



12th International Workshop on the Mechanism of Vacuum Arcs

**Numerical Simulation of Vacuum Breakdown
Characteristics with Two Emission Sources Based on
Particle-in-Cell Method**

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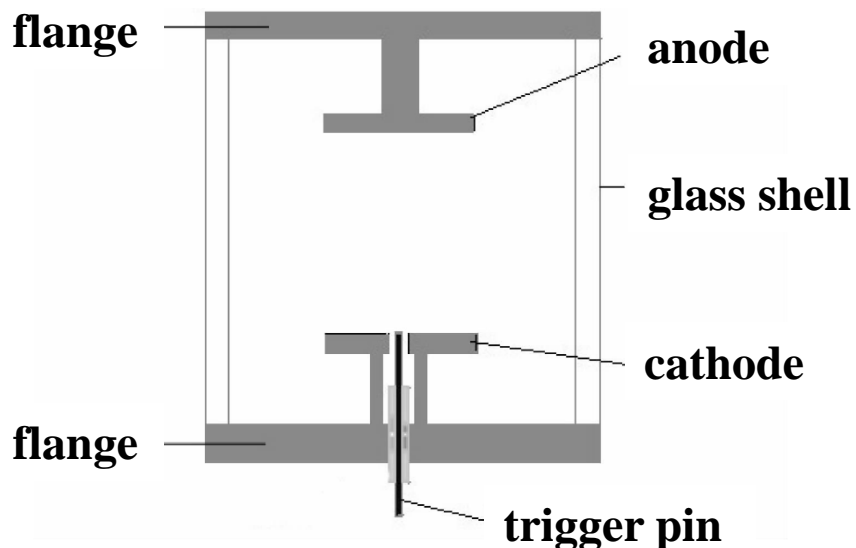
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II. SIMULATION MODEL

III. SIMULATION RESULTS AND DISCUSSION

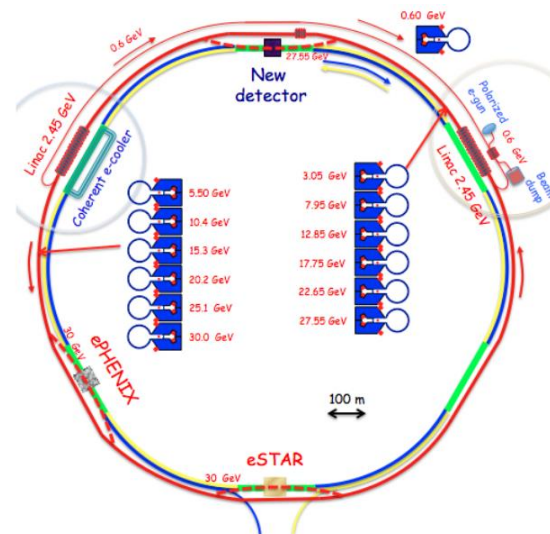
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Research Background

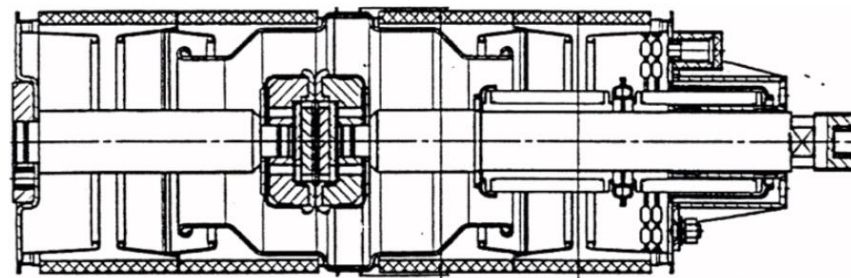


Trigger switch

Vacuum gap breakdown is widespread in vacuum circuit breakers, trigger switches and particle accelerators.

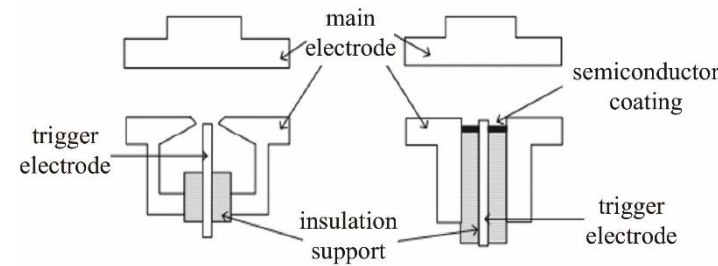
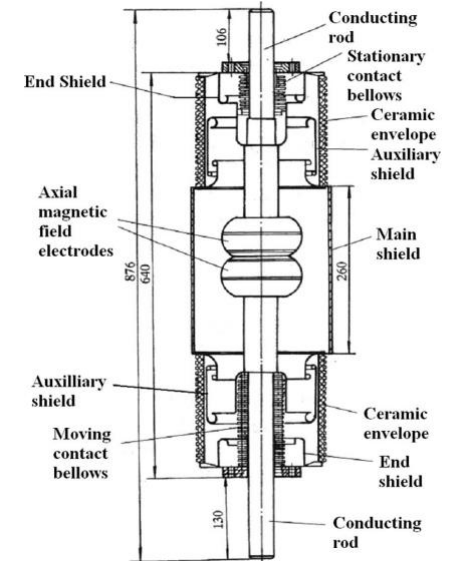


Particle accelerators

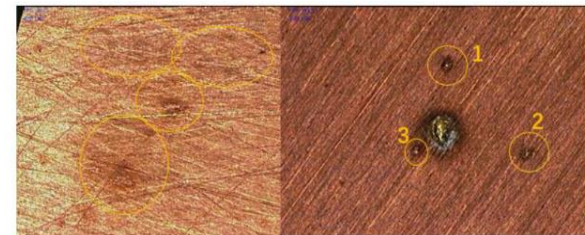


Vacuum circuit breaker

- ◆ Vacuum, as an excellent insulating medium, is well-known to everyone due to its extensive development prospects. In vacuum circuit breakers, trigger switches, and particle accelerators, the vacuum breakdown phenomenon in the gap will limit its insulation performance at high voltage conditions.
- ◆ The **trigger switch** usually needs to ignite the initial plasma by triggering the vacuum breakdown between the trigger electrode and the cathode electrode, thereby achieving the conduction of the main gap.
- ◆ **Pre-strike** phenomenon in small vacuum gap is widely existed in vacuum circuit breaker closing process.



