How to switch off high voltage DC current without using semiconductors

Frontiers in Energy Research – 24. April 2018

Lorenz Bort

Content

- Introduction into HVDC
- How to switch off high voltage AC & DC

- Passive oscillation scheme for DC switching

- Arc characterization
- Results: axial voltage distribution

What is high voltage DC transmission?

- > 100‘000 Volt (up to +/- 800kV)
- > 1‘000A nominal current (up to 5kA)
- 100 MW to 8 GW transmission capacity

- (typical load of switzerland: 8GW)

[technologyreview.com]

High Voltage DC Links offer advantages over High Voltage AC

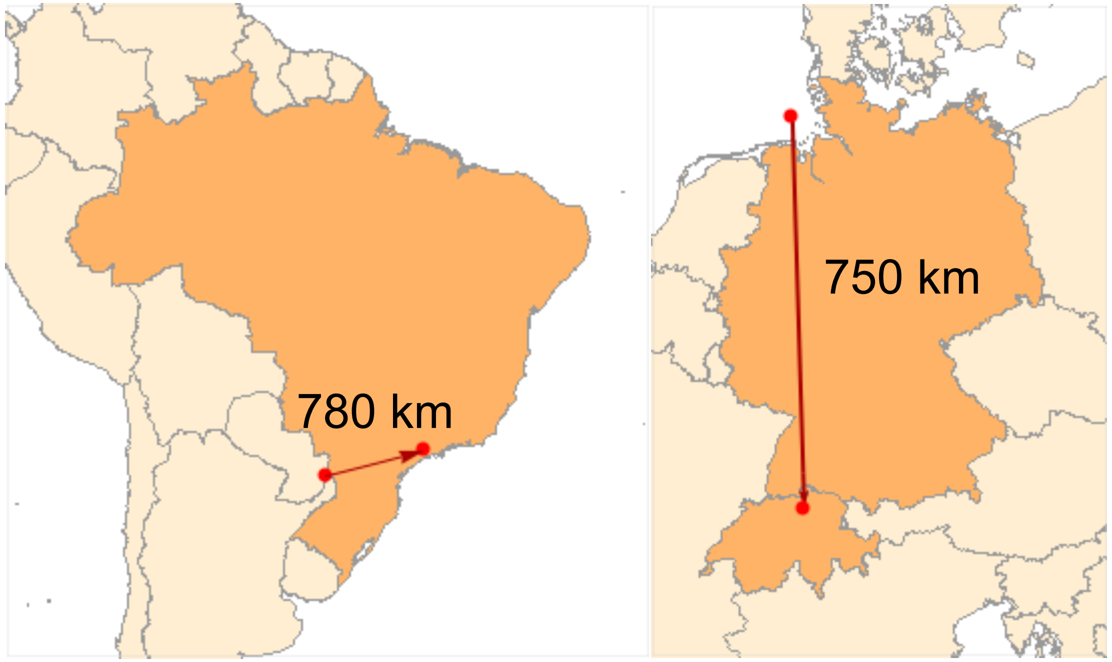
1. Power flow control
2. Lower losses over >1000km Overhead lines (and >50km cable)
3. Possibility to connect un-synchronized networks, even different frequencies.

Since the 1960s HVDC links are used where they are useful

- Itaipu → unsynchronized network, long distance (780 km)
- China → many of them, most long distance (>2000km)
- Europe/Russia/North (NOR/DEN/SWE/UK…?) unsynchronized & subsea
- DE/CZ back to back coupling

Itaipu – São Paulo is similar to Helgoland – Switzerland

- Large generation capacity (several GW)
- Loads far away (>500km)
- HVDC helps control power flow and lower the losses



[Wolframalpha.com]

Itaipu (Paraguay/Brazil)

- $700\ MW$ each generator
- $700 m^3/s$ each turbine

- 9x @ 60Hz (BRA)
- 9x @ 50Hz (PAR)

[atomictoasters.com]

[Engineers Journal]

Itaipu Powerplant Numbers (Paraguay/Brazil)

- Limmat (Zürisee): $70\ m^3/s$
- Rheinfall: $600\ m^3/s$
- 1 Penstock Itaipu: $700\ m^3/s$
- Rhein (Basel): $1000\ m^3/s$
- Iguaçu falls: $1500\ m^3/s$

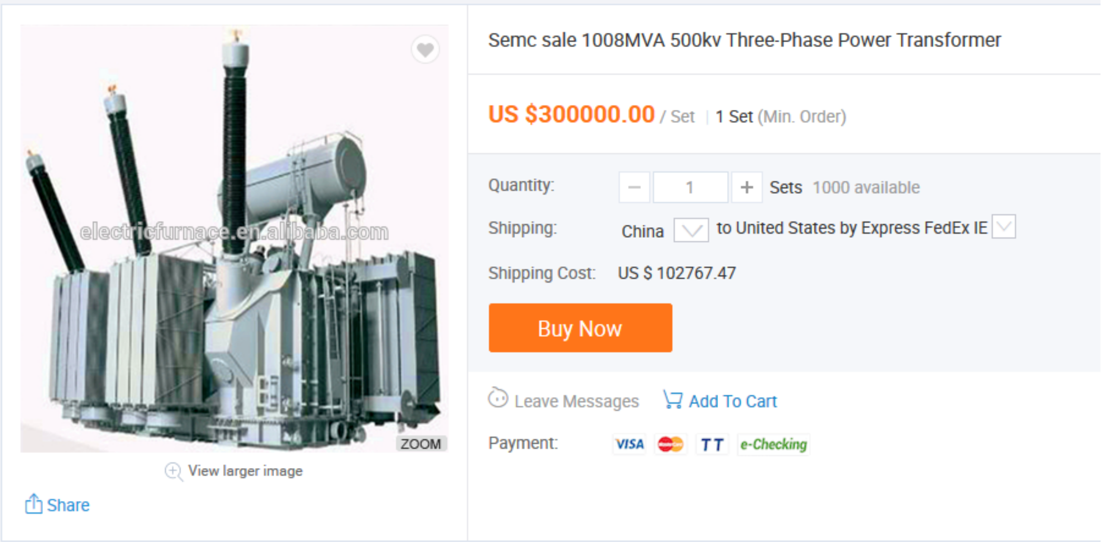
- At Itaipu, there are 18 penstocks, 700MW each, 100m head, 90 TWh / year

- HVDC: 2 systems, each +/-600kV, 2x3GW from Paraguay side to São Paulo

HVDC also has drawbacks compared with HVAC

- Transformers are not working with DC
- Converter Stations are huge, expensive and lossy
- Meshed Grids require breakers, which are huge, expensive and lossy

HVDC also has drawbacks compared with HVAC



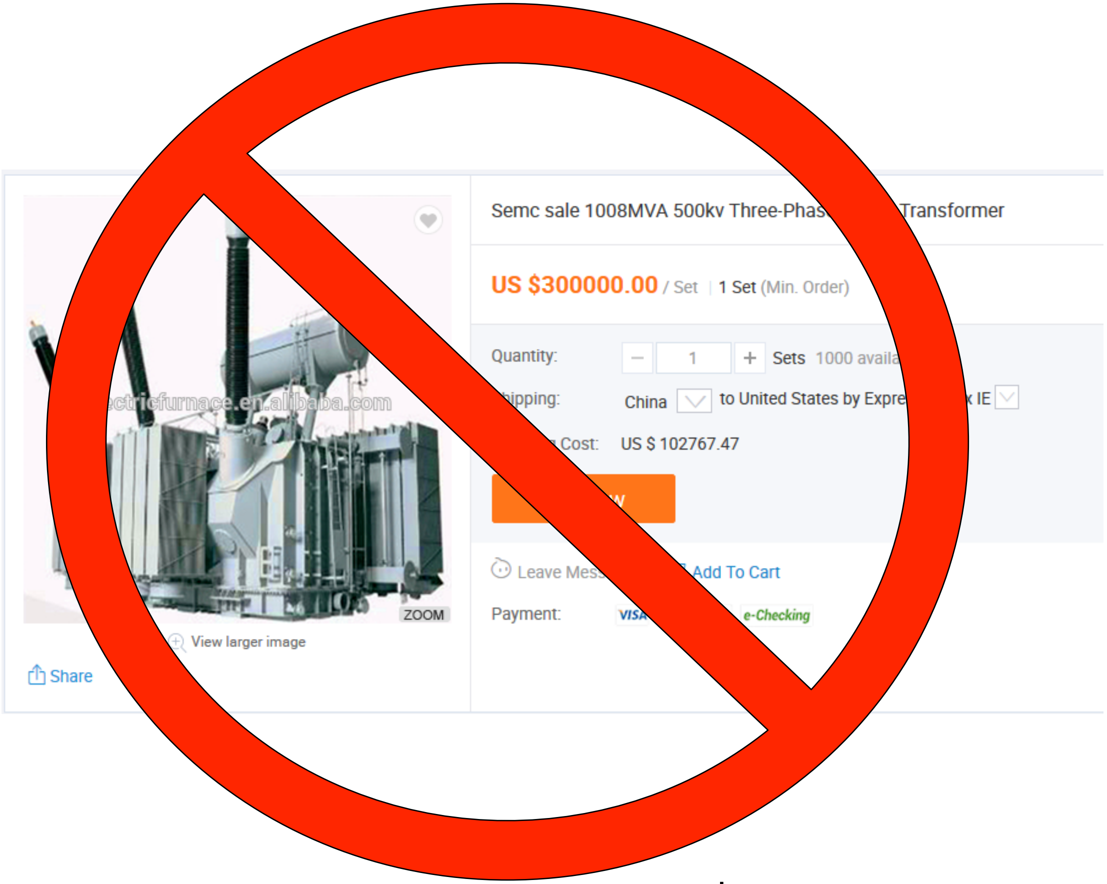
[alibaba.com]

[Wikimedia.org]

Transformers: 1M$?

AC/DC converter: 100M$?

HVDC also has drawbacks compared with HVAC



Transformers: 1M$?

AC/DC converter: 100M$?

[ABB.com]

Switchgear is required for grids

[ABB.com]

3-phase AC-breaker 10‘000$

Switchgear is required for grids

3-phase AC-breaker 10‘000$

DC-breaker: basically half a converter

Switching 101

AC switching means: wait for next current zero crossing and „just“ stop conducting.

