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

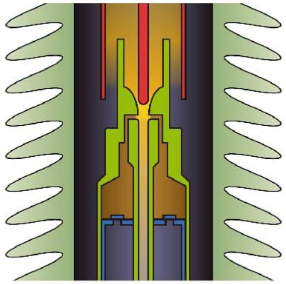
- Aligned with CIGRE Study Committee A3 (T&D equipment)

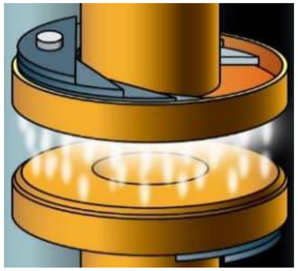
- 30 members (upon invitation) from industry and academia
- Scientific and independent

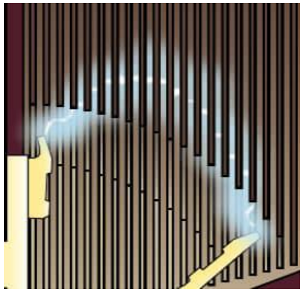
- Founded in 1961

- Specialists' circles on dedicated topics:
    - Gas circle
    - Vacuum circle
    - Low-voltage circle

- http://currentzeroclub.org/
  Today's presentation will be posted there and on e-cigre.org







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  - Dr. Thomas Heinz (Siemens Energy, Germany)

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
- 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.
- The present webinar 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)
    - Thierry Delachaux (Hyosung R&D Center in the Netherlands)
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    - 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)

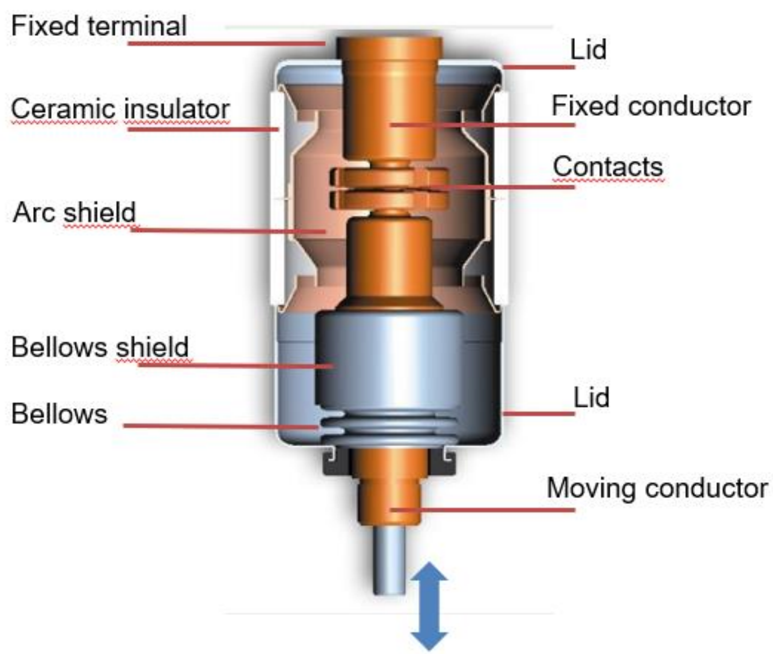
Structure and main properties of vacuum interrupters

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.

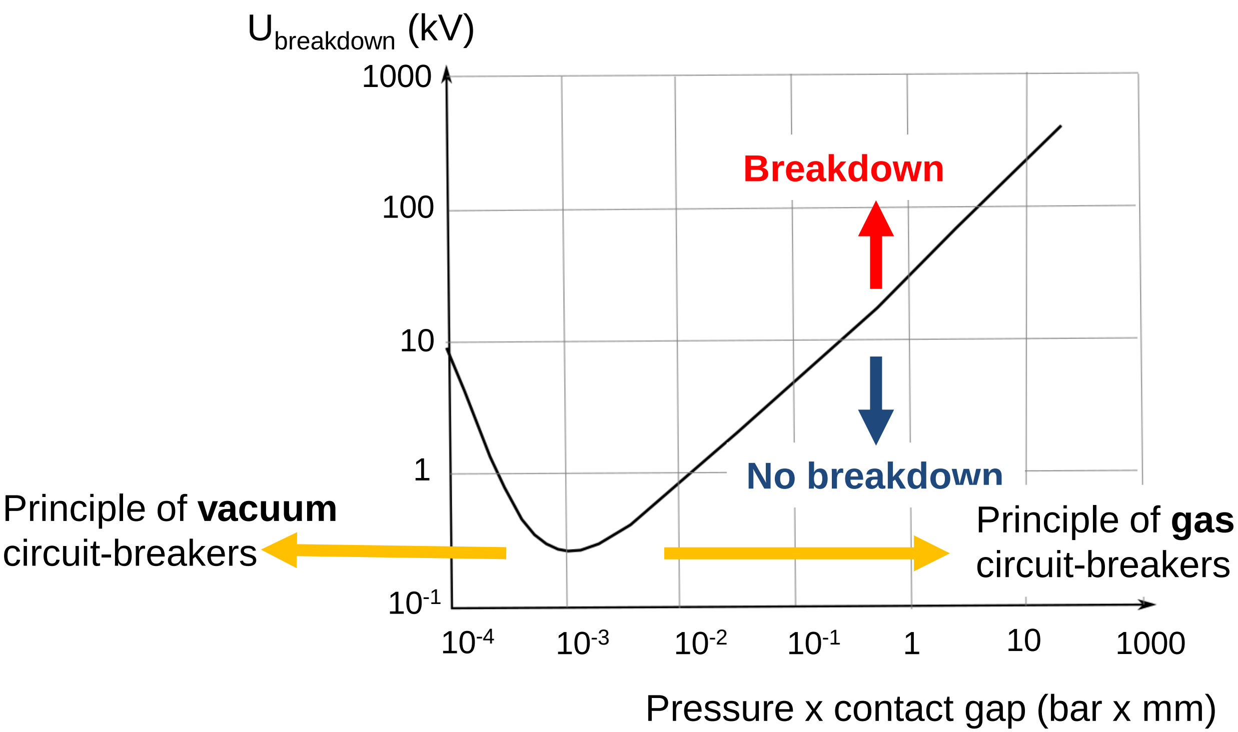


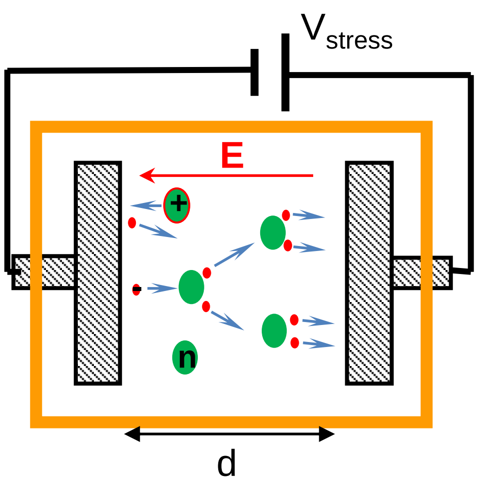
Properties

- 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

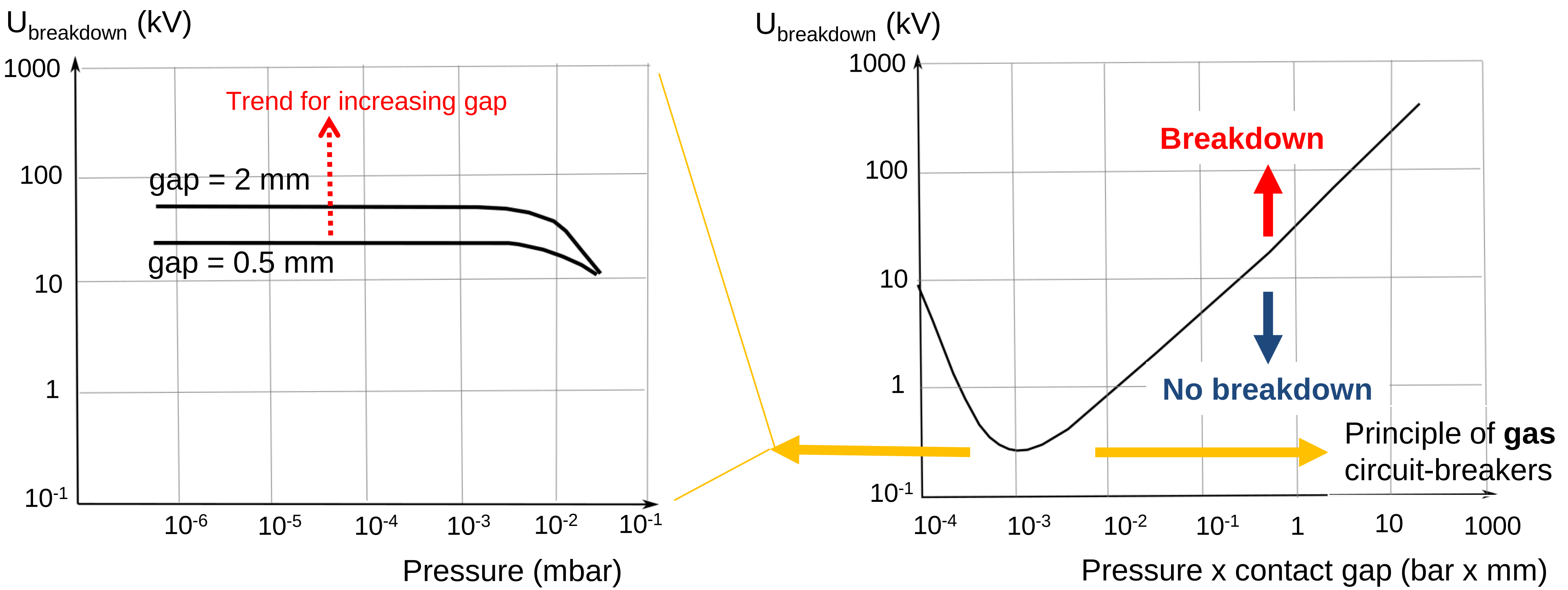




Gas ionization and electron multiplication (avalanche effect) eventually lead to a volume (gas) breakdown

Why using vacuum?

Voltage breakdown in vacuum | **Voltage breakdown in gas**



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

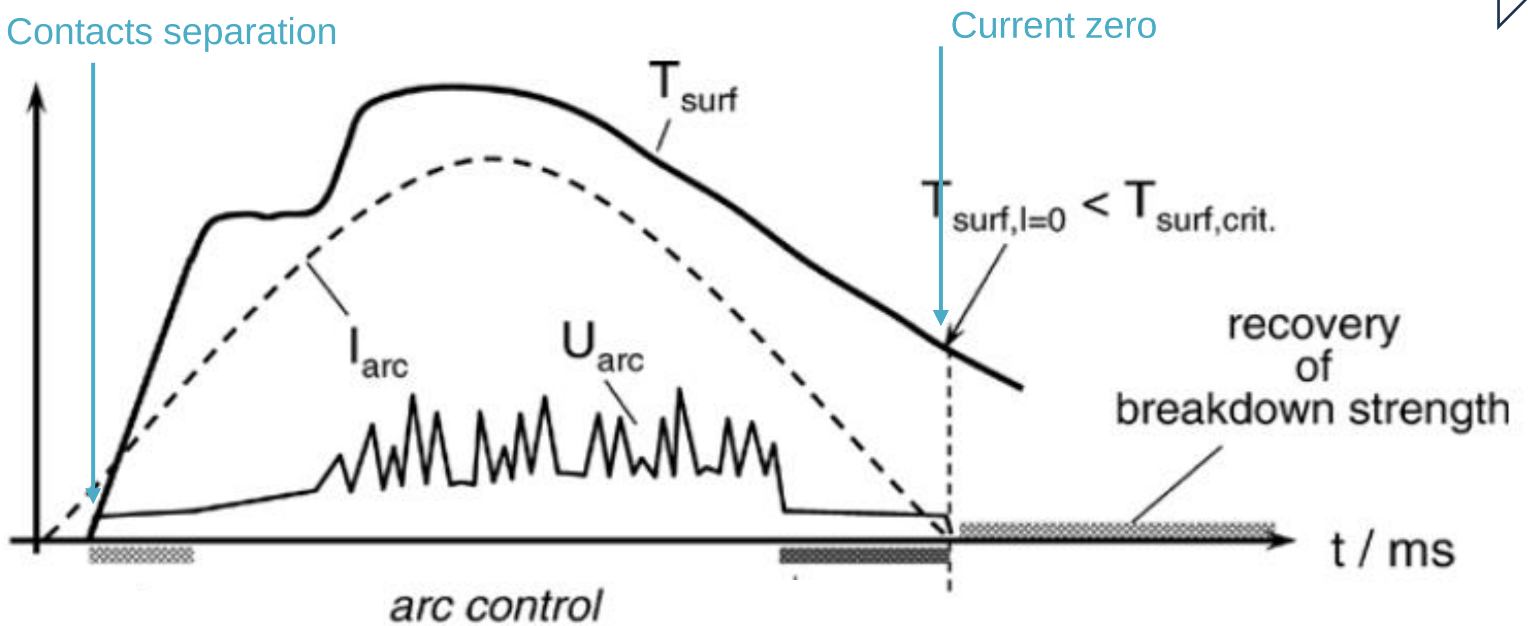
- Breakdown voltage in gases is a function of contact gap, pressure and gas.
- It is driven by volume mechanisms.

