



Model created in COMSOL Multiphysics 6.4

Coil Optimization of an ICP Reactor

Introduction

This model shows how shape optimization can be used to design the coils of an ICP reactor to obtain plasma uniformity. The reactor under study is a planar ICP with the coils distributed along the radial direction. The Optimization study step is used to find the best coil placement so that the gradient of the electron density in the reactor center is minimized. A target electron density in the reactor center is also imposed by varying the coil power.

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

Model Definition

OPTIMIZATION SETUP

The coils are moved along the radial direction using the **Free Shape Domain**, the **Linear Shape Domain**, and the **Symmetry/Roller** features. The objective function is expressed as a minimization problem of the gradient of the electron density along the radial direction

$$\min(\text{Gn}), \quad \text{where Gn} = \frac{1}{n_{e0}} \int \sqrt{\nabla n_e^2} dr$$

where n_{e0} is a normalization constant. This type of problem can be solved using the GCMMA optimization method. The electron density is fixed at the reactor center and the power of the coil is allowed to vary to match this density. Constraining the density is not necessary but it is used here to demonstrate the possibility.

PLASMA MODEL

Electron transport is modeled by solving the continuity equation, the momentum equation under the drift-diffusion approximation, and the mean electron energy equation (for detailed information on electron transport, see *Theory for the Drift Diffusion Interface* in the *Plasma Module User's Guide*)

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

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

The source coefficients in the above equations are determined by the plasma chemistry. The electron rate expression is defined as

$$R_e = N_A \sum_j \nu_{e,j} r_j$$

where $\nu_{e,j}$ is the stoichiometric coefficient, and the reaction rate is defined as

$$r_j = k_j^f \prod_{i \in \text{react}} c_i^{-\nu_{i,j}} + k_j^r \prod_{i \in \text{prod}} c_k^{\nu_{i,j}}$$

where k_j^f is the forward rate constant and k_j^r is the reversed rate constant. Both the Electron Impact Reaction feature and Reaction feature can contribute to the electron rate expression. However, when using the Reaction feature it is important to note that the associated electron energy gain or loss is not included in the source term of the electron mean energy equation.

The rate constants can be computed from electron impact cross-section data

$$k^f = N_A \gamma \int_0^{\infty} \epsilon \sigma(\epsilon) f(\epsilon) d\epsilon$$

where $\gamma = (2q/m_e)^{1/2}$ (SI unit: $C^{1/2}/kg^{1/2}$), m_e is the electron mass (SI unit: kg), ϵ is the electron energy (SI unit: V), σ is the electron impact collision cross section (SI unit: m^2), and f is the electron energy distribution function.

When *Townsend coefficients* are used, the reaction rate is defined as

$$r_j = \frac{\alpha_j}{N_n} |\Gamma_e| \prod_{i \neq e \in \text{react}} c_i^{-\nu_{i,j}}$$

where α_j/N_n is the reduced Townsend coefficient for reaction j (SI unit: m^2) and Γ_e is the electron flux as defined above (SI unit: $1/(m^2 \cdot s)$). Townsend coefficients can increase the stability of the numerical scheme when the electron flux is field driven as is the case with DC discharges.

The total electron energy loss or gained is calculated by summing the collisional energy changes from all reactions defined with the Electron Impact Reaction feature as

$$S_{\text{en}} = - \sum_j r_j \Delta \epsilon_j F$$

where $\Delta\epsilon_j$ is the energy loss from reaction j (SI unit: V) and F is the Faraday constant (SI unit: C/mol). For excitation and ionization collisions $\Delta\epsilon_j$ corresponds to the energy of the excited state being excited/deexcited or ionized, for attachment $\Delta\epsilon_j$ is set to zero, and for elastic collisions

$$\Delta\epsilon = 2\frac{m_e}{m_k}\frac{3}{2}\left[T_e(\text{eV}) - \frac{k_B}{e}T_{\text{gas}}(\text{K})\right]$$

where m_e and m_k are the electron and heavy species mass in kg, T_e is the electron temperature in eV, and T_{gas} is the gas temperature in K.

For heavy species, the following equation is solved for the mass fraction of each species (for detailed information on the transport of the nonelectron species, see *Theory for the Heavy Species Transport Interface* in the *Plasma Module User's Guide*):

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

The electrostatic field is computed using the following equation:

$$-\nabla \cdot \epsilon_0 \epsilon_r \nabla V = \rho$$

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*.

For a nonmagnetized, nonpolarized plasma, the induction currents are computed in the frequency domain using the following equation:

$$(j\omega\sigma - \omega^2\epsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1}\nabla \times \mathbf{A}) = \mathbf{J}^e$$

The plasma conductivity needs to be specified as a material property, usually from the cold plasma approximation:

$$\sigma = \frac{n_e q^2}{m_e(\nu_e + j\omega)}$$

where n_e is the electron density, q is the electron charge, m_e is the electron mass, ν_e is the collision frequency, and ω is the angular frequency.

BOUNDARY CONDITIONS

Electrons are lost to the wall due to random motion within a few mean free paths of the wall and gained due to secondary emission effects, resulting in the following boundary condition for the electron flux:

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

and the electron energy flux:

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

For the heavy species, ions are lost to the wall due to surface reactions and the fact that the electric field is directed toward the wall:

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

The walls of the reactor are grounded.

