

Scaling Laws

and Peculiarities of Micro and Macro Plasmas

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Scaling Laws and Micro-Plasmas





The term micro-plasma refers to discharges with dimensions ranging from a few μ m up to a few mm.

The optimal conditions for plasma generation are observed near Paschen minimum at *pd* values of 0.1-10 Torr cm => discharge operation at atmospheric pressures corresponds to gaps with *d* ~100 μ m.

At $\omega \tau_i << 1$ an AC discharge can be seen as a sequence of DC discharges at different voltages

Recently, it has been realized that non-local electron kinetics plays an important role in micro-plasmas operating near Paschen minimum.

The Dark-to-Glow transition takes place at

 U_t is the voltage at Pashen's minimum

 $\frac{J}{p^2} > \frac{(\mu_i p)U_t^2}{8\pi (nL)^3}$

*j/p*² scaling



Calculated static current-voltage characteristics for Ne discharges with gaps of 0.1 and 0.6 mm near Pashen's minimum. The characteristic minimum in the U(j) dependence is very narrow. The j/p^2 scaling is well satisfied under these conditions.

Spatial distributions of charged species in Ne at 600 Torr, 1A. Even at high currents, the difference between the total ion density and the electron density is still noticeable – no plasma.



• Micro-discharges at high gas pressures often operate in the Townsend regime due to j/p^2 scaling.

• Strong regular current oscillations are observed in Townsend regimes at $\omega \tau_i << 1$ in DBDs with electrodes covered by dielectric layers. Same phenomena should be observed in discharges with naked electrodes when an external capacitance is present in series with the discharge.

• Theory of DBD discharges relates parameters of these oscillations to finite transit time of ions and electron emission processes at electrodes.

 Photo electron emission has stabilizing effect and results in the decay and disappearance of the current oscillations.



Dielectric Barrier Discharges (DBD) are characterized by the presence of dielectric layer(s) between the gas and electrode(s). The Townsend mode usually has current oscillations.



The frequency restriction:

$$\tau = \frac{L}{E_{br}b_i} << \frac{2\pi}{\omega}$$

 E_{br} is the breakdown field; b_i - the ion mobility; ω - the applied voltage frequency; τ - the ion transit time at $E=E_{br}$.

From the Gauss' theorem, the relation between the applied voltage U(t), the electric field in the discharge gap E, and the surface charge is:

$$E = U \frac{1}{L + \frac{2d}{\varepsilon}} + \sigma \frac{8\pi}{L + \frac{2d}{\varepsilon}} \frac{d}{\varepsilon}$$



At the time scale exceeding $\boldsymbol{\tau}$ the conductivity current behaves as

$$\tau \frac{dj}{dt} = -j \ln M(E) + j_{ext}$$

where the multiplication factor *M* is equal to the number of electrons generated by one cathode-emitted electron during τ . If the standard local approximation for the ionization rate is valid,

$$M = \gamma \left(e^{\alpha(E)L} - 1 \right)$$

The electric field in DBD obeys the equation

$$\frac{dE}{dt} = \frac{dU}{dt} \frac{1}{L + \frac{2d}{\varepsilon}} - j \frac{8\pi}{L + \frac{2d}{\varepsilon}} \frac{d}{\varepsilon}$$

D.S.Nikandrov and L.D.Tsendin, Technical Physics 50 (2005) 1284

Main Equation



$$\begin{cases} \frac{d^{2}E}{d\theta^{2}} - \frac{d^{2}\Phi}{d\theta^{2}} - \ln\left(M(E)\right) \left(\frac{dE}{d\theta} - \frac{d\Phi}{d\theta}\right) = -\iota \kappa;\\ E\Big|_{\theta=0} = 1, \quad \frac{dE}{d\theta}\Big|_{\theta=0} = \frac{d\Phi}{d\theta}\Big|_{\theta=0} - \kappa\end{cases}$$

Here
$$\theta = \frac{t}{\tau}$$
 $E = \frac{E}{E_{br}}$ $t = \frac{j_{ext}}{j\Big|_{t=0}}$ $\Phi = \frac{U}{1 + \frac{2d}{\varepsilon L}} \frac{1}{E_{br}L}$ $\kappa = \frac{8\pi d}{(\varepsilon L + 2d)} \frac{j\Big|_{t=0}}{E_{br}}\tau$

• At low frequency and smooth voltage, the term $\Phi^{"}$ can be neglected

Since during the active phase, the external current is negligible, the righthand side can be replaced by zero.

As a result, one obtains a classical equation for non-damping oscillations

 A mechanical analogy corresponds to the particle motion under effect of nonlinear force, which changes its sign at E=1. Using this analogy, expressions for the maximal and minimal electric field values, and the oscillation frequency have been derived in

D.S.Nikandrov and L.D.Tsendin, Technical Physics 50 (2005) 1284

Comparison with experiments



Experiments [+] for DBD in He at atmospheric pressure, L=0.3 cm, d=0.23 cm, ϵ =7.63, γ =0.01. Theory [o]



[+] J. Shin and L. L. Raja, J. Appl. Phys. 94, 7408 (2003).
[0] D.S.Nikandrov and L.D.Tsendin, Technical Physics 50 (2005) 1284



The presence of serial capacitor in external circuit is equivalent to dielectric layer on electrode: 100 Ω , 10pF, $\gamma_c=0.1$, $\gamma_a=0$, d=6 mm





Time Dependence of Voltage and Current for 100 Ω , 100pF





600 Hz, 100 Ω, 10 pF , $\gamma_c=0.1$, $\gamma_a=0$, photo electron flux = 10^10 (left) and 10^12 (right)



Photo electron emission has stabilizing effect and results in the decay and disappearance of current oscillations.

