8th International Workshop on Mechanisms of Vacuum Arcs
(MeVArc 2019)

Study on the post-arc sheath and the post-arc current in vacuum interrupters

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Modeling and Simulations

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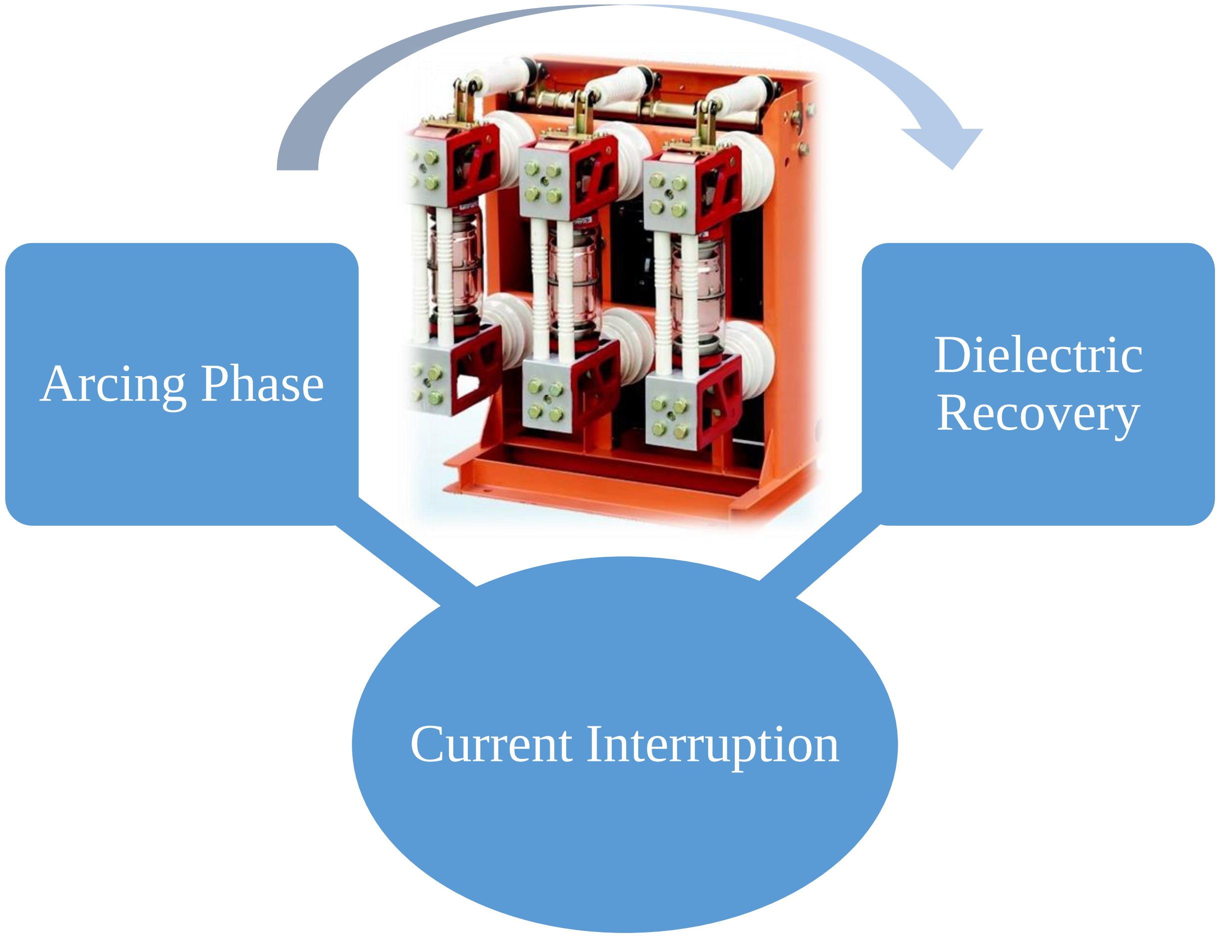
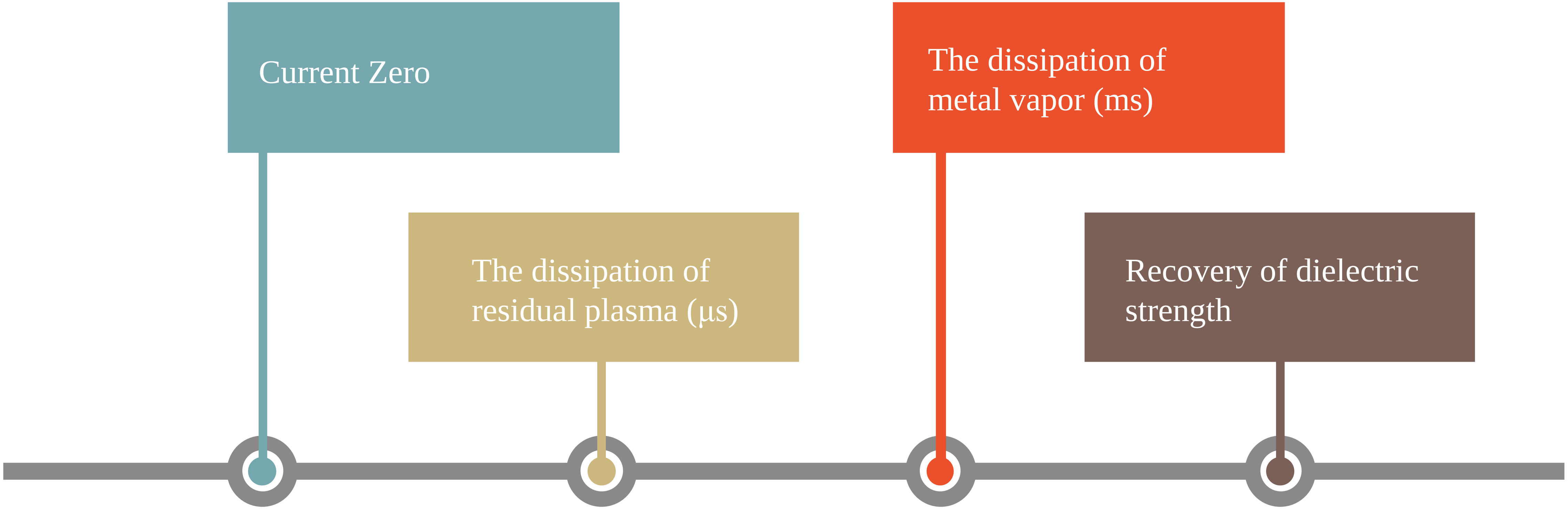
01. Background



The dielectric recovery process is important for a successful interruption.

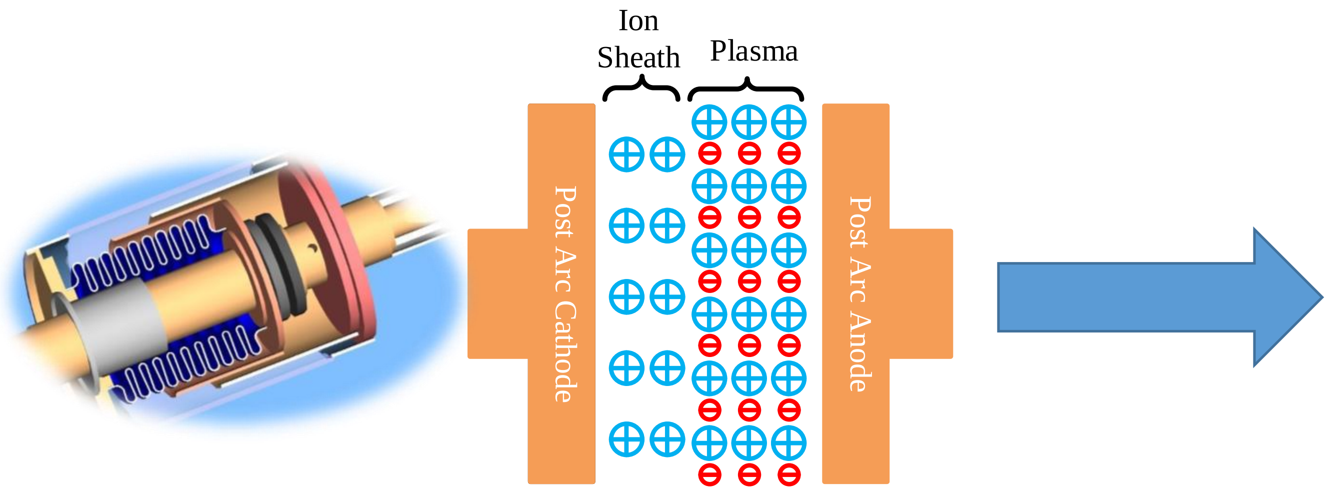
01. Background



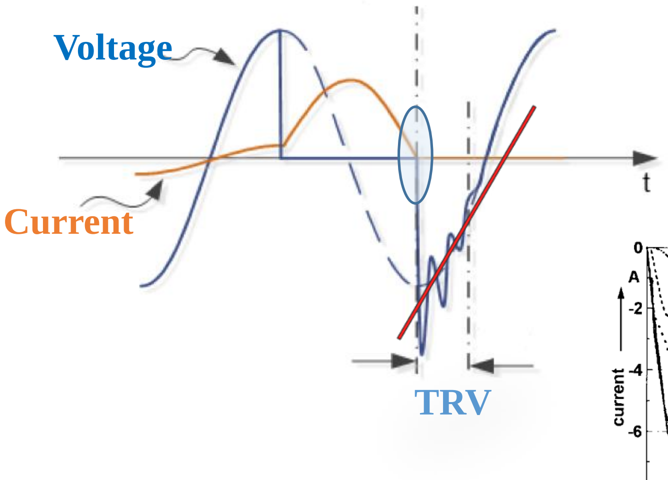
The dissipation of residual plasma starts immediately after current zero, which is important for the study of dielectric recovery process.

