Created in COMSOL Multiphysics 6.1

# Iron Sphere in a 13.56 MHz Magnetic Field

## Introduction

An iron sphere is exposed to a spatially uniform, sinusoidally time-varying, background magnetic field. The frequency of the field is so high that the skin depth in the sphere is much smaller than the radius. At such high frequencies it is possible to model only the fields and induced currents on the surface of the sphere, thus avoiding the need for solving for the fields within the volume of the sphere, resulting in significantly reduced model size.

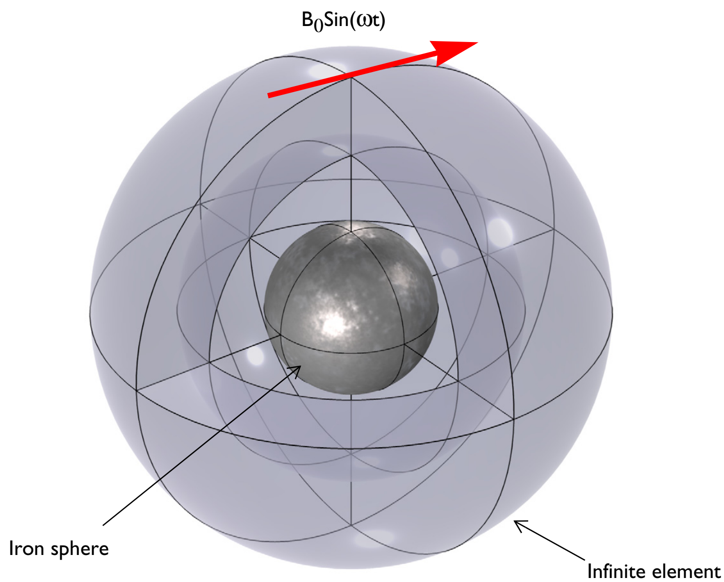


*Figure 1: An iron sphere is exposed to a spatially uniform, sinusoidally time-varying, background magnetic field.*

## Model Definition

Figure 1 shows the setup, with an iron sphere placed in a spatially uniform time-harmonic background magnetic field. The background field is applied using the Reduced field formulation available in the Magnetic Fields interface. The model space is truncated by an Infinite Elements region, a domain condition approximating a domain that extends to infinity. When using Infinite Element Domain features, the boundary condition on the outside of the modeling domain only marginally affects the solution, since it is placed at a large physical distance.

At 13.56 MHz the skin depth of iron is ~0.65 μm. The surrounding air has $\varepsilon_r = 1$, $\mu_r = 1$, and $\sigma = 0$ S/m, which implies an infinite skin depth. To improve the stability of the solver, the application uses a small but nonzero artificial conductivity in the air ($\sigma = 0.1$ S/m).

Because the skin depth in the iron sphere is much smaller than the sphere radius, it is possible to assume that the induced currents flow only in a thin surface layer with negligible thickness. This phenomenon can be modeled using the Impedance Boundary Condition on the iron sphere surface. The inside of the iron sphere is not modeled at all, since it is assumed that there are no significant currents, and the fields are negligible, within the sphere.

The interior of the sphere is explicitly removed from the geometry by means of a Delete operation. An alternative approach is to modify the selection of the Magnetic Fields interface to exclude the interior of the sphere, without deleting the corresponding geometrical domain. This second solution can be useful for example in multiphysics applications when another physics interface (such as Heat Transfer) must be solved in the core as well.

## *Results and Discussion*

Figure 2 plots the magnetic field outside of the sphere, as well as the induced current density along with a visualization of the mesh at the sphere surface.

