Magnetic Lens

Introduction

Scanning electron microscopes image samples by scanning with a high-energy beam of electrons. The subsequent electron interactions produce signals such as secondary and back-scattered electrons than contain information about the sample surface topography. Electromagnetic lenses are used to focus this electron beam down to a spot about 10 nm wide on the sample surface.

Note: This model requires the Particle Tracing Module.

Model Definition

Particles (electrons) are released from near the bottom boundary of the simulation space and pass through a collimator. This collimator can typically be adjusted to remove stray electrons. A simple DC coil produces an axial magnetic field. This rotationally symmetric, inhomogeneous magnetic field results in non-axial electrons experiencing a radial force causing them to spiral about the axis. As they begin to spiral, they have a larger velocity component perpendicular to the mainly axial magnetic field, therefore the radius of their spiral/helical path decreases. Thus, a parallel beam of electrons entering the lens will converge to a point.

If the region in which the magnetic field acts upon the electrons is sufficiently small, this coil acts as a 'thin' convex lens and the thin lens expression holds.

MODEL EQUATIONS

A simple model is set up to test the magnetic force within the Particle Tracing for ACDC interface. The equations solved are the equation of motion of a charged particle in a magnetic field (Lorentz force):

$$\frac{d}{dt}(m\mathbf{v}) = q(\mathbf{v} \times \boldsymbol{B}) \tag{1}$$

where q is the particle charge (C), $\mathbf{v}$ is the particle velocity (m/s) and $\mathbf{B}$ is the magnetic flux density (SI unit: T). The total work done on a particle by a magnetic field is zero.

Results and Discussion

The magnetic flux density is plotted in Figure 1. The strength of the lens depends upon the coil configuration and current. The lens within electron microscopes are generally very strong, in some cases focusing the electron beam within the lens itself.
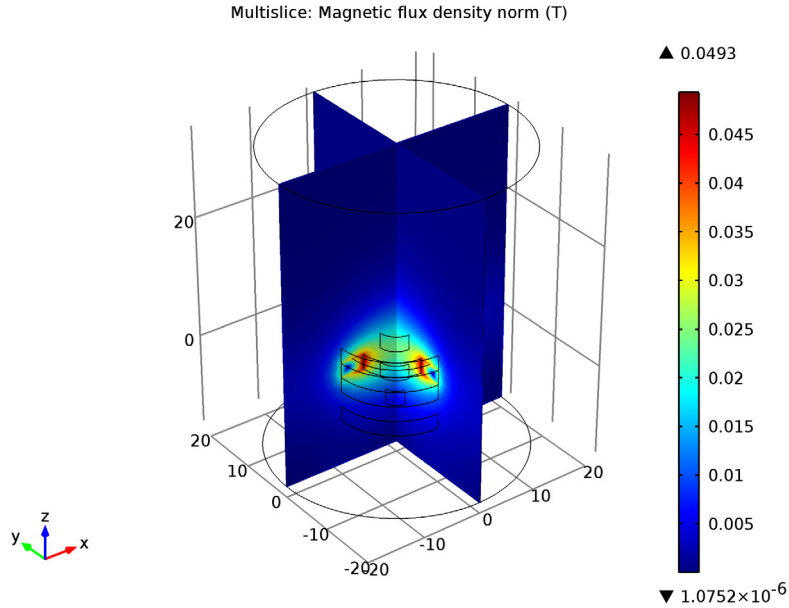
Multislice: Magnetic flux density norm (T)

Figure 1: Plot of the magnetic flux density in the magnetic lens.

