BURSTS OF FAST ELECTRONS GENERATED IN ATMOSPHERIC PRESSURE DISCHARGES BY APPLICATION OF NANOSECOND VOLTAGE PULSES

Natalia Yu. Babaeva, George V. Naidis

Joint Institute for High Temperatures RAS, Izhorskaya 13, Moscow, Russia
nybabaeva@gmail.com

Victor F. Tarasenko

Institute of High Current Electronics SB RAS, Tomsk

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DIFFUSE DISCHARGES

- **Space forms of the diffuse discharge at atmospheric pressure air in point-to-plane or point-to-point gaps depend on voltage pulse rise time, pulse duration and amplitude as well as on the inter-electrode gap.**
- **The diffuse discharge in the gap are usually ignited by electrodes of small radius of curvature.**
- **According to the experiments, the diffuse discharge is attributed to the enhancement of the electric field at the cathode and generation of fast and runaway electrons.**
- **It was also shown that the amplitude of the voltage across the gap can depend on the cathode material.**

[1] N. Yu. Babaeva, Ch. Zhang, J. Qiu, X. Hou, V. F. Tarasenko, Tao Shao, “The role of fast electrons in diffuse discharge formation: Monte Carlo simulation”, Plasma Sources Sci. Technol., vol. 26, Article Number 085008, 2017.

[2] N. Yu. Babaeva , G. V. Naidis , D. V. Tereshonok and E. E. Son, “Development of nanosecond discharges in atmospheric pressure air: two competing mechanisms of precursor electrons production”, J Phys. D: Appl. Phys., vol. 51, Article Number 434002, 2018.

[3] V. F. Tarasenko, “Runaway electrons in diffuse gas discharges”, Plasma Sources Sci. Technol., vol. 29, Article Number 034001, 2020.

AGENDA

- **Description of the model *nonPDPSIM***
- **Diffuse discharges with beams of fast electrons 20 eV and 20 keV: Model study**
- **Two competing mechanisms of precursor electrons production: conventional photoionization and preionization by fast electrons from the cathode**
- **Fast electrons generated from a streamer front**

MODELING PLATFORM:
nonPDPSIM

MODELING PLATFORM: *nonPDPSIM*

- **Poisson's equation:**

$$\nabla\left(\varepsilon\,\nabla\Phi\right)=-\left(\sum_j q_j\,N_j+\rho\right)$$

- **Transport of charged and neutral species:**

$$\frac{\partial N_j}{\partial t}=-\nabla\cdot\vec{\Gamma}+S$$

  - **Charged Species: Γ = Sharffeter-Gummel**
  - **Neutral Species: Γ = Diffusion**

- **Surface Charge:**

$$\frac{\partial\rho}{\partial t}=\left[\sum_j q_j\left(-\nabla\,\vec{\Gamma}+S\right)-\nabla\left(\sigma\left(-\nabla\Phi\right)\right)\right]_{material}$$

- **Electron Temperature:**

$$\partial\left(\frac{3}{2}n_e kT_e\right)/\partial t=S\left(T_e\right)-L\left(T_e\right)-\nabla\cdot\left(\frac{5}{2}\Phi kT_e-\overline{\overline{\kappa}}\left(T_e\right)\cdot\nabla T_e\right)$$

- **Solution:**
  - **Unstructured mesh discretized using finite volumes.**
  - **Fully implicit transport algorithms with time slicing between modules.**

MODELING PLATFORM: *nonPDPSIM*

- **Radiation transport and photoionization:**

$$S_m(\vec{r}_i) = N_m(\vec{r}_i) \cdot \sum_k \sigma_{mk} A_k \int N_k\left(\vec{r}_j{}'\right) G_k\left(\vec{r}_j{}', \vec{r}_i\right) d^3\vec{r}_j{}'$$

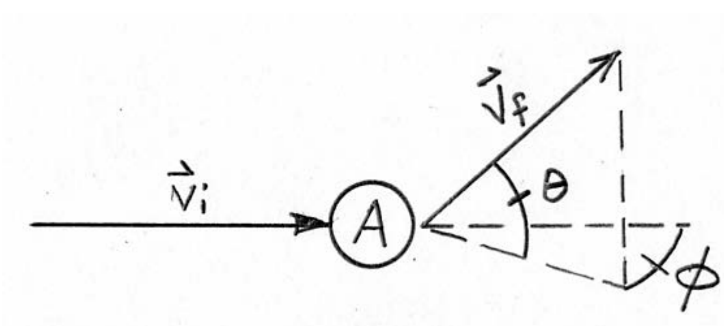
$$G\left(\vec{r}_j{}', \vec{r}_i\right) = \frac{\exp\left(-\sum_l \int_{\vec{r}_j{}'}^{\vec{r}_i} \sigma_{lk} N_l\left(\vec{r}_j{}'\right) d\vec{r}_j{}'\right)}{4\pi\left|\vec{r}_j{}' - \vec{r}_i\right|^2}$$

- **Photoionization processes:**
- **N_2** (higher than $C^3\Pi$):**
  - **$N_2^{**} \rightarrow N_2 + h\nu$ (12.1 eV)**
- **The emitted photons then ionize O_2**
  - **$O_2 + h\nu \rightarrow O_2^+ + e$**

- **Photoinization occurs by absorption of photons emitted by N_2 ($b^1\Pi$, $b'^1\Sigma$) states by O_2 molecules in the wavelength range 98–102 nm.**
- **The gas mixture is atmospheric-pressure air at 300 K. The species included in the reaction mechanism are: N2, N2, N 2 , N+2 , N, O2, O2(1Δ), O+2 , O2(1Σ), O−2 , O−, O, O3 and electrons.**

MONTE CARLO METHOD

- **Conventional fluid equations describe the bulk electrons with relatively low mean energy.**
- **Secondary electron emission generates highly energetic components to the electron energy distribution. The energetic electrons are handled by the kinetic portion of the model using Monte Carlo methods.**
- **Electron pseudoparticles are periodically launched from the surface having weightings proportional to the rate of secondary electron emission by ion or photon bombardment.**
- **The trajectories of the sheath accelerated secondary electrons and their ionization progeny are tracked until they hit boundaries or fall below a specified energy and join the bulk electron distribution.**



