西安交通大學
XI'AN JIAOTONG UNIVERSITY

<u>9th International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2021)</u>

Kinetic Simulation of the Plasma Dynamics in the Post-arc Stage

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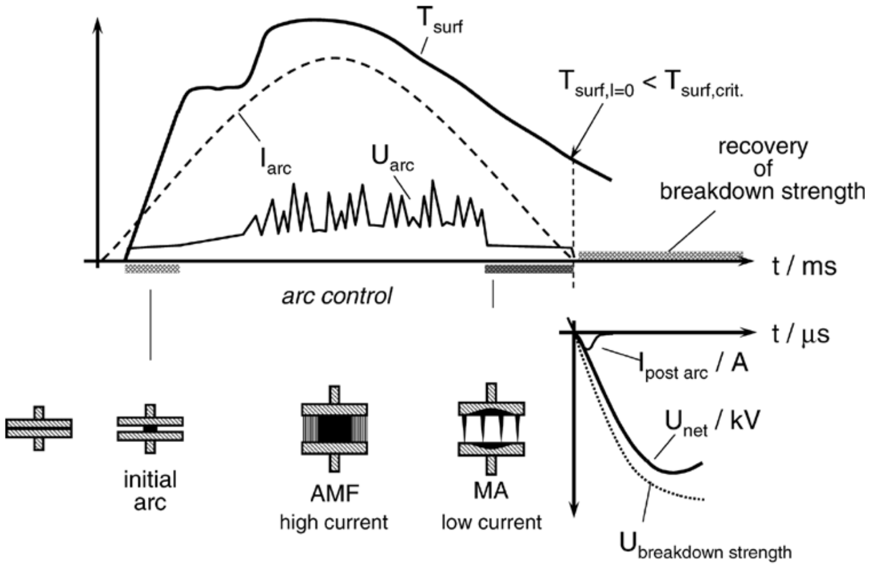
1. MOTIVATION

Post-arc stage of vacuum circuit breakers



Schade, E. and E. Dullni, "Recovery of breakdown strength of a vacuum interrupter after extinction of high currents". Ieee Transactions on Dielectrics and Electrical Insulation, 2002. 9(2): p. 207-215.

- A rapidly increased **transient recovery voltage (TRV)** generated by the external circuit is applied on the electrode gap.
- **Residual plasma decay**: Residual plasma coming from the arc stage is expelled from the gap.
- **Instant breakdown/delayed breakdown**: fail to interrupt the fault current.

outlines

Residual Plasma Decay

↓

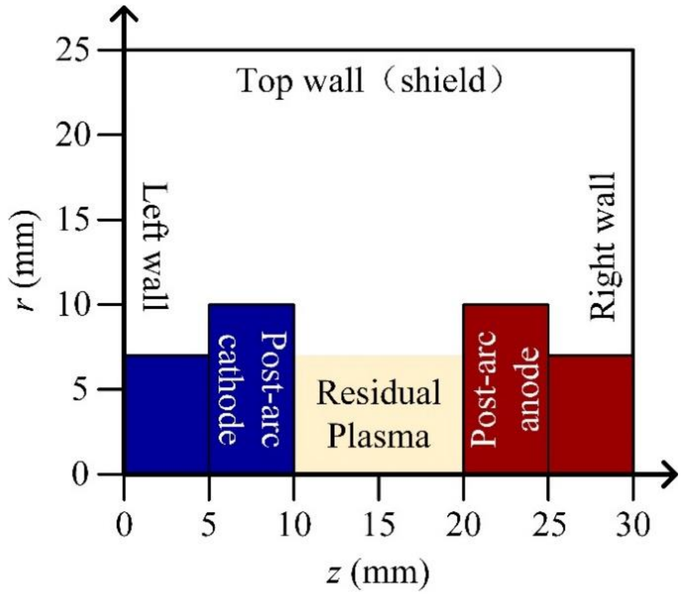
Effect of metal vapor

↓

Breakdown in the post-arc stage

2. MODEL

PIC/MCC Model

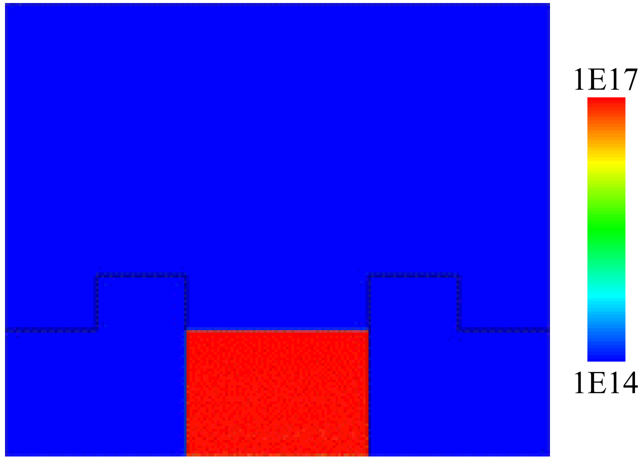


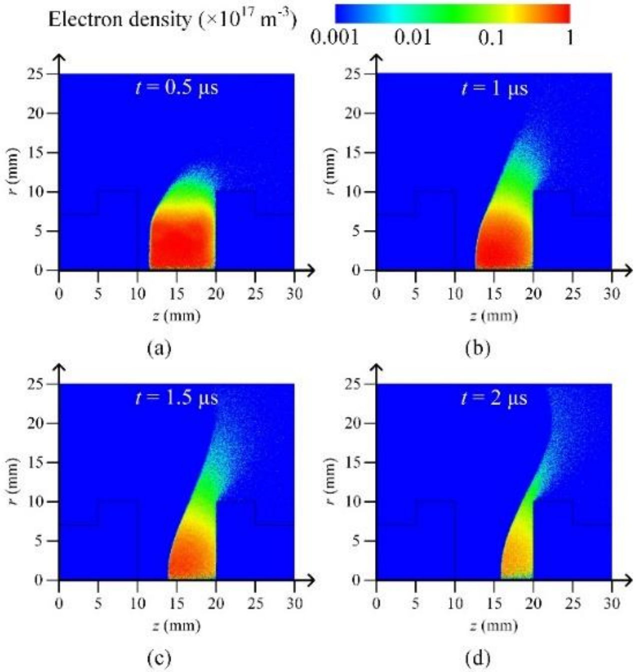
- Post-arc anode is grounded; post-arc cathode is at TRV -1kV/μs.
- Left wall is open condition; top and right walls are grounded and absorbing.
- Initial residual plasma density 1×10^{17} m^{-3}.
- Initial electron temperature 3eV; initial ion (Cu^{+}) temperature 2eV.
- Collisions in collisional model include elastic scattering, excitation, ionization, charge exchange and moment transfer.

