# COMSOL Simulation Study of Microwave Plasma in Cavity Resonator as a Transmitter-receiver Switch

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**Research Article**

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# COMSOL simulation study of microwave plasma in cavity resonator as a transmitter-receiver switch

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**Abstract**:

Microwave discharge characteristics and variable plasma conductivity play an important role in design of microwave filters and the efficiency of radars and electronic warfare devices. A three dimension model was designed to study the effect of plasma formation on high power microwave (HPM) transmittance in cavity resonator based on COMSOL platform. The effect of gap length, electrode shape and size, coaxial port dimensions and gas pressure, on the electric field in the gap and insertion loss in cavity were investigated. The effect of the cross-section of coaxial port on the electric field created in the gap was investigated and the best values were calculated and determined. The electron density profile, electron temperature, electric conductivity, elastic and inelastic collision frequency were calculated. The performance of plasma limiter was optimized. Results were compared with the experimental data.

Keywords: Cavity resonator, COMSOL, simulation, Microwave discharge, Optimization

## 1. Introduction

With the development of new horizons in science such as: space technology , radars and other microwave systems, transmitter-receiver devices have been a very interesting topic for scientists in applied physics[1] .Most of these equipment work with high power microwave (HPM). Sensitive microwave receiver systems are under the threat of high power microwave (HPM) [2]. To protect sensitive and vulnerable equipment from HPM, protective devices need to be used [3]. In order to protect electronic components and systems from HPM, a gas-discharge tube (GDT) is used [4] [5] [6]. Devices with GDT perform better than other protective devices. These advantages are the ability to conduct high currents, low intrinsic capacity, high insulating resistance and the high range of voltage protection [7] [8].

A type of plasma limiter systems that protects from radars sensitive receivers are Transmitter receiver switches (TR switches) [9]. In this type of limiters, plasma played an important role to produce a suitable condition to transmit, absorb or reflect the input microwave signal. Two modes occur when the microwave signal reach the limiter: normal and cut-off operation modes [10].

In normal operation mode, (OFF regime) the electric field amplitude caused by input microwave signal in GDT is less than the gas breakdown threshold electric field. In this mode, the breakdown doesn't occur and the considerable of input power can pass through the device with least loss [11].

In cut-off operation mode (ON regime) when a microwave signal enters the limiter, it causes the increase of electric field in GDT and when the electric field amplitude reaches the breakdown threshold, breakdown occurs [12]. According to the plasma physics, when the plasma density increases to such a level that the corresponding plasma frequency becomes comparable to the frequency of the incident field, the electrons in the plasma bulk can oscillate fast enough, and the resulting secondary fields radiated from the electron oscillation cancel the incident fields. Macroscopically, the plasma bulk is acting like a piece of electromagnetic (EM) shield that prevents the EM waves from propagating through. This leads to the decrease of the total electric field intensity in the plasma bulk, commonly known as the tail erosion, which will result in a lower ionization rate. Since plasma has electrical conductivity due to the high electron density in GDT ($n_e$), the insertion loss increases.

By increasing input microwave power ($P_{in}$) results in higher $n_e$ and thus larger conductivity and higher insertion loss, and output microwave power ( $P_{out}$) always remains in a safe regime even though $P_{in}$ increases up to 100 W so the device acts as a band pass filter [13]. Many numerical and experimental studies have done on transmitter-receiver devices and plasma limiters have calculated the reflection, absorption and transmission coefficients of microwave using different methods [14] [15].

Osamu Sakai has used finite difference method with complex-amplitude fields to study the distinctive wave propagation in periodic plasma structure [15]. There has been a lot of work in this area, but rarely were the parameters involved in the formation of plasma such as frequency of incident wave and gas pressure to optimize the device discussed. Therefore, these physical characteristics were further studied in this paper. The purpose of this article is to study the variation in distribution of electron density, electric potential, and electron temperature in relation to the shape of the electrodes, the port dimensions, by using COMSOL Multi physics. By controlling parameters such as power and pressure, the spatial distribution of plasma density and electron temperature was investigated in the argon discharge.

The gas breakdown time in the proposed plasma limiter is a time when in the field amplitude suddenly changes at the center of GDT. In general, the response time is defined by the time from when HPM enters the limiter until the limiter is activated and the microwave amplitude drop. This is a very important parameter and the response time should be as short as possible [15].

This numerical results are important to determine the optimum conditions for the best performance of the device in cutting off the HPM.

The proposed model are first described in Section II. Then, governing equations are exposed in Section III. Finally, results are discussed in Section IV followed by conclusions in Section V.

## 2. Description model

Interaction between electromagnetic waves and plasma is described by the coupling system EM-plasma. The physics of electromagnetic is obtained by Maxwell equations while the physics of plasma described by diffusion equations with the momentum transform equation.

In solving the EM-plasma coupled nonlinear systems must be specified the time step and the space meshing of the problem. For the space domain, the characteristics length of the EM wave and plasma are the wavelength and the Debye length, respectively. For the time domain, the characteristics time of the EM wave is the period. The diffusion and ionization mechanisms specify the characteristics time of the plasma. As a result, the time and space domains of the coupled problem were defined on the order of the characteristics time of the Electromagnetic waves (EM waves) and the characteristics length of the plasma, respectively. [16]

Figure1.a shows the schematic of designed plasma limiter in which a cavity resonator was loaded by an axial GDT. The cavity radius is 14mm and cavity height 22mm .The quartz tube, by outer diameter 5 mm and inner diameter of 4.5 mm. The argon under variable pressure [0.1-3] torr in room-temperature enters the GDT from the bottom. All dimensions are shown in Table I. As shown in figure1.a the GDT is a parallel-plate structure with quartz wall and copper electrodes that can be filled with a halogen gas such as argon, neon and helium at a controlled pressure.

In the designed plasma limiter the actual gap size over the post is 0.6 mm that can be easily changed its size.

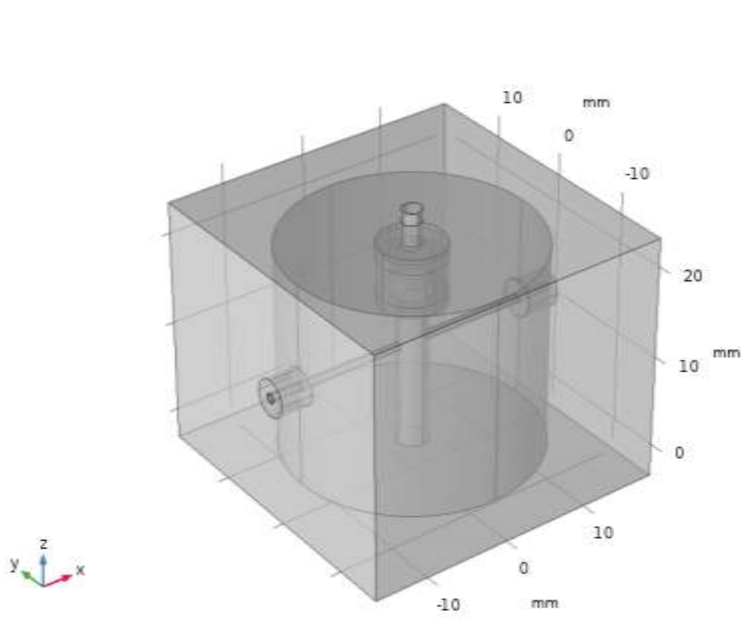
Electromagnetic waves (frequency: 2.2 GHz, peak power 1-100 W) in Transverse Electro-Magnetic (TEM) mode pass through the coaxial port.

