University of Stuttgart
Institute of Power Transmission and High Voltage Technology (IEH)

- Basic principles of vacuum interrupters
- Experimental test setup
- Statistical evaluation
- Conclusion of the results
- Outlook on further aspects

Factors influencing the Chopping Current in Vacuum Interrupters

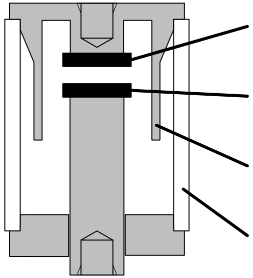
M. Fischer[1], M. Beltle[1], S. Tenbohlen[1], D. Gentsch[2], W. Ebbinghaus[2]
[1]University of Stuttgart
[2]ABB AG

9th ITG International Vacuum Electronics Workshop (IVEW) 2024
Bad Honnef, Germany

Vacuum interrupters Basics

Vacuum interrupters
Overview

- Mainly used in the medium voltage switchgear

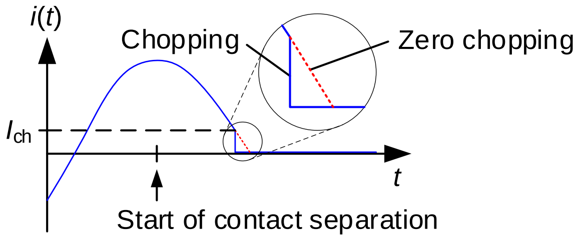


- Properties:
  - 👍 Compact size
  - 👍 No maintenance required
  - 👍 Long life (up to 1.000.000 switching cycles)
  - 👎 Current chopping during opening operations
    - ➢ Transient overvoltages especially at inductive loads → damages and EMC issues

- Two fundamental types
  - Contactors/load break switches: Interruption of operational currents
  - Circuit breakers (CBs): Interruption of short circuit currents

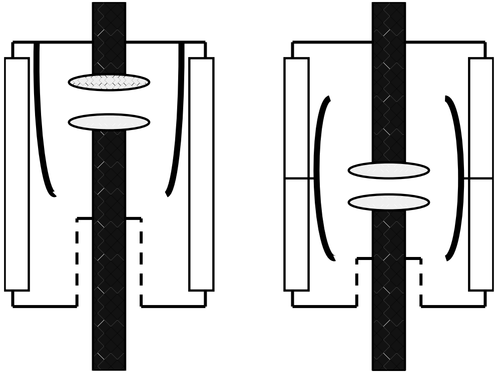
Vacuum interrupters
Current chopping

After passing the current peak	• Decreasing number of cathode hotspots building the arc
Decreasing energy	• Vapor generation decreases → Decreasing charges
Current chopping	• Abrupt at I_{ch} before natural zero crossing
At inductive loads	• OVERVOLTAGES: $u(t) = L \cdot di(t)/dt$
Target: Minimization of I_{ch}	• Optimized contact materials • Superimposed external magnetic field • Synchronized switching → Expensive equipment • Surge arresters → Only addressing the effects of chopping



Vacuum interrupters
Influencing the chopping phenomena I

- **Contact material**
  - Arc consists of vaporized material → Target: Increasing of emission rate [2]
    (Partly conflicting with breaking capacity of circuit breakers → Erosion resistance)
  - Example, Cu: $I_{ch} \geq 20$ A [3]
    - ➢ Using composite materials
    - WCAg (contactor): $I_{ch} \approx 0.7$ to 2.5 A
    - CuCr (circuit breaker): $I_{ch} \approx 5$ A
- **Electrical connection of vapor shield**
  General purpose: Prevention of vapor accumulation
  - Fixed potential (mechanically connected with fixed contact) or floating potential
  - Impact only for superimposed magnetic field



P. G. Slade: "The Vacuum Interrupter: Theory, Design, and Application: Second Edition," Boca Raton: CRC Press Taylor & Francis Group, 2021.