3. RESULTS

Residual plasma decay

Electron density

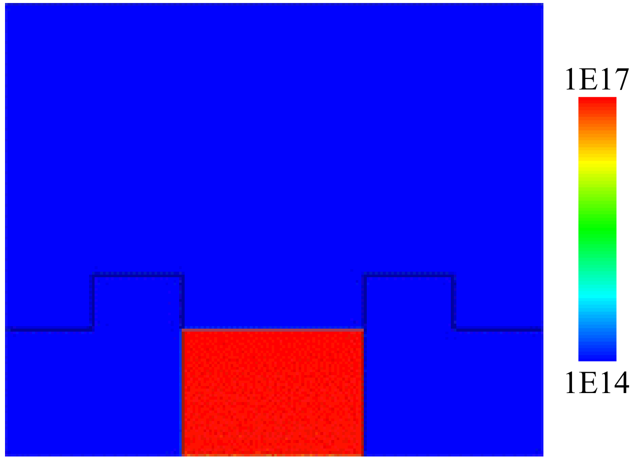


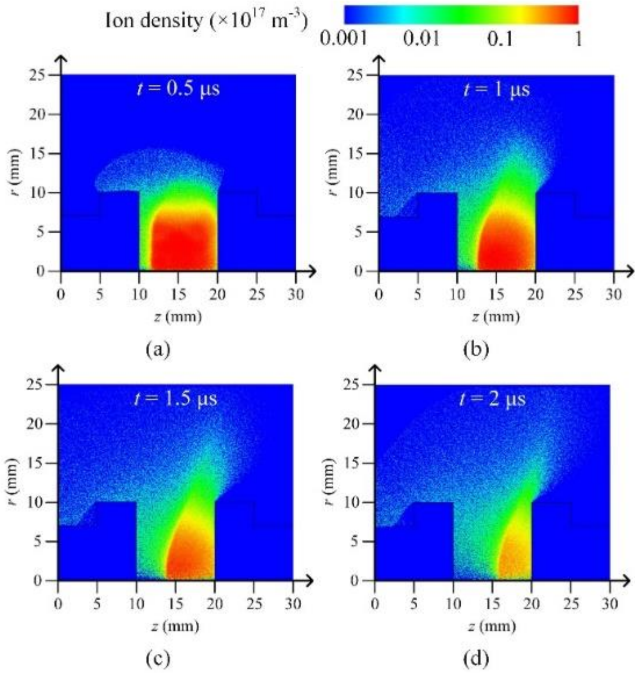


- It takes about 2.7 μs for electrons to be expelled from the calculation domain. Under the TRV, electrons are accelerated toward the post-arc anode, and the shield.
- First, the electron density partially decreases at the edge of the plasma, and then the overall decrease occurs.

Residual plasma decay

Cu$^+$ density

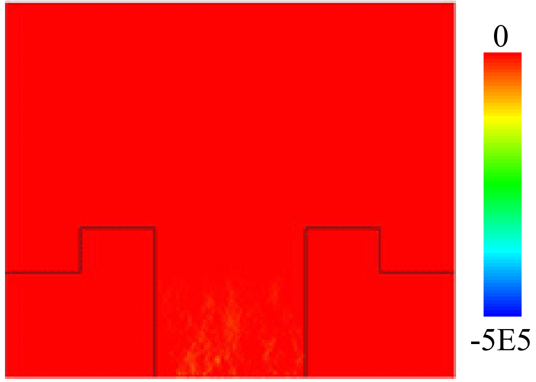


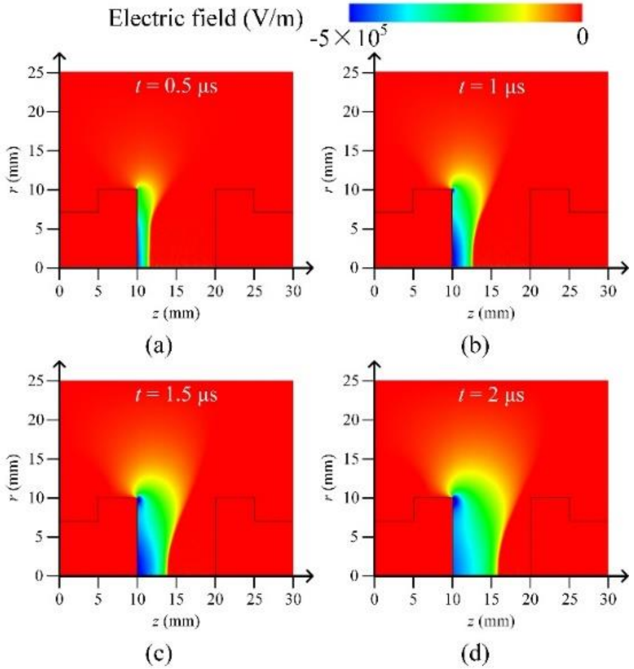


- Time for ions to be expelled from the inter-electrode gap is longer than it for electrons. It is about 3 μs.
- While electrons are absorbed by the post-arc anode, an ion sheath is left near the post-arc cathode. Ions are extracted from the plasma into the sheath and then absorbed by the post-arc cathode.

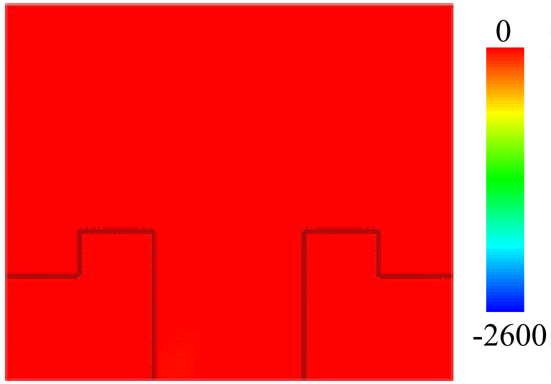
Residual plasma decay

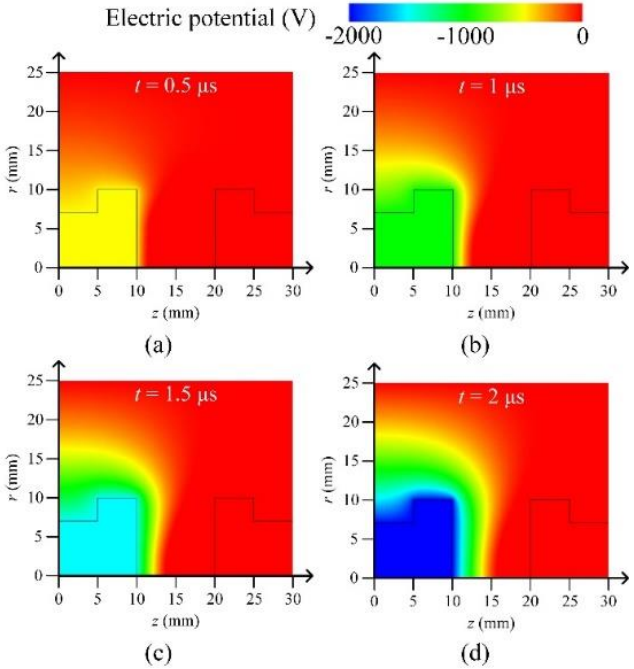
Electric field





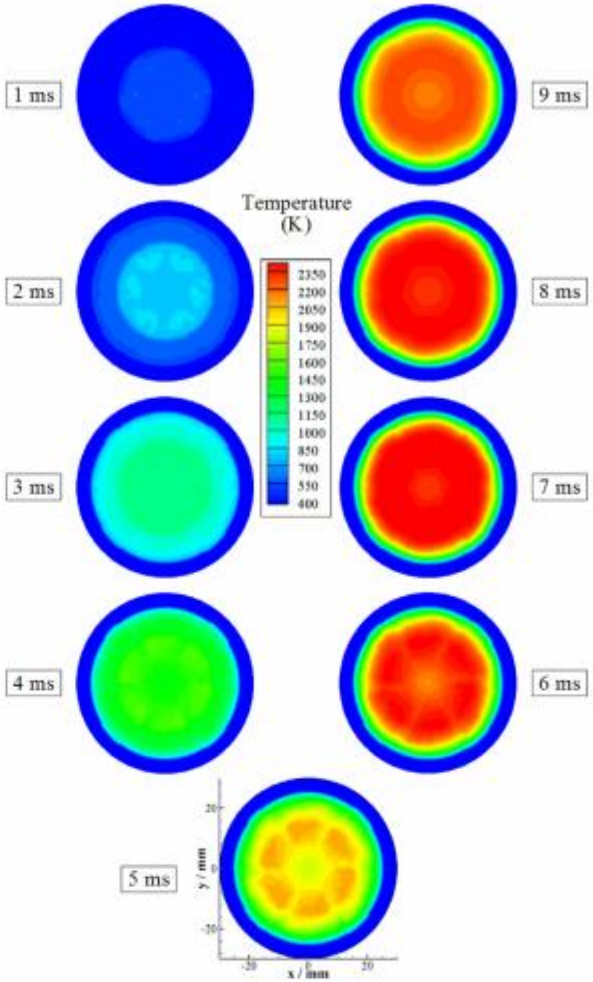
Electric potential





- The TRV is almost applied on this sheath and the electric field in it is significantly enhanced.