PLASMA CHEMISTRY

Because the physics occurring in an inductively coupled plasma is rather complex, it is always best to start a modeling project with a simple chemical mechanism. Argon is one of the simplest mechanisms to implement at low pressures. The electronically excited states can be lumped into a single species, which results in a chemical mechanism consisting of only 3 species and 7 reactions (electron impact cross sections are obtained from [Ref. 3](#)):

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

REACTION	FORMULA	TYPE	$\Delta\varepsilon$ (eV)
1	$e + \text{Ar} \Rightarrow e + \text{Ar}$	Elastic	0
2	$e + \text{Ar} \Rightarrow e + \text{Ar}_s$	Excitation	11.5
3	$e + \text{Ar}_s \Rightarrow e + \text{Ar}$	Superelastic	-11.5
4	$e + \text{Ar} \Rightarrow 2e + \text{Ar}^+$	Ionization	15.8
5	$e + \text{Ar}_s \Rightarrow 2e + \text{Ar}^+$	Ionization	4.24
6	$\text{Ar}_s + \text{Ar}_s \Rightarrow e + \text{Ar} + \text{Ar}^+$	Penning ionization	-
7	$\text{Ar}_s + \text{Ar} \Rightarrow \text{Ar} + \text{Ar}$	Metastable quenching	-

Stepwise ionization (reaction 5) can play an important role in sustaining low pressure argon discharges. Excited argon atoms are consumed via superelastic collisions with electrons, quenching with neutral argon atoms, ionization or Penning ionization where two metastable argon atoms react to form a neutral argon atom, an argon ion and an electron. In addition to volumetric reactions, the following surface reactions are implemented:

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT
1	$Ar_s \Rightarrow Ar$	1
2	$Ar^+ \Rightarrow Ar$	1

When a metastable argon atom makes contact with the wall, it reverts to the ground state argon atom with some probability (the sticking coefficient).

ELECTRICAL EXCITATION

From an electrical point of view, the reactor behaves as a transformer. A current is applied to the driving coil (the primary) and this induces a current in the plasma (the secondary). The plasma then induces an opposing current back in the coil, increasing its resistance. The current flowing in the plasma depends on the current applied to the coil and the reaction kinetics. The total plasma current can vary from no current (plasma not sustained) to the same current as the primary which corresponds to perfect coupling between the coil and the plasma.

Results and Discussion

Figure 1 and Figure 2 show the electron density and the ion flux along the radial direction. The optimized solution is obviously more uniform along the radial direction.

Figure 3 and Figure 4 show 2D plots of the electron density and the power absorbed by electrons. In these figures it possible to observe the optimized coil position. The two outer coils are placed away from the center to control the plasma density drop at the reactor edge. The two inner coils are moved toward the center thus creating a pattern in the power absorbed by the electrons with two distinct maxima that sit below the inner and outer final coil arrangement.

The coil power needs to increase to 1800 W from the 1500 W of the initial design to obtain the desired density set for the optimization study.

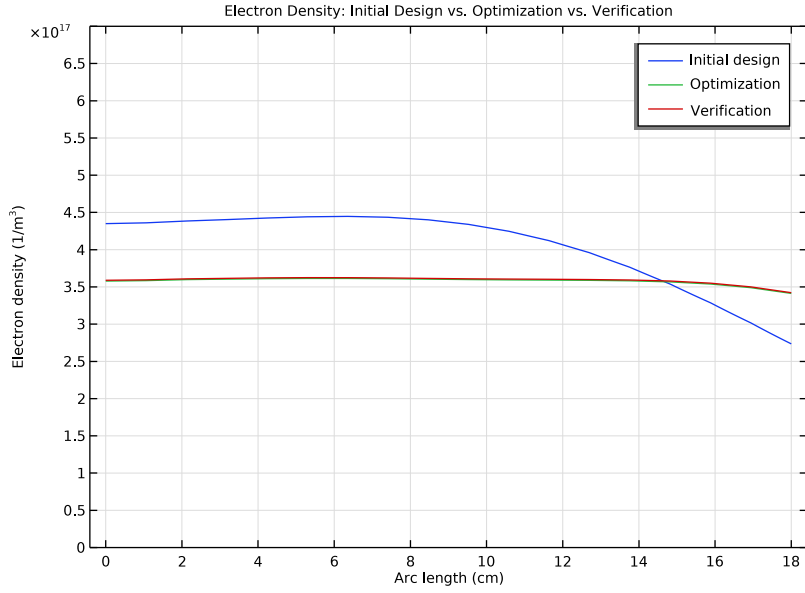


Figure 1: Electron density along the radial direction at $z = 7$ cm.

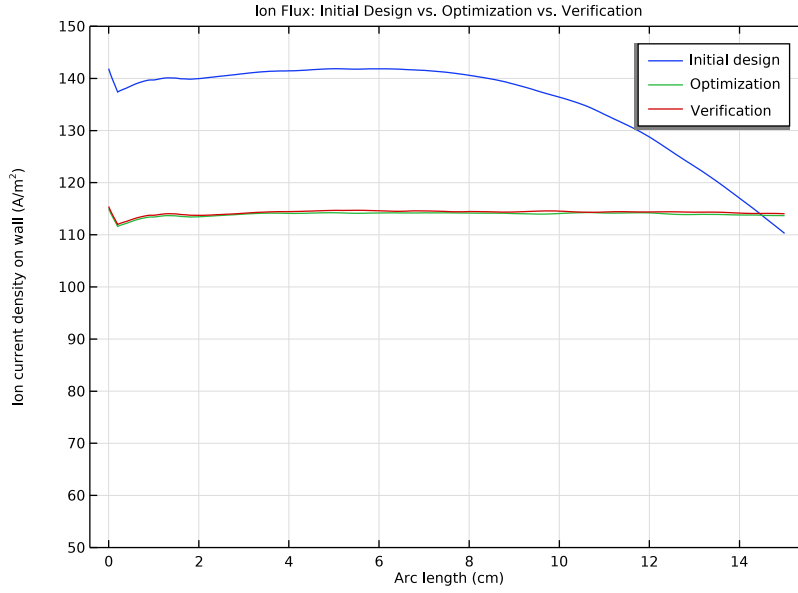


Figure 2: Ion flux perpendicular to the surface at the bottom surface.

