Molecular Dynamics Simulation of Cathode Spot Formation and Contact Erosion in Vacuum Circuit Breakers

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SC A3 – PS 2

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The University of Manchester

Table of contents

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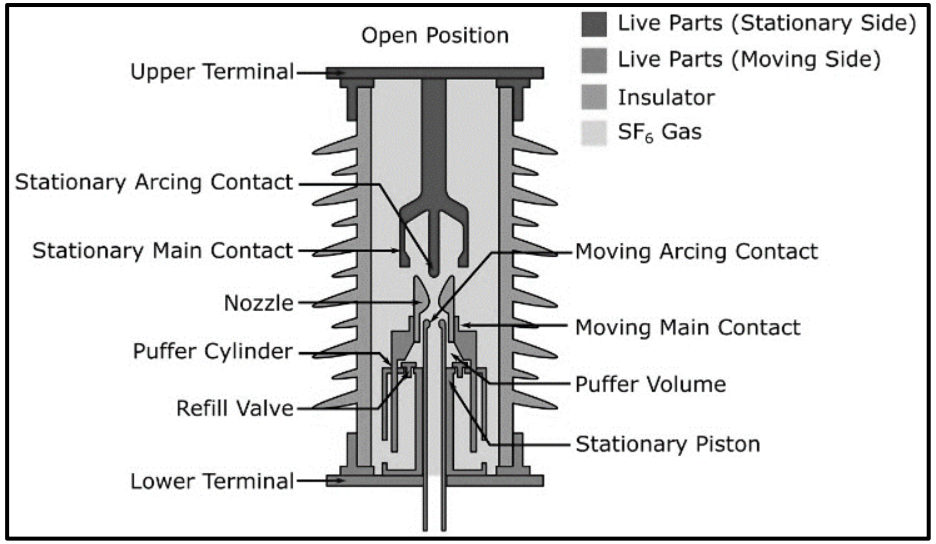
Background and Motivation

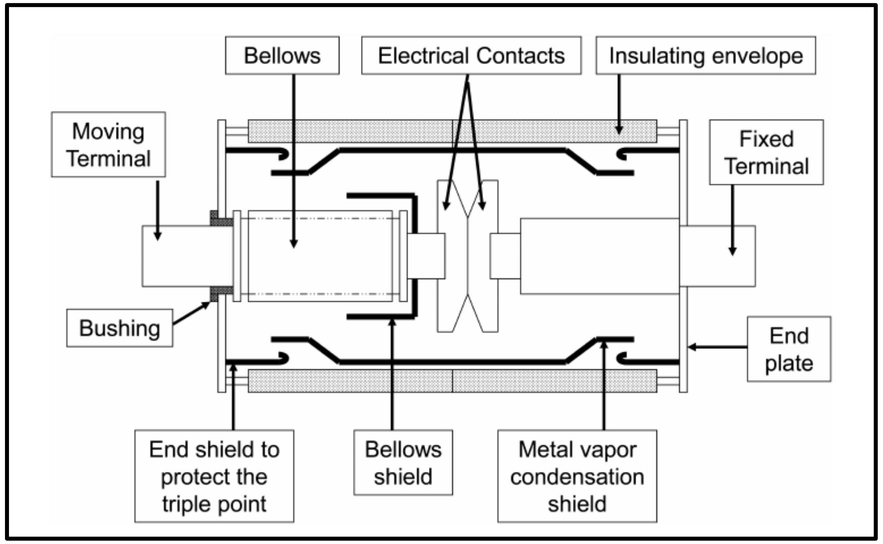
SF6 Circuit Breakers replacement by Vacuum Circuit Breakers

SF6 Replacement – Vacuum Circuit Breakers

Circuit breakers:

- Conducting, interrupting, and closing normal current & short-circuit current.
- Applied voltage level, current interruption performance, electrical lifetime, operation frequency, …





➢ Typical structure of SF6 circuit breaker & Vacuum circuit breaker.

SF6 Replacement

- SF6-alternative gases.
- Develop VCBs into higher voltage levels.

- **SF6 circuit breaker:** HV ≥ 252kV, greenhouse gas.
- **Vacuum Circuit breaker:** MV ≤145kV, outstanding interruption performance.