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

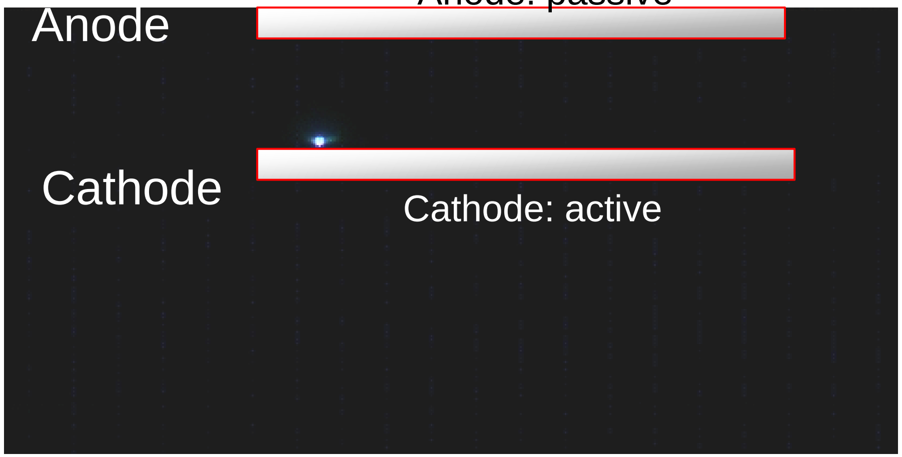


Surface temperature is one of the most decisive parameter for a successful interruption. Therefore, the **goal for a successfull current interruption in vacuum is to limit the heat to the electrodes by an adequate contact design.**

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

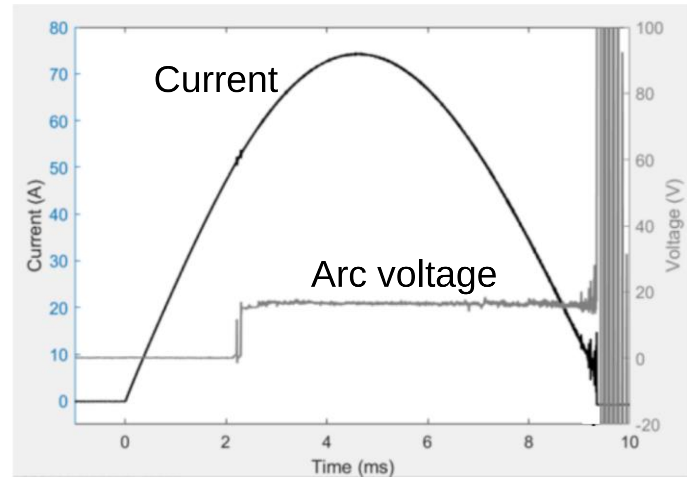
Low current vacuum arc : the cathode spot (I/II)

Appearance of a 25 A vacuum arc



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

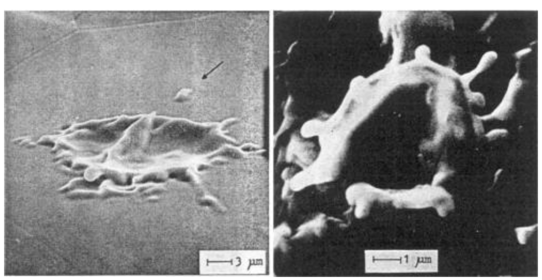
Electrical characteristics

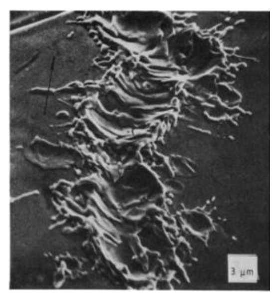


Constant arc voltage ~15 V (Cu)

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

Microscopic characterization





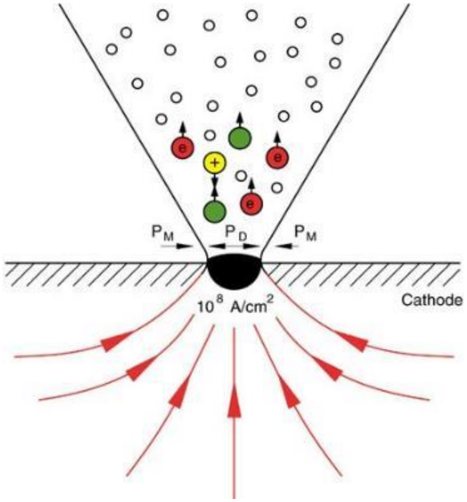
Craters visible on the cathode,highlighting the explosive character of the spots.

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)

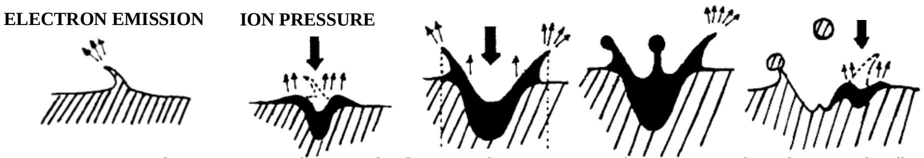
Cathode spots are the **unique** source of metallic vapor, plasma, electrons and droplets (at low current)



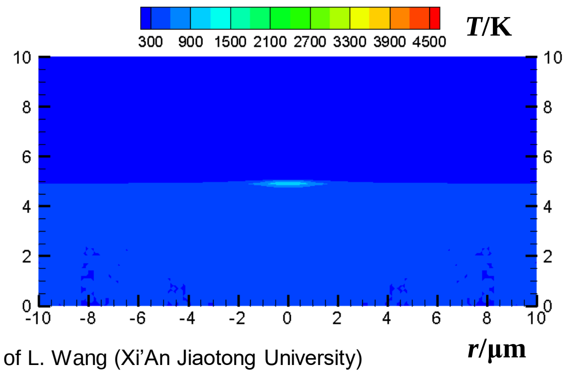
- Each spot carries about 30 A (for Cu)
- Spot diameter: ∅1-10 um
- Current density: j ~ 10^{12} A-m^2
- Composition:
  - Cu^+ 25%
  - Cu^{++} 60%
  - Cu^{+++} 15%
- Erosion rate: ~ 50 μg/C

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

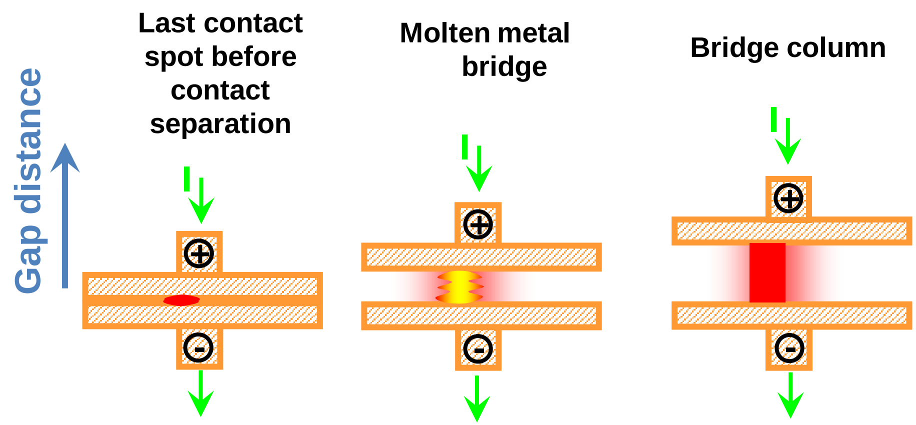
D = 80mm; h = 20mm; I_0 = 18kA (rms); CuCr50

- 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

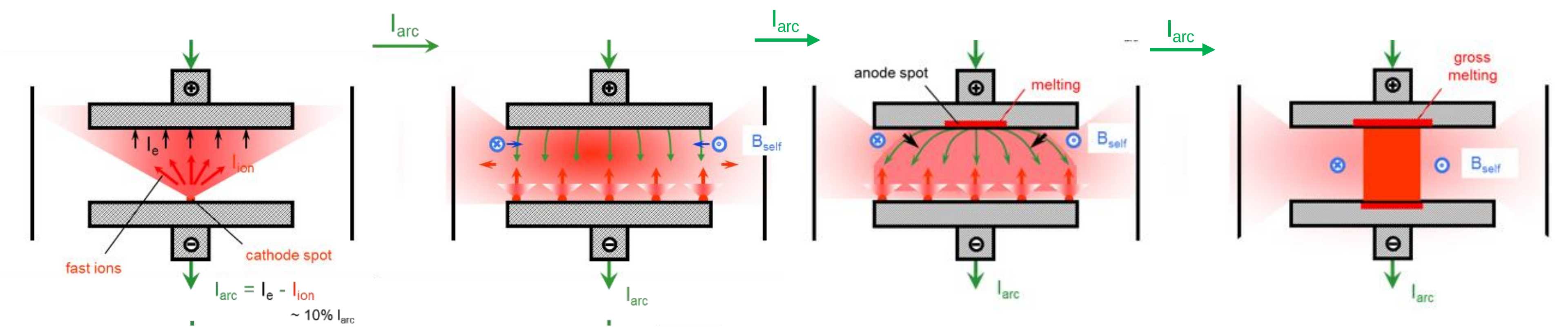
1. Arc initiation stage : electrode separation (< 1mm)



2. Current increase stages

a. Multiple cathode spots development

b. Pinch effect and arc constriction development



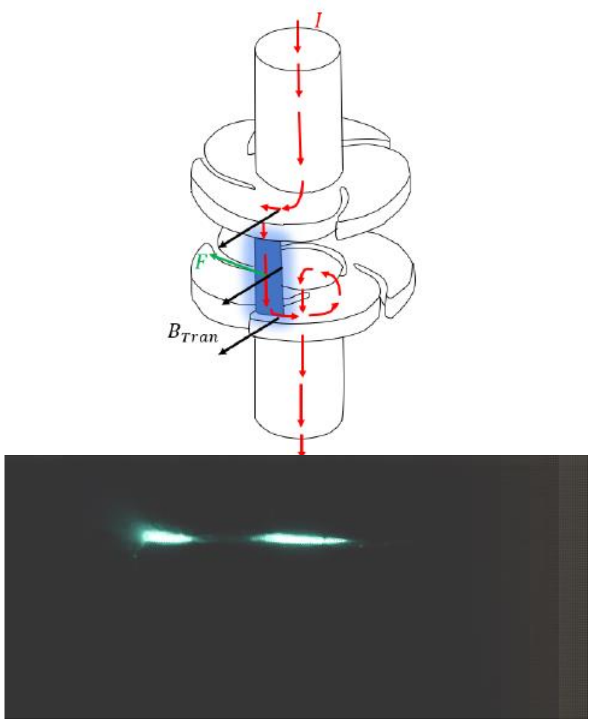
The arc constriction involves the melting of the anode (it is a function of instantenous current AND gap distance between the electrodes).

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

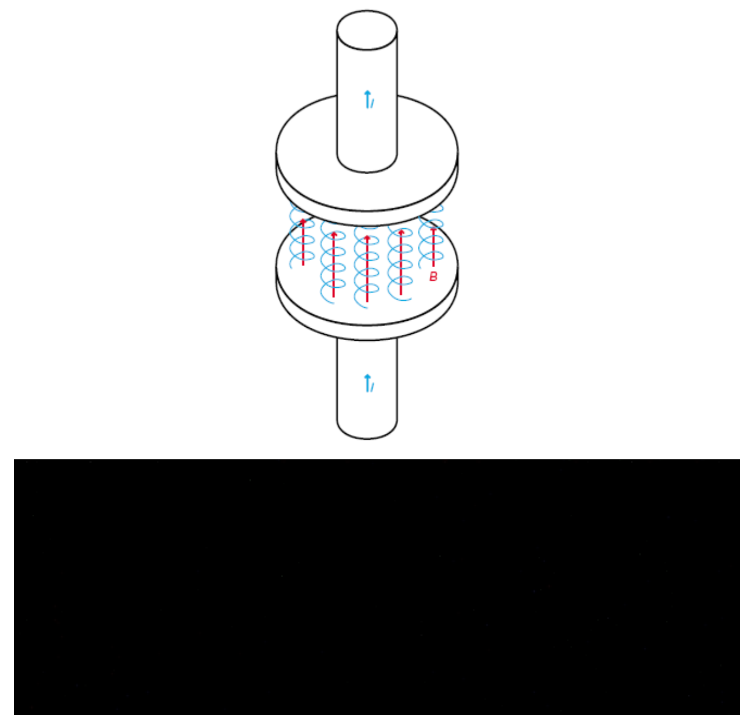
-Heat flux improvement can be done through “arc control” with magnetic fields

Transverse Magnetic Field (TMF) type



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

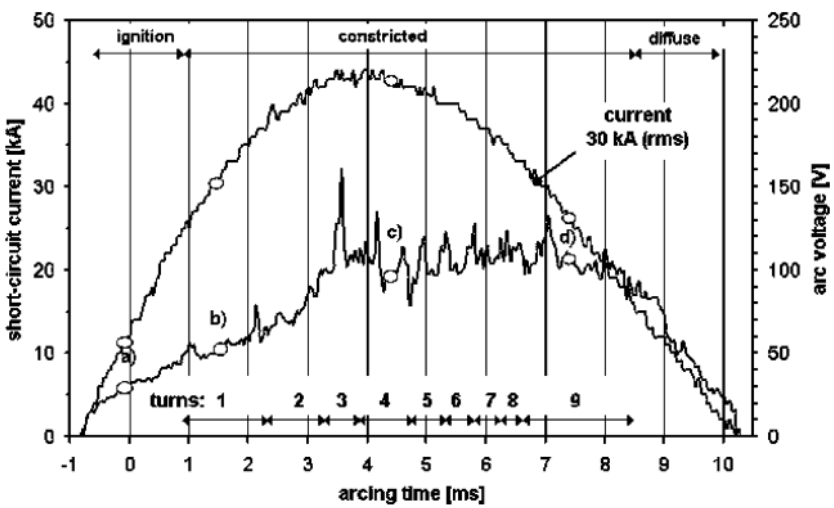
Axial Magnetic Field (AMF) type



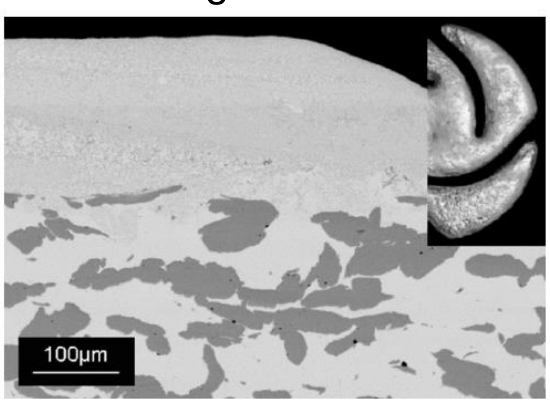
Source: By courtesy of S. Jia (Sichuan University)

