Current Zero Club

CZC

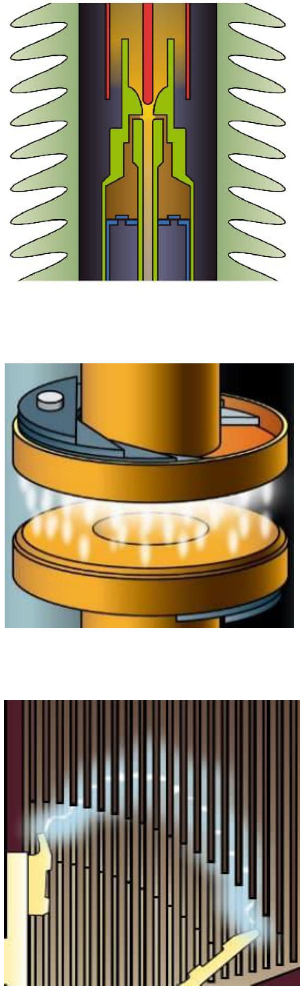
Fundamentals of Current Interruption in (high-voltage) vacuum circuit breakers

Current Zero Club

International Research Group on Interruption Phenomena of Power Switching Devices

Current Zero Club

- International Research Group on Interruption Phenomena of Power Switching Devices
- Webinar presented through CIGRE channels, January 2024, > 750 attendants
  - recording accessible through www.e-cirge.org
- Aligned with CIGRE Study Committee A3 (T&D equipment)
- Founded in 1961
- Scientific and independent
- 30 members (upon invitation) from industry and academia
- Specialists' circles on dedicated topics:
  - Gas circle
  - Vacuum circle
  - Low-voltage circle
- http://currentzeroclub.org/



Content

- **Current Zero Club (CZC)**
  - Dr. Rene Smeets (KEMA Labs, Arnhem, the Netherlands.) [Chair Current Zero Club]
- **Introduction**
  - Prof. Shenli Jia (Sichuan University, China) [Chair ISDEIV PISC]
- **Part 1: Vacuum arc fundamentals**
  - Dr. Thierry Delachaux (Hyosung R&D Center in the Netherlands)
  - Prof. Eiji Kaneko, Japan (originally prepared by prof. Yuki Inada, Saitama University, Japan)
- **Part 2: Processes after current zero**
  - Dr. Dietmar Gentsch, ABB Germany (originally prepared with dr. Edgar Dullni)
- **Part 3: Extension of Vacuum Interrupter to Higher Voltages**
  - Prof. Ziyuan Liu, Xi‘an Jiaotong Uni., China (originally prepared by dr. Thomas Heinz, Siemens Energy, Germany)

Disclaimer: All presenters speak on behalf of Current Zero Club and not necessarily on behalf of their organisation

Introduction

- SF_6 has high Global Warming Potential (GWP) and long lifetime in the atmosphere, which makes it highly desirable to replace SF_6 in electric power equipment with environmentally friendly solutions
- Increasingly stringent policies and regulations from more and more countries and governments are also making sulfur hexafluoride substitution more urgent (eg. Regulation - EU - 2024/573 - EN - EUR-Lex)
- Apart from the technology of arc quenching and insulation with SF_6-alternative gases, replacement of SF_6 can also be done with vacuum circuit breakers.
- Vacuum switches are environmentally benign and can be easily recycled. The vacuum interrupter has long life, require no maintenance for the life of the vacuum interrupter.
- Vacuum switching technology has been widely used in the field of medium voltage, and a single vacuum interrupter has reached the 252 kV level at present.
- The present presentation focuses on the fundamentals of current interruption in vacuum.
- The content mainly includes the basic physics of vacuum switching arc, current interruption in vacuum, and special issue for high-voltage interruption in vacuum.
- This work was prepared within the «vacuum circle» of the «Current Zero Club» (CZC, http://currentzeroclub.org/) and will be presented by representatives of the organization.

Introduction

Contributors

- Group Leader： Shenli Jia (Sichuan University, China)) [Chair ISDEIV PISC]
    - Thierry Delachaux (Hyosung R&D Center in the Netherlands)
    - Edgar Dullni (Consultant for ABB, Germany)
    - Leslie Falkingham (VIL, United Kingdom) [Chair Current Zero Club Vacuum Circle]
    - Thomas Heinz (Siemens Energy, Germany)
    - Xiaolong Huang (Sichuan University, China)
    - Yuki Inada (Saitama University, Japan)
    - Michael Kurrat (Braunschweig University, Germany)
    - Zhiyuan Liu (Xi’an Jiaotong University, China)
    - Rene Smeets (KEMA Labs, The Netherlands) [Chair Current Zero Club]
    - Erik Taylor (S&C, USA)
    - Lijun Wang (Xi’an Jiaotong University, China)

Part 1: Vacuum arc fundamentals

Vacuum interrupter structure and vacuum arc

Source: By courtesy of M.B.J. Leusenkamp (Eaton Corporation)

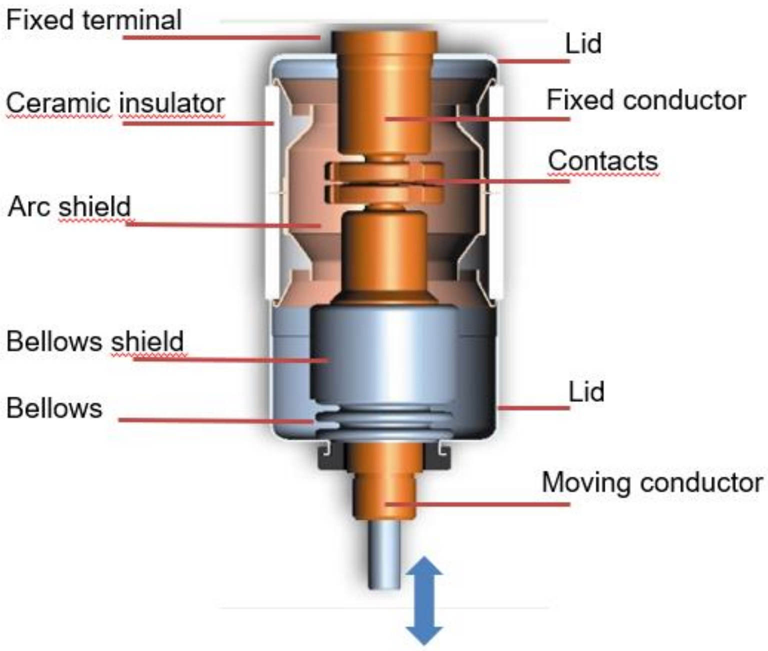
Structure and main properties of vacuum interrupters

Structure

Contacts
carry current in closed position at low resistance.
Interruption when contacts separate.

Ceramic insulator
ensures inner and outer dielectric withstand of the interrupter.

Arc shield
protects ceramic insulator from metallic vapor deposition.

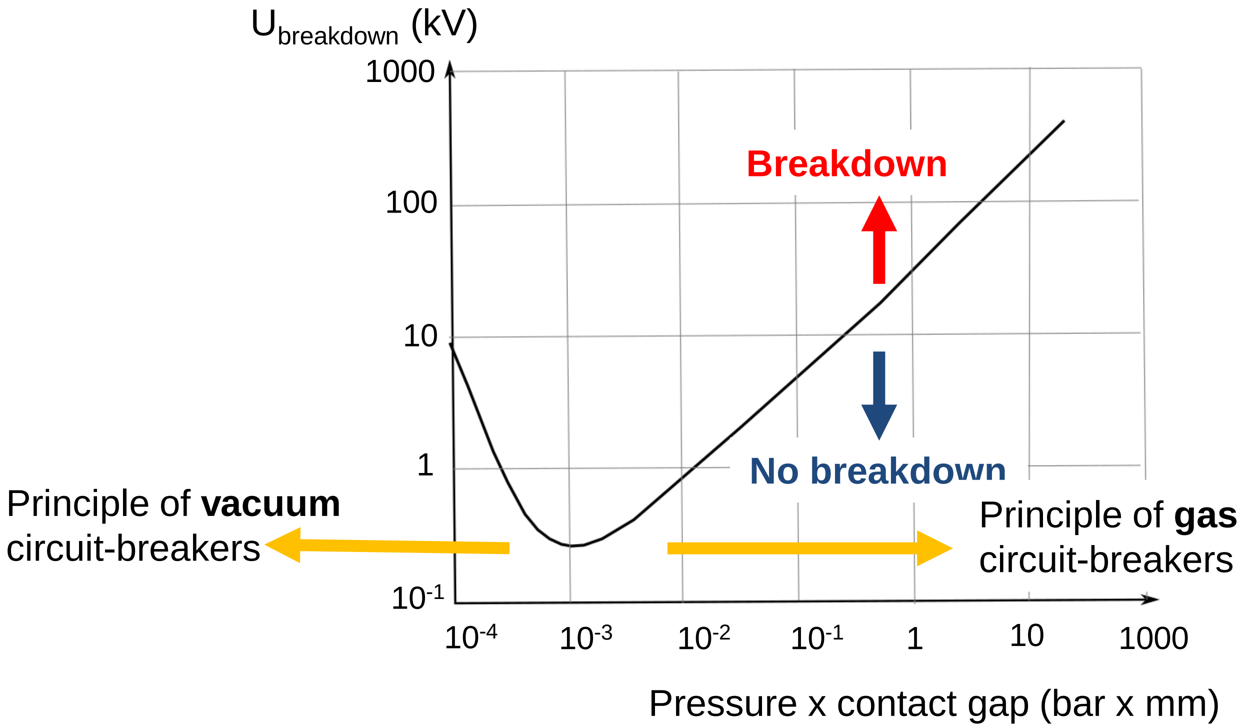


Properties

- Environmentally-friendly (no gas)
- Pressure < 10^{-7} mbar (UHV)
- Arc is enclosed
- Sealed for life (> 30 years)
- Maintenance-free
- Life time :
  - Up to 30 interruptions at full rated short-circuit current
  - > 10’000 interruptions at rated current and below

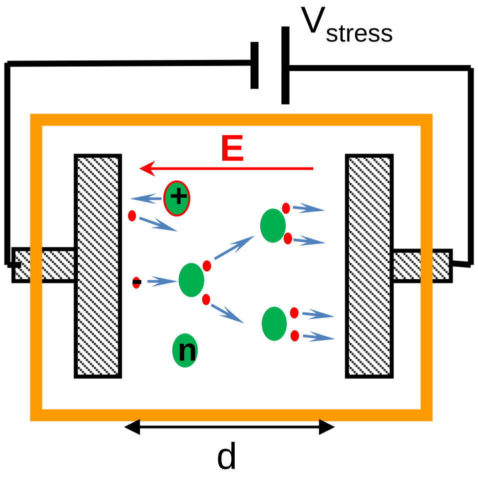
Why using vacuum?

Paschen curve gives the voltage breakdown of gases as a function of pressure and contact gap



Principle of **vacuum** circuit-breakers

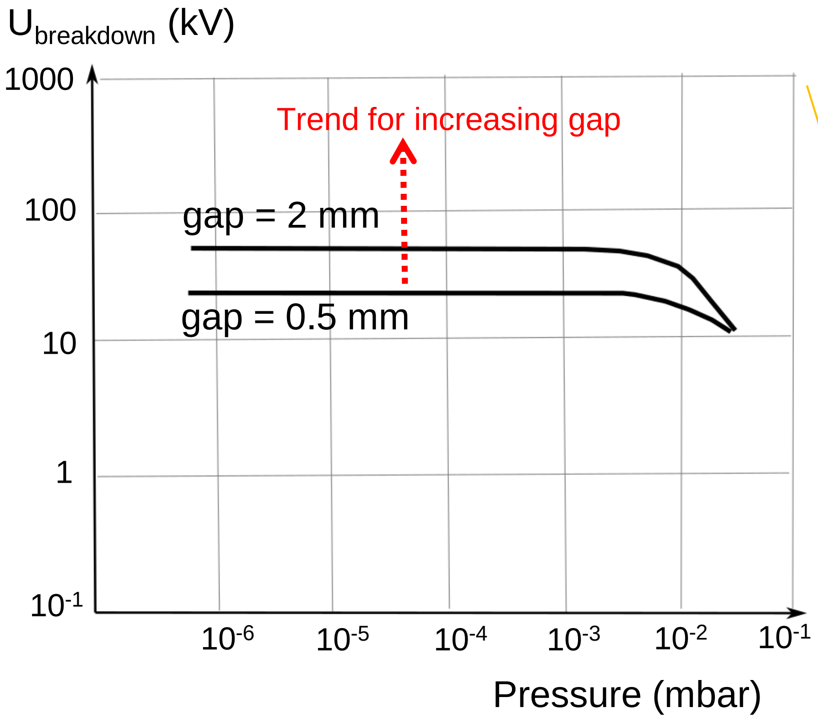
Principle of **gas** circuit-breakers



Gas ionization and electron multiplication (avalanche effect) eventually lead to a volume (gas) breakdown

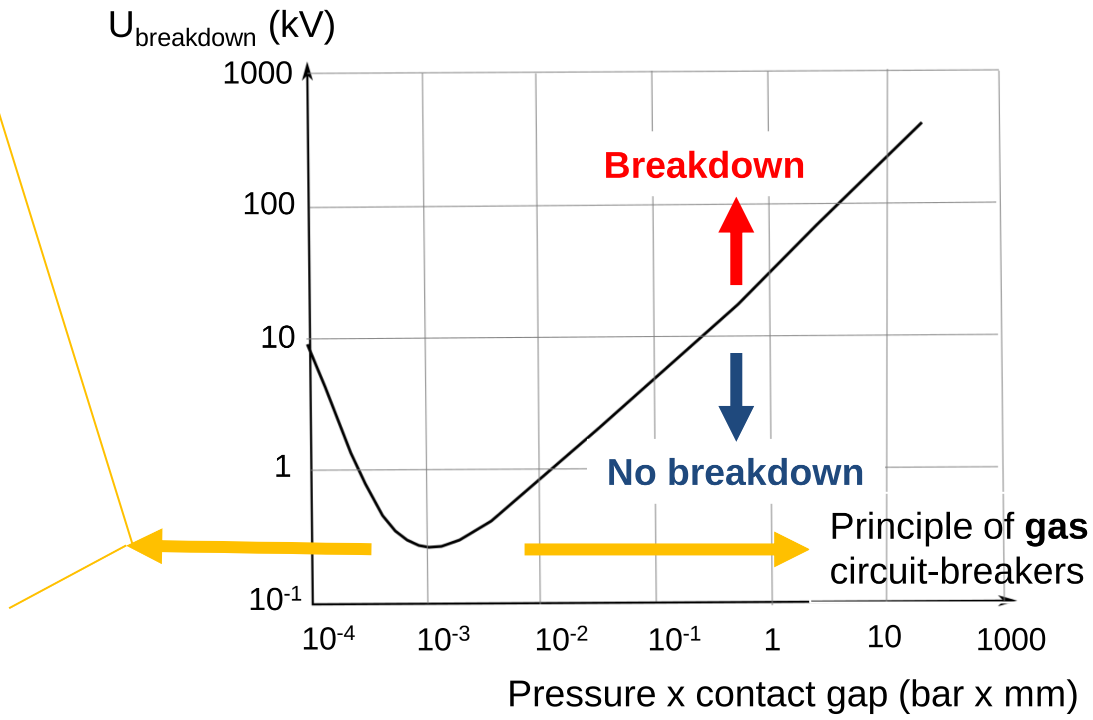
Why using vacuum?

Voltage breakdown in vacuum



- Breakdown voltage in vacuum is a function of contact gap and contact material.
- It is driven by surface mechanisms.

Voltage breakdown in gas



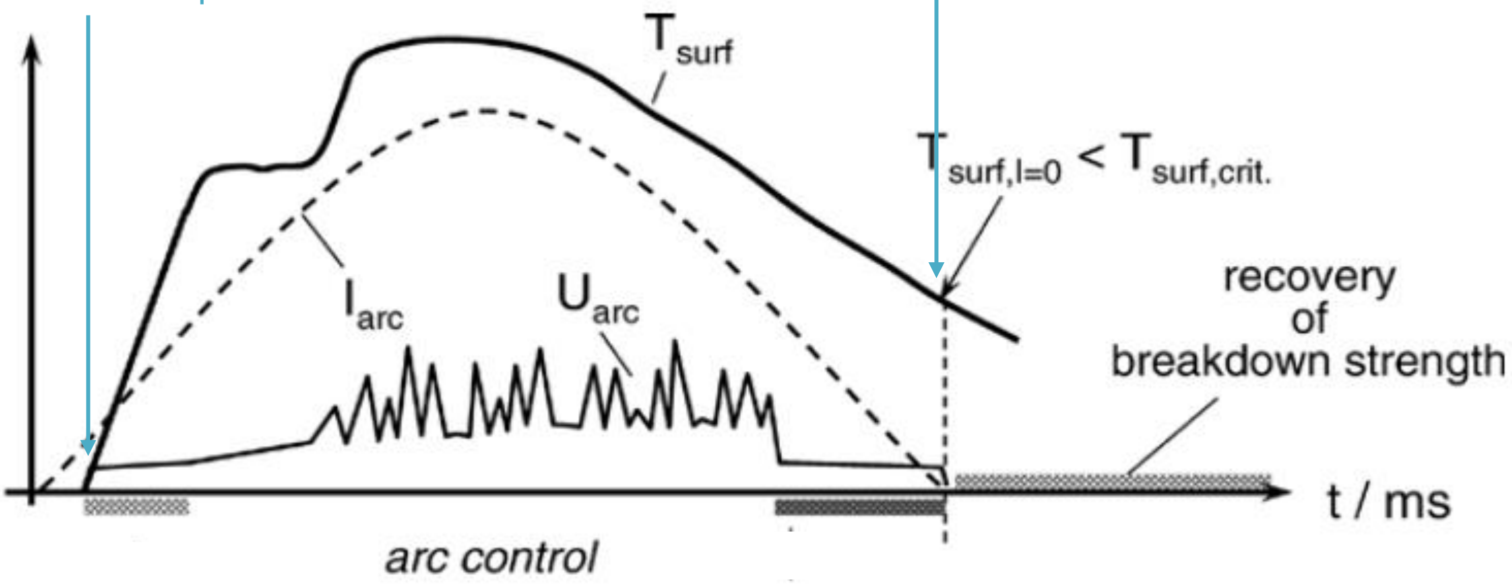
- Breakdown voltage in gases is a function of contact gap, pressure and gas.
- It is driven by volume mechanisms.