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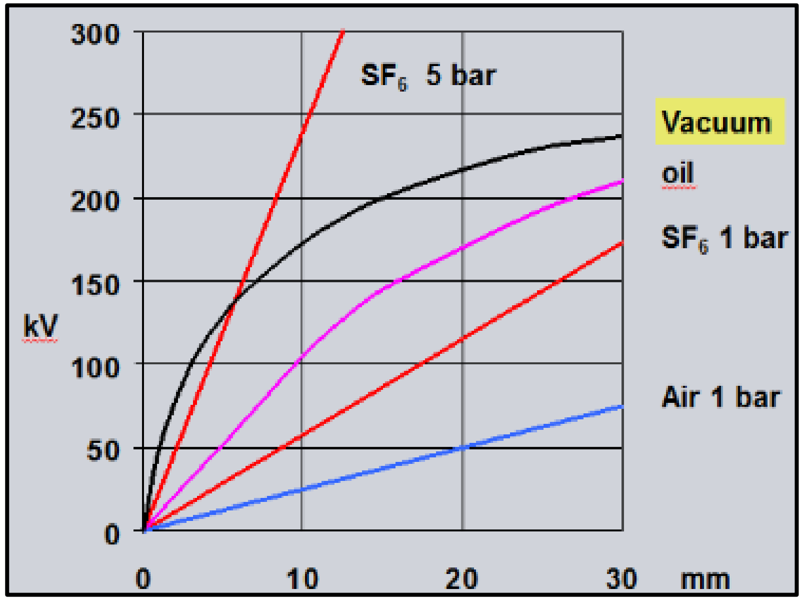
[1] Working Group A3.27 CIGRE. "The impact of the Application of Vacuum Switchgear at Transmission Voltages" (Electra number 589 July 2014 pages 83-98)

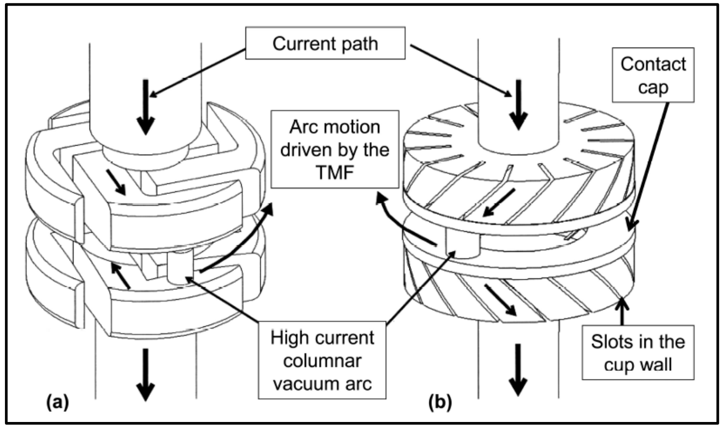
SF6 Replacement – Vacuum Circuit Breakers

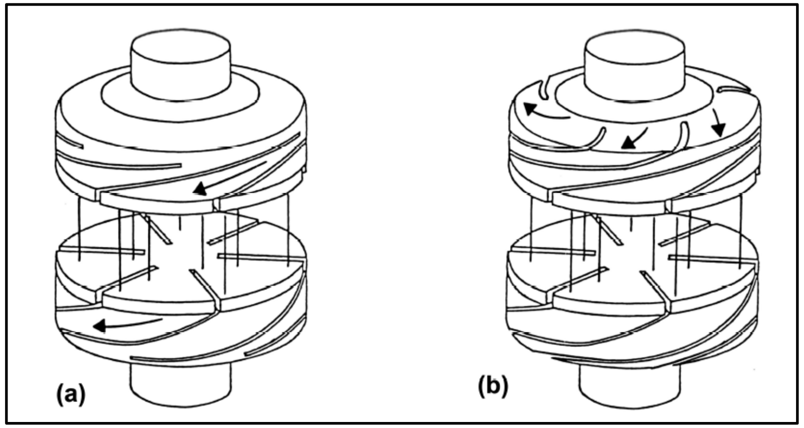
➢ Breakdown strength ~ gap length.



