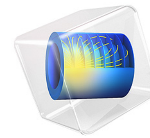
Created in COMSOL Multiphysics 6.2



Dipolar Microwave Plasma Source

Introduction

This model presents a 2D axisymmetric dipolar microwave plasma source sustained through resonant heating of the electrons. This is known as electron cyclotron resonance (ECR), which occurs when a suitable high magnetic flux density is present along with the microwaves.

This is an advanced model that showcases many of the features that make COMSOL Multiphysics unique, including:

- Infinite elements for the magnetostatic model.
- Functional-based mesh adaptation to create a fine mesh on the ECR surface.
- PMLs for the electromagnetic waves to represent infinite space.
- Degrees of freedom for all 3 components of the high-frequency electric field despite the fact that the problem is geometrically axisymmetric.
- Full anisotropic tensors for the plasma conductivity and charged particle transport properties.
- Resonant power absorption in the ECR surface by the electrons.
- Solver sequencing to first compute the static magnetic field, then solve for all the plasma components.

Note: This application requires the Plasma Module, AC/DC Module, and RF Module.

Model Definition — Static Magnetic Field

For the static magnetic field, Ampère's law governs the azimuthal component of the magnetic vector potential:

$$\nabla \times \mu_r^{-1} \mu_0^{-1} (\nabla \times A_\varphi) = J_\varphi$$

where the external current density, J_φ only has an azimuthal component and is defined in the coil as:

$$J_\varphi = \frac{NI}{A}$$

where N is the number of turns in the coil I is the total current and A is the cross-sectional area. To represent the fact that the coil is in free space, infinite elements are used far away from the coil, as shown in Figure 1. A stationary study type is used to compute the static magnetic field. This field is then fed into a self-consistent model for the plasma.

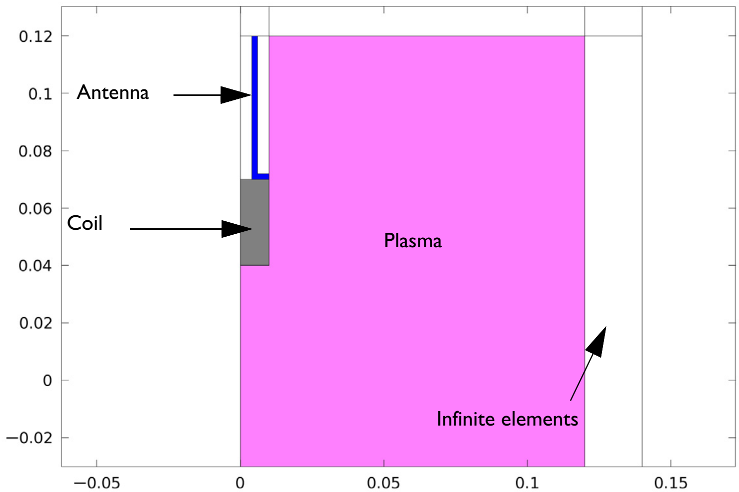


Figure 1: Basic concept for the plasma source. A stationary azimuthal current flows in the coil which generates a static magnetic field in the surroundings. Resonant heating of the electrons occurs on the contour of the critical magnetic flux density.

The plasma conductivity becomes a full tensor in the presence of a static magnetic field. At some critical magnetic field the electrons continually gain energy from the electric fields. This leads to a resonance zone in the plasma where the incoming electromagnetic wave is absorbed over a very short distance. The critical magnetic field is only dependent on the angular frequency, the electron mass, and the charge:

$$B_{\mathrm{cr}} = \frac{\omega m_e}{q}$$

At 2.45 GHz the critical magnetic flux density is 875 gauss or 0.0875 T. Therefore you can use functional-based mesh adaptation to ensure that the ECR surface is adequately meshed for the plasma model. The functional is somewhat arbitrary; it is chosen such that it is zero everywhere but becomes large at the resonant magnetic flux density. In this model, use the functional

$$f = \frac{1}{|\|\mathbf{B}\| - 0.0875| + \delta} \tag{1}$$

where δ is a small number to prevent division by zero.

In this example, you solve the following wave equation for the high-frequency component of the electric field in the frequency domain:

$$\nabla \times \mu_0^{-1}(\nabla \times \mathbf{E}) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right) \cdot \mathbf{E} = 0$$

Here σ is the plasma conductivity, which is a full tensor and a function of the electron density, collision frequency, and the static magnetic flux density. Using the definitions

$$\alpha = \frac{q}{m_e(\nu_e + j\omega)} \tag{2}$$

where q is the electron charge, m_e is the electron mass, ν_e is the electron-neutral collision frequency, and ω is the angular frequency. The inverse of the plasma conductivity is defined as

$$qn_e\sigma^{-1} = \begin{bmatrix} 1 & -\alpha B_z & \alpha B_y \\ \alpha B_z & 1 & -\alpha B_x \\ -\alpha B_y & \alpha B_x & 1 \end{bmatrix} \tag{3}$$

where n_e is the electron number density. Using the inverse of the plasma conductivity is convenient because it can be written in a compact form. COMSOL Multiphysics automatically computes the tensor form of the plasma conductivity for you by inverting Equation 3. Because the plasma conductivity tensor is a full tensor, all three components of the electric field are computed despite the fact that the only excitation from the coaxial port occurs in the rz-plane.

In Ref. 1 the size of the resonance is smoothed over a distance which can be resolved by the mesh. It is argued that this has a physical basis corresponding to collision-less heating. In Ref. 2 the physical reasoning behind the broadening of the resonance zone is Doppler shifting of the electrons into resonance. The same smoothing used in Ref. 1 is available in the COMSOL software by selecting the **Doppler broadening** check box in the Microwave Plasma interface properties. In this case, the collision frequency, ν_e in Equation 2 is replaced by an effective collision frequency:

$$\tilde{\nu}_e = \nu_e + \frac{\omega}{\delta} \tag{4}$$

where δ is chosen to be 20. This is very simple from an implementation point of view but does lead to unphysical power absorption away from the resonance zone. The approach taken in Ref. 2 leads to the ECR surface being broadened only at the resonance zone.

For the electrons, the continuity and electron mean energy equations are solved and the drift-diffusion approximation is used to simplify the momentum equation:

$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot [-n_e(\mu_e \bullet \mathbf{E}) - \mathbf{D}_e \bullet \nabla n_e] = R_e$$

$$\frac{\partial}{\partial t}(n_\varepsilon) + \nabla \cdot [-n_\varepsilon(\mu_\varepsilon \bullet \mathbf{E}) - \mathbf{D}_\varepsilon \bullet \nabla n_\varepsilon] + \mathbf{E} \cdot \Gamma_e = R_\varepsilon$$

The electron source R_e and the energy loss due to inelastic collisions R_ε are defined later. The electron diffusivity, energy mobility and energy diffusivity are calculated from the electron mobility using

$$\mathbf{D}_e = \mu_e T_e,\ \mu_\varepsilon = \left(\frac{5}{3}\right)\mu_e,\ \mathbf{D}_\varepsilon = \mu_\varepsilon T_e$$

The electron transport properties are, like the plasma conductivity, full tensors. The electron mobility in the direction of the magnetic field lines is up to 8 orders of magnitude higher than the cross-field electron mobility. As such, electrons are only transported along magnetic field lines. The inverse of the electron mobility can be written in compact form as

$$\mu_e^{-1} = \begin{bmatrix} \frac{1}{\mu_{dc}} & -B_z & B_y \\ B_z & \frac{1}{\mu_{dc}} & -B_x \\ -B_y & B_x & \frac{1}{\mu_{dc}} \end{bmatrix} \tag{5}$$

where μ_{dc} is the electron mobility in the absence of a magnetic field. The COMSOL software automatically inverts the matrix in Equation 5 for you. The source coefficients in the above equations are determined by the plasma chemistry and are written using rate coefficients.

$$R_e = \sum_j x_j k_j N_n n_e$$

where x_j is the mole fraction of the target species for reaction j, k_j is the rate coefficient for reaction j ($\mathrm{m^3/s}$), and N_n is the total neutral number density ($1/\mathrm{m^3}$).The electron energy loss is obtained by summing the collisional energy loss over all reactions:

$$R_\varepsilon = \sum_j x_j k_j N_n n_e \Delta\varepsilon_j$$

where $\Delta\varepsilon_j$ is the energy loss from reaction j (V). The electron source and inelastic energy loss are automatically computed. The rate coefficients can be computed from cross-section data by the following integral:

$$k_k = \gamma\int_0^\infty \varepsilon\sigma_k(\varepsilon)f(\varepsilon)d\varepsilon$$

where $\gamma = (2q/m_e)^{1/2}$ ($\mathrm{C^{1/2}/kg^{1/2}}$), m_e is the electron mass (kg), ε is energy (V), σ_k is the collision cross section ($\mathrm{m^2}$), and f is the electron energy distribution function. In this model the distribution function is chosen to be Maxwellian:

$$f(\varepsilon) = \phi^{-3/2}\beta_1\exp(-(\varepsilon\beta_2/\phi))$$

where ϕ is the mean electron energy:

$$\phi = \frac{n_\varepsilon}{n_e}$$

and

$$\beta_1 = \Gamma(5/2)^{3/2}\Gamma(3/2)^{-5/2},\ \beta_2 = \Gamma(5/2)\Gamma(3/2)^{-1}$$

where Γ is the gamma function. The Joule term $\mathbf{E}\cdot\Gamma_e$ in this model, is separated in two parts. One in the time domain that includes motion in the ambipolar field in the *rz*-plane and another in the frequency domain representing the heating term from the electromagnetic waves.

