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.
- Equation-based modeling using integrated quantities to fix the total absorbed power.
- 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.
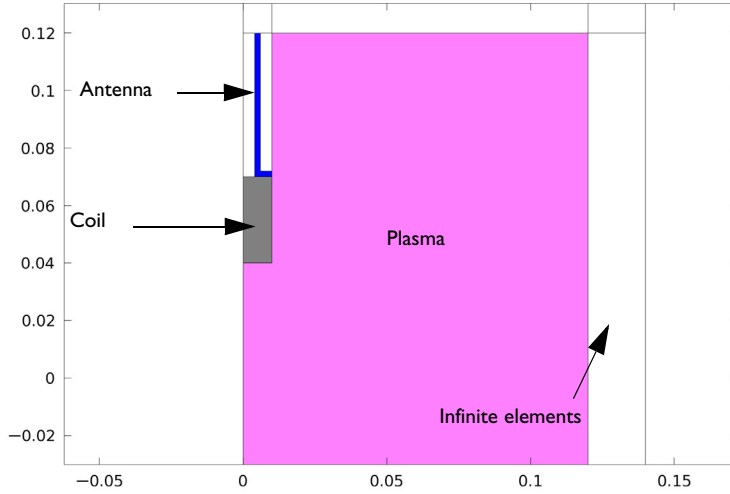

Figure 1: Basic concept for the plasma source. A stationary azimuthal current flows in the coil which generates a static magnetic field in the surroundings. Resonant heating of the electrons occurs on the contour of the critical magnetic flux density.

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 both the electric and magnetic fields over one RF cycle. This leads to a resonance zone in the plasma where the incoming electromagnetic wave is completely absorbed over a very short distance. The critical magnetic field is only dependent on the angular frequency, the electron mass, and the charge:

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

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. The nonlinearity in the plasma conductivity can be seen in Figure 2. The surface represents four of the components of the nondimensional plasma conductivity versus the r- and z-components of the magnetic flux density (indicated by the x-axis and y-axis, respectively) on a log scale. At the resonant flux density (0.0875 T) the plasma conductivity is more than 10^6 higher than the case where no static magnetic field is present.

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, v_e in Equation 2 is replaced by an effective collision frequency:

$$\tilde{v}_e = v_e + \frac{\omega}{\delta} \tag{4}$$

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.
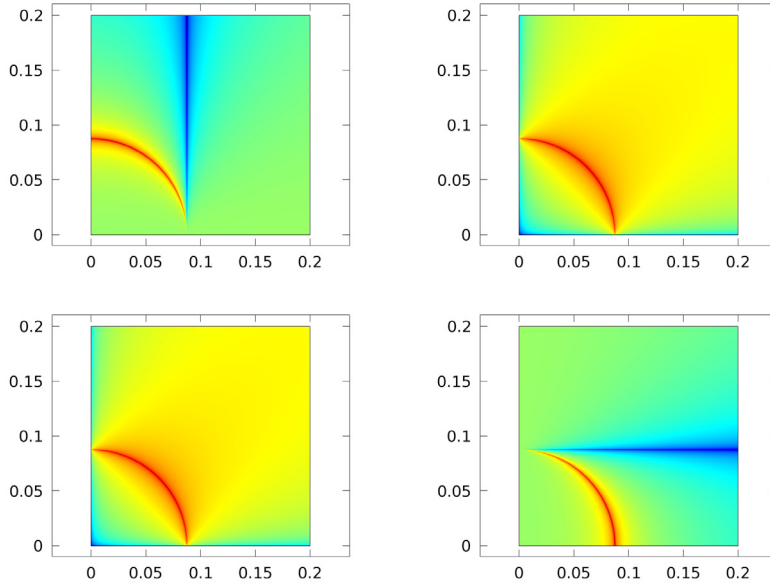
Figure 2: Plots of the four components of the plasma conductivity tensor.

