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*Workshop on Non-equilibrium Flow Phenomena in Honor of Mikhail Ivanov's 70th Birthday*

# Mechanism of Subnanosecond Current Front Rise in High-Voltage Pulse Open Discharge

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in collaboration with

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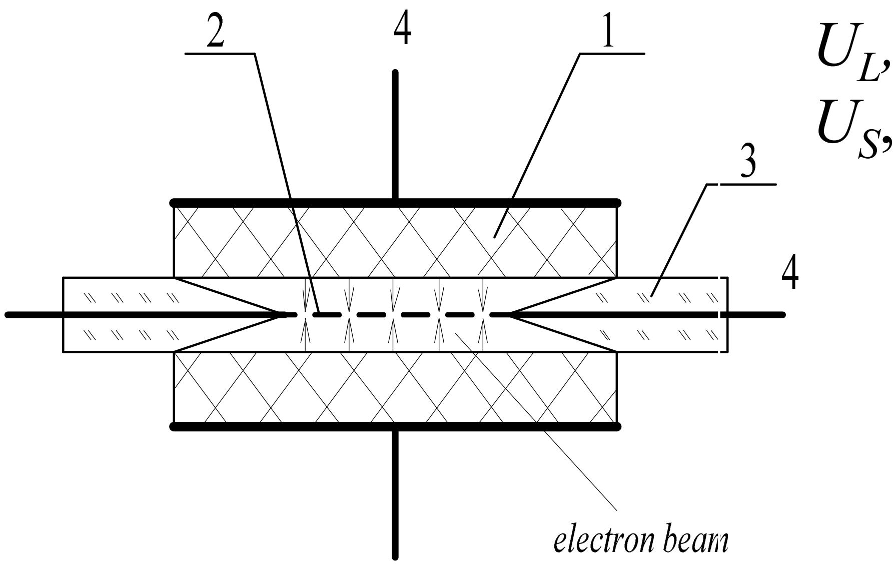
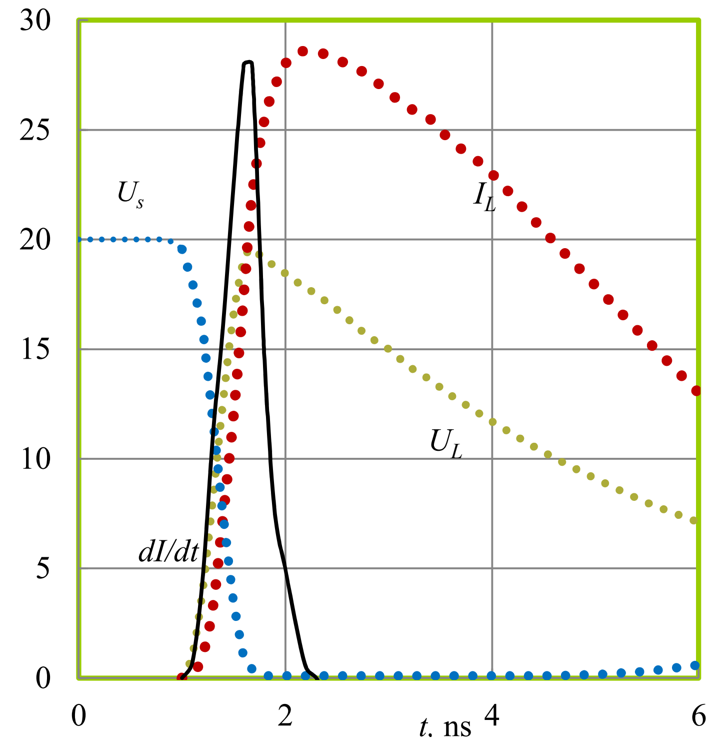
# Motivation

- High-voltage open discharge experiments in helium [1,2] showed a possibility to control the electron avalanche development on a subnanosecond timescale. The controlled current growth rate was of 500 A/(cm$^2$ns) for an applied voltage of 20 kV and gas pressure of 6 Torr.


