SHORT-CIRCUIT CURRENT INTERRUPTION IN LIQUID NITROGEN ENVIRONMENT

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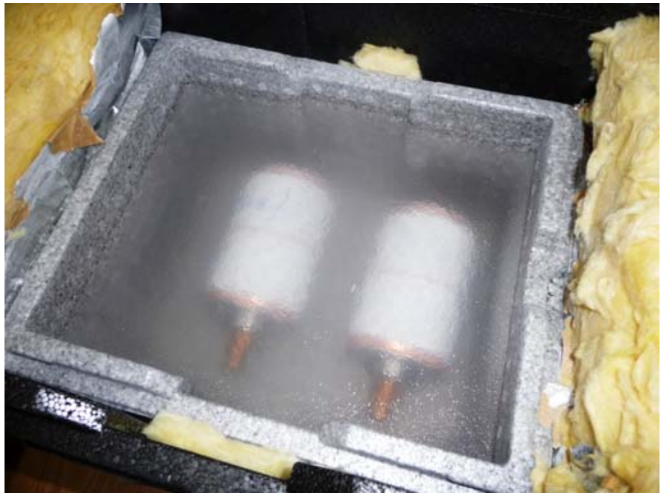

[Siemens]

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- Goals of the research
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  - mechanics, durability
  - electric on-state resistance
  - dielectric strength, internal and external
  - chopping current
  - short-circuit interruption capability
- Summary and outlook

Motivation

Feasibility Study (2009):

Konzept für eine effiziente Energieversorgung von Ballungsräumen

(Concept of an efficient electric power supply of urban load centers)

A study on superconducting equipment of electrical power supply systems

- state of the art
- required development
- recommended action for politics and the energy sector

[EW Medien und Kongresse GmbH]

Motivation

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Statements given:

- Ever changing load distribution and feed-in locations

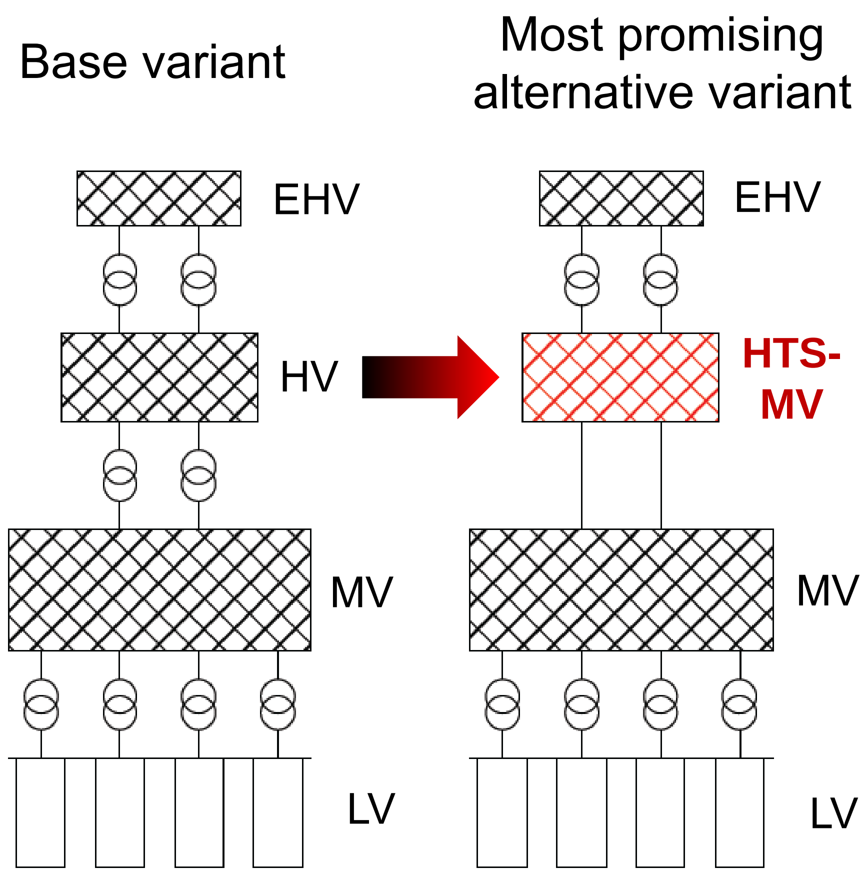
- Future electric power supply must be
    - *flexible/reliable*: adaptability to changing system conditions
    - *efficient*: in generation, transmission, distribution, and consumption

