

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 in 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 gap¹ will be 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 timescale. Electrons created via electron impact ionization rush towards 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 towards 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 allows us to

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

quickly gain some insight into the characteristics of the discharge without excessive computation time.

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

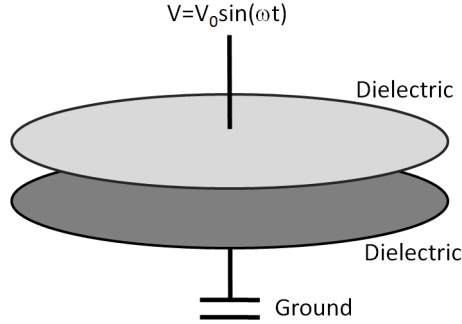


Figure 1: Graphic illustration of a typical dielectric barrier discharge.

DOMAIN EQUATIONS

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*.

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

$$\frac{\partial}{\partial t}(n_\epsilon) + \nabla \cdot [-n_\epsilon(\boldsymbol{\mu}_\epsilon \cdot \mathbf{E}) - \mathbf{D}_\epsilon \cdot \nabla n_\epsilon] + \mathbf{E} \cdot \boldsymbol{\Gamma}_e = R_\epsilon$$

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:

$$\mathbf{D}_e = \boldsymbol{\mu}_e T_e, \boldsymbol{\mu}_\epsilon = \left(\frac{5}{3}\right)\boldsymbol{\mu}_e, \mathbf{D}_\epsilon = \boldsymbol{\mu}_\epsilon T_e$$

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 $P \gg M$. 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: $1/\text{m}^3$). 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: $\text{C}^{1/2}/\text{kg}^{1/2}$), 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 non-electron species, the following equation is solved for the mass fraction of each species. For detailed information on the transport of the non-electron 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:

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

and the electron energy flux:

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

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 towards the wall:

$$-\mathbf{n} \cdot \mathbf{j}_k = M_w R_k + M_w c_k Z_k \mu_k (\mathbf{E} \cdot \mathbf{n}) [Z_k \mu_k (\mathbf{E} \cdot \mathbf{n}) > 0] \quad (3)$$

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

$$\mathbf{n} \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s \quad (4)$$

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

$$\frac{d\rho_s}{dt} = \mathbf{n} \cdot \mathbf{J}_i + \mathbf{n} \cdot \mathbf{J}_e \quad (5)$$

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:

$$V = V_0 \sin(\omega t) \quad (6)$$

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:

TABLE 1: TABLE OF COLLISIONS AND REACTIONS MODELED

REACTION	FORMULA	TYPE	$\Delta\epsilon$ (eV)
1	$e+Ar \Rightarrow e+Ar$	Elastic	0
2	$e+Ar \Rightarrow e+Ar_s$	Excitation	11.5
3	$e+Ar_s \Rightarrow e+Ar$	Superelastic	-11.5
4	$e+Ar \Rightarrow 2e+Ar^+$	Ionization	15.8
5	$e+Ar_s \Rightarrow 2e+Ar^+$	Ionization	4.24
6	$Ar_s+Ar_s \Rightarrow e+Ar+Ar^+$	Penning ionization	-
7	$Ar_s+Ar \Rightarrow Ar+Ar$	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	$Ar_s \Rightarrow Ar$	1
2	$Ar^+ \Rightarrow Ar$	1

When the ion Atoms 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* data set. 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.

