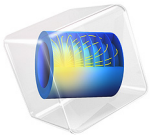

Model created in COMSOL Multiphysics 6.4

GEC ICP Reactor, Argon Chemistry

Introduction

The GEC cell was introduced by NIST (National Institute of Standards and Technology) in order to provide a standardized platform for experimental and modeling studies of discharges in different laboratories. The plasma is sustained via inductive heating. The Reference Cell operates as an inductively-coupled plasma in this model.

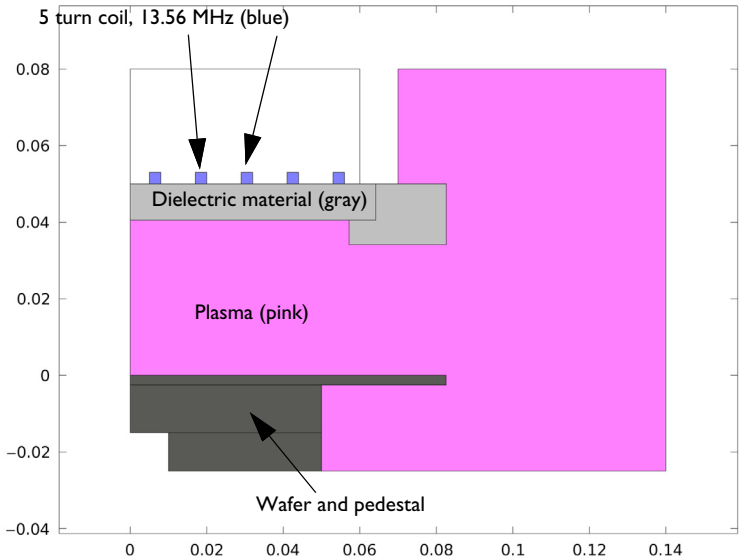

Figure 1: GEC ICP reactor geometry consisting of a 5 turn copper coil, plasma volume, dielectrics, and wafer with pedestal.

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

Model Definition

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*)

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

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

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

$$k^f = N_A \gamma \int_0^\infty \varepsilon \sigma(\varepsilon) f(\varepsilon) d\varepsilon$$

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

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

where $\Delta\varepsilon_j$ 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 $\Delta\varepsilon_j$ corresponds to the energy of the excited state being excited/deexcited or ionized, for attachment $\Delta\varepsilon_j$ is set to zero, and for elastic collisions

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

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:

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

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:

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

The electromagnetic wave "sees" a plasma defined by the plasma conductivity in the cold plasma approximation that is set in the **Plasma Conductivity Coupling** multiphysics feature:

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

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. The Joule heating term that is responsible to heat the electrons is set in the **Electron Heat Source** multiphysics feature.

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

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED.

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

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 GEC 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.

In this example a fixed power of 1500 W is applied to the coil. Some of this power is dissipated in the coil, some is deposited into the plasma.

The peak electron density occurs at the center of the reactor, underneath the RF coil. The electron density in this case is high enough to cause some shielding of the azimuthal electric field.

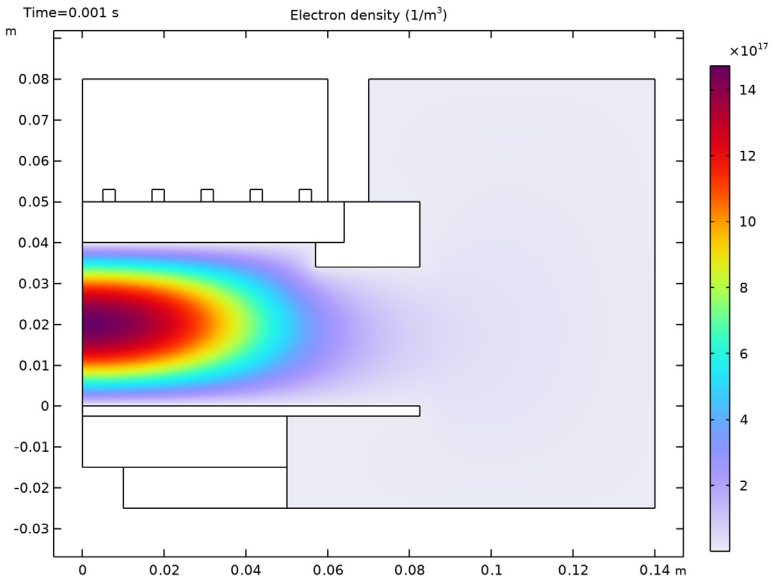

Figure 2: Plot of the electron density inside the GEC ICP reactor.

