Time-dependent study of Capacitively Coupled Plasma using fixed power condition

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Abstract: A power source is generally used in most plasma equipment for supplying constant power. When using a current source in time-dependent models of COMSOL Multiphysics, the value of applied current should be properly controlled with time in order to fix the power. Such logic for the variable current is realized by using State Variable feature in a time-dependent Capacitively Coupled Plasma model. This research shows how to fix the power in time-dependent models and the logic to control the source is expected to be also adopted in AC/DC module.

Keywords: Capacitively Coupled Plasma, CCP, RF, Power source

Introduction

A power supply is widely used in many electrical devices and most plasma equipment also uses a power source in order to supply uniform power independently of time and thus its application in plasma simulations is essential. When using a current source in time-dependent plasma models, the value of applied current has to be moderately adjusted with time in order to fix the power.

Since Plasma, Time Periodic (ptp) interface in Plasma module of COMSOL Multiphysics provides the power terminal type via Metal Contact node (and Terminal node), Capacitively Coupled Plasma (CCP) simulations applied the power condition can be achieved by using this interface up to 2 dimension. We, however, sometimes need to make 3-dimensional or time-dependent CCP models due to limitations in Plasma, Time Periodic interface such as multiple frequency, symmetry, reality and etc. In this case, Plasma (plas) interface should be used for CCP studies despite substantial solution times. Since this interface is generally used for the Time Dependent or Frequency-Transient study type, the power source feature on Metal contact node is not available, yet.

In this study, a time-dependent CCP model using a fixed power condition will be introduced. The model is made based on *GEC CCP Reactor, Argon Chemistry* tutorial model for comparisons between the time-dependent and time-periodic models [1]. In the model, Plasma interface is used for the time-dependent study instead of Plasma, Time Periodic interface. In order to obtain the results at the periodic steady state, 20,000 RF cycles are considered in this study. With a variable current source, the power is nearly fixed at 1 W during the computation and other results such as electron density, electron temperature, current and voltage and so on in the time-dependent model are consistent with those of the time-periodic model.

Assumptions for Simulation

In this study, several assumptions are needed to realize the fixed power condition in the time-dependent CCP model.

1. Due to a self DC bias, the current source is selected instead of the voltage source and the applied current is perfectly sinusoidal.
2. An initial current is given by a constant value of 0.12 A and it can be adjusted by some factors depending on power values calculated at the end of each period.
3. If the calculated power is lower than the set power, the current will be increased and if not, decreased.
4. 20,000 RF cycles for the periodic steady state
5. For stability on computations, the mesh is changed as shown in the bottom panel of Figure 1.
6. At each iteration, instantaneous power (in Watts) : $p(t) = v(t) \times i(t)$ [2]

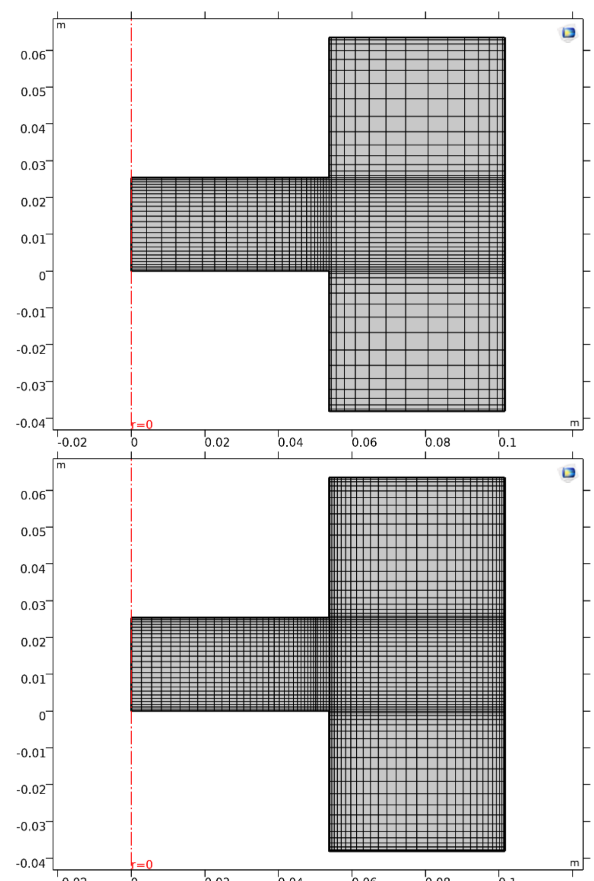

Figure 1. Mesh configurations for the time-periodic (Top panel) and time-dependent model (Bottom panel), respectively.