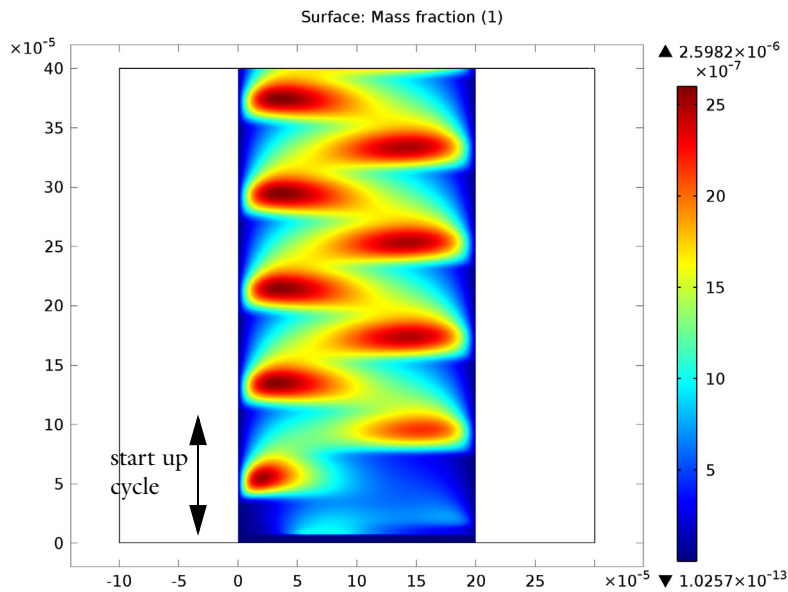


Figure 2: Mass fraction of excited argon.

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.

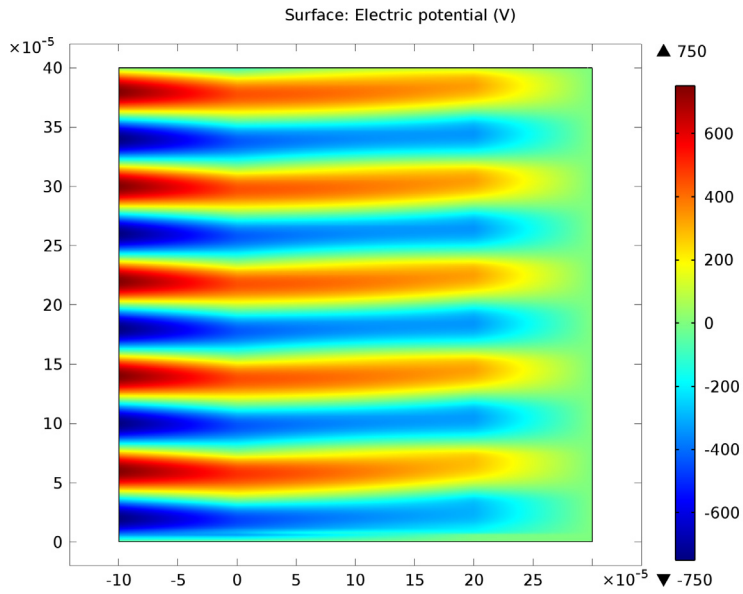


Figure 3: Electric potential (*x*-axis) v.s. time (*y*-axis).

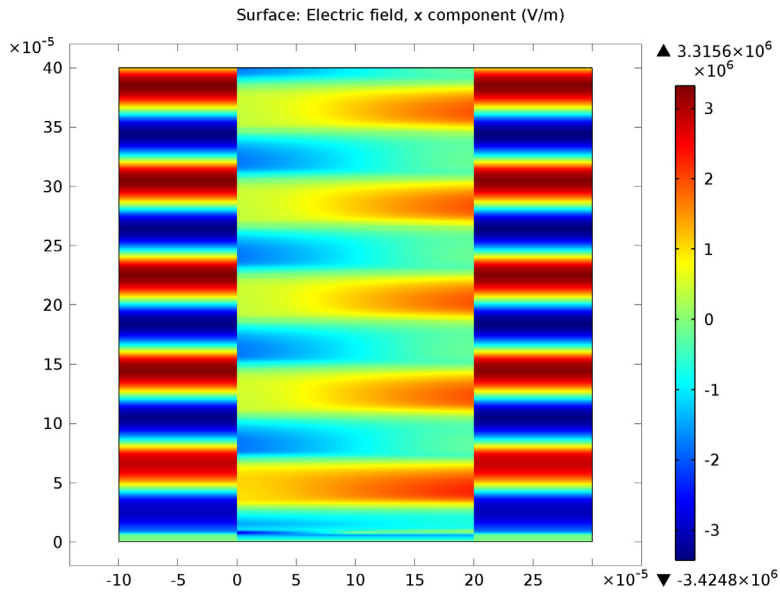


Figure 4: Electric field across the gap (*x*-axis) v.s. time (*y*-axis).