Source: R.Hackam and L.Altcheh, JAP, 46 (1975) p 627

Vacuum arc fundamentals : arc physics before current zero

Part. I : Vacuum arc fundamental

Part 2: Processes after CZ

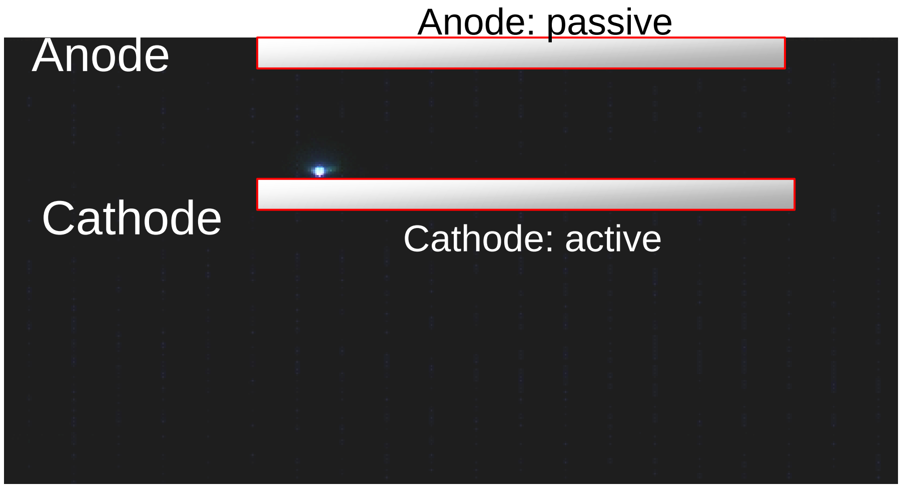


Surface temperature is one of the most decisive parameter for a successful interruption. Therefore, the **goal for a successfull current interruption in vacuum is to limit the heat to the electrodes by an adequate contact design.**

Source: E. Schade, “Physics of high-current interruption of vacuum circuit breakers”, IEEE Trans. On Plasma Sci., vol. 33 (2005), 1564

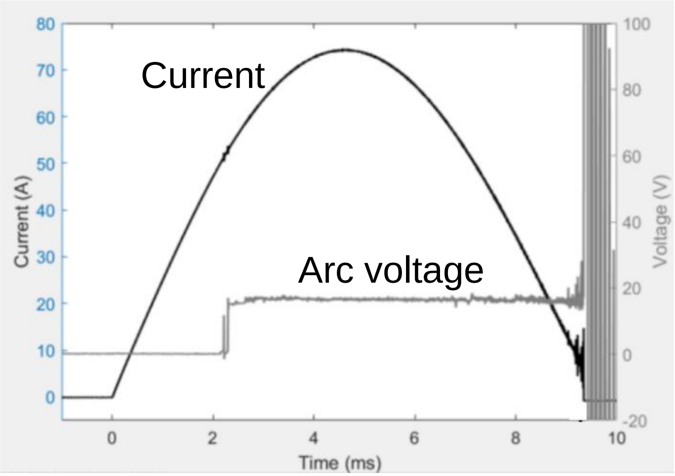
Low current vacuum arc : the cathode spot (I/II)

Appearance of a 25 A vacuum arc



Source: By courtesy of S. Jia (Sichuan University)

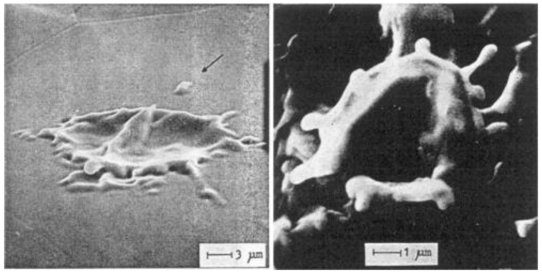
Electrical characteristics

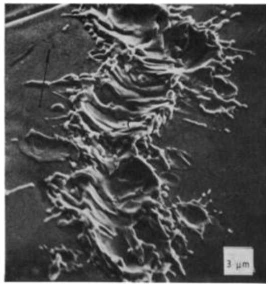


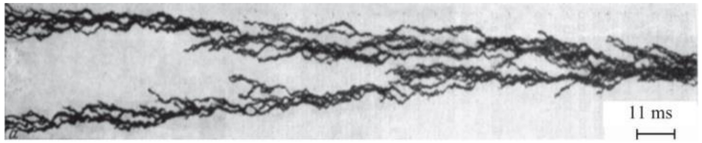
Constant arc voltage ~15 V (Cu)

Source: T. Delachaux *et al.*, “Influence of anisotropic contact materials on the vacuum arc’s chopping behavior”, ISDEIV in Okinawa (JP), 2023

Microscopic characterization







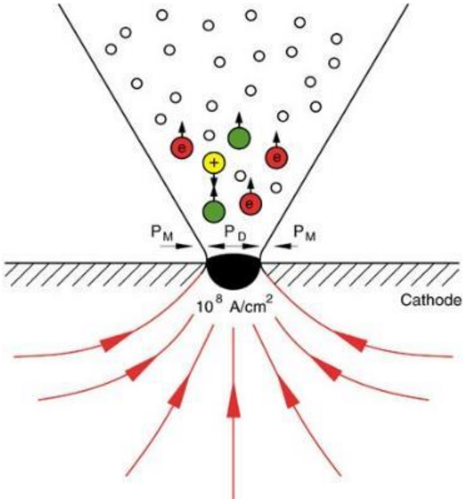
Craters visible on the cathode,highlighting the explosive character of the spots.

Source: B. Jüttner, “Katodenprozesse Elektrischer Entladungen in Vakuum”, Dissertation, Zentralinst. Electronenphys., Berlin, 1982

Source: V.F. Puchkarev and A.M. Murzakayev, “Current density and the cathode spot lifetime in a vacuum arc at threshold currents”, J.Phys.D: Appl.Phys., vol.23 (1990), pp26

Low current vacuum arc : the cathode spot (II/II)

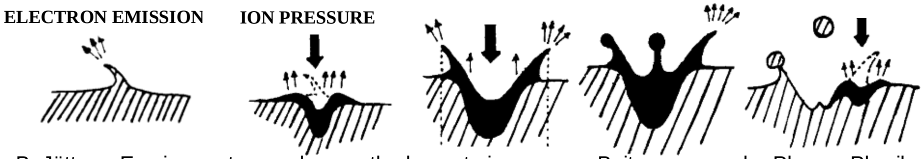
Cathode spots are the **unique** source of metallic vapor, plasma, electrons and droplets (at low current)



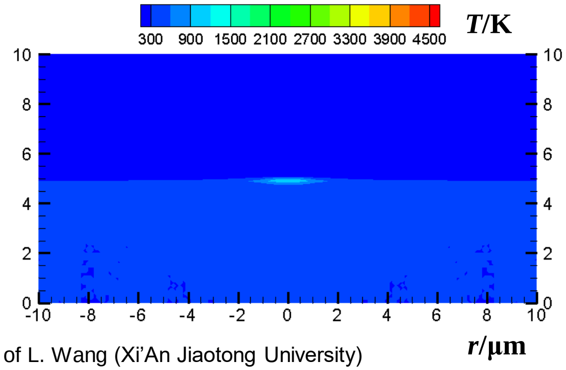
- Each spot carries about 30 A (for Cu)
- Spot diameter: ∅1-10 um
- Current density: j ~ 10^{12} A-m^2
- Composition:
  - Cu^+ 25%
  - Cu^{++} 60%
  - Cu^{+++} 15%
- Erosion rate: ~ 50 μg/C

Source: J. Kutzner and H. Miller, “Integrated ion flux emitted from the cathode spot region of a difuse vacuum arc”, J Phys. D: Appl. Phys., vol.25, (1992) pp686

Dynamic process of life and death.
Lifetime: 50-100 ns



Source: B. Jüttner Erosion craters and arc cathode spots in vacuum. Beitraege aus der Plasma Physik, 1979



Source: By courtesy of L. Wang (Xi’An Jiaotong University)

Source: L. Wang , S. Jia , X. Zhang *et al*, J Phys. D: Appl. Phys., 2017, 50(45): 455203

High current vacuum arc : multiple cathode spots

Appearance of a high current vacuum arc

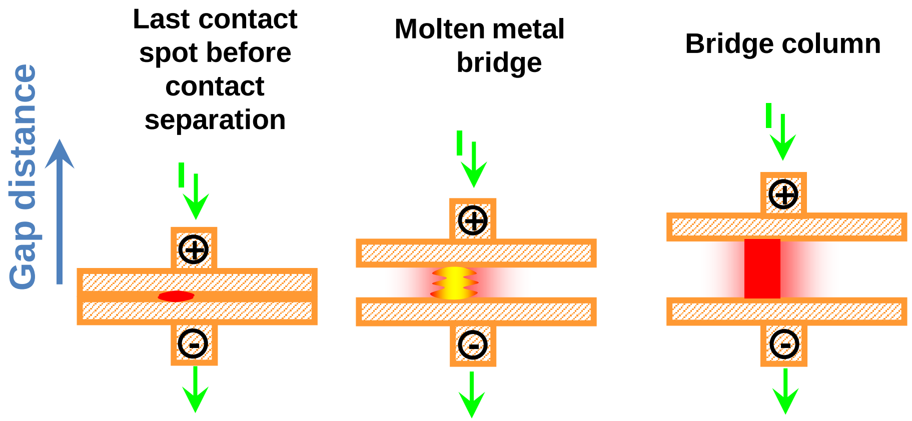
D = 80mm; h = 20mm; I_0 = 18kA (rms); CuCr50

- Multiple cathode spots visible (each with ~ 30 A)
- Spots repulsing each other

Source: By courtesy of L. Wang (Xi'An Jiaotong University)

High current vacuum arc : physics of vacuum arc switching – the vacuum arc development

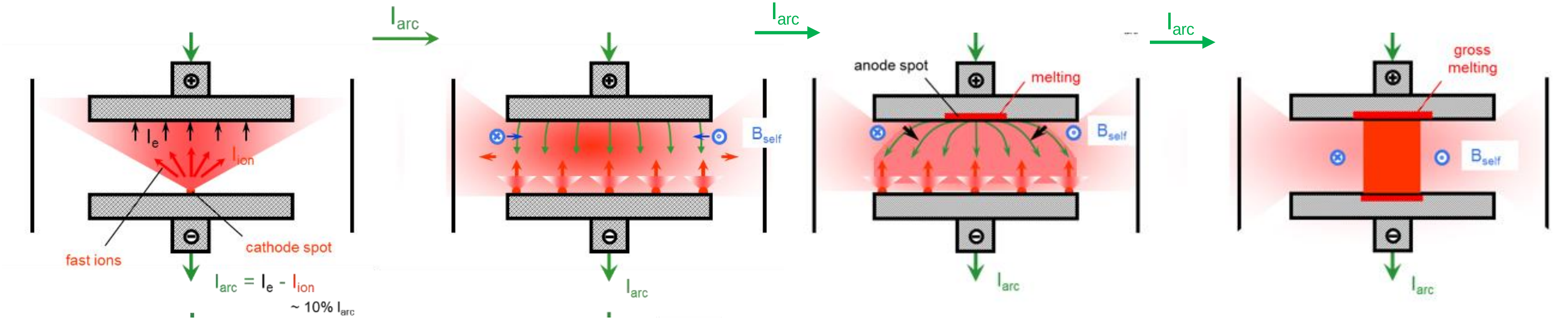
1. Arc initiation stage : electrode separation (< 1mm)



2. Current increase stages

a. Multiple cathode spots development

b. Pinch effect and arc constriction development



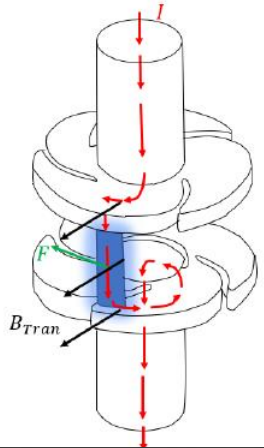
The arc constriction involves the melting of the anode (it is a function of instantenous current AND gap distance between the electrodes).

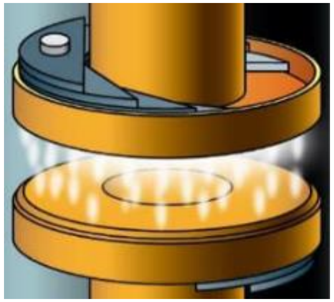
High current vacuum arc : arc control with magnetic fields

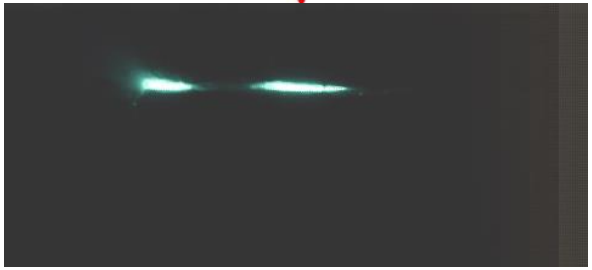
-Arc jets and anode spots lead to excessive contact melting which is detrimental for current interruption

-Heat flux improvement can be done through “arc control” with magnetic fields

Transverse Magnetic Field (TMF) type

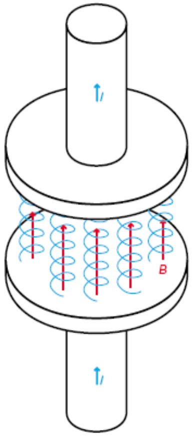


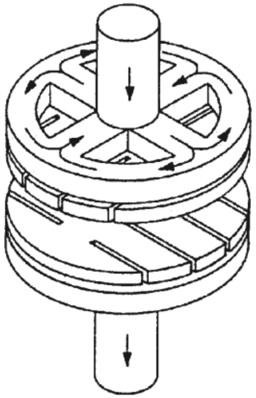


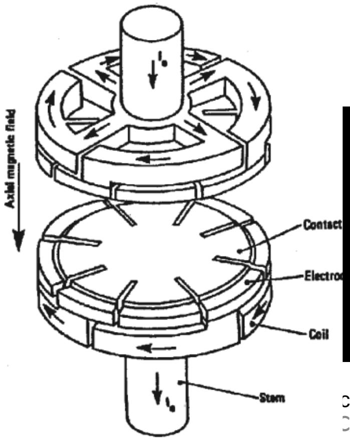


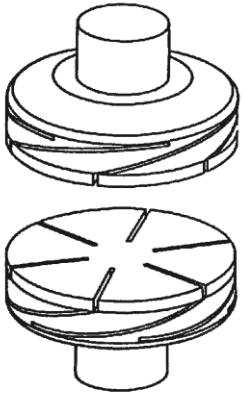
Source: By courtesy of L. Wang (Xi’An Jiaotong University)

Axial Magnetic Field (AMF) type





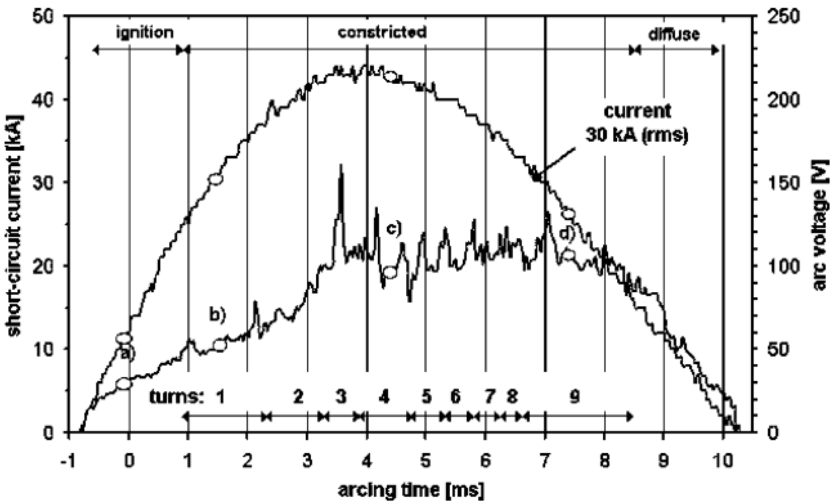




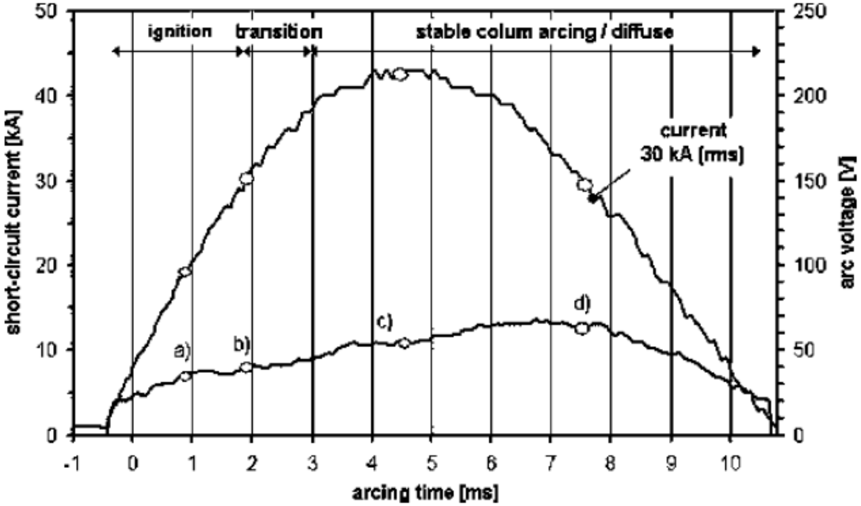
courtesy of S. Jia (Sichuan University)

High current vacuum arc : arc control with magnetic fields

Transverse Magnetic Field (TMF) type

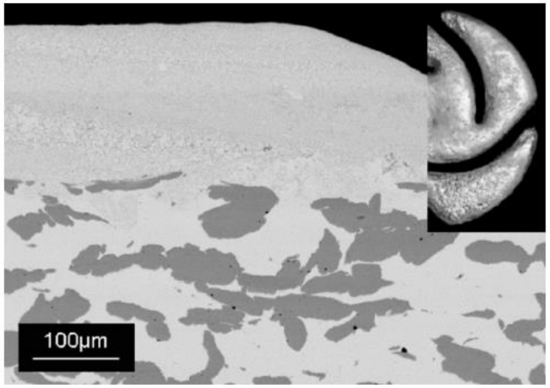


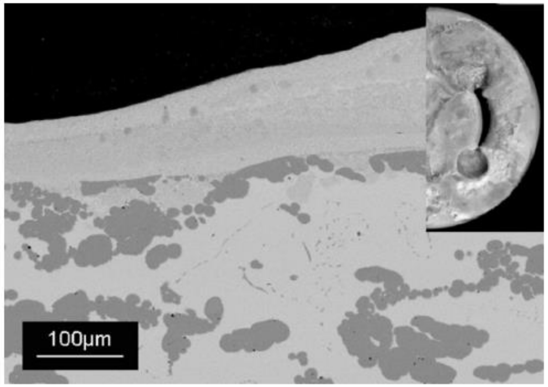
Axial Magnetic Field (AMF) type



Arc voltage: ~100-300 V

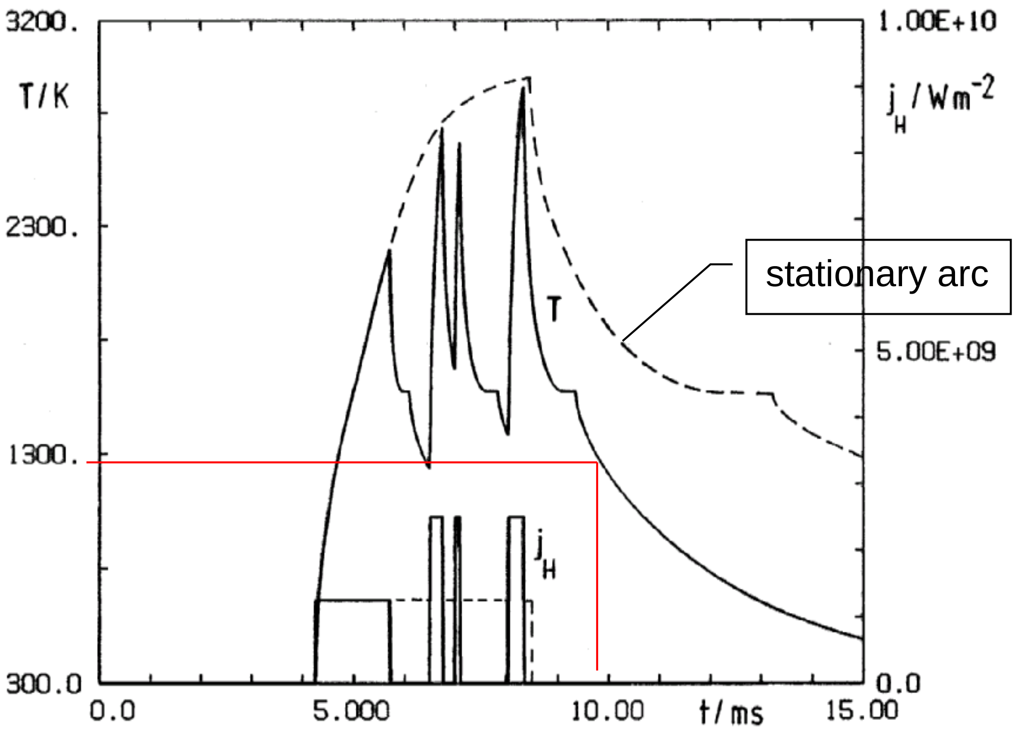
Arc voltage: ~ 60 V



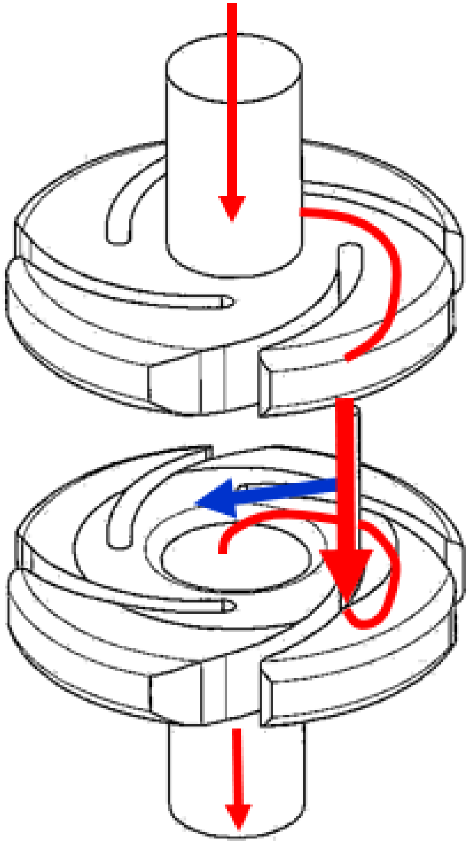


Source: D, Gentsch and W. Shang, “High-speed observations of arc modes and material erosion on RMF- and AMF- contact electrodes, *IEEE Plasma Science*, vol. 33 (2005), 1605