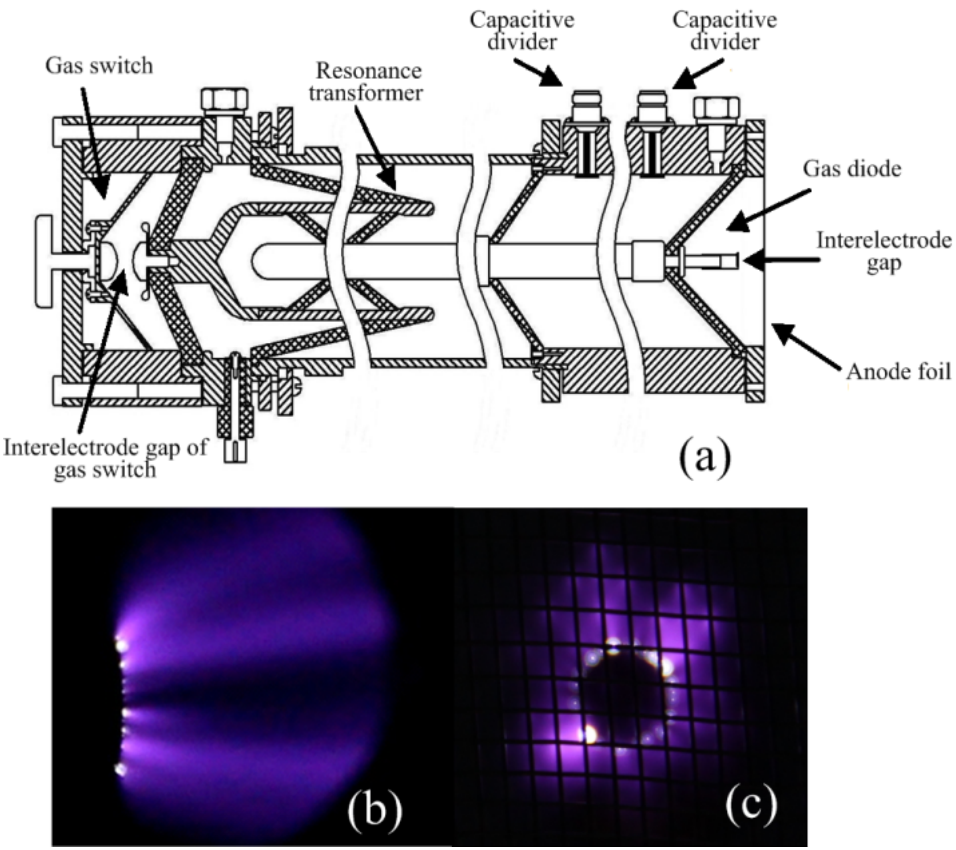
Secondary electron emission by ions (Auger neutralization): When an ion approaches the surface an electron from the surface tunnels into the ion and neutralizes it. If the energy released thereby, *I-W,* is greater than *W* it may be spent on ejecting of another emission electron. The energy difference *I-2W* is thus the kinetic energy of the emitted electron.

M. J. Kushner, J. Appl. Phys*.* **95** (2004) 846.

- L = 7 mm

DIFFUSE DISCHARGE WITH BEAMS OF FAST ELECTRONS 20 EV AND 20 KEV: MODEL STUDY

EXPERIMENTAL SET-UP

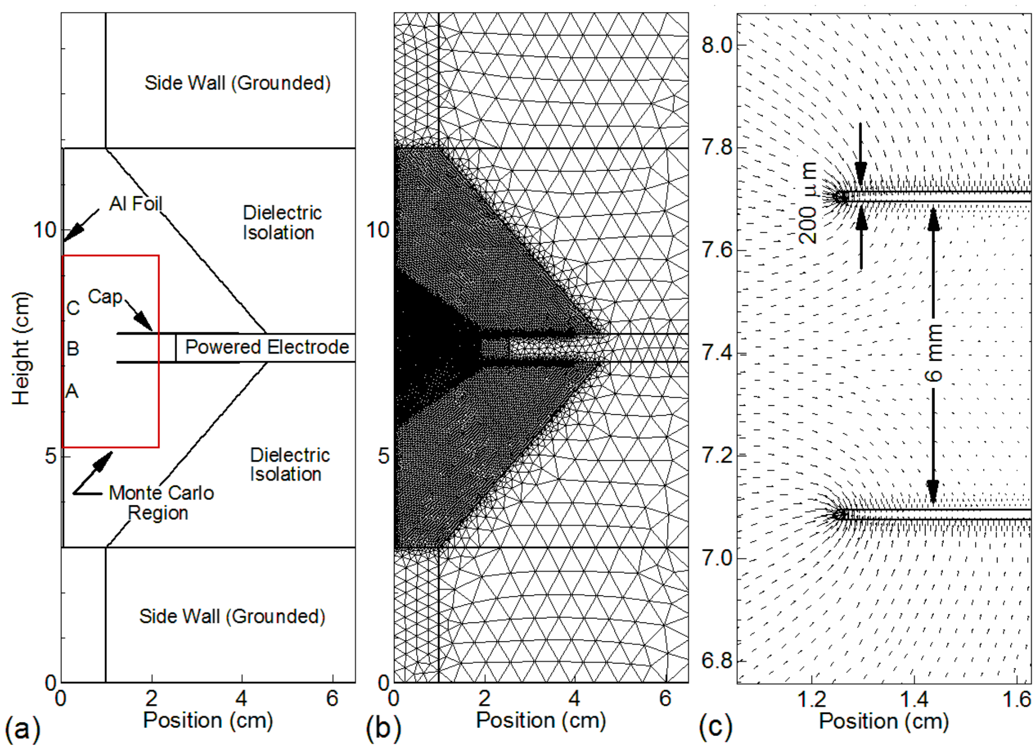


Experimental set-up. (a) Schematic picture of the nanosecond-pulse generator, (b) discharge image from the side view, and (c) discharge image from the front view.

- A VPG-30-200 nanosecond-pulse generator is used to produce the diffuse discharge in atmospheric pressure air. The output voltage pulse has a rise time of ~1.6 ns and a full width at half maximum of 3~5 ns.
- The discharges are created in the gas diode with a tube-to-plane gap.
- The anode is a grounded aluminum foil, the inter-electrode gap is fixed to12 mm.
- The overlapping plasma channels appear in the gap thus indicating the generation of the diffuse discharge.

Zhang C, Tarasenko V F, Gu J, Baksht E K, Wang R, Shao T and Yan P *Phys. Plasmas* 22 123516 (2015).

