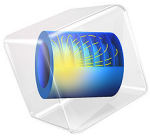

Dielectric Barrier Discharge

Introduction

This model simulates electrical breakdown in an atmospheric pressure gas. Because electrical breakdown is a complicated process, a 1D model is considered. To highlight the physics of the breakdown process, this example uses a simple argon chemistry, which keeps the number of species and reactions to a minimum.

Model Definition

The operating principle for a dielectric barrier discharge is as follows: there is a small gap filled with a gas between two dielectric plates. The gap between the two dielectric plates is typically less than one millimeter. On one of the dielectric plates, a sinusoidal voltage is applied. The other plate is electrically grounded. As the voltage applied to the top plate increases, a stronger electric field forms in the gap between the plates. Any free electrons in the gap[1] are accelerated, and if the electric field is strong enough they may acquire enough energy to cause ionization. This can lead to a cascade effect where the number of electrons in the gap increases exponentially on a nanosecond time scale. Electrons created via electron impact ionization rush toward one of the dielectric plates, in the opposite direction to the electric field. An equal number of ions are also generated during electron impact ionization (electrons and ions must be created in equal pairs to preserve the overall charge balance). The ions rush toward the opposite dielectric plate in the same direction as the electric field. As a result, surface charge with opposite sign accumulates on both dielectric plates. This causes the electric field to become shielded from the gas filled gap. In fact, the electric field across the gap cannot exceed the breakdown electric field, which is highly dependent on the gas. The breakdown electric field is also a function of the surface properties of the dielectric material. Surface charge accumulation temporarily terminates the discharge until the field reverses direction and the process repeats in the opposing direction.

Modeling dielectric barrier discharges in more than one dimension is, of course possible, but the results can be difficult to interpret due to the amount of competing physics in the problem. In this simple model the problem is reduced to 1D by assuming the dielectric gap is much smaller than the diameter of the plates. It also makes it possible to quickly gain some insight into the characteristics of the discharge without excessive computation time.

1. There are typically around 1,000,000 m^{-3} free electrons in air at sea level.

The geometry for a typical dielectric barrier discharge is shown in Figure 1. The dielectric plates may be up to 15 cm in diameter; the dielectric and gap thickness are typically less than 1 millimeter.

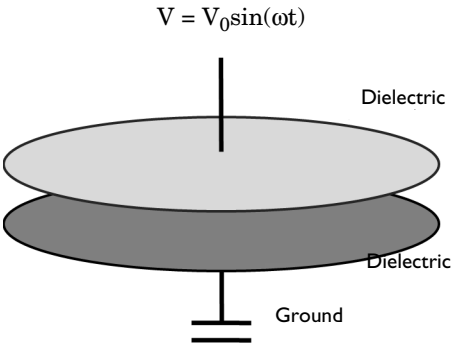

Figure 1: Graphic illustration of a typical dielectric barrier discharge.

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. Convection of electrons due to fluid motion is neglected. 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. Suppose that there are M reactions that contribute to the growth or decay of electron density and P inelastic electron-neutral collisions. In general, $P >> M$. In the case of rate coefficients, the electron source term is given by:

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

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

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:

$$\mathbf{n} \cdot \Gamma_e = \left(\frac{1}{2} v_{e,\text{th}} n_e\right) - \sum_p \gamma_p (\Gamma_p \cdot \mathbf{n}) \tag{1}$$

and the electron energy flux:

$$\mathbf{n} \cdot \Gamma_\varepsilon = \left(\frac{5}{6} v_{e,\text{th}} n_\varepsilon\right) - \sum_p \varepsilon_p \gamma_p (\Gamma_p \cdot \mathbf{n}) \tag{2}$$

The second term on the right-hand side of Equation 1 is the gain of electrons due to secondary emission effects, γ_p being the secondary emission coefficient. The second term in Equation 2 is the secondary emission energy flux, ε_p being the mean energy of the secondary electrons. 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:

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

Surface charge accumulation is added to the dielectric surfaces that are adjacent to the gap where the plasma forms by way of the following boundary condition:

$$\mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$$

where ρ_s is the surface charge density, which is computed by solving the following distributed ODE on the surfaces:

$$\frac{d\rho_s}{dt} = \mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e$$

where $\mathbf{n} \cdot \mathbf{J}_i$ is the normal component of the total ion current density at the wall, and $\mathbf{n} \cdot \mathbf{J}_e$ is the normal component of the total electron current density at the wall.