Simulation of TMF contact heating



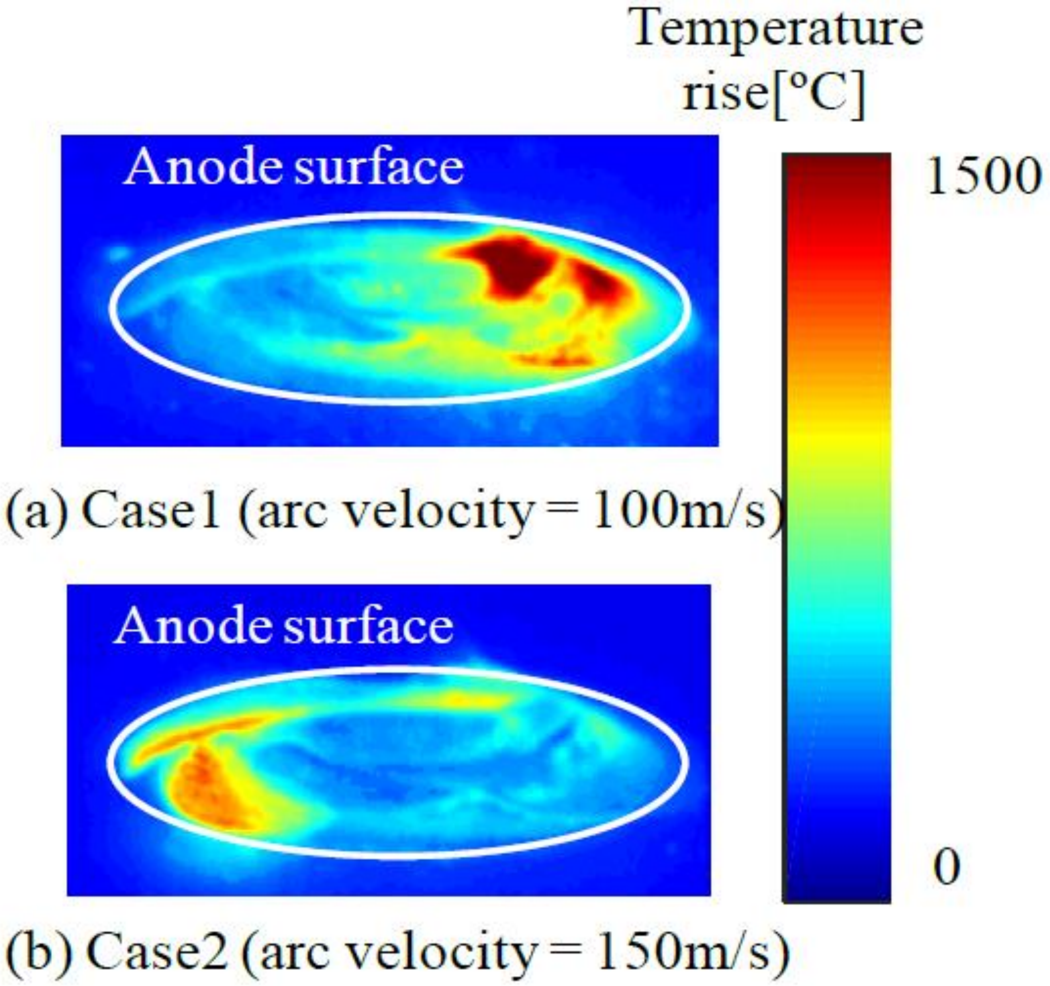
stationary arc



TMF causes arc moving, thus reducing local contact surface temperature, contact heat and erosion.

Source: E. Dullni, E. Schade, Wenkai Shang, “Vacuum arcs driven by cross-magnetic fields (RMF)”, IEEE TPS, Vol. 31, 2003, pp 902-908

Temperature measurements on TMF contacts



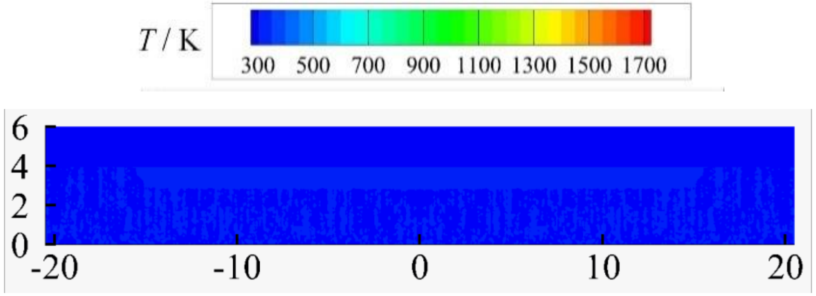
(a) Case1 (arc velocity = 100m/s)

(b) Case2 (arc velocity = 150m/s)

- Temperature on spiral-type contacts measured by a fast thermographic video camera
- Distribution of temperature on the anode at the end of the last rotation of the arc before current-zero
- Two cases with different arc velocities.

Source: T. Donen, J. Abe, M. Tsukima, Y. Takai, S. Miki, S. Ochi, 23rd ISDEIV, Suzhou, 2016

Simulation and experiment of AMF contact heating

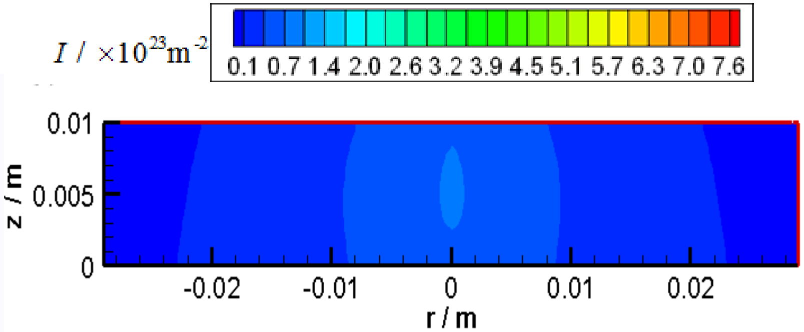


Thermal activity simulation of high current vacuum arc anode

Source: By courtesy of Xiaolong Huang(Sichuan University)

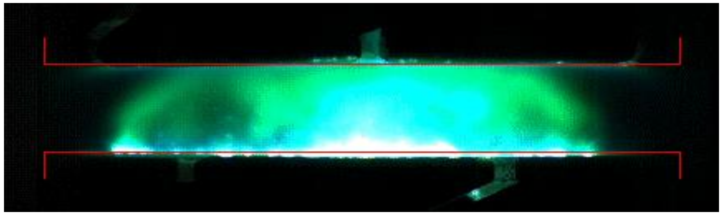
Thermal activity experiment of high current vacuum arc anode

Shenli Jia *et al* 2012 *J. Appl. Phys.* **111** 043301



Simulation results of arc interrupting process

Shenli Jia *et al* 2014 *J. Phys. D: Appl. Phys.* **47** 403001



Experimental results of arc interrupting process

Shenli Jia *et al* 2011 *IEEE Plasma Sci.* **39** 3233-43

AMF makes arc diffused, thus reducing contact surface temperature, contact heat and erosion.

Part 1: Summary

- Vacuum interrupters have been commercialized since about 60 years, mainly at the distribution level and lowest ratings of transmission level.

- Vacuum arcs are sustained by the ionized metallic vapor originating from contacts. This ionized metallic vapor is supplied through cathode spots explosion (at “low” currents) or contact melting (at “high” currents).

- Successful current interruption is linked to contact temperature, which depends on how the heat is distributed over the contacts.

- The interaction of the vacuum arc with magnetic fields is key to suppress the contact temperature rise, obtain performance, and compact vacuum interrupters. Such magnetic fields are effectively generated by smart contact design.

- In a transverse magnetic field (TMF), the constricted arc is rotated on the whole contact surface by the Lorentz force, which suppresses the contact temperature rise.

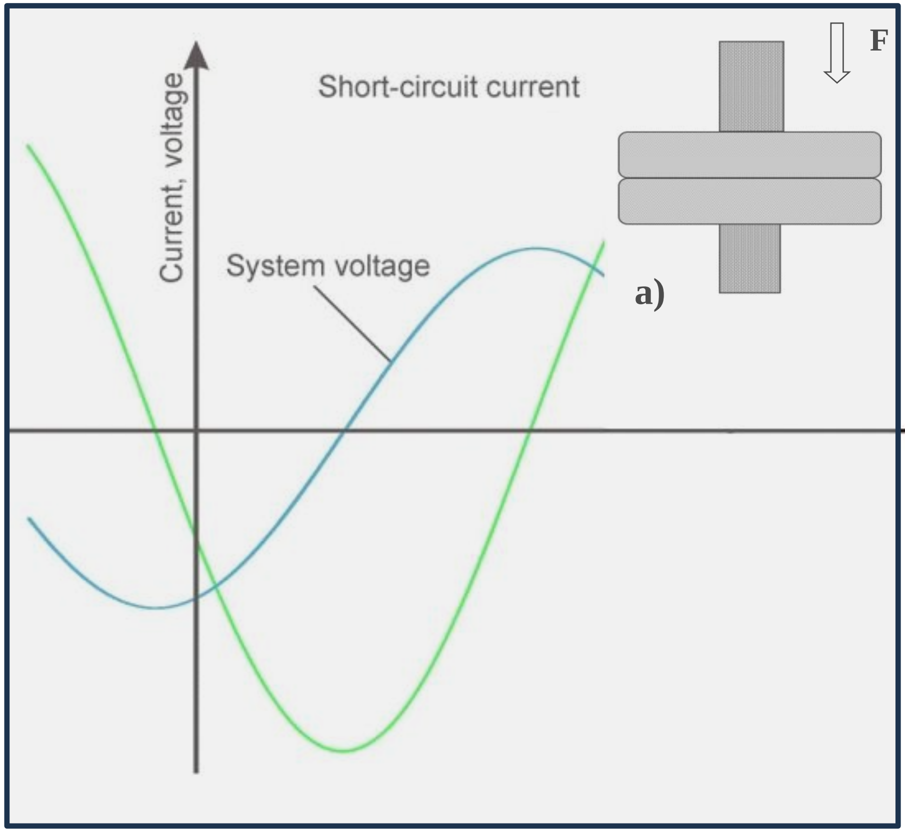
- In an axial magnetic field (AMF), multiple-cathode-spots arc spreads on the whole cathode and suppresses the contact temperature rise.

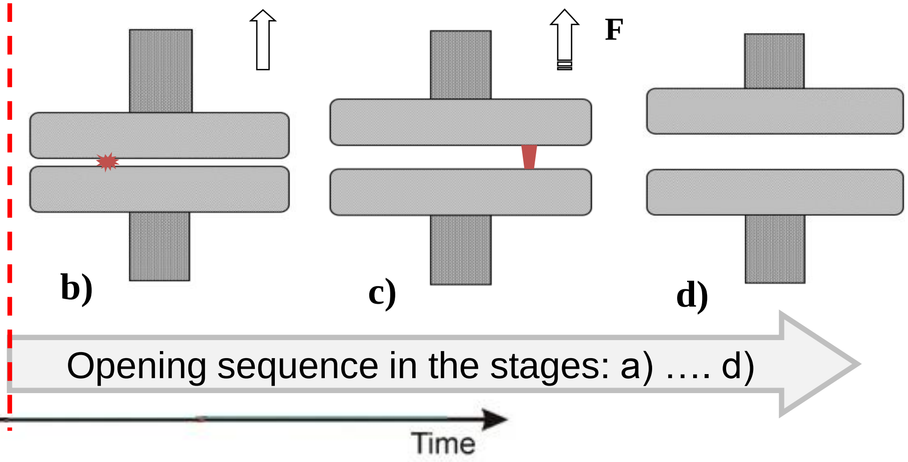
Part 2: Processes after current zero

Arcing phase determines current-zero conditions

Part 1: Vacuum arc fundamental

Part 2: Processes after CZ

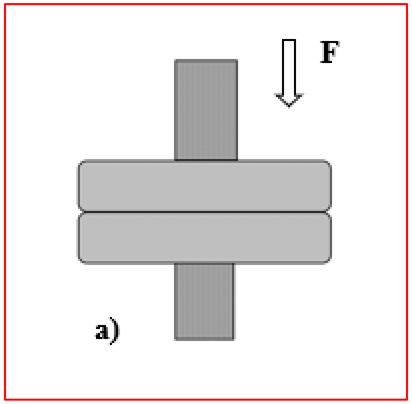




Opening sequence in the stages: a) …. d)

a) Keep contact pieces closed under contact pressure

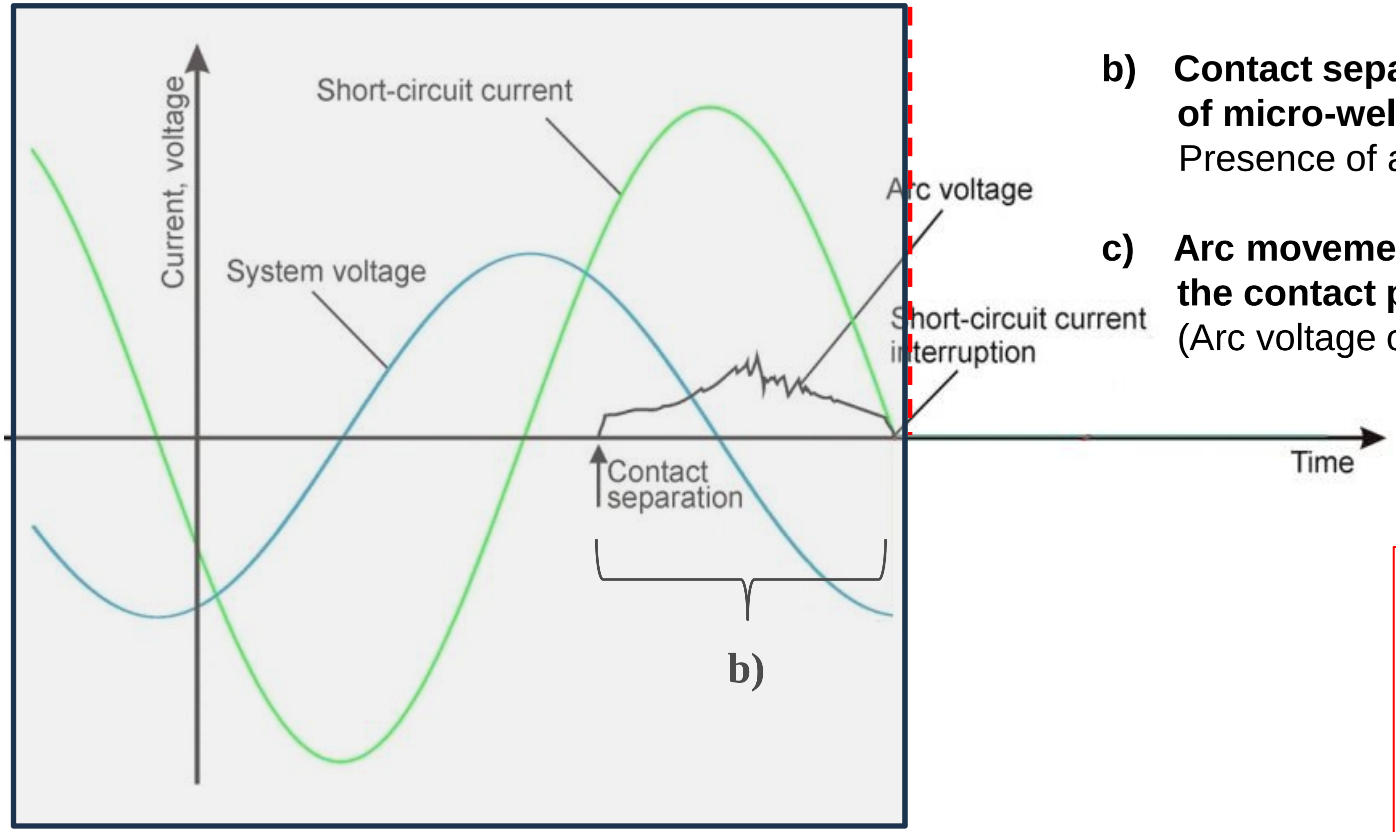
Typically, CuCr 25 ... 50% by weight as electrode material



Arcing phase determines current-zero conditions

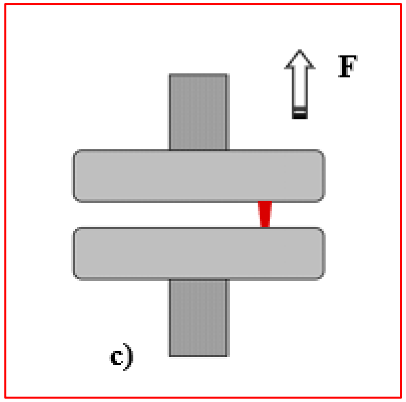
Part 1: Vacuum arc fundamental

Part 2: Processes after CZ



b) Contact separation and release of micro-welding
Presence of a concentrated arc