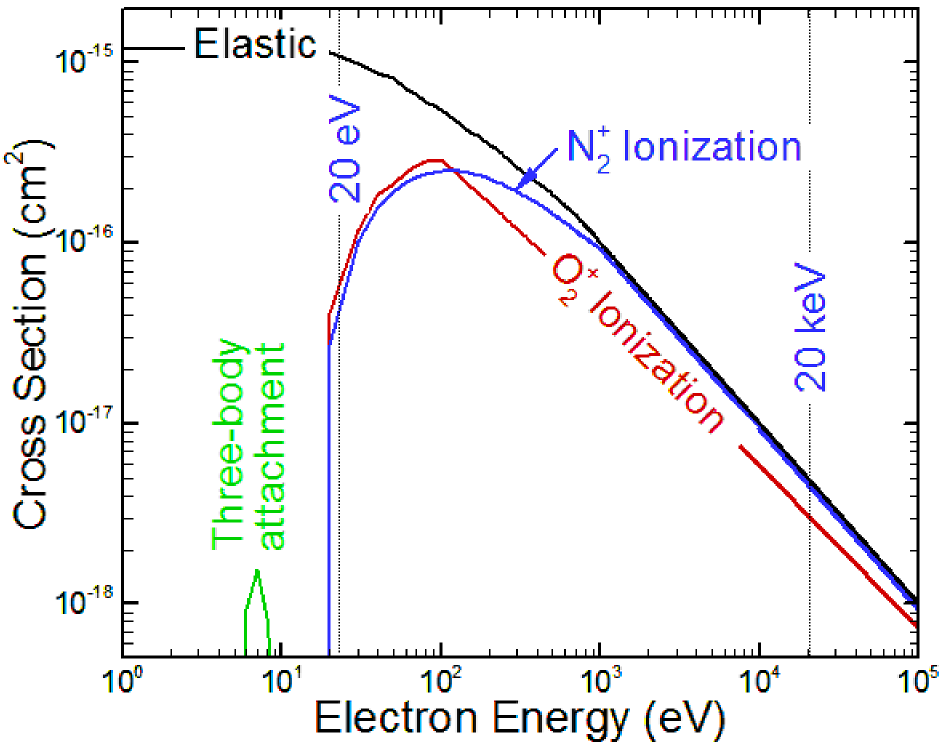
SIMULATIONS: GEOMETRY



- **The discharge is ignited in a cylindrical chamber between a tubular electrode with the inner diameter of 6 mm and thickness of 200 µm and a plane electrode (aluminum foil). The inter-electrode gap spacing is 12 mm.**
- **The unstructured numerical mesh has triangular elements.**
- **The voltage pulse amplitude is 120 kV and the pulse rise time is 1 ns.**

Geometry of the computational region. (a) Cylindrical chamber, (b) meshing of the computational region with several refinement zones, and (c) close-up of the tubular cathode with electric field vectors shown at the full pulse rise time.

AIR CROSS SECTIONS VS ELECTRON ENERGY

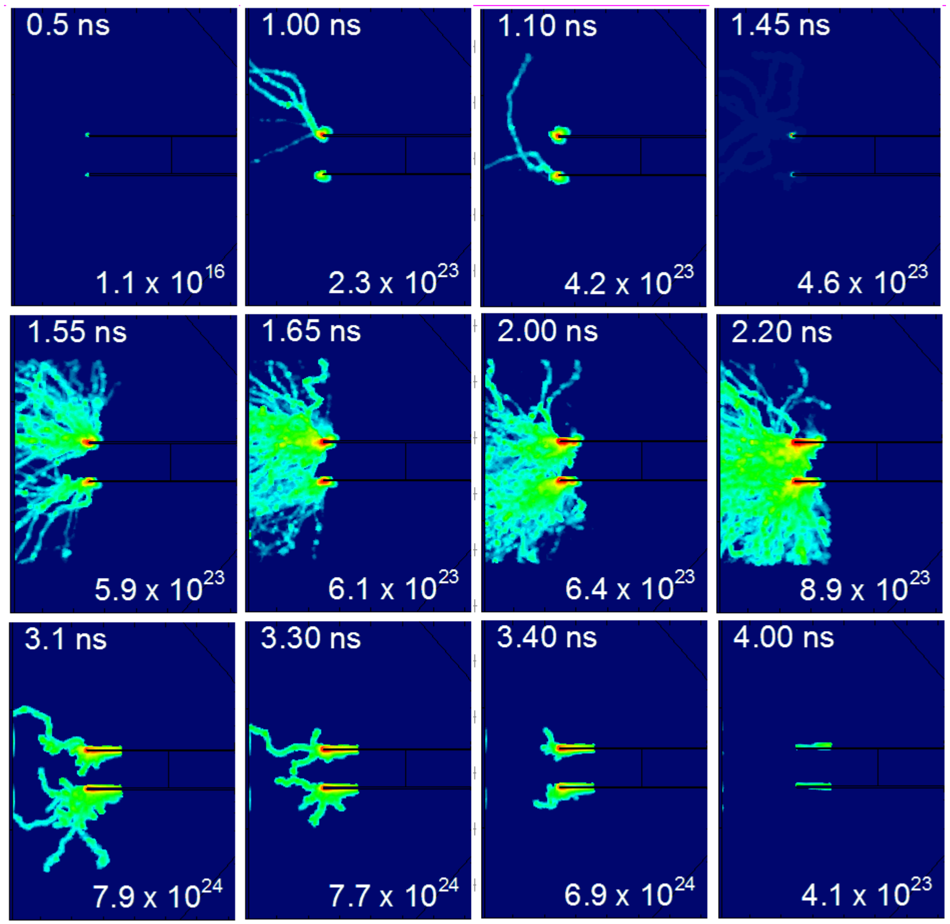


Set of air cross sections vs electron energy

- L = 7 mm
- **In our model simulations, we launch two groups of beam electrons.**
- **One group is a low energy beam of 20 eV. In this case, the electron collisions with neutral particles dominate. These electrons decelerate in the neutral gas and are quickly thermalize while populating bulk electrons ensemble.**
- **The second group of beam electrons (20 keV) belongs to the energy range with decreasing cross sections well beyond the ionization threshold.**
- **These fast electrons can travel almost without collisions through the entire inter-electrode gap. They are continuously accelerated by the electric field and may transit into the runaway mode.**

IONIZATION SOURCES BY FAST ELECTRONS (20 eV)

20 eV

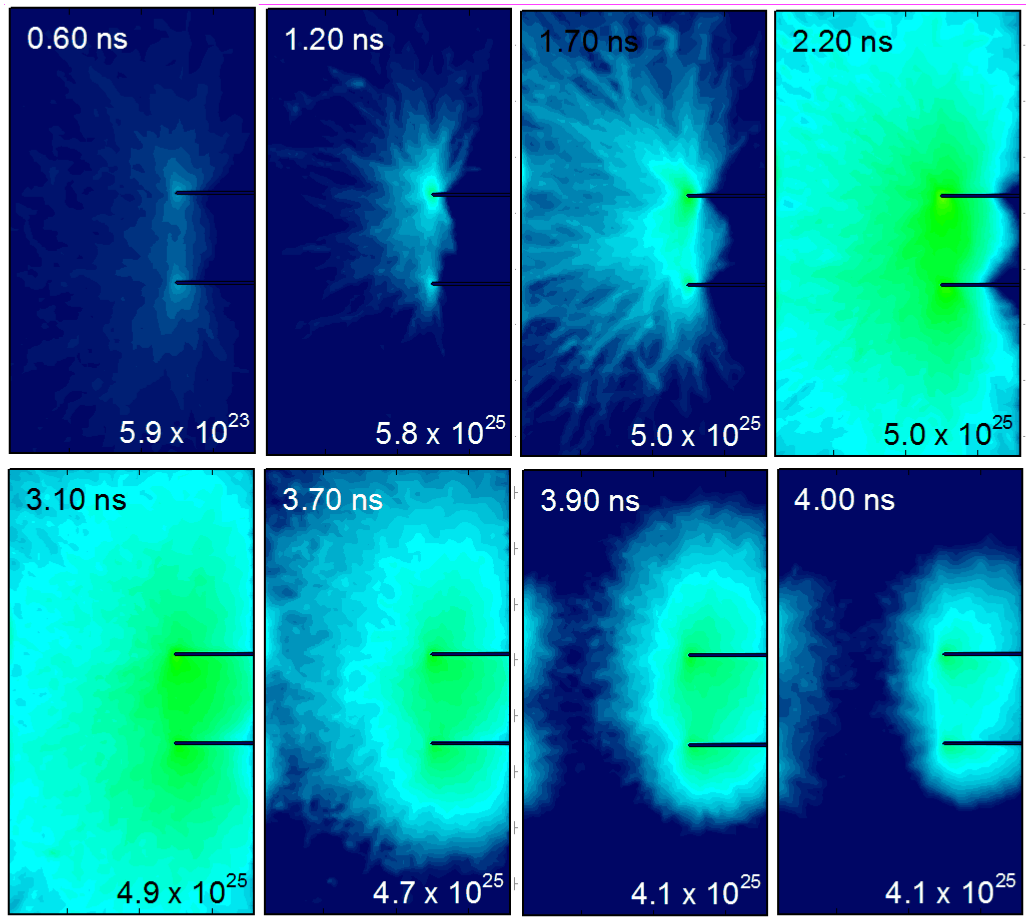


- **The majority of the initial beam electrons lose their energy on elastic scattering, excitation and ionization.**
- **The number of the fast electrons decreases as they move towards the anode.**
- **The electron can be scattered transversely to the initial trajectory.**