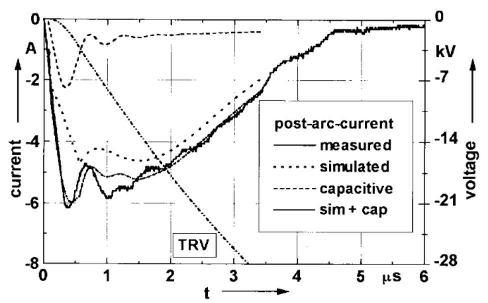
01. Background

Post-arc current



The dissipation of residual plasma





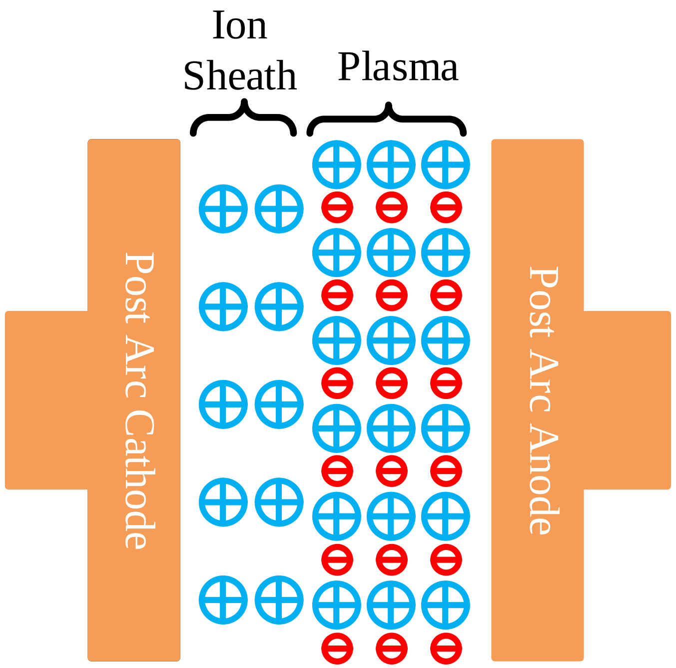
The post-arc sheath forms under the effect of transient recovery voltage. Meanwhile, the post-arc current forms when the charged particle are absorbed by the electrodes.

01. Background

Researches on post-arc current

Modeling & Simulations

- **Continuous transition model (CTM)**
  - **The derivation of this model is based on a semi-infinite collisionless plasma.**
  - **It is numerically instable and not so self-consist**
  - **It requires little computational time**
  - **The simulations with CTM agree well with the post-arc current obtain with experiments in relatively low current interruptions**



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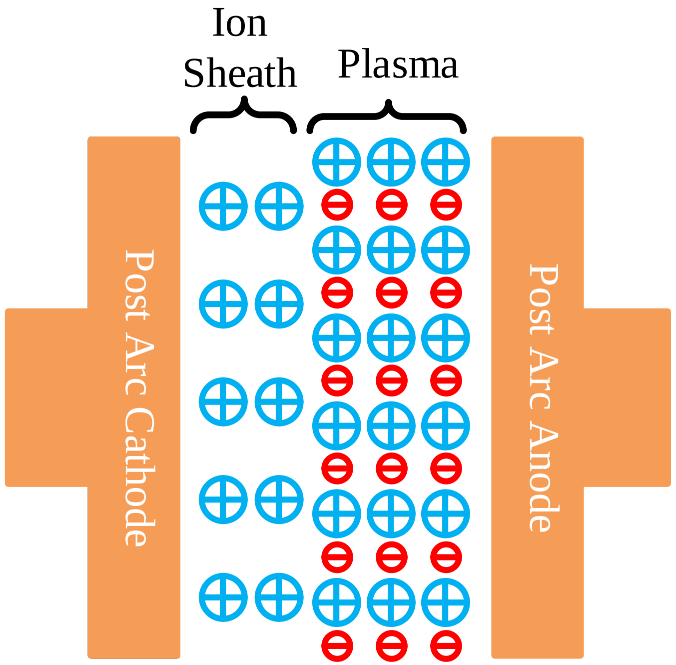
2. R. Holmes and S. Yanabu, "Post-arc current mechanism in vacuum interrupters," Journal of Physics D: Applied Physics, vol. 6, no. 10, p. 1217, 1973.
3. J. Kaumanns, "Measurements and modeling in the current zero region of vacuum circuit breakers for high current interruption," IEEE Transactions on Plasma Science, vol. 25, no. 4, pp. 632-636, 1997.

01. Background

Researches on post-arc current

Modeling & Simulations

- **Hybrid Maxwell-Boltzmann model (Hybrid-MB model)**
  - **The electron density is obtained from Maxwell-Boltzmann relation**
  - **The ions are treated as particles**
  - **It requires less computational time**
  - **The influences of plasma density, the rising rate of transient recovery voltage, metal vapor, evaporation of electrodes, polarity effect on the post-arc sheath**



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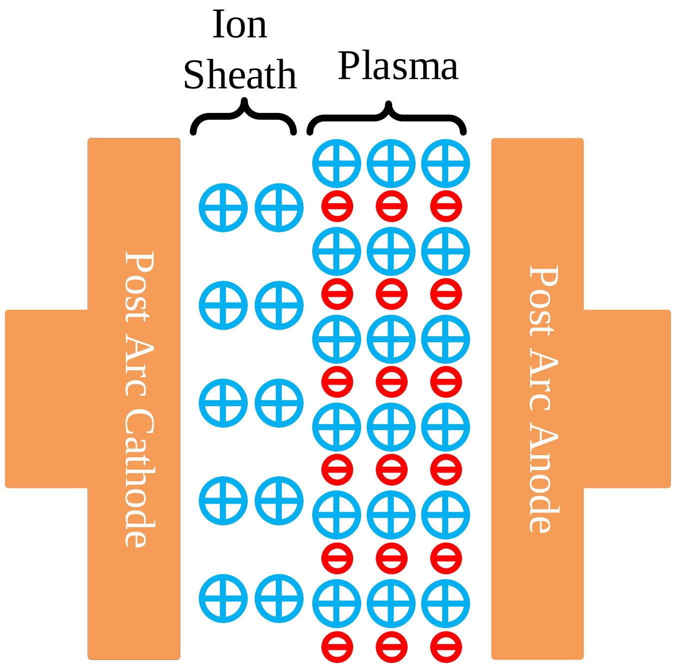
2. P. Sarrailh *et al.*, "Expanding sheath in a bounded plasma in the context of the post-arc phase of a vacuum arc," *Journal of Physics D: Applied Physics*, vol. 41, no. 1, p. 015203, 2008.
3. P. Sarrailh *et al.*, "Two-Dimensional Simulation of the Post-Arc Phase of a Vacuum Circuit Breaker," *IEEE Transactions on Plasma Science*, vol. 36, no. 4, pp. 1046-1047, 2008.

01. Background

Researches on post-arc current

Modeling & Simulations

- **PIC model**
  - **Both the electrons and ions are treated as particles**
  - **It is more self-consistent and costs more computational time than the hybrid Maxwell-Boltzmann model**
  - **The PIC model has been applied to the study of post-arc sheath in recent years. The influence of metal vapor on post-arc sheath and post-arc breakdown has been studied.**



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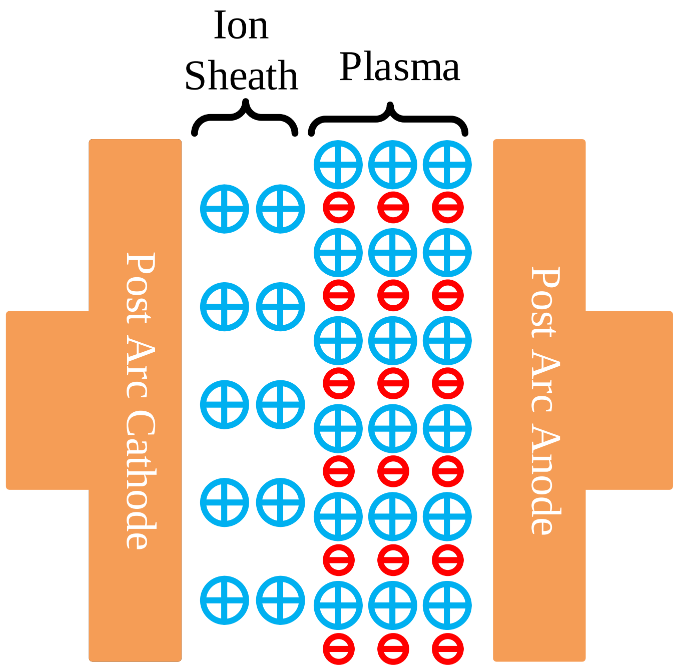
2. Y. P. Mo, Z. Q. Shi, Z. B. Bai, S. L. Jia, and L. J. Wang, "Influence of residual plasma drift velocity on the post-arc sheath expansion of vacuum circuit breakers," Physics of Plasmas, vol. 23, no. 5, p. 053506, 2016.
3. Y. P. Mo, Z. Q. Shi, S. L. Jia, and L. J. Wang, "One-dimensional particle-in-cell simulation on the influence of electron and ion temperature on the sheath expansion process in the post-arc stage of vacuum circuit breaker," Physics of Plasmas, vol. 22, no. 2, p. 023511, 2015.
4. Y. Mo, Z. Shi, S. Jia, and J. Li, "Experimental Investigation on the Postarc Current in Vacuum Circuit Breakers and the Influence of Arcing Memory Effect," IEEE Transactions on Plasma Science, pp. 1-8, 2019.

01. Background

Further study about post-arc current

- **Some questions**
  - **How do the vacuum arc influence the formation of post-arc current still remains controversial in vacuum circuit breakers?**
  - **How do the residual plasma influence the post-arc sheath expansion process are not very clear in vacuum circuit breakers ?**



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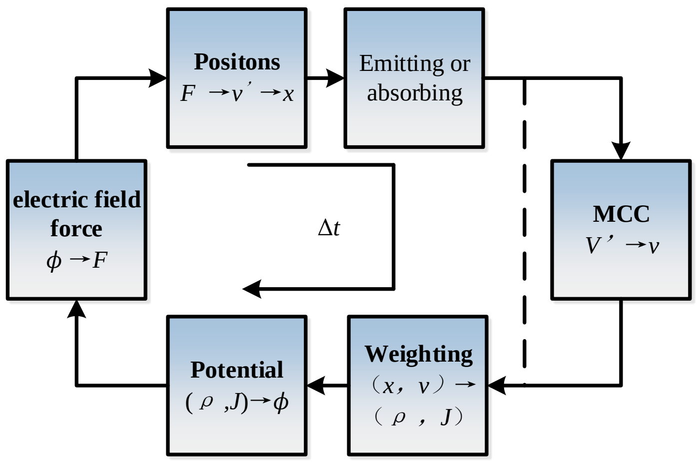
02. Simulations of post-arc sheath

1-D PIC model (both ions and electrons are treated as macro particles)