The electron "temperature" is highest directly underneath the coil, which is where the bulk of the power deposition occurs.

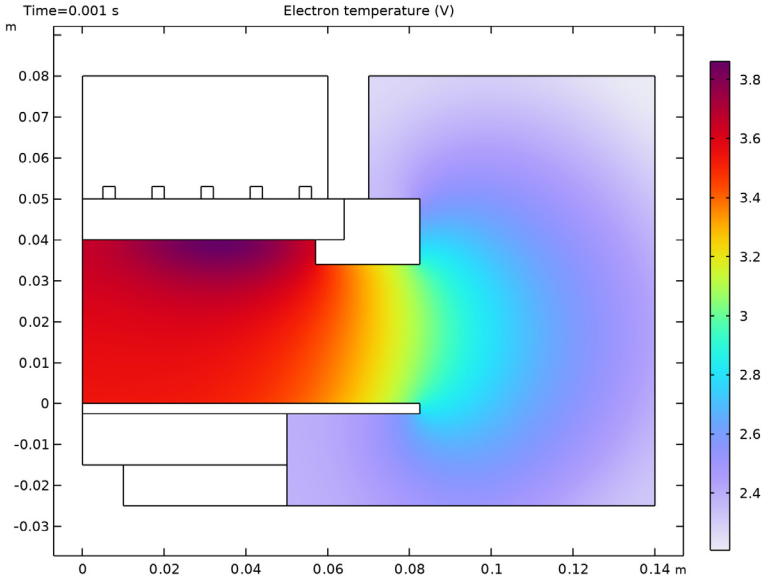

Figure 3: Plot of the electron "temperature" inside the GEC ICP reactor.

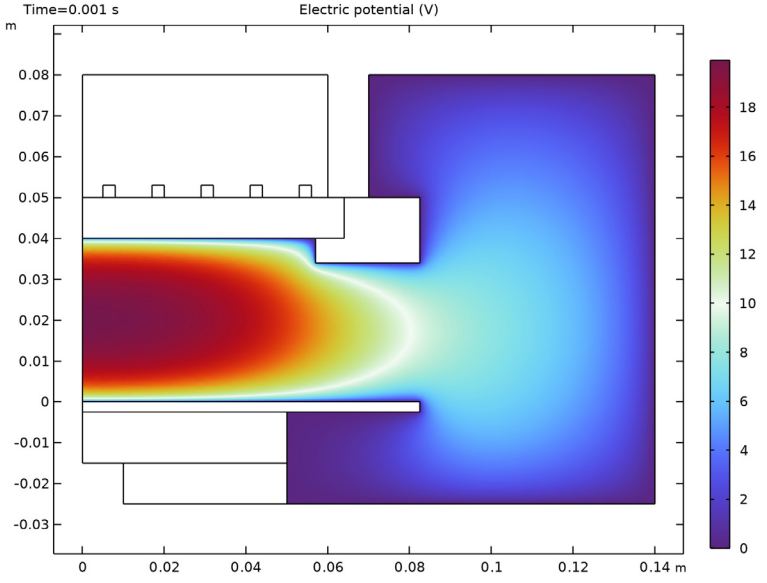

Figure 4: Plot of the electric potential inside the GEC ICP reactor.

From an electrical standpoint, the quantities of interest are total power deposition, coil resistance and inductance, and reactor efficiency. These "global" parameters are relatively easy to measure when the plasma is on or off, so such quantities provide an easy route for comparison with experimental data, without the need for expensive optical emission spectroscopy equipment or Langmuir probes.

The resistance of the coil increases by a little less than a factor of 4 when the plasma is on. When the plasma is on, there is a substantial opposing current induced back into the coil from the plasma. The electric potential applied across the coil needs to increase in order to maintain the same total current.