- ◆ Many research works about vacuum breakdown are based on experimental study. However numerical simulation technology is an effective research tool about the vacuum breakdown and discharge phenomenon.
- ◆ Shmelev et al. established **an one-dimensional PIC-MCC** model for vacuum breakdown and presented the **phase space distribution** of particle velocities. Yang Wei et al. utilized **a two-dimensional axisymmetric PIC** model to simulate the breakdown process in vacuum space and presented the **ion energies** of different valence states.
- ◆ In previous work, the phenomenon of vacuum breakdown at a **single emission** source has been extensively studied. In this work, a **two-dimensional model** is established to consider the effect of **multi-emission sources**.



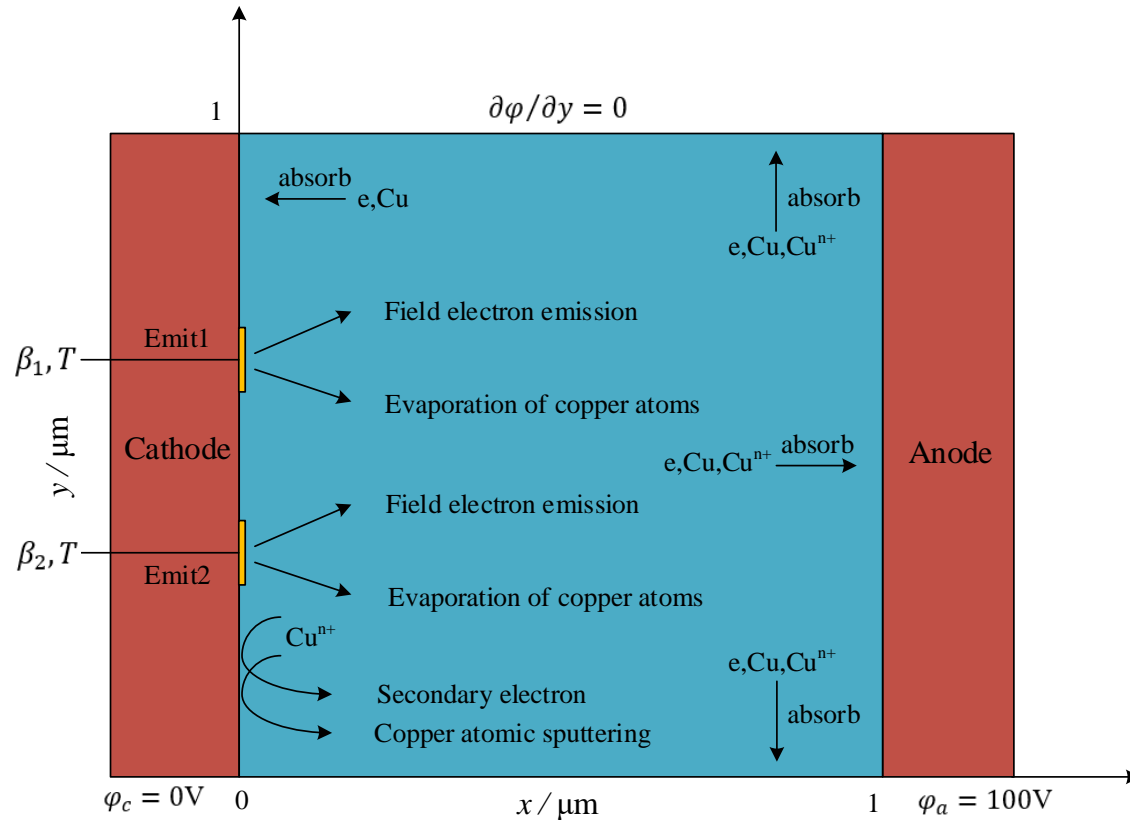
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Physical model



- **2D Particle-In-Cell / Monte Carlo Collision (PIC/MCC) model is used.**
- **Different components are considered (ions, atoms and electrons).**
- **Field emission electrons, evaporation of copper atoms, secondary electron emission and sputtering are considered.**
- **All boundaries are absorbing boundaries.**

◆ Particle Emission Modeling

- ✓ Field emission electron: Fowler-Nordheim equation

$$j_{FN} = \frac{A_{FN} E_{LOC}^2}{\phi_w t^2} \exp\left(-\frac{B_{FN} \nu \phi_w^{3/2}}{E_{LOC}}\right)$$

$$A_{FN} = \frac{e^3}{8\pi h_p} \quad B_{FN} = \frac{8\pi\sqrt{2m_e}}{3eh_p} \quad E_{LOC} = \beta E_m$$

E_{LOC} is local electric field strength considering field enhancement coefficient.

- ✓ Evaporation of copper atoms: Hertz-Knudsen equation

$$j_{Cu} = \frac{p}{\sqrt{2\pi m k_B T}} \quad p = 133.33 \times 10^{-17650/T+13.39} \times T^{-1.25}$$

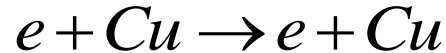
◆ Grid Size

$$\sqrt{\Delta z^2 + \Delta r^2} < \lambda_{Db} \quad \Delta t < 0.2 \omega_{pe}^{-1}$$

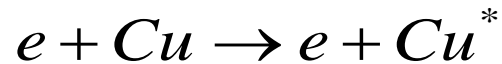
λ_{Db} is Debye length, ω_{pe} is plasma oscillation frequency.

◆ Collision model

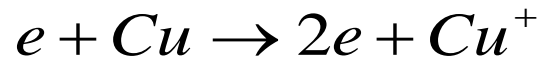
- **Elastic collision:**



- **Excitation collision:**



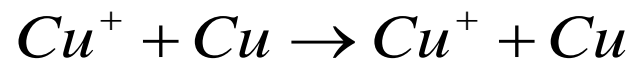
- **Ionization collision:**



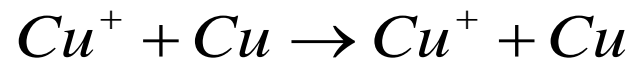
- **Ionization collision between electrons and ions:**



