Sensitive High-Resolution Ion Microprobe

Introduction

A spectrometer designed to measure the energy, energy spread, and mass-to-charge ratio of a particle beam, can be simulated by solving the equations of motion for ions in an electric and magnetic field. Such a device can be most easily understood by looking at the ideal design, where the electric and magnetic fields are at their theoretically optimum values, which are easily derived.

Model Definition

Using some basic mathematics, the magnitude and direction of the electric and magnetic fields (or to be precise, the magnetic flux density) can be computed to ensure 100 % transmission for an ion of a given initial energy and charge to mass ratio.

The geometry of a basic Sensitive High-Resolution Ion Microprobe (SHRIMP) is shown below. The basic operating principle involves isolating particles of a specified energy and mass-to-charge ratio by subjecting the beam to a radial electric field followed by a uniform magnetic field.

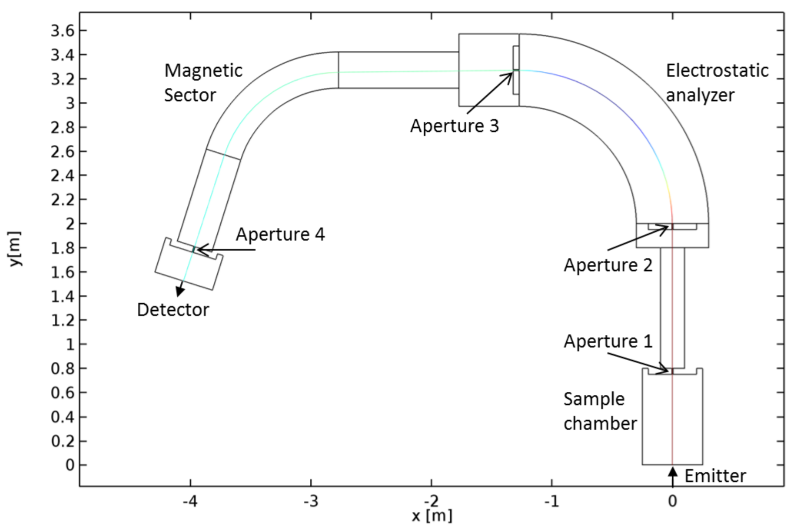

Figure 1: Basic SHRIMP geometry. Particles enter through the emitter, and are subjected first to an electric field directed radially inward, and then to a uniform out-of-plane magnetic flux density.

FORCE BALANCE

The toroidal electrostatic analyzer filters particles according to their kinetic energy. For a particle to propagate through the analyzer along a circular arc of radius r (SI unit: m), the centrifugal force acting on the particle must balance the electric force, that is:

$$\frac{mv^2}{r} = qE_r \tag{1}$$

where

- m (SI unit: kg) is the particle mass,
- v (SI unit: m/s) is the particle velocity magnitude,
- q (SI unit: C) is the absolute value of the particle charge, and
- E_r (SI unit: V/m) is the radial component of the electric field.

Using the classical definition of kinetic energy, $\varepsilon = mv^2/2$, the radial component of the electric field should be:

$$E_r = \frac{2\varepsilon}{qr} \tag{2}$$

This can be conveniently entered into COMSOL using an expression.

The magnetic sector filters particles according to their mass-to-charge ratio. For particles to propagate through a toroidal region along a circular arc of radius r while subjected to a uniform magnetic flux density $\mathbf{B}$ (SI unit: T), the centrifugal force must once again balance the magnetic force:

$$\frac{mv^2}{r} = q(\mathbf{v} \times \mathbf{B}) \tag{3}$$

where $\mathbf{v}$ (SI unit: m/s) is the particle velocity. Since the force should only be produced in the xy-plane, the magnetic flux density should only have a z-component:

$$B_z = -\frac{mv}{qr} \tag{4}$$

For a sulfur hexafluoride ion with an initial energy of 50 eV, electrostatic analyzer with mean radius 1.272 m, and magnetic sector of mean radius 1 m, this results in an electric field magnitude of 78.616 V/m and a magnetic flux density magnitude of 0.012346 T.

The goal of the model is to compute the nominal trajectory of the particle beam and the fraction of ions that reach various points along the beam path (transmission probability).