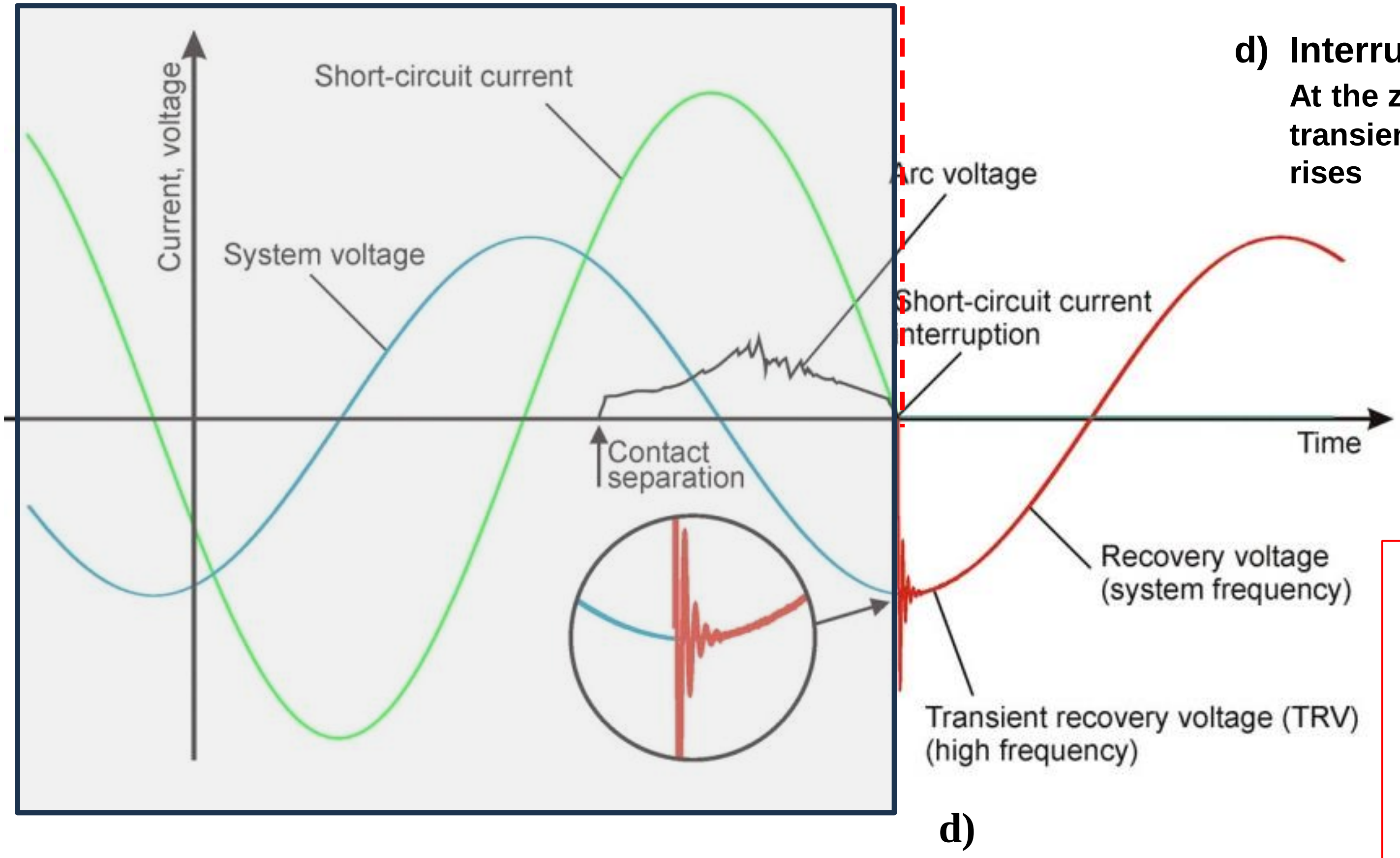
c) Arc movement in the gap between the contact pieces
(Arc voltage over the interruption section)



Arcing phase determines current-zero conditions

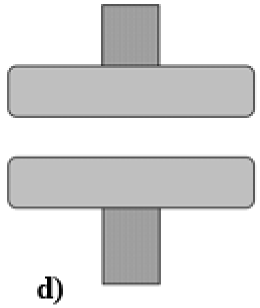
Part 1: Vacuum arc fundamental

Part 2: Processes after CZ



d) Interruption completed

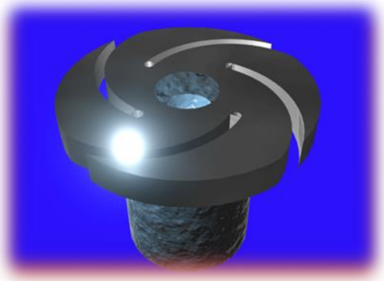
At the zero current crossing, the transient recovery voltage rises



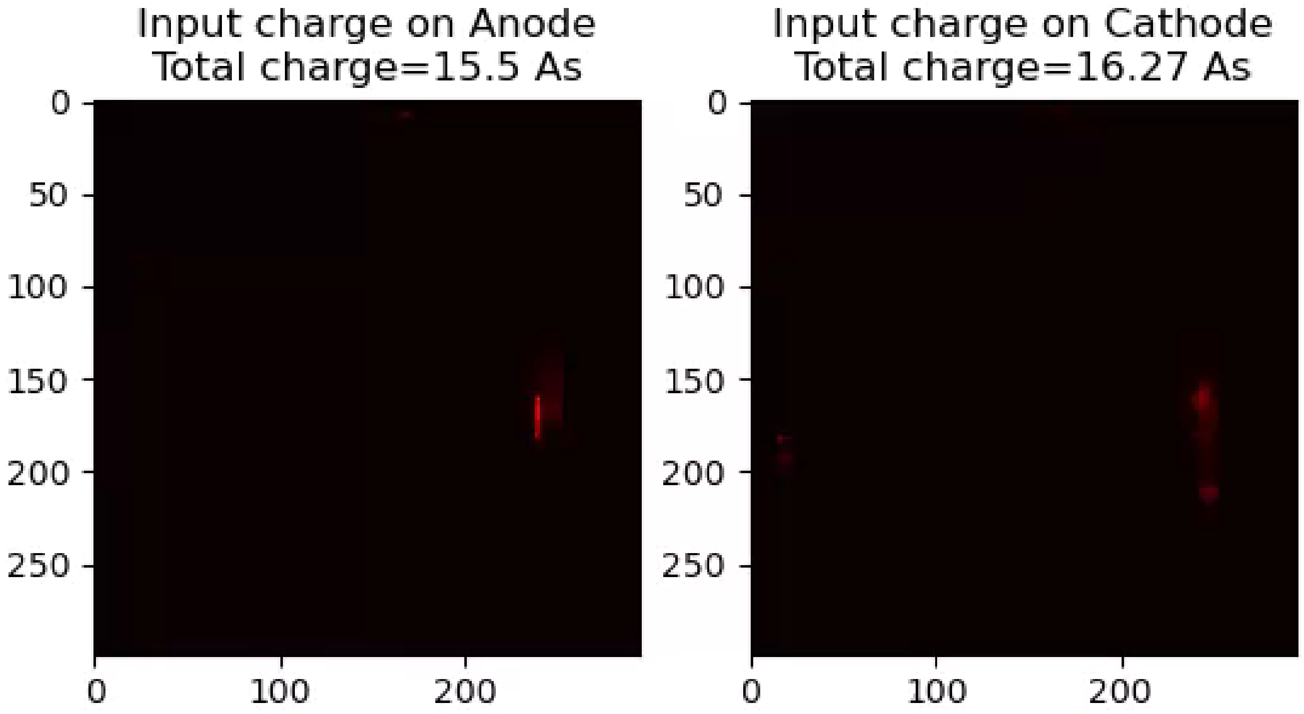
Metal vapor evaporated from hot contact surfaces after current-zero

Charge distribution over contact lifetime

Part 1: Vacuum arc fundamental



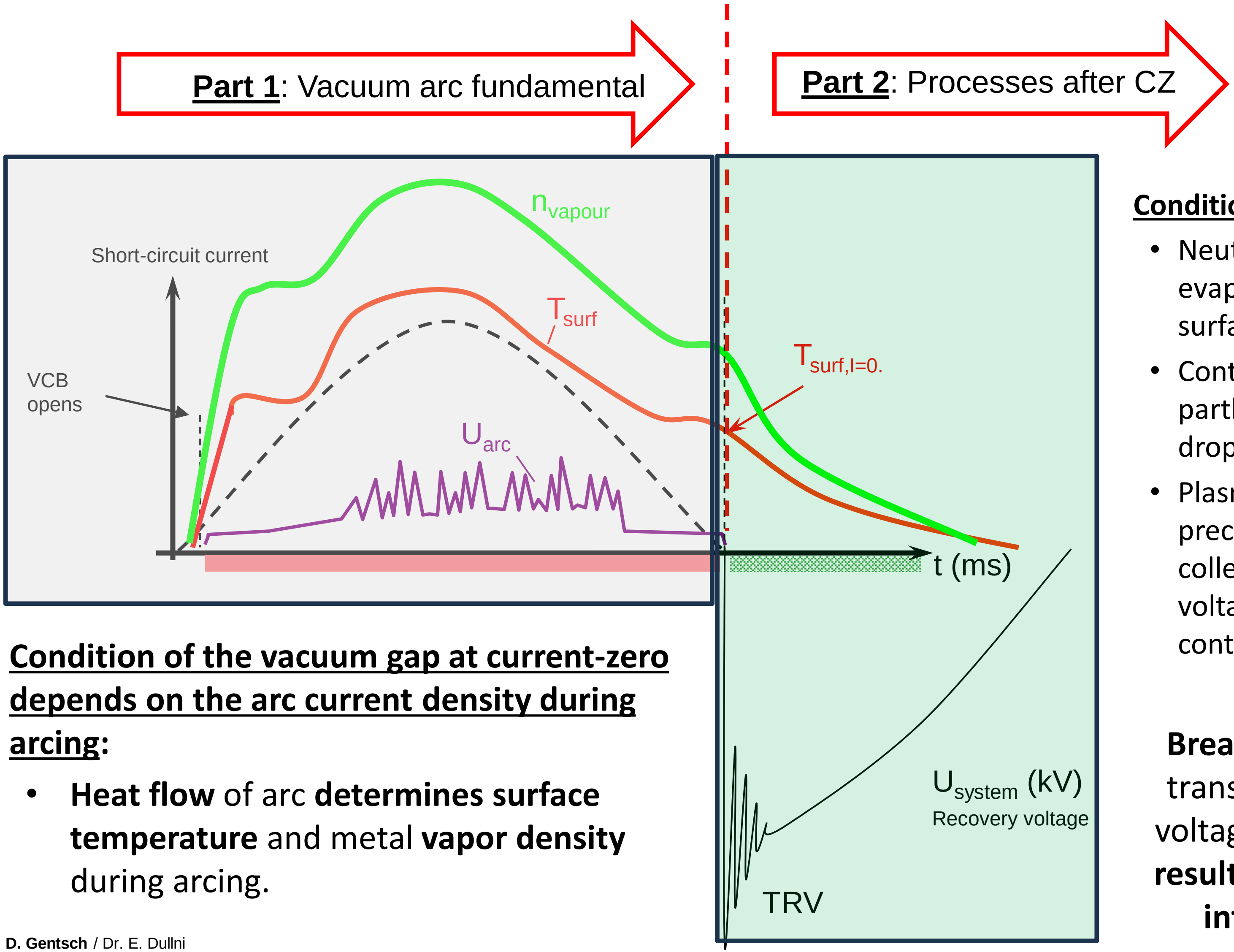
- **25mm** Contact **gap; TMF – Contact diameter: 70mm**
- **3x 2kA; 5x 20kA; 5x 25kA; 3x 31,5kA**



Summary:
Cumulative Charge

Source: B. Weber; D. Gentsch, “TMF-Contacts in Vacuum Interrupters with gaps above 20 mm”, ITG Vacuum Workshop, Germany, 09-2022

Arcing phase determines current-zero conditions



Part 1: Vacuum arc fundamental

Part 2: Processes after CZ

Condition of the vacuum gap at current-zero depends on the arc current density during arcing:

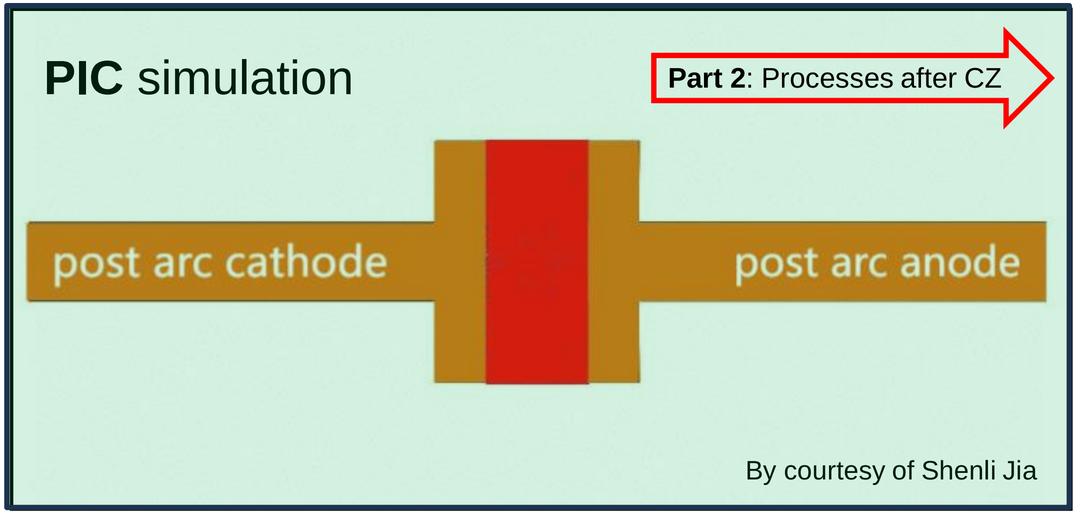
- **Heat flow** of arc **determines surface temperature** and metal **vapor density** during arcing.

Condition of gap after CZ:

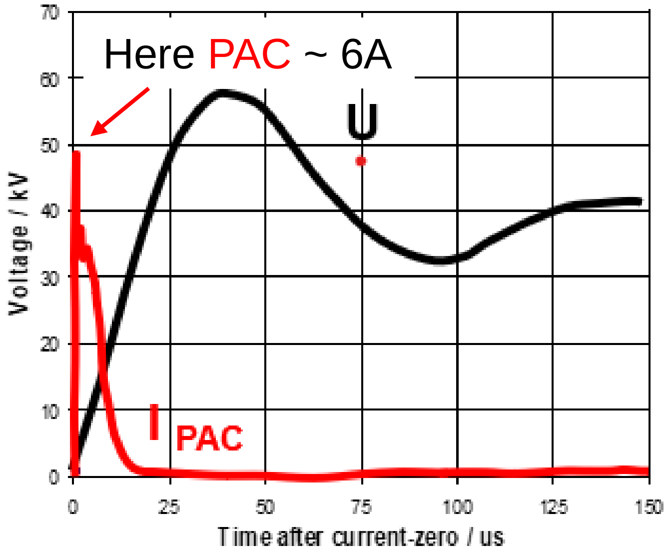
- Neutral metal vapor is evaporated from hot surfaces
- Contact surfaces are partly liquid and eject droplets.
- Plasma remains from the preceding arc and is collected under the rising voltage or recombines at contacts and walls.

Breakdown of the transient recovery voltage (TRV) **might result in a failure of interruption.**

Simulation of space charge sheath development and post-arc current (PAC)



By courtesy of Shenli Jia

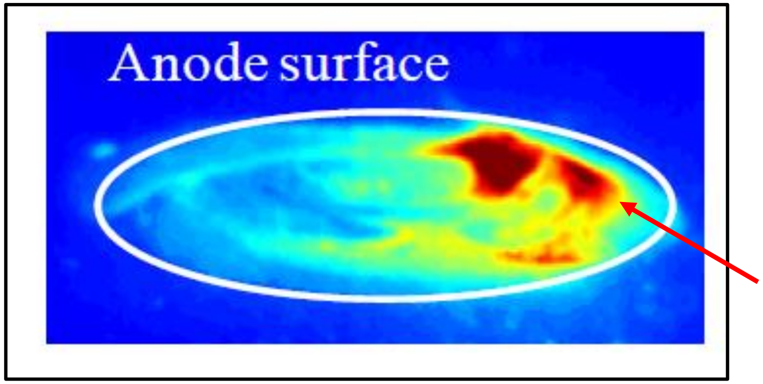


- The „**blue dots**“ represent **ions**
- The „**red area**“ depicts **neutral plasma**
- A space **charge sheath forms** in front of the high voltage cathode and attracts ions and repels electrons until the gap is empty.
- The **post-arc current** is composed of ions **impinging on the cathode**, **secondary electrons** leaving the cathode and electrons collected by the anode
- In addition, there are **ions and electrons recombining on walls**.

Summary:

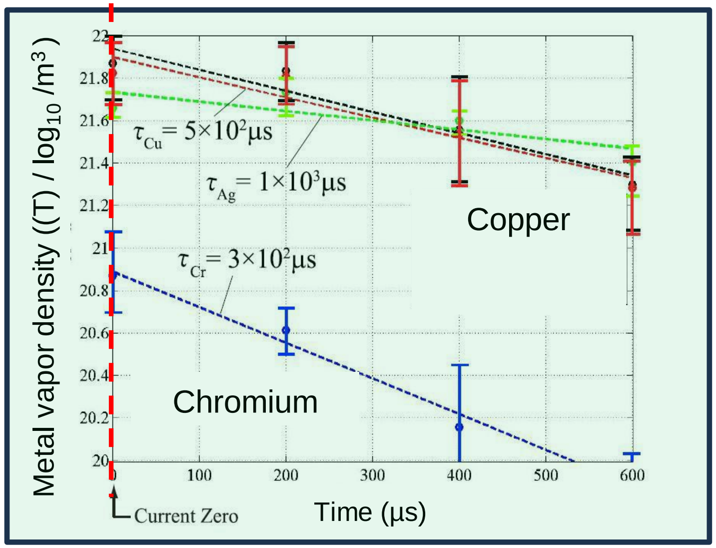
- This **collected charge** i.e. the integrated post-arc current (PAC) presents the number of charge carriers in between the contacts
- The **charge is related to the interrupted arc current** as well as to the **di/dt**.