For nonelectron species, the following equation is solved for the mass fraction of species k:

$$\rho\frac{\partial}{\partial t}(w_k) + \rho(\mathbf{u}\cdot\nabla)w_k = \nabla\cdot\mathbf{j}_k + R_k \tag{6}$$

As with the electrons, the ion transport properties are functions of the static magnetic flux density. The magnetic force is included as it can generate a significant ion velocity in the azimuthal direction close to the antenna. The ion mobility is also a function of the ambipolar electric field and is specified as a lookup table. The ion diffusion velocity, $\mathbf{v}_k$, is related to the diffusive flux via

$$\mathbf{j}_k = \rho\omega\mathbf{v}_k$$

where

$$\mathbf{v}_k = D_m\nabla\ln(w) + D_m\nabla\ln(M) + Z\mu(\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) \tag{7}$$

Equation 6 can be re-arranged to give an expression for the diffusion velocity as

$$\mathbf{v}_k = \mathbf{A}^{-1}[D_m\nabla\ln(w) + D_m\nabla\ln(M) + Z\mu\mathbf{E}]$$

where

$$\mathbf{A} = \begin{bmatrix} 1 & -Z\mu B_z & Z\mu B_y \\ Z\mu B_z & 1 & -Z\mu B_x \\ -Z\mu B_y & Z\mu B_x & 1 \end{bmatrix} \tag{8}$$

COMSOL automatically inverts Equation 8 when defining the diffusion velocity for each of the ionic species. The electrostatic field is computed using the equation

$$-\nabla \cdot \varepsilon_0\varepsilon_r\nabla V = \rho$$

The space charge density ρ is automatically computed based on the plasma chemistry specified in the model using the formula

$$\rho = q\left(\sum_{k=1}^{N} Z_k n_k - n_e\right)$$

PLASMA CHEMISTRY

The model considers argon plasma chemistry with the following set of collisions including elastic, excitation, direct ionization and stepwise ionization. Penning ionization and metastable quenching are also included in the model (electron cross sections are obtained from Ref. 3).

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$(eV)
1	e+Ar=>e+Ar	Elastic	0
2	e+Ar=>e+Ars	Excitation	11.5

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon(\mathrm{eV})$
3	e+Ars=>e+Ar	Superelastic	-11.5
4	e+Ar=>2e+Ar+	Ionization	15.8
5	e+Ars=>2e+Ar+	Ionization	4.24
6	Ars+Ars=>e+Ar+Ar+	Penning ionization	-
7	Ars+Ar=>Ar+Ar	Metastable quenching	-

On surfaces, the following two reactions are considered:

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT
1	Ar+=>Ar	1
2	Ars=>Ar	1

BOUNDARY CONDITIONS

The above partial differential equations must be supplemented with a suitable set of boundary conditions.

For the electrons, neglect reflection as well as secondary and thermal emission to get the following boundary condition on the electron flux:

$$\mathbf{n} \cdot \Gamma_e = \left(\frac{1}{2} \nu_{e,\,\mathrm{th}} n_e\right)$$

and the electron energy flux:

$$\mathbf{n} \cdot \Gamma_\varepsilon = \left(\frac{5}{6} \nu_{e,\,\mathrm{th}} n_\varepsilon\right)$$

Losses at the wall for the heavy species is due to surface reactions and migration due to the ambipolar field:

$$\mathbf{n} \cdot \mathbf{j}_k = M_w R_k + M_w c_k Z \mu_k [(\mathbf{A}^{-1} \cdot \mathbf{E}) \cdot \mathbf{n}][(Z_k \mu_k (\mathbf{A}^{-1} \cdot \mathbf{E}) \cdot \mathbf{n}) > 0]$$

The reactor walls are grounded.

Solution Strategy

This problem is solved in two stages. First, compute the static magnetic field using adaptive mesh refinement. Then, in separate study steps, solve for the plasma problem.

The magnetic flux density computed in the first study step is used to define the tensor plasma conductivity as well as electron and ion transport properties.

The plasma problem also uses a two-study approach (giving a total of 3 studies in this model). In the first study that solves for the plasma problem (labeled Pin=20 W) a **Frequency-Transient** study step is used to obtain a solution. In the next study (labeled Pin 20 to 80 W) a **Frequency-Stationary** study step is used to ramp the input power using the **Auxiliary sweep** option. Using a stationary solver to make parameterizations is very efficient but it is difficult to obtain a solution for a plasma problem using arbitrary flat profiles for the initial conditions.

For resonant plasma problems such as this one some effort is needed in choosing the input power and the initial electron density. If the input power is too high it might happen the electron density grows to values where the model used is not valid. Another problem is that if the initial electron density is too low a plasma might not be formed (the electron density goes to zero). The search for the right initial conditions and input power tend to be easier with a transient solver. And once a solution is found a stationary solver can be used to efficiently make parameterizations.

It is possible to set the power absorbed by the plasma as the input quantity instead of the input power by checking the box **Enable active port feedback** in the **Port** feature. However, this approach is not robust in resonant problems like this one and it is not recommended.

Results and Discussion — Static Magnetic Field Model

Figure 2 and Figure 3 present the results from the first study step. As expected, the azimuthal current in the coil generates a static magnetic field that has a “3”-shaped contour at a flux density of 0.0875 T. The magnetic field lines form a circular pattern around the coil, which is important to bear in mind when discuss the transport of the charged particles later.

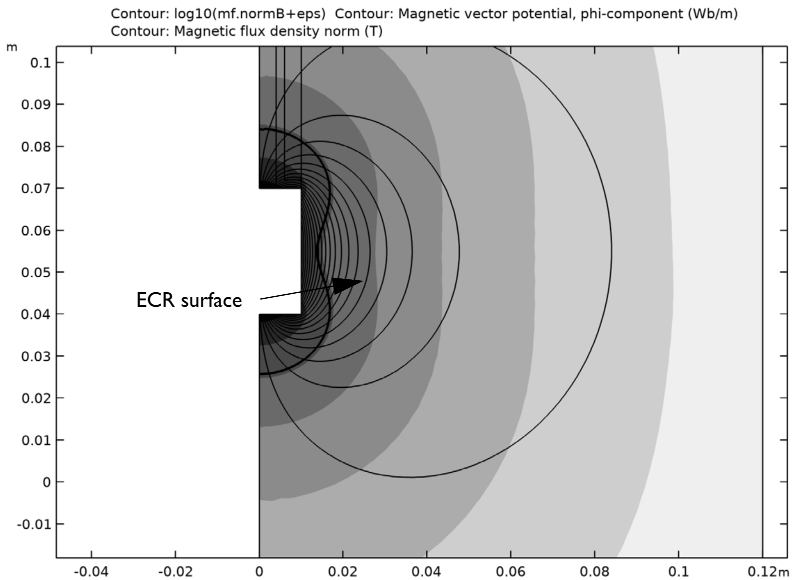


Figure 2: Plot of the static magnetic flux density on a log scale (filled contour), magnetic field lines (thin lines), and the ECR surface at 0.0875 T (thick black line).

In Figure 3 the mesh, which has adapted based on the functional given in Equation 1 is shown. The mesh has clearly been significantly refined around the contour of the resonant magnetic flux density. This is required to accurately resolve the region where all the power deposition to the electrons occurs.