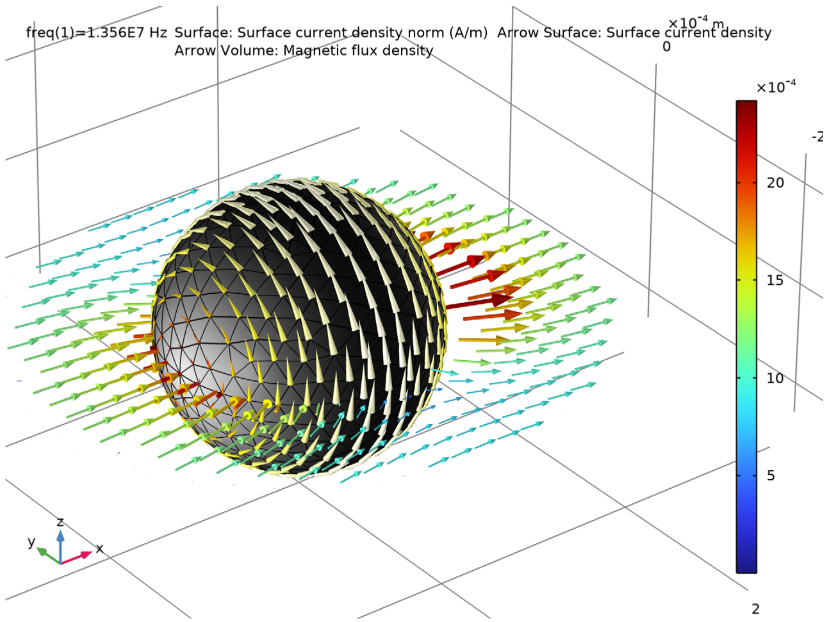


*Figure 2: The induced currents on the surface of the iron sphere and the magnetic field in the surrounding space.*

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**Application Library path:** `ACDC_Module/Introductory_Electromagnetics/iron_sphere_13mhz_bfield`

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## *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>Electromagnetic Fields>Magnetic Fields (mf)**.
3. Click **Add**.

4 Click Study.

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

6 Click **Done**.

## GLOBAL DEFINITIONS

Define a few parameters to be used in the model setup.

### *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 |
|---|---|---|---|
| B0 | 1[mT] | 0.001 T | Background magnetic fields |
| r0 | 0.125[mm] | 1.25E-4 m | Radius, iron sphere |

## GEOMETRY 1

### *Sphere 1 (sph1)*

Create a sphere with two layers plus an inner core. The outermost layer represents the exterior air region, scaled using the Infinite Element Domain, the middle layer is the unscaled air domain, and the core represents the iron sphere.

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 `3*r0`.

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

| Layer name | Thickness (m) |
|---|---|
| Layer 1 | r0 |
| Layer 2 | r0 |

Remove the core domain from the model domain.

### *Delete Entities 1 (del1)*

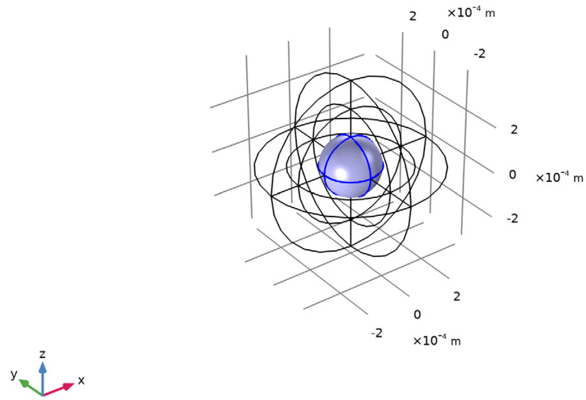
1 In the **Model Builder** window, right-click **Geometry 1** and choose **Delete Entities**.

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

3 In the **Settings** window for **Delete Entities**, locate the **Entities or Objects to Delete** section.

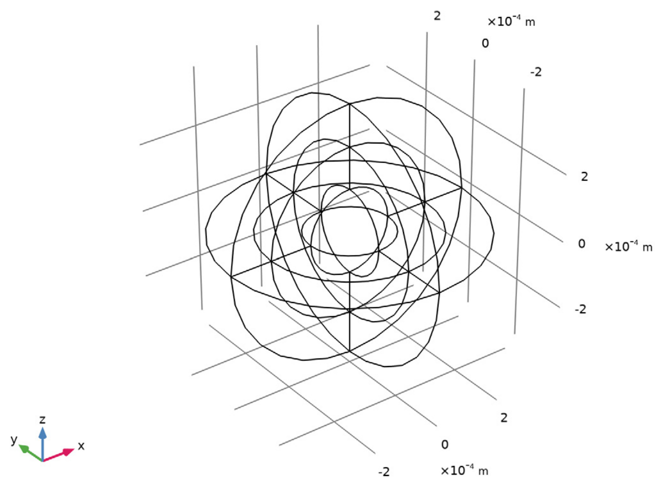
4 From the **Geometric entity level** list, choose **Domain**.

**5** On the object **sph1**, select Domain 9 only.




**6** Click **Build All Objects**.

The surface of the iron sphere is now an exterior boundary and it is now possible to apply the Impedance boundary condition.



