Miteinander forschen
Wirtschaft stärken
Perspektiven schaffen

ILK DRESDEN

Exzellenz ab null Kelvin




Energy recuperating 4-quadrant power supply for inductive loads

Superconductivity for Sustainable Energy Systems and Particle Accelerators

GSI Darmstadt, 18th – 20th October 2023

U. Zerweck, N. Gust, A. Wesenbeck, F. Donat, T. Jande, S. Rackow, S. Richter, A. Kade

Motivation

– Test of superconducting magnets

– Available:

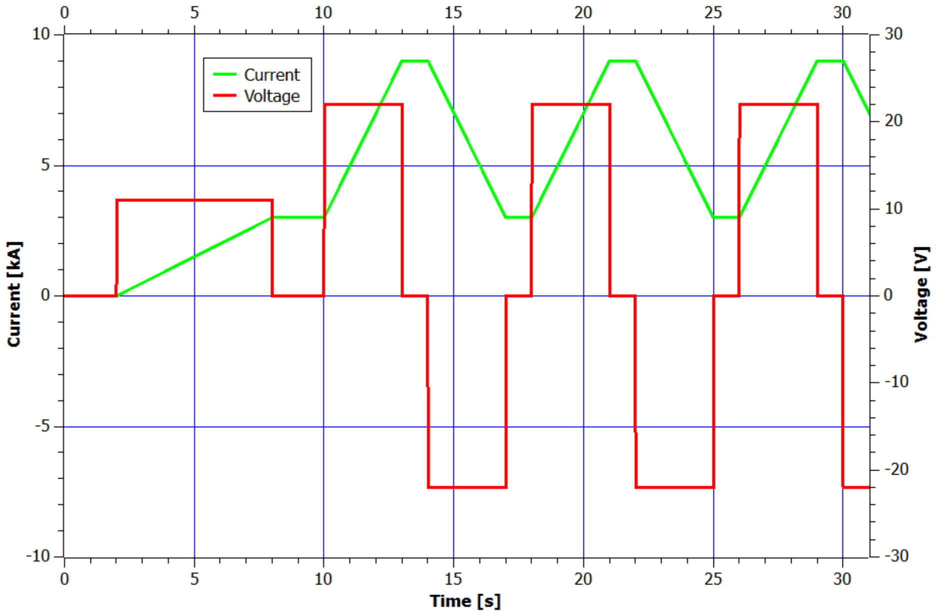
Laboratory grid supply:
400 V 3~ 130 A 90 kW

Helium infrastructure + rest:
400 V 3~ 100 A 70 kW

High current power supply:
400 V 3~ 30 A 21 kW

– Needed:

High current power needed:
25 V 1- 14 kA 350 kW



SIS300 dipole magnet:

L = 11.4mH

I_{max} = 8926 A

U = 22 V

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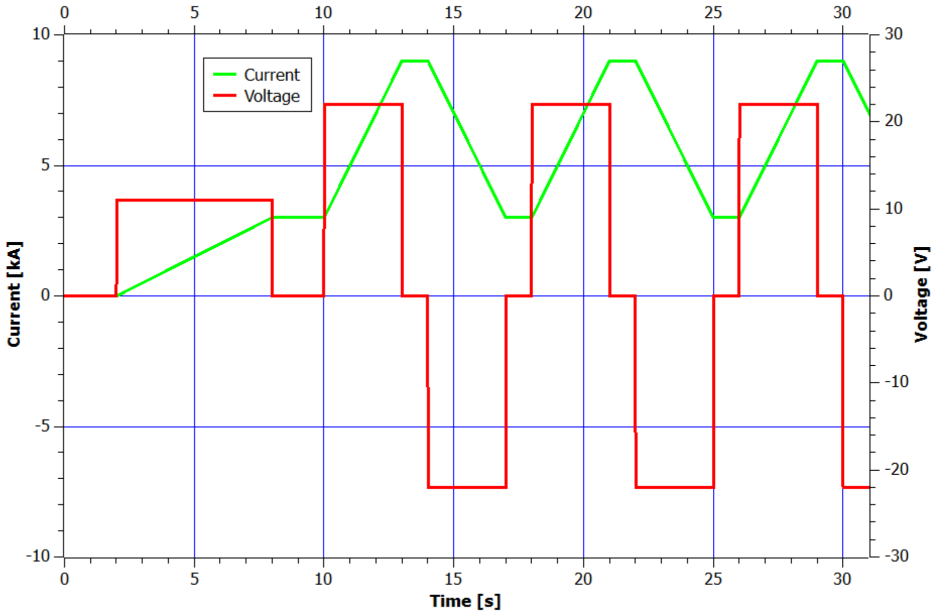

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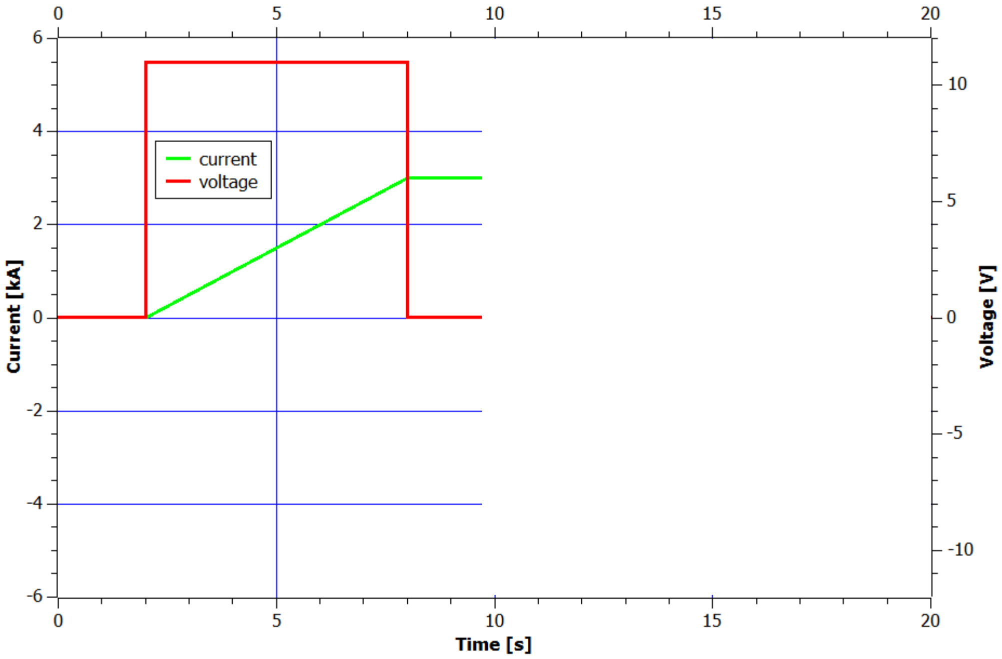
Outline

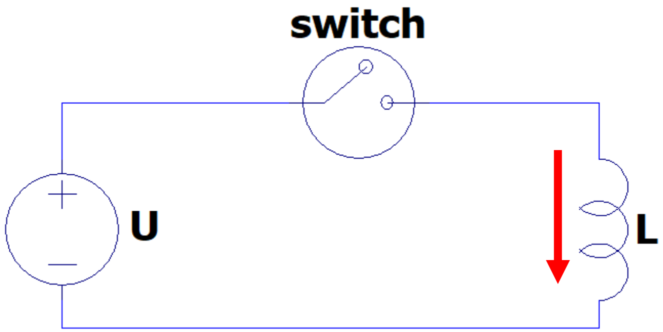
- How To: drive an inductive load
  recuperate inductive energy
  store recuperated energy
  store MJ safely, control kA with mV sensitivity
- Test results of capacitor bank, 4-quadrant converter and quench protection
- Test with GSI SIS300 magnet (9 kA, 0.5 MJ)

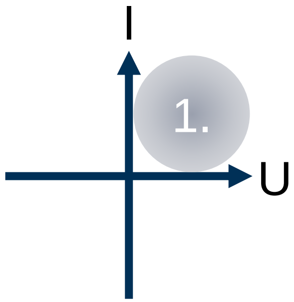
Current through an inductor



- voltage = torque, current = speed, inductance = moment of inertia
- apply dc voltage on inductance via switch
- current rises linearly
- massive arcing when opening switch

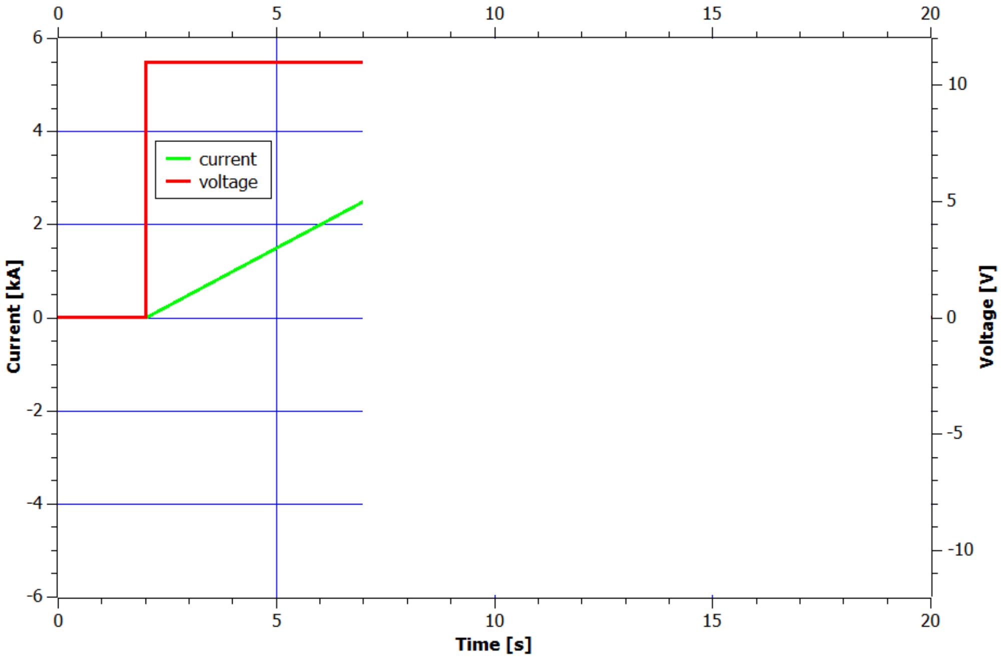
[1]





Current through an inductor

– voltage = torque, current = speed, inductance = moment of inertia
– replace switch by MOSFETS
– highside increases current

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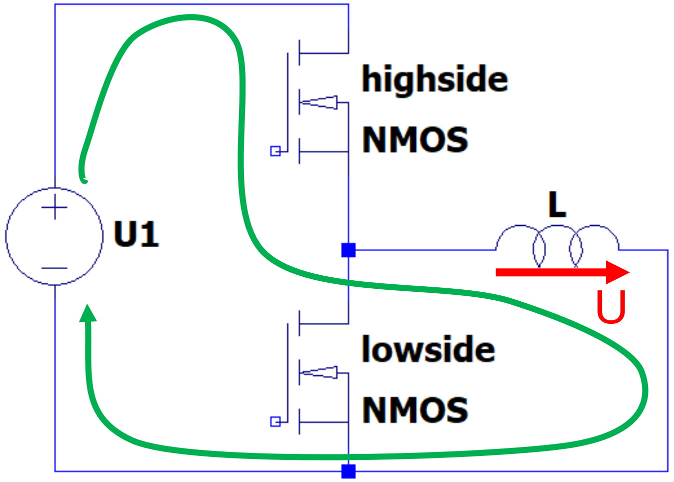

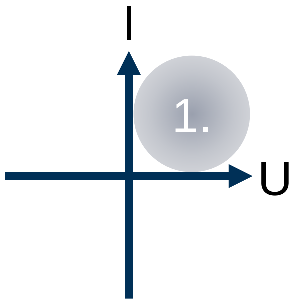

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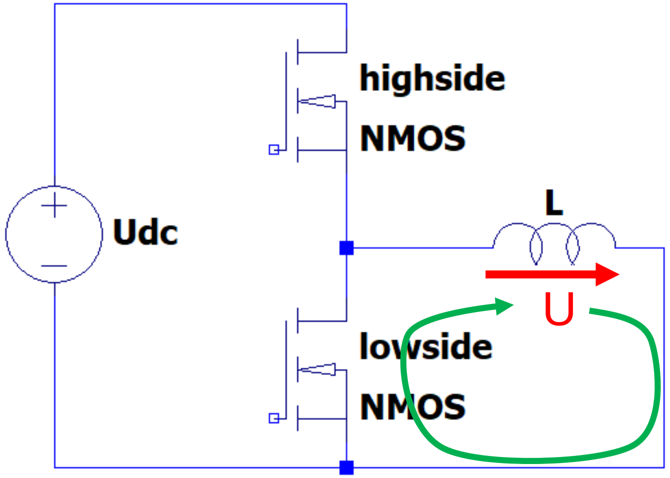

