Vacuum Technology in Electrical Switches

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III Vacuum Arc and Its Effect

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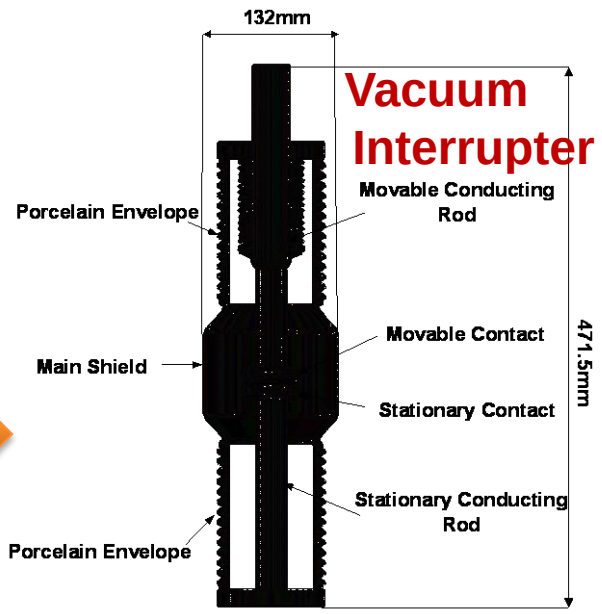
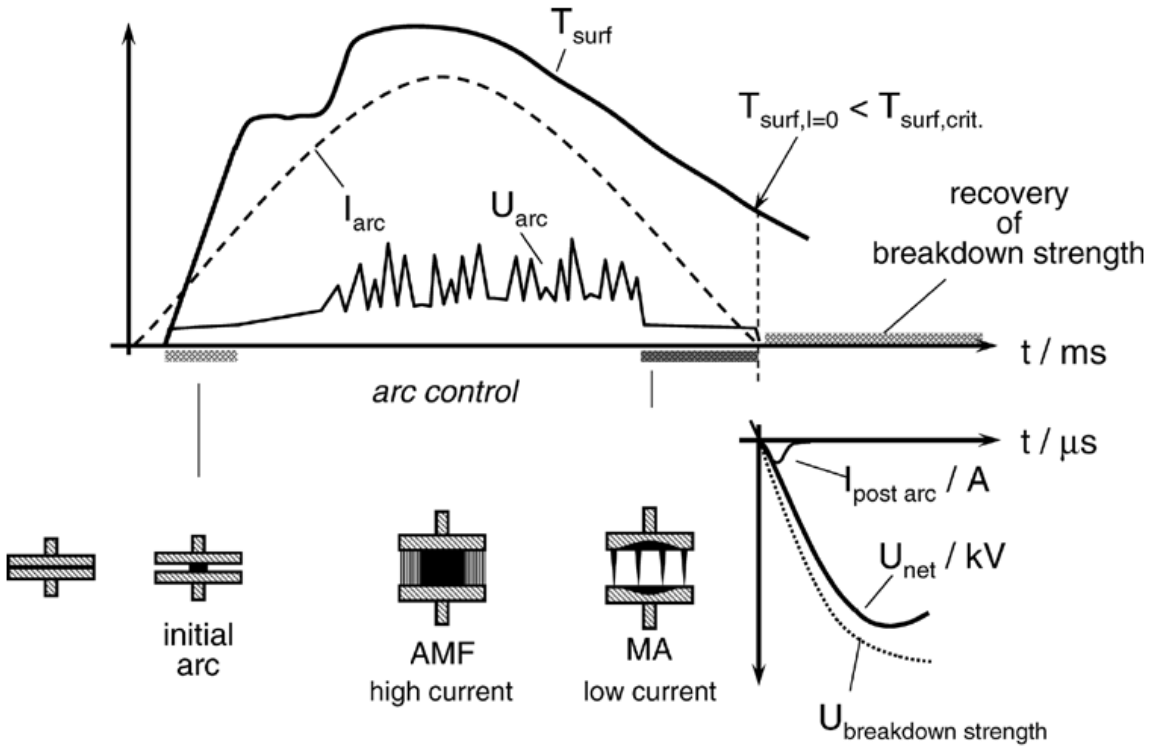
I Background

This is a 126kV vacuum circuit breaker designed by my group in XJTU



- Vacuum technology is one good solution for electrical insulation, and the environment-friendly merit makes it suitable for substituting SF6 gas switches.
- Now vacuum switches dominate the medium voltage level of power system(3kV - 40.5kV).
- We would like to develop a vacuum switch can be used in the power system above 70.5kV - 126kV or above.

I Background: The Interrupting Processes



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.

- **Vacuum arc can destroy the contact surfaces severely.**
- **There are three stages in the post –arc stage:**
  - ✓ **Residual plasma dissipates from the gap.**
  - ✓ **Metal vapor dissipates from the gap.**
  - ✓ **The gap recovers to vacuum.**
- **If the contacts can withstand the transient voltage and turn to be vacuum again the current is interrupted successfully. Otherwise the contact gap will restrike.**

I Background: Three Major Problems

Problem I

Vacuum Breakdown

The breakdown mechanism in long vacuum gap (>10mm).

Does the same mechanism dominate breakdowns between the processes in short and long vacuum gap?

Problem II

Vacuum Arc Interruption

The arc burning process and erosion of contact material.

How to get a more precise plasma arc model and calculate the erosion of the arc on the surfaces?

