



INTRODUCTION TO Plasma Module

Introduction to the Plasma Module

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Contents

Introduction	5
The Use of the Plasma Module.....	5
Plasma Modeling	14
Physics Guide	14
Physics Interface List by Space Dimension and Preset Study Type	15
Application Specific Interfaces.....	18
Argon Discharge in the GEC Reference Cell.....	22

Introduction

The Plasma Module is specifically designed for the modeling and simulation of both low-temperature and equilibrium plasma systems. It empowers engineers and scientists to investigate discharge physics and assess the performance of both existing and conceptual plasma designs.

Supporting simulations in 0D, 1D, 2D, and 3D, the Plasma Module addresses the complex and highly nonlinear nature of plasma behavior, where even small changes in parameters like electrical input, pressure, or plasma chemistry can lead to significant variations in discharge characteristics.

Plasma systems involve a wide range of interconnected physical phenomena, including fluid dynamics, reaction kinetics, heat and mass transfer, and electromagnetism. The Plasma Module offers specialized tools for accurately simulating both non-equilibrium and equilibrium discharges across a broad spectrum of engineering applications. It includes:

- A comprehensive suite of physics interfaces for building custom models
- A library of fully documented example models
- A detailed user manual to support both new and advanced users

The Use of the Plasma Module

The Plasma Module provides advanced capabilities for simulating a wide range of plasmas, plasma reactors, and plasma-related surface processes relevant to both scientific research and engineering applications. The following sections highlight several representative use cases. The module supports simulations of plasmas sustained by various types of electromagnetic excitation sources. In the low-temperature (cold plasma) regime, typical applications include:

- [Direct Current Discharges](#)
- [Inductively coupled plasmas](#)
- [Capacitively Coupled Plasmas](#)
- [Microwave Plasmas](#)
- [Dielectric Barrier Discharges](#)

The Plasma Module also enables the simulation of plasma-enhanced surface processes, such as:

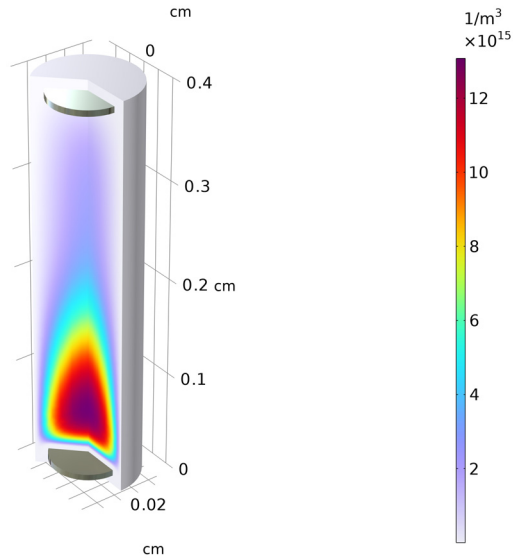
- [Plasma Enhanced Chemical Vapor Deposition](#)
- [Plasma Enhanced Etching](#)

In addition, the Plasma Module supports the modeling of [Equilibrium Discharges](#), where all species share a common temperature and the plasma is assumed to be fully ionized.

DIRECT CURRENT DISCHARGES

Direct current (DC) discharges are typically sustained through secondary electron emission from the cathode, triggered by ion bombardment. Electrons emitted from the cathode are accelerated through the cathode fall region, gaining energy as they enter the bulk plasma. If they acquire sufficient energy, these electrons can ionize the background gas, producing new electron-ion pairs. The resulting electrons travel toward the anode, while the ions migrate back to the cathode, where they may generate additional secondary electrons.

The discharge dynamics are such that most of the applied electric potential drops across the cathode fall region, a narrow zone near the cathode. Within this region, electron density and flux increase exponentially. Under certain conditions, the cathode fall is followed by a region of weak electric field, known as the positive column. In the positive column, the discharge becomes more uniform, and the electron-ion pairs produced are primarily lost to the surrounding walls in the radial direction.

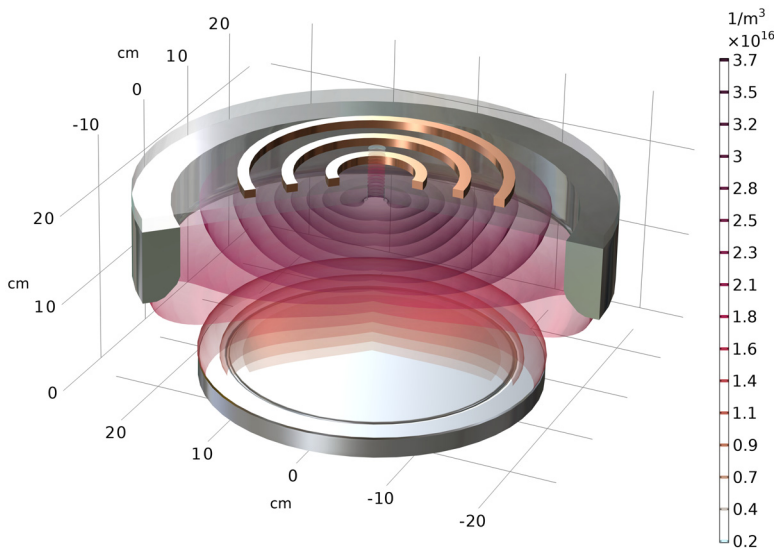


Electron density distribution in a DC argon discharge at 0.5 Torr and an applied voltage of 125 V.

INDUCTIVELY COUPLED PLASMAS

Inductively Coupled Plasmas (ICPs) were initially developed in the 1960s as high-temperature thermal plasmas for coating applications. These early systems operated near atmospheric pressure, producing gas temperatures on the order of 10,000 K. By the 1990s, ICP technology transitioned into the semiconductor industry, where it became widely adopted for film processing and large-area wafer fabrication. Modern ICP reactors operate in a low-pressure range (typically between 0.002 and 1 Torr) maintaining gas temperatures close to ambient conditions. Low-pressure ICPs are favored for their ability to generate highly uniform plasma densities over large volumes and sustain high plasma densities, resulting in strong ion fluxes to wafer surfaces, which are critical for precise etching and deposition.

From an electrical standpoint, ICPs function similarly to transformers, with the driving coil acting as the primary winding and the plasma serving as the secondary. An alternating current in the coil induces a time-varying magnetic field, which generates currents within the plasma. The electron current in the plasma flows opposite to the coil current, inducing a reactive current back into the coil. Electron heating primarily occurs within the plasma's skin depth, which decreases as plasma density or driving frequency increases, thereby limiting the volume where power is deposited into the electrons.

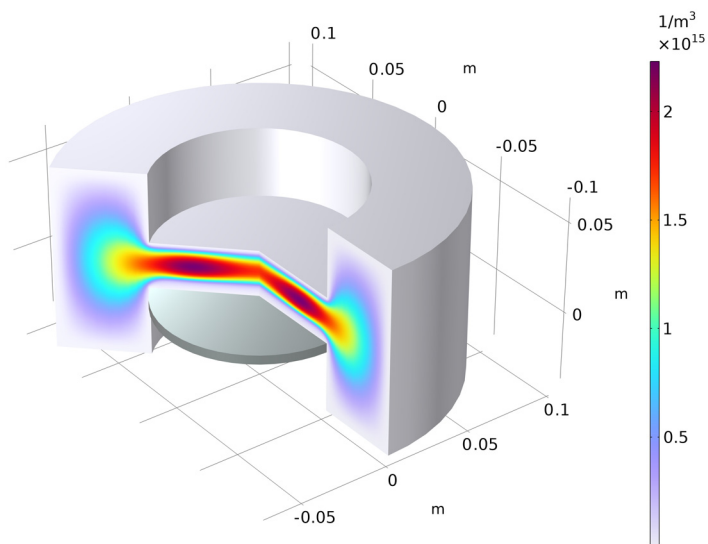


Silyl radical number density in an ICP reactor operating in a silane-argon mixture at 13.56 MHz and 50 W.

CAPACITIVELY COUPLED PLASMAS

Capacitively coupled plasmas (CCPs) are widely used in the semiconductor industry for thin film deposition and etching applications. In typical industrial setups, the plasma is generated between parallel plate electrodes spaced about 3 cm apart, with electrode diameters often reaching 30 cm. These systems usually operate at frequencies ranging from 100 kHz to 100 MHz and at pressures between 2 and 200 Pa. Although CCP sources can also operate at atmospheric pressure, doing so requires a much smaller discharge gap, typically on the order of a millimeter, to maintain a manageable pressure–distance (pd) product and ensure stable discharge conditions.