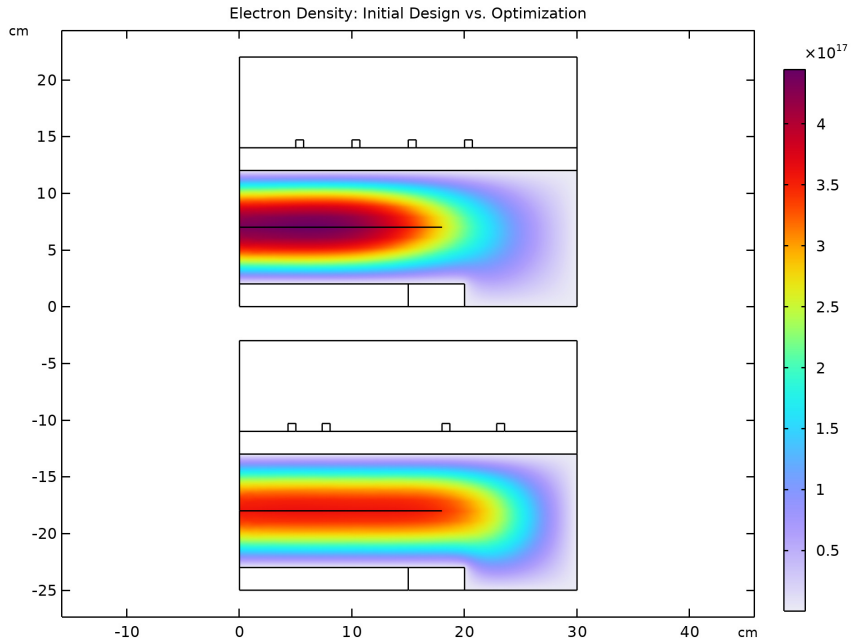


Figure 3: Electron densities obtained with the initial design (top) and the optimized configuration (bottom).

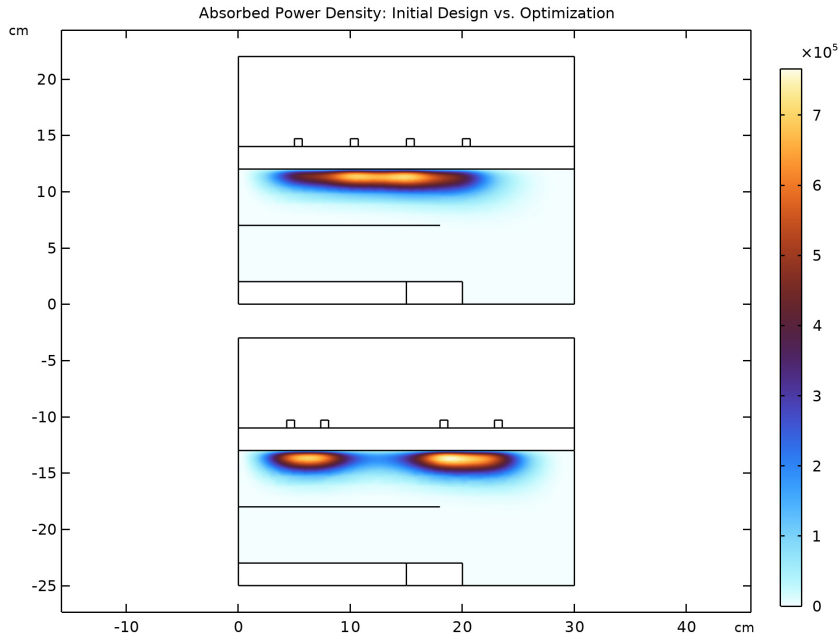


Figure 4: Power absorbed by the electrons obtained with the initial design (top) and the optimized configuration (bottom).

References

1. G.J.M. Hagelaar and L.C. Pitchford, “Solving the Boltzmann Equation to Obtain Electron Transport Coefficients and Rate Coefficients for Fluid Models,” *Plasma Sources Sci. Technol.*, vol. 14, pp. 722–733, 2005.
2. D.P. Lymeropoulos and D.J. Economou, “Two-Dimensional Self-Consistent Radio Frequency Plasma Simulations Relevant to the Gaseous Electronics Conference RF Reference Cell,” *J. Res. Natl. Inst. Stand. Technol.*, vol. 100, pp. 473–494, 1995.
3. Phelps database, www.lxcat.net, retrieved 2017.

Application Library path: Plasma_Module/Inductively_Coupled_Plasmas/
icp_coil_optimization


Modeling Instructions

The following instructions show how to create a 2D model of a planar ICP reactor whose coil positioning is optimized to enhance plasma uniformity. Three studies are used:




- 1 The first study solves for the initial design.
- 2 The second study uses an Optimization study step to optimize plasma uniformity. The optimization process moves the coils but there is no remeshing. The mesh is deformed and this process can introduce artifacts in the final solution if the displacements of the geometric entities are large. For this reason, a final verification is always good practice.
- 3 The third study does this verification by remeshing the optimized configuration and solves the problem again.

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 **Plasma > Inductively Coupled Plasma**.
- 3 Click **Add**.
- 4 Click  **Study**.
- 5 In the **Select Study** tree, select **Preset Studies for Selected Multiphysics > Frequency–Stationary**.
- 6 Click  **Done**.

GLOBAL DEFINITIONS

Add some parameters for the reactor dimensions, power, and pressure.

Parameters 1

- 1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.
- 2 In the **Settings** window for **Parameters**, locate the **Parameters** section.
- 3 Click  **Load from File**.
- 4 Browse to the model's Application Libraries folder and double-click the file `icp_coil_optimization_parameters.txt`.

Create the geometry and add selections to avoid using explicit selections in the rest of the model. Using implicit selection ensures a better compatibility with the optimization

process, for example, when topological changes are introduced by increasing the number of coils.


Some of the selections will make sense when preparing the optimization in the second study.

To facilitate integration along the center of the reactor, a line is introduced; the optimization will minimize the gradient of the electron density along this line.


GEOMETRY 1

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Geometry 1**.
- 2 In the **Settings** window for **Geometry**, locate the **Units** section.
- 3 From the **Length unit** list, choose **cm**.


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 W_c .
- 4 In the **Height** text field, type H_c .


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 W_s .
- 4 In the **Height** text field, type H_s .
- 5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


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 W_d .
- 4 In the **Height** text field, type H_d .
- 5 Locate the **Position** section. In the **r** text field, type W_s .
- 6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


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 Ww.
- 4 In the **Height** text field, type Hw.
- 5 Locate the **Position** section. In the **z** text field, type Hs+dp1asma.
- 6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


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 Ww.
- 4 In the **Height** text field, type Hs+dp1asma.
- 5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


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 Ww.
- 4 In the **Height** text field, type Hc - dp1asma - Hw - Hs.
- 5 Locate the **Position** section. In the **z** text field, type Hs+dp1asma+Hw.
- 6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


Coils

- 1 In the **Geometry** toolbar, click  **Rectangle**.
- 2 In the **Settings** window for **Rectangle**, type Coils in the **Label** text field.
- 3 Locate the **Size and Shape** section. In the **Width** text field, type Lcoil.
- 4 In the **Height** text field, type Lcoil.
- 5 Locate the **Position** section. In the **r** text field, type rc.
- 6 In the **z** text field, type Zcoil.
- 7 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** checkbox.