SF6 gap: breakdown strength ~ gap length

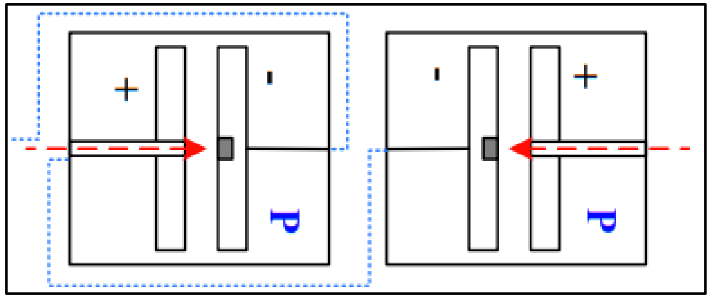
Vacuum gap: breakdown strength ~ contact surface condition





➢ Up :Structure of TMF contact and AMF contact.

➢ Down: Example of double-gap.



Technical Routes:

- Series-connection of vacuum gaps, 1968, UK - 8×132kV
  - Voltage equalisation?
  - Synchronisation?
- Single vacuum gap – reduce contact erosion
  - Magnetic field contact (AMF, TMF)
  - **Material Modifications**

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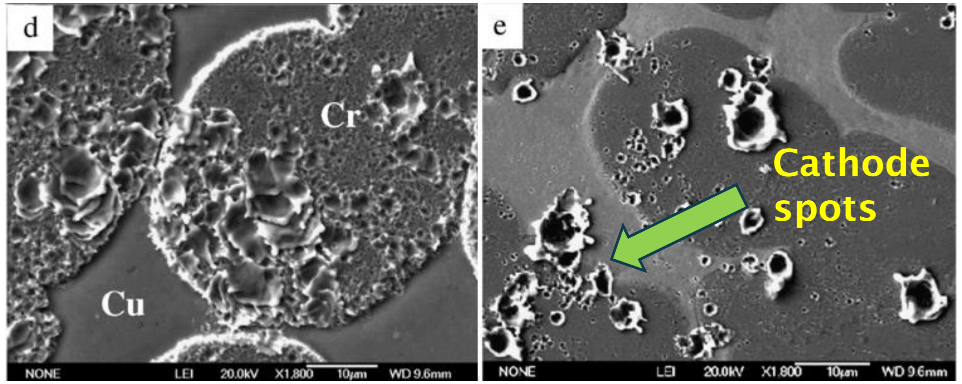
[1] Working Group A3.27 CIGRE. "The impact of the Application of Vacuum Switchgear at Transmission Voltages" (Electra number 589 July 2014 pages 83-98)

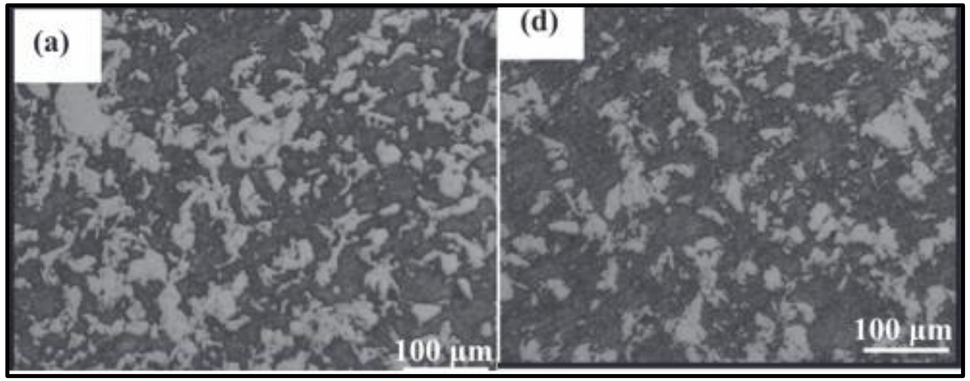
Specified Problem

Mitigation of Contact Erosion by Materials Modification – Cathode spot theory

Contact Erosion Mitigation by Material Modification



➢ Case study 1. CuCr50 vs. CuCr45Fe5



➢ Case study 2. CuCr25 vs. Gr/CuCr25

Experiments: Additions in Cu/Cr could lead do

- Different phase distributions
- More distributed erosion pits (cathode spots)
- Improved erosion resistance

❑ What is the erosion mechanism – what are the material properties influential?

❑ What is the enhancement mechanism of material modification on the erosion resistance?

❑ How to select addition phases and optimise the material design of multi-phase alloy?

