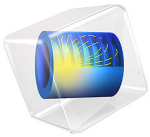


GEC CCP Reactor, Argon Chemistry

Introduction

The NIST (National Institute of Standards and Technology) Gaseous Electronics Conference (GEC) Capacitively Coupled Plasma (CCP) reactor provides a standardized platform for studying capacitively coupled plasmas. Even the simplest plasma models are quite involved, so a 2D example helps in understanding the physics without excessive CPU time. The periodic steady state solution of an Argon discharge is computed and good agreement is obtained when comparing with measurements and simulations in the literature Ref. 1.

Model Definition

In this example, the GEC CCP reactor is simulated using the COMSOL Multiphysics Plasma Module. The simulations are for an Argon plasma sustained at a pressure of 100 mTorr by a periodic electric excitation of 13.56 MHz. The model is 2–dimensional and describes the space and time–periodic evolution of several macroscopic properties of the discharge. The reactor is electric asymmetric with a powered electrode of approximately 10 cm diameter and a gap between electrodes of 2.45 cm.

The mechanisms of power deposition into a CCP reactor is highly nonlinear and occurs at multiple different frequencies. Therefore, the electrostatic potential cannot be solved for in the frequency domain; the model must describe the periodic evolution of the charged particles to capture the nonlinear power absorption behavior.

ELECTRICAL EXCITATION

The driven electrode has a fixed power which computes the self DC bias. This corresponds to the following expression and set of constraints on the electric potential:

$$V_s = V_a \cos(2\pi f_p t + \alpha) + V_{\mathrm{dc,b}} \tag{1}$$

$$0 = f_p \int_{\partial t} \int_{\partial \Omega} (\mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e + \mathbf{n} \cdot \mathbf{J}_d) dS dt \tag{2}$$

$$P_{rf} = f_p \int_{\partial t} \int_{\partial \Omega} (V_s - V_{\mathrm{dc,b}})(\mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e + \mathbf{n} \cdot \mathbf{J}_d) dS dt \,. \tag{3}$$

The constraint in Equation 2 is used to compute the self DC bias, $V_{\mathrm{dc,b}}$. The constraint in Equation 3 is used to compute the RF potential, V_a such that a fixed amount of power is deposited into the plasma.

PLASMA CHEMISTRY

Argon has 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 2 species and 3 reactions presented in Table 1. As in Ref. 1, the mass fraction of the metastable state is not computed. Electron impact cross-sections are obtained from Ref. 2.

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
4	e+Ar=>2e+Ar+	Ionization	15.8

In addition to volumetric reactions, the following surface reaction is implemented:

TABLE 2: TABLE OF SURFACE REACTIONS.

REACTION	FORMULA	STICKING COEFFICIENT	SECONDARY EMISSION COEFFICIENT	MEAN ENERGY OF SECONDARY ELECTRONS (V)
1	Ar+=>Ar	0	0.07	5.8

The ion use his internal energy to extract one electron from the wall with a probability of 0.07 and a mean energy of 5.8 V. The sticking coefficient is zero meaning that losses to the wall are assumed to be due to migration only.

Results and Discussion

The results presented in this section are for 1 W of power absorbed by the plasma. The voltage and current at the power electrode are presented in Figure 1. The amplitude of the applied voltage excitation and the DC self bias are numerically found to be approximately 100 V and -78 V, respectively. A DC self bias is present because the reactor is electrically asymmetric. This voltage ensures that the period averaged conduction current through the powered electrode is zero. Note also that the current collected at the electrode is not sinusoidal, meaning that there is power absorbed at harmonics higher than the fundamental.

Figure 2 to Figure 6 present different period–averaged plasma quantities. Figure 2 shows that the plasma is more dense within the small gap and attains the maximum density off–axis, as in the simulations of Ref. 1 and the measurements from Overzet *et al* (taken from Ref. 1). As expected, the period averaged potential presents an off–axis maximum related

with the maximum of the plasma density, and a DC component at the powered electrode imposed by the calculated DC self–bias.

The ionization rate presented in Figure 6 also exhibits the off–axis behavior but the maximum does not coincide with the maximum electron density as reported in Ref. 1.