High current vacuum arc : arc control with magnetic fields

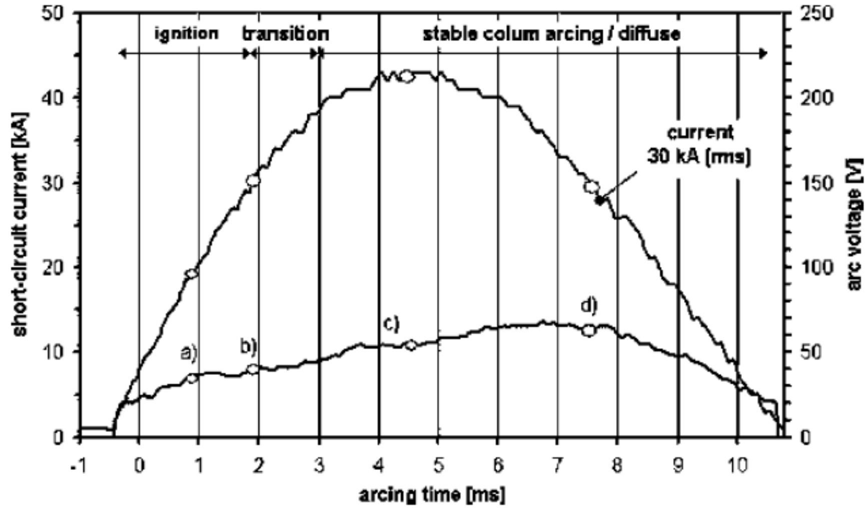
Transverse Magnetic Field (TMF) type



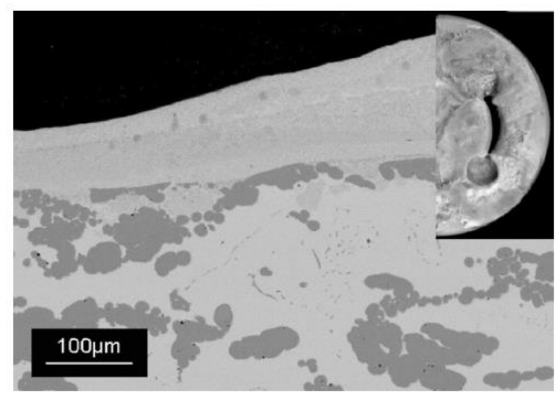
Arc voltage: ~100-300 V



Axial Magnetic Field (AMF) type

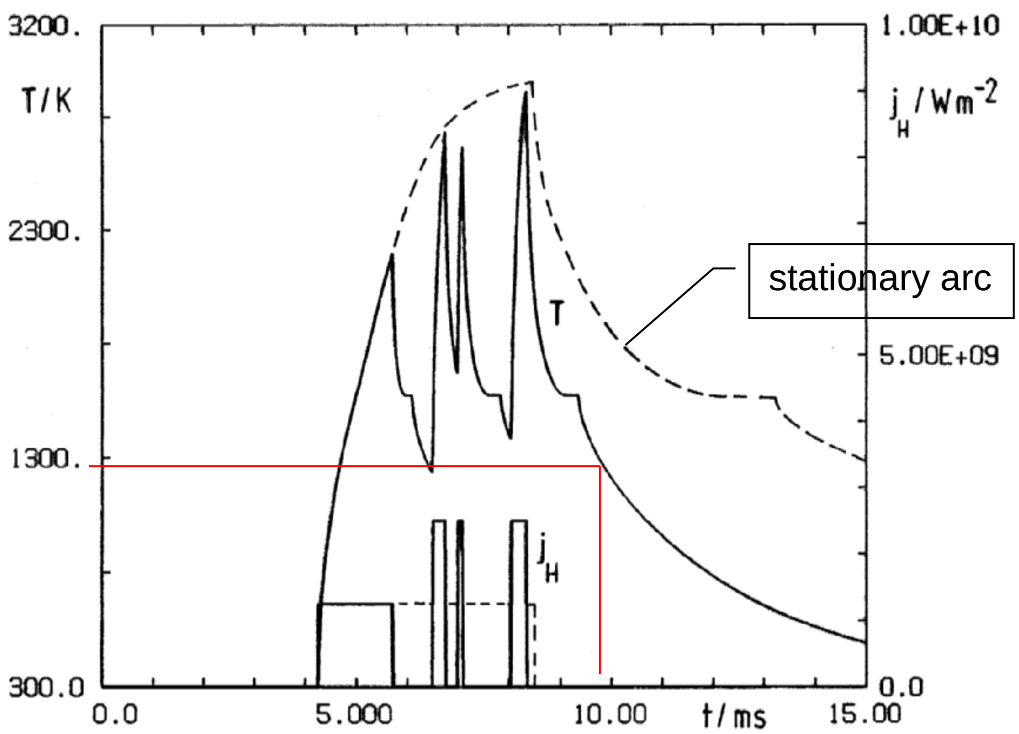


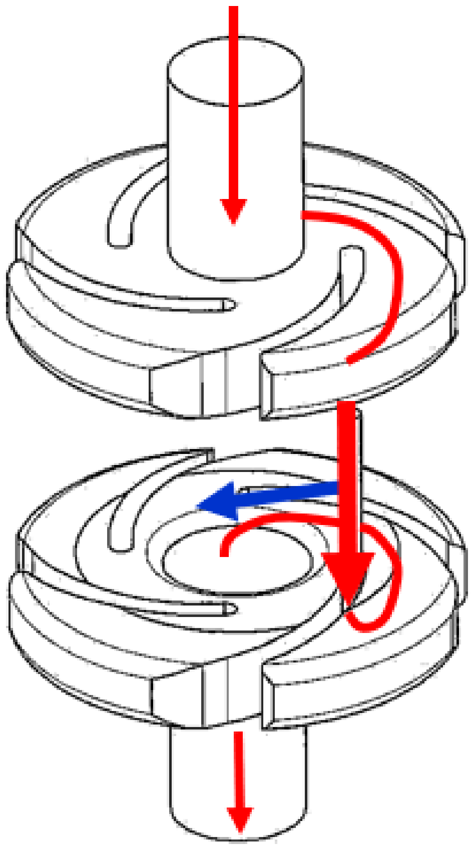
Arc voltage: ~ 60 V



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

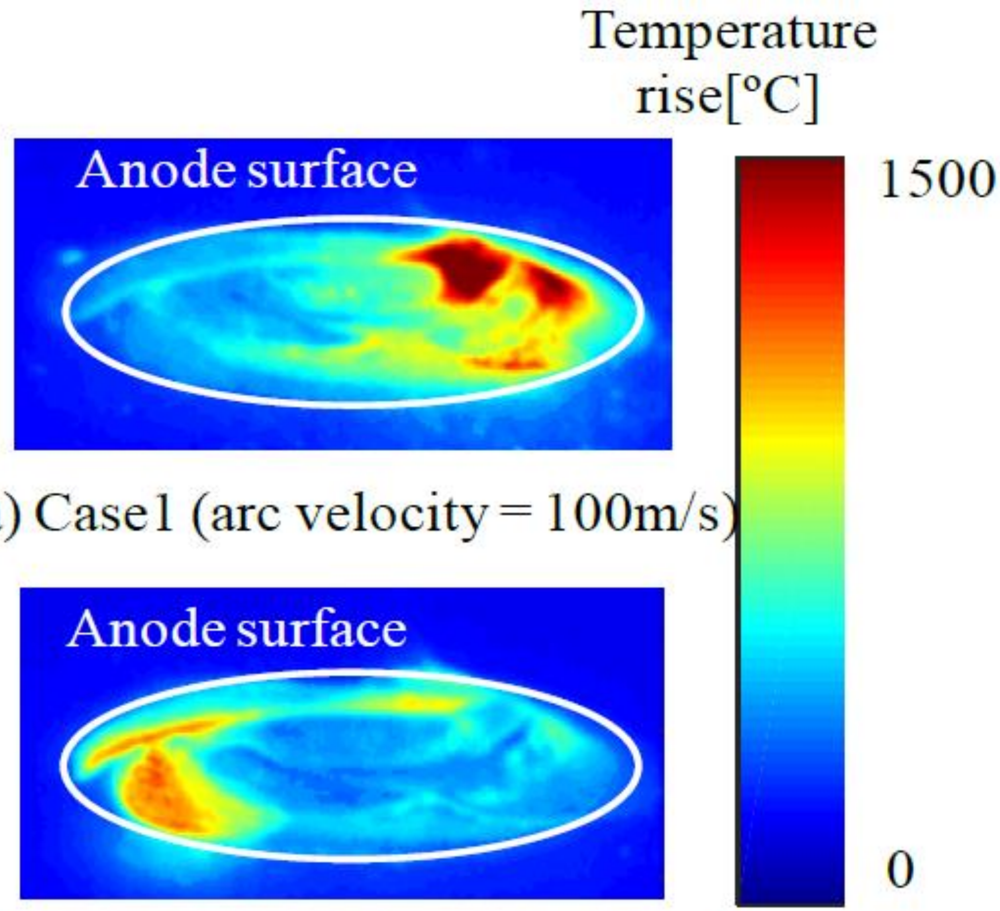




TMF causes arc moving, thus reducing local contact surface temperature, contact heat and erosion.

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



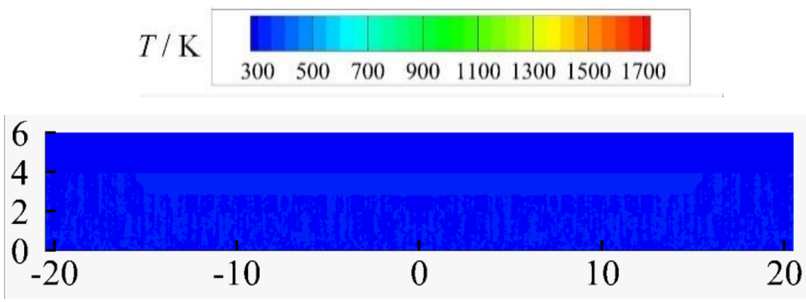
(a) Case1 (arc velocity = 100m/s)

(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

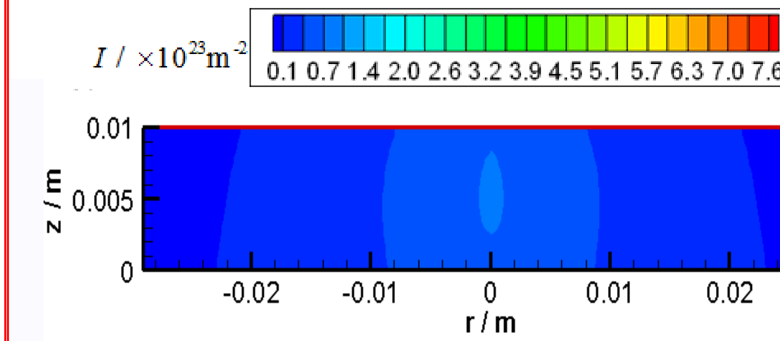


Thermal activity simulation of high current vacuum arc anode

Source: By courtesy of Xiaolong Huang(Sichuan University)

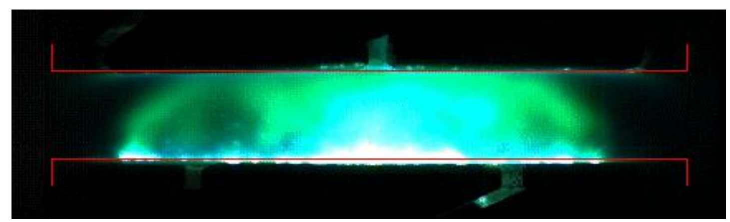
Thermal activity experiment of high current vacuum arc anode

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

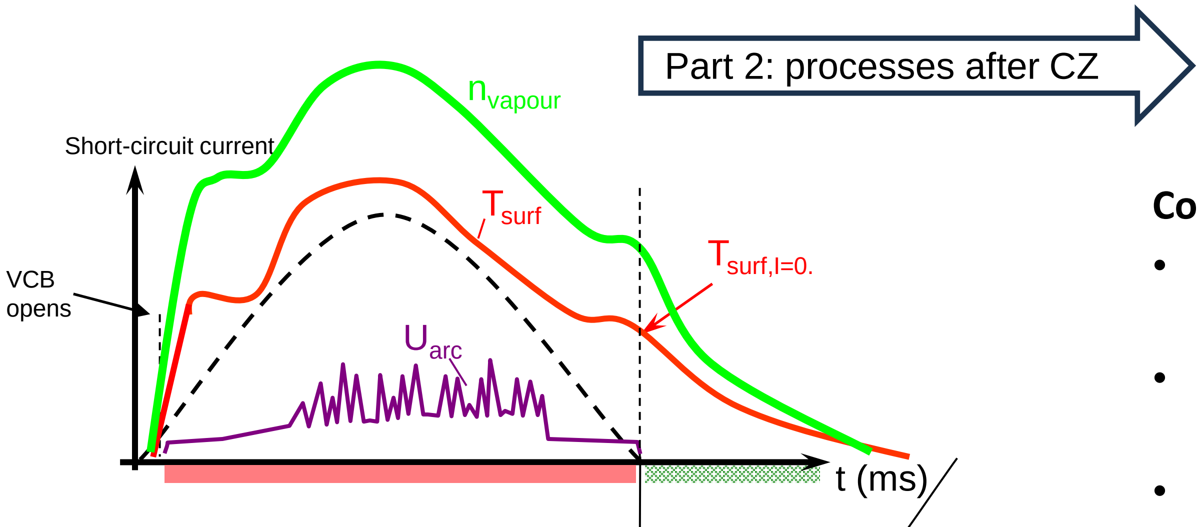
AMF makes arc diffused, thus reducing contact surface temperature, contact heat and erosion.

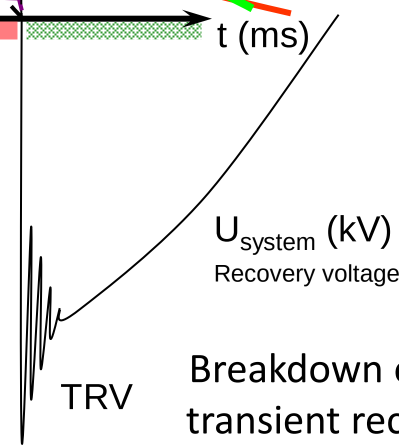
Part 1: Summary

- 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





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

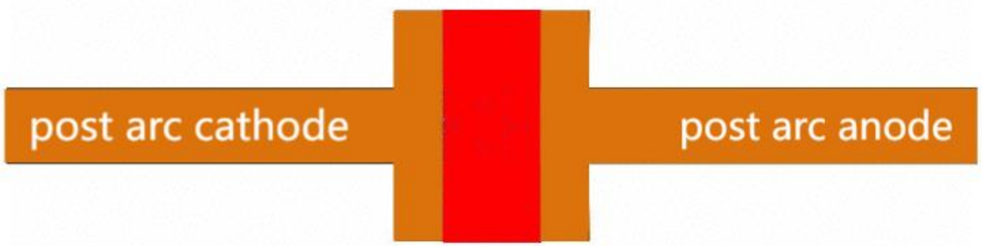
- Heat flow of arc determines surface temperature and metal vapor density during arcing.