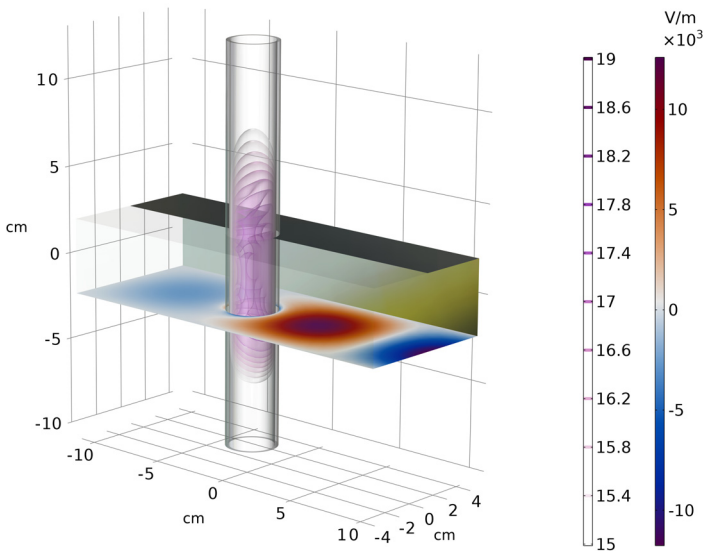
In CCP discharges, the charged species dynamics can create regions of intense charge separation at the electrodes that are strongly time modulated, the so-called plasma sheaths. Within the sheaths, intense electric fields accelerate electrons to energies sufficient for ionization, thus sustaining the discharge. In contrast, the plasma bulk (the region between the sheath) features much weaker electric fields and tends to remain quasi-neutral, with minimal net charge.



Period-averaged electron density in a GEC CCP reactor operating at 13.56 MHz with 1 W of power absorbed by the plasma.

MICROWAVE PLASMAS

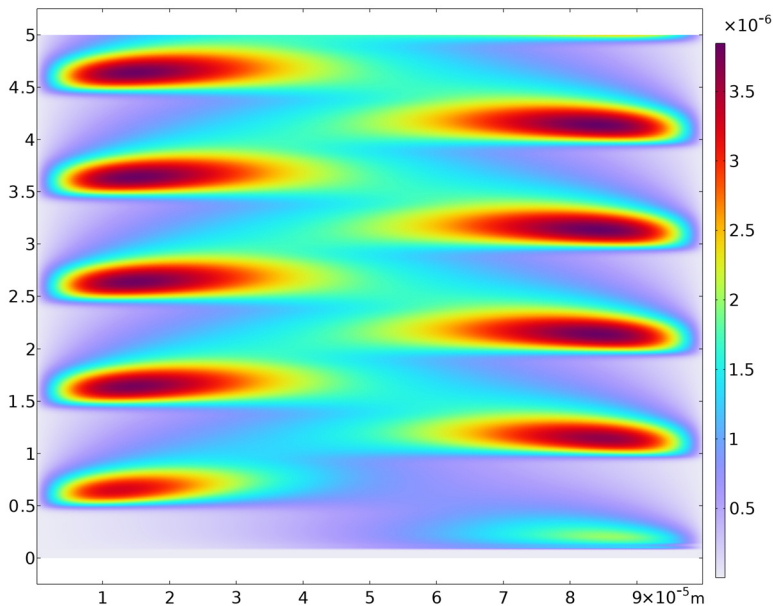
Microwave plasmas, also known as wave-heated discharges, are sustained when electrons gain energy directly from an electromagnetic wave as it penetrates into the plasma. The behavior of a microwave plasma depends significantly on the mode of the electromagnetic wave, either TE (transverse electric) or TM (transverse magnetic). In 2D axisymmetric models, the TE mode involves computing only the azimuthal component of the electric field (out-of-plane), while the TM mode involves computing the radial and axial components (in-plane) of the electric field. These differences lead to distinct electromagnetic field distributions and energy deposition profiles. Regardless of the mode, electromagnetic waves cannot propagate into regions where the electron density exceeds the critical value. At this critical electron density contour, the wave transitions from propagating to evanescent, meaning that it decays exponentially instead of transmitting energy further into the plasma. As a result, all the wave power is absorbed within a very thin layer, which can lead to strong localization of heating. The operating pressure for microwave plasmas spans a wide range. For electron cyclotron resonance (ECR) plasmas, pressures are typically 1 Pa or lower. For non-ECR microwave plasmas, pressures usually range from 100 Pa to atmospheric pressure. Power levels can also vary greatly, from just a few watts to several kilowatts, depending on the application and plasma configuration.



Electron number density isosurfaces (in logarithmic scale, m^{-3}) and electric field norm in a microwave plasma torch operating at 2.45 GHz with an input power of 50 W.

DIELECTRIC BARRIER DISCHARGES

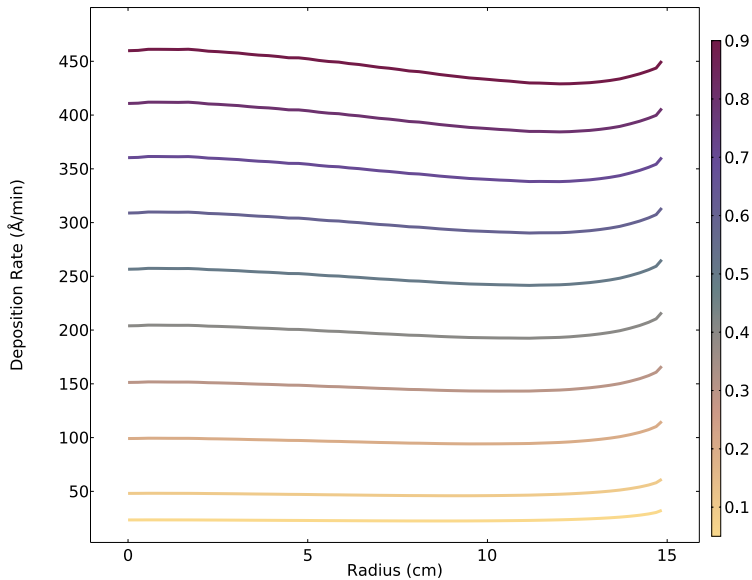
Dielectric barrier discharges (DBDs) are used in a variety of applications, including ultraviolet (UV) and extreme ultraviolet (EUV) light sources, ozone generation, and surface modification. The fundamental operating principle of a DBD involves a gas-filled gap between typically two dielectric-covered electrodes. A time-varying voltage is applied to one electrode. As the applied voltage increases, the electric field within the gap strengthens. Free electrons present in the gas are accelerated by the field, and if the field is sufficiently strong, they can gain enough energy to ionize neutral gas molecules. This initiates an avalanche effect, rapidly increasing the electron population on a nanosecond timescale. During each voltage cycle, free charges accumulate on the surfaces of the dielectric barriers, effectively shielding the gap from the applied electric field. This accumulation suppresses further ionization and can lead to temporary plasma extinction, until the applied voltage reverses polarity, and the process begins again. Dielectric barrier discharges typically operate in the pressure range of 0.1–3 atm with an applied voltage of 1–100 kV and a frequency of kHz up to MHz.



Space distribution and temporal evolution of the mass fraction of electronically excited argon atoms in a dielectric barrier discharge driven at 50 kHz with a sinusoidal voltage amplitude of 750 V at 1 atm. The x-axis represents space and the y-axis period fraction.

PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION

Plasma enhanced chemical vapor deposition (PECVD) is a widely used plasma-assisted thin-film deposition technique that enables the formation of high-quality coatings at relatively low substrate temperatures. By utilizing reactive plasma species generated from precursor gases, PECVD facilitates enhanced chemical reactions on the substrate surface, resulting in improved film properties. Modeling PECVD processes requires capturing the complex interplay between plasma dynamics, gas-phase chemistry, surface reactions, and transport phenomena. The Plasma Module provides comprehensive tools to simulate these coupled physical and chemical processes, enabling detailed analysis and optimization of PECVD reactor performance.

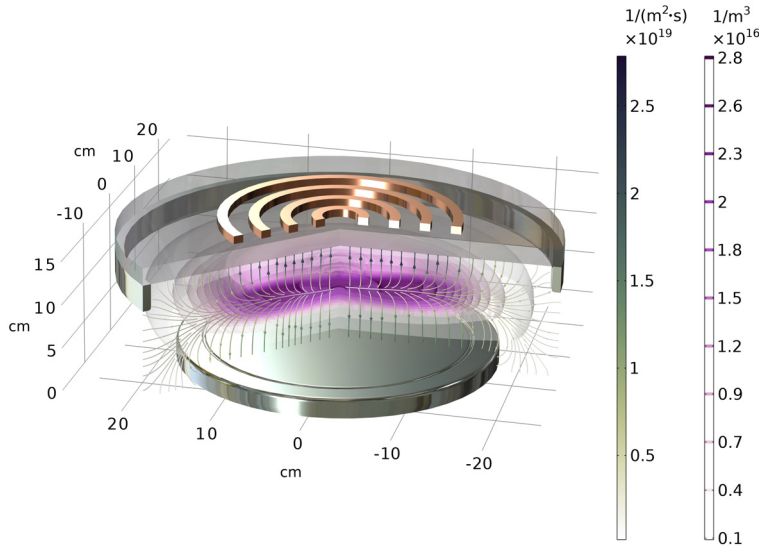


Variation of silicon deposition rate along the wafer with silane mole fraction in an inductively coupled plasma reactor using a silane-argon mixture at 13.56 MHz and 50 W.