- The potential and positions

$$\nabla^2\varphi=-e\left(\frac{n_i-n_e}{\varepsilon_0}\right)$$

$$\frac{d^2x}{dt^2}=\frac{qE}{m}$$



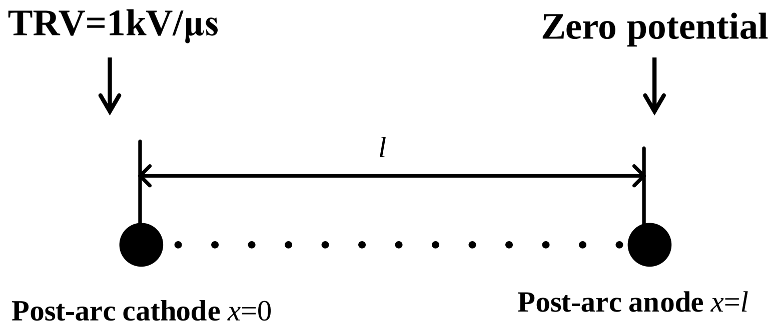
Simulating program flowchart

- Constraint condition

$\Delta x < \lambda_D$ — λ_D is the Debye length

$\Delta t < 2/\omega_p$ — ω_p is the plasma frequency

$\Delta t < \frac{\Delta x}{v_e}$ — v_e is the thermal velocity



Schematic diagram of simulation model

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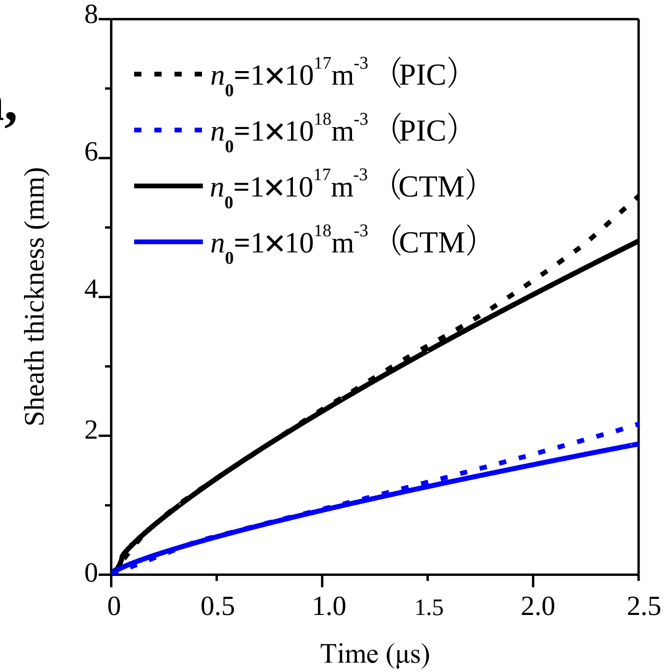
Comparison of 1-D PIC model and CTM

- **Introduction of CTM (Deduced from Poisson Equation, Continuity Equation and Momentum Equation)**

$$s^2=\left[\frac{4\varepsilon_0 V_0}{9en_0}\right]\left[\left(1+\frac{V(t)}{V_0}\right)^{3/2}+\frac{3V(t)}{V_0}-1\right]$$

$$eV_0=\frac{1}{2}M\left(u_0-\frac{ds(t)}{dt}\right)^2$$



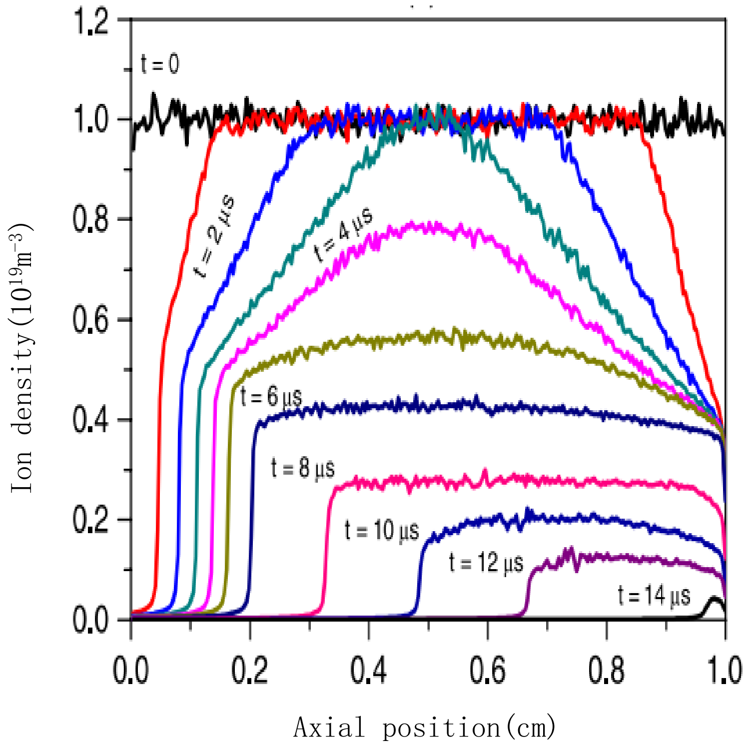
Comparison with CTM and PIC

- **Results**
  - **The sheath expansion process with CTM and PIC are similar in the initial stage**
  - **The sheath with PIC expands faster than that with CTM after about 2 μs which is more close to actual value.**

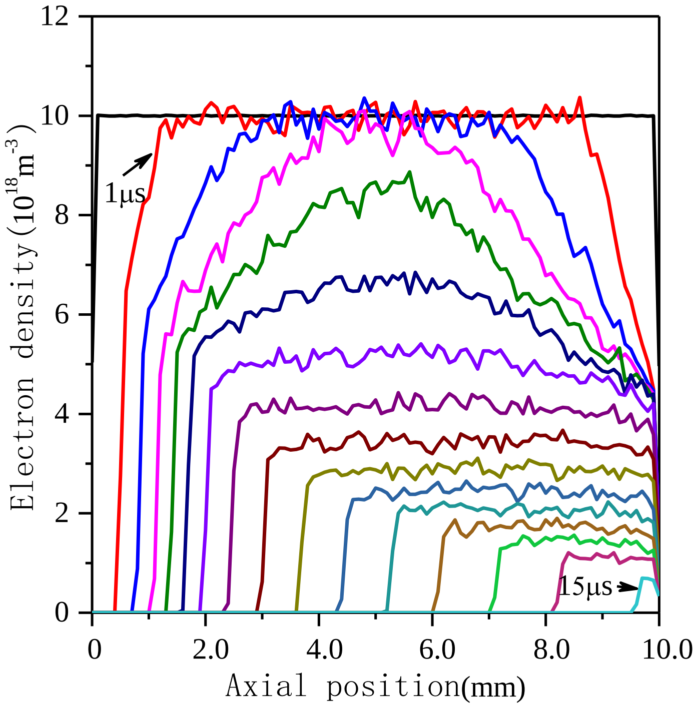
02. Simulations of post-arc sheath

Comparison of PIC model and Hybrid-MB model

- **The results with two models are close**



Results with hybrid-MB model in Ref



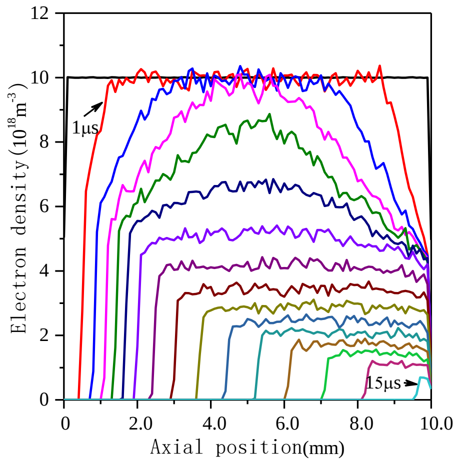
Results with PIC model

Parameters： n_0=1×10^{19} m^{-3}, T_e= 1 eV, T_i=1800 K, TRV=1kV/μs

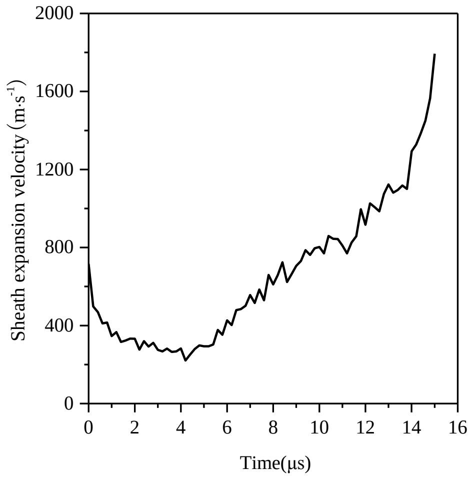
02. Simulations of post-arc sheath

Introduction of ion rarefaction wave

- **The ion rarefaction wave seems can be to explain the variation of plasma in the contact gap**
  - **When the sheath are stable, the plasma density of sheath edge are 0.4 times of the plasma density of wave front**
  - **Two ion rarefaction waves forms in both two electrodes and develop to the middle of the gap**
  - **When the two rarefaction waves meets in the middle of gap, the overall plasma density begins to decrease and the sheath expansion velocity begins to increase**



Electron density taken from PIC model



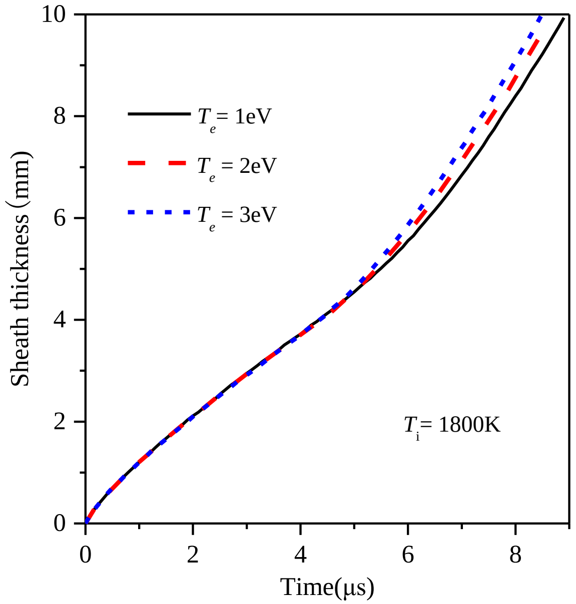
Sheath expansion velocity taken from PIC model

02. Simulations of post-arc sheath

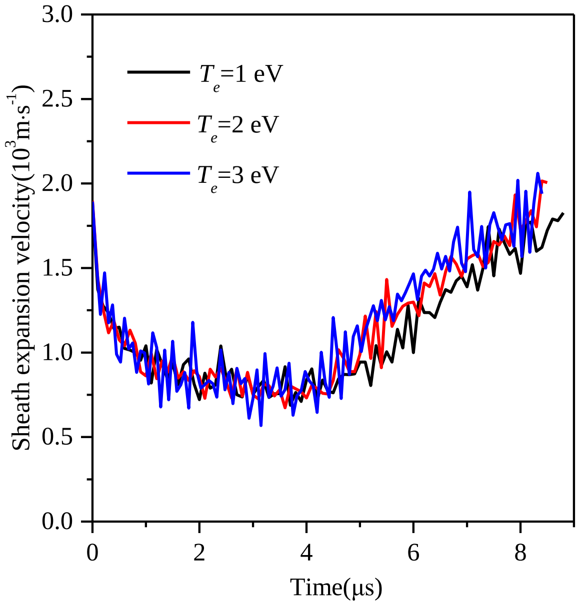
The post-arc sheath with different plasma temperatures