- Options to increase efficiency:
    - conventional technology often very close to its theoretical limits
    - **use of virtually loss-less high temperature superconducting equipment, and if possible, complete HTS subgrids**

Motivation

- Advantages of HTS grids:
  - lower losses
  - distinctly higher transmission capacity

- Most promising scenario:
  HTS medium voltage (MV) distribution grid, replacing the next higher system voltage (high voltage) level



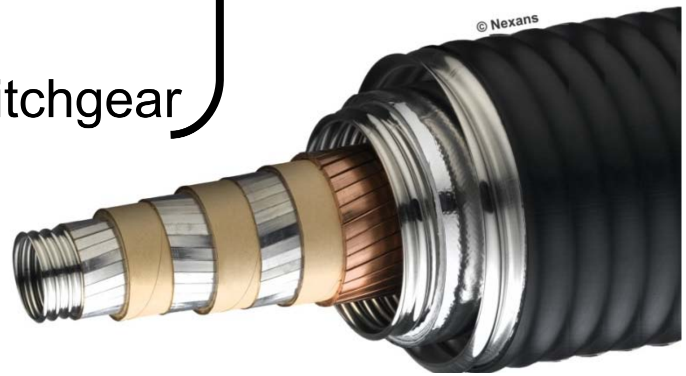
[EW Medien und Kongresse GmbH]

Motivation

Components of a high-temperature superconducting (HTS) power distribution network:

- ☑ cables
- ☑ fault current limiters
- ☑ transformers
- ☒ standard switchgear

} integration into the closed cycle cooling system (liquid nitrogen)



[Stadtwerke Augsburg]

Motivation

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Special requirements on switchgear for operation in LN_2:

- o switching of operating currents (network configuration) in the range of 5 kA
- o usually no short-circuit interruption due to HTS-FCLs, but short-circuit interruption capability as an option
- o very low on-state resistance (preferably ≤ 1 µΩ) to avoid losses at the high operating currents
- o temperature resistant down to 77 K (boiling temperature of LN_2)

Further general requirements: same as for conventional switchgear (dielectric performance, chopping current, …)

➡ **Vacuum breakers** **Why?**

A short consideration of alternative switching principles at 77 K

- Gas breakers (sulfur hexafluoride - SF_6):
  - condensation temperature of SF_6 at 1013 mbar: 209.35 K
  - even higher at higher pressures
  - ➢ **liquefaction**

- Oil or minimum oil breakers:
  - pourpoint typically in the range of 210 to 220 K
  - ➢ **solidification**

- Power semiconductor switches:
  - ➢ insufficient thermal activation of dopants („carrier freeze out")
  - ➢ intrinsic charge carrier density of silicon:

    @ 300 K: $9.7 \cdot 10^{9}$ cm^{-3}

    @ 77.8 K: $5.0 \cdot 10^{-20}$ cm^{-3}
  - ➢ **passivation**

…. and why not directly in LN_2?