Ionization sources S_e (cm^{-3} s^{-1}) produced by electrons of the initial beam of 20 eV. The sources indicate trajectories of fast electrons. Due to collisions, the trajectories are bent and screwed.

IONIZATION SOURCES BY FAST ELECTRONS (20 keV)

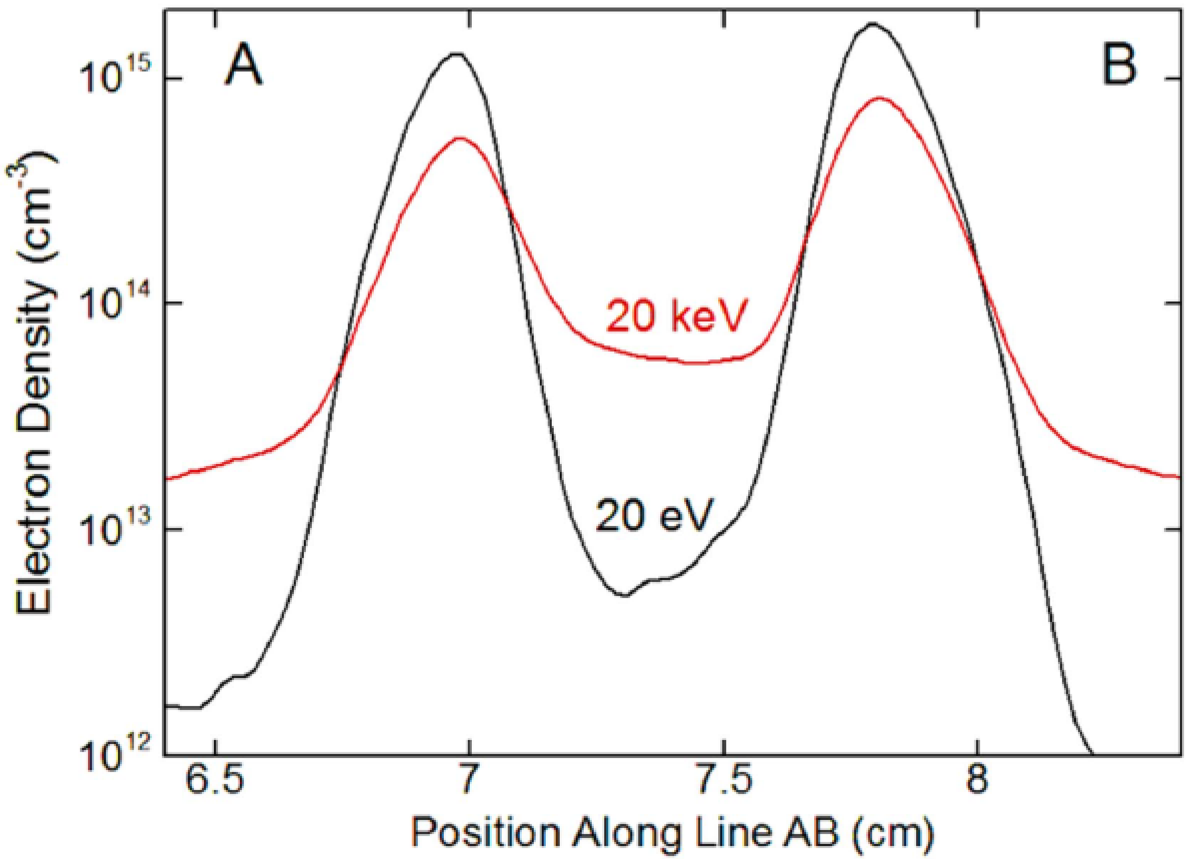
20 keV



- **Ionization sources produced by electrons of the initial beam of 20 keV**
- **Due to small collision frequencies, the trajectories are strait lines.**
- **The avalanches overlap and result in essential pre-ionization in the gap.**

ELECTRON DENSITY PROFILES: 20 eV vs 20 keV

- L = 7 mm



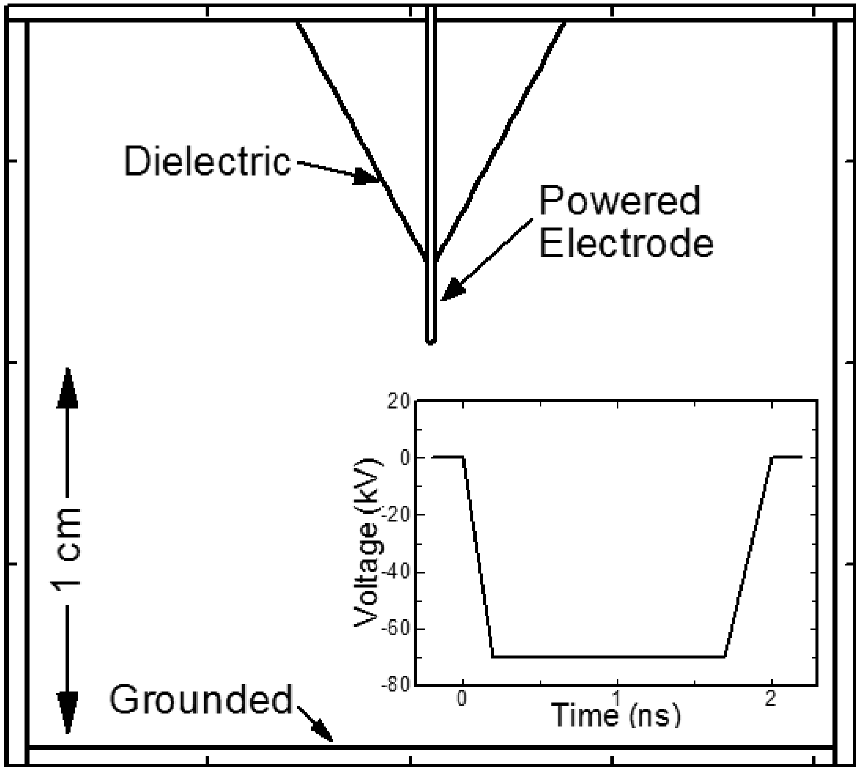
- **Electron density profiles for initial beams of electrons 20 eV and 20 keV.**