Metal vapor in post-arc stage



Anode temperature in arcing stage

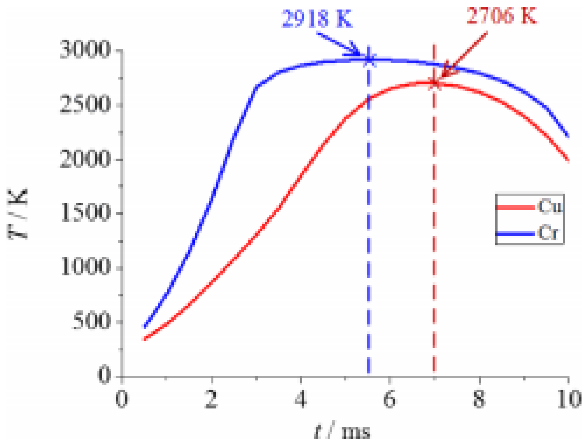


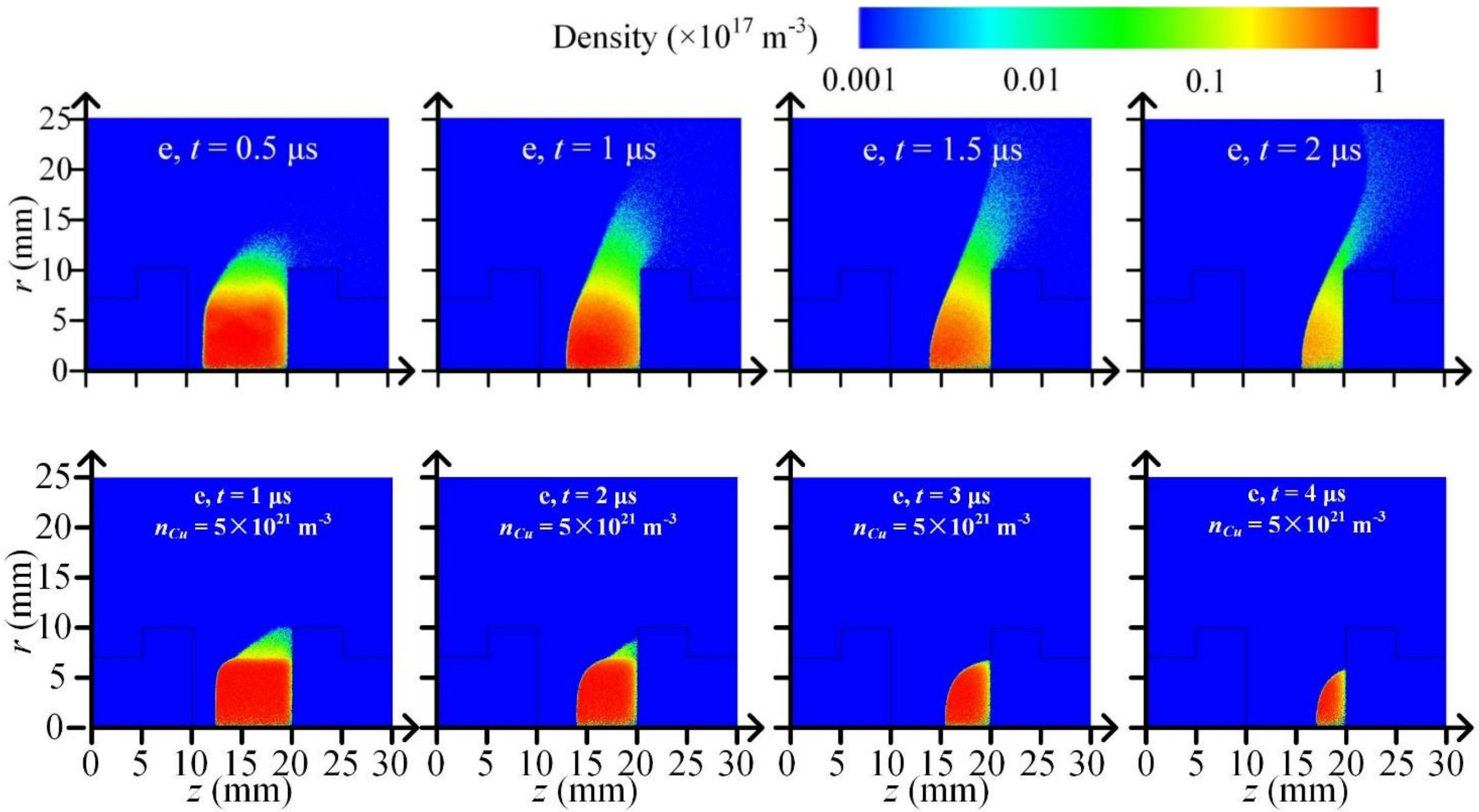
FIG. 9. Temperature of different material anode.

- Metal vapor evaporated in the arcing stage cannot be removed instantly
- The contact surface with high temperature keeps evaporating in post-arc stage
- Experiments showed metal vapor density 10^{18}~10^{22} m^{-3} in post-arc stage depending on the fault current

Lijun Wang, X. Huang, Shenli Jia et al., 3D Numerical simulation of high current vacuum arc in realistic magnetic fields considering anode evaporation, Journal of Applied Physics 117, 243301 (2015);