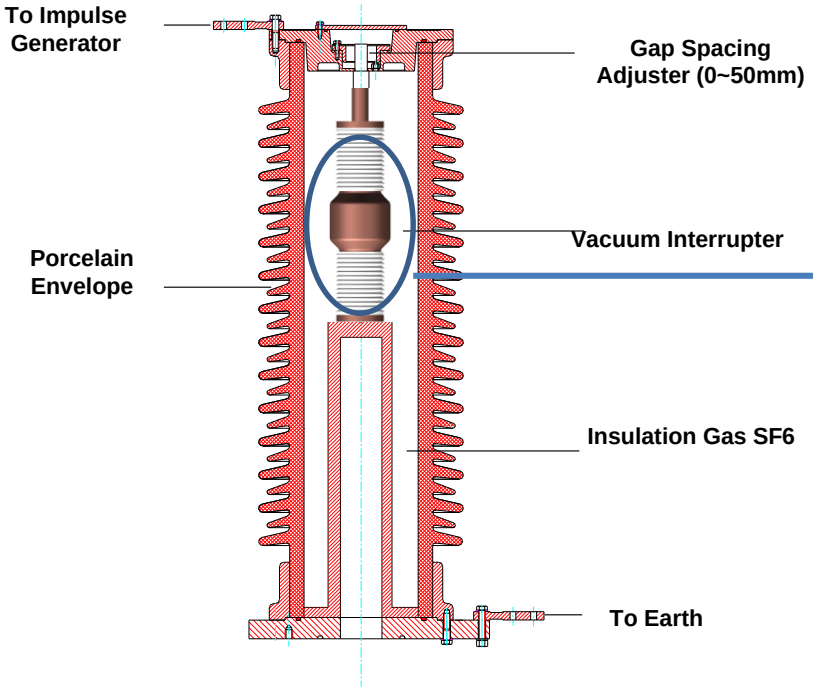
Problem III

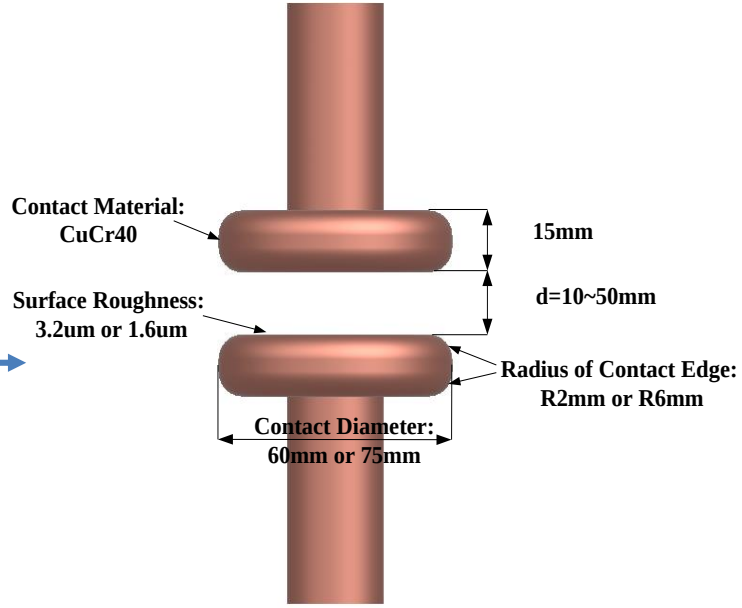
Post-arc Breakdown

The breakdown mechanism in low-pressure metal vapor on the destructed surfaces.

How to give a more reliable estimation to dielectric recovery strength?

II Vacuum BDs in 126kV VIs: Experimental Setup





VI	Radius of Contact Edge(mm)	Roughness(μm)	Contact Radius(mm)
No.1	6	1.6	60
No.2	2	1.6	60
No.3	6	3.2	60
No.4	6	1.6	75

◆**Adopting 126kV vacuum interrupters to study the behaviors of breakdowns with a contact gap of 10~50mm**