TWO COMPETING MECHANISMS OF PRECURSOR ELECTRONS PRODUCTION: CONVENTIONAL PHOTOIONIZATION AND PREIONIZATION BY FAST ELECTRONS FROM THE CATHODE

TWO COMPETING MECHANISMS

- **Domination of one or another mechanisms depends on the pulse duration and voltage amplitude.**
- **We treat low energy electrons with the fluid model, while energetic beam electrons are treated in a fully kinetic manner by using Electron Monte Carlo Simulation.**
- **To discriminate between the two mechanisms we simulate a negative streamer evolution under conditions when**
  - **photoionization is zero/non-zero**
  - **fast electrons are present/absent.**
- **In the absence of all factors producing the precursor electrons the streamer eventually stalls.**
- **We show that the effect of fast electrons on streamer evolution is similar to that of the photoionization but it is more stochastic by nature.**
- **The domination of one or another of the mechanisms considered depends on the pulse duration and voltage amplitude (other conditions being equal).**

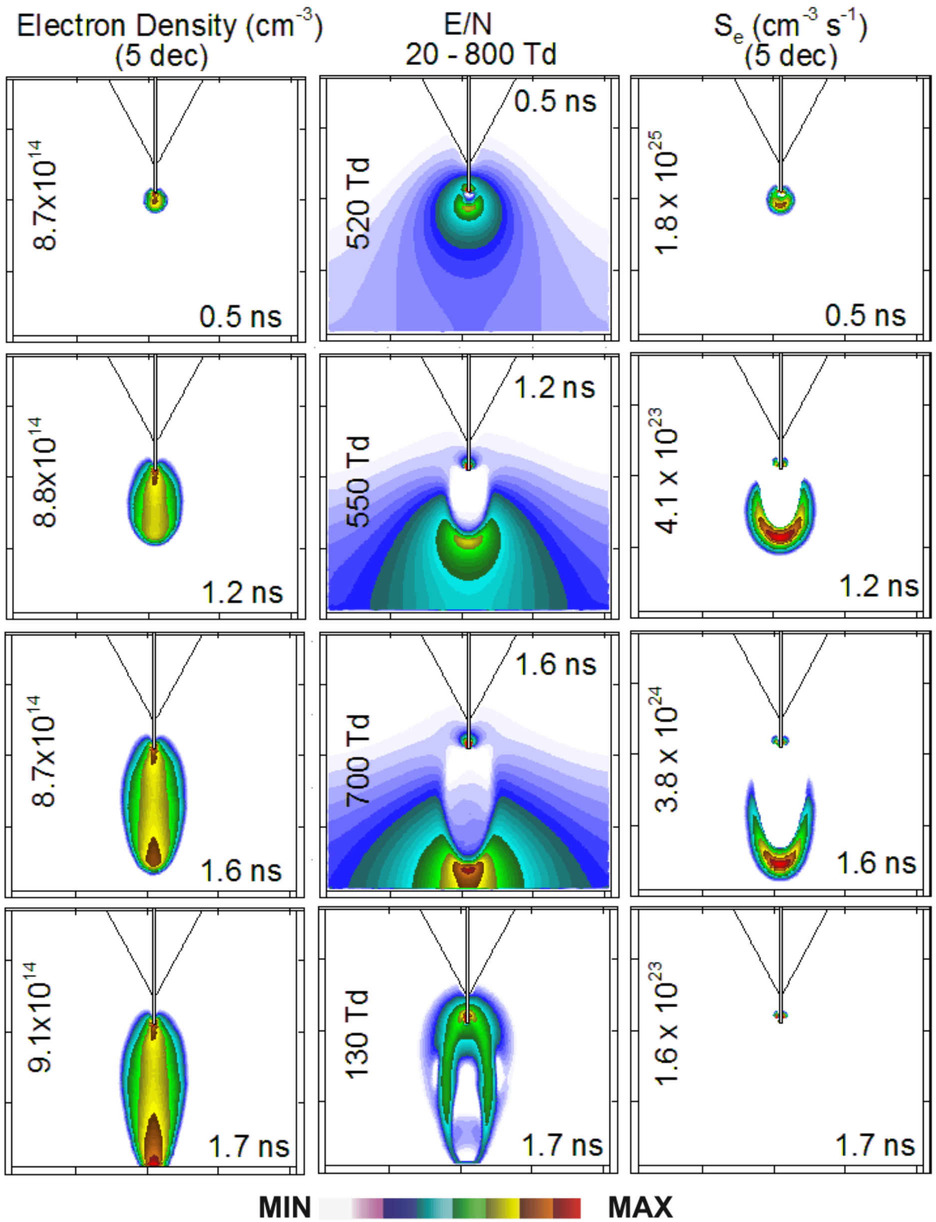
GEOMETRY AND CONDITIONS



- The negative high voltage pulse is applied to the top electrode with amplitude −70 or −100 kV
- Pulse rise time is 0.2 ns and the total pulse duration is 2 ns.
- The electrode radius of curvature is 100 μm. The gas gap is 1 cm.

- The cathode is bounded by dielectric having $\varepsilon/\varepsilon_0 = 3.5$.
- The modeling is performed in 2D planar geometry. Because of using statistical module for the fast Monte Carlo electrons there is no symmetry across the electrode (cathode).
- Sources responsible for photoionization (*Sph*) or for the production of fast electrons from EMCM (*SMC*) are included into (or excluded from) the right-hand-side of the continuity equations.