Compute the electron number density and electron energy density by solving a pair of drift-diffusion equations:

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

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

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

$$\mu_e^{-1} = \begin{bmatrix} \dfrac{1}{\mu_{dc}} & -B_z & B_y \\[2mm] B_z & \dfrac{1}{\mu_{dc}} & -B_x \\[2mm] -B_y & B_x & \dfrac{1}{\mu_{dc}} \end{bmatrix} \tag{5}$$

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. Suppose that there are M reactions that contribute to the growth or decay of electron density and P inelastic electron-neutral collisions. In general, $P \gg M$. In the case of rate coefficients, the electron source term is given by

$$R_e = \sum_{j=1}^{M} x_j k_j N_n n_e$$

where x_j is the mole fraction of the target species for reaction j, k_j is the rate coefficient for reaction j (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:

$$R_\varepsilon = \sum_{j=1}^{P} x_j k_j N_n n_e \Delta\varepsilon_j$$

where $\Delta\varepsilon_j$ is the energy loss from reaction j (V). The electron source and inelastic energy loss are automatically computed by the multiphysics interface. 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 $\gamma = (2q/m_e)^{1/2}$ $(C^{1/2}/kg^{1/2})$, m_e is the electron mass (kg), ε is energy (V), σ_k is the collision cross section (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 heating term, $\mathbf{E} \cdot \Gamma_e$ has two components, one due to electron motion in the ambipolar field in the rz-plane and one due to heating of the electrons by the microwaves. Heating due to the microwaves is handled in the same way as described in Ref. 1. The power transferred from the electromagnetic field to the electrons is normalized so that 10 W of total power is absorbed by the electrons. This is accomplished by multiplying the heating term by a factor, α, which is defined as:

$$\alpha = \frac{10\,W}{\iiint Q_{\text{ind}} dV} \tag{6}$$

The result of this is that exactly 10 W of total power is transferred from the electromagnetic field to the electrons. If you did not apply this renormalization of the absorbed power then there would be nothing to stop the plasma from simply self-extinguishing or absorbing an inordinate amount of power. This approach is perfectly valid because the microwave equations are linear. The only drawback from this method is that the S-parameters given on the coaxial port are not valid because the fields are decoupled from the plasma model. Furthermore, it is not possible to self-consistently compute the ratio of the absorbed and reflected power through the excitation port, a quantity that may be of interest.

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

$$\rho\frac{\partial}{\partial t}(w_k) + \rho(\mathbf{u} \cdot \nabla)w_k = \nabla \cdot \mathbf{j}_k + R_k \tag{7}$$

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

$$\mathbf{v}_k = D_m\nabla\ln(w) + D_m\nabla\ln(M) + Z\mu(\mathbf{E} + \mathbf{v}_k \times \mathbf{B}) \tag{8}$$

Equation 7 can be re-arranged to give an expression for the diffusion velocity as a function of the other variables:

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

where

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

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

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

For detailed information about electrostatics see *Theory for the Electrostatics Interface* in the *Plasma Module User's Guide*.

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
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. The coaxial port boundary condition is used to drive the electromagnetic waves. The port power is inconsequential due to the normalization scheme used on the absorbed power.

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

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

and the electron energy flux:

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

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.

Results and Discussion — Static Magnetic Field Model

Figure 3 and Figure 4 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.
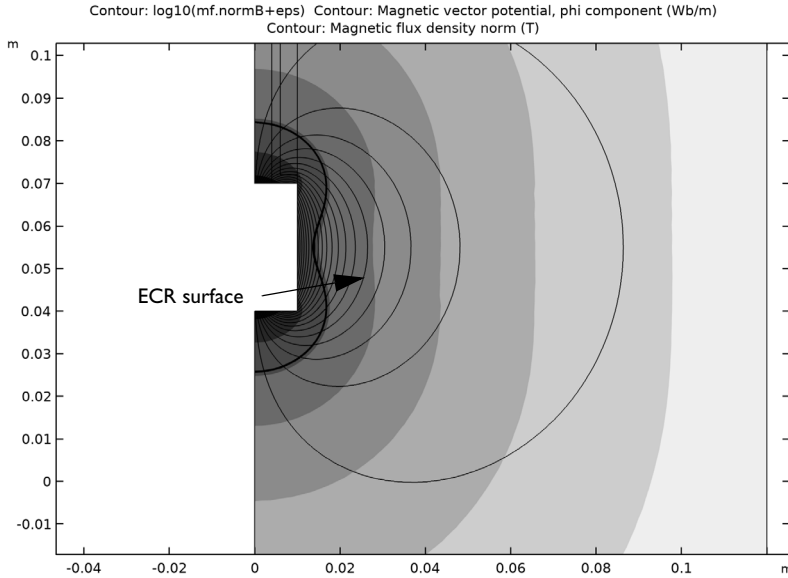
Figure 3: Plot of the static magnetic flux density on a log scale (filled contour), magnetic field lines (thin lines), and the ECR surface at 0.0875 T (thick black line).