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

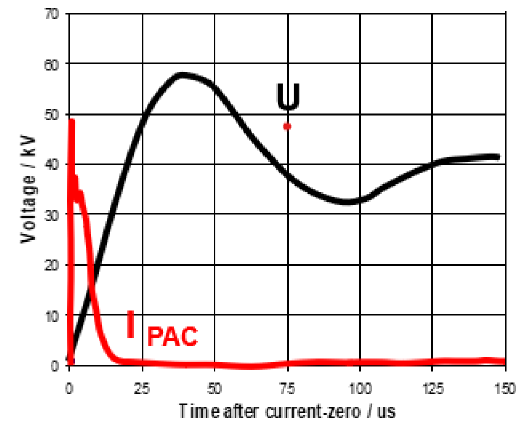
Condition of gap after CZ:

- 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.

Simulation of space charge sheath development and post-arc current



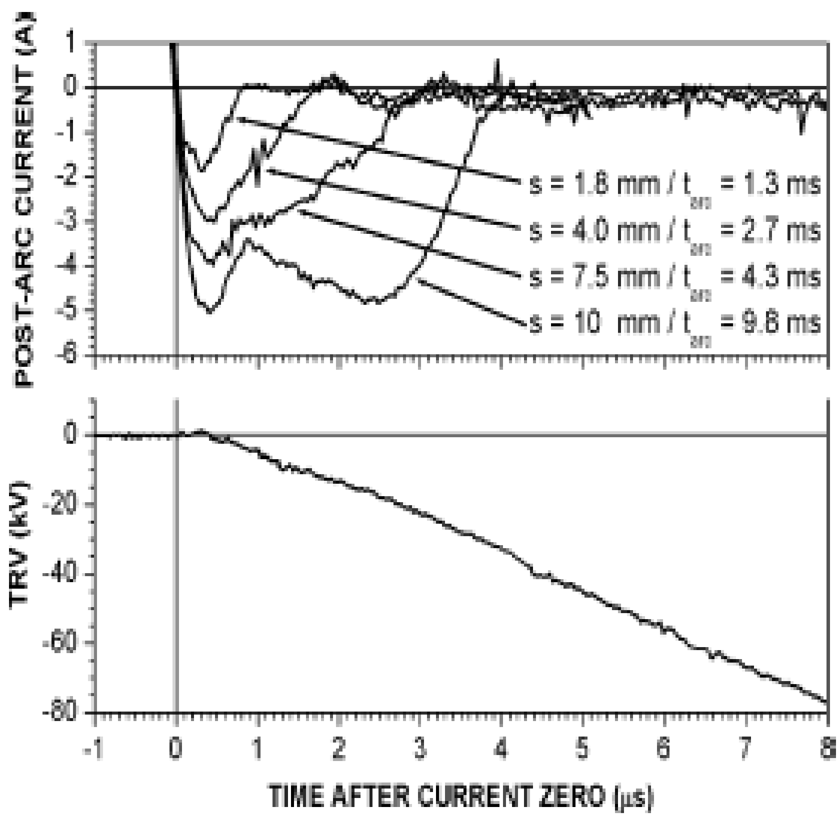
By courtesy of Shenli Jia



- 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.

- This collected charge i.e. the integrated post-arc current 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.

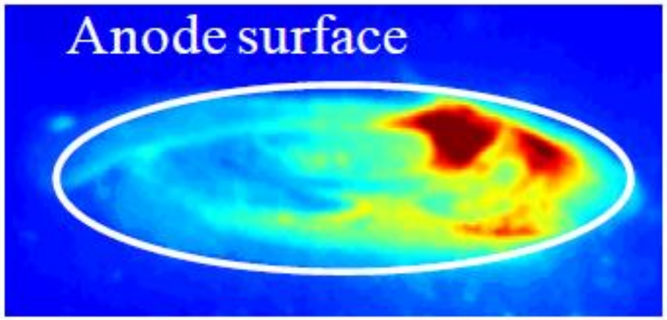
Post-arc current and plasma



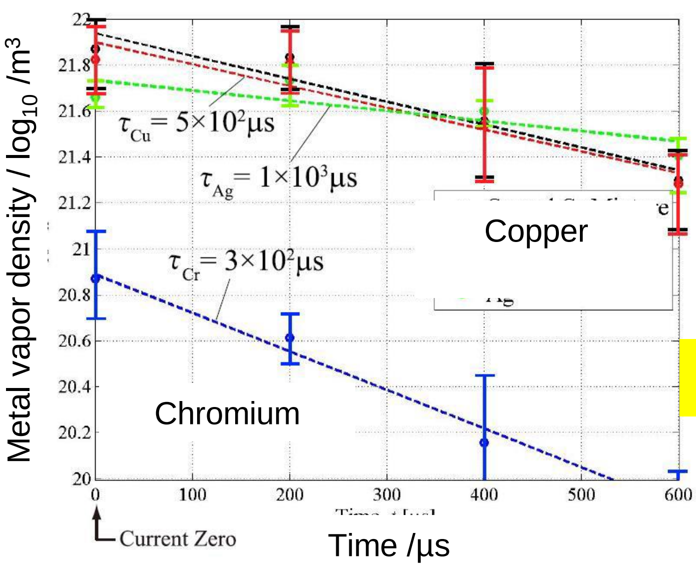
- Typical PAC measured after high current arcs with different arcing times and contact gaps.
- After high current arcs, the amount of residual plasma is much larger than after low current arcs.
- And the residual plasma stays much longer in the contact gap.
  - Reason is the higher density of metal vapor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

Metal vapor evaporated from hot contact surfaces after current-zero



1800 – 2000 K

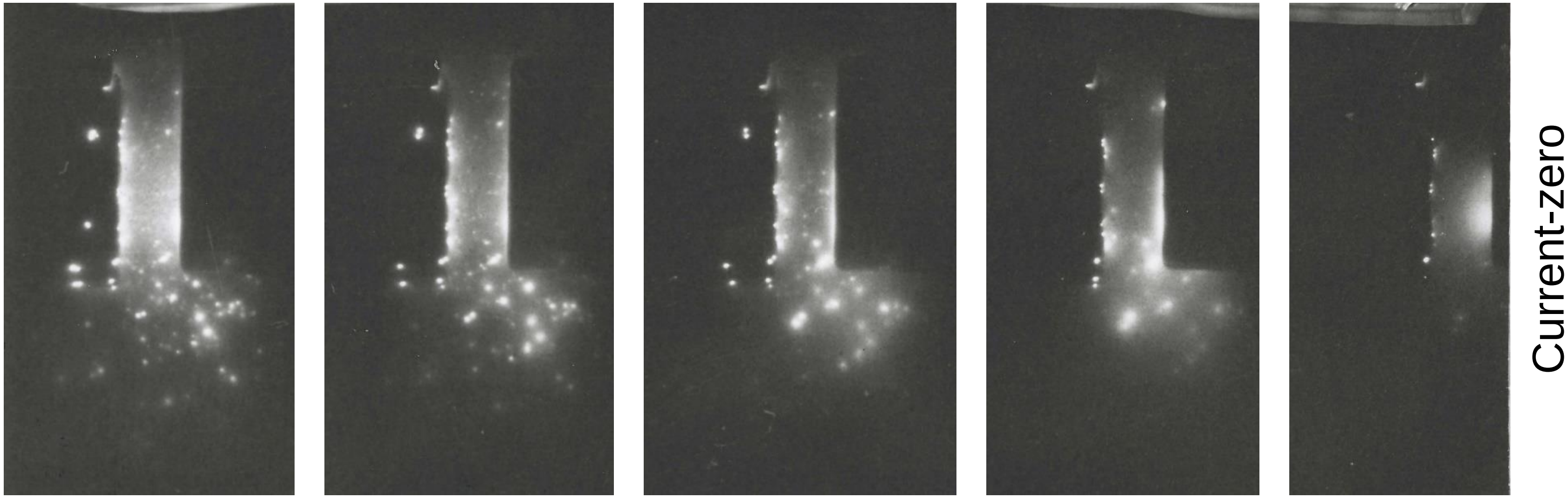


$10^{21} – 10^{22}$ /m³

- 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

Hot droplets ejected from contact surface during and after arcing

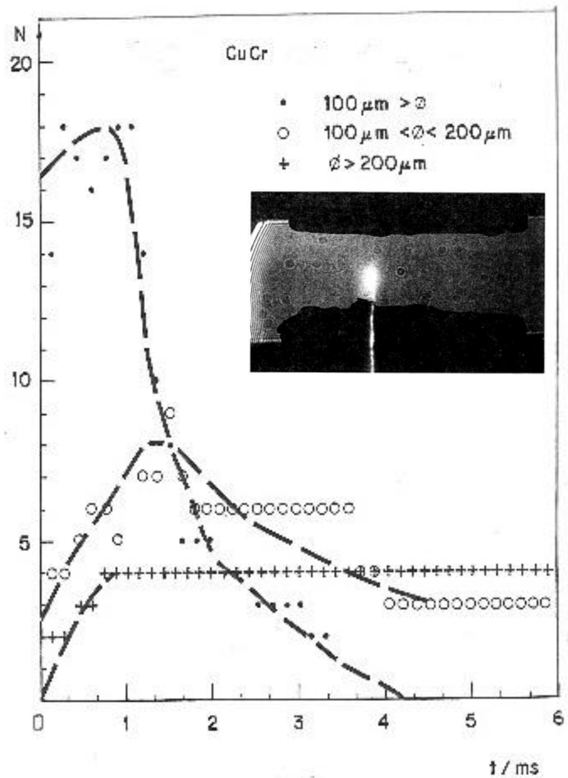


0.9 ms 0.7 ms 0.5 ms 0.3 ms 0.1 ms

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

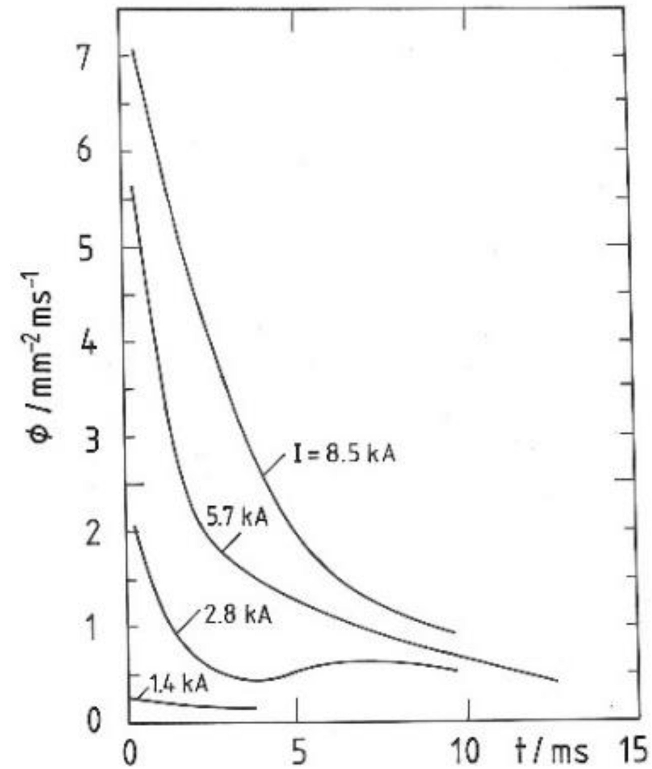
By courtesy of Edgar Dullni

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

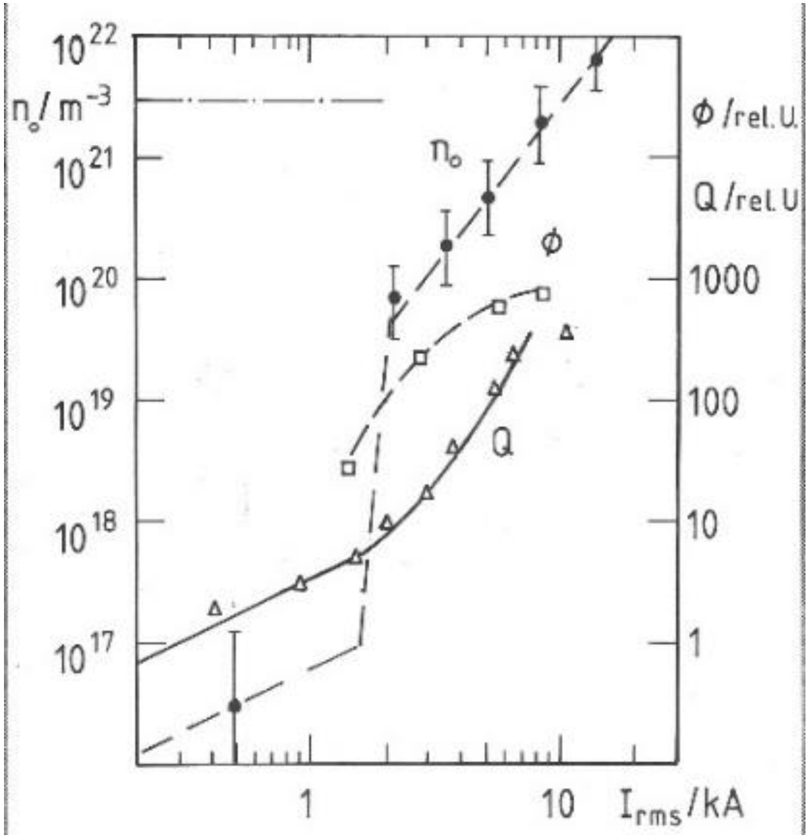


Flux density of small droplets (< 10 µm) versus time after CZ for different 50 Hz-currents