DC switching means: actively push current to zero

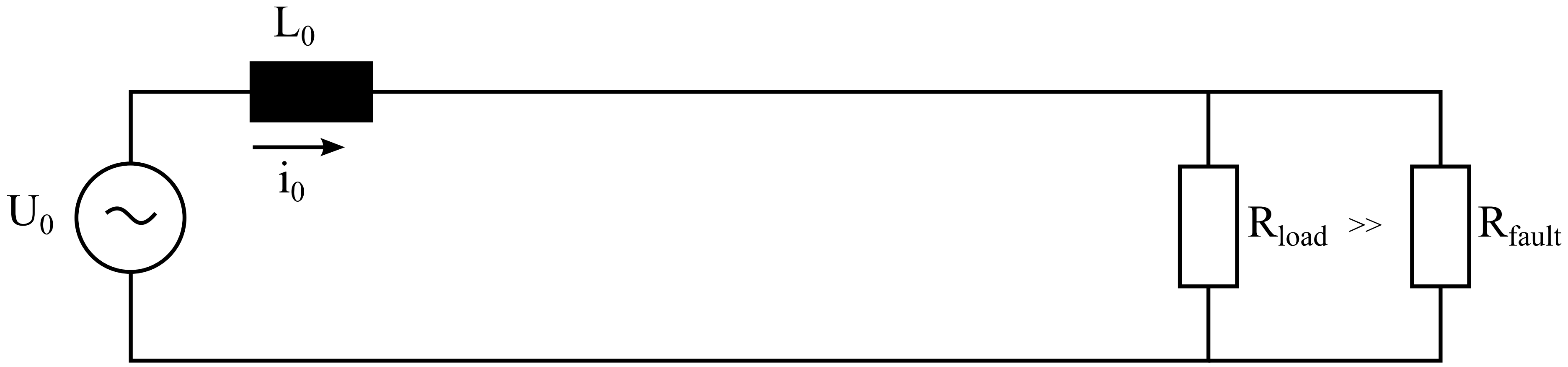
Switching (fault) currents in AC

[own work]

Switching (fault) currents in AC

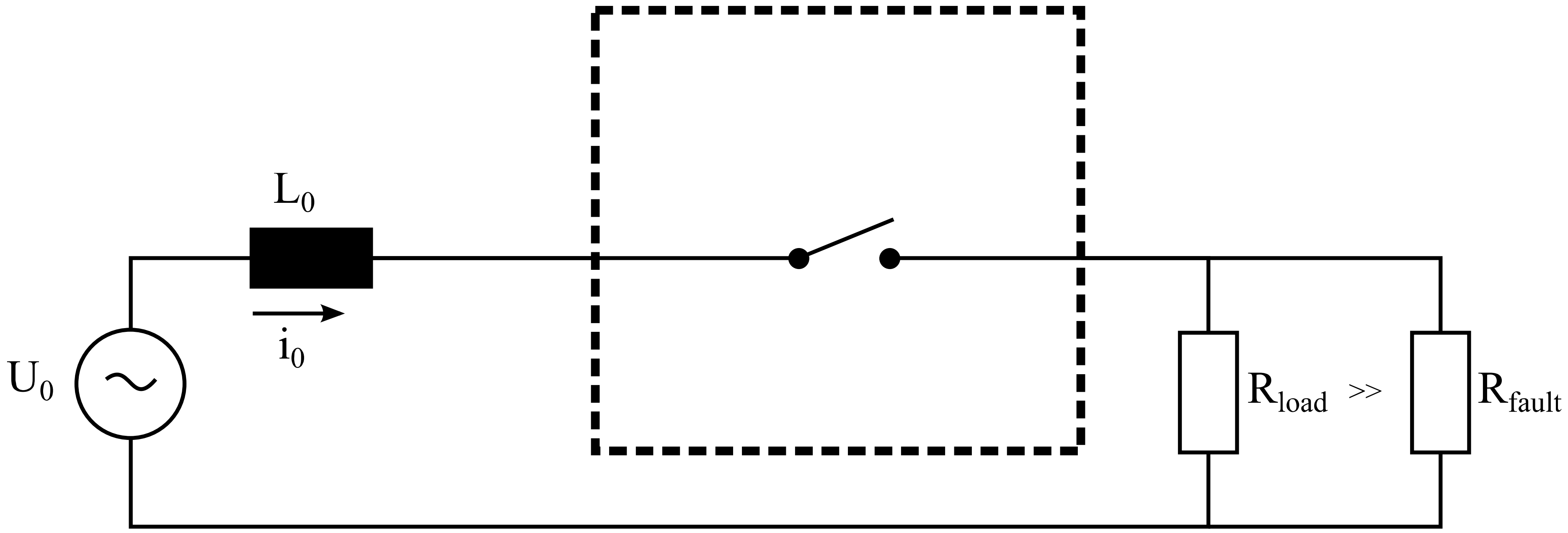
[own work]

Switching (fault) currents in AC



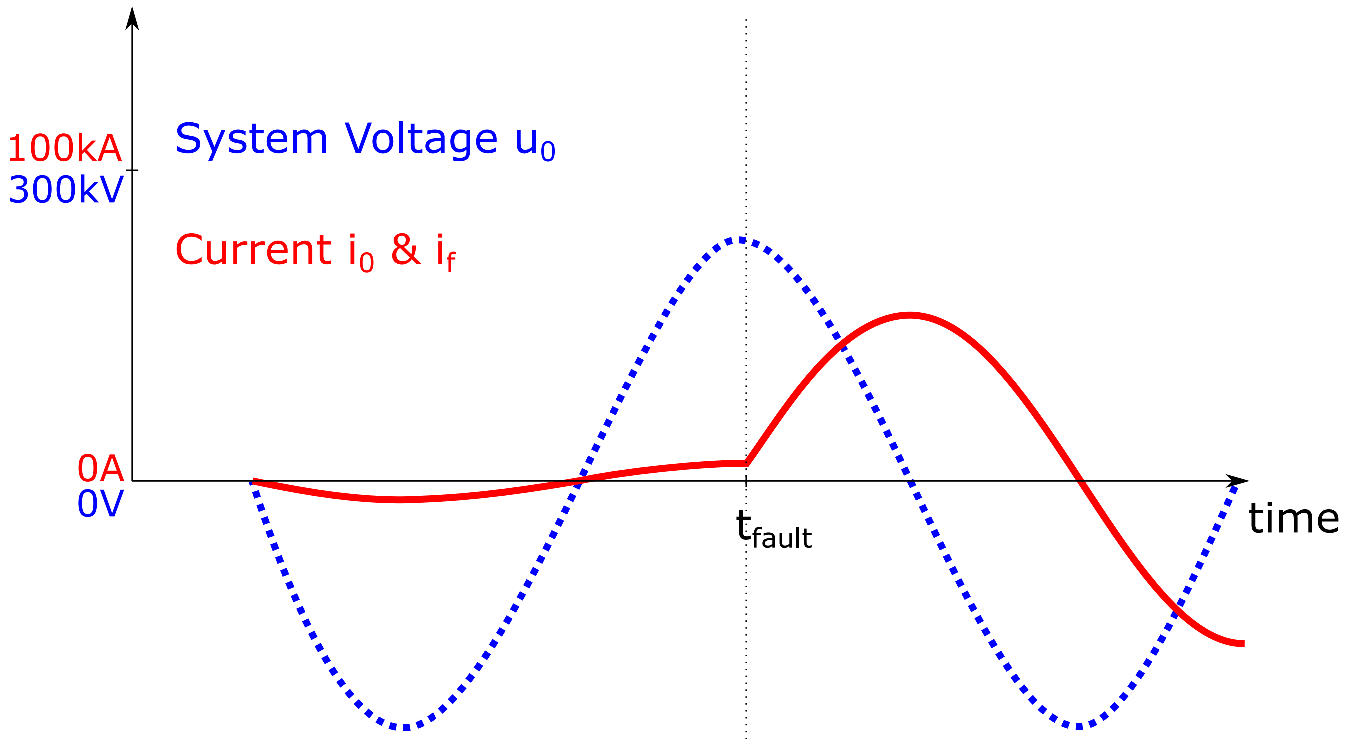
[own work]

Switching (fault) currents in AC



[own work]