In Figure 4 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. Functional-based mesh adaptation is a feature that makes the finite element approach more attractive than the finite difference approach for ECR modeling.
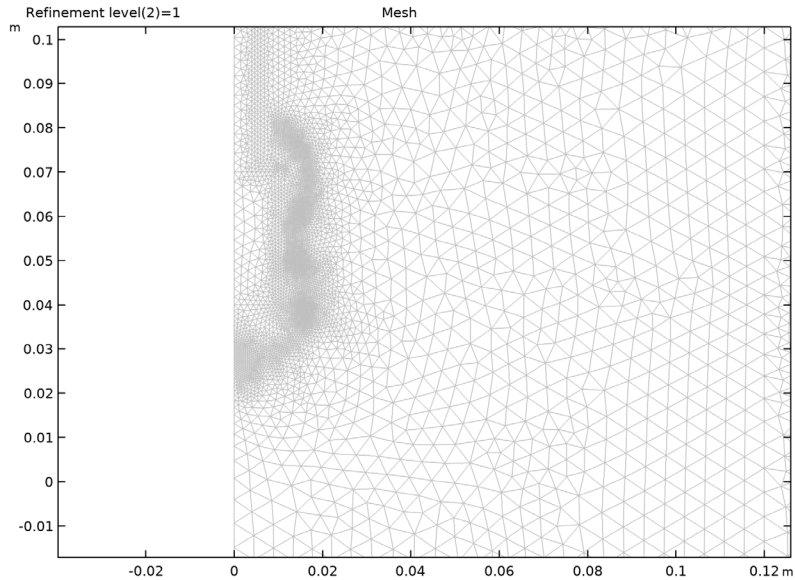
Figure 4: Mesh generated after one refinement using functional-based mesh adaptation. The mesh is very fine on the ECR surface and relatively coarse away from the resonance zone.

Results and Discussion — Microwave Plasma Model

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.
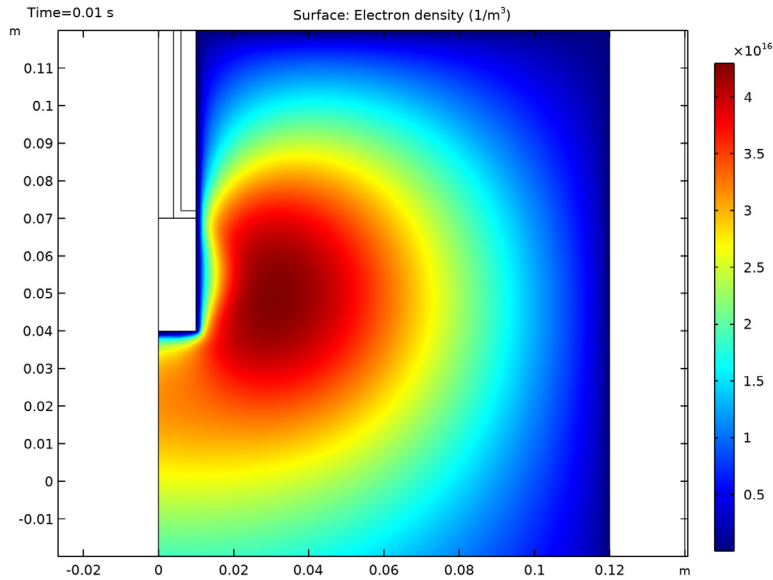
Figure 5: Plot of the electron density at the quasi steady-state condition. The peak electron density is still below the critical electron density at the chosen operating frequency.