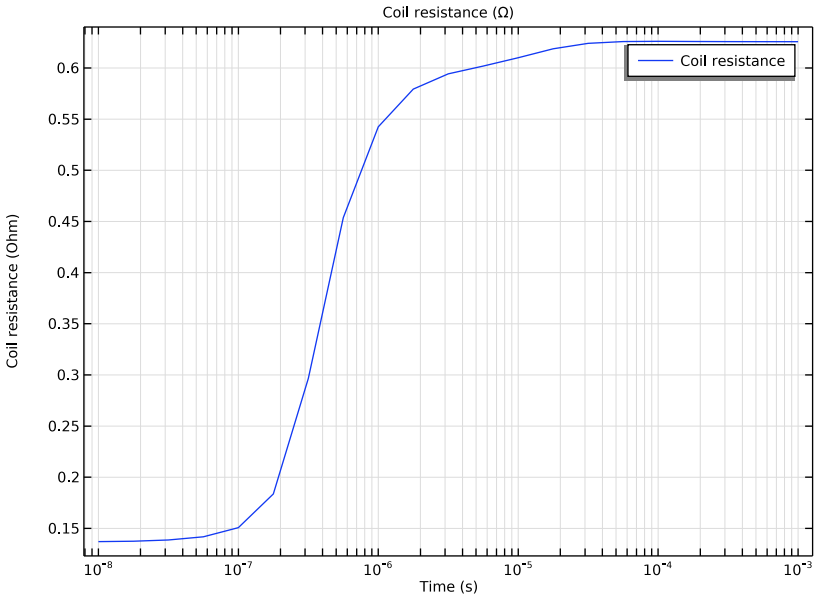

Figure 5: Plot of coil resistance versus time in GEC ICP reactor.

Initially the power dissipated is all dissipated in the coil (~1400 W). After about 1 microsecond, the plasma ignition begins and as the neutral gas atoms split into electrons and ions, the electrons begin to absorb more and more power. Over a period of 2 microseconds, the plasma goes from absorbing no power to absorbing around 1200 W.

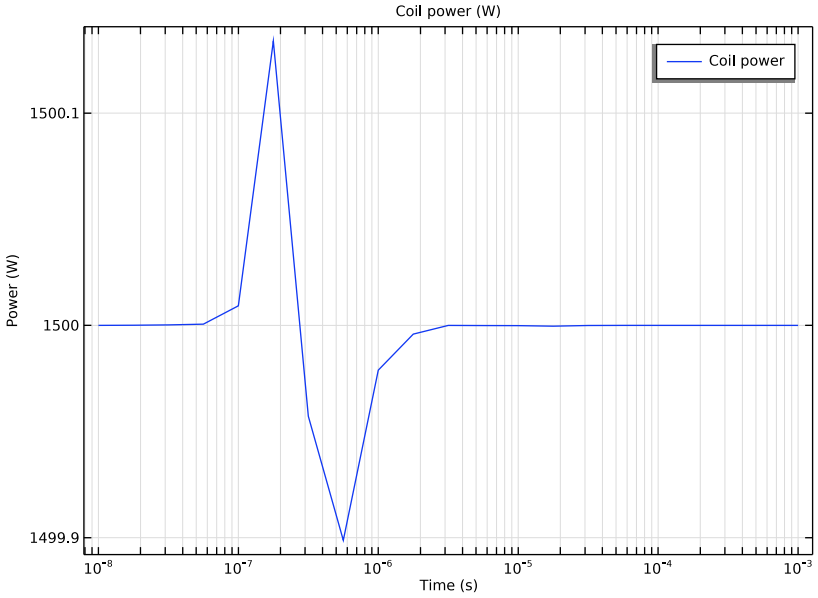

Figure 6: Plot of total power versus time in GEC ICP reactor.

The ion density is exactly the same except from in a thin region close to the walls. In this region, the ion density dominates the electron density which leads to a positive potential in the plasma bulk with respect to the walls. The positive potential increases the flux of ions and reduces the flux of electrons to the wall.