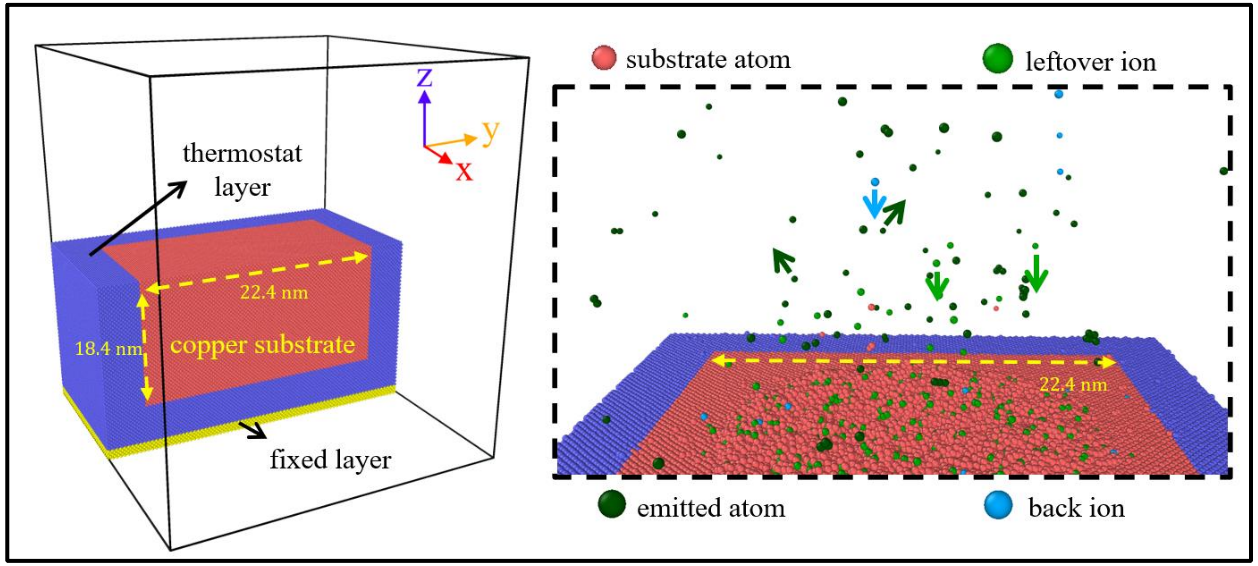
—— **Experiments are costly, while simulation tools help.**

[1] Weichan C, Shuhua L, Xiao Z, et al. Effect of Fe on microstructures and vacuum arc characteristics of CuCr alloys[J]. International Journal of Refractory Metals and Hard Materials, 2011, 29(2): 237-243.
[2] Leng J, Dong Y, Chen X, et al. Effect of Cr@ RGO structure on microstructure and properties of RGO/CuCr25 composite[J]. Materials Research Express, 2021, 8(6): 066515.