Influences of electron temperature

- The post-arc sheath expands faster to post-arc anode with higher electron temperature
- The sheath expansion process are similar in the initial stage with different electron temperature
- The sheath expansion velocity increases earlier with higher plasma temperature



The variation of sheath thickness



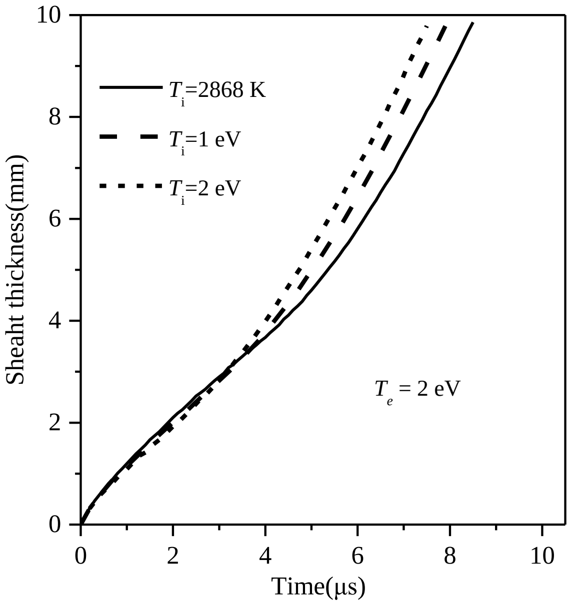
The variation of sheath expansion velocity

02. Simulations of post-arc sheath

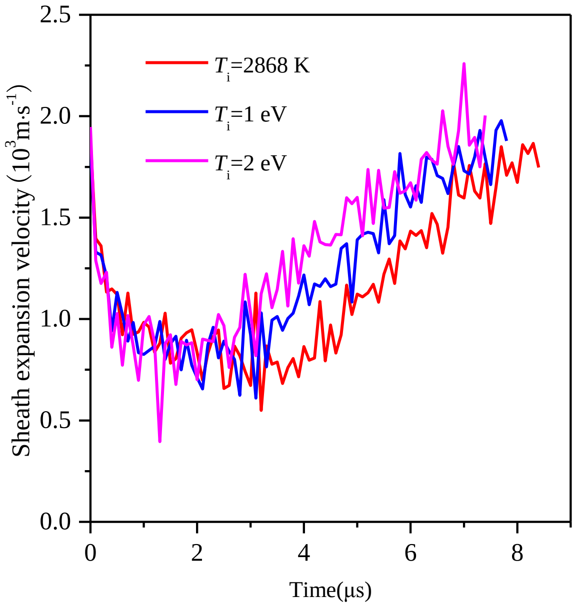
The post-arc sheath with different plasma temperatures

The influence of ion temperature

- The post-arc sheath expands faster with higher ion temperature



The variation of sheath thickness

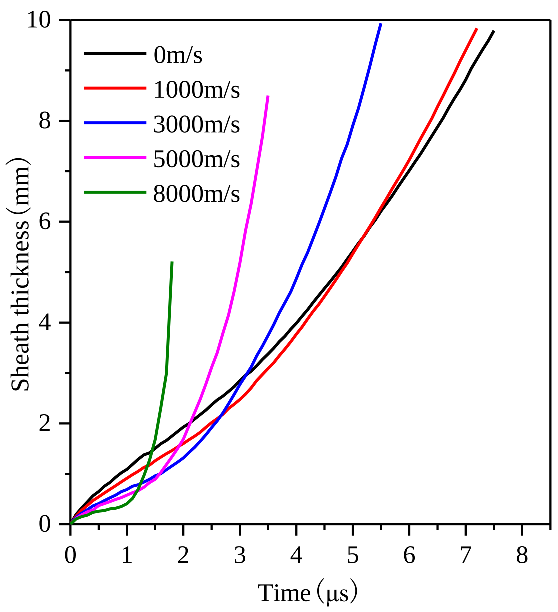


The variation of sheath expansion velocity

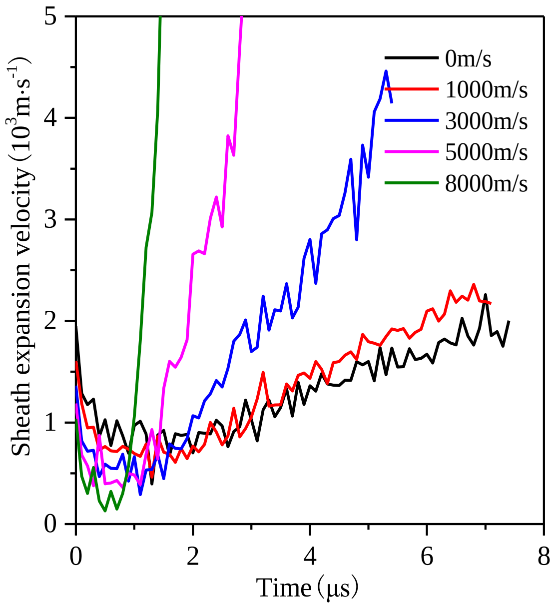
The post-arc sheath with different initial plasma drift velocities

The influence of initial plasma drift velocity

- The sheath expands faster with higher v_{drift}
- The sheath expands slower with higher v_{drift} in the initial stage.



The variation of sheath thickness



The variation of sheath expansion velocity

02. Simulations of post-arc sheath

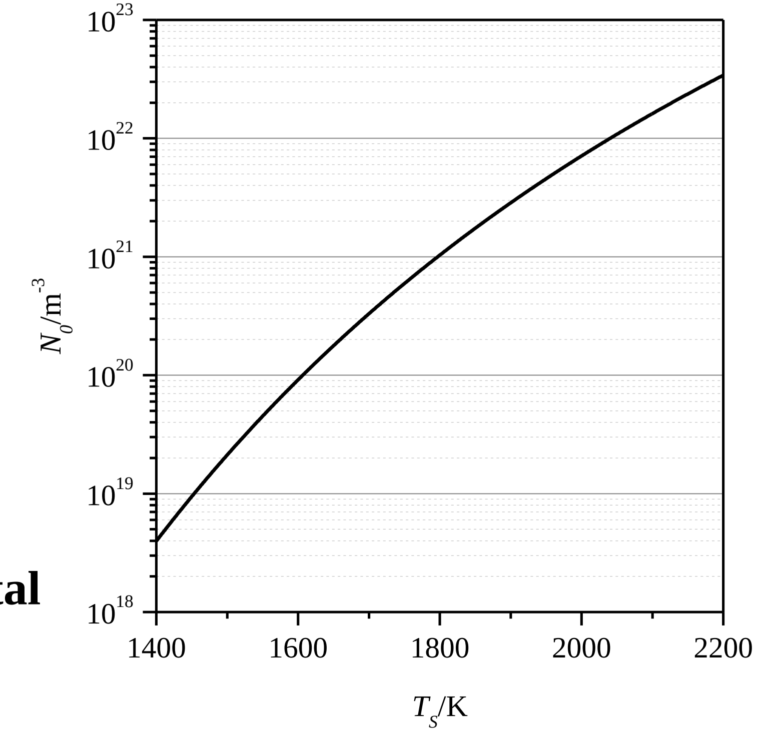
The influence of metal vapor-estimation of metal vapor

$$N_0 = N_s/2$$

$$N_s = P_s/(k_B T_s)$$

$$P_s = P_{atm} \exp\left[-\frac{L}{R}\left(\frac{1}{T_s} - \frac{1}{T_{boil}}\right)\right]$$

T_s is the contact temperature



The relationship between the contact temperature and metal vapor density

- **The temperature of contact can achieve 2200 K，the metal vapor density also could achieve 10^{22} m^{-3}**
- **The variation of plasma density ranges from 10^{18} m^{-3}~10^{22}m^{-3}**

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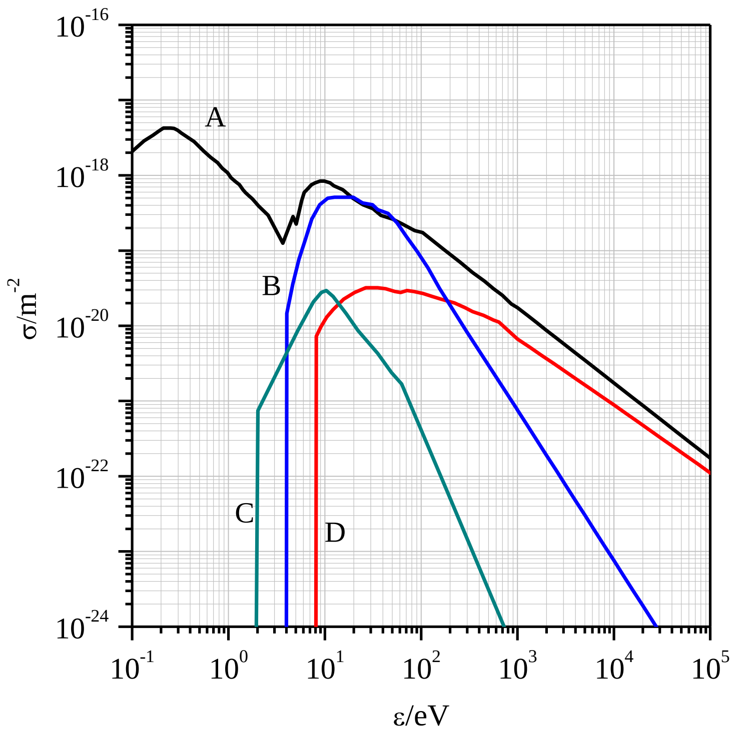
The influence of metal vapor-introduction of PIC-MCC model

- **Electron and metal vapor**
  - **Elastic collision**
  - **Ionization collisions**
  - **Excitation collision**

- **Ion and metal vapor**
  - **Charge exchange collision**
  - **Momentum exchange collision**

The collisions between the charged particles and metal vapor are dealt with Monte Carlo collision method (MCC)



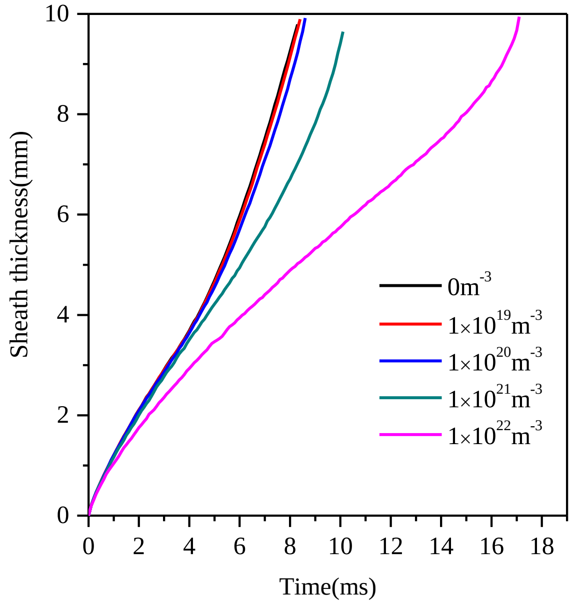
collision cross section between electrons and copper atoms. A: elastic collisions, B: excitation for the $3d^{10}4p^2P_{1/2}$ and $3d^{10}4p^2P_{3/2}$, C: excitation for the $3d^94s^2\ ^2D_{5/2}$ D: ionization.