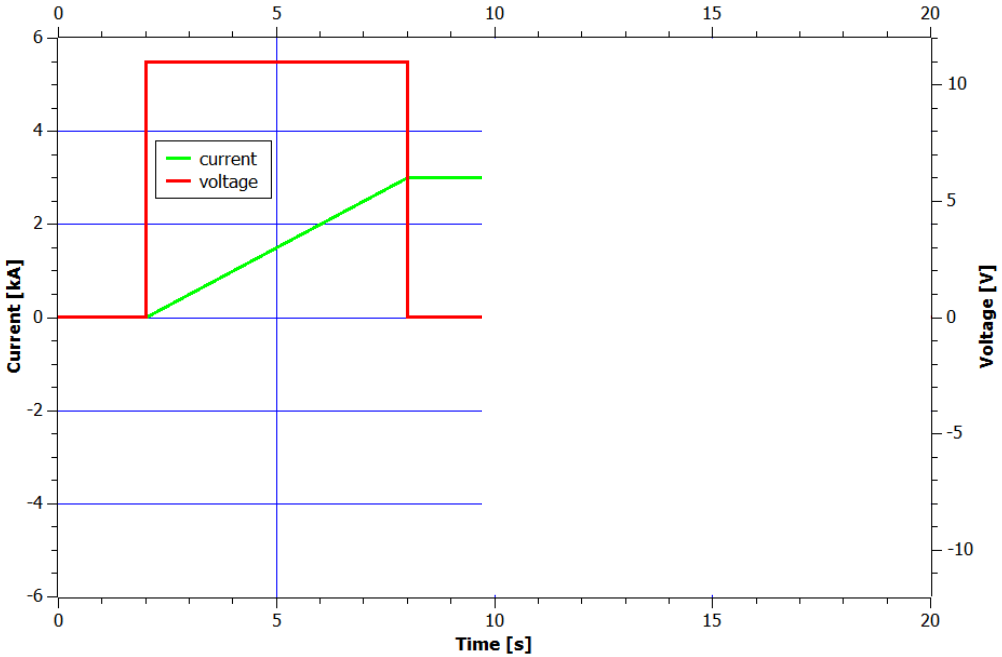

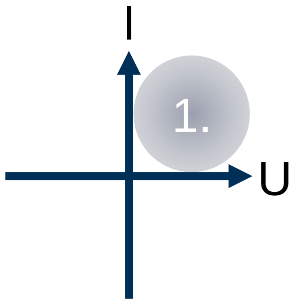

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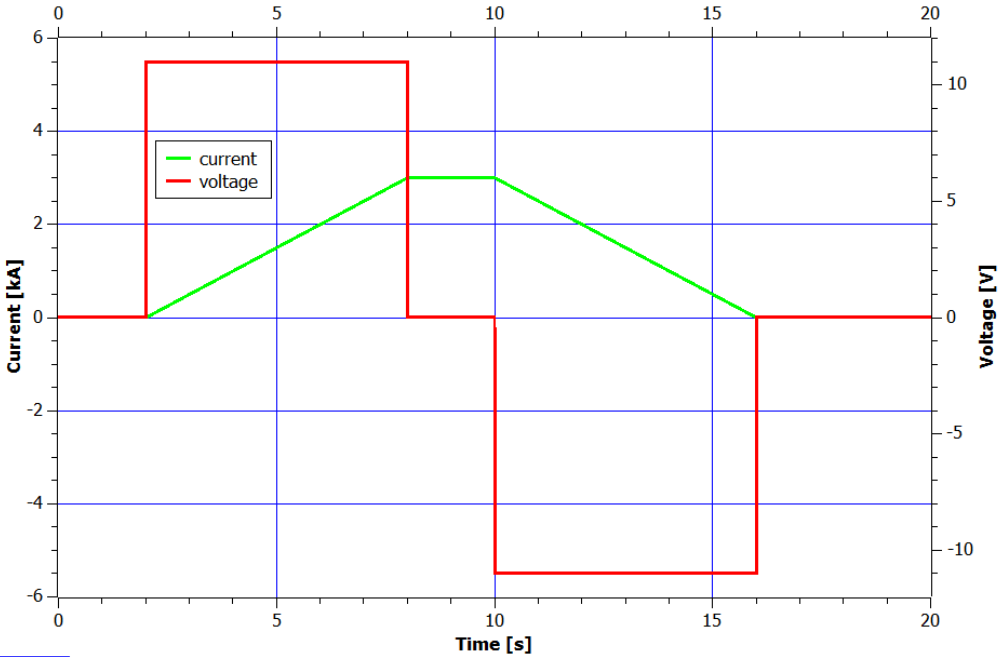
- recuperation into power supply



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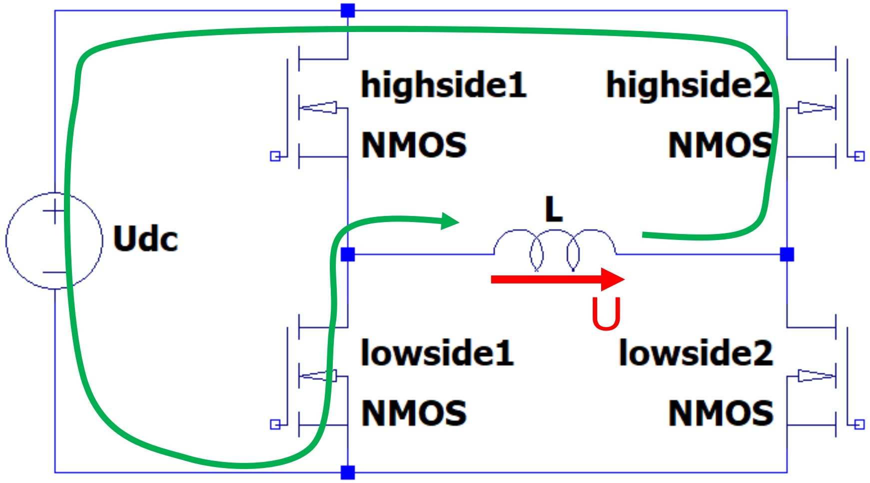

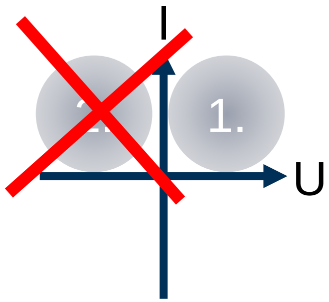

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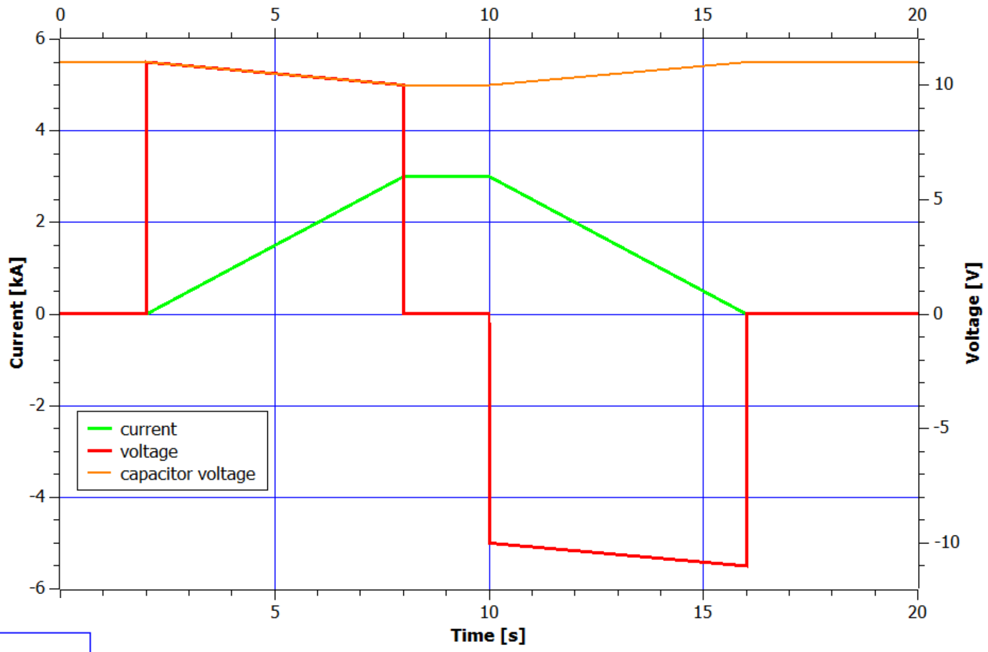