TABLE I

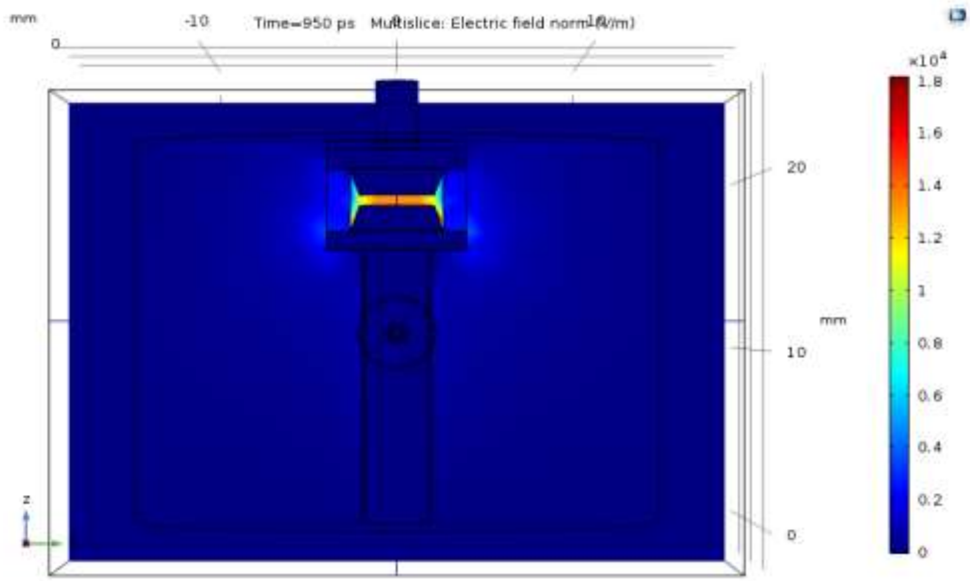
Dimensions of cavity resonator [mm]

| Cavity radius | Cavity height | GDT radius | Gap length |
|---|---|---|---|
| 14 | 22 | 4.5 | 0.6 |

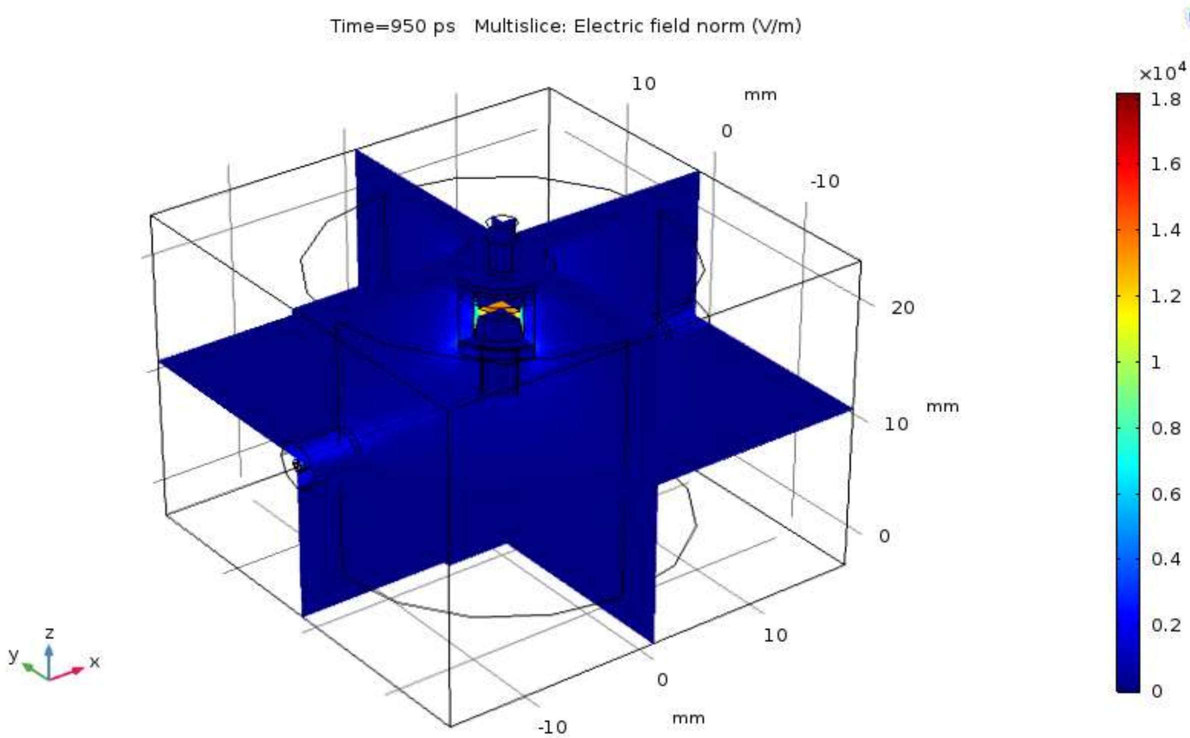
To gain higher electrical field intensity at the discharge position (gap area), the GDT location is also optimized. Here we are interested on the interaction of the electromagnetic wave with the argon gas inside the GDT.




(a)




(b)




(c)

Fig. 1. 3D Schematic of the designed cavity resonator (a). Vertical view of cavity with the input coaxial port and GDT (b) Overview of cavity with its ports and GDT distributions of electric fields display in off mode(c).

## 3. Governing equation

The integration of two module in COMSOL Multi physics (microwave plasma and electromagnetic wave module) were used in order to investigate the effect of microwave discharge phenomena on filtering behavior on device. To investigate the factors affecting on the magnitude of the electric field created in the gap, the shape and size of the electrodes and their material were examined. Also the effect of the cross section of the input coaxial port on the magnitude of the electric field created in the gap and insertion loss was calculated in each case. Plasma properties such as the distribution of electron density, electric potential, and electron temperature inside the GDT also were computed in each cases.

The governing equations are used to model the microwave plasma physics inside the GDT by numerical analysis, and the meshing sequence of finite element analysis is utilized to converge the solutions.

To better understand the limiting effect, consider interaction of electromagnetic (EM) waves with a plasma layer. This interplay primarily depends on the plasma frequency, $\omega_p$ [16].

$$\omega_p{}^2 = \frac{n_e e^2}{\varepsilon_0 m} \qquad (1)$$

Where $e$ and $m$ represent electron's charge and mass, respectively, and $\varepsilon_0$ denotes the free space permittivity and $n_e$ is electron density.

If $\omega_p$ becomes comparable to the operating frequency ($\omega$) (by increasing $n_e$), EM waves get attenuated and reflected by the plasma layer. Larger input power results in additional ionization, thus higher $n_e$ and electrical conductivity ($\sigma$), and consequently higher loss, which manifests itself in the power limiting behavior. [16]

### 3.1. Plasma equations

When micro wave discharge happens, the free electrons in GDT will increase and it causes creation of the plasma current density .The current density is calculated as:

$$J = -neU \qquad (2)$$

That J is plasma current density and U is the particle flow velocity. This quantity (J) has a special significance that pairs wave equations with plasma fluid equations. Interaction between electromagnetic waves and plasma is described by the coupling system EM- plasma. The physics of electromagnetic describe by Maxwell equations while the physics of plasma described by a diffusion equation with the momentum transform equation. In the fluid equations, must be taken into account electron-neutral collision and ionization, diffusion and recombination mechanisms. These equations form a set of self-consistent equations that can simulate and describe the microwave breakdown.