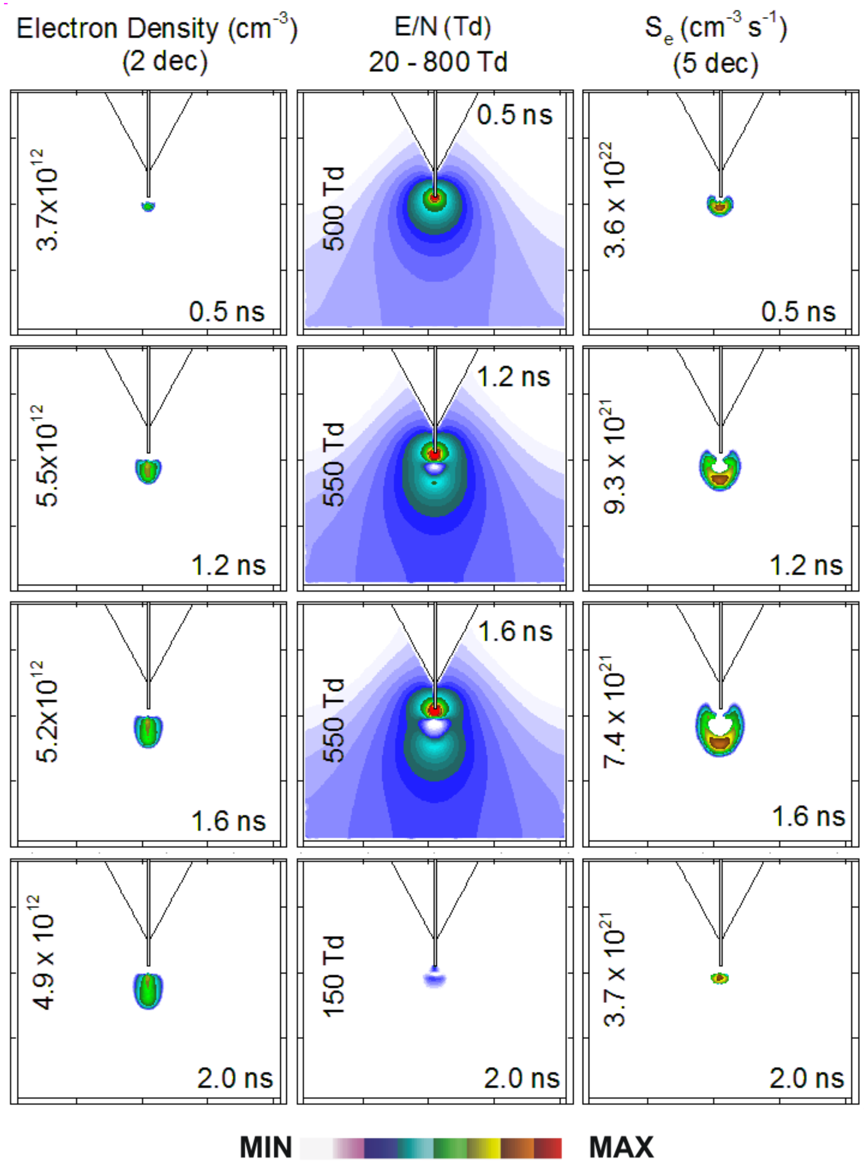
CONVENTIONAL STREAMER



- **Evolution of a streamer with 'conventional' photoionization mechanism for precursor electrons production. A streamer is initiated in the high electric field near the cathode. The streamer then moves towards the plane anode.**
- **The streamer bridges the gap thus producing the quasi-neutral channel with plasma density exceeding 9×10^{14} cm−3. The propagation time of the streamer across the 1 cm gap is 1.7 ns, resulting in a streamer speed of 5.8×10^{8} cm/s.**

Conditions: −70 kV, photoionization source *Sph* is included, the source term for fast electrons *SMC* is excluded.

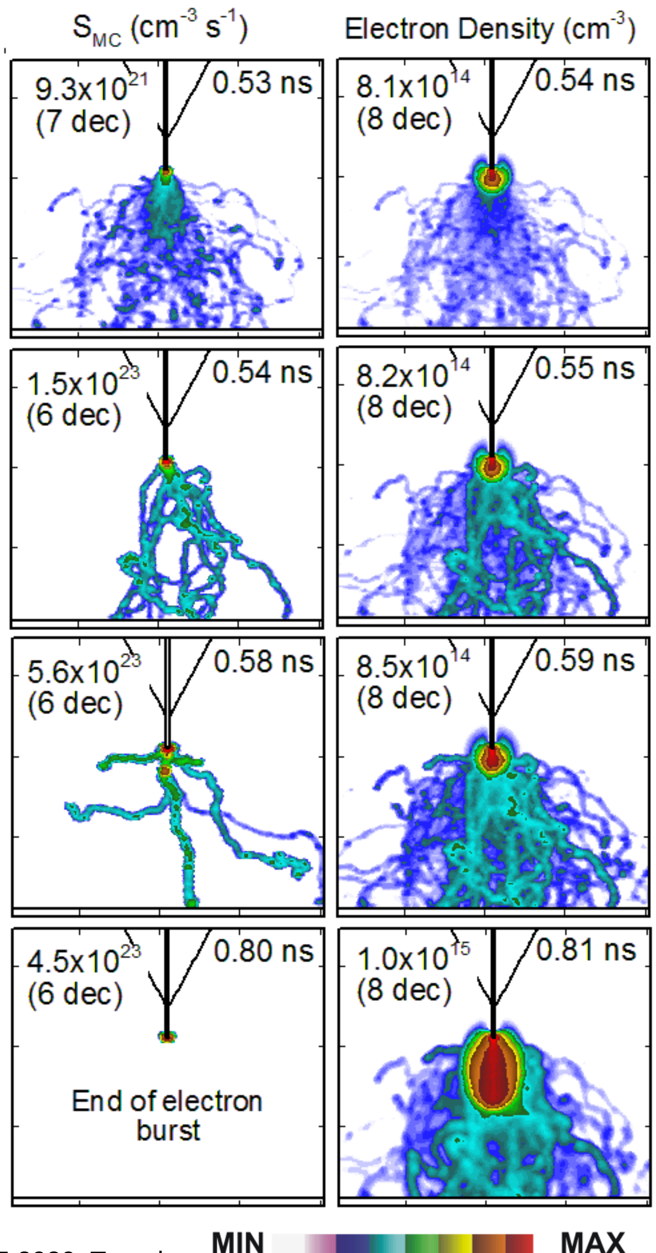
ALL SOURCES FOR PRECURSOR ELECTRONS ARE ABSENT: STREAMER STALLS



- **Evolution of the negative streamer in the absence of any mechanism for precursor electron formation.**
- **The streamer crosses approximately 1/3 of the gap and then fails to propagate.**
- **It eventually stalls, the electric field decays and, as a consequence, the electron impact ionization source *Se* vanishes.**

Conditions: −70 kV, photoionization source *Sph and* the source term for fast electrons *SMC are* excluded.

PREIONIZATION ONLY BY FAST ELECTRONS: -70 kV



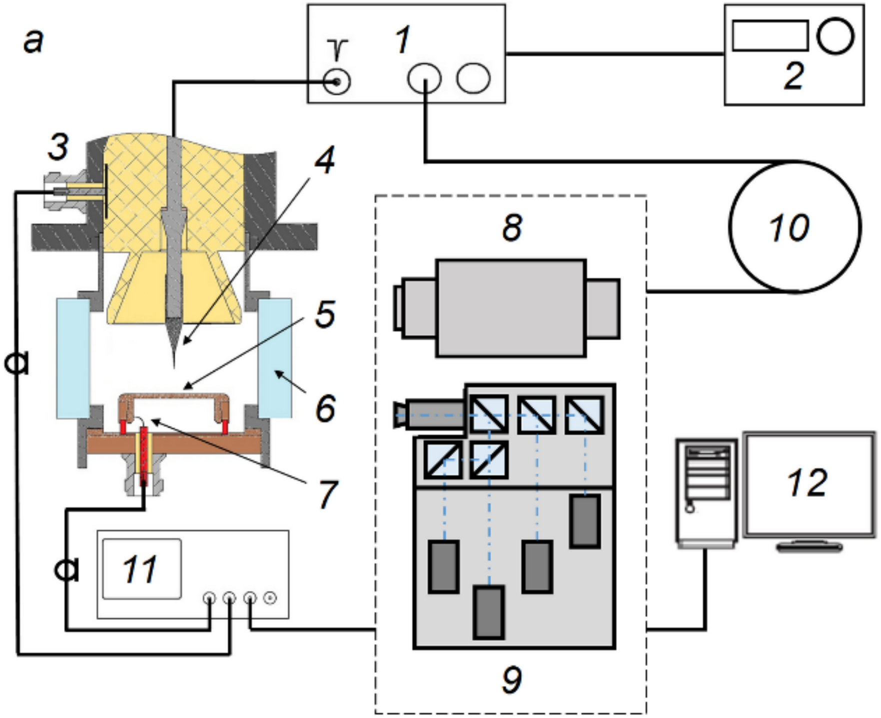
- **The accelerated fast electrons form avalanches, whose trajectories are clearly visible.**
- **Due to collisions, the trajectories of these electrons are bent and screwed.**
- **The tracks of electron densities shown in the second column replicate the tracks of fast electrons sources shown in the first column.**
- **The burst of fast electrons terminates at 0.58–0.6 ns. The termination is caused by the screening of the electric field by the space charge of already developed streamer.**
- **At *t* > 0.8 ns the streamer propagates through the background of electron density produced earlier by fast electrons.**

