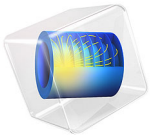

Coil Optimization of an ICP Reactor

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

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

where n_{e0} is a normalization constant. This type of problem can be solved using the IPOPT 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

The electron density and mean electron energy are computed by solving a pair of drift-diffusion equations for the electron density and mean electron energy. For detailed information on electron transport, see *Theory for the Drift Diffusion Interface* in the *Plasma Module User's Guide*.

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

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

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 computed 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 source coefficients in the above equations are determined by the plasma chemistry using rate coefficients. 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 (SI unit: m^3/s), and N_n is the total neutral number density (SI unit: $1/\mathrm{m}^3$). 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 (SI unit: V). 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 $\gamma = (2q/m_e)^{1/2}$ (SI unit: $\mathrm{C}^{1/2}/\mathrm{kg}^{1/2}$), m_e is the electron mass (SI unit: kg), ε is energy (SI unit: V), σ_k is the collision cross section (SI unit: m^2), and f is the electron energy distribution function. In this case, a Maxwellian EEDF is assumed.

For nonelectron 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:

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

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*.

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

$$(j\omega\sigma - \omega^2\varepsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1}\nabla \times \mathbf{A}) = \mathbf{J}^e$$

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:

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

and the electron energy flux:

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

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+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	-

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	Ars=>Ar	1
2	Ar+=>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.

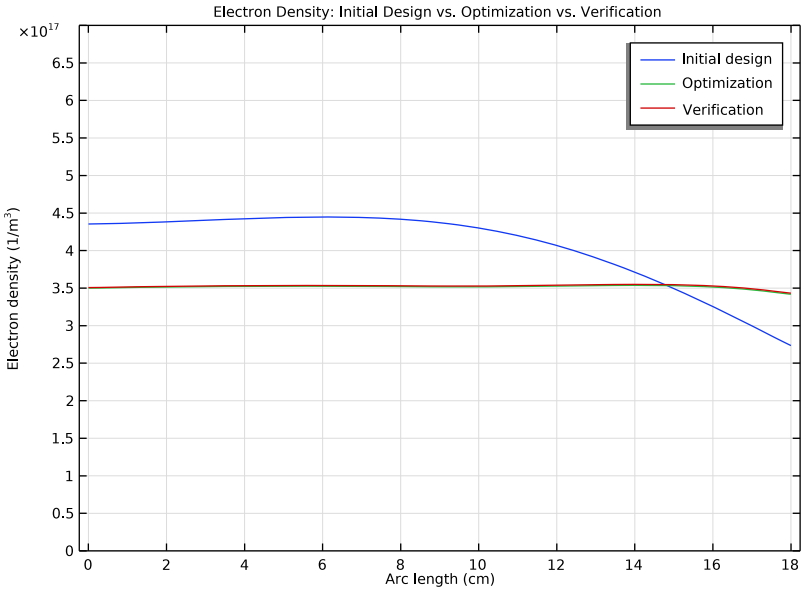

Figure 1: Electron density along the radial direction at z = 7 cm.

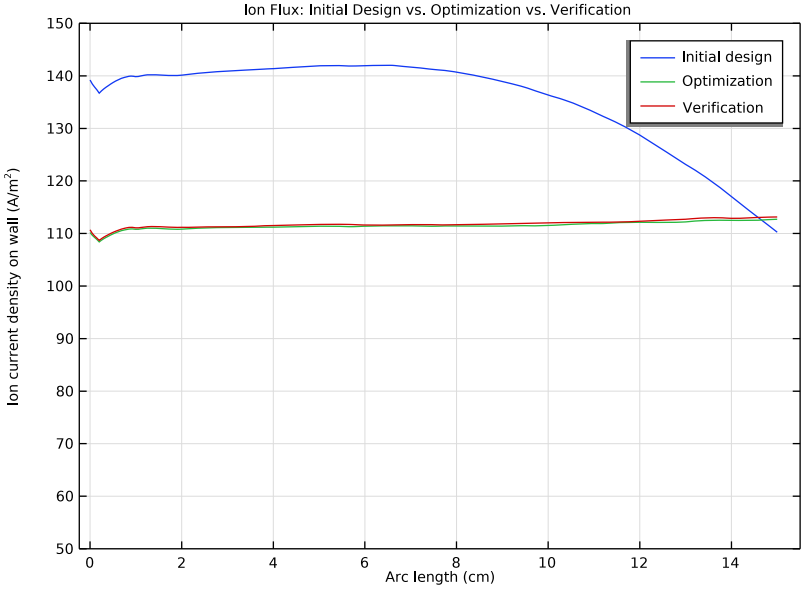

Figure 2: Ion flux perpendicular to the surface at the bottom surface.