AC fault current dominated by line inductance



$\hat{I} = \hat{U}/R_{Load} = 1000A$

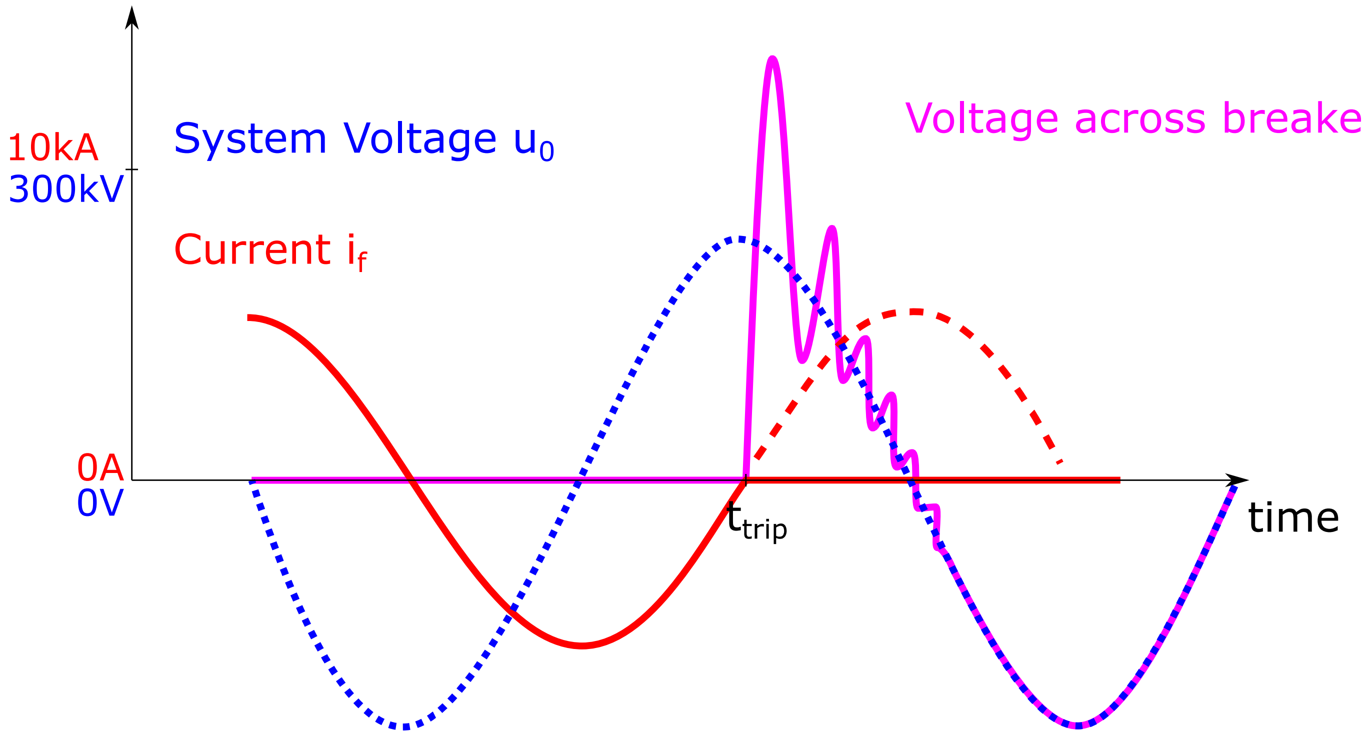
$\varphi = 0°$

$\hat{I} = \hat{U} / \omega L_{Line} = 50'000A$

$\varphi = 90°$

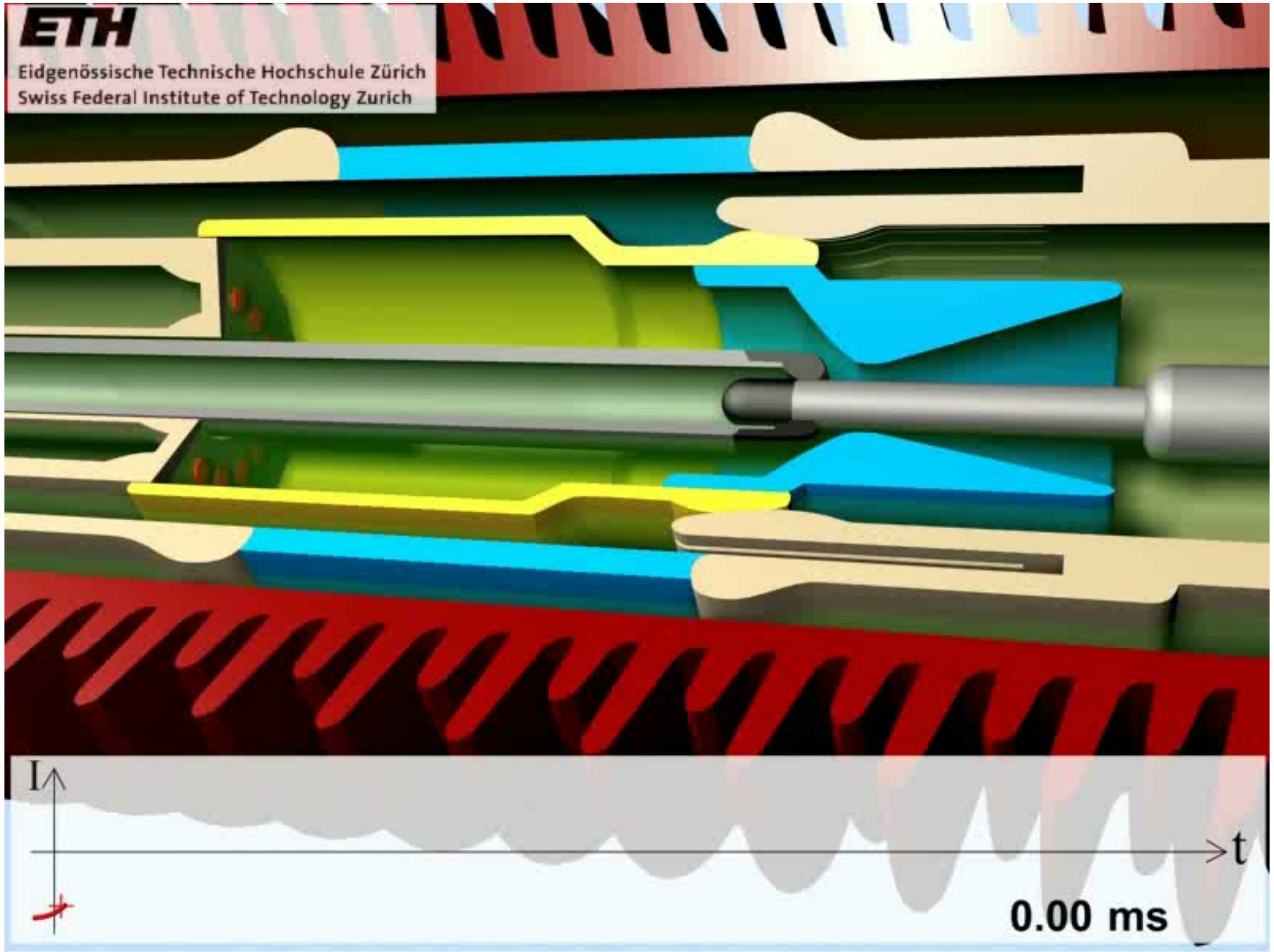
[own work]

There are natural current zero crossings every 10ms → stop there



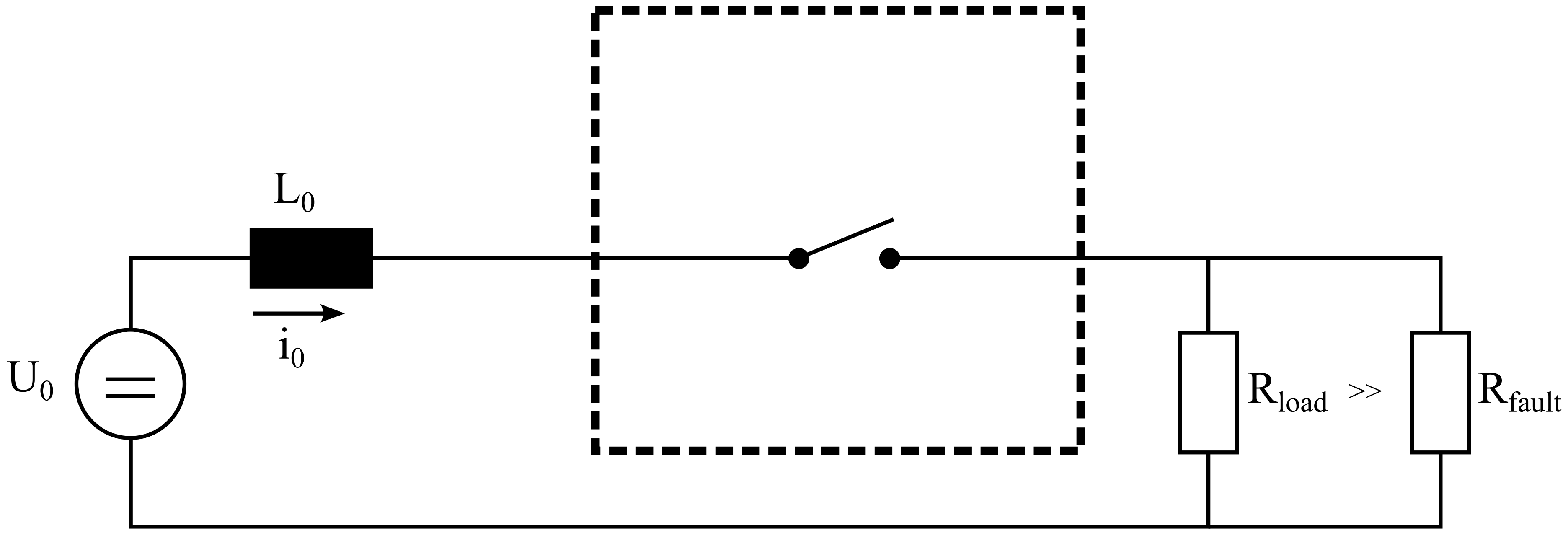
[own work]

AC-Solution: Gas circuit breakers



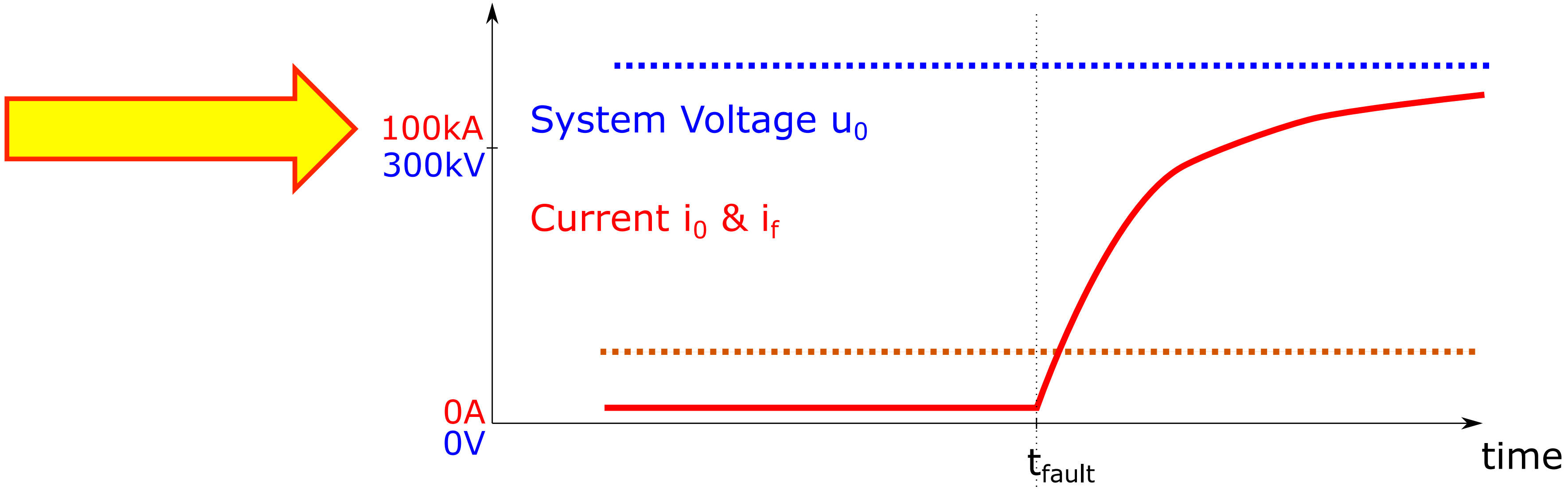
[hvl.ee.ethz.ch]

But in DC, the current does not go to zero by itself



[own work]