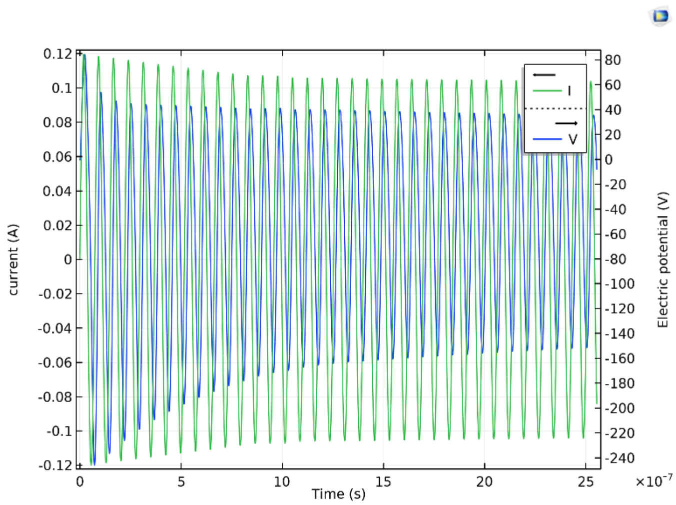

Figure 2. Time-dependent current and voltage profiles for the first few periods.

Simulation Methods

Plasma interface in Plasma module is used for the time-dependent CCP model in this study. To compare the results between the time-dependent and time-periodic models, argon chemistries as well as most parameters such as frequency, pressure and lengths of geometry and so on in *GEC CCP Reactor, Argon Chemistry* tutorial model are used without any changes [1].

In this time-dependent model, the current source on Metal Contact node is defined as :

$$I = I_0 \times \sin(2\pi ft), \quad (1)$$

where I_0 is the initial current, whereas the power source is set to a constant value in the tutorial model. At the end of each period, the current is changed by some adjusting factors with comparisons between the set and calculated power values. Four adjusting factors are adopted for delicate controls of the current.

In general, the average power can be computed by integrating the instantaneous power for one period and then dividing by the period, which is expressed as [2] :

$$P_{av} = \frac{1}{T}\int_{t_i}^{t_i+T} p(t)\,dt. \quad (2)$$

Due to the limitation for calculating the integration during the computation, the average power at the end of each period is obtained by the summation of the instantaneous power for each iteration within one period and counting the number of iterations in the period. It is thus necessary to apply logics for circular dependency of variables (e.g. a=a+1) in order to calculate the summation, which can be realized by using State Variable feature with *nojac* operator (See Appendix). And the maximum step in Time-Dependent Solver is limited by the value of 1/frequency/60 for more accuracy of the average power.

Since the results such as electron density, electron temperature, electric potential and so forth obtained using Time Periodic study show the averaged values for one period at the periodic steady state, the figures used in this paper are obtained using Time Periodic to Time Dependent study for more efficient comparisons between both models.