- **Momentum exchange between ions and atoms:**



- **Charge exchange between ions and atoms:**

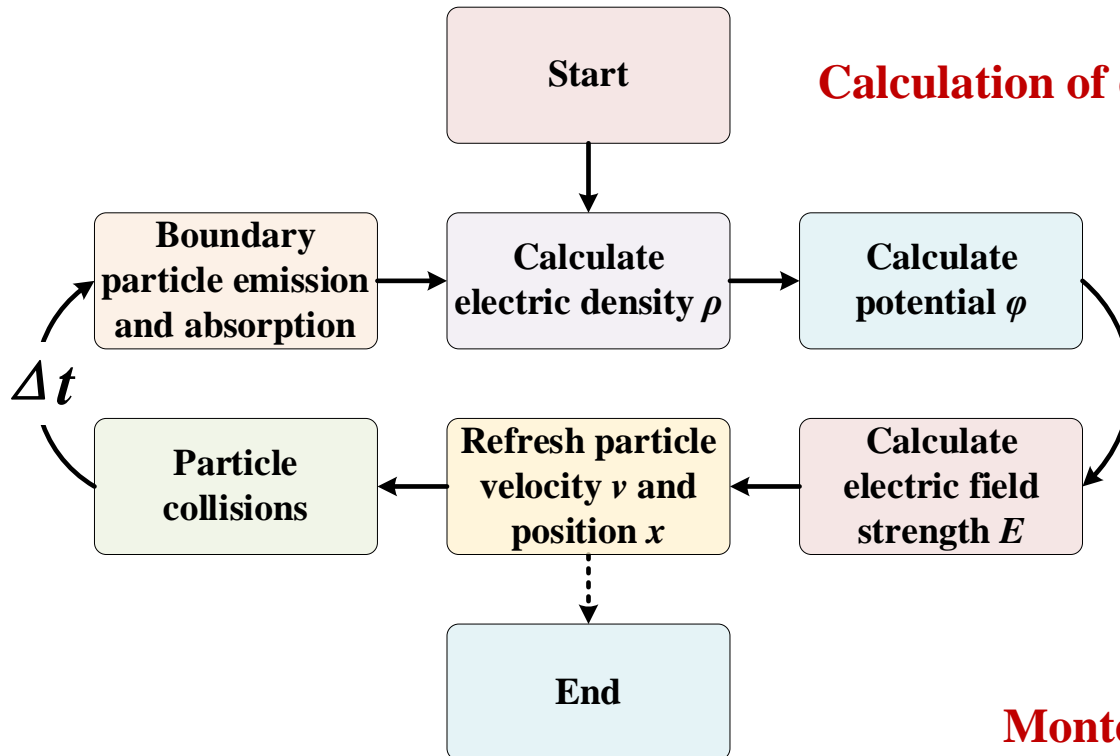
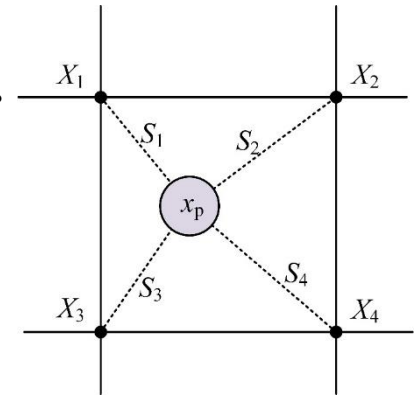


◆ Basic settings

Parameter	Value	Unit	Description
L	1	μm	gap length
H	1	μm	Gap height
Δx	5	nm	Grid size
Δy	5	nm	Grid size
Δt	1	fs	Time step
β_1	100		field enhancement factor
β_2	75 (85, 65)		field enhancement factor
L_{em}	0.1	μm	Emission area length
T	6000	K	Emission area temperature
φ_c	0	V	Cathode voltage
φ_a	100	V	anode voltage
d	0.3 (0.4, 0.6)	μm	Distance between centers of emission sources

◆ PIC/MCC Simulation model

- In the PIC model, the simulation space is divided into many grids. The spatial electric field distribution is solved by **calculating the charge density** at the grid points, and the movement of the charged particles is further promoted. The MCC method is used to **handle particle collisions**.



Calculation of charge density:

$$\rho_i = \frac{1}{V} \sum_p q S(\mathbf{x}_p - \mathbf{X}_i)$$

Solution of electric field: $\nabla^2 \phi = -\frac{\rho}{\epsilon_0}$

$$\mathbf{E} = -\nabla \phi$$

Particle motion: $\mathbf{E}_p = \sum_i \mathbf{E}_i S(\mathbf{x}_p - \mathbf{X}_i)$

$$\frac{d\mathbf{v}}{dt} = \frac{q\mathbf{E}_p}{m}$$

$$\frac{d\mathbf{x}}{dt} = d\mathbf{v}$$

Monte Carlo collision: $P = 1 - \exp[-N\delta_e v_e \Delta t]$

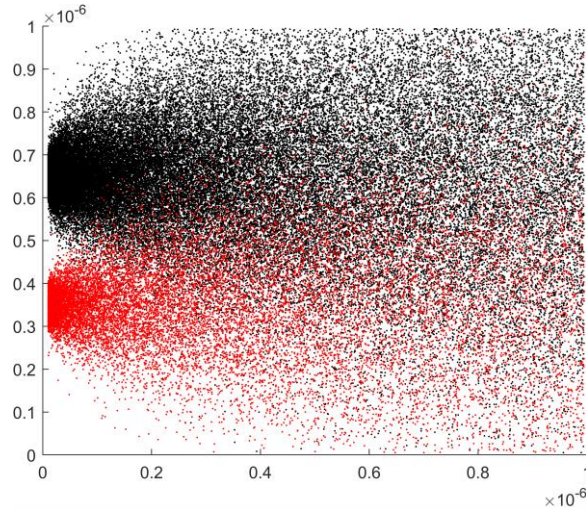
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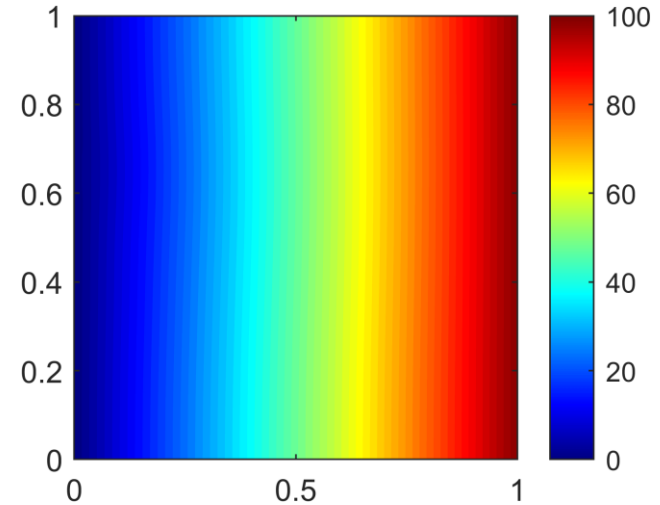
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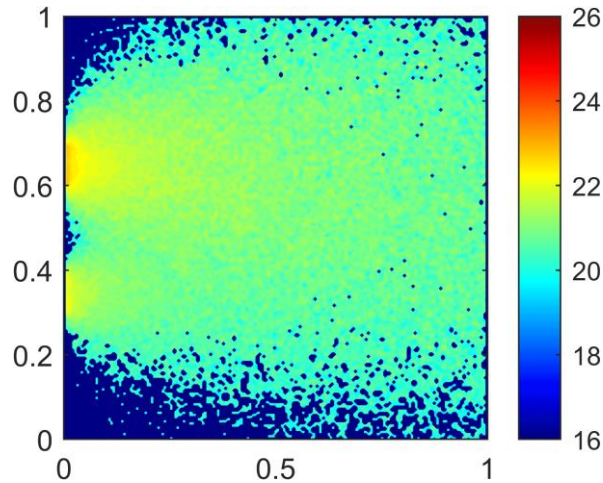
◆ **Typical results** From 0ps to 300ps, The interval between each picture is 30 ps.



