MeVArc 2013

1D PIC/DSMC computer modeling of near-cathode plasma layers and expansion of cathode plasma flare of vacuum arc cathode spot

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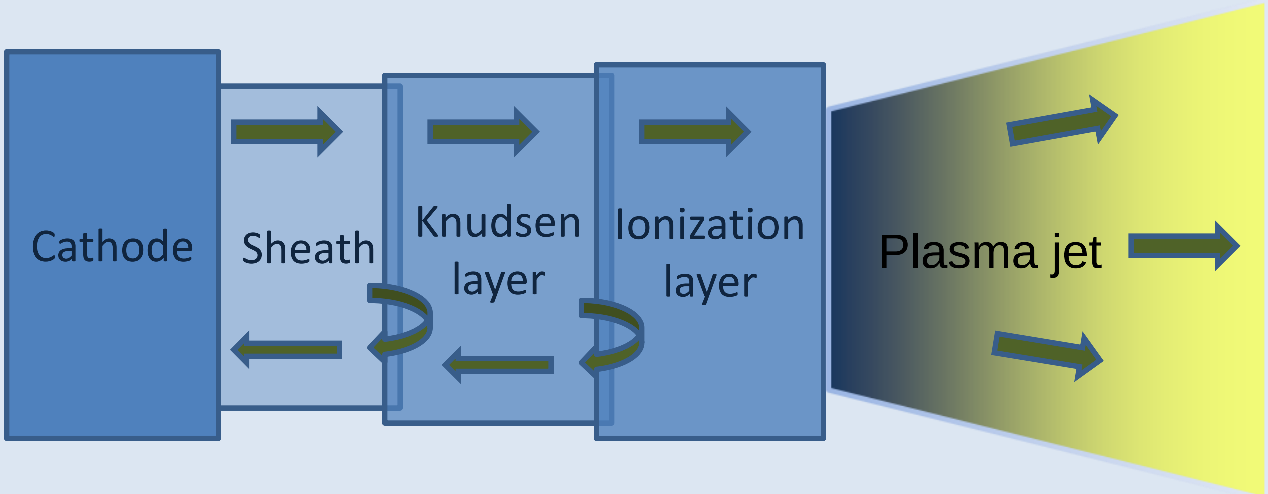
Near-cathode plasma layer of cathode spot



As it widely assumed, the near-cathode plasma layer consists of   the several partially interpenetrating sub-layers responsible for different physical processes. However, this separation is not unique one and demands many additional assumptions.

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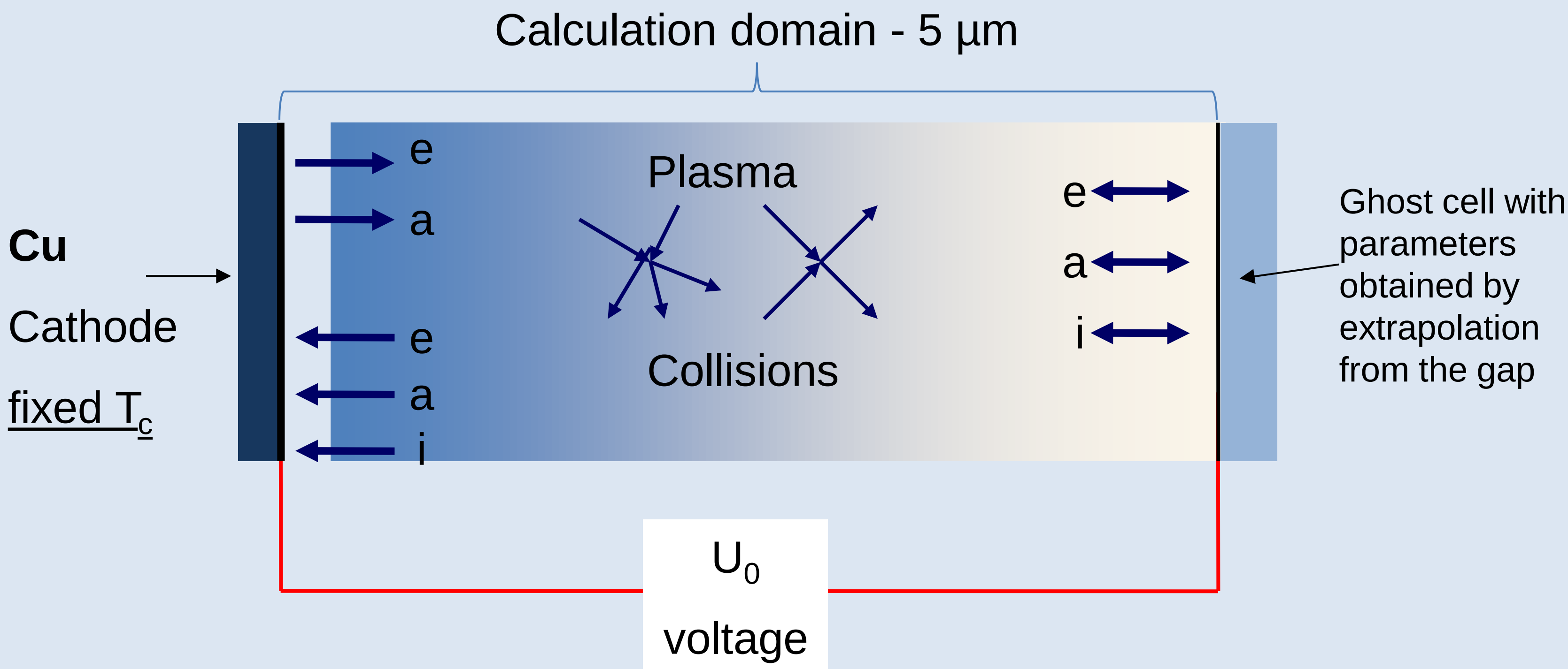
1D3V PIC/DSMC model of cathode layer

Problem geometry



Flux of the atoms from the cathode is calculated according to Hertz-Knudsen approximation

$$nv_a = \frac{P(T_0)}{\sqrt{2\pi \cdot m_a \cdot T_0}}$$

Flux of the electron is calculated according to Murphy and Good approx.

$$nv_e = \int_{-W_a}^{\infty} D(E,W)\,N(W,T_0,\phi)\,dW$$

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1D3V PIC/DSMC model of cathode layer

Main features

- Motion of the electrons, ions and atoms and the non-Coulomb collisions between them are calculated with the help of 1D3V electrostatic Particle-In-Cell and Direct Simulation Monte Carlo (PIC/DSMC) methods.
- Coulomb collisions between the charged particles are calculated according to the Takizuka and Abe method.
- Cu^{+}, Cu^{+2}, Cu^{+3}, Cu^{+4} ions are considered.
- Several excitation levels for Cu^{0} and Cu^{+} taken into account.
- Charge transfer reaction and elastic momentum transfer scattering are considered for the atom-ion interaction.
- Electron-ion three-body recombination is considered.

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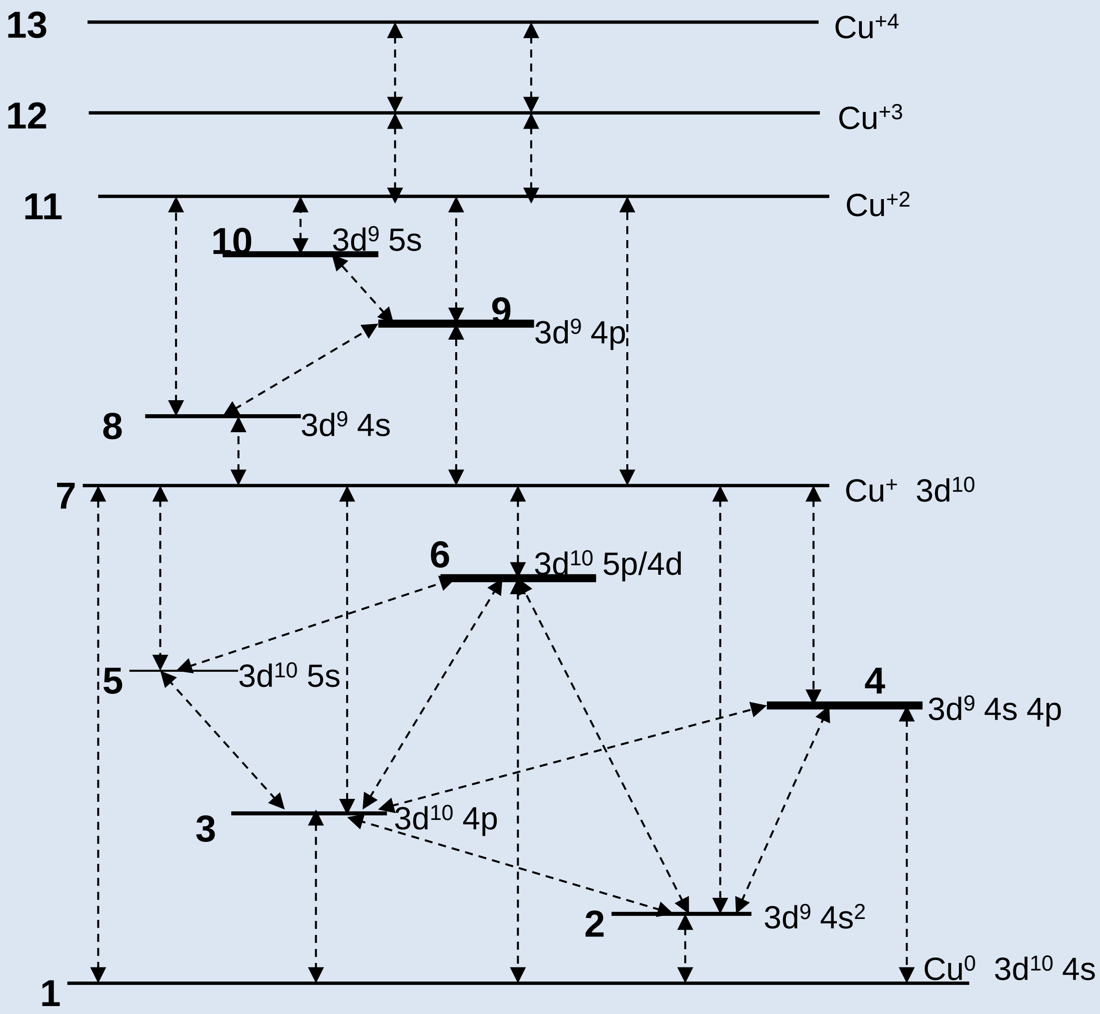
Scheme of transitions used for calculations of inelastic electron-atom and electron-ion scattering