Despite the sharply peaked heating the electron temperature, plotted in Figure 6 does not show such peaks. Recall from Figure 3 that the magnetic field lines show the circular pattern away from the coil. This leads to strong energy transport along the field lines and very 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. 2.
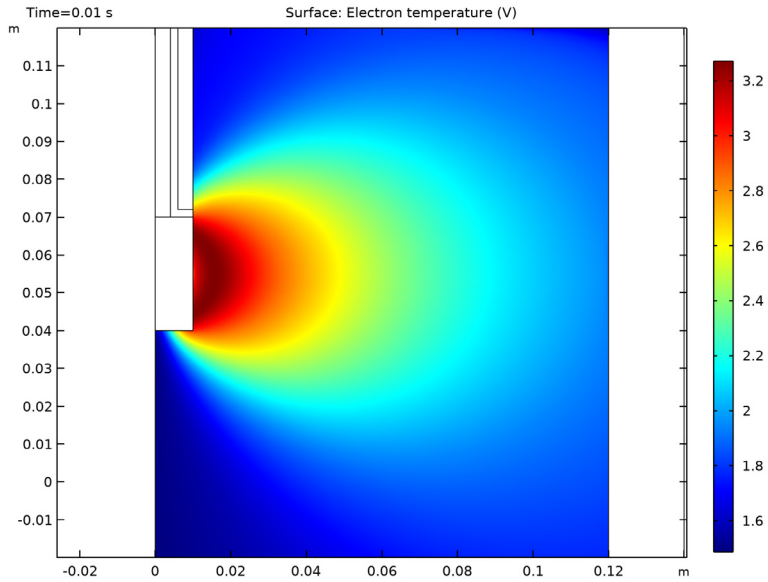
Figure 6: Plot of the electron temperature, which peaks at around 3.8 eV.

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 3 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. 2.
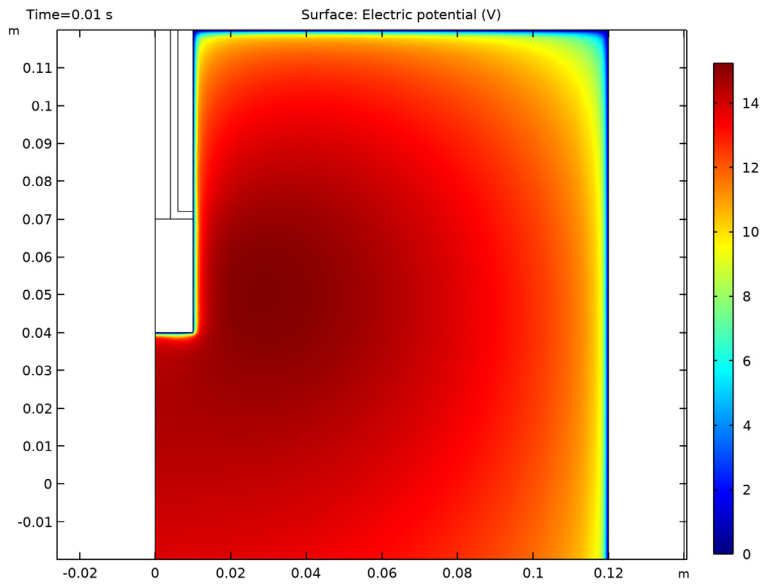
Figure 7: Plot of the plasma potential.

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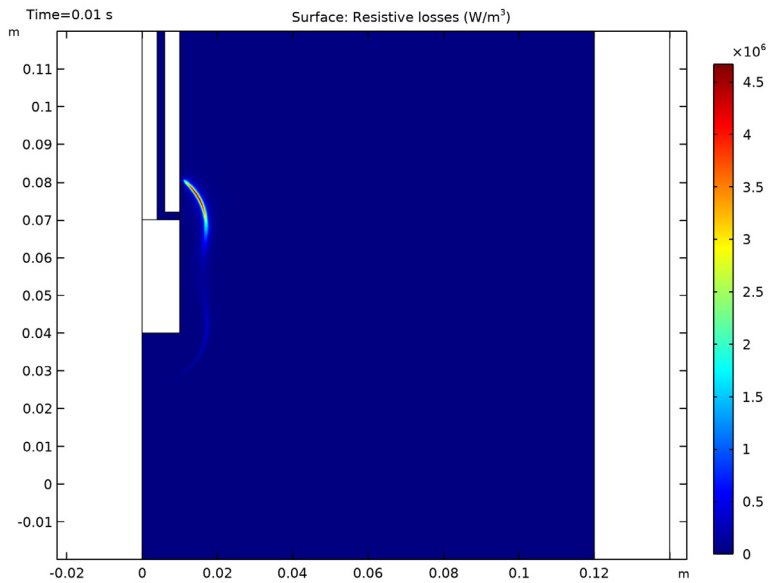
Figure 8: Plot of the power deposition into the plasma. Nearly all the power deposition occurs on the ECR surface.