PLASMA ENHANCED ETCHING

Plasma enhanced etching is a critical plasma-assisted process widely used in microfabrication to selectively remove material from a substrate with high precision and anisotropy. This technique leverages reactive plasma species, such as ions, radicals, and neutral particles, to chemically and physically etch target surfaces, enabling the fabrication of intricate micro- and nanoscale features. Accurate modeling of plasma enhanced etching involves capturing the complex

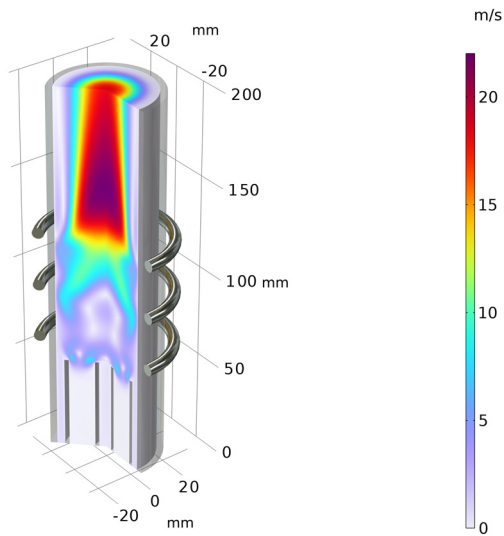
interactions between plasma chemistry, surface reactions, ion bombardment, and transport phenomena within the reactor. The Plasma Module offers advanced simulation capabilities to analyze and optimize these processes, providing valuable insights into etch rates, and uniformity.



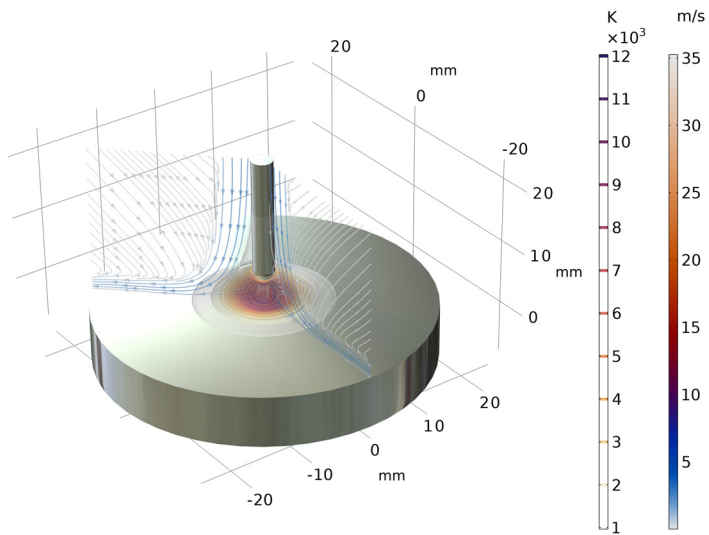
Number density and flux streamlines of CF_3^+ ions in an ICP reactor with an RF bias of 100 V amplitude. The color scale on the streamlines represents the magnitude of the CF_3^+ flux.

EQUILIBRIUM DISCHARGES

Equilibrium discharges, also known as thermal plasmas, have a wide range of industrial applications, including cutting, welding, thermal spraying, waste destruction, and surface treatment. These plasmas are typically assumed to operate under partial to full local thermodynamic equilibrium (LTE) conditions. Under LTE, the electron temperature is equal to the temperature of the background gas, and the plasma behaves like a conductive fluid mixture. As a result, thermal plasmas are modeled using the magnetohydrodynamics (MHD) equations, which treat the plasma as a continuum governed by fluid dynamics and electromagnetic interactions. Unlike non-equilibrium plasmas, equilibrium discharges do not require computation of the detailed chemical composition. Instead, the focus is on solving for gas temperature and electric fields. This modeling approach enables more efficient and numerically stable simulations, particularly when estimating thermal loads on surfaces, a critical factor in many industrial processes.



Fluid velocity in an atmospheric-pressure thermal plasma torch operating in air at 11 kW.



Temperature isosurfaces and fluid velocity magnitude streamlines in an atmospheric-pressure DC arc operating in air at 80 A.

Plasma Modeling

Plasma modeling is typically approached using one of three methods: kinetic, fluid approximation, or hybrid. Each method involves solving an appropriate transport equation in conjunction with Maxwell's equations

- The kinetic method solves for the distribution functions of ions and electrons using the Boltzmann equation. Alternatively, a Lagrangian approach may be used, where ordinary differential equations describe the motion of individual particles, as seen in particle-in-cell (PIC) simulations. This method allows the electron energy distribution function (EEDF) to assume any shape in energy space and captures non-equilibrium effects that fluid models may miss. However, it is computationally intensive and poses challenges in handling complex plasma chemistries.
- In fluid models, the plasma is described in terms of macroscopic quantities. This is done by taking velocity moments of the Boltzmann equation, resulting in a system of coupled partial differential equations that can be solved using a finite element method. The Plasma Module uses this approach. Advantages of the fluid approximation include computational efficiency, ease of incorporating complex plasma chemistries, and straightforward coupling of electron dynamics with electromagnetic fields, which also computed using the finite element method.
- Hybrid models combine aspects of both kinetic and fluid approaches. Typically, electrons are treated kinetically (via the Boltzmann equation or Monte Carlo methods), while ions and neutral species are modeled using fluid equations. This approach balances the high accuracy of kinetic models with the lower computational cost and flexibility of fluid models.

Physics Guide










Plasma modeling is inherently complex because it integrates concepts from reaction engineering, statistical physics, fluid mechanics, physical kinetics, heat and mass transfer, and electromagnetics. This creates a true multiphysics challenge, characterized by intricate coupling between these various physical processes. The Plasma Module is designed to streamline the setup of self-consistent models for low-temperature and LTE plasmas.
















The physics interfaces provide all the essential tools to simulate plasma discharges, starting with a Boltzmann Equation Two-Term Approximation solver. This physics interface calculates electron transport properties and source coefficients based on a set of electron-impact collision cross sections. Using this interface, many key discharge characteristics can be predicted by inputting parameters such





as the electric field and electron-impact reactions that define the plasma chemistry, all without needing to solve a space-dependent problem.

For space-dependent models, the plasma chemistry (comprising reactions and species) is conveniently managed within the Model Builder. When fluid velocity and gas temperature are relevant, dedicated physics interfaces for laminar flow and heat transfer are available. Additionally, several options exist to couple charged species transport with electromagnetic fields, offering flexibility in modeling the plasma environment.

Physics Interface List by Space Dimension and Preset Study Type

PHYSICS INTERFACE	ICON	TAG	SPACE DIMENSION	AVAILABLE STUDY TYPE
 AC/DC				
Electrical Circuit		cir	Not space dependent	stationary; frequency domain; time dependent; frequency domain; eigenfrequency
Electrostatics ¹		es	all dimensions	stationary; time dependent; stationary source sweep
 Fluid Flow				
 Single-Phase Flow				
Laminar Flow ¹		spf	3D, 2D, 2D axisymmetric	stationary; time dependent
 Plasma				
Boltzmann Equation, Two-Term Approximation		be	0D	mean energies; reduced electric fields; time dependent
Plasma, Time Periodic		ptp	1D, 2D axisymmetric	time periodic; time periodic to time dependent
Plasma		plas	all dimensions	time dependent; stationary

PHYSICS INTERFACE	ICON	TAG	SPACE DIMENSION	AVAILABLE STUDY TYPE
Inductively Coupled Plasma ^{2,4}		—	3D, 2D, 2D axisymmetric.	frequency–transient; frequency–stationary
Inductively Coupled Plasma with RF Bias ^{2,4}		—	2D, 2D axisymmetric.	frequency-time periodic; time periodic to time dependent
Microwave Plasma ^{3,4}		—	3D, 2D, 2D axisymmetric	frequency–transient
 Nonisothermal Plasma Flow				
Plasma, Nonisothermal Flow ⁴		—	3D, 2D, 2D axisymmetric.	time dependent; stationary
Inductively Coupled Plasma, Nonisothermal Flow ^{2,4}		—	3D, 2D, 2D axisymmetric.	frequency–transient; frequency–stationary
Microwave Plasma, Nonisothermal Flow ^{3,4}		—	3D, 2D, 2D axisymmetric.	frequency-transient
Plasma, Time Periodic, Nonisothermal Flow ⁴		—	2D, 2D axisymmetric.	time periodic; time periodic to time dependent
Inductively Coupled Plasma with RF Bias, Nonisothermal Flow ^{2,4}		—	2D, 2D axisymmetric.	frequency-time periodic; time periodic to time dependent
 Equilibrium Discharges				
Equilibrium Discharges, Out-of-Plane Currents ^{2,4}		—	2D, 2D axisymmetric	stationary; time dependent; frequency–transient; frequency–stationary
Equilibrium Discharges, In-Plane Currents ^{2,4}		—	2D, 2D axisymmetric	stationary; time dependent; frequency–transient; frequency–stationary
Equilibrium Discharges ^{2,4}		—	3D	stationary; time dependent; frequency–transient; frequency–stationary
 Species Transport				
Drift Diffusion		dd	all dimensions	time dependent

PHYSICS INTERFACE	ICON	TAG	SPACE DIMENSION	AVAILABLE STUDY TYPE
Heavy Species Transport		hs	all dimensions	time dependent
Charge Transport		ct	all dimensions	stationary
Corona Discharge ⁴		—	all dimensions	stationary
Electrical Breakdown Detection		ebd	3D, 2D, 2D axisymmetric	time dependent

¹ This physics interface is included with the core COMSOL package but has added functionality for this module.

² Requires the addition of the AC/DC Module.