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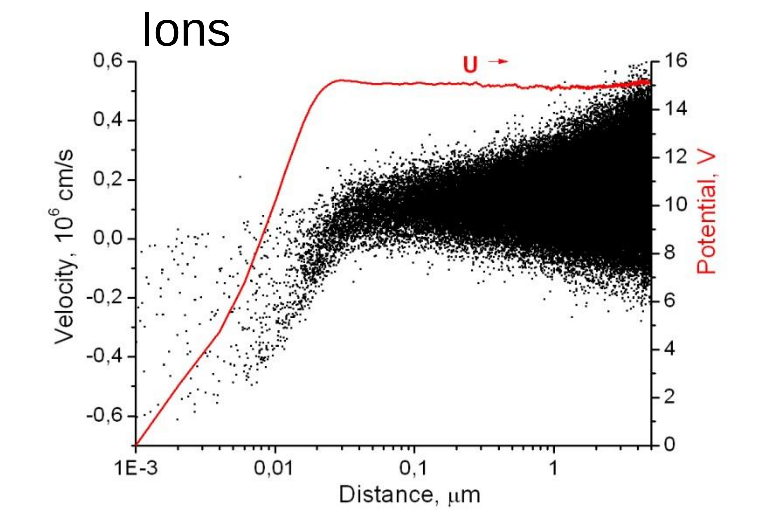
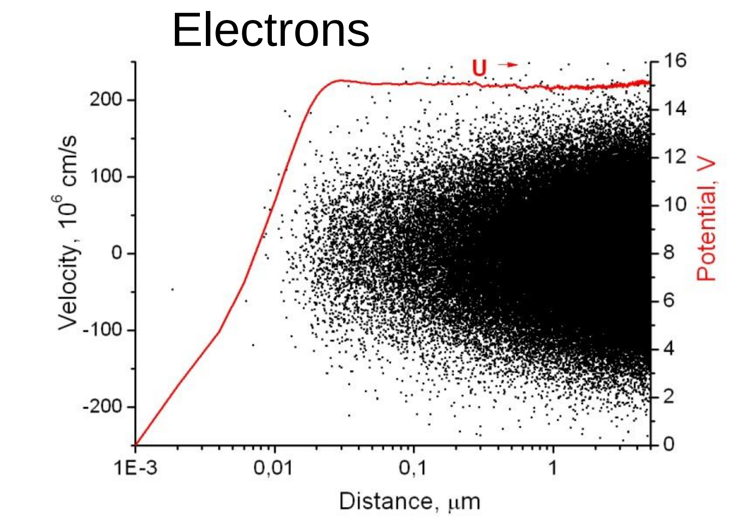
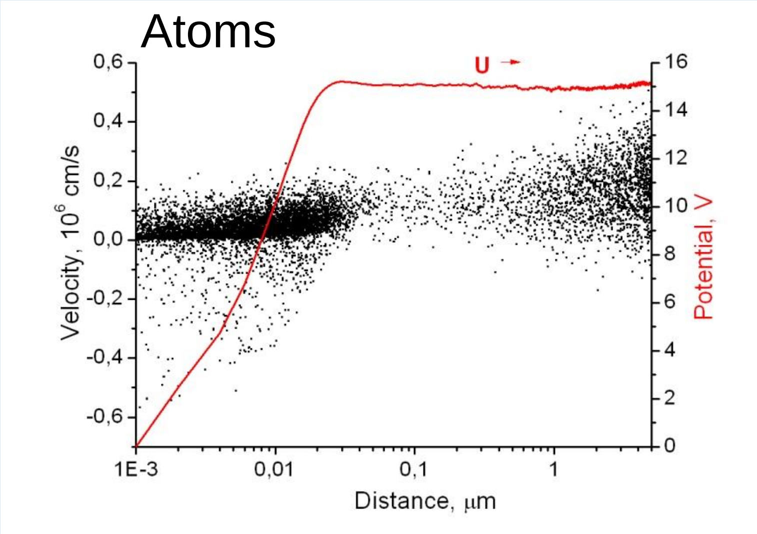
1D3V PIC/DSMC model of cathode layer

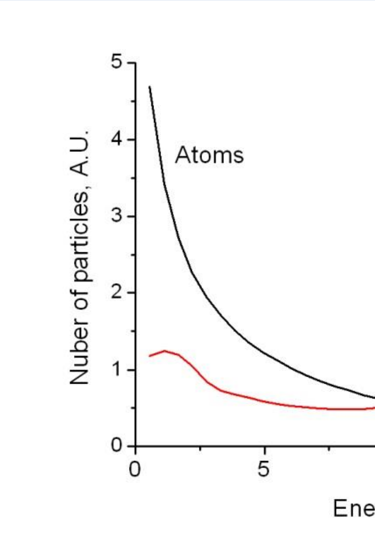
Results

T_c=4100 K, U_0=15 V.









Distribution of particles returned to cathode

Cathode sheath is collisional layer for ions

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1D3V PIC/DSMC model of cathode layer

Results (2)

Plasma parameters for two set of control parameters

I) T_c=3800 K, U_0=20 V.

II) T_c=4100 K, U_0=15 V.

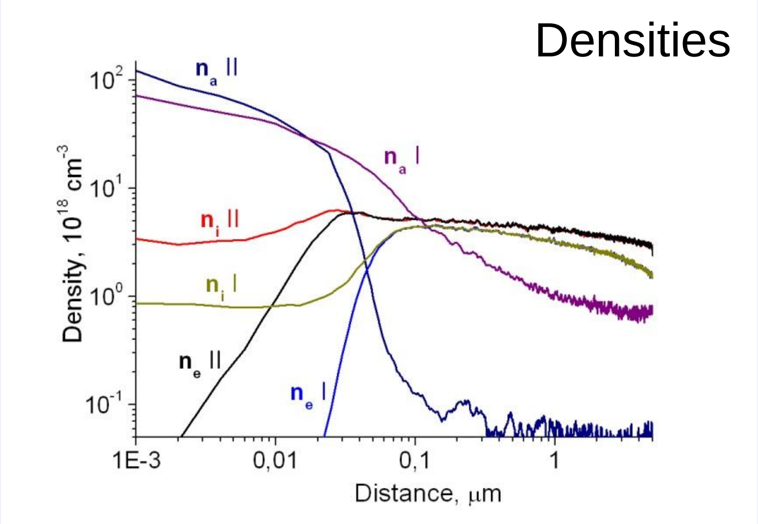
Typical values:

n_e, n_i - 10^{18}-10^{19} cm^{-3}

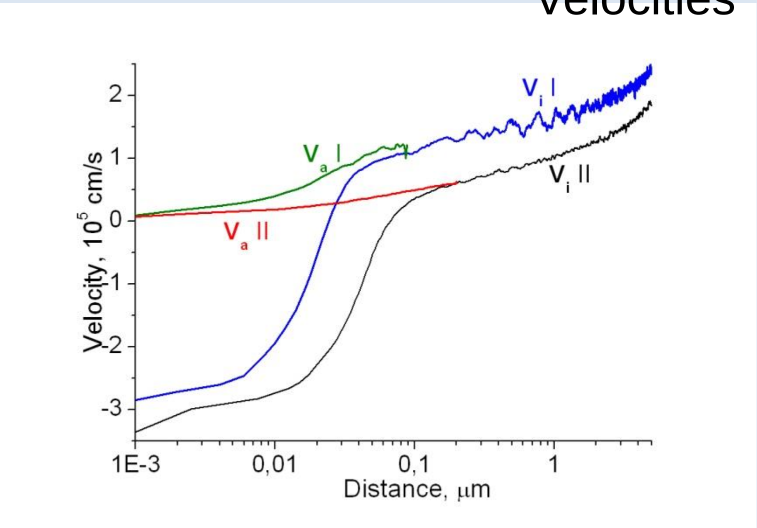
n_a~ 10^{20} cm^{-3}

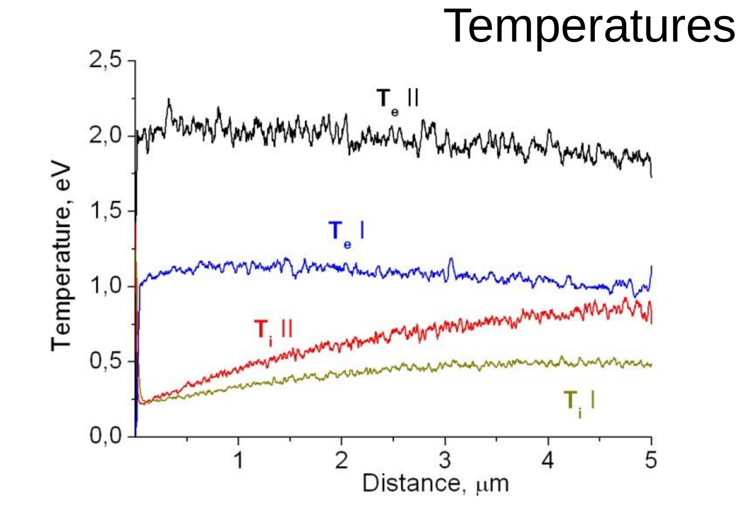
V_i ~10^5 cm/s

T_i ~1 eV; T_e ~1-3 eV;



Velocities





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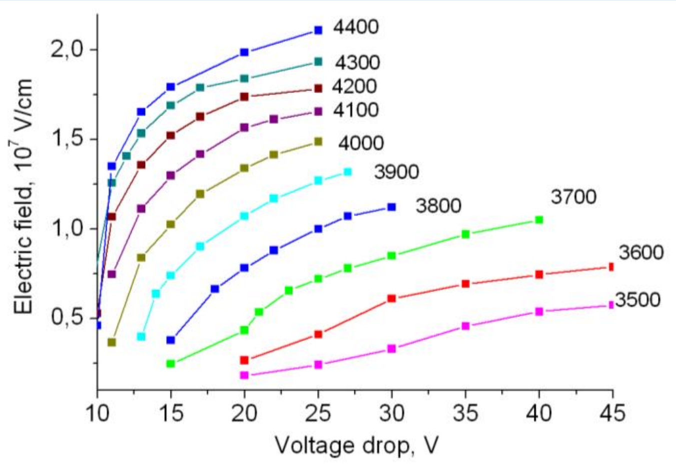
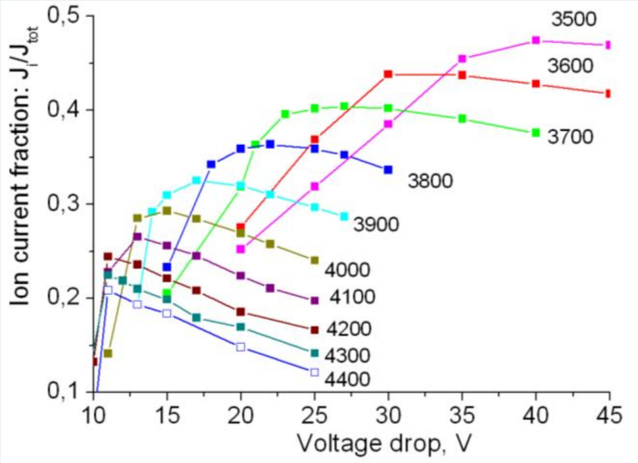
1D3V PIC/DSMC model of cathode layer

Results (3)

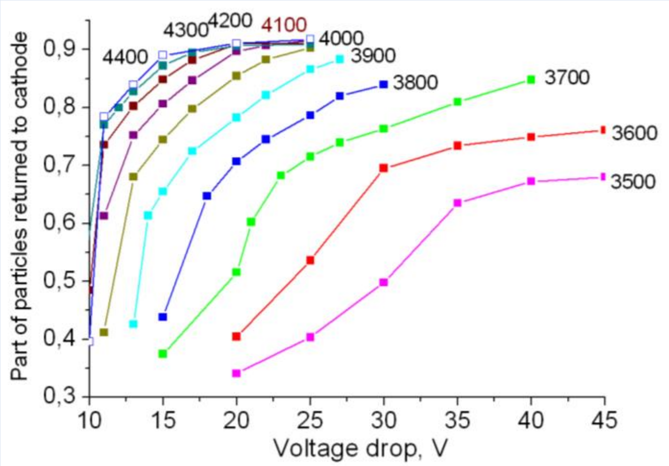
Electric field strength at cathode



Ion current fraction



Part of particles (ion + atoms) returning to the cathode



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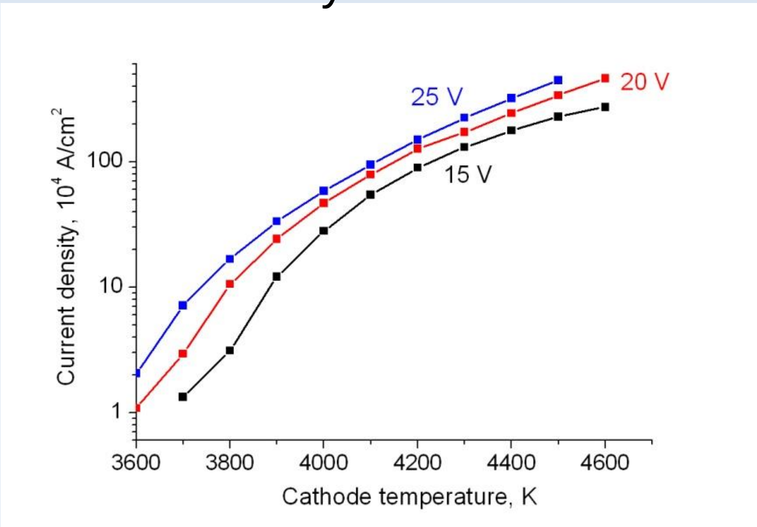
1D3V PIC/DSMC model of cathode layer

Results (4)

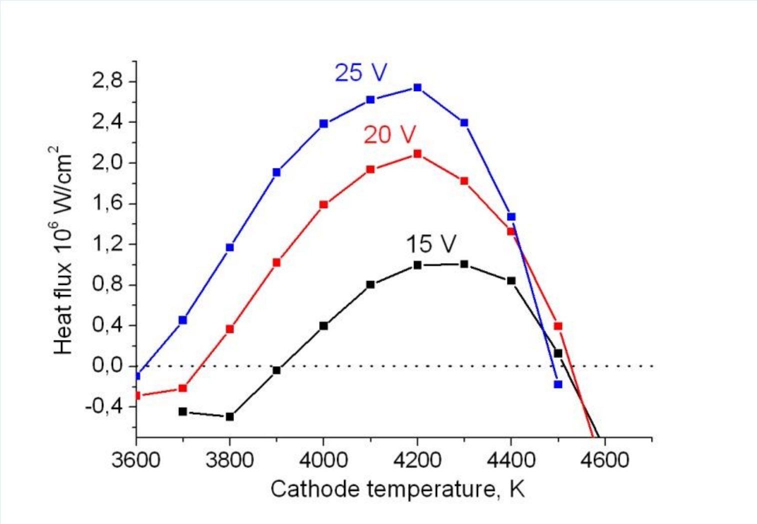
Current density



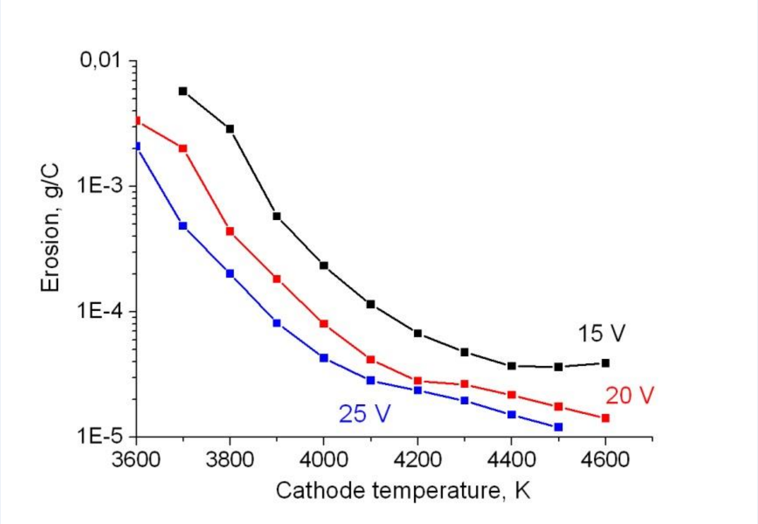
Results for series of calculations.
T_c varies in range 3600-4600 K.
U_0- 15, 20, 25 V