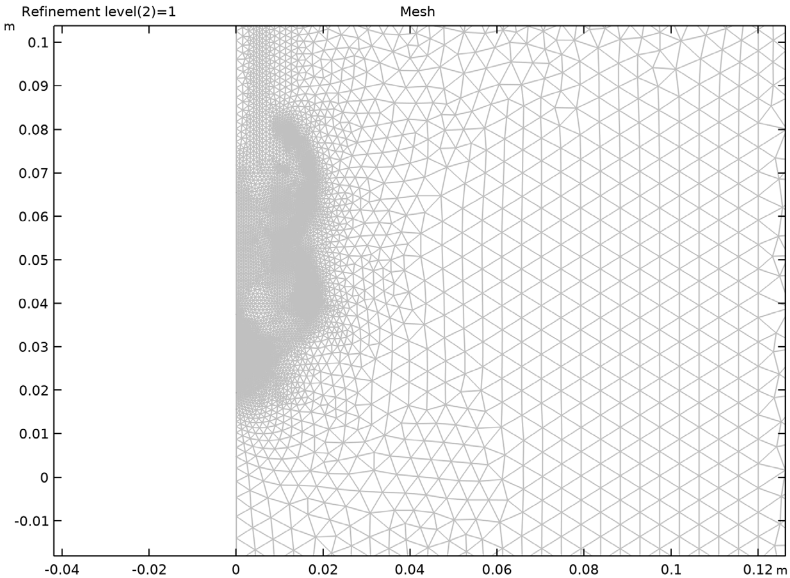


Figure 3: Mesh generated after one refinement using functional-based mesh adaptation. The mesh is very fine on the ECR surface and relatively coarse away from the resonance zone.

Results and Discussion — Microwave Plasma Model

Figure 4 shows the absorbed power absorbed by the plasma as a function of the input power. As can be seen only a small amount of power is absorbed by the plasma. In the following, only results for the case where the plasma absorbs 10 W (corresponding to an input power of 73.5 W) are presented to compare directly to results of Ref. 1.

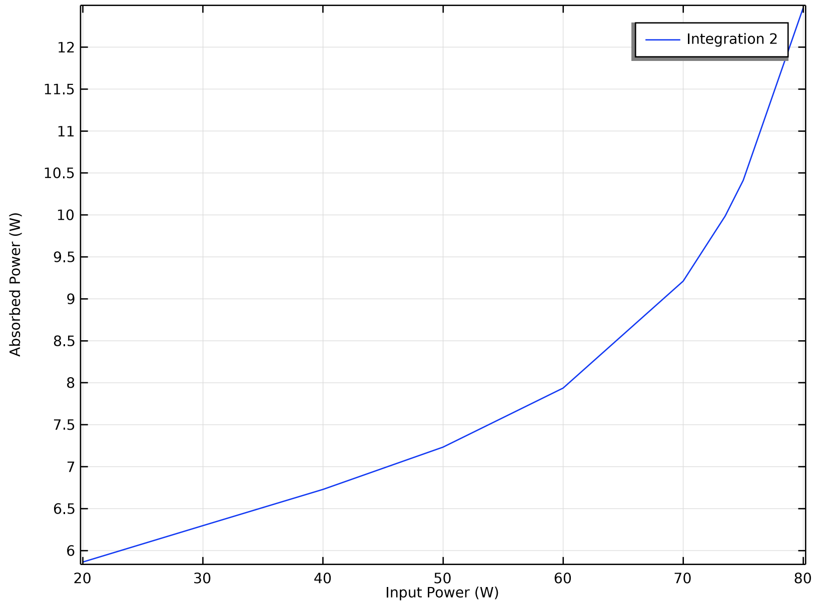


Figure 4: Power absorbed by the plasma as a function of input power.

The electron density at the quasi steady state solution is plotted in Figure 5. The peak electron density is around $5{\cdot}10^{16}$ m^{-3} and peaks radially outward from the center of the coil. The magnitude of the electron number density and its profile agree well with the results in Ref. 1.

Despite the fact that power is only deposited to the plasma on the ECR surface, the electron temperature, plotted in Figure 6, is not sharply peaked at the critical magnetic flux density. Recall from Figure 2 that the magnetic field lines show the circular pattern away from the coil. The high degree of anisotropy in the electron transport properties results in strong energy transport along the magnetic field lines and little transport across the magnetic field lines. Indeed, the circular pattern along which the electron temperature is constant is consistent with the magnetic field lines. The peak electron temperature is around 3.8 eV and around 1.78 eV below the coil, which is again consistent with the results in Ref. 1.

The electron density profile shows no signs of the resonance zone, which is clearly seen in Figure 8. The power deposition is very high, peaking at 35 W/cm^3. All of the power deposition into the plasma from the electromagnetic field occurs in this resonance zone.

The ionization source, plotted in Figure 9 is localized around the coil. This corresponds to the region where the electron density and electron temperature are highest. Because the ionization rate scales linearly with the electron density and exponentially with the electron temperature this is to be expected.

The plasma potential, plotted in Figure 7, peaks at around 16 V. The plasma potential is uniform throughout the plasma, even though the electron temperature shows large variations. The physical basis for the flat plasma potential is explained in Ref. 1.

The degree of anisotropy in the electron transport properties can be seen in Figure 10 and Figure 11. In Figure 10 the electron mobility varies by 8 orders of magnitude, it is $4 \cdot 10^4$ $m^2/(Vs)$ toward the coil edges and 10^{-4} $m^2/(Vs)$ radially outward from the coil center. In Figure 11 the opposite is true, the electron mobility is very high in the z direction at the center of the coil, and very small toward the coil edges. This leads to migration of electrons along the magnetic field lines when they are produced in the ionization region (see Figure 9).

The conduction current due to the microwaves is plotted in Figure 12, Figure 13, and Figure 14. The largest component of the conduction current is actually in the azimuthal direction despite the coaxial port only propagating in the TM mode. Despite this, the heating (cooling) due to the dot product of the azimuthal components of the current and electric fields is small, due to the much lower value of the azimuthal component of the electric field.

Finally, the trace of the plasma conductivity is plotted in Figure 15. The resonance zone is evident and the locally high electrical conductivity leads to the propagating electromagnetic waves to be absorbed.

It is worth mentioning that the electron density in this example model is below the critical plasma density everywhere ($7.4 \cdot 10^{16}$ m^{-3} at 2.45 GHz). If either the pressure or the power is increased, the power absorption can shift from the ECR surface to the contour where the plasma density is equal to the critical plasma density. On this contour the phase velocity approaches infinity whereas the group velocity approaches zero. The numerical instabilities caused by this are also smoothed out by adding an effective collision frequency to the actual collision frequency using Equation 4.

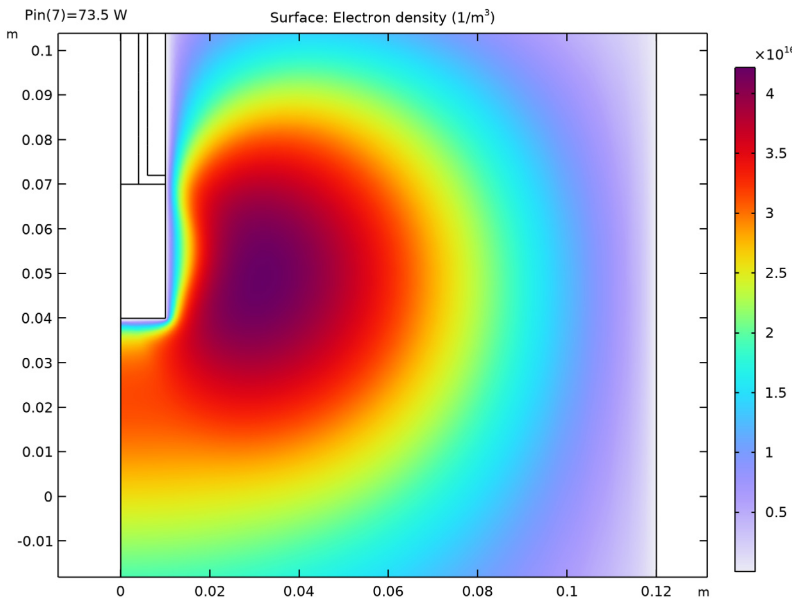


Figure 5: Plot of the electron density for an input power of 73.5 W and absorbed power of 10 W.

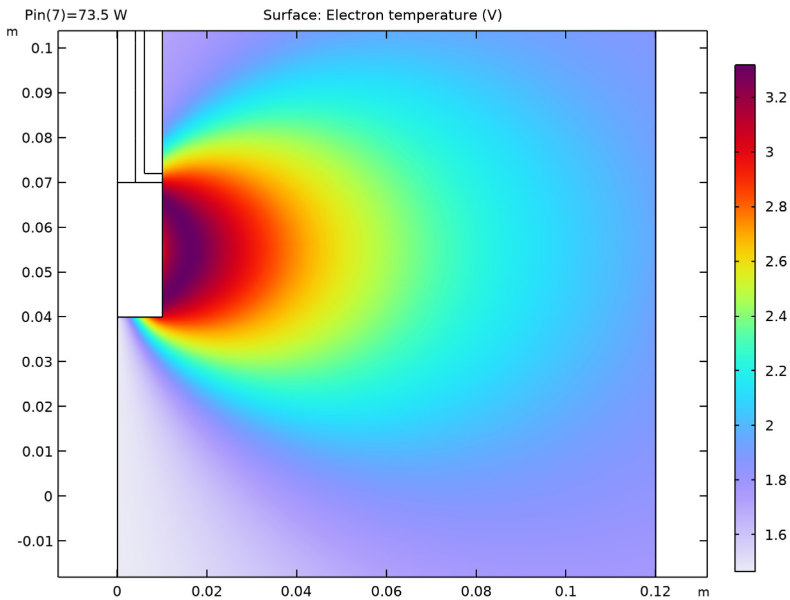


Figure 6: Plot of the electron temperature.