³ Requires the addition of the RF Module.

⁴ This physics interface is a predefined multiphysics coupling that automatically adds all the physics interfaces and coupling features required.


AC/DC INTERFACES

The AC/DC Branch chapter describes the two physics interfaces available with this module under the AC/DC branch of the Model Wizard. Many of the plasma interfaces already solve Poisson's equation, and volume and surface charges are automatically accounted for. This means that the Electrostatics interface will rarely need to be used.


FLUID FLOW INTERFACES

The Fluid Flow Branch describes the Laminar Flow interface, which has a few additional features available for this module compared to the basic license.

BOLTZMANN EQUATION, TWO-TERM APPROXIMATION INTERFACE

The Boltzmann Equation, Two-Term Approximation interface  computes the electron energy distribution function (EEDF) from a set of collision cross sections for some mean discharge conditions. The interface can be used as a preprocessing stage before solving a full space dependent model. The main purpose of this interface is to compute electron source coefficients and transport properties.

DRIFT DIFFUSION INTERFACE


The Drift Diffusion interface  is used to compute the electron density and mean electron energy for any type of plasma. A wide range of boundary conditions are

available to handle secondary emission, thermionic emission, and wall losses. This interface rarely needs to be used by itself as it makes up part of the application specific interfaces described later.

CHARGE TRANSPORT

The Charge Transport interface computes the density of charge carriers in a background gas under the assumption that the transport is dominated by migration. This is typically only used as part of the Corona Discharge multiphysics interface (see below).


THE HEAVY SPECIES INTERFACE

The Heavy Species Transport interface  solves a mass balance equation for all nonelectron species. This includes charged, neutral, and electronically excited species. The interface also allows you to add electron impact reactions, chemical reactions, surface reactions, volumetric species, and surface species via the Model Builder. This interface rarely needs to be used by itself as it makes up part of the application specific interfaces described later.


Application Specific Interfaces

The Plasma Module provides four application specific multiphysics interfaces for modeling the most common types of discharge.

PLASMA


The Plasma interface  can be used to model positive columns, DBD discharges, glow discharges, CCP reactors, and corona discharges. The complicated coupling between the electron transport, heavy species transport, and electrostatic field is handled automatically by the software. Furthermore, the secondary emission flux from ion bombardment on an electrode is automatically computed and used in the boundary condition for electrons.

PLASMA, TIME PERIODIC


The Plasma, Time Periodic interface  can be used to model capacitively coupled plasmas. Instead of solving the problem in the time domain, the periodic steady-state solution is computed. This avoids having to solve for tens or hundreds of thousands of RF cycles, which is typically how long it takes before the plasma reaches the periodic steady-state solution. This approach maintains all the nonlinearity of the model while dramatically reducing computation time. The physics interface accomplishes this by attaching an extra dimension to the

underlying mathematical equations representing one RF cycle, and enforcing periodic boundary conditions in the aforementioned extra dimension.


INDUCTIVELY COUPLED PLASMA

The Inductively Coupled Plasma interface  can be used to model discharges sustained through induction currents. These discharges typically operate in the MHz frequency range. Inductively coupled plasmas (ICP) are important in plasma processing and plasma sources because the plasma density can be considerably higher than in capacitively coupled discharges. Inductively coupled plasmas are also attractive from the modeling perspective because they are relatively straightforward to model, due to the fact that the induction currents can be solved for in the frequency domain. This means that the RF cycle applied to the driving coil does not need to be explicitly resolved when solving. As such, the quasi steady-state solution is reached in relatively few time steps.


INDUCTIVELY COUPLED PLASMA WITH RF BIAS

The Inductively Coupled Plasma with Rf Bias interface  can be used to model discharges sustained through induction currents and that have a periodic RF biased electrode. This interface uses the Plasma, Time Periodic interface to solve the periodic steady state for the RF bias. The inductive currents are solved in the frequency domain as in the Inductively Coupled Plasma interface. This type of discharges are interesting because the plasma density and the ions flux at a surface can be controlled somewhat independently.

MICROWAVE PLASMA


The Microwave Plasma interface  can be used to model discharges which are sustained through heating of electrons due to electromagnetic waves. These discharges typically operate in the GHz frequency range. Wave-heated discharges usually fall into one of two categories: discharges with no external DC magnetic field and discharges with a high intensity static magnetic field. If a suitably high DC magnetic field is present then electron cyclotron resonance (ECR) can occur where electrons continually gain energy from the electric field over 1 RF period. Modeling microwave plasmas involves solving equations for the electron density, mean electron energy, heavy species, the electrostatic potential, and the high frequency electric field. The high frequency electric field is computed in the frequency domain and losses are introduced via a complex plasma conductivity.

NONISOTHERMAL PLASMA FLOW


The Nonisothermal Plasma Flow interface  couples existent plasma interfaces with Laminar Flow and Heat Transfer in Fluids interfaces. Use these interfaces

when there are important fluid velocities and when the background gas temperature depends strongly on the operation conditions.


EQUILIBRIUM DISCHARGES, OUT-OF-PLANE CURRENTS

The Equilibrium Discharges, Out-of-plane Currents  multiphysics interface, available in 2D and 2D axisymmetric, is used to study equilibrium discharges in a magnetohydrodynamics (MHD) framework where the currents are out-of-plane. This multiphysics interface adds three single physics interfaces: Magnetic Fields, Heat Transfer in Fluids, and Laminar Flow, together with several multiphysics coupling features. The multiphysics couplings add the MHD coupling between the Magnetic Fields and the Laminar Flow interfaces. The multiphysics couplings also add heating and cooling of the equilibrium plasma by enthalpy transport, Joule heating and radiation loss.

EQUILIBRIUM DISCHARGES, IN-PLANE CURRENTS

The Equilibrium Discharges, in-plane Currents  multiphysics interface, available in 2D and 2D axisymmetric, is used to study equilibrium discharges in a magnetohydrodynamics (MHD) framework where the currents are in-plane. This multiphysics interface adds three single physics interfaces: Magnetic and Electric Fields, Heat Transfer in Fluids, and Laminar Flow, together with several multiphysics coupling features. The multiphysics couplings add the MHD coupling between the Magnetic and Electric Fields and the Laminar Flow interfaces. The multiphysics couplings also add heating and cooling of the equilibrium plasma by enthalpy transport, Joule heating and radiation loss as well as special boundary conditions to model the ion and electron heating at the plasma boundaries.

EQUILIBRIUM DISCHARGES

The Equilibrium Discharges  multiphysics interface, available in 3D, is used to study equilibrium discharges in a magnetohydrodynamics (MHD) framework. This multiphysics interface adds three single physics interfaces: Magnetic and Electric Fields, Heat Transfer in Fluids, and Laminar Flow, together with several multiphysics coupling features. The multiphysics couplings add the MHD coupling between the Magnetic and Electric Fields and the Laminar Flow interfaces. The multiphysics couplings also add heating and cooling of the equilibrium plasma by enthalpy transport, Joule heating, and radiation loss as well as special boundary conditions to model the ion and electron heating at the plasma boundaries.

CORONA DISCHARGE

The Corona Discharge interface employs a simplified charge transport model combined with electrostatics to approximate the charge density and electrostatic field in stationary corona discharges. This model does not include the ionization layer of corona discharges, instead utilizing an approximate boundary condition. Additionally, electron dynamics are not solved in this approach.

ELECTRICAL BREAKDOWN DETECTION

The Electrical Breakdown Detection interfaces uses an approximate method to determine if electrical breakdown will occur in a given design by integrating Townsend growth coefficients along electric field lines.

LIMITATIONS OF THE PLASMA MODULE

The Plasma module cannot model plasmas that are not collisional enough for the fluid-type equations used to be valid. For reactors with characteristic dimensions of 10 cm the lower possible pressure would be 20 mTorr.

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Argon Discharge in the GEC Reference Cell

The GEC cell was introduced by NIST in order to provide a standardized platform for experimental and modeling studies of discharges in different laboratories (Ref. 1). The plasma is sustained via inductive heating. The Reference Cell operates as an inductively-coupled plasma in this model.

Due to the complex physics involved in inductively coupled plasmas, it is advisable to begin modeling with a simplified chemical mechanism. Argon serves as an ideal starting point at low pressures because of its relative simplicity. In this approach, the electronically excited states are grouped into a single species, resulting in a chemical mechanism comprising only three species and seven reactions:

LIST OF VOLUMETRIC PLASMA CHEMICAL REACTIONS CONSIDERED

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

Stepwise ionization (reaction 5) can play an important role in sustaining low pressure argon discharges. Excited argon atoms are consumed via superelastic collisions with electrons, quenching with neutral argon atoms, and ionization or Penning ionization where two metastable argon atoms react to form a neutral argon atom, an argon ion and an electron. In addition to volumetric reactions, the following surface reactions are implemented:

LIST OF SURFACE REACTIONS CONSIDERED

REACTION	FORMULA	STICKING COEFFICIENT
1	$\text{Ar}_s \Rightarrow \text{Ar}$	1
2	$\text{Ar}^+ \Rightarrow \text{Ar}$	1

When a metastable argon atom or ion makes contact with the wall, it will revert to the ground state argon atom with some probability (the sticking coefficient).