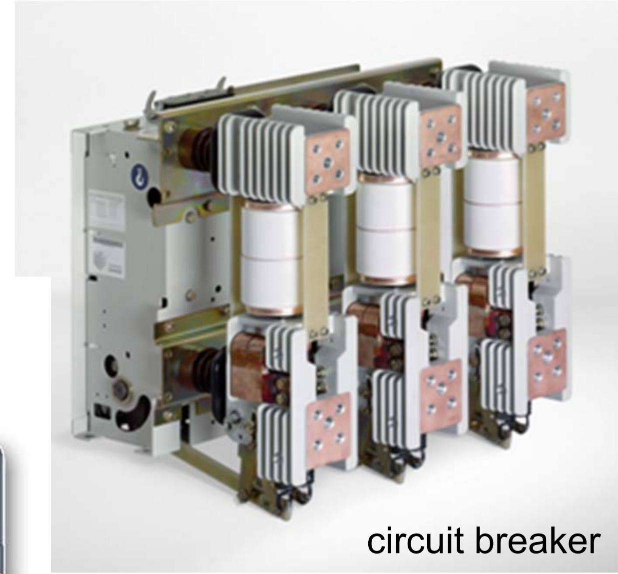
Goal would be: arc cooling and extinction by the low temperature, by pressure build-up, and by controlled gas/liquid flows

- using basically the same working principle as for SF_6-, oil- or water circuit breakers
- nitrogen expansion rate from liquid to gaseous: **1:694** – explosion like!
  - high-pressure tank necessary
  - direct integration in the closed cooling cycle not possible
  - additional active cooling required
- high recovery time (to be ready for next operation)
  - ➢ Applicability to short-circuit interruption and automatic reclosing cycles (e.g. O – 0.2 s – C – O – 3 min – C – O) **questionable**

General project goal (Ph.D. project Golde)

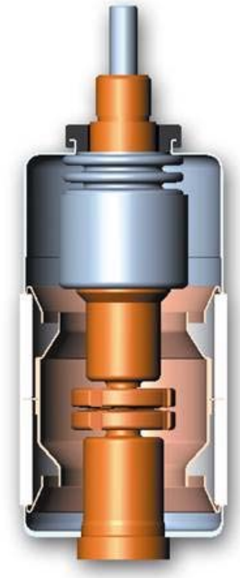
Investigations on all major electrical aspects of feasibility of vacuum switching technology in LN_2 environment

- basic research on performance and required adaptions
- but no development of a ready-to-use circuit breaker
- use of commercially available, state-of-the art vacuum bottles
- two different manufacturers
- different types per manufacturer



circuit breaker

[Siemens)



[ABB]

vacuum bottle

Overall project details

- Investigated aspects:
  - mechanics of the vacuum bottle (sealing integrity, durability of bellow)
  - electrical on-state resistance, new and after switching
  - internal and external dielectric strength under normally pressurized boiling LN_2
  - magnitude of chopping current
  - ***short-circuit current interruption capability***

- Final evaluation
  - general applicability
  - recommendations for future development

Short-circuit interruption capability

Not a general "must" for all future HTS applications, but one of the most important performance characteristics of a VI – therefore considered a "benchmark" of the impact of LN_2 environment

Nominal data of the investigated vacuum bottles (12 samples in sum from two different manufacturers):

- U_r = 24 kV
- I_s (r.m.s. value) = 20 kA
- TRV (peak value) = 41 kV
- time to peak = 87 µs

(test conditions acc. to common test standards)

[ABB, Siemens]