Due to the reactor electric asymmetry, the smaller electrode (the powered electrode in this simulation) has a larger sheath with more intense electric fields. The consequences are higher electron temperatures and power deposition near the powered electrode.

The period averaged electron temperature in the COMSOL Multiphysics Plasma Module is computed from

$$\langle T_e \rangle = \frac{2}{3}\langle n_\varepsilon / n_e \rangle \tag{4}$$

where the brackets represent the period averaged. To obtain electron temperatures similar to the ones in Ref. 1the average should be computed as

$$\langle T_e \rangle = \frac{2}{3}\frac{\langle n_\varepsilon \rangle}{\langle n_e \rangle}. \tag{5}$$

Figure 7 and Figure 8 shows profiles of the electron density along the axial and radial coordinate. These results are in good agreement with the data of figure 7 in Ref. 1 where simulations and measurements are compared.

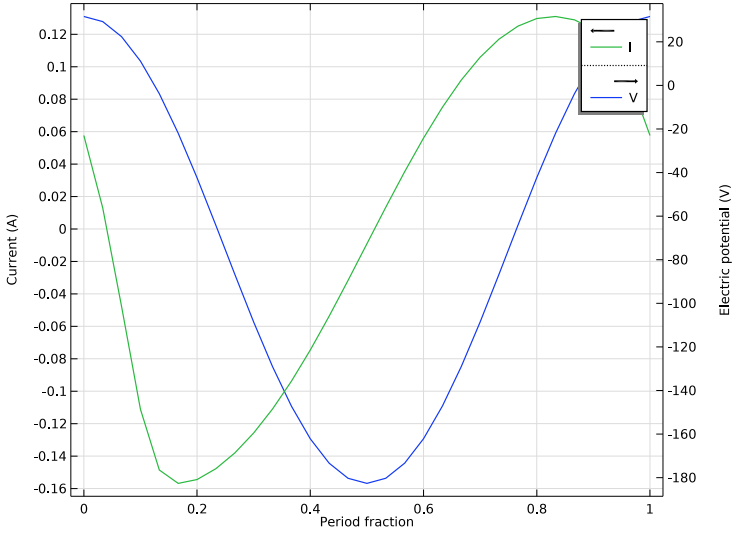


Figure 1: Plot of the V-I characteristics of the discharge. Note the significant self DC bias due to the asymmetry of the discharge.

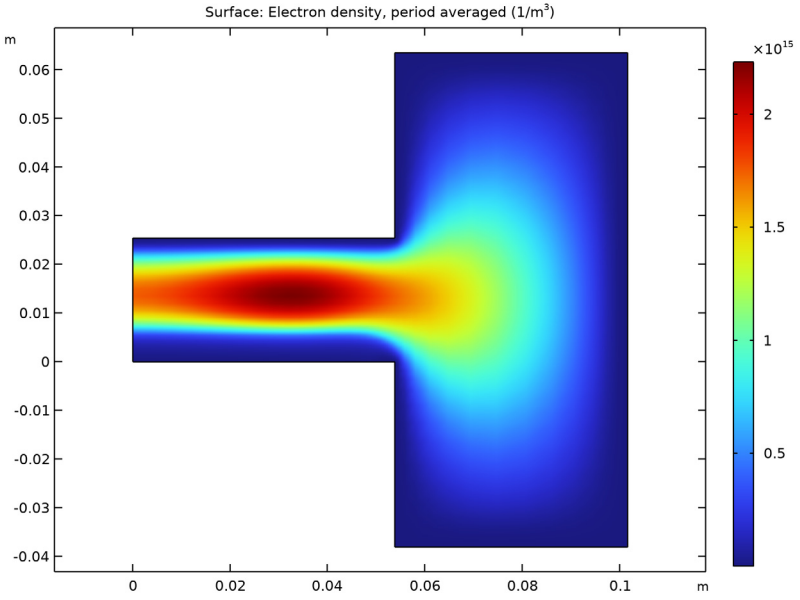


Figure 2: Plot of the period averaged electron density.