From an electrical perspective, the GEC reactor functions like a transformer. A current applied to the driving coil (the primary) induces a current in the plasma (the secondary). In turn, the plasma generates an opposing current in the coil,

which increases the coil's effective resistance. The current flowing through the plasma depends both on the coil current and the plasma's reaction kinetics. The total plasma current can range from zero (when the plasma is not sustained) to matching the primary coil current, which represents perfect coupling between the coil and plasma. In this example, the coil is powered at a fixed input of 1500 W.

Model Wizard

The first step to build a model is to open the COMSOL Desktop and then specify the type of analysis you want to do — in this case, a frequency-transient inductively coupled plasma analysis. The frequency-transient study type means that the high frequency electromagnetic field is computed in the frequency domain and all other variables are computed in the time domain.


Note: These instructions are for the user interface on Windows® but apply, with minor differences, also to Linux® and macOS.

- 1 Open COMSOL Multiphysics. In the New window, click the Model Wizard button .
- 2 In the Model Wizard window, click the 2D Axisymmetric button .
- 3 In the Select physics tree, select Plasma > Inductively Coupled Plasma .
- 4 Click the Add button.
- 5 Click the Study button .
- 6 In the tree, select Frequency-Transient .
- 7 Click Done .

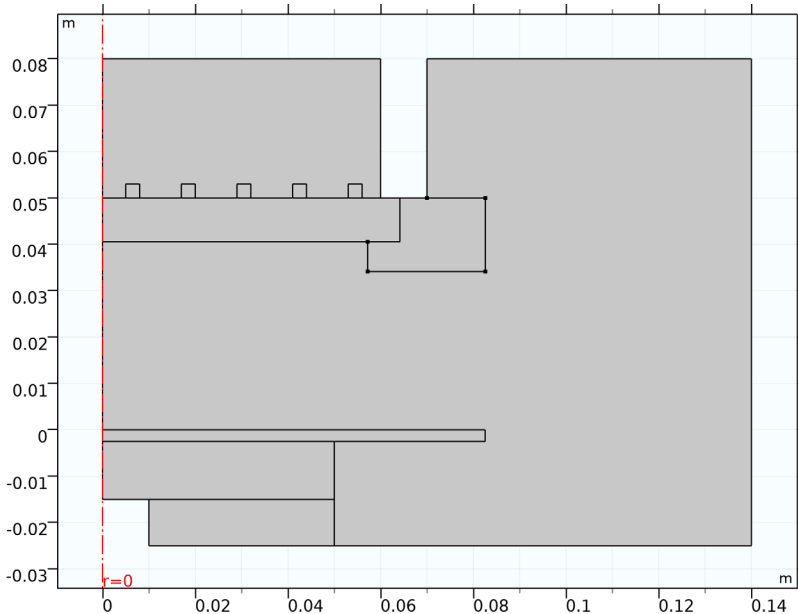
Importing the Geometry

The next step is to create your geometry, which also can be imported from an external program. COMSOL Multiphysics supports a multitude of CAD programs and file formats. In this example, insert the prepared geometry sequence from a file in the COMSOL Multiphysics file format (.mph). The file contains the geometry of the GEC reference cell.



The location of the files used in this exercise varies based on your installation. For example, if the installation is on your hard drive, the file path might be similar to C:\Program Files\COMSOL\COMSOL64\applications\.







- 1 In the Geometry toolbar, click Insert Sequence .

- 2 Browse to the folder Plasma_Module\Inductively_Coupled_Plasmas under the COMSOL installation directory and double-click on the file argon_gec_icp_geom.mph.
- 3 Click the Import button. The geometry should appear in the Graphics window as shown below.

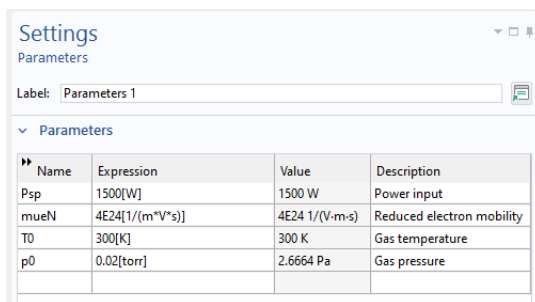


Definitions

- 1 In the Definitions toolbar, click Explicit .
- 2 In the Settings window, type Walls in the Label field.
- 3 Locate the Input Entities section.
- 4 From the Geometric entity level list, choose Boundary.
- 5 Go to the Home tab on the Model desktop toolbar, then choose Windows > Selection List.
- 6 Select Boundaries 6, 8, 35–38, 44, 45, and 51–56 only (by holding shown shift and clicking on the list), then click the Add to selection button  at the top of the Selection List settings window. The selected boundaries in the graphics window will turn blue, indicating that the selection is confirmed.
- 7 Click back on the Model Builder tab.

- 8 In the Definitions toolbar, click Explicit .
- 9 In the Settings window, type Coils in the Label field.
- 10 Click on the Selection List tab and select Domains 6 and 8–11 only, then click the Add to selection button  at the top of the Selection List settings window.
- 11 Click back on the Model Builder tab.
- 12 In the Definitions toolbar, click Explicit .
- 13 In the Settings window, type Coil Boundaries in the Label field.
- 14 Click on the Selection List tab and select Domains 6 and 8–11 only, then click the Add to selection button  at the top of the Selection List settings window.
- 15 Click back on the Model Builder tab. In the Explicit settings window, locate the Output Entities section.
- 16 From the Output entities list, choose Adjacent boundaries.
- 17 Go to the Model desktop toolbar.
- 18 In the Home toolbar, click Parameters  and select Parameters 1 .
- 19 In the Parameters settings window, locate the Parameters section.


In the table, enter the following settings:



The screenshot shows the 'Settings' window for 'Parameters'. The 'Label' field is set to 'Parameters 1'. Below the 'Parameters' section, there is a table with the following data:



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

Plasma and Magnetic Fields


- 1 In the Model Builder window, under Component 1 click on the Plasma  node.
- 2 In the settings window, Locate the Plasma Properties section and select the Use reduced electron transport properties checkbox.
- 3 Click on the Selection List window. Select Domain 3 only.

- 4 In the Model Builder window, right-click Plasma and choose Cross Section Import.
- 5 In the Cross Section Import settings window, locate the Cross Section Import section.
- 6 Click the Browse button.
- 7 Browse to the module Application Library folder and double-click the file Ar_xsecs.txt.


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

- 1 In the Model Builder window, right-click Plasma and choose the domain setting Heavy Species Transport > Reaction .
- 2 In the Reaction settings window, locate the Reaction Formula section.
- 3 In the Formula field, type $\text{Ar}^s + \text{Ar}^s \Rightarrow \text{e} + \text{Ar} + \text{Ar}^+$. Click off the settings window.
- 4 Locate the Kinetics Expressions section. In the k^f field, type $3.734\text{E}8$.
- 5 In the Model Builder window, right-click Plasma and choose the domain setting Heavy Species Transport > Reaction .
- 6 In the Reaction settings window, locate the Reaction Formula section.
- 7 In the Formula field, type $\text{Ar}^s + \text{Ar} \Rightarrow \text{Ar} + \text{Ar}$. Click off the settings window.
- 8 Locate the Kinetics Expressions section. In the k^f field, type 1807.

When solving any type of reacting flow problem there always needs to be one species which is selected to fulfill the mass constraint. This should be taken as the species with the largest mass fraction.

- 1 In the Model Builder window, under Component 1 > Plasma click Species: Ar .
- 2 In the Species settings window, locate the Species Formula section.
- 3 Select the From mass constraint checkbox.

When solving a plasma problem the plasma must be initially charge neutral. COMSOL automatically computes the initial concentration of a selected ionic species such that the initial electroneutrality constraint is satisfied. Once the simulation begins to time step, the plasma need not be charge neutral. In fact, the separation of space charge between the ions and electrons close to the wall is a critical component in sustaining the discharge.

- 1 In the Model Builder window, under Component 1 > Plasma click Species: Ar+ .
- 2 In the Species settings window, locate the Species Formula section.

3 Select the Initial value from electroneutrality constraint checkbox.

Initial conditions for the electron number density and mean electron energy are critical for any plasma model. If the initial electron density is too low then the plasma may not be able to sustain itself and may self-extinguish. If the initial electron density is too high then convergence problems may occur during initial time steps.

1 In the Model Builder window, under Component 1 > Plasma click Initial Values .

2 In the Initial Values settings window, locate the Initial Values section.

3 In the $n_{e,0}$ field, type $1E15[1/m^3]$.

4 In the ϵ_0 field, type $5[V]$.

5 In the Model Builder window, under Component 1 > Plasma click Plasma Model 1 .

6 In the Plasma Model settings window, locate the Model Inputs section.

7 In the T field, type T_0 .

8 In the p_A field, type p_0 .

9 Locate the Electron Density and Energy section. In the $\mu_e N_n$ field, type $\mu_e n$.


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

1 In the Model Builder window, under Component 1 right-click Plasma and choose the boundary condition Heavy Species Transport > Surface Reaction .

2 In the Surface Reaction settings window, locate the Reaction Formula section.

3 In the Formula field, type $Ar_s=>Ar$.

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


5 In the Model Builder window, right-click Plasma and choose the boundary condition Heavy Species Transport > Surface Reaction .