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 In the **z** text field, type 7.
- 5 Locate the **Endpoint** section. From the **Specify** list, choose **Coordinates**.
- 6 In the **r** text field, type 18.
- 7 In the **z** text field, type 7.


Array 1 (arr1)

- 1 In the **Geometry** toolbar, click  **Transforms** and choose **Array**.
- 2 In the **Settings** window for **Array**, locate the **Input** section.
- 3 From the **Input objects** list, choose **Coils**.
- 4 Locate the **Size** section. In the **r size** text field, type nCoil.
- 5 Locate the **Displacement** section. In the **r** text field, type coilSpace.


Form Union (fin)

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

Plasma

- 1 In the **Geometry** toolbar, click  **Selections** and choose **Difference Selection**.
- 2 In the **Settings** window for **Difference Selection**, type Plasma in the **Label** text field.
- 3 Locate the **Input Entities** section. Click the **+** **Add** button for **Selections to add**.
- 4 In the **Add** dialog, select **Rectangle 5** in the **Selections to add** list.
- 5 Click **OK**.
- 6 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.
- 7 Click the **+** **Add** button for **Selections to subtract**.
- 8 In the **Add** dialog, in the **Selections to subtract** list, choose **Rectangle 2** and **Rectangle 3**.
- 9 Click **OK**.

Axis

- 1 In the **Geometry** toolbar, click  **Selections** and choose **Box Selection**.
- 2 In the **Settings** window for **Box Selection**, locate the **Geometric Entity Level** section.
- 3 From the **Level** list, choose **Boundary**.
- 4 Locate the **Box Limits** section. In the **r maximum** text field, type eps.

5 Locate the **Output Entities** section. From the **Include entity if** list, choose **Entity inside box**.

6 In the **Label** text field, type **Axis**.

Adjacent Selection 1 (adjsel1)

1 In the **Geometry** toolbar, click  **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, locate the **Input Entities** section.

3 Click **+ Add**.

4 In the **Add** dialog, select **Plasma** in the **Input selections** list.

5 Click **OK**.

Walls

1 In the **Geometry** toolbar, click  **Selections** and choose **Difference Selection**.

2 In the **Settings** window for **Difference Selection**, type **Walls** in the **Label** text field.

3 Locate the **Geometric Entity Level** section. From the **Level** list, choose **Boundary**.

4 Locate the **Input Entities** section. Click the **+ Add** button for **Selections to add**.

5 In the **Add** dialog, select **Adjacent Selection 1** in the **Selections to add** list.

6 Click **OK**.

7 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.

8 Click the **+ Add** button for **Selections to subtract**.

9 In the **Add** dialog, select **Axis** in the **Selections to subtract** list.

10 Click **OK**.

Adjacent Domains to Coils

1 In the **Geometry** toolbar, click  **Selections** and choose **Adjacent Selection**.

2 In the **Settings** window for **Adjacent Selection**, type **Adjacent Domains to Coils** in the **Label** text field.

3 Locate the **Input Entities** section. Click **+ Add**.

4 In the **Add** dialog, select **Coils** in the **Input selections** list.

5 Click **OK**.

6 In the **Settings** window for **Adjacent Selection**, locate the **Output Entities** section.


7 From the **Geometric entity level** list, choose **Adjacent domains**.

Coil Boundaries


1 In the **Geometry** toolbar, click  **Selections** and choose **Adjacent Selection**.

- 2 In the **Settings** window for **Adjacent Selection**, type Coil Boundaries in the **Label** text field.
- 3 Locate the **Input Entities** section. Click **+ Add**.
- 4 In the **Add** dialog, select **Coils** in the **Input selections** list.
- 5 Click **OK**.


Magnetic Fields


- 1 In the **Geometry** toolbar, click  **Selections** and choose **Union Selection**.
- 2 In the **Settings** window for **Union Selection**, type Magnetic Fields in the **Label** text field.
- 3 Locate the **Input Entities** section. Click **+ Add**.
- 4 In the **Add** dialog, in the **Selections to add** list, choose **Rectangle 4**, **Coils**, **Plasma**, and **Adjacent Domains to Coils**.
- 5 Click **OK**.

Top Dielectric

- 1 In the **Geometry** toolbar, click  **Selections** and choose **Intersection Selection**.
- 2 In the **Settings** window for **Intersection Selection**, locate the **Geometric Entity Level** section.
- 3 From the **Level** list, choose **Boundary**.
- 4 Locate the **Input Entities** section. Click **+ Add**.
- 5 In the **Add** dialog, in the **Selections to intersect** list, choose **Rectangle 4** and **Rectangle 6**.
- 6 Click **OK**.
- 7 In the **Settings** window for **Intersection Selection**, type Top Dielectric in the **Label** text field.

Roller

- 1 In the **Geometry** toolbar, click  **Selections** and choose **Difference Selection**.
- 2 In the **Settings** window for **Difference Selection**, locate the **Geometric Entity Level** section.
- 3 From the **Level** list, choose **Boundary**.
- 4 Locate the **Input Entities** section. Click the **+ Add** button for **Selections to add**.
- 5 In the **Add** dialog, select **Top Dielectric** in the **Selections to add** list.
- 6 Click **OK**.
- 7 In the **Settings** window for **Difference Selection**, locate the **Input Entities** section.
- 8 Click the **+ Add** button for **Selections to subtract**.

- 9 In the **Add** dialog, select **Coils** in the **Selections to subtract** list.
- 10 Click **OK**.
- 11 In the **Settings** window for **Difference Selection**, type **Roller** in the **Label** text field.
- 12 In the **Geometry** toolbar, click  **Build All**.

MATERIALS

Define the material properties to use in the model.