The discharge is driven by a sinusoidal electric potential applied to the exterior boundary of one of the dielectric plates:

$$V = V_0 \sin(\omega t)$$

where the applied peak voltage, V_0 is 750 V and the angular frequency, the RF frequency being 50 kHz. The exterior boundary of the other dielectric plate is grounded.

PLASMA CHEMISTRY

Argon is an attractive gas to use in a benchmark problem since only a handful of reactions and a few species need to be considered. The list of chemical reactions considered is as follows (electron impact cross-section are obtained from Ref. 1):

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	-

Initially a small number of seed electrons are present. These are necessary in order to initiate the discharge on the first RF cycle. In addition to the 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 the ions reach the wall they are assumed to change back to neutral argon atoms and donate their charge to the wall.

Results and Discussion

It is more convenient to analyze the results of this one-dimensional problem by extruding the solution into two dimensions. The extra dimension represents time. In COMSOL Multiphysics this is accomplished by adding a *Parametric Extrusion 1D* dataset. The surface plot is convenient because you can immediately see how the variables of interest evolve over time.

The mass fraction of excited argon atoms is plotted in Figure 2. The excited species have a much longer lifetime in the gap than the electrons or ions. This is because the primary mechanism for destruction of excited argon species is de-excitation upon contact with the wall. The excited argon atoms can only reach the wall via diffusion whereas the electrons

and ions reach the wall very rapidly due to migration. It is also apparent from Figure 2 that the discharge reaches a periodic steady state solution after only two RF cycles.

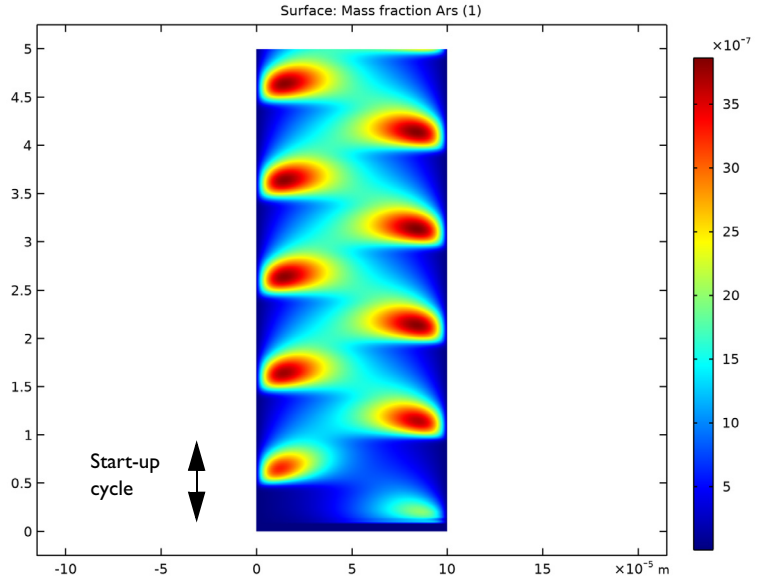

Figure 2: Mass fraction of excited argon.

The electric potential is plotted in Figure 3. The voltage is relatively uniform across the discharge gap. This can be seen more clearly by examining the electric field in Figure 4. There is a much stronger electric field in the dielectric materials than in the gap. This is because the surface charge which accumulates on the dielectric surfaces tends to shield out the electric field.