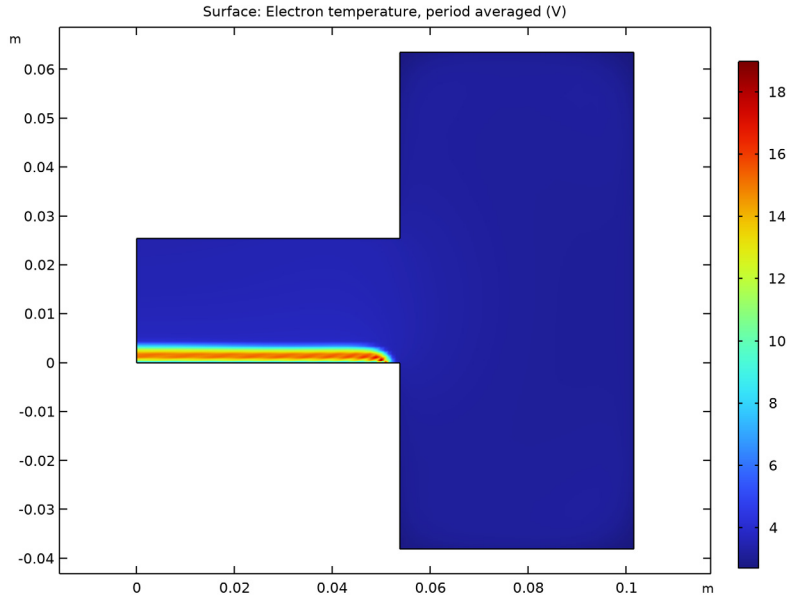


Figure 3: Plot of the period averaged electron temperature.

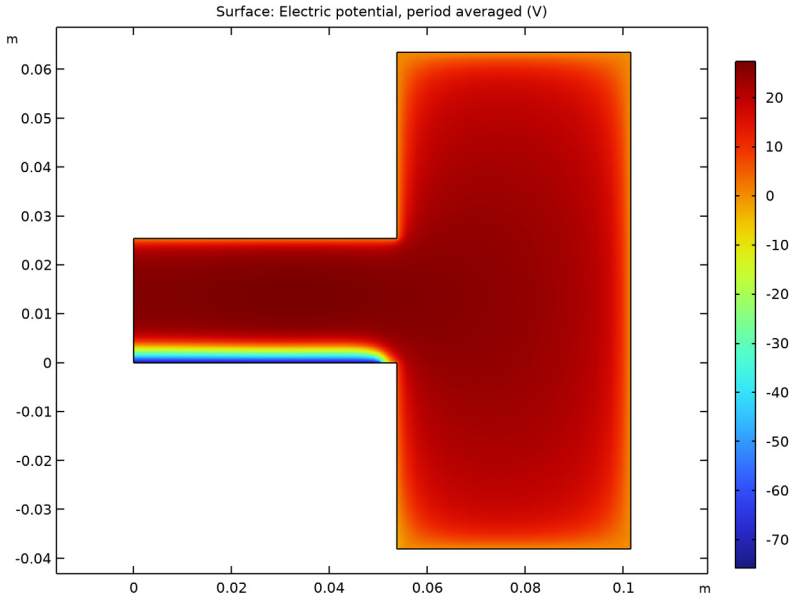


Figure 4: Plot of the period averaged electric potential.

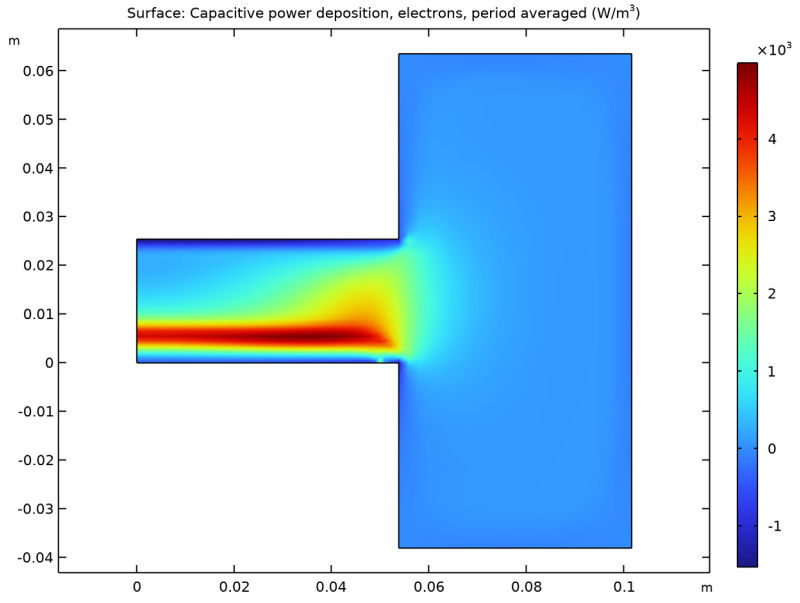


Figure 5: Plot of the period averaged power deposition to the electrons.