Material 1 (mat1)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.
- 2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
- 3 From the **Selection** list, choose **Coils**.
- 4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1		Basic
Electric conductivity	sigma_iso ; sigmai = sigma_iso, sigmaj = 0	6e7	S/m	Basic
Relative permittivity	epsilon_iso ; epsilon_ii = epsilon_iso, epsilon_ij = 0	1		Basic

Material 2 (mat2)

- 1 Right-click **Materials** and choose **Blank Material**.
- 2 Select Domains 2 and 4 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		Basic
Electric conductivity	sigma_iso ; sigmair = sigma_iso, sigmairj = 0	0	S/m	Basic
Relative permittivity	epsilon_r_iso ; epsilon_r_ii = epsilon_r_iso, epsilon_r_ij = 0	1		Basic

Material 3 (mat3)

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		Basic
Electric conductivity	sigma_iso ; sigmair = sigma_iso, sigmairj = 0	0	S/m	Basic
Relative permittivity	epsilon_r_iso ; epsilon_r_ii = epsilon_r_iso, epsilon_r_ij = 0	4.2		Basic




Prepare the plasma model. Choose to use reduced transport properties, import electron impact reactions for argon, and add two heavy-species reactions.

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 From the **Selection** list, choose **Plasma**.
- 4 Locate the **Plasma Properties** section. Select the **Use reduced electron transport properties** checkbox.

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 $\text{Ar} + \text{Ar} \Rightarrow \text{e} + \text{Ar} + \text{Ar}^+$.
- 4 Locate the **Reaction Parameters** section. In the k^f text field, type 3.734E8.

7: $\text{Ar} + \text{Ar} \Rightarrow \text{e} + \text{Ar} + \text{Ar}^+$

- 1 Right-click **6: $\text{Ar} + \text{Ar} \Rightarrow \text{e} + \text{Ar} + \text{Ar}^+$** and choose **Duplicate**.
- 2 In the **Settings** window for **Reaction**, locate the **Reaction Formula** section.
- 3 In the **Formula** text field, type $\text{Ar} + \text{Ar} \Rightarrow \text{Ar} + \text{Ar}$.
- 4 Locate the **Reaction Parameters** section. In the k^f text field, type 1807.

When solving any type of reacting-flow problem, one species always needs to be selected to fulfill the mass constraint. This should be taken as the species with the largest mass fraction.

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** checkbox.
- 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**.

When solving a plasma problem, the plasma must be initially charge neutral. COMSOL Multiphysics automatically computes the initial concentration of a selected ionic species so that the initial electroneutrality constraint is satisfied. Once the simulation begins to time step, the plasma does not have to be charge neutral. In fact, the separation of space charge between the ions and electrons close to the wall is a critical component in sustaining the discharge.

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

Plasma Model I

- 1 In the **Model Builder** window, click **Plasma Model I**.
- 2 In the **Settings** window for **Plasma Model**, locate the **Model Inputs** section.
- 3 In the T text field, type T0.
- 4 In the p_A text field, type p0.
- 5 Locate the **Electron Density and Energy** section. In the $\mu_e N_n$ text field, type mueN.

Initial conditions for the electron number density and mean electron energy are critical for any plasma model. If the initial electron density is too low, the plasma may not be able to sustain itself and may self extinguish.

Initial Values I

- 1 In the **Model Builder** window, click **Initial Values I**.
- 2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.
- 3 In the $n_{e,0}$ text field, type 1E16[1/m^3].
- 4 In the ϵ_0 text field, type 2[V].

Add boundary conditions to the plasma transport and Poisson's equations.


Surface reactions must always be included in a plasma model since they describe how ionic, excited, and radical species interact with the wall.

Wall I


- 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**.
- 4 Locate the **General Wall Settings** section. In the r_e text field, type 0.2.

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**.

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 $\text{Ar}_s \Rightarrow \text{Ar}$.
- 4 Locate the **Boundary Selection** section. From the **Selection** list, choose **Walls**.

2: $\text{Ar}_s \Rightarrow \text{Ar}$

- 1 Right-click **1: $\text{Ar}_s \Rightarrow \text{Ar}$** and choose **Duplicate**.
- 2 In the **Settings** window for **Surface Reaction**, locate the **Reaction Formula** section.
- 3 In the **Formula** text field, type $\text{Ar}^+ \Rightarrow \text{Ar}$.


Prepare the model to compute the **Magnetic Fields**. This simple step is only needed to create a coil.

The **Coil** feature is used to electrically excite the system. The coil operates with a fixed total power of 1500 W in the first study.

MAGNETIC FIELDS (MF)

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic Fields (mf)**.
- 2 In the **Settings** window for **Magnetic Fields**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **Magnetic Fields**.

Domain Coil 1

- 1 In the **Physics** toolbar, click  **Domains** and choose **Domain Coil**.
- 2 In the **Settings** window for **Domain Coil**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **Coils**.
- 4 Locate the **Coil** section. Select the **Coil group** checkbox.
- 5 From the **Coil excitation** list, choose **Power**.
- 6 In the P_{coil} text field, type Psp.

Meshing is a critical step in any plasma model; boundary layer meshing on the reactor walls is nearly always necessary to capture the separation of space charge between the electrons and ions close to the wall. Also, add a fine mesh in the coil domains since the skin depth needs to be resolved.

MESH I

- 1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.
- 2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.
- 3 In the table, clear the **Use** checkboxes for **Plasma (plas)**, **Magnetic Fields (mf)**, **Plasma Conductivity Coupling 1 (pcc1)**, and **Electron Heat Source 1 (ehs1)**.
- 4 Locate the **Sequence Type** section. From the list, choose **User-controlled mesh**.

Size

- 1 In the **Model Builder** window, under **Component 1 (comp1) > Mesh 1** click **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 From the **Predefined** list, choose **Finer**.


Free Triangular 1

- 1 In the **Model Builder** window, click **Free Triangular 1**.
- 2 In the **Settings** window for **Free Triangular**, locate the **Domain Selection** section.
- 3 From the **Geometric entity level** list, choose **Domain**.
- 4 From the **Selection** list, choose **Plasma**.

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 **Finer**.

Edge 1


- 1 In the **Mesh** toolbar, click  **More Generators** and choose **Edge**.
- 2 In the **Settings** window for **Edge**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Walls**.