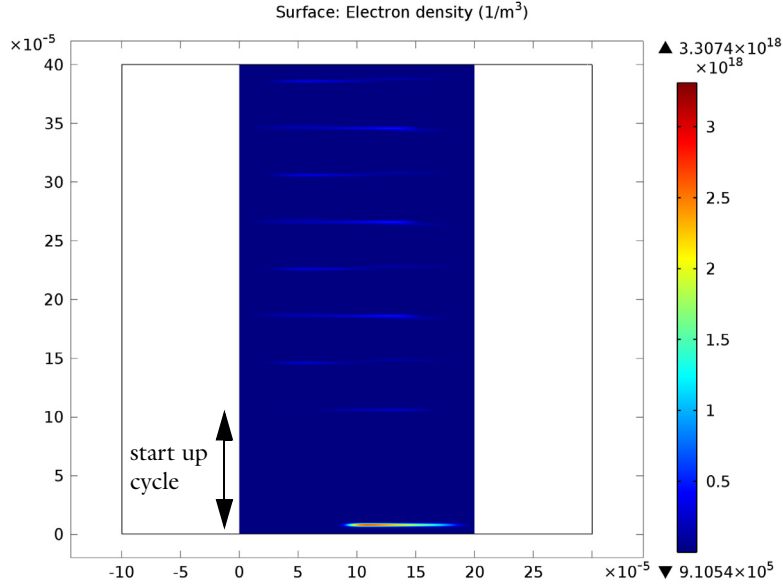


Figure 5: Extruded plot of the electron density.

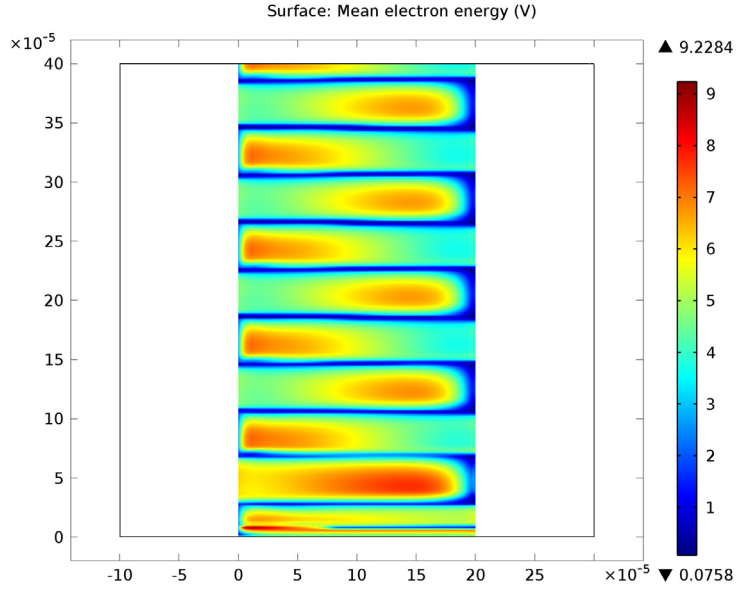


Figure 6: Extruded plot of the mean electron energy.

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:

$$\nabla \cdot \mathbf{J} = -\frac{\partial \rho}{\partial t} \approx 0 \quad (7)$$

where \mathbf{J} is the total plasma current density [A/m^2] and ρ is the space charge density [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.