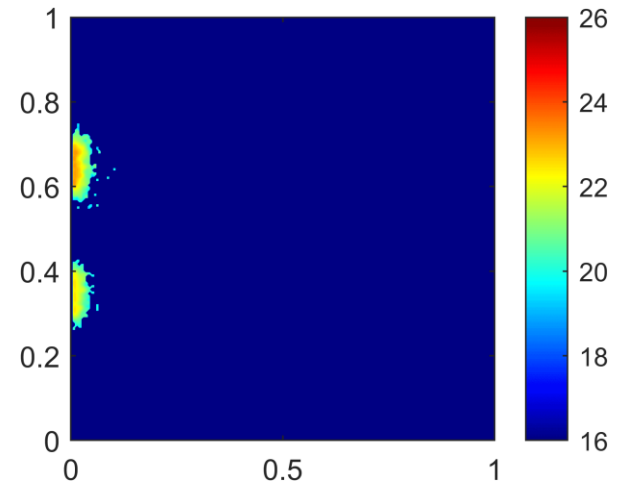
Electrons position variation



Electrical potential variation

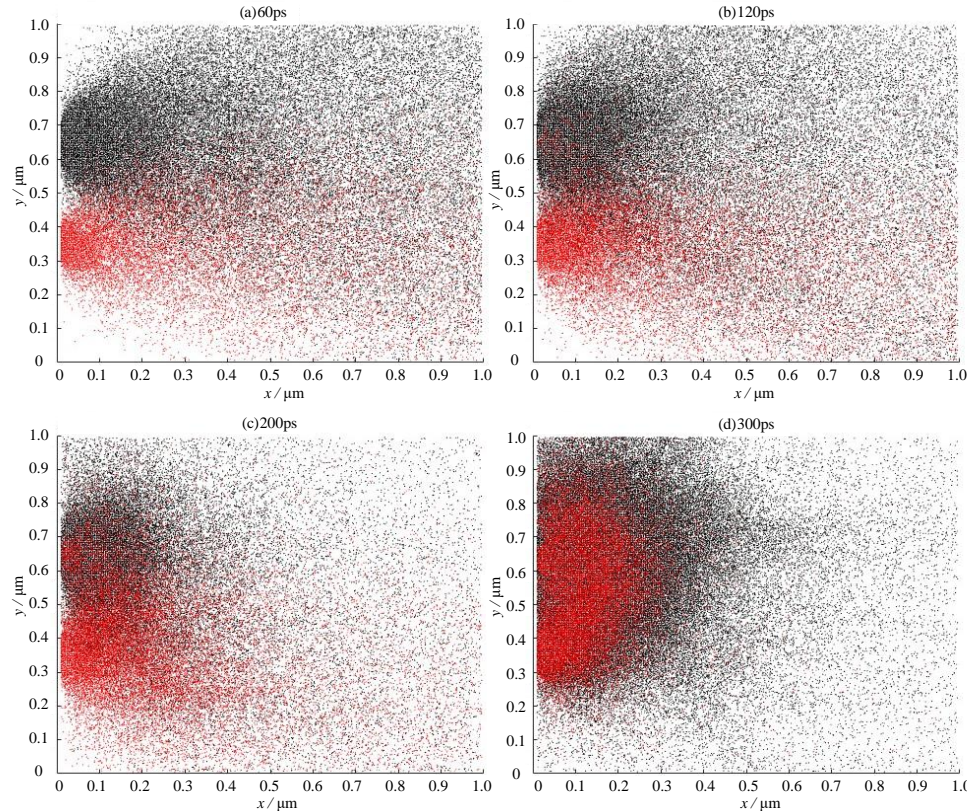


Electrons density variation



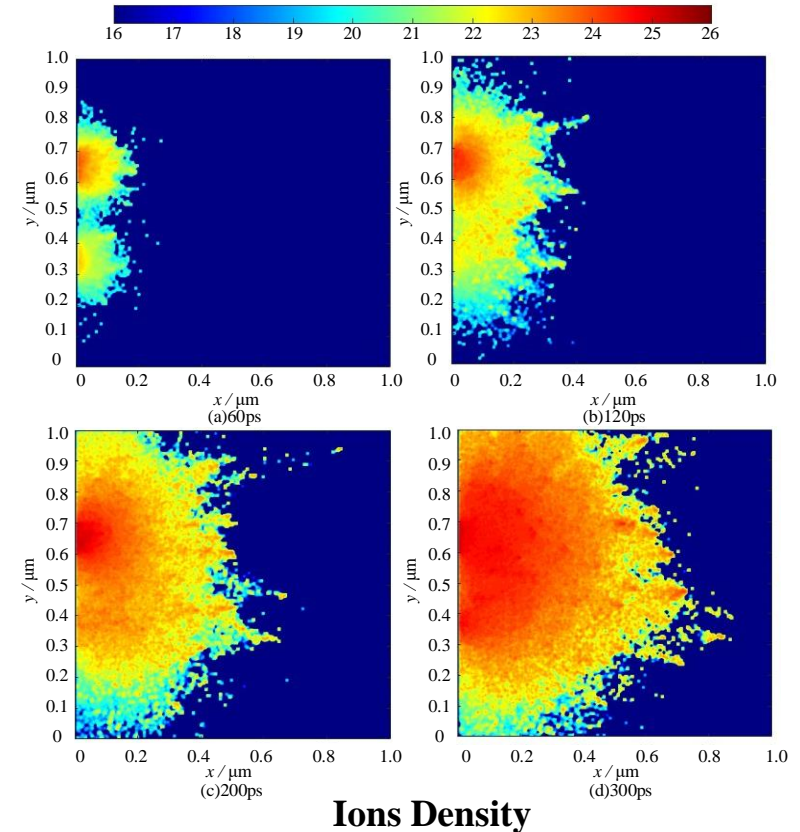
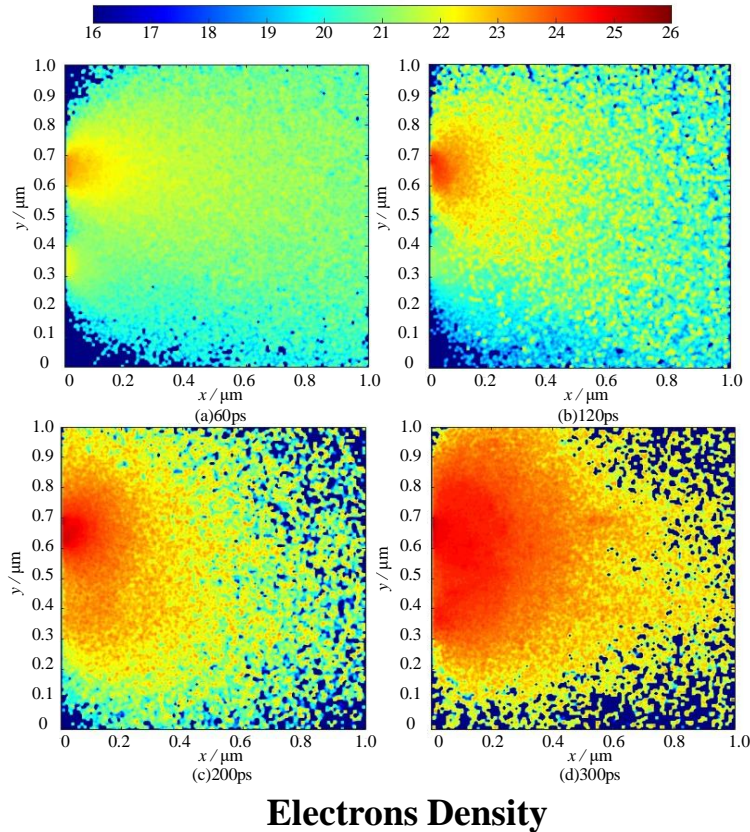
Ions density variation