Figure 2 plots the electron trajectories as they travel through the coil. The electrons are focused at a point along the z-axis. The focal length is given by:

$$f = K\frac{V}{i^2} \tag{2}$$

where K is a constant based on the coil geometry and number of turns, V is the accelerating voltage and i is the coil current. The focal length increases with electron energy (i.e. V) because their high velocity means they spend less time experiencing a force due the magnetic field. However, as the current increases so does the magnetic

field strength, therefore the electrons spiral in tighter paths bringing the focal length closer.
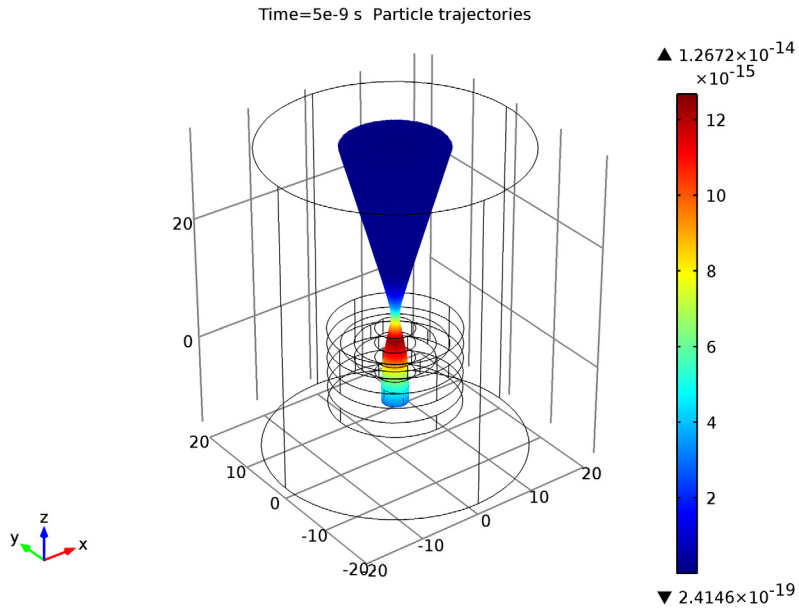
Time=5e-9 s Particle trajectories

Figure 2: Plot of the electron trajectories travelling through the magnetic lens.

The ability to change the focal length of a lens is useful as it allows the focusing onto a surface in addition to adjusting the magnification. The effect of the focusing can be seen in Figure 3 which shows a Poincaré map of the particle position at three different snapshots in time. The sharpness of the cross-over can be improved using multiple lenses.
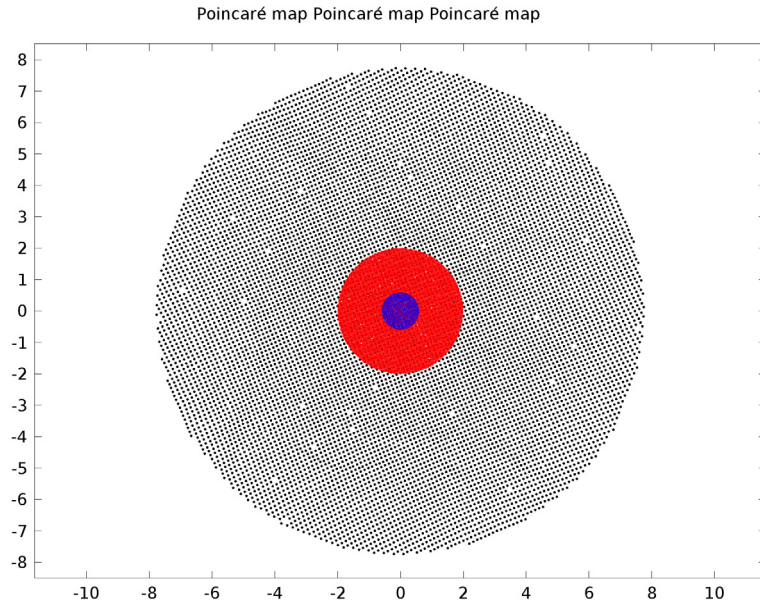
Figure 3: Poincaré plot of the particle location in the xy-plane initially (red), at the focal point of the lens (blue) and at the last time step (black).