RELEASE MECHANISM

A realistic velocity distribution of the ions entering the modeling domain is necessary. The **Particle Beam** feature provides may different ways to characterize the initial beam position and velocity. A common way of characterizing the beam is to use Twiss parameters and emittance, which give a measure of the transverse velocity distribution of the particles. It is also possible to specify the phase space ellipse dimensions directly, as indicated in Figure 2.

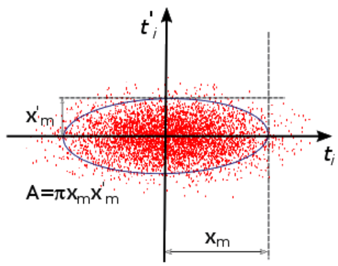

Figure 2: Beam specification using phase space ellipse dimensions.

In this case, the maximum transverse displacement is equal to the size of the inlet aperture and the maximum transverse velocity is 0.001 times the velocity norm, corresponding to a beam which diverges very slowly. Despite this, a significant fraction of the beam current will be lost as the beam travels through 4 additional apertures en route to the detector.

Results and Discussion

The trajectories of the particle beam are indicated in Figure 3 below. The beam starts at (0,0,0) and travels along the y direction. Part of the beam is lost at the first aperture. After traveling 2 m in the y direction, the beam encounters the radial electrostatic force, whose magnitude is selected to ensure maximum transmittance. If there were ions present with a different charge number or initial energy, they would not reach the third aperture, at the other end of the electrostatic separator.

At the boundaries where the electric and magnetic forces change discontinuously, a **Wall** node with a **Pass through** condition is used. This improves the accuracy of the calculation of the particle trajectories during time steps in which they enter or leave one of these regions.

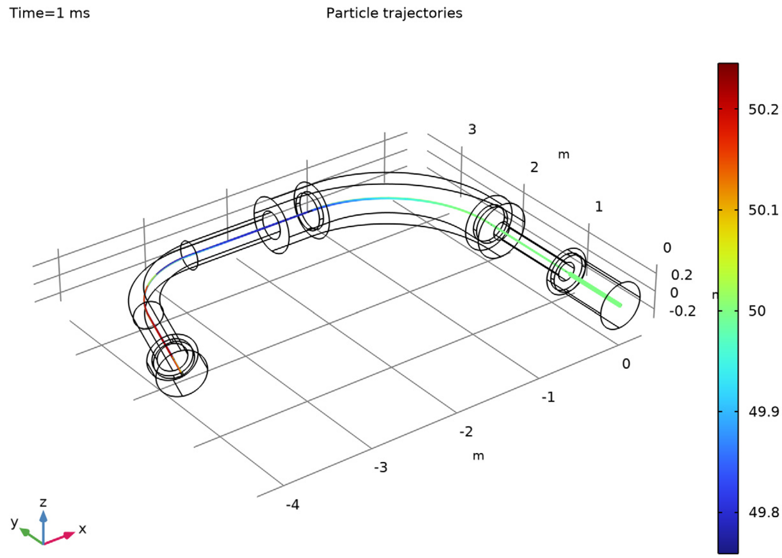

Figure 3: Plot of the particle trajectories through the system.

Once the ions cross the third aperture, they travel in the negative *x* direction until they enter the domain containing the magnetic filter. The uniform out-of-plane magnetic flux density causes the beam to follow a circular arc in this region. The magnetic flux density is chosen so that only the sulfur hexafluoride ions are transmitted through the forth aperture toward the detector. Any ions with a different initial energy or charge to mass ratio would be separated during this stage.

The nominal trajectory of the beam is shown in Figure 4. This is the average position of the beam, where the averaging only occurs for particles which reach the detector. Each **Particle Counter** feature in the model creates variables to filter particles based on the domain or boundary they occupy, allowing convenient visualization of the nominal trajectory of a beam which connects a source and a detector.