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



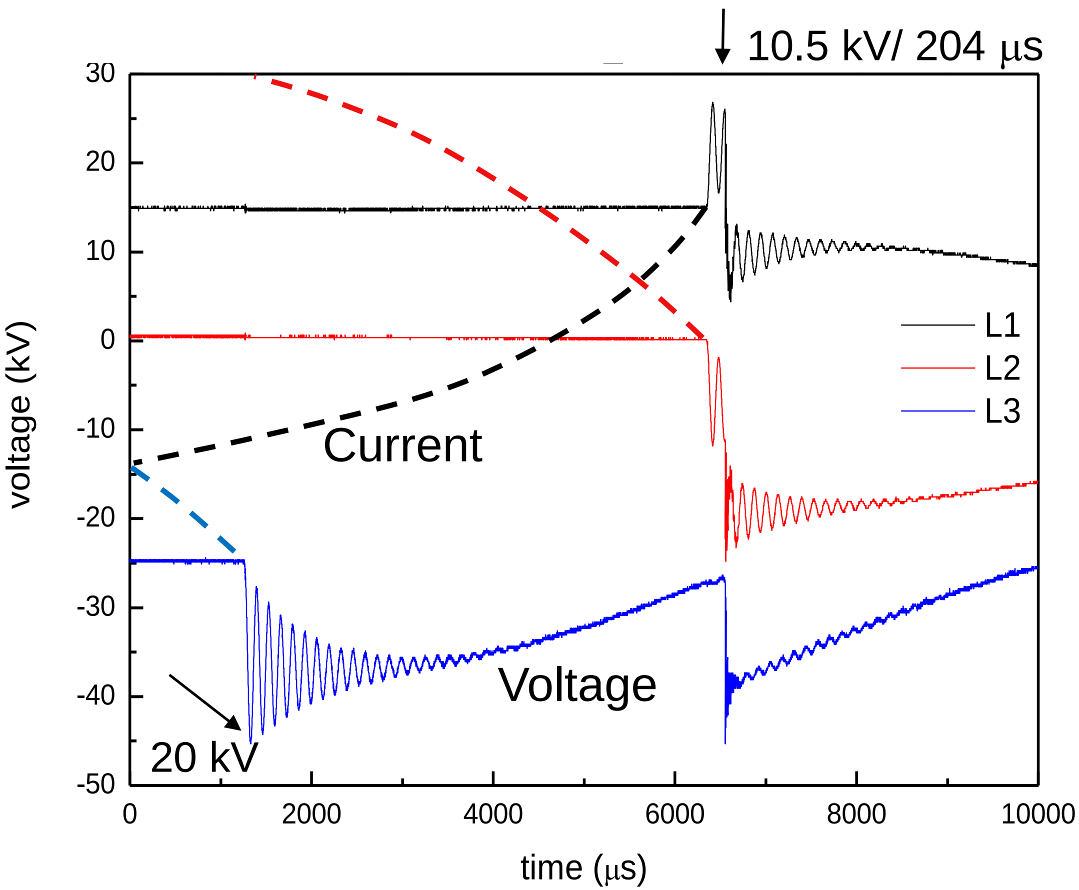
I_{rms} of 50 Hz current

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

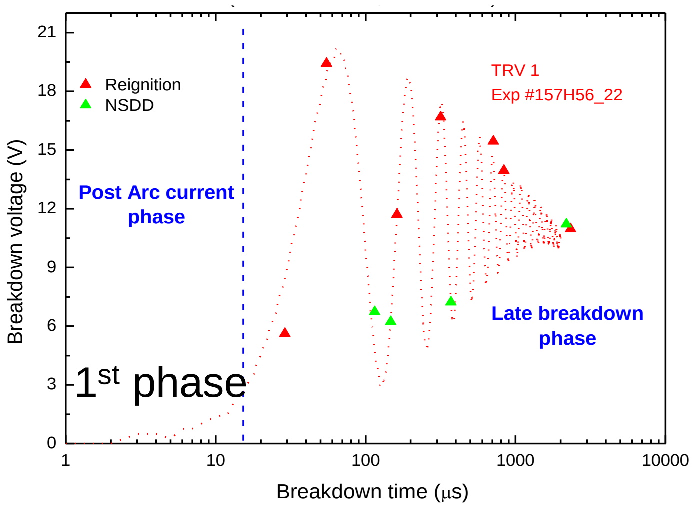
source: E. Schade, E. Dullni, "Recovery of breakdown strength of a vacuum interrupter after extinction of high currents", IEEE TDEI, Vol. 9, 2002, pp 207 – 215

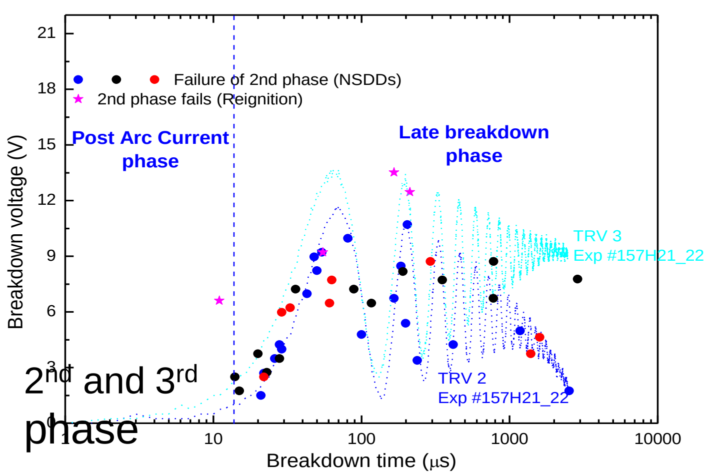
Voltage breakdown after current-zero



- 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

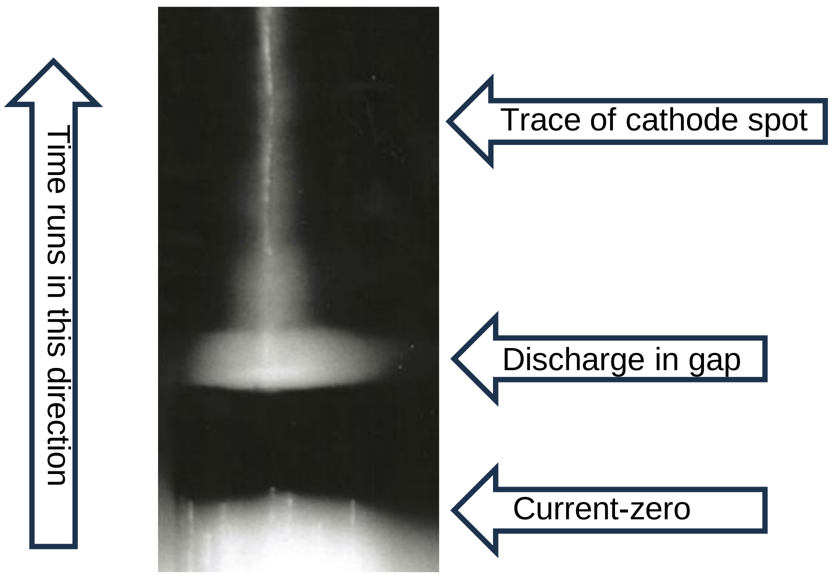


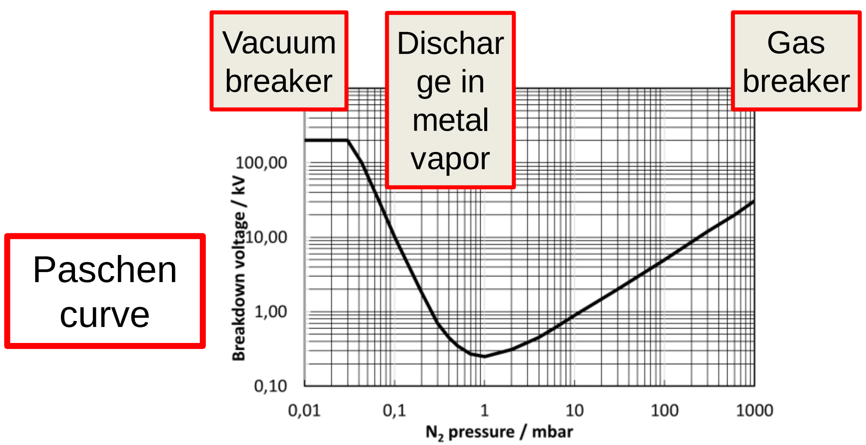


Courteously provided by ABB

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

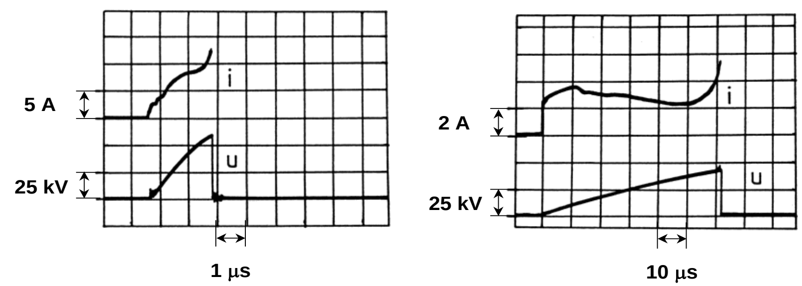
Breakdown after interruption of currents beyond rated values ($I_{rms} > 3\ I_{sc}$)





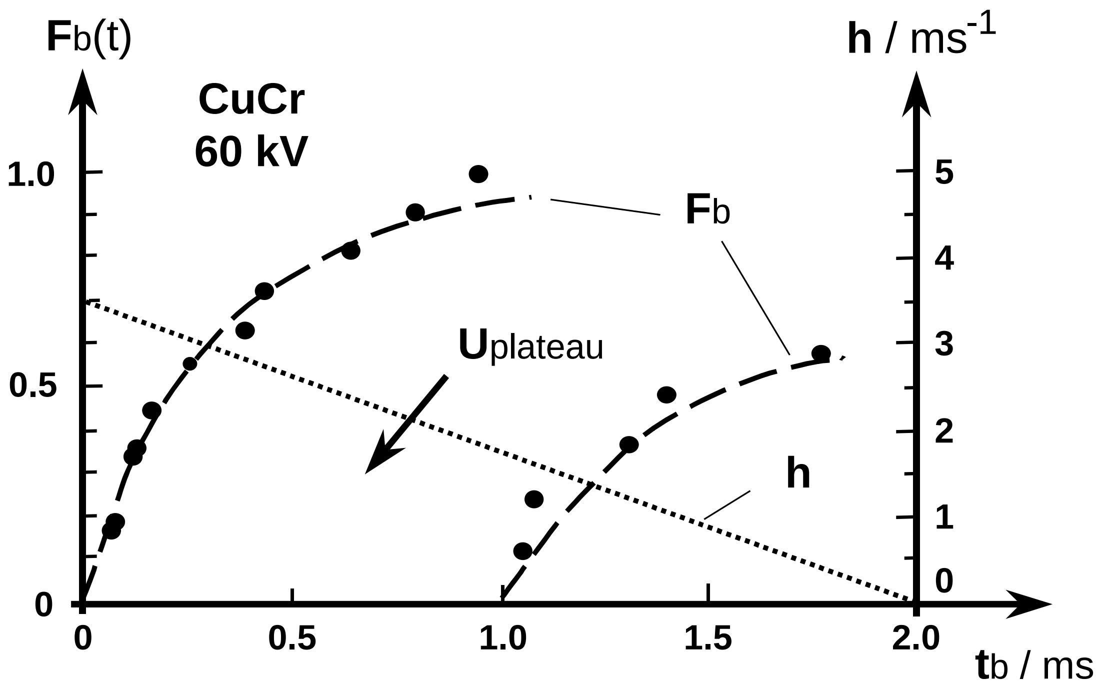
Source: E. Schade, E. Dullni, IEEE TDEI, Vol. 9, 2002, pp 207 – 215

- 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 > 2 x 10^{22} /m^3 or 0.7 mbar
- An electron avalanche develops similar to that occurring on the left branch of the Paschen curve.

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



- 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 2 ms after CZ.
- A linearly decreasing breakdown rate h matches the breakdown rate and probability.

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

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	50 Hz 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

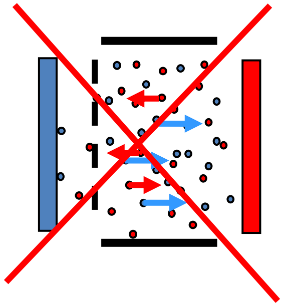
- The yellow column shows measured thermionic currents extrapolated to CZ being a measure of the surface temperature at CZ.

- 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 (3 m/s v. 1 m/s)
- **The contact temperature remaining at current-zero is the decisive parameter for successful interruptions.**

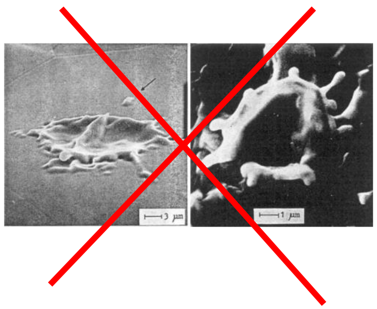
Source of upper graph: E. Dullni, "High current interruption of vacuum interrupters and voltage breakdown during recovery", 30th ISDEIV, Naha, 2023

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

What causes can be excluded?



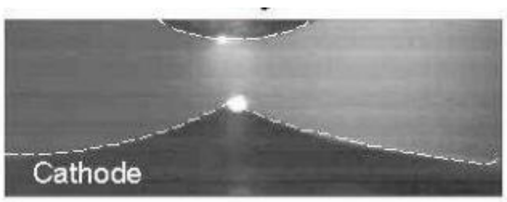
- A discharge in metal vapor is not feasible since the metal vapor density in the gap is too small (less than 3 x 10^{21} /m^3 or 0,1 mbar).
- The post-arc plasma does not play a role since all breakdowns happen after the plasma has vanished.



- 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.

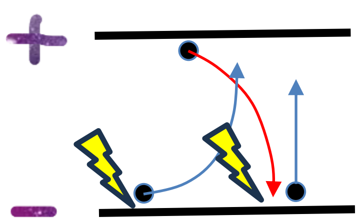
Root cause for failed interruptions of currents at or below the interruption limit

What causes are likely?



- The <u>surface stays liquid</u> for several ms after current-zero and might cause breakdown via the occurrance 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.