1. Bokhan P, Gugin P, Zakrevsky Dm and Lavrukhin M 2013 Phys. Plasmas, 20(3) 033507;
2. Bokhan P, Gugin P, Zakrevsky Dm and Lavrukhin M 2013 Tech. Phys. Lett. 39(9) 775

# Scheme of experimental setup




Plasma is between two cathodes (S=50 cm$^2$), anode is a grid (98% transparency), cathode-anode gap =0.3cm, He, P=3, 6, 15 Torr, U=20 kV. Cathode (1), anode-grid (2), dielectric plate (3), lead-in (4).

Discharge current (red line) increases to 27 kA during 1 ns. dI/dt=560 A/cm$^2$ns.

# Possible mechanism of subnanosecond breakdown

Production of photons with a Doppler shift due to the excitation of the background atoms by heavy particles

a) ions,
b) fast atoms

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# Theoretical model

*Kinetic equations for electron, ion and neutral distribution functions:*

$$\frac{\partial f_e}{\partial t} + \vec{v}_e \frac{\partial f_e}{\partial x} - \frac{e\vec{E}}{m}\frac{\partial f_e}{\partial \vec{v}_e} = J_e^e + J_i^e + J_N^e, \quad n_e = \int f_e d\vec{v}_e,$$

$$\frac{\partial f_i}{\partial t} + \vec{v}_i \frac{\partial f_i}{\partial x} + \frac{e\vec{E}}{M}\frac{\partial f_i}{\partial \vec{v}_i} = J_e^i + J_i^i + J_N^i, \quad n_i = \int f_i d\vec{v}_i,$$

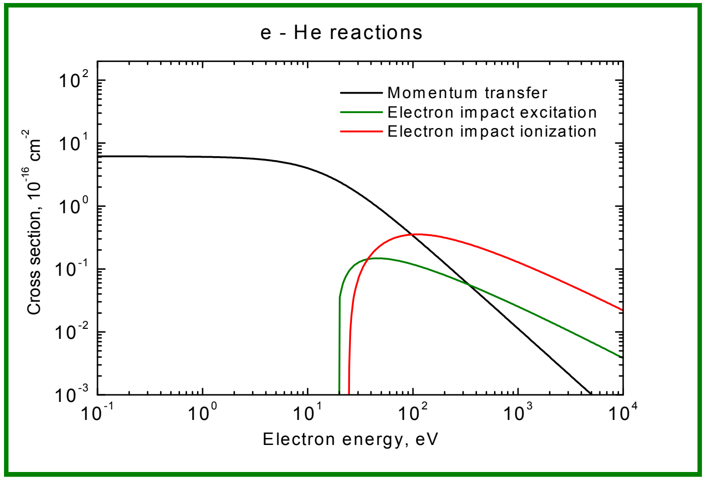
$$\frac{\partial f_N}{\partial t} + \vec{v}_N \frac{\partial f_N}{\partial x} = J_e^N + J_i^N + J_N^N, \quad n_N = \int f_N d\vec{v}_N,$$

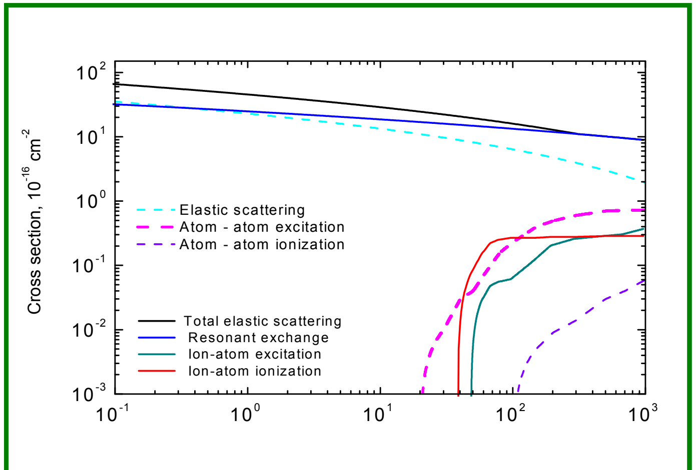
*Poisson equation for electrical potential and field:*