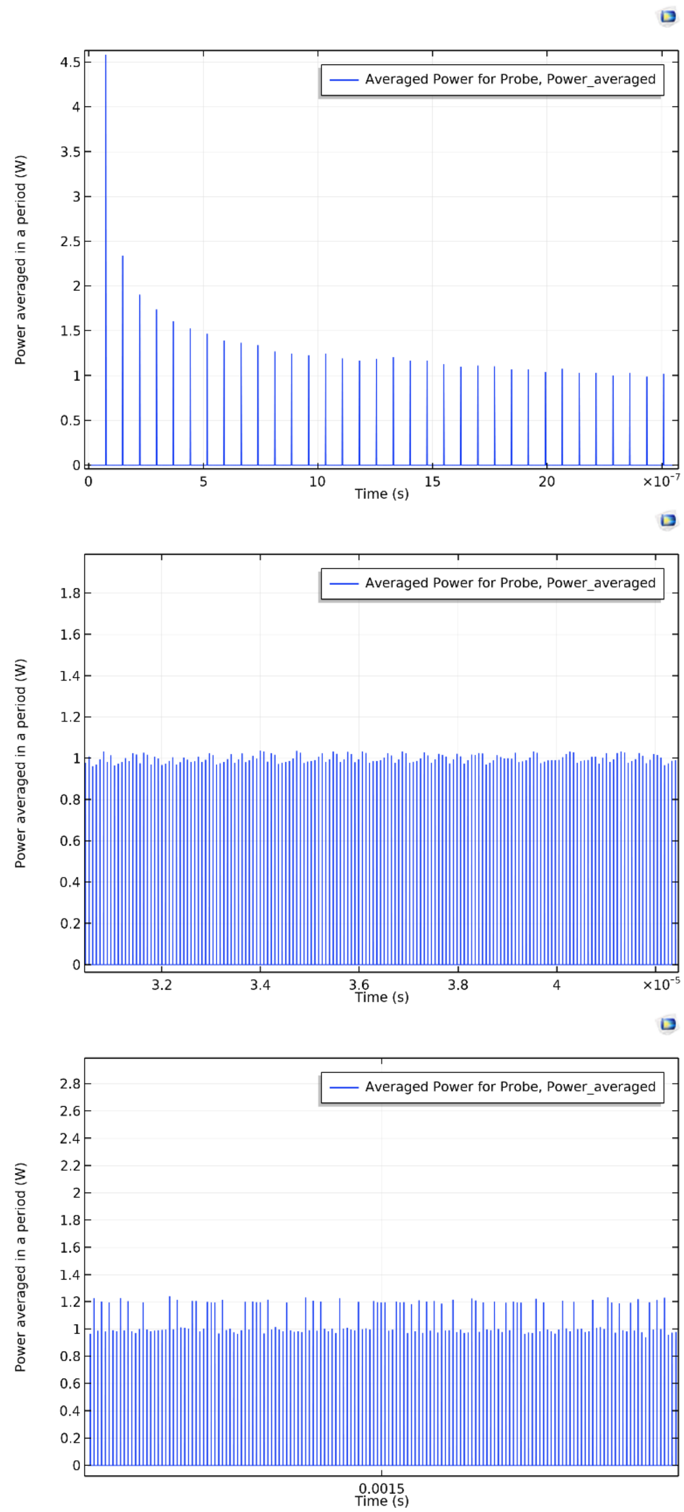

Figure 3. Time-dependent power averaged at the end of each period for the first few periods (Top), specific time periods (Middle) and the last few periods (Bottom), respectively.

Simulation Results and Discussion

With the initial current of 0.12 A in the time-dependent model, the initial power is calculated as 4.59 W at the end of the first period as shown in Figure 2 and the top panel of Figure 3. And then the current is adjusted to reduce the power. Such logic for the variable current is kept during the computation to maintain the set power of 1 W. The time dependences of the power