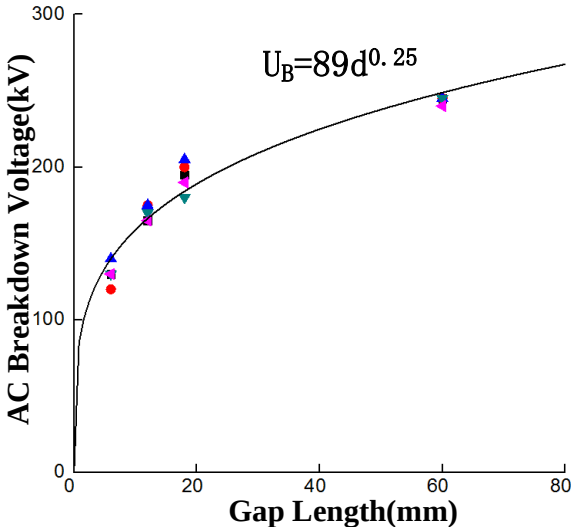
◆**Voltage type:**

✓**1min AC voltages**

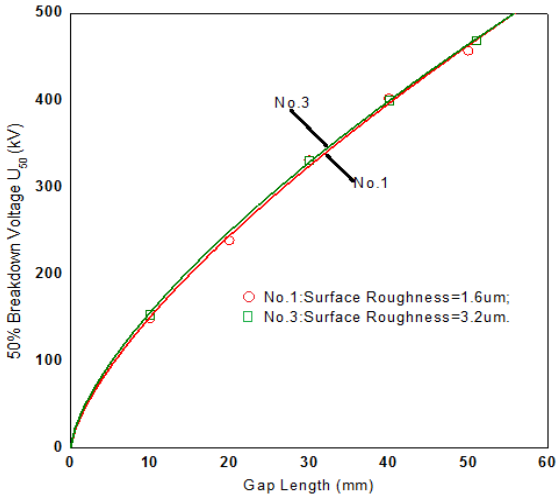
✓**impulse voltages**

II Vacuum BDs in 126kV VIs: Results

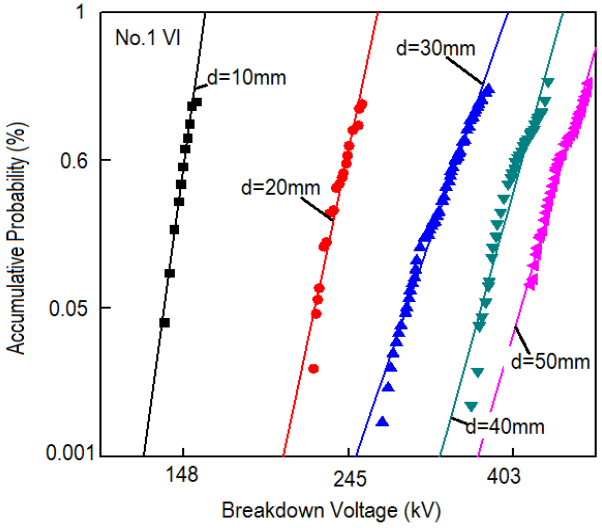
- The relation between contact gaps and AC breakdown voltages can be expressed as behaviors of $U_B=89d^{0.25}$
- The possibilities of impulse voltage breakdowns in a vacuum interrupter satisfy **Weibull distribution.**
- The discrepancies between the contact with roughness 1.6um and the one with 3.2um are within **3%.**
- The discrepancies between the contact with a diameter of 60mm and the one with 75mm are within **10%.**