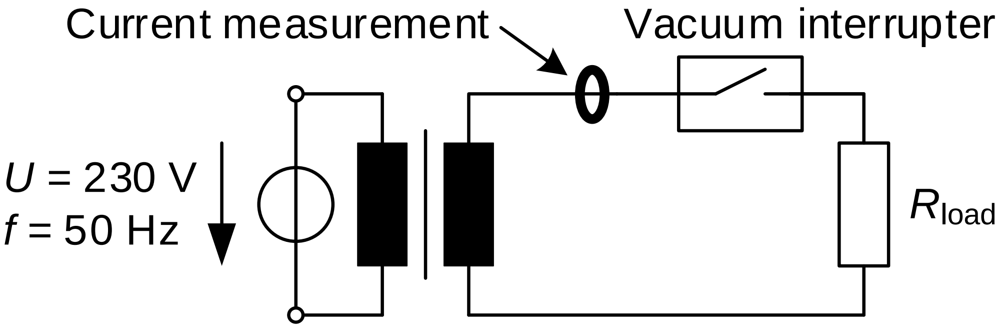
Vacuum interrupters
Influencing the chopping phenomena II

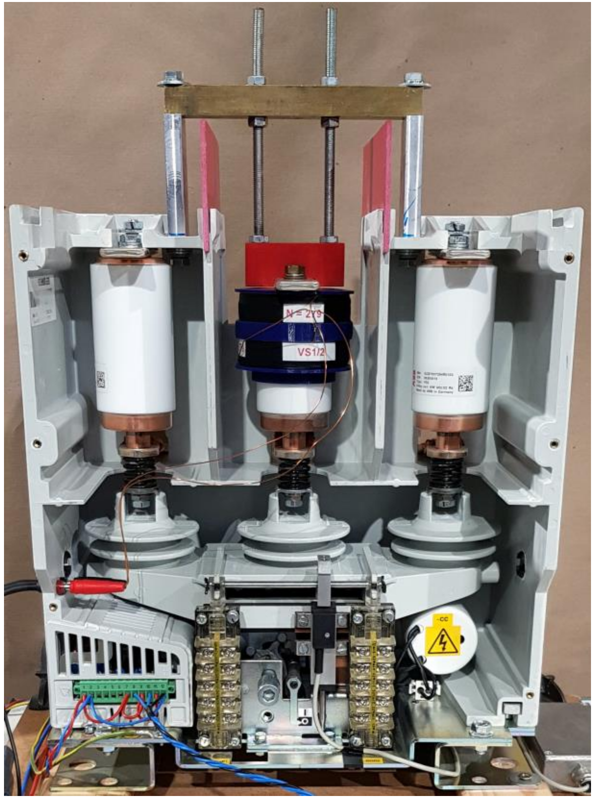
- **Axial magnetic field**
  - Effect depending on used material
  - Increasing I_{ch} with rising magnetic flux density for contactor materials 
    - ➢ Best case without applied field (B = 0 T)
  - Parabolic trend for CB materials 
    - ➢ Minimization for $B \geq 80$ mT
- **Opening speed (contact separation)**
  - Correlation between arcing time and opening speed in [4, 5] 
    - ➢ Faster opening speeds lead to reduced arc burning time → increased I_{ch}
  - Result in [6]: Slower speed reduces I_{ch} by extending the arcing time

Experimental test setup

Experimental test setup
Mechanical components

- **Commercial contactor**
  - ➢ Modified for different chamber sizes
- **Resistive load circuit**
  - ➢ Only chopping phenomena and not its effect on an inductive load is considered

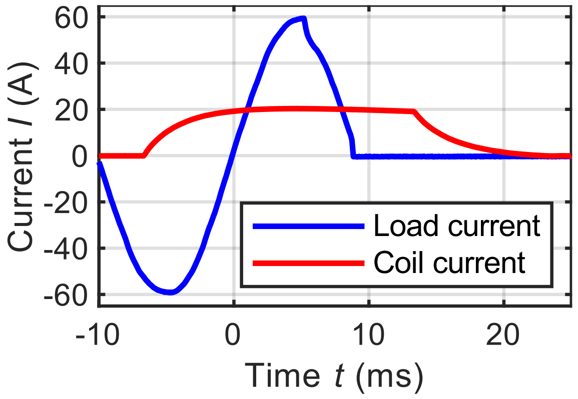




Experimental test setup

Automated statistical evaluation of switching operations (interruptions)