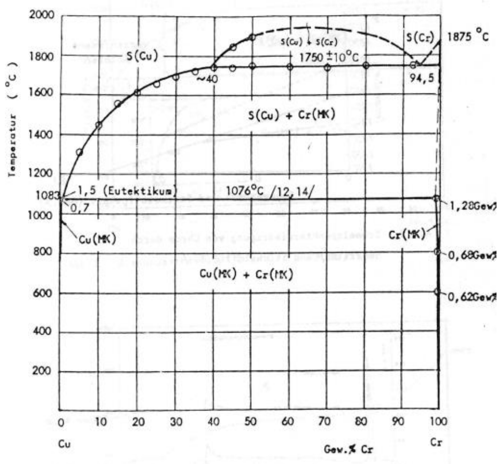
Film provided by Yuki Inada:
Best film Award ISDEIV 2018

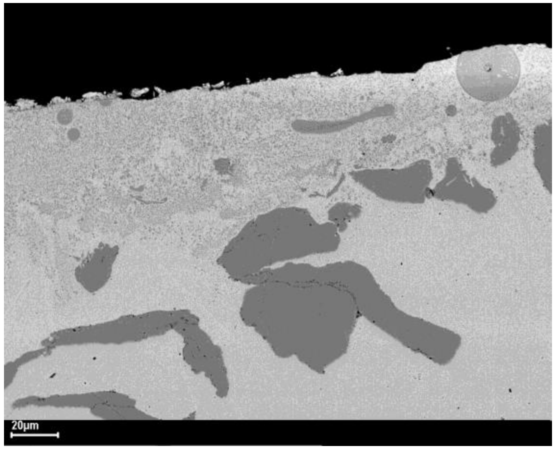


- <u>Large droplets</u> are present even late after CZ. Droplets with diameter > 20 µm might trigger breakdown when approaching or leaving the high voltage cathode.

Extract from Best Film Award ISDEIV 2019

Role of a liquid surface in the initiation of breakdown

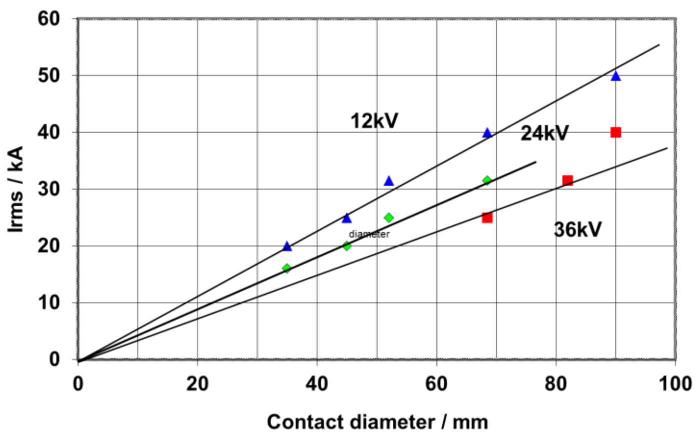




- For the 2-component sintered material CuCr, the liquidus temperature varies with the concentration of Cr and Cu.
  - The melting temperature of pure Cr is 2133 K.
  - For a concentration of 75/25, both Cu and Cr are molten above a temperature of 1900 K.
  - Below 1900 K, Cr solidifies into small solid grains, at 1360 K also Copper solidifies.
- Parts of the contact surfaces remain liquid for several milliseconds after current zero in dependence of the interrupted arc current.
- Solid Cr-grains will play a role.

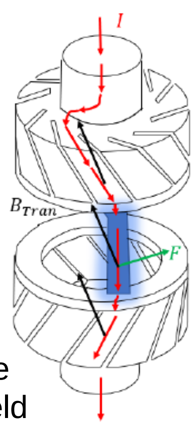
Source: R. Müller "Arc-melted CuCr Allloys as contact material for vacuum interrupters", Siemens Forschungsberichte Bd. 17, 105, 1988

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

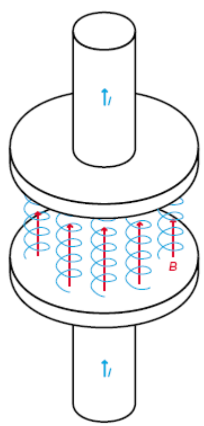


- The contact temperature should drop below 1900 K at current-zero so that metal vapor density is low and part of the contact material is solidified (Cr-grains).
  - However, neutral metal vapor emitted from hot surfaces is not likely causing breakdown, unless too high currents are accidentally applied.
- 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.



Transverse magnetic field contact



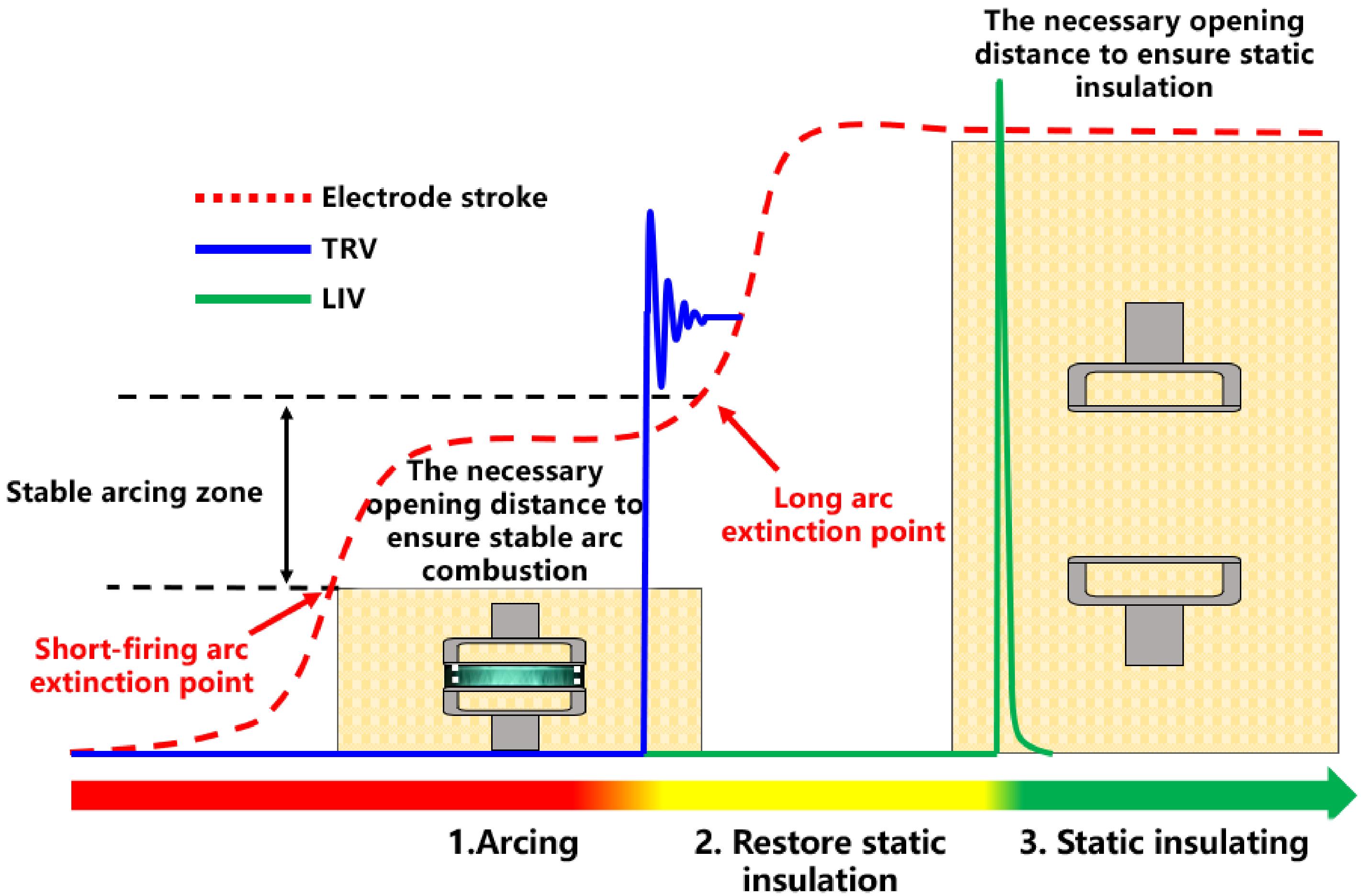
Axial magnetic field contact

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

Part 3: Extension of Vacuum Interrupter to Higher Voltages

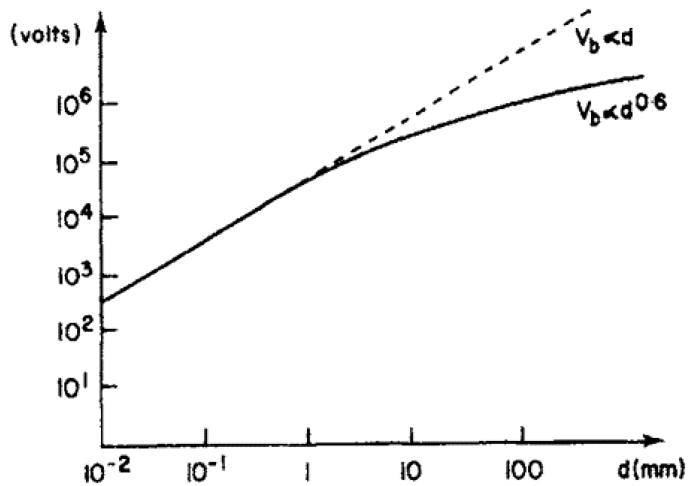
Current interruption at higher rated voltages

Higher rated voltage requires higher contact gap distance.

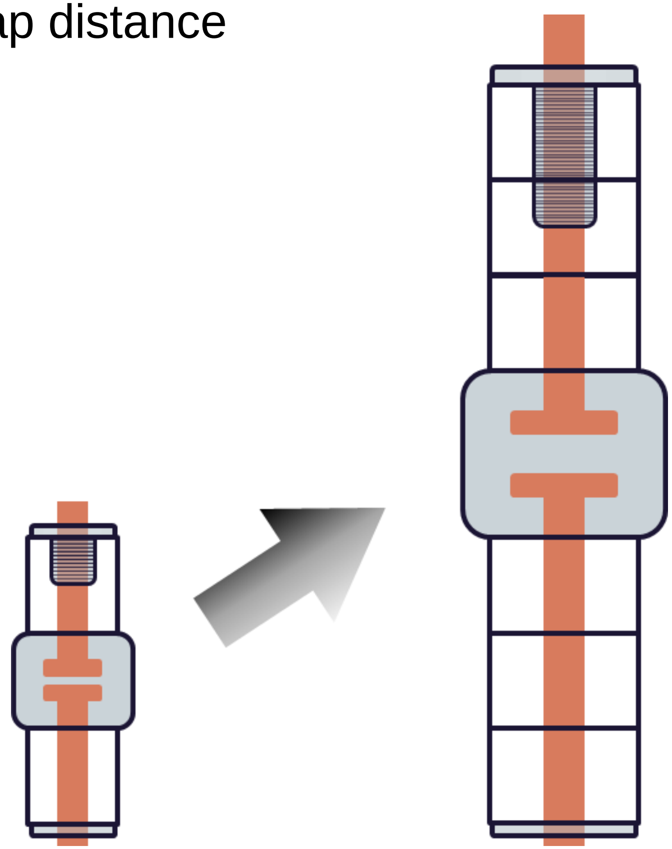


Vacuum Insulation for High Voltage Vacuum Interrupters

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 …

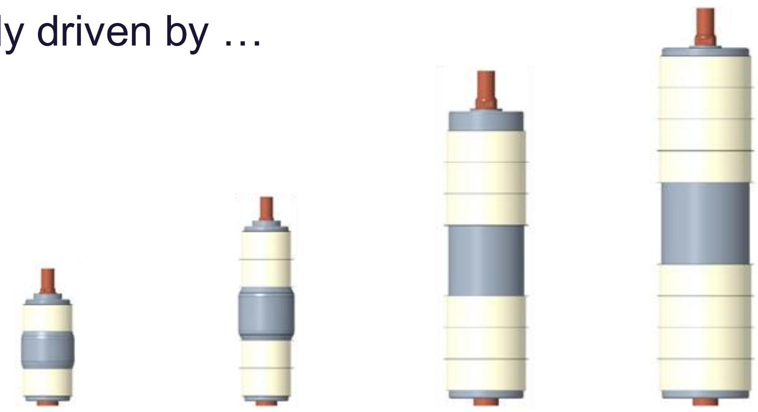
- length
- diameter

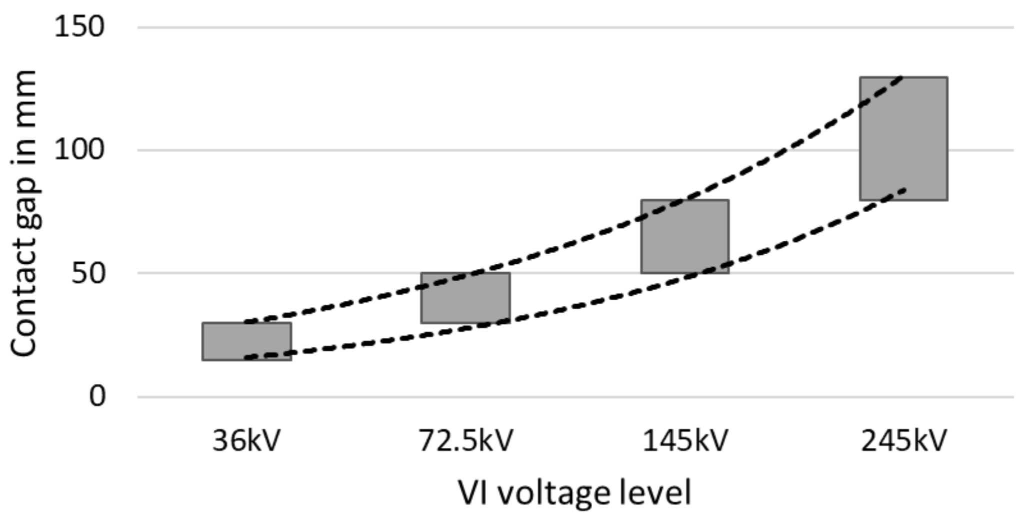
Medium to high voltage

→ 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





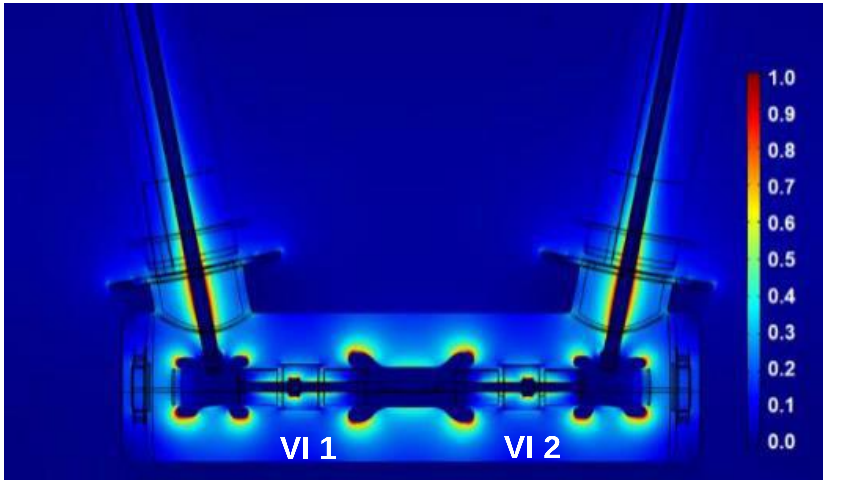
Single break VIs for all voltage levels …
… or better series connections of HV VIs?