◆ Typical results



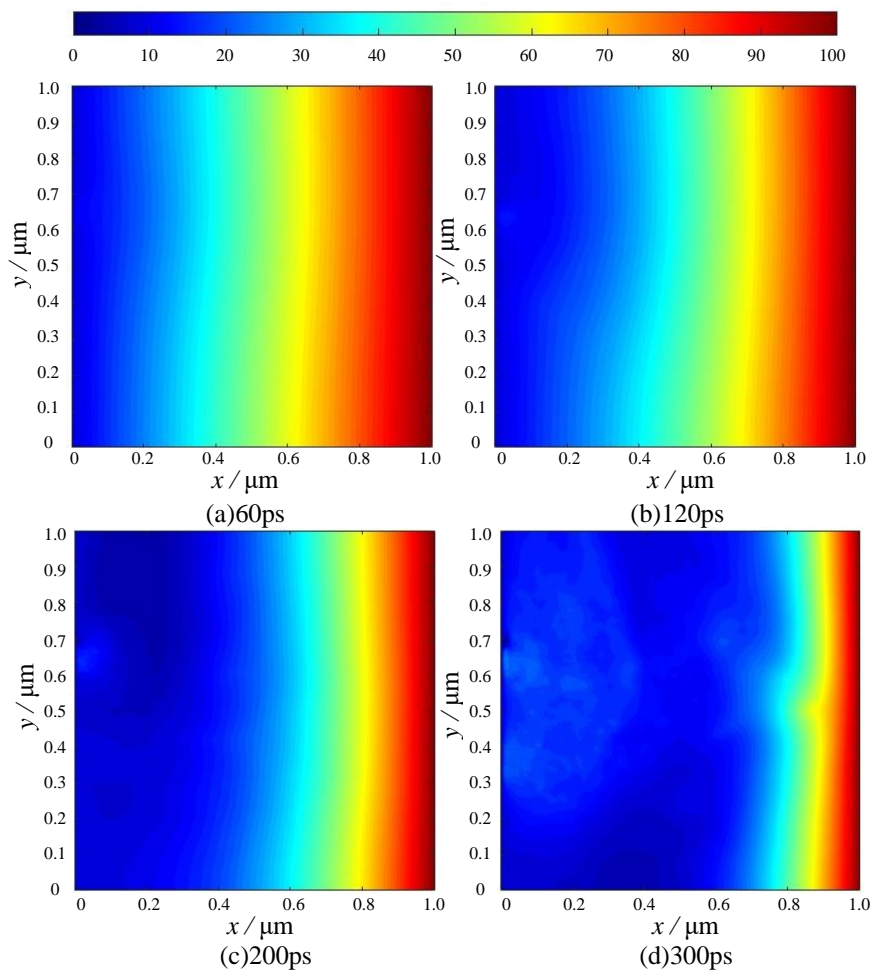
- The electrons emitted from the two emission sources are set to be of **two different colors**.
- The electrons emitted from the two emission sources will **accelerate the discharge process** near their respective emission sources.

Typical results



- The entire discharge process still centers around the emission sources with **larger field enhancement coefficients.**
- A denser area emerged in the region **between the two emission sources.**