Current density: up to $5 \cdot 10^6$ A/cm^2
Heat flux: up to $2.8 \cdot 10^6$ W/cm^2
Erosion: from $1 \cdot 10^{-2}$ to $1 \cdot 10^{-5}$ g/C

Heat flux

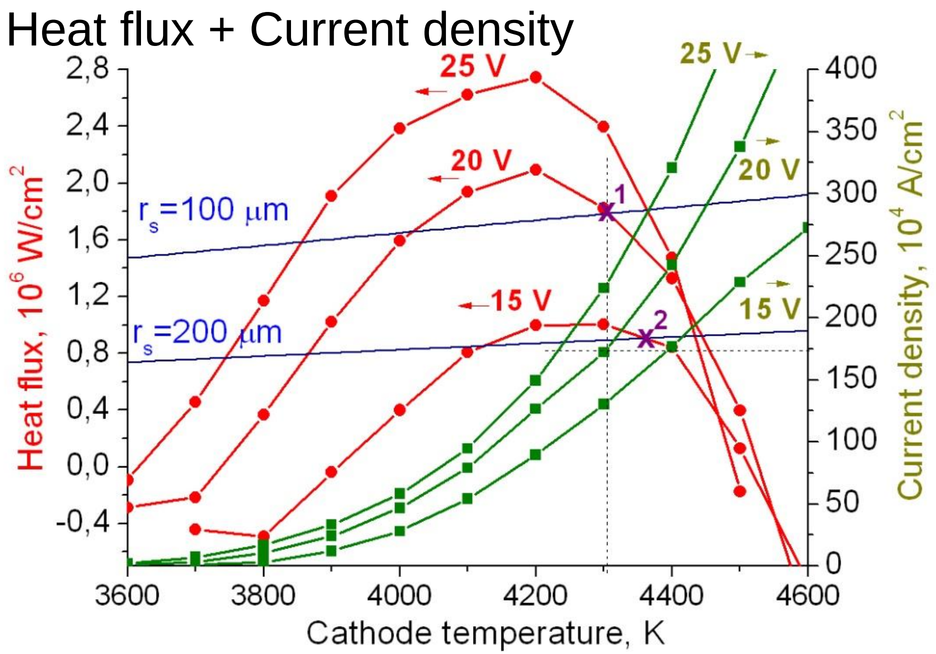


Erosion



1D3V PIC/DSMC model of cathode layer

Cathode spot quasistationary solution



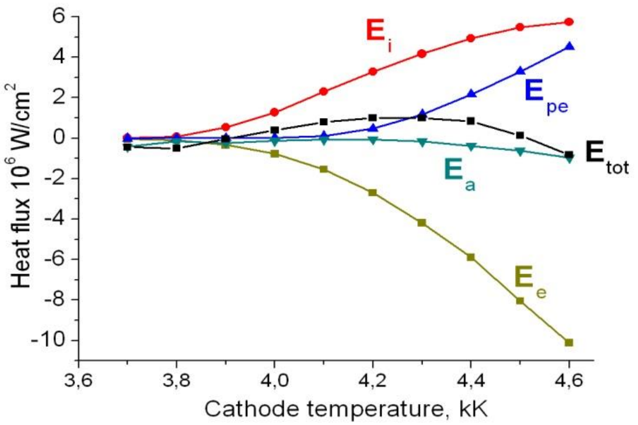
Intersection of heat flux curve by line

$$Q = (T_S - T_\infty)\frac{4}{\pi}\frac{K}{r_s}$$

(r_s-spot radius) gives the possible solution for existence of stationary cathode spot.

Solution x1: Tc=4300 K; Q=1.8 $\cdot 10^6$ W/cm^2
Spot current=550 A

Solution x2: Tc=4360 K; Q=0.9 $\cdot 10^6$ W/cm^2
Spot current=2000 A



Components of heat flux to cathode

E_i-ion heat flux
E_{pe}-plasma electron heat flux
E_a- atom heat flux (evap. incl.)
E_e-emission heat flux
E_{tot}-total flux

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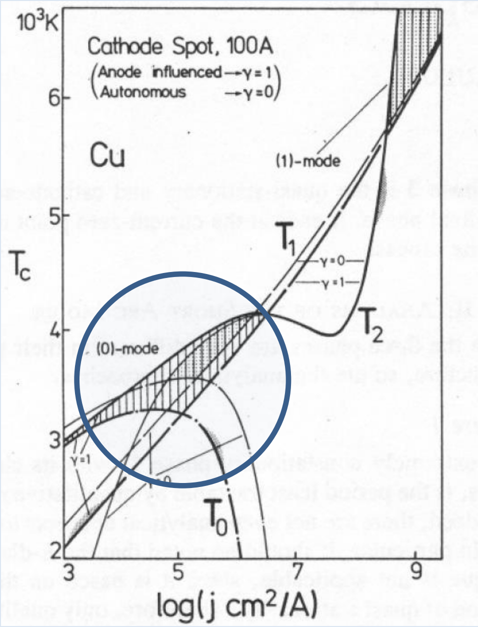
1D3V PIC/DSMC model of cathode layer

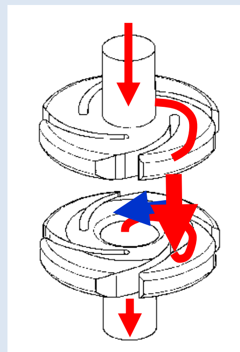
Cathode spot quasistationary solution, discussion

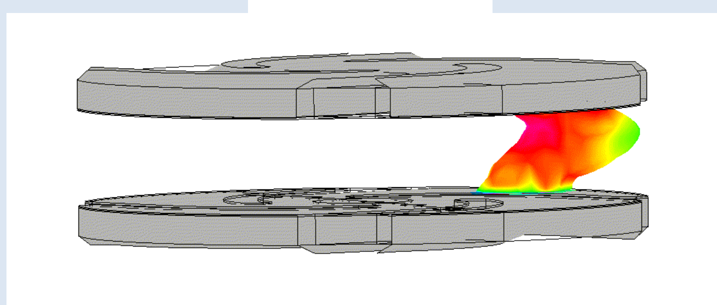


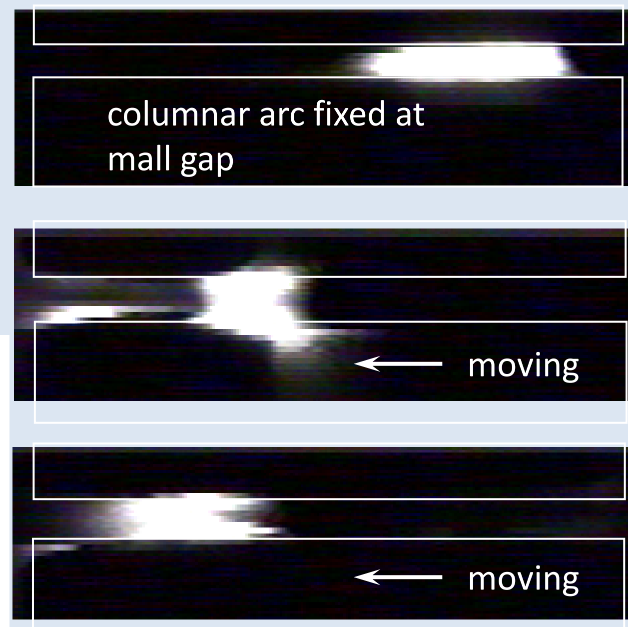
Existence diagram of cathode spot on copper electrode. [G. Ecker]

The obtained solution corresponds to <u>0-mode cathode spot </u>(Ecker notation).

It is possible that this type of solution describes the cathode attachment zone of high current constricted vacuum arc typical for current interrupters.