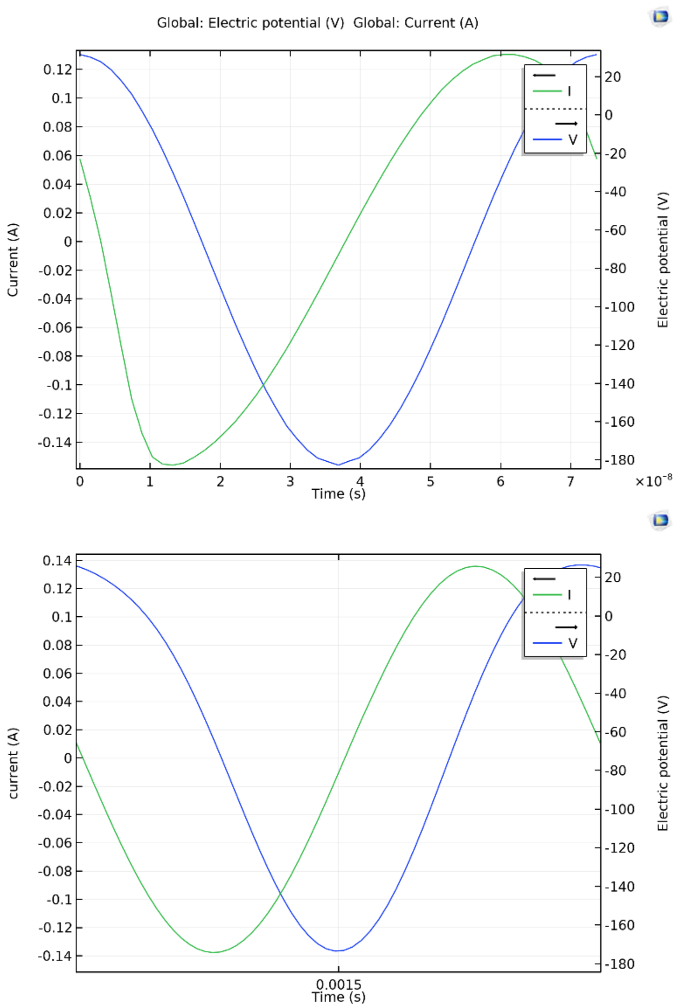

Figure 4. Current and electric potential profiles at the periodic steady state obtained using Time periodic to Time dependent study (Top) and Time dependent study (Bottom), respectively.

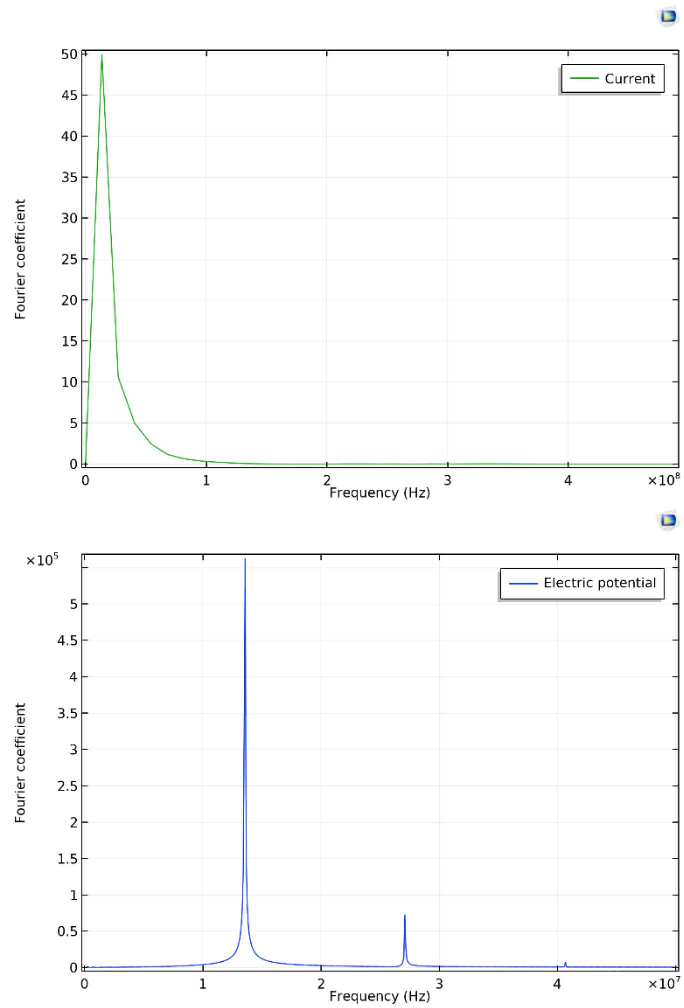

Figure 5. Fourier transform of the discharge current in the time-periodic model (Top) and that of voltage in the time-dependent model (Bottom), respectively. The second and third harmonics are observed in the electric potential.

averaged at the end of each period for the first few periods (Top panel), specific time periods (Middle) and the last few periods (Bottom) are plotted in Figure 3, respectively. Except for the bottom panel of Figure 3, the calculated power at each period is nearly fixed at 1 W. Near the periodic steady state, the power is often calculated as over 1.1 W due to applying the constant adjusting factor for the current as shown in the bottom panel of Figure 3. The adjusting factors, therefore, are needed to be controlled by elaborate logics.