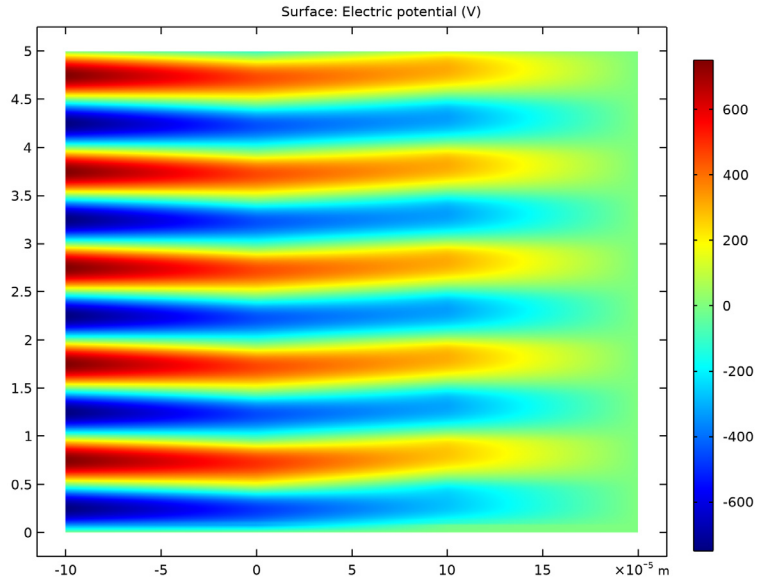

Figure 3: Electric potential (x-axis) vs. time (y-axis).

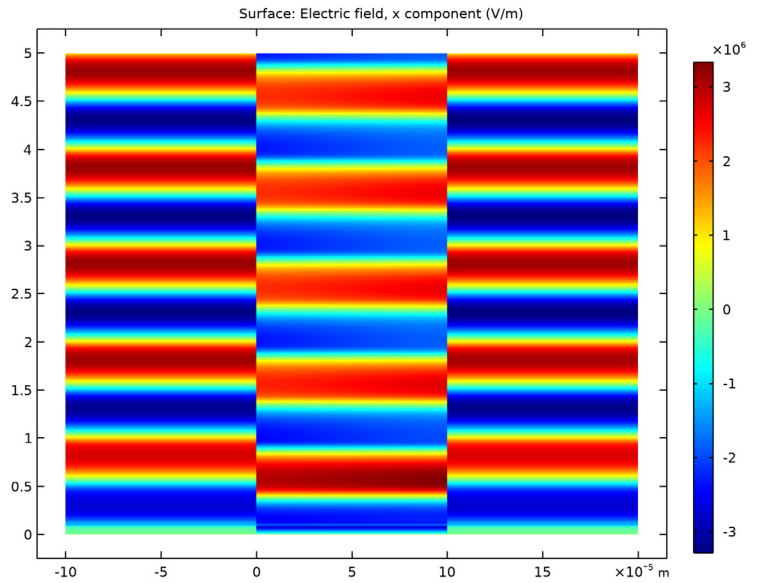

Figure 4: Electric field across the gap (x-axis) vs. time (y-axis).

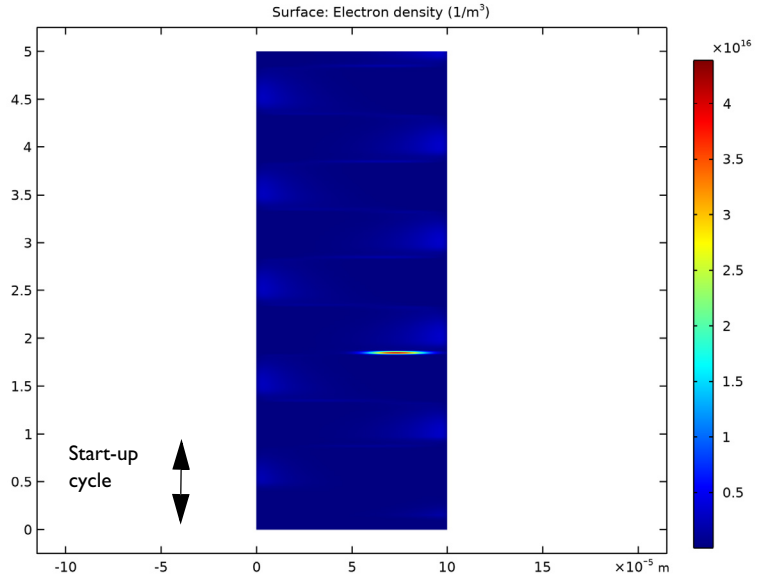

Figure 5: Extruded plot of the electron density.