When metal vapor is included …

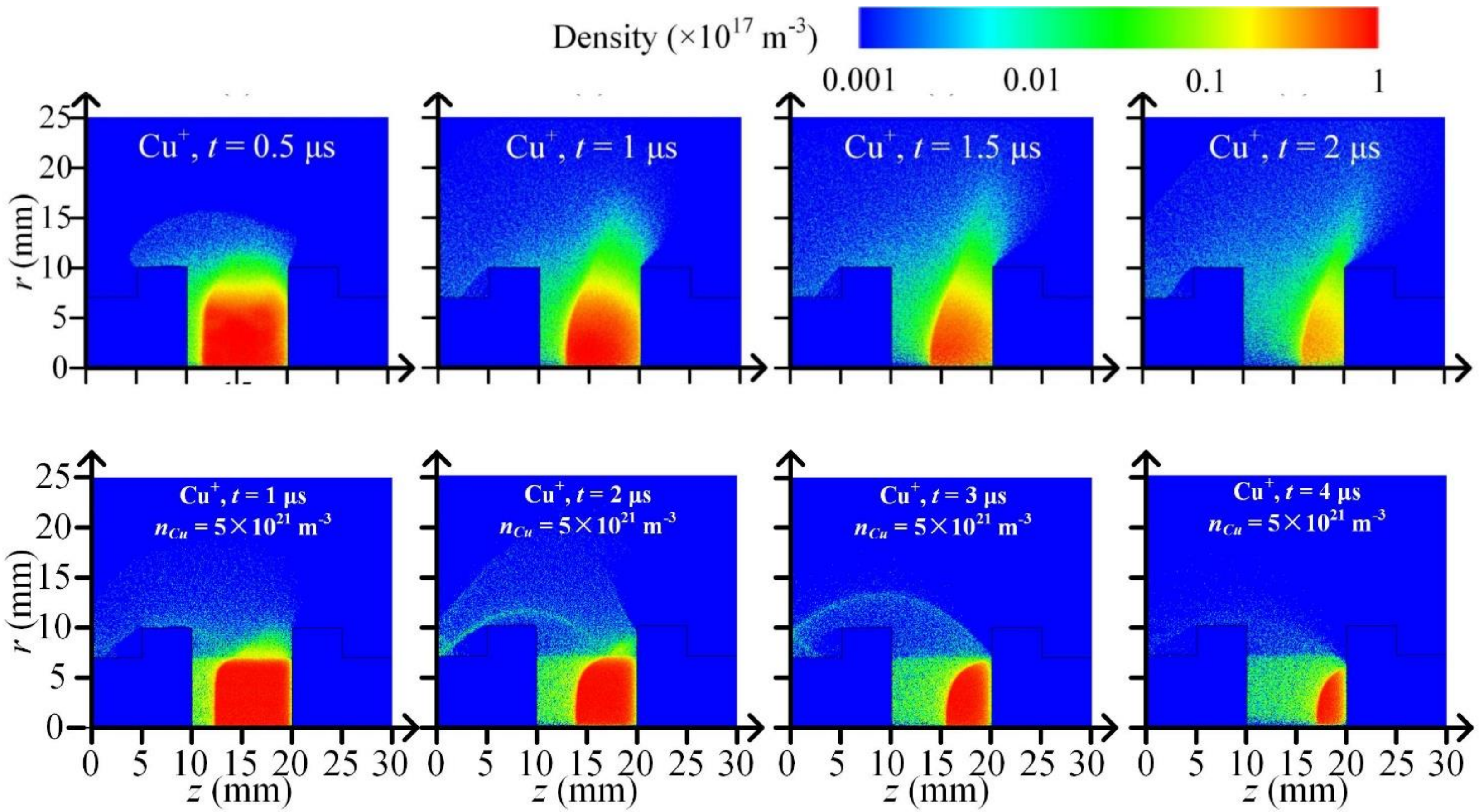
Electron density



- In the collisional model, the density of the residual copper vapor is 5×10^{21} m^{-3}, and it only distributes in the inter-electrode gap.
- Collisions can limit the plasma expansion in both radial and axial directions. It takes about 4 μs for the charged particles to be expelled in the calculation domain.

When metal vapor is included …

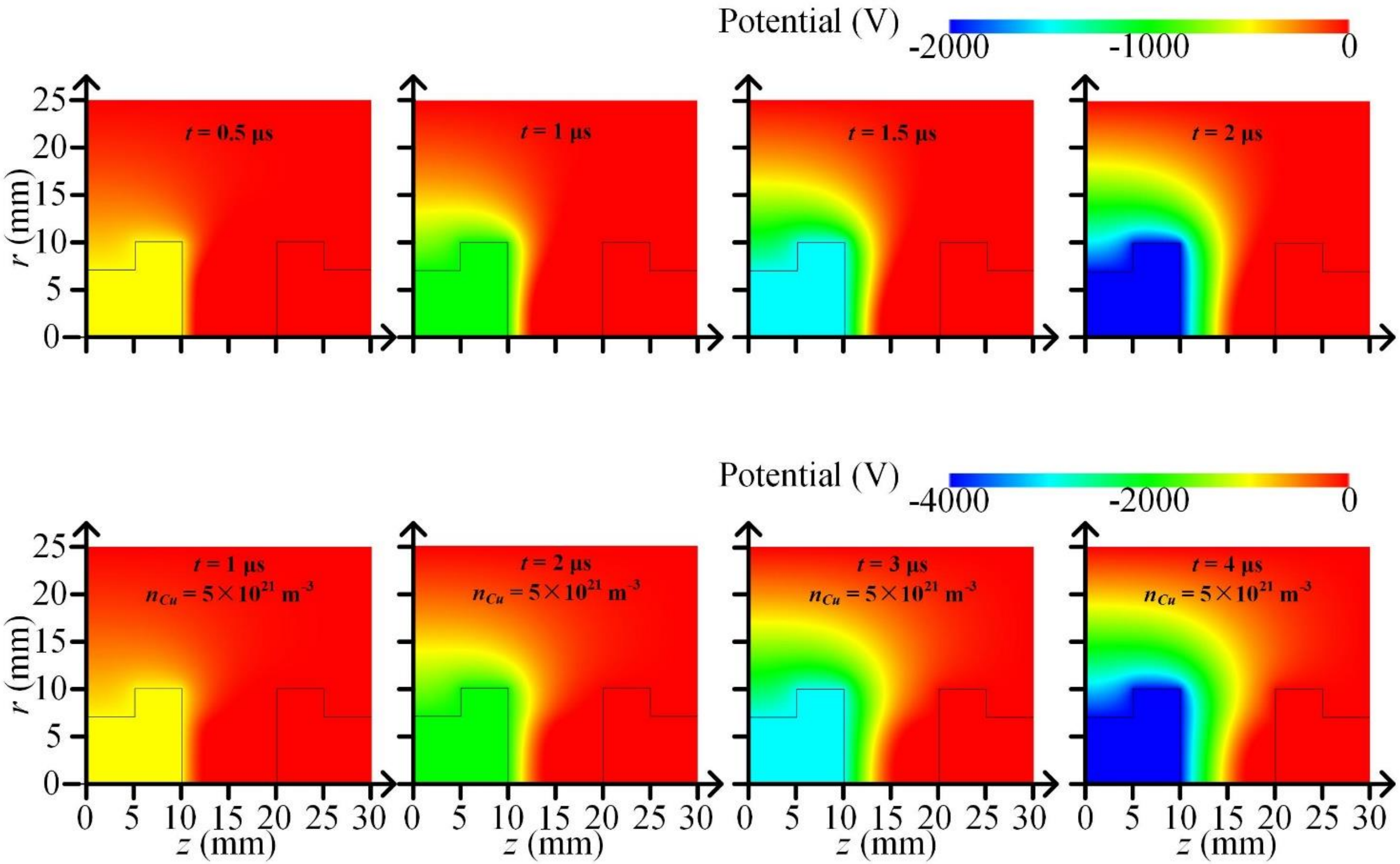
Cu^+ density



- Ions in the cathode sheath are denser than those in the collisionless cases.
- Momentum transfer and charge exchange between ions and copper atoms impede the absorption of ions .