Metal vapor evaporated from hot contact surfaces after current-zero



1800 – 2000 K

Part 2: Processes after CZ



$10^{21} – 10^{22}$ T/m^3

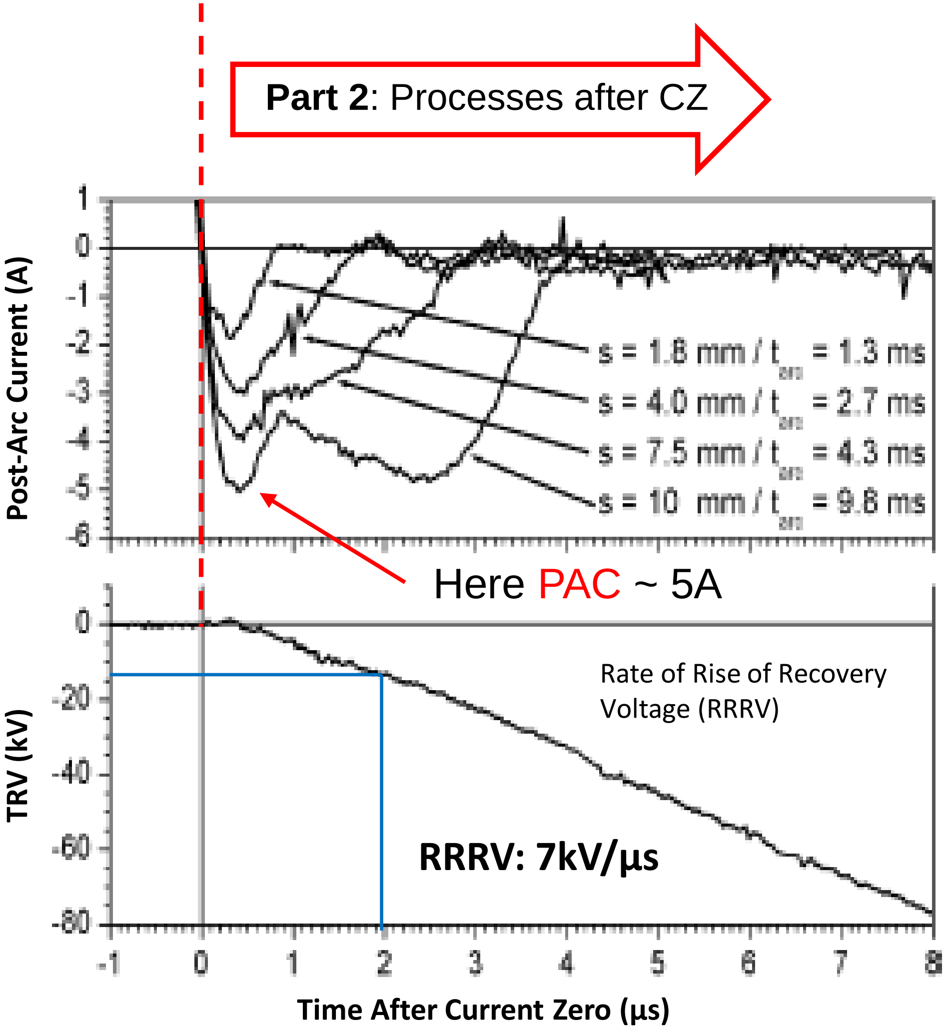
Part 2: Processes after CZ

Summary:

- **Continuum light** (acc. to Planck's law) **emitted from the hot contact surface**
- By **calibration** of the detection elements, the **surface temperature can be determined**.
- **Metal vapor densities** can then be **calculated from temperatures**.
- **Metal vapor density** can also be **measured by the light emitted** or absorbed by atoms in the gap.
- The graph shows the decay of metal vapor in the gap after CZ.

Source: T. Donen, J. Abe, M. Tsukima, Y. Takai, S. Miki, S. Ochi, 23rd ISDEIV, Suzhou, 2016
Source: Yuki Inada, et al: IEEE Trans. Plasma Sci., Vol. 48, pp. 2224-2236, 2020

Post-arc current (PAC) and plasma



Part 2: Processes after CZ

Here PAC ~ 5A

Rate of Rise of Recovery Voltage (RRRV)

RRRV: 7kV/µs

Typical PAC measured after high current arcs:

- With **different arcing times** and **contact gaps** @ 31,5kA.
- **After high current arcs**, the amount of residual plasma is much larger than after low current arcs.
- **And the residual plasma stays much longer** in the contact gap.
  - **Reason is the higher density** of **metal vapor** slowing down the ions via charge exchange and thermal collisions.

Summary:

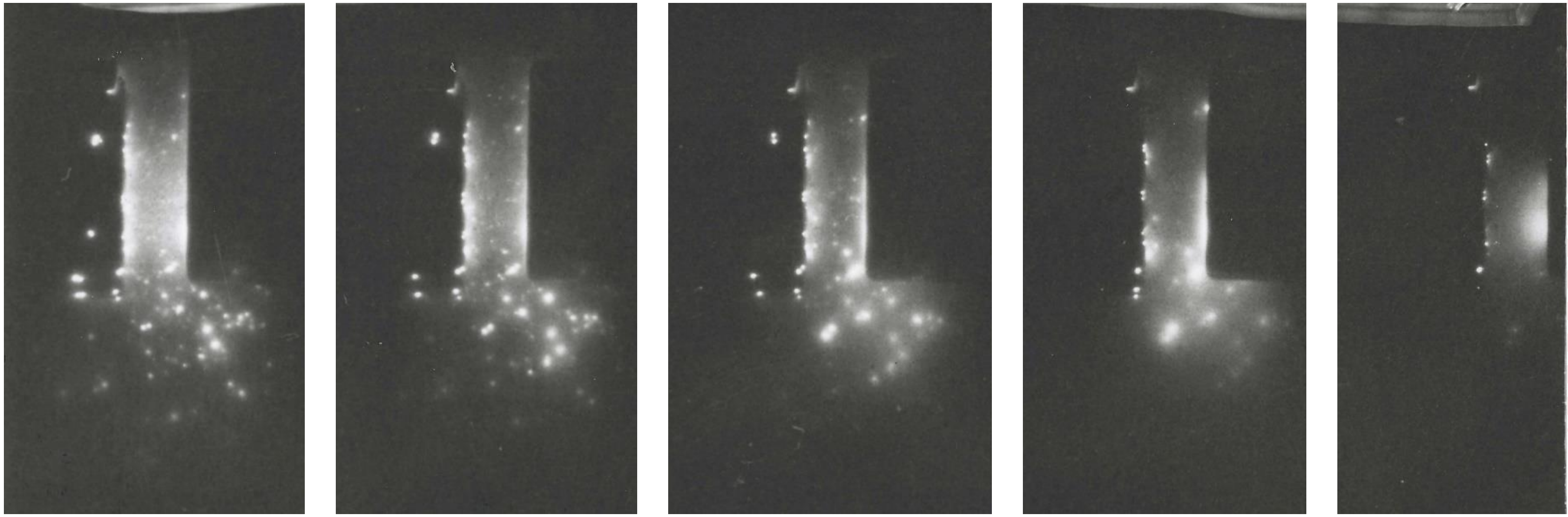
- **The presence of ions and electrons could impact the recovery behavior only for several µs up to several 10 µs after current-zero.**

Source: K. Steinke, M. Lindmayer, K-D. Weltmann, 19th ISDEIV, Xian, pp.475-480, 2000

Hot droplets ejected from contact surface during and after arcing

Part 2: Processes after CZ

Droplets before current zero (CZ)



0.9ms 0.7ms 0.5ms 0.3ms 0.1ms

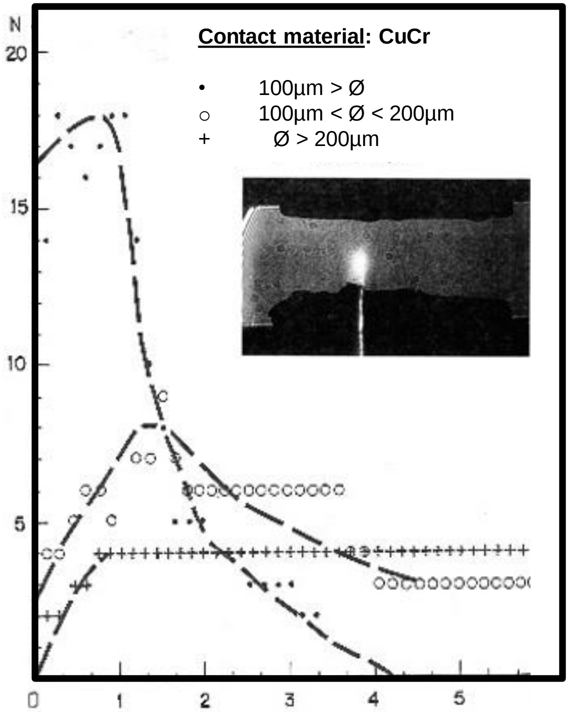
Current-zero

Summary:

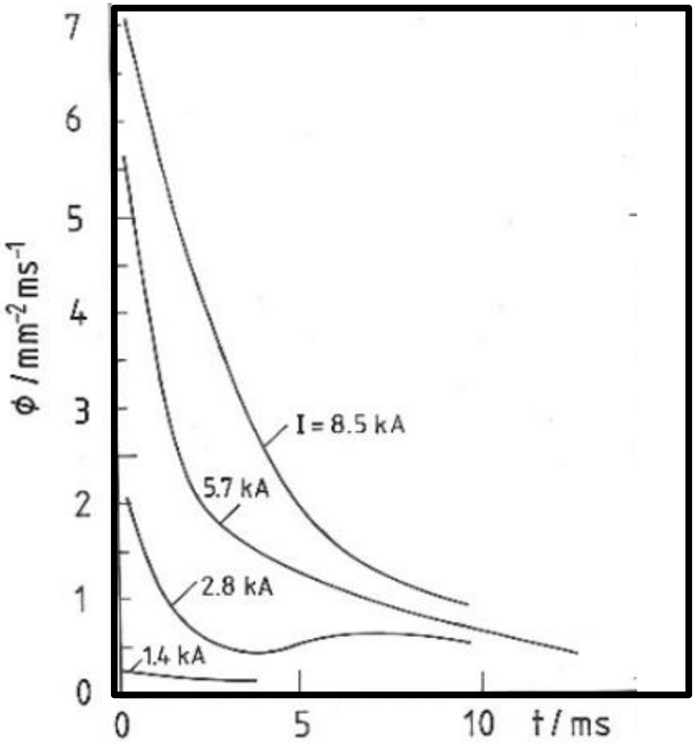
- Sequence of fast camera shots shortly before the end of a high current arc.
- Light originates from hot droplets.
  - **50Hz arc,** current with **8.8kA$_{(rms)}$** on butt-type **Cu – contacts**.
- Vacuum arc ejects numerous droplets at all sizes.

By courtesy of E. Dullni

Droplet density measured after current zero



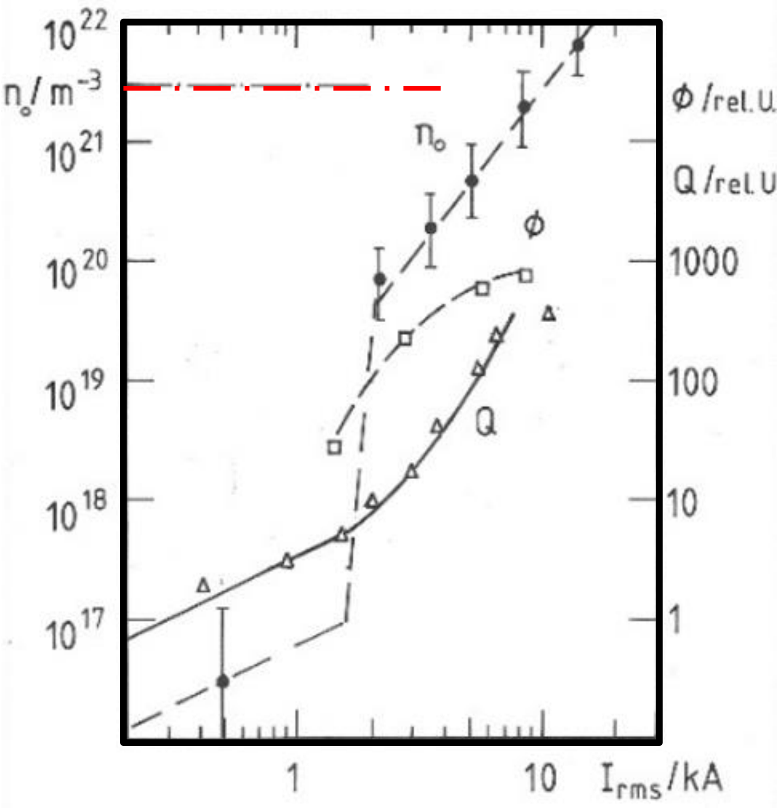
Number of large droplets (**> 50 µm**)
versus time after CZ of a 12.5 kA arc
“**Determined from Laser Shadowgraphs**”



Flux density of small droplets (**< 10 µm**)
versus time after CZ for different 50 Hz-currents
“**Determined by laser Mie-scattering**”

Source: B. Gellert, E. Schade, “Optical investigations of droplet emission in vacuum interrupters to improve contact material”, 14th ISDEIV, Santa Fe, 1990, pp 450-454

Condition of vacuum gap at current-zero as function of short-circuit current



I $_{(rms)}$ of 50 Hz current

Model experiment with butt-type CuCr contacts of 32 mm diameter:

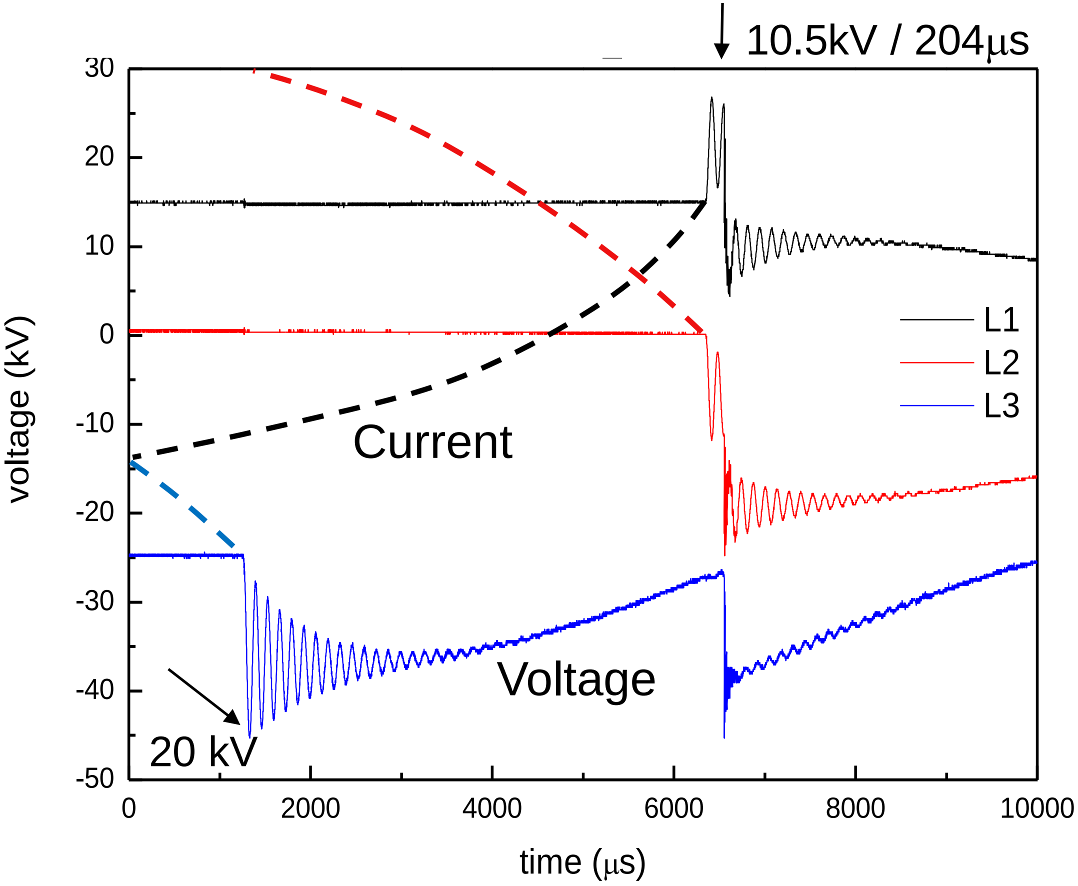
- **Metal vapor density n_0** estimated from maximum surface temperature
- Flux density of **small droplets Φ**
- Integral of **post-arc current Q**

Summary:

- **Interruption limit is indicated as horizontal dashed line and equals a metal vapor density n_0 of approx. 5 x 10^{21} /m^3.**

Source: E. Schade, E. Dullni, “Recovery of breakdown strength of a vacuum interrupter after extinction of high currents”, IEEE TDEI, Vol. 9, 2002, pp 207 – 215

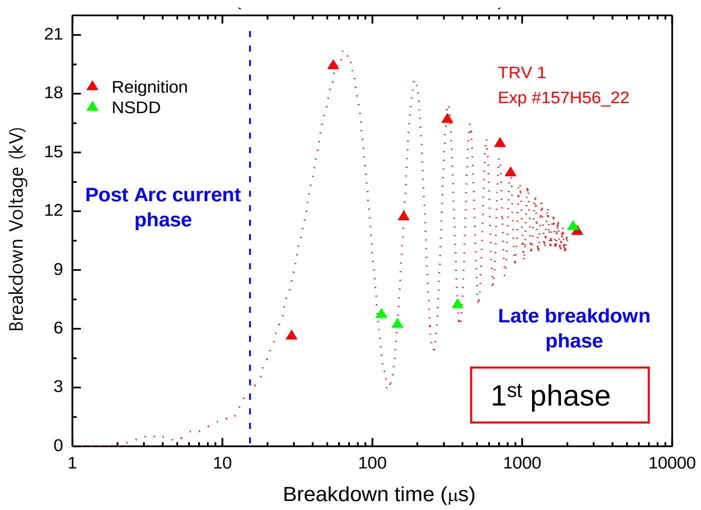
Voltage breakdown after current-zero

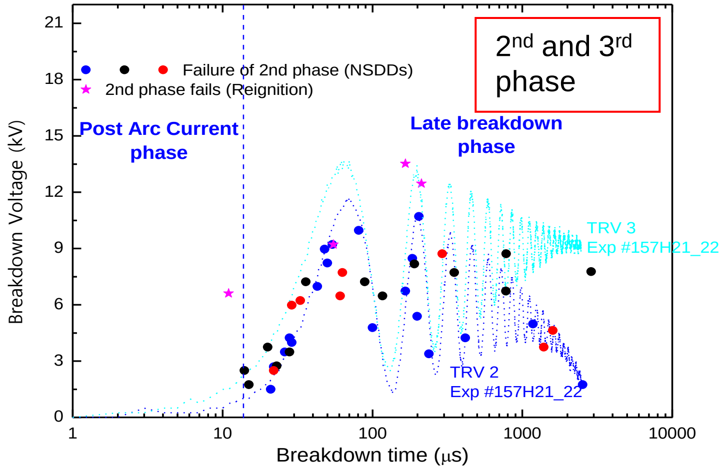


Example of a 3-phase current interruption with voltage breakdown during recovery:

- **L1 breaks down** at a voltage difference of 10.5 kV in the second peak of the recovery voltage
- **L2 and L3 interrupt successfully** and withstand a TRV peak of even 20 kV
- **Voltage escalation is caused by a voltage jump** of the neutral point.

Distribution of breakdown voltage and delay in the interrupting phases





Evaluation of breakdown voltage and delay after CZ from short-circuit interruption tests of many circuit breakers of the same current rating:

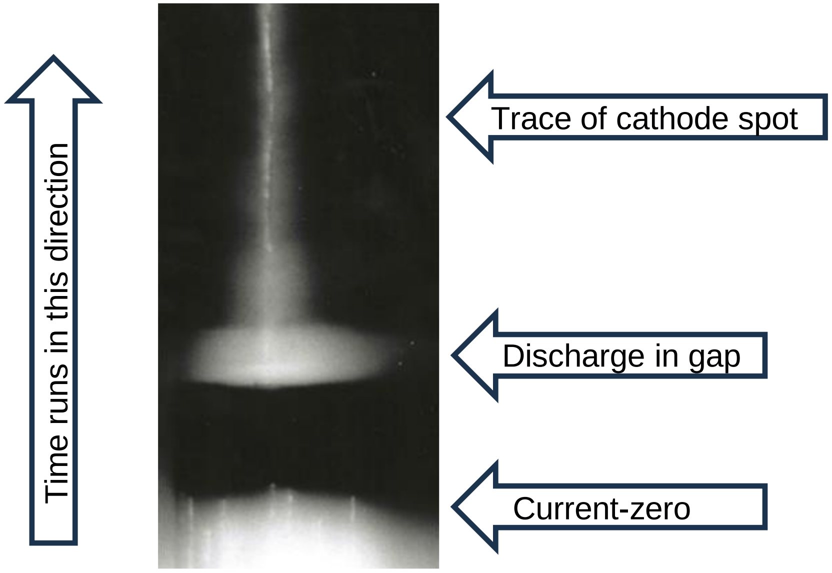
- – Dashed curve is the TRV in logarithmic time scale
- – Breakdowns are rare events, therefore numerous tests were evaluated
- – Every breakdown was considered

- **20 - 50% of breakdowns** occurred **before the first peak** of the recovery voltage.
- **50 - 80%** of breakdowns occurred **after the peak** and are late breakdowns.