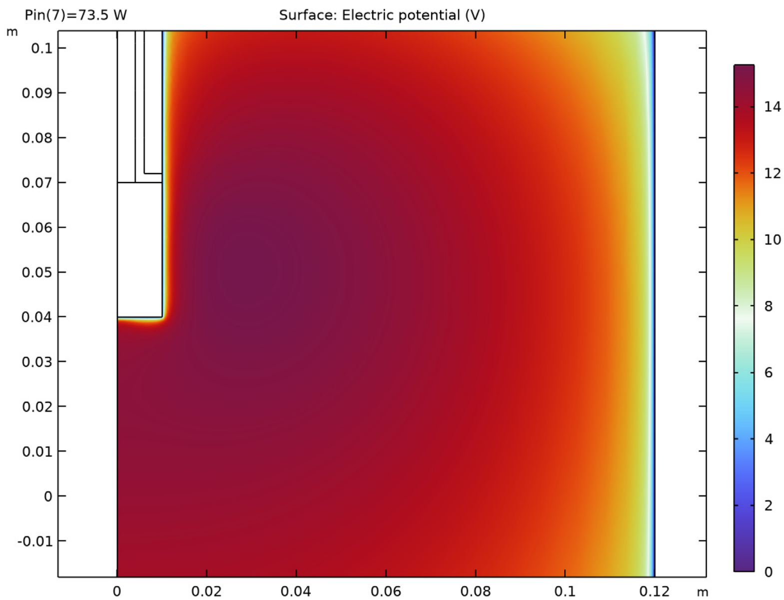


Figure 7: Plot of the plasma potential.

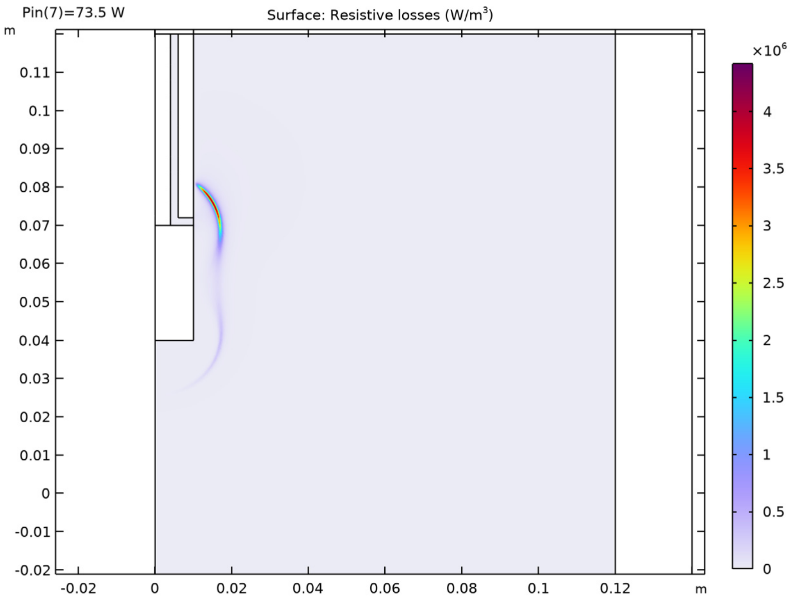


Figure 8: Plot of the power deposition into the plasma. Nearly all the power deposition occurs on the ECR surface.

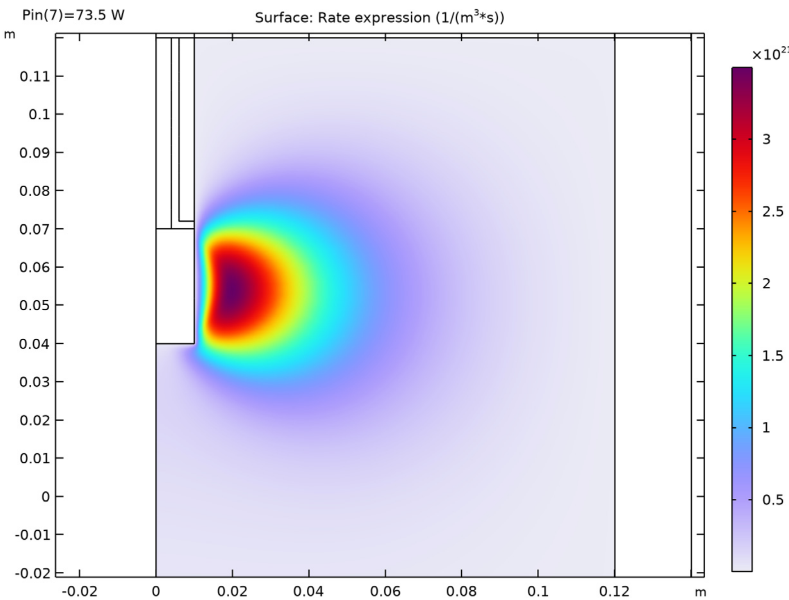


Figure 9: Plot of the rate expression for electrons generated via ionization.

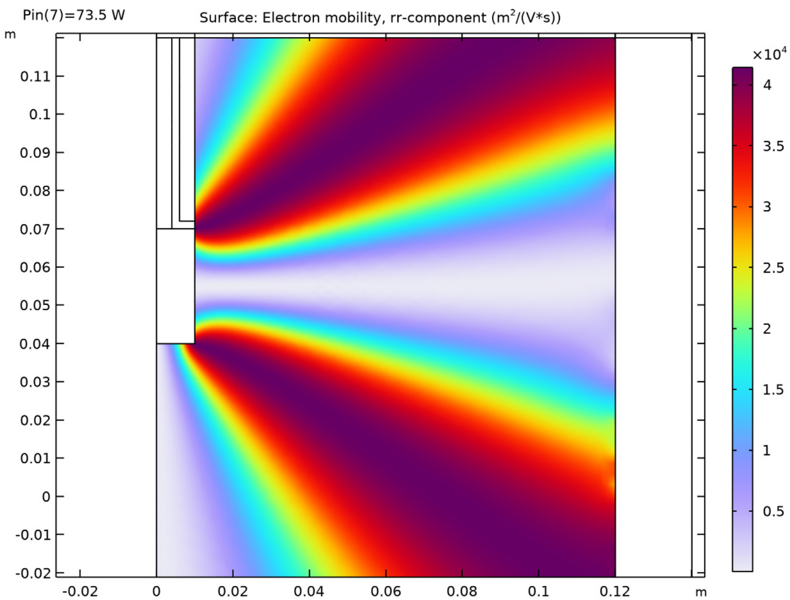


Figure 10: Plot of the electron mobility tensor's rr-component. The mobility varies by 8 orders of magnitude over the space of only a couple of centimeters.

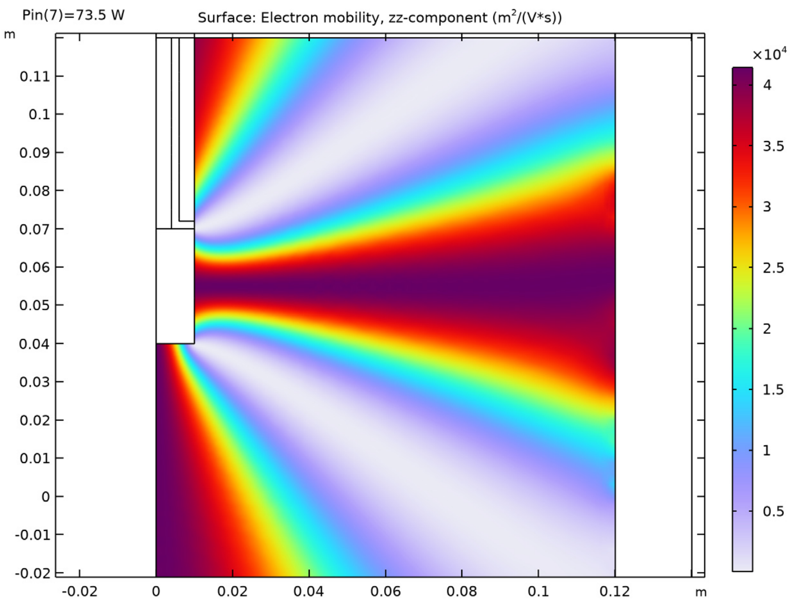


Figure 11: Plot of the electron mobility tensor's zz-component.