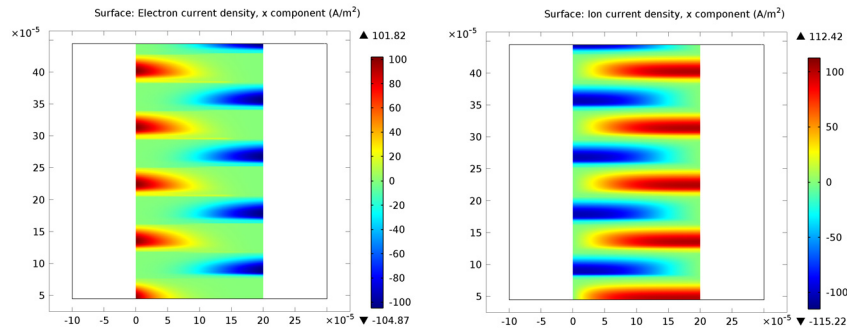


Figure 7: Plot of the electron current density (left) and the ion current density (right) in the discharge, excluding the first RF cycle.

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.

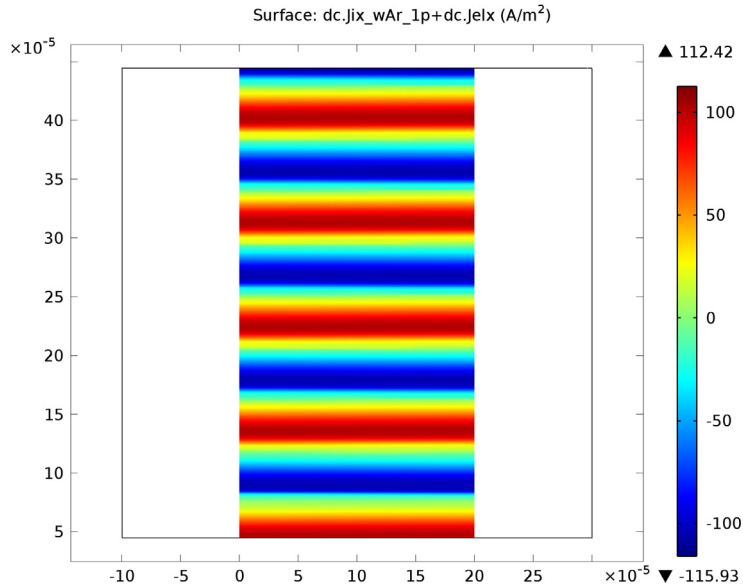


Figure 8: Plot of the total plasma current density (sum of the electron and ion current density), excluding the first RF cycle. Conservation of charge requires that the total current density be constant across the gap at any point in time.

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 due to the fact that the secondary emission coefficients are different on the upper and lower plates.

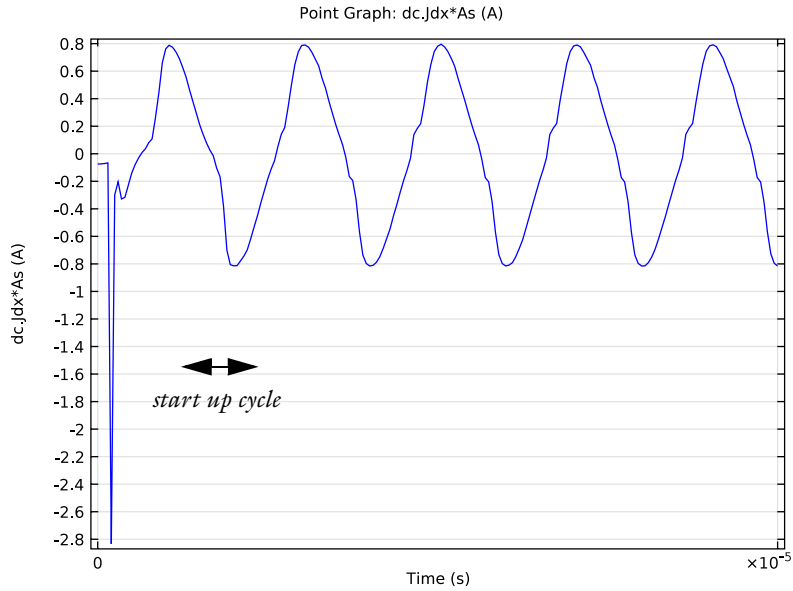


Figure 9: Plot of the total discharge current v.s. time.