$$\Delta\phi = 4\pi e(n_e - n_i), \quad E = -\frac{\partial \phi}{\partial x}.$$

**Schweigert et al 2014 Phys. Rev. E 90(5) 051101(R)**
**Schweigert et al 2015 Plasma Source Sci and Technol, accepted**

# Cross sections of electron, ion and fast neutral collisions with He atoms



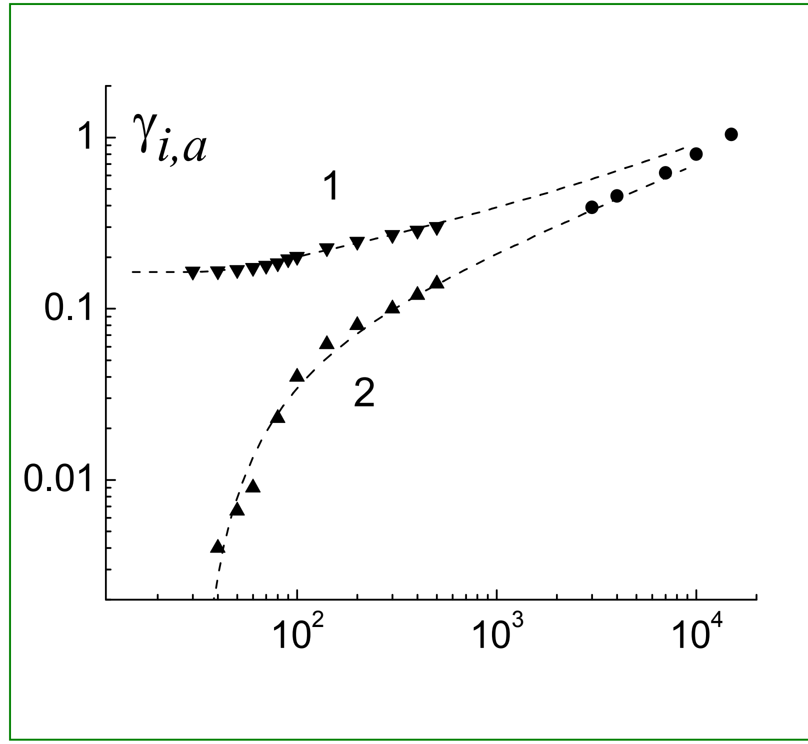

| N | Reaction | Crossection |
|---|---|---|
| | Electron reactions | |
| 1. Momentum transfer | $e + He = e + He$ | [14] |
| 2. Excitation | $e + He = e + He^*$ | [15] |
| 3. Ionization | $e + He = 2e + He^+$ | [15] |
| | Ion reactions | |
| 1. Isotropic scattering | $He^+ + He = He^+ + He_f$ | [18] |
| 2. Charge exchange | $He^+ + He = He_f + He^+$ | [18] |
| 3. Excitation | $He^+ + He = He^+ + He_f^*$ | [19] |
| 4. Ionization | $He^+ + He = 2He^+$ | [20] |
| | Fast atom reactions: | |
| 1. Elastic scattering | $He_f + He = 2He_f$ | [21] |
| 2. Excitation | $He_f + He = He_f + He_f^*$ | [22] |
| 3. Ionization | $He_f + He = He_f + He^+$ | [23] |
| 4. Excitation transfer | $He_f + He^* = He_f^* + He$ | see text |

TABLE I. The reactions included in PIC-MCC simulations.