6 In the Surface Reaction settings window, locate the Reaction Formula section.


7 In the Formula field, type $Ar+=>Ar$.

8 Locate the Boundary Selection section. From the Selection list, choose Walls.

Now add boundary conditions to describe how the electrons interact with the wall and specify that the walls are grounded.

1 In the Model Builder window, right-click Plasma and choose the boundary condition Drift Diffusion > Wall .


2 In the Wall settings window, locate the General Wall Settings section.

- 3 In the r_c field, type 0.2.
- 4 Locate the Boundary Selection section. From the Selection list, choose Walls.
- 5 In the Physics toolbar, click Boundaries and choose Ground .
- 6 In the Ground settings window, locate the Boundary Selection section.
- 7 From the Selection list, choose Walls.

You need to compute the AC electric field both inside and outside the plasma. It is not necessary to compute the high frequency fields in the wafer or wafer pedestal, so start by modifying the selection for the Magnetic Fields interface.

- 1 In the Model Builder window, click Magnetic Fields.
- 2 Select Domains 3–6 and 8–12 only.


The Coil feature allows you to drive the system with a fixed total power. Some of this power will be dissipated in the coil, the rest will be coupled into the plasma. In this example 1500 W are applied to the system. This results in a plasma with a high number density. You also need to specify the gas temperature and pressure.

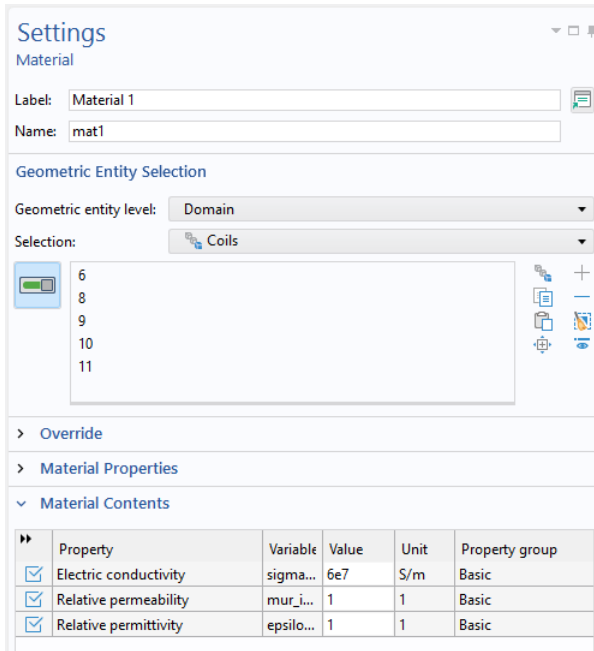
- 1 In the Model Builder window, right-click Magnetic Fields and choose the domain setting Coil .
- 2 In the Coil settings window, locate the Domain Selection section.
- 3 From the Selection list, choose Coils.
- 4 Locate the Coil section. Select the Coil group checkbox.


In the Coil excitation, select Power and in the P_{coil} field, type Psp.

Materials

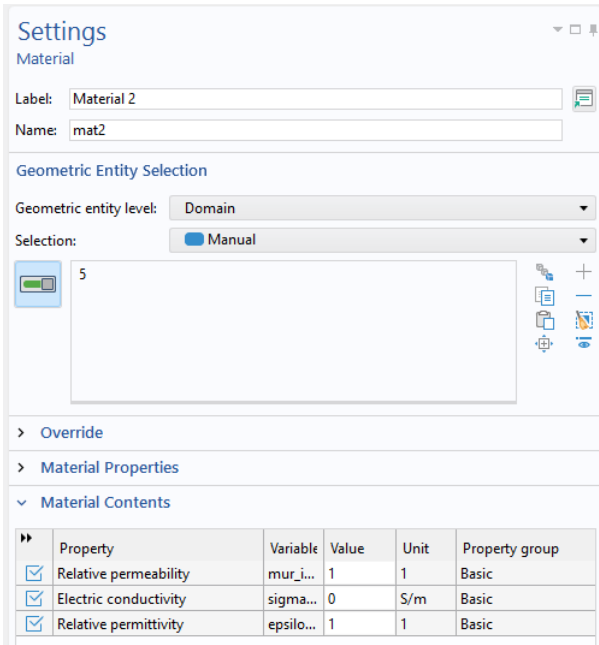
Now assign material properties to the air, coil, and dielectric domains.


- 1 In the Model Builder window, under Component 1 right-click Materials and choose Blank Material .
- 2 In the Material settings window, locate the Geometric Entity Selection section.
- 3 From the Selection list, choose Coils.
- 4 Locate the Material Contents section. In the table, enter the following settings:

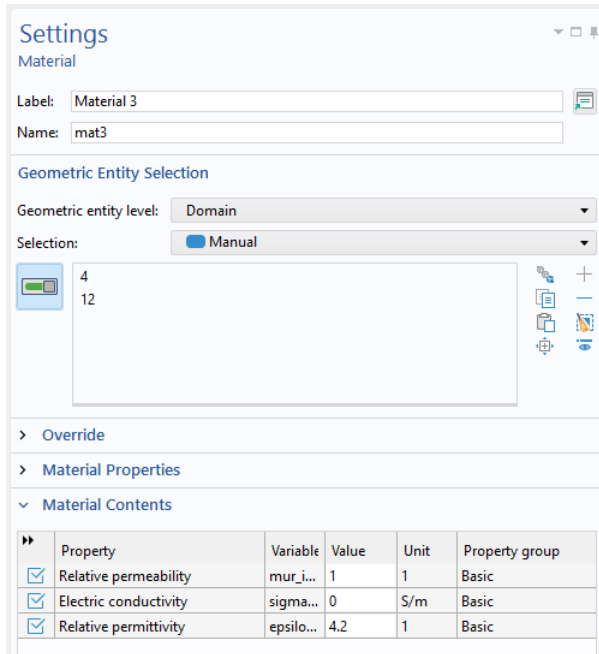


- 5 In the Model Builder window, under Component 1 right-click Materials and choose Blank Material .
- 6 In the Material settings window, locate the Geometric Entity Selection section. Select Domain 5 only. In the table, enter the following settings:

7












- 8 In the Model Builder window, under Component 1 right-click Materials and choose Blank Material .
- 9 In the Material settings window, locate the Geometric Entity Selection section. Select Domains 4 and 12 only. In the table, enter the following settings:





Mesh

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




- 1 In the Model Builder window, click Mesh 1 .
- 2 In the Mesh settings window, locate the Mesh Settings section.
- 3 From the Element size list, choose Finer.
- 4 Right-click Mesh 1 and choose More Operations > Edge .
- 5 Select Boundaries 6, 8, 44, 45, and 54 only.
- 6 Right-click Component 1 > Mesh 1 > Edge 1 and choose Size .
- 7 In the Size settings window, locate the Element Size section.
- 8 Click the Custom button.

- 9 Locate the Element Size Parameters section. Select the Maximum element size checkbox.
- 10 In the associated text field, type 1E-3.
- 11 In the Model Builder window, right-click Mesh 1 and choose Free Triangular .
- 12 In the Free Triangular settings window, locate the Domain Selection section.
- 13 From the Geometric entity level list, choose Domain.
- 14 Select Domain 3 only.
- 15 Right-click Component 1 > Mesh 1 > Free Triangular 1 and choose Size .
- 16 In the Size settings window, locate the Element Size section.
- 17 From the Predefined list, choose Extra fine.
- 18 In the Model Builder window, right-click Mesh 1 and choose Boundary Layers .
- 19 In the Boundary Layers settings window, locate the Domain Selection section.
- 20 From the Geometric entity level list, choose Domain.
- 21 Select Domain 3 only.
- 22 In the Model Builder window, under Component 1 > Mesh 1 > Boundary Layers 1 click Boundary Layer Properties .
- 23 In the Boundary Layer Properties settings window, locate the Boundary Selection section.
- 24 From the Selection list, choose Walls.
- 25 Locate the Boundary Layer Properties section. In the Number of boundary layers field, type 5.
- 26 In the Boundary layer stretching factor field, type 1.4.
- 27 In the Model Builder window, right-click Mesh 1 and choose Mapped .
- 28 In the Mapped settings window, locate the Domain Selection section.
- 29 From the Geometric entity level list, choose Domain.
- 30 From the Selection list, choose Coils.
- 31 Right-click Component 1 > Mesh 1 > Mapped 1 and choose Distribution .
- 32 In the Distribution settings window, locate the Boundary Selection section.
- 33 From the Selection list, choose Coil Boundaries.
- 34 In the Distribution settings window, locate the Distribution section.
- 35 From the Distribution type list, choose Predefined distribution type.
- 36 In the Number of elements field, type 25.
- 37 In the Element ratio field, type 20.

- 38 From the Growth formula list, choose Geometric sequence.
- 39 Select the Symmetric distribution checkbox.
- 40 In the Model Builder window, right-click Mesh 1 and choose Free Triangular .
- 41 Right-click Mesh 1 and choose Build All .