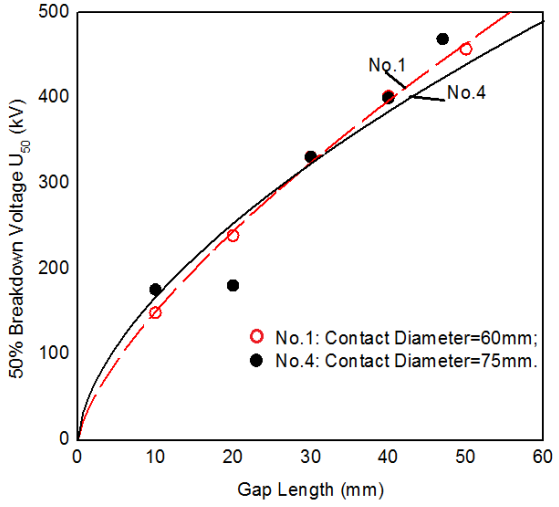
AC Voltage breakdowns



The Effect of roughness

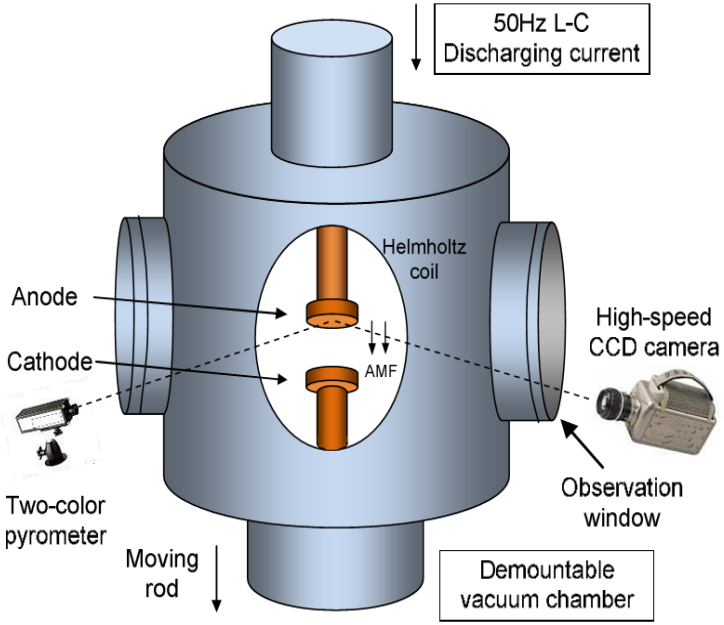


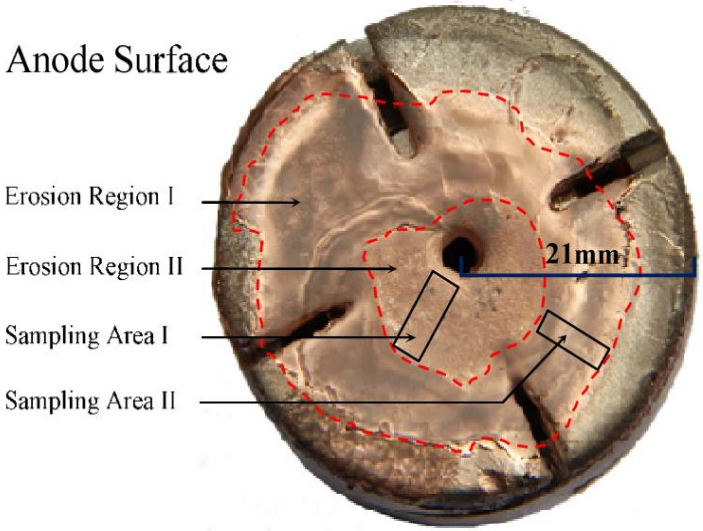
Impulse Voltage breakdowns



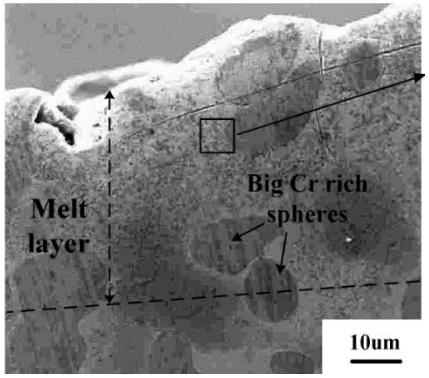
The Effect of Contact Diameter

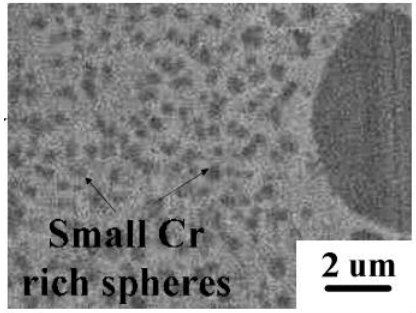
III High Current Vacuum Arc: Experiments

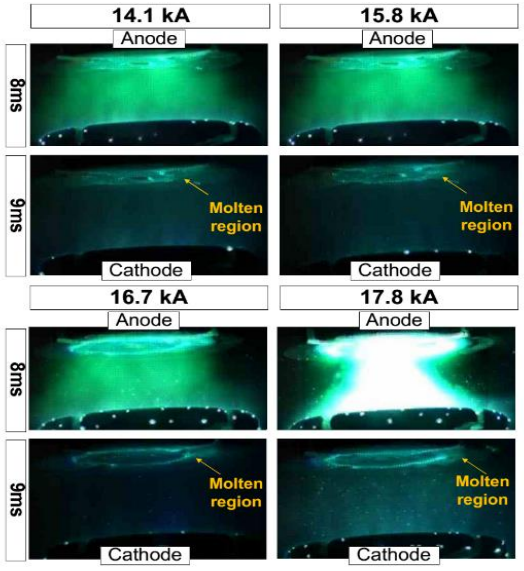




Results from Electron Scanning Microscope

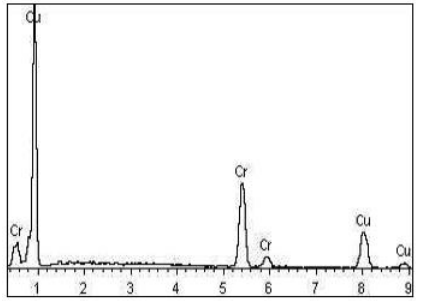






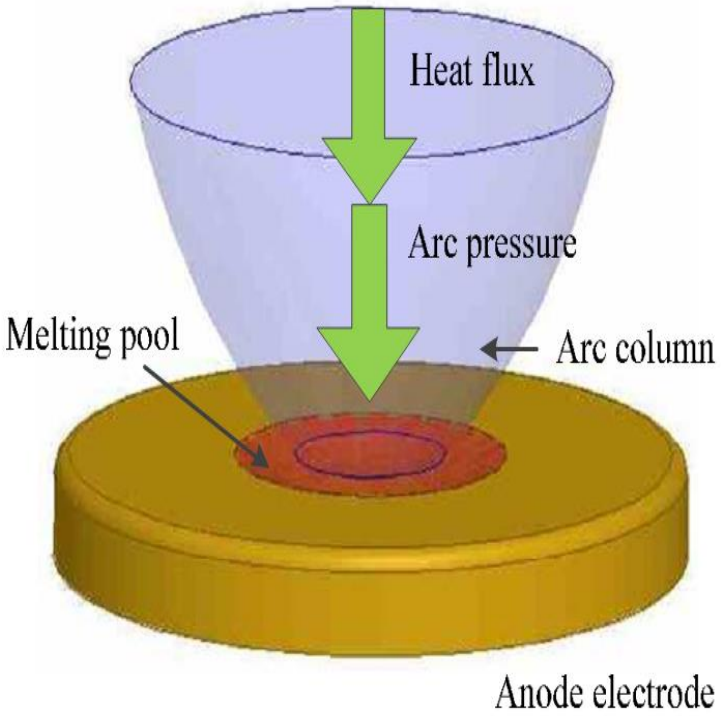
Composition of Melt Layer in Different Regions

Materials	Region I %	Region II %	Before %
Cr	31	18	25
Cu	69	82	75



III High Current Vacuum Arc: Simulation Model

Physical Model



Physical Process:

- ✓ Melting/Solidification,
- ✓ Free Surface,
- ✓ Heat Flux from Arc Column,
- ✓ Arc pressure.

Mathematical Model

Anode Region

Heat Conduction:

$$\rho \cdot C_P \cdot \frac{\partial T}{\partial t} = \nabla(k \nabla T)$$

Enthalpy:

$$H = h + \beta L$$

Liquid fraction:

$$\begin{cases} \beta = 0 & \text{if } T < T_s \\ \beta = 1 & \text{if } T > T_l \\ \beta = (T - T_s)/(T_l - T_s) & \text{if } T_s < T < T_l \end{cases}$$

Free Surface

$$\frac{\mathrm{d}F}{\mathrm{d}t} = \frac{\partial F}{\partial t} + (V \cdot \nabla)F = 0$$

Arc Column

Electric potential:

$$\nabla \cdot [\sigma(\nabla \phi_E)] = 0$$

Magnetic potential:

$$\nabla^2 \vec{A} = \mu_0 \sigma(\nabla \phi_E)$$

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0,$$

Momentum equation:

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot \phi \vec{U} - \nabla \cdot \mu \nabla \vec{U} = -\nabla p + (\vec{J} \times \vec{B})$$

Energy equation:

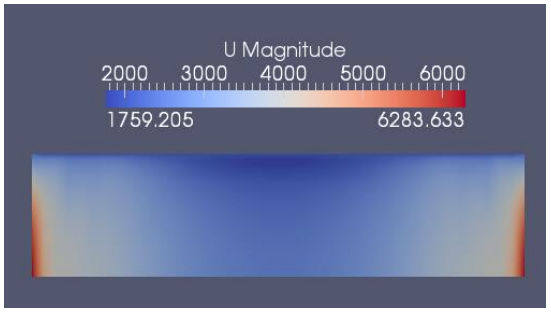
$$\frac{\partial \rho h}{\partial t} + \nabla \cdot \phi h = \frac{\vec{J}^2}{\sigma}$$

Boundary Condition

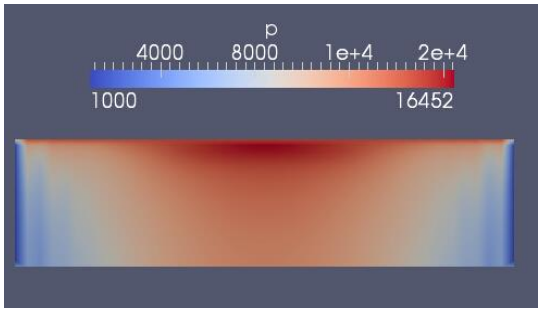
Adopting pressure and heat from arc calculation as the boundary of anode surface