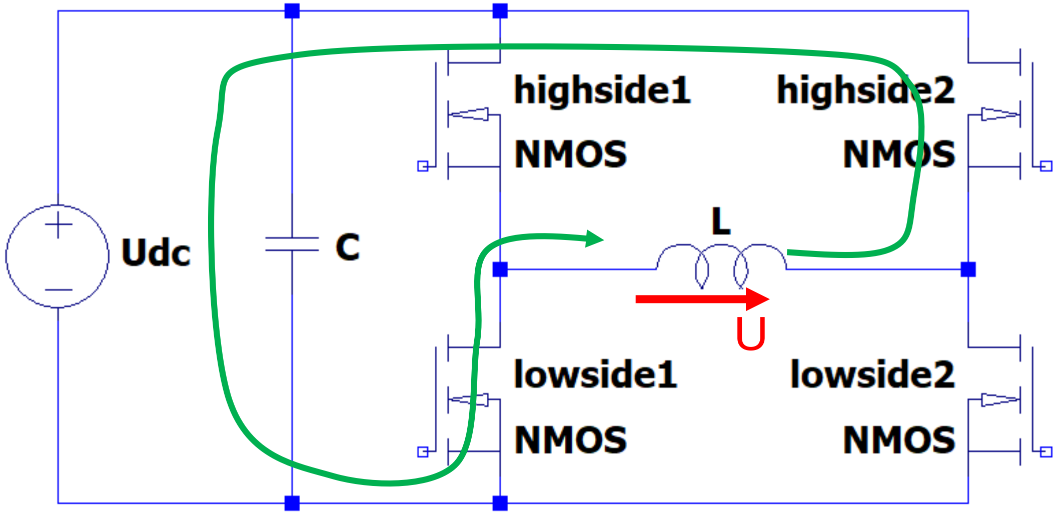

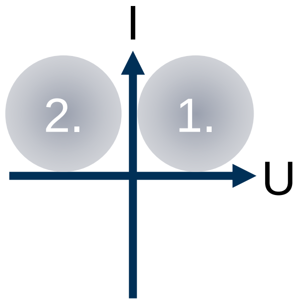

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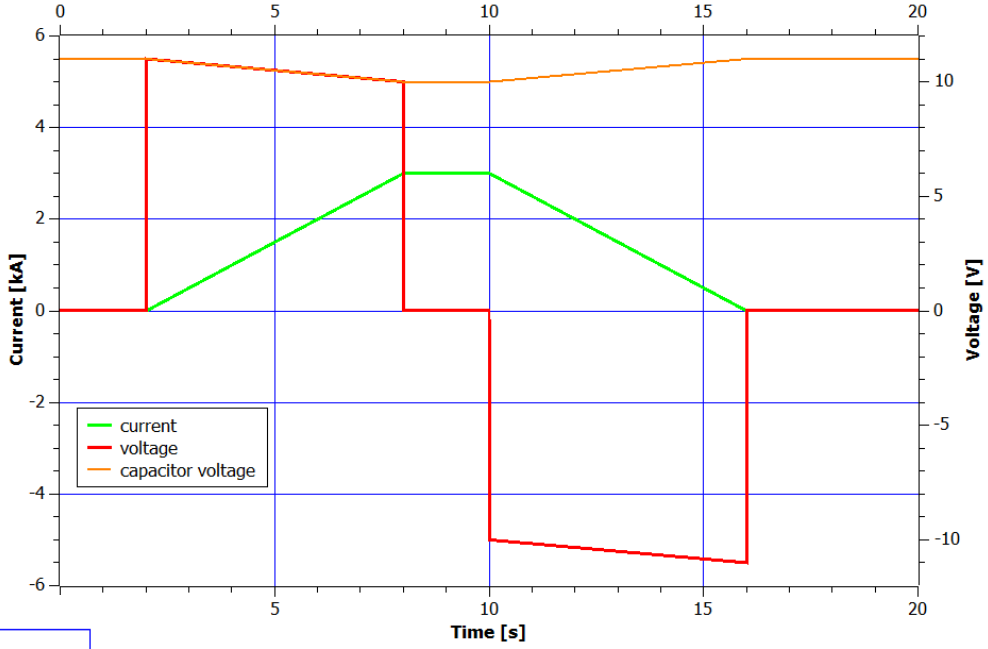
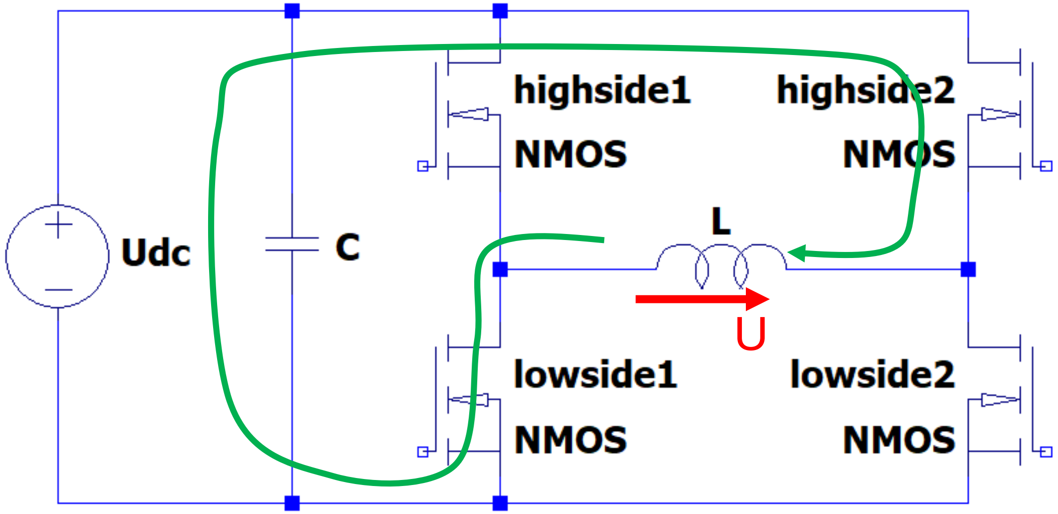
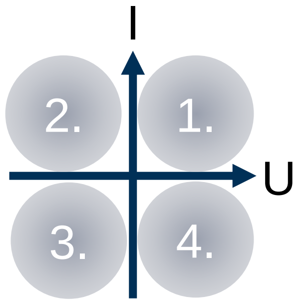


- E_L=1/2 L I^2 = 500 kJ

→E_C=1/2 C U^2 = 5 MJ





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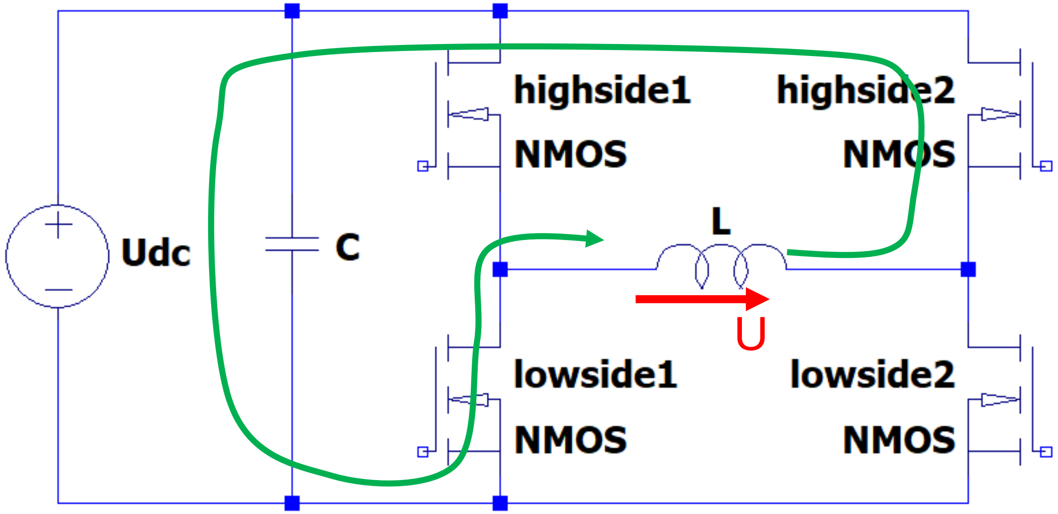
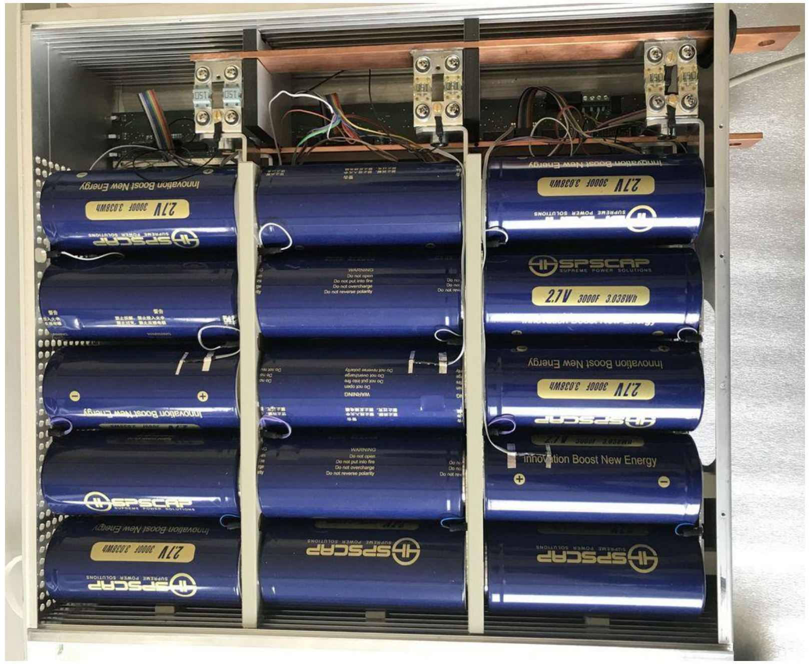
- 2.7 V Supercapacitors



Current through an inductor



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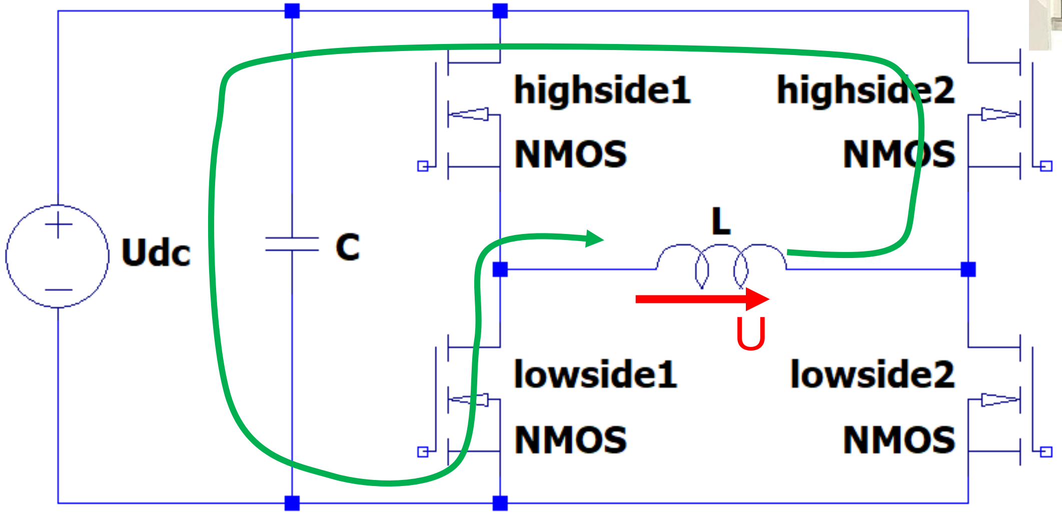
- 10x → 27 V_{max}

→10x 3x in one rack insert

→ 15,3 kF in 17 inserts



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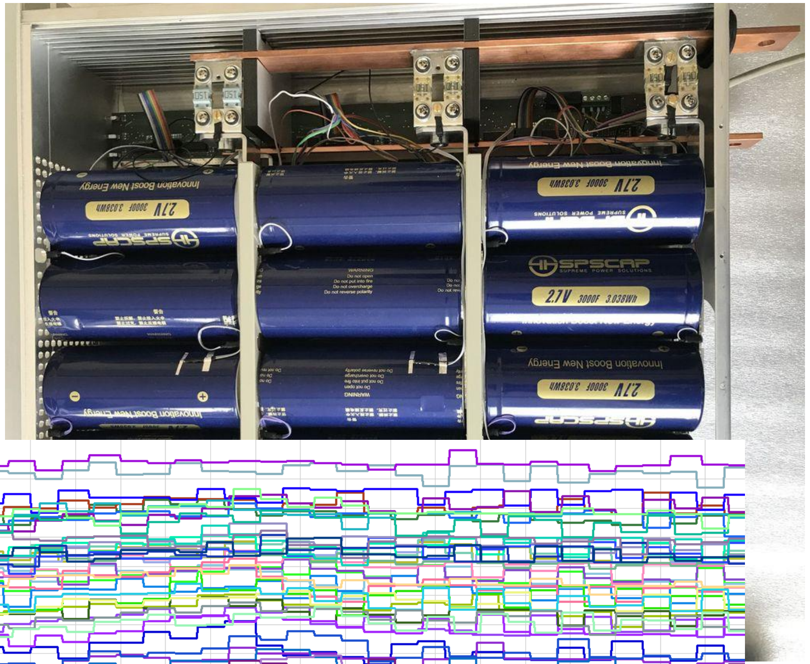
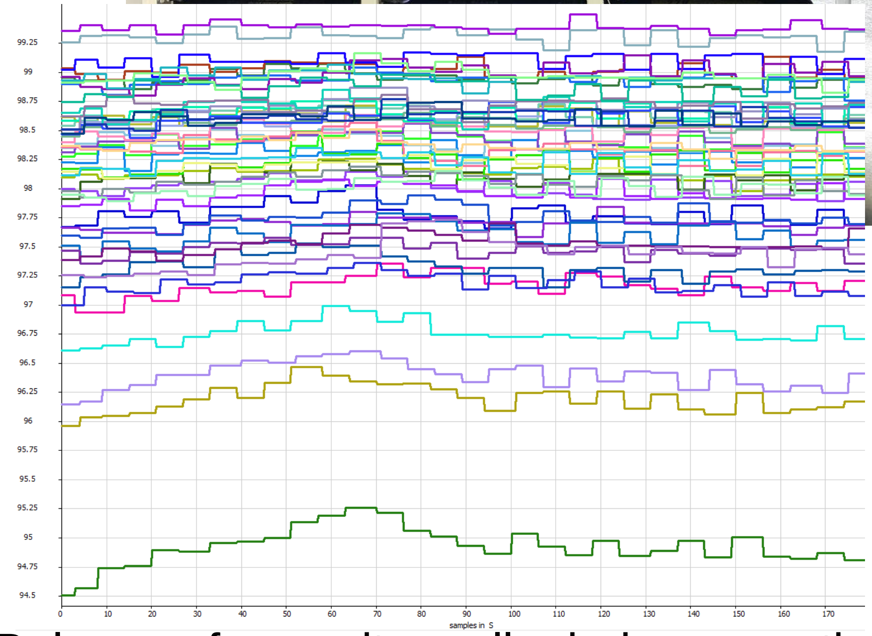
- security:
  active MOSFETS
  passive fuses
  short cirquit proof
- ILK temperature sensor multiplexer:
  each capacitor monitored
  individually (µC)





