Theoretical Studying and Numerical Simulation of an Electrical Discharge in Vaccum

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Abstract

Dielectric discharges are a well known source of perturbations on Spacecraft, see for example some papers of the 6th Conference. Many questions occur about their mecanisms but *few detailed physical insights* are proposed and still less are the subject of a numerical simulation. In this paper, we focused on a discharge model proposed by Jean-Pierre Marque [1, 2]. The theoretical and numerical study of this discharge is made in [3]. This paper is devoted to the physical aspects of the propagation modelling.

1 Introduction

The principle of the discharge is schown on Figure 1. The discharge is a high density channel of plasma which propagates at the surface of a charged dielectric. The metal part represents the grounded sample holder in the lab or th S/C structure at some absolute potentiel V_0. As this plasma is expanding into the vacuum, electrons are repelled by the charge-induced electric field and ions are attracted towards the surface. Stimulated desorption occurs as they hit the surface, giving raise to a neutrals cloud which is further ionised. Propagation is maintained along the surface if this desorption-ionisation process can be self-sustained. The aim of the simulation was to establish the favourable conditions for the propagation.

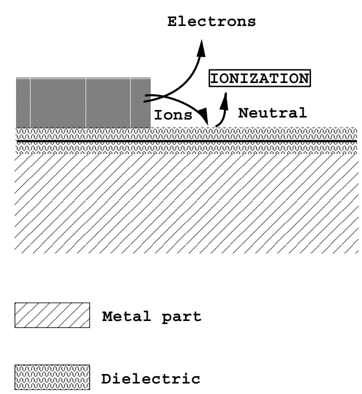

Figure 1: Mechanism of the discharge

2 The equations

To study the discharge, a $2D$ fluid model is used. The charged and uncharged particles are governed by the Euler system. Nevertheless, the charged particles are assumed to be isothermal and the plasma to be *weakly ionized*. They lead to the Drift-Diffusion equations [4]. Denoting by J_η the flux of the particle $\eta = i, e$,

$$J_\eta := -D_\eta \nabla n_\eta + \mu_\eta n_\eta E,$$

where n_η is the density, D_η is the coefficient of diffusion, μ_η the mobility of the particle η and E is the electrical field. The Drift-Diffusion eqation writes

$$\partial_t n_\eta + \nabla . J_\eta \quad = \quad S_i - S_r \tag{1}$$

where S_i and S_r stand for the ionisation and recombination source term. The electrostatic field E comes from the potential Φ ($E = -\nabla \Phi$) which satisfies Poisson equation.

$$\Delta \Phi = \frac{e}{\epsilon_0}(n_e - n_i). \tag{2}$$

where e is the electronic charge and ϵ_0 the permittivity of the vacuum. Hence, the electrical field depends on both ions and electrons. The neutral particles are gouverned by Euler equations.

The boundary conditions are the following. For the electrons $J_e.\nu = 0$, and for the ions $n_i = 0$. The boundary condition for the neutral particles is given by the desorption law

$$(\rho U)|_\Gamma = \begin{cases} -\beta m_i J_i.\nu & \text{if } J_i.\nu \geq 0, \\ 0 & \text{otherwise}. \end{cases}$$

where Γ is the boundary, β the desorption yield, ν is its normal and m_i is the mass of an ion. Here, $(\rho U)|_\Gamma$ represents the flux of the neutral particles emitted on the boundary Γ. Incident ions deposited on the surface are taken into account into the space charge evolution.

Two models are studied in [3]. The first one is based on the Drift-Diffusion-Poisson-Euler (isothermal) equations. It is used for the theoretical study of the discharge. The second one is based on the Drift-Diffusion-Poisson-Euler equations and is used for the numerical simulations. The numerical methods are the followings,

- Finite Differences for the Drift-Diffusion equations,
- Finite Volumes for Euler equations,
- Finite Elements for Poisson equation.