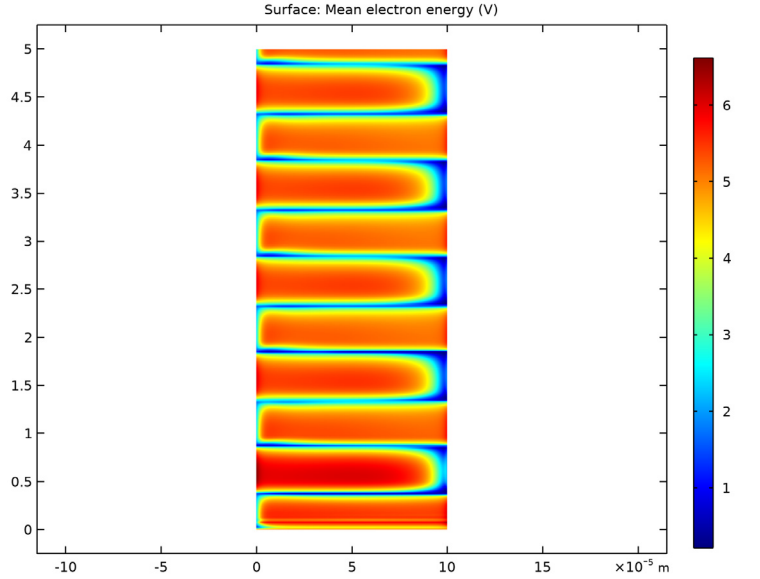

Figure 6: Extruded plot of the mean electron energy.

Implicit in the equations solved for the number of charged particles and electrostatic potential is that the total electrical current is conserved. Mathematically, this means that:

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \approx 0$$

where $\mathbf{J}$ is the total plasma current density (SI unit: A/m^2), and ρ is the space charge density (SI unit: C/m^3). Since electrons and ions are created in equal pairs the time derivative of the space charge density should be approximately zero. For this 1D model, this means the total current density must be constant across the gap at any snapshot in time. In Figure 7, the current density due to electrons (left) and ions (right) is plotted. The current density is not symmetric because of the different secondary emission coefficients used on the dielectric surfaces.

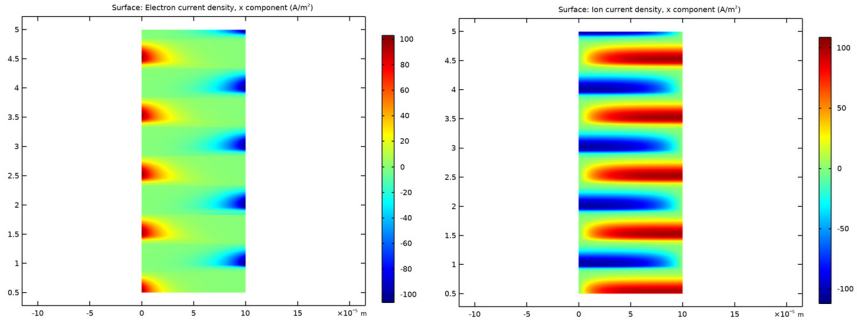

Figure 7: Plot of the electron current density (left) and the ion current density (right) in the discharge, excluding the first RF cycle.

The total plasma current density is plotted in Figure 8. As expected, the total current density is constant across the gap at any point in time.