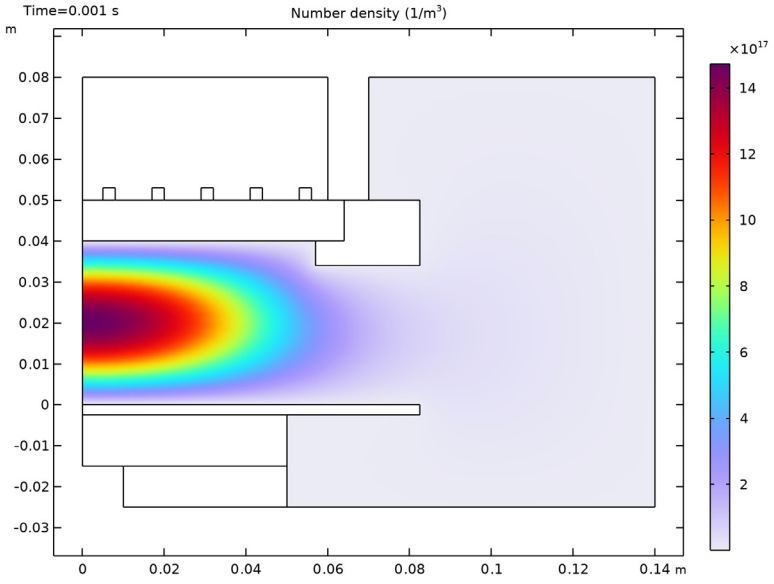

Figure 7: Plot of number density of argon ions in the GEC ICP reactor.

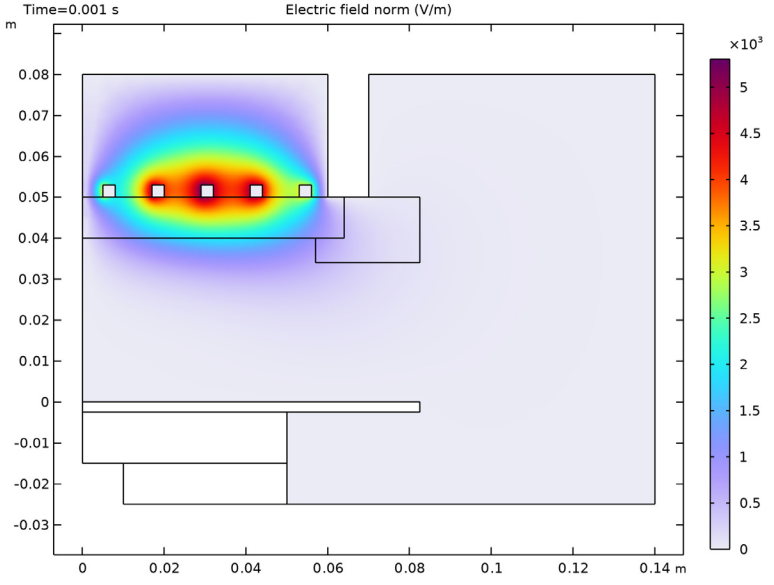

Figure 8: Plot of the norm of the electric field due to the induction currents.

The number density of excited species is also greatest in the center of the reactor. Unlike the charged species, there is no rapid drop off in number density close to the walls. The physics of the excited species is relatively simple: they are formed in the center of the reactor by high energy electrons and are lost to the via either stepwise ionization or diffusion to the wall. Because the excited argon atoms are not susceptible to migration due to the electric field, they can exist in much higher quantities than ions. The peak number density of excited argon atoms represents a mass fraction of around 0.02.

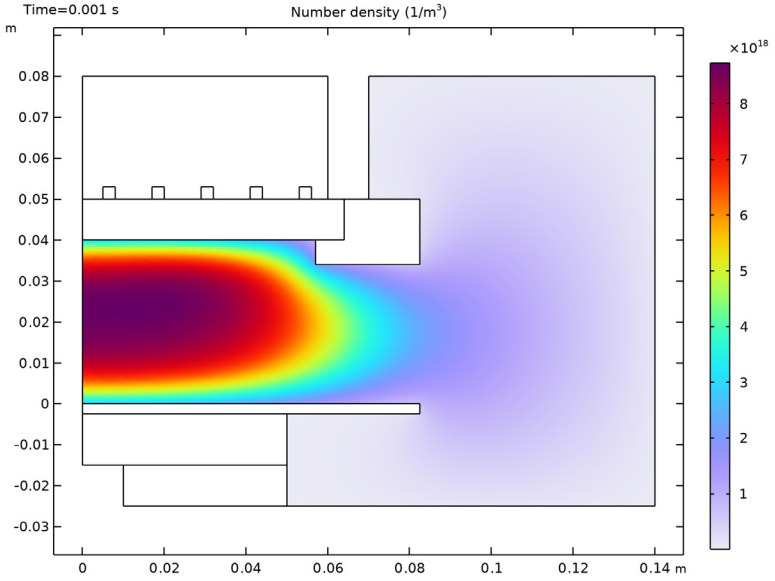

Figure 9: Plot of the number density of excited argon atoms in the GEC ICP reactor.