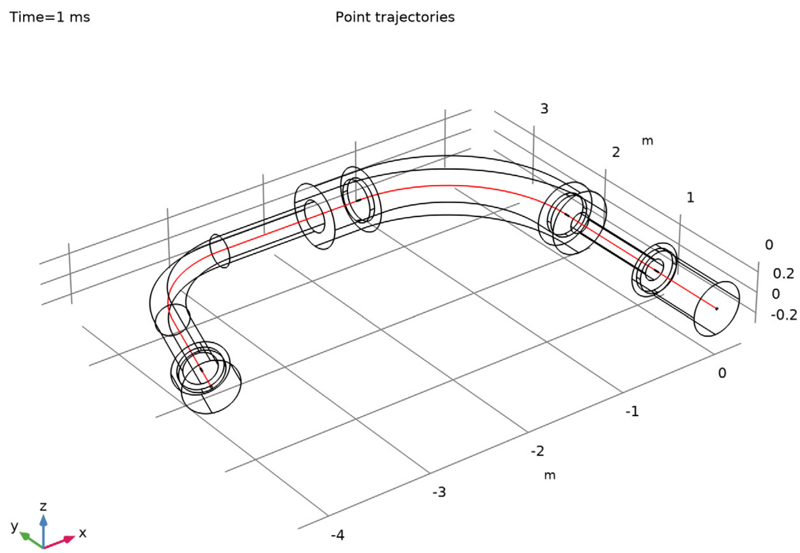

Figure 4: Plot of the nominal trajectory of the particles transmitted from the inlet to the detector.

The transmission probability of the beam in this example is about 0.3.

Reference

1. https://en.wikipedia.org/wiki/Sensitive_high-resolution_ion_microprobe

Application Library path: `Particle_Tracing_Module/Charged_Particle_Tracing/sensitive_high_resolution_ion_microprobe`

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>Particle Tracing>Charged Particle Tracing (cpt)**.
3 Click **Add**.
4 Click **Study**.
5 In the **Select Study** tree, select **General Studies>Time Dependent**.
6 Click **Done**.

GEOMETRY 1

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
2 Browse to the model's Application Libraries folder and double-click the file `sensitive_high_resolution_ion_microprobe_geom_sequence.mph`.
3 In the **Insert Sequence** dialog box, click **OK**.
4 In the **Geometry** toolbar, click **Build All**.

Load the model's variables, which define the electric and magnetic fields.

DEFINITIONS

Variables 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Definitions** and choose **Variables**.
2 In the **Settings** window for **Variables**, locate the **Variables** section.
3 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `sensitive_high_resolution_ion_microprobe_variables.txt`.

GLOBAL DEFINITIONS

Load the model's physics parameters.

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 Click **Load from File**.
4 Browse to the model's Application Libraries folder and double-click the file `sensitive_high_resolution_ion_microprobe_phys_parameters.txt`.

Define selections.

DEFINITIONS

Electrostatic Analyzer

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

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

3 Select Domain 6 only.

Magnetic Sector

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

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

3 Select Domain 3 only.

Sample Chamber

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

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

3 Select Domain 8 only.

Detector

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

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

3 Select Domain 1 only.

Filters

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

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

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

4 Select Boundaries 5–8, 14–20, 39–47, 51, 52, 63–69, 72, 75–80, 83–86, and 91–94 only.

Apertures

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

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

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

4 Select Boundaries 23, 28, 52, and 80 only.

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

Specify the particle mass and charge. Then define the forces that will act on the particles.

CHARGED PARTICLE TRACING (CPT)

1. In the **Model Builder** window, under **Component 1 (comp1)** click **Charged Particle Tracing (cpt)**.
2. In the **Settings** window for **Charged Particle Tracing**, locate the **Particle Release and Propagation** section.
3. From the **Particle release specification** list, choose **Specify current**.
4. From the **Formulation** list, choose **Newtonian, first order**.
5. Locate the **Additional Variables** section. Select the **Store particle status data** check box.

Particle Properties 1

1. In the **Model Builder** window, under **Component 1 (comp1)>Charged Particle Tracing (cpt)** click **Particle Properties 1**.
2. In the **Settings** window for **Particle Properties**, locate the **Particle Mass** section.
3. In the m_{p} text field, type `Mr*mp_const`.
4. Locate the **Charge Number** section. In the Z text field, type `1`.

Electric Force 1

1. In the **Physics** toolbar, click **Domains** and choose **Electric Force**.
2. In the **Settings** window for **Electric Force**, locate the **Domain Selection** section.
3. From the **Selection** list, choose **Electrostatic Analyzer**.
4. Locate the **Electric Force** section. Specify the $\mathbf{E}$ vector as

Ex	x
Ey	y
Ez	z

Magnetic Force 1

1. In the **Physics** toolbar, click **Domains** and choose **Magnetic Force**.
2. In the **Settings** window for **Magnetic Force**, locate the **Domain Selection** section.
3. From the **Selection** list, choose **Magnetic Sector**.
4. Locate the **Magnetic Force** section. Specify the $\mathbf{B}$ vector as

Bx	x

By	y
Bz	z

Particle Beam 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Beam**.