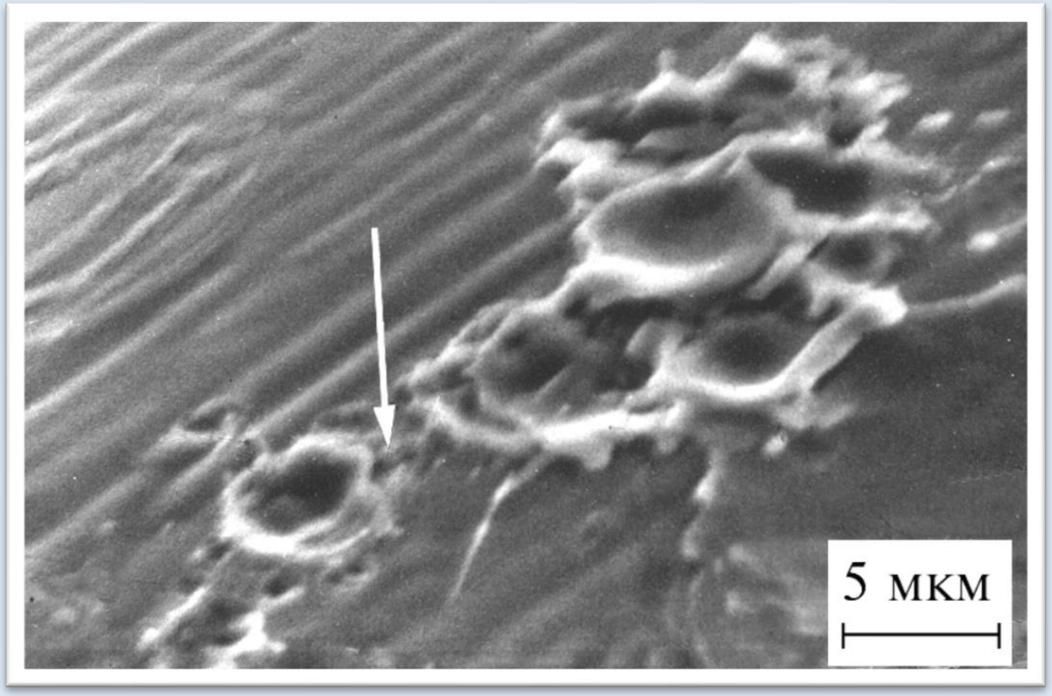






1D3V PIC/DSMC model of cathode layer

Low current cathode spot

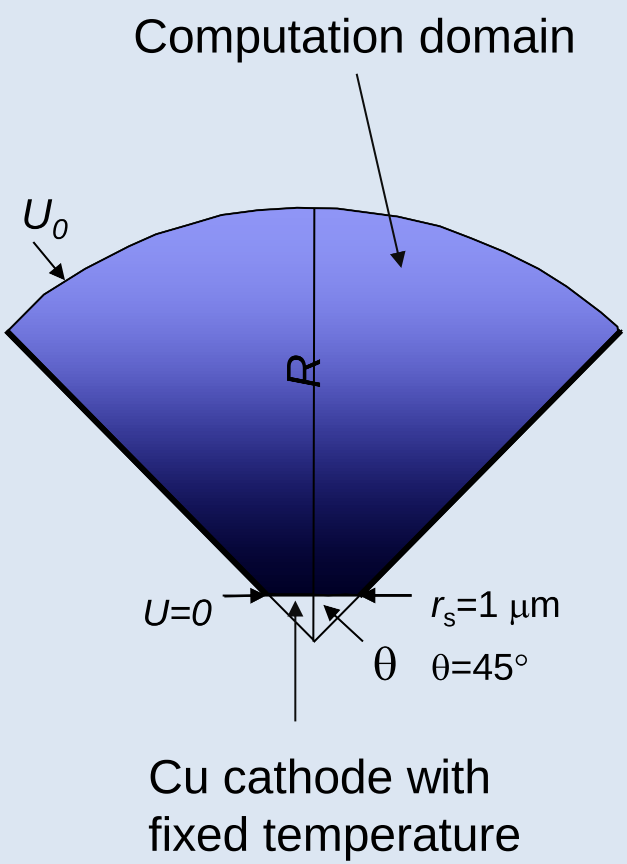


Erosion trace on tungsten cathode. Arc current 2 A.
[V. Puchkarev, A. Murzakaev]

Cathode spots of low current vacuum arcs have typical radiuses about 1 μm.

Plasma spreading from these spot can not be described in framework of 1D flat geometry.

1D geometry to model near cathode plasma of cathode spot

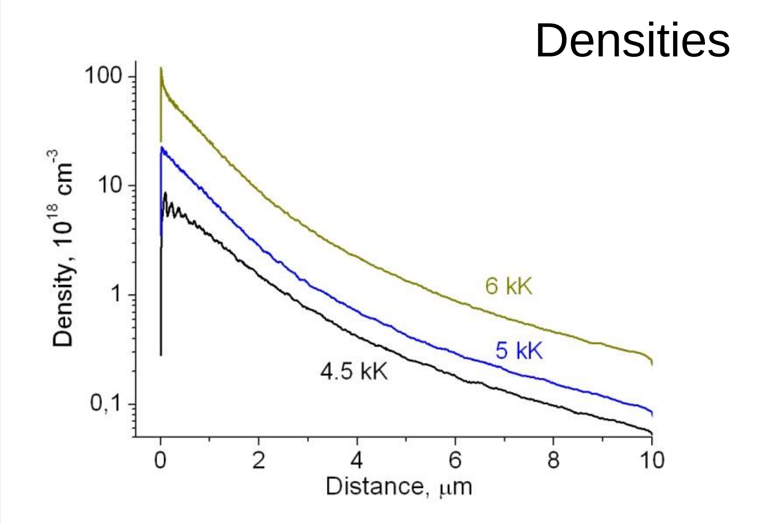


- The model calculation domain is a spherical cone with flat footpoint.
- It is assumed that the flat footpoint (with radius of 1 μm) corresponds to the cathode spot.
- Spherically shaped anode of proper solid angle is disposed in the distance of R=10 μm from the cathode.
- Cathode spot has fixed temperature T_c
- Voltage U0 specified at the anode.

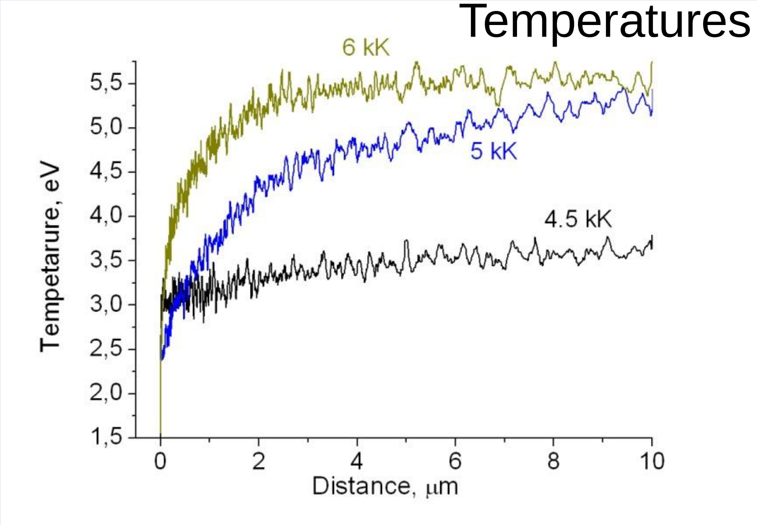
Model of near cathode plasma of cathode spot
Results.

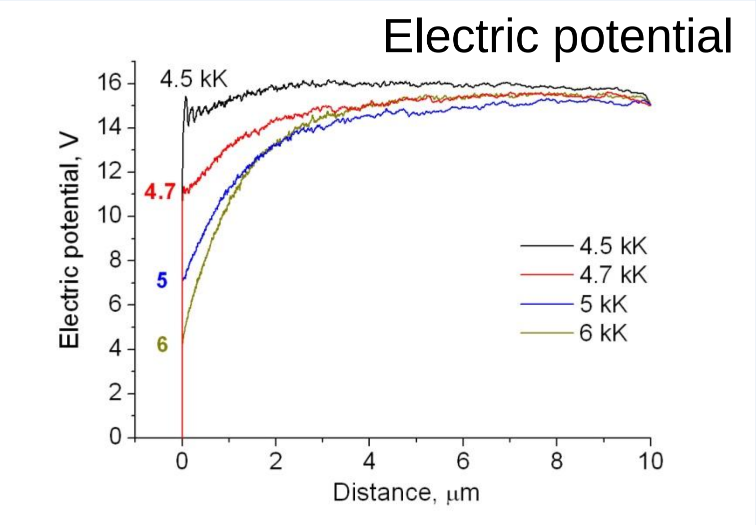
Plasma parameters for control parameters
T_c=(3800 – 6000)K; U_0=15 V

Typical values:
n_e, n_i- up to 10^{20} cm^{-3}
n_a~ 10^{21} cm^{-3}
V_i ~10^6 cm/s
T_i ~1 eV; T_e ~up to 6 eV;

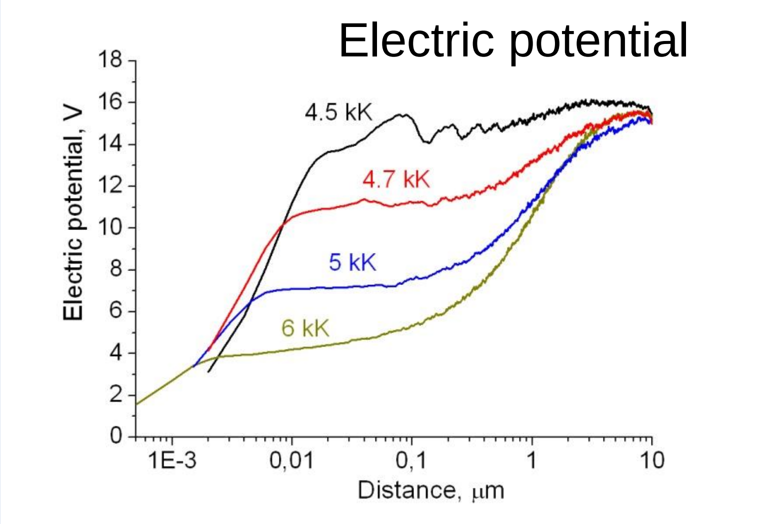


Lowering of cathode potential drop with cathode temperature increase.