Size 1

- 1 Right-click **Edge 1** and choose **Size**.
- 2 In the **Settings** window for **Size**, locate the **Element Size** section.
- 3 Click the **Custom** button.

- 4 Locate the **Element Size Parameters** section.
- 5 Select the **Maximum element size** checkbox. In the associated text field, type $2E-3[m]$.


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 From the **Selection** list, choose **Plasma**.
- 5 Click to expand the **Transition** section. Clear the **Smooth transition to interior mesh** checkbox.

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 5.
- 5 In the **Stretching factor** text field, type 1.4.

Mapped 1

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


Distribution 1

- 1 Right-click **Mapped 1** and choose **Distribution**.
- 2 In the **Settings** window for **Distribution**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Coil Boundaries**.
- 4 Locate the **Distribution** section. From the **Distribution type** list, choose **Predefined**.
- 5 In the **Number of elements** text field, type 25.
- 6 In the **Element ratio** text field, type 20.
- 7 Select the **Symmetric distribution** checkbox.

Free Triangular 2

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

Edge 1

- 1 In the **Model Builder** window, click **Edge 1**.
- 2 Drag and drop below **Size**.
- 3 In the **Settings** window for **Edge**, click  **Build All**.

Get the initial values and group them so that the Results section stays organized when adding more studies.

Then, label the study, choose to look at the results while solving, and solve the problem.

STUDY 1

In the **Study** toolbar, click  **Get Initial Value**.

RESULTS

Electric Potential (plas), Electron Density (plas), Electron Temperature (plas), Magnetic Flux Density (mf), Magnetic Flux Density, Revolved Geometry (mf)

- 1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electron Density (plas)**, **Electron Temperature (plas)**, **Electric Potential (plas)**, **Magnetic Flux Density (mf)**, and **Magnetic Flux Density, Revolved Geometry (mf)**.
- 2 Right-click and choose **Group**.

Initial Design


In the **Settings** window for **Group**, type Initial Design in the **Label** text field.

STUDY 1

Step 1: Frequency–Stationary

- 1 In the **Model Builder** window, expand the **Study 1 > Solver Configurations** node, then click **Study 1 > Step 1: Frequency–Stationary**.
- 2 In the **Settings** window for **Frequency–Stationary**, locate the **Study Settings** section.
- 3 In the **Frequency** text field, type 13.56[MHz].

Solution 1 (sol1)



- 1 In the **Model Builder** window, expand the **Study 1 > Solver Configurations > Solution 1 (sol1) > Stationary Solver 1** node, then click **Fully Coupled 1**.
- 2 In the **Settings** window for **Fully Coupled**, click to expand the **Results While Solving** section.
- 3 Select the **Plot** checkbox.
- 4 In the **Study** toolbar, click  **Compute**.

- 5 In the **Model Builder** window, click **Study 1**.
- 6 In the **Settings** window for **Study**, type Study 1: Initial Design in the **Label** text field.



DEFINITIONS

Next, add two probes for use in the Optimization study step.

Gradient Minimization

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Boundary Probe**.
- 2 In the **Settings** window for **Boundary Probe**, type Gradient Minimization in the **Label** text field.
- 3 In the **Variable name** text field, type int_grad_ne.
- 4 Locate the **Source Selection** section. Click  **Clear Selection**.
- 5 Select Boundary 6 only.
- 6 Locate the **Probe Type** section. From the **Type** list, choose **Integral**.
- 7 Locate the **Expression** section. In the **Expression** text field, type $\sqrt{(d(p_{las}.ne, r)^2)}$.
- 8 Locate the **Integration Settings** section. Clear the **Compute surface integral** checkbox.


Constraint for Electron Density at the Center

- 1 In the **Definitions** toolbar, click  **Probes** and choose **Point Probe**.
- 2 In the **Settings** window for **Point Probe**, type Constraint for Electron Density at the Center in the **Label** text field.
- 3 In the **Variable name** text field, type ne_center. This variable will be used to fix the electron density.
- 4 Locate the **Source Selection** section. Click  **Clear Selection**.
- 5 Select Point 3 only.
- 6 Locate the **Expression** section. In the **Expression** text field, type $p_{las}.ne/ne0$.

COMPONENT 1 (COMP1)


Use a Shape Optimization feature to define the domain to be optimized.

Free Shape Domain 1

- 1 In the **Physics** toolbar, click  **Optimization** and choose **Shape Optimization**.
- 2 In the **Settings** window for **Free Shape Domain**, locate the **Domain Selection** section.
- 3 From the **Selection** list, choose **Adjacent Domains to Coils**.

In a Transformation feature, specify that the coils can be displaced only along the radial direction in an interval of $[-3, +3]$ cm from their initial positions.

Transformation I


- 1 In the **Shape Optimization** toolbar, click  **Transformation**.
- 2 In the **Settings** window for **Transformation**, locate the **Translation** section.
- 3 In the table, enter the following settings:

	Lock	Lower bound (m)	Upper bound (m)
R		-3 [cm]	3 [cm]

- 4 Locate the **Scaling** section. From the **Scaling type** list, choose **No scaling**.
- 5 Locate the **Geometric Entity Selection** section. From the **Selection** list, choose **Coils**.


Use a Symmetry/Roller feature to ensure that the top of the dielectric is not deformed.

Symmetry/Roller I

- 1 In the **Shape Optimization** toolbar, click  **Symmetry/Roller**.
- 2 In the **Settings** window for **Symmetry/Roller**, locate the **Boundary Selection** section.
- 3 From the **Selection** list, choose **Roller**.

DEFINITIONS


Variables I


- 1 In the **Definitions** toolbar, click  **Local Variables**.
- 2 In the **Settings** window for **Variables**, locate the **Variables** section.
- 3 In the table, enter the following settings:

Name	Expression	Unit	Description
ne0	$3.5E17 [m^{-3}]$	l/m^3	
obj_negrad	$int_grad_ne/ne0$		Objective gradient

Add a study with a Frequency-Stationary study step, then add an Optimization study step to it.

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 **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Multiphysics > Frequency–Stationary**.
- 4 Click the **Add Study** button in the window toolbar.
- 5 In the **Home** toolbar, click  **Add Study** to close the **Add Study** window.