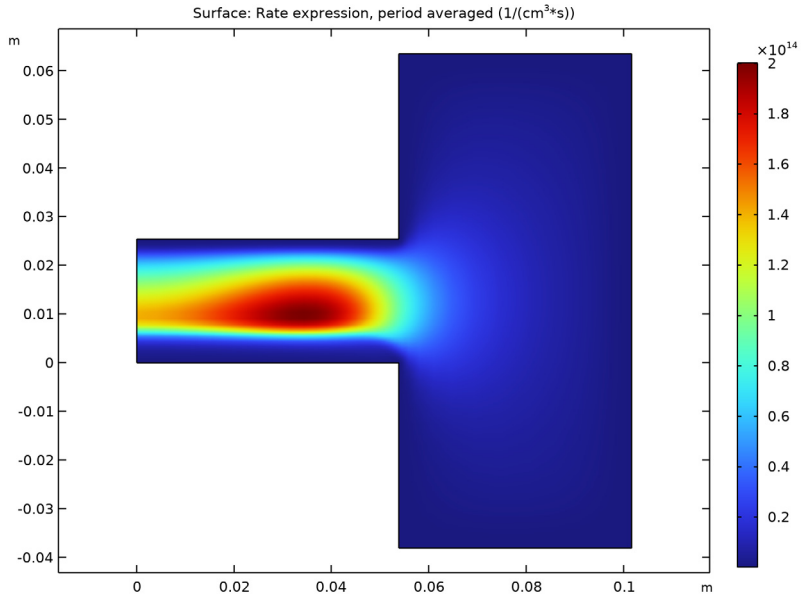


Figure 6: Plot of the period averaged ionization rate (note the units are non-SI in this plot, for easier comparison with Ref. 1*).*

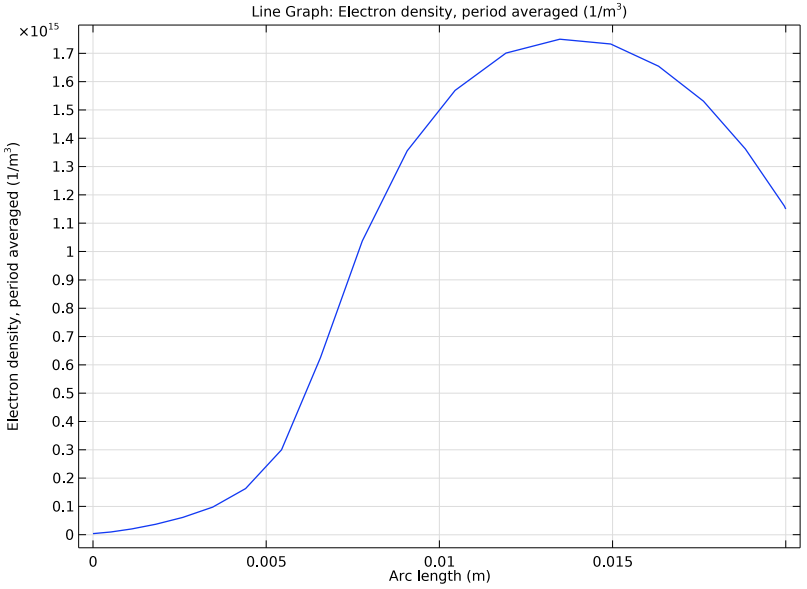


Figure 7: Plot of the on–axis electron density. Here, x=0 corresponds to the driven electrode.