When metal vapor is included …

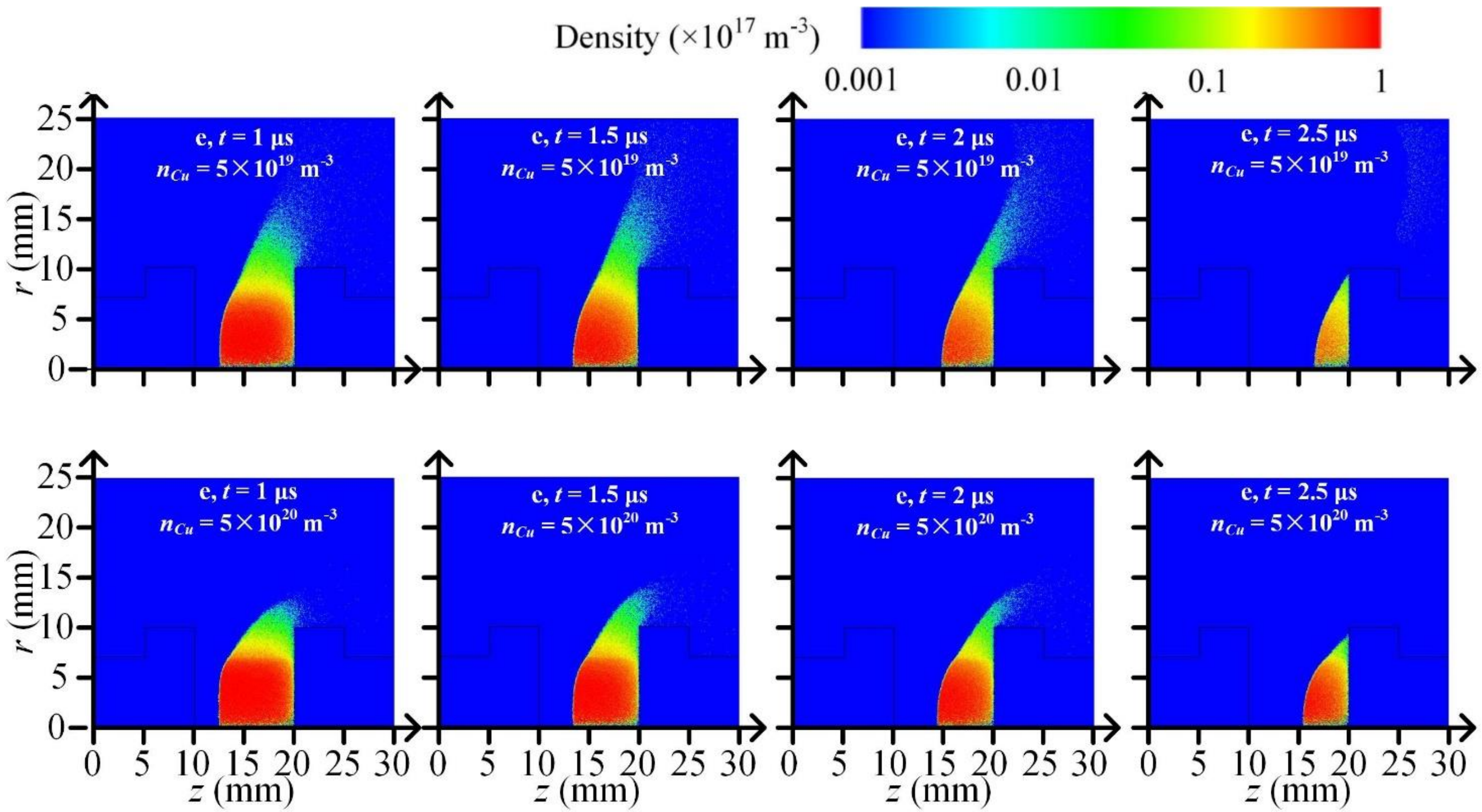
Electric potential



- At the same time, the electric field in collisional model is twice that in collisionless model.

Effect of metal vapor density

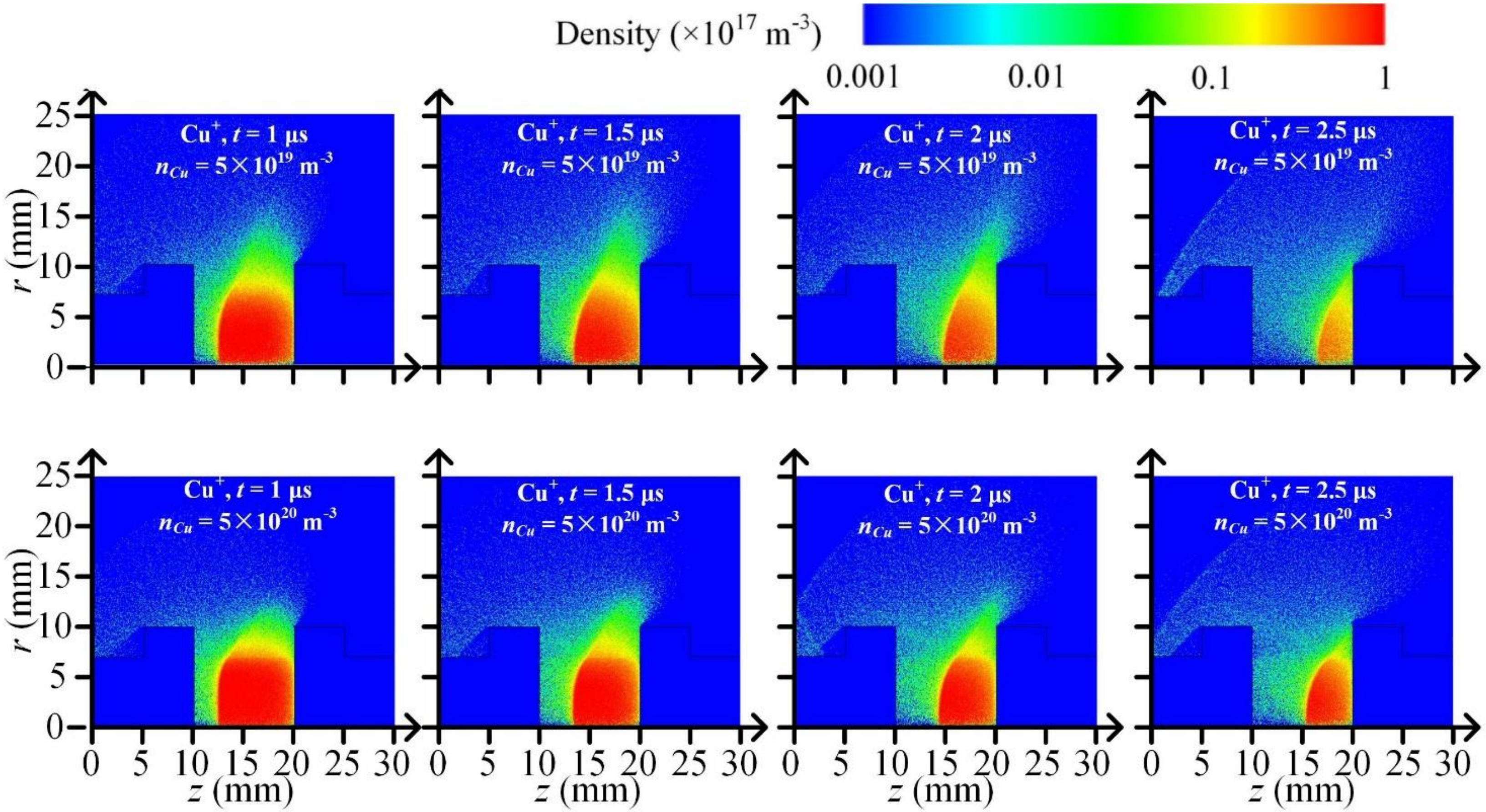
Electron density



- The plasma decays more quickly with lower metal vapor density.