III High Current Vacuum Arc: Simulation Results

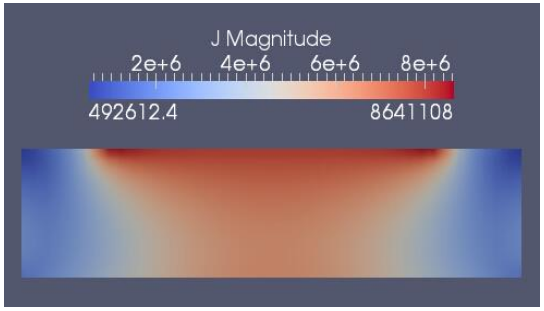
Velocity



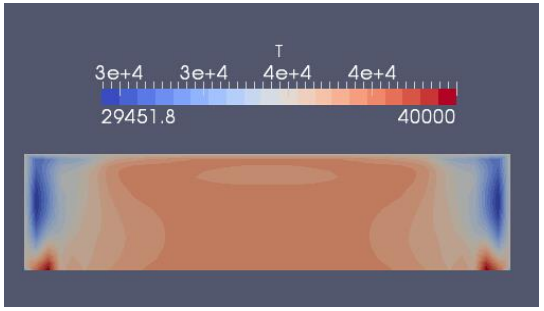
Pressure

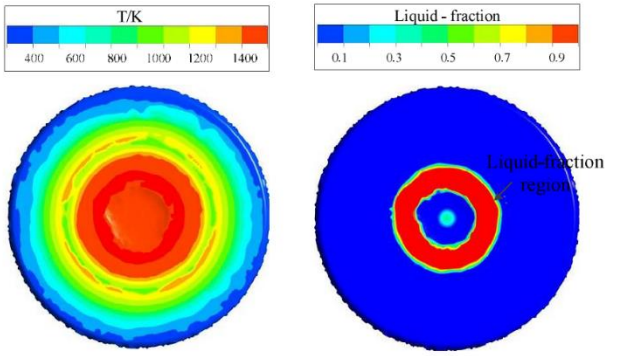


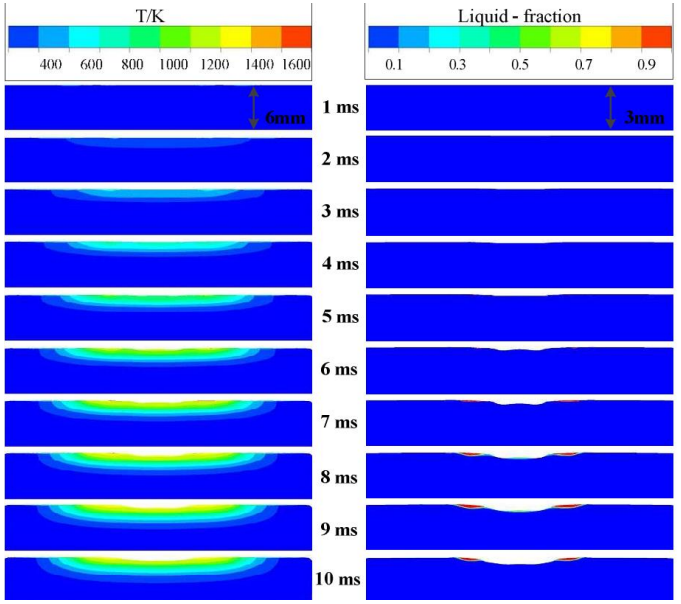
Current Density



Temperature





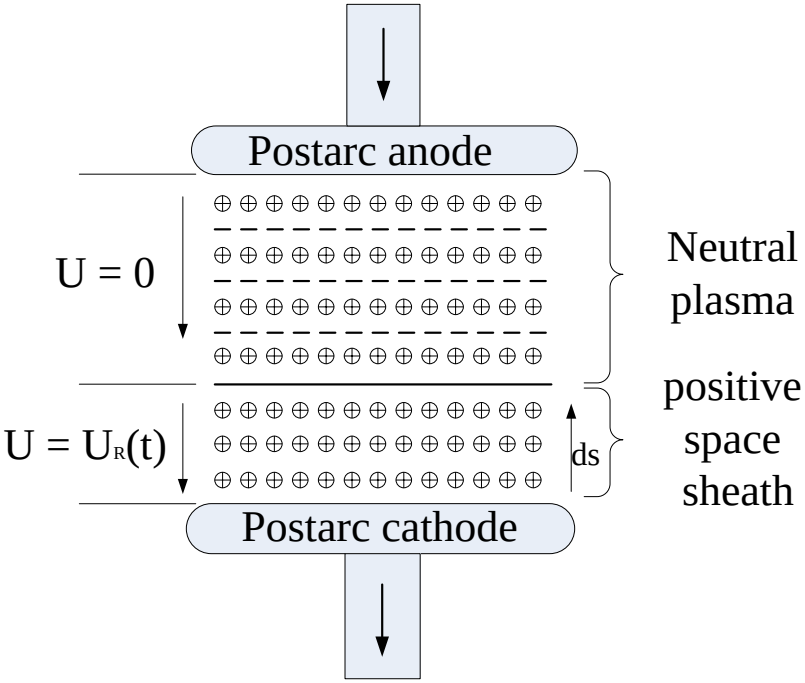


Evolution of Temperature and Surface

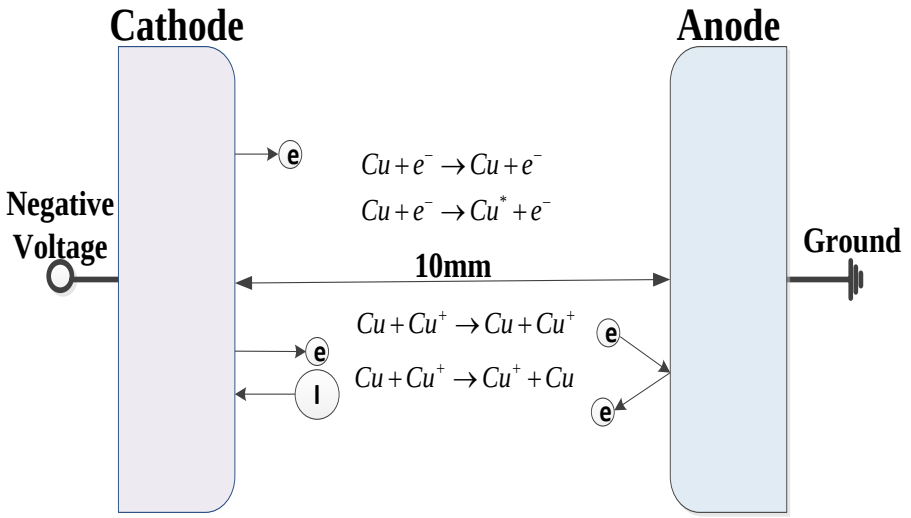
- ✓ **This process reshapes the contact surface and energy distribution.**
- ✓ **Pressure from arc can be a dominant force to shape the surface of anode contact.**
- ✓ **The influence of the process has a significant impact on the post-arc period.**

IV Post-arc BDs : Simulation Model

A 1D3V PIC-MCC model of sheath development



2D3V PIC-MCC model of post-arc breakdown



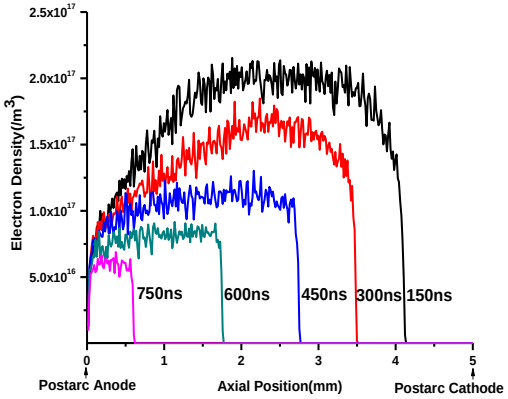
Physical Process:

Plasma transportation under TRV.
The effect of existing background neutral vapor.

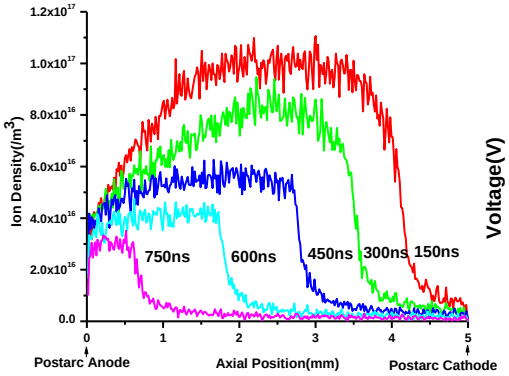
Physical Process:

Breakdowns in a low density metal vapor.
The effect of destructed surface.