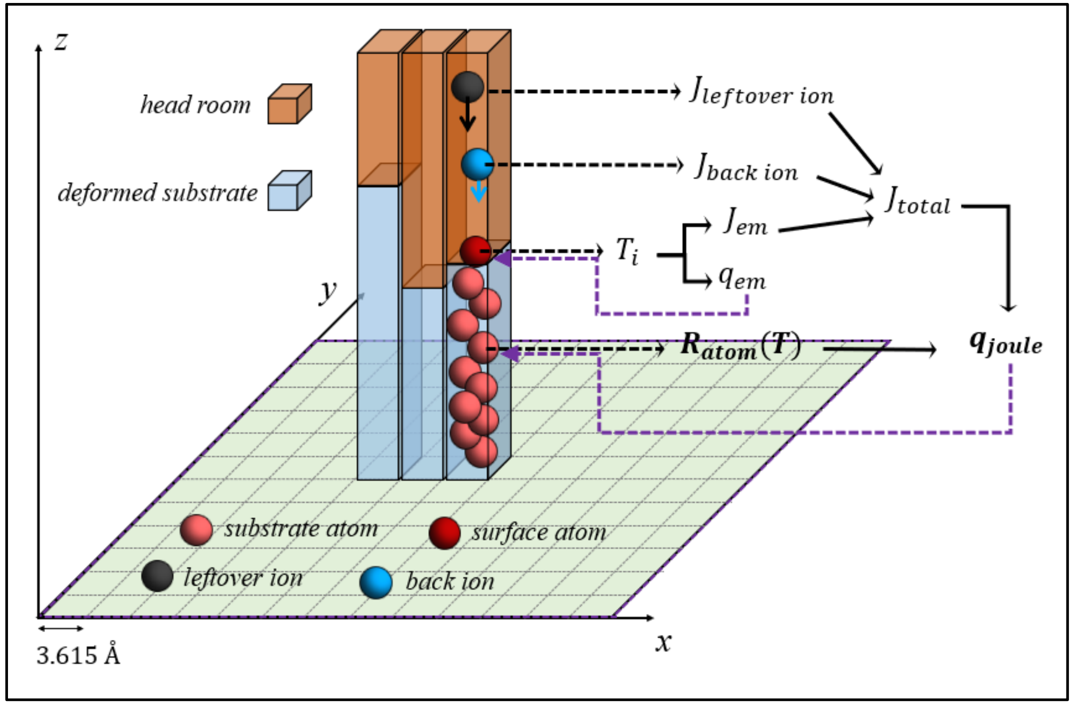
Model and Analysis

Cathode Spot Formation & Contact Erosion

Model: Cathode spot formation



➢ MD simulation model of an individual cathode spot.



➢ The methodology of coupling MD simulation of cathode surface with multiple plasma effects.

- Physical Problem: Arc plasma + Metal surface process + Material composition.
- **Molecular Dynamics**: Excellent capability of presenting the complex material properties & plasma-surface interactions in atomic level.

Cathode substrate – material design

Temperature & Current
Surface emission & Plasma effects

Headroom – coupling plasma effect

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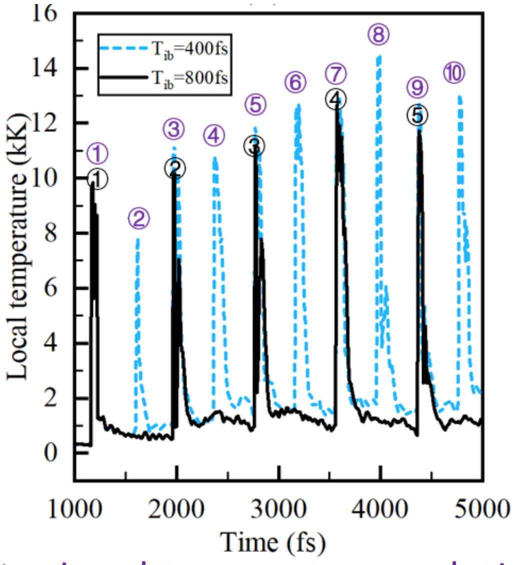
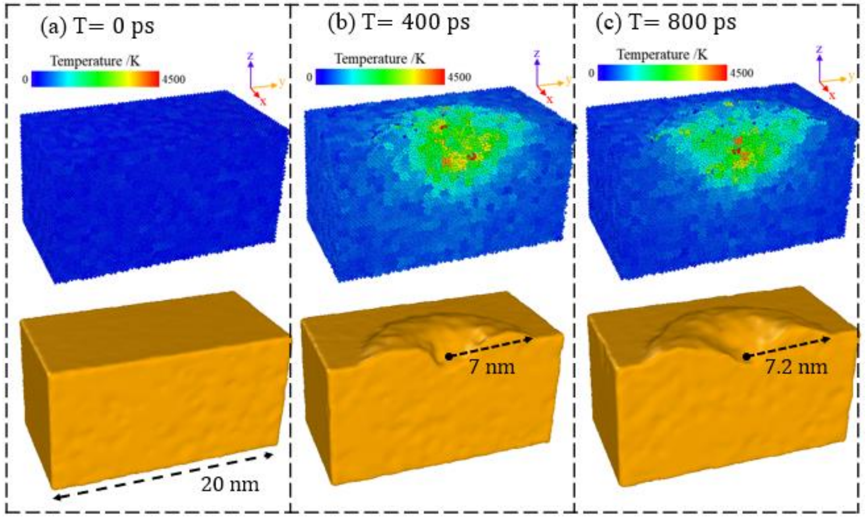
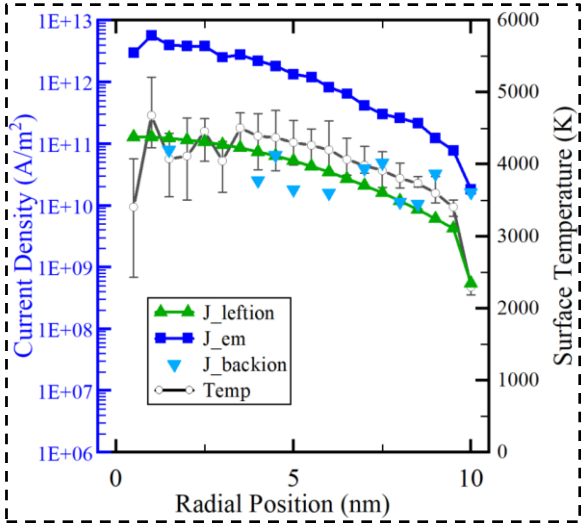
Model: Cathode spot formation