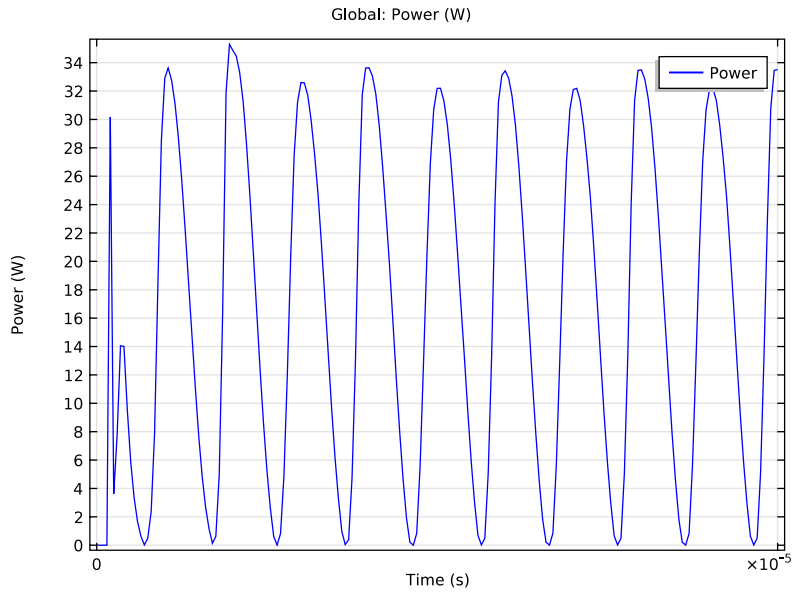


Figure 10: Plot of power v.s. time for the dielectric barrier discharge.

Model Library path: Plasma_Module/Direct_Current_Discharges/
argon_dbd_1d

Modeling Instructions

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

NEW

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

MODEL WIZARD

- 1** In the **Model Wizard** window, click the **ID** button.
- 2** In the **Select physics** tree, select **Plasma>DC Discharge (dc)**.
- 3** Click the **Add** button.
- 4** Click the **Study** button.
- 5** In the tree, select **Preset Studies>Time Dependent**.
- 6** Click the **Done** button.

GEOMETRY I

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

- 1** In the **Model Builder** window, under **Component 1** right-click **Geometry 1** and choose **Interval**.
- 2** In the **Interval** settings window, locate the **Interval** section.
- 3** From the **Number of intervals** list, choose **Many**.
- 4** In the **Points** edit field, type $-1e-4$, 0 , $2e-4$, $3e-4$.
- 5** Click the **Build All Objects** button.

DEFINITIONS*Variables 1*

- 1** In the **Model Builder** window, under **Component 1** right-click **Definitions** and choose **Variables**.
- 2** In the **Variables** settings window, locate the **Variables** section.
- 3** In the table, enter the following settings:

Name	Expression	Unit	Description
freq	50e3[Hz]	Hz	RF Frequency
omega	2*pi*freq	1/s	Angular frequency
mueN	1E25[1/(m*V*s)]	s ² ·A/(m ³ ·kg)	Reduced electron mobility
Vrf	-750[V]*sin(omega*t)	V	Applied voltage
dplate	0.1[m]	m	Plate diameter
As	0.25*pi*dplate^2	m ²	Plate area
P	intop1(dc.Pcap)*As		Power

Add an integration coupling operator which is used to calculate the amount of power absorbed by the plasma.

Integration 1

- 1** On the **Definitions** toolbar, click **Component Couplings** and choose **Integration**.
- 2** Select Domain 2 only.

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.

DC DISCHARGE*Charge Conservation 1*

- 1** On the **Physics** toolbar, click **Domains** and choose **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** On the **Physics** toolbar, click **Domains** and choose **Cross Section Import**.
- 2** In the **Cross Section Import** settings window, locate the **Cross Section Import** section.

- 3 Click the **Browse** button.
- 4 Browse to the model's Model Library folder and double-click the file `Ar_xsecs.txt`.
- 5 In the **Model Builder** window, click **DC Discharge**.
- 6 In the **DC Discharge** settings window, locate the **Plasma Properties** section.
- 7 Select the **Use reduced electron transport properties** check box.