02. Simulations of post-arc sheath

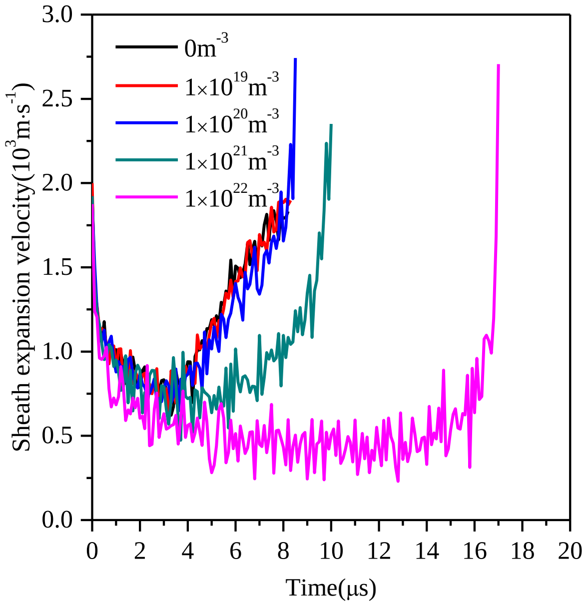
The influence of metal vapor

The post-arc sheath without initial plasma drift velocity

- **The metal vapor shows small influence on the post-arc sheath when the metal vapor density is smaller than $10^{20}m^{-3}$**
- **The metal vapor slows down the post-arc sheath expansion process when the metal vapor density is larger than $10^{21}m^{-3}$**



The variation of sheath thickness



The variation of sheath expansion velocity

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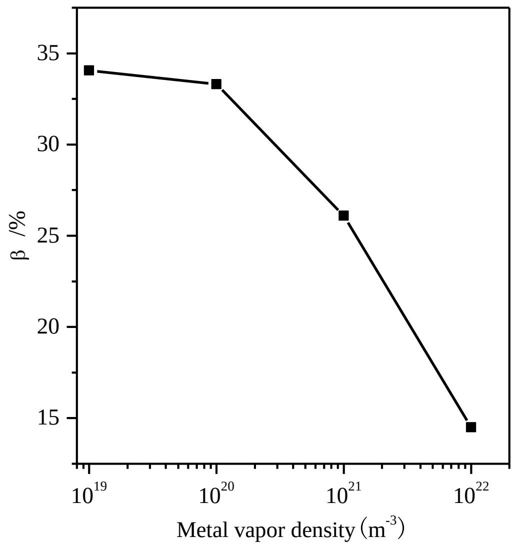
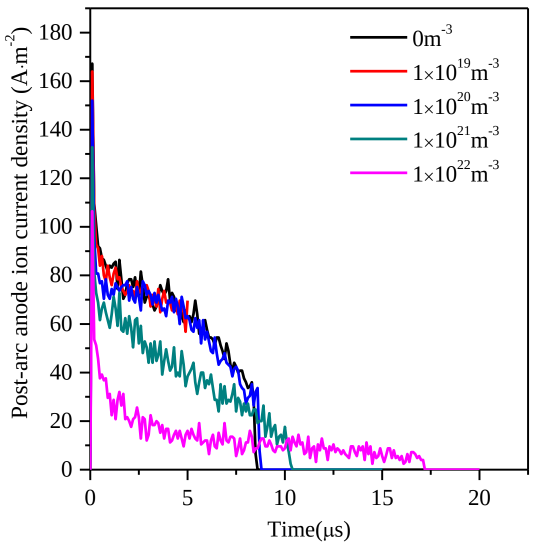
The influence of metal vapor

The proportion of ions entering post-arc anode and total electrons β

- The metal vapor shows small influence on the β and the post-arc anode ionic current density when it is smaller than $10^{20}m^{-3}$
- the β and the post-arc anode ionic current density decreases obviously when the metal vapor density is larger than $10^{21}m^{-3}$



The variation of β



The variation of post-arc anode ionic current density

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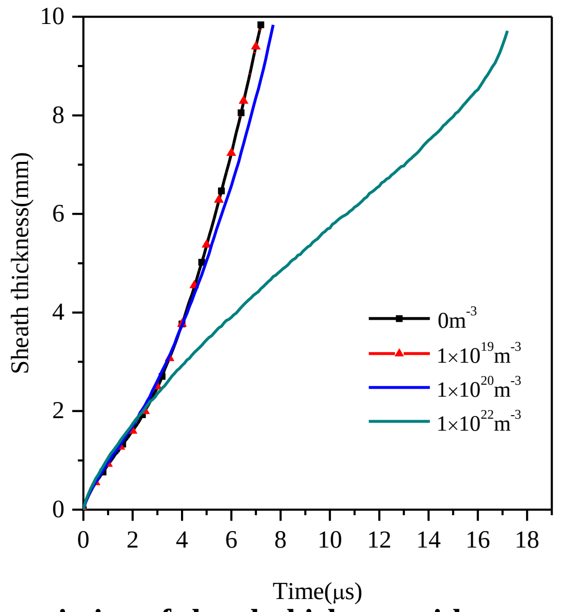
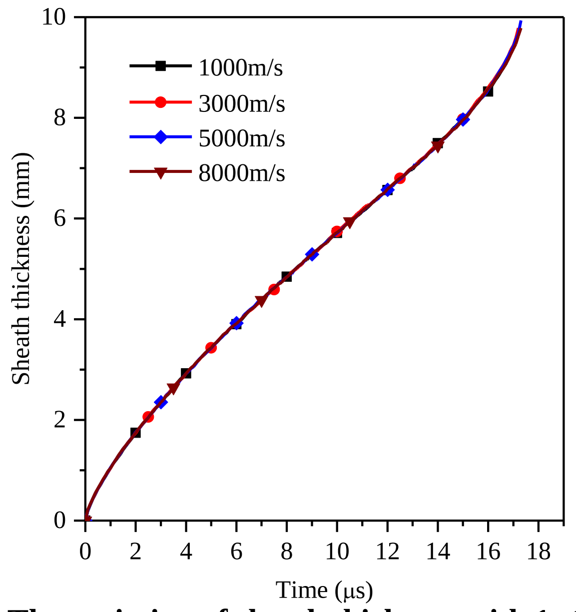
The influence of metal vapor

The post-arc sheath with initial plasma drift velocity

- The metal vapor show small influence on the post-arc sheath when it is small than $10^{20}m^{-3}$
- The metal vapor shows dominant influence on the post-sheath when it is $10^{22}m^{-3}$. Meanwhile the v_{drift} shows no influence on the post-arc sheath



The variation of sheath thickness with v_{drift} =1000m/s



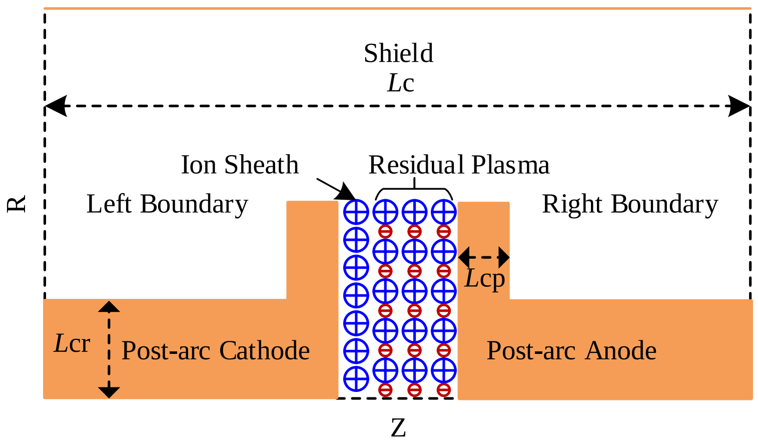
The variation of sheath thickness with 1×10^{22} m^{-3}

02. Simulations of post-arc sheath

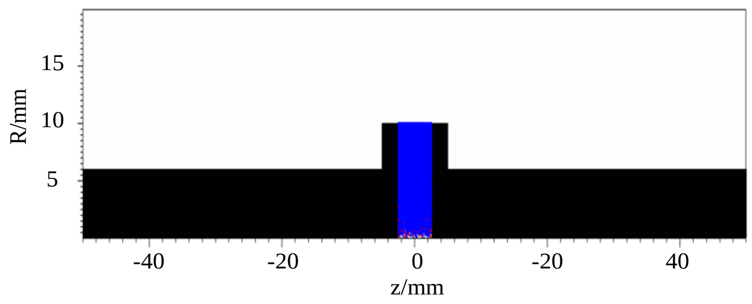
The plasma radial motions

2-D PIC model

- Shield, right boundary and post-arc anode are zero potential
- The plasma is distributed uniformly in the gap
- The equipotential lines in the left boundary is supposed to be parallel to the axis of contacts



Schematic diagram of two-dimensional PIC model



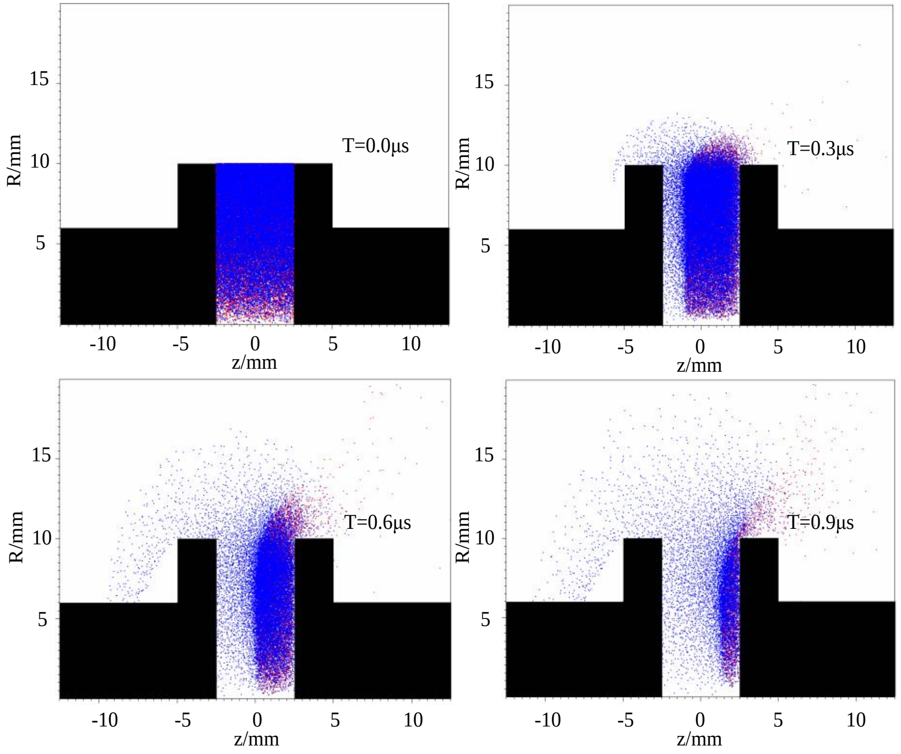
PIC model with L_c=100 mm
(ions are in blue and electrons are in red)

