Design, construction and test of thermally activated *Re*BCO switches

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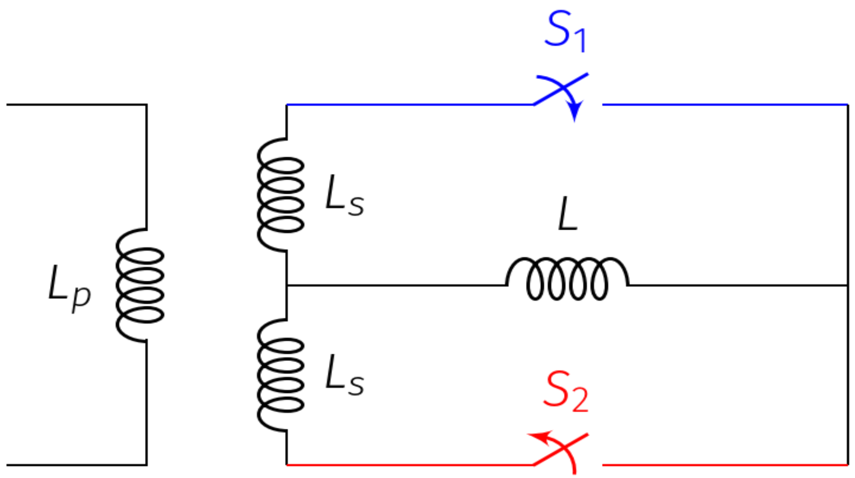
Introduction: superconducting rectifiers



The feasibility of technology was demonstrated in late 70's using LTS switches and since that time it is in occasional use for detector magnets.

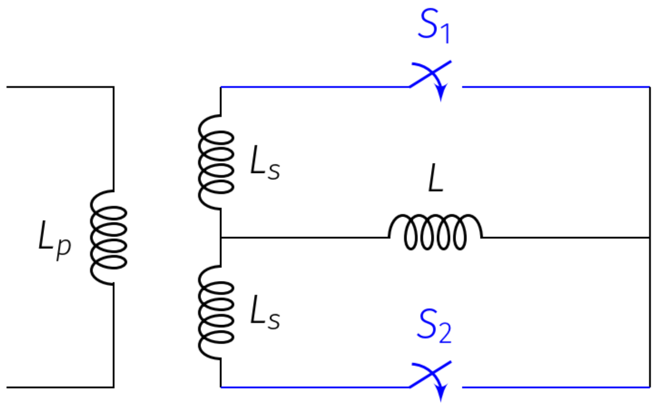
Pros:

- Minimized heats load at large current
- Compact size, even at very high currents, thus low impact of I_{op} on the overall cost
- Persistent mode when idle

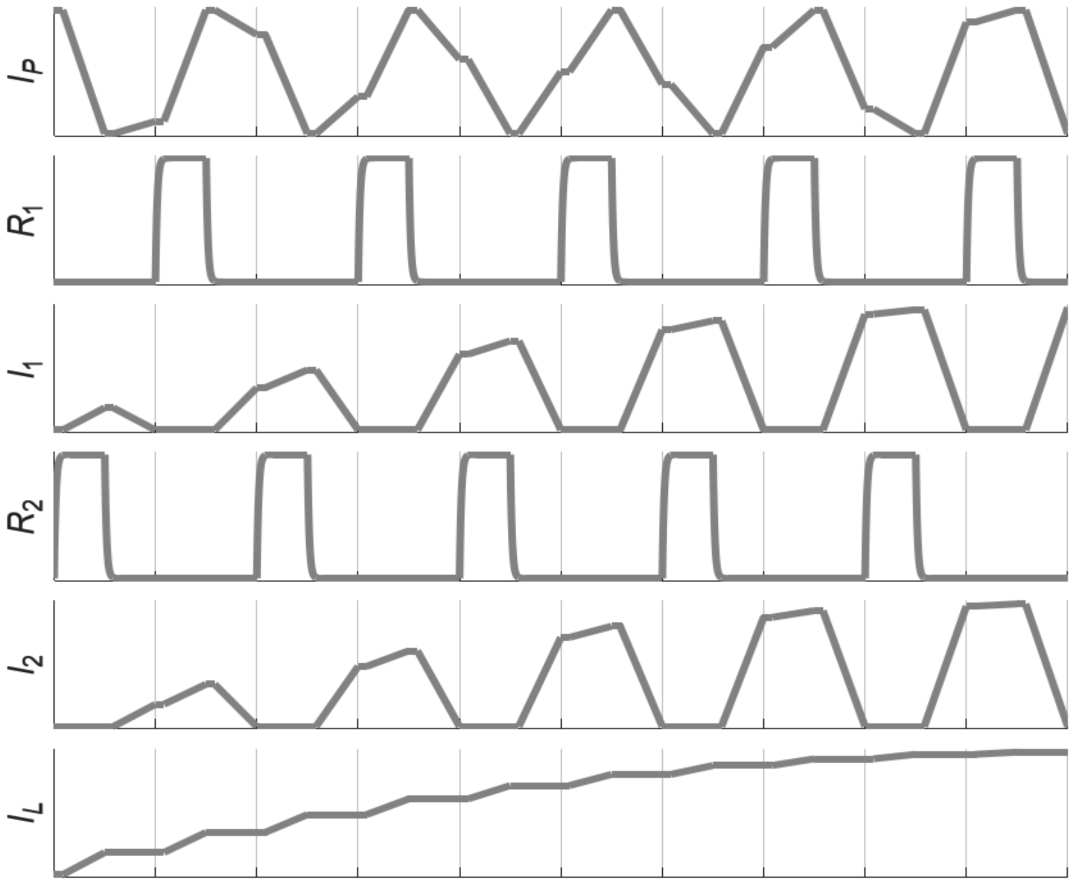
Cons:

- Relatively slow charging of magnet and troublesome control of switches
- Low stability of LTS switches

Introduction: diagram of operation



Every half-cycle consists of
4 stages:



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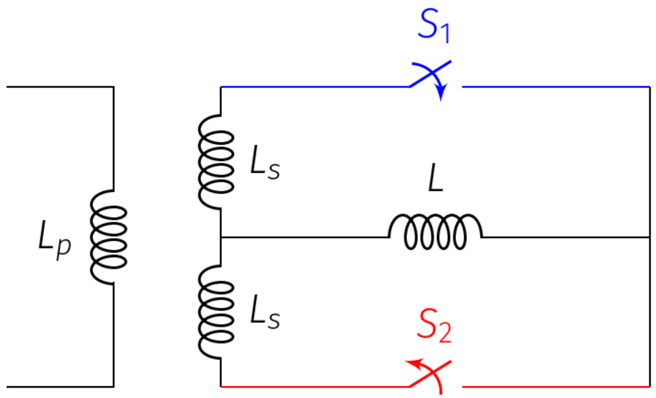

Every half-cycle consists of

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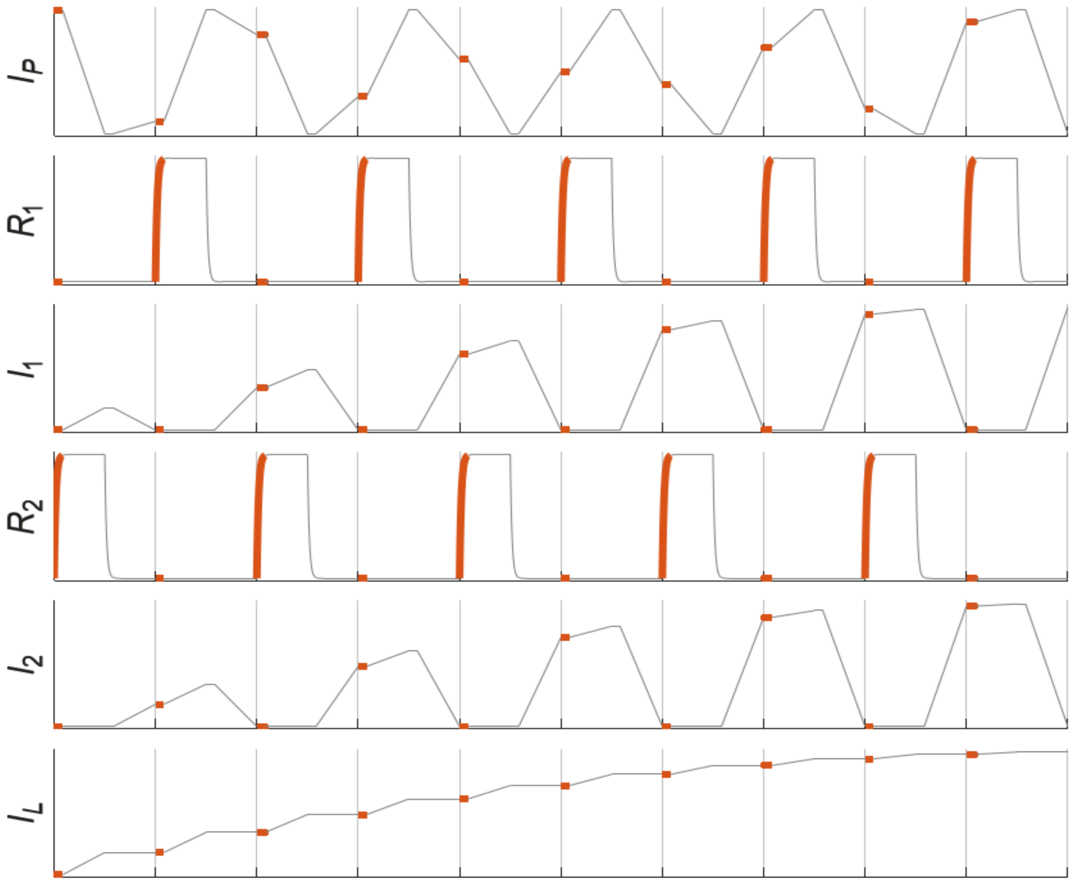
1. opening a switch



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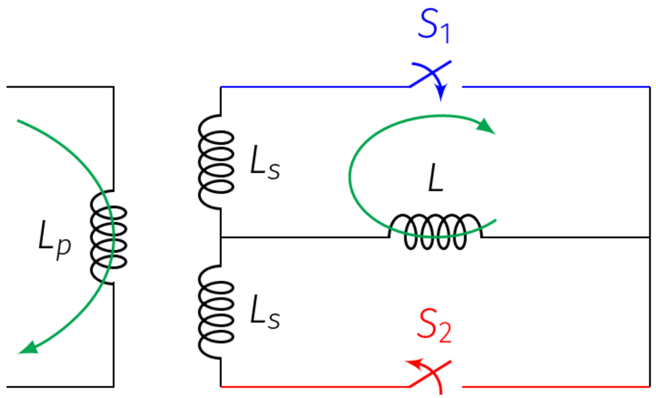
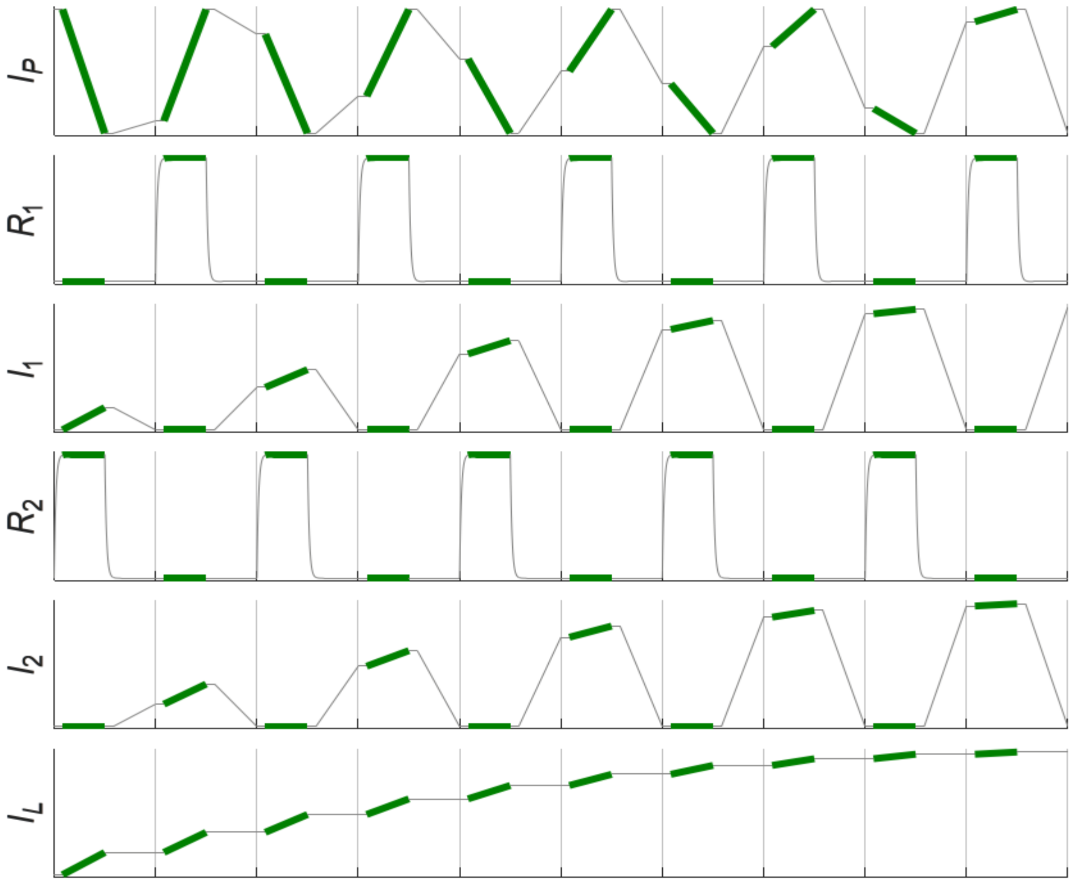


Every half-cycle consists of 4 stages:

1. opening a switch
2. pumping



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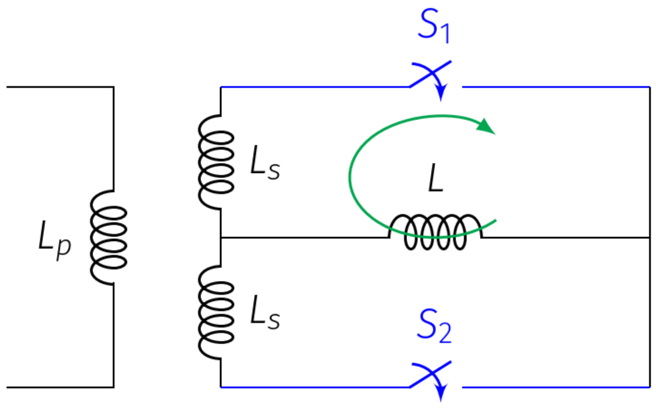
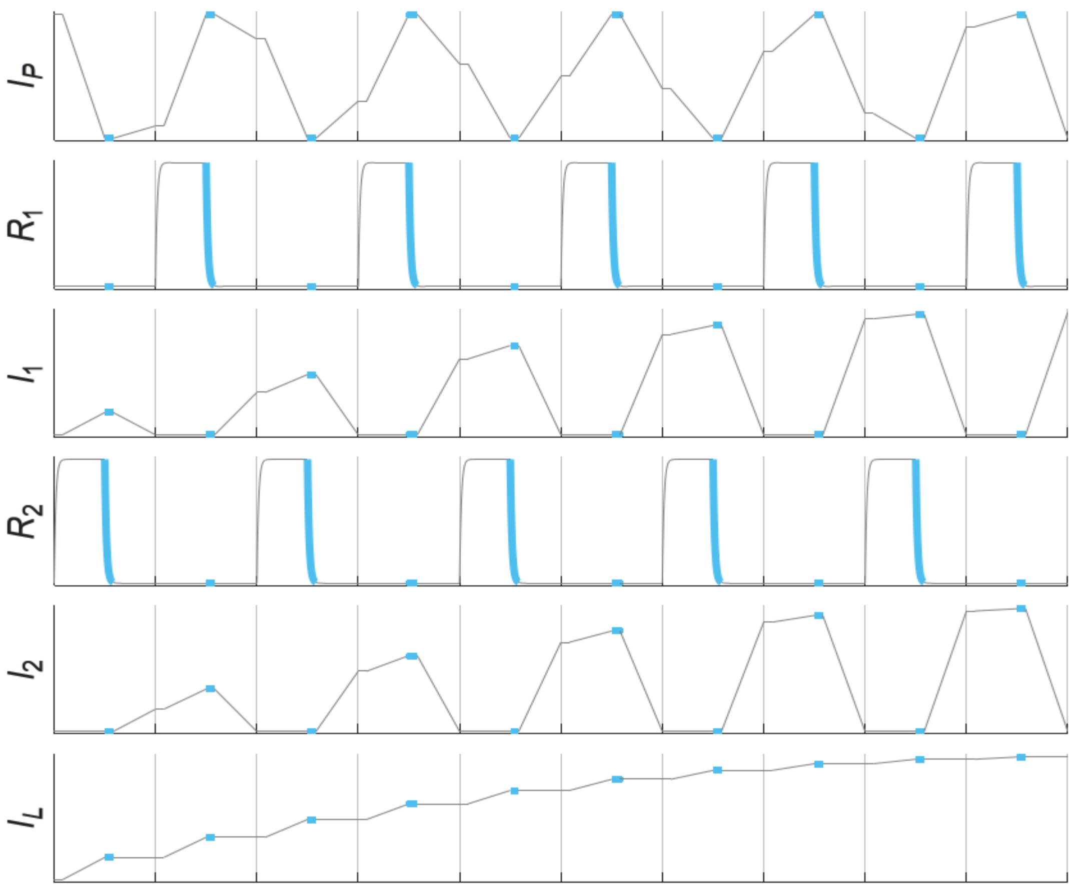
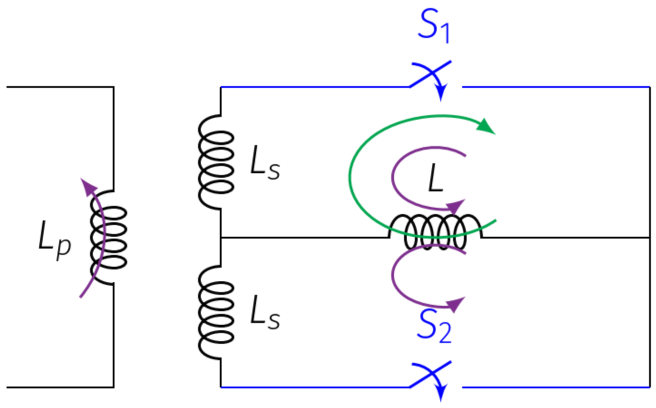




Every half-cycle consists of 4 stages:

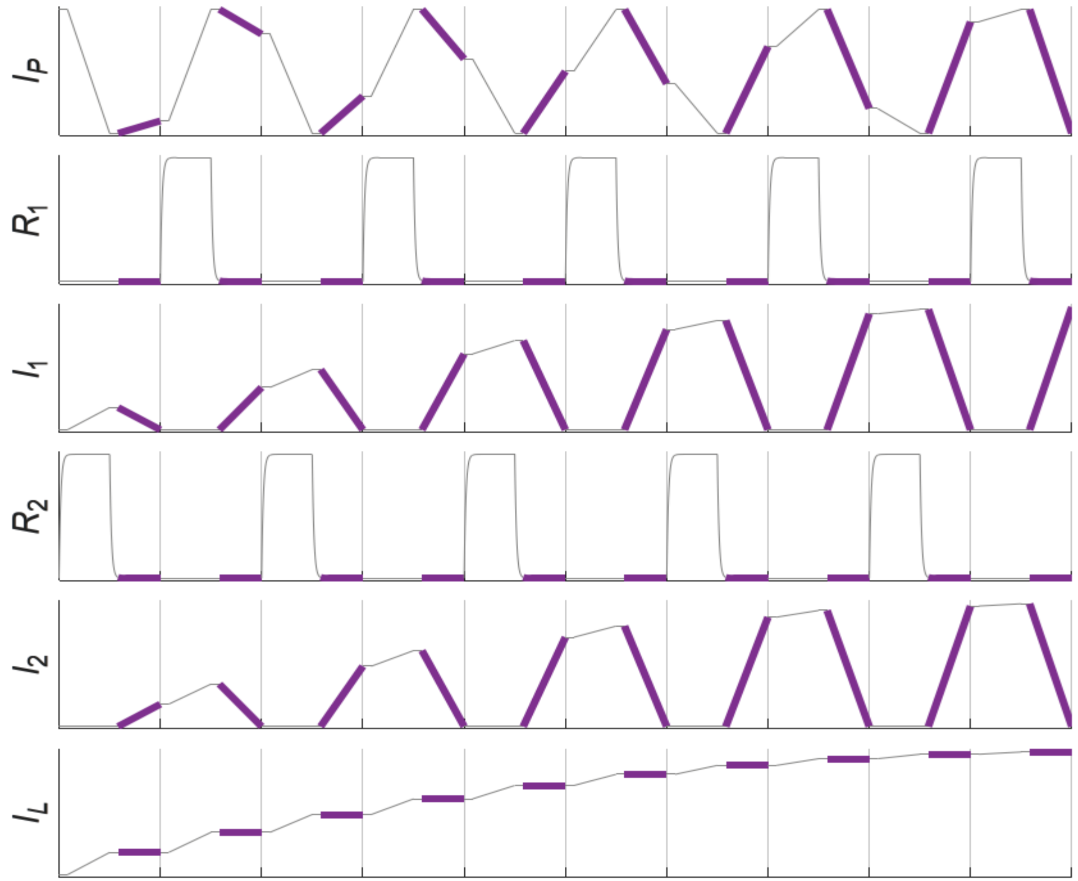
1. opening a switch
2. pumping
3. closing a switch

Introduction: diagram of operation



Every half-cycle consists of 4 stages:

1. opening a switch
2. pumping
3. closing a switch
4. commutation



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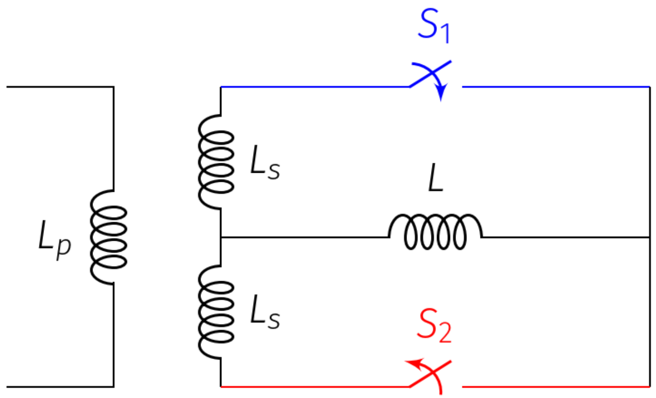

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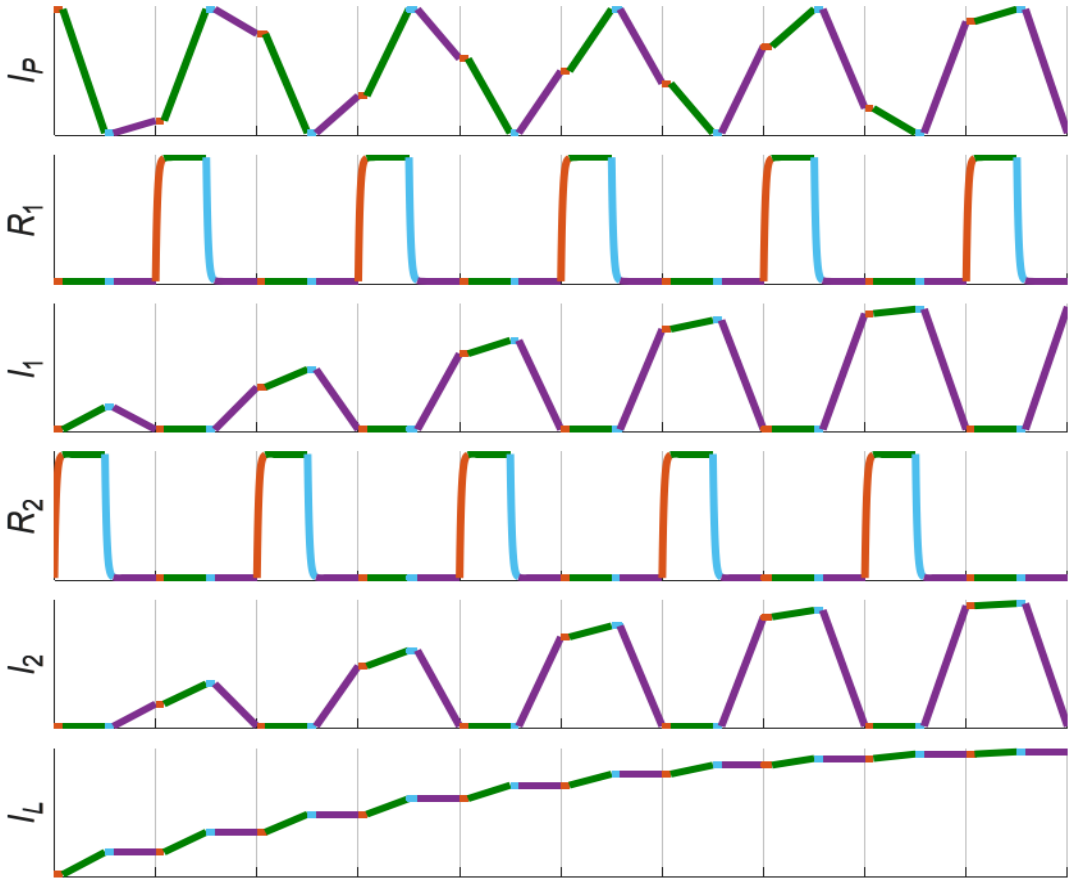
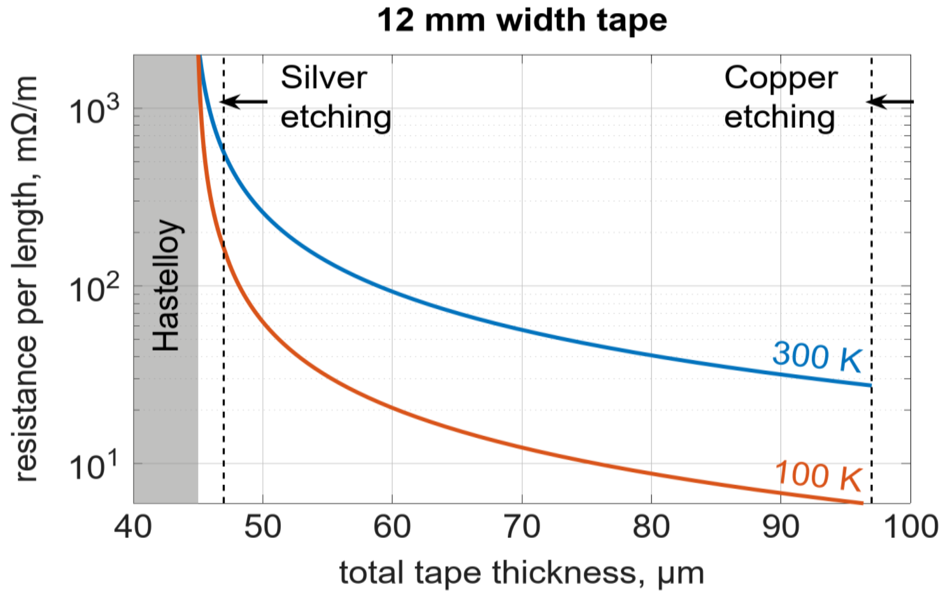


- $I_{max} \sim I_p \sqrt{L_p / L_s}$, not dependent on the load inductance L!
- Typically, I_{max}/I_p is order from hundreds to thousands
- Power loss in the open switch is proportional to $1/R$

Introduction: using ReBCO tapes for switches

Specific features of *Re*BCO switches:

- **high stability** margin in a closed state
- possibility to operate at **elevated temperatures**, i.e. more efficient removal of heat loads
- resistance in the normal state is very promising for etched tapes:

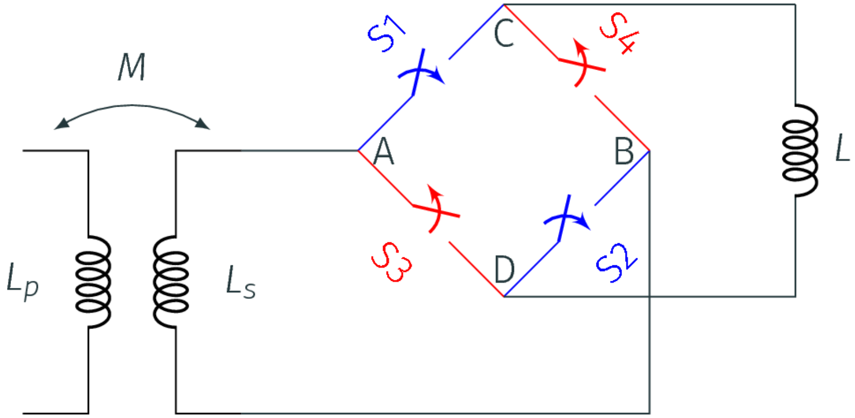


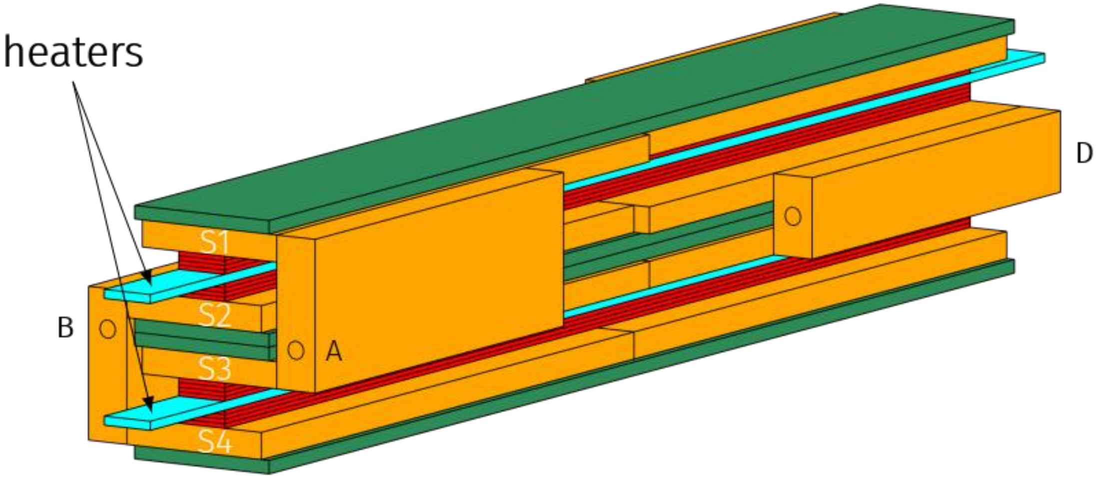
idealized tape composition (longitudinal cut)

Using 'in-house' etching method provides **both** the high 'off'-state and low joint resistances.

✓ Desired tape composition can be achieved (0.1 µm Ag limit) by etching in $FeCl_3$, using tape **resistance as a feedback** and **magnetic stirrer** to get the process uniform.

Motivation: development of switch bridge





A full-wave bridge rectifier:

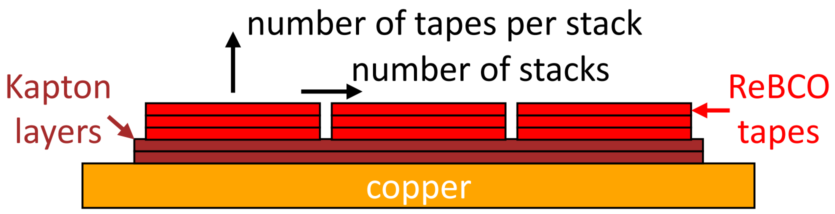
- modularity of the switch bridge, can be used with already existing sc transformers or be combined in parallel or in series
- simple design of the transformer secondary coil
- potential for faster charging, since the mutual inductance can be highest possible.

Features of the switch bridge layout:

- straightforward manufacturing and assembly of components
- use of 4 switches is simplified since only 2 heaters are required
- self-field effect on I_c is minimized due to anti-parallel current flow in the neighbouring stacks
- long length for connections with load coil and secondary winding and large surface to provide conduction cooling

Design study of switch bridge: selected layout

Schematic of tape arrangement:

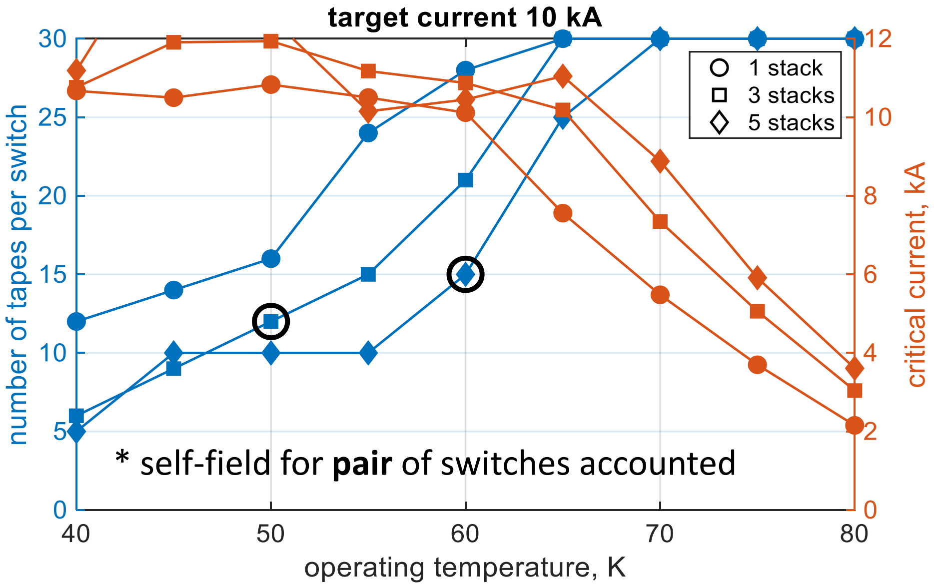


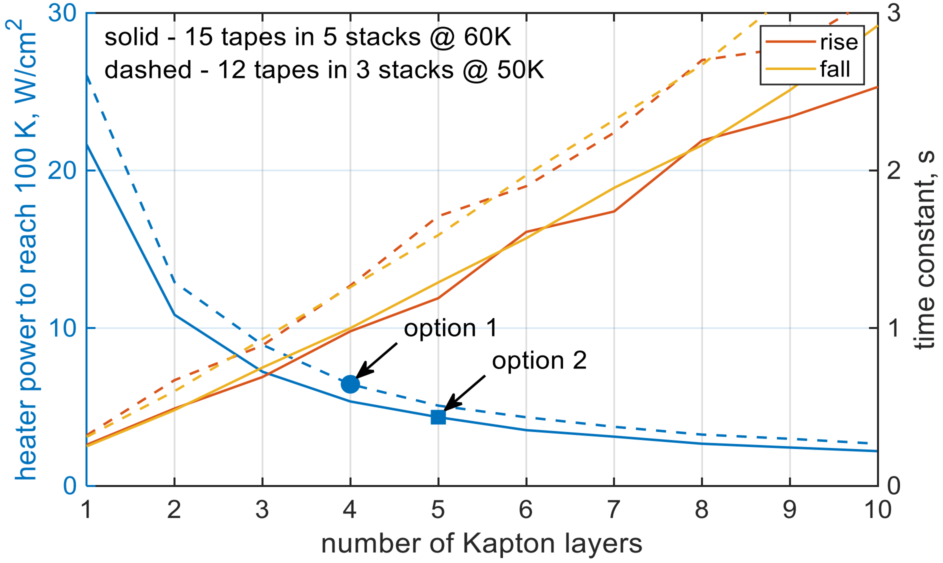
Requirements:

- **10 kA** current capacity @ 50-60 K
- Balancing **heat power** to reach 'off' state vs rise and fall **time constants** of transition vs 'off' state **resistance** of switch
- Low joint resistance

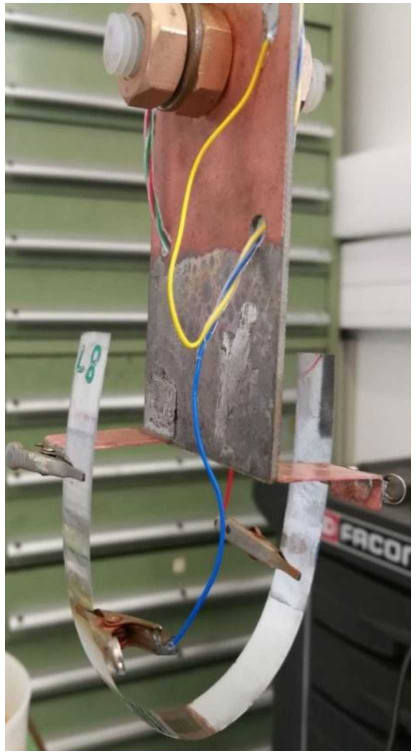
Selected switch layout (option 1):

Number of tapes	12
Number of stacks	3
Number of Kapton layers	4
Heater power to reach 100 K	6.4 W/cm^2
'Off' state resistance per switch	1.2 mΩ/cm

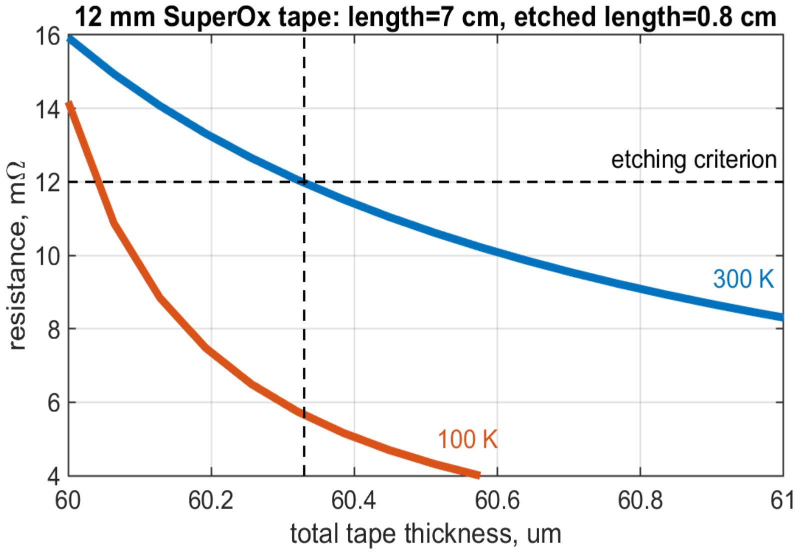


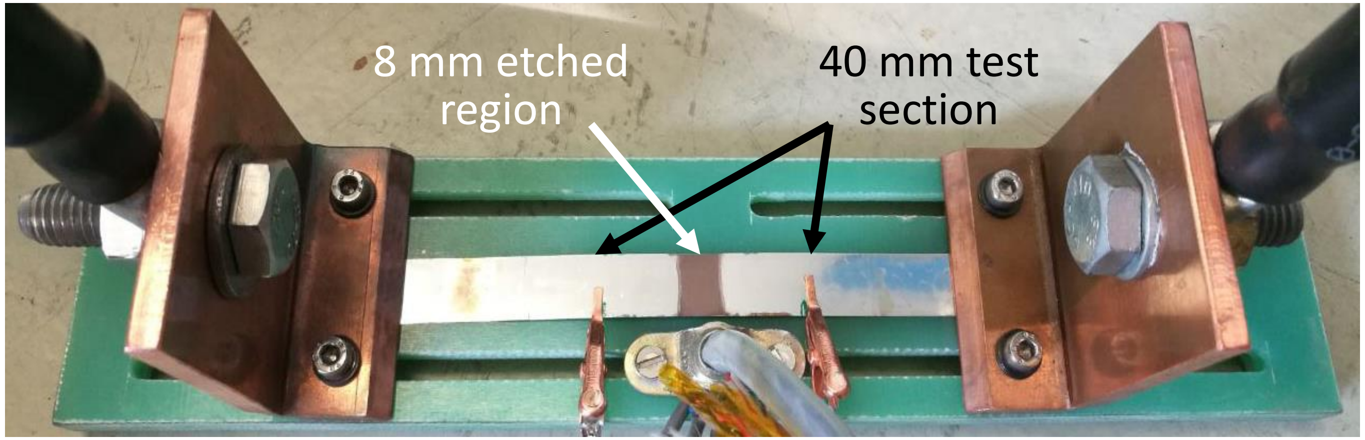


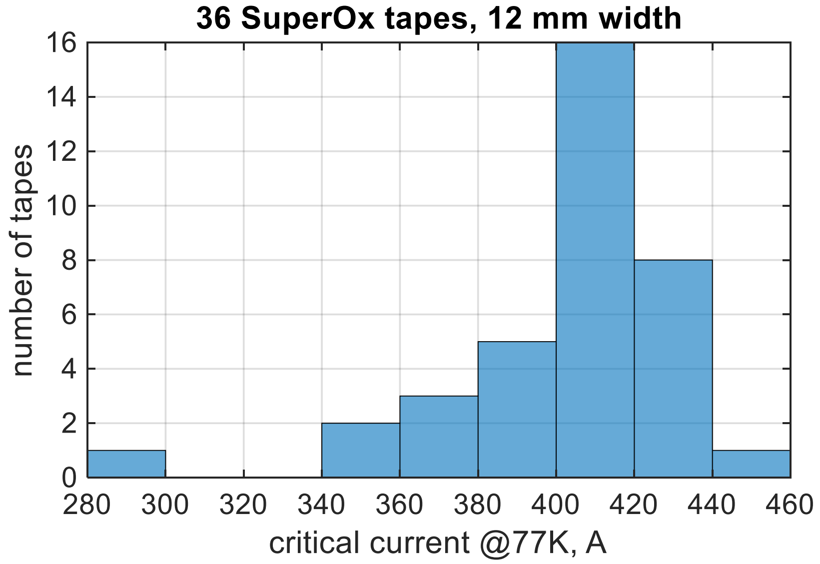
Sample construction: tape etching



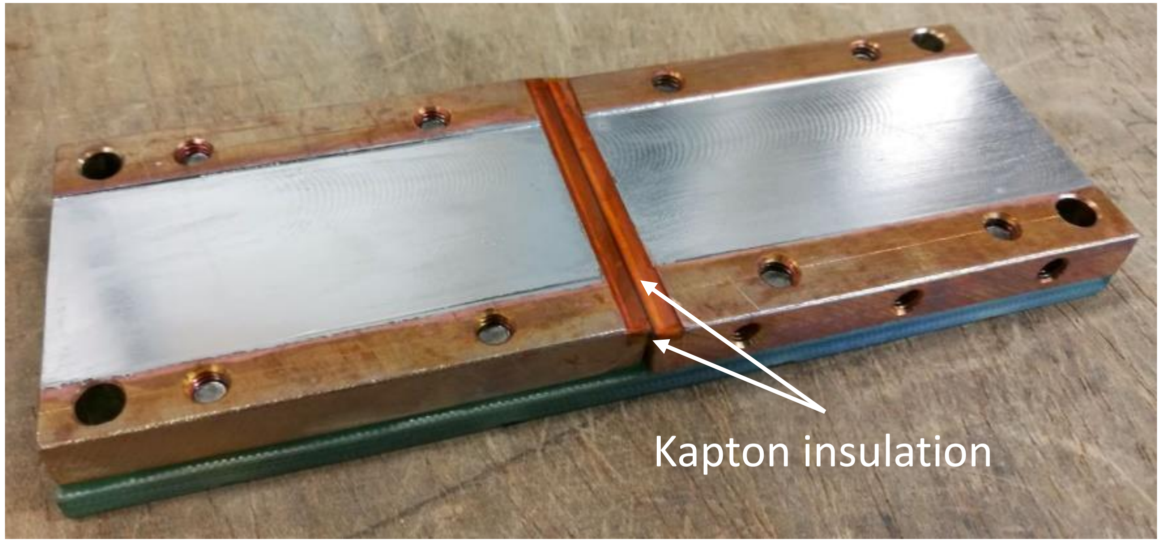
- Etching of **12 mm SuperOx pre-tinned tapes** in $FeCl_3$ using tape resistance as a feedback and magnetic stirrer for uniform process:
  - Varnish coating used to etch **8 mm section**, resistance measured over 70 mm section.
  - 12 mΩ etching threshold: SnPb and Cu layers removed, **≈ 0.3 µm** thick Ag layer remained.
- I_c of tapes measured at 77 K after etching over 40 mm section, on average 400 A (**no reduction**).
- **36 tapes** prepared in total, 9 tapes per switch.







Sample construction: soldering & assembly



1. Copper plates pre-tinned

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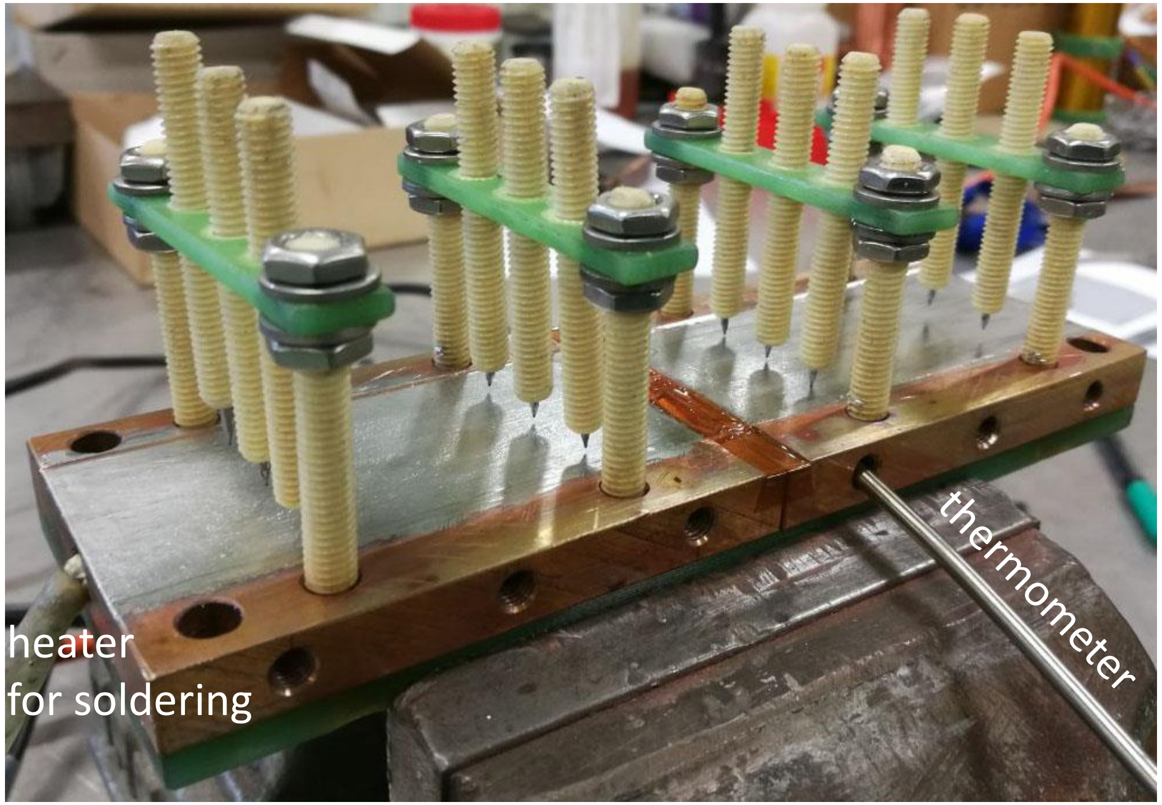

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2. G10 fixators attached

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4. Packing and soldering

   * Ic tests in LN2 (next slide)

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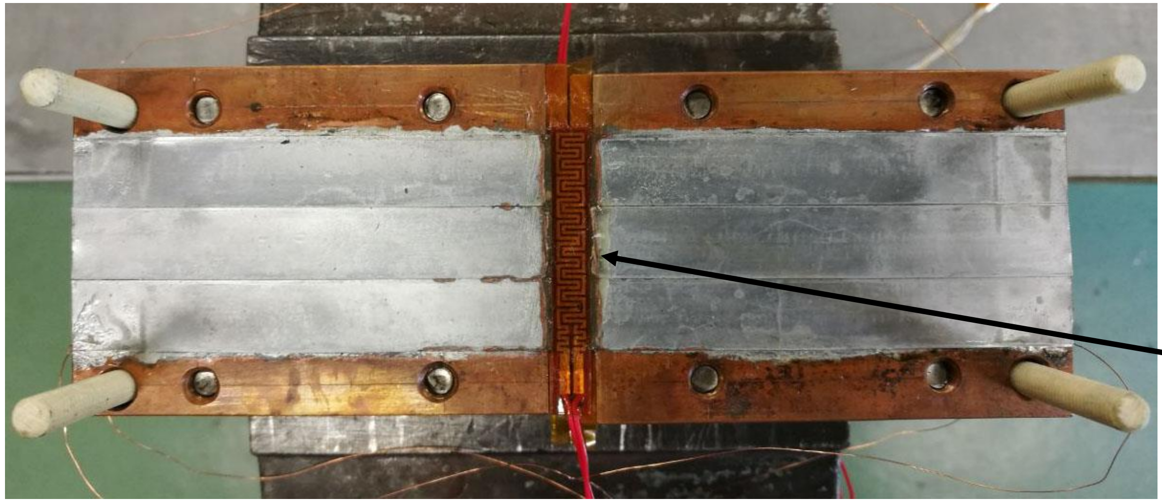

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5. Control heater attached

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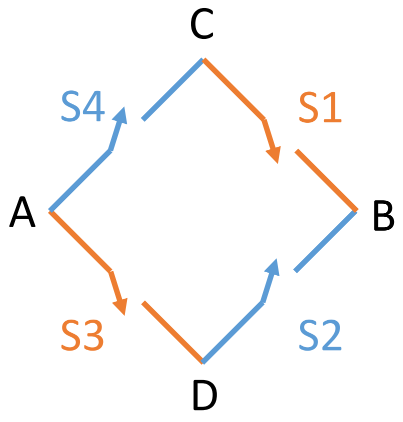
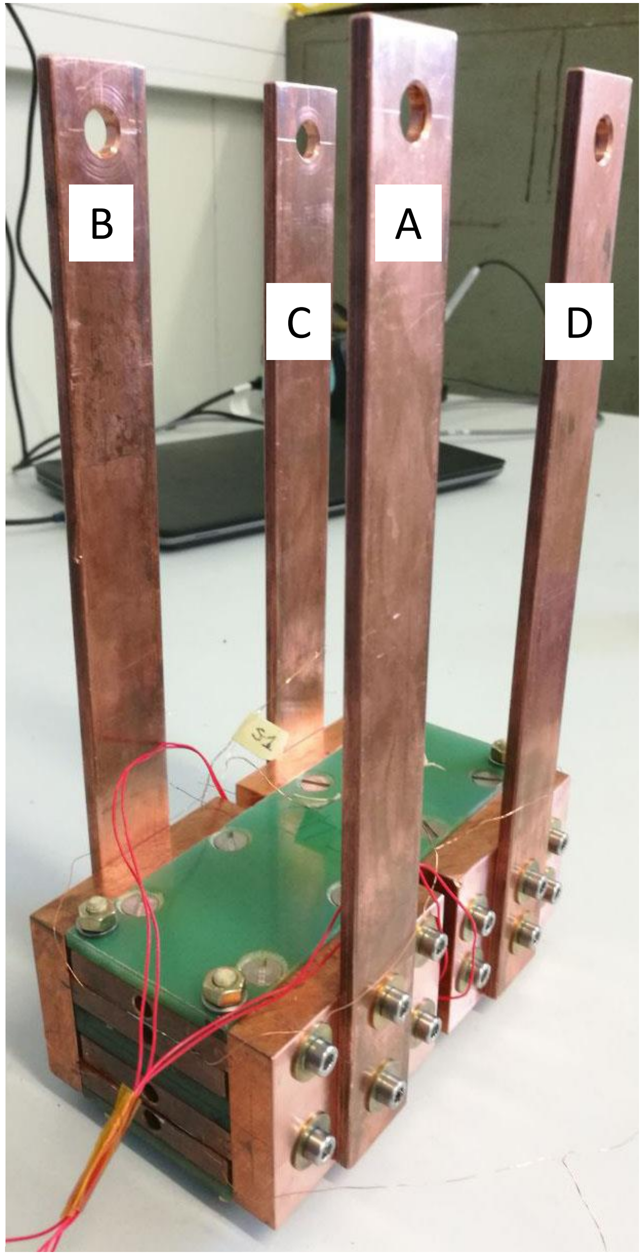


Standalone testing:
A-B: power supply
C-D: open



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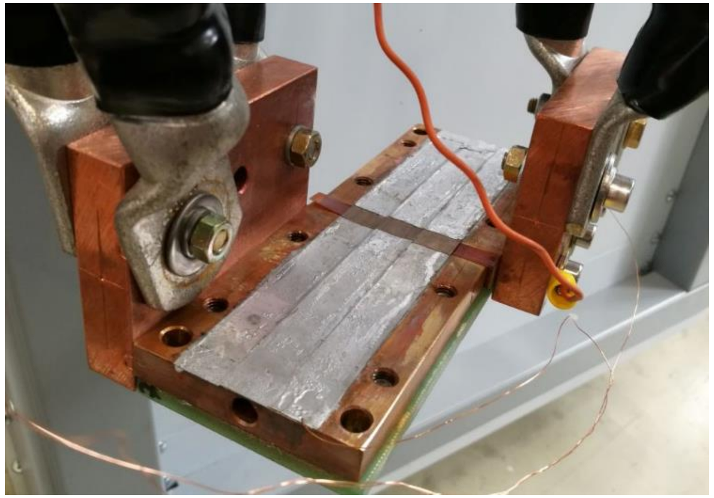
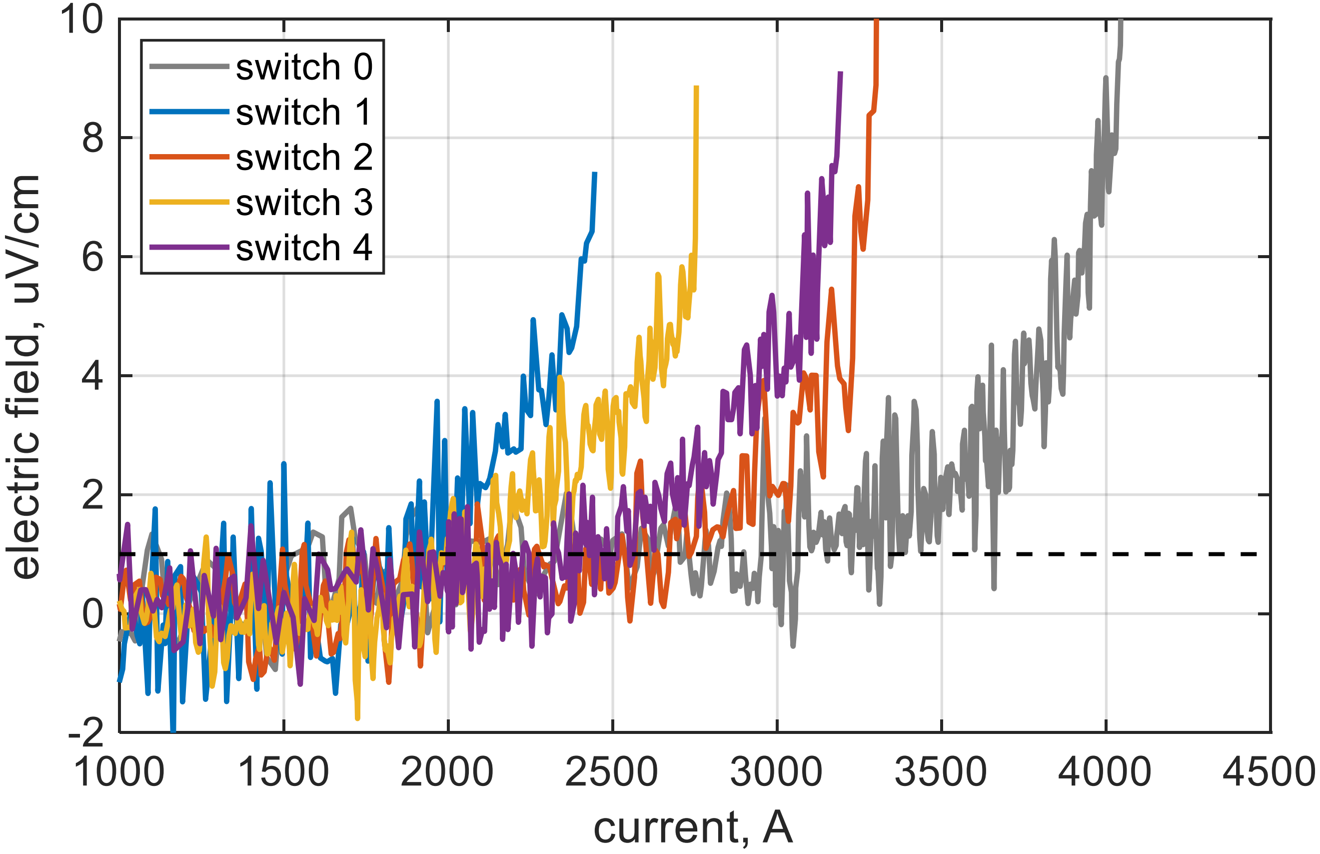
5. Control heater attached
6. Complete assembly

   * testing in LN2, but rather conduction cooling conditions for ReBCO tapes

Sample construction: intermediate Ic tests



	S0	S1	S2	S3	S4
Sum tape Ic, kA	3.8	3.4	3.6	3.6	3.6
Expected Ic, kA	3.2	3.0	3.1	3.1	3.1
Measured Ic, kA	3.1	1.9	2.6	2.1	2.4
Retention	**98 %**	**64 %**	**85 %**	**69 %**	**78 %**



- S0 performed as expected, but noticeable reduction of I_c observed on S1-S4 (further discussed next)
- After quench of S2 and S4:

  I_c reduced negligibly at 1 μV/cm criterion, but ≈10% reduction at the higher threshold

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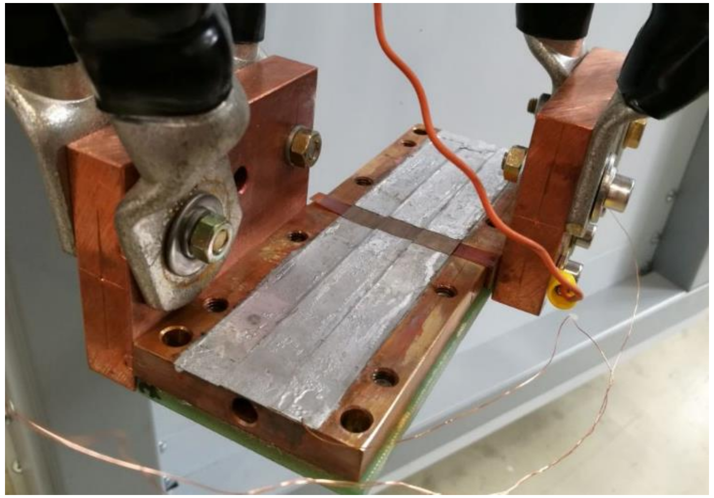

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