Reference

1. M.J.Pritchard, *Manipulation of Ultracold Atoms Using Magnetic and Optical Fields*, PhD thesis, Durham University, September 2006, http://massey.dur.ac.uk/ resources/mjpritchard/thesis_pritchard.pdf.

Model Library path: ACDC_Module/Particle_Tracing/magnetic_lens

Modeling Instructions

NEW

1 In the **New** window, click the **Model Wizard** button.

MODEL WIZARD

1 In the **Model Wizard** window, click the **3D** button.

2 In the **Select physics** tree, select **AC/DC>Magnetic Fields (mf)**.

3 Click the **Add** button.

4 Click the **Study** button.

5 In the tree, select **Preset Studies>Stationary**.

6 Click the **Done** button.

GLOBAL DEFINITIONS

Parameters

1 On the **Home** toolbar, click **Parameters**.

2 In the **Parameters** settings window, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression
Vaccel	500[V]
Ic	0.32[A]
velec	sqrt((2*Vaccel*e_const)/(me_const))
Nc	1000

GEOMETRY 1

Build a simple coil geometry using cylinders.

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

2 In the **Geometry** settings window, locate the **Units** section.

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

Cylinder 1

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

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

3 In the **Radius** edit field, type 10.

4 In the **Height** edit field, type 2.5.

Cylinder 2

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

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

3 In the **Radius** edit field, type 6.

4 In the **Height** edit field, type 2.5.

5 Click the **Build Selected** button.

Cylinder 3

1 In the **Model Builder** window, under **Component 1>Geometry 1** right-click **Cylinder 1** and choose **Duplicate**.

2 In the **Cylinder** settings window, locate the **Position** section.

3 In the **z** edit field, type -7.5.

Cylinder 4

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

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

3 In the **Radius** edit field, type 2.

4 In the **Height** edit field, type 2.5.

5 Locate the **Position** section. In the **z** edit field, type -7.5.

Cylinder 5

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

2 In the **Cylinder** settings window, locate the **Position** section.

3 In the **z** edit field, type -2.5.

Cylinder 6

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

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

3 In the **Radius** edit field, type 3.

4 In the **Height** edit field, type 2.5.

5 Locate the **Position** section. In the **z** edit field, type -2.5.

Cylinder 7

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

2 In the **Cylinder** settings window, locate the **Position** section.

3 In the **z** edit field, type 2.5.

Cylinder 8

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

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

3 In the **Radius** edit field, type 3.

4 In the **Height** edit field, type 2.5.

5 Locate the **Position** section. In the **z** edit field, type 2.5.

Cylinder 9

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

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

3 In the **Radius** edit field, type 20.

4 In the **Height** edit field, type 50.

5 Locate the **Position** section. In the **z** edit field, type -15.

Difference 1

1 On the **Geometry** toolbar, click **Difference**.

2 Select the objects **cyl5**, **cyl3**, **cyl1**, and **cyl7** only.

3 In the **Difference** settings window, locate the **Difference** section.

4 Select the **Objects to subtract** toggle button.

5 Select the objects **cyl2**, **cyl8**, **cyl6**, and **cyl4** only.

6 Click the **Build Selected** button.

7 Click the **Go to Default 3D View** button on the Graphics toolbar.

Work Plane 1

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

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

3 In the **Work Plane** settings window, locate the **Plane Definition** section.

4 From the **Plane type** list, choose **Face parallel**.

5 Select the **Planar face** toggle button.

6 On the object **dif1**, select Boundary 3 only.

Plane Geometry

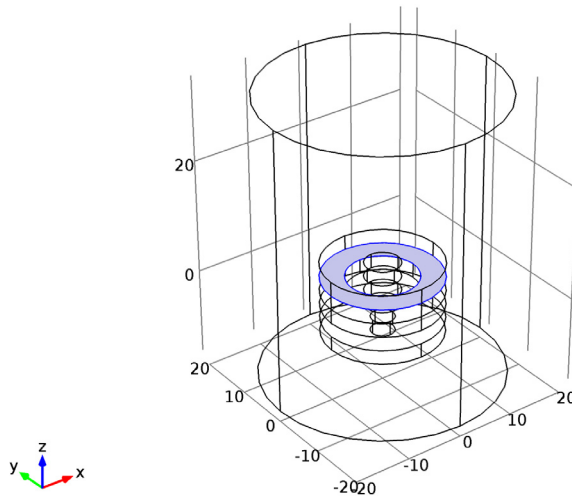Click the **Zoom Extents** button on the Graphics toolbar.