3 The simulation

The plasma is caracterised by three parameters, $\lambda_D := \sqrt{\frac{\epsilon_0 K T_e}{n e^2}}, N_D := \pi n^{\frac{4}{3}} \lambda_D^3, \omega_{pe} := \sqrt{\frac{n e^2}{\epsilon_0 m}}$. It requires that [4] $\lambda_D < L$, $N_D > 1$, and that the plasma frequency must be higher than the electronic frequency collision. The initial conditions for the density is $n_{g0} = 10^{23} m^{-3}$ for the neutral particles, and $n_0 = 10^{21} m^{-3}$ for the charged particles . The energy for all the particles is $KT = 2eV$. The geometry is $Lx = 1000\mu m$ $(3000\lambda_D)$, $Ly = 500\mu m$ $(1500\lambda_D)$, and we have $\frac{\Delta_x}{\lambda_D} = 30$, where $\Delta x = \Delta y$ is the mesh size.

In that case, the plasma frequency is $\omega_{pe} = 2 \times 10^{12} sec^{-1}$. It can be related to the time step Δt which is $\Delta t = 5 \times 10^{-14} sec$. As $\Delta t < \omega_{pe}^{-1}$, we are able to describe what happens at the collision time scale.

The collision frequency is kept constant to give sense to the drift-diffusion equation which is no more valid far from the surface in a low density region where a kinetic description is necessary. This may be considered as valid for a first approach in which we are more interested in the way particles appear near the surface through collisions than the way they escape.

Different scenarii can be proposed for the growth of ionisation in the desorbed cloud. In this work, we tested the influence of the electron diffusion ahead of the channel, in the neutral gas. So the ionisation source term is only due to electrons. Ionisation and Recombination functions are expressed as :

$$S_i(t,x) = A\rho(t,x)E^{\gamma}e^{-B\frac{\rho(t,x)}{E(t,x)}}n_e(t,x),$$
$$S_r(t,x) = rn_e(t,x)n_i(t,x),$$

where A, B, γ and r are some positive constants.

The discharge is triggered at some point of the structure at V_0 = -5 kV. Ohmic drop of potential between the initiation site and the head of the channel we are considering is neglected. So V_0 is the boundary value of the plasma potential . The buried charge density is $10^{-4}Cm^{-2}$ which corresponds to an electric field intensity of $5.3 \times 10^6 Vm^{-1}$ in the non-irradiated zone of a FEP film. The differential potential is less than 1 kV on a $100\mu m$ film.

4 Results

The initial condition for the electronic density is drawn on Figure 2. In the plasma the density is equal to $10^{21}m^{-3}$ while it is equal to 0 in the vacuum.

For the first simulation, neither ionisation nor desorption are taken into account. On Figure 3 is represented the electronic density at the end of the computation ($5 \times 10^{-10}sec$). The maximum of the density (normalized to the initial density) is equal to 1 and the lowest is equal to 0. The step between two isolines is 0.05. Figure 4 represents also the electronic density, but for another maximum which is 0.01; the step between two isolines is now 0.0005. It shows that expansion of the electrons in the vacuum is vertical. The electrical potential (which is not represented here) doesn't change a lot with regards to its initial condition. In this first simulation, there is no propagation, only an expansion of the electrons.

The situation is different when we consider ionisation and desorption. In that case, there is propaga-

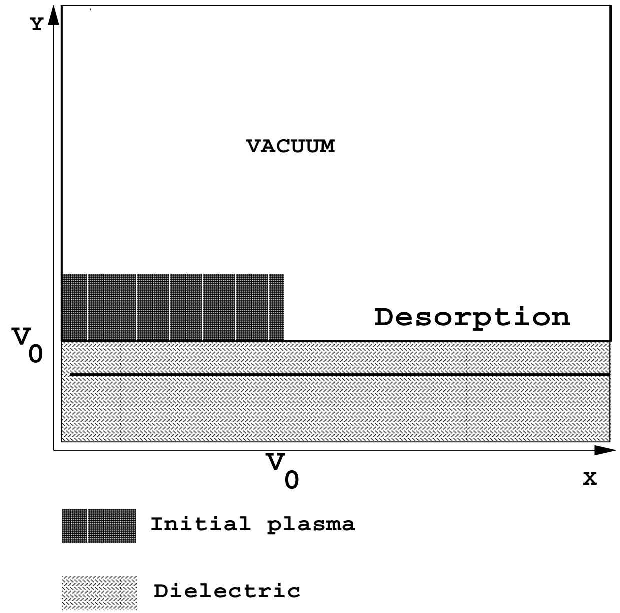

Figure 2: Initial electronic density, Max 10^{21}.