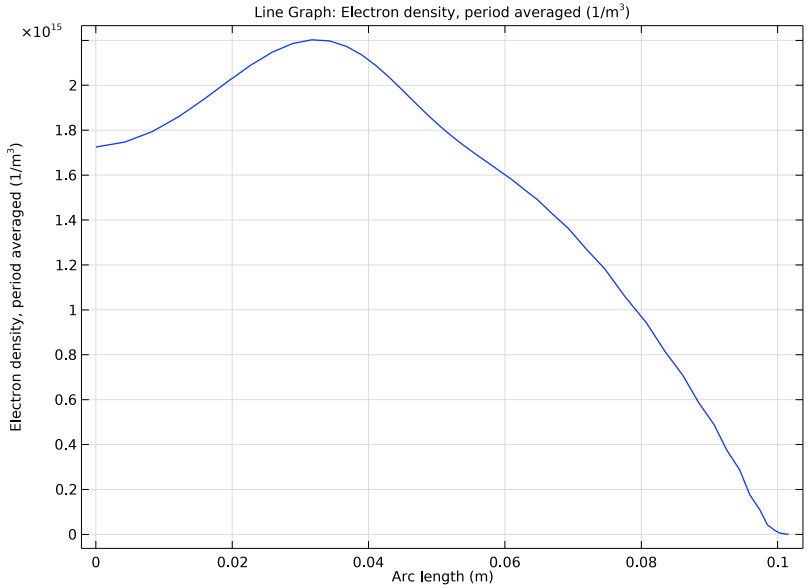


Figure 8: Plot of the radial electron density profile half way across the discharge gap.

References

1. J.P.Boeuf and L.C. Pitchford, "Two-dimensional model of a capacitively coupled rf discharge and comparisons with experiments in the Gaseous Electronics Conference reference reactor," *Physical Review E*, vol. 51, no .2, pp. 1376–1390, 1995.

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

Application Library path: `Plasma_Module/Capacitively_Coupled_Plasmas/argon_gec_ccp`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, The **Plasma, Time Periodic** interface will be used to compute the periodic steady state solution for the GEC reference cell, using the **Time Periodic** study.

2 click **2D Axisymmetric**.

3 In the **Select Physics** tree, select **Plasma>Plasma, Time Periodic (ptp)**.

4 Click **Add**.

5 Click **Study**.

6 In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces> Time Periodic**.

7 Click **Done**.

Add some parameters for the geometric dimensions, the frequency and the input power.

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
L	2.54[cm]	0.0254 m	Discharge gap
R1	5.38[cm]	0.0538 m	Inner radius
R2	10.16[cm]	0.1016 m	Outer radius
Hd	10.16[cm]	0.1016 m	Chamber height
dThick	3[mm]	0.003 m	Dielectric thickness
f0	13.56[MHz]	1.356E7 Hz	Frequency
P0	1[W]	1 W	Power

GEOMETRY 1

The geometry includes a point for the dielectric break, and three additional points to help create a mapped mesh later on. Since the **Plasma, Time Periodic** interface generates a

tremendous number of degrees of freedom, creating a geometry which can be efficiently meshed will help reduce computation time and memory requirements when solving.

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 `R1`.

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

5 Click **Build Selected**.

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 `R2-R1`.

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

5 Locate the **Position** section. In the **r** text field, type `R1`.

6 In the **z** text field, type `-Hd/2+L/2`.

7 Click **Build All Objects**.

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

Point 1 (pt1)

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

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

3 In the **r** text field, type `R1-dThick`.

4 Click **Build Selected**.

Point 2 (pt2)

1 Right-click **Point 1 (pt1)** and choose **Duplicate**.

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

3 In the **z** text field, type `L`.

4 Click **Build Selected**.

Point 3 (pt3)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Point 1 (pt1)** and choose **Duplicate**.

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

3 In the **r** text field, type R2.

4 Click **Build Selected**.

Point 4 (pt4)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** right-click **Point 2 (pt2)** and choose **Duplicate**.