Circle 1

1 In the **Model Builder** window, under **Component 1>Geometry 1>Work Plane 1** right-click **Plane Geometry** and choose **Circle**.

2 In the **Circle** settings window, locate the **Size and Shape** section.

3 In the **Radius** edit field, type 2.

4 Click the **Build Selected** button.

Last, create a circular edge to be used in the Multi-Turn Coil feature as a reference edge.

Work Plane 2

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

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

3 From the **Plane type** list, choose **Face parallel**.

4 Select the **Planar face** toggle button.

5 On the object **dif1**, select Boundary 13 only.

Circle 1

1 In the **Model Builder** window, under **Component 1>Geometry 1>Work Plane 2** right-click **Plane Geometry** and choose **Circle**.

2 In the **Circle** settings window, locate the **Object Type** section.

3 From the **Type** list, choose **Curve**.

4 Locate the **Size and Shape** section. In the **Radius** edit field, type 8.

5 On the **Home** toolbar, click **Build All**.

MATERIALS

Add materials for the air domain and metal collimator and coil.

Material 1

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

2 In the **Material** settings window, locate the **Material Contents** section.

3 In the table, enter the following settings:

Property	Name	Value
Electrical conductivity	sigma	6e7
Relative permittivity	epsilonr	1
Relative permeability	mur	1

Material 2

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

2 Select Domain 1 only.

3 In the **Material** settings window, locate the **Material Contents** section.

4 In the table, enter the following settings:

Property	Name	Value
Electrical conductivity	sigma	0
Relative permittivity	epsilonr	1
Relative permeability	mur	1

MAGNETIC FIELDS

Multi-Turn Coil 1

1 On the **Physics** toolbar, click **Domains** and choose **Multi-Turn Coil**.

2 Select Domain 4 only.

3 In the **Multi-Turn Coil** settings window, locate the **Coil Type** section.

4 From the list, choose **Circular**.

5 Locate the **Multi-Turn Coil** section. In the N edit field, type Nc.

6 In the I_{coil} edit field, type Ic.

Specify the reference edges to be used in the calculation of the current path for the circular coil. To obtain the best results, the selected edges should have a radius close

to the average coil radius. In this case, select the edges intentionally created in previous steps.

Reference Edge 1

1 Right-click **Component 1>Magnetic Fields>Multi-Turn Coil 1** and choose **Edges>Reference Edge**.

2 In the **Reference Edge** settings window, locate the **Edge Selection** section.

3 Click **Clear Selection**.

4 Select Edges 22, 23, 57, and 82 only.

MESH 1

Scale 1

1 In the **Model Builder** window, under **Component 1** right-click **Mesh 1** and choose **Scale**.

2 In the **Scale** settings window, locate the **Geometric Entity Selection** section.

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

4 Select Domains 2–5 only.

5 Locate the **Scale** section. In the **Element size scale** edit field, type 0.5.

Free Triangular 1

1 On the **Mesh** toolbar, click **Boundary** and choose **Free Triangular**.

2 Select Boundary 30 only.

Size 1

1 Right-click **Component 1>Mesh 1>Free Triangular 1** and choose **Size**.

2 In the **Size** settings window, locate the **Element Size** section.

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

4 Click to expand the **Element size parameters** section. Locate the **Element Size** section. Click the **Custom** button.

