2D numerical modelling of Trichel pulses in oxygen

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1. Introduction

Negative corona exhibits a self-pulsating regime when the voltage applied to the cathode is slightly above the threshold of corona discharge. These pulses, named as Trichel pulses after G. W. Trichel [1], can be easily produced in electronegative gases, like oxygen, but it has recently been shown that they can also occur in non-electronegative gases, like nitrogen or argon [2]. Trichel pulses are characterized by a short duration, of the order of tens to hundreds of nanoseconds, which makes its numerical simulation a challenging task. Frequently, only three generic species are considered in these studies: electrons, positive ions and negative ions [3, 4]. Therefore, the plasma kinetics is reduced to the fundamental processes of ionization, electron attachment and recombination. However, even in simple gases, like oxygen, different ions may play an important role during the development of each pulse, and neutral species (excited and in their ground states) also contribute to the electrical discharge. In fact, more than 100 reactions between electrons, ions and neutral species have been reported in electrical discharges in oxygen [5].

2. Problem formulation

In the present study, the temporal evolution of Trichel pulses is described by means of a plasma chemical model of twelve species and 32 reactions, which include ionization, electron attachment and detachment (dissociative and non-dissociative), charge transfer, and reactions between neutral species (including de-excitation).

Trichel pulses are assumed to develop in oxygen, at a absolute pressure of 50 Torr, between a spherical cathode and a flat node. The cathode, with radius 2 mm, is located at a distance of 20 mm from the anode. The transport equations governing the evolution of these species can be written as follows:

$$\frac{\partial N_e}{\partial t} + \nabla \cdot \left[-D_e \nabla N_e + N_e \mathbf{W}_e \right] = S_e, \tag{1}$$

$$\frac{\partial N_i}{\partial t} + \nabla \cdot \left[N_i \mathbf{W}_i \right] = S_i, \tag{2}$$

$$\frac{\partial N_j}{\partial t} + \nabla \cdot \left[N_j \mathbf{W}_j \right] = S_j, \tag{3}$$

$$\frac{\partial N_k}{\partial t} + \nabla \cdot \left[-D_k \nabla N_k \right] = S_k, \tag{4}$$

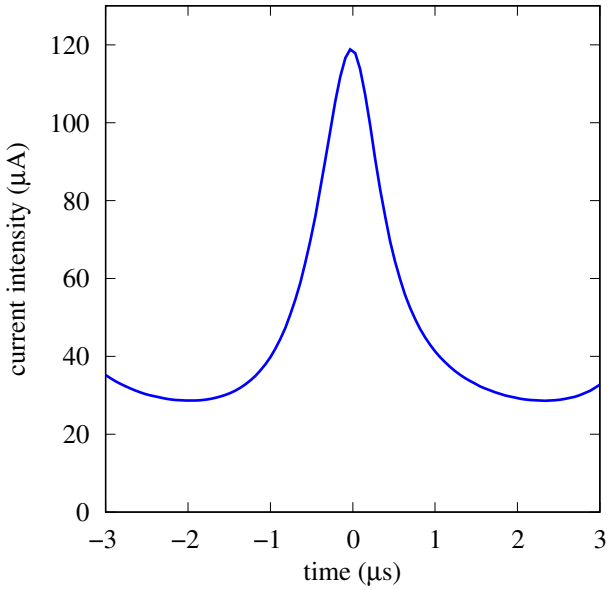

Figure 1: *Regular Trichel pulse for an applied voltage of* -3500 *V. The origin of time has been taken at 0.1948 ms, which corresponds to the peak of current of the pulse.*

where N is the number density, D is the diffusion coefficient, $\mathbf{W}$ is the drift velocity, S is the gain/loss rate of species, and subscripts e, i, j and k denote, respectively, electrons, negative ions ($i = O^-$, O_2^-, O_3^-), positive ions ($j = O_2^+$, O_4^+), and neutral species ($k = O$, O_3, $O(^1D)$, $O_2(^1\Delta_g)$, $O_2(^1\Sigma_g^+)$). These equations are coupled to Gauss's law

$$\nabla \cdot (\varepsilon \mathbf{E}) = e_0 \big[-N_e + \sum_i N_i - \sum_j N_j \big], \tag{5}$$

where e_0 is the positive elementary charge, ε is the dielectric permittivity of the gas, and E is the electric field, which can be obtained as the gradient of an electrical potential, ϕ, that is, $\mathbf{E} = -\nabla\phi$.

Assuming axisymmetrical symmetry, the set of equations (1)-(5) has been solved in 2D using the finite elements method, and the spatial distribution of species and electric field has been obtained at different moments of the Trichel current pulse. Appropriate boundary conditions for each charged and neutral species have been imposed at both electrodes, including secondary electron emission by ion impact at the cathode. The flat anode is grounded, while a high negative voltage of -3500 V is imposed on the cathode, which is high enough to ensure the development of stable Trichel pulses. In order to trigger the onset of pulses, a small number of free electrons (~ 400) is introduced in front of the cathode ($\sim 55\,\mu$m) as initial condition. The rest of species, with the exception of O_2, are assumed to have zero number density at $t = 0$.