Study

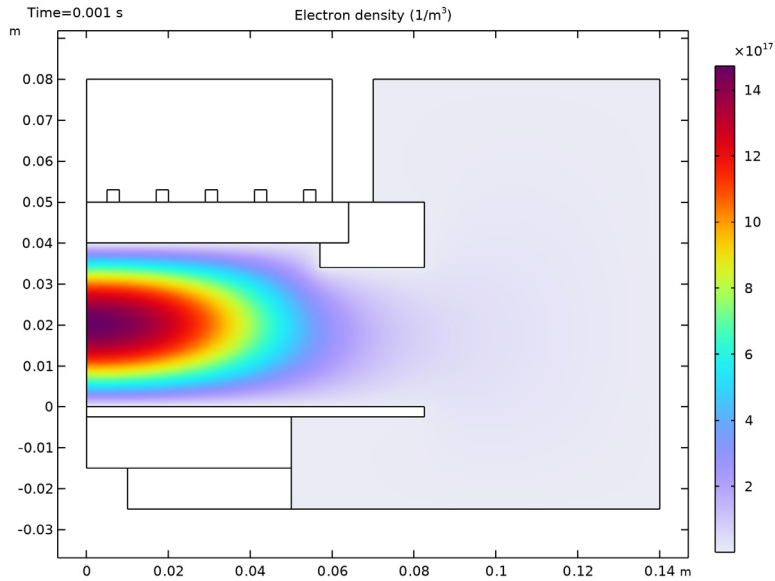
The model is now ready to be solved. You just need to enter the list of output times and the frequency for the induction currents.

- 1 In the Model Builder window, expand the Study 1 node, then click Step 1: Frequency-Transient .
- 2 In the Frequency-Transient settings window, locate the Study Settings section.
- 3 In the Times field, type 0 (the number zero followed by a space)
- 4 Click the Range button .
- 5 Go to the Range dialog.
- 6 From the Entry method list, choose Number of values.
- 7 In the Start field, type -8.
- 8 In the Stop field, type -3.
- 9 In the Number of values field, type 21.
- 10 From the Function to apply to all values list, choose $\exp 10$. The text field should now contain $0 \cdot 10^{\{\text{range}(-8, 5/20, -3)\}}$.
- 11 Click the Add button.
- 12 In the Frequency field, type 13.56E6.
- 13 In the Model Builder window, right-click Study 1 and choose Compute .

Results

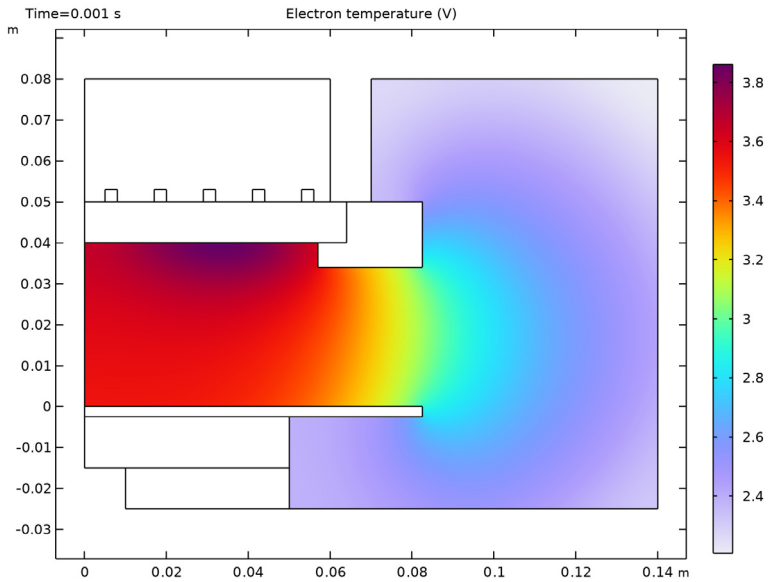
There are three default plots generated, one for the electron number density, one for the electron temperature and one for the electrostatic potential. After the model has solved, the default plot is of the electron density. The peak electron density occurs at the center of the reactor, underneath the RF coil. The electron


density in this case is high enough to cause some shielding of the azimuthal electric field.

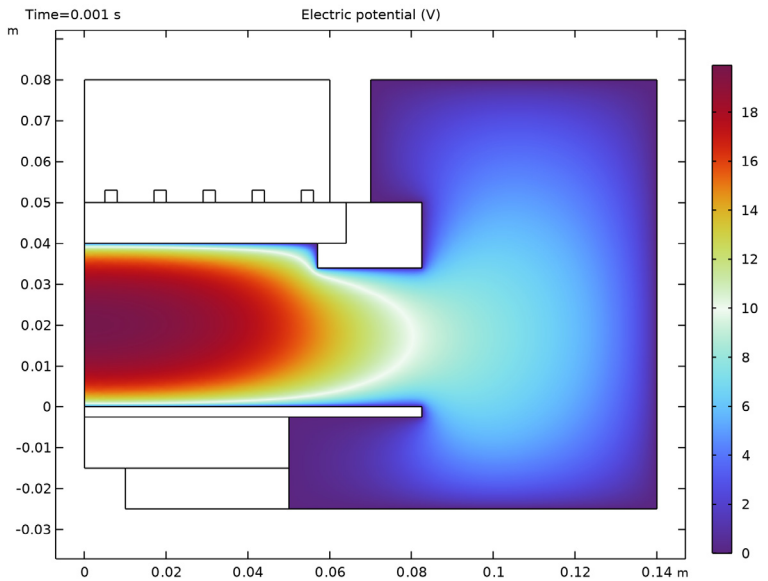


! To view the electron temperature, click on the Electron Temperature (plas) plot group .






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

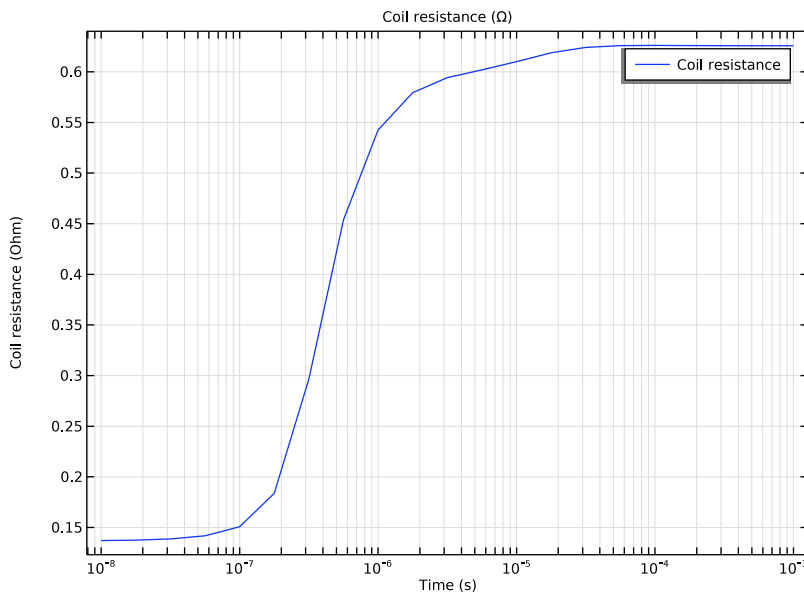


- 2 To view the electric potential, click on the Electric Potential (plas) plot group  .






Now add a global plot for the coil resistance. This is defined as the real part of the total voltage drop over the coil divided by the current.

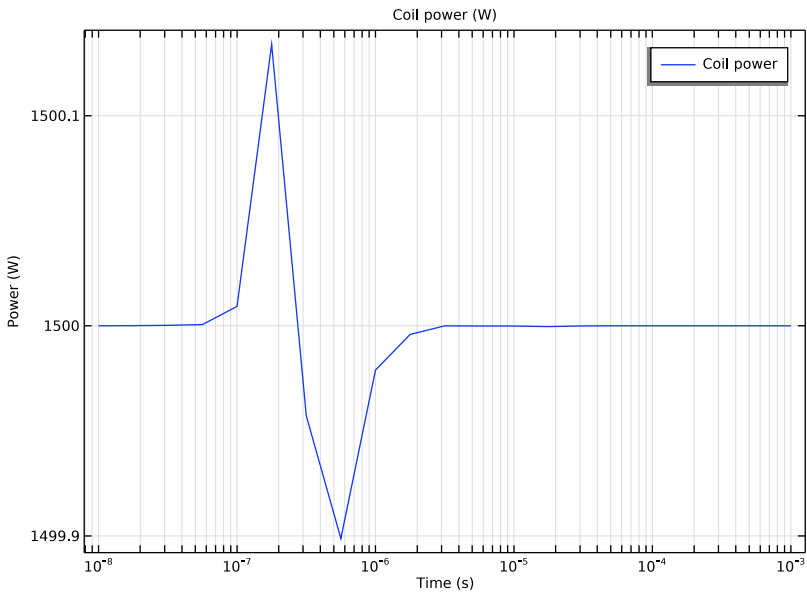
- 3 In the Model Builder window, right-click Results and choose 1D Plot Group .
- 4 Right-click Results > 1D Plot Group 6 and choose Global .
- 5 In the Global settings window, locate the y-Axis Data section. Click Replace Expression . Select Magnetic Fields > Coil Parameters > Coil Resistance (mf.RCoil_1) from the list.
- 6 Click the x-Axis Log Scale button  in the Graphics toolbar.
- 7 Click the Plot button .








Now add a plot for the total power dissipated in the system. This is one half of the real part of the total voltage drop over the coil multiplied by the applied current.