Effect of metal vapor density

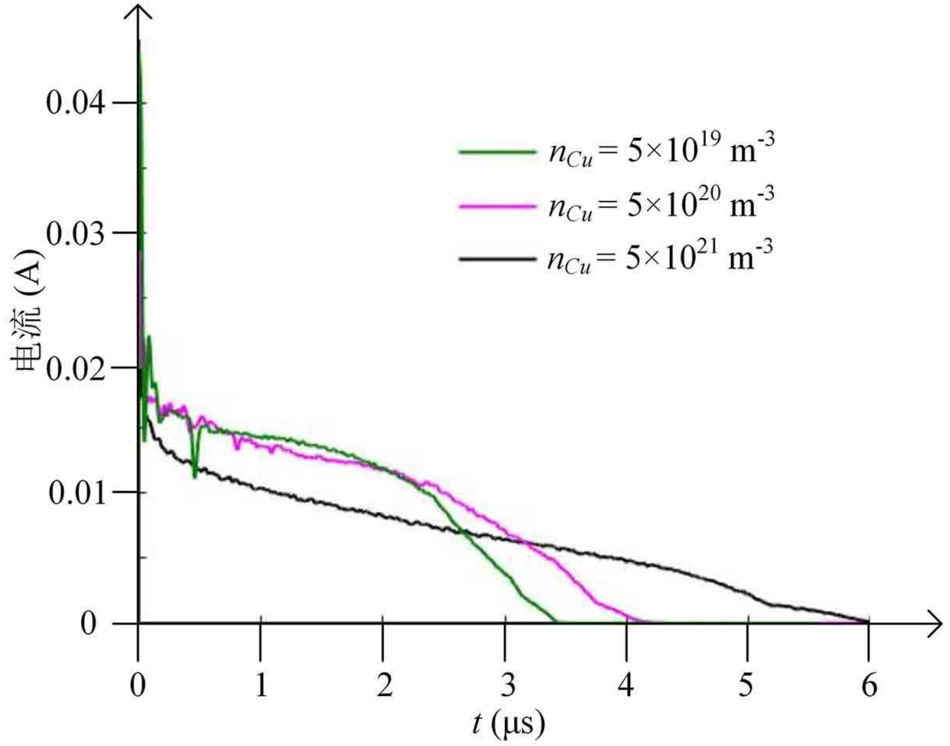
Cu^+ density



- Ion density in the sheath is higher in simulations with denser metal vapor.

Effect of metal vapor density

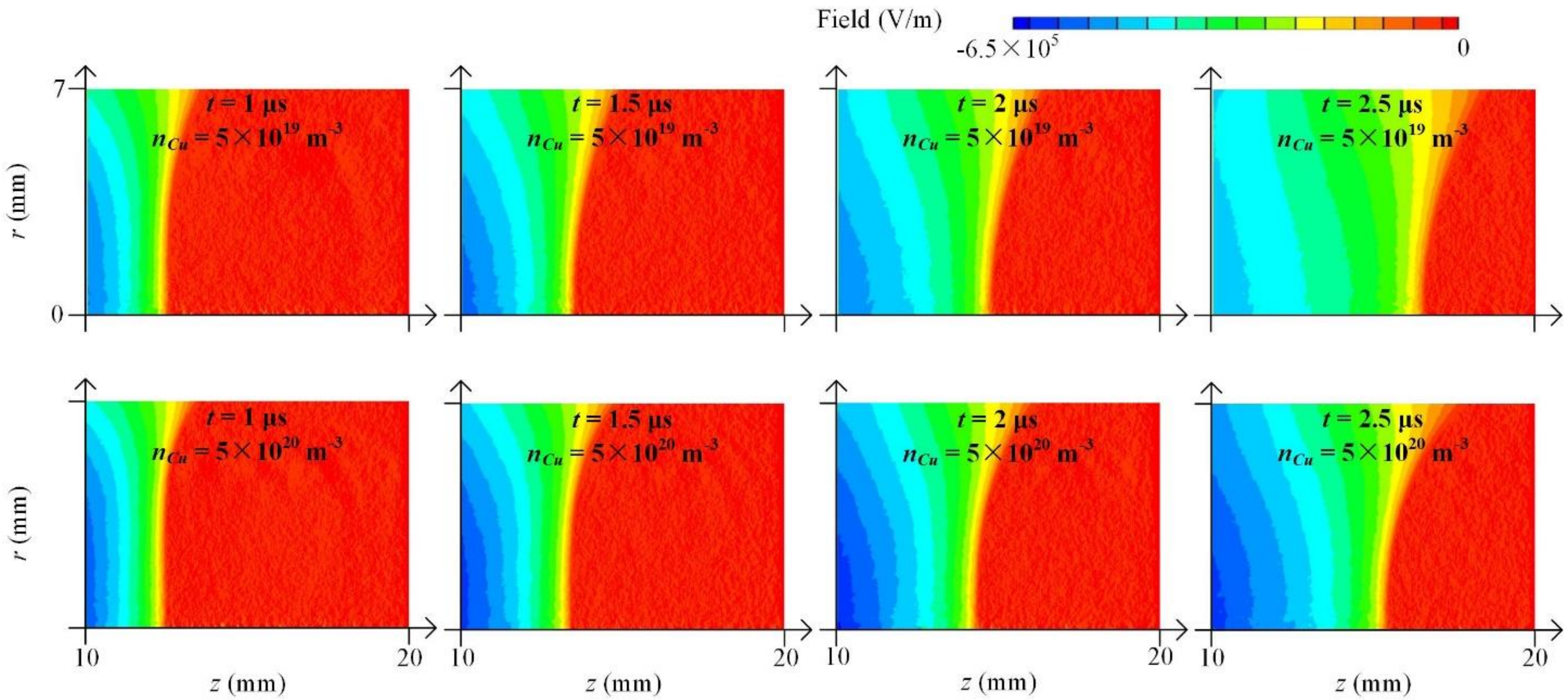
Post-arc current



- 10^{21} m^{-3}: the **mean free path** is much smaller than the gap. Results show significant difference.
- 10^{20} m^{-3}: the mean free path is comparable to the gap length.
- 10^{19} m^{-3}: the mean free path is longer than the gap. Results are similar to those in the collisionless case.

Effect of metal vapor density

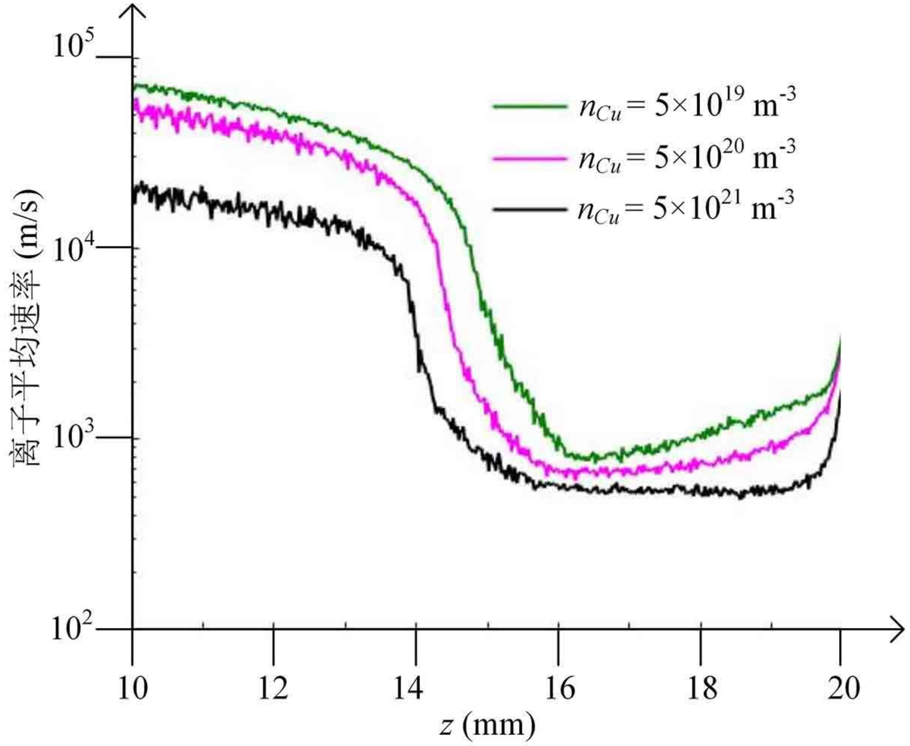
Electric field



- Electric field in the case with metal vapor density of 5×10^{19} m^{-3} first increases and then decreases with time.