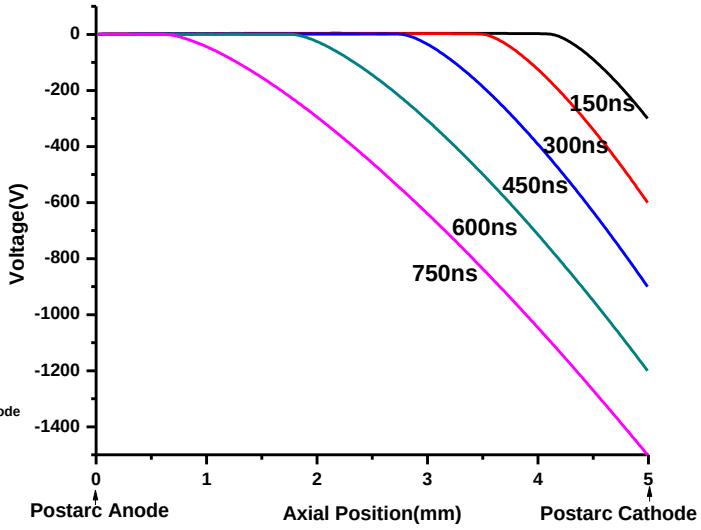
IV Post-arc BDs : Sheath Development



The distribution of electron

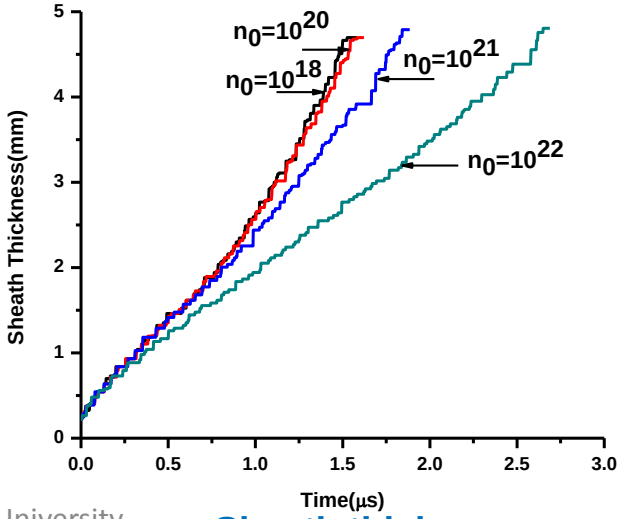


The distribution of ion



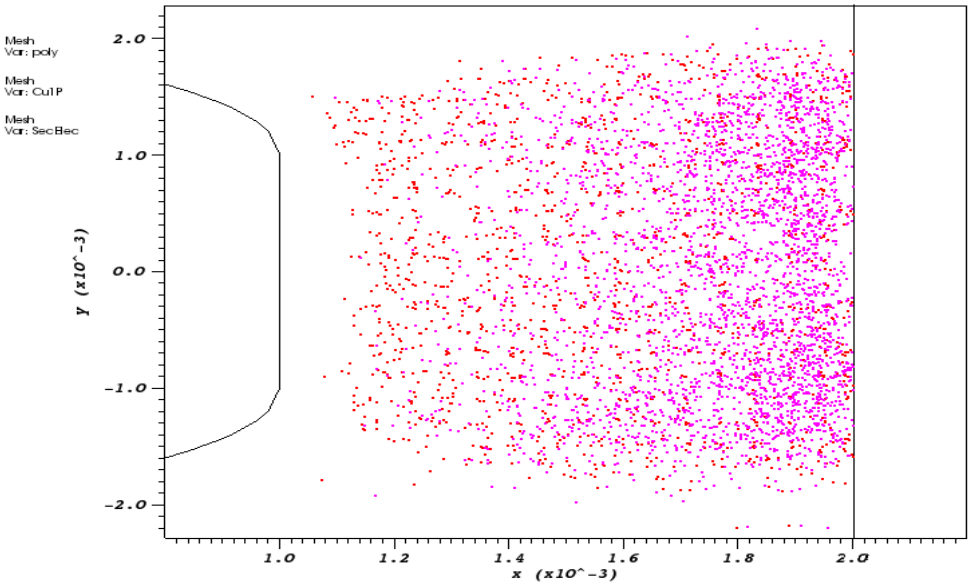
The distribution of voltage across gap

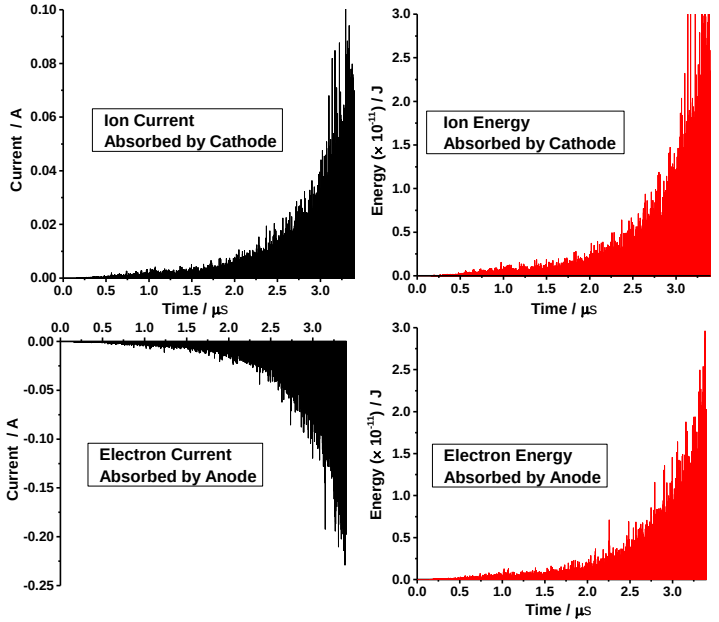
- Sheath development can last for several microseconds.
- The existing of metal vapor can affect the development of residual plasma only in a high density situation.