Summary:

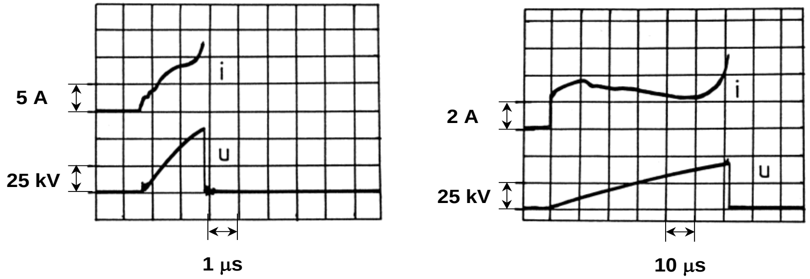
- **Breakdowns in vacuum interrupters after high current interruption are typically delayed by 20µs up to 1ms and occur with wide spread of breakdown voltage.**

Breakdown after interruption of currents beyond rated values ($I_{(rms)} > 3\, I_{(sc)}$)

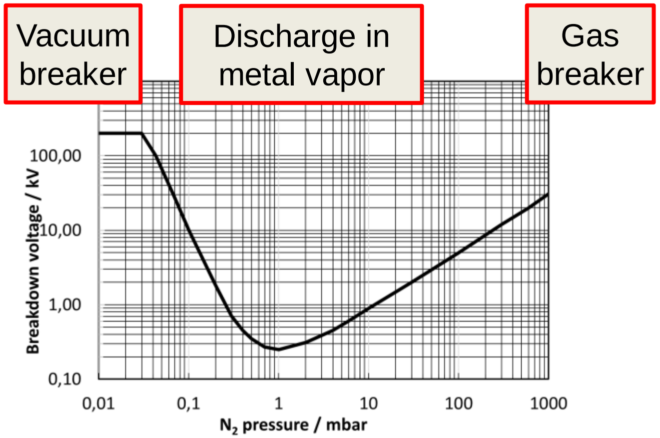


Model experiment with butt-type CuCr contacts of 32 mm diameter:

- Breakdowns occurred up to 400 µs after CZ with 100 % probability.
- In 50 to 80 % of all breakdowns, an exponential rise of the post-arc current was visible before final current rise.
- Breakdowns happened during the presence of plasma.



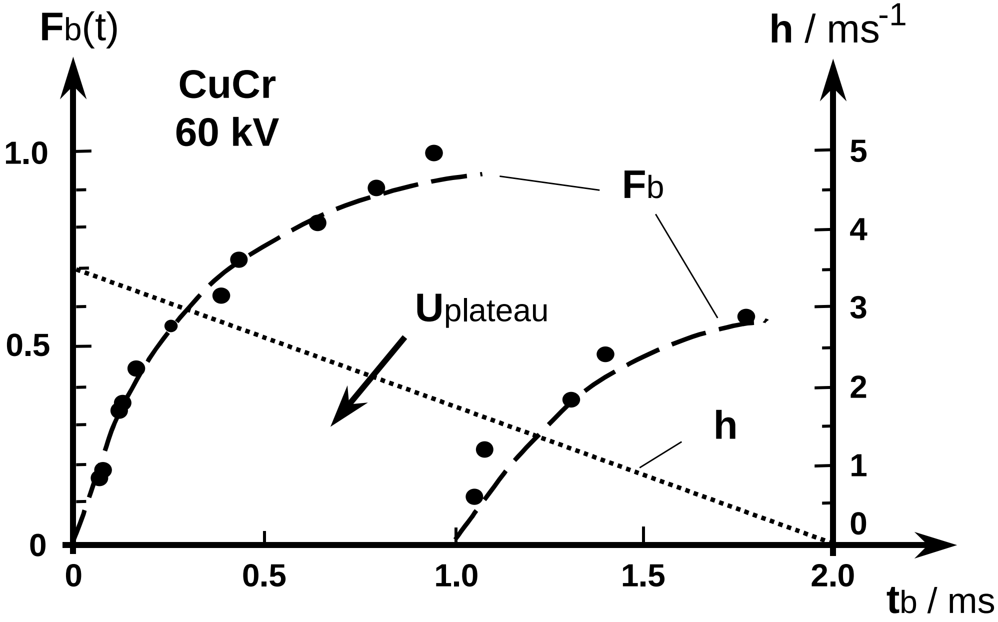
- **Metal vapor is present at current-zero** with a density of > 10^{22} /m^3 or 0.7 hPa
- An electron avalanche develops similar to that occurring on the left branch of the Paschen curve.



Paschen curve

Source: E. Schade, E. Dullni, IEEE TDEI, Vol. 9, 2002, pp 207 – 215

Breakdown after interruption of currents at the interruption limit ($I_{(rms)} > 1.5\ I_{(sc)}$)



Parameter:

- 50Hz current with $13.4kA_{(rms)}$ on butt-type CuCr contacts
- Fast HV pulses were applied with a **slope of 2kV/µs directly at current-zero** or with a **delay time of 1ms**

Figure shows the cumulative probability F_b of breakdown versus breakdown time t_b with probability < 100 %:

- **All breakdowns occur spontaneously** without any pre-current with delays of up to 2ms after CZ.
- **A linearly decreasing breakdown rate h** matches the breakdown rate and probability.

Source: E. Schade, E. Dullni, IEEE TDEI, Vol. 9, 2002, pp 207 – 215

Probability of breakdown at currents below the interruption limit ($I_{rms} = I_{sc}$) under diff. conditions

Contact type	50Hz current kA $_{(rms)}$	Voltage kV $_{(peak)}$	Opening speed $_{(m/s)}$	Breakdown probability	Mean / Max thermionic current /mA	Number of attempts
butt	**13.4**	60	2.3	100 %	12.2 / 17	11
butt	**13.4**	40	2.3	44 %	9.1 / 16	9
butt	**8.5**	40	2.3	0 %	3.6 / 5.4	8
spiral	14	30	**1.0**	**60 %**	5.3 / 9.4	10
spiral	14	40	**3.0**	**2.6 %**	2.3	37

The “bright” yellow column shows measured thermionic currents extrapolated to CZ being a measure of the surface temperature at CZ.

Breakdown (BD) probability decreases with lower applied voltages e.g. 44% at 40 kV:

- **BD probability** becomes **0 % below 8.5 kA** arcing current.
- **For spiral-type contacts**, BD probability becomes low (2.6%) only if the arc rotates on the contact i.e. at high opening speeds (**3m/s v. 1m/s**)

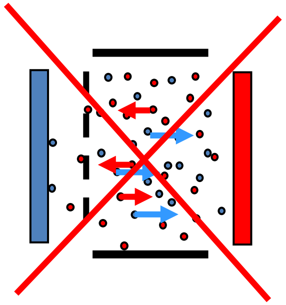
Summary:

- The **contact temperature remaining** at current-zero is the decisive parameter for successful interruptions.

Source of upper table: E. Dullni, “High current interruption of vacuum interrupters and voltage breakdown during recovery”, 30th ISDEIV, Naha, 2023

Root cause for failed interruptions of currents at or below the interruption limit

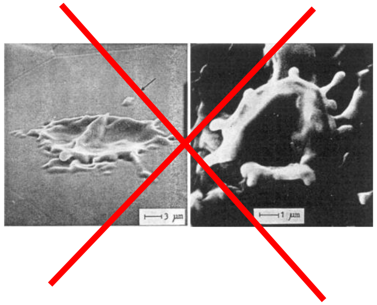
What causes can be excluded?



- A discharge in metal vapor is not feasible since the metal vapor density in the gap is too small

  (less than 3×10^{21} /m^3 or 0,1 mbar).

- The post-arc plasma does not play a role since all breakdowns happen after the plasma has vanished.



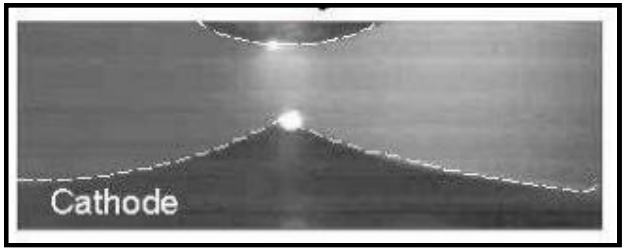
- Small droplets with a diameter < 10 µm are present in high numbers. They are not able to initiate breakdown since they are ejected from cathode spots even at low current arcs with no breakdown.

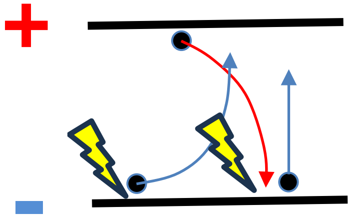
- Field emitting protrusions on the solid surface are not likely since contacts get a smooth surface appearance after high current arcs and are known to exhibit reduced field emission currents.

Root cause for failed interruptions of currents at or below the interruption limit

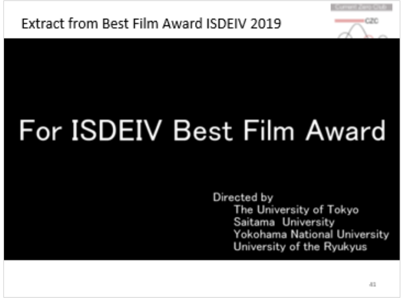
What causes are likely?

- The surface stays liquid for several ms after current-zero and might cause breakdown via the occurrence of the so-called Rayleigh Taylor instability of the liquid excited by the electric field.
  An instability of the liquid surface is feasible e.g. for pure Cu contacts at voltages above 8 kV/mm.





Film provided by Yuki Inada:
Best film Award ISDEIV 2018


Extract from Best Film Award ISDEIV 2019

For ISDEIV Best Film Award

Directed by
The University of Tokyo
Saitama University
Yokohama National University
University of the Ryukyus

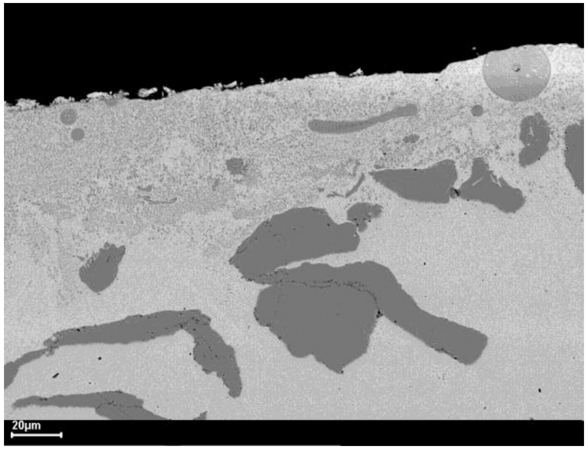
- Large droplets are present even late after CZ. Droplets with diameter > 20 µm might trigger breakdown when approaching or leaving the high voltage cathode.

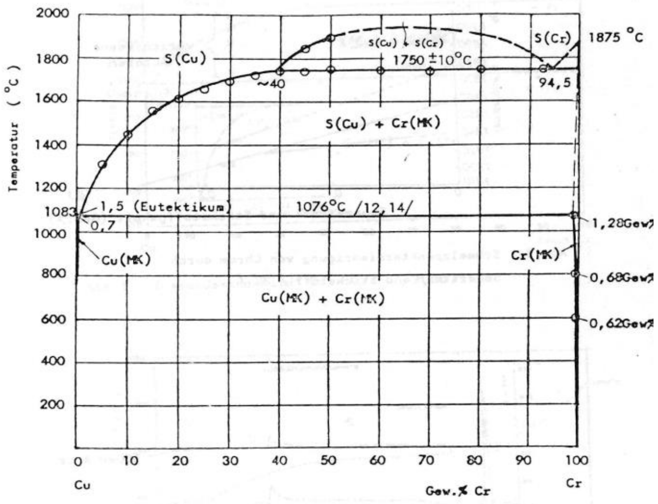
Extract from Best Film Award ISDEIV 2019

For ISDEIV Best Film Award

Directed by
The University of Tokyo
Saitama University
Yokohama National University
University of the Ryukyus

Role of a liquid surface in the initiation of breakdown





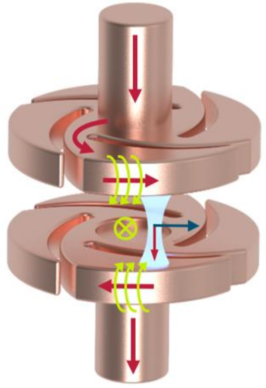
For the 2-component sintered material CuCr, the liquidus temperature varies with the concentration of Cr and Cu:

- The melting temperature of **pure Cr is 2133** K.
- For a concentration of **75/25, both Cu and Cr** are **molten** above a temperature of **1900 K**.
- **Below 1900 K, Cr solidifies into small solid grains**, at 1360 K also Copper solidifies.

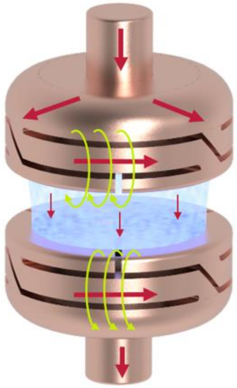
- Parts of the contact surfaces **remain liquid for several milliseconds after current zero (CZ)** in dependence of the interrupted arc current.
- Solid Cr-grains will play a role.

Source: R. Müller "Arc-melted CuCr Allloys as contact material for vacuum interrupters", Siemens Forschungsberichte Bd. 17, 105, 1988

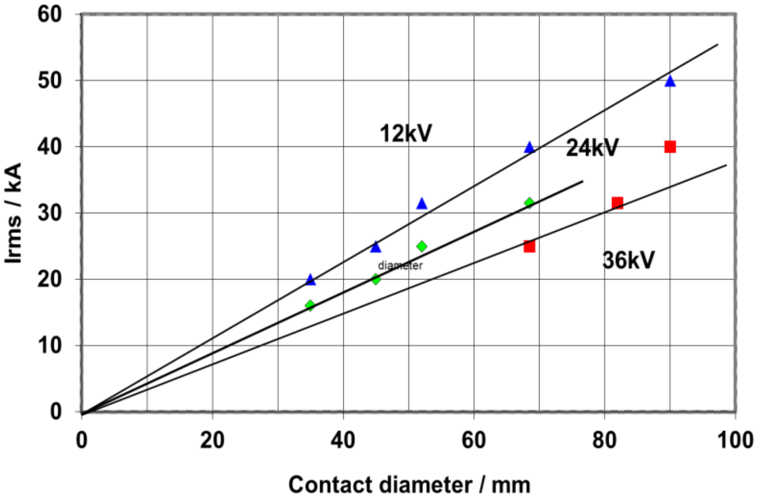
What is required for successful interruptions at rated short-circuit currents?



Transverse magnetic field contact



Axial magnetic field contact



Summary:

The contact temperature should drop below 1900 K at current-zero so that metal vapor density is low and part of the contact material is solidified (Cr-grains):

  - However, neutral metal vapor emitted from hot surfaces is not likely causing breakdown, unless too high currents are accidentally applied.

- **Voltage breakdown of the TRV can be caused by**:
  - Hot droplets hitting the contacts esp. the cathode.
  - Instabilities of the liquid surface.

  Successful interruptions are ensured by
  - selecting the right contact material and diameter,
  - utilizing TMF or AMF contacts

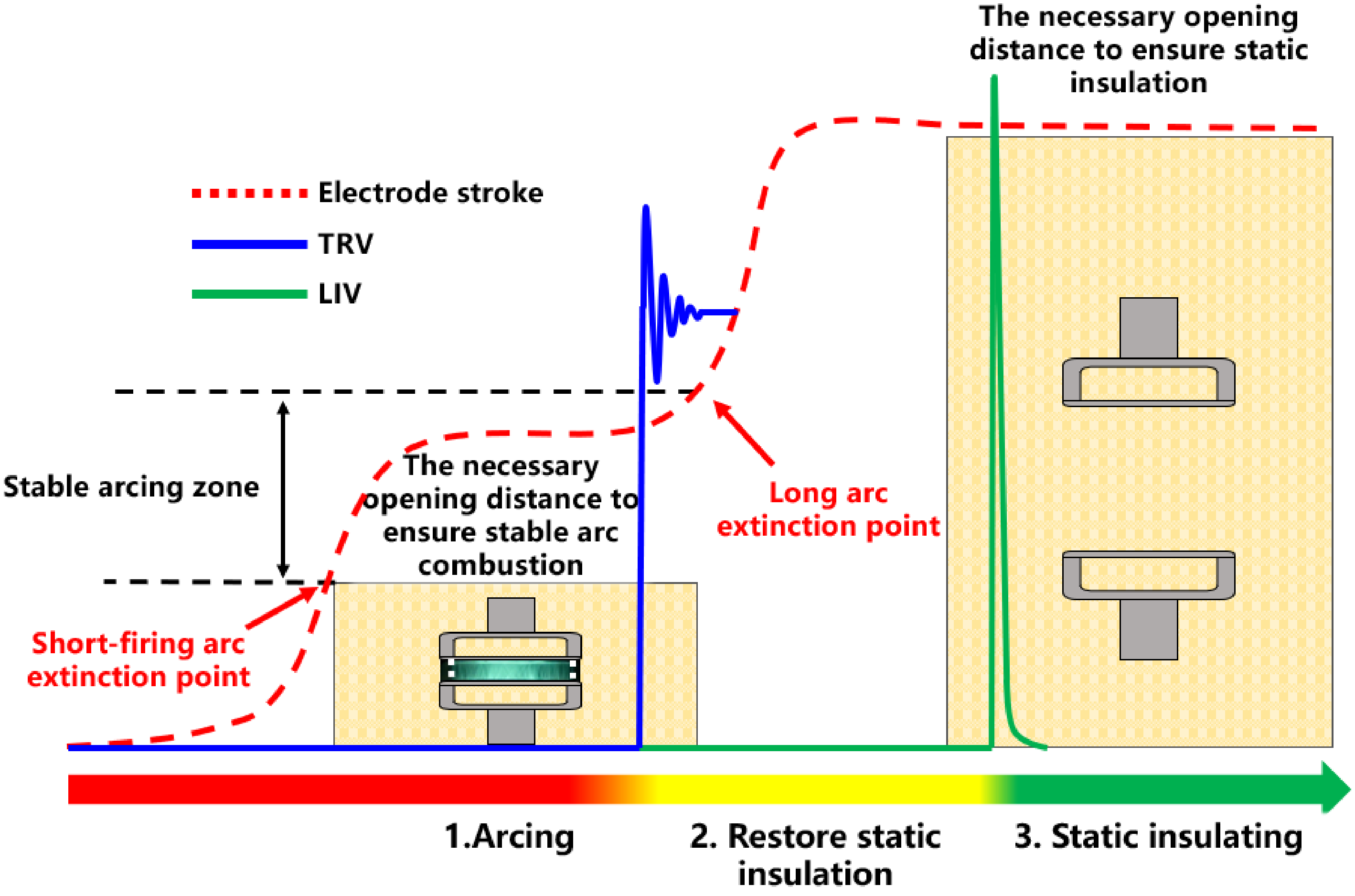
- **At higher voltages, breakdown probability increases** and has to be compensated by an increasing contact gap.