2 Select Boundary 74 only.

3 In the **Settings** window for **Particle Beam**, locate the **Initial Position** section.

4 In the N text field, type `5000`.

5 Locate the **Initial Transverse Velocity** section. From the **Transverse velocity distribution specification** list, choose **Specify phase space ellipse dimensions**.

6 In the x_{m} text field, type `1[cm]`.

7 In the x_{m}' text field, type `0.001`.

8 Locate the **Initial Longitudinal Velocity** section. In the E text field, type `Ei0`.

Add **Particle Counter** features at the detector as well as at the lens apertures. The particle counters will be used to visualize the nominal trajectory of the beam ions that reach the detector.

Particle Counter 1

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Counter**.

2 Select Boundary 11 only.

3 In the **Settings** window for **Particle Counter**, locate the **Particle Counter** section.

4 From the **Release feature** list, choose **Particle Beam 1**.

Particle Counter 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Counter**.

2 Select Boundary 65 only.

3 In the **Settings** window for **Particle Counter**, locate the **Particle Counter** section.

4 From the **Release feature** list, choose **Particle Beam 1**.

Particle Counter 3

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Counter**.

2 Select Boundary 68 only.

3 In the **Settings** window for **Particle Counter**, locate the **Particle Counter** section.

4 From the **Release feature** list, choose **Particle Beam 1**.

Particle Counter 4

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Counter**.

2 Select Boundary 51 only.

3 In the **Settings** window for **Particle Counter**, locate the **Particle Counter** section.

4 From the **Release feature** list, choose **Particle Beam 1**.

Particle Counter 5

1 In the **Physics** toolbar, click **Boundaries** and choose **Particle Counter**.

2 Select Boundary 8 only.

3 In the **Settings** window for **Particle Counter**, locate the **Particle Counter** section.

4 From the **Release feature** list, choose **Particle Beam 1**.

Wall 2

1 In the **Physics** toolbar, click **Boundaries** and choose **Wall**.

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

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

4 Locate the **Wall Condition** section. From the **Wall condition** list, choose **Pass through**.

Specifying a **Pass through** condition at boundaries where the force changes discontinuously will increase the accuracy of the solution.

MESH 1

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

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Finer**.

Free Triangular 1

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

2 Select Boundaries 3, 11, 61, and 74 only.

Size 1

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

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

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

4 Click **Build Selected**.

Free Triangular 2

1 In the **Model Builder** window, under **Component 1 (comp1)>Mesh 1** right-click **Free Triangular 1** and choose **Duplicate**.

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

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

Size 1

1 In the **Model Builder** window, expand the **Free Triangular 2** node, then click **Size 1**.

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

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

4 Click **Build Selected**.

5 Click the **Go to Default View** button in the **Graphics** toolbar.

Free Tetrahedral 1

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

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

Because **Newtonian, first order** was selected from the **Formulation** list, the default solver uses explicit time stepping. This can significantly improve simulation time in some classes of nonstiff problems.

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

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

3 From the **Time unit** list, choose **ms**.

4 In the **Output times** text field, type `range(0,0.01,1)`.

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

RESULTS

Particle Trajectories 1

1 In the **Model Builder** window, expand the **Particle Trajectories (cpt)** node, then click **Particle Trajectories 1**.

2 In the **Settings** window for **Particle Trajectories**, 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 **Particle Trajectories (cpt)** toolbar, click **Plot**.

Color Expression 1

1 In the **Model Builder** window, expand the **Particle Trajectories 1** node, then click **Color Expression 1**.

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)> Charged Particle Tracing>Velocity and energy>cpt.Ep - Particle kinetic energy - J**.

3 Locate the **Expression** section. From the **Unit** list, choose **eV**.

4 In the **Particle Trajectories (cpt)** toolbar, click **Plot**.

5 Click the **Zoom Extents** button in the **Graphics** toolbar. The resulting image should look like Figure 3.

The nominal trajectory of the fraction of the beam which reaches the detector can be visualized by modifying the default **Point Trajectories** plot.