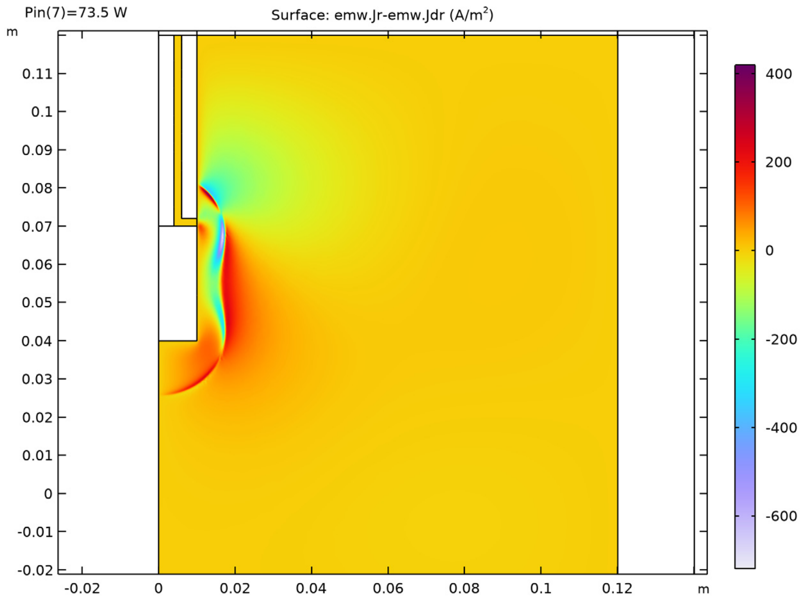


Figure 12: Unnormalized radial component of the microwave conduction current.

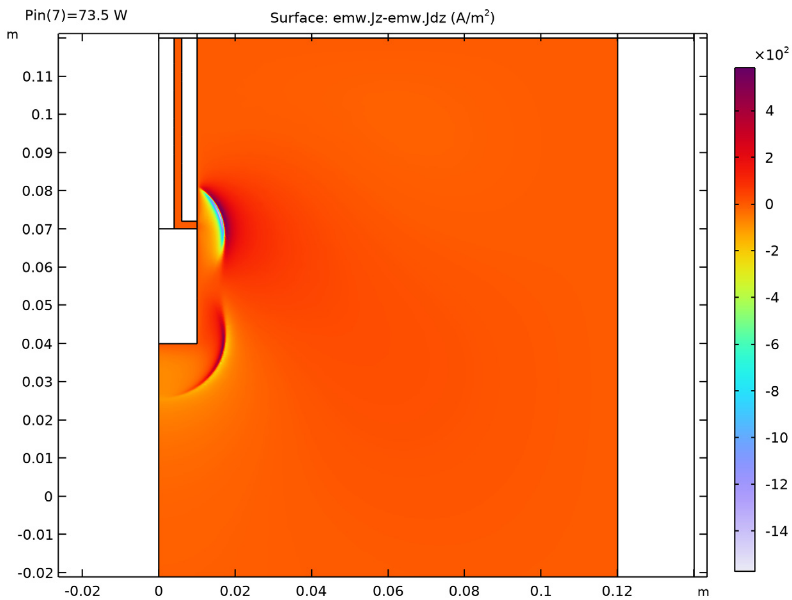


Figure 13: Unnormalized axial component of the microwave conduction current.

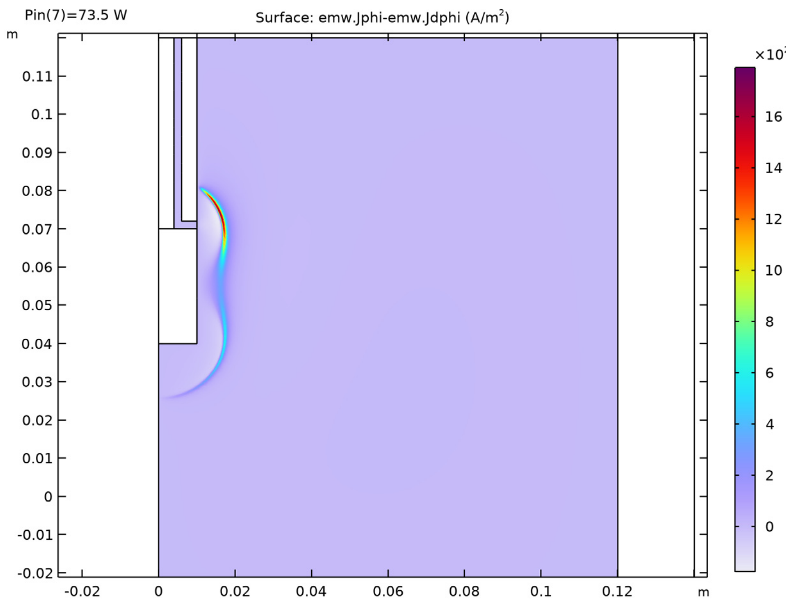


Figure 14: Unnormalized azimuthal component of the microwave conduction current.

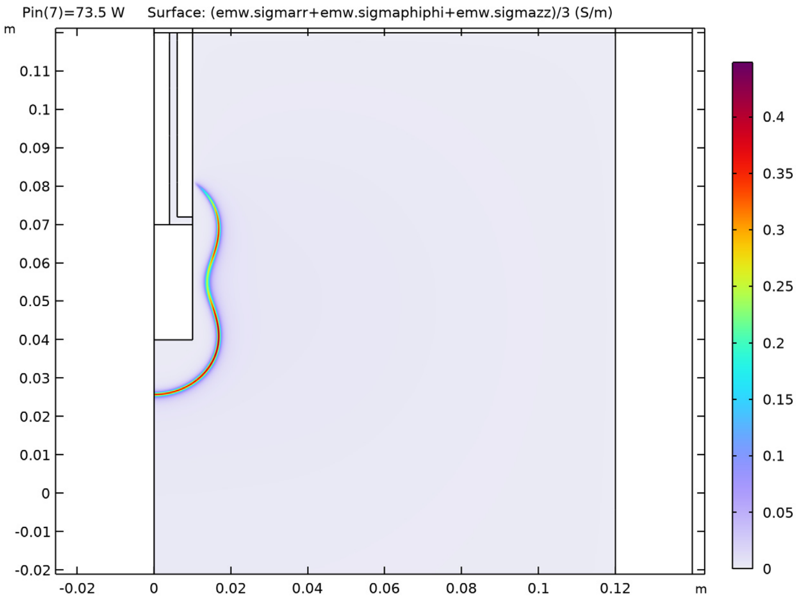


Figure 15: Plot of the trace of the plasma conductivity tensor.

References

1. G.J.M. Hagelaar, K. Makasheva, L. Garrigues, and J.-P. Boeuf, "Modelling of a dipolar microwave plasma sustained by electron cyclotron resonance," *J. Phys. D: Appl. Phys.*, vol. 42, p. 194019 (12pp), 2009.

2. R.L. Kinder and M.J. Kushner, "Consequences of mode structure on plasma properties in electron cyclotron resonance sources," *J. Vac. Sci. Technol. A*, vol. 175, 1999.

3. Phelps database, www.lxcat.net, retrieved 2017.

Application Library path: `Plasma_Module/Wave-Heated_Discharges/dipolar_ecr_source`

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 **2D Axisymmetric**.

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>Stationary**.

6 Click **Done**.

GEOMETRY 1

1 Click the **Show More Options** button in the **Model Builder** toolbar.

2 In the **Show More Options** dialog box, in the tree, select the check box for the node **Physics>Advanced Physics Options**.

3 Click **OK**.

Add parameters to use in the model, such as the power input into the reactor.

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
r0	0.12	0.12	Plasma source radius
z0	0.24	0.24	Plasma source height
Pin	20[W]	20 W	Input power

GEOMETRY 1

Create the geometry of an ECR reactor.