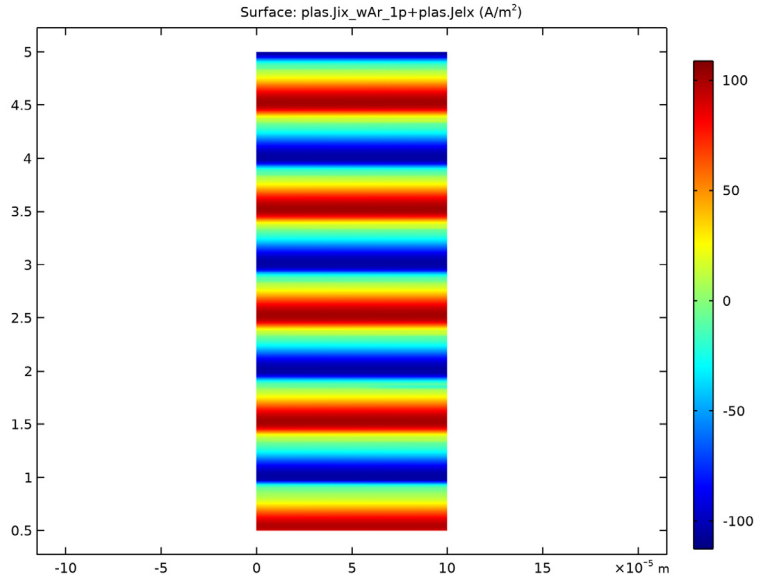

Figure 8: Plot of the total plasma current density (sum of the electron and ion current density), excluding the first RF cycle. Conservation of charge requires that the total current density be constant across the gap at any point in time.

The total current at the grounded electrode is plotted in Figure 9. In the absence of the plasma, the current would be a perfect cosine wave. However, the presence of the plasma and flow of charged particles leads to a non-sinusoidal current waveform. The instantaneously absorbed power in the plasma is plotted in Figure 10. Time averaging this over 1 RF cycle yields the power absorbed by the plasma. The power is around 16.7 W on one half cycle and 17.7 W on the other half cycle. The difference is because the secondary emission coefficients are different on the upper and lower plates.

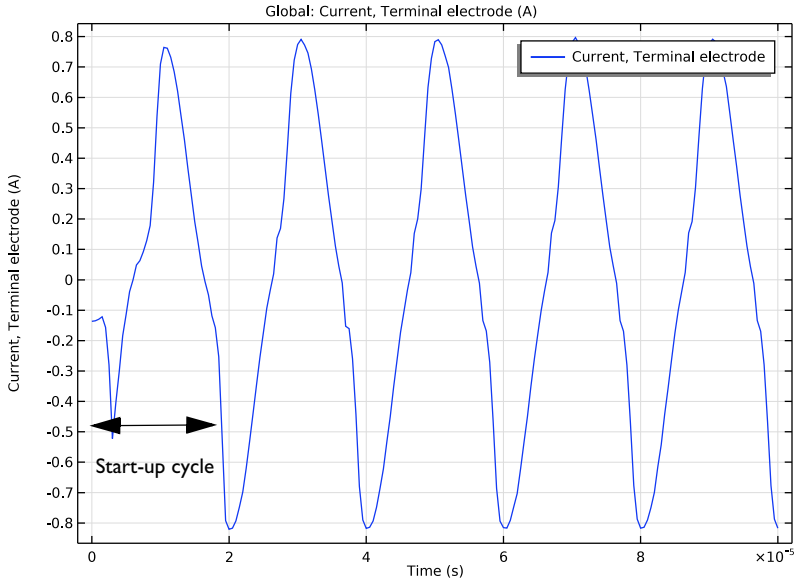

Figure 9: Plot of the total discharge current vs. time.