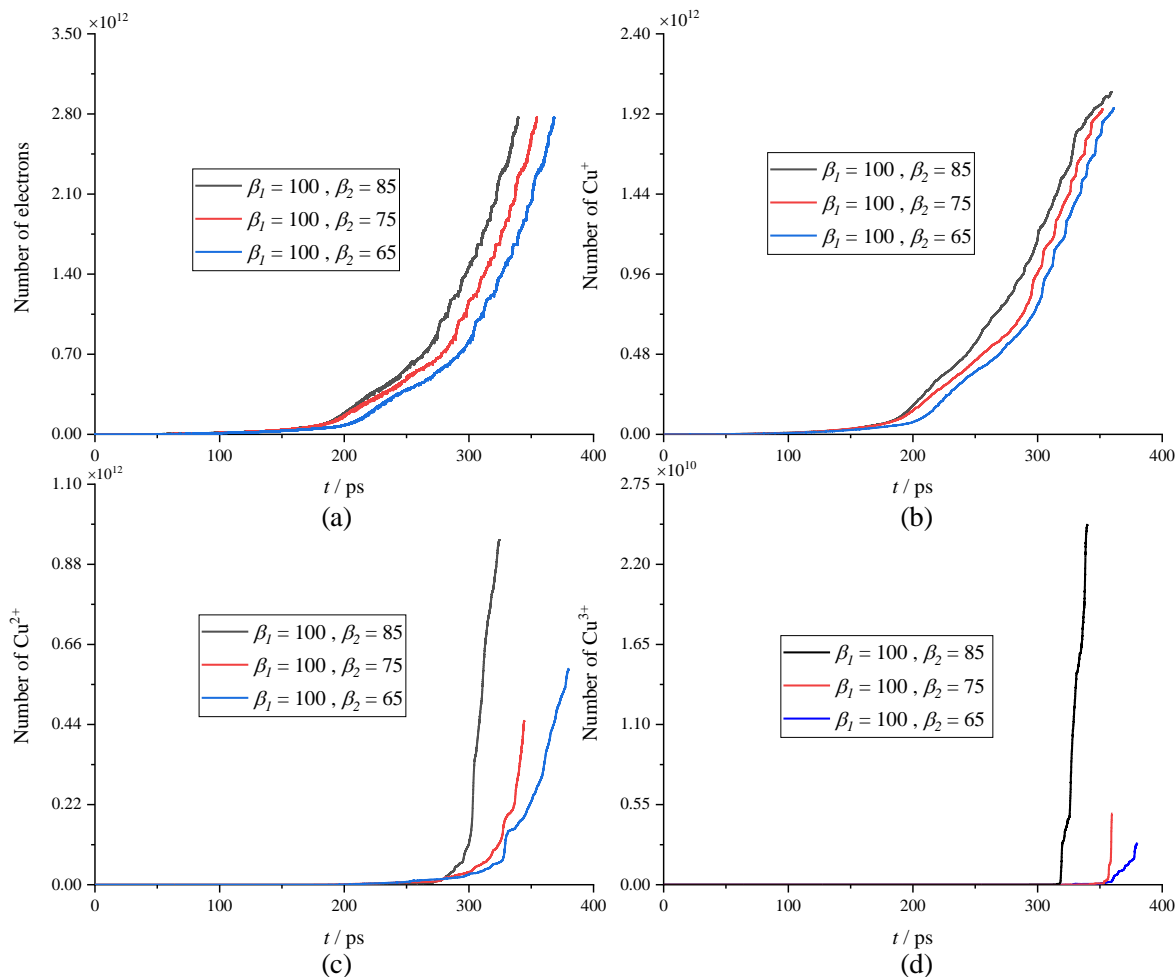
◆ Typical results



Potential variation

- The internal electric potential of the plasma is **zero**.
- The distortion of electric potential is concentrated **near the emission sources**, and the distortion in **the middle part** between the two emission sources is **more obvious**.
- The existence of **potential peaks** enables ions to form an acceleration layer in the region of potential drop, which helps the plasma advance forward **more rapidly**.

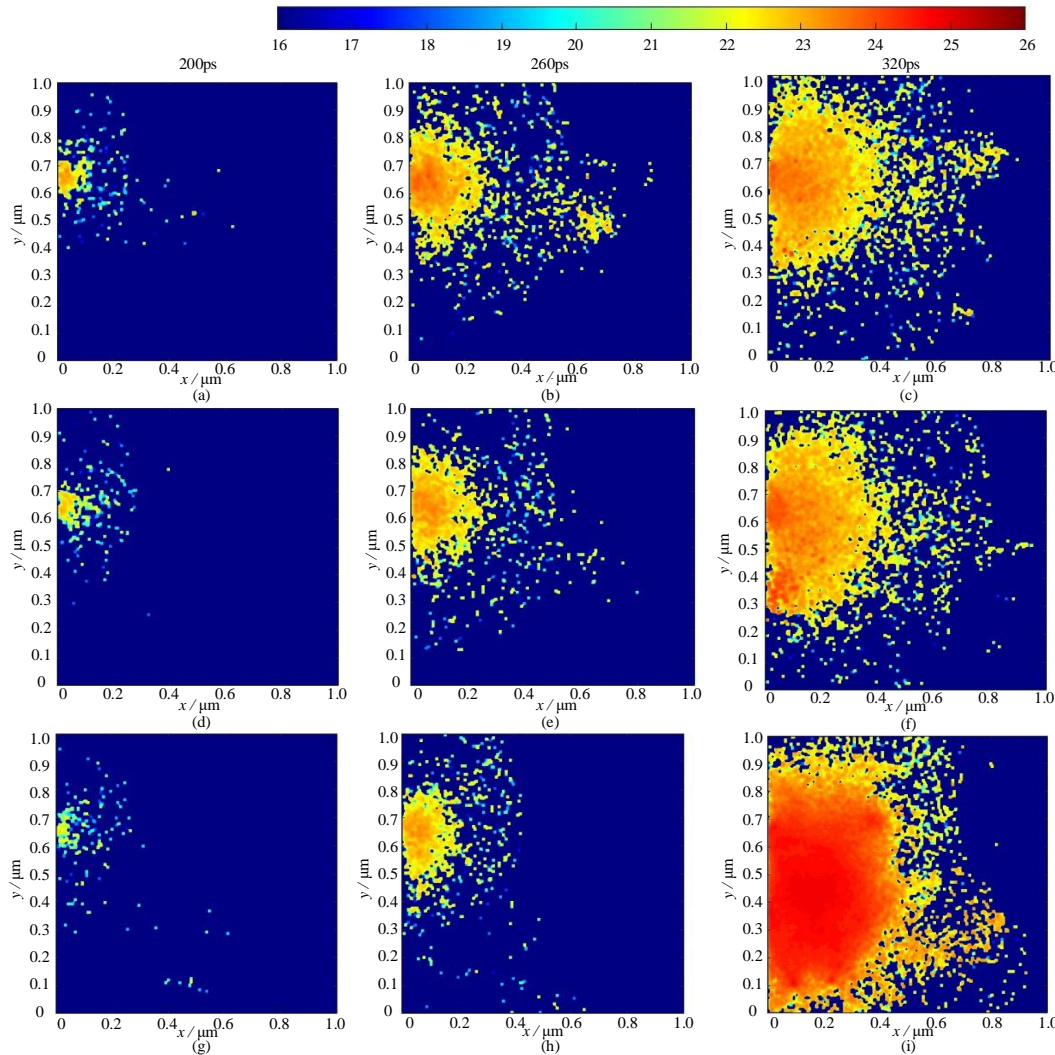
◆ The effect of field enhancement factor on vacuum breakdown



- The **larger** the field enhancement coefficient at the emission source 2 is, the **faster** the discharge process will be.
- As the emission source 2 increases, the time when high-energy particles appear **shortens**.