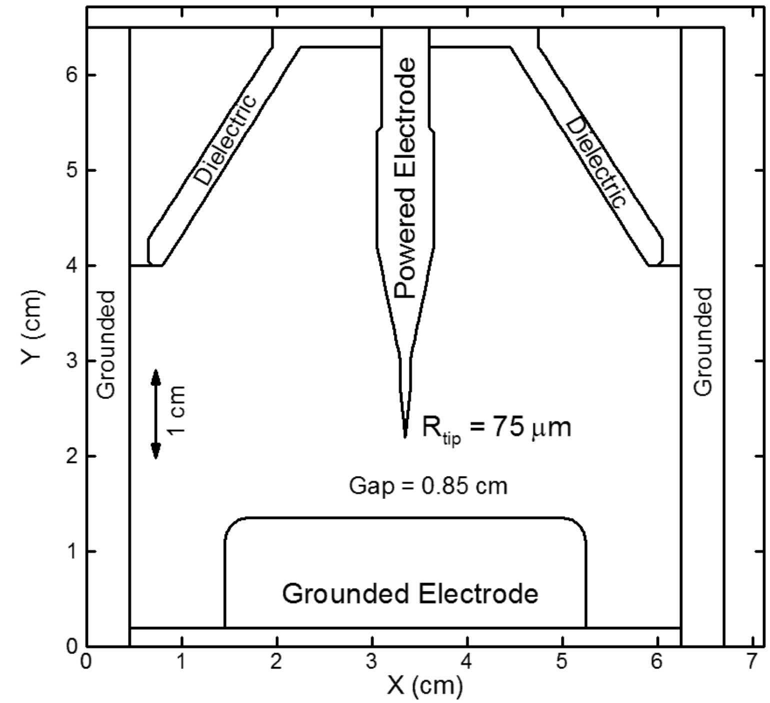
Conditions: −70 kV, photoionization source *Sph is excluded* the source term for fast electrons *SMC is in*cluded.

- L = 7 mm

FAST ELECTRONS GENERATED FROM STREAMER FRONT

EXPERIMENTAL SET-UP AND COMPUTATIONAL REGION



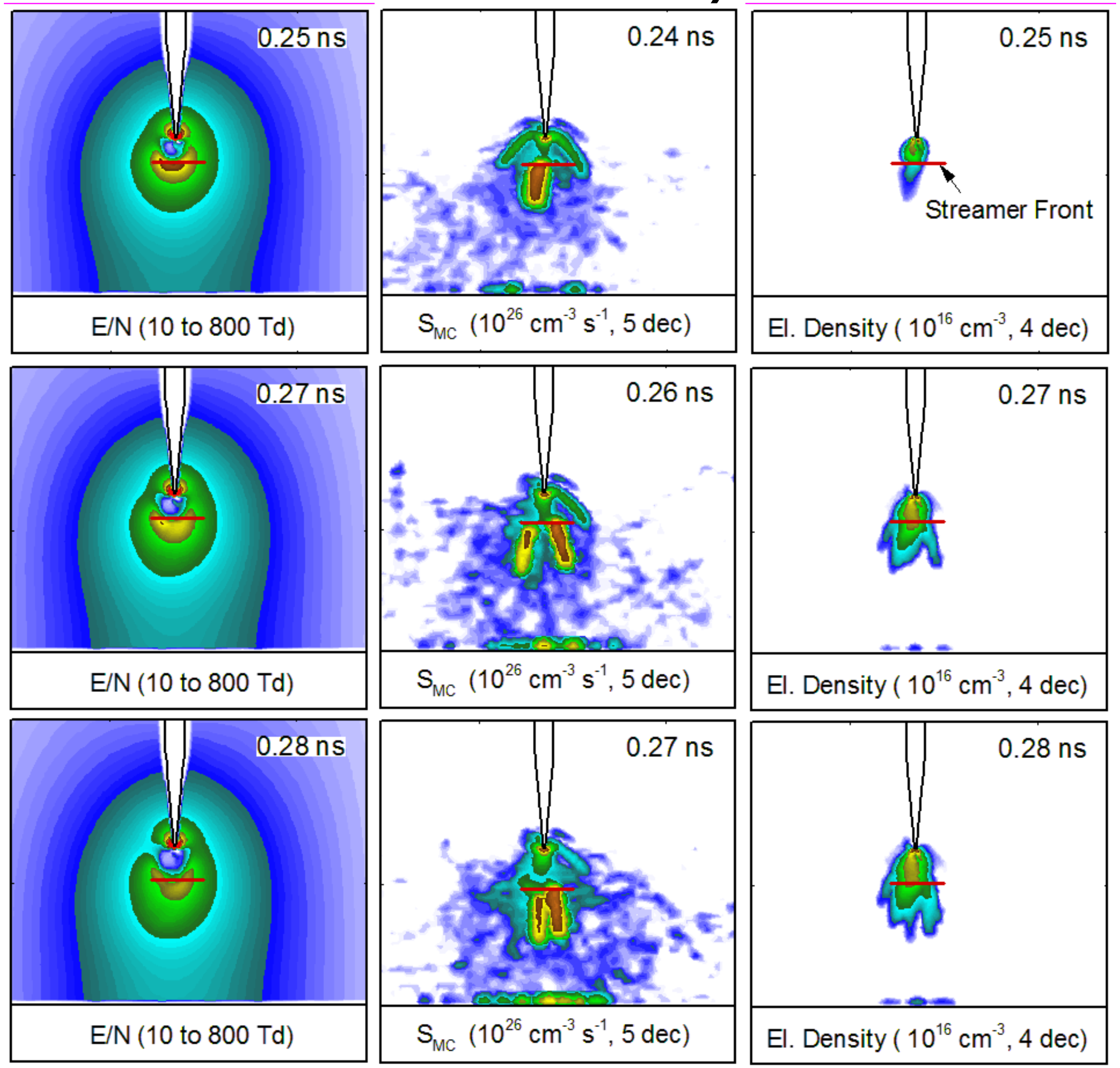


Experimental set-up and geometry of the computational region

- **The discharge is initiated near the cathode having a small radius of curvature and propagates towards the flat anode.**
- **The electric field near such electrodes is amplified resulting in the formation of fast and runaway electrons which ensure the diffuse discharge formation.**
- **The pulse is of 2 ns duration, 0.2 ns rise and 0.2 ns fall time with a peak voltage 100 kV.**