To compare the results between the time-periodic and time-dependent models, the current and electric potential profiles for one period at the periodic steady state are plotted in Figure 4. Under the constant power condition in the time-periodic model, the current curve seems to contain harmonic contents while the voltage curve looks nearly sinusoidal as shown in the top panel of Figure 4. This can be confirmed by Fourier transform of the current which shows the peak broadening near 13.56 MHz due to the harmonic contents as shown in the top panel of Figure 5. For the time-dependent model, the current is perfectly sinusoidal because of using a sine function whereas the voltage curve has the second and third harmonics at 27.12 MHz and 40.68 MHz, respectively as plotted in the bottom of Figure 4 and 5. The self DC bias due to asymmetric discharges is observed in this model and thus the current source is selected instead of the voltage source for considering time-varying self DC bias [3-5]. This can make a difference between both models. Applying the current source, however, is the best way when considering the self DC bias in this study. Although the forms of the curve are somewhat different between both models, the amplitudes of the current and voltage in the time-dependent model are consistent with those of the time-periodic model. At the periodic steady state in the time-dependent model, the self DC bias and the amplitude of the voltage are found to be approximately -73 V and 100 V, respectively. These results are in good agreement with those of the time-periodic model.

Figure 6 and 7 show the electric potential and electron temperature distributions at a specific time of the periodic steady state, respectively. The time of the top panels is not real because the results are obtained using Time Periodic to Time Dependent study. Thus the difference of the time between the top and bottom panels is also not important. In spite of quite similar form in the electric potential distributions of both models, the maximum and minimum values of the electric potential are somewhat different, which is because the current is considered as the sine function in the time-dependent model as mentioned above. A little difference for the maximum value is also observed in both electron temperature plots in which it is hard to find differences for the form of the distributions. It is assumed that such difference comes from their mesh

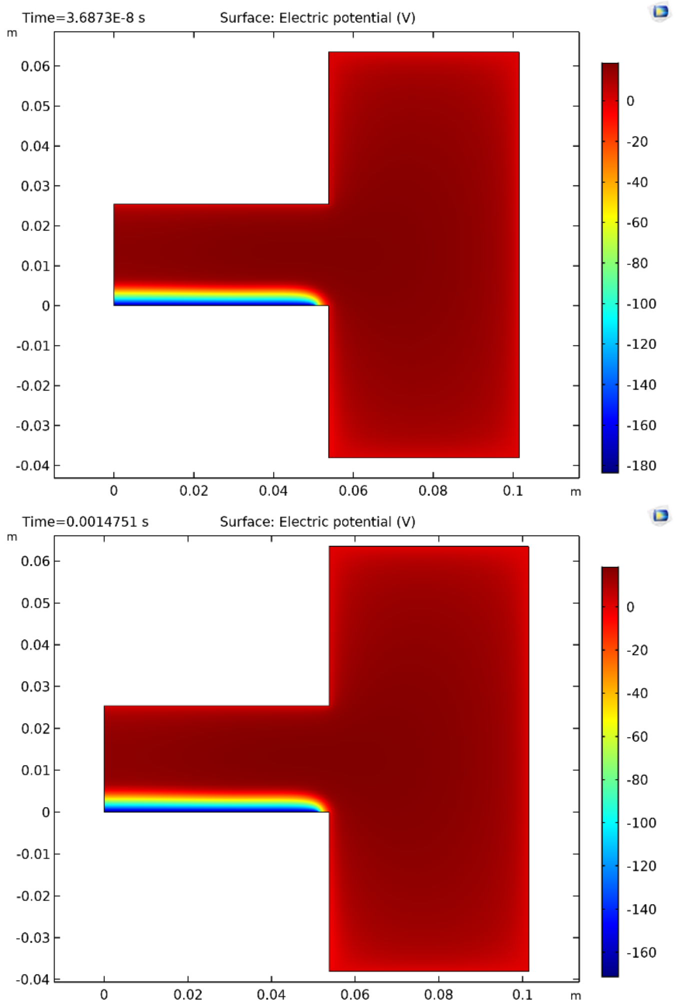

Figure 6. Electric potential distributions obtained using Time Periodic to Time Dependent study (Top) and Time Dependent study (Bottom), respectively.