Balance of capacitor cells during operation

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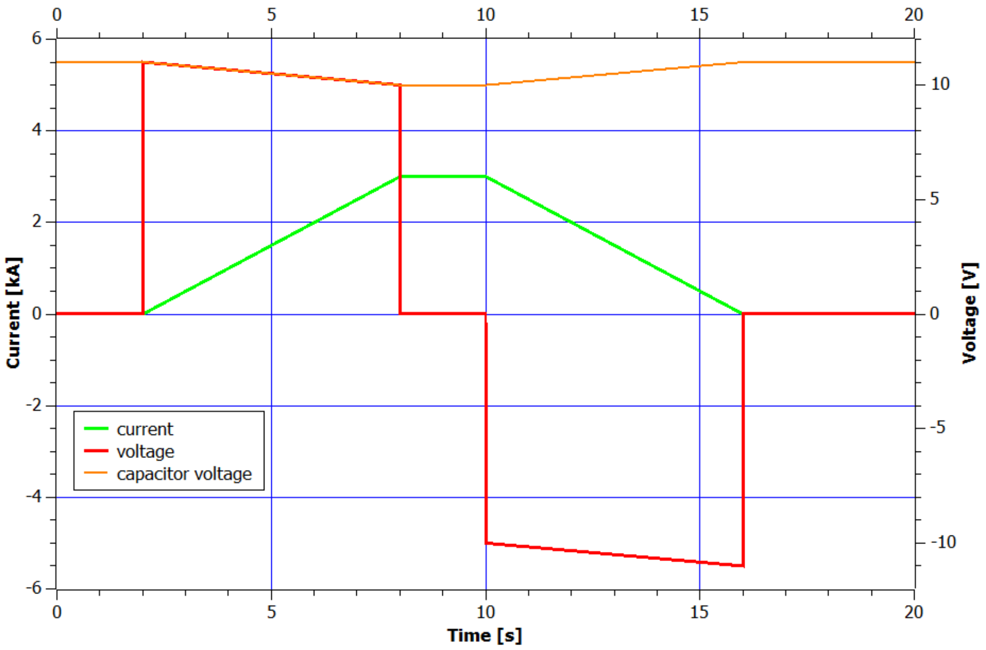

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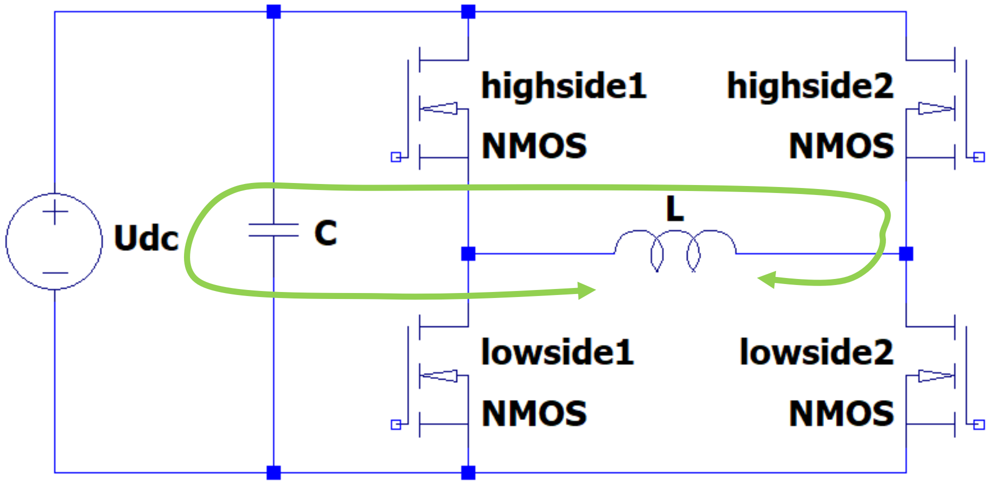


High-current voltage supply

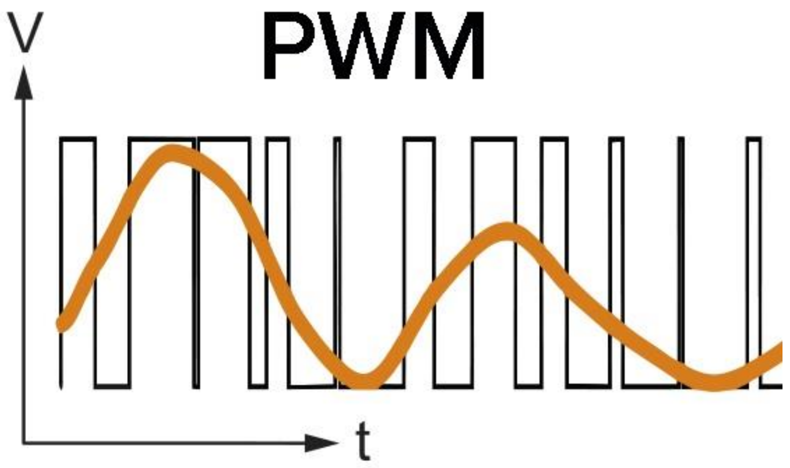
– **variable** output voltage required ~~27V~~

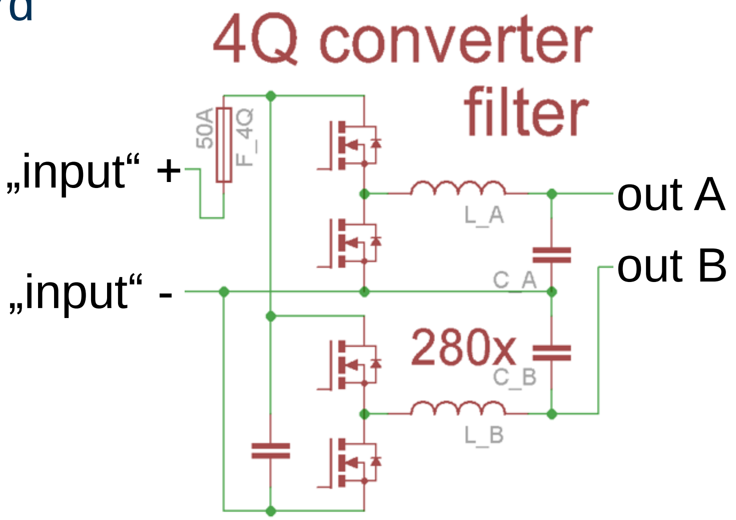
→ pulse width modulation of output 0% .. 100%

– steep transients with high harmonics ←→ quench detection !

– filtering required, as close as possible

– 30 V 50 A per board





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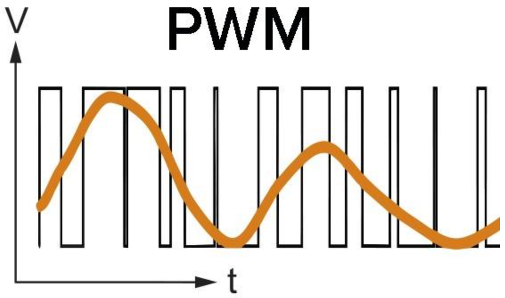

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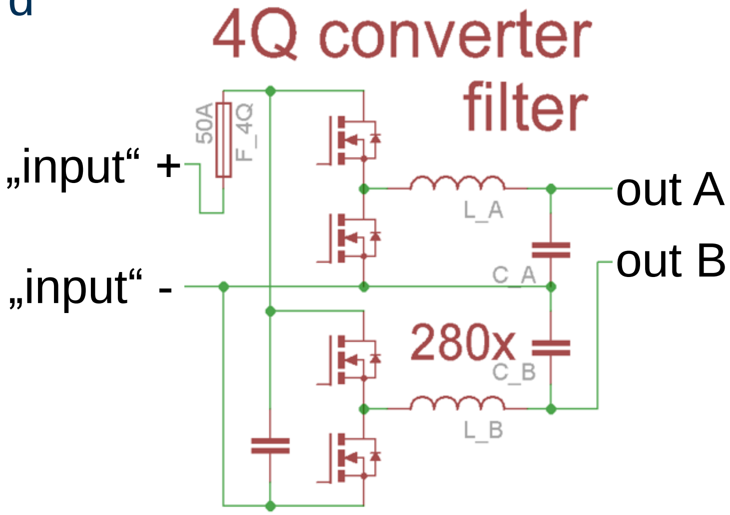

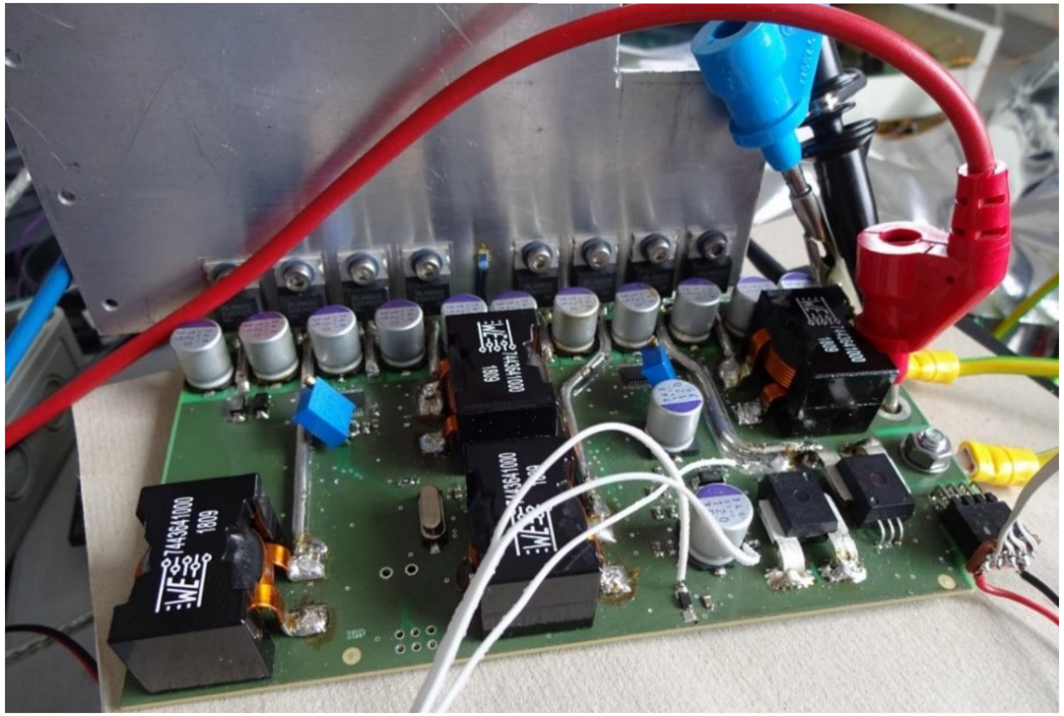

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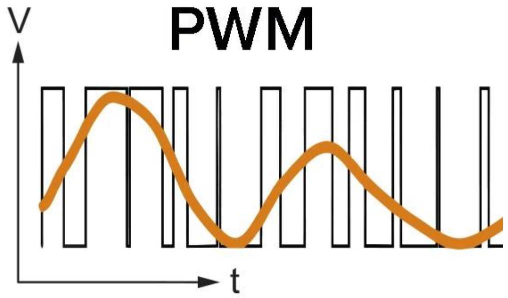

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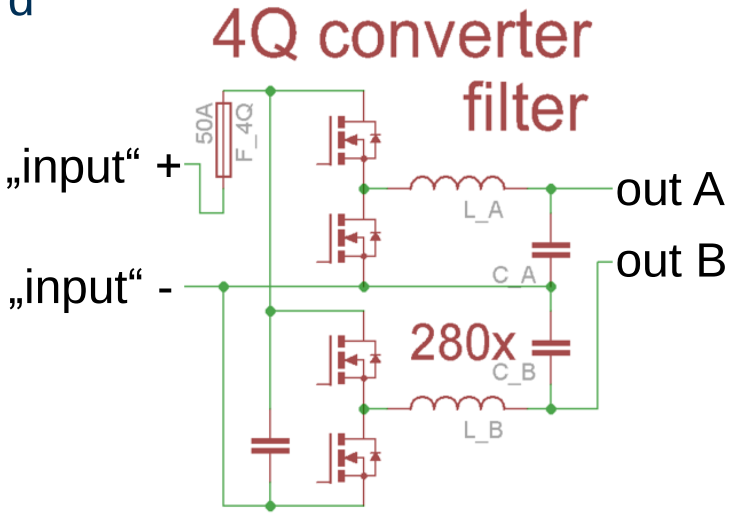