STUDY 2

Step 1: Frequency–Stationary

- 1 In the **Settings** window for **Frequency–Stationary**, locate the **Study Settings** section.
- 2 In the **Frequency** text field, type 13.56 [MHz].
- 3 In the **Model Builder** window, click **Study 2**.
- 4 In the **Settings** window for **Study**, type Study 2: Optimization in the **Label** text field.


General Optimization

- 1 In the **Study** toolbar, click  **Optimization** and choose **General Optimization**.
- 2 In the **Settings** window for **General Optimization**, locate the **Optimization Solver** section.
- 3 From the **Method** list, choose **GCMMA**.
- 4 In the **Maximum number of model evaluations** text field, type 20.

Specify the objective function for the minimization of the electron density gradient.

- 5 Click **Add Expression** in the upper-right corner of the **Objective Function** section. From the menu, choose **Component 1 (comp1) > Definitions > Variables > comp1.obj_negrad - Objective gradient - 1**.

Add the coil power as a control parameter so that it can be adjusted to match the electron density constraint.


- 6 Locate the **Control Variables and Parameters** section. Click  **Add**.
- 7 In the table, enter the following settings:

Parameter	Initial value	Scale	Lower bound	Upper bound	Unit
Psp (Power input)	1500 [W]	1000 [W]	500 [W]	5000 [W]	W

Add a density constraint in the reactor center.

- 8 Locate the **Constraints** section. In the table, enter the following settings:

Expression	Lower bound	Upper bound	Evaluate for
comp1.ne_center	1	1.1	Frequency-Stationary

9 In the **Study** toolbar, click  **Get Initial Value**.

RESULTS

Electric Potential (plas) 1, Electron Density (plas) 1, Electron Temperature (plas) 1, Magnetic Flux Density (mf) 1, Magnetic Flux Density, Revolved Geometry (mf) 1, Probe Plot Group 6, Shape Optimization

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Probe Plot Group 6**, **Electron Density (plas) 1**, **Electron Temperature (plas) 1**, **Electric Potential (plas) 1**, **Magnetic Flux Density (mf) 1**, **Magnetic Flux Density, Revolved Geometry (mf) 1**, and **Shape Optimization**.

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

Optimization

In the **Settings** window for **Group**, type **Optimization** in the **Label** text field.

STUDY 2: OPTIMIZATION

General Optimization

1 In the **Model Builder** window, under **Study 2: Optimization** click **General Optimization**.

2 In the **Settings** window for **General Optimization**, click to expand the **Output** section.

3 Select the **Plot** checkbox.

4 In the table, enter the following settings:

Plot group	Plot window
Shape Optimization	Graphics

5 From the **Probes** list, choose **None**.

Solver Configurations


In the **Model Builder** window, expand the **Study 2: Optimization > Solver Configurations** node.

Solution 2 (sol2)

1 In the **Model Builder** window, expand the **Study 2: Optimization > Solver Configurations > Solution 2 (sol2) > Optimization Solver 1 > Stationary Solver 1** node, then click **Direct (Merged)**.

2 In the **Settings** window for **Direct**, click to expand the **Error** section.

3 From the **Check error estimate** list, choose **No**.

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

The next set of instructions mesh the optimized geometry.

RESULTS

Study 2: Optimization/Solution 2 (sol2)



- 1 In the **Model Builder** window, expand the **Results > Datasets** node.
- 2 Right-click **Results > Datasets > Study 2: Optimization/Solution 2 (sol2)** and choose **Remesh Deformed Configuration**.

MESH 2

- 1 In the **Model Builder** window, expand the **Deformed Configuration 1 (frommesh1)** node.
- 2 Right-click **Component 1 (comp1) > Meshes > Deformed Configuration 1 (frommesh1) > Mesh 2** and choose **Build All**.

Next, add a final study to verify that there are no artifacts introduced by the mesh deformation.


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 **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Multiphysics > Frequency–Stationary**.
- 4 Click the **Add Study** button in the window toolbar.
- 5 In the **Home** 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 13.56[MHz].
- 3 Locate the **Physics and Variables Selection** section. In the **Solve for** column of the table, under **Component 1 (comp1)**, clear the checkbox for **Deformed Geometry**.
- 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 **Study 2: Optimization, Frequency–Stationary**.

- 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 **Study 2: Optimization, Frequency–Stationary**.
- 10 In the **Model Builder** window, click **Study 3**.
- 11 In the **Settings** window for **Study**, type Study 3: Verification in the **Label** text field.
- 12 In the **Study** toolbar, click  **Compute**.

RESULTS

Electric Potential (plas) 2, Electron Density (plas) 2, Electron Temperature (plas) 2, Magnetic Flux Density (mf) 2, Magnetic Flux Density, Revolved Geometry (mf) 2, Shape Optimization 1

Right-click and choose **Group**.


Verification

In the **Settings** window for **Group**, type Verification in the **Label** text field.

Add a set of plots to show the results of the optimization.

Begin by adding 1D plots of the electron density and the ion flux to show the radial uniformity obtained. Next, create 2D plots of the electron density and the power absorbed by the electrons.

Electron Density: Initial Design vs. Optimization vs. Verification

- 1 In the **Results** toolbar, click  **ID Plot Group**.
- 2 In the **Settings** window for **ID Plot Group**, type Electron Density: Initial Design vs. Optimization vs. Verification in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Line Graph 1

- 1 Right-click **Electron Density: Initial Design vs. Optimization vs. Verification** and choose **Line Graph**.
- 2 Select Boundary 6 only.
- 3 In the **Settings** window for **Line Graph**, click to expand the **Legends** section.
- 4 Select the **Show legends** checkbox.
- 5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends

Initial design

7 In the **Electron Density: Initial Design vs. Optimization vs. Verification** toolbar, click

 **Plot.**

Line Graph 2

1 Right-click **Line Graph 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 2: Optimization/Solution 2 (sol2)**.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends

Optimization

Line Graph 3

1 Right-click **Line Graph 2** and choose **Duplicate**.

2 In the **Settings** window for **Line Graph**, locate the **Data** section.

3 From the **Dataset** list, choose **Study 3: Verification/Solution 3 (sol3)**.

4 Locate the **Legends** section. In the table, enter the following settings:

Legends

Verification

5 In the **Electron Density: Initial Design vs. Optimization vs. Verification** toolbar, click

 **Plot.**

Electron Density: Initial Design vs. Optimization vs. Verification

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

Electron Density: Initial Design vs. Optimization vs. Verification.