The electron density and mean electron energy are calculated by solving drift-diffusion equations. The plasma model defined as follows [17]:

The continuity equations for the particle densities (electrons, ions, and neutrals):

$$\frac{\partial n_j}{\partial t} + \nabla.\Gamma_j + -(U.\nabla)n_j = R_j \qquad (3)$$

Where $n_j$the density of j-th species $\Gamma_j$ is the flux, and U is the particle flow velocity (considered same for all species) and $R_j$ is the source term.

$$\Gamma_j = -\mu_j \mathbf{E} n_j - D_j . \nabla j \qquad (4)$$

Where $\mu_j$ is the mobility and $D_j$ is the diffusivity coefficient. The electron energy density $n_\varepsilon$ , is computed by:

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla . \Gamma_\varepsilon + E . \Gamma_e = R_\varepsilon \qquad (5)$$

$$\Gamma_\varepsilon = -(\mu_\varepsilon . E) n_\varepsilon - D_\varepsilon . \nabla n_\varepsilon \qquad (6)$$

Where the $R_\varepsilon$ is the electron energy loss due to inelastic collisions. $D_\varepsilon$ and $\mu_e$ are the energy diffusion coefficient and the electron mobility respectively, $D_\varepsilon$ and $\mu_\varepsilon$ are the energy diffusivity coefficient and the energy mobility.

In COMSOL Multi physics platform, the source coefficients in the above equations are determined by the plasma chemistry using rate coefficients. The electron diffusivity, energy mobility and energy diffusivity are computed by the electron mobility using:

$$D_e = \mu_e T_e D_\varepsilon = \mu_\varepsilon T_e \qquad (7)$$

$$\mu_\varepsilon = (\frac{5}{3}) \mu_e \qquad (8)$$

The mean electron velocity on the microwave time scale, U is obtained by assuming a Maxwellian distribution function and taking a first moment of the Boltzmann equation:

$$\frac{\partial U}{\partial t} = -\frac{e}{m_e} \tilde{E} - v_m U \qquad (9)$$

Where $m_e$the electron is mass in Kg and $v_m$ is the momentum transfer frequency between the electrons and background gas in 1/s. In addition to the equation above, a set of equations are solved in the time domain for the electron density $n_e$ , electron energy density $n_\varepsilon$ , plasma potential V, and all ionic and neutral species.

3.2. **The boundary conditions**

The boundary conditions for the electron and ion fluxes are [21]:

$$n . J_e = \frac{1}{2} V_{th} n_e \qquad (10)$$

$$n . J_i = V_{Bohm} n_i \qquad (11)$$

Where $V_{th}$ is the electron thermal velocity and $V_{Bohm} = \sqrt{e T_e / M_i}$ is the Bohm velocity of ions.

3.3. **Plasma chemistry**

The chemical mechanism for the plasma consists of only 3 species and 7 reactions:

TABLE II

Table of modeled collisions and reactions

| # | Reaction | Process | Energy threshold, process rate(eV) |
|---|---|---|---|
| $R1$ | $Ar + e \rightarrow Ar + e$ | Elastic scattering | …. |
| $R2$ | $Ar^{*} + e \rightarrow Ar + e$ | Excitation | 11.56 |
| $R3$ | $Ar + e \rightarrow Ar^{+} + e$ | Ionization | 15.8 |
| $R4$ | $Ar^{*} + e \rightarrow Ar^{+} + e$ | Step ionization | 4.14 |
| $R5$ | $Ar^{*} + Ar^{*} \rightarrow Ar^{+} + e + Ar$ | Chemical ionization | $6.2 * 10^{-10}$ |
| $R6$ | $Ar^{+} + wall \rightarrow Ar$ | Loss on the wall | $\gamma$=1 |
| $R7$ | $Ar^{*} + wall \rightarrow Ar + e$ | Loss on the wall | $\gamma = 0.8$ |

In addition to volumetric reactions, the following surface reactions are implemented:

TABLE III

Table of surface reactions

| Reaction | Formula | Sticking coefficient | Secondary emission coefficient | Mean energy of secondary electrons(ev) |
|---|---|---|---|---|
| 1 | Ars=>Ar | 1 | 0 | 0 |
| 2 | Ar+=>Ar | 0 | 0.1 | 5.8 |
| 3 | Ar2+=>2Ar | 0 | 0.1 | 5.8 |

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

3.4. **Electromagnetic wave equations**

The electromagnetic waves are computed in the frequency domain for off regime and for calculating the time evolution of plasma variables we use the Frequency- Transient module in COMSOL multi physic software.

The distributions of the electromagnetic fields are described by Maxwell's equations, which are solved in the three-dimensional axisymmetric geometry. In this case, Maxwell's equations can be reduced to the following equations:

$$\nabla \times \tilde{E} = -\frac{\partial \tilde{B}}{\partial t} \quad (12)$$

$$\nabla \times \widetilde{H} = \mathrm{J} + \frac{\partial \widetilde{D}}{\partial t} \quad (13)$$

Where $\tilde{E}$ is the electric field V/m, $\tilde{B}$ is the magnetic flux density T, $\widetilde{H}$ is the magnetic field A/m, J is the electron flux Solving the above equations with appropriate boundary conditions allows for the power transferred from the electromagnetic fields to the electrons to be calculated:

$$Q_{rh} = \frac{1}{2} Re(\bar{J}.\bar{E}^{*}) \quad (14)$$

Where $\bar{J}$ is the total current density (the plasma current plus the displacement current density) and * denotes the complex density A/$m^2$, and $\widetilde{D}$ is the electrical displacement C/$m^2$.

Equations (10) and (11) can be re-arranged by taking the time derivative of (11) and substituting in (10):

$$\nabla \times \mu^{-1} \nabla \times \bar{E} = (\omega^2 \varepsilon_0 \varepsilon_r - j\omega\boldsymbol{\sigma})\bar{E} \quad (15)$$

Where $m_e$ the electron is mass Kg and $v_m$ is the momentum transfer frequency between the electrons and background gas 1/s. So by taking a Fourier transform and arranging for conductivity we have:

$$\boldsymbol{\sigma} = \frac{n_e e^2}{m_e(v_{m,e} + j\omega_{RF})} \quad (16)$$

$$\varepsilon_{rp} = 1 - \frac{n_e e^2}{\varepsilon_0 m_e (v_{m,e} + j\omega_{RF})} \quad (17)$$

Where $\mu$ is the permeability, $\boldsymbol{\sigma}$ is plasma conductivity $\varepsilon_{rp}$ is relative permittivity of plasma.

External metal walls of the cavity are assumed to be grounded.

## 4. Results

The model was tested against the available theoretical and experimental data on discharges in argon for different input power and geometries and material of the electrodes.
The filter behavior of switch was tested under the following conditions: the electron density was $n_e = 6.5 * 10^{16} \frac{1}{cm^3}$, the frequency was 2.45 GHz, the gas pressure was 0.1 torr up to 3Torr, the power applied to the device was 1-100 W, and the gas temperature was 300 K. The cylindrical discharge chamber (GDT with 1mm thick quartz glass) was 4.5 mm in radius and 5 mm in height. The gap length at first was 0.6mm. The simulation results are in good agreement with the results of experiments [43] performed in the same geometry, as well as with the simulation results [24].