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

3 In the **r** text field, type R2.

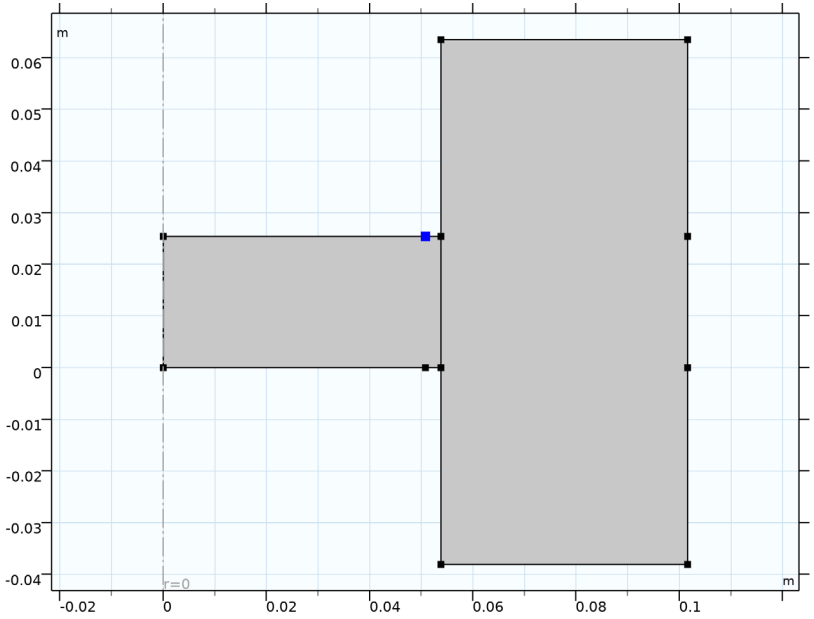
4 Click **Build Selected**.

Line Segment 1 (ls1)

1 In the **Geometry** toolbar, click **More Primitives** and choose **Line Segment**.

2 On the object **pt2**, select Point 1 only.

It might be easier to select the correct by using the **Selection List** window. To open this window, in the **Home** toolbar click **Windows** and choose **Selection List**. (If you are running the cross-platform desktop, you find **Windows** in the main menu.)



3 In the **Settings** window for **Line Segment**, locate the **Endpoint** section.

4 Find the **End vertex** subsection. Click to select the **Activate Selection** toggle button.

5 On the object **pt1**, select Point 1 only.

Add some mesh control edges to facilitate meshing without affecting the setup of the physics or postprocessing.

Mesh Control Edges 1 (mce1)

1 In the **Geometry** toolbar, click **Virtual Operations** and choose **Mesh Control Edges**.

2 In the **Settings** window for **Mesh Control Edges**, locate the **Input** section.

3 Clear the **Include adjacent vertices** check box.

4 On the object **fin**, select Boundaries 4 and 9 only.

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

Now that the geometry is defined, add some selections to facilitate the setup of the physics.

DEFINITIONS (COMP1)

Walls

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

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

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

4 Select the **All boundaries** check box.

5 Select Boundaries 2–12 only.

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

Driven Electrode

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

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

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

4 Select Boundary 2 only.

5 In the **Label** text field, type `Driven Electrode`.

Dielectric Contact

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

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

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

4 Select Boundaries 4 and 6 only.

5 In the **Label** text field, type `Dielectric Contact`.

Grounded Walls

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

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

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

4 Select Boundaries 3, 5, and 7–12 only.

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

For the physics, we will solve for the heavy species only in the base geometry, and use 30 elements in the extra dimension which represents one RF period.

PLASMA, TIME PERIODIC (PTP)

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

2 In the **Settings** window for **Plasma, Time Periodic**, locate the **Extra Dimension Settings** section.

3 In the P_{xd} text field, type `1/f0`.

4 In the N text field, type `30`.

5 From the **Heavy species selection** list, choose **Base geometry**.

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_reduced.txt`.

Species: Ar

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

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

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

4 Locate the **Species Formula** section. Select the **From mass constraint** check box.

Species: Ars

Disable the metastable species, since this is not included in the reference paper.

1 In the **Model Builder** window, right-click **Species: Ars** and choose **Disable**.

For the Argon ions, use the built in lookup table for the mobility, and the local field approximation for the ion temperature.

Species: Ar+

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

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

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

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

5 Click to collapse the **Species Formula** section. Click to expand the **Mobility and Diffusivity Expressions** section. From the **Specification** list, choose **Specify mobility, compute diffusivity**.

6 From the **Ion temperature** list, choose **Use local field approximation**.

7 Click to expand the **Mobility Specification** section. From the **Specify using** list, choose **Argon ion in argon**.