The ionization source, plotted in Figure 9 is more highly 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.
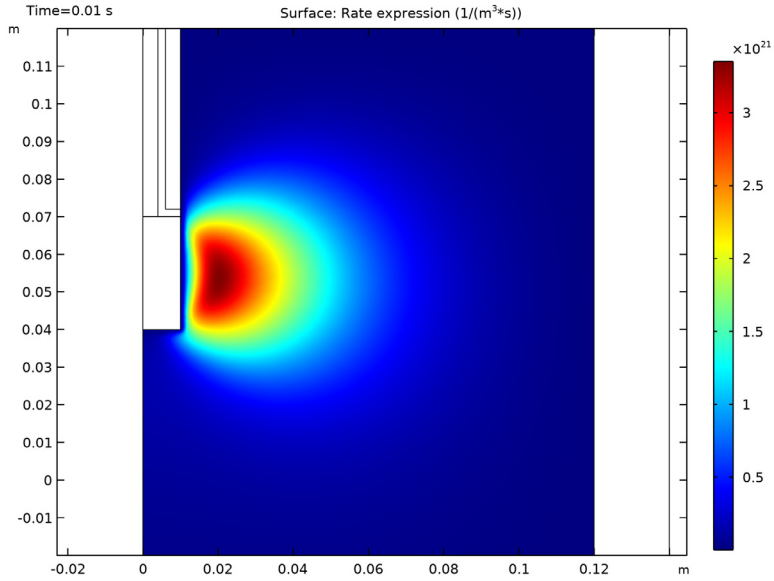
Figure 9: Plot of the rate expression for electrons generated via ionization.

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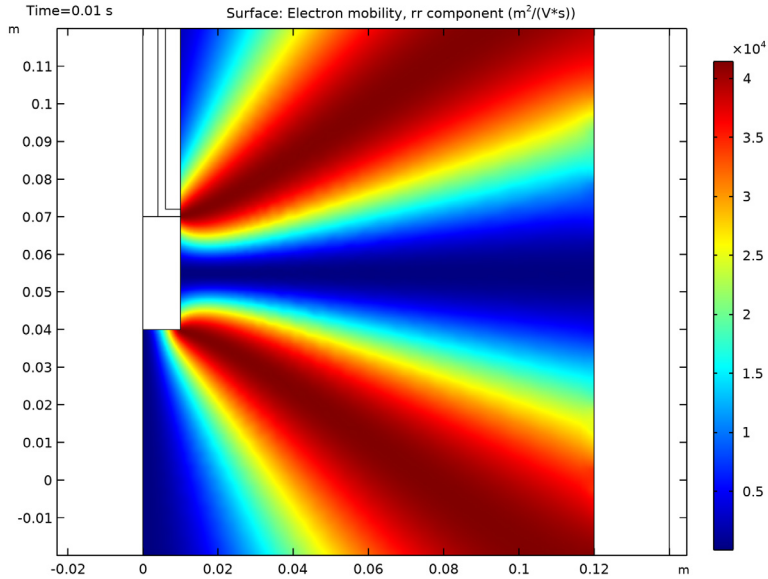
Figure 10: Plot of the electron mobility tensor's rr-component. The mobility varies by 8 orders of magnitude over the space of only a couple of centimeters.