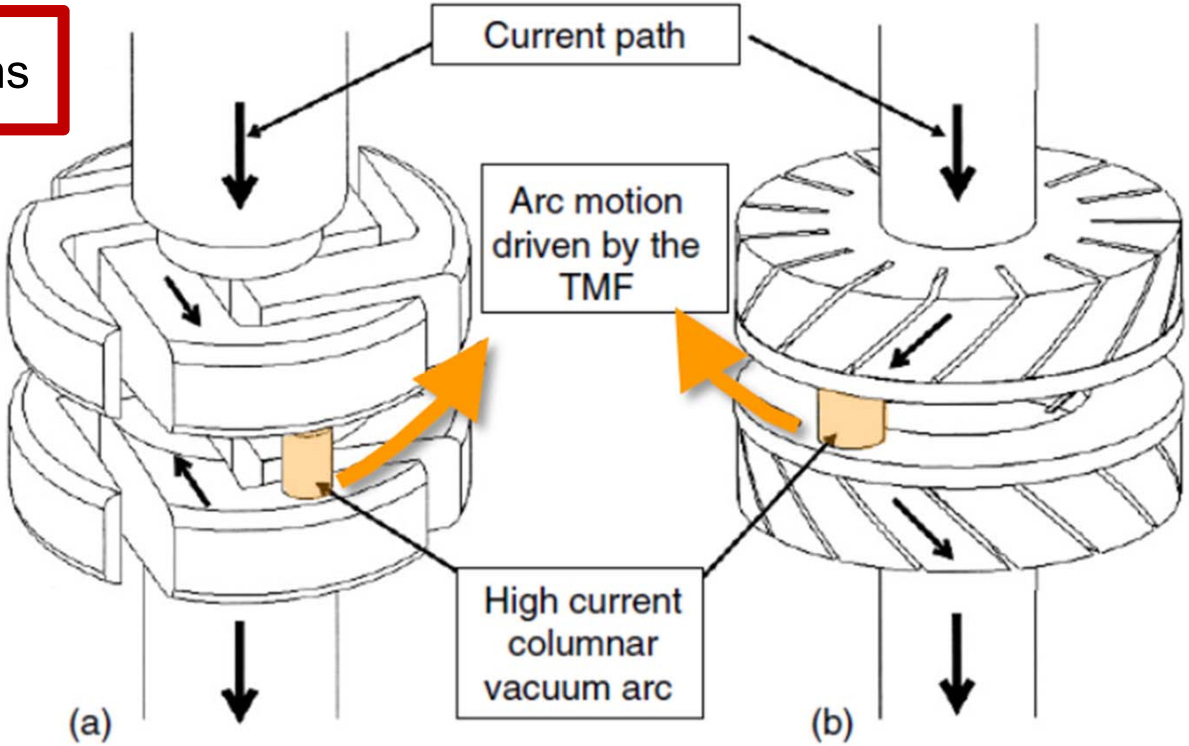
Short-circuit interruption capability

Possible effects of low temperature (77 K)

RMF/TMF contacts (**R**adial or **T**ransversal **M**agnetic **F**ield)

Spiral arms

Slotted cup



[acc. to Slade]

Short-circuit interruption capability

Speed of arc rotation (acc. to Dullni):

$$v_{\text{arc}} = \frac{8U_{\text{f}}^{2}(j/\pi)^{3/2}\sqrt{i}}{\lambda\zeta c(T_{\text{b}} - T_{0})^{2}}$$

U_{f} …. voltage across the contacts
j …. electron current density
i …. total current within the arc
λ …. thermal conductivity
ζ …. density of contact material
c …. specific heat capacitance
T_0 …. initial contact temperature
T_{b} …. final contact temperature