- **Automated interruption operations via microcontroller and Python/MATLAB**
  - 50 operations for each setup with continuous plausibility check
    - ➢ Statistical evaluation
  - Synchronization on load current
    - ➢ Arcing always in positive maximum before zero crossing
  - Generation of external axial magnetic field

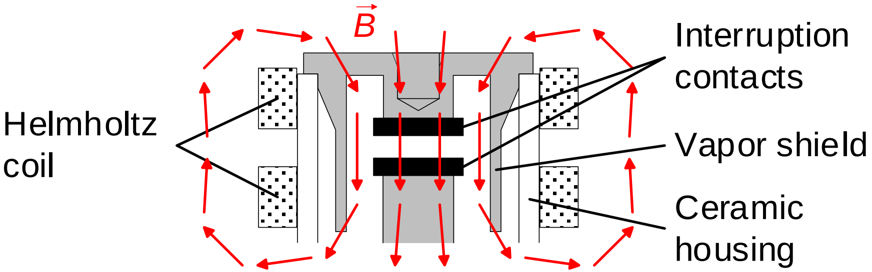


- **Measurement of**
  - Load current & chamber voltage
  - Coil current → Magnetic field generation
  - Travel curve of interruption contacts
- **Interruption speeds**: $v_1 \approx 0.7$ m/s and $v_2 \approx 0.35$ m/s

Experimental test setup

Generation of axial magnetic field I

- Homogeneous axial magnet field at contact area
  - ➢ Using a Helmholtz coil
- Range of magnetic flux density *B*
  - ➢ From 0 mT up to 100 mT: 10 mT steps
  - ➢ From 100 mT up to 200 mT: 20 mT steps
- *B* within the chamber not measurable
  - ➢ Step I: Calculation via geometric properties of the coil and feeding current:



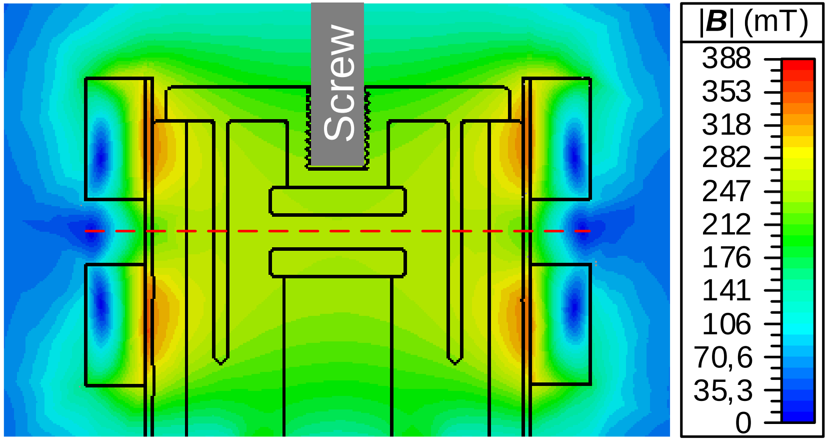
$$B = \frac{8 \cdot \mu_0 \cdot N \cdot I}{\sqrt{125} \cdot r}$$

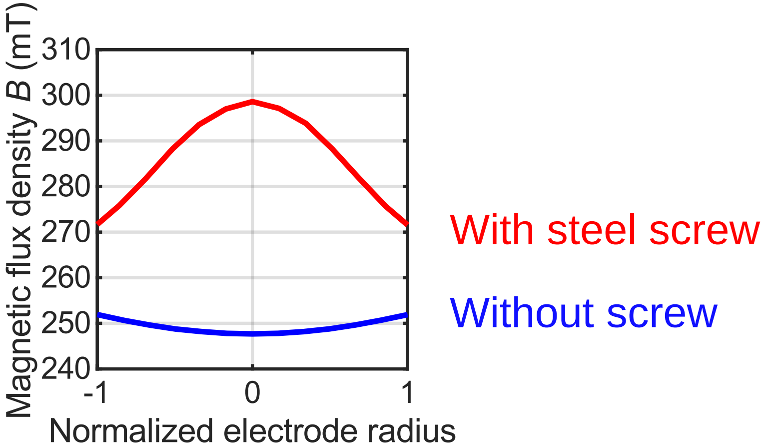
N = number of windings per coil; r = average coil radius