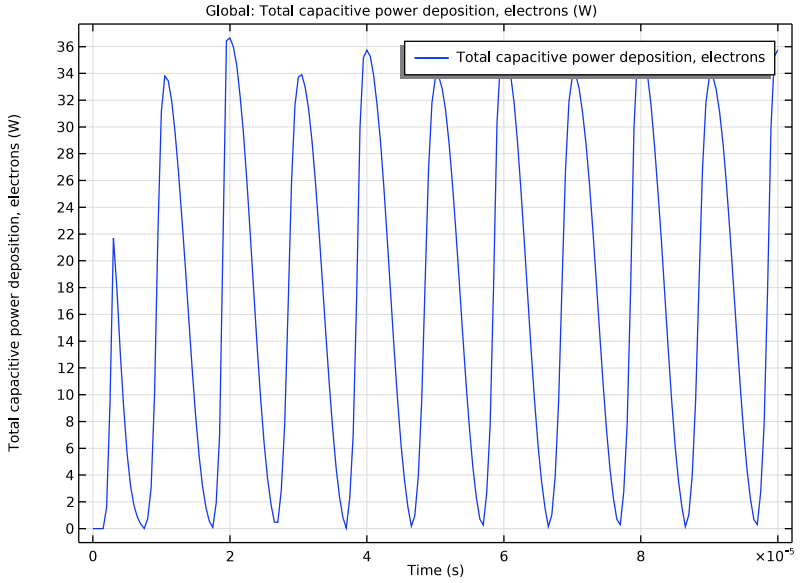

Figure 10: Plot of power vs. time for the dielectric barrier discharge.

Reference

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

Application Library path: `Plasma_Module/Direct_Current_Discharges/argon_dbd_1d`

Modeling Instructions

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

NEW

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

MODEL WIZARD

1. In the **Model Wizard** window, click **1D**.
2. In the **Select Physics** tree, select **Plasma>Plasma (plas)**.
3. Click **Add**.
4. Click **Study**.
5. In the **Select Study** tree, select **General Studies>Time Dependent**.
6. Click **Done**.

GEOMETRY 1

You start by defining the geometry for the problem. This model has a simple 1D geometry consisting of 3 domains. Two dielectric domains and a gap where the plasma forms.

Interval 1 (i1)

1. In the **Model Builder** window, under **Component 1 (comp1)** right-click **Geometry 1** and choose **Interval**.
2. In the **Settings** window for **Interval**, locate the **Interval** section.
3. From the **Specify** list, choose **Interval lengths**.
4. In the **Left endpoint** text field, type `-1e-4`.

5 In the table, enter the following settings:

Lengths (m)
1e-4
1e-4
1e-4

6 Click **Build All Objects**.

Add some parameters for the plate dimensions and excitation frequency.

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
f0	50e3[Hz]	50000 Hz	RF Frequency
w0	2*pi*f0	3.1416E5 Hz	Angular frequency
dplate	0.1[m]	0.1 m	Plate diameter
As	0.25*pi*dplate^2	0.007854 m²	Plate area

DEFINITIONS

Variables 1

1 In the **Home** toolbar, click a= **Variables** and choose **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
Vrf	-750[V]*sin(w0*t)	V	Applied voltage

Now add the charge conservation to the dielectric materials. This means that only a charge conservation equation is solved in the dielectric material and all the plasma components are solved for in the gap between the dielectrics.

PLASMA (PLAS)

Charge Conservation 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Plasma (plas)** and choose the domain setting **Electrostatics>Charge Conservation**.

2 Select Domains 1 and 3 only.

Load in the argon cross sections from file. They form the basis of the plasma chemistry under investigation.

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 **Cross-Section Area** section.

8 In the A text field, type `As`.

9 Locate the **Plasma Properties** section. Select the **Use reduced electron transport properties** check box.

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 `3.3734e8`.

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`.

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 In the x_0 text field, type `1e-11`.

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

Now let the initial number density of Argon ions be the same as the initial number of electrons. This forces the plasma to be initially charge neutral.

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 **Electron Density and Energy** section.

3 From the **Electron transport properties** list, choose **From electron impact reactions**.

4 Locate the **Model Inputs** section. In the T text field, type `400[K]`.

The initial number density of seed electrons is very small, only one million free electrons per cubic meter. This corresponds to a near zero conductivity. So, the gap is truly acting as an insulator initially.

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 `1e6`.