### 4.1 Off Regime

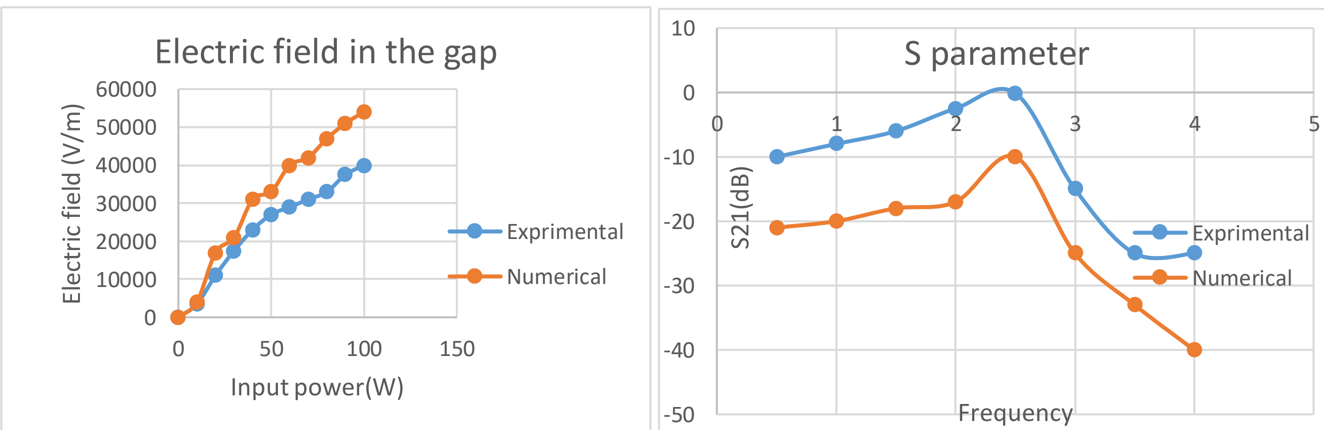
As stated in the introduction in normal operation mode, (Off regime) if the electric field amplitude in GDT be less than the gas breakdown threshold electric field, then the breakdown not occurs and the considerable of input power can pass through the device with least loss [11].

Fig. 2 shows the simulated (COMSOL Multi physics software) transmission coefficient $S_{21}$ of the designed limiter in its Off-state. In this proof-of-principle demonstration, the resonant frequency ($f_r$) is equal to 2.5 GHz with 10-dB loss.

The E-field distribution over the post area [Fig. 2(b)] is quite uniform except at the edges of the electrodes as expected. The E-field magnitude of the gap has been found to be $5 * 10^3$ (V/m) for a 1-W input power. This value increases to $1.2 * 10^4$ and $4 * 10^4$ (V/m) for 10- and 100-W input power, respectively. Fig. 2. (b)

4.1.1 **Input power**

Now, we examine the effects of the parameters involved in this part. First, we examine the effect of input microwave power. For investigation and optimization of the electrode dimensions in the proposed TR switch, two basic parameters must be considered. These parameters are insertion loss and the electric field at the center of gap. The electric field is very important in reaching the gas breakdown threshold and consequently the breakdown time and response time of the TR switch. These quantities are the most important parameters that optimize the TR switch dimensions.




(a) (b)

Fig. 2. (a) Electric field magnitude in the gap as a function of input power (b) Simulated S21 in the non-limiting (GDT off) regime representing 10-dB loss at the resonant frequency of 2.5 GHz. Comparing with the experimental results tested in [1].

The modeling results show that with increasing microwave power input, the Electric field magnitude in the gap increases significantly. To determination the resonance frequency of cavity, the S parameter chart was calculated and drawn. And the resonance frequency of cavity amounts 2.52 GHz obtained.

4.1.2 **Electrode shape and dimensions**

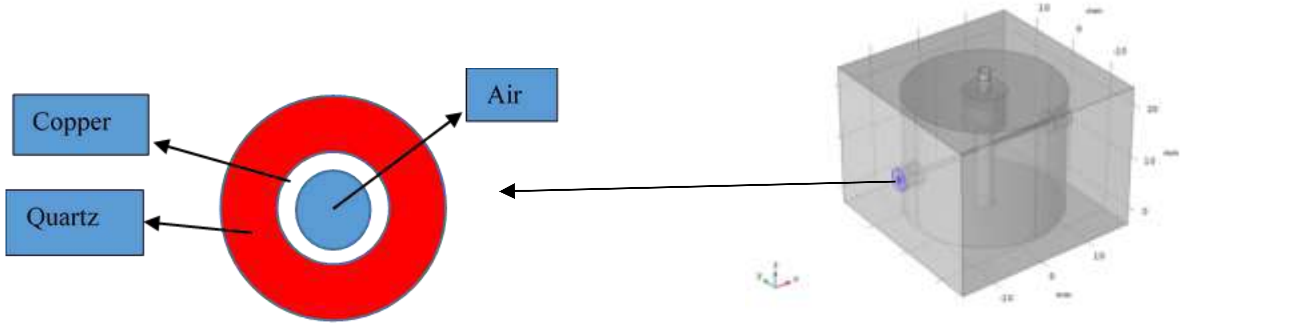
The geometric shape and dimensions of the electrodes have a great impact on the convergence of the electric field in the gap area. The electric field is very important in reaching the gas breakdown threshold and consequently the breakdown time and response time of the TR switch. These quantities are the most important parameters that optimize the TR switch dimensions. The simulations carried out for a pair of electrodes with 1.5, 2 and 2.5 mm radius and gap length 0.2, 0.4, 0.6, 0.8 mm with cone and cylindrical shape end. In this section, the plasma limiter is filled with the Argon at 0.1torr.

TABLE IV.

Electric field norm and Insertion Loss of plasma limiter for different dimension of the Electrode and Gap Length in normal operation

| Top Radius of Electrode (mm) | | 1.5 | 2 | 2.5 | |
|---|---|---|---|---|---|
| Gap Length(mm) | 0.2 | $4.5*10^{2}$ | $1.372*10^{3}$ | $2.13*10^{-5}$ | |
| | | -15.5 | -11.235 | -10.87 | |
| | 0.4 | $8.8*10^{2}$ | $8.85*10^{2}$ | $1.255*10^{-5}$ | $E_{max}$ (V/m) |
| | | -10.8 | -15.4 | -16 | |
| | 0.6 | $6.02*10^{3}$ | $1.186*10^{2}$ | $1.4*10^{3}$ | Insertion Loss(dB) |
| | | -12.9 | -17 | -10.9 | |
| | 0.8 | $4.45*10^{2}$ | $8.5*10^{2}$ | $9.1*10^{-6}$ | |
| | | -14.6 | -12 | -14.1 | |

We defined a domain probe to acquire maximum electric field in the gap area ($E_{max}$) and insertion loss in each situations. Results have shown that when gap length is 0.6 mm and cone shape electrodes with bottom radius 2.5 mm and top radius 1.5, the $E_{max}$ is $6.02*10^{3}$ V/m.




(a) (b)

Figure .3 (a) Schematic of port cross section that the white ring is copper and inner cycle is air and external ring is quartz (b) Coaxial port in cavity

We find that when the cross section of copper ring (by fixing the inner radius and growth the outer one) increases, then $E_{max}$ in the gap decreases but insertion loss increases. See Table V.

TABLE V.

Electric field norm and Insertion Loss of cavity by fixing the inner radius of copper ring and growth the outer one

| Cross section(mm) | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|
| $E_{max}$(V/m) | $1.452*10^3$ | $1.140*10^3$ | $8.870*10^2$ | $7.1*10^2$ |
| Insertion loss(dB) | -2.77 | -3 | -3.89 | -4.7 |

If we increase the cross section of copper ring (by scale down the inner radius and fixing the outer one) then $E_{max}$ in the gap decreases but insertion loss increases.