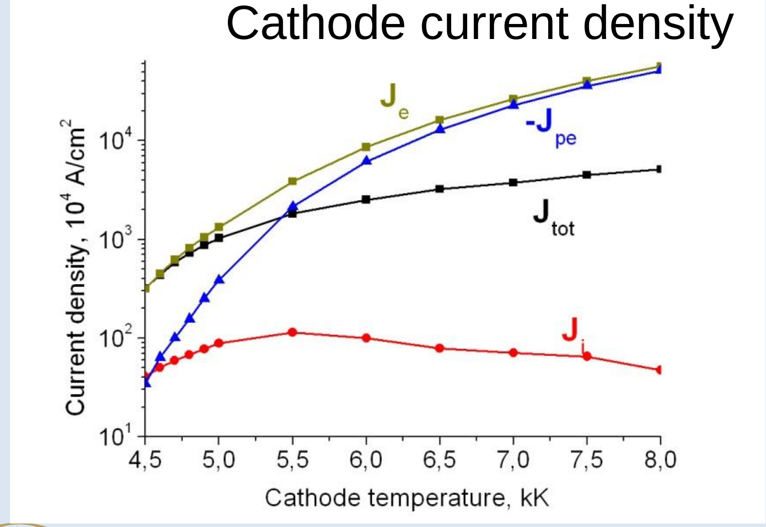




Model of near cathode plasma of cathode spot
Stationary solution for plasma.



Lowering of cathode potential drop with cathode temperature increase and correspondent current density increase.
U_0=15 V



Components of current density at the cathode; U_0=15 V

J_i-ion current
J_{pe}-plasma electron current
J_e-emission current
J_{tot}-total current

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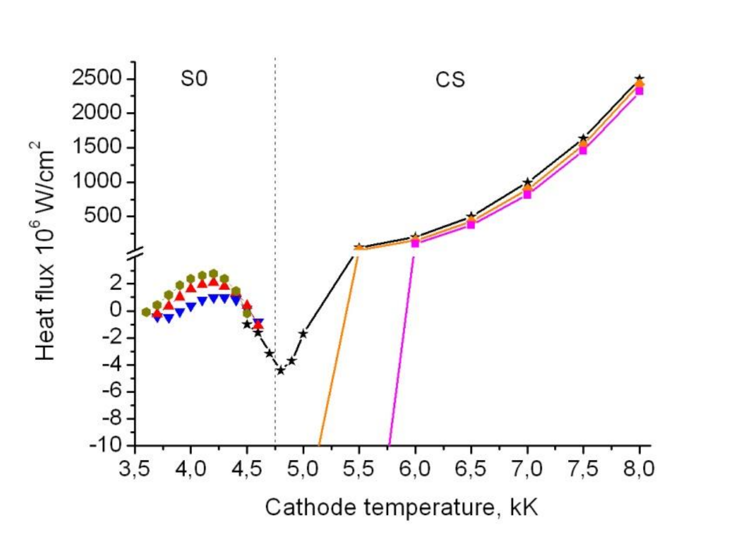
Model of near cathode plasma of cathode spot (CS)
Comparison with 0-mode spot (S0)

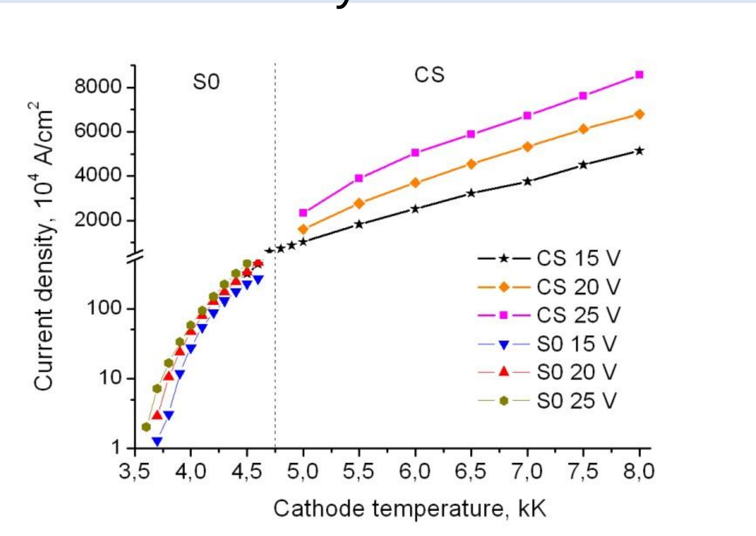
Heat flux



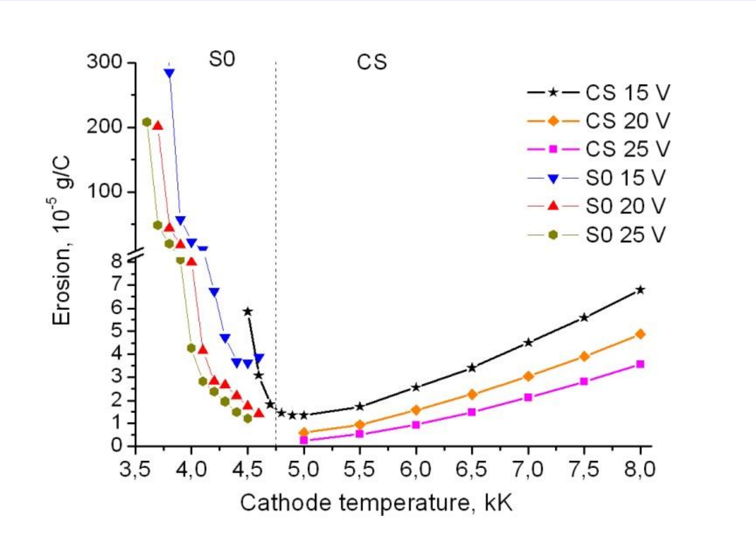
Results for series of calculations.
T_c varies in range 4500-8000 K.
U_0- 15, 20, 25 V

Current density: up to $8\cdot10^7$ A/cm^2
Heat flux: up to $2.5\cdot10^9$ W/cm^2
Erosion: from $1\cdot10^{-5}$ to $6\cdot10^{-5}$ g/C

Current density



Erosion



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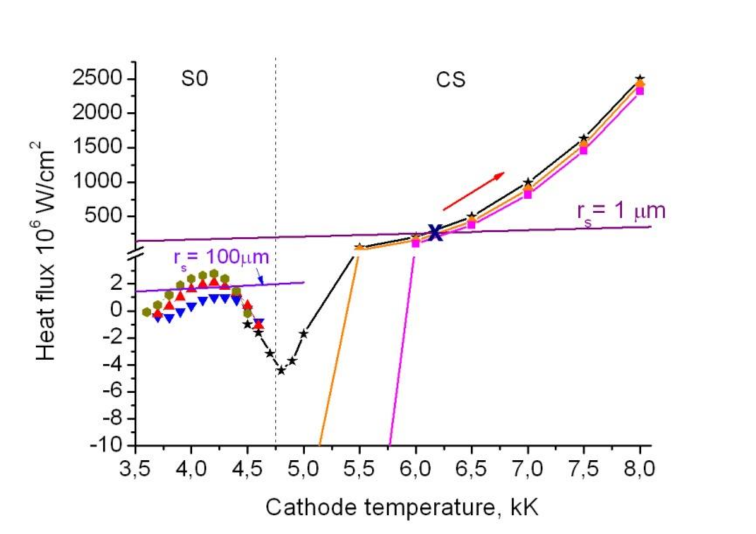
Model of near cathode plasma of cathode spot (CS)
Comparison with 0-mode spot (S0)

Heat flux



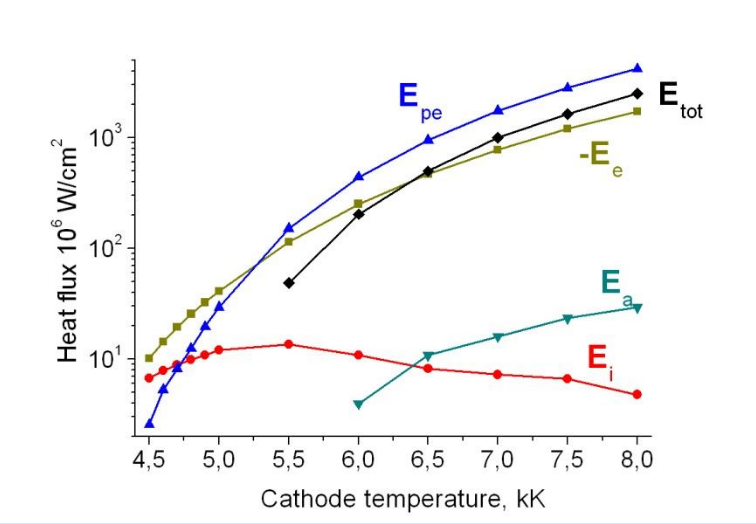
Intersection of heat flux curve by line

$$Q = (T_S - T_\infty)\frac{4}{\pi}\frac{K}{r_S}$$

(r_s-spot radius) gives the possible solution for stationary cathode spot.