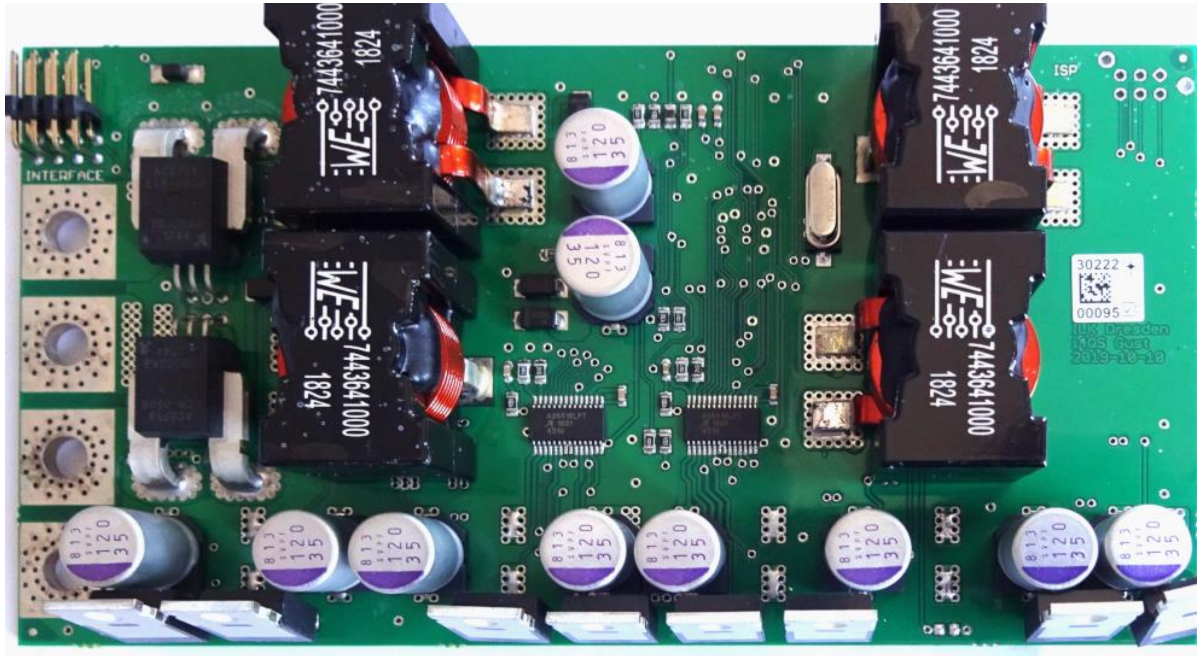

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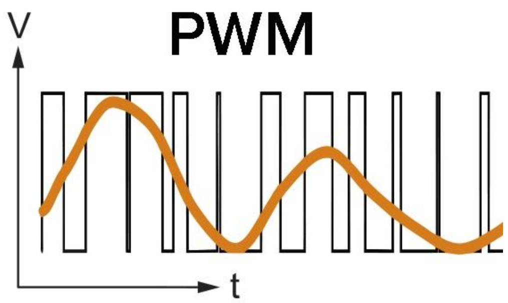

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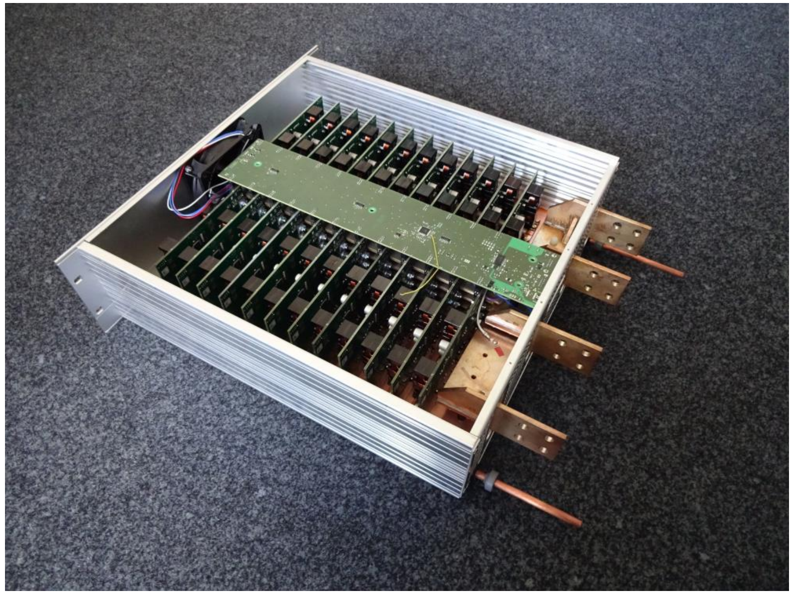
– 30 V   50 A per board
– 20 boards per rack insert
– 20x output current regulation in parallel
– 1x setpoint distribution and data communication board



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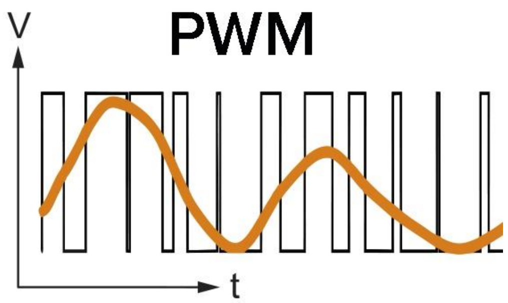

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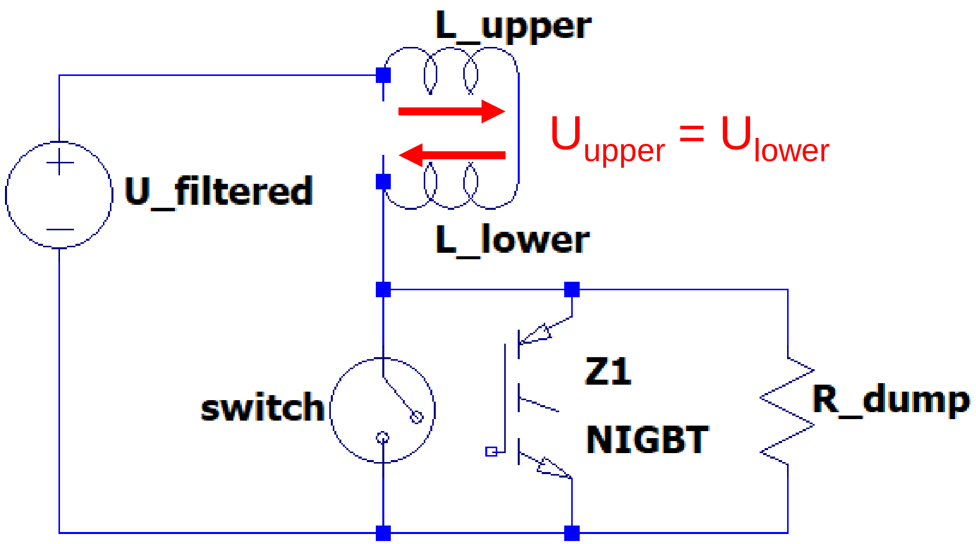
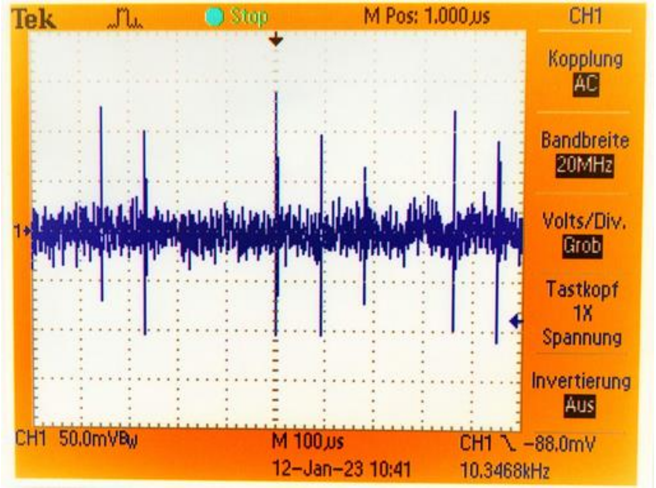
→ pulse width modulation of output 0% .. 100%

– steep transients with high harmonics ←→ quench detection !
– filtering required, as close as possible
– 30 V   50 A per board
– 20 boards per rack insert
– 14 rack inserts
– 280 4-qadrant musketeers – one (master) for all, all for one (magnet)

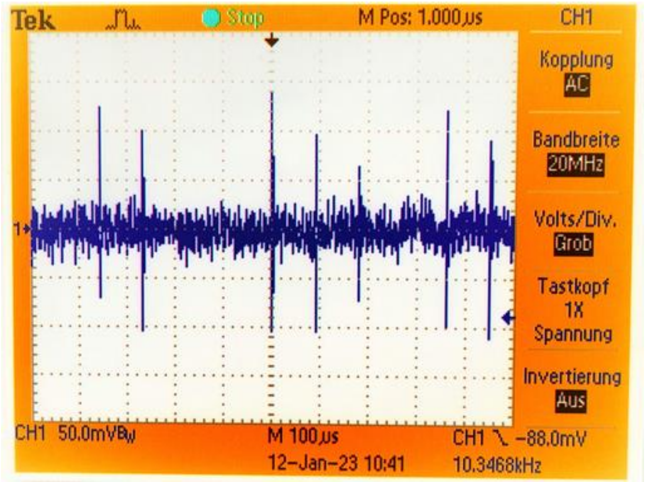
Quench detection and protection

- filtered output: < 1 mV ripple, theoretically
- measured: 20/100 mV ripple. Culprit: grid power supply
- no noise from 4-quadrant converter measurable
- filtered detection: bipolar, <1 ms, >2 mV adjustable





4Q converter off



4Q converter on, 1 kA

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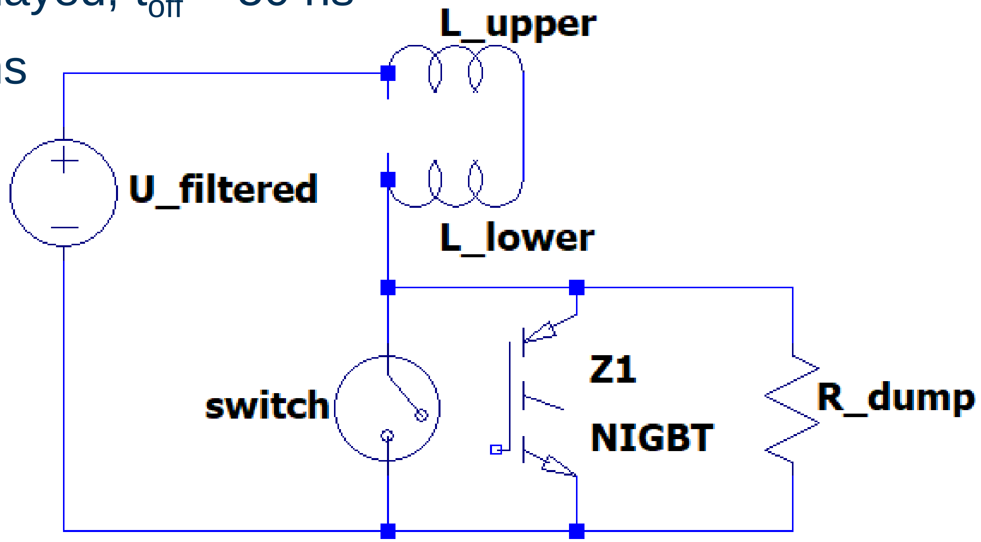
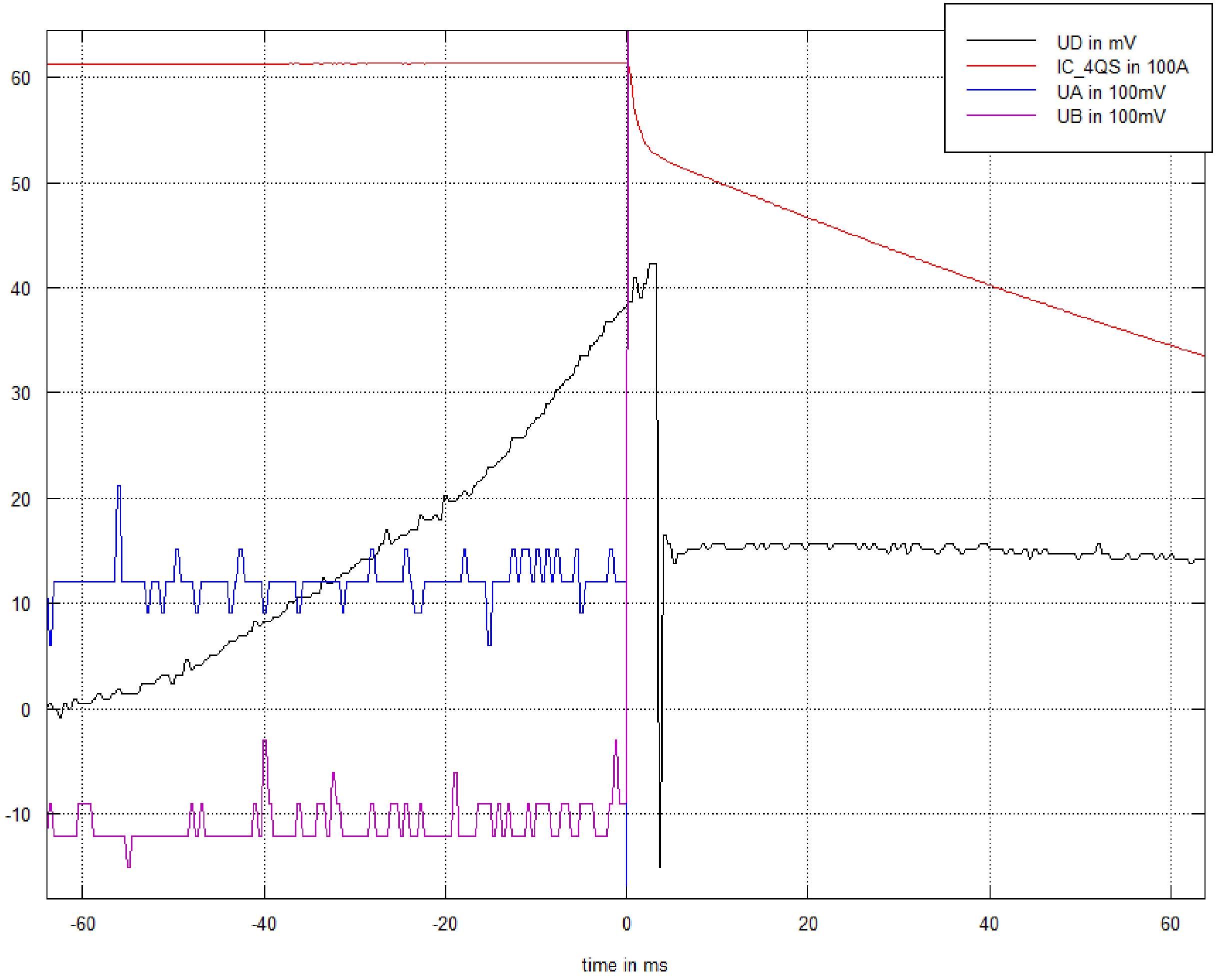
- switch: 30x 500 A, t_{open}= 2 ms
- IGBT: delayed, t_{off} = 50 ns
- total: 5 ms