Reaction 1

- 1 On the **Physics** toolbar, click **Domains** and choose **Reaction**.
- 2 Select Domain 2 only.
- 3 In the **Reaction** settings window, locate the **Reaction Formula** section.
- 4 In the **Formula** edit field, type $\text{Ar} + \text{Ar} \Rightarrow \text{e} + \text{Ar} + \text{Ar}^+$.
- 5 Locate the **Kinetics Expressions** section. In the k^f edit field, type $3.3734\text{e}8$.

Reaction 2

- 1 On the **Physics** toolbar, click **Domains** and choose **Reaction**.
- 2 Select Domain 2 only.
- 3 In the **Reaction** settings window, locate the **Reaction Formula** section.
- 4 In the **Formula** edit field, type $\text{Ar} + \text{Ar} \Rightarrow \text{Ar} + \text{Ar}$.
- 5 Locate the **Kinetics Expressions** section. In the k^f edit field, type 1807.

Species: Ar

- 1 In the **Model Builder** window, under **Component 1 > DC Discharge** click **Species: Ar**.
- 2 In the **Species** settings window, locate the **Species Formula** section.
- 3 Select the **From mass constraint** check box.

Species: Ars

- 1 In the **Model Builder** window, under **Component 1 > DC Discharge** click **Species: Ars**.
- 2 In the **Species** settings window, locate the **General Parameters** section.
- 3 In the x_0 edit field, type $1\text{e}-11$.

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, under **Component 1 > DC Discharge** click **Species: Ar+**.
- 2 In the **Species** settings window, locate the **Species Formula** section.

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

Plasma Model 1

- 1 In the **Model Builder** window, under **Component 1 >DC Discharge** click **Plasma Model 1**.
- 2 In the **Plasma Model** settings window, locate the **Electron Density and Energy** section.
- 3 In the $\mu_e N_n$ edit field, type $\mu_e N$.
- 4 Locate the **Model Inputs** section. In the T edit 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 conductivity of 9×10^{-14} S/m. So, the gap is truly acting as an insulator initially.

Initial Values 1

- 1 In the **Model Builder** window, under **Component 1 >DC Discharge** click **Initial Values 1**.
- 2 In the **Initial Values** settings window, locate the **Initial Values** section.
- 3 In the $n_{e,0}$ edit field, type 1e6.
- 4 In the ϵ_0 edit field, type 5.

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

Surface Reaction 1

- 1 On the **Physics** toolbar, click **Boundaries** and choose **Surface Reaction**.
- 2 Select Boundary 2 only.
- 3 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.
- 4 In the **Formula** edit field, type $\text{Ar}^{+} \Rightarrow \text{Ar}$.
- 5 Locate the **Secondary Emission Parameters** section. In the γ_i edit field, type 0.01.
- 6 In the ϵ_i edit field, type 2.5.

Surface Reaction 2

- 1 On the **Physics** toolbar, click **Boundaries** and choose **Surface Reaction**.
- 2 Select Boundary 3 only.
- 3 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.
- 4 In the **Formula** edit field, type $\text{Ar}^{+} \Rightarrow \text{Ar}$.
- 5 Locate the **Secondary Emission Parameters** section. In the γ_i edit field, type 1E-6.
- 6 In the ϵ_i edit field, type 2.5.

Surface Reaction 3

- 1 On the **Physics** toolbar, click **Boundaries** and choose **Surface Reaction**.
- 2 Select Boundaries 2 and 3 only.
- 3 In the **Surface Reaction** settings window, locate the **Reaction Formula** section.
- 4 In the **Formula** edit field, type $Ar_s \Rightarrow Ar$.

Wall 1

- 1 On 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 On the **Physics** toolbar, click **Boundaries** and choose **Surface Charge Accumulation**.
- 2 Select Boundaries 2 and 3 only.

Ground 1

- 1 On the **Physics** toolbar, click **Boundaries** and choose **Ground**.
- 2 Select Boundary 4 only.