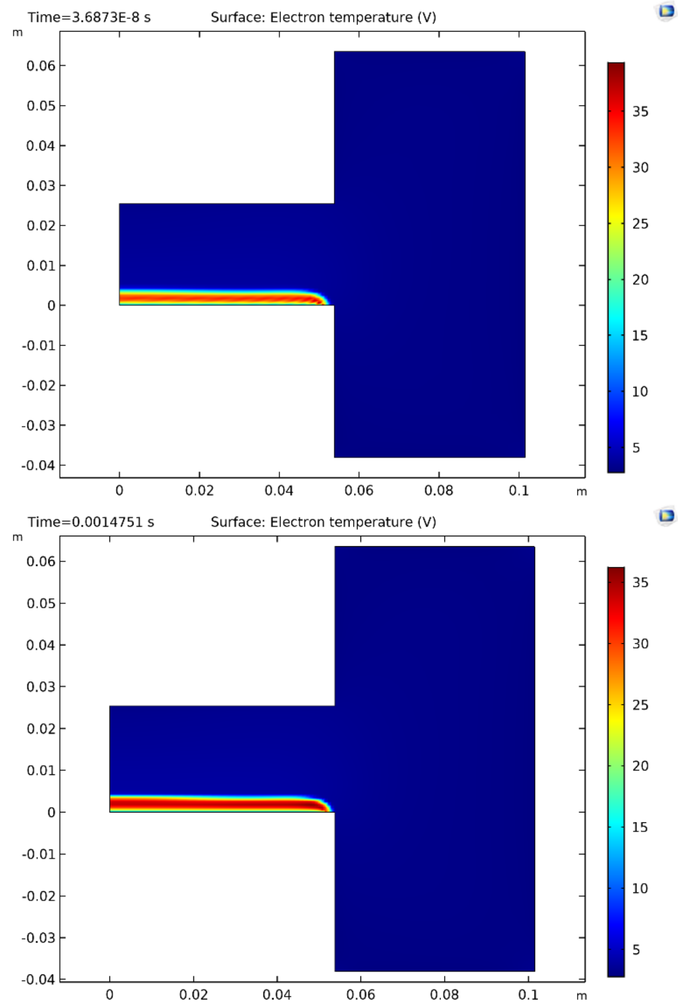

Figure 7. Electron temperature distributions obtained using Time Periodic to Time Dependent study (Top) and Time Dependent study (Bottom), respectively.

configurations because the maximum value of the electron temperature in the time-periodic model is only observed at very tiny regions while the values of the electron temperature in the sheath are nearly same for both studies. On the other hand, a possibility that it is originated from the differences in the current and voltage profiles cannot be also ignored.

Finally, the electron density distributions for both models are compared in Figure 8. Though they look similar to each other, the maximum value of the density in the time-dependent model (Bottom) is a little smaller than that in the time-periodic model (Top). It may also be caused by the differences in the current and voltage profiles as shown in Figure 4. Although there are some differences due to applying the sinusoidal current and several assumptions are essential in this study, these results show a probability of realization for fixing power in time-dependent models.

Conclusions

Based on *GEC CCP Reactor, Argon Chemistry* tutorial model, the time-dependent Capacitively Coupled Plasma simulation with the fixed power condition is successfully implemented by using Plasma interface. With the initial current value, the initial power is calculated and compared with the set power and then the current is adjusted in order to fix the power. Under the assumption of the sinusoidal current source, the amplitudes of the current and voltage are in good agreement with those of the time-periodic model, though the harmonics of the voltage are observed in the time-dependent model whereas the harmonic contents are contained only in the current curve for the time-periodic model. All the other results in the time-dependent model are also consistent with those in the time-periodic model. These results indicate that the fixed power condition may be realized in time-dependent models and such logics to control the quantity of the current or voltage for fixing the power can also be applied in AC/DC module.