Experimental test setup

Generation of axial magnetic field II

- Step II: FEM simulation (static magnetic field)
  - Design for maximum flux densities with B = 250 mT at I_{coil} = 30 A





- Homogeneous distribution if screw with μ_r = 1 is used (e.g. copper, brass)

Experimental test setup
Contact materials

- Investigated composite materials:

Name	Material	Application
Material A	Cu-based + small ratio of carbon-based additive	Contactor
Material B	CuCr-based + small ratio of oxide additive	Circuit breaker
Material C	CuCr-based + higher ratio of oxide additive	Circuit breaker
Material D (Reference)	WCAg40-wt%[1]	Contactor
Material E (Reference)	CuCr35-wt%[1]	Circuit breaker

Note: all vacuum interrupters are provided by ABB and close to series production

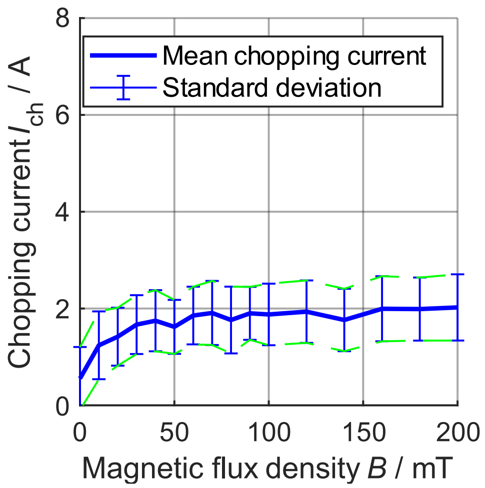
[1] wt%: weight percent

Statistical evaluation

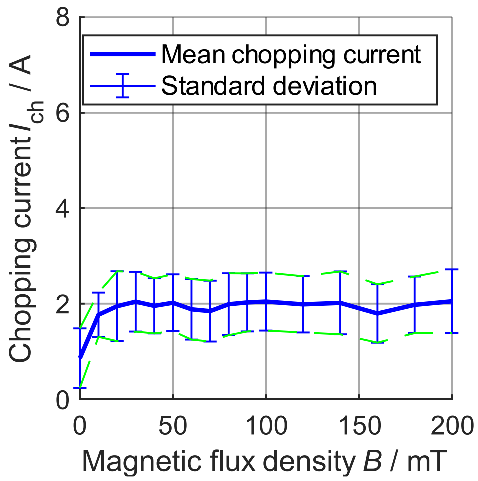
Statistical evaluation

Contact materials and superimposed magnetic field I ([6])

Material A: Cu-based *plus*



Material D: WCAg40-wt%

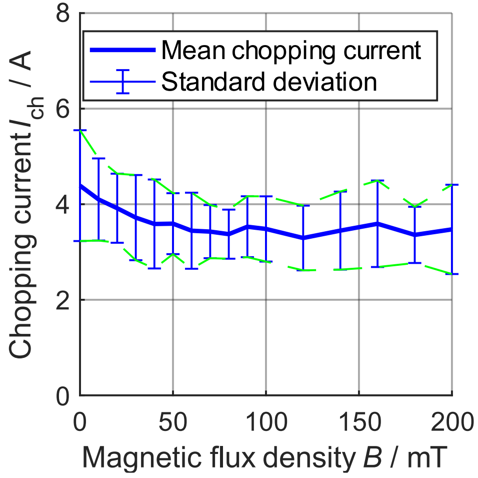


- Min. I_{ch} without superimposed magnetic field
- Increasing I_{ch} with rising B
  - Negative impact on chopping behavior

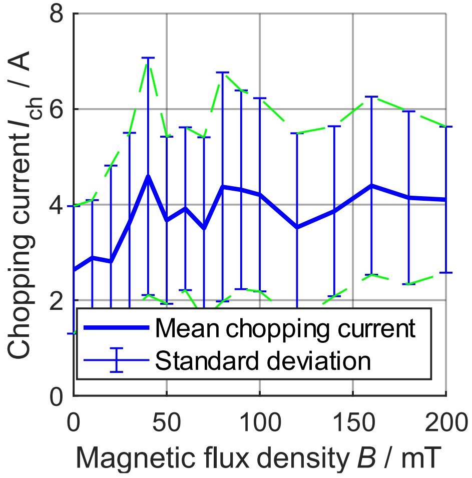
Statistical evaluation

Contact materials and superimposed magnetic field II ([6])