02. Simulations of post-arc sheath

The plasma radial motions

The dissipation of residual plasma

- The residual plasma diffuses out the contact gap
- The shape of sheath edge develops from flat to curve
- The ions would fly to 5~10 mm away with the post-arc cathode surface and then be absorbed



The variation of residual plasma with *L*c =25 mm

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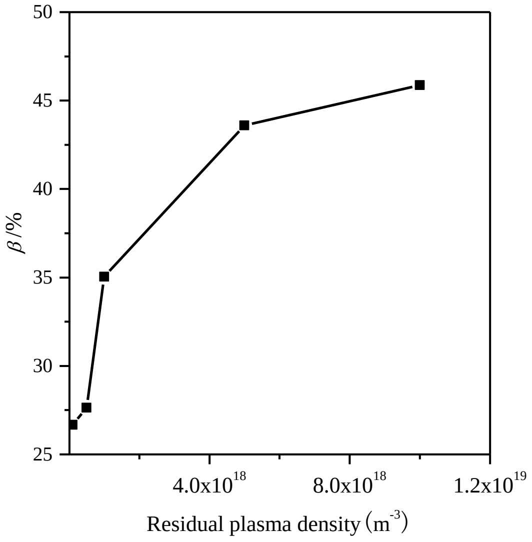
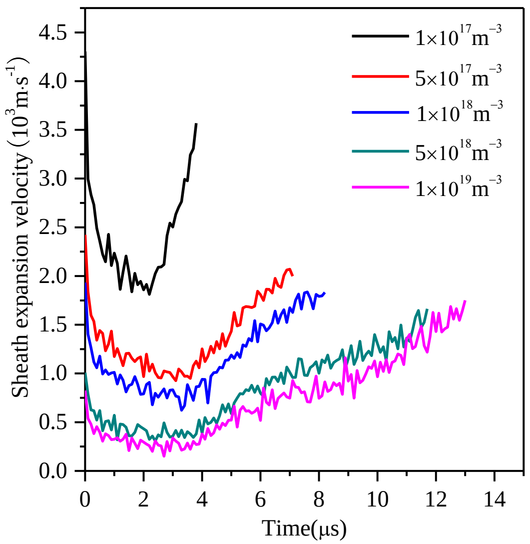
03. Simulations of post-arc current

- **Influences on the proportion of ions and total electrons entering post-arc anode (β) are studied as part of ions are absorbed by the post-arc anode**
  - **Influence of residual plasma density**
    - **The post-arc sheath expansion process becomes slower with the increase of residual plasma density**
    - **The β also increases with the residual plasma density**
    - **The β approaches saturation when the residual plasma density is larger than 5×10^{18} m^{-3}**



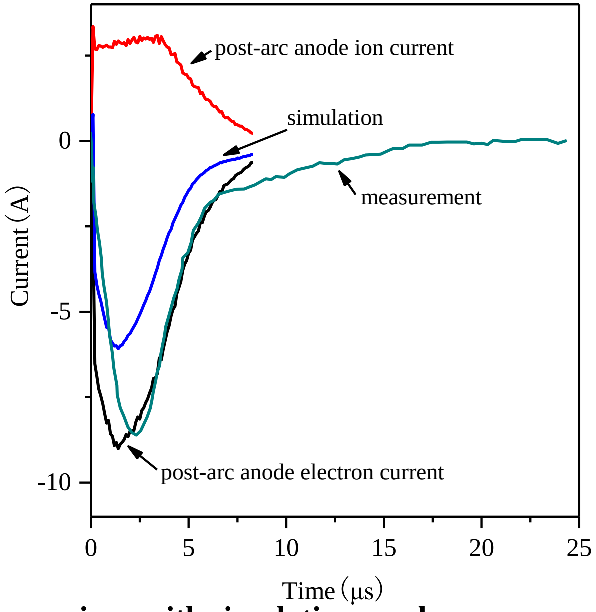
The β with different residual plasma densities



The sheath expansion velocity with different residual plasma densities

Influences on the post-arc current density

- **Comparison with measurement and simulation**
  - **The variation of simulation results is smaller than measurement**
  - **The peak value and duration time of post-arc current obtained from simulation is smaller than measurement.**



Comparison with simulations and measurements

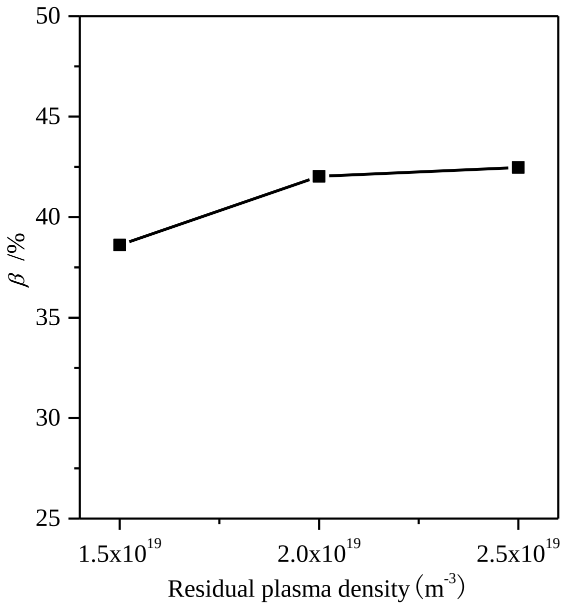
The ions entering the post-arc anode are neglected when estimating the residual plasma. As a result, the estimated residual plasma density is small

03. Simulations of post-arc current

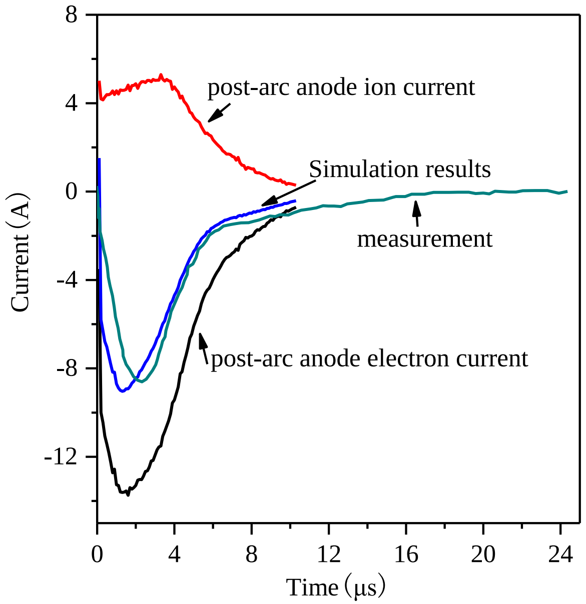
Influences on the post-arc current density

- **Comparison with simulations and measurements**
  - **Adjusting the residual plasma density according to β**
  - **The simulated post-arc current is more closer to measurement after adjustment.**

$Q/(1-\beta)$



The β with different residual plasma density



Comparison with measurement and simulations

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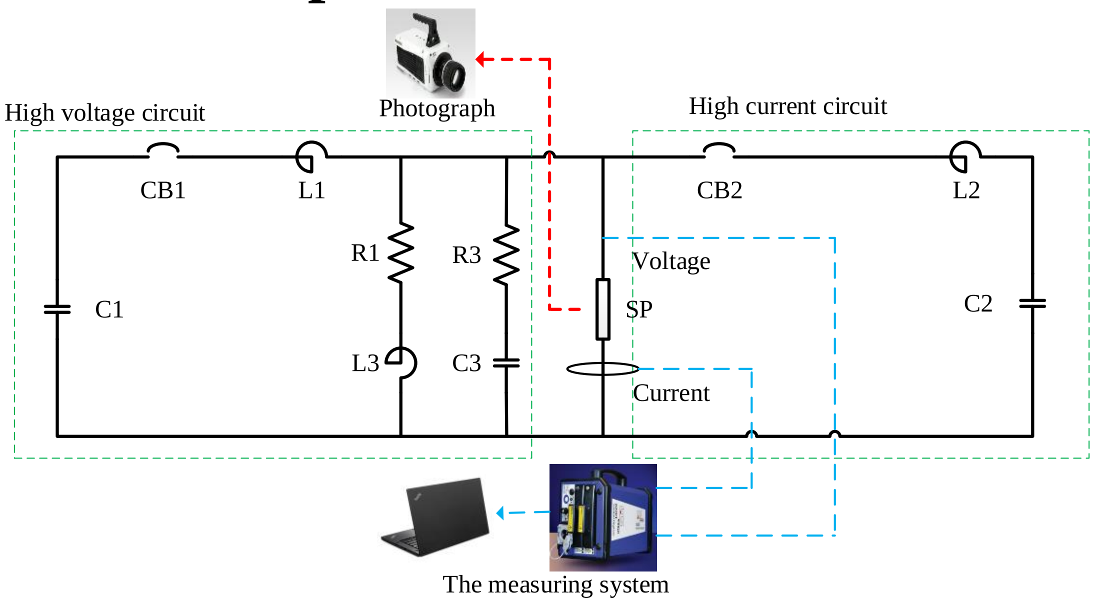
Experimental setup

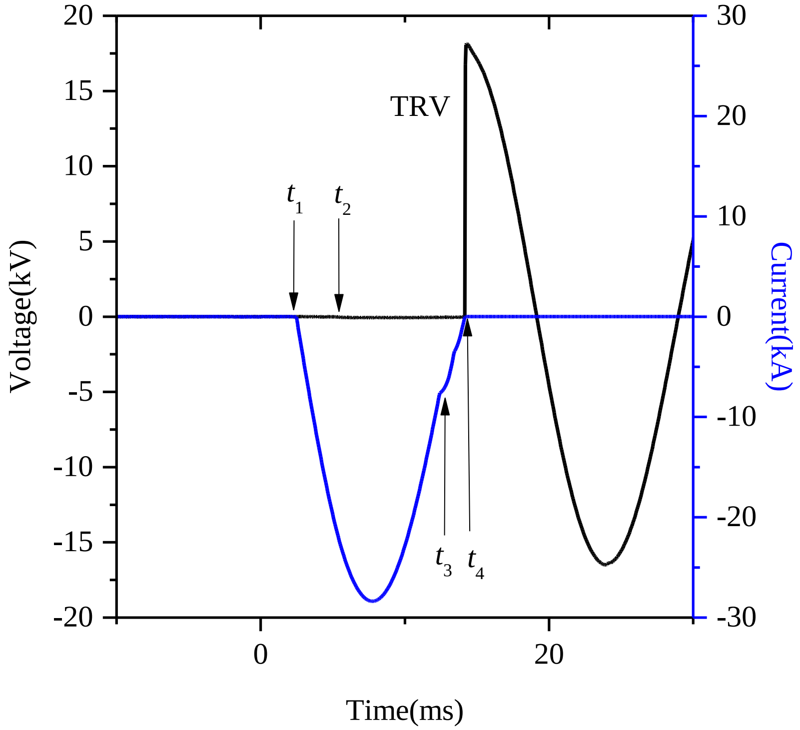


Synthetic circuit

- The post-arc current is measured by a high-resolution current-zero diagnostic system.
- The vacuum arc is recorded by a high speed camera (exposure: 2 μs, frame rate : 19000 fps)