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.
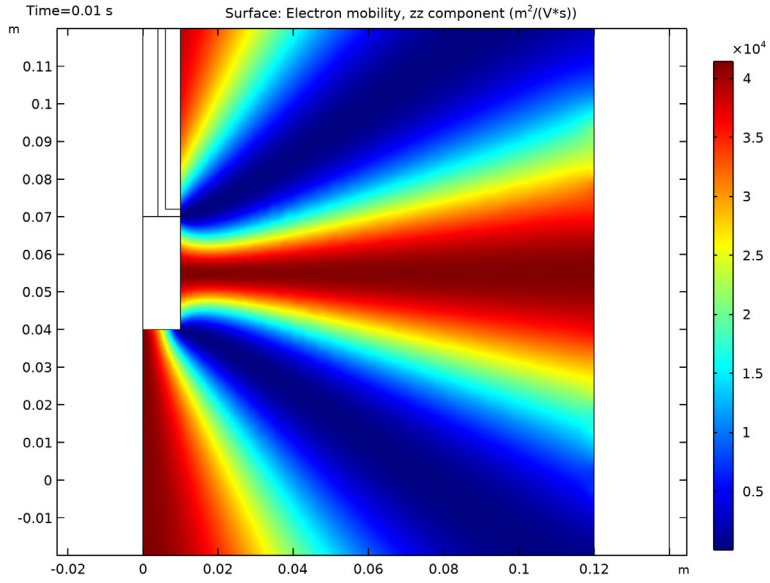
Figure 11: Plot of the electron mobility tensor's zz-component.
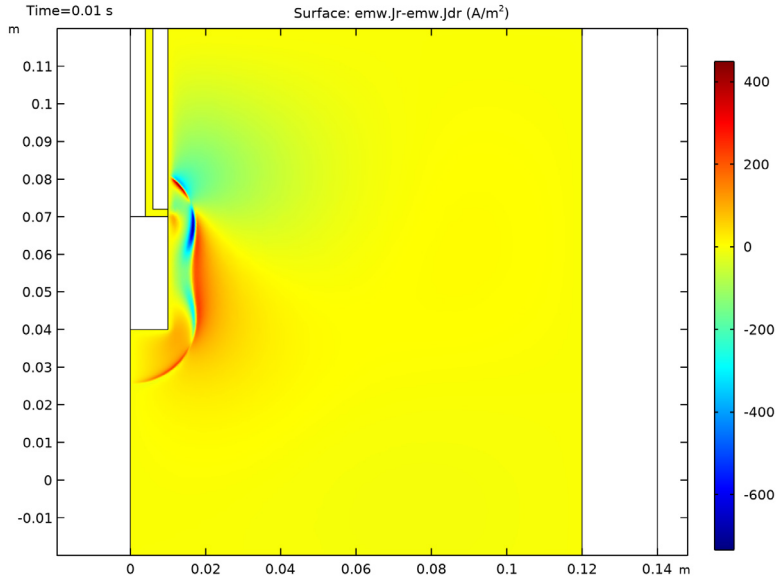
Figure 12: Unnormalized radial component of the microwave conduction current.