Electric Potential 1

- 1 On the **Physics** toolbar, click **Boundaries** and choose **Electric Potential**.
- 2 Select Boundary 1 only.
- 3 In the **Electric Potential** settings window, locate the **Electric Potential** section.
- 4 In the V_0 edit field, type Vrf .

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

MATERIALS*Material 1*

- 1 In the **Model Builder** window, under **Component 1** right-click **Materials** and choose **New Material**.

- 2 Right-click **Material 1** and choose **Rename**.
- 3 Go to the **Rename Material** dialog box and type **Dielectric 1** in the **New name** edit field.
- 4 Click **OK**.
- 5 Select Domains 1 and 3 only.
- 6 In the **Material** settings window, locate the **Material Contents** section.
- 7 In the table, enter the following settings:

Property	Name	Value	Unit	Property group
Relative permittivity	epsilon _r	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 **Mesh** settings window, locate the **Mesh Settings** section.
- 2 From the **Element size** list, choose **Extremely fine**.

Edge 1

Right-click **Component 1 > Mesh 1** and choose **Edge**.

Distribution 1

- 1 In the **Model Builder** window, under **Component 1 > Mesh 1** right-click **Edge 1** and choose **Distribution**.
- 2 In the **Distribution** settings window, locate the **Domain Selection** section.
- 3 Click **Clear Selection**.
- 4 Select Domain 2 only.
- 5 Locate the **Distribution** section. From the **Distribution properties** list, choose **Predefined distribution type**.
- 6 In the **Number of elements** edit field, type 200.
- 7 In the **Element ratio** edit field, type 5.
- 8 From the **Distribution method** list, choose **Geometric sequence**.
- 9 Select the **Symmetric distribution** check box.
- 10 Click the **Build All** button.

STUDY 1*Step 1: Time Dependent*

- 1 In the **Model Builder** window, expand the **Study 1** node, then click **Step 1: Time Dependent**.
- 2 In the **Time Dependent** settings window, locate the **Study Settings** section.
- 3 Click the **Range** button.
- 4 Go to the **Range** dialog box.
- 5 From the **Entry method** list, choose **Number of values**.
- 6 In the **Stop** edit field, type $1e-4$.
- 7 In the **Number of values** edit field, type 201.
- 8 Click the **Replace** button.
- 9 On the **Home** toolbar, click **Compute**.

RESULTS*Data Sets*

- 1 On the **Results** toolbar, click **More Data Sets** and choose **Parametric Extrusion ID**.
- 2 In the **Parametric Extrusion ID** settings window, locate the **Settings** section.
- 3 Clear the **Separate levels** check box.
Now create a new parametric dataset which ignores the first startup RF cycle so the current density can be visualized later.
- 4 Right-click **Results>Data Sets>Parametric Extrusion ID 1** and choose **Duplicate**.
- 5 In the **Parametric Extrusion ID** settings window, locate the **Data** section.
- 6 From the **Time selection** list, choose **From list**.
- 7 In the **Times (s)** list, choose all times between $1e-5$ and $1e-4$.

2D Plot Group 4

- 1 On the **Home** toolbar, click **Add Plot Group** and choose **2D Plot Group**.
- 2 In the **Model Builder** window, under **Results** right-click **2D Plot Group 4** and choose **Surface**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Heavy Species Transport)>Mass fractions>Mass fraction (dc.wArs)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

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

2D Plot Group 5

- 1 In the **Model Builder** window, right-click **2D Plot Group 4** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 5** node, then click **Surface 1**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Electrostatics)>Electric>Electric potential (V)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 6

- 1 In the **Model Builder** window, right-click **2D Plot Group 5** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 6** node, then click **Surface 1**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Electrostatics)>Electric>Electric field>Electric field, x component (dc.Ex)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 7

- 1 In the **Model Builder** window, right-click **2D Plot Group 6** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 7** node, then click **Surface 1**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Drift Diffusion)>Electron density>Electron density (dc.ne)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 8

- 1 In the **Model Builder** window, right-click **2D Plot Group 7** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 8** node, then click **Surface 1**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Drift Diffusion)>Electron energy density>Mean electron energy (dc.ebar)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 9

- 1 In the **Model Builder** window, right-click **2D Plot Group 8** and choose **Duplicate**.
- 2 In the **2D Plot Group** settings window, locate the **Data** section.