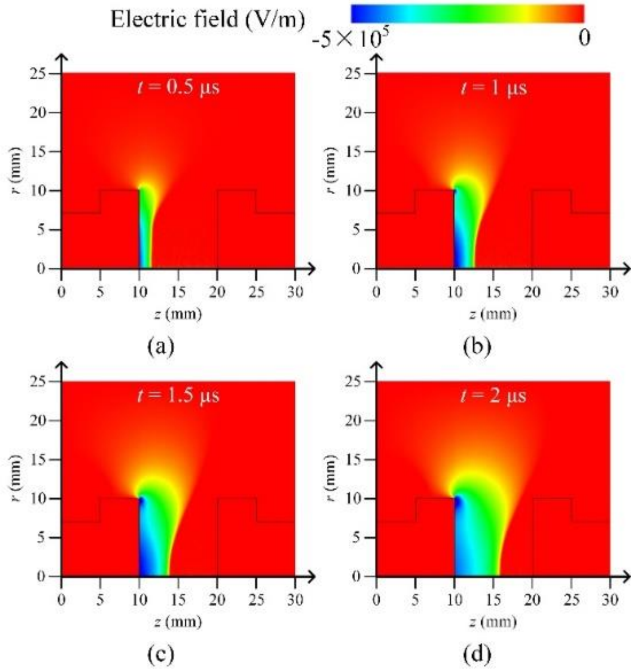
Effect of metal vapor density

Cu^+ velocity



- Although the electric field is higher in collisional case, the ion velocity is lower due to the energy loss in the collisions between ions and neutrals.

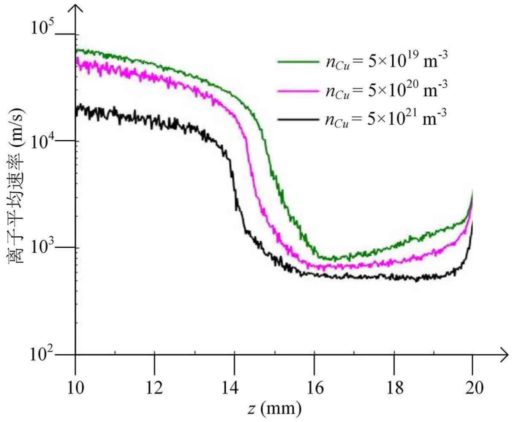
Townsend breakdown



- Ionization occurs in the sheath
- No residual electrons in the sheath

Possible sources for electrons leading to ionization:

1. Secondary emission by ions/neutrals impact



$$\gamma = 2.6 \times 10^{-4}[\mathrm{eV}^{-1}]\varepsilon_i.$$

2. Field emission

3. Thermal emission

Richardson-Dushman equation

T=2700 K decreases with radius

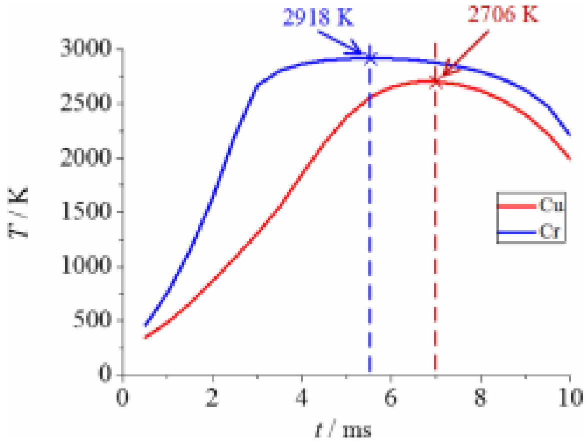
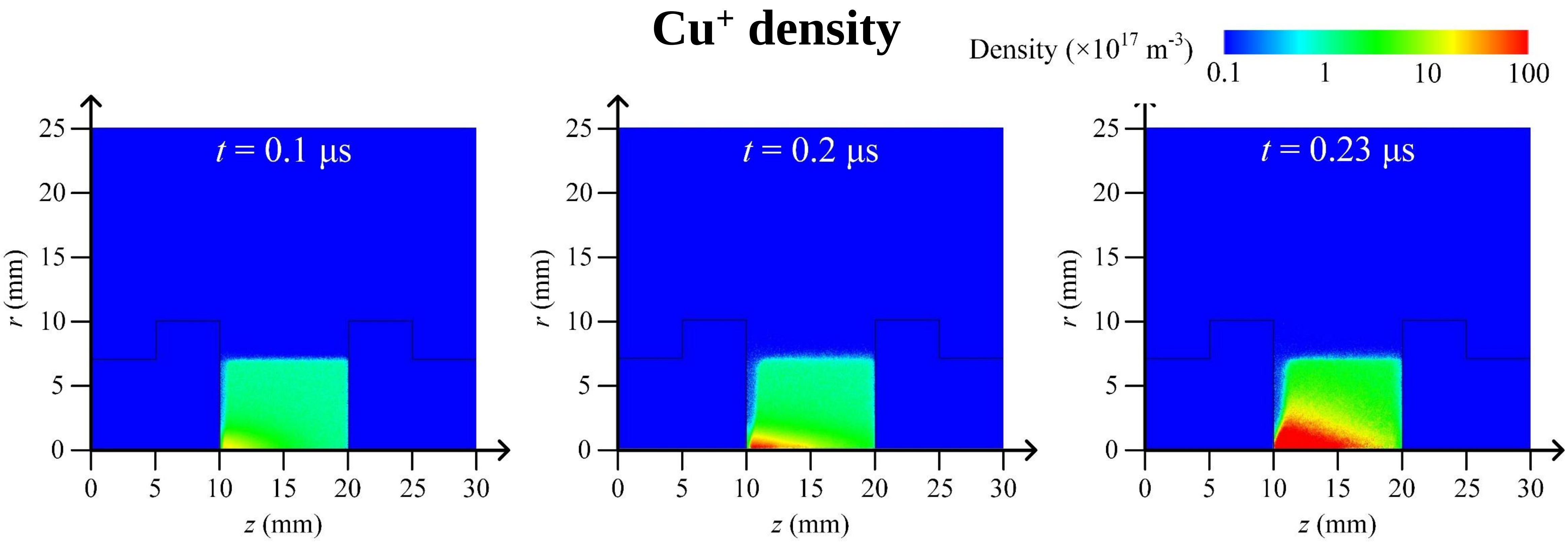


FIG. 9. Temperature of different material anode.

Lijun Wang, X. Huang, Shenli Jia et al., Journal of Applied Physics 117, 243301 (2015);

Breakdown in post-arc stage



- When the thermal electron emitting is included in the model, the breakdown in the post-arc stage quickly occurs with metal vapor density of 2.5×10^{21} m^{-3}.
- Electrons accelerated in the thin sheath ionize neutrals increasing the plasma density

Breakdown in post-arc stage

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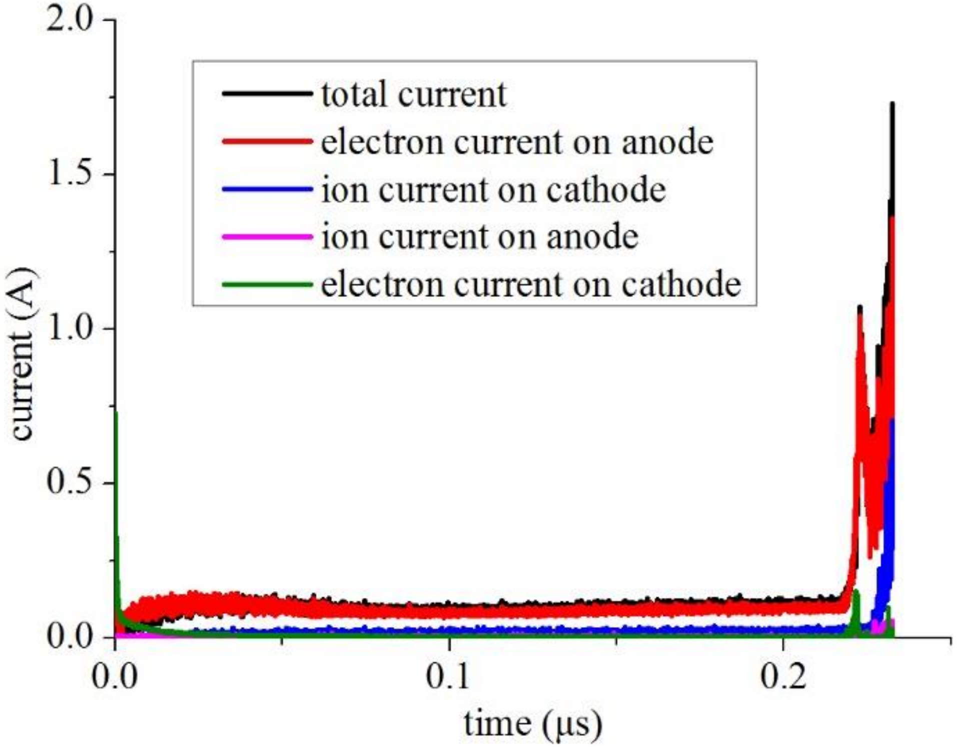
Post-arc current



