

Photoionization effects in electric discharges

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1. Introduction

Streamer discharge: Plasma channel which propagates in a gas.

The discharge propagates by ionizing the medium in front of its charged head due to a strong electric field induced by the head itself.



- Raether (1939) realized that impact ionization was not enough to explain the velocity of propagation of a streamer discharge.
- He proposed photoionization to be the process which enhances the propagation of the streamer.
- Photons, emitted by atoms that previous collisions have excited, initiate secondary avalanches in the vicinity of the head.

2. Objective and Approach

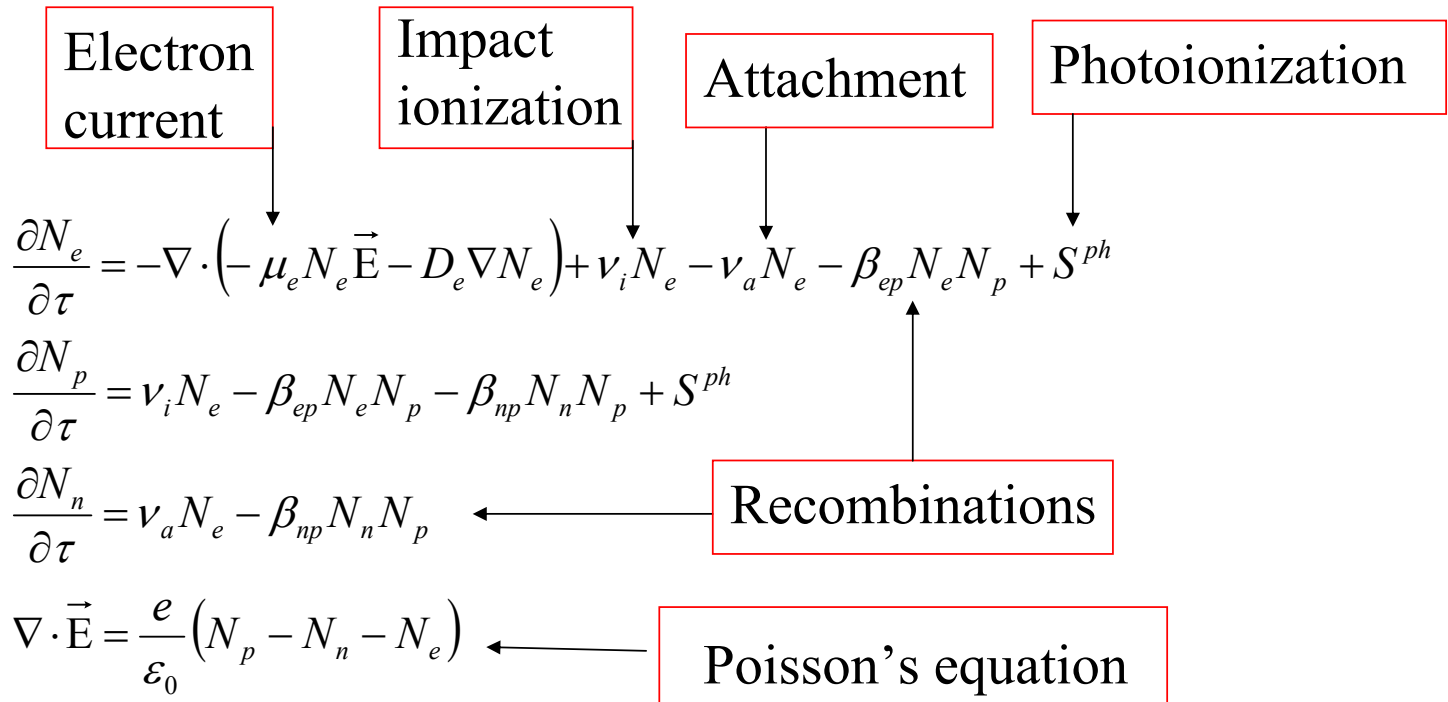
Objective:

To study the role played by photoionization in the propagation of (negative and positive) ionization fronts.

Approach:

- We take a model widely used in numerical simulations and find an effective simplified model.
- We study the case of air, considering emissions from nitrogen molecules.
- First, we consider the role of photoionization in negative planar shock fronts.
- Second, we analyse the case of positive planar fronts and propose a mechanism for their propagation.

3. Model for a streamer discharge



Liu and Pasko, *J. Geophys. Res.* **109** (2004) A04301.

4. A reduced model for the case of air

For air, and for large electric fields, we have:

- Impact ionization is two orders of magnitude bigger than attachment and recombination.
- The number of negative ions is much smaller than the numbers of positive ions or electrons.

$$\frac{\partial N_e}{\partial \tau} = \nabla \cdot (\mu_e N_e \vec{E} + D_e \nabla N_e) + \nu_i N_e + S^{ph}$$

$$\frac{\partial N_p}{\partial \tau} = \nu_i N_e + S^{ph}$$

$$\nu_i = \mu_e E \alpha_0 e^{-(E_0/E)}$$

$$\nabla \cdot \vec{E} = \frac{e}{\epsilon_0} (N_p - N_e)$$

5. Dimensionless reduced model

Townsend approximation provides physical scales and intrinsic parameters.