04. Experimental studies of post-arc current

Experimental setup



A typical waveform of the current interruption process in a vacuum circuit breaker.

t_1 Current flows through VCB

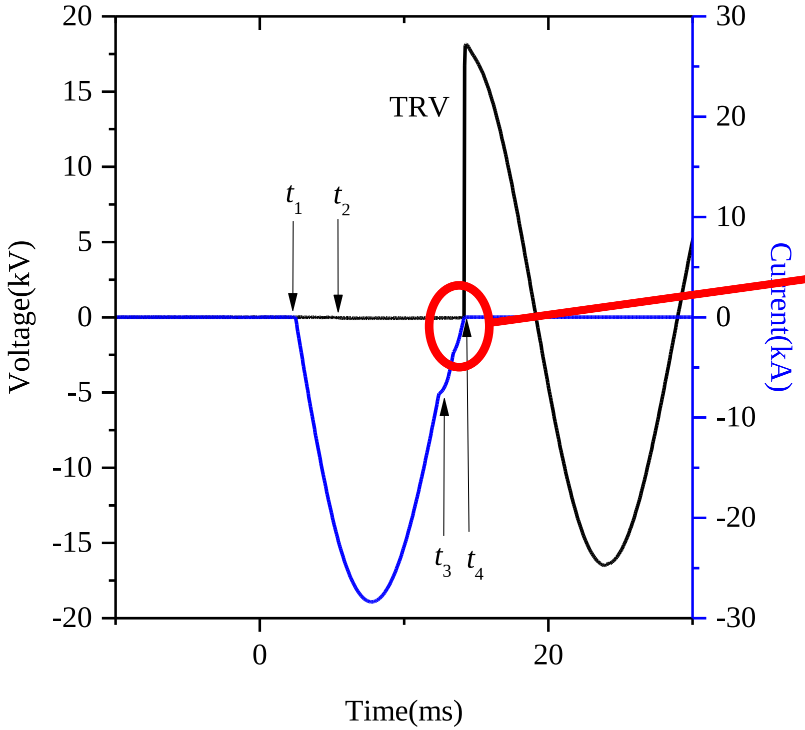
t_2 VCB begins to open

t_3 Reversed current flows through VCB

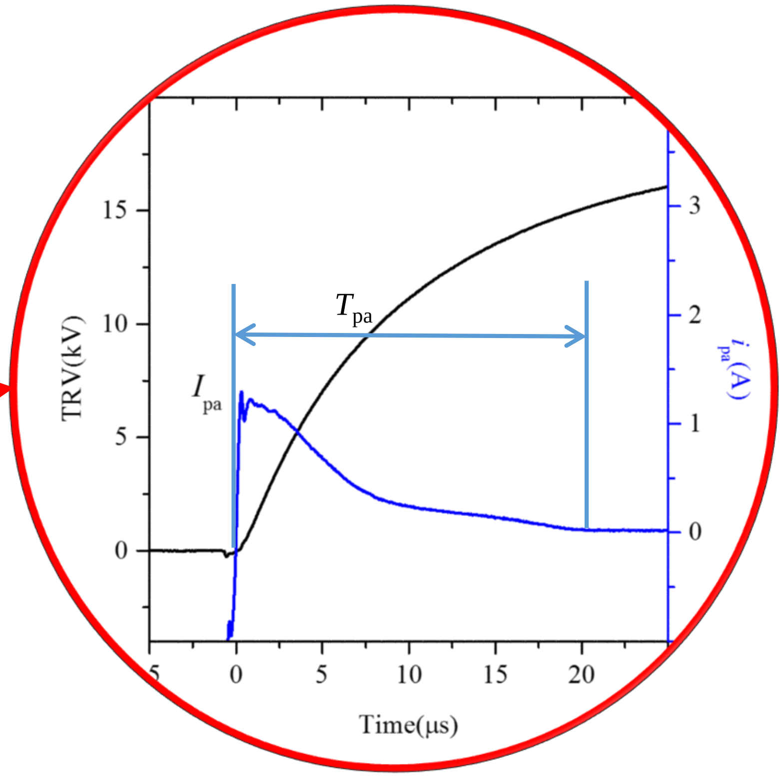
t_4 Current decreases to zero

04. Experimental studies of post-arc current

Typical post-arc current



A typical waveform of the current interruption process in a vacuum circuit breaker.



$$Q=\int_{T_{pa}} i_{pa}(t)\mathrm{d}t$$

04. Experimental studies of post-arc current

Contact parameters

TABLE. 1 Types of different contacts

Abbreviations	Diameter(mm)	Materials	Structure
30mm-Cu-butt	30	Cu	Butt
58mm-Cu-butt	58	Cu	Butt
58mm-Cu-TMF	58	Cu	TMF
58mm-CuCr50-AMF	58	CuCr50	AMF
58mm-CuCr50-TMF	58	CuCr50	TMF

Five types of contacts are adopted to study the influence of **diameter**, **material** and **structure** on the post-arc current.

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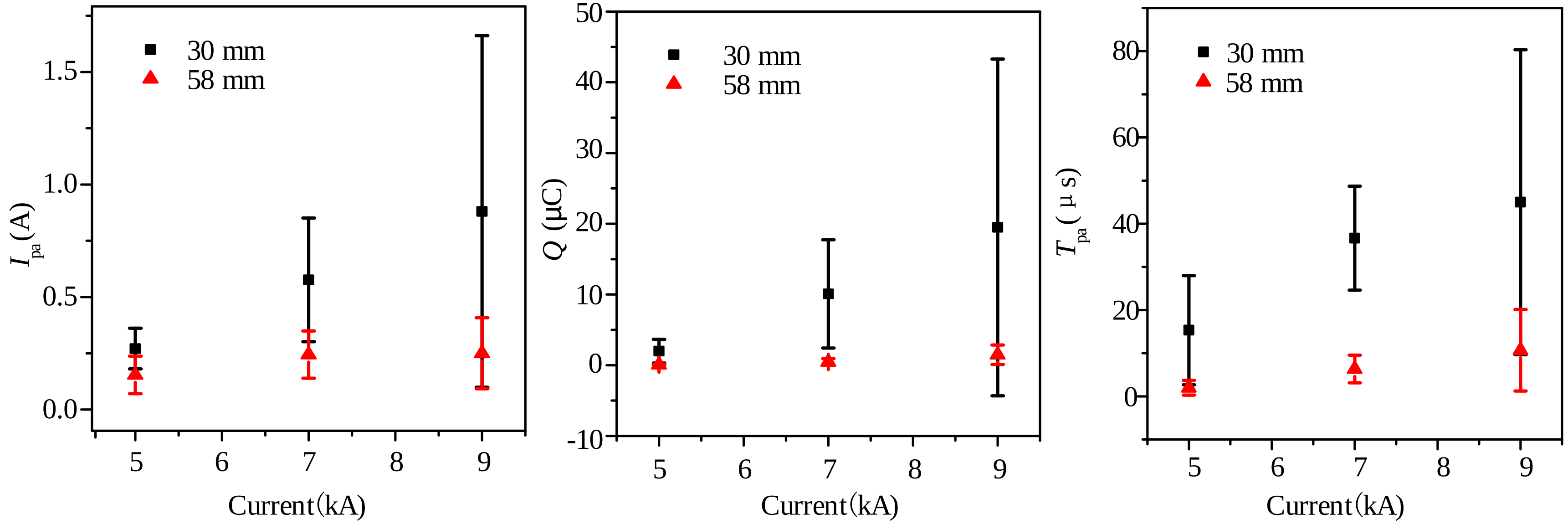
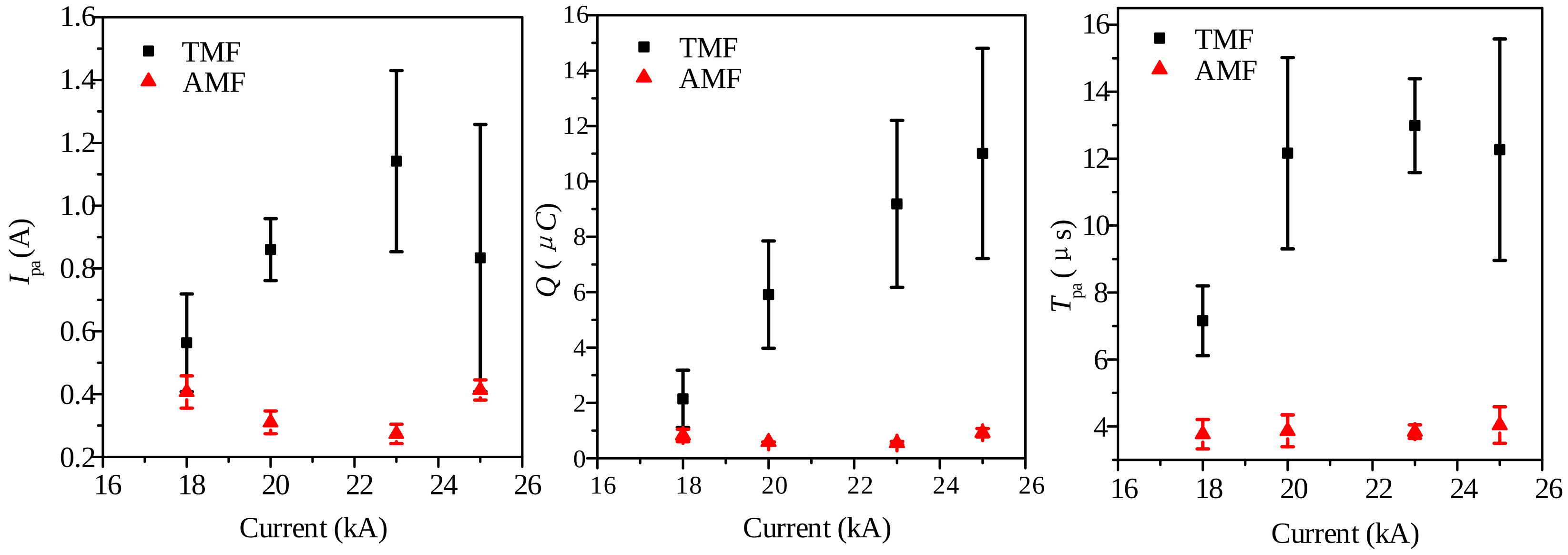
The influence of diameter



A comparison of I_{pa} ,Q and T_{pa} with different diameters

- The I_{pa} , Q and T_{pa} of 30mm-Cu-butt contact is higher than that of 58mm-Cu-butt contact with the same current.