# Electron emission from cathode

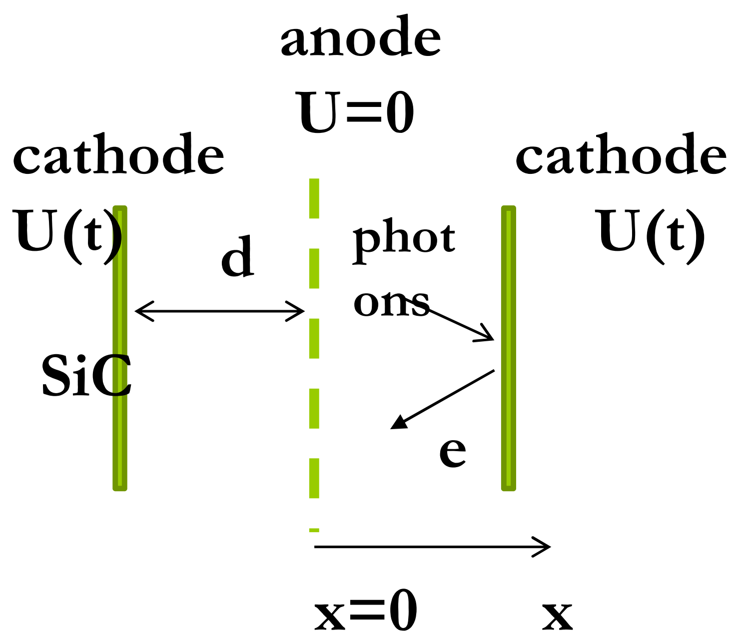
Electron emission from **cathode**:
due to bombardment
- by photons, $\gamma_{ph}$= 0.3
- by ions, $\gamma_i$ (1 in Figure
- by fast atoms, $\gamma_a$ (2 in Figure)

Bokhan, Zakrevskiy, JTF, 77, 109 (2007).

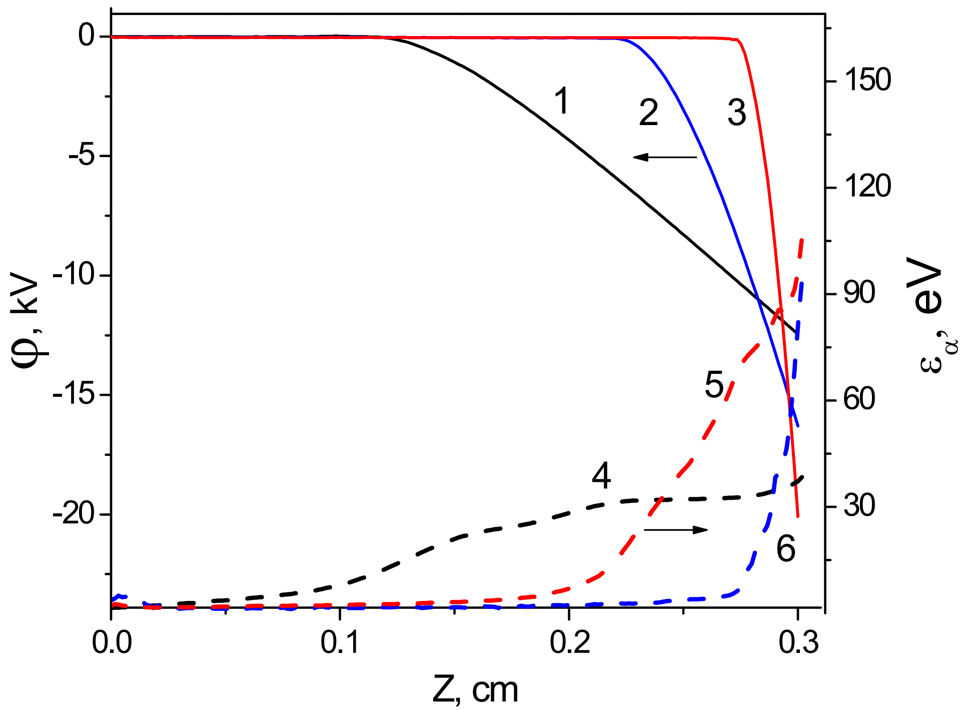



On **anode** grid:
in calculations, grid absorption,
$\alpha$=0.02 for all types of particles,
since in the experiment the grid has 98% transparency.
Electrons with the energy < 100 eV are reflected from the anode grid, because of floating grid potential

# PIC simulation results. Potential distribution.




Electrodes are made from semiconductor ceramics




Potential (1,2,3) and fast atom energy distributions (4,5,6) during breakdown, P=6 Torr, the anode (Z=0), the cathode (Z=0.3 cm).