Point Trajectories 1

1 In the **Model Builder** window, expand the **Average Beam Position (cpt)** node, then click **Point Trajectories 1**.

2 In the **Settings** window for **Point Trajectories**, click **Replace Expression** in the upper-right corner of the **Trajectory Data** section. From the menu, choose **Component 1 (comp1)> Charged Particle Tracing>Particle Counter 1>cpt.pcnt1.qavtx,...,cpt.pcnt1.qavtz - Average position of transmitted particles, Particle Beam 1 to Particle Counter 1**.

Color Expression 1

1 In the **Model Builder** window, expand the **Point Trajectories 1** node.

2 Right-click **Color Expression 1** and choose **Disable**.

Average Beam Position (cpt)

Click the **Zoom Extents** button in the **Graphics** toolbar. The resulting image should look like Figure 4.

Finally, compute the transmission probability of the particles reaching the detector.

Global Evaluation 1

1 In the **Results** toolbar, click **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, locate the **Data** section.

3 From the **Time selection** list, choose **Last**.

4 Click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Charged Particle Tracing>Particle Counter 1> cpt.pcnt1.alpha - Transmission probability - 1**.

5 Click **Evaluate**.

Appendix A — Geometry Instructions

ADD COMPONENT

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

GLOBAL DEFINITIONS

Load the model's parameters.

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 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file `sensitive_high_resolution_ion_microprobe_parameters.txt`.

Create a parameterized geometry part for the four lenses used in the model.

LENS

1 In the **Model Builder** window, right-click **Global Definitions** and choose **Geometry Parts> 3D Part**.

2 In the **Settings** window for **Part**, type `Lens` in the **Label** text field.

3 Locate the **Input Parameters** section. In the table, enter the following settings:

Name	Default expression	Value	Description
`rinner`	`0.5[cm]`	0.005 m	`Inner radius`
`router`	`0.2[m]`	0.2 m	`Outer radius`
`hlens`	`0.05[m]`	0.05 m	`Lens thickness`

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 `router`.

4 In the **Height** text field, type `hlens`.

5 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

Cylinder 2 (cyl2)

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 `rinner`.

4 In the **Height** text field, type `hlens`.

5 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the object **cyl1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **cyl2** only.

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

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

5 In the **Geometry** toolbar, click **Build All**.

GEOMETRY 1

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 `rsample`.

4 In the **Height** text field, type `hsample`.

5 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

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

4 On the object **cyl1**, select Boundary 3 only.

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 `rin`.

Cylinder 2 (cyl2)

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

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

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

4 In the **Height** text field, type `hentrance`.

5 Locate the **Position** section. In the **y** text field, type `hsample`.

6 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

Cylinder 3 (cyl3)

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 `r1_analyzer`.

4 In the **Height** text field, type `h_analyzer_pre`.

5 Locate the **Position** section. In the **y** text field, type `hsample+hentrance`.

6 Locate the **Axis** section. From the **Axis type** list, choose **y-axis**.

Work Plane 2 (wp2)

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

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

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

4 On the object **cyl3**, select Boundary 4 only.

5 Click **Go to Plane Geometry**.

Work Plane 2 (wp2)>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 `r1_analyzer`.

Revolve 1 (rev1)

1 Right-click **Geometry 1** and choose **Revolve**.

2 In the **Settings** window for **Revolve**, locate the **Revolution Angles** section.

3 Click the **Angles** button.

4 In the **End angle** text field, type `ang_analyzer`.

5 Locate the **Revolution Axis** section. From the **Axis type** list, choose **3D**.

6 Find the **Point on the revolution axis** subsection. In the **x** text field, type `-r0_analyzer`.

7 In the **y** text field, type `hsample+hentrance+h_analyzer_pre`.

8 Find the **Direction of revolution axis** subsection. In the **y** text field, type `0`.

9 In the **z** text field, type `1`.

Work Plane 3 (wp3)

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

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

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

4 On the object **rev1**, select Boundary 1 only.

5 Click **Go to Plane Geometry**.

Work Plane 3 (wp3)>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 `r1_analyzer`.