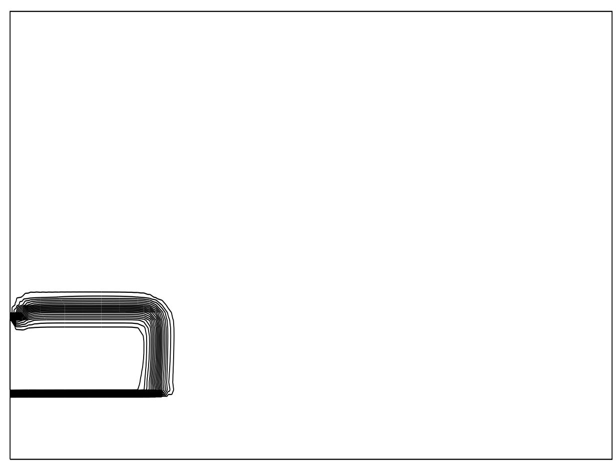

Figure 3: Electronic density, Max:1., ($5 \times 10^{-10}sec$)

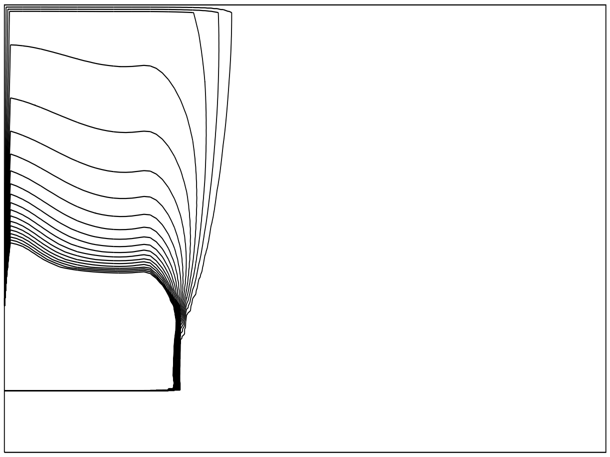

Figure 4: Electronic density, Max:0.01, ($5 \times 10^{-10} sec$)

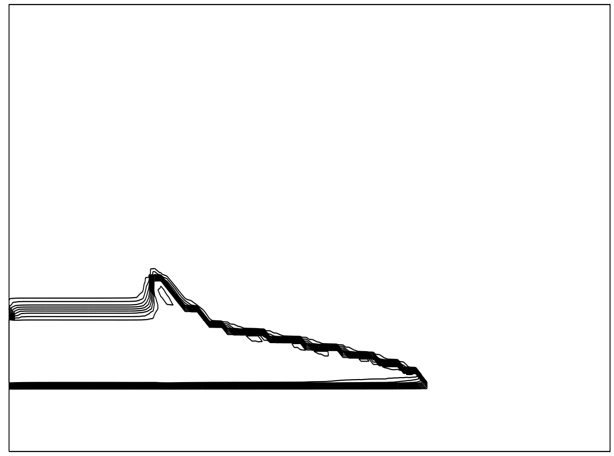

Figure 5: Electronic density, Max:1.

tion of the discharge and its speed is about $10^6 ms^{-1}$.

The electronic density (figure 5) increases from 0 (initial condition) to 1 at the neighbourhood of the dielectric. The ionic density is very similar. Electron diffusion ahead is sufficient to initiate and maintain ionisation at low field value. At higher field value (higher charge density) electrical drift may counterbalance it and other processes maybe necessary as neutral-ion collision or secondary electrons emission together with desorption. The relative contribution of each of these processes can be easily evaluated.