# Second possible mechanism of subnanosecond breakdown

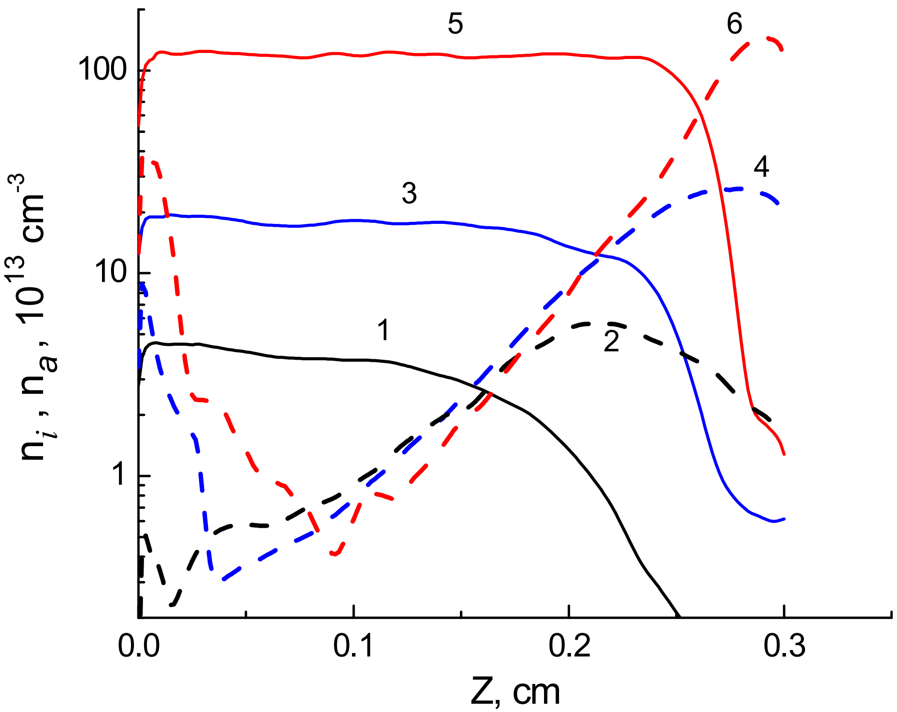
Collisinal excitation transfer (CET) reaction is

$$He_f + He^* = He_f^* + He.$$

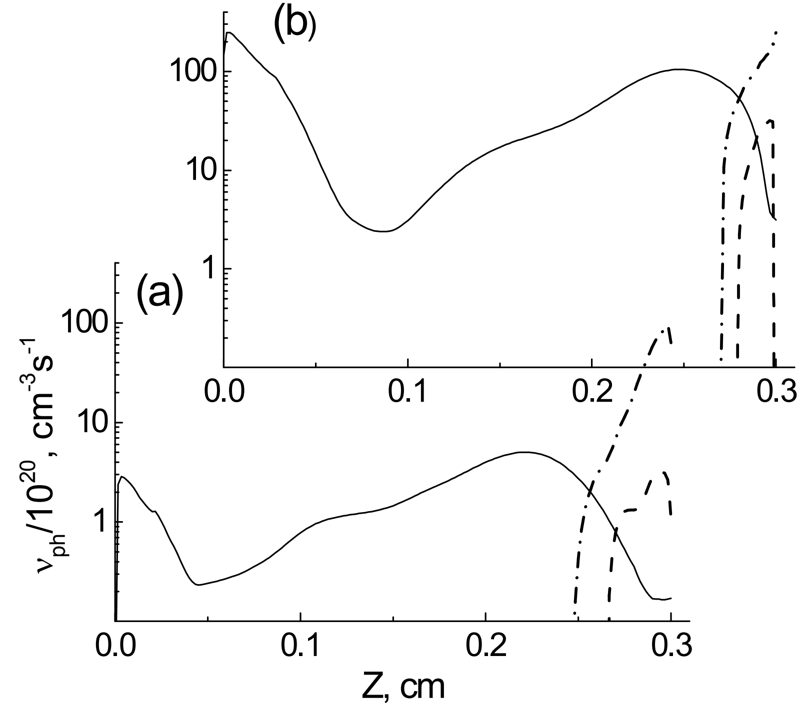
The CET reactions were found to be dominant in the production of DS photons.