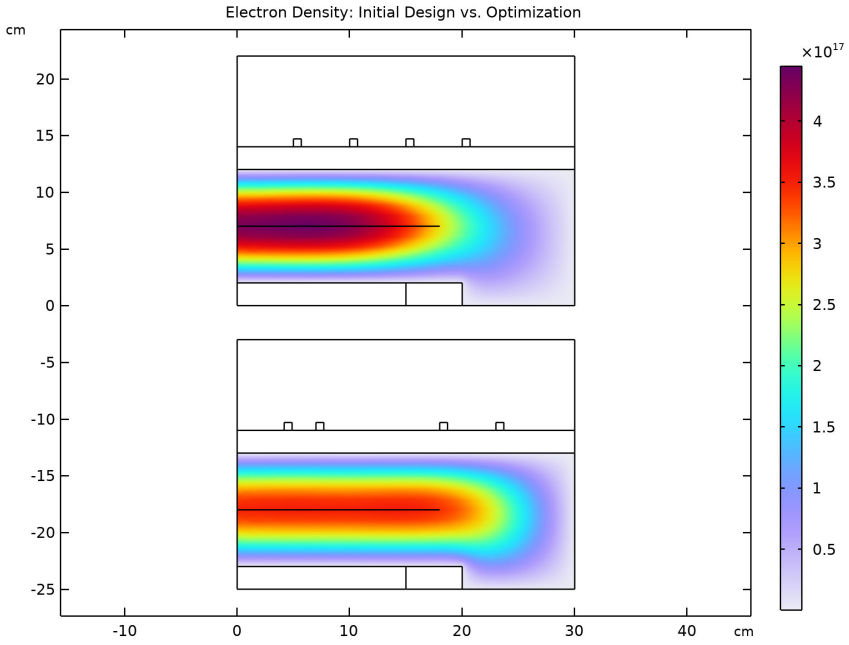

Figure 3: Electron densities obtained with the initial design (top) and the optimized configuration (bottom).

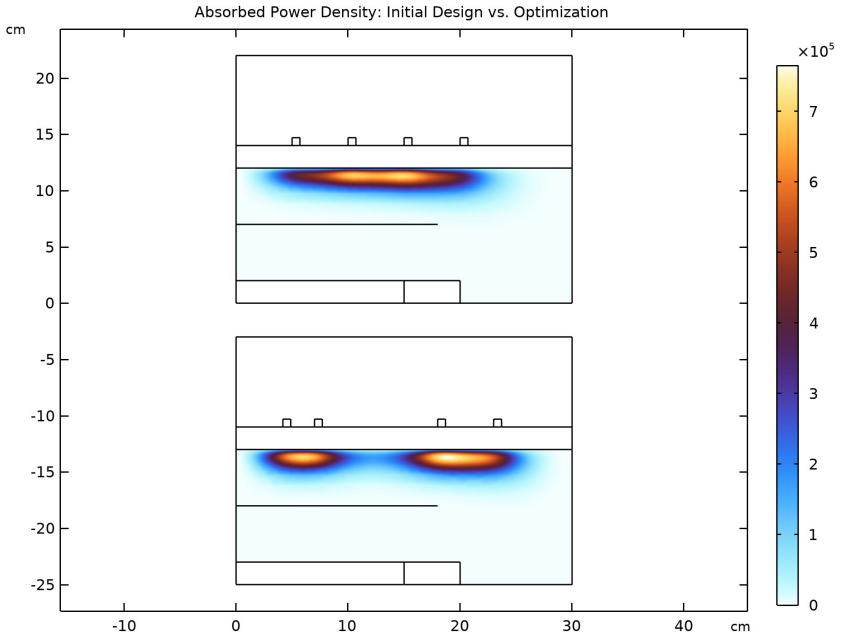

Figure 4: Power absorbed by the electrons obtained with the initial design (top) and the optimized configuration (bottom).

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. Lymberopoulos 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 `Wc`.

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

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 `Ws`.

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

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

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 `Wd`.

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

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

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

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+dplasma`.

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

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+dplasma`.

5 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

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-dplasma-Hw-Hs`.

5 Locate the **Position** section. In the **z** text field, type `Hs+dplasma+Hw`.

6 Locate the **Selections of Resulting Entities** section. Select the **Resulting objects selection** check box.

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** check box.

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 **Add**.

4 In the **Add** dialog box, 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 **Add**.

8 In the **Add** dialog box, 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 box, 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 **Add**.

5 In the **Add** dialog box, 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 **Add**.

9 In the **Add** dialog box, 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 box, 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 box, 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 box, 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 box, 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 **Add**.