The skin depth of the plasma is on the order of 1cm which prevents the electric field from penetrating into the core of the plasma. The skin depth is defined as:

$$\delta = \sqrt{\frac{2}{\mu\omega\sigma}}$$

where μ is the permeability, σ is the plasma conductivity, and ω is the angular frequency. This tells us that increasing the driving frequency does not necessarily couple more power into the plasma. As the frequency increases, the plasma tends to shield the region over which power is deposited into a thin layer close to the upper wall.

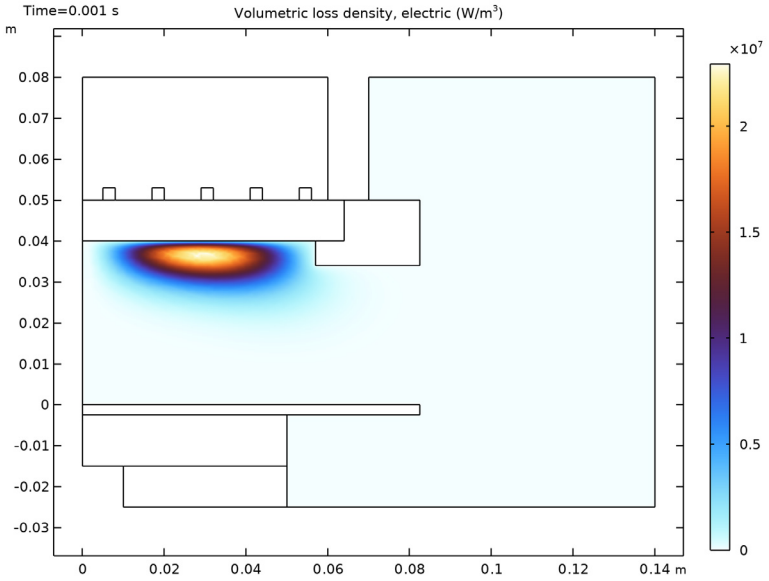

Figure 10: Plot of the power deposition into the plasma in the GEC ICP reactor. The region over which power is deposited to the plasma is governed by the plasma skin depth.

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/argon_gec_icp`

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–Transient**.
6. Click **Done**.

GEOMETRY 1

Insert the prepared geometry sequence from file. You can read the instructions for creating the geometry in the appendix.

1. In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.
2. Browse to the model's Application Libraries folder and double-click the file `argon_gec_icp_geom_sequence.mph`.

   Add some predefined selections for the geometric entities which will be referenced later on.

DEFINITIONS

Walls

1. In the **Definitions** toolbar, click **Explicit**.
2. In the **Settings** window for **Explicit**, type `Walls` in the **Label** text field.
3. Locate the **Input Entities** section. From the **Geometric entity level** list, choose **Boundary**.
4. Select Boundaries 6, 8, 35–38, 44, 45, and 51–56 only.

Coils

1. In the **Definitions** toolbar, click **Explicit**.
2. In the **Settings** window for **Explicit**, type `Coils` in the **Label** text field.
3. Select Domains 6 and 8–11 only.

Coil Boundaries

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

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

3 Select Domains 6 and 8–11 only.

4 Locate the **Output Entities** section. From the **Output entities** list, choose **Adjacent boundaries**.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

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

3 In the table, enter the following settings:

Name	Expression	Value	Description
Psp	1500[W]	1500 W	Power input
mueN	4E24[1/(m*V*s)]	4E24 1/(V·m·s)	Reduced electron mobility
T0	300[K]	300 K	Gas temperature
p0	0.02[torr]	2.6664 Pa	Gas pressure

PLASMA (PLAS)

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

2 Select Domain 3 only.

Cross Section Import 1

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

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

3 Click **Browse**.

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

5 Click **Import**.

6 In the **Model Builder** window, click **Plasma (plas)**.

7 In the **Settings** window for **Plasma**, locate the **Plasma Properties** section.

8 Select the **Use reduced electron transport properties** checkbox.

Now you add two more regular reactions which describe how electronically excited argon atoms are consumed on the volumetric level. The rate coefficients for these reactions are taken from the literature.