TABLE VI.

Electric field norm and Insertion Loss of cavity by scale down the inner radius and fixing the outer one

| Cross section(mm) | 0.1 | 0.2 | 0.3 |
|---|---|---|---|
| $E_{max}$(V/m) | $9.55*10^2$ | $7.91*10^2$ | $5.91*10^2$ |
| Insertion loss (dB) | -14.6 | -13.6 | -13.9 |

### 4.1.4 **Material effect**

To investigate the effect of the type of metal used in the metal part of the device on energy dissipation, we tested four different types of metal under particular configurations at low pressure. Four materials (copper, aluminum, steel and titanium) were tested. Maximum electric field in GDT and insertion loss in device were also calculated under specific conditions-equal gap length, equal electrode in shape and size, and results were recorded in table VII which display that maximum electric field in the GDT with titanium are largest in comparison with the other types of material. The insertion losses in cavity were approximately equal. It can be concluded that, since more $E_{max}$ in GDT will be formed by titanium, so, in order to decrease discharge time, titanium is far more proper.  The insertion loss in cavity for all of them was partly equal time [26] [27].

TABLE VII.

Electric field norm and Insertion Loss of cavity

| Cavity material | copper | Aluminum | Steel Alsl4340 | Titanium beta-215 |
|---|---|---|---|---|
| **$E_{max}$ (V/m)** | **1187** | **1340** | **2320** | **3530** |
| **Insertion loss (dB)** | **10.8** | **-10.8** | **-10.8** | **10.83** |

## 4.2 On regime

The argon discharge under the HPM operation and the formation and time evolution of the plasma is simulated in this section. This problem is adopted from [28] and was originally simulated with FDTD and finite-volume time-domain methods in three dimensions. The electromagnetic module in COMSOL multi physics software coupled to the plasma module by using the Frequency- Transient study to describe the microwave gas discharge and the operational research on the TR switch [29]. Simulations for the nonlocal RF discharges are performed in argon with the finite element method.

We account for the elastic, excitation, and ionization for electron–neutral collisions, and the elastic scattering and charge exchange for ion–neutral collisions.

### 4.2.1 Initial parameters

To better understand the process of plasma formation and change the conductivity of the gas environment, we have provided complete information from the initial parameters in the table below.

TABLEVIII

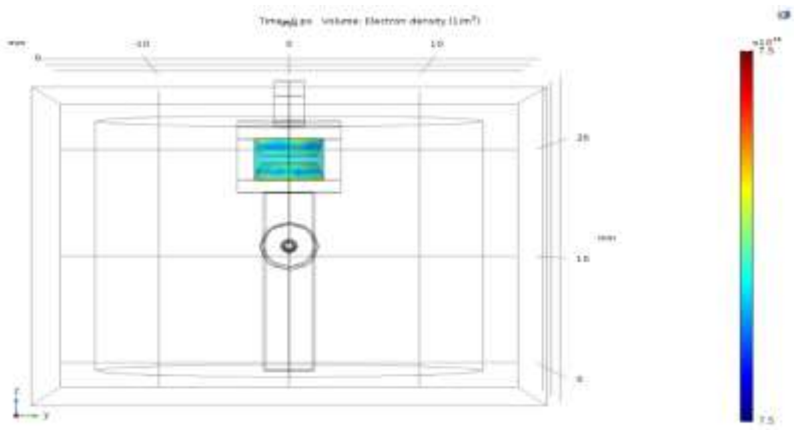
The input parameters for ON mode that cases to microwave argon discharge GDT

| Parameter | Value | Unit |
|---|---|---|
| Gas pressure | 0.1-3 | torr |
| Gas temperature | 300 | k |
| Power amplitude | 1-100 | W |
| Driven frequency | 2.45 | GHz |
| Electrode high | 1.5 | mm |
| Initial electron | $6.5*10^{16}$ | $\frac{1}{m^3}$ |
| Electrode high | 1.5 | mm |
| Electron induce coefficient( δ) | 0 | ....... |
| Ion induce coefficient(γ) | 0 | ...... |

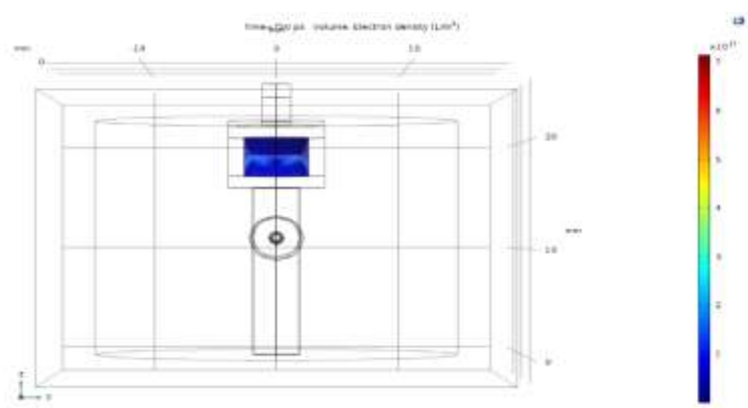
The GDT surface diameter is sufficiently large 2.2mm compared to the gap size. Pure argon gas in the room temperature was used with thermal energy of 0.026 eV. Also, copper electrodes with work function equal to 4.7 eV are considered according to the fabricated resonator [17]. The electron mobility and other electron transport properties are automatically computed based on the electron impact reactions. For the ions, the mobility is given as a function of the reduced electric field using a look up table. The ion diffusivity is obtained from the Einstein relation where the ion has the same mobility as the atomic ion. When an excited state make contact with the wall, they revert to the ground state argon atom with some probabilities. The ions use their internal energy to extract one electron from the wall with a probability of 0.1 and mean energy of 5.8 eV. For the ions, the sticking coefficient is zero, meaning that losses to the wall are assumed to be due to migration only [17].

4.2.2 **Electron density**

Density variation charts in terms of time are very important to investigation the plasma behavior and its effect on the input microwave power.



(a)



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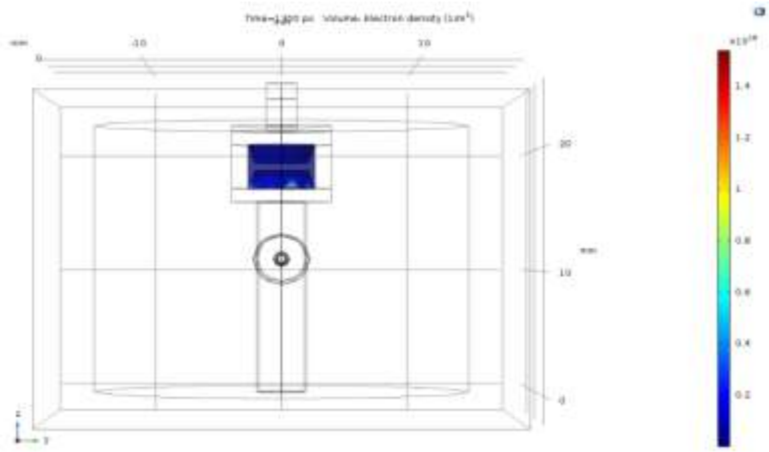