DC fault current needs to be cleared in transient phase



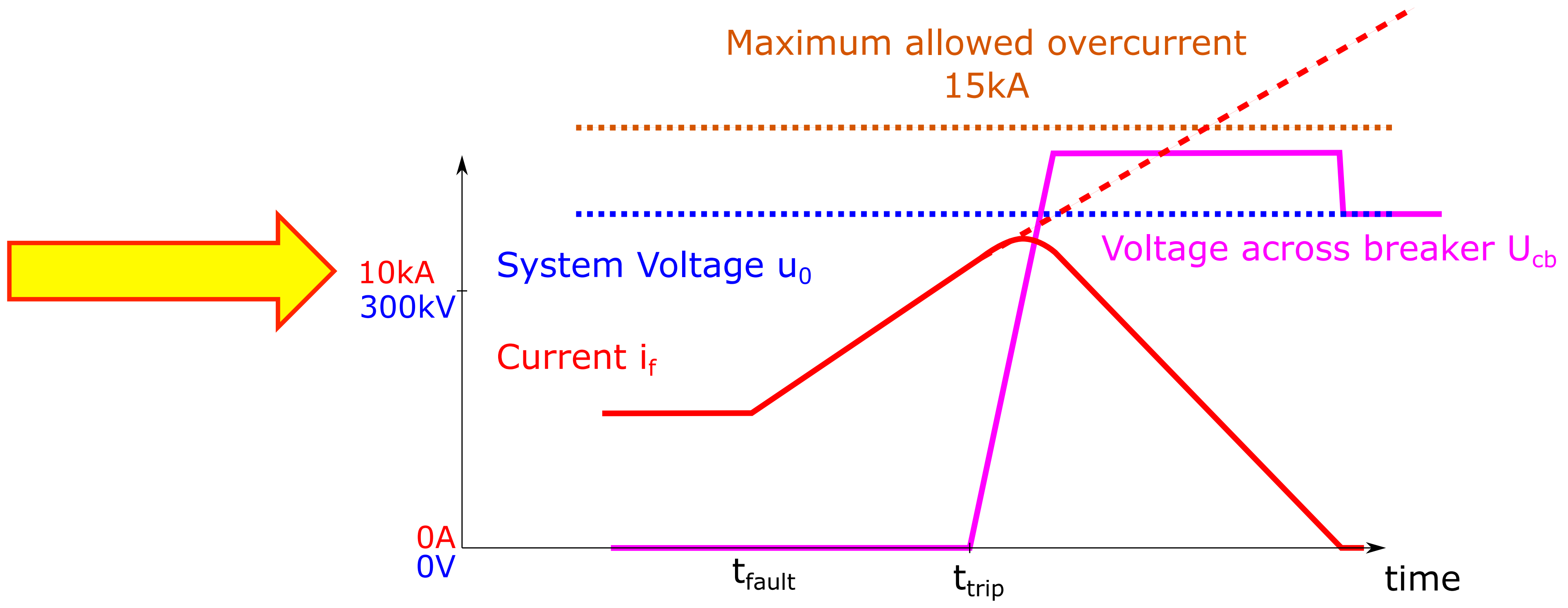
Maximum allowed overcurrent
15kA

$I = U/R_{Load} = 1000A$ | $I = I / R_{fault} > 100'000A$

$dI/dt = 0$ | $dI/dt = 3kA/ms$

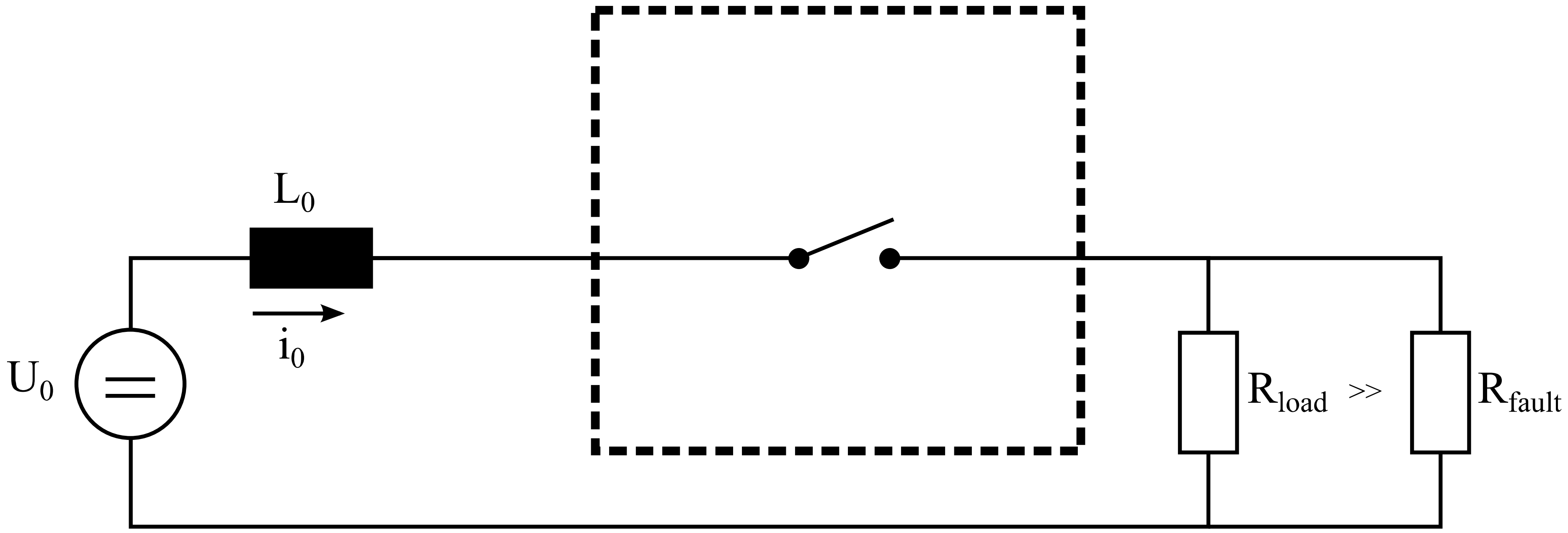
[own work]

DC breakers need to create countervoltage to stop current



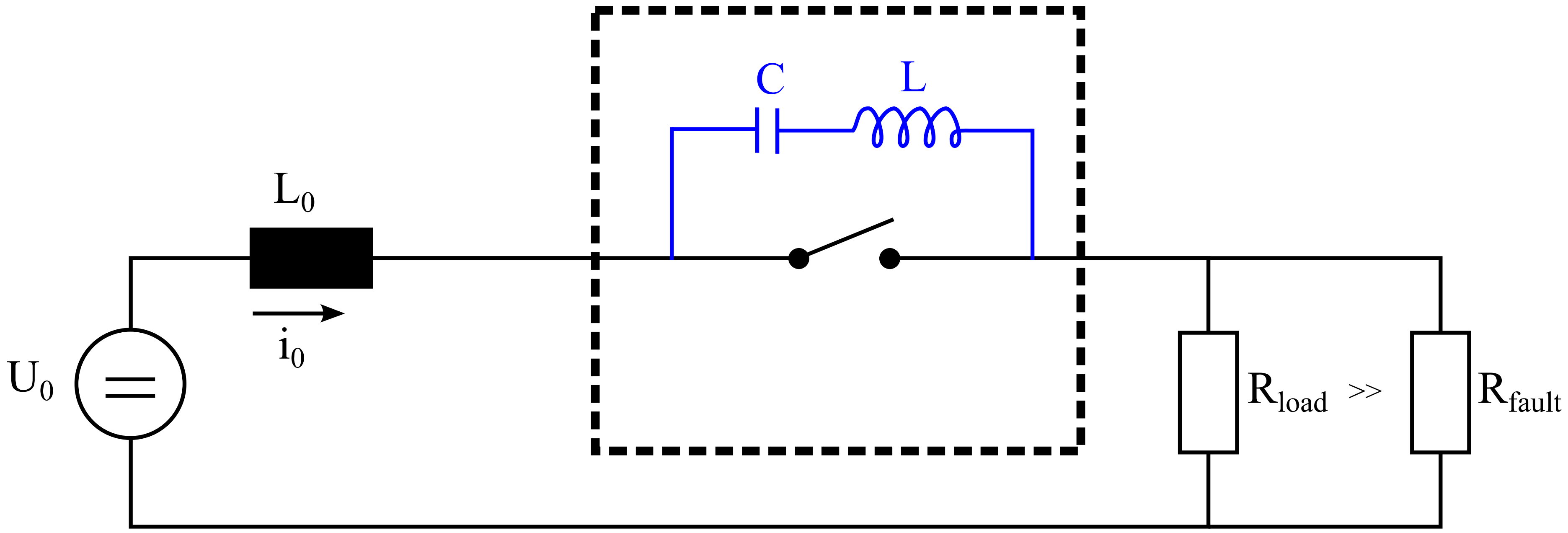
[own work]

Our AC gas circuit breaker cannot provide countervoltage



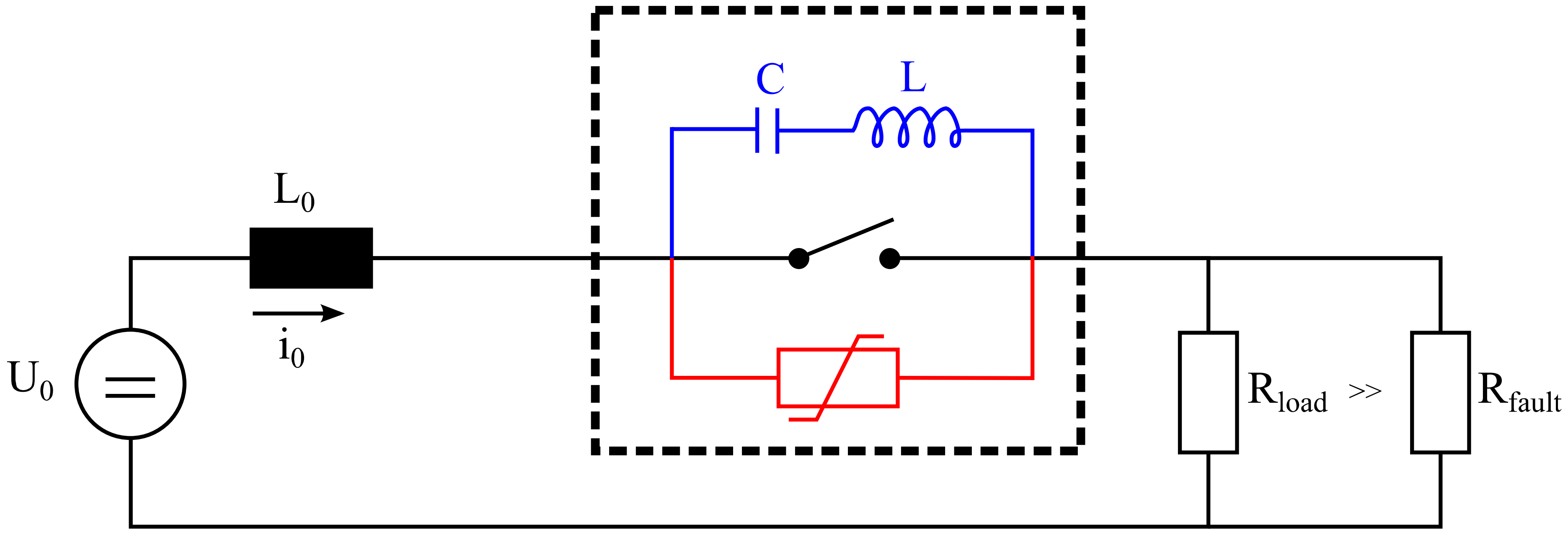
[own work]

Maybe we can use gas CBs in a clever way



[own work]

First commutate the current, then absorb the remaining Energy



Commutation path

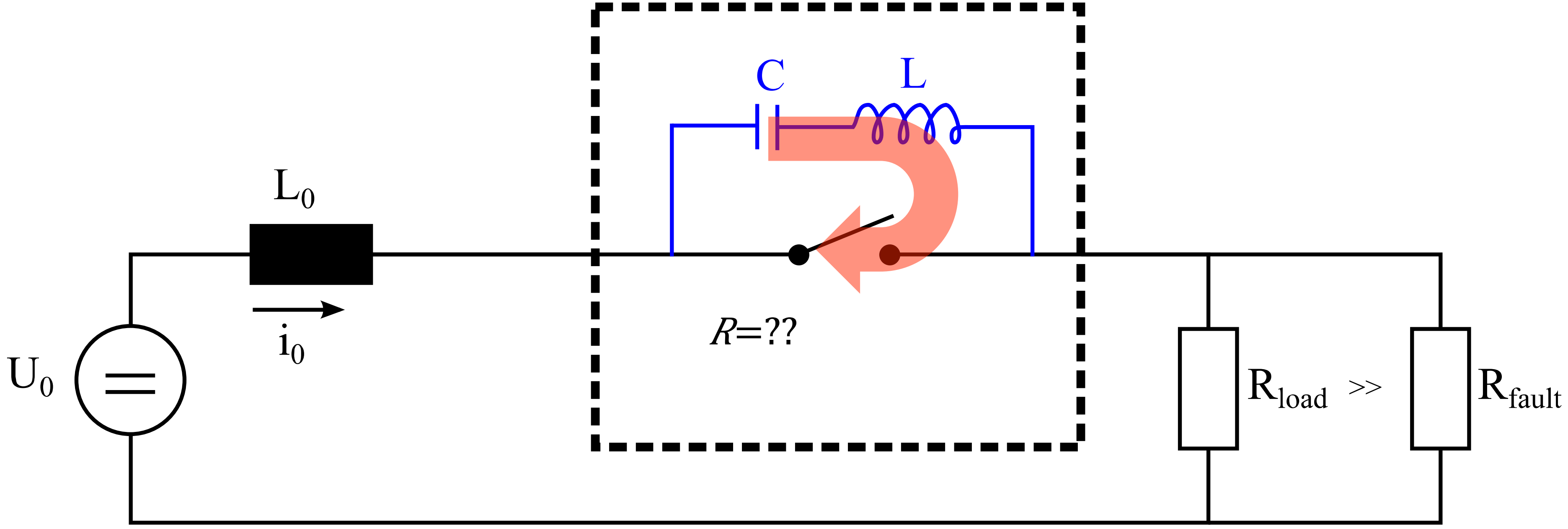
Nominal current path

Energy absoption path

[own work]