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`.

Reaction 2

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

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

3 In the **Formula** text field, type `Ars+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 there always needs to be one species which is 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.

When solving a plasma problem the plasma must be initially charge neutral. COMSOL automatically computes the initial concentration of a selected ionic species such that the initial electroneutrality constraint is satisfied. Once the simulation begins to time step, the plasma need not 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.

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 then the plasma may not

be able to sustain itself and may self extinguish. If the initial electron density is too high then convergence problems may occur during initial time steps.

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 `1E15`.

4 In the ε_0 text field, type `5`.

The **Magnetic Fields** are computed everywhere except the wafer and the wafer pedestal.

MAGNETIC FIELDS (MF)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Magnetic Fields (mf)**.

2 Select Domains 3–6 and 8–12 only.

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

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. From the **Coil excitation** list, choose **Power**.

5 Select the **Coil group** checkbox.

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

PLASMA (PLAS)

Plasma Model 1

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

Next, define the material properties. There is no need to define the material properties in the plasma domain, as these are defined by the **Plasma Conductivity Coupling** feature.

MATERIALS

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
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	6e7	S/m	Basic
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Material 2 (mat2)

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

2 Select Domain 5 only.

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

4 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic

Property	Variable	Value	Unit	Property group
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic

Material 3 (mat3)

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

2 Select Domains 4 and 12 only.

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

4 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	1	1	Basic
Electric conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	4.2	1	Basic

PLASMA (PLAS)

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

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**.

Surface Reaction 2

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

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

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

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

Now, add boundary conditions to describe how the electrons 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 **General Wall Settings** section.

3 In the r_e text field, type `0.2`.

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

Ground 1

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

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

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

MESH 1

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

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

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

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

Edge 1

1 In the **Mesh** toolbar, click **More Generators** and choose **Edge**.

2 Select Boundaries 6, 8, 44, 45, and 54 only.

Size 1

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

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

3 From the **Geometric entity level** list, choose **Entire geometry**.

4 Locate the **Element Size** section. Click the **Custom** button.

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

6 Select the **Maximum element size** checkbox. In the associated text field, type `1E-3`.

Free Triangular 1

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

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

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

4 Select Domain 3 only.

Size 1

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

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

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

Boundary Layers 1

1 In the **Mesh** toolbar, click  **Boundary Layers**.

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

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

4 Select Domain 3 only.

Boundary Layer Properties

1 In the **Model Builder** window, click **Boundary Layer Properties**.

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

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

4 Locate the **Layers** section. In the **Number of layers** text field, type `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 From the **Growth rate** list, choose **Exponential**.

8 Select the **Symmetric distribution** checkbox.

Free Triangular 2

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

2 In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

STUDY 1

Step 1: Frequency–Transient

1 In the **Model Builder** window, under **Study 1** click **Step 1: Frequency–Transient**.

2 In the **Settings** window for **Frequency–Transient**, locate the **Study Settings** section.

3 In the **Output times** text field, type `0 10^{range(-8,5/20,-3)}`.

4 In the **Frequency** text field, type `13.56E6`.

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

RESULTS

Electron Density (plas)

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

Electron Temperature (plas)

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

Electric Potential (plas)

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

Now add a global plot for the coil resistance. This is defined as the real part of the total voltage drop over the coil divided by the applied current. The **Coil** feature creates predefined expressions for the resistance.

Coil Resistance

1 In the **Results** toolbar, click  **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Coil Resistance` in the **Label** text field.

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.

5 Select the **y-axis label** checkbox. In the associated text field, type `Coil resistance (Ohm)`.

Global 1

1 Right-click **Coil Resistance** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mf.RCoil_1`	Ω	`Coil resistance`

4 Click the  **x-Axis Log Scale** button in the **Graphics** toolbar.

5 In the **Coil Resistance** toolbar, click  **Plot**.

Now verify that 1500 watts is being applied to the system.

Coil Power

1 In the **Results** toolbar, click  **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Coil Power` in the **Label** text field.