Single break VIs

- 145/170kV are state-of-the-art
- 245/252kV are in development
- Higher voltage levels are conceivable, obstacles i.e.:
  - manufacturability, weight, handling, …
  - economic reasons

Series connections of VIs

- VCB designs with double- or multi-breaks are an appropriate measure
- High voltage: solution with MV and HV VIs are well-known and partly in operation
- **Extra** high voltage: solutions with HV VIs are currently in development



Electric field in a metal-enclosed circuit breaker with series-connected vacuum interrupter units for 420kV

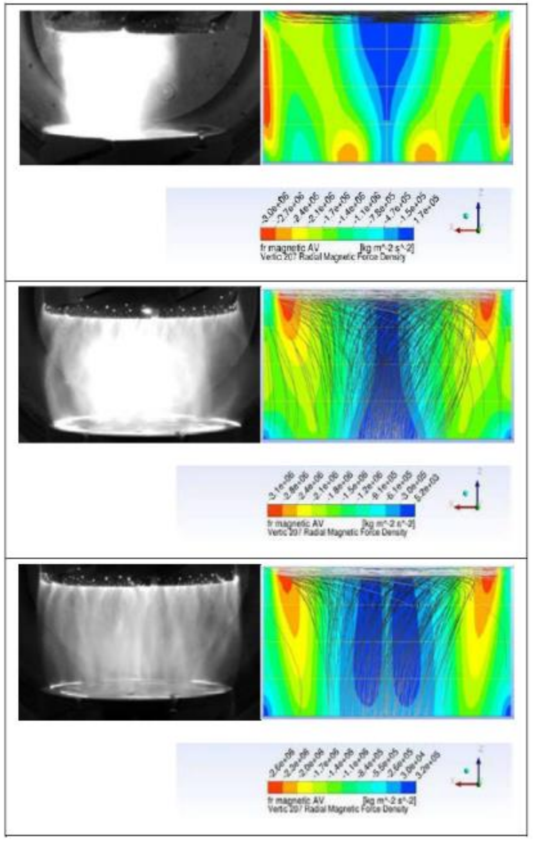
G. Nikolic et al. "Basic aspects of switching with series-connected vacuum interrupter units in high-voltage metal-enclosed and live tank arrangements", CIGRE Conference paper A3-112, 2020

Plasma control for large contact gaps
High power aspects

A successful and reliable current interruption is based on the control of the arc plasma state in the large contact gap.

- TMF contacts:
  - Constricted arc mode (high energy impact on contact surface)
  - Arc is difficult to control at high currents and large contact gaps with direct unpredictable interaction with the interrupter chamber
- AMF contacts:
  - Diffuse arc mode (makes use of the entire contact surface)
  - Arc can be controlled over the whole switching operation in the desired volume

→ AMF contacts mostly used in HV VIs, due to better controllability of the arc @ larger contact gaps



Constricted Arc
Insufficient plasma control (weak AMF)

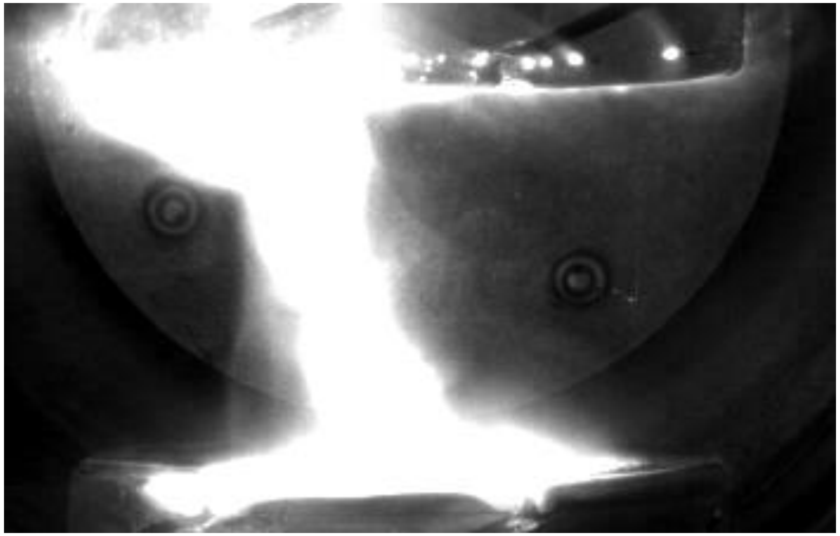
Partly constricted Arc (marginal AMF)

Diffuse Arc
Sufficient plasma control (strong AMF)

High-speed videography of AMF contact in combination with 3D simulation

N. Wenzel et al., "Combined experimental and theoretical study of constriction threshold of large-gap AMF vacuum arcs", ISDEIV 2014

Plasma control for large contact gaps
High power aspects



Diffuse Arc
Sufficient plasma control
(strong AMF)

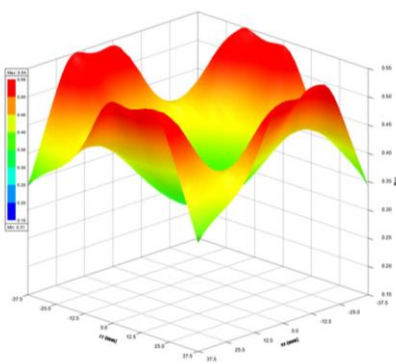
Constricted Arc
Insufficient plasma control
(weak AMF)

Gap control for large contact gaps High power aspects

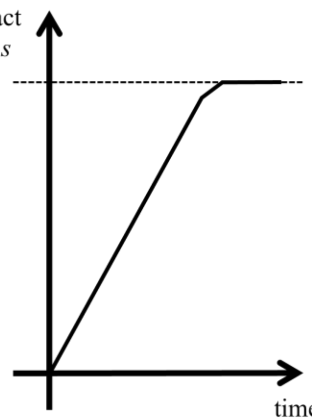
To keep the arc diffuse in a large contact gap …

- Coil formers integrated in the contact system
- Stepped motion characteristic (becomes more important with increasing voltage level)

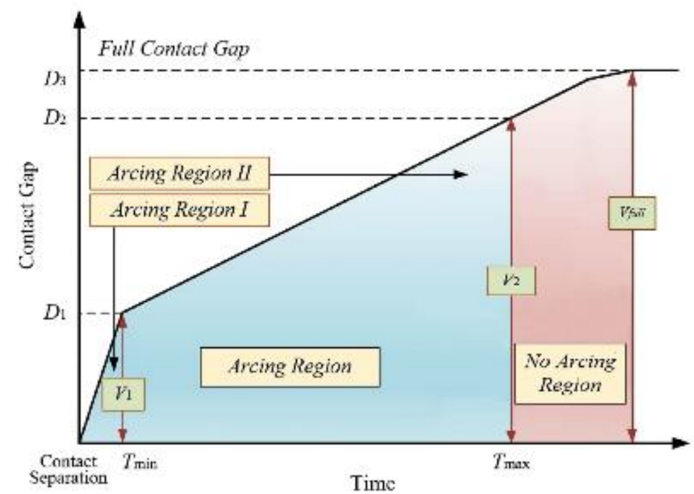
AMF decreases with the increase of contact gap



Typically for 72.5kV and below



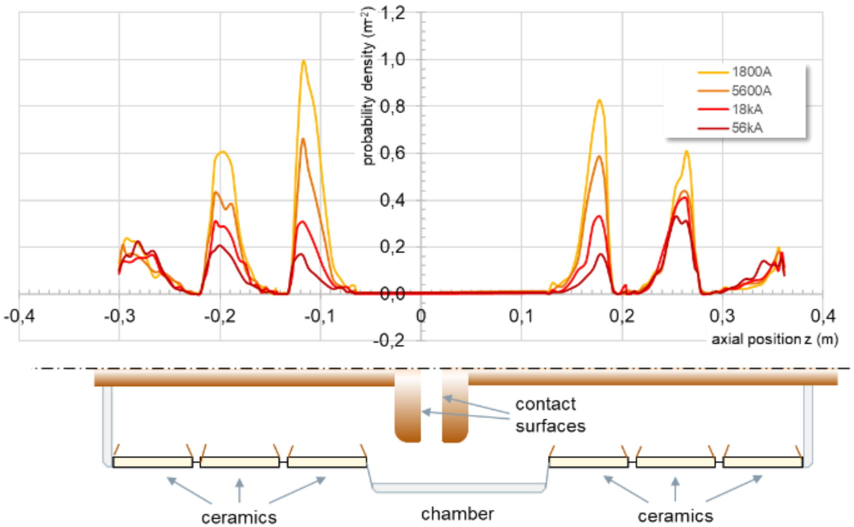
Proposal for higher voltages



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

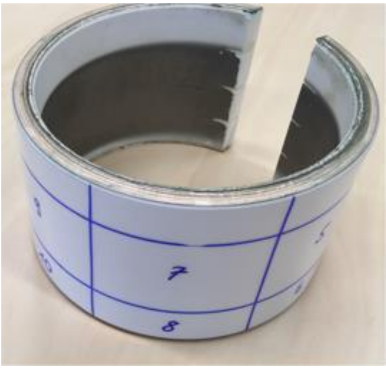
Metal vapor deposition control on the ceramic insulation as aspect for the dielectric

- During switching operation, part of the metal vapor may condense on the ceramic
  - ➢ Vapor shields prevent the build-up of a metal layer

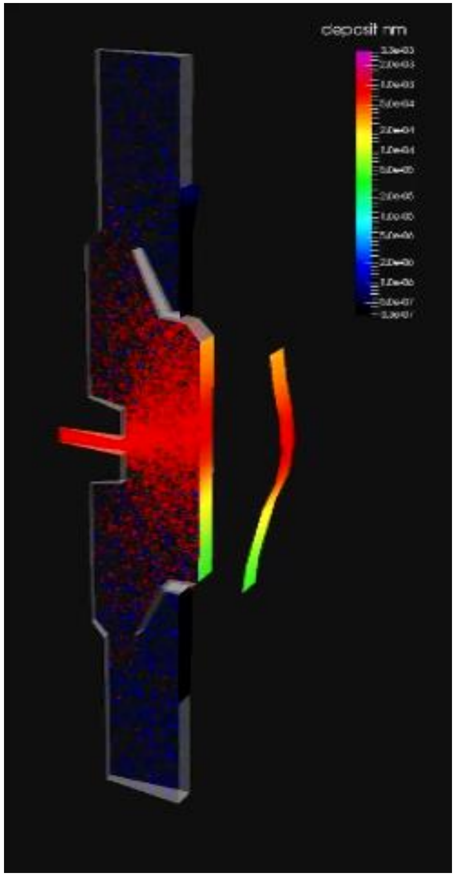


Probability of particle deposition on the ceramic surface

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



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



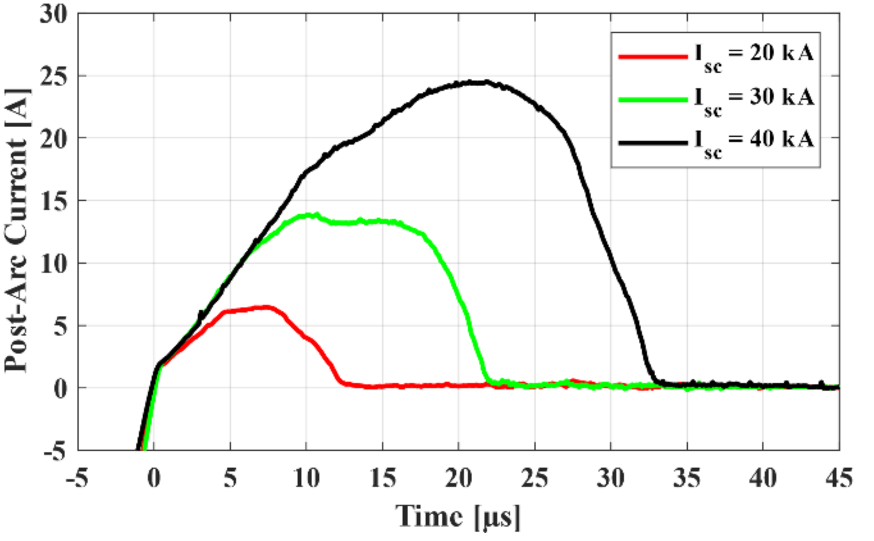
Animation of particle movement and deposition

- Different current levels yield to different evaporation rates
  - ➢ Simulations shows that the probability drops with increasing current for ceramics close to the contact gap

Plasma control for large contact gaps

Post-arc currents are small currents after short-circuit current interruptions

- Represent the flow of charge carriers out of the contact gap
- Well-known from medium voltage and sufficiently investigated
- For HV VIs, the post-arc currents tends to much higher values
  - Duration: some µs to some tens of µs
  - Peak of current flow: several amperes
- Behavior is of particular interest for HV levels (characterization of current interruption process)



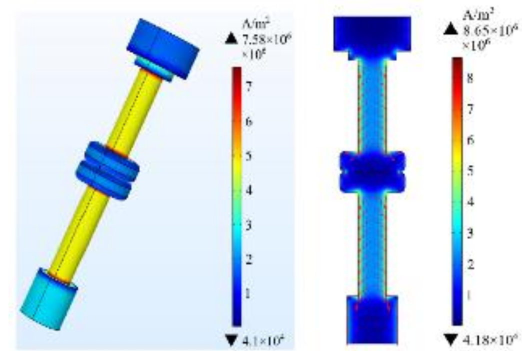
Post-arc currents after breaking operations with different short-circuit currents in a HV VI