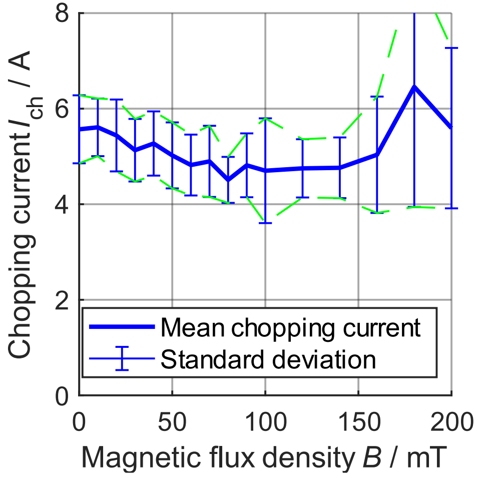
Material B: CuCr-based small *plus*



Material C: CuCr-based higher *plus*



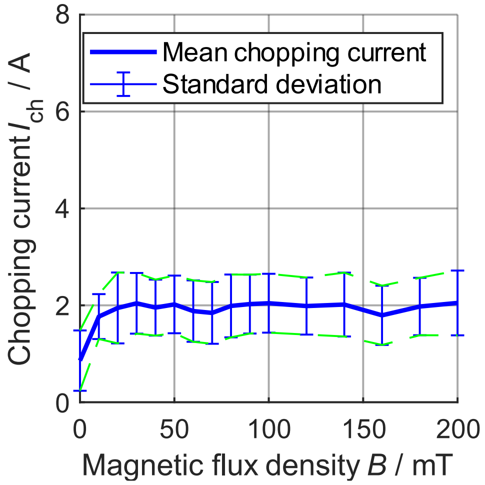
Material E: CuCr35-wt%



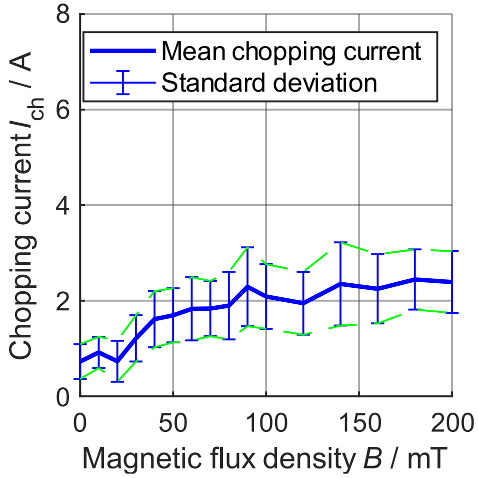
- Min. I_{ch} at $B \geq 80$ mT for material B and E
  - Typical parabolic trend for CuCr materials
- Low I_{ch} without magnetic field for material C
  - Comparable to material A (contactor application), high standard deviation

Statistical evaluation
Connection of vapor shield and superimposed magnetic field I ([7])

Material D (WCAg): Shield on fixed potential



Material D (WCAg): Shield on floating potential



- Comparable I_{ch} without superimposed magnetic field
- Greater impact at low B for shield on fixed potential
  - Fast increase to a nearly constant level

Statistical evaluation
Opening speed without superimposed magnetic field ([6])

Material	I_{ch} / A at $v_2 \approx 0.35$ m/s	I_{ch} / A at $v_1 \approx 0.7$ m/s
A (Cu-based *plus*)	1.12	1.02
B (CuCr-based small *plus*)	3.97	4.41
C (CuCr-based higher *plus*)	3.39	5.53
D (WCAg40-wt%)	1.06	1.62
E (CuCr35-wt%)	3.67	4.03

- No optimization for material A
- Reduction of I_{ch} at lower speed for other materials
  - Material B (ΔI = 0.4 A), D (ΔI = 0.6 A) and E (ΔI = 0.4 A): Low optimization
  - Material C (ΔI = 2.2 A): High optimization