Heat flux grows with the cathode temperature increase. This is a source of thermal instability.

The solution is not stable. So, CS stationary solution cannot exist.



Components of heat flux to cathode

E_i-ion heat flux
E_{pe}-plasma electron heat flux
E_a- atom heat flux (evap. incl.)
E_e-emission heat flux
E_{tot}-total flux

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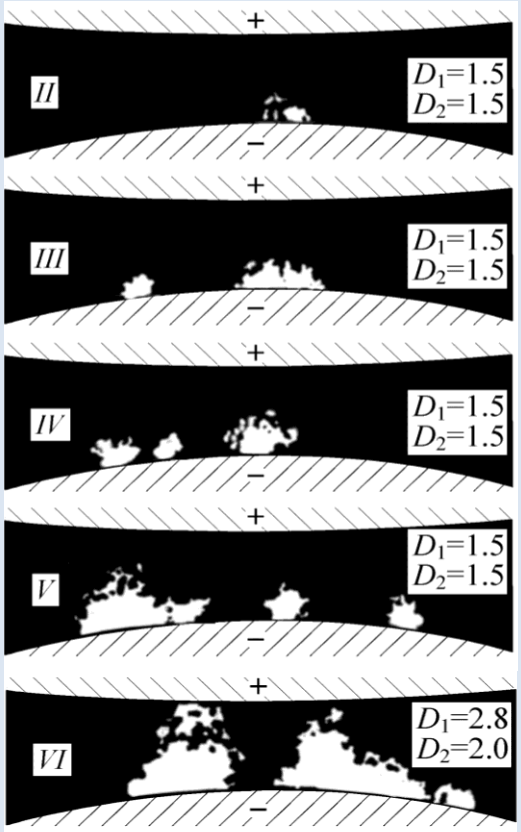
Cathode plasma flare



Pictures of vacuum breakdown.
[G. Mesyats, D. Proskurovsky]

- Cathode plasma flare extension is the integral part of an explosive emission.

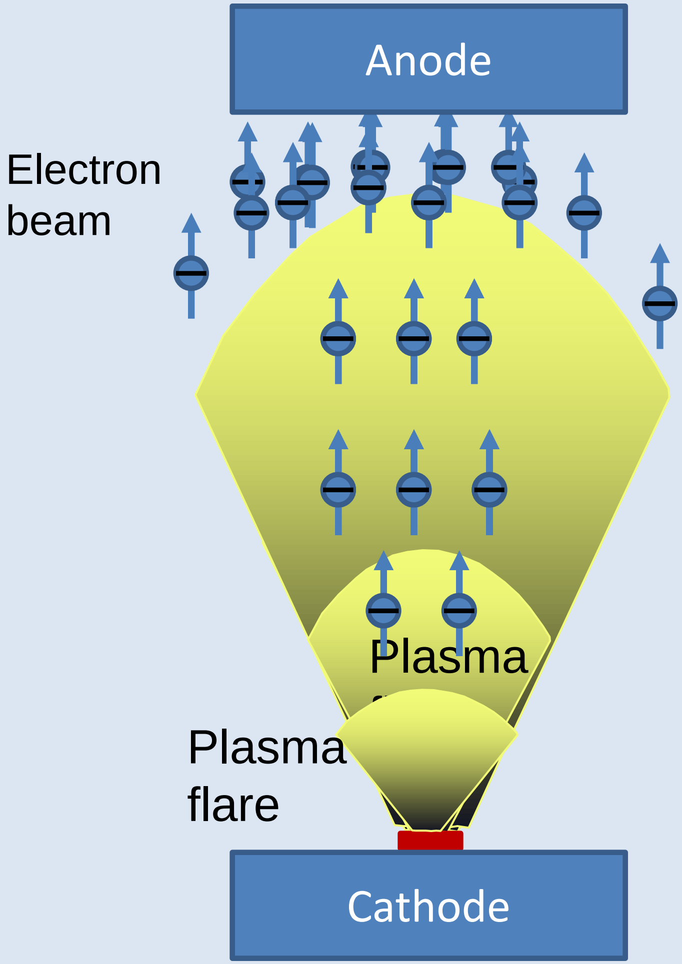
- Plasma flare expands in the direction of the anode with typical velocity of about $2{\cdot}10^6$ cm/s

- Plasma of the plasma flare is completely ionized. Significant part of the ions is multiply charged.

- Electrons are emitted from the plasma-vacuum boundary.

- The electron current is restricted by space charge. The current grows with the plasma flare expansion.

Cathode plasma flare



- ◈Cathode plasma flare extension is the integral part of an explosive emission.
- ◈Plasma flare expands in the direction of the anode with typical velocity of about $2 \cdot 10^6$ cm/s
- ◈Plasma of the plasma flare is completely ionized. Significant part of the ions is multiply charged.
- ◈Electrons are emitted from the plasma-vacuum boundary.
- ◈The electron current is restricted by space charge. The current grows with the plasma flare expansion.

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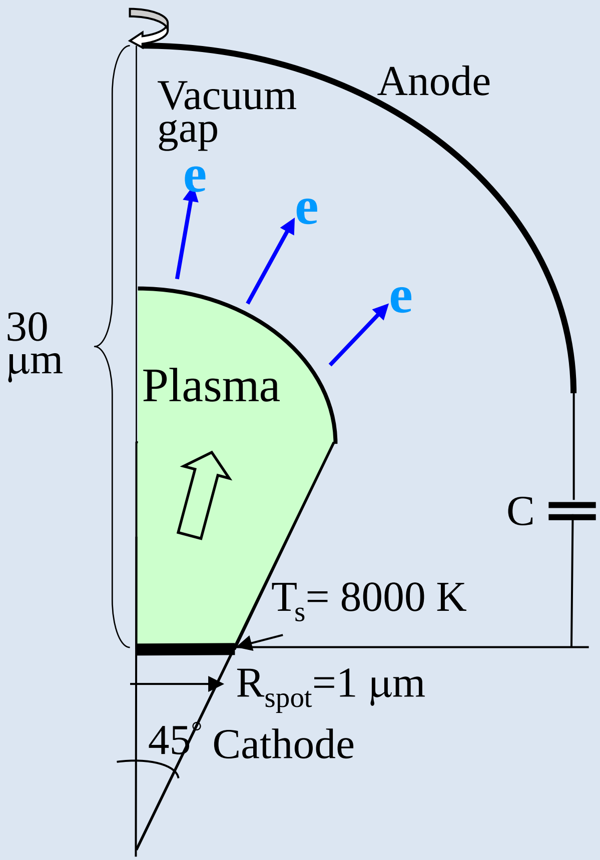
1D Cathode plasma flare computational model
Geometry and main feature.



Sketch of task geometry

- The model calculation domain is a spherical cone with flat footpoint.
- Cu^{+}, Cu^{+2}, Cu^{+3}, Cu^{+4} ions are considered.
- Lowering of the ionization energy according to Debye-Huckel theory is considered
- Surface temperature in the spot - $T_{surface}$ is artificially kept constant during the calculation to provide enough erosion and emission capability.
  This temperature roughly represents the certain temperature that is averaged over the time cycle of the cathode explosive emission center operating.