FAST ELECTRONS GENERATED FROM STREAMER FRONT

- E/N
- S_{MC} (tracks of fast electrons)
- Electron density

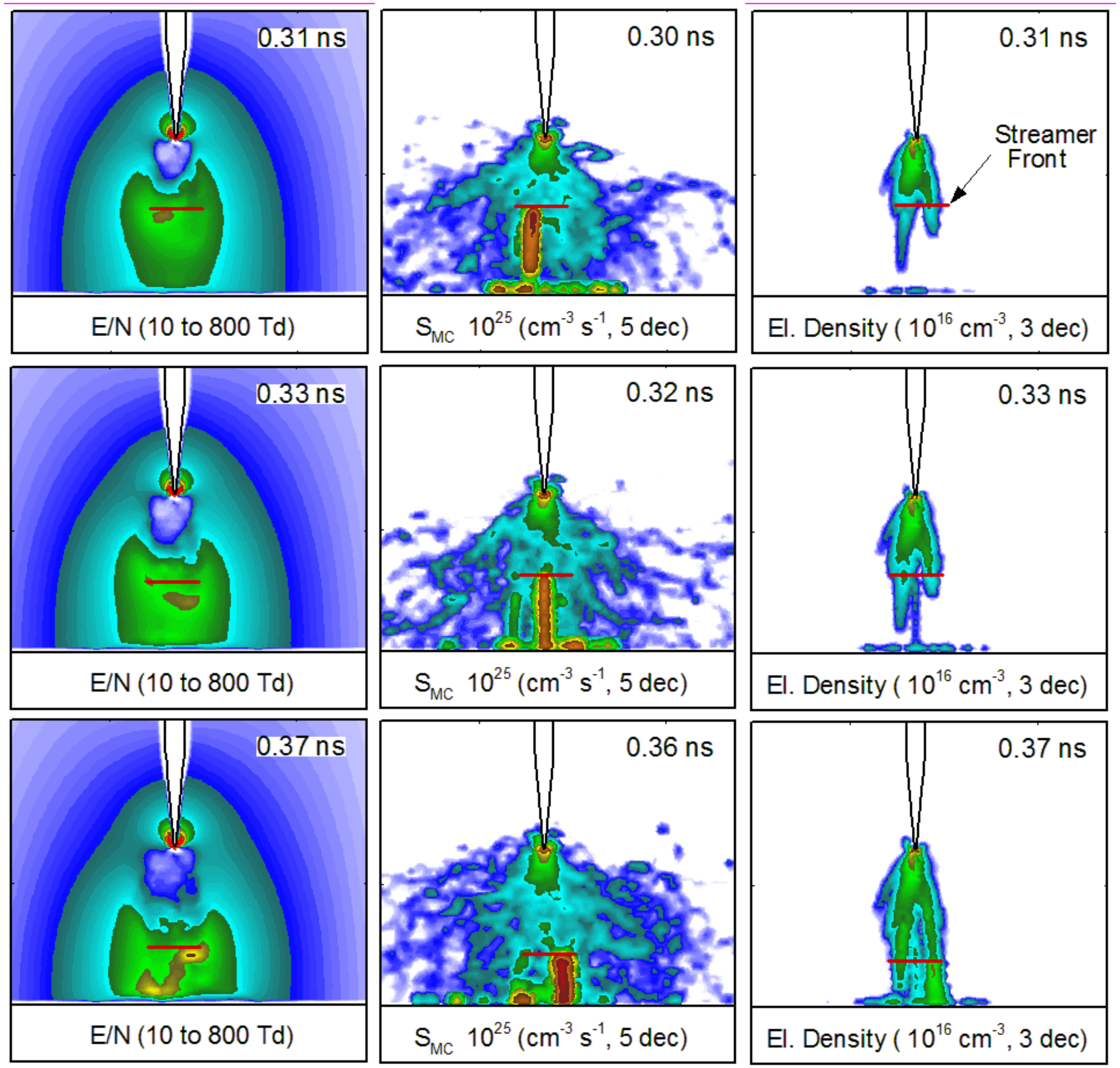


- **Tracks of fast electrons obtained from Monte Carlo simulations.**
- **Red lines in each frame indicate the position of the moving streamer front.**
- **Fast electron emitted from the cathode are visible in these frames as the blue background.**
- **Fast electrons can be also produced in the streamer head where the electric field is high enough to further accelerate the electrons and their progenies.**
- **More intense tracks of fast electrons first appear at the front of the streamer after the streamer travels approximately 1/4 of its path.**

MIN MAX

FAST ELECTRONS FROM STREAMER FRONT (CONTINUED)

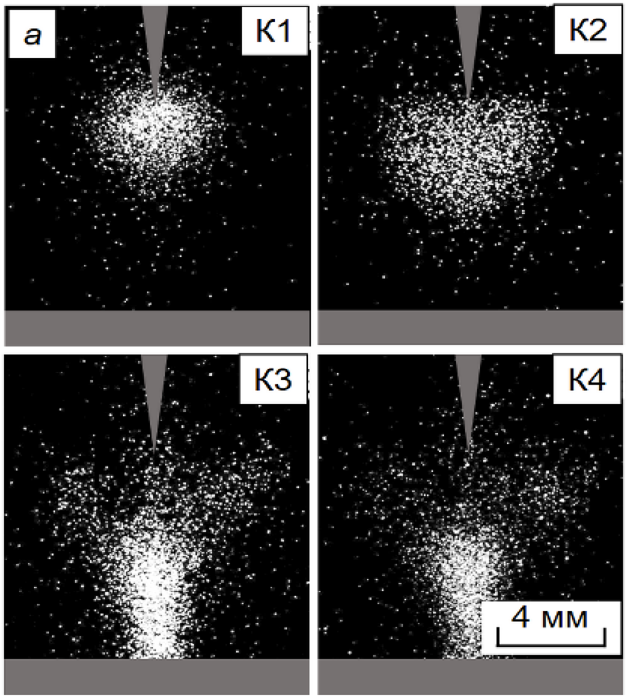
- E/N
- S_{MC} (tracks of fast electrons)
- Electron density



- **We demonstrate that fast electrons can be also produced in the streamer head where the electric field is high enough to further accelerate the electrons and their progenies.**
- **These intensive tracks first appear when the streamer crosses approximately 1/4 of the gap.**

MIN MAX

IMAGES OF STREAMER GLOW



- **Images of streamer glow formed in the point-to-plane gap filled with atmospheric pressure air**

- **Electron density (simulations)**

Dmitry V. Beloplotov, Dmitry E. Genin, Dmitry S. Pechenitsin “**The polarity effect of nanosecond voltage pulses on the propagation of streamers in a point-to-plane gap filled with air**”

CONCLUSIONS

- In this work, the structure and dynamics of a negative streamer in nanosecond pulsed discharges have been investigated computationally using 2D fluid and fluid-EMCS model.
- We analyze the mechanisms of diffuse discharges formation and demonstrate the role of fast electrons in the atmospheric pressure gas breakdown.
- We show that the effect of fast electrons on streamer evolution is similar to that of the photoionization but it is more stochastic by nature. Two competitive mechanisms of the negative streamer propagation—photoionization and pre-ionization by fast electrons were investigated.
- We demonstrate that fast electrons can be also produced in the streamer head where the electric field is high enough to further accelerate the electrons and their progenies.