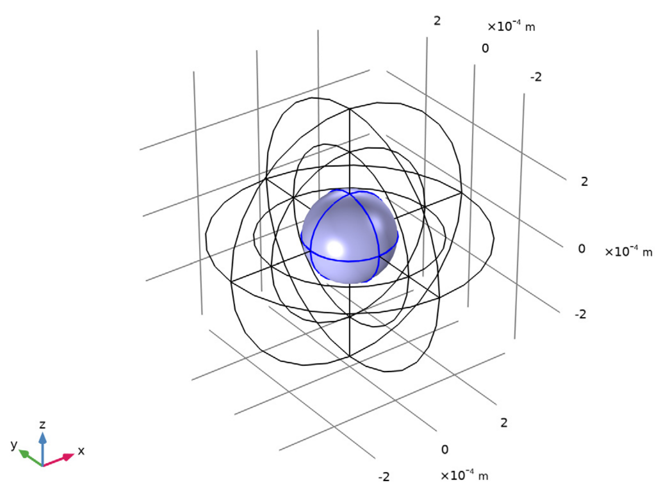
### DEFINITIONS

Create a set of selections before setting up the physics. First, create a selection for the surface of the iron sphere.

*Iron surface*

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 Select Boundaries 17–20, 31, 32, 39, and 42 only.

   The simplest way to do this is to select the **Group by continuous tangent** check box, then click on any boundary on the surface of the iron sphere.

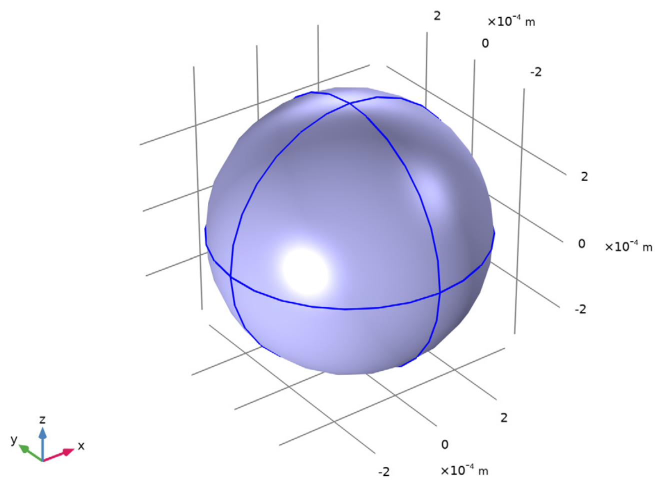



5 In the **Label** text field, type `Iron surface`.

*Infinite Element Domain 1 (ie1)*

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

**2** Select Domains 1–4, 9, 10, 13, and 16 only.




**3** In the **Settings** window for **Infinite Element Domain**, locate the **Geometry** section.

**4** From the **Type** list, choose **Spherical**.

### MAGNETIC FIELDS (MF)

Set up the physics interface to apply a uniform background magnetic fields. In the **Magnetic Fields** interface, the background field must be specified in terms of a vector potential field.

**1** In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic Fields (mf)**.

**2** In the **Settings** window for **Magnetic Fields**, locate the **Background Field** section.

**3** From the **Solve for** list, choose **Reduced field**.

**4** Specify the $\mathbf{A}_b$ vector as

| | |
|---|---|
| 0 | x |
| 0 | y |
| B0*y | z |

*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 surface**.

## MATERIALS

Assign the material properties. First, use air for all domains.

### 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)*

Specify the conductivity of the air to a small value in order to improve the convergence rate.

1 In the **Settings** window for **Material**, locate the **Material Contents** section.

2 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 |
| Relative permittivity | epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0 | 1 | 1 | Basic |
| Electrical conductivity | sigma_iso ; sigmaii = sigma_iso, sigmaij = 0 | `0.1[S/m]` | S/m | Basic |

Override the core sphere surface with iron.

### ADD MATERIAL

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

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

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

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

## MATERIALS

*Iron (mat2)*

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 **Iron surface**.

## MESH 1

Specify an extra fine mesh on the surface of the iron sphere.

*Size*

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

*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 surface**.

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

6 Click **Build All**.

Plot the meshed structure to review the quality of the mesh.

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

## RESULTS

*Mesh 1*

By default, the boundary mesh is plotted, so only the triangular elements on the outer boundaries are visible. Perform the following operations to inspect the tetrahedral elements in the interior of the geometry.