Input: leftover plasma ions (ion energy & ion density)

❑ **Model 1. An equivalent entire cathode spot**







➢ Local temperature evolution.

➢ Crater profile, temperature, current & energy flux densities.

- Continuous Ion Bombardments:
  - Kinetic effect – Ion energy & surface temperature
  - Thermal effect – Bombardment frequency (Ion density)
- Crater profile: Crater radius balanced around the size of the leftover plasma ion cloud
- Validation: Temperature, Current densities, Energy flux densities

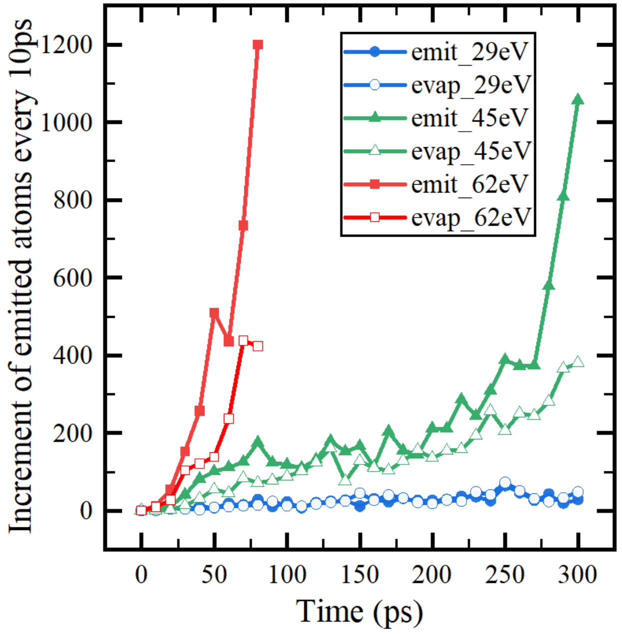
Model: Cathode spot formation

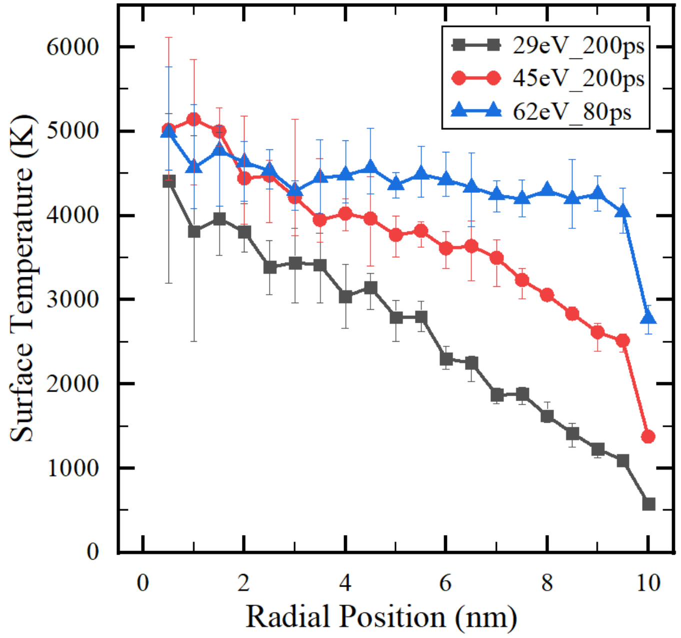
➢ Left: Emission rate vs. Evaporation rate under ion energy of 29eV, 45eV, and 62 eV.
➢ Right: Surface temperature evolution with corresponding ion energies.