5 Locate the **Element Size Parameters** section. Select the **Maximum element size** check box.

6 In the associated edit field, type 0.4.

Free Tetrahedral 1

1 In the **Model Builder** window, right-click **Mesh 1** and choose **Free Tetrahedral**.

2 In the Settings window, click **Build All**.

STUDY 1

On the **Home** toolbar, click **Compute**.

RESULTS

Magnetic Flux Density Norm (mf)

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

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

3 Find the **z-planes** subsection. In the **Planes** edit field, type 0.

4 On the **3D plot group** toolbar, click **Plot**.

COMPONENT 1

On the **Home** toolbar, click **Add Physics**.

ADD PHYSICS

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

2 In the **Add physics** tree, select **AC/DC>Charged Particle Tracing (cpt)**.

3 Find the **Physics in study** subsection. In the table, enter the following settings:

Studies	Solve
Study 1	×

4 In the **Add physics** window, click **Add to Component**.

5 On the **Home** toolbar, click **Add Physics**.

ROOT

On the **Home** toolbar, click **Add Study**.

ADD STUDY

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

2 Find the **Studies** subsection. In the tree, select **Preset Studies>Time Dependent**.

3 Find the **Physics in study** subsection. In the table, enter the following settings:

Physics	Solve
Magnetic Fields (mf)	×

4 In the **Add study** window, click **Add Study**.

5 On the **Home** toolbar, click **Add Study**.

GEOMETRY 1

In the **Model Builder** window, collapse the **Component 1>Geometry 1** node.

CHARGED PARTICLE TRACING

1 In the **Model Builder** window, click **Component 1>Charged Particle Tracing**.

2 In the **Charged Particle Tracing** settings window, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Select Domain 1 only.

Magnetic Force 1

You need to provide the forces acting on the particles; in this case, the magnetic (Lorentz) force.

1 On the **Physics** toolbar, click **Domains** and choose **Magnetic Force**.

2 Select Domain 1 only.

3 In the **Magnetic Force** settings window, locate the **Magnetic Force** section.

4 From the **B** list, choose **Magnetic flux density (mf)**.

Inlet 1

1 On the **Physics** toolbar, click **Boundaries** and choose **Inlet**.

2 Select Boundary 30 only.

3 In the **Inlet** settings window, locate the **Initial Position** section.

4 From the **Initial position** list, choose **Projected plane grid**.

5 In the N edit field, type 10000.

6 Locate the **Initial Velocity** section. Specify the $\mathbf{v}_0$ vector as

|	
0	x
0	y
velec	z

STUDY 2

Step 1: Time Dependent

1 In the **Model Builder** window, expand the **Study 2** node, then click **Step 1: Time Dependent**.

2 In the **Time Dependent** settings window, click to expand the **Values of dependent variables** section.

3 Locate the **Values of Dependent Variables** section. Select the **Values of variables not solved for** check box.

4 From the **Method** list, choose **Solution**.

5 From the **Study** list, choose **Study 1, Stationary**.

6 Locate the **Study Settings** section. Click the **Range** button.

7 Go to the **Range** dialog box.

8 From the **Entry method** list, choose **Number of values**.

9 In the **Stop** edit field, type 5e-9.

10 In the **Number of values** edit field, type 25.

11 Click the **Replace** button.

12 On the **Home** toolbar, click **Compute**.

RESULTS

Particle Trajectories (cpt)

1 In the **Model Builder** window, under **Results>Particle Trajectories (cpt)** click **Particle Trajectories 1**.

2 In the **Particle Trajectories** settings window, locate the **Coloring and Style** section.

3 Find the **Line style** subsection. From the **Type** list, choose **Line**.

4 Find the **Point style** subsection. From the **Type** list, choose **None**.

5 In the **Model Builder** window, under **Results>Particle Trajectories (cpt)>Particle Trajectories 1** click **Color Expression 1**.