3 Locate the **Plot Settings** section.

4 Select the **x-axis label** checkbox. In the associated text field, type `Time (s)`.

5 Select the **y-axis label** checkbox. In the associated text field, type `Power (W)`.

Global 1

1 Right-click **Coil Power** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`mf.PCoil_1`	`W`	`Coil power`

4 Click the  **x-Axis Log Scale** button in the **Graphics** toolbar.

5 In the **Coil Power** toolbar, click  **Plot**.

Ion Number Density

1 In the **Results** toolbar, click  **2D Plot Group**.

2 In the **Settings** window for **2D Plot Group**, type `Ion Number Density` in the **Label** text field.

Surface 1

1 Right-click **Ion Number Density** and choose **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Plasma** > **Number densities** > **plas.n_wAr_1p - Number density - 1/m³**.

3 In the **Ion Number Density** toolbar, click **Plot**.

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

High Frequency Electric Field

1 In the **Model Builder** window, right-click **Ion Number Density** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `High Frequency Electric Field` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **High Frequency Electric Field** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Fields** > **Electric** > **mf.normE - Electric field norm - V/m**.

3 In the **High Frequency Electric Field** toolbar, click **Plot**.

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

Observe that the electric field is slightly shielded by the plasma. This is due to the skin effect in the plasma. As the electron number density increases, the plasma tends to shield itself from the electric field.

Excited Argon Number Density

1 In the **Model Builder** window, right-click **High Frequency Electric Field** and choose **Duplicate**.

2 In the **Settings** window for **2D Plot Group**, type `Excited Argon Number Density` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Excited Argon Number Density** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Plasma** > **Number densities** > **plas.n_wArs - Number density - 1/m³**.

3 In the **Excited Argon Number Density** toolbar, click **Plot**.

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

Power Deposition

1 In the **Results** toolbar, click **2D Plot Group**.

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

Surface 1

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

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Fields** > **Heating and losses** > **mf.Qrh - Volumetric loss density, electric - W/m³**.

3 Locate the **Coloring and Style** section. From the **Color table** list, choose **ThermalWave**.

Selection 1

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

2 Select Domain 3 only.

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

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

The effect of the shielding of the electric field due to the skin depth of the plasma is also apparent when plotting the power deposition.

Appendix — Geometry Instructions

ADD COMPONENT

In the **Home** toolbar, click **Add Component** and choose **2D Axisymmetric**.

GEOMETRY 1

Polygon 1 (pol1)

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

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 From the **Data source** list, choose **Vectors**.

4 In the **r** text field, type `0.01 0.01 0.14 0.14 0.07 0.07 0 0 0.01`.

5 In the **z** text field, type `-0.015 -0.025 -0.025 0.08 0.08 0.05 0.05 -0.015 -0.015`.

6 Click **Build All Objects**.

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 `0.064`.

4 In the **Height** text field, type `0.01`.

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

Rectangle 2 (r2)

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

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

3 In the **Width** text field, type `0.06`.

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

5 Locate the **Position** section. In the **z** text field, type `0.05`.

Rectangle 3 (r3)

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

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

3 In the **Width** text field, type `0.0825`.

4 In the **Height** text field, type `0.0025`.

5 Locate the **Position** section. In the **z** text field, type `-0.0025`.

Rectangle 4 (r4)

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

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

3 In the **Width** text field, type `0.05`.

4 In the **Height** text field, type `0.015-0.0025`.

5 Locate the **Position** section. In the **z** text field, type `-0.015`.

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 `0.04`.

4 In the **Height** text field, type `0.01`.

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

6 In the **z** text field, type `-0.025`.

Polygon 2 (pol2)

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

2 In the **Settings** window for **Polygon**, locate the **Coordinates** section.

3 From the **Data source** list, choose **Vectors**.

4 In the **r** text field, type `0.057 0.057 0.0825 0.0825 0.064 0.064 0.057`.

5 In the **z** text field, type `0.04 0.034 0.034 0.05 0.05 0.04 0.04`.

6 Click **Build All Objects**.

Rectangle 6 (r6)

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

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

3 In the **Width** text field, type `0.003`.

4 In the **Height** text field, type `0.003`.

5 Locate the **Position** section. In the **r** text field, type `0.005`.

6 In the **z** text field, type `0.05`.

Array 1 (arr1)

1 In the **Geometry** toolbar, click **Transforms** and choose **Array**.

2 Select the object **r6** only.

3 In the **Settings** window for **Array**, locate the **Size** section.

4 In the **r size** text field, type `5`.

5 Locate the **Displacement** section. In the **r** text field, type `0.012`.

6 Click **Build All Objects**.