5 In the **Add** dialog box, 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 **Add**.

9 In the **Add** dialog box, 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	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 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	I	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	I	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	I	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	4.2	I	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** check box.

Cross Section Import 1

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

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

3 Click **Browse**.

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

5 Click **Import**.

Reaction 1

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

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

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

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

7: Ars+Ars=>e+Ar+Ar+

1 Right-click **6: Ars+Ars=>e+Ar+Ar+** and choose **Duplicate**.

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`.

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** 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**.

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** check box.

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

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 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 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 `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 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**.

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 `Ars=>Ar`.

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

2: Ars=>Ar

1 Right-click **1: Ars=>Ar** and choose **Duplicate**.

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

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

Coil 1

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

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

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

4 Locate the **Coil** section. Select the **Coil group** check box.

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 1

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

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

3 In the table, clear the **Use** check boxes 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  **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** check box. 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** check box.

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** check box.

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 Norm (mf), Magnetic Flux Density Norm, 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 Norm (mf)**, and **Magnetic Flux Density Norm, 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** check box.

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

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

6 In the **Settings** window for **Study**, type `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(plas.ne, r)^2)`.

8 Locate the **Integration Settings** section. Clear the **Compute surface integral** check box.

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 `plas.ne/ne0`.

COMPONENT 1 (COMP1)

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

Free Shape Domain 1

1 In the **Definitions** toolbar, click **Optimization** and choose **Shape Optimization> Free Shape Domain**.

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 1

1 In the **Definitions** toolbar, click **Optimization** and choose **Shape Optimization>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 1

1 In the **Definitions** toolbar, click **Optimization** and choose **Shape Optimization>Symmetry/Roller**.

2 In the **Settings** window for **Symmetry/Roller**, locate the **Boundary Selection** section.

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

DEFINITIONS

Variables 1

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]	1/m³	
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 **Add Study** 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 `Optimization` in the **Label** text field.

Optimization

1 In the **Study** toolbar, click **Optimization** and choose **Optimization**.

2 In the **Settings** window for **Optimization**, locate the **Optimization Solver** section.

3 From the **Method** list, choose **IPOPT**.

4 In the **Optimality tolerance** text field, type `0.0005`.

5 Find the **Solver settings** subsection. In the **Maximum number of model evaluations** text field, type `20`.

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

6 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**.

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

7 Locate the **Control Variables and Parameters** section. Click **Add**.

8 In the table, enter the following settings:

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

Add a density constraint in the reactor center.

9 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

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

RESULTS

Electric Potential (plas) 1, Electron Density (plas) 1, Electron Temperature (plas) 1, Magnetic Flux Density Norm (mf) 1, Magnetic Flux Density Norm, Revolved Geometry (mf) 1, Probe Plot Group 12, Shape Optimization

1 In the **Model Builder** window, under **Results**, Ctrl-click to select **Electron Density (plas) 1**, **Electron Temperature (plas) 1**, **Electric Potential (plas) 1**, **Magnetic Flux Density Norm (mf) 1**, **Magnetic Flux Density Norm, Revolved Geometry (mf) 1**, **Shape Optimization**, and **Probe Plot Group 12**.

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

Optimization

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

OPTIMIZATION

Optimization

1 In the **Model Builder** window, under **Optimization** click **Optimization**.

2 In the **Settings** window for **Optimization**, locate the **Output While Solving** section.

3 Select the **Plot** check box.

4 From the **Plot group** list, choose **Probe Plot Group 12**.

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

Solver Configurations

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

Solution 2 (sol2)

1 In the **Model Builder** window, expand the **Optimization>Solver Configurations> Solution 2 (sol2)>Optimization Solver 1>Stationary 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

Optimization/Solution 2 (sol2)

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

2 Right-click **Results>Datasets>Optimization/Solution 2 (sol2)** and choose **Remesh Deformed Configuration**.

MESH 2

Deformed Configuration 1 (frommesh1)

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 **Add Study** 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 table, clear the **Solve for** check box for **Deformed geometry (Component 1)**.

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 **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 **Optimization, Frequency-Stationary**.

10 Click to expand the **Mesh Selection** section. In the **Model Builder** window, click **Study 3**.

11 In the **Settings** window for **Study**, type `Verification` in the **Label** text field.

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

RESULTS

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

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

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

2 In the **Settings** window for **1D 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** check box.

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 **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 **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 **1D Plot Group**, locate the **Axis** section.

3 Select the **Manual axis limits** check box.

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 **1D 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 **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 **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 **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 **1D 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 **Home** toolbar, click **Add Plot Group** and choose **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 **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 **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** check box. 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 **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** check box. 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.Qrh`.

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

5 In the **Color Table** dialog box, select **Thermal>ThermalWave** in the tree.

6 Click **OK**.

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.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**.