1. Schweigert I V, Alexandrov A L, Zakrevsky Dm E, Bokhan P A 2014 Phys. Rev. E 90(5) 051101(R)
2. Schweigert I V, Alexandrov A L, Zakrevsky Dm E, Bokhan P A 2015, Plasma Sources Sci and Technol., accepted

# Density of ions, fast atoms, DS-photon production

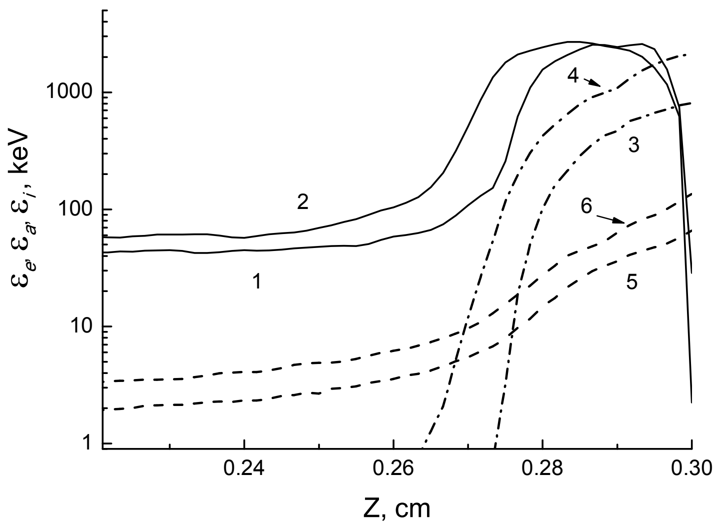


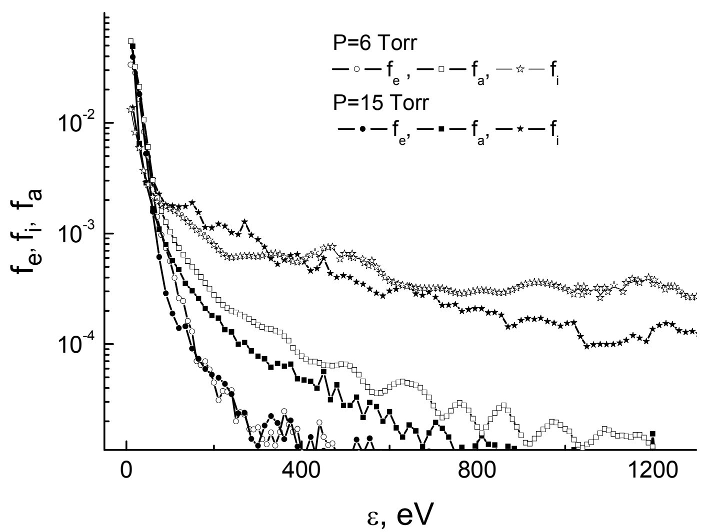

Ion (solid) and fast atom (dashed curves) density distributions at t=52 ns (1,2), 56 ns (3,4), and 60 ns (5,6).