Surface Reaction 1

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

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

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

4 Locate the **Reaction Formula** section. In the **Formula** text field, type `Ar+=>Ar`.

5 Locate the **Reaction Parameters** section. In the γ_f text field, type `0`.

Enter the temperature, pressure and electron mobility as defined in the reference.

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 `300[K]`.

4 In the p_A text field, type `0.1[torr]`.

5 Locate the **Electron Density and Energy** section. From the **Electron transport properties** list, choose **Specify mobility only**.

6 In the μ_e text field, type `3E5[cm^2/(V*s)]/0.1`.

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 `5/11`.

It is much more stable to drive the electrode with a fixed power rather than a voltage. Activate computation of the DC self bias since that is included in the reference.

Metal Contact 1

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

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

3 From the **Selection** list, choose **Driven Electrode**.

4 Locate the **RF Source** section. In the P_{rf} text field, type `P0`.

5 In the f_p text field, type `f0`.

6 Locate the **DC Source** section. Select the **Compute DC self-bias** check box.

Dielectric Contact 1

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

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

3 From the **Selection** list, choose **Dielectric Contact**.

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 **Grounded Walls**.

To minimize the number of degrees of freedom, take some time to create a mesh which is fine where the discharge is expected to show large gradients, and use a much coarser mesh elsewhere.

MESH 1

Mapped 1

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

2 In the **Settings** window for **Mapped**, click to expand the **Control Entities** section.

3 Clear the **Smooth across removed control entities** check box.

Distribution 1

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 4 and 5 only.

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

4 In the **Number of elements** text field, type `4`.

Distribution 2

1 In the **Model Builder** window, right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 2 and 3 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 20.

6 In the **Element ratio** text field, type 5.

Distribution 3

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 7 and 9 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 15.

6 In the **Element ratio** text field, type 10.

7 Select the **Symmetric distribution** check box.

Distribution 4

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 6, 8, 10, and 12 only.

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

4 From the **Distribution type** list, choose **Predefined**.

5 In the **Number of elements** text field, type 15.

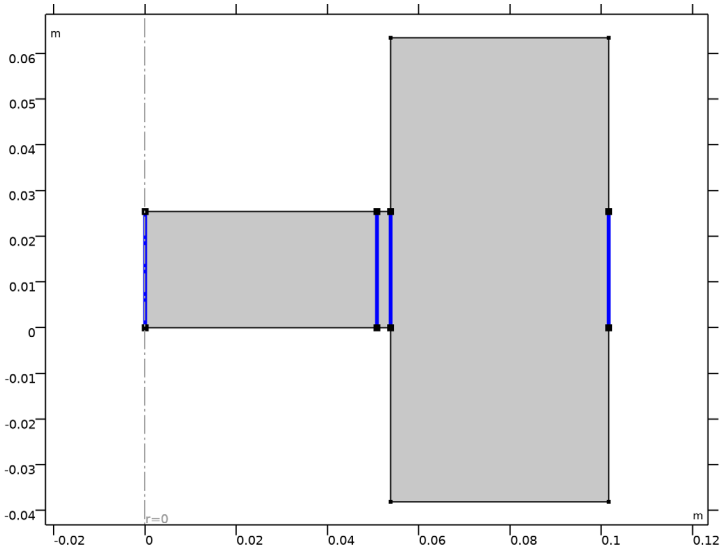
6 In the **Element ratio** text field, type 8.

7 Select the **Symmetric distribution** check box.

Distribution 5

1 Right-click **Mapped 1** and choose **Distribution**.

2 Select Boundaries 1, 11, 13, and 14 only.



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

4 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 3.

7 Select the **Symmetric distribution** check box.

8 Click **Build All**.

The model will take about 20 minutes to solve, depending on hardware. Using **Results while solving>**, it is possible to visualize the evolution of the electron density at each nonlinear iteration. To do this, first get the initial value.

TIME PERIODIC STUDY

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

2 In the **Settings** window for **Study**, type `Time Periodic Study` in the **Label** text field.

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

TIME PERIODIC STUDY

Solver Configurations

In the **Model Builder** window, expand the **Time Periodic Study>Solver Configurations** node.

Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Time Periodic Study>Solver Configurations> Solution 1 (sol1)** node.

Now choose that the electron density should be plotted while solving.