4 In the ε_0 text field, type `5`.

Secondary emission of electrons is important when studying discharge curves from DBDs. In this example you add a higher secondary emission coefficient on the left wall.

Surface Reaction 1

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

2 Select Boundary 2 only.

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

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

5 Locate the **Secondary Emission Parameters** section. In the γ_i text field, type `0.01`.

6 In the ε_i text field, type `2.5`.

Surface Reaction 2

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

2 Select Boundary 3 only.

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

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

5 Locate the **Secondary Emission Parameters** section. In the γ_i text field, type `1E-6`.

6 In the ε_i text field, type `2.5`.

Surface Reaction 3

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

2 Select Boundaries 2 and 3 only.

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

4 In the **Formula** text field, type `Ars=>Ar`.

Wall 1

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

2 Select Boundaries 2 and 3 only.

Surface charge will begin to accumulate when the gas begins to break down. This will cause the electric field to be shielded in the gap. This is the phenomena responsible for terminating the discharge and also the reason why the breakdown voltage cannot be exceeded across the gap. COMSOL automatically computes the amount of surface charge accumulation when the feature is added to the model. The surface charge accumulation is computed by integration the electron and ion fluxes to the wall.

Surface Charge Accumulation 1

1 In the **Physics** toolbar, click → **Boundaries** and choose **Surface Charge Accumulation**.

2 Select Boundaries 2 and 3 only.

Ground 1

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

2 Select Boundary 4 only.

Terminal 1

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

2 Select Boundary 1 only.

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

4 In the **Terminal name** text field, type `electrode`.

5 In the V_0 text field, type `Vrf`.

Now assign the relative permittivity to the dielectric material and the air gap where the plasma forms.

MATERIALS

Dielectric 1

1 In the **Model Builder** window, under **Component 1 (comp1)** right-click **Materials** and choose **Blank Material**.

2 Right-click **Material 1 (mat1)** and choose **Rename**.

3 In the **Rename Material** dialog box, type `Dielectric 1` in the **New label** text field.

4 Click **OK**.

5 Select Domains 1 and 3 only.

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

7 In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	10	1	Basic

MESH 1

There must be sufficient mesh density to resolve the sharp gradients in the electron and ion density in the gap. Therefore you specify that there are 200 elements across the width of the gap.

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 **Extremely fine**.

Edge 1

In the **Mesh** toolbar, click **Edge**.

Distribution 1

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

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

3 Click **Clear Selection**.

4 Select Domain 2 only.

5 Locate the **Distribution** section. From the **Distribution type** list, choose **Predefined**.

6 In the **Number of elements** text field, type 200.

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

8 From the **Growth formula** list, choose **Geometric sequence**.

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

10 Click **Build All**.

STUDY 1

Step 1: Time Dependent

1 In the **Model Builder** window, under **Study 1** click **Step 1: Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 Click **Range**.

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

5 In the **Stop** text field, type 1e-4.

6 In the **Number of values** text field, type 201.

7 Click **Replace**.

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

RESULTS

Parametric Extrusion 1D 1

1 In the **Results** toolbar, click **More Datasets** and choose **Parametric Extrusion 1D**.

2 In the **Settings** window for **Parametric Extrusion 1D**, locate the **Settings** section.

3 Clear the **Separate levels** check box.

4 In the **Level scale factor** text field, type `50e3`.

Now create a new parametric dataset, which ignores the first startup RF cycle so the current density can be visualized later.

Parametric Extrusion 1D 2

1 Right-click **Parametric Extrusion 1D 1** and choose **Duplicate**.

2 In the **Settings** window for **Parametric Extrusion 1D**, locate the **Data** section.

3 From the **Time selection** list, choose **From list**. In the **Times (s)** list, choose **1E-5** through **1E-4**.

Excited Argon Mass Fraction

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

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

Surface 1

1 Right-click **Excited Argon Mass Fraction** 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> Mass fractions>plas.wArs - Mass fraction**.