Extrude 1 (ext1)

1 Right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
`h_analyzer_post`

Work Plane 4 (wp4)

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

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

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

4 On the object **ext1**, select Boundary 1 only.

5 Click **Go to Plane Geometry**.

Work Plane 4 (wp4)>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 `rexit`.

Extrude 2 (ext2)

1 Right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
hexit

Work Plane 5 (wp5)

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

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

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

4 On the object **ext2**, select Boundary 1 only.

5 Click **Go to Plane Geometry**.

Work Plane 5 (wp5)>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 `rexit`.

Revolve 2 (rev2)

1 Right-click **Geometry 1** and choose **Revolve**.

2 In the **Settings** window for **Revolve**, locate the **Revolution Angles** section.

3 Click the **Angles** button.

4 In the **End angle** text field, type `ang_magnet`.

5 Locate the **Revolution Axis** section. From the **Axis type** list, choose **3D**.

6 Find the **Point on the revolution axis** subsection. In the **x** text field, type `-r0_analyzer-h_analyzer_post-hexit`.

7 In the **y** text field, type `hsample+hentrance+h_analyzer_pre+r0_analyzer-r_magnet`.

8 Find the **Direction of revolution axis** subsection. In the **y** text field, type `0`.

9 In the **z** text field, type `1`.

Work Plane 6 (wp6)

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

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

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

4 On the object **rev2**, select Boundary 1 only.

5 Click **Go to Plane Geometry**.

Work Plane 6 (wp6)>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 `rexit`.

Extrude 3 (ext3)

1 Right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
`hout`

Work Plane 7 (wp7)

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

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

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

4 On the object **ext3**, select Boundary 1 only.

5 Click **Go to Plane Geometry**.

Work Plane 7 (wp7)>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 `rdetector`.

Extrude 4 (ext4)

1 Right-click **Geometry 1** and choose **Extrude**.

2 In the **Settings** window for **Extrude**, locate the **Distances** section.

3 In the table, enter the following settings:

Distances (m)
`hdetector`

Work Plane 8 (wp8)

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

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

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

4 On the object **ext4**, select Boundary 3 only.

5 Click **Go to Plane Geometry**.

Work Plane 8 (wp8)>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 `rtarget`.

Add additional work planes for lens placement.

Work Plane 9 (wp9)

1 Right-click **Geometry 1** and choose **Work Plane**.

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

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

4 On the object **cyl1**, select Boundary 4 only.

Work Plane 10 (wp10)

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

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

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

4 On the object **rev1**, select Boundary 1 only.

5 In the **Offset in normal direction** text field, type `hoffset`.

Work Plane 11 (wp11)

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

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

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

4 On the object **ext4**, select Boundary 4 only.

5 In the **Offset in normal direction** text field, type `hoffset`.

6 Select the **Reverse normal direction** check box.

Lens 1 (pi1)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Lens**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Work Plane 1 (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Work Plane 9 (wp9)**.

5 Locate the **Selection Settings** section. Select the **Keep noncontributing selections** check box.

Lens 2 (pi2)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Lens**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Work Plane 1 (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Work Plane 2 (wp2)**.

5 Locate the **Selection Settings** section. Select the **Keep noncontributing selections** check box.

Lens 3 (pi3)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Lens**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Work Plane 1 (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Work Plane 10 (wp10)**.

5 Locate the **Selection Settings** section. Select the **Keep noncontributing selections** check box.

Lens 4 (pi4)

1 In the **Geometry** toolbar, click **Part Instance** and choose **Lens**.

2 In the **Settings** window for **Part Instance**, locate the **Position and Orientation of Output** section.

3 Find the **Coordinate system in part** subsection. From the **Work plane in part** list, choose **Work Plane 1 (wp1)**.

4 Find the **Coordinate system to match** subsection. From the **Work plane** list, choose **Work Plane 11 (wp11)**.

5 Locate the **Selection Settings** section. Select the **Keep noncontributing selections** check box.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click **Booleans and Partitions** and choose **Difference**.

2 Select the objects **cyl1**, **cyl2**, **cyl3**, **ext1**, **ext2**, **ext3**, **ext4**, **rev1**, and **rev2** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the **Activate Selection** toggle button for **Objects to subtract**.

5 Select the objects **pi1**, **pi2**, **pi3**, and **pi4** only.

6 Click **Build All Objects**.

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