Rectangle 1 (r1)

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

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

3 In the **Width** text field, type `r0`.

4 In the **Height** text field, type `z0`.

5 Locate the **Position** section. In the **z** text field, type `-z0/2`.

Rectangle 2 (r2)

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

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

3 In the **Width** text field, type `0.01`.

4 In the **Height** text field, type `0.03`.

5 Locate the **Position** section. In the **z** text field, type `0.04`.

Rectangle 3 (r3)

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

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

3 In the **Width** text field, type `0.004`.

4 In the **Height** text field, type `0.048`.

5 Locate the **Position** section. In the **r** text field, type `0.006`.

6 In the **z** text field, type `0.072`.

Rectangle 4 (r4)

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

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

3 In the **Width** text field, type `0.004`.

4 In the **Height** text field, type `0.05`.

5 Locate the **Position** section. In the **z** text field, type `0.07`.

Rectangle 5 (r5)

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

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

3 In the **Width** text field, type `r0-0.01`.

4 In the **Height** text field, type `0.02`.

5 Locate the **Position** section. In the **r** text field, type `0.01`.

6 In the **z** text field, type `0.12`.

Rectangle 6 (r6)

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

2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `0.02`.
4. In the **Height** text field, type `0.02`.
5. Locate the **Position** section. In the **r** text field, type `r0`.
6. In the **z** text field, type `0.12`.

Rectangle 7 (r7)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `0.02`.
4. In the **Height** text field, type `z0`.
5. Locate the **Position** section. In the **r** text field, type `r0`.
6. In the **z** text field, type `-z0/2`.

Rectangle 8 (r8)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `0.02`.
4. In the **Height** text field, type `0.02`.
5. Locate the **Position** section. In the **r** text field, type `r0`.
6. In the **z** text field, type `-0.02-z0/2`.

Rectangle 9 (r9)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `r0`.
4. In the **Height** text field, type `0.02`.
5. Locate the **Position** section. In the **z** text field, type `-0.02-z0/2`.

Rectangle 10 (r10)

1. In the **Geometry** toolbar, click **Rectangle**.
2. In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.
3. In the **Width** text field, type `0.01`.
4. In the **Height** text field, type `0.02`.
5. Locate the **Position** section. In the **z** text field, type `0.12`.

Line Segment 1 (ls1)

1. In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.
2. In the **Settings** window for **Line Segment**, locate the **Starting Point** section.
3. From the **Specify** list, choose **Coordinates**.
4. Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.
5. Locate the **Starting Point** section. In the **r** text field, type `0.01`.
6. Locate the **Endpoint** section. In the **r** text field, type `0.01`.
7. Locate the **Starting Point** section. In the **z** text field, type `0.072`.
8. Locate the **Endpoint** section. In the **z** text field, type `0.07`.
9. Click **Build All Objects**.

DEFINITIONS

Make a **View** that zooms in the resonant region.

View 2

1. In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.
2. Right-click **Definitions** and choose **View**.

Axis

1. In the **Model Builder** window, expand the **View 2** node, then click **Axis**.
2. In the **Settings** window for **Axis**, locate the **Axis** section.
3. In the **r minimum** text field, type `-0.05`.
4. In the **r maximum** text field, type `0.16`.
5. In the **z minimum** text field, type `-0.02`.
6. In the **z maximum** text field, type `0.12`.
7. Click **Update**.

View 2

1. In the **Model Builder** window, click **View 2**.
2. In the **Settings** window for **View**, locate the **View** section.
3. Select the **Lock axis** check box.

Add an explicit selection to make it easier to specify feature selections below.

Walls

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 4, 6, 18–20, 22, and 26 only.

5 In the **Label** text field, type `Walls`.

Add an **Infinite Element Domain** to the region outside the plasma reactor.

Infinite Element Domain 1 (ie1)

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

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

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

4 Select Domains 1, 5, and 8–11 only.

Add materials and define the electromagnetic properties of the domains.

MATERIALS

Material 1 (mat1)

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

2 Select Domains 1, 2, 4, 5, and 7–11 only.

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

4 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
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Material 2 (mat2)

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

2 Select Domain 3 only.

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

4 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
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	6e7	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Material 3 (mat3)

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

2 Select Domain 6 only.

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

4 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
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	2	1	Basic

Add two Integration operators. One to be used in the mesh adaptation process and the other to compute the power absorbed by the plasma in the results analysis.

DEFINITIONS

Integration 1 (intop1)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 Select Domain 2 only.

3 In the **Settings** window for **Integration**, locate the **Advanced** section.

4 Clear the **Compute integral in revolved geometry** check box.

Integration 2 (intop2)

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

2 Select Domain 2 only.

MAGNETIC FIELDS (MF)

In the following add a **Magnetic Fields** interface and prepare the model to compute the stationary magnetic field that is going to be used in the plasma simulation.

An adaptive mesh refinement is used to refine the mesh in the resonant region. This mesh is going to be used in the plasma simulation.

Coil 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Magnetic Fields (mf)** and choose the domain setting **Coil**.

2 Select Domain 3 only.

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

4 From the **Conductor model** list, choose **Homogenized multiturn**.

5 Locate the **Homogenized Multiturn Conductor** section. In the N text field, type 5000.

6 Locate the **Coil** section. In the I_{coil} text field, type 14.

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

MESH 1

Edge 1

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

2 Select Boundary 19 only.

Size 1

1 Right-click **Edge 1** and choose **Size**.

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

3. From the **Predefined** list, choose **Extremely fine**.
4. Click the **Custom** button.
5. Locate the **Element Size Parameters** section.
6. Select the **Maximum element size** check box. In the associated text field, type `0.0005`.

Edge 2

1. In the **Mesh** toolbar, click **Edge**.
2. Select Boundaries 6, 18, 20, and 22 only.

Size 1

1. Right-click **Edge 2** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Extremely fine**.
4. Click the **Custom** button.
5. Locate the **Element Size Parameters** section.
6. Select the **Maximum element size** check box. In the associated text field, type `0.0015`.

Free Triangular 1

1. In the **Mesh** toolbar, click **Free Triangular**.
2. In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 2 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**.

Free Triangular 2

1. In the **Mesh** toolbar, click **Free Triangular**.
2. In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 6 only.

Size 1

1. Right-click **Free Triangular 2** and choose **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.

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

4 Click the **Custom** button.

5 Locate the **Element Size Parameters** section.

6 Select the **Maximum element size** check box. In the associated text field, type `0.001`.

Free Triangular 3

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

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

STUDY 1

Step 1: Stationary

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

2 In the **Settings** window for **Stationary**, click to expand the **Adaptation and Error Estimates** section.

3 From the **Adaptation and error estimates** list, choose **Adaptation and error estimates**.

4 From the **Error estimate** list, choose **Functional**.

5 From the **Functional type** list, choose **Manual**.

6 In the **Functional** text field, type `comp1.intop1(1/(abs(comp1.mf.normB-0.0875)+1e-4))`.

7 Find the **Mesh adaptation** subsection. From the **Adaptation method** list, choose **Rebuild mesh**.

8 Select the **Maximum number of adaptations** check box.

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

10 In the **Settings** window for **Study**, type `Static Magnetic Field` in the **Label** text field.

11 Locate the **Study Settings** section. Clear the **Generate default plots** check box.

Solution 1 (sol1)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 1 (sol1)** node.

3 In the **Model Builder** window, expand the **Static Magnetic Field>Solver Configurations>Solution 1 (sol1)>Stationary Solver 1** node, then click **Adaptive Mesh Refinement**.

4 In the **Settings** window for **Adaptive Mesh Refinement**, locate the **General** section.

5 Find the **Mesh adaptation** subsection. In the **Maximum coarsening factor** text field, type `1`.

6 In the **Study** toolbar, click **Compute**.

RESULTS

In the **Model Builder** window, expand the **Results** node.

Selection

1 In the **Model Builder** window, expand the **Results>Datasets** node.

2 Right-click **Static Magnetic Field/Solution 1 (sol1)** and choose **Selection**.

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

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

5 Select Domains 2, 4, 6, and 7 only.

Stationary Magnetic Flux Density

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

2 In the **Settings** window for **2D Plot Group**, type `Stationary Magnetic Flux Density` in the **Label** text field.

Contour 1

1 Right-click **Stationary Magnetic Flux Density** and choose **Contour**.

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

3 In the **Expression** text field, type `log10(mf.normB+eps)`.

4 Locate the **Levels** section. In the **Total levels** text field, type `8`.

5 Locate the **Coloring and Style** section. From the **Contour type** list, choose **Filled**.

6 Click **Change Color Table**.

7 In the **Color Table** dialog box, select **Linear>GrayScale** in the tree.

8 Click **OK**.

9 In the **Settings** window for **Contour**, locate the **Coloring and Style** section.

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

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

Contour 2

1 In the **Model Builder** window, right-click **Stationary Magnetic Flux Density** and choose **Contour**.

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

3 In the **Expression** text field, type `Aphi`.

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

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

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

Contour 3

1 Right-click **Contour 2** and choose **Duplicate**.

2 In the **Settings** window for **Contour**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Magnetic Fields> Magnetic>mf.normB - Magnetic flux density norm - T**.