1 In the **Settings** window for **Mesh**, locate the **Coloring and Style** section.

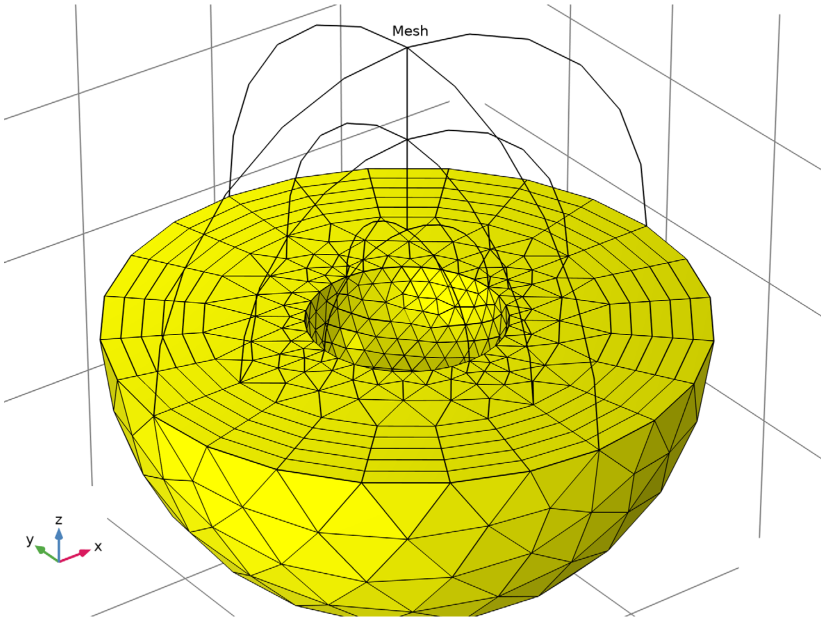
2 From the **Element color** list, choose **Yellow**.

3 Click to expand the **Element Filter** section. Select the **Enable filter** check box.

4 In the **Expression** text field, type `z<0` to plot a section of the mesh.

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

As it is apparent from the plot, no mesh is generated in the core since it was removed from the geometry.




### STUDY 1

*Step 1: Frequency Domain*

1 In the **Model Builder** window, under **Study 1** click **Step 1: Frequency Domain**.

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

3 In the **Frequencies** text field, type `13.56[MHz]`.

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

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

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

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

### RESULTS

*Study 1/Solution 1 (sol1)*

Add a selection to the dataset to plot quantities on the surface of the iron sphere.

1 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 **Iron surface**.

Create surface plots for the surface current density norm and the mesh on the iron sphere.

### *Surface Current Density (mf)*

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

2 In the **Settings** window for **3D Plot Group**, type `Surface Current Density (mf)` in the **Label** text field.

### *Surface 1*

1 Right-click **Surface Current Density (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 **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 **Linear>GrayPrint** in the tree.

5 Click **OK**.

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

7 Clear the **Color legend** check box.

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

### *Surface 2*

1 Right-click **Surface 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface**, click to expand the **Title** section.

3 From the **Title type** list, choose **None**.

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

5 From the **Color** list, choose **Black**.

6 Select the **Wireframe** check box.

### *Surface Current Density (mf)*

Add an arrow surface plot for the surface current density and an arrow volume plot showing the magnetic flux density.

### *Arrow Surface 1*

1 In the **Model Builder** window, right-click **Surface Current Density (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.Jsx,...,mf.Jsz - Surface current density**.
3 Locate the **Coloring and Style** section. From the **Arrow type** list, choose **Cone**.
4 Select the **Scale factor** check box. In the associated text field, type `6E-7`.
5 Locate the **Arrow Positioning** section. From the **Placement** list, choose **Mesh nodes**.

### *Color Expression 1*

1 Right-click **Arrow Surface 1** and choose **Color Expression**.
2 In the **Settings** window for **Color Expression**, 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 **Color Expression**, locate the **Coloring and Style** section.
7 Clear the **Color legend** check box.

### *Arrow Volume 1*

1 In the **Model Builder** window, right-click **Surface Current Density (mf)** and choose **Arrow Volume**.
2 In the **Arrow Positioning** section, specify the grid points according to the following table:

| Direction | Value |
|---|---|
| x | 31 |
| y | 31 |
| z | 1 |

### *Color Expression 1*

1 In the **Model Builder** window, right-click **Arrow Volume 1** and choose **Color Expression**.

   The default settings color the arrows according to the local magnetic flux density norm.

   Compare the resulting plot with that in Figure 2.