6 In the **Color Expression** settings window, locate the **Expression** section.

7 In the **Expression** edit field, type sqrt(cpt.Ftx^2+cpt.Fty^2+cpt.Ftz^2).

8 On the **3D plot group** toolbar, click **Plot**.

Time=5e-9 s Particle trajectories
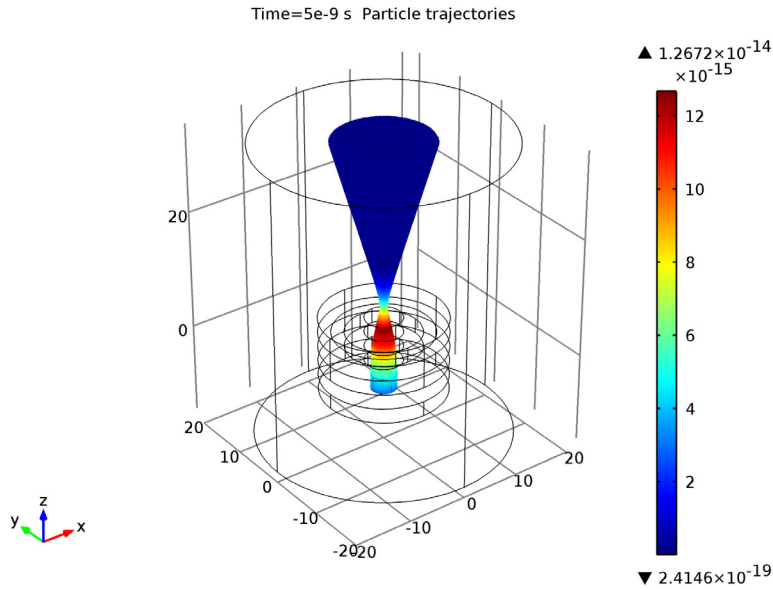
Now construct a Poincaré map to visualize the radial distribution of particles initially, at the focal point and at the exit of the modeling domain.

Data Sets

1 On the **Results** toolbar, click **Cut Plane**.

2 In the **Cut Plane** settings window, locate the **Plane Data** section.

3 From the **Plane** list, choose **xy-planes**.

4 In the **z-coordinate** edit field, type -6.

5 Locate the **Data** section. From the **Data set** list, choose **Particle 1**.

6 Right-click **Results>Data Sets>Cut Plane 1** and choose **Duplicate**.

7 In the **Cut Plane** settings window, locate the **Plane Data** section.

8 In the **z-coordinate** edit field, type 7.

9 Right-click **Results>Data Sets>Cut Plane 2** and choose **Duplicate**.

10 In the **Cut Plane** settings window, locate the **Plane Data** section.

11 In the **z-coordinate** edit field, type 34.

2D Plot Group 3

1 On the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.

2 On the **2D plot group** toolbar, click **More Plots** and choose **Poincaré Map**.

3 In the **Poincaré Map** settings window, locate the **Data** section.

4 From the **Cut plane** list, choose **Cut Plane 3**.

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

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

7 Select the **Radius scale factor** check box.

8 In the associated edit field, type 4E-2.

9 Right-click **Results>2D Plot Group 3>Poincaré Map 1** and choose **Duplicate**.

10 In the **Poincaré Map** settings window, locate the **Data** section.

11 From the **Cut plane** list, choose **Cut Plane 1**.

12 Locate the **Coloring and Style** section. In the **Radius scale factor** edit field, type 2E-2.

13 From the **Color** list, choose **Red**.

14 Right-click **Results>2D Plot Group 3>Poincaré Map 2** and choose **Duplicate**.

15 In the **Poincaré Map** settings window, locate the **Data** section.

16 From the **Cut plane** list, choose **Cut Plane 2**.

17 Locate the **Coloring and Style** section. From the **Color** list, choose **Blue**.

18 In the **Radius scale factor** edit field, type 5E-3.

19 On the **2D plot group** toolbar, click **Plot**.

20 Click the **Zoom Extents** button on the Graphics toolbar.

Poincaré map Poincaré map Poincaré map