↑ Increase with temperature: λ, ζ

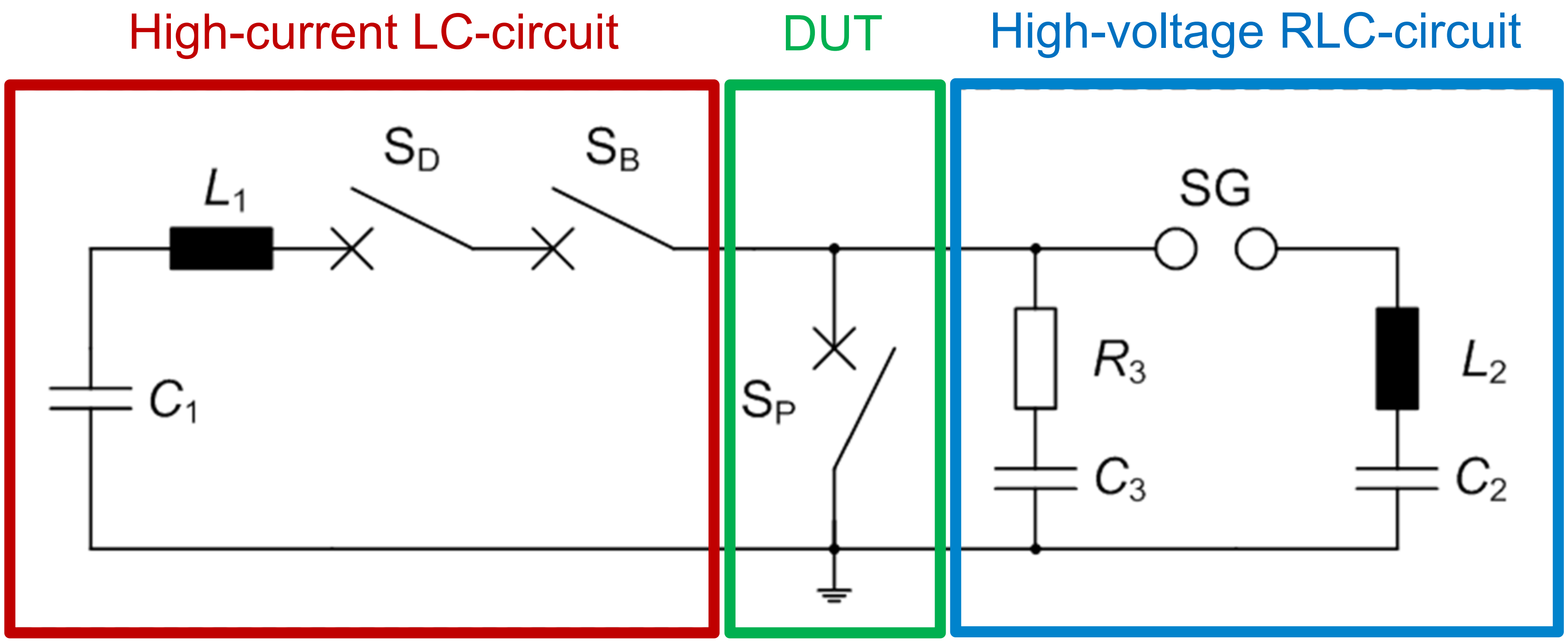
↓ Decrease with temperature: T_0, c

In sum, a decrease of v_{arc} can be theoretically estimated for 77 K.