The conduction current due to the microwaves is plotted in Figure 12 – 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.
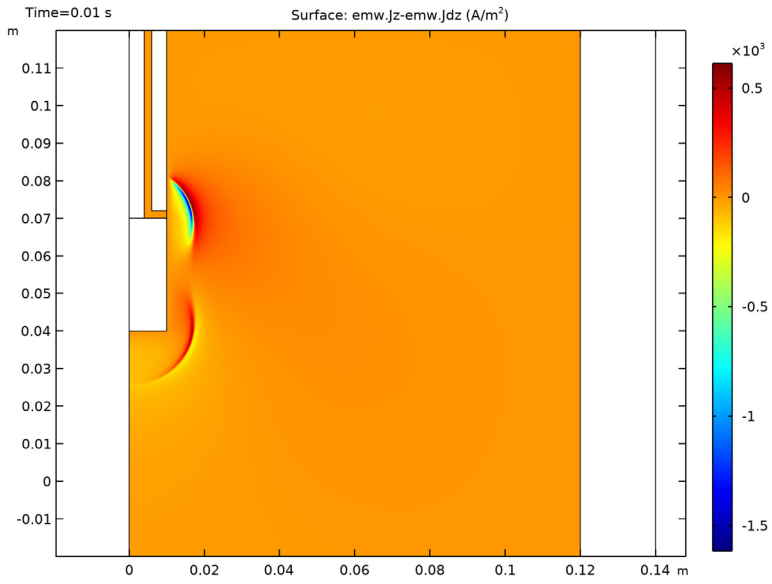
Figure 13: Unnormalized axial component of the microwave conduction current.
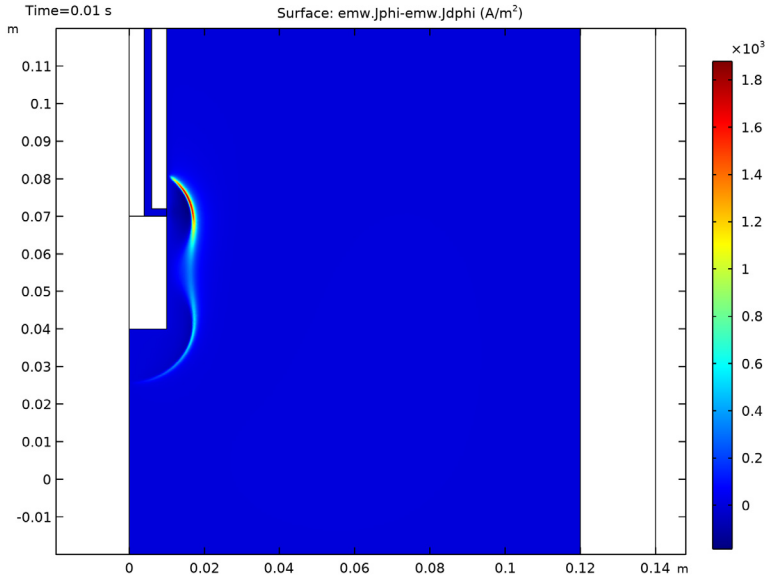
Figure 14: Unnormalized azimuthal component of the microwave conduction current.

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 $(7.4 \cdot 10^{16} \text{ m}^{-3}$ 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.
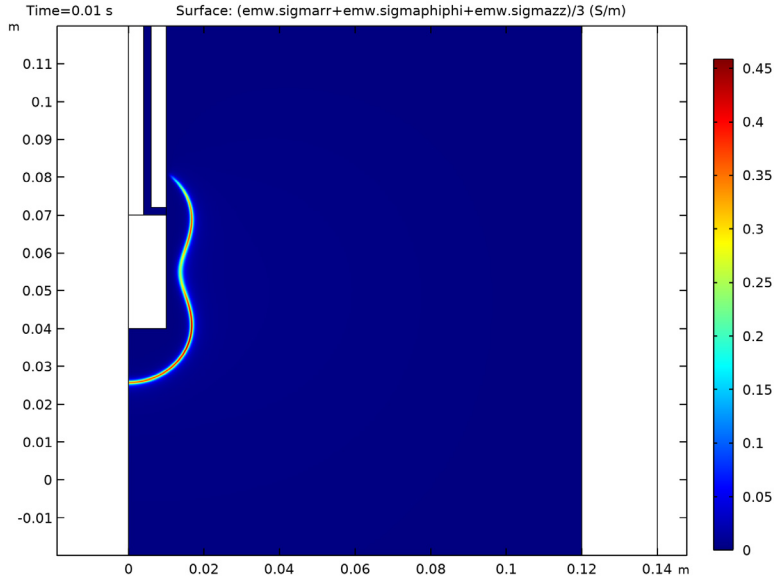
Figure 15: Plot of the trace of the plasma conductivity tensor.

Reference

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, Sep/Oct 1999.

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

Notes About the COMSOL Implementation

This problem is solved in two stages. First, compute the static magnetic field using adaptive mesh refinement. Then, in a separate study step, solve for the electron density, electron energy density, mass fraction of argon ions, and mass fraction of electronically excited argon atoms, as well as the plasma potential and the 3 components of the high-

frequency electric field. 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.

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 ![icon] **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click ![icon] **2D Axisymmetric**.