Conclusion & Outlook

Conclusion

- **Significant improvement using additives especially for materials in circuit breakers**
  - Behavior like contactor application for material C (CuCr-based higher *plus*)
- **Influence of superimposed axial magnetic field depends on contact material**
  - Contactors: Worsening for increasing B
  - CBs: Min. I_{ch} at middle flux densities; typical parabolic trend
- **Electrical connection of vapor shield shows only qualitatively changes over B**
  - No improvement in I_{ch}
- **Lower interruption speeds can reduce I_{ch}; but no direct correlation between materials**
  - No changes for material A (Cu-based)
  - Highest improvement for material C (CuCr-based higher *plus*) → $\Delta I = 2.2$ A

Outlook

- **More precise statistical analysis of the chopping behavior**
  - Evaluation of the median and outliers for the entire range of magnetic field (50 measurements for each B) using a boxplot
  - Probability distribution of all I_{ch} for interruption operations without superimposed magnetic field (B = 0 T)
- **Investigation of the influence of the load used**
  - Inductance instead of resistance
  - Varying resistance value in resistive circuit

University of Stuttgart
Institute of Power Transmission and High Voltage Technology (IEH)

Thank you!

Markus Fischer, M.Sc.

e-mail markus.fischer@ieh.uni-stuttgart.de
phone +49 (0) 711 685-61525
www.ieh.uni-stuttgart.de/en

University of Stuttgart
Institute of Power Transmission and High Voltage Technology (IEH)

High Voltage Laboratory Ostfildern
Nielsenstrasse 18, 73760 Ostfildern, Germany

References

[1] D. Broekere, A. Purczyński and K. Stefaniak, “Distribution of Chopping Current for Copper Electrodes in Vacuum in Axial Magnetic Field,” IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol. 8, no. 1, pp. 182-186, March 1985.

[2] L. Czarnecki, “Einfluß des Kontaktwerkstoffes auf Stromabriß und Löschung des Vakuumbogens,” Technische Universität Braunschweig: Dissertation, 1985.

[3] H. J. Lippmann, “Schalten im Vakuum,” Berlin: VDE Verlag, 2003.

[4] B. Zhang, J. Wang, S. Yanabu, J.Chen, Z. Liu, L. Sun and Y. Geng, “Minimum Arcing Interrupting Capability and Opening Velocity of Vacuum Interrupters: An Impact of Contact Diameters,” 28th International Symposium on Discharges and Electrical Insulation in Vacuum, pp. 591-594, 2018.

[5] W. Shi, B. Zhang, J. Wang, S. Ai, X. Yao, Z. Liu, Y. Geng, J. Wang and S. Yanabu, “Minimum Arcing Interrupting Capability and Opening Velocity of Vacuum Interrupters: An Impact of Magnetic Field,” 28th International Symposium on Discharges and Electrical Insulation in Vacuum, pp. 271-274, 2018.

[6] M. Fischer, M. Beltle, S. Tenbohlen, D. Gentsch, W. Ebbinghaus, “Influence of Switching Contact Materials with Superimposed Axial Magnetic Field on the Vacuum Arc’s Chopping Behavior,” 30th International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), Okinawa, Japan, June 25-30, 2023, pp. 177-180.

[7] M. Fischer, D. Christl, M. Beltle, S. Tenbohlen, D. Gentsch and W. Ebbinghaus, “Influences of Axial Magnetic Fields and Different Contact Materials in Vacuum Interrupters on the Chopping Behaviour of Switching Arcs,” 26th International Conference and Exhibition on Electricity Distribution – CIRED, Geneva/online, 2021.