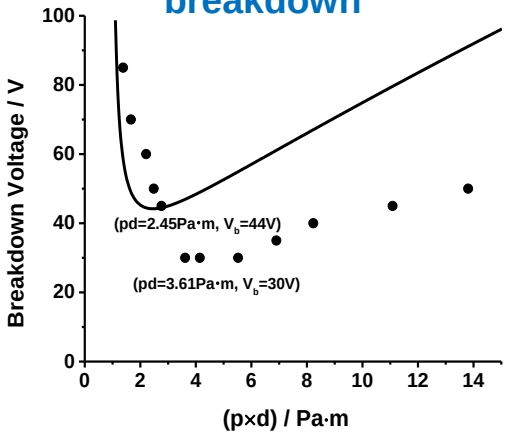
Sheath thickness

IV Post-arc BDs : Metal Vapor BD





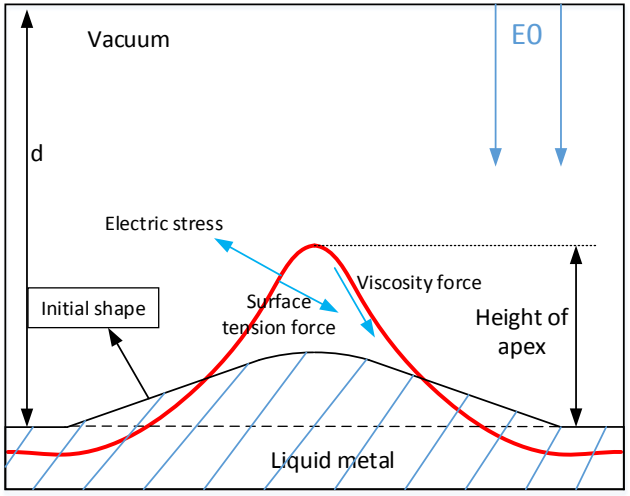
The evolution of particles during a breakdown

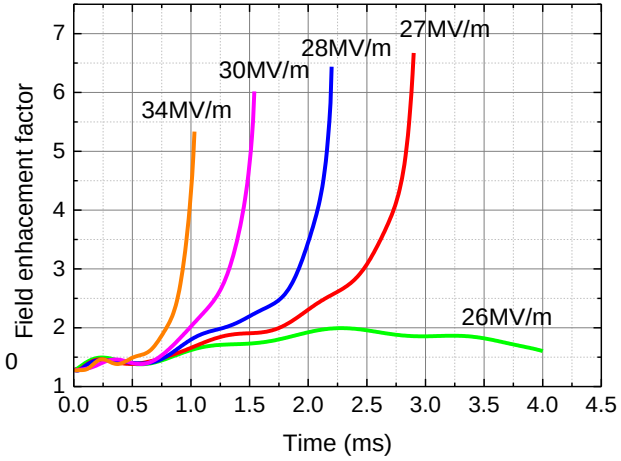


Paschen curve of copper

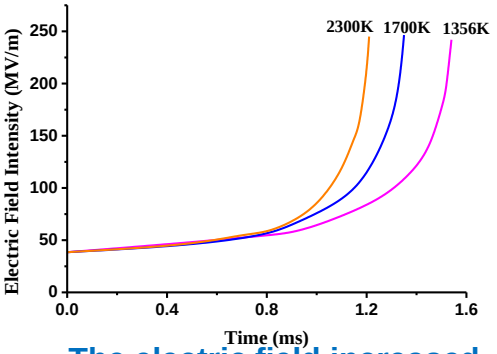
- **The paschen curve for copper are only limited available from experiments.**
- **PIC-MCC is helpful for estimating the breakdowns in a low-density metal vapor.**

IV Post-arc BDs : Micro Tip Induced by Electric Field

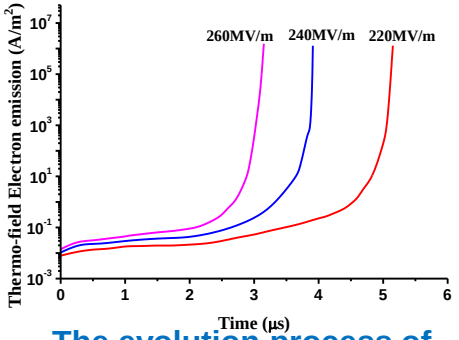




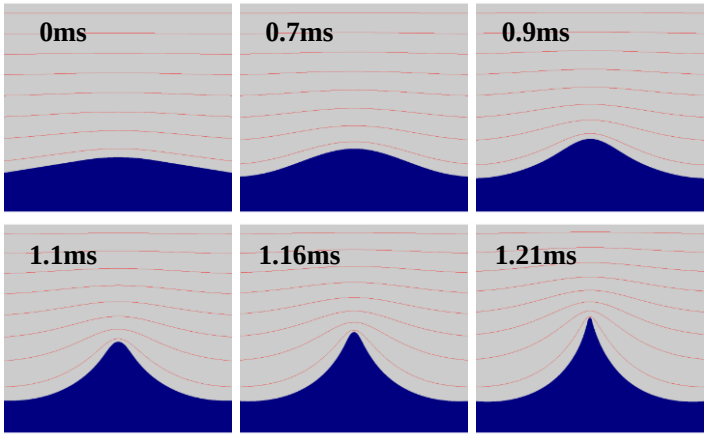
The evolution process of field enhancement factor in the micrometer level



The electric field increased further in the nanometer level



The evolution process of electron emission



- Tip Formed → Electric Field Enhanced→ Current Emission Increased
- The existence of micro tip can reduce the BD voltages significantly.

Conclusion

- **Breakdowns in vacuum and low density metal vapor are the most fundamental issues in designing a high voltage interrupter.**
- **The mechanism of vacuum breakdowns with a large contact gap (10mm~60mm) still does not be understood.**
- **It is necessary to integrate the process of vacuum arcs and post-arc breakdowns for the purpose of better understanding the interrupting processes.**

Thanks For Your Attention!