The variation of the quantities of different particles

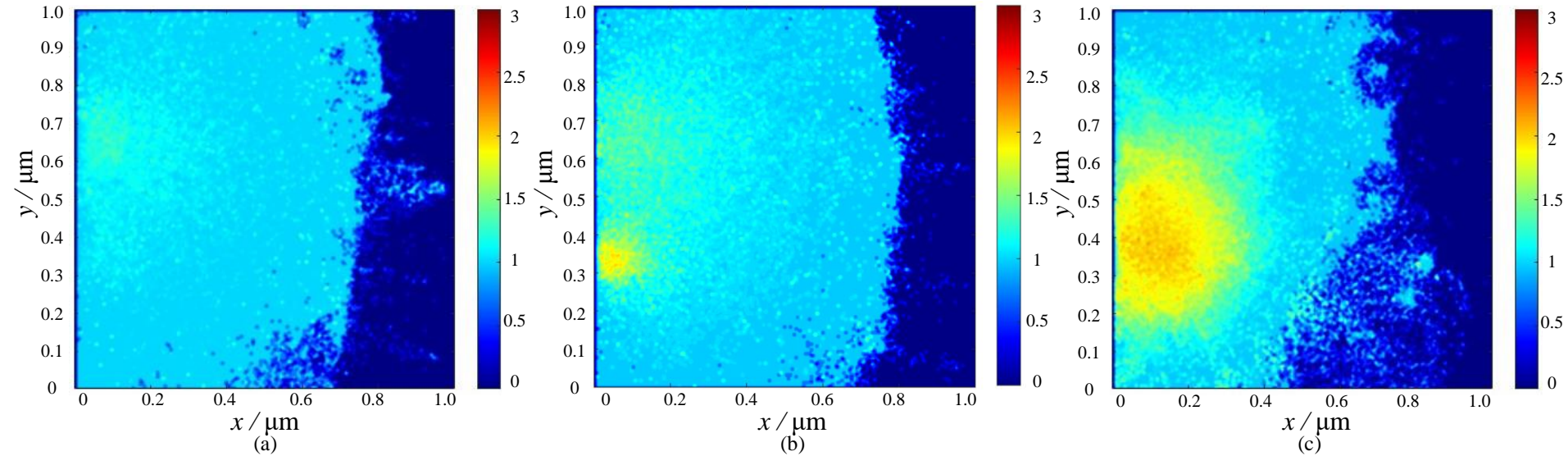
◆ The effect of field enhancement factor on vacuum breakdown



The density of divalent copper ions

- When the field enhancement coefficient at the emission source 2 increases, the number of high-valence ions near the emission source 2 **significantly increases**.
- The position where the high-valence ions appear also **shifts** from near the emission source 1 to the **position between the emission sources 1 and 2**.

◆ The effect of field enhancement factor on vacuum breakdown

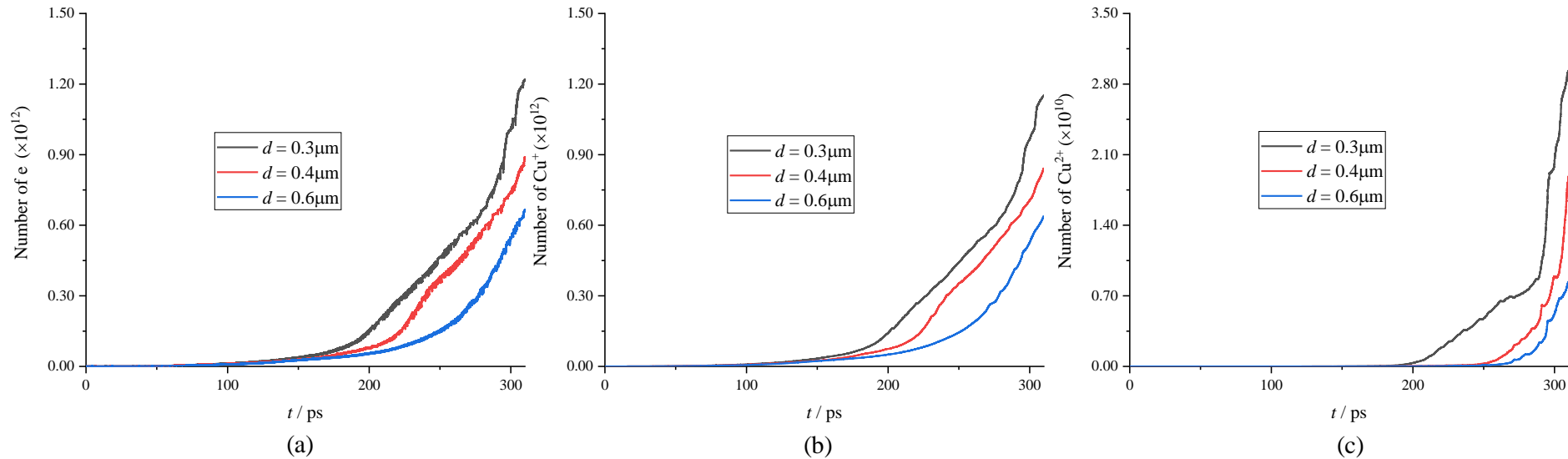


The average charge state of ions at 300 ps under different field enhancement factors

The field enhancement coefficients of (a), (b), (c) are 65, 75 and 85 respectively.

- After changing the field enhancement coefficient, the discharge mode **remains similar**.
- When the field enhancement coefficient at the emission source 2 **increases**, the number of high-valence ions near the emission source 2 **significantly increases**.
- The **area between the two emission sources** shows the presence of high-valence ions.