Source: D. Gentsch, "Leistungsschalter – Vakuumschaltkammern – Polteile – Lichtbogenschutz: UFES"; Schalterseminar – Aachen Colloquium, June 2024

Part 3: Extension of Vacuum Interrupter to Higher Voltages

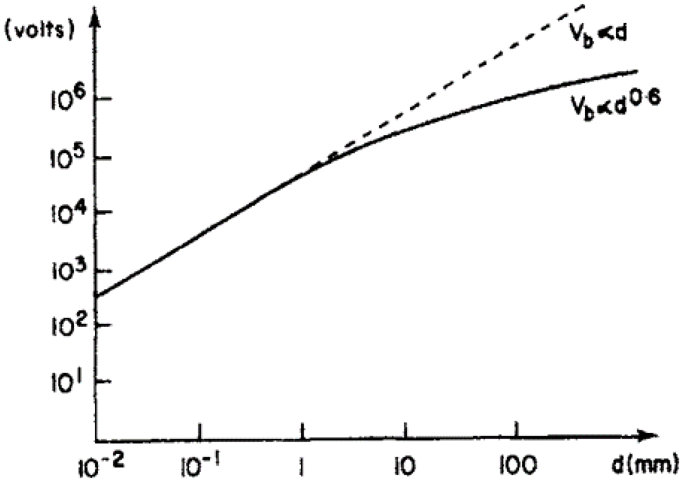
Current interruption at higher rated voltages

Higher rated voltage requires higher contact gap distance.

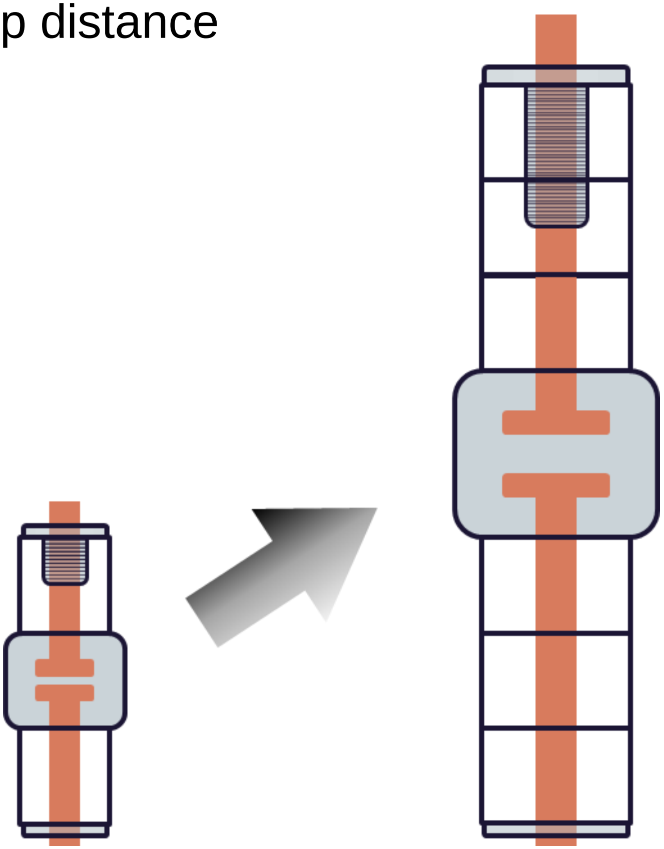


Vacuum Insulation for High Voltage Vacuum Interrupters

Non-linear Curve of Vacuum Insulation at higher gap distance



Illustrating how the breakdown voltage V_b of a plane parallel high voltage gap typically depends on the electrode separation d.



Rod Latham, High Voltage Vacuum Insulation: Basic concepts and technological practice, Academic Press, 1995

High voltage vacuum interrupter designs
Dielectric aspects

Envelope dimensions of vacuum interrupter mainly driven by …

- length → external insulation
- diameter → inner insulation

Additionally, contact gap influences …

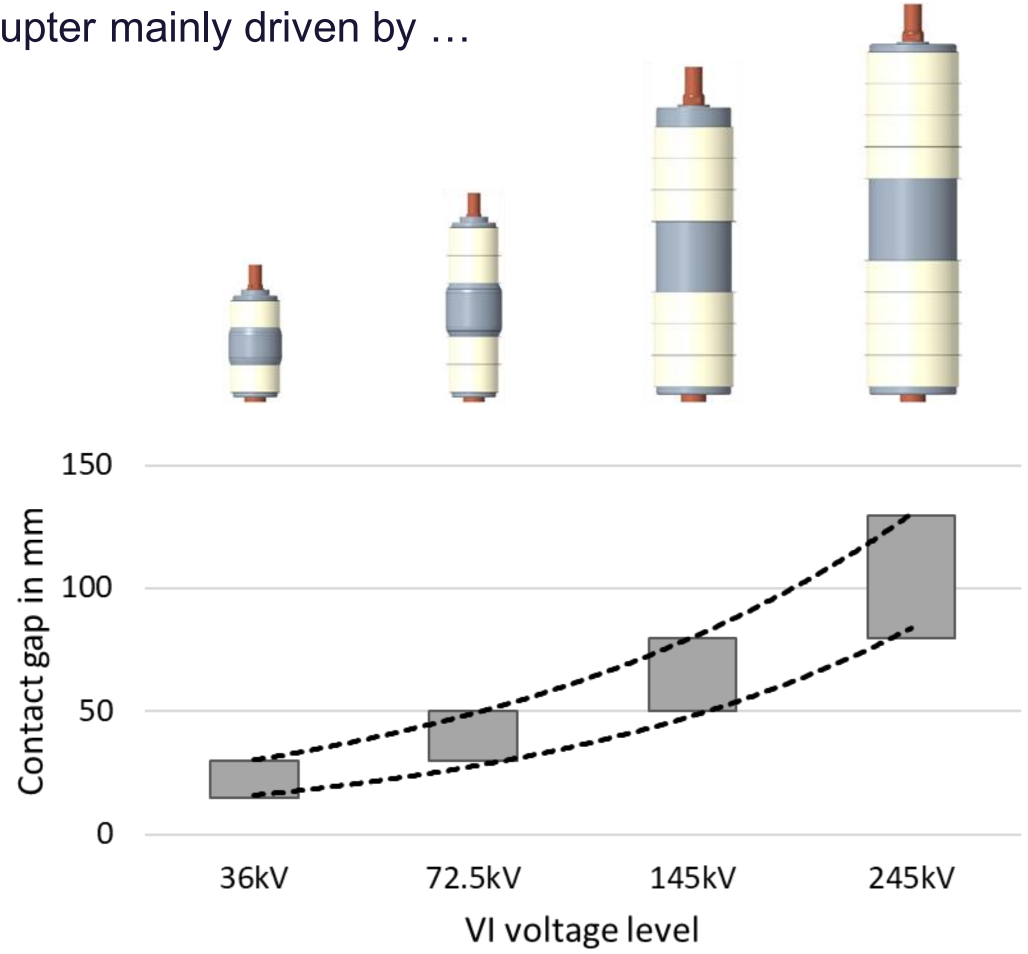
- length
- diameter

Medium to high voltage

→ Increase gaps
length, diameters, distances

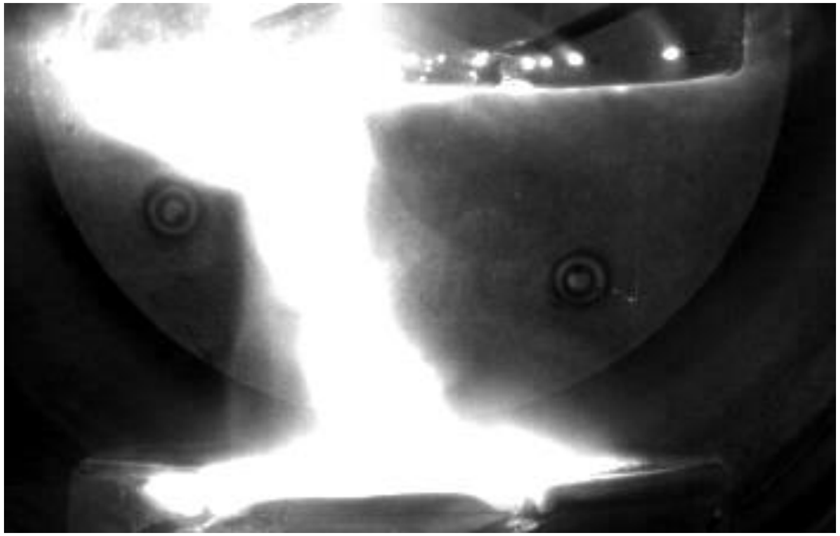
→ Dielectric adaptation
typically, larger radii, e.g., metal vapor condensation shields and voltage grading shields

→ Stacking of insulators,
e.g., multi-ceramic VI



Plasma control for large contact gaps
High power aspects

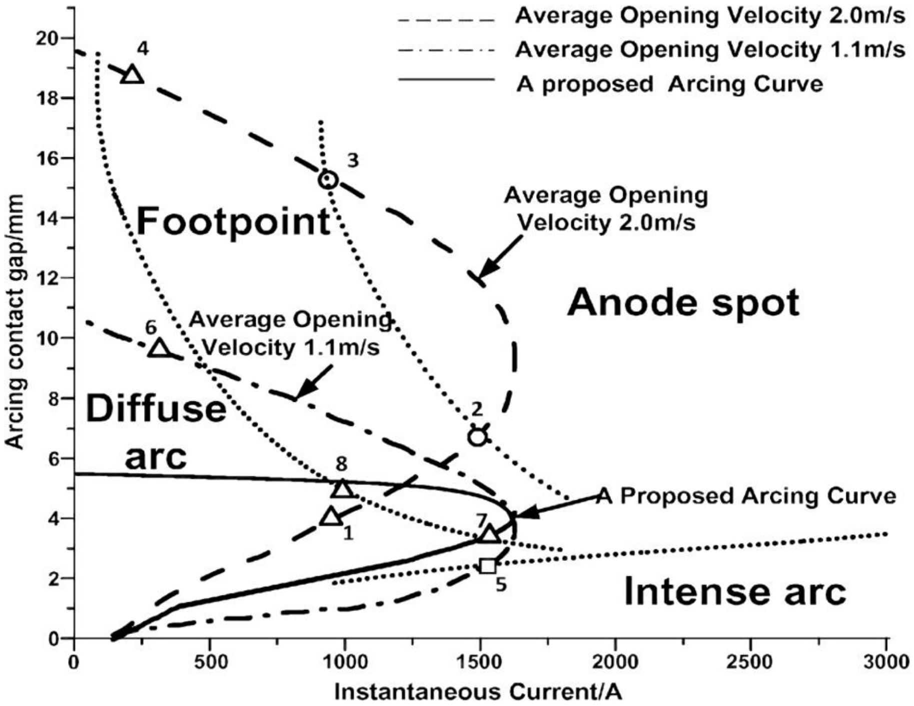
Diffuse Arc
Sufficient plasma control
(strong AMF)



Constricted Arc
Insufficient plasma control
(weak AMF)

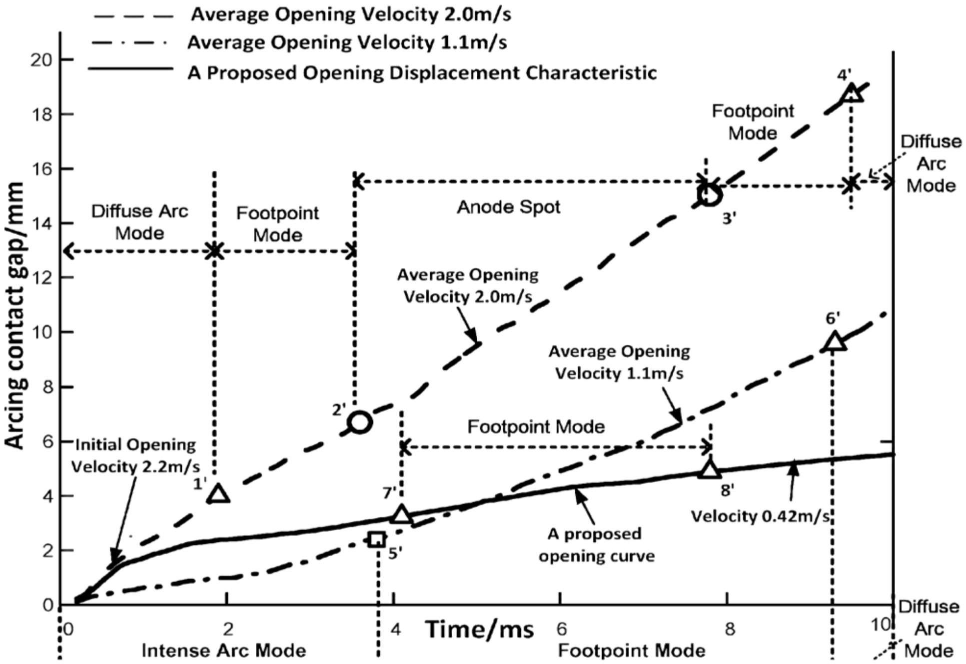
Gap control for large contact gaps High power aspects

To keep the arc diffuse in a large contact gap …



Arcing curve

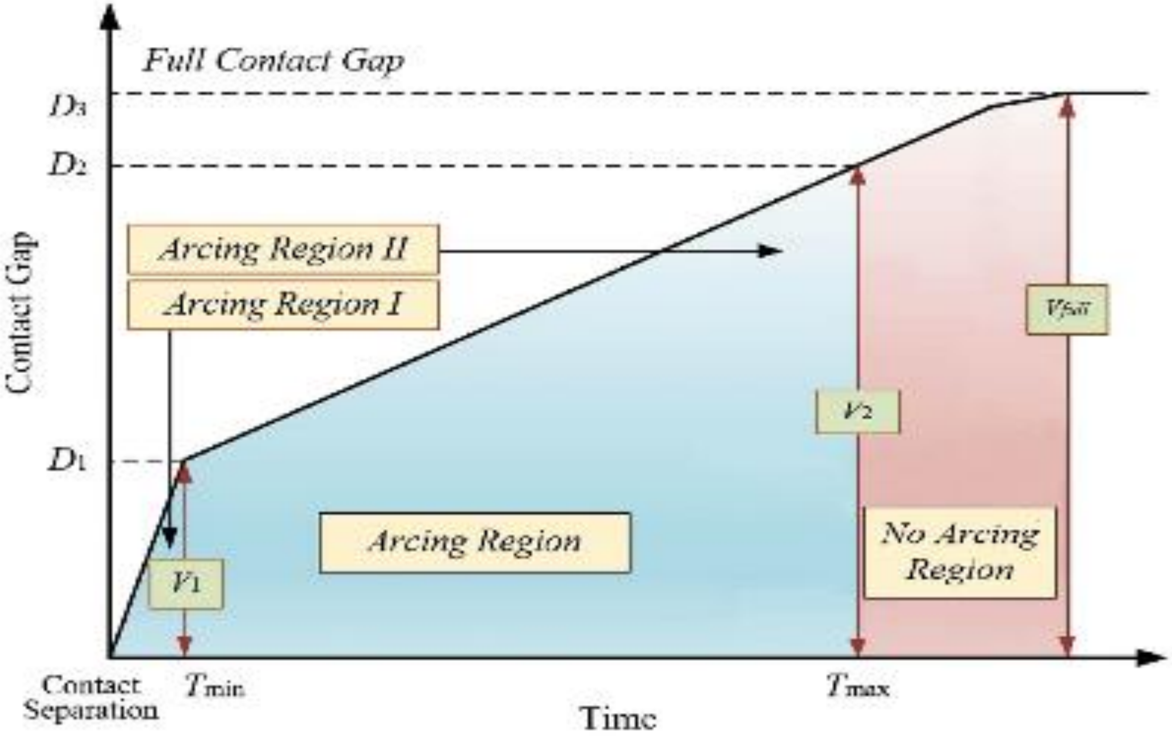
Displacement curve



source: Liqiong Sun, Li Yu, Zhiyuan Liu, Jianhua Wang and Yingsan Geng. An Opening Displacement Curve Characteristic Determined by High-Current Anode Phenomena of a Vacuum Interrupter, IEEE Trans. Power Delivery, Vol. 28, 2013, pp 2585-2593

Gap control for large contact gaps High power aspects

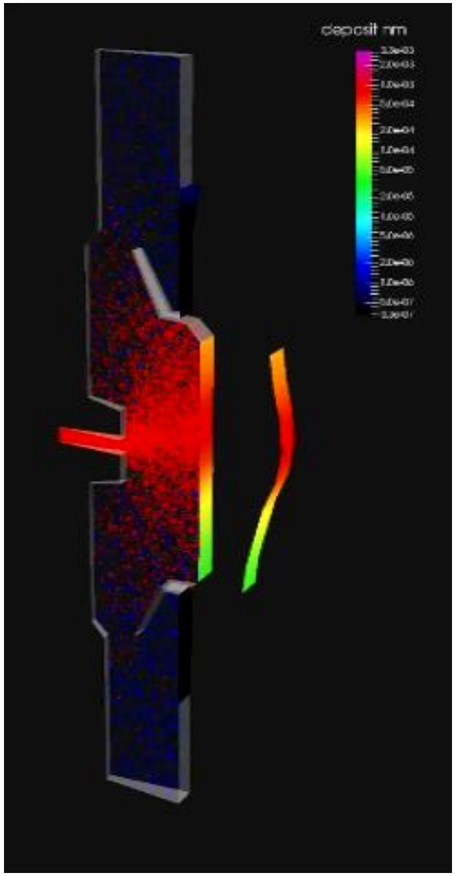
Proposal for displacement curve in higher voltages VCB

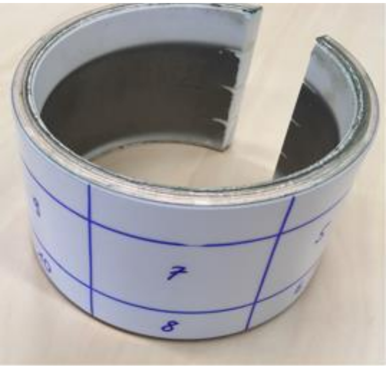


Z. Liu et al., “Switching Arc Phenomena in Transmission Voltage Level Vacuum Circuit Breakers”, 2021

Metal vapor deposition control on the ceramic insulation as aspect for the dielectric

- During switching operation, part of the metal vapor may condense on the ceramic

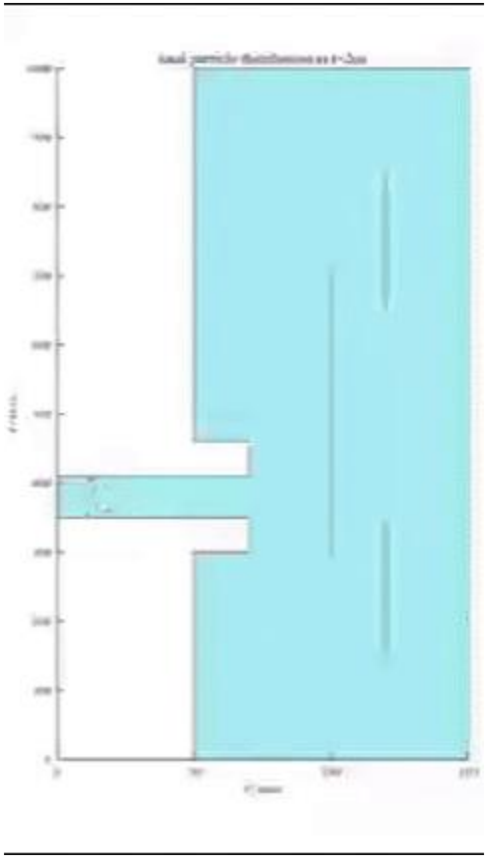




A. Geisler et al., “Impact of the Metal Evaporation Rate in Vacuum Interrupters on Vapor Expansion and Deposition”, XXIII Symposium on Physics of Switching Arc, 2019