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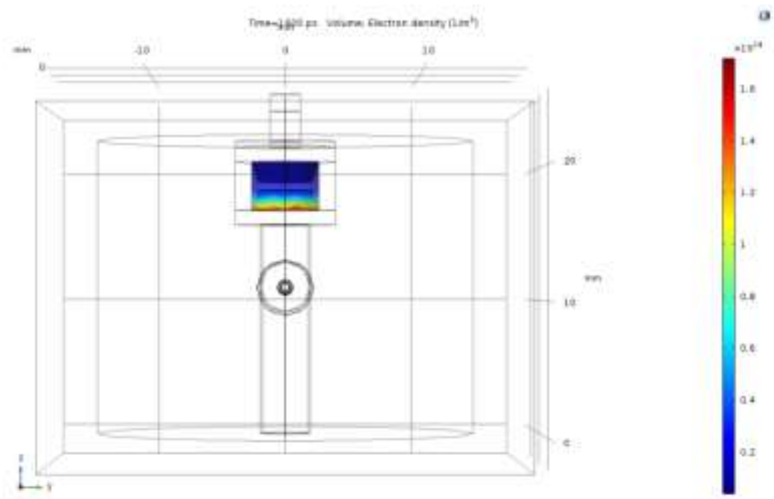
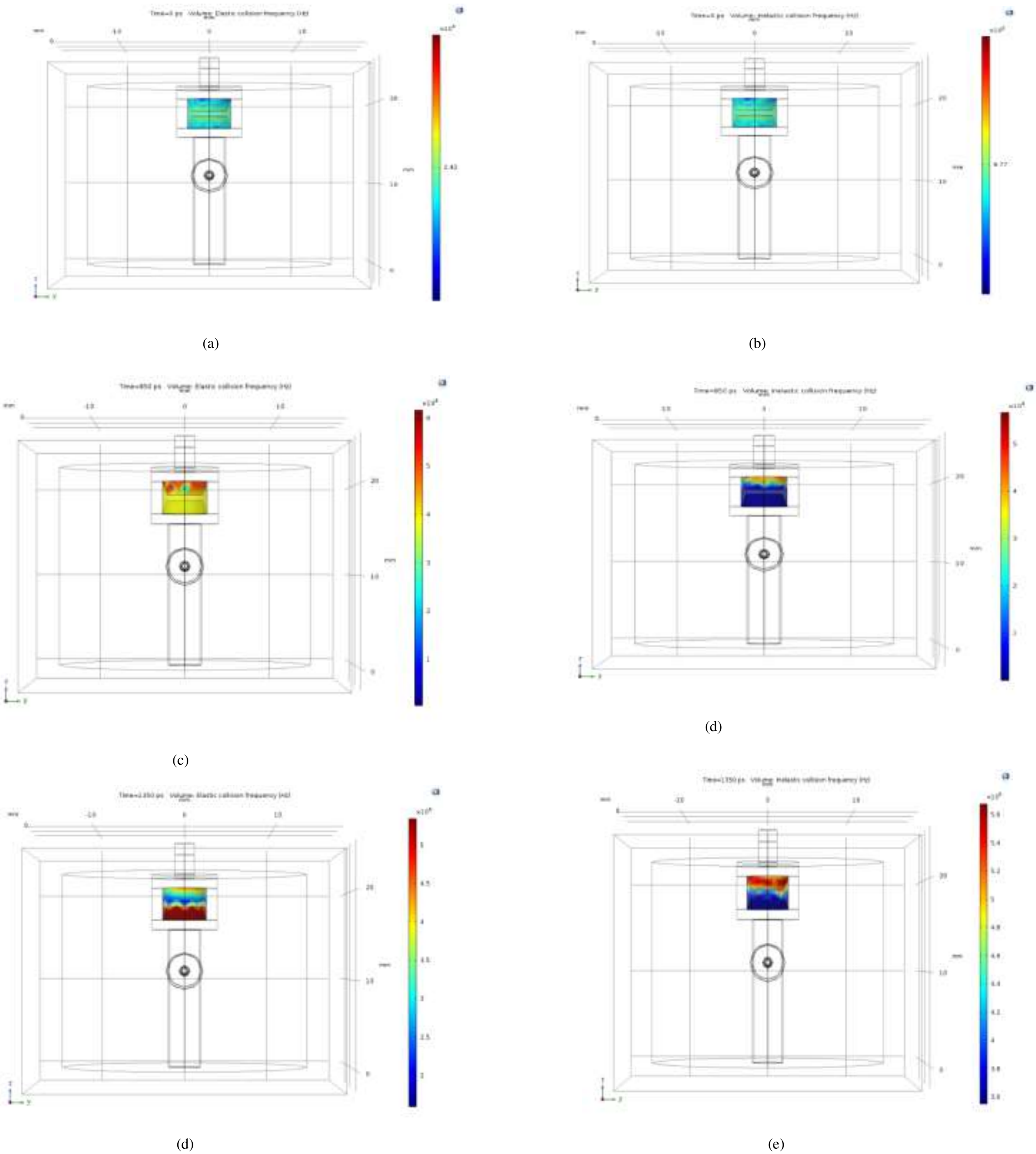


(d)

Fig. 4. Electron density as a function of time in GDT (a) in t=0ps (b) t=750ps(c) t=1300ps (d) t=1600p

### 4.2.3 **Elastic and inelastic collision frequency**

To examine the filtering behavior of the cavity, plasma conductivity should be investigated. Elastic and inelasticity of collisions, determines the amount of energy waste and climbing gas temperature. For this reason, the 3D graph has obtained the frequency of elastic and non-elastic encounters at different times and brought below. The frequency of collisions are from the order GHz and at first most of them are elastic, but after a while, collisions are inelastic.

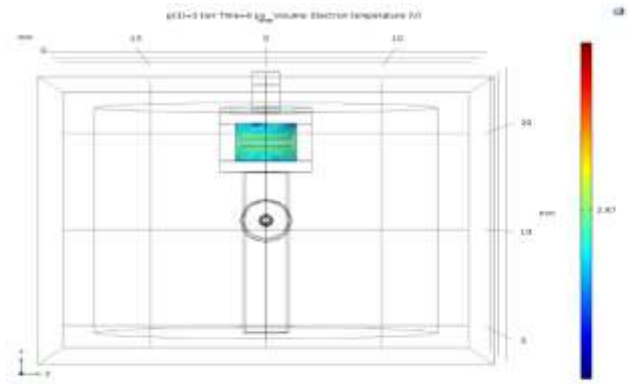


(a) (b) (c) (d) (d) (e)

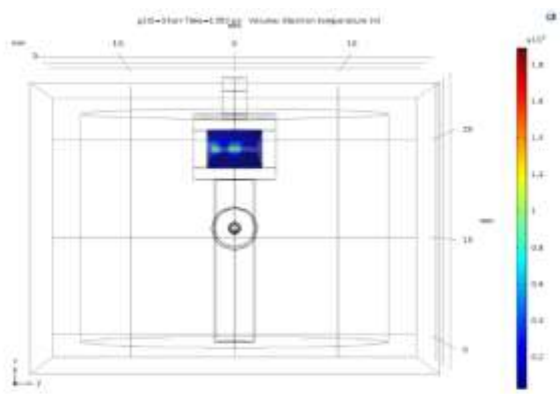
Fig. 5. 3D diagram elastic and inelastic collision frequency (Hz) as a function of time in GDT in t=0, 850, 1350 (ps)

4.2.4 **Electron temperature**

The second most important parameter for determining the behavior of the plasma environment is an electron temperature. At the first temperature grows slowly and after some time increases very fast. It can be argued that initially collision of particles is elastic, but after some time, the collisions are inelastic.