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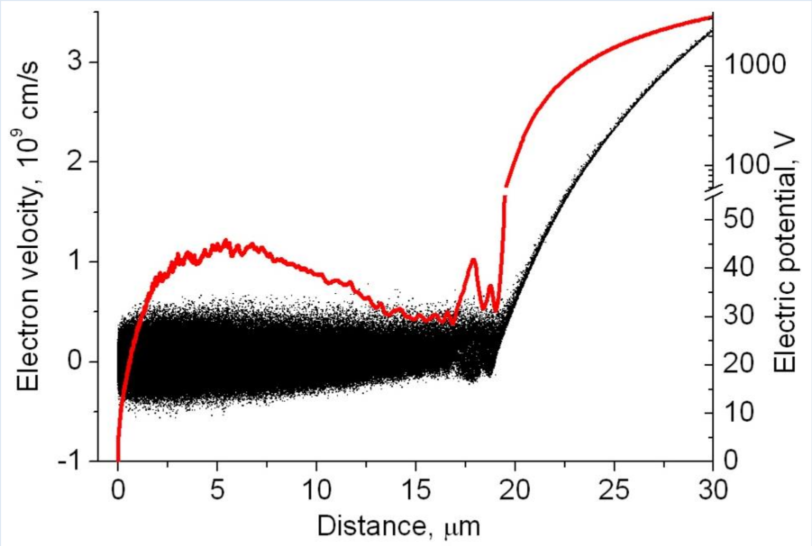
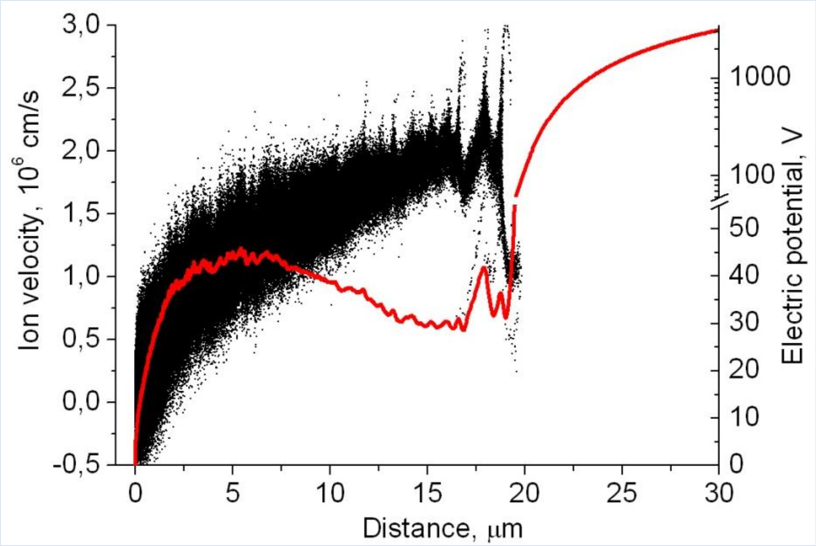
1D Cathode plasma flare computational model
Results

Electrons



Phase portraits of electrons (points) for time t =1 ns, and correspondent electric potential distribution (red curve) along the gap.

Ions



Phase portraits of ions (points) for time t =1 ns, and correspondent electric potential distribution (red curve) along the gap.

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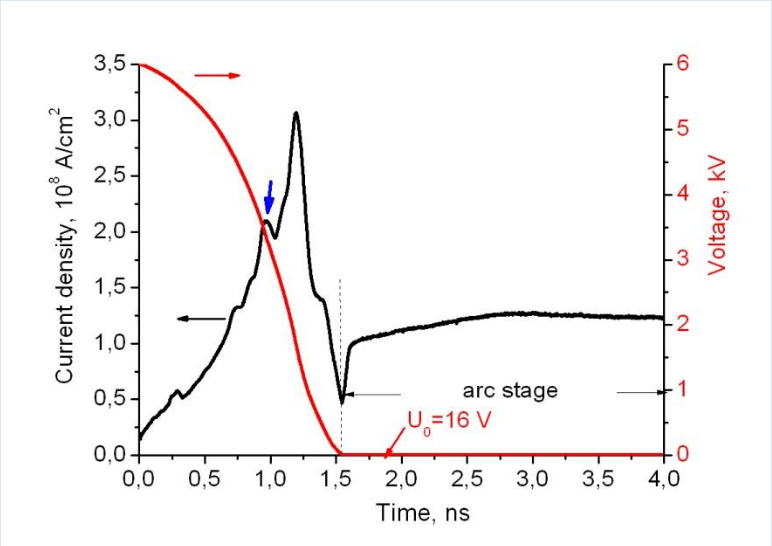
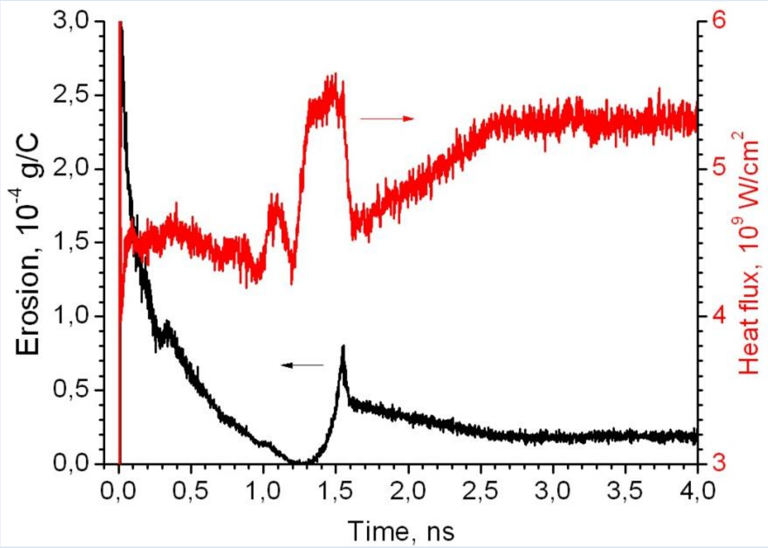
1D Cathode plasma flare computational model
Results (2)





Voltage applied to the anode U_0 (red curve) and current density (black curve) at the cathode as functions of time.

Heat flux from plasma to cathode (red curve) and specific cathode erosion (black curve) as functions of time.

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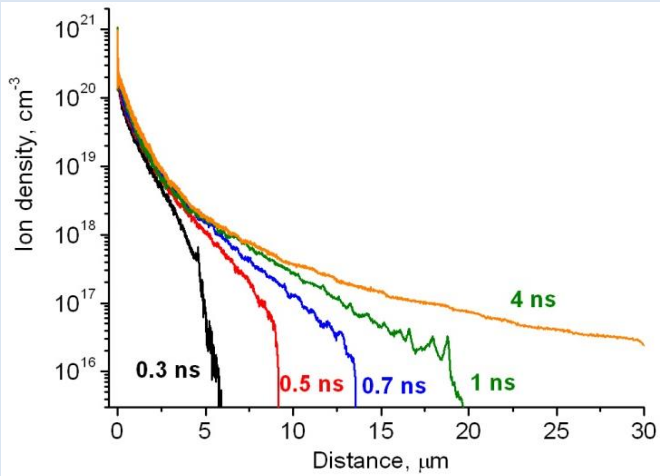
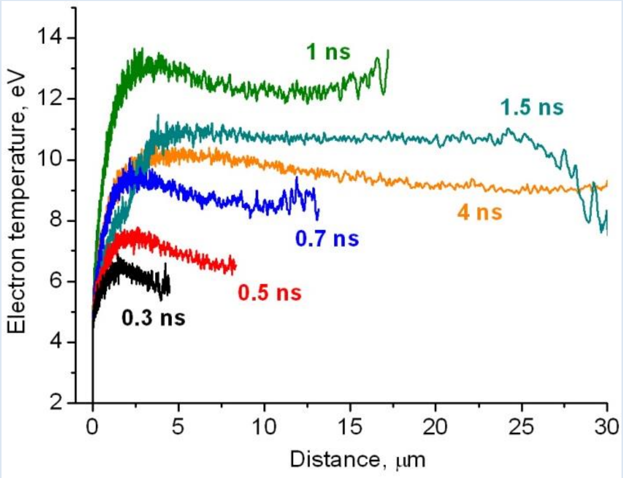
1D Cathode plasma flare computational model
Results (3)

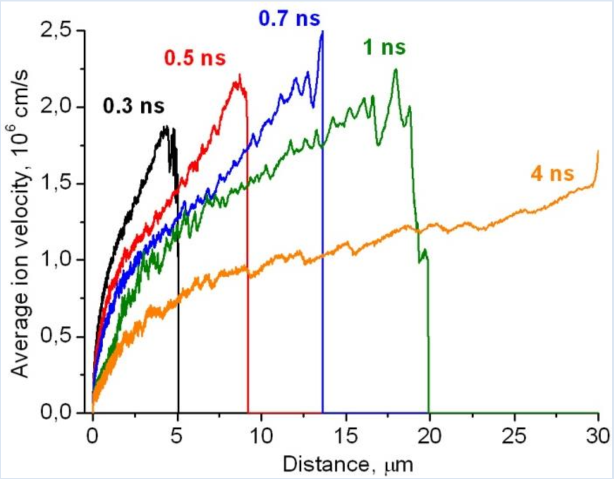
Density



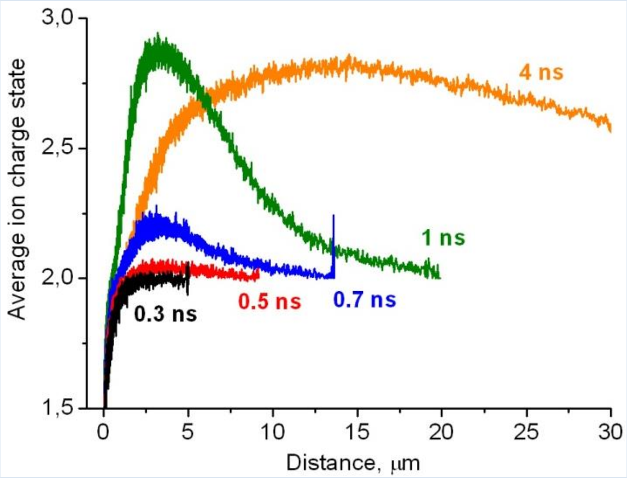
Electron temperature



Velocity



Ion charge state



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Thank you for attention