Particle deposition on the ceramic surface

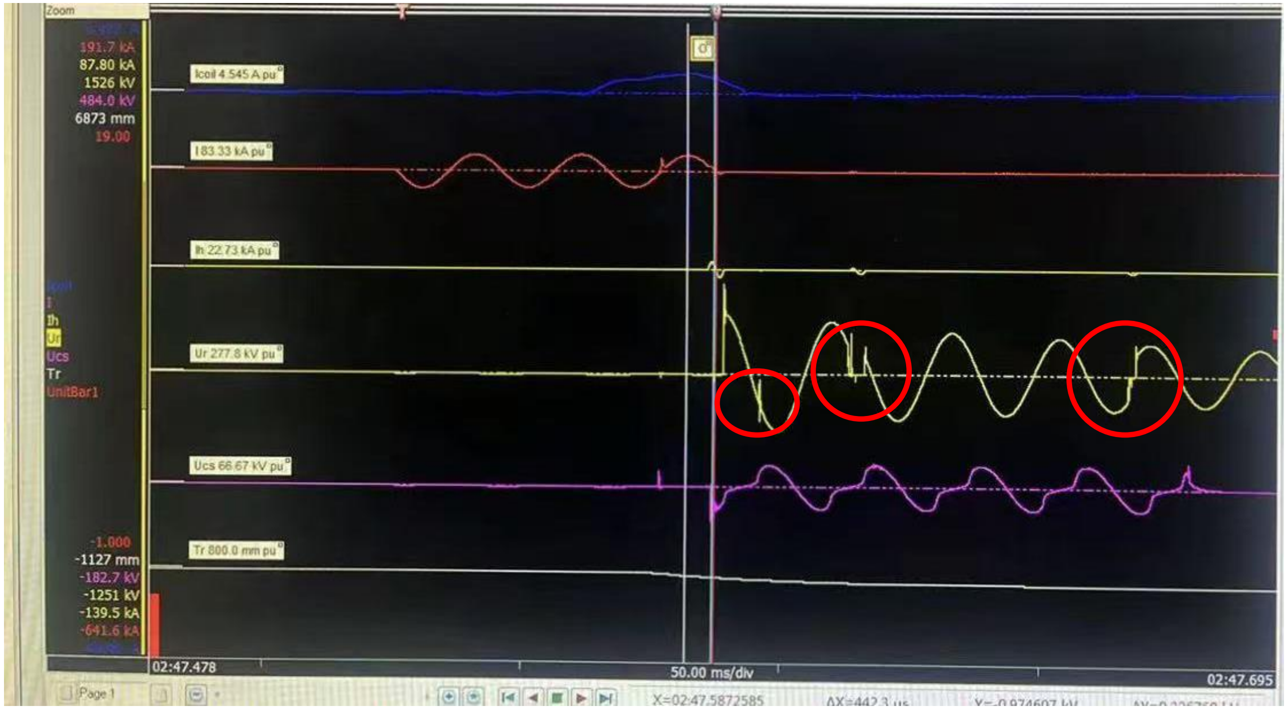
T. Heinz et al., “Why vacuum technology is not a simple scaling from medium to high voltage”, ISDEIV 2023



Animation of particle movement and deposition

Late Breakdown in HV vacuum interruption

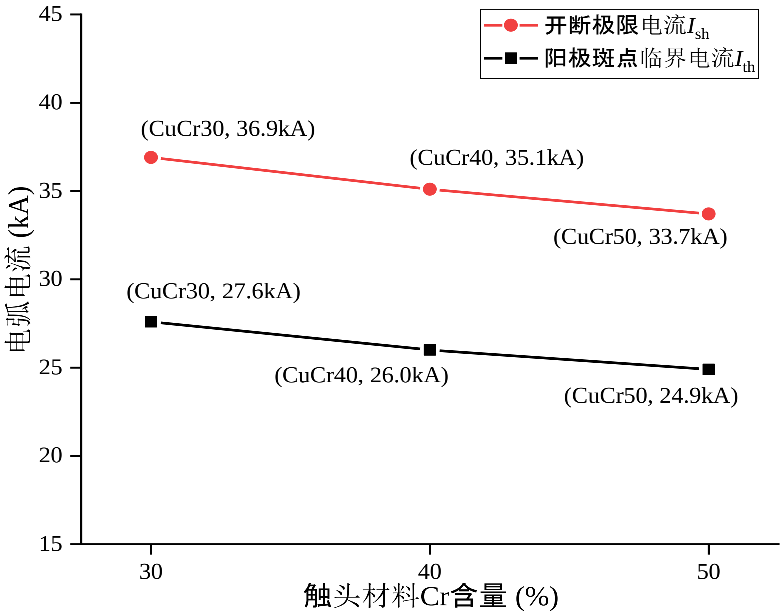
HV VCB in testing



- HV vacuum interruption
- Late breakdown may happen several ms to hundred of ms

Late Breakdown in HV vacuum interruption

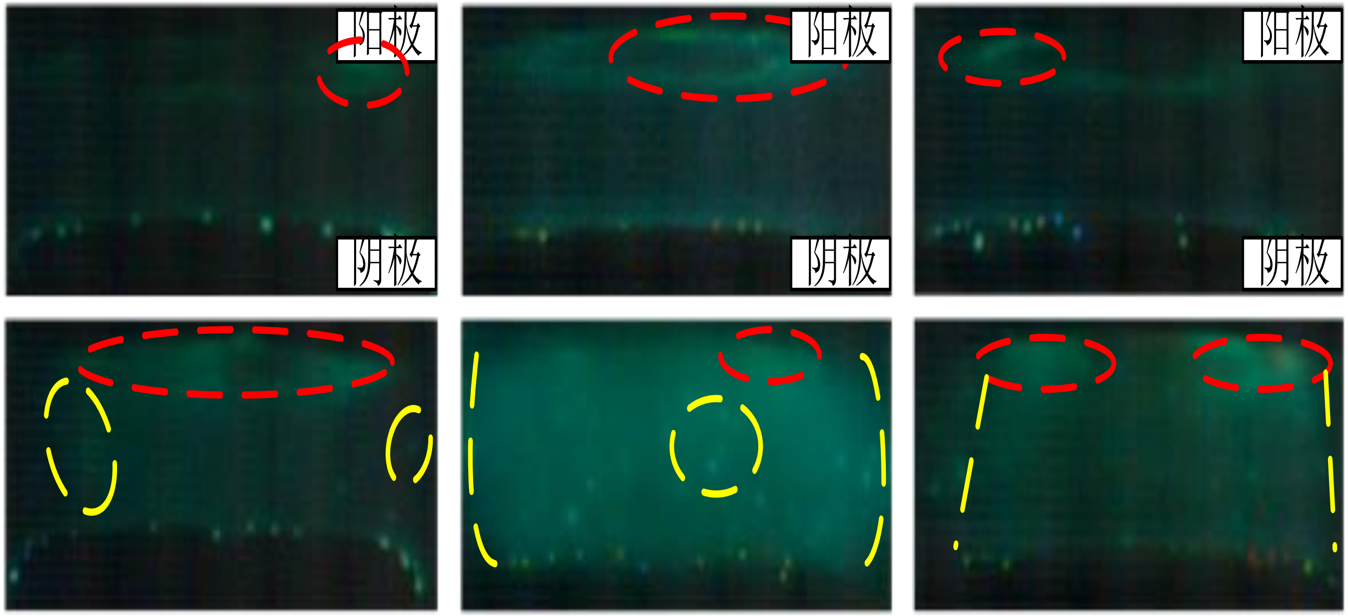
Limit of current interruption v.s. Anode spot formation



- The limit of current interruption capacity of vacuum interrupter
- The anode spot formation current

Late Breakdown in HV vacuum interruption

- At the limit of current interruption
- The key point is appearing both anode melting and metal droplets



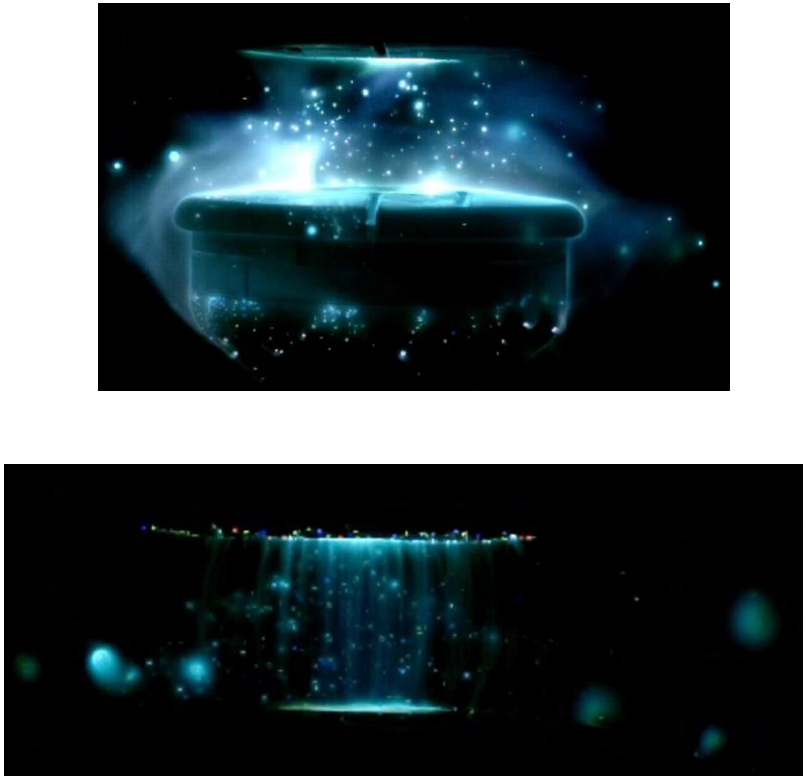
阳极斑点临界电流
过零前200μs

极限短路开断电流
过零前200μs

触头材料：CuCr30 触头材料：CuCr40 触头材料：CuCr50

Late Breakdown in HV vacuum interruption

Significant droplets appears

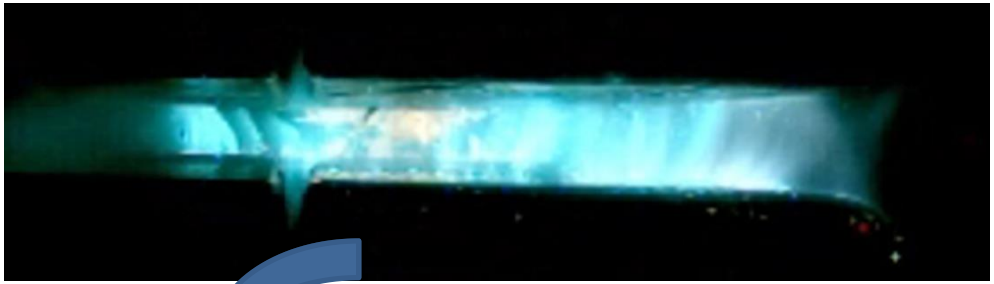


Vacuum interruption @ 45kA

Late Breakdown in HV vacuum interruption

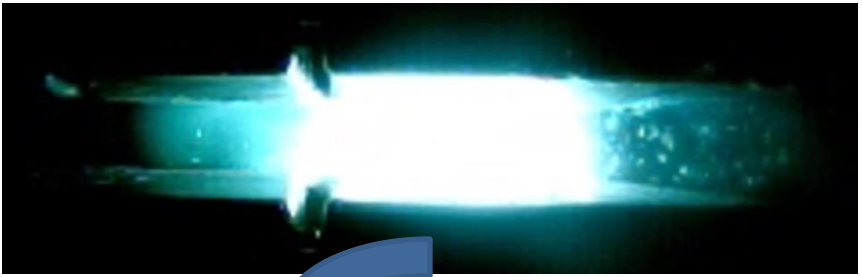
Contact material film formed after arcing tests

Late Breakdown in HV vacuum interruption



Contact material films formation

The films peeled off in arcing



Metal droplets appear

Late breakdowns happen

Part 3: Summary and outlook

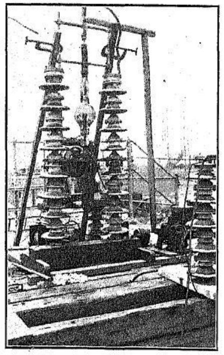
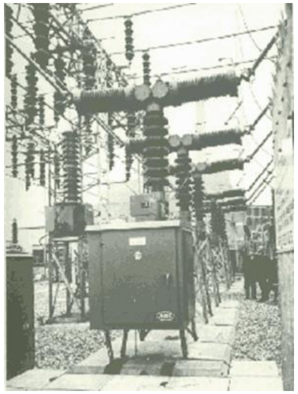


Fig. 7—Vacuum Switch No. 3

1926



1968

2023

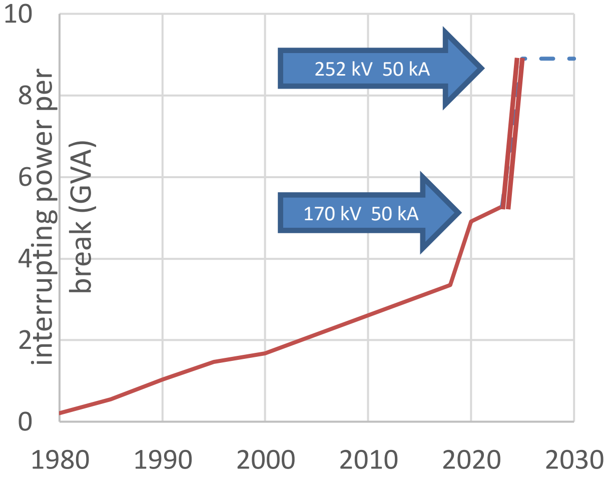
2024

High Voltage Vacuum Interrupters:

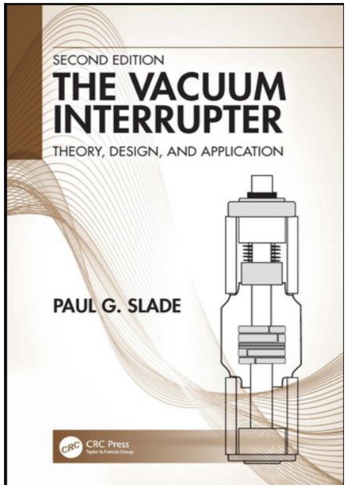
- Dielectric requirements → larger contact gaps
- Current interruption → plasma control essential for successful current interruption
- Normal rated current → up to 4000A

Future development:

- multi-break above 252kV
- Normal rated current: 4000A → 5000A
- Short circuit current: 63kA → 80kA
- Special applications → capacitor banks (B2B)



Further reading



SECOND EDITION

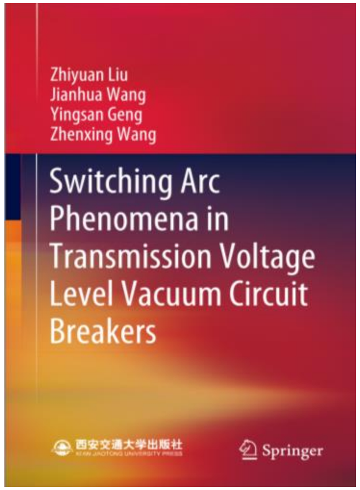
THE VACUUM INTERRUPTER

THEORY, DESIGN, AND APPLICATION

PAUL G. SLADE

CRC Press
Taylor & Francis Group

2021



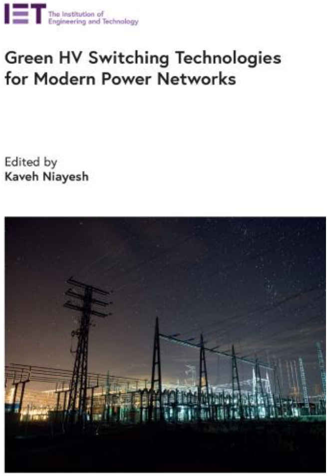
Zhiyuan Liu
Jianhua Wang
Yingsan Geng
Zhenxing Wang

Switching Arc Phenomena in Transmission Voltage Level Vacuum Circuit Breakers

西安交通大学出版社

Springer

2021



IET The Institution of Engineering and Technology

Green HV Switching Technologies for Modern Power Networks

Edited by
Kaveh Niayesh

2023

CIGRE Technical Brochures on (HV) vacuum switchgear:

The Impact of the Application of Vacuum Switchgear at Transmission Voltage	589 (2014)
Shunt Capacitor Switching in Transmission and Distribution Systems	817 (2020)
Current Interruption in SF_6-free Switchgear	871 (2022)

The 31st International Symposium on Discharge and Electrical Insulation in Vacuum (ISDEIV)

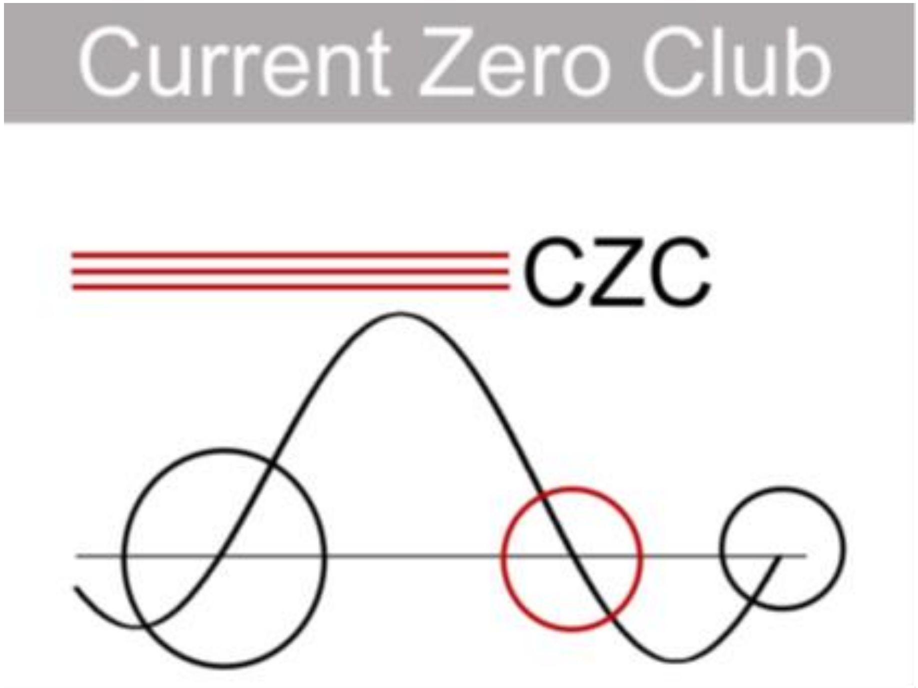
Sept. 21 - 26, 2025|Chengdu, China

Hosted by Sichuan University Technically sponsored by IEEE DEIS

Conferences related to vacuum switchgear:

- Intern. Symp. on Diel. Insulation and Discharges in Vacuum ISDEIV 2025/09/21-26 Chengdu, China

https://isdeiv2025.org/


Current Zero Club
CZC