(a)



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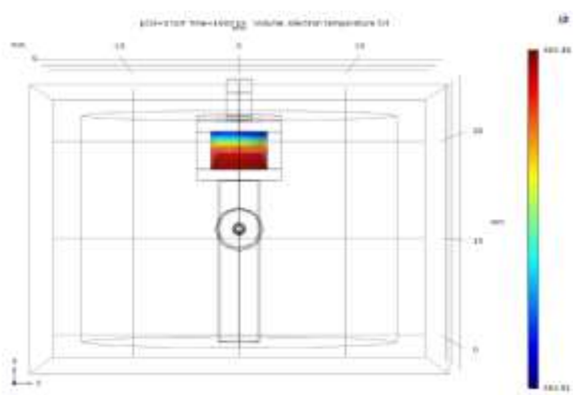
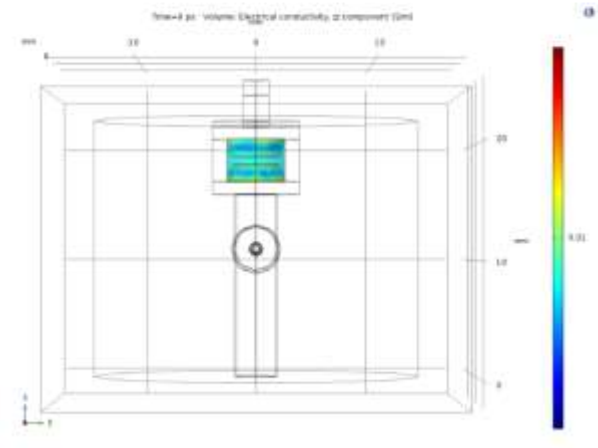


(c)

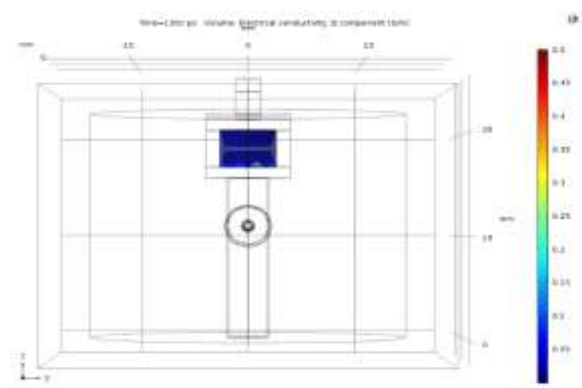
Fig. 6. Temperature profiles for electron as a function of time in the GDT (a) in t=0 ps (b) t=1350 ps (c) t=1600 ps

4.2.5 **Electrical Conductivity zz Component(S/m)**

If plasma frequency ( $\omega_p$ ) becomes comparable to the operating frequency ($\omega_{RF}$) by increasing($n_e$), EM waves get attenuated and reflected by the plasma layer. Larger input power results in additional ionization, thus higher $n_e$ and electrical conductivity.



(a)



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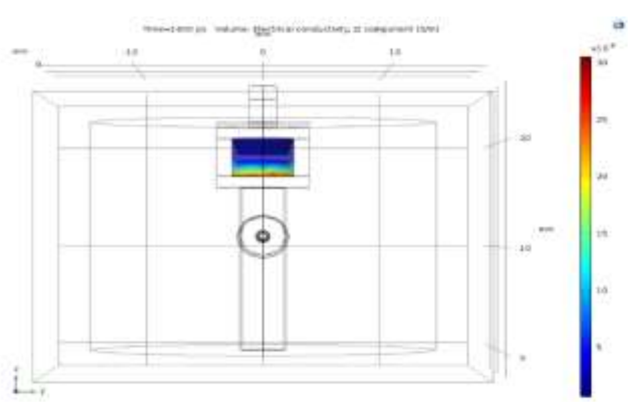


(c)

Fig. 7. Electrical conductivity profiles as a function of time in the GDT (a) in t=0 ps (b) t=1350 ps (c) t=1600 ps

## 5. Conclusions

### 5.1 Effect of pressure on breakdown time and "Late Breakdown"

Modeling results show that if input power is 50 W and its frequency is $\omega_{RF}$ =2.2 GHz and $n_{e0}$ =6.5*$10^{16}$ $\frac{1}{m^3}$ , $\omega_p$ = 2.29GHz (equation1)if gas pressure is 0.1torr, then maximum electron density when breakdown happens is $n_{emax}$ =6*$10^{17}$ $\frac{1}{m^3}$, and under the same conditions, if gas pressure is 3torr, maximum electron density in the gap will be 2*$10^{18}$ $\frac{1}{m^3}$ Meanwhile, the needed time to reach the maximum end of electron density and for the evolution to happen or breakdown time, when the gas pressure was 0.1 torr is 1330 ps and when we increased the gas pressure to 3torr, the reaching time to the breakdown time is 1400 ps.

Our results show when the pressure is p=0.1torr, the electron density reaches its maximum 400 ps after the microwave signal enters the device, but when the pressure reaches 3 torr, it takes 200 ps under the same conditions for the electron density to reach its maximum in GDT, so electron density and gas temperature and threshold power ($\boldsymbol{P_{th}}$) increases by increasing gas pressure. At the beginning, the temperature will increase slowly, but after 1000 ps, it increases very fast. Fig 6.

This means that at first most of the collisions were elastic, but over time the collisions between the particles have become inelastic, which has been associated with energy loss and heat production, resulting in an increase in gas temperature. One of the purposes of this section was to investigate the influence of pressure on the delay to breakdown and to analyses it as a possible candidate for explaining "**Late Breakdowns**" in TR switch [19]. Therefore, by increasing the gas pressure from 0.1 torr to 3 torr we will have a 300 ps delay in breakdown so we can concluded that by increase at 0.1 to 3 torr in pressure, leads to a "Late Breakdown" as 300 ps.Fig.8

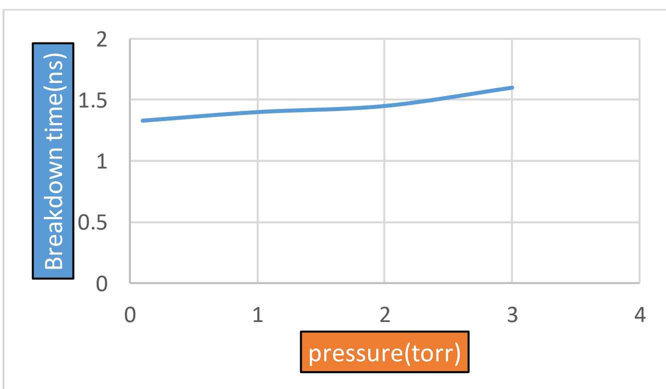
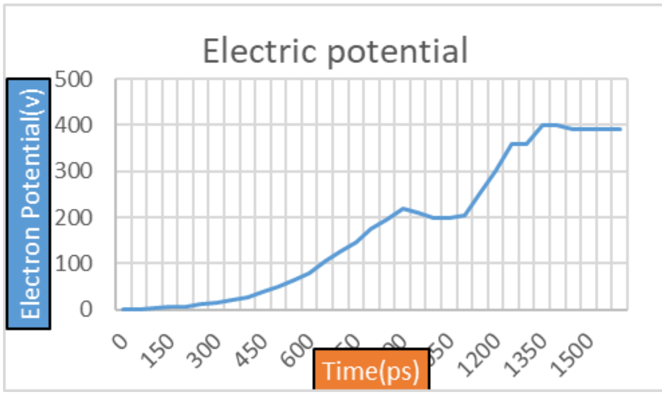