Appendix

Vacuum interrupters
General creation of the switching arc

Rough contact surface

- Only few current-carrying points
- High current density
- Increased local heating during interruption

Liquid metal bridge

- Evaporating contact material at the moment of separation
- Bridge of liquid metal is formed

Vaporized particles

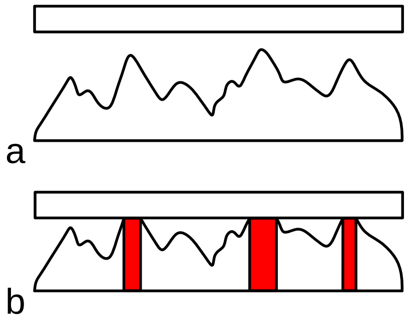
- Liquid evaporation when critical temperature is reached

Ionization

- Vaporized particles ionized trough electron collisions
- Additional ionization of metal vapor by avalanche mechanisms

Hot Spots & ARC

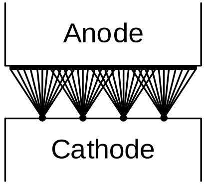
- High vaporization temperature creating hot spots on the cathode surface
- **Switching arc is being formed**

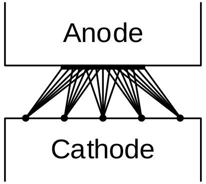


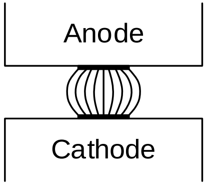
E. Vinaricky et al., “Elektrische Kontakte, Werkstoffe und Anwendungen,” Pforzheim: Springer-Verlag, 2016.

Vacuum interrupters
Different switching arc modes

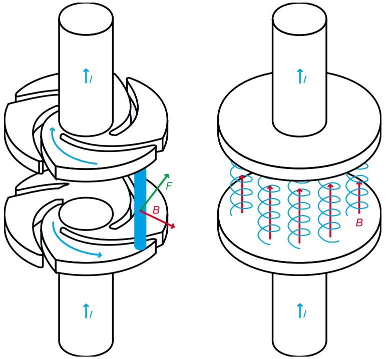
I ≤ 10 kA	• Diffuse mode with multiple homogeneous distributed hot spots on cathode and homogeneous distribution over anode surface
Above 10 kA	• Contraction on anode
Further increase	• Contraction on anode and cathode to column ➢High local stress for CBs ➢Prevention by magnetic field controlling contact geometries → Axial or radial magnetic fields [1]







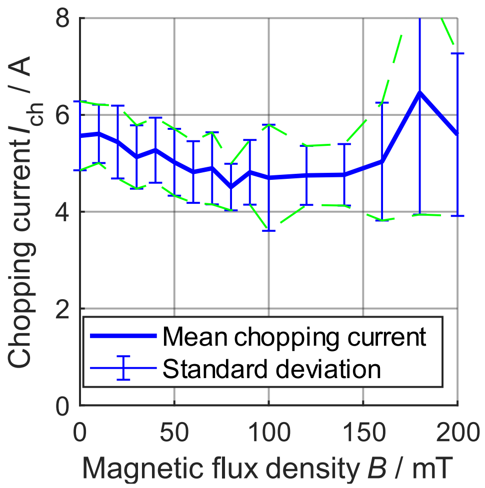
E. Vinaricky et al., "Elektrische Kontakte, Werkstoffe und Anwendungen," Pforzheim: Springer-Verlag, 2016.



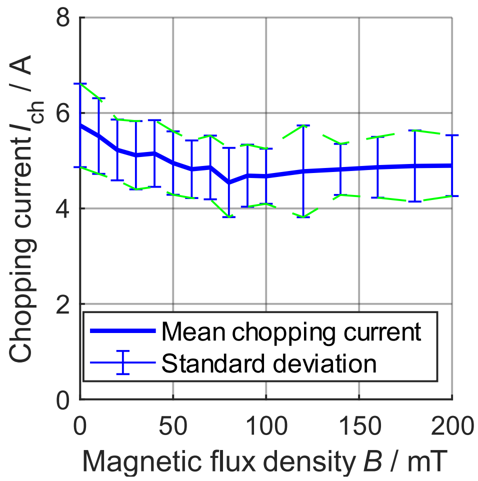
H. Fink, D. Gentsch, M. Heimbach: "Vakuumschaltkammern für Schütze und Lastschalter," ABB Technik 3/1999, pp. 32–36.

Statistical evaluation
Connection of vapor shield and superimposed magnetic field II ([7])

Material E (CuCr): Shield on fixed potential



Material E (CuCr): Shield on floating potential



- Also, comparable I_{ch} without superimposed magnetic field
- Stronger increase in I_{ch} at high B for shield on fixed potential