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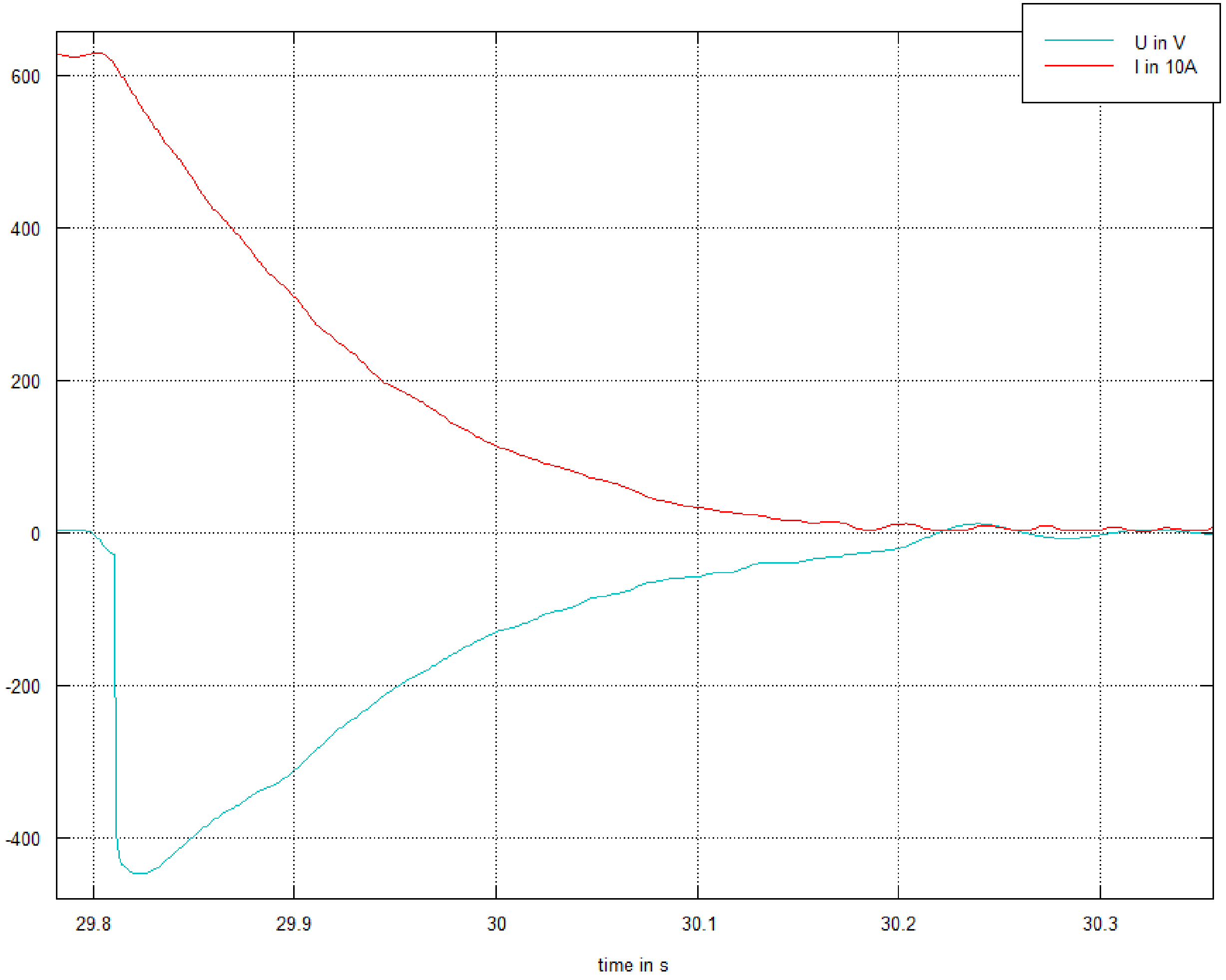
– total: 5 ms
– peak quench power 12.6 MW
– 90% de-energized in 200 ms



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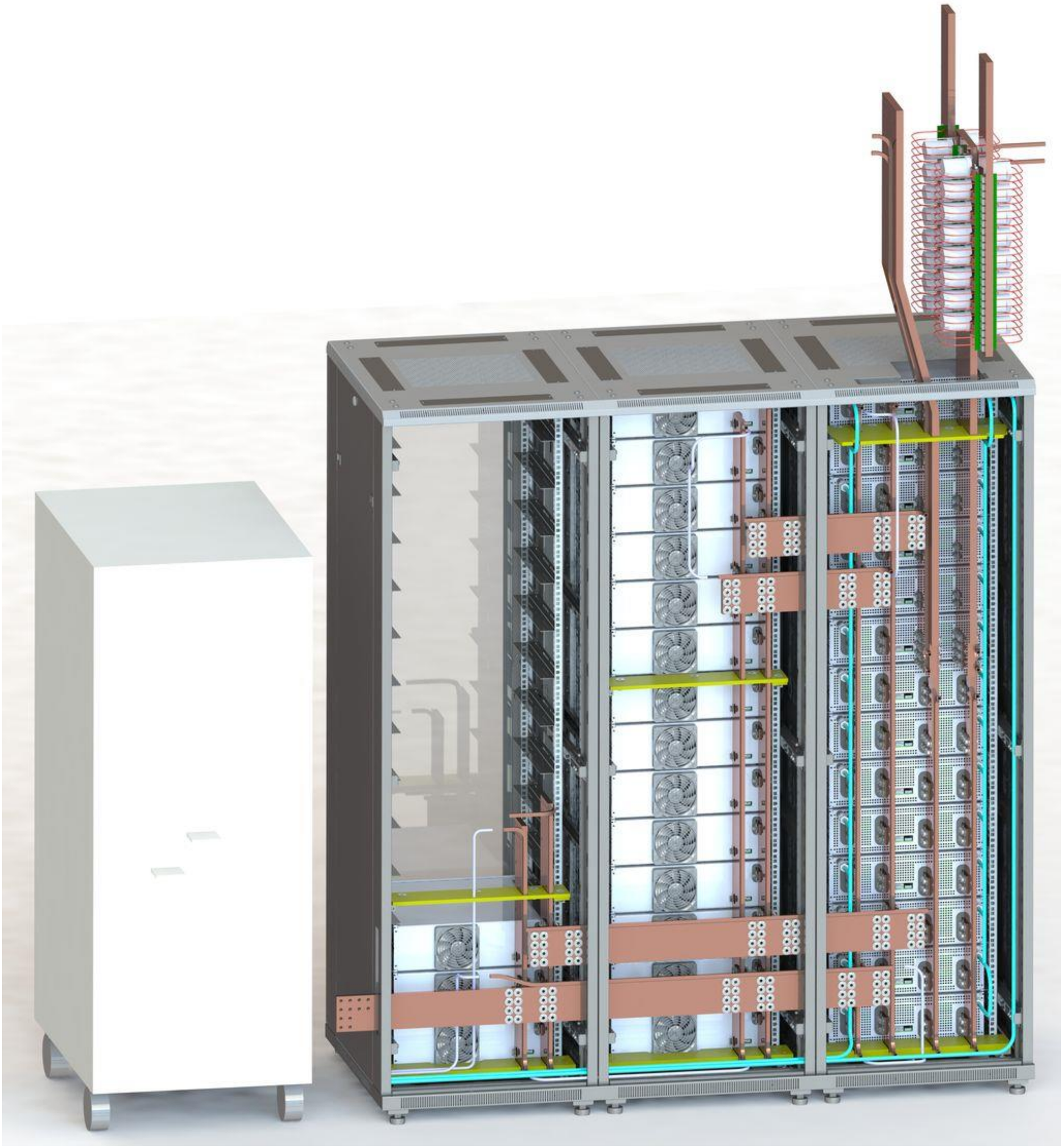


Test with GSI SIS300 magnet

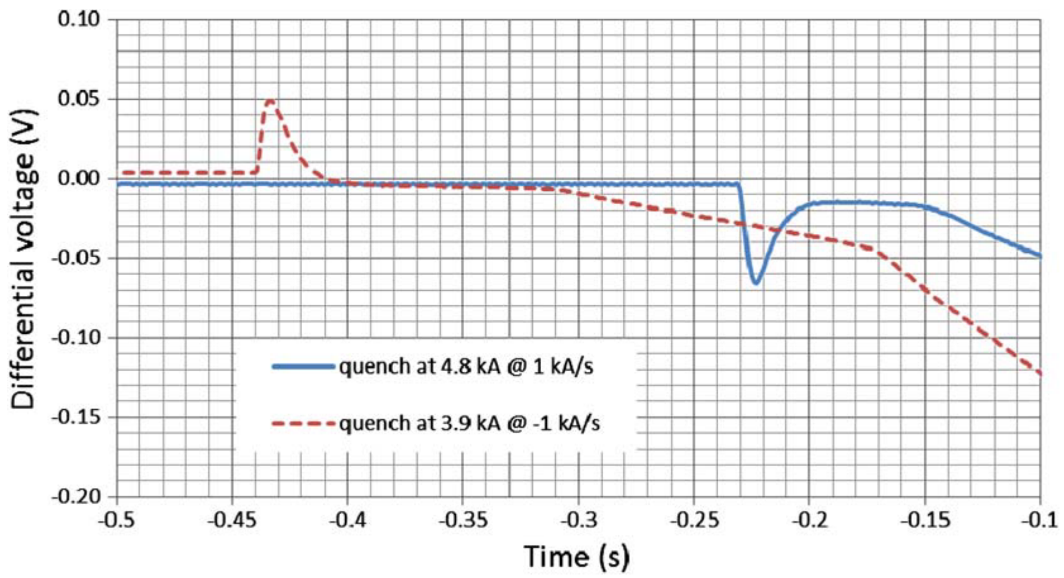
SIS 300 magnet at ILK Dresden for testing:

- ramping with different rates and regimes (start and hold current, timing)
- determination of quench characteristics
- inductance 11 mH
- current 3 … 9 kA
- magnetic field 1.5 ... 4.5 T
- ramp-rate up to 2 kA/s
- ramp-voltage up to 22 V
- magnetic energy up to 500 kJ