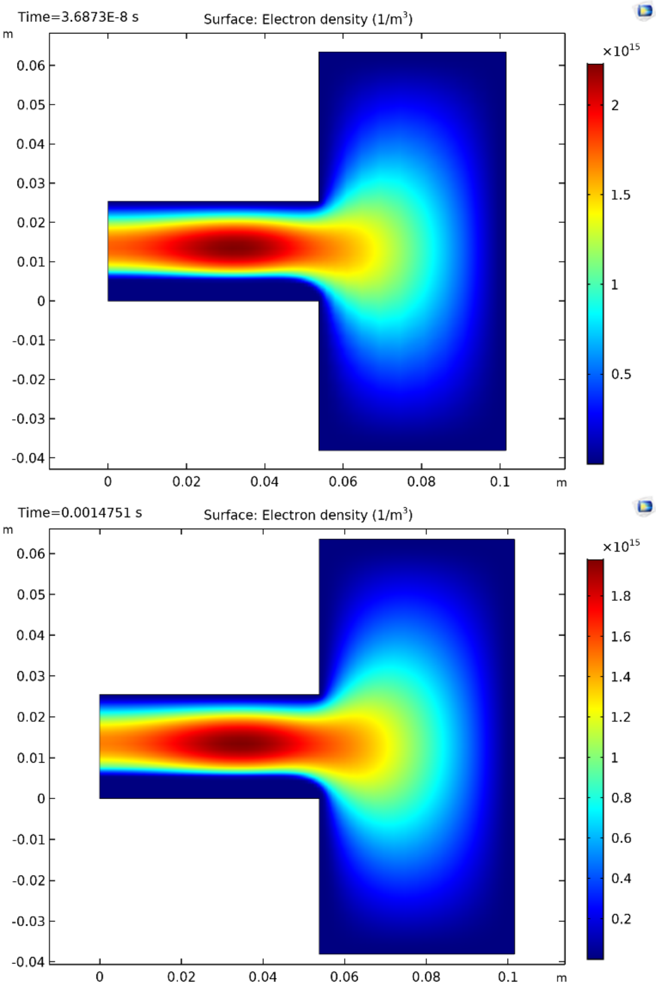

Figure 8. Electron density distributions obtained using Time Periodic to Time Dependent study (Top) and Time Dependent study (Bottom), respectively.

References

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Appendix

The parameters, variables and state variables used in this study are summarized in the tables below.

Table 1: Parameters used in this study

Name	Expression	Description
L	2.54[cm]	Discharge gap
R1	5.38[cm]	Inner radius
R2	10.16[cm]	Outer radius
Hd	10.16[cm]	Chamber height
dThick	3[mm]	Dielectric thickness
f0	13.56[MHz]	Frequency
Power	1	Set Power (W)
init_I	0.12	Initial current (A)
down_factor_min	0.999	Low reduction rate of Current
down_factor_max	0.99	High reduction rate of Current
up_factor_min	1.001	Low increasing rate of Current
up_factor_max	1.01	High increasing rate of Current
upper_limit	1.15	Apply down_facor_max
lower_limit	0.85	Apply up_facor_max

Table 2: Variables used in this study

Name	Expression	Description
t1	(n+1)*(1/f0)	End time of the Period
pow1	comp1.plas.I0_1*comp1.plas.mct1.V0e_1	Power=Voltage *Current

Table 3: State Variables used in this study

State	Initial value	Update expression	Description
I0	init_I	if(t1<t ,if(pow_avg>Power,down_I,up_I),nojac(I0))	Current
TimeInt	eps	if(t1<t ,eps,nojac(TimeInt)+pow1)	Summation of Power for one period
nT	0	if(t1<t ,0,round(nojac(nT)+1.0))	The number of iterations within one period
pow_avg	0	abs(TimeInt/nT)	Average Power for one period
n	0	if(t1<t,round(nojac(n)+1.0),round(nojac(n)))	Number of Periods
pow_avg1	0	if(t1<t, pow_avg,0)	Average Power for Probe
down_I	0	I0*down_factor	Decreased current
up_I	0	I0*up_factor	Increased current
down_factor	1.0	if(pow_avg/Power>upper_limit,down_factor_max,if(1.0<pow_avg/Power<=upper_limit, down_factor_min,up_factor))	Down Factor
up_factor	1.0	if(pow_avg/Power<lower_limit,up_factor_min,if(lower_limit<=pow_avg/Power<=1.0, up_factor_min,down_factor))	Up Factor