→ Reduced interruption capability to be expected in doubt → **Tests!**

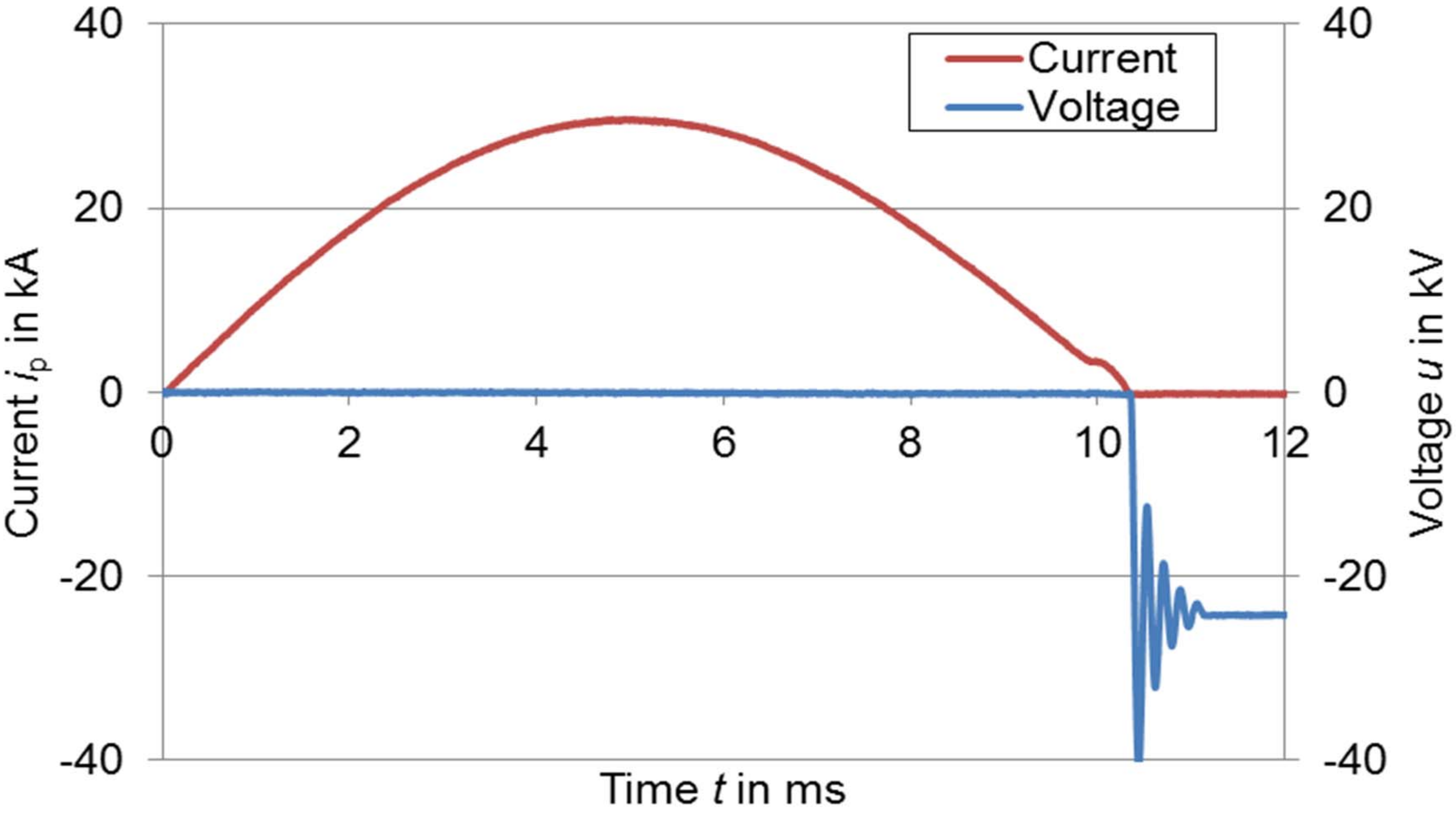
Short-circuit interruption capability

Synthetic test circuit acc. to *Weil-Dobke*:



Short-circuit interruption capability

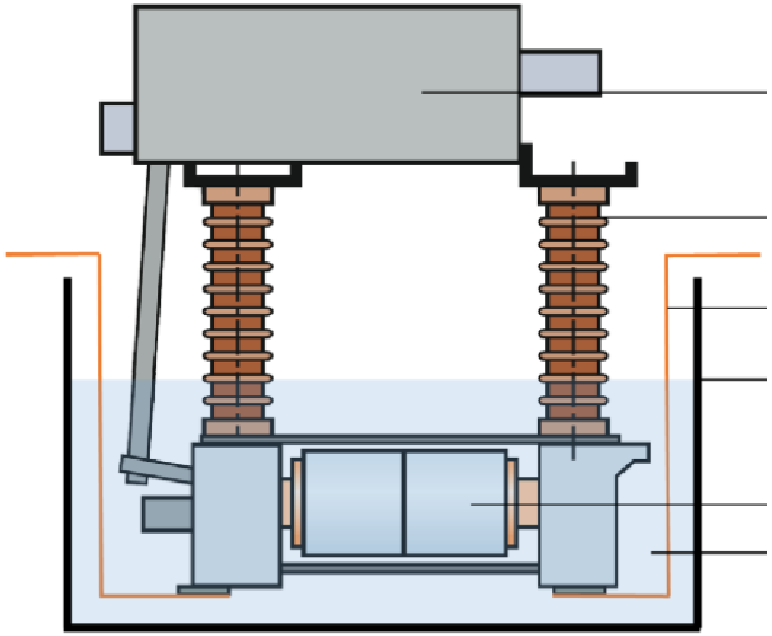
Example oscillogram of interrupted current and TRV