- The breakdown occurs at about 0.23 μs. At the same time the plasma density in the channel is more than 2 orders higher than the initial density.

Breakdown in post-arc stage

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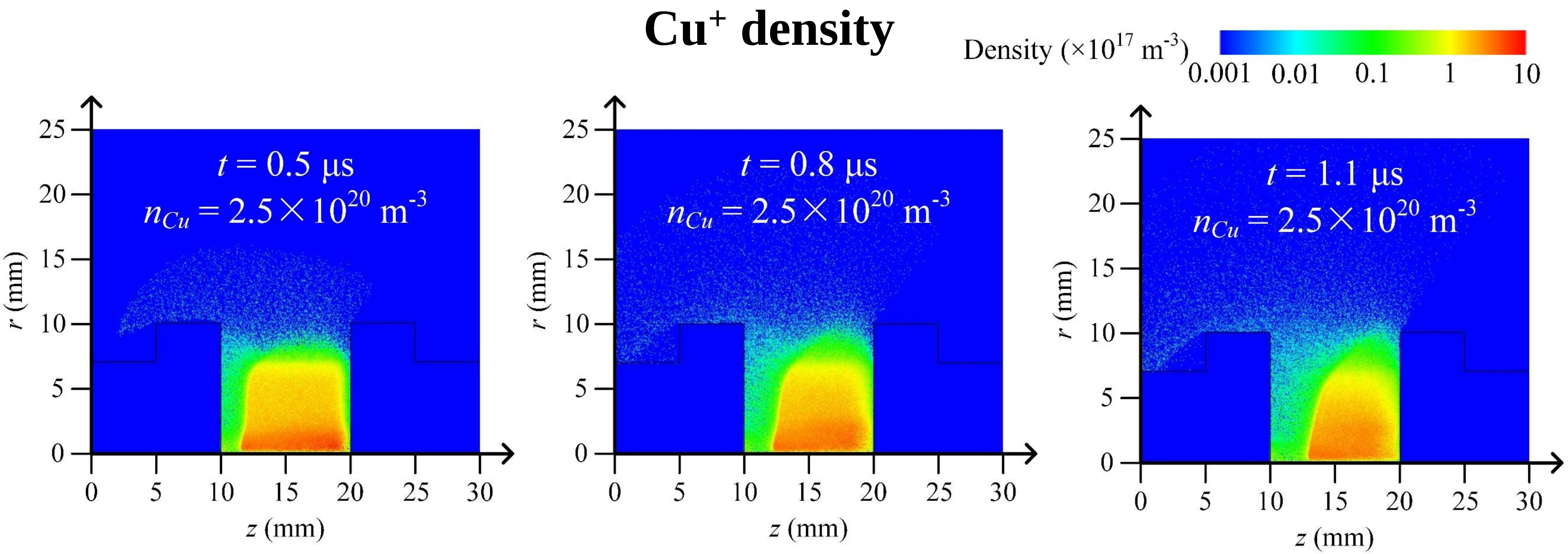
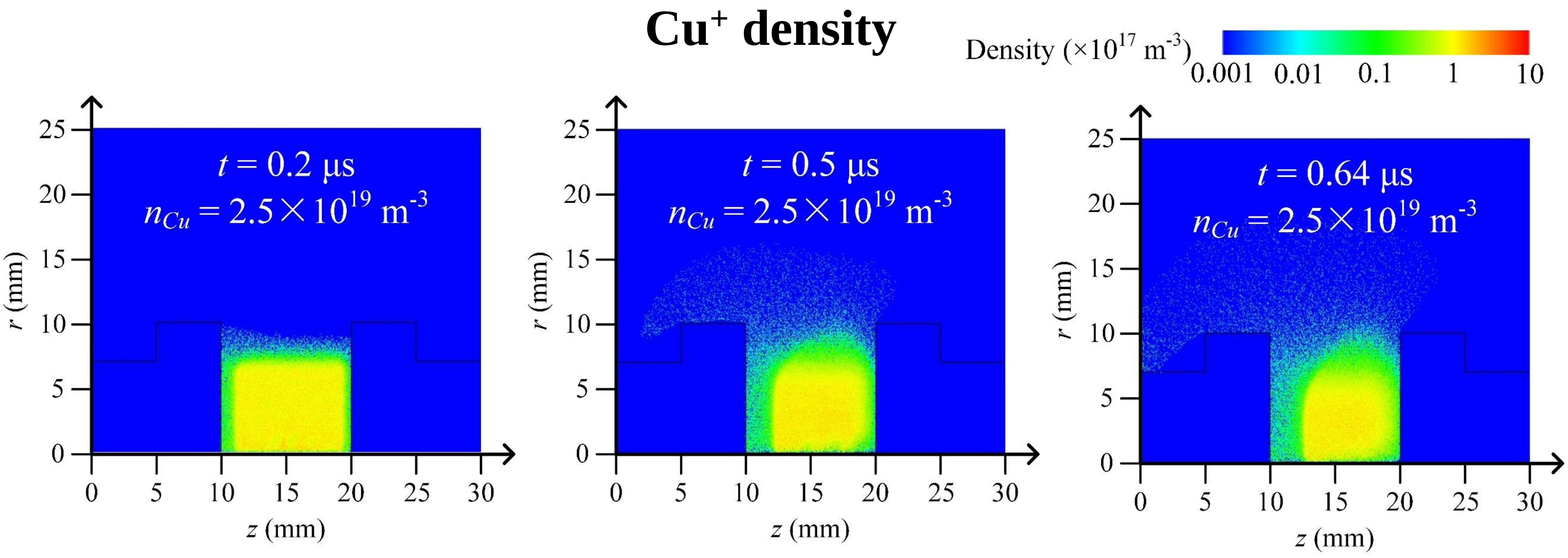


- Sheath expands; the plasma density increases one order higher than the initial density.
- The breakdown has not been obtained until 1.1 μs.

Breakdown in post-arc stage



- There is no increase in the density of plasma.

4. CONCLUSIONS

- The plasma decay in the post-arc phase of vacuum circuit breakers is simulated in the 2D3V model with PIC/MCC method. Under the acceleration of the TRV , charged particles move in axial and radial directions at the same time, and an ion sheath forms near the post-arc cathode.
- The velocity of plasma decay decreases and the electric field increases when the copper vapor is included in the simulation. However, when the neutral density is lower than 10^{20} m^{-3}, the mean free path is larger than the gap length, so the results are similar to those in collisionless model.
- The breakdown may occur when the thermal emitting on the post-arc surface is included in the model depending on the metal vapor density.
- Breakdown in this work occurs almost instantly after the current zero. The delay strikes cannot be investigated using the current model.

THANK YOU!