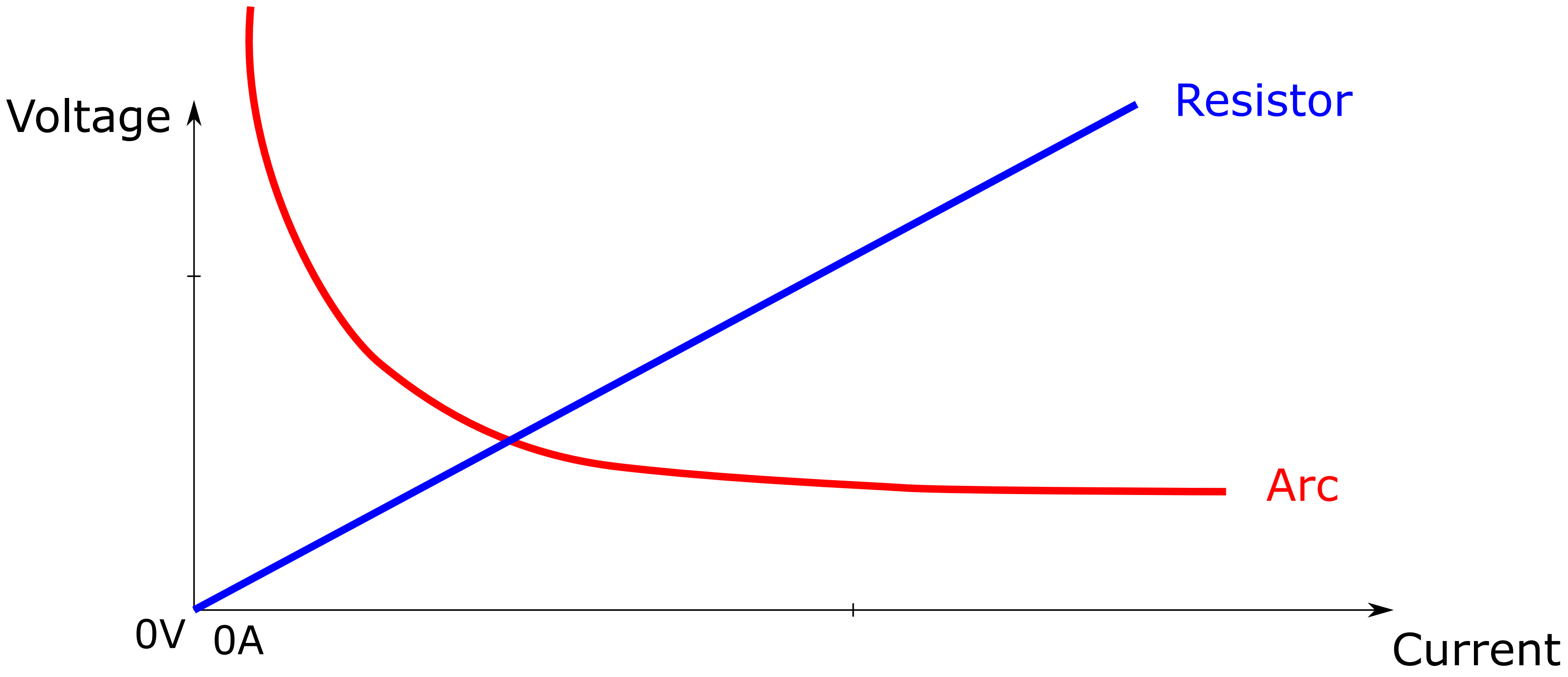
To commutate: Lets repeat LC-circuit theory

$\omega_0 = 1/\sqrt{LC}$ $\delta = R\,1/2L$



[own work]

Arcs are wierd, not resistive at all



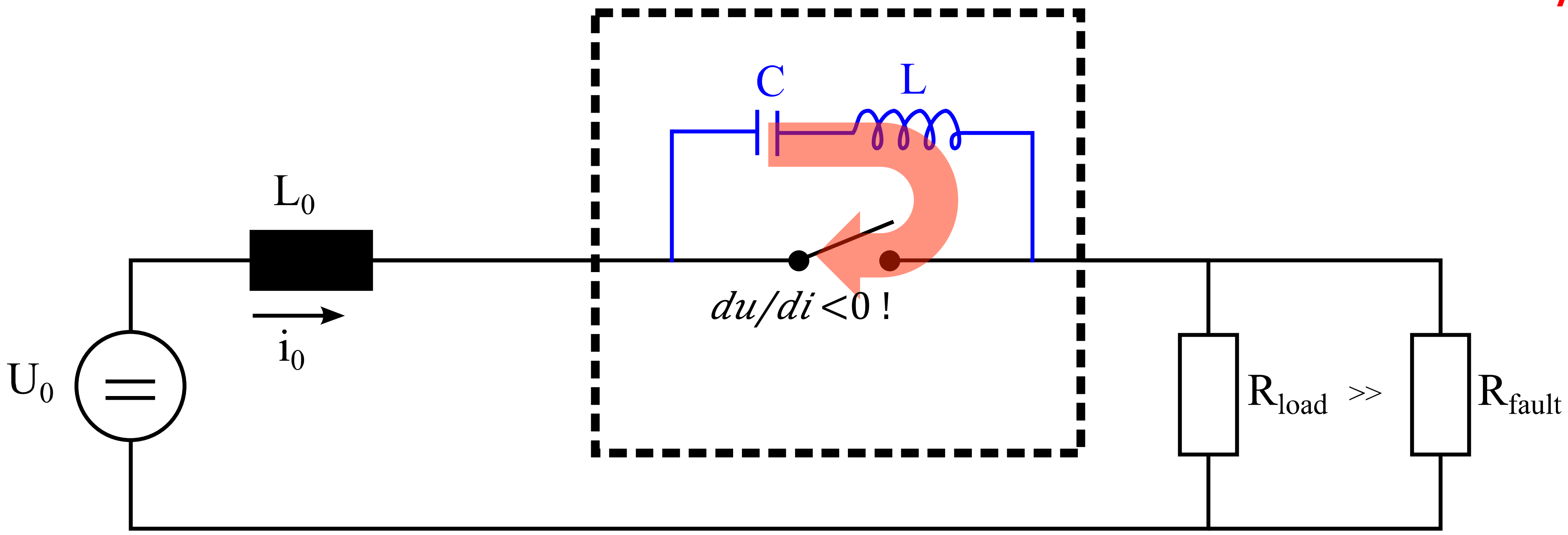
[own work]

We can generate a current zero crossing passively!

$\omega_0 = 1/\sqrt{LC}$

$\delta = du/di \; 1/2L$ < 0

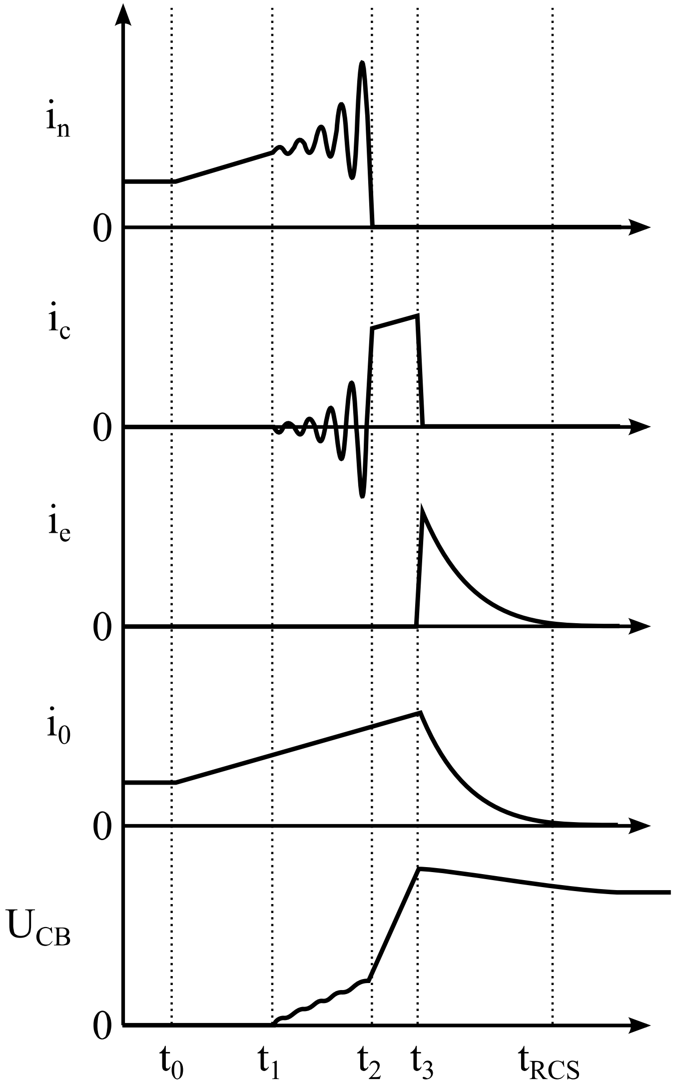
Negative Damping
=
Amplification!



[own work]

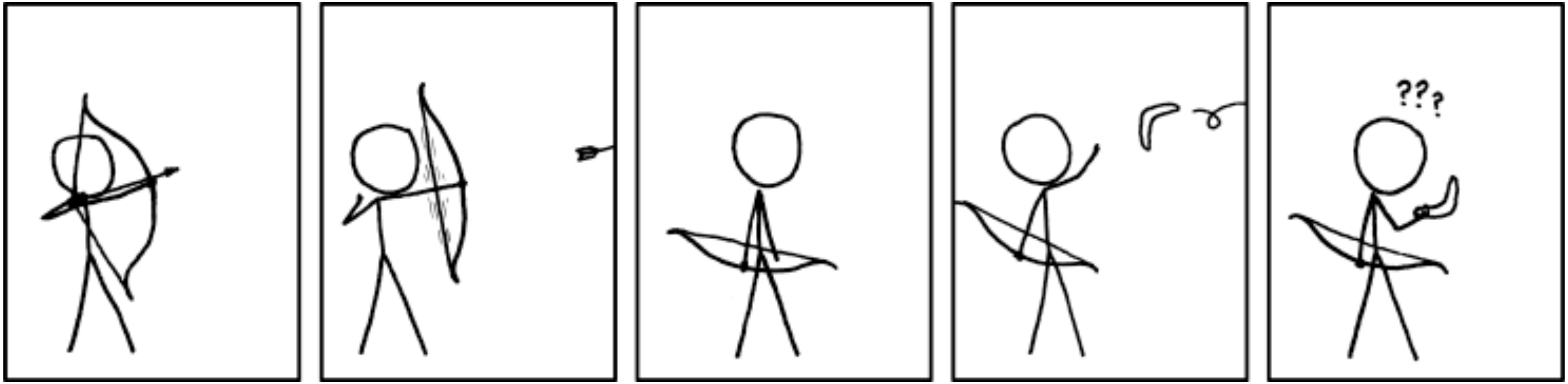
After current zero in the gas breaker, the grid recovers

- t0 – fault
- t1 – open gas breaker & start oscillation
- t2 – current zero in breaker
- t3 – capacitor charged up to arrester voltage
- trcs – current is zero, auxillary switch opens



[sorry, no source]

Now, we have everything to interrupt.
Are we done now?