2 In the **Model Builder** window, expand the **Time Periodic Study>Solver Configurations> Solution 1 (sol1)>Stationary Solver 1** node, then click **Fully Coupled 1**.

3 In the **Settings** window for **Fully Coupled**, click to expand the **Results While Solving** section.

4 Select the **Plot** check box.

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

Cycle through the default plots so that the results can be compared with the reference.

RESULTS

Current and Voltage, Metal Contact 1 (ptp)

Create a new plot for the period-averaged ionization rate.

Ionization Source, Period-Averaged

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

2 In the **Settings** window for **2D Plot Group**, type `Ionization Source, Period-Averaged` in the **Label** text field.

Surface 1

1 Right-click **Ionization Source, Period-Averaged** 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, Time Periodic>Reaction rates>ptp.Re_av - Rate expression, period averaged - 1/(m³·s)**.

3 Locate the **Expression** section. In the **Unit** field, type `1/(cm^3*s)`.

4 In the **Ionization Source, Period-Averaged** toolbar, click **Plot**.

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

Create some cut lines so the on-axis and radial period-averaged electron density can be visualized.

Cut Line 2D 1

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

2 Right-click **Results>Datasets** and choose **Cut Line 2D**.

3 In the **Settings** window for **Cut Line 2D**, locate the **Line Data** section.

4 In row **Point 2**, set **R** to `0`.

5 In row **Point 2**, set **Z** to `2[cm]`.

6 From the **Snapping** list, choose **Snap to closest boundary**.

On Axis Electron Density

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

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

3 From the **Dataset** list, choose **Cut Line 2D 1**.

4 In the **Label** text field, type `On Axis Electron Density`.

Line Graph 1

1 Right-click **On Axis Electron Density** and choose **Line Graph**.

2 In the **On Axis Electron Density** toolbar, click **Plot**.

Cut Line 2D 2

1 In the **Results** toolbar, click **Cut Line 2D**.

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

3 In row **Point 1**, set **Z** to `L/2`.

4 In row **Point 2**, set **R** to `R2`.

5 In row **Point 2**, set **Z** to `L/2`.

Radial Electron Density

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

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

3 From the **Dataset** list, choose **Cut Line 2D 2**.

4 In the **Label** text field, type `Radial Electron Density`.

Line Graph 1

1 Right-click **Radial Electron Density** and choose **Line Graph**.

2 In the **Radial Electron Density** toolbar, click **Plot**.

Evaluate the RF and self DC bias potentials.

Global Evaluation 1

1 In the **Results** toolbar, click **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, click **Replace Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)> Plasma, Time Periodic>Metal Contact 1>ptp.mct1.Va_per - Voltage amplitude - V**.

3 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)>Plasma, Time Periodic>Metal Contact 1> ptp.mct1.Vdcb_per - DC bias voltage - V**.

4 Click **Evaluate**.

Finally, add a study to convert the solution into the time domain. This allows all variables to be plotted at instantaneous points in time, rather than period averaged quantities. This study runs in seconds.

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 Physics Interfaces>Time Periodic to Time Dependent**.

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: Time Periodic to Time Dependent

1 In the **Settings** window for **Time Periodic to Time Dependent**, locate the **Study Settings** section.

2 Click **Range**.

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

4 In the **Stop** text field, type `1/f0`.

5 In the **Number of values** text field, type `51`.

6 Click **Replace**.

7 In the **Settings** window for **Time Periodic to Time Dependent**, click to expand the **Values of Dependent Variables** section.

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

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

10 From the **Study** list, choose **Time Periodic Study, Time Periodic**.

11 In the **Model Builder** window, click **Study 2**.

12 In the **Settings** window for **Study**, type `Time Periodic to Time Dependent` in the **Label** text field.

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

Create an animation of the electric potential.

RESULTS

Electric Potential (ptp)

In the **Model Builder** window, under **Results** click **Electric Potential (ptp)**.

Animation 1

In the **Electric Potential (ptp)** toolbar, click **Animation** and choose **Player**.

Electron Density, Period Averaged (ptp)

Set a thumbnail image for the plot of the period-averaged electron density.

ROOT

1. In the **Model Builder** window, click the root node.
2. In the root node's **Settings** window, locate the **Presentation** section.
3. Find the **Thumbnail** subsection. Click **Set from Graphics Window**.