Volume production of Doppler-shifted photons in excitation by ions (dashed), fast atoms (dash-dotted) and in by excitation transfer (solid curves), at t=56 (a) and 60 ns (b)

# Mean energy and energy distribution function

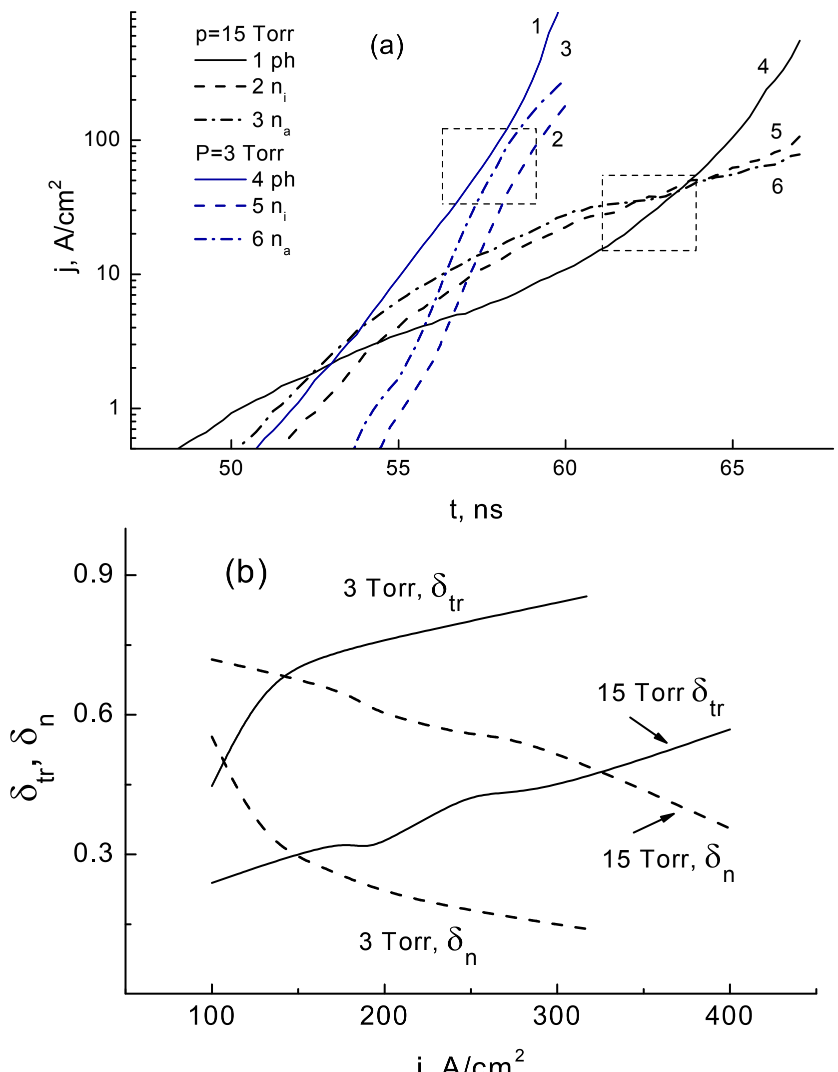



Mean electron energy of electrons (1,2), ions (3,4) and fast atoms (5,6) for j=100 A/cm$^2$, P=15 Torr (1,3,5) and P= 6 Torr (2,4,6).

Energy distribution function for electrons (circles) in the bulk plasma (at z=0.1 cm), and for ions (stars), fast atoms (squares) approaching the cathode, P=6 Torr (open symbols), 15 Torr (solid).