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

High voltage vacuum interrupter specific aspects

Continuous current:

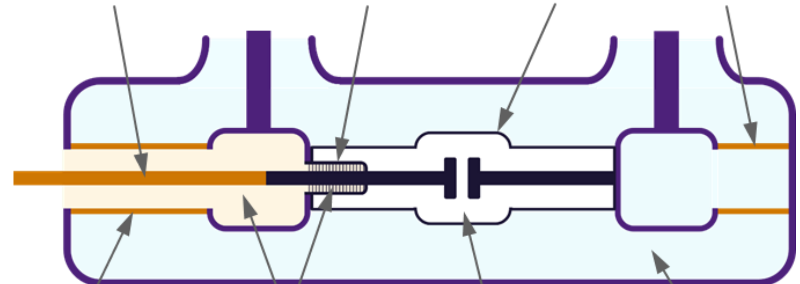
- Contact configuration needs to conduct very high continuous current (3150A → 6300A)
- Long contact stem makes heat conduction from the contact system more challenging



X. Yu et al., "Investigation on the Thermal Performance of a 363 kV Vacuum Circuit Breaker Using a 3D Coupled Model", IEEE Access 2019, D0I1109/ACCESS.2019.2938313

Environment for HV VIs with external gas insulation:

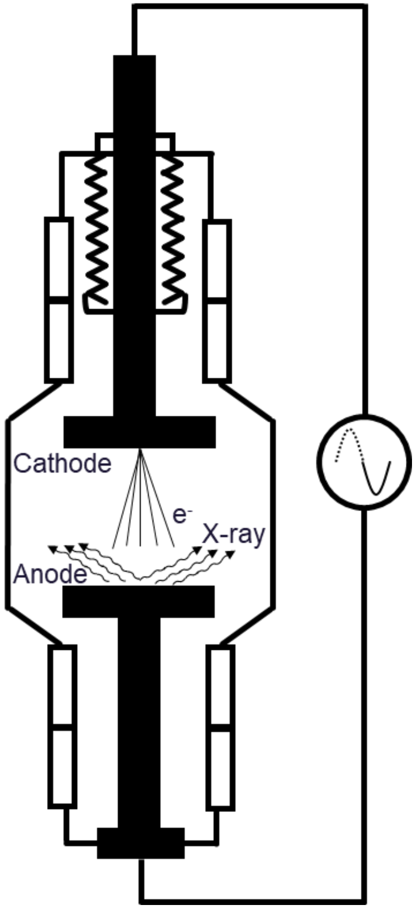
- High external insulation pressure (in case of SF6-free) requires mechanical design modification for the VI bellows, end caps etc.



Sketch of a dead tank VCB with two gas compartments; metal bellows are kept at low or nearly ambient pressure

X-rays by HV VIs

- VIs can be a source of stray radiation when HV is applied to the open contacts
  - Characteristic X-radiation and *Bremsstrahlung* can occur
  - Dose rate increases with U^4, decreases with $1/g^2$ (contact gap)
- Typically, international standards propose limits for the X-radiation (e.g., IEC, IEEE/ANSI)
  - Differentiation between service condition (e.g. line to ground voltage in the grid) and test situation (e.g., type test, routine test)
  - Experience: Initiation voltage of X-radiation is significantly higher than the rated voltage U_r



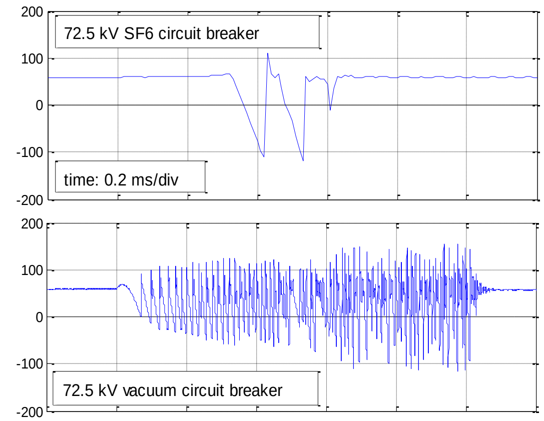
Type test condition (IEC & IEEE/ANSI)		
Rated voltage U_r	$U_d \leq 160$kV(1)	$U_d > 160$kV(1)
Emission level shall not exceed 5µSv/h @1m distance	Emission level shall not exceed 150µSv/h @1m distance	If the emission level exceed 150µSv/h @1m distance → actual value shall be declared by manufacture

(1) Rated short-duration power-frequency withstand voltage U_d = 140…160kV corresponds to U_r = 72.5kV

Special switching applications
Switching of small inductive currents

Inductive current switching can be classified in two main categories:

- Switching of transformers
  - in general, uncritical
  - transformer-limited faults: VIs offers better performance than gas CB
- Switching of shunt reactors, mitigations:
  - oversized VCBs (e.g., tertiary winding)
  - point on wave switching
  - RC filter circuits, well proven concept from MV
- <u>Experience</u>:
  Pilots in service without any issues



K. Niayesh et al., “Green HV Switching Technologies for Modern Power Networks”, IET book ISBN-13: 978-1-83953-710-3, 2023

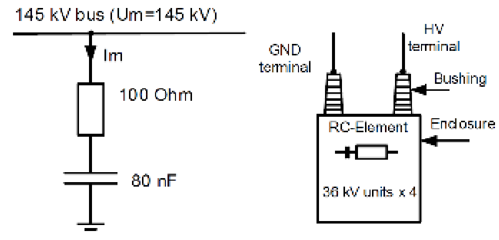


Fig. 7. Rating of RC suppressor for 145 kV system

K. Trunk et al., “Small Inductive Current Switching with High-Voltage Vacuum Circuit Breakers”, ISDEIV conference 2021

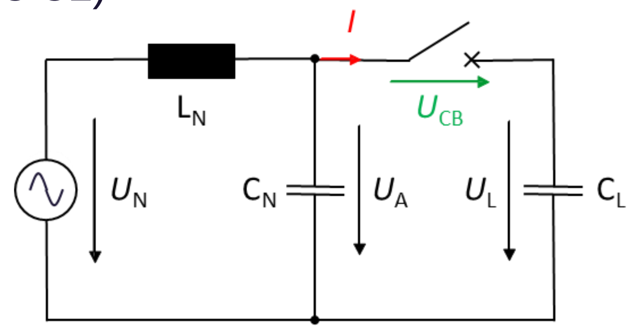
RC filter circuit for 145kV application with VCB

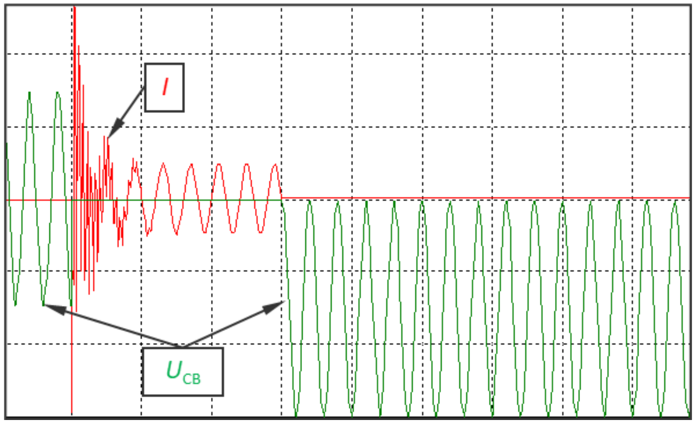
T. Heinz et al., “Why vacuum technology is not a simple scaling from medium to high voltage”, ISDEIV 2023

Special switching applications
Switching of capacitor banks at higher voltages

Switching of capacitive currents mostly requires CBs with low or very low probability of restrikes (e.g., IEC 62271-100; class C2)

Load case	Inrush current	Load current	Difficulty to meet the requirements
Unloaded lines and cables	Negligible	up to several 100A	Low
Single capacitor bank	Small	several 100A	Medium
Back-to-back capacitor bank	High	several 100A	High





Switching of lines and cable: CO - Operation

Cigre Paris 2012, SC A3-12 Discussion Group Meeting

<u>Unloaded lines and cables</u>:
- Solutions based on HV VCB are commercially available

<u>Capacitor banks (B2B):</u>
- Solutions for higher voltages are in development
  - micro-weldings on the contact surfaces (i.e., 20kA with 4250Hz)
  - pre-arcing time and limiting of the energy

Part 3: Summary and outlook

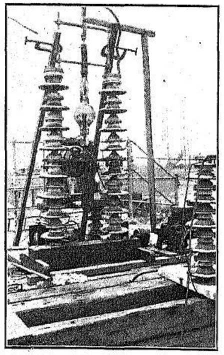
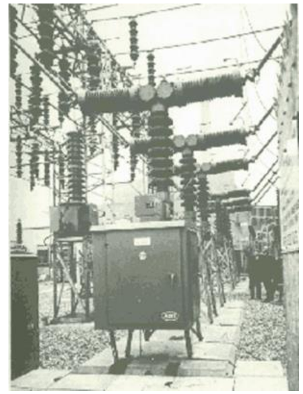


Fig. 7—Vacuum Switch No. 3

1926



1968

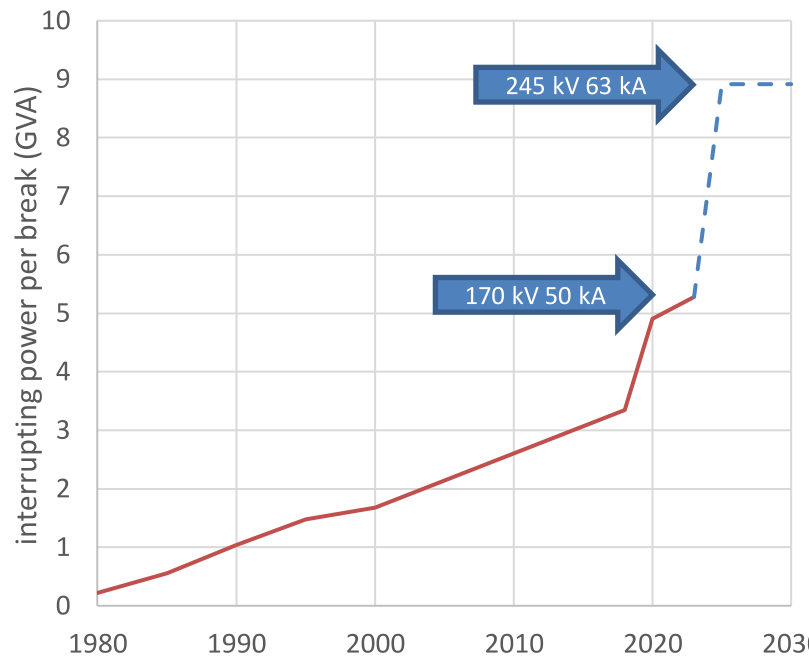
2023

<u>High Voltage Vacuum Interrupters:</u>

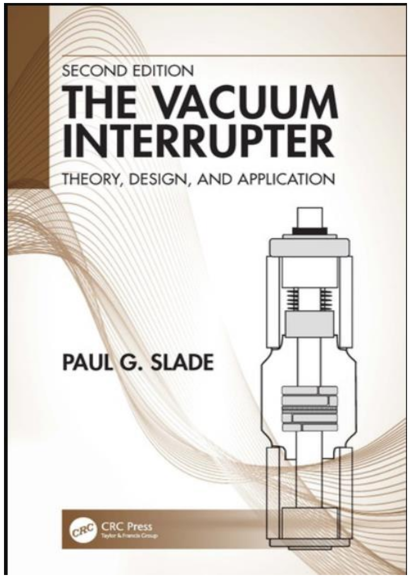
- Dielectric requirements → larger contact gaps
- Current interruption → plasma control essential for successful current interruption
- Normal rated current → up to 4000A

<u>Future development:</u>

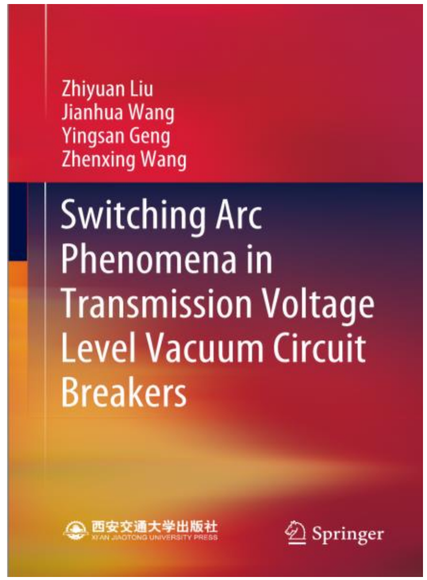
- Dielectric → 252kV single-break & multi-break above 252kV
- Normal rated current: 4000A → 5000A
- Short circuit current: 63kA → 80kA
- Special applications → capacitor banks (B2B)



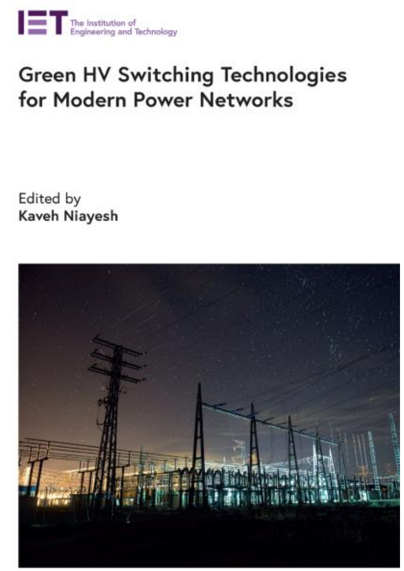
Further reading



2021



2021



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)

Conferences related to vacuum switchgear:

- CIGRE Conference — 2024/08 Paris, France
  https://www.cigre.org/GB/events/paris-session-2024
- Intern. Conf. on Electr. Power Equipm. - Switching Techn. — ICEPE-ST — 2024/11 Xiamen, China
  https://icepe2024.aconf.org/
- Intern. Symp. on Diel. Insulation and Discharges in Vacuum — ISDEIV — 2025/09 Chengdu, China
  https://isdeiv.events/home

Current Zero Club

CZC