Short-circuit interruption capability

Test setup, test samples and test procedure

- VIs of 2 manufacturers
- 6 VIs each
  - 3 VIs: tested at 293 K
  - 3 VIs: tested at 77 K
- "up-and-down" method:
  - start with $0.75 \cdot I_{\mathrm{n}}$
  - steps of ΔI
    - increase in case of "pass"
    - decrease in case of "fail"



→ **In sum, more than 200 current interruption tests performed**

Short-circuit interruption capability

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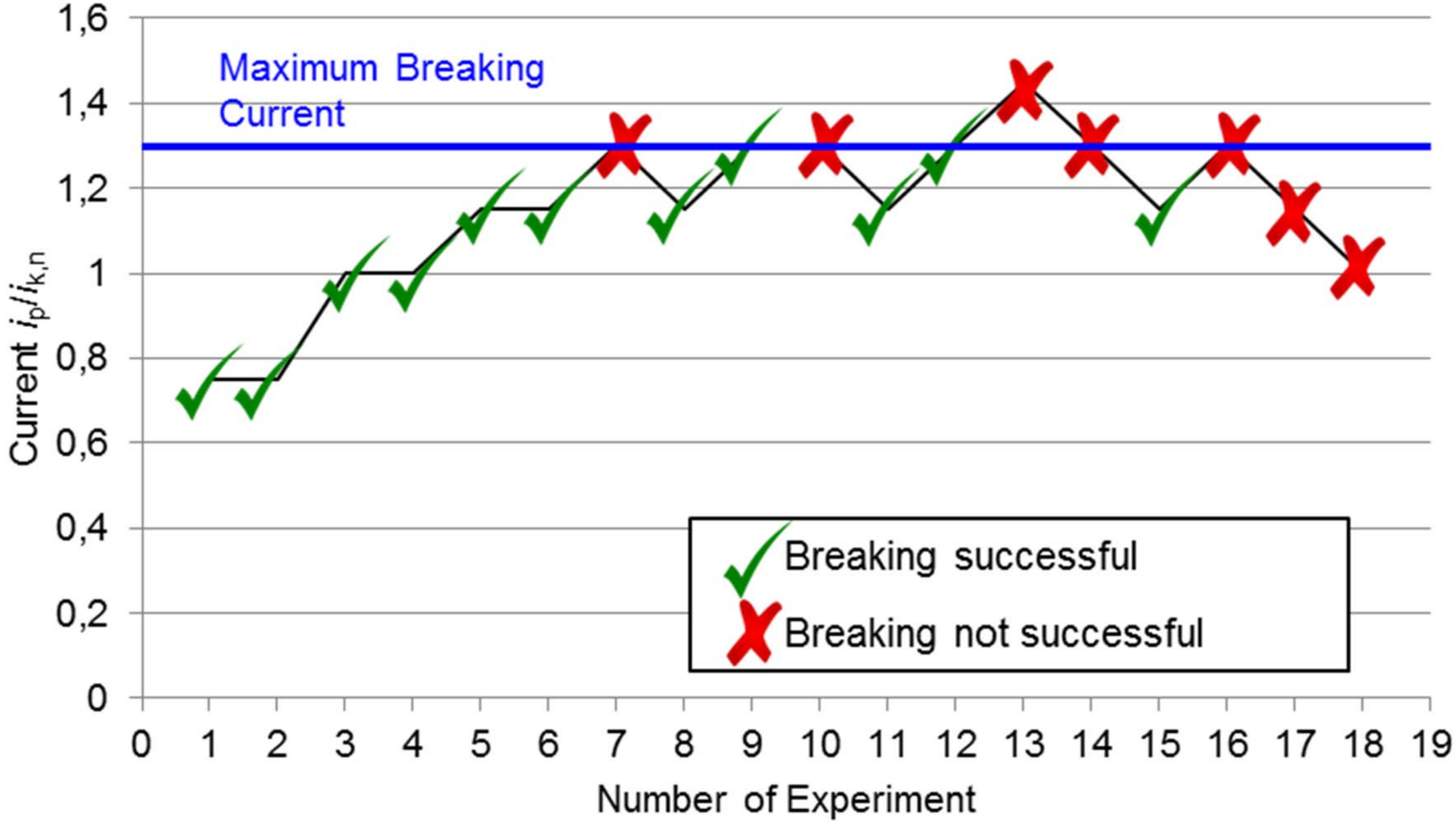
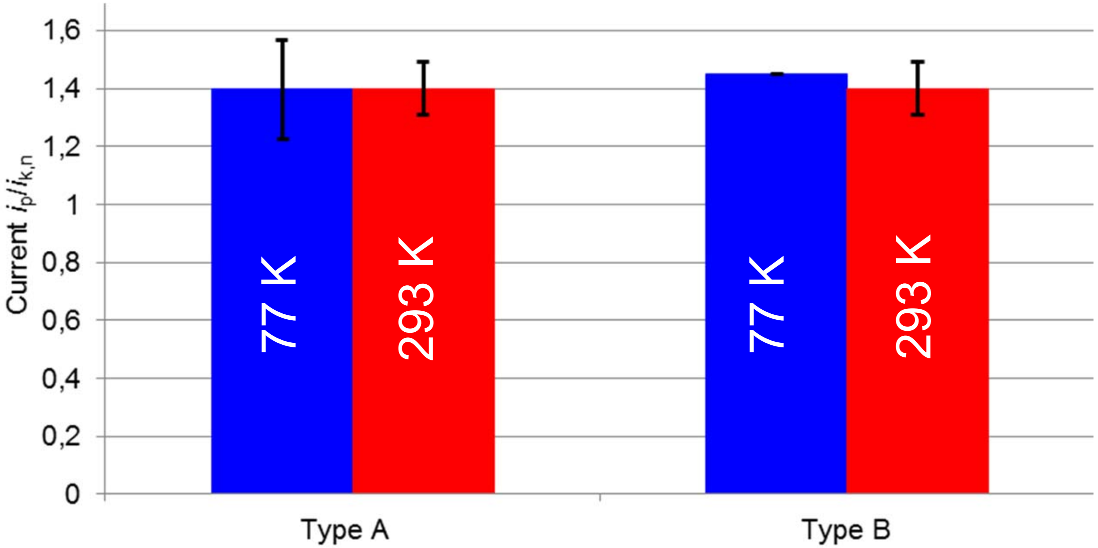
Example of a test cycle



Short-circuit interruption capability - Results

Value	Type A		Type B	
	77 K	293 K	77 K	293 K
Mean	1.40	1.40	1.45	1.40
Minimum	1.30	1.30	1.45	1.30
Maximum	1.45	1.45	1.45	1.6
Std. Deviation	0.17	0.09	0.00	0.09



→ No impact of the temperature of 77 K!

Summary of results

Aspects investigated in the project:

- ☑ mechanics, durability
- ? electrical resistance to be decided case by case
- ☑ dielectric strength (internal and external)
- ☑ chopping current
- ☑ short-circuit current

Discussion and outlook

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- Basic applicability of VI technology in LN_2 proven
- Detailed requirements not yet specified
- Further investigations then possibly necessary
- Mechanical part (drive) still to be developed

From a to date's point of view:
Application possible without any restrictions!

Impressing performance of VI interrupter technology over a huge temperature range!

Thank you for your attention!

Ph.D. Thesis Karsten Golde available for download under

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