3 Locate the **Levels** section. From the **Entry method** list, choose **Levels**.

4 Click **Range**.

5 In the **Range** dialog box, choose **Number of values** from the **Entry method** list.

6 In the **Start** text field, type `0.086`.

7 In the **Stop** text field, type `0.089`.

8 In the **Number of values** text field, type `20`.

9 Click **Replace**.

10 In the **Stationary Magnetic Flux Density** toolbar, click **Plot**.

Next, visualize the refined mesh.

Adaptive Mesh

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

2 In the **Settings** window for **2D Plot Group**, type `Adaptive Mesh` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Static Magnetic Field/ Adaptive Mesh Refinement Solutions 1 (sol2)**.

Mesh 1

1 Right-click **Adaptive Mesh** and choose **Mesh**.

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

3 From the **Element color** list, choose **None**.

4 From the **Wireframe color** list, choose **Custom**.

5 Click **Define custom colors**.

6 Set the RGB values to 192, 192, and 192, respectively.

7 Click **Add to custom colors**.

8 Click **Show color palette only** or **OK** on the cross-platform desktop.

9 In the **Adaptive Mesh** toolbar, click **Plot**.

Add a **Microwave Plasma** interface and prepare the ECR model. By selecting **Compute tensor electron transport properties** and **Compute tensor ion transport properties** both electrons and ions have tensor transport properties that depend on the magnetic field.

The plasma conductivity is also set to be a tensor that depends on the magnetic field by checking the box **Compute tensor plasma conductivity** in the multiphysics feature **Plasma Conductivity Coupling**.

ADD PHYSICS

1 In the **Home** toolbar, click **Add Physics** to open the **Add Physics** window.

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

3 In the tree, select **Plasma>Microwave Plasma**.

4 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Static Magnetic Field**.

5 Click **Add to Component 1** in the window toolbar.

6 In the **Home** toolbar, click **Add Physics** to close the **Add Physics** window.

PLASMA (PLAS)

Select Domains 1, 2, 5, 6, and 8–11 only.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

2 In the **Settings** window for **Electromagnetic Waves, Frequency Domain**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Select Domains 2 and 6 only.

PLASMA (PLAS)

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

2 In the **Settings** window for **Plasma**, locate the **Transport Settings** section.

3 Find the **Include** subsection. Select the **Full expression for diffusivity** check box.

4 Select the **Compute tensor ion transport properties** check box.

5 Locate the **Plasma Properties** section. Select the **Compute tensor electron transport properties** check box.

MULTIPHYSICS

Plasma Conductivity Coupling 1 (pcc1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Multiphysics** click **Plasma Conductivity Coupling 1 (pcc1)**.

2 In the **Settings** window for **Plasma Conductivity Coupling**, locate the **Compute Tensor Plasma Conductivity** section.

3 Select the **Compute tensor plasma conductivity** check box.

4 In the δ text field, type `20`.

PLASMA (PLAS)

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

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

3 Click **Clear Selection**.

4 Select Domain 2 only.

Cross Section Import 1

1 In the **Physics** toolbar, click **Global** and choose **Cross Section Import**.

2 In the **Settings** window for **Cross Section Import**, locate the **Cross Section Import** section.

3 Click **Browse**.

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

5 Click **Import**.

Reaction 1

1 In the **Physics** toolbar, click **Domains** and choose **Reaction**.

2 In the **Settings** window for **Reaction**, locate the **Reaction Formula** section.

3 In the **Formula** text field, type `Ars+Ar=>Ar+Ar`.

4 Locate the **Reaction Parameters** section. In the k^f text field, type `1807`.

Reaction 2

1 In the **Physics** toolbar, click **Domains** and choose **Reaction**.

2 In the **Settings** window for **Reaction**, locate the **Reaction Formula** section.

3 In the **Formula** text field, type `Ars+Ars=>e+Ar+Ar+`.

4 Locate the **Reaction Parameters** section. In the k^f text field, type `3.734E8`.

Species: Ar

1 In the **Model Builder** window, click **Species: Ar**.

2 In the **Settings** window for **Species**, locate the **Species Formula** section.

3 Select the **From mass constraint** check box.

4 Locate the **General Parameters** section. From the **Preset species data** list, choose **Ar**.

Species: Ars

1 In the **Model Builder** window, click **Species: Ars**.

2 In the **Settings** window for **Species**, locate the **General Parameters** section.

3 From the **Preset species data** list, choose **Ar**.

4 In the x_0 text field, type `1E-4`.

Species: Ar+

1 In the **Model Builder** window, click **Species: Ar+**.

2 In the **Settings** window for **Species**, locate the **Species Formula** section.

3 Select the **Initial value from electroneutrality constraint** check box.

4 Locate the **General Parameters** section. From the **Preset species data** list, choose **Ar**.

5 Locate the **Mobility and Diffusivity Expressions** section. From the **Specification** list, choose **Specify mobility, compute diffusivity**.

6 Locate the **Mobility Specification** section. From the **Specify using** list, choose **Lookup table**.

7 Find the **Ion mobility** subsection. Click **Load from File**.

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

Surface Reaction 1

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

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

3 In the **Formula** text field, type `Ar+=>Ar`.

4 Locate the **Boundary Selection** section. From the **Selection** list, choose **Walls**.

Surface Reaction 2

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

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

3 In the **Formula** text field, type `Ars=>Ar`.

4 Locate the **Boundary Selection** section. From the **Selection** list, choose **Walls**.

Wall 1

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 **Walls**.

Ground 1

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

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

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

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the $n_{e,0}$ text field, type `1E17[1/m^3]`.

4 In the ε_0 text field, type `2[V]`.

Plasma Model 1

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

2 In the **Settings** window for **Plasma Model**, locate the **Model Inputs** section.

3 From the $\mathbf{B}$ list, choose **Magnetic flux density (mf)**.

4 In the T text field, type `300`.

5 In the p_A text field, type `1`.

6 Locate the **DC Electron Mobility** section. In the μ_{dc} text field, type `1E25[1/(m*V*s)]/plas.Nn`.

ELECTROMAGNETIC WAVES, FREQUENCY DOMAIN (EMW)

In the **Model Builder** window, under **Component 1 (comp1)** click **Electromagnetic Waves, Frequency Domain (emw)**.

Port 1

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

In the **Port** feature set the input power. This is different that the power absorbed by the plasma as it will be shown in the **Results** section.

2 Select Boundary 14 only.

3 In the **Settings** window for **Port**, locate the **Port Properties** section.

4 From the **Type of port** list, choose **Coaxial**.

5 In the P_{in} text field, type `Pin`.

MESH 2

In the **Mesh** toolbar, click **Add Mesh** and choose **Add Mesh**.

Reference 1

1. In the **Mesh** toolbar, click **Modify** and choose **Reference**.
2. In the **Settings** window for **Reference**, locate the **Reference** section.
3. From the **Mesh** list, choose **Level 1 Adapted Mesh 1**.

Refine 1

1. In the **Mesh** toolbar, click **Modify** and choose **Refine**.
2. In the **Settings** window for **Refine**, locate the **Geometric Entity Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 6 only.
5. Locate the **Refine Options** section. From the **Number of refinements** list, choose **2**.

Boundary Layers 1

1. In the **Mesh** toolbar, click **Boundary Layers**.
2. In the **Settings** window for **Boundary Layers**, locate the **Domain Selection** section.
3. From the **Geometric entity level** list, choose **Domain**.
4. Select Domain 2 only.

Boundary Layer Properties

1. In the **Model Builder** window, click **Boundary Layer Properties**.
2. In the **Settings** window for **Boundary Layer Properties**, locate the **Boundary Selection** section.
3. From the **Selection** list, choose **Walls**.
4. Locate the **Layers** section. In the **Number of layers** text field, type `4`.
5. In the **Stretching factor** text field, type `1.4`.
6. Click **Build All**.

Add a **Frequency-Transient** study to solve for an input power of 20 W. The solution of this study is going to be used as initial conditions of a following **Frequency-Stationary** study.

In this and following studies, the magnetic field is not solved for and the refined mesh is used.

ADD STUDY

1. In the **Home** toolbar, click **Add Study** to open the **Add Study** window.
2. Go to the **Add Study** window.

3 Find the **Physics interfaces in study** subsection. In the table, clear the **Solve** check box for **Magnetic Fields (mf)**.
4 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Multiphysics>Frequency-Transient**.
5 Click **Add Study** in the window toolbar.
6 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency-Transient

1 In the **Settings** window for **Frequency-Transient**, locate the **Study Settings** section.
2 In the **Output times** text field, type `0 10^{range(-8,6/10,0)}`.
3 In the **Frequency** text field, type `2.45E9`.
4 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check box for **Magnetic Fields (mf)**.
5 Click to expand the **Mesh Selection** section. In the table, enter the following settings:

Component	Mesh
Component 1	Mesh 2

6 Click to expand the **Values of Dependent Variables** section. Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.
7 From the **Method** list, choose **Solution**.
8 From the **Study** list, choose **Static Magnetic Field, Stationary**.
9 From the **Solution** list, choose **Adaptive Mesh Refinement Solutions 1 (sol2)**.
10 From the **Use** list, choose **Level 1 Refined Solution 4 (sol4)**.