Test with GSI SIS300 magnet

Test results from INFN-LASA, Milano, 2012

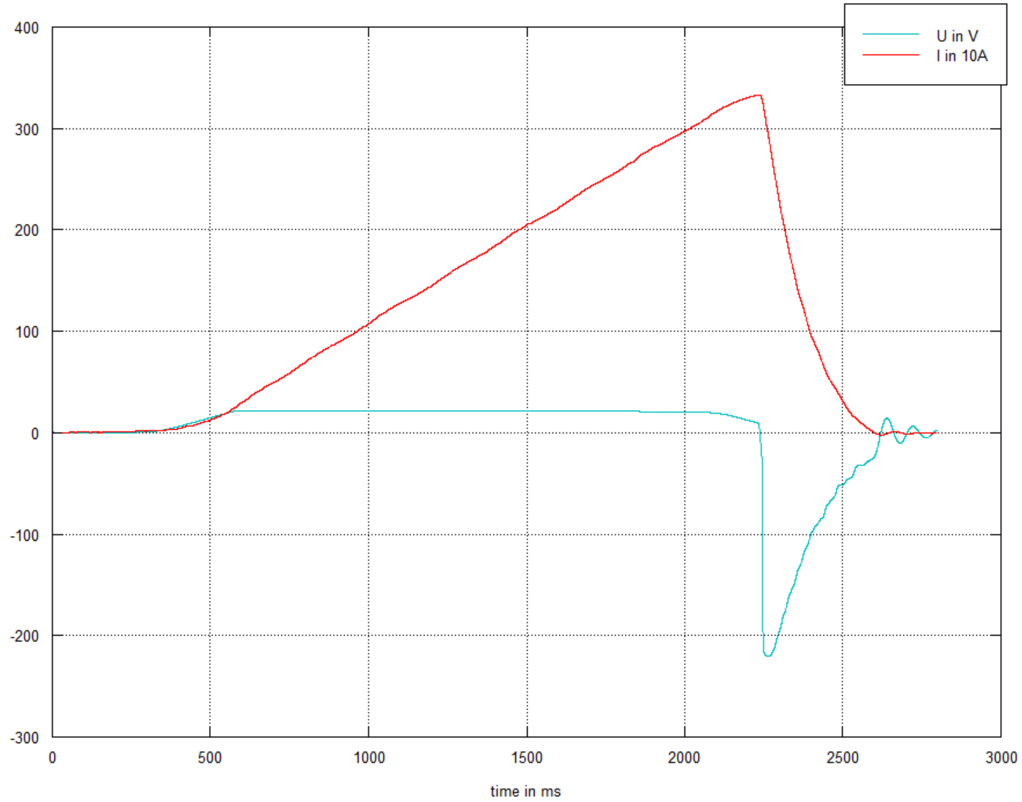
- 9 kA reached
- quenches if:
  too much ΔI in combination with
  too much dI/dt
- 50 mV coil difference voltage pulse
  60 … 100 ms before quench
- pulse missing during training quench
- theory: sc loop current in coil head
- current loop compensates flux locally until quench
- flux redistribution in coil → voltage pulse

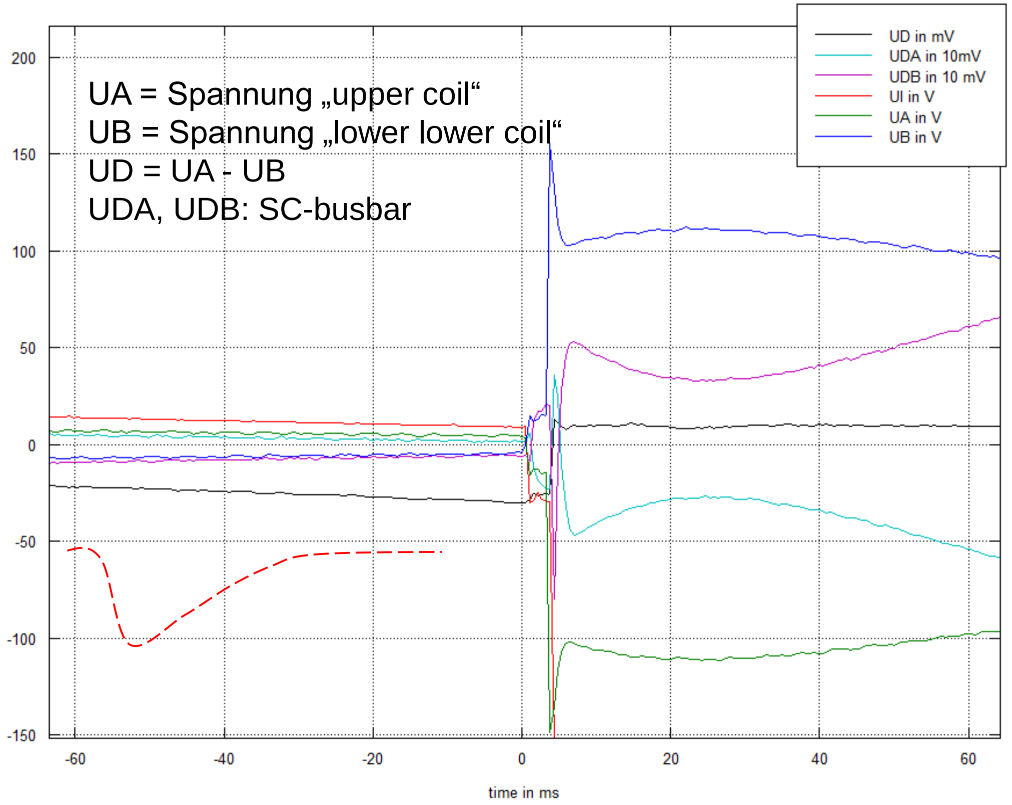


Test with GSI SIS300 magnet

Measurement #1

- 0 A → 3191 A @ 1900 A/s
  triggered @ -20 mV with -0.12 V/s
  peak ramping power 64 kW

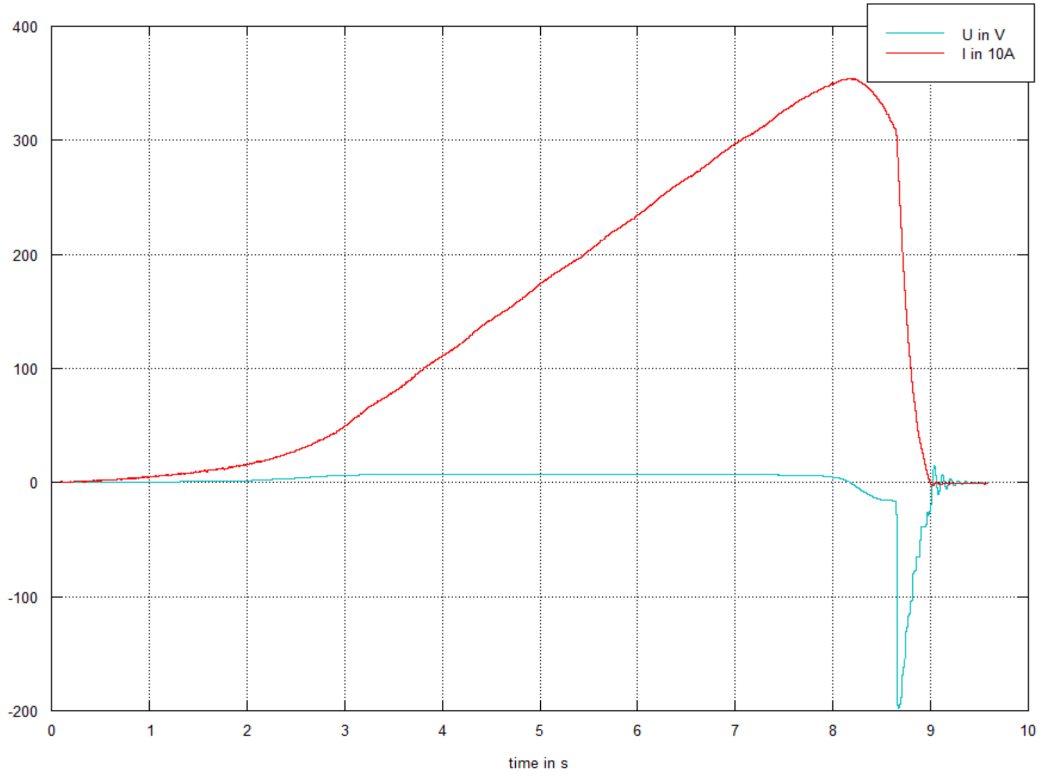


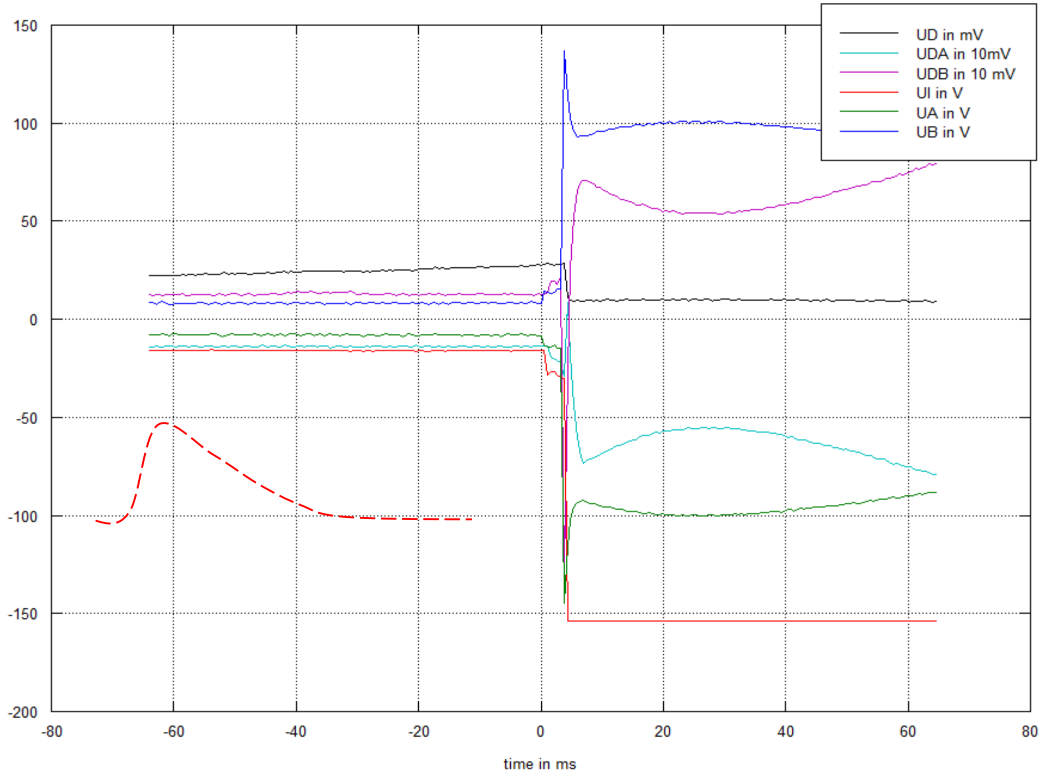


Test with GSI SIS300 magnet

Measurement #5

- 3540 A → 3100 A @ -1,6 kA/s
  triggered @ +30 mV with +0,09 V/s
  peak ramping power -50 kW