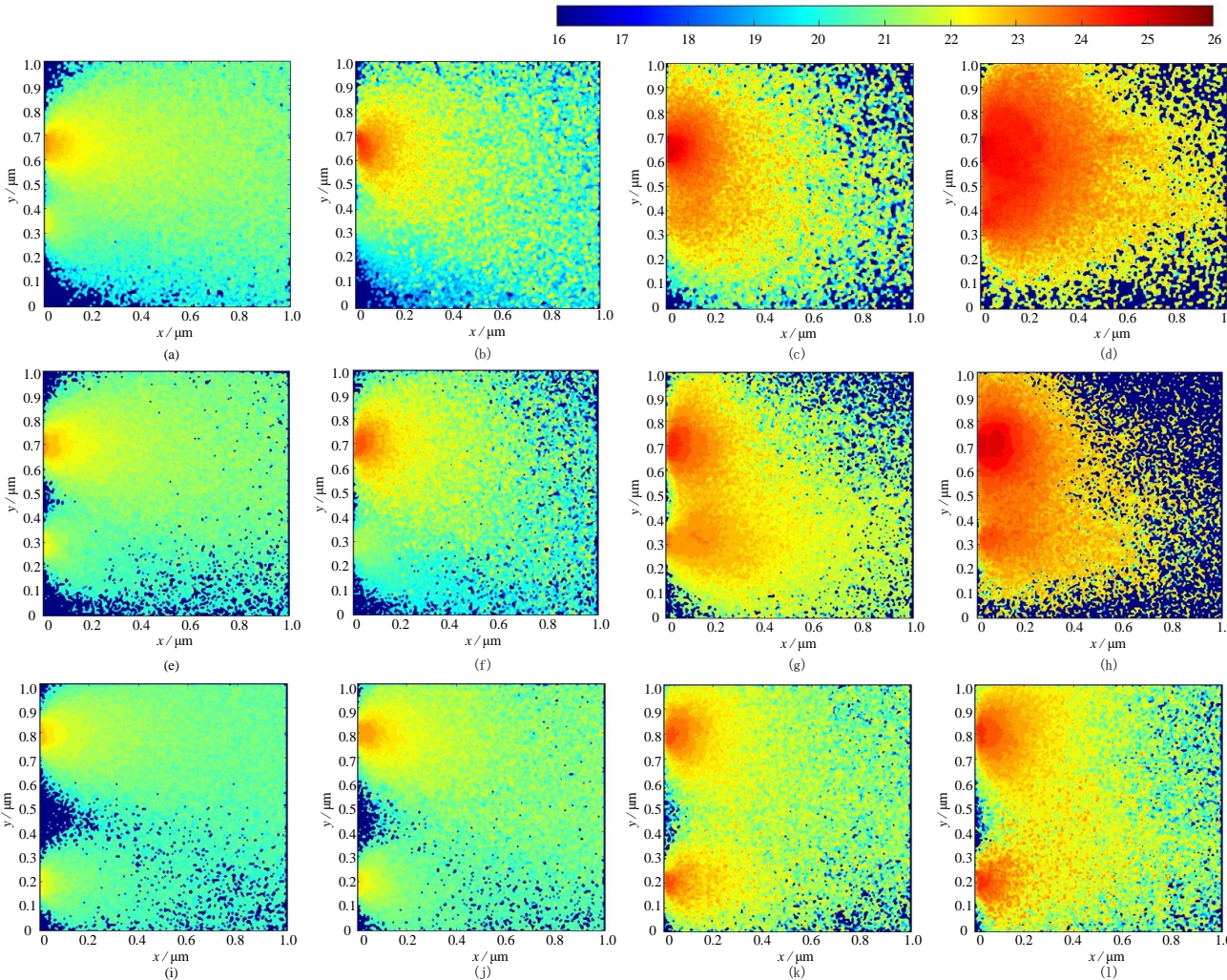
◆ The effect of the distance between emission sources



The average charge state of ions at 300 ps under different distance between emission sources

- The **increase** in the distance between the two emission sources leads to a **slower discharge process**.
- An increase in distance will lead to a **decrease in the number of electrons** near the emission source, further **slowing down** the ionization process of copper atoms.

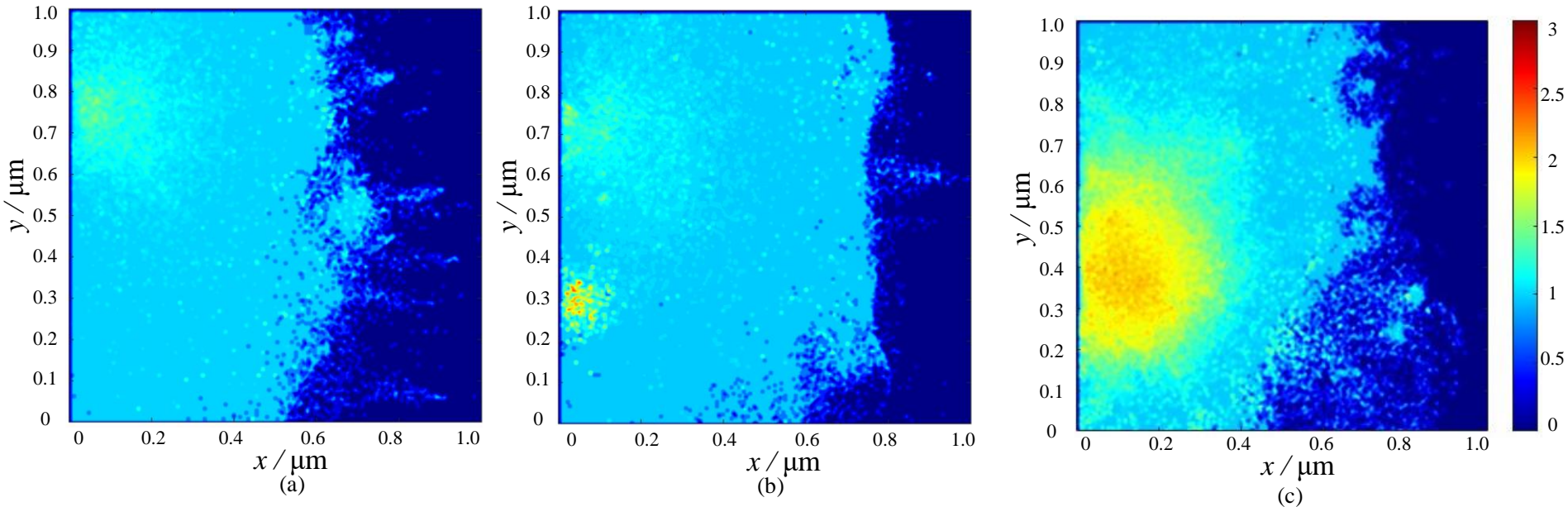
◆ The effect of the distance between emission sources



Electrons Density

- The distances of the emission sources are 0.3, 0.4 and 0.5 respectively from the first row to the third row.
- After the distance between the two emission sources is increased, the mutual influence between them also **decreases accordingly**.
- When the distance increases to a certain extent, the situation where the two discharge sources operate **independently** occurs.

◆ The effect of the distance between emission sources



The average charge state of ions at 300 ps under different distance factors

The distances of the emission sources for (a), (b), (c) are 0.5, 0.4 and 0.3 respectively.

- The mutual **influence** between the two emission sources will cause the average valence state near the emission sources to **rise**.
- The increase in distance leads to a **reduction in the influence** between the two emission sources and a **decrease in the average valence state**.

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- In the model with two emission sources, the **initial discharge** is mainly dominated by the emission source with a **larger field enhancement coefficient**.
- The closer the field enhancement coefficients are, the more the discharge area **shifts to the part between the two emission sources**. The greater the difference in field enhancement coefficients, the more the discharge is dominated by the source with **the larger field enhancement coefficient**.
- **The greater** the distance between the two emission sources, **the smaller** the mutual influence will be. Reducing the distance between the emission sources will cause **the average valence state of the ions** near a single emission source to **increase**.



**Thank you for your
attention**