Effect of Dielectric Barrier (Serial Capacitor)

CFDRC 🐲

600 Hz, **100** Ω, γ_c=0.1, γ_a=0













We have used a Fokker-Plank solver for electrons to study nonhydrodynamic effects in Townsend discharges in Neon near the Paschen minimum.

$$\frac{\partial}{\partial t}(vf) - \frac{\partial \phi}{\partial t} \frac{\partial}{\partial \varepsilon}(vf) - \nabla \cdot \chi \nabla f - \frac{\partial}{\partial \varepsilon} \left[Y_{ee} \left(Cf + D \frac{\partial f}{\partial u} \right) + vV_T f + vD_E \frac{\partial f}{\partial u} \right] = vS$$

Total Energy Formulation

$$\varepsilon = u - \phi(\vec{r}, t)$$

V.I.Kolobov, Computational Materials Science 28 (2003) 302

25 Torr



Spatial distributions of electron density (left) and temperature (right) obtained with FP solver

Electron temperature exhibits dumped oscillations near the cathode. The period of these oscillations is about the distance $\lambda_{\varepsilon} = \varepsilon_1/(eE)$ that electrons travel in the electric field *E* to gain kinetic energy equal to the first excitation potential of the atoms, ε_1 . Damping of these oscillations is due to the energy loss in elastic collisions with atoms and inelastic collisions (such as excitations of several atomic levels and direct ionization). The optimal values of the reduced electric field, *E/N*, for the appearance of the striations are observed near the Paschen minimum.

50 Torr





Spatial distributions of electron density (left) and temperature (right) obtained with FP solver

The oscillations of electron temperature become stronger at 50 Torr. One can even observe slight modulation of electron density.

200 Torr





Spatial distributions of electron density (left) and temperature (right) obtained with FP solver

At 200 Torr, oscillations of electron density and temperature are much weaker compared to the 50 Torr case.

In summary, we have observed non-hydrodynamic effects in Townsend discharges in pure Neon near the Paschen minimum. The nature of standing striations in micro-plasmas is similar to the nature of these striations in classical discharges. Due to j/p^2 scaling, one should expect standing rather then moving striations in micro-plasmas.



Neon, 150 V, 50 Torr, two-level model



In rare gases, a number of amazing kinetic effects appear due to the large difference between the energy relaxation length and the mean free path, $\chi = \delta (\lambda_{\varepsilon} / \lambda_{e})^{2} \ll 1$:

Electron trajectories in a spatially periodic DC electric field in the (\mathcal{E}, x) **plane**



$$\frac{\partial}{\partial z} D_r \frac{\partial f_0}{\partial z} - \frac{1}{\sqrt{\varepsilon}} \frac{\partial}{\partial \varepsilon} \left(\sqrt{\varepsilon} \Gamma_u \right) = S - G$$

In the absence of energy loss in elastic collisions and the "black wall" approximation

$$f_0(\varepsilon,z) = \Phi(\varepsilon) \int_{z}^{z_1(\varepsilon)} \frac{dz}{D_r},$$

The differential density flux $\Phi(\varepsilon)$ is a periodic function of energy $\Phi(\varepsilon) = \Phi(\varepsilon + \varepsilon_1)$

In spatially periodic fields, small energy loss in elastic collisions results in resonance peaks on $\Phi(\varepsilon)$

for the field periods $\lambda = q U_{\lambda} / (lE_0)$

where $U_{\lambda} = \varepsilon_1(1+\chi)$

and l and q are small integer numbers ,

Ionization waves in molecular and electro-negative gases remain purely understood.

V. Kolobov, Striations in rare gas plasmas (Topical Review), J. Phys. D 39 (2006), R487



Striations = Ionization Waves



- Striations have been studied for more than a century. They were observed at pressures 10⁻³-10³ Torr and currents 10⁻⁴-10 A in almost all gases
- Striations as a test bead for advanced plasma models: accuracy of kinetic models of gas discharges can be checked versus experimental observations accumulated over a century of studies
- **Striations as a research tool:** detailed information about the high energy part of the EEDF can be obtained, cross section set can be verified
- Striations as nonlinear systems: ideal object for studies of nonlinear





• 2 Torr, 100 mA, cylindrical tube of length L = 20 cm and radius R = 1 cm, cathode on the left, anode on the right. The tube wall is dielectric. Simulation takes about 30 hours on a 1 GHz computer.

• Negative-glow region near the cathode with a large plasma density, about 3-4 striations excited along the tube.

• Striations are self-excited; they initially appear near the cathode and propagate towards the anode, group velocity is directed from cathode to anode. The phase velocity is directed from the anode to the cathode ("backward waves")



Moving Striations in Dynamics



Pattern Formation in DBD



Experimental measurements of pattern formation dynamics in He DBD 200kHz, 30kPa, 690 V. Stollenwerk et al. Phys. Rev. Letters 96 (2006) 255001 Our simulations: fluid model with local Boltzmann solver for EEDF and LUTs



Open questions

•Effect of computational mesh

- •Operating conditions (gas, pressure, voltage)
- •Electrode resistivity



• Due to *j/p*² scaling, micro-discharges exhibit an extended Townsend regime

• Current pulses are observed in Townsend regimes at $\omega \tau_i << 1$ in the presence of dielectric layers or serial capacitors

 Nonlocal electron kinetics plays an important role in high-pressure micro-plasmas operating near Pashen minimum.

• Deterministic Fokker Planck solver is suitable for studies of electron kinetics with transient non-local effects in micro and macro plasmas

• Preliminary simulations show that nonlocal electrons are more efficient in producing ionization (under conditions near Pashen minimum) than local non-Maxwellian and Maxwellian EEDF

 Steady and transient structures observed in DBD micro plasmas can be studied using today's 3D models of gas discharges