Fig.8. A plot of the breakdown time as a function of pressure in (torr)

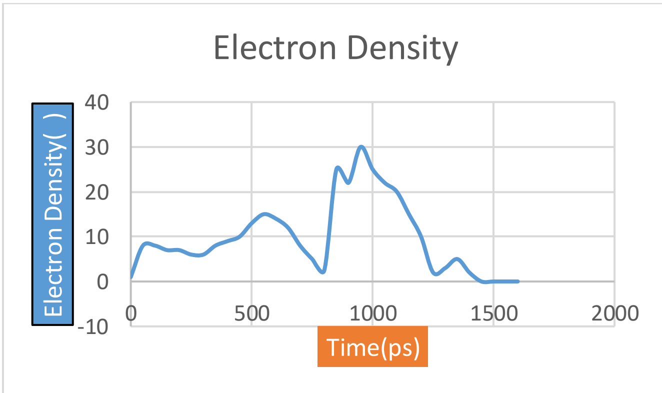
### 5.2 Microwave plasma discharge phenomena

We know that when microwave with $\boldsymbol{P_{in}}$ >$\boldsymbol{P_{th}}$ (threshold power) reaches to the machine, the collision between different species increases so electron-neutral collision frequency increases. Fig.5

Density and σ (collisional cross section) of the electron are higher than other particles, so the electron has sufficient time to acquire energy from the resulted electric field, leading to high mobility. As a result, the electron-neutral collision frequency increases with an increase in pressure, hence the electron temperature sharply increases after 1000 ps. Increase in power or pressure both increase the electron density and hence the plasma frequency.




(a)

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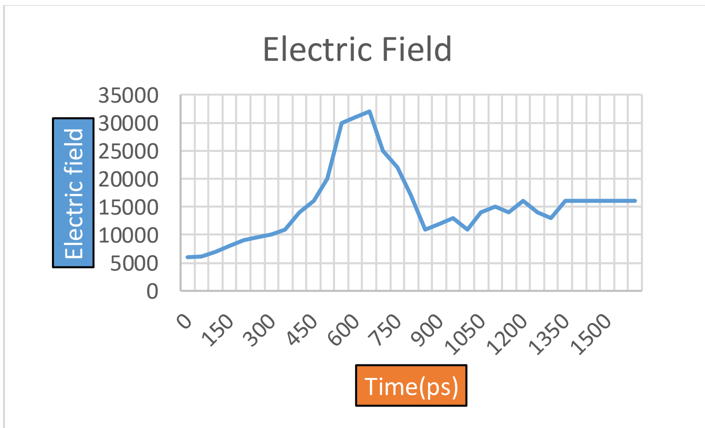


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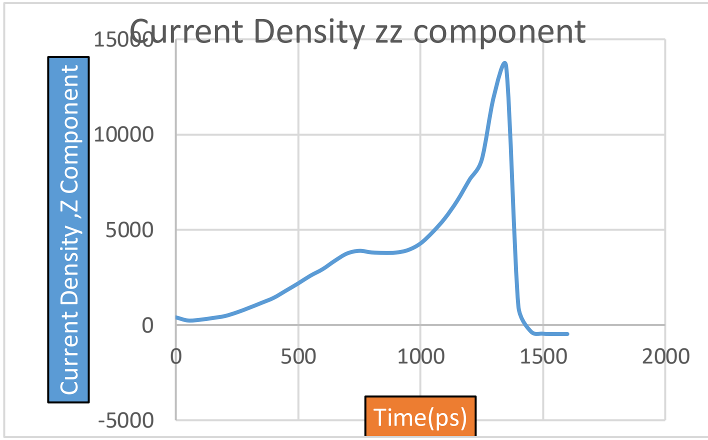


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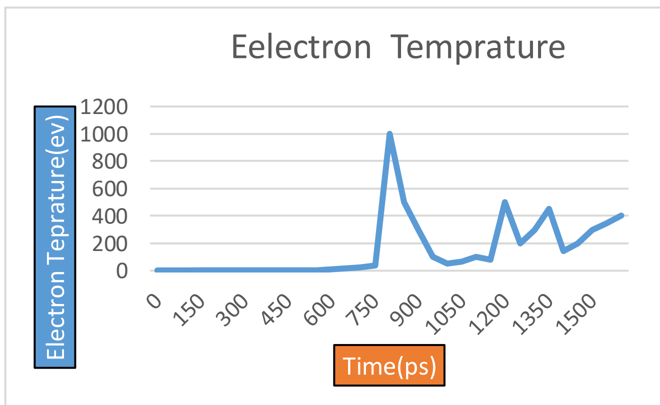


(e)

FIG. 9. (a) Time evolution of electron potential in GDT, when input power is 10 W with 2.2 GHz frequency at 0.1 torr pressure. (b) Electron density $\frac{1}{m^3}$ (c) Electric field (d) Electron temperature.(e)Electron temperature

To accurately analyze the complex discharge plasma phenomenon, we need to examine the changes in basic parameters. Priority and graduation in reaching the maximum amount, is determining the evolutions in gas before formation of plasma. As we in fig 9.c at first electric field reaches its maximum amount then the electron temperature, electron density, current density Z component and at the end electric potential.

In fact, an increase in pressure leads to higher kinetic energy of the electrons which, in turn, increases the electron-neutral collision frequency, hence more ionizations will take place. An increase in the $\boldsymbol{P_{in}}$ also leads to an increase of ionizing activity in GDT. This increases the inelastic collisions between electrons and neutral species which decreases mean free path of the electrons resulting in an increase in temperature and power loss [28]

The reason may be that at first most of collisions are elastic, so naturally, loss is very small; however, after receiving enough energy from input wave, collisions will be inelastic and electrons contact with neutrals and ions, so we have dissipation and heat production and the electron temperature will increase at a higher rate Fig. 8.

As the pressure increases (in α regime), electron collision frequency with neutral atoms also increases, so breakdown time and insertion loss, increase, too. [29]

### 5.3 **Optimization**

In this paper, the TR switch operational characterizations have been optimized in both normal and cut off operation regimes. It was found, the best gap length is 0.6mm and the cone was the most appropriate shape for electrodes in which the top radius of electrode is 1.5mm.All these results are based on calculations. In addition, following the research on the coaxial port parameter, it was discovered that minor changes in the thickness of copper ring radius in input coaxial port, make significant changes in electric field in the gap. Therefore, when the cross section is 0.1mm (by keeping the inner radius constant and increasing the outer radius), electric field in the GDT will be maximum, it results in a better function of TR switch. By the way, when the electric field in GDT is much, the amount of the response time will drop, the sensitivity of device will increase. Generally, it will be functioning far better [30]

If the TR switch is made with titanium, the electric field in the gap will then be much more and much better in contrast with other materials.

Furthermore, when electric field in the gap is more, both the breakdown time and response time will decrease. Thereby, the result is that the device will have a far better function.

This study demonstrated a band pass filter that composed of a cavity resonator as a TR switch that in where embedded a GDT. In this paper, a fluid plasma model for simulating argon microwave plasma characteristics was created. The governing equations were solved in 3-D using the finite element method. Feasible way to optimize performance of the TR switch was analyzed. Very good band pass performance of this machine was described through rigorous simulation results [31] [32].

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