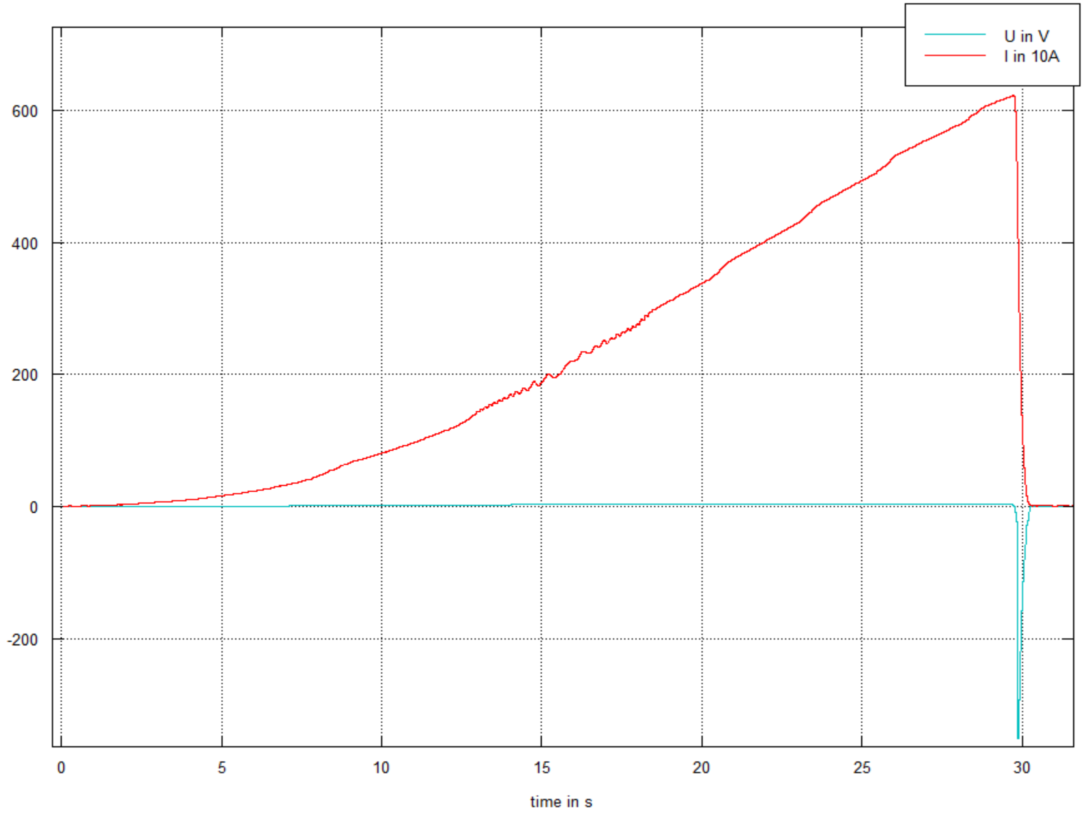


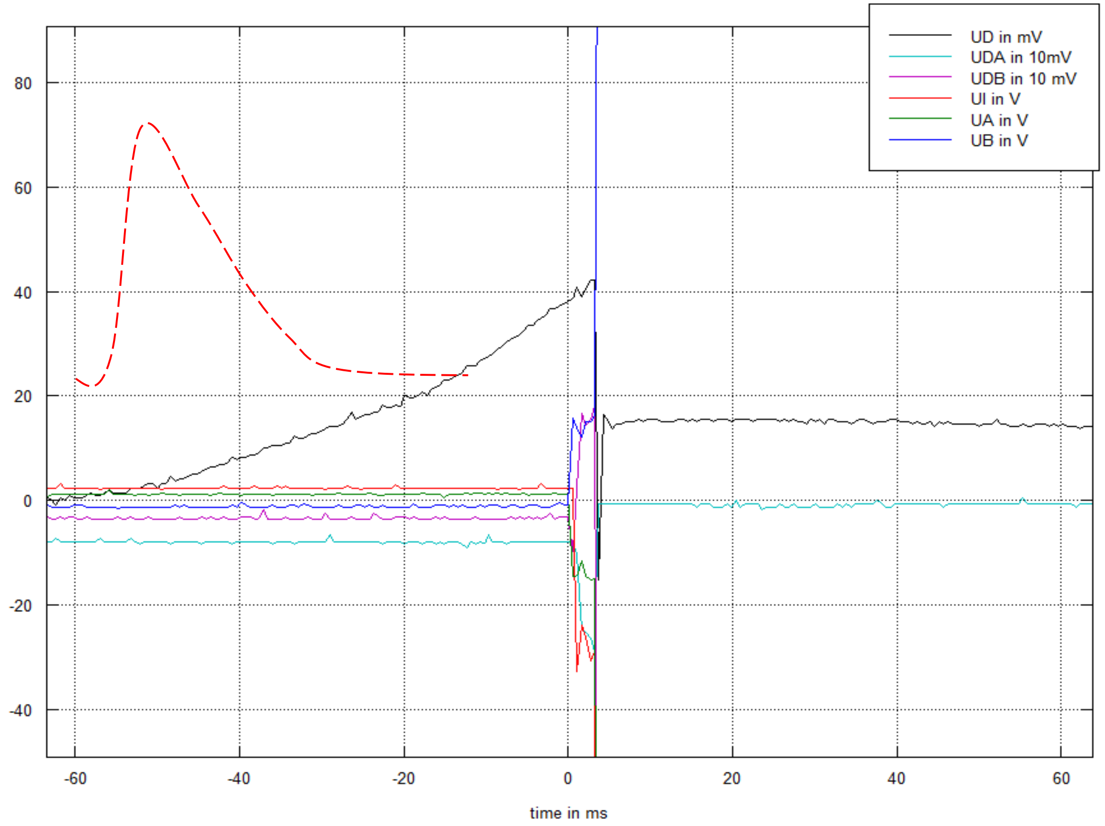


Test with GSI SIS300 magnet

Measurement #21

- 0 A → 6310 A @ +0,20 kA/s
  triggered at +40 mV with +0,67 V/s
  peak ramping power 23 kW, quench 2.8 MW

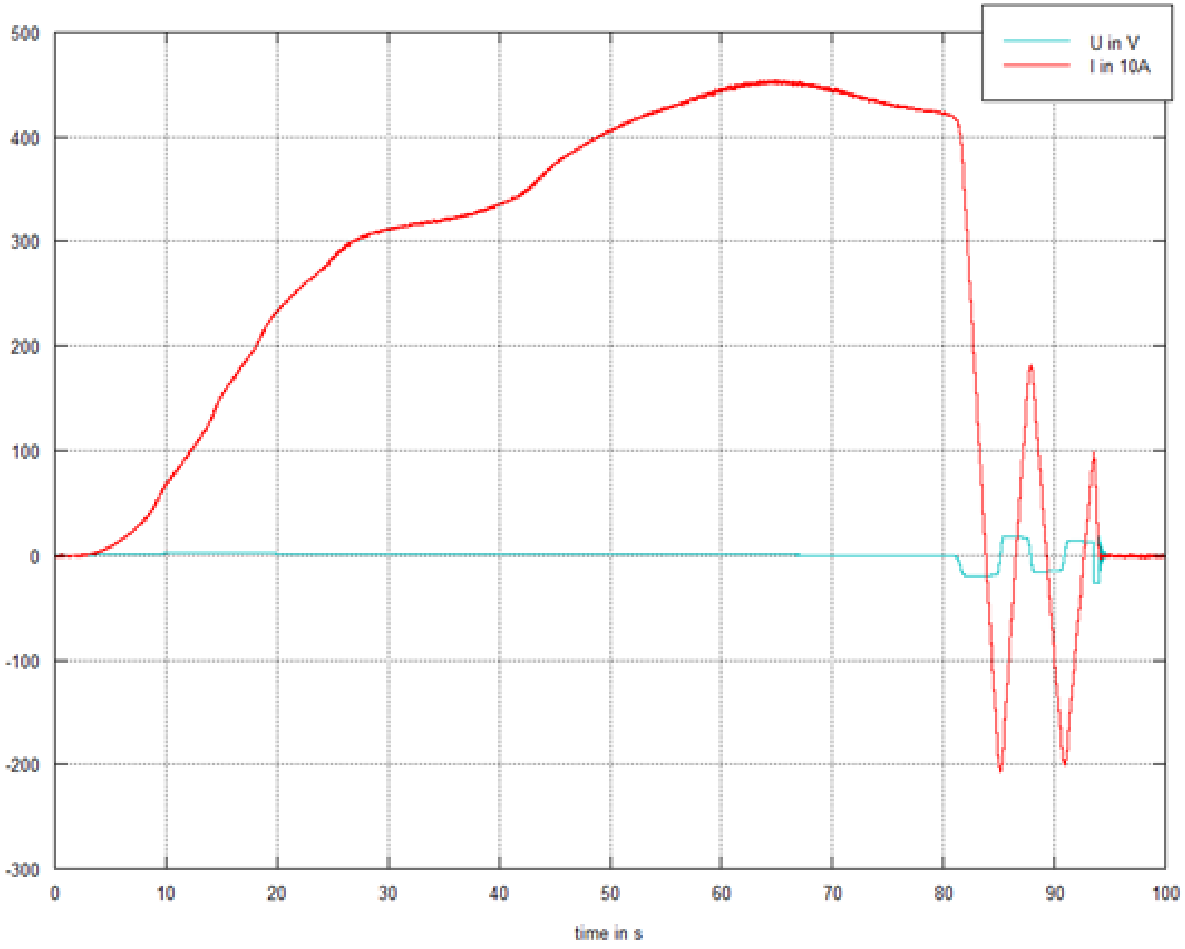




Test with GSI SIS300 magnet

Measurement #18

- +4.3 kA → - 2 kA @ -1,7 kA/s
  no trigger at 20 mV threshold
- quench expected at +0,1 kA
- peak ramping power -84 kW



Test with GSI SIS300 magnet

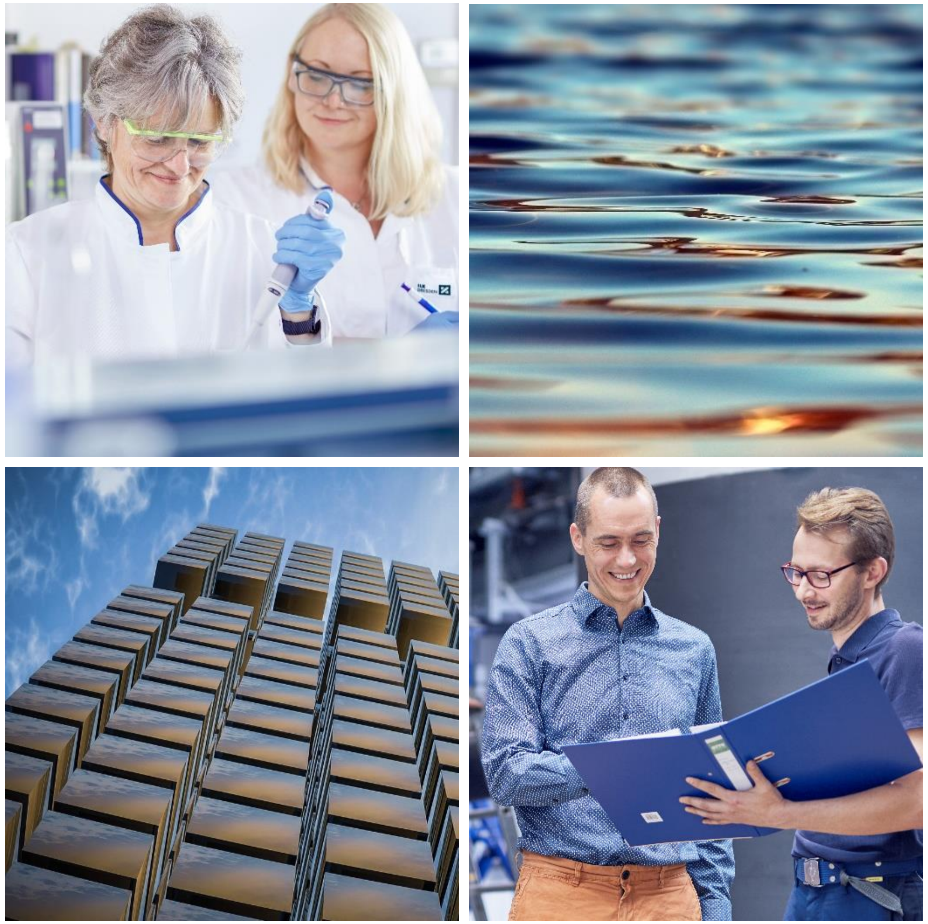
Two modes of quenches are observed:

- Magnet quenches in upper coil if ramped fast (no. 1-5, 7-13, 15, 19, 20), differential voltage is inverted from ramp rate
- Magnet quenches in lower coil if ramped slow (no. 6, 10, 14, 16, 21)
- Results need more clarification

Quench	Initial current in A	Quench current in A	Ramprate in A/s	UD in mV
1	0	3191	1905	-20
2	0	3180	1515	-30
3	0	3350	1666	-30
4	0	3320	1894	-30
5	3540	3100	-1583	28
6	0	3080	333	40
7	0	4870	375	-92
8	0	4020	715	-100
9	0	3660	1430	-83
10	0	3660	1500	-70
11	0	3695	1765	-78
12	0	3920	820	-100
13	0	4190	577	-100
14	0	5810	333	100
15	0	4800	416	-91
16	0	5610	285	100
17	0	4520	100	73
18	0	4400	100	-20
19	0	3380	1953	-30
20	-500	3530	1765	-40
21	0	6320	200	40

Conclusion

- The recuperative 4 quadrant supply system works
- Ramping of magnets: -23 V … +23 V; -14 kA … +14 kA
- High efficiency 97 % (capacitors + converter); total 94 ... 90 % (+ thin copper hoses)
- Grid power: only ~10 % (e.g. 20 kW / 220 kW)
- Noise of converter: <10 mV; grid power supply 
- Current regulation works, was improved in the meantime
- High compactness (3 cabinets 19”)
- Adjustable fast quench protection system (reaction time < 5 ms)



Thank you for your attention!

Questions???

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References

[1] https://www.fotocommunity.de/photo/schwungrad-maexken/44108211