Solution 5 (sol5)

1 In the **Study** toolbar, click **Show Default Solver**.
2 In the **Model Builder** window, expand the **Solution 5 (sol5)** node, then click **Dependent Variables 1**.
3 In the **Settings** window for **Dependent Variables**, locate the **General** section.
4 From the **Defined by study step** list, choose **User defined**.
5 In the **Model Builder** window, click **Study 2**.
6 In the **Settings** window for **Study**, type `Pin=20 W` in the **Label** text field.

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

RESULTS

Electric Field (emw), Electric Potential (plas), Electron Density (plas), Electron Temperature (plas)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electron Density (plas)**, **Electron Temperature (plas)**, **Electric Potential (plas)**, and **Electric Field (emw)**.

2 Right-click and choose **Group**.

Pin=20 W

In the **Settings** window for **Group**, type `Pin=20 W` in the **Label** text field.

Add a **Frequency-Stationary** study to ramp up the input power. It is difficult to obtain a solution for a plasma problem using a stationary solver using arbitrary flat profiles as initial conditions. That is why the solution of the **Frequency-Transient** study is used as initial conditions.

ADD STUDY

1 In the **Study** toolbar, click **Add Study** to open the **Add Study** window.

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

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Multiphysics>Frequency-Stationary**.

4 Click **Add Study** in the window toolbar.

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

STUDY 3

Step 1: Frequency-Stationary

1 In the **Settings** window for **Frequency-Stationary**, locate the **Study Settings** section.

2 In the **Frequency** text field, type `2.45e9`.

3 Locate the **Physics and Variables Selection** section. In the table, clear the **Solve for** check box for **Magnetic Fields (mf)**.

4 Click to expand the **Values of Dependent Variables** section. Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.

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

6 From the **Study** list, choose **Pin=20 W, Frequency-Transient**.

7 Find the **Values of variables not solved for** subsection. From the **Settings** list, choose **User controlled**.

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

9 From the **Study** list, choose **Static Magnetic Field, Stationary**.

10 From the **Solution** list, choose **Adaptive Mesh Refinement Solutions 1 (sol2)**.

11 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

12 Click **Add**.

13 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
Pin (Input power)	`range(20,10,70) 73.5 75 80`	`W`

14 In the **Study** toolbar, click **Compute**.

RESULTS

Electric Field (emw) 1, Electric Potential (plas) 1, Electron Density (plas) 1, Electron Temperature (plas) 1, S-parameter (emw), Smith Plot (emw)

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electron Density (plas) 1**, **Electron Temperature (plas) 1**, **Electric Potential (plas) 1**, **Electric Field (emw) 1**, **S-parameter (emw)**, and **Smith Plot (emw)**.

2 Right-click and choose **Group**.

Pin 20 to 80 W

In the **Settings** window for **Group**, type `Pin 20 to 80 W` in the **Label** text field.

PIN 20 TO 80 W

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Pin 20 to 80 W` in the **Label** text field.

RESULTS

Electron Density (plas) 1

1 In the **Model Builder** window, under **Results>Pin 20 to 80 W** click **Electron Density (plas) 1**.

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Parameter value (Pin (W))** list, choose **73.5**.

4 In the **Electron Density (plas) 1** toolbar, click **Plot**.

Electron Temperature (plas) 1

1 In the **Model Builder** window, click **Electron Temperature (plas) 1**.
2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.
3 From the **Parameter value (Pin (W))** list, choose **73.5**.
4 In the **Electron Temperature (plas) 1** toolbar, click **Plot**.

Electric Potential (plas) 1

1 In the **Model Builder** window, click **Electric Potential (plas) 1**.
2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.
3 From the **Parameter value (Pin (W))** list, choose **73.5**.
4 In the **Electric Potential (plas) 1** toolbar, click **Plot**.

Electric Field (emw) 1

1 In the **Model Builder** window, click **Electric Field (emw) 1**.
2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.
3 From the **Parameter value (Pin (W))** list, choose **73.5**.
4 In the **Electric Field (emw) 1** toolbar, click **Plot**.

Absorbed Power vs. Input Power

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
2 In the **Settings** window for **1D Plot Group**, type `Absorbed Power vs. Input Power` in the **Label** text field.
3 Locate the **Data** section. From the **Dataset** list, choose **Pin 20 to 80 W/Solution 6 (sol6)**.
4 Locate the **Legend** section. Clear the **Show legends** check box.
5 Click to expand the **Title** section. From the **Title type** list, choose **None**.

Global 1

1 Right-click **Absorbed Power vs. Input Power** and choose **Global**.
2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.
3 In the table, enter the following settings:

Expression	Unit	Description
`intop2(emw.Qrh)`	`W`	`Integration 2`

4 In the **Absorbed Power vs. Input Power** toolbar, click **Plot**.

Absorbed Power vs. Input Power

1 In the **Model Builder** window, click **Absorbed Power vs. Input Power**.

2 In the **Settings** window for **1D Plot Group**, locate the **Plot Settings** section.

3 Select the **x-axis label** check box. In the associated text field, type `Input Power (W)`.

4 Select the **y-axis label** check box. In the associated text field, type `Absorbed Power (W)`.

5 In the **Absorbed Power vs. Input Power** toolbar, click **Plot**.

Power Deposition

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

2 In the **Settings** window for **2D Plot Group**, locate the **Data** section.

3 From the **Dataset** list, choose **Pin 20 to 80 W/Solution 6 (sol6)**.

4 From the **Parameter value (Pin (W))** list, choose **73.5**.

5 In the **Label** text field, type `Power Deposition`.

Surface 1

1 Right-click **Power Deposition** and choose **Surface**.

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

3 In the **Expression** text field, type `emw.Qrh`.

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

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

6 Click **OK**.

7 In the **Power Deposition** toolbar, click **Plot**.

Electron Source

1 In the **Model Builder** window, right-click **Power Deposition** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Electron Source` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Electron Source** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `plas.Re`.

4 In the **Electron Source** toolbar, click **Plot**.

Electron Mobility, rr Component

1 In the **Model Builder** window, right-click **Electron Source** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Electron Mobility, rr Component` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Electron Mobility, rr Component** node, then click **Surface 1**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `plas.muerr`.
4 In the **Electron Mobility, rr Component** toolbar, click **Plot**.

Electron Mobility, zz-Component

1 In the **Model Builder** window, right-click **Electron Mobility, rr Component** and choose **Duplicate**.
2 In the **Model Builder** window, click **Electron Mobility, rr Component 1**.
3 In the **Settings** window for **2D Plot Group**, type `Electron Mobility, zz-Component` in the **Label** text field.

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 `plas.muezz`.
4 In the **Electron Mobility, zz-Component** toolbar, click **Plot**.

Conduction Current Density, r-Component

1 In the **Model Builder** window, right-click **Electron Mobility, zz-Component** and choose **Duplicate**.
2 In the **Settings** window for **2D Plot Group**, type `Conduction Current Density, r-Component` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Conduction Current Density, r-Component** node, then click **Surface 1**.
2 In the **Settings** window for **Surface**, locate the **Expression** section.
3 In the **Expression** text field, type `emw.Jr-emw.Jdr`.
4 In the **Conduction Current Density, r-Component** toolbar, click **Plot**.

Conduction Current Density, z-Component

1 In the **Model Builder** window, right-click **Conduction Current Density, r-Component** and choose **Duplicate**.
2 In the **Model Builder** window, click **Conduction Current Density, r-Component 1**.

3 In the **Settings** window for **2D Plot Group**, type `Conduction Current Density, z-Component` in the **Label** text field.

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 `emw.Jz-emw.Jdz`.

4 In the **Conduction Current Density, z-Component** toolbar, click **Plot**.

Conduction Current Density, phi-Component

1 In the **Model Builder** window, right-click **Conduction Current Density, z-Component** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Conduction Current Density, phi-Component` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Conduction Current Density, phi-Component** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `emw.Jphi-emw.Jdphi`.

4 In the **Conduction Current Density, phi-Component** toolbar, click **Plot**.

Mean Plasma Electrical Conductivity

1 In the **Model Builder** window, right-click **Conduction Current Density, phi-Component** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Mean Plasma Electrical Conductivity` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Mean Plasma Electrical Conductivity** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `(emw.sigmarr+emw.sigmaphiphi+emw.sigmazz)/3`.

4 In the **Mean Plasma Electrical Conductivity** toolbar, click **Plot**.