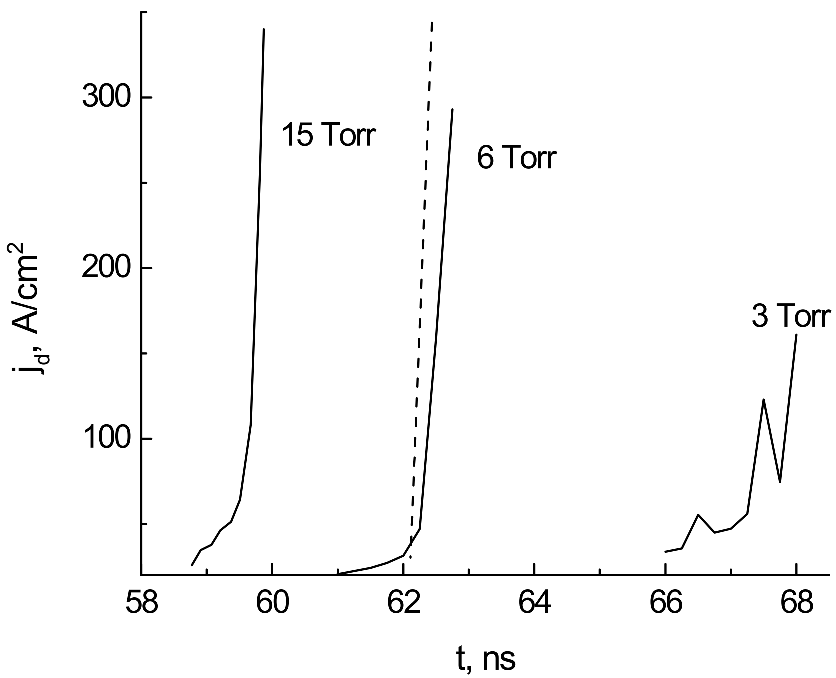
# Contributions in emission current



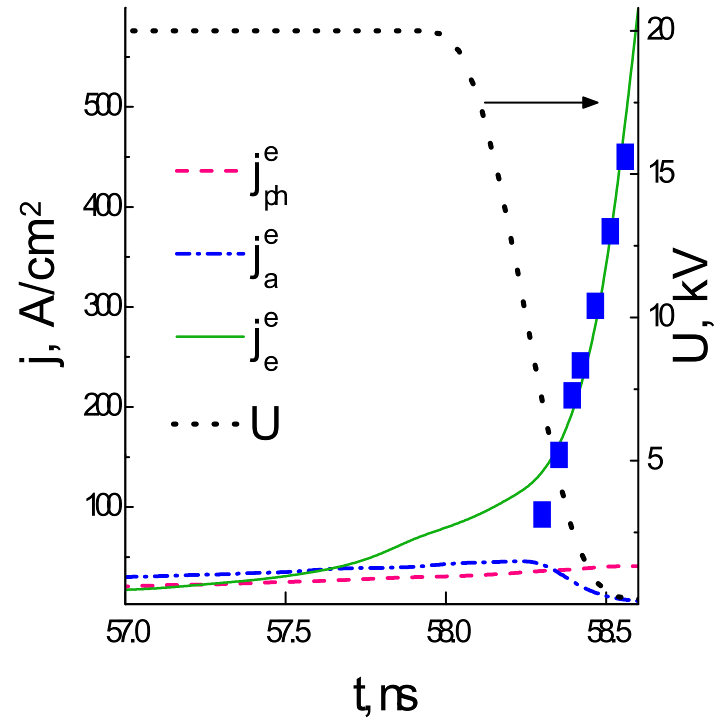

(a) Electron currents from cathode due to photo-emission (1,4), ions (2,5), fast atoms (3,6). 15 Torr (1,2,3), P=3 Torr (4,5,6).

(b) $\delta_n$ is a fraction of DS photons approaching the cathode from excitation by fast atoms and $\delta_{tr}$ is from the CET reactions, $He_f$ + He* = $He_f$* + He, for P=3 Torr and P=15 Torr

# Discharge current during breakdown (experiment and simulations)




Evolution of anode current density for 15 Torr (1), 6 Torr (2) and 3 Torr (3), U=const.




Computed emission current with time at P= 6 Torr.
U decreases during breakdown. □ - experiments

# Conclusion

- We reported results of experimental and theoretical studies of the subnanosecond breakdown in 20 kV open discharge in He for P=3 - 15 Torr.

- The kinetic model of breakdown was developed which includes the production of photons with a Doppler shift due to the excitation of the background atoms by ions, fast atoms and in the collisional excitation transfer (CET) reactions, $He_f + He^* = He_f^* + He$.

- PIC MCC simulations were done with our kinetic model and the CET reactions were found to be dominant in the production of DS photons.

- The measured and calculated breakdown time $\tau_b$ and current growth rate well agree, showing a decrease of $\tau_b$ with gas pressure.