The influence of structure



A comparison of I_{pa} ,Q and T_{pa} with different structure

- The I_{pa}, Q and T_{pa} of 58mm-CuCr50-TMF contact is higher than that of 58mm-CuCr50-AMF contact with the same current.

04. Experimental studies of post-arc current

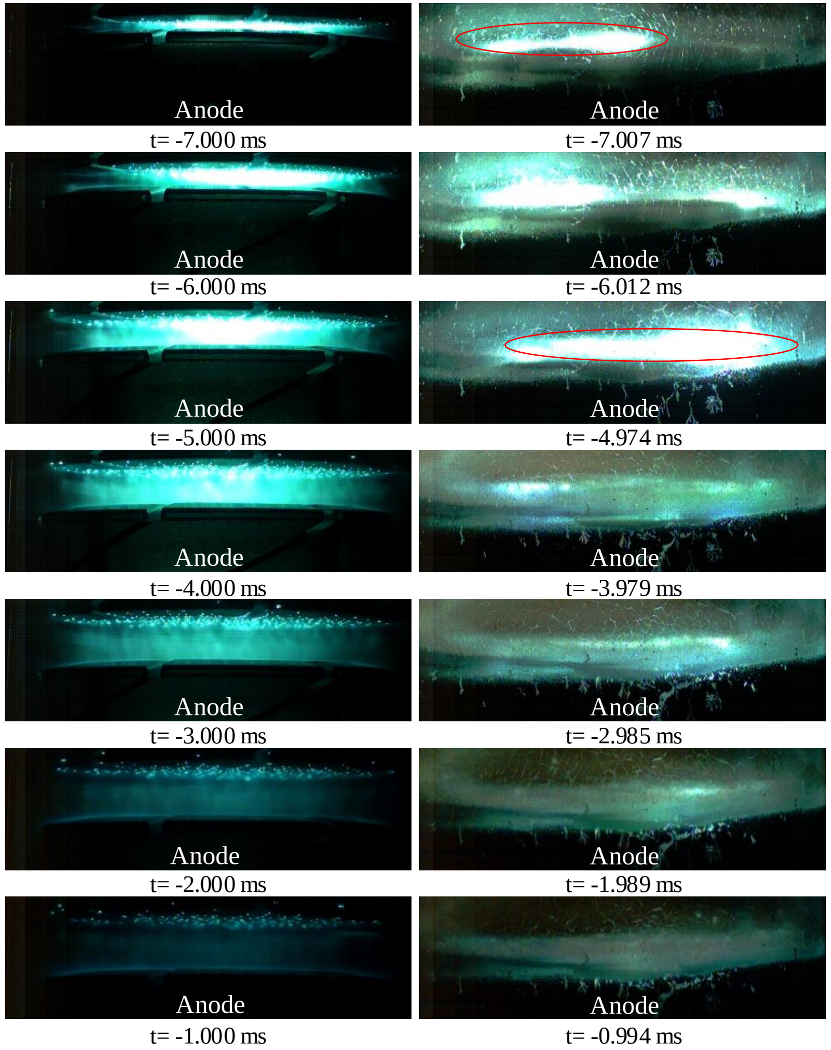
The influence of structure

AMF 18kA

TMF 18kA

19000fps

- The vacuum arc of TMF contact burns more intensely than that of AMF contact.
- The vacuum arc of TMF contact are more unstable.
- The more intense vacuum arc of TMF contact results in a higher post-arc current.



AMF 18kA TMF 18kA

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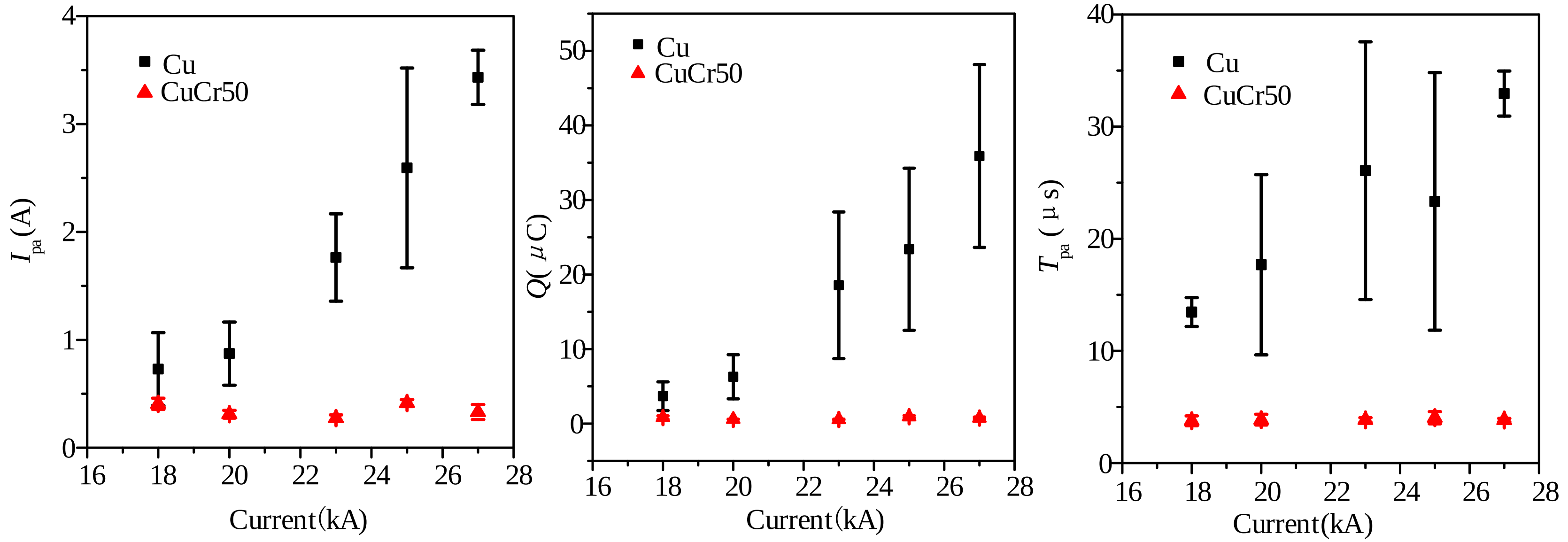
The influence of materials



A comparison of I_{pa} ,Q and T_{pa} with different materials

- The I_{pa} , Q and T_{pa} of the Cu contact is higher than that of CuCr50 contact with the same current.

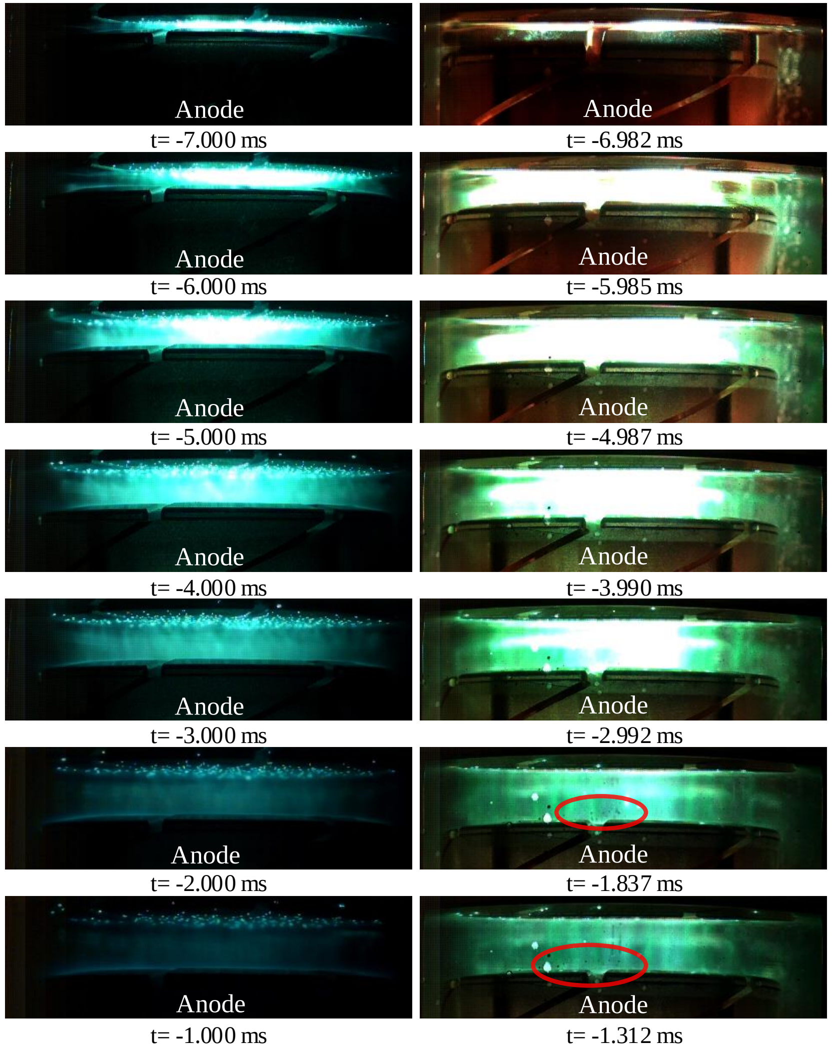
04. Experimental studies of post-arc current

The influence of materials

CuCr50 18kA   Cu 18kA

19000fps

- Droplets occurs between the Cu contact.
- The vacuum arc of Cu contact burns more intensely than that of CuCr50 contact.
- The more intense vacuum arc of Cu contact also results in higher post-arc current.



CuCr50 18kA   Cu 18kA

04. Summary

- The plasma temperature, initial plasma drift velocity and plasma radial motion have effect on the post-arc sheath expansion processes and post-arc current. The post-arc sheath expands fast with higher plasma temperature or initial plasma drift velocity.

- The ions absorbed by the post-arc anode has a significant affect on post arc current. The simulations indicate that the residual plasma density, the metal vapor density show relatively obvious influence on the ions absorbed by the post-arc anode.

- The experimental results indicates that the vacuum arc modes can influence the post-arc current. The post-arc current value and duration time increase when the vacuum arcs more intense.

Thank you for your attention !

2019