- 3 From the **Data set** list, choose **Parametric Extrusion ID 2**.
- 4 In the **Model Builder** window, expand the **2D Plot Group 9** node, then click **Surface 1**.
- 5 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Drift Diffusion)>Current>Electron current density>Electron current density, x component (dc.Jelx)**.
- 6 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 10

- 1 In the **Model Builder** window, right-click **2D Plot Group 9** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 10** node, then click **Surface 1**.
- 3 In the **Surface** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Heavy Species Transport)>Species>Species wAr_1p>Ion current density>Ion current density, x component (dc.Jix_wAr_1p)**.
- 4 On the **2D plot group** toolbar, click **Plot**.

2D Plot Group 11

- 1 In the **Model Builder** window, right-click **2D Plot Group 10** and choose **Duplicate**.
- 2 In the **Model Builder** window, expand the **2D Plot Group 11** node, then click **Surface 1**.
- 3 In the **Surface** settings window, locate the **Expression** section.
- 4 In the **Expression** edit field, type `dc.Jix_wAr_1p+dc.Jelx`.
- 5 On the **2D plot group** toolbar, click **Plot**.

1D Plot Group 12

- 1 On the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.
- 2 On the **1D plot group** toolbar, click **Point Graph**.
- 3 Select Boundary 4 only.
- 4 In the **Point Graph** settings window, click **Replace Expression** in the upper-right corner of the **y-axis data** section. From the menu, choose **DC Discharge (Electrostatics)>Currents and charge>Displacement current density>Displacement current density, x component (dc.Jdx)**.
- 5 Locate the **y-Axis Data** section. In the **Expression** edit field, type `dc.Jdx*As`.
- 6 On the **1D plot group** toolbar, click **Plot**.

1D Plot Group 13

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

- 2 On the **ID plot group** toolbar, click **Global**.
- 3 In the **Global** settings window, locate the **y-Axis Data** section.
- 4 In the table, enter the following settings:

Expression	Unit	Description
P	W	Power

- 5 On the **ID plot group** toolbar, click **Plot**.

Derived Values

- 1 On the **Results** toolbar, click **Global Evaluation**.
- 2 In the **Global Evaluation** settings window, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **DC Discharge (Drift Diffusion)>Power and collisions>Total capacitive power deposition (dc.Pcap_tot)**.
- 3 Locate the **Data** section. From the **Time selection** list, choose **From list**.
- 4 In the **Times (s)** list, choose all times between **0** and **1e-5**.
- 5 Locate the **Data Series Operation** section. From the **Operation** list, choose **Average**.
- 6 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>New Table**.
- 7 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>New Table**.
- 8 In the **Global Evaluation** settings window, locate the **Data** section.
- 9 In the **Times (s)** list, choose all times between **1e-5** and **2e-5**.
- 10 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 11 In the **Times (s)** list, choose all times between **2e-5** and **3e-5**.
- 12 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 13 In the **Times (s)** list, choose all times between **3e-5** and **4e-5**.
- 14 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 15 In the **Times (s)** list, choose all times between **4e-5** and **5e-5**.
- 16 Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 17 In the **Times (s)** list, choose all times between **5e-5** and **6e-5**.

- 18** Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 19** In the **Times (s)** list, choose all times between **6e-5** and **7e-5**.
- 20** Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 21** In the **Times (s)** list, choose all times between **7e-5** and **8e-5**.
- 22** Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 23** In the **Times (s)** list, choose all times between **8e-5** and **9e-5**.
- 24** Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.
- 25** In the **Times (s)** list, choose all times between **9e-5** and **1e-4**.
- 26** Right-click **Results>Derived Values>Global Evaluation 1** and choose **Evaluate>Table 1 - Global Evaluation 1 (dc.Pcap_tot)**.

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.