3. Results and discussion

The first Trichel pulse is trigger a short time ($\sim 1\,\mu$s) after the application of the negative high voltage. Since this first pulse develops in the absence of any space charge, its current am-

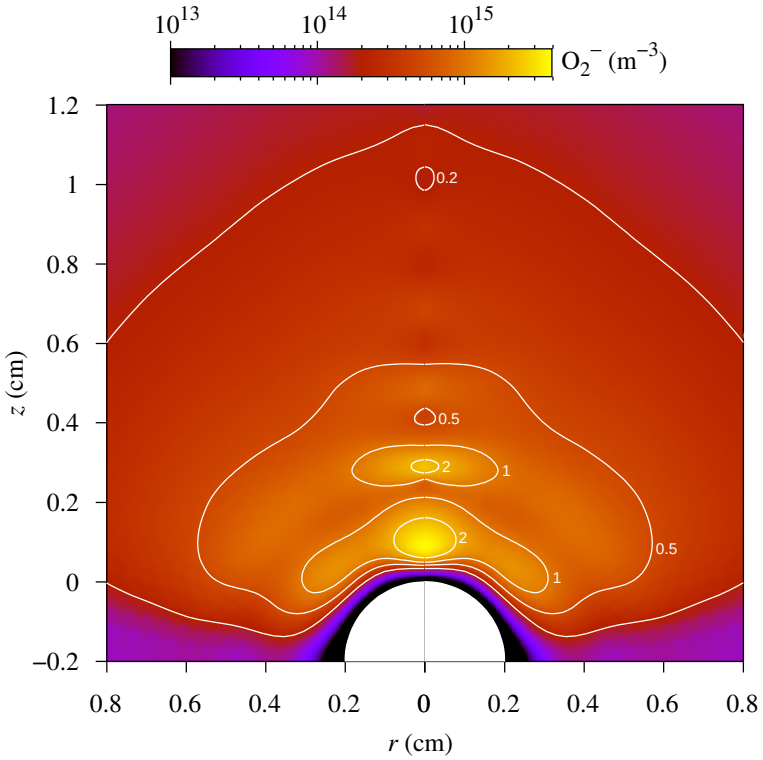

Figure 2: *Spatial distribution of O_2^- at the peak of current of the regular Trichel pulse shown in Fig. 1, corresponding to an applied voltage of* -3500 *V.*

plitude is very high (~ 1 mA). However, after a certain time, which may last some tens of microseconds, a regular regime of Trichel pulses, with much smaller amplitudes, is established [6]. Figure 1 shows the temporal evolution of one of these regular Trichel pulses, according to the numerical simulation.

Of course, the spatial distribution of electrons and positive and negative charged species are substantially modified during the duration of each pulse. Of particular interest are the spatial distributions of negative ion molecules, specially O_2^-. Since the time between consecutive Trichel pulses is shorter that the drift time of negative ions between the cathode and the anode, the number density of these species show a certain spatial segregation due to the contributions of preceding pulses. This fact can be appreciated in figure 2, where the spatial distribution of O_2^- is shown at the time corresponding to the peak of current.

In contrast, neutral species (with the exception of $O(^1D)$) exhibit a much slower temporal variation of their spatial distributions during the pulse, because their lifetime is long compared to the time interval between pulses. Since the plasma chemical activity during the Trichel pulse is ultimately initiated by electron induced-reactions, the maximum values of their number densities are reached near the cathode, where the electron density is high and the electric field is very intense. This fact can be appreciated in figure 3, where the spatial distribution of ozone is shown at time $t = 0.1948$ ms, after a sequence of some tens of regular Trichel pulses. Of

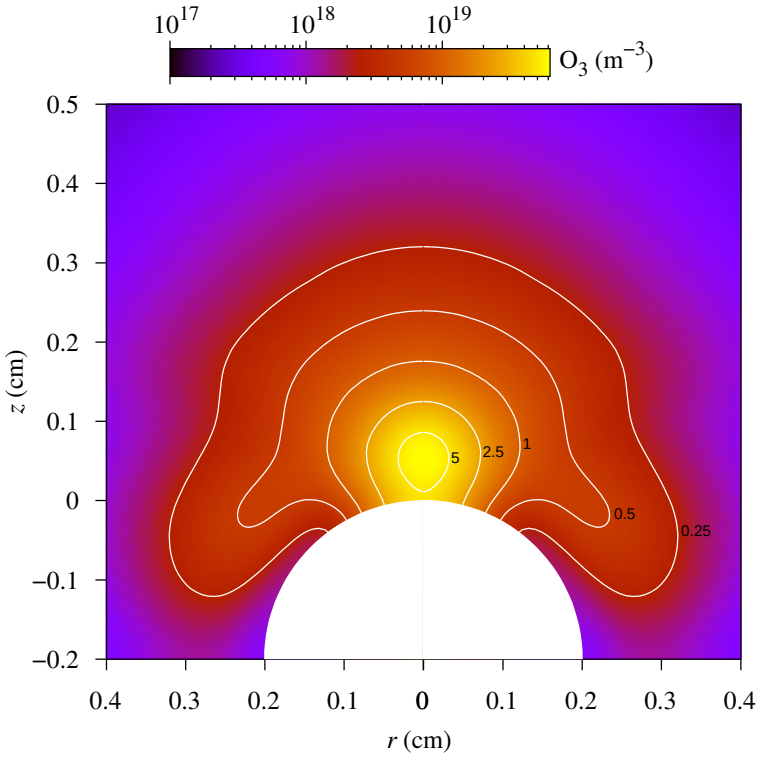

Figure 3: *Spatial distribution of O_3 at the peak of current of the regular Trichel pulse shown in Fig. 1), corresponding to an applied voltage of* -3500 *V.*

course, as time elapses and a large number of pulses is accumulated, molecular diffusion and the electrohidrodynamic motion of the gas will expand the distribution of long life molecules (like O_3) beyond that region.

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