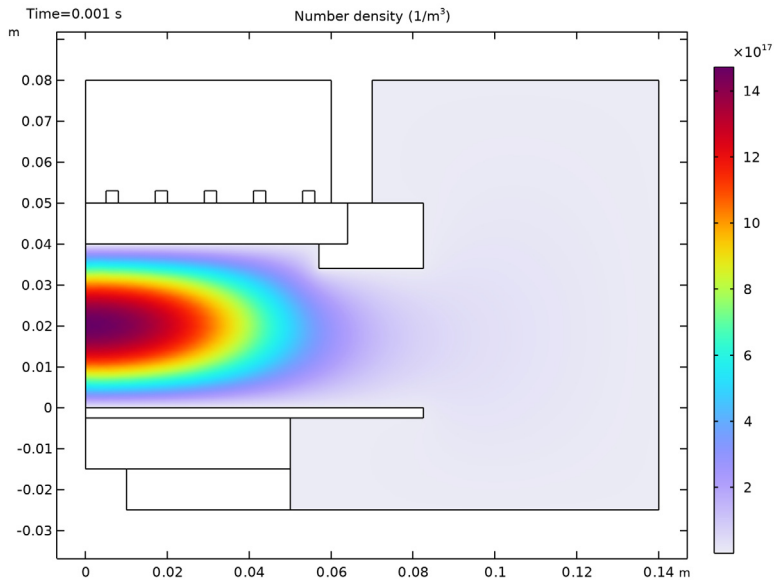
- 8 In the Model Builder window, right-click Results and choose 1D Plot Group .
- 9 Right-click Results > 1D Plot Group 5 and choose Global.
- 10 In the Global settings window, locate the y-Axis Data section. Click Replace Expression . Select Magnetic Fields > Coil Parameters > Coil Power (mf.PCoil_1) from the list.
- 11 Click the x-Axis Log Scale button  in the Graphics toolbar.

2 Click the Plot button .








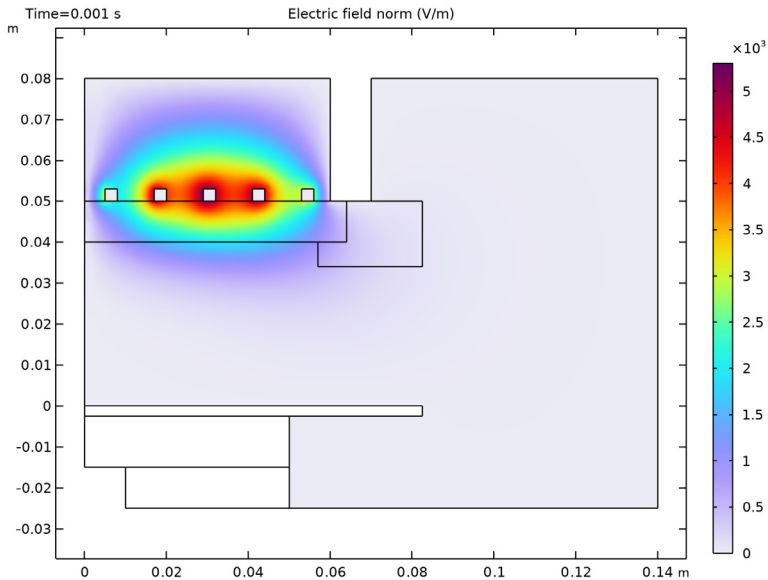
Now you add some additional two dimensional plots.

- 1 In the Model Builder window, right-click Results and choose 2D Plot Group .
- 2 Right-click 2D Plot Group 6 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 Plasma (Heavy Species Transport) > Number densities > Number density (plas.n_wAr_1p).
- 4 Click the Plot button .
- 5 Click the Zoom Extents  button in the Graphics toolbar.








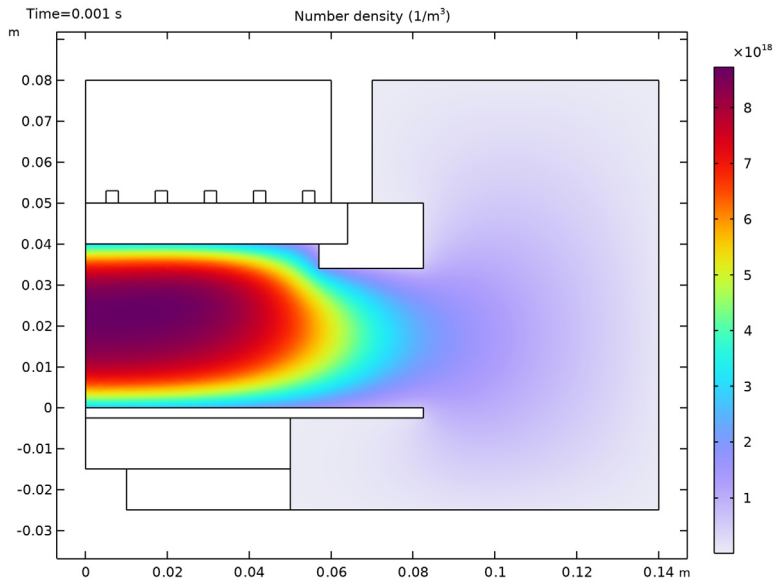
A quick way of creating additional plots is to use the Duplicate option. Now create a plot of the norm of the high frequency electric field.

- 6 In the Model Builder window, right-click 2D Plot Group 6 and choose Duplicate .
- 7 In the Model Builder window, expand the 2D Plot Group 7 node, then click Surface 1 .
- 8 In the Surface settings window, click Replace Expression  in the upper-right corner of the Expression section. From the menu, choose Magnetic Fields > Electric > Electric field norm (mf.normE).
- 9 Click the Plot button .
- 10 Click the Zoom Extents button  in the Graphics toolbar.








Observe that the electric field is slightly shielded by the plasma. This is due to the skin effect in the plasma. As the electron number density increases, the plasma tends to shield itself from the electric field. Now create a plot of the number density of electronically excited argon atoms.

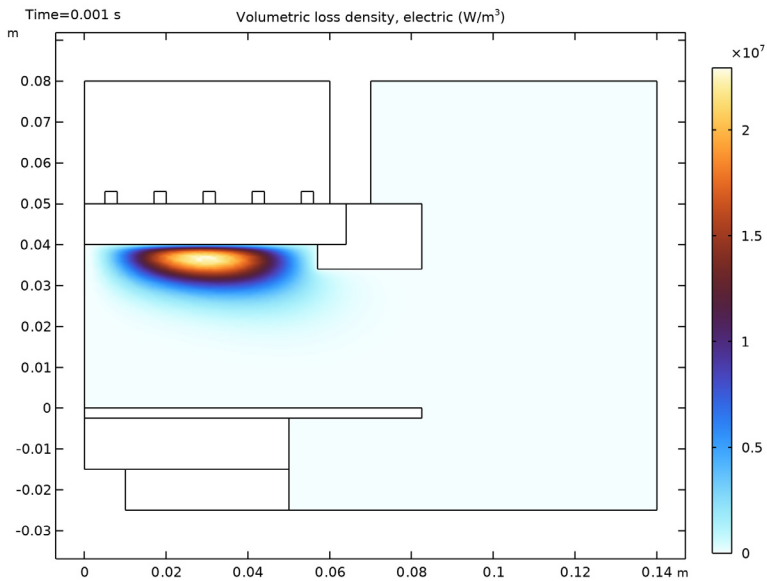
- 11 In the Model Builder window, right-click 2D Plot Group 7 and choose Duplicate .
- 12 In the Model Builder window, expand the 2D Plot Group 8 node, then click Surface 1 .
- 13 In the Surface settings window, click Replace Expression  in the upper-right corner of the Expression section. From the menu, choose Plasma (Heavy Species Transport) > Number densities > Number density (plas.n_wArs).
- 14 Click the Plot button .
- 15 Click the Zoom Extents button  in the Graphics toolbar.



Finally, create a new dataset only active on the plasma domain in order to make it easier to visualize the power deposition into the plasma.

- 1 In the Model Builder window, expand the Results > Datasets node.
- 2 Right-click Solution 1 and choose Duplicate .
- 3 Right-click Results > Datasets > Study 1/Solution 1 (2) and choose Selection.
- 4 In the Selection settings window, locate the Geometric Entity Selection section.
- 5 From the Geometric entity level list, choose Domain.
- 6 Select Domain 3 only.
- 7 Deactivate Propagate to lower dimensions.
- 8 In the Model Builder window, right-click Results and choose 2D Plot Group .
- 9 Right-click 2D Plot Group 9 and choose Surface .
- 10 In the Surface settings window, locate the Data section.
- 11 From the Dataset list, choose Study 1/Solution 1(2).
- 12 Click Replace Expression  in the upper-right corner of the Expression section. From the menu, choose Magnetic Fields > Heating and losses > Volumetric loss density (mf.Qrh).
- 13 Click the Plot button .

4 Click the Zoom Extents button  in the Graphics toolbar.



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

Bibliography

1. D.P. Lymberopoulos and D.J. Economou, "Two-Dimensional Self-Consistent Radio Frequency Plasma Simulations Relevant to the Gaseous Electronics Conference RF Reference Cell," *J. Res. Natl. Inst. Stand. Technol.*, vol. 100, pp. 473–494, 1995.