The electrostatic potential (figure 6) tends to V_0 in the created plasma. The minimum for the potential is $-8800V$ is du to the buried electrons σ_e. The step between two lines is $180V$. The electrical field is about $5 \times 10^4 V/m$ inside while it is about $10^6 V/m$ outside the plasma.

The Figure 7 shows a comparison between blowoff currents obtained with and without a ionisation source term. At the beginning, the curves are very similar, but the curve obtained with the ionisation grows much faster than the other.

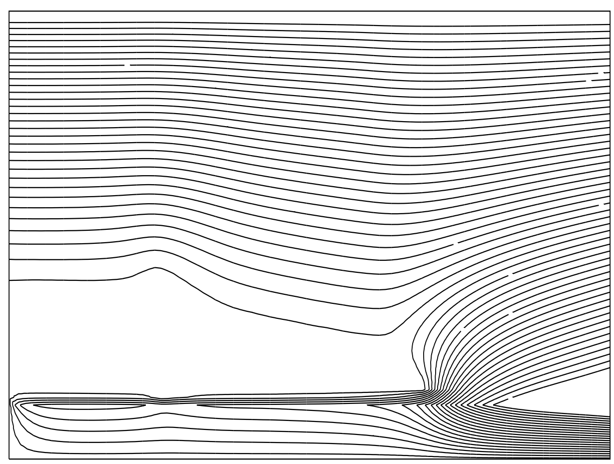

Figure 6: Electrostatic potential.

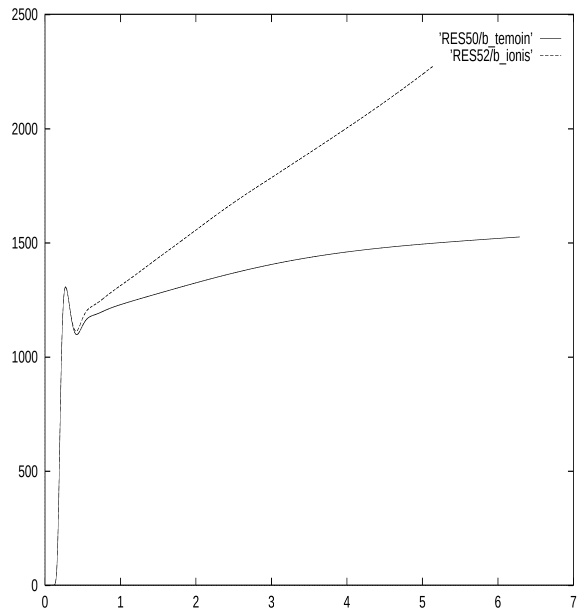

Figure 7: Comparition of the blowoff currents (with and without ionisation).

The results of the simulation confirm the ideas of the physical model. It is difficult to compare the numerical simulations with real experiments. But if we assume that the width of the discharge is a few $1mm$, then, the intensity of the currents are a few $1A$.

5 Conclusion

In this paper, the first results of simulations based on Marque's of dielectrical discharge propagation model are presented. The simulations show that desorption and ionisation are the main paramet ers of the discharge. If there is neither desorption, nor ionisation, there is *no* discharge. Further simulations are in progress to test the effiency of the various parameters. This model can also be used for other geometries met on Spacecraft such as solar arrays.

References

[1] Marque J.P., *Phenomenology of e-irradiated polymer breakdown*, Vacuum, 39 n^o5, P443-452 (1989).

[2] Marque J.P., *Décharges sous vide et environnement spatial*, Workshop SPARCH-PPSO, Avril 97, Nice.

[3] Sévérin F., *Etude théorique et simulation numérique d'une décharge électrique dans le vide* Thèse de l'Ecole Nationale des Ponts et Chaussées, 1998, France.

[4] Chen F., *Plasma Physics and controlled fusion*, Second Edition 1984.