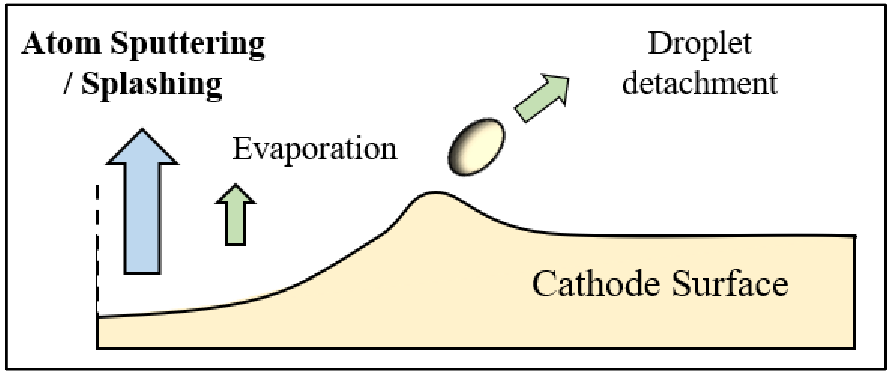
Input: leftover plasma ions (ion energy & ion density)

❑ **Model 1. An equivalent entire cathode spot**

- Qualitative analysis of surface atom emission
  - Emission pattern: evaporation & sputtering
  - Threshold of sputtering: high-temperature surface region, with the threshold value varying with ion energy.







➢ Patterns of mass loss from cathode spots

- Mass loss:
  - Evaporation
  - Droplet detachment (volume & velocity)
  - **Atom sputtering** (establishment of high-temperature surface region)

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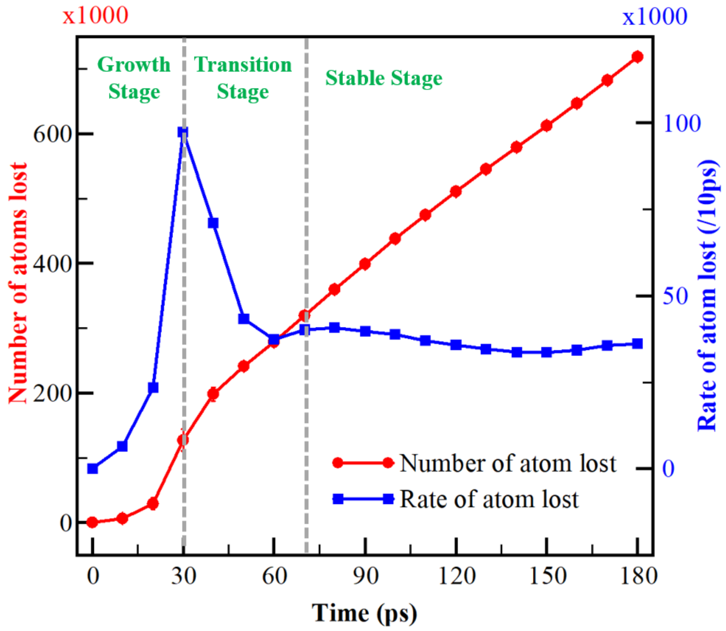
Model: Mass loss

Input: leftover plasma ions (ion energy & ion density)

❑ **Model 2. Local position in a cathode spot**



➢ Evolution of lost atom number and lost rate in the central position of a cathode spot.

- Quantitative analysis of mass loss
  - Three-stage pattern of mass loss: growth stage, transition stage, and stable stage.
  - Growth stage: establishment of high-temperature surface region – intense sputtering & back ions.
  - Transition stage: elastic collisions between sputtered atoms and back ions.
  - Stable stage: a constant mass loss rate.

↕

Constant net erosion rate measured of Copper cathode: 120 μg/C

Summary & Prospect

Summary and Prospect

- A comprehensive MD model of a cathode spot is established.
- The surface deformation is a direct result of ion bombardment on gradually heated surface.
- The contact erosion is dominated by intense atom sputtering, appeared after the establishment of high-temperature surface region.
- Erosion behaviours in the cathode spot exhibit a three-stage pattern and will evolve into a stable stage with constant rate of mass lost.

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By comparing the erosion mechanism and mass loss rate under various substrate structure, this simulation provides guidance to the material design in industry to mitigate the contact erosion, and thus, upgrade the applied voltage level of vacuum circuit breakers.

Thanks for listening!

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