2 In the **Settings** window for **ID Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** checkbox.

4 In the **y minimum** text field, type 0.

5 In the **y maximum** text field, type $7e17$.



6 In the **Electron Density: Initial Design vs. Optimization vs. Verification** toolbar, click

 **Plot.**



Ion Flux: Initial Design vs. Optimization vs. Verification

- 1 Right-click **Electron Density: Initial Design vs. Optimization vs. Verification** and choose **Duplicate**.
- 2 In the **Model Builder** window, click **Electron Density: Initial Design vs. Optimization vs. Verification 1**.
- 3 In the **Settings** window for **ID Plot Group**, type Ion Flux: Initial Design vs. Optimization vs. Verification in the **Label** text field.



Line Graph 1

- 1 In the **Model Builder** window, click **Line Graph 1**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 Click to select the  **Activate Selection** toggle button.
- 4 Click  **Clear Selection**.
- 5 Select Boundary 4 only.
- 6 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.nji_wAr_1p`.
- 7 Click to expand the **Quality** section. From the **Evaluation settings** list, choose **Manual**.
- 8 From the **Recover** list, choose **Within domains**.

Line Graph 2


- 1 In the **Model Builder** window, click **Line Graph 2**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 Click to select the  **Activate Selection** toggle button.
- 4 Click  **Clear Selection**.
- 5 Select Boundary 4 only.
- 6 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.nji_wAr_1p`.
- 7 Locate the **Quality** section. From the **Evaluation settings** list, choose **Manual**.
- 8 From the **Recover** list, choose **Within domains**.

Line Graph 3


- 1 In the **Model Builder** window, click **Line Graph 3**.
- 2 In the **Settings** window for **Line Graph**, locate the **Selection** section.
- 3 Click to select the  **Activate Selection** toggle button.
- 4 Click  **Clear Selection**.
- 5 Select Boundary 4 only.
- 6 Locate the **y-Axis Data** section. In the **Expression** text field, type `plas.nji_wAr_1p`.

- 7 Locate the **Quality** section. From the **Evaluation settings** list, choose **Manual**.
- 8 From the **Recover** list, choose **Within domains**.

Ion Flux: Initial Design vs. Optimization vs. Verification

- 1 In the **Model Builder** window, click **Ion Flux: Initial Design vs. Optimization vs. Verification**.
- 2 In the **Settings** window for **ID Plot Group**, locate the **Axis** section.
- 3 In the **y maximum** text field, type 150.
- 4 In the **y minimum** text field, type 50.
- 5 In the **x maximum** text field, type 15.5.
- 6 In the **Ion Flux: Initial Design vs. Optimization vs. Verification** toolbar, click  **Plot**.

Electron Density: Initial Design vs. Optimization

- 1 In the **Results** toolbar, click  **2D Plot Group**.
- 2 In the **Settings** window for **2D Plot Group**, type Electron Density: Initial Design vs. Optimization in the **Label** text field.
- 3 Click to expand the **Title** section. From the **Title type** list, choose **Label**.

Surface 1

- 1 Right-click **Electron Density: Initial Design vs. Optimization** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study 1: Initial Design/Solution 1 (sol1)**.

Surface 2

- 1 In the **Model Builder** window, right-click **Electron Density: Initial Design vs. Optimization** and choose **Surface**.
- 2 In the **Settings** window for **Surface**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study 3: Verification/Solution 3 (sol3)**.
- 4 Click to expand the **Inherit Style** section. From the **Plot** list, choose **Surface 1**.



Deformation 1

- 1 Right-click **Surface 2** and choose **Deformation**.
- 2 In the **Settings** window for **Deformation**, locate the **Expression** section.
- 3 In the **z-component** text field, type -25.
- 4 Locate the **Scale** section.
- 5 Select the **Scale factor** checkbox. In the associated text field, type 1.

Line 1

- 1 In the **Model Builder** window, right-click **Electron Density: Initial Design vs. Optimization** and choose **Line**.
- 2 In the **Settings** window for **Line**, locate the **Data** section.
- 3 From the **Dataset** list, choose **Study 3: Verification/Solution 3 (sol3)**.
- 4 Locate the **Expression** section. In the **Expression** text field, type 1.
- 5 Locate the **Coloring and Style** section. From the **Coloring** list, choose **Uniform**.
- 6 From the **Color** list, choose **Black**.

Deformation 1

- 1 Right-click **Line 1** and choose **Deformation**.
- 2 In the **Settings** window for **Deformation**, locate the **Expression** section.
- 3 In the **z-component** text field, type -25.
- 4 Locate the **Scale** section.
- 5 Select the **Scale factor** checkbox. In the associated text field, type 1.
- 6 In the **Electron Density: Initial Design vs. Optimization** toolbar, click  **Plot**.
- 7 Click the  **Zoom Extents** button in the **Graphics** toolbar.

Absorbed Power Density: Initial Design vs. Optimization

- 1 In the **Model Builder** window, right-click **Electron Density: Initial Design vs. Optimization** and choose **Duplicate**.
- 2 In the **Settings** window for **2D Plot Group**, type Absorbed Power Density: Initial Design vs. Optimization in the **Label** text field.

Surface 1

- 1 In the **Model Builder** window, expand the **Absorbed Power Density: Initial Design vs. Optimization** node, then click **Surface 1**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type $mf \cdot Qrh$.
- 4 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalWave**.

Surface 2

- 1 In the **Model Builder** window, click **Surface 2**.
- 2 In the **Settings** window for **Surface**, locate the **Expression** section.
- 3 In the **Expression** text field, type $mf \cdot Qrh$.

Selection 1

1 Right-click **Surface 2** and choose **Selection**.

2 Select Domain 2 only.

Selection 1

1 In the **Model Builder** window, right-click **Surface 1** and choose **Selection**.

2 Select Domain 2 only.

3 In the **Absorbed Power Density: Initial Design vs. Optimization** toolbar, click  **Plot**.