface**.

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

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 **Iron Sphere Surface**.

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

6 Click **Build All**.

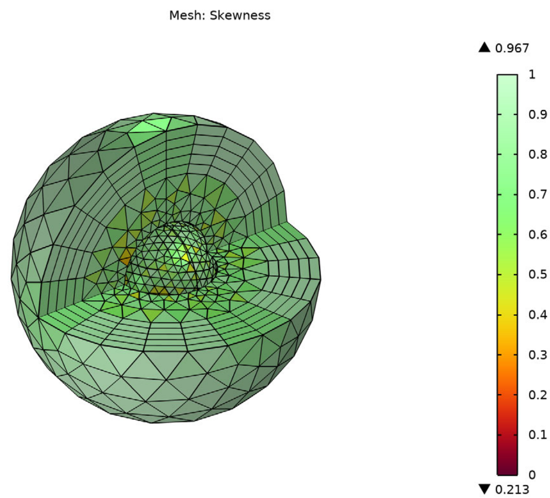
7 In the **Mesh** toolbar, click **Plot**.

RESULTS

Mesh 1

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

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



The mesh plot shows the details on the surface of the iron sphere but the inner volume is not meshed as it is not included in the physics.

STUDY 1

Step 1: Frequency Domain

1 In the **Model Builder** window, expand the **Study 1** node, then 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 `13.56 [MHz]`.

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

RESULTS

Magnetic Flux Density Norm (mf)

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

2 In the **Settings** window for **3D Plot Group**, click to expand the **Selection** section.

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

4 From the **Selection** list, choose **Analysis domain**.

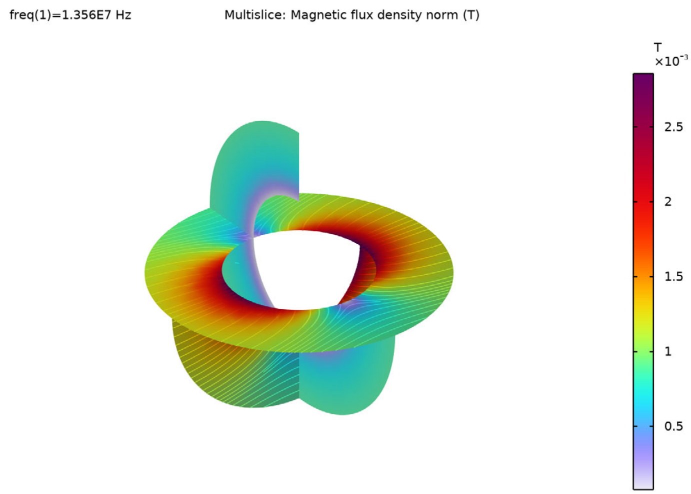
5 Locate the **Plot Settings** section. Clear the **Plot dataset edges** check box.

6 Locate the **Color Legend** section. Clear the **Show maximum and minimum values** check box.

7 Select the **Show units** check box.

8 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

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



The model has calculated the magnetic flux density in the analysis domain surrounding the iron sphere but there is nothing inside the sphere volume. As the magnetic field is only interacting with the outer shell of the iron sphere using the impedance boundary condition, the current is only induced on the surface.

Surface 1

The final section of this tutorial covers plotting the current density on the surface of the iron sphere and the perturbed background magnetic field. We can also include a material appearance on the surface for completeness.

1 Right-click **Magnetic Flux Density Norm (mf)** 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 **Materials>material.boundary - Material settings**.

3 Click to expand the **Title** section. From the **Title type** list, choose **None**.

Material Appearance 1

1 Right-click **Surface 1** and choose **Material Appearance**.

2 In the **Settings** window for **Material Appearance**, locate the **Appearance** section.

3 From the **Appearance** list, choose **Custom**.

4 From the **Material type** list, choose **Iron (scratched)**.

Set the background magnetic field plot to just the horizontal plane.

Selection 1

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

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

3 From the **Selection** list, choose **Iron Sphere Surface**.

4 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

Multislice 1

1 In the **Model Builder** window, under **Results>Magnetic Flux Density Norm (mf)** click **Multislice 1**.

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

3 From the **Unit** list, choose **mT**.

4 Locate the **Multiplane Data** section. Find the **x-planes** subsection. Clear the **Coordinates** text field.

5 Find the **y-planes** subsection. Clear the **Coordinates** text field.

Transparency 1

1 Right-click **Multislice 1** and choose **Transparency**.

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

3 In the **Transparency** text field, type `0.15`.

4 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

Streamline Multislice 1

1 In the **Model Builder** window, under **Results>Magnetic Flux Density Norm (mf)** click **Streamline Multislice 1**.

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

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

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

Transparency 1

Right-click **Streamline Multislice 1** and choose **Transparency**.

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

Add an arrow surface to visualize the induced current direction.

Arrow Surface 1

1 In the **Model Builder** window, right-click **Magnetic Flux Density Norm (mf)** and choose **Arrow Surface**.

2 In the **Settings** window for **Arrow Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields>Currents and charge>mf.Jx,mf.Jy,mf.Jz - Current density**.

3 Locate the **Arrow Positioning** section. From the **Placement** list, choose **Mesh nodes**.

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

5 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

Selection 1

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

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

3 From the **Selection** list, choose **Iron Sphere Surface**.

4 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.

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

Surface 2

1 In the **Model Builder** window, right-click **Magnetic Flux Density Norm (mf)** and choose **Surface**.

Setting half of the sphere surface to show the current density.

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>Currents and charge>mf.normJs - Surface current density norm - A/m**.

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

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

5 Click **OK**.

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

7 From the **Color table transformation** list, choose **Reverse**.

Filter 1

1 Right-click **Surface 2** and choose **Filter**.

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

3 In the **Logical expression for inclusion** text field, type `x<0`.

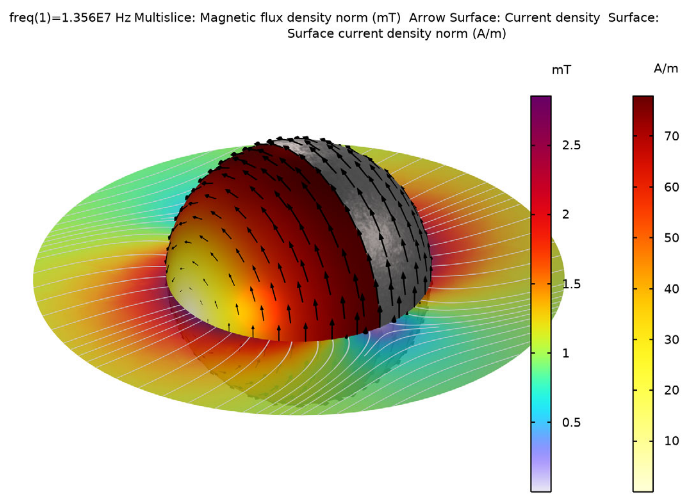
Selection 1

1 In the **Model Builder** window, right-click **Surface 2** and choose **Selection**.

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

3 From the **Selection** list, choose **Iron Sphere Surface**.

4 In the **Magnetic Flux Density Norm (mf)** toolbar, click **Plot**.



This surface plot shows that there is a peak surface current density of ~ 78 A/m around the circumference of the sphere.

This tutorial demonstrated the efficacy of using only the surface of the iron sphere for models using a negligible skin depth. For comparison, the user can investigate and recreate these results using the sphere volume and adding a mesh with a very high detail near the surface. This can be accomplished by constructing a mesh similar to that demonstrated in the 20 kHz oscillating magnetic field tutorial but with an even smaller layer thickness.