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

3 Click **Add**.

4 Click ![icon] **Study**.

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

6 Click ![icon] **Done**.

GEOMETRY 1

1 Click the ![icon] **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**.

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
Psp	10[W]	10 W	Total power absorbed by the plasma setpoint

GEOMETRY 1

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

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.

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 Right-click **Explicit 1** and choose **Rename**.

6 In the **Rename Explicit** dialog box, type Walls in the **New label** text field.

7 Click **OK**.

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.

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

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.

MAGNETIC FIELDS (MF)

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. Select the **Maximum element size** check box.

6 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. Select the **Maximum element size** check box.

6 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. Select the **Maximum element size** check box.

6 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 In the **Maximum coarsening factor** text field, type 1.

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

10 In the associated text field, type 1.

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

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

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

14 In the **Home** toolbar, click ▬ **Compute**.

RESULTS

Reproduce the magnetic flux density plot in Figure 3 with the following steps.

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

Study 1/Solution 1 (sol1)

In the **Model Builder** window, expand the **Results>Datasets** node, then click **Study 1/Solution 1 (sol1)**.

Selection

1 In the **Results** toolbar, click 🗃 **Attributes** and choose **Selection**.

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

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

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

Stationary Magnetic Flux Density

1 In the **Results** toolbar, click ■ **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 From the **Color table** list, choose **GrayScale**.

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

8 Select the **Reverse color table** check box.

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 **Study 1/ 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 On Windows, click the colored bar underneath, or — if you are running the cross-platform desktop — the **Color** button.

6 Click **Define custom colors**.

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

8 Click **Add to custom colors**.

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

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

Compare the result with the plot in Figure 4.

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 **Study 1**.

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.

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 [icon] **Clear Selection**.

4 Select Domain 2 only.

Cross Section Import 1

1 In the **Physics** toolbar, click [icon] **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 [icon] **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 [icon] **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 1E14.

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**.

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 Select the **Enable active port feedback** check box.

6 In the P_{dep} text field, type Psp.

MESH 2

In the **Mesh** toolbar, click ▲ **Add Mesh**.

Reference 1

1 In the **Mesh** toolbar, click ▲ **Modify** and choose **Mesh>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 **Elements>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 **Boundary Layer Properties** section. In the **Number of boundary layers** text field, type 4.

5 In the **Boundary layer stretching factor** text field, type 1.4.

6 Click ▦ **Build All**.

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,-2)}.

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:

Geometry	Mesh
Geometry 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 **Study 1, 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 **Study** toolbar, click ═ **Compute**.

RESULTS

Three new default plots show the electron density, electron temperature, and plasma
potential respectively; compare with those in Figure 5, Figure 6, and Figure 7.

Electric Potential (plas)

Follow the instructions below to reproduce Figure 8 through Figure 15.

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**, type Power Deposition in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2/Solution 5 (sol5)**.

Surface 1

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

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)> Electromagnetic Waves, Frequency Domain>Heating and losses>emw.Qrh - Resistive losses - W/m³**.

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

Compare with Figure 8.

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**.

Compare with Figure 9.

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**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Plasma> Electron transport properties>Electron mobility - m²/(V·s)>plas.muerr - Electron mobility, rr component**.

3 In the **Electron Mobility, rr Component** toolbar, click ⊡ **Plot**.

Compare with Figure 10.

Electron Mobility, zz Component

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

2 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, expand the **Electron Mobility, zz Component** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Plasma> Electron transport properties>Electron mobility - m²/(V·s)>plas.muezz - Electron mobility, zz component**.

3 In the **Electron Mobility, zz Component** toolbar, click ⊡ **Plot**.

Compare with Figure 11.

Conduction Current Density, r-Component

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

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

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2/Solution 5 (sol5)**.

Surface 1

1 Right-click **Conduction Current Density, r-Component** and choose **Surface**.

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**.

Compare with Figure 12.

Conduction Current Density, z-Component

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

2 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, expand the **Conduction Current Density, z-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.Jz-emw.Jdz.

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

Compare with Figure 13.

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**.

Compare with Figure 14.

Mean Plasma Electrical Conductivity

1 In the **Model Builder** window, right-click **Electron Mobility, *rr* 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**.

Compare with Figure 15.