$$\vec{R} = \frac{\vec{r}}{\alpha_0} \approx \frac{(2.3 \times 10^{-6} \text{ m})}{p} \vec{r}$$

$$\tau = \frac{t}{\alpha_0 \mu_e E_0} \approx \frac{(3 \times 10^{-12} \text{ s})}{p} t$$

$$\vec{E} = E_0 \vec{E} \approx (2 \times 10^7 \text{ V/m})(p) \vec{E}$$

$$N_e = \frac{\alpha_0 \epsilon_0 E_0 n_e}{e} \approx (4.7 \times 10^{20} \text{ m}^{-3})(p^2) n_e$$

$$N_p = \frac{\alpha_0 \epsilon_0 E_0 n_p}{e} \approx (4.7 \times 10^{20} \text{ m}^{-3})(p^2) n_p$$

$$D_e = \frac{\mu_e E_0 D}{\alpha_0} \approx \frac{(1.8 \text{ m}^2/\text{s})}{p} D$$

$$\frac{\partial n_e}{\partial t} = \nabla \cdot (n_e \vec{E} + D \nabla n_e) + n_e E e^{-1/E} + S$$

$$\frac{\partial n_p}{\partial t} = n_e E e^{-1/E} + S$$

$$\nabla \cdot \vec{E} = n_p - n_e$$

6. Approximation for the photoionization term

- We restrict ourselves to planar ionization fronts in air.
- We consider that emissions from nitrogen molecules can ionize oxygen molecules.

$$S(z) = \varphi_0 \int dz' n_e(z', t) E(z', t) e^{-1/E(z', t)} k(z - z')$$

$$\varphi_0 = \frac{0.37}{30 + p(\text{Torr})}$$

$$k(s > 1) = \frac{e^{-0.006\gamma s}}{0.006\gamma s^2} - \frac{e^{-0.34\gamma s}}{0.34\gamma s^2}$$

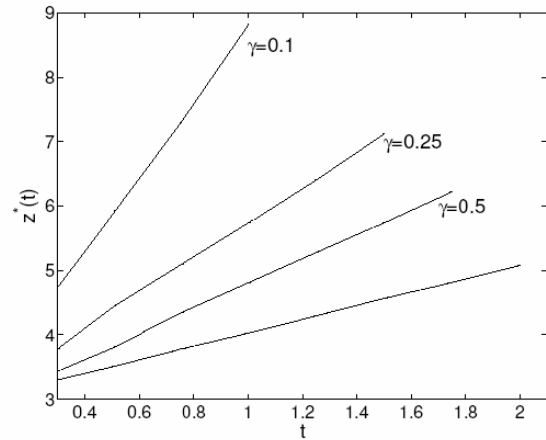
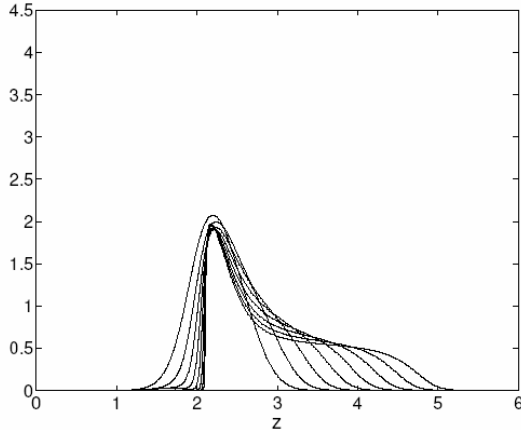
$$k(s \leq 1) = -0.34\gamma \ln(s) + \frac{e^{-0.006\gamma}}{0.006\gamma} - \frac{e^{-0.34\gamma}}{0.34\gamma}$$

$$\gamma = \frac{p_{O_2}}{p} \approx 0.21$$

$$p \approx 750 \text{Torr}$$

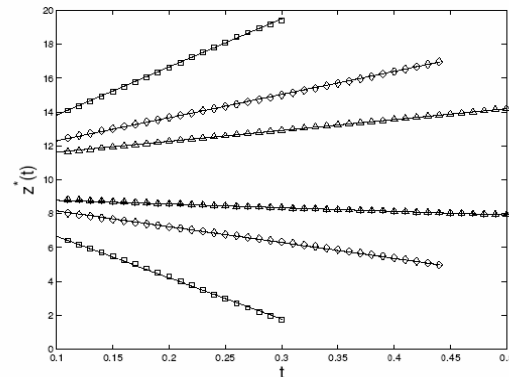
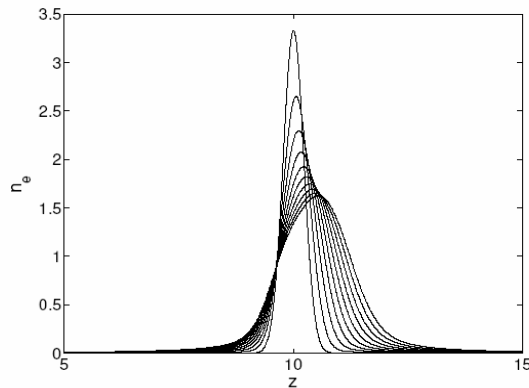
7. Photoionization without diffusion

- Initial data: Gaussian distribution of both electrons and positive ions at $z=2$ ($z=0$ is the cathode)
- When photoionization range ($1/\gamma$) is increased, the front moves faster.



8. Photoionization with diffusion

- Initial data: Gaussian distribution of both electrons and positive ions at $z=10$ ($z=0$ is the cathode). $D=0.57$.
- A negative front moves towards the anode and a positive front towards the cathode. The ratio (c_p/c_n) grows as the photoionization range ($1/\gamma$) increases.



9. Conclusions

- A minimal model including photoionization has been deduced for the evolution of streamer discharges in air.
- With this model, we have studied the propagation of both positive and negative fronts in the planar case.
- We have found the appearance of travelling waves which accelerate when the photoionization range increases.
- For negative fronts we have studied the effect of photoionization both when electronic diffusion is neglected and included.
- For positive fronts, electronic diffusion has to be taken into account and we have shown how photoionization plays a crucial role.
- The control parameter is the photoionization range, i. e. the typical distance at which photons are able to ionize the medium.
- In the atmosphere, this parameter varies with the altitude.