[xkcd.com]

Passive Oscillation Concept not new, but it is not optimized

- Improving the arc characteristics

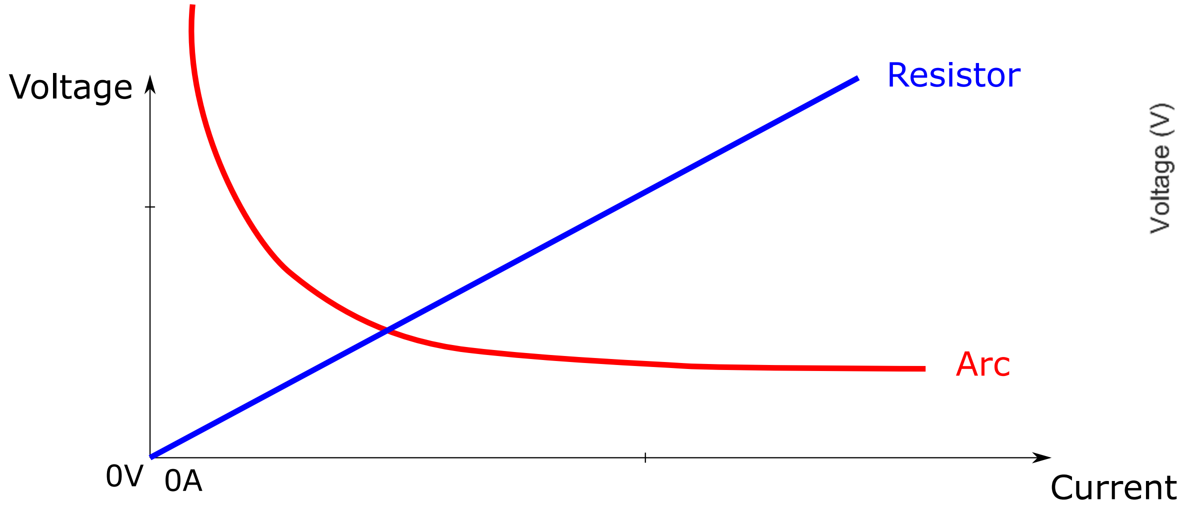
  → Decreases time of commutation

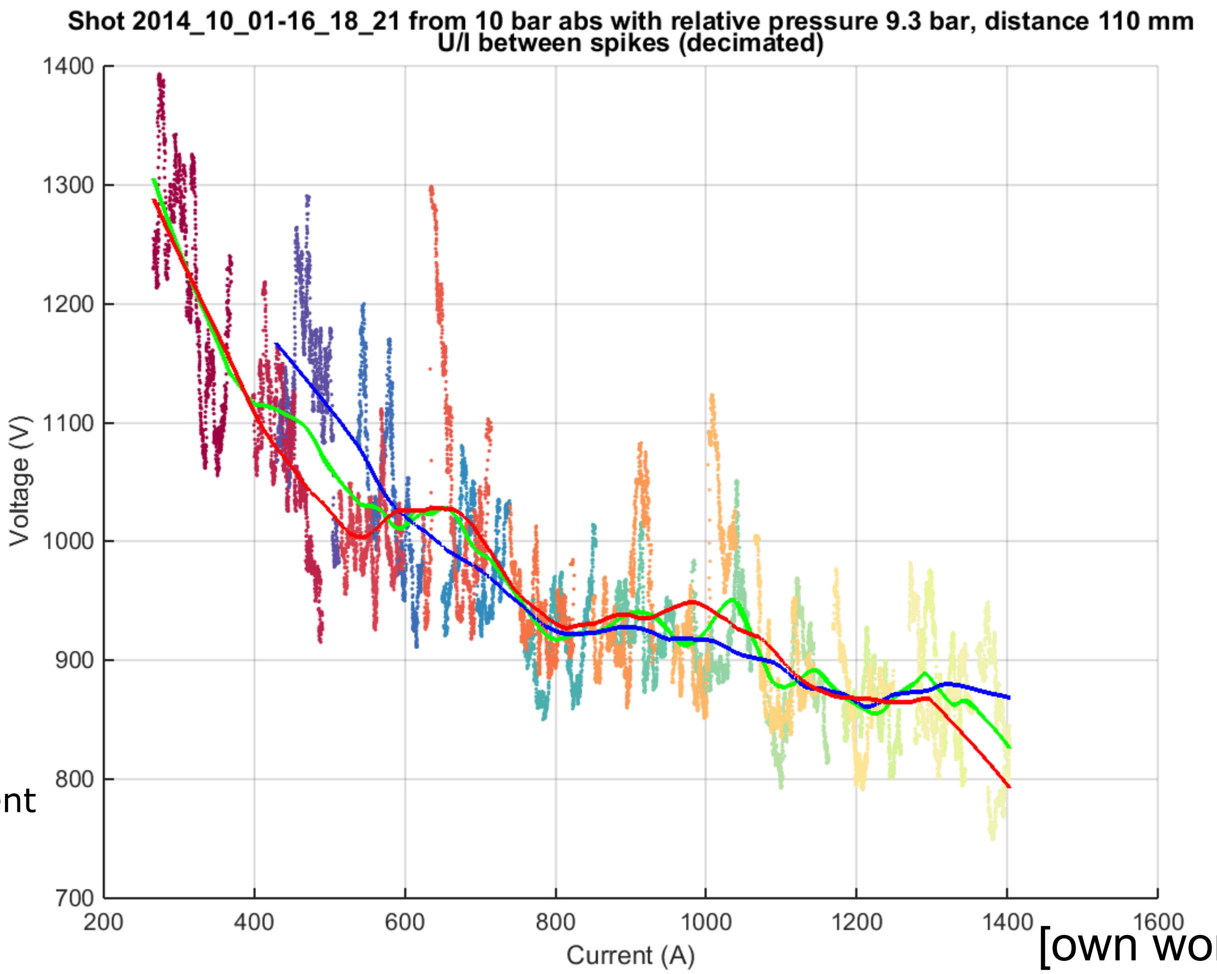
  → Increases maximum current that can be commutated

  → Decreases footprint inside substation
  (if L&C can be reduced)

  → Decreases cost
  (if L&C can be reduced)

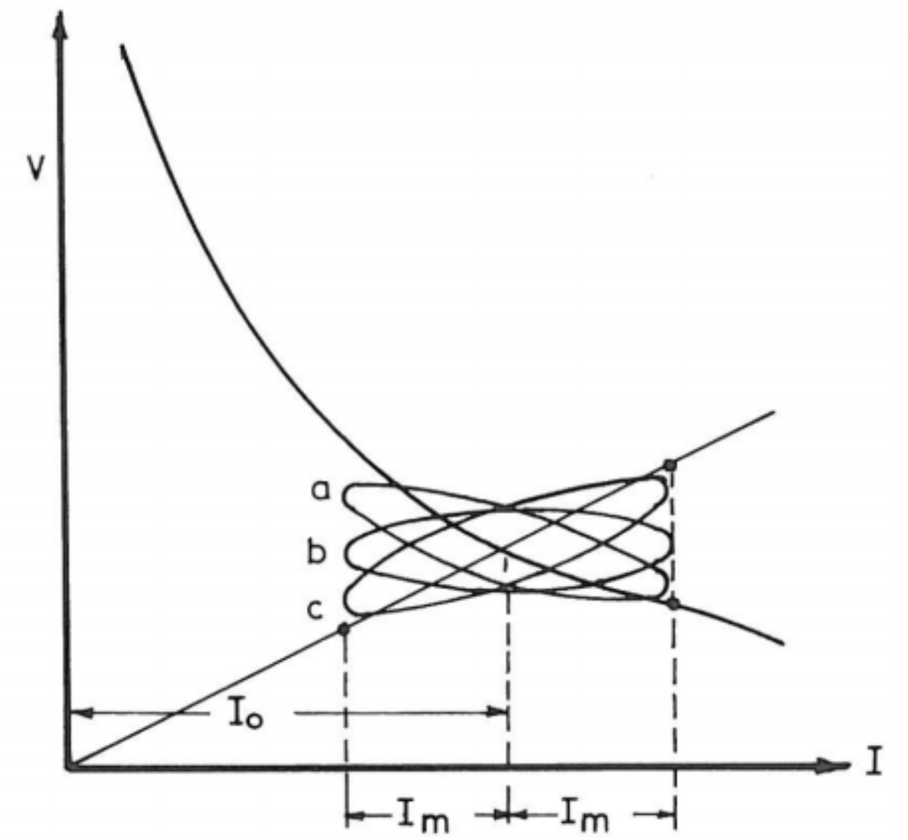
And the reality is not ideal





[own work]

The arc cannot react instantly



[sorry, no source]

- a: low frequency
- b: medium frequency
- c: high frequency

- Definition of „high“ depends on dynamic arc time constant τ

- The lower τ, the higher f we can use
→ can break faster.

We have a sophisitated current source

3 Modules

1kA current each

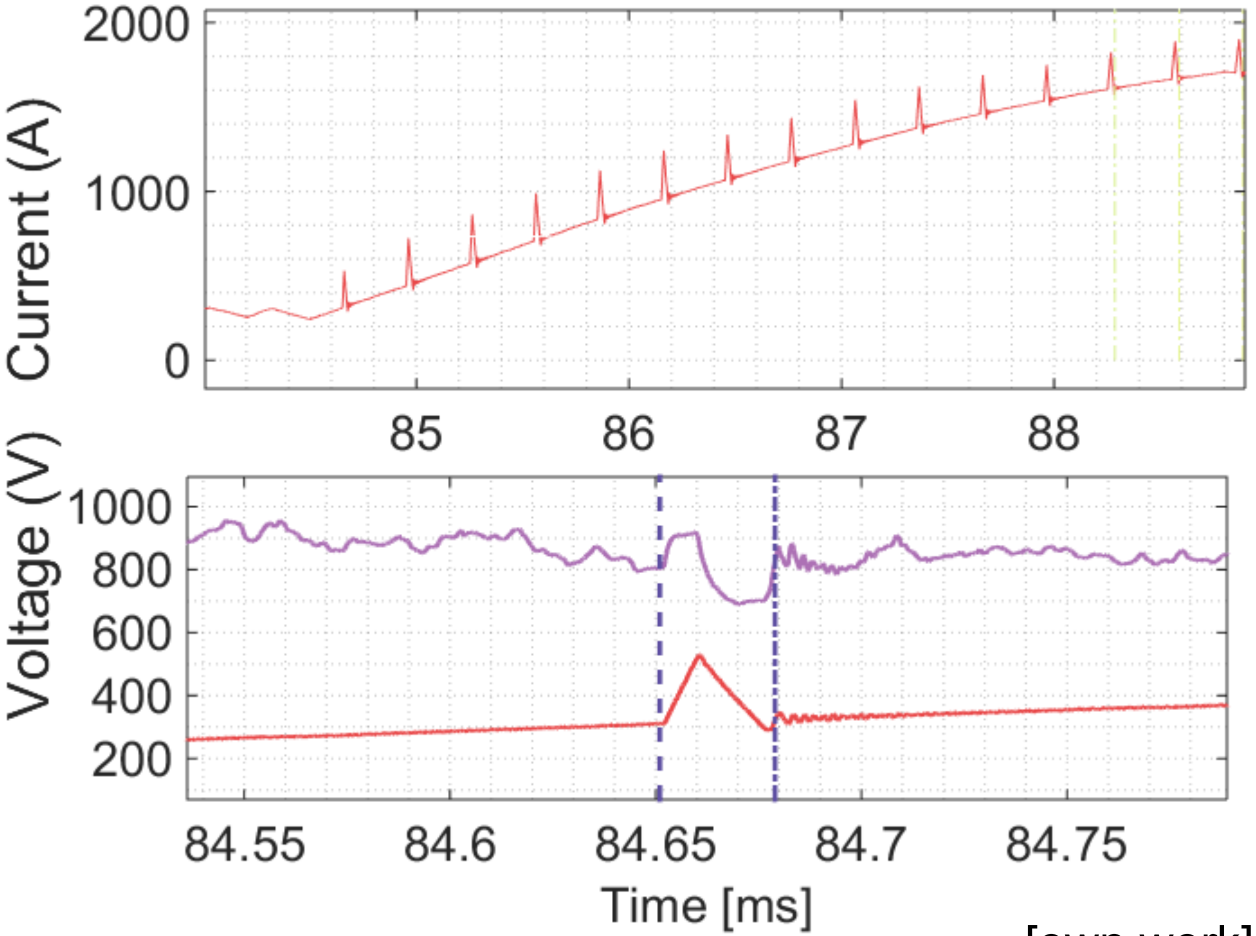
3kV maximum voltage

Flexible current waveform

[own work]