3 In the **Excited Argon Mass Fraction** toolbar, click **Plot**.

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

Electric Potential

1 In the **Model Builder** window, right-click **Excited Argon Mass Fraction** and choose **Duplicate**.

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

Surface 1

1 In the **Model Builder** window, expand the **Electric Potential** 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>Electric> V - Electric potential - V**.

3 In the **Electric Potential** toolbar, click **Plot**.

4 Click **Plot**.

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

Electric Field

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

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

Surface 1

1 In the **Model Builder** window, expand the **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)>Plasma>Electric> Electric field - V/m>plas.Ex - Electric field, x component**.

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

4 Click **Plot**.

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

Electron Density

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

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

Surface 1

1 In the **Model Builder** window, expand the **Electron 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> Electron density>plas.ne - Electron density - 1/m³**.

3 In the **Electron Density** toolbar, click **Plot**.

4 Click **Plot**.

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

Mean Electron Energy

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

2 In the **Settings** window for **2D Plot Group**, type `Mean Electron Energy` in the **Label** text field.

Surface 1

1 In the **Model Builder** window, expand the **Mean Electron Energy** node, then click **Surface 1**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)>Plasma> Electron energy density>plas.ebar - Mean electron energy - V**.

3 In the **Mean Electron Energy** toolbar, click **Plot**.

4 Click **Plot**.

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

Electron Current Density

1 In the **Model Builder** window, right-click **Mean Electron Energy** and choose **Duplicate**.

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

3 Locate the **Data** section. From the **Dataset** list, choose **Parametric Extrusion 1D 2**.

Surface 1

1 In the **Model Builder** window, expand the **Electron Current 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>Current> Electron current density - A/m²>plas.Jelx - Electron current density, x component**.

3 In the **Electron Current Density** toolbar, click **Plot**.

4 Click **Plot**.

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

Argon Ion Current Density

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

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

Surface 1

1 In the **Model Builder** window, expand the **Argon Ion Current 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>Species> Species wAr_1p>Ion current density - A/m²>plas.Jix_wAr_1p - Ion current density, x component**.

3 In the **Argon Ion Current Density** toolbar, click **Plot**.

4 Click **Plot**.

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

Total Conduction Current Density

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

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

Surface 1

1 In the **Model Builder** window, expand the **Total Conduction Current Density** node, then click **Surface 1**.

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

3 In the **Expression** text field, type `plas.Jix_wAr_1p+plas.Jelx`.

4 In the **Total Conduction Current Density** toolbar, click  **Plot**.

5 Click  **Plot**.

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

Terminal Current

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

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

Global 1

1 Right-click **Terminal Current** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Plasma> plas.I_electrode - Current, Terminal electrode - A**.

3 In the **Terminal Current** toolbar, click  **Plot**.

Total Power Deposition

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

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

Global 1

1 Right-click **Total Power Deposition** and choose **Global**.

2 In the **Settings** window for **Global**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)>Plasma> Power and collisions>plas.Pcap_tot - Total capacitive power deposition, electrons - W**.

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

Global Evaluation 1

1 In the **Results** toolbar, click 8.5 **Global Evaluation**.

Use the `timeavg` operator to compute the time averaged power deposition for cycles 2-10.

2 In the **Settings** window for **Global Evaluation**, locate the **Data** section.

3 From the **Time selection** list, choose **Last**.

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

Expression	Unit	Description
`timeavg(1e-5,2e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 2
`timeavg(2e-5,3e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 3
`timeavg(3e-5,4e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 4
`timeavg(4e-5,5e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 5
`timeavg(5e-5,6e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 6
`timeavg(6e-5,7e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 7
`timeavg(7e-5,8e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 8
`timeavg(8e-5,9e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 9
`timeavg(9e-5,10e-5,plas.Pcap_tot,'nointerp')`	W	Cycle 10

As you can see, the average power deposited to the plasma remains the same for each cycle after only 3 RF cycles. The power is around 16.7 W on one half cycle and 17.7 W on the other half cycle. The difference is due to the fact that the secondary emission coefficients are different on the upper and lower plates.

5 Click = **Evaluate**.