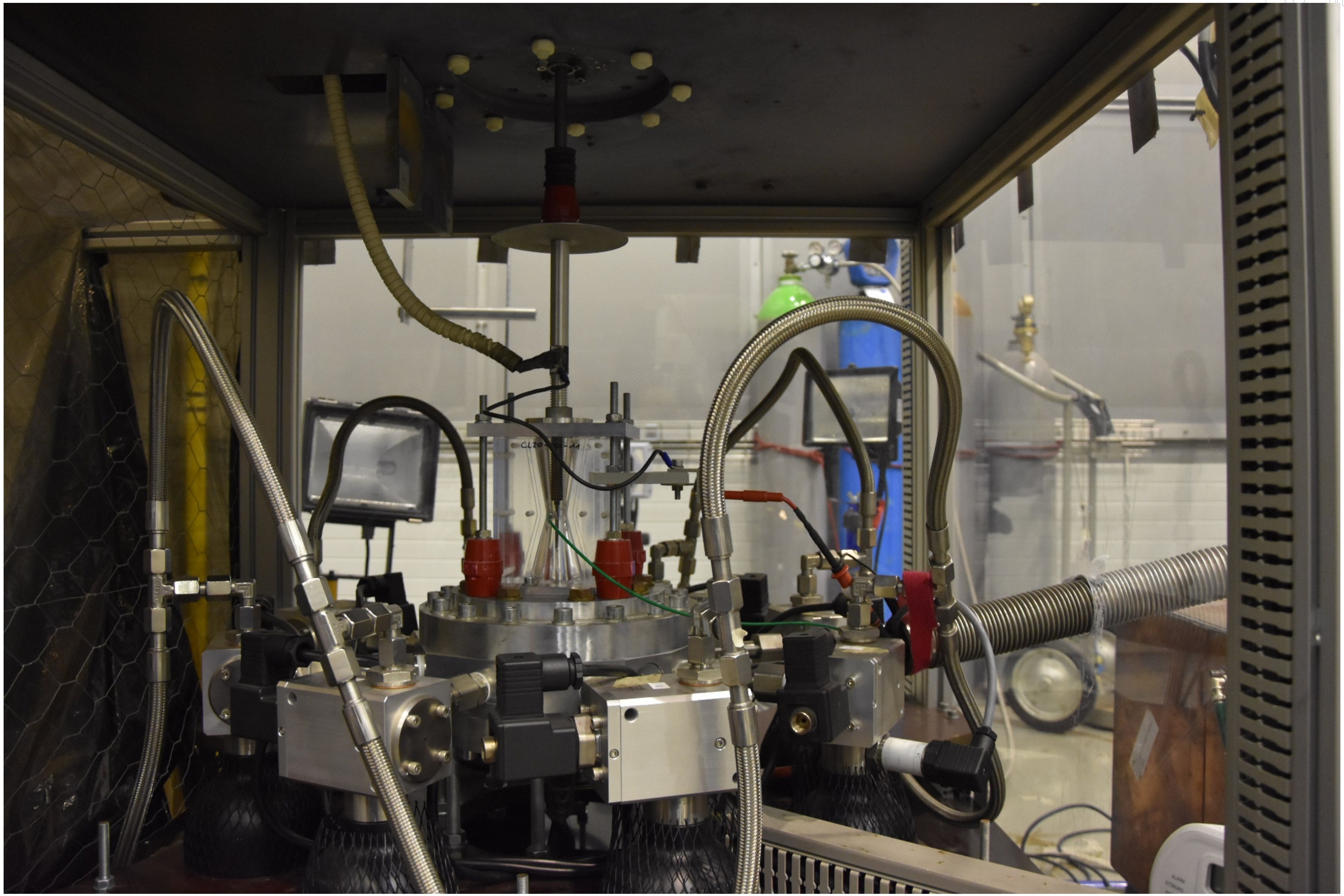
We have a sophisitated current source

- Slow current ramp
  → determine static u(i)
- Fast „spikes“ (~10us rising/falling)
  → determine dynamic τ



[own work]

Lab Setup



[own work]

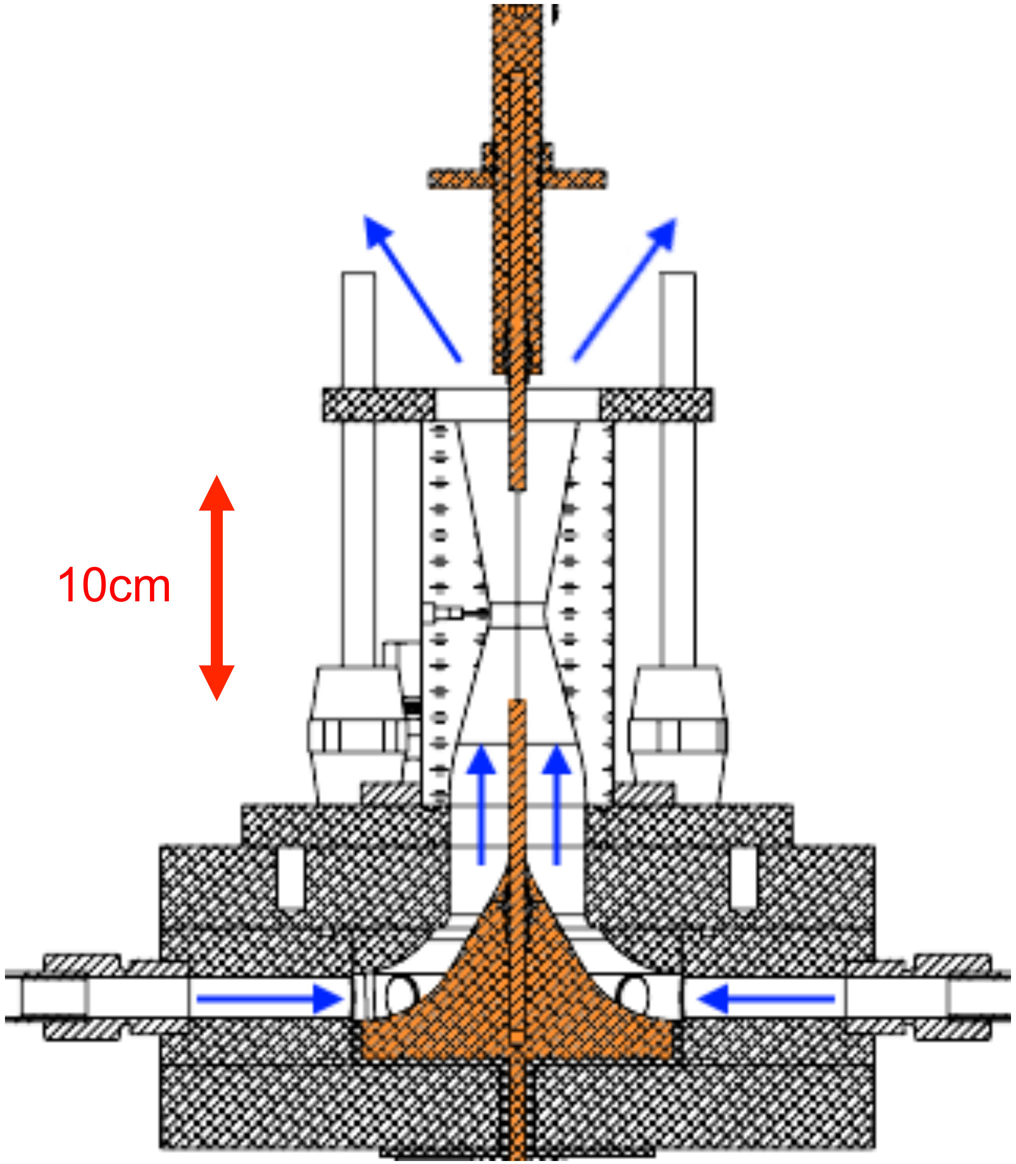
There are many many free parameters…

- Gas type
- Gas pressure
- Wall material (ablation)
- Nozzle shape (determines speed, density etc)
- Contact position
- Contact material (vaporizes)
- …

… and processes

- supersonic flow
- 1-5 MW energy input
- radiative wall ablation
- turbulent mixing of „cold“ (<1000K) gas with
- >10000K plasma
- everything is over after a few ms
- …

Lab Setup



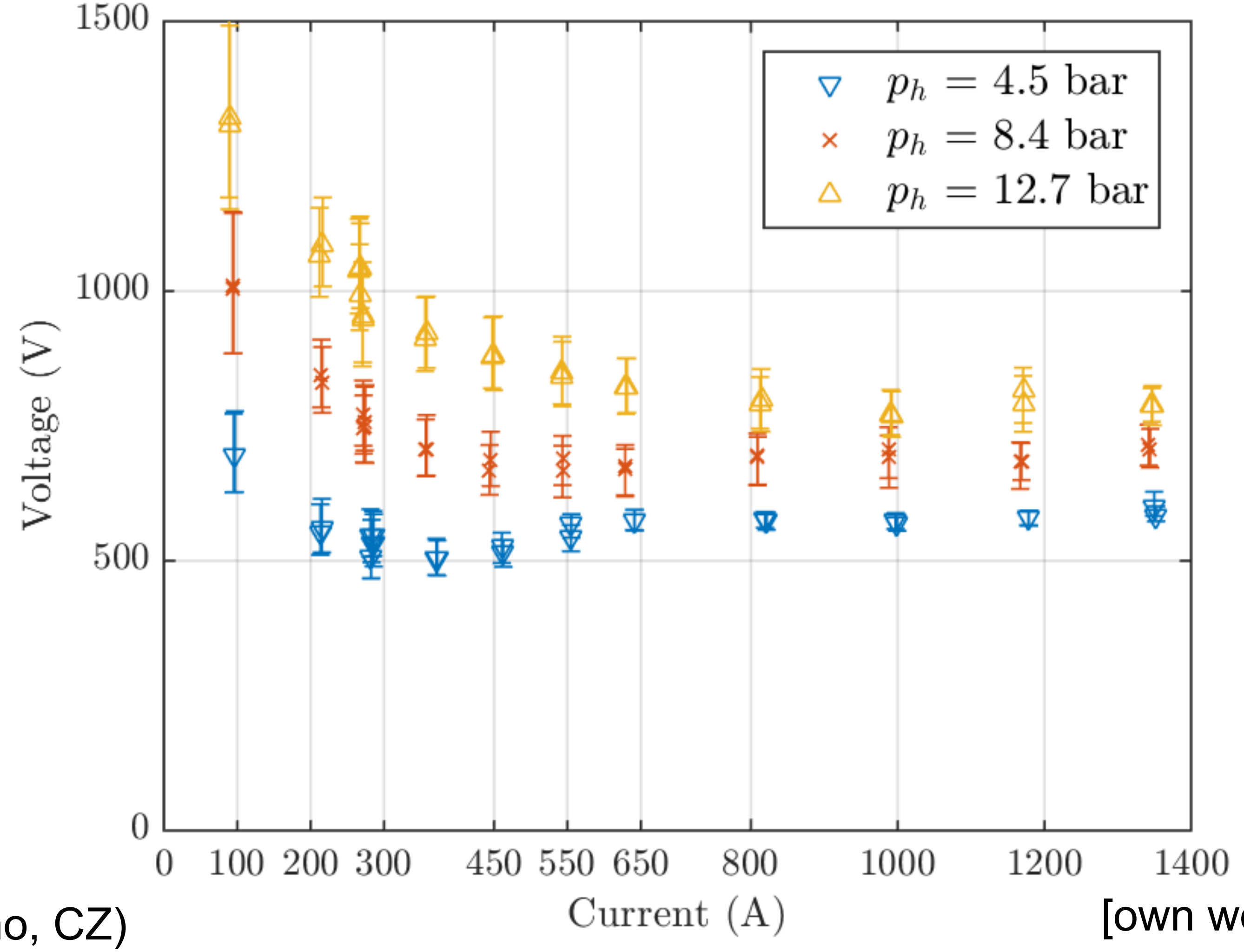
- Adjustable contacts
- Nozzle easy to change
- Gas flow easily controllable (0-20bar)

- Measurement equipment
  - Current
  - Voltage
  - Pressure
  - Ablation (weighing)
  - Highspeed camera

[Miriam Vonesch]
[own work]

Now we have all the tools toghether, lets look at results

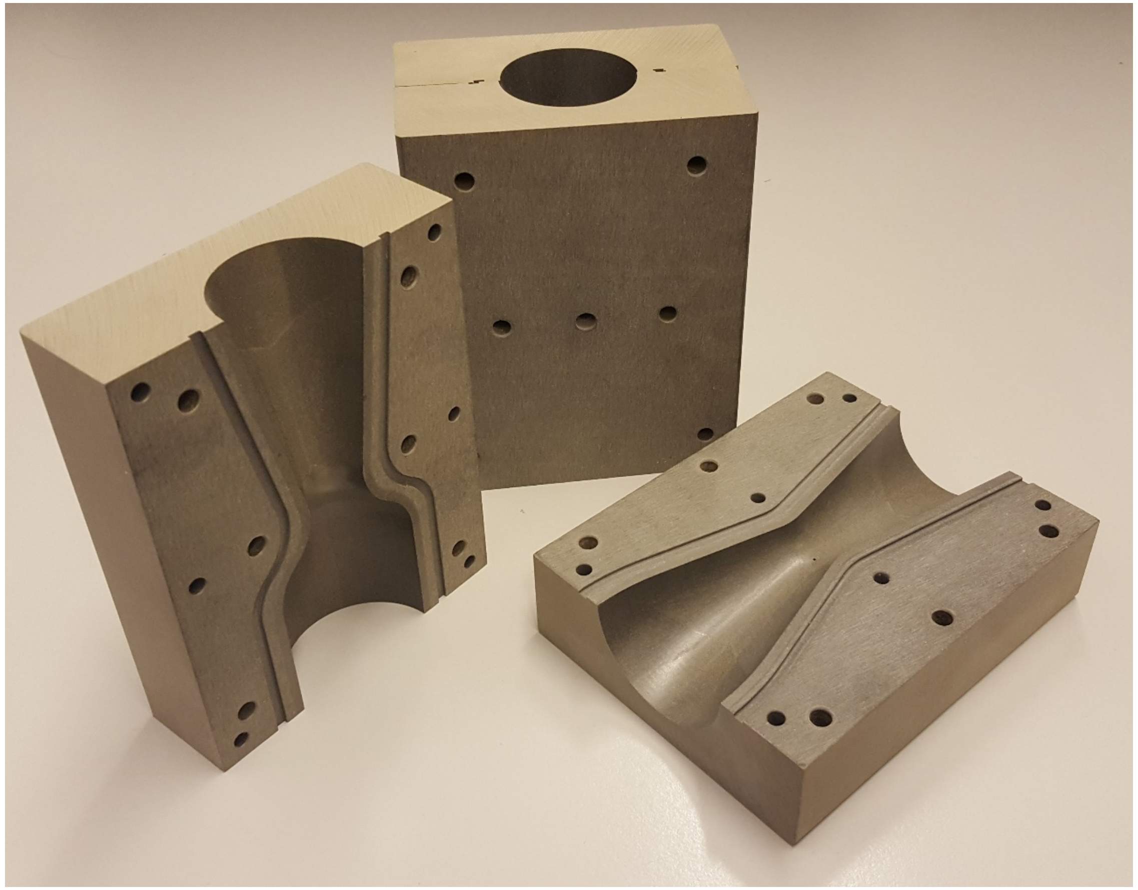
- More Pressure = „better“ u(i)
- More Ablation = „worse“ u(i)



[own work]

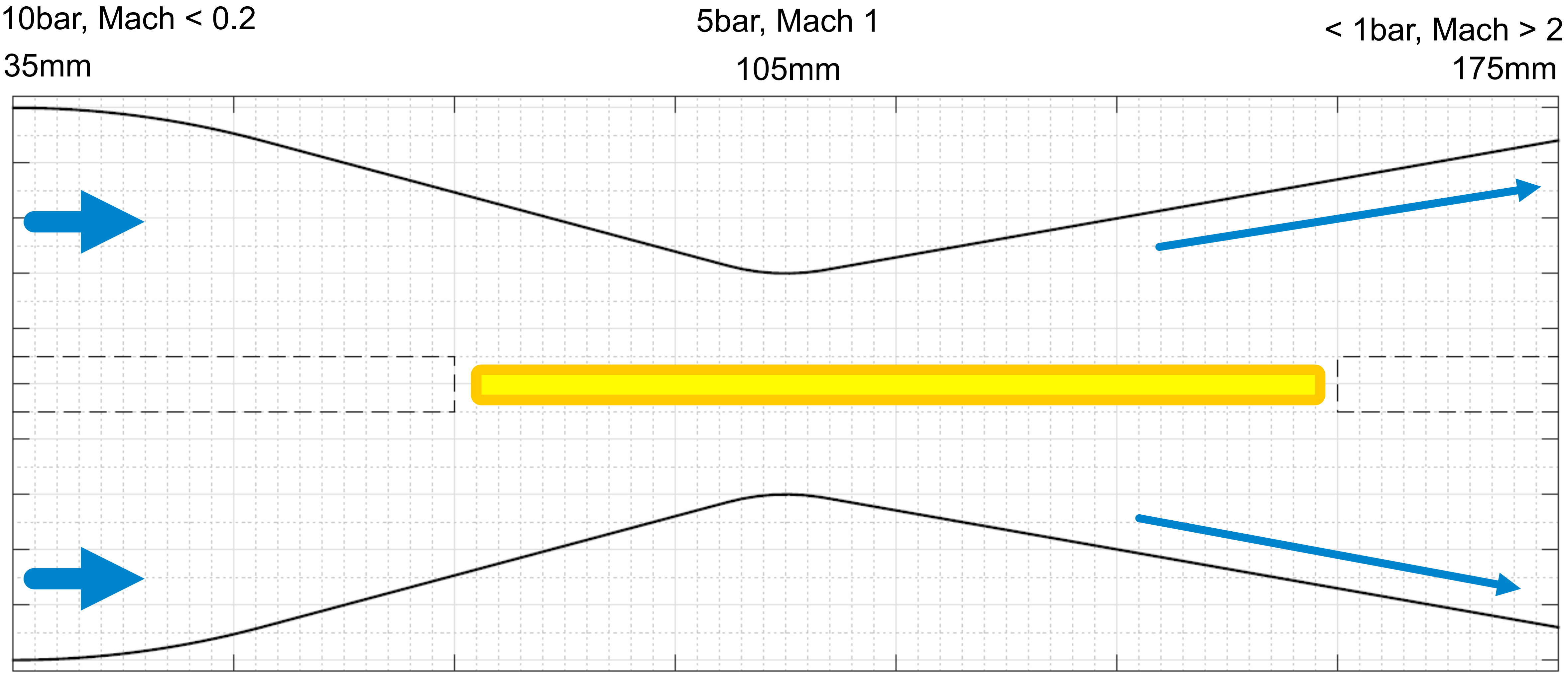
[1]: Bort, Franck (presented at FSO 2017, Brno, CZ)
Influence of Ablation on Differential Arc Resistance

Nozzle ablation measurements



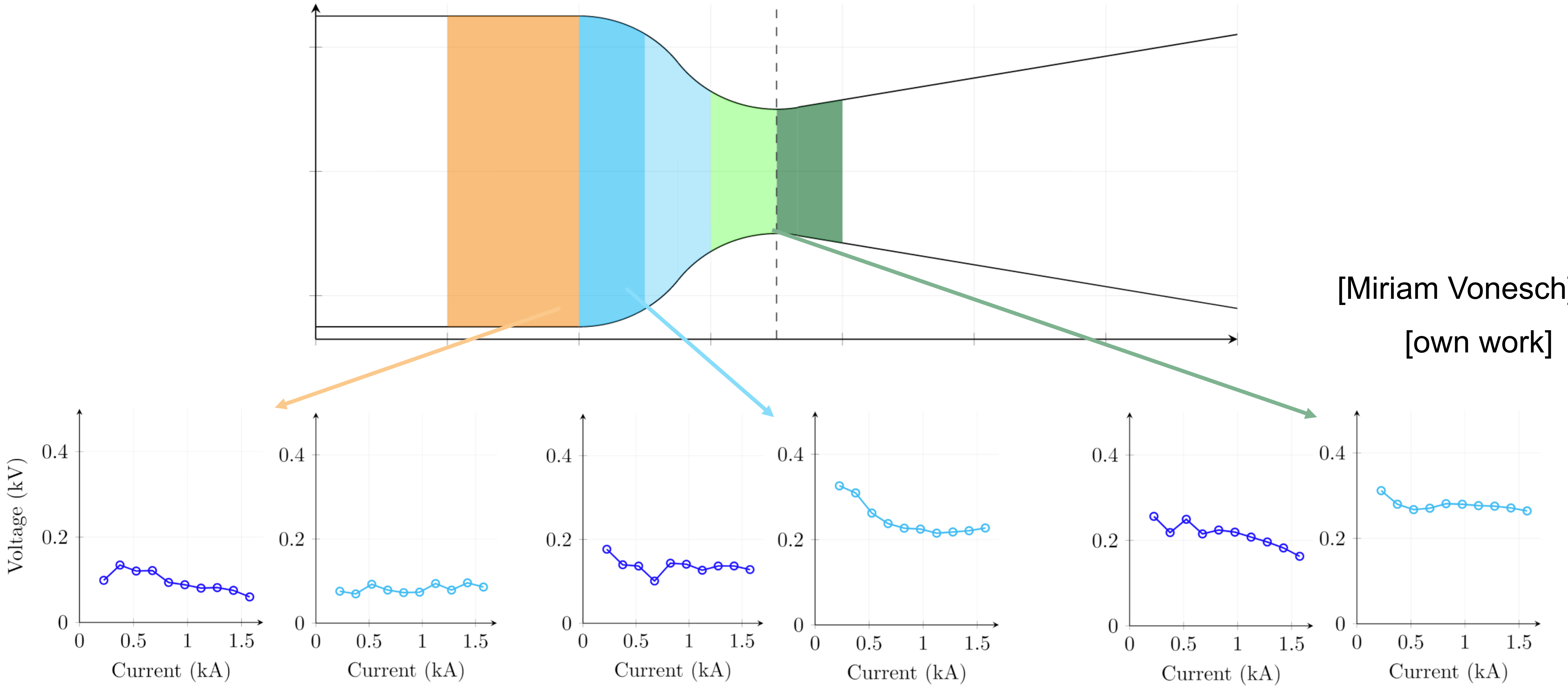
[Miriam Vonesch]
[own work]

Arc voltage is a strong function of axial position



[own work]

Determining where the “good” part of the voltage is created



[Miriam Vonesch]

[own work]

Conclusion

- There is still much to do and to understand in 40-year old equipment
- We will see if we can really get fast enough
- (Highspeed cameras are awesome)

How to switch off high voltage DC current without using semiconductors

Questions?

Contact Information:
Lorenz Bort
bort@eeh.ee.ethz.ch

Add-on

- Although not following perfectly, I tried to follow the advice of this nice talk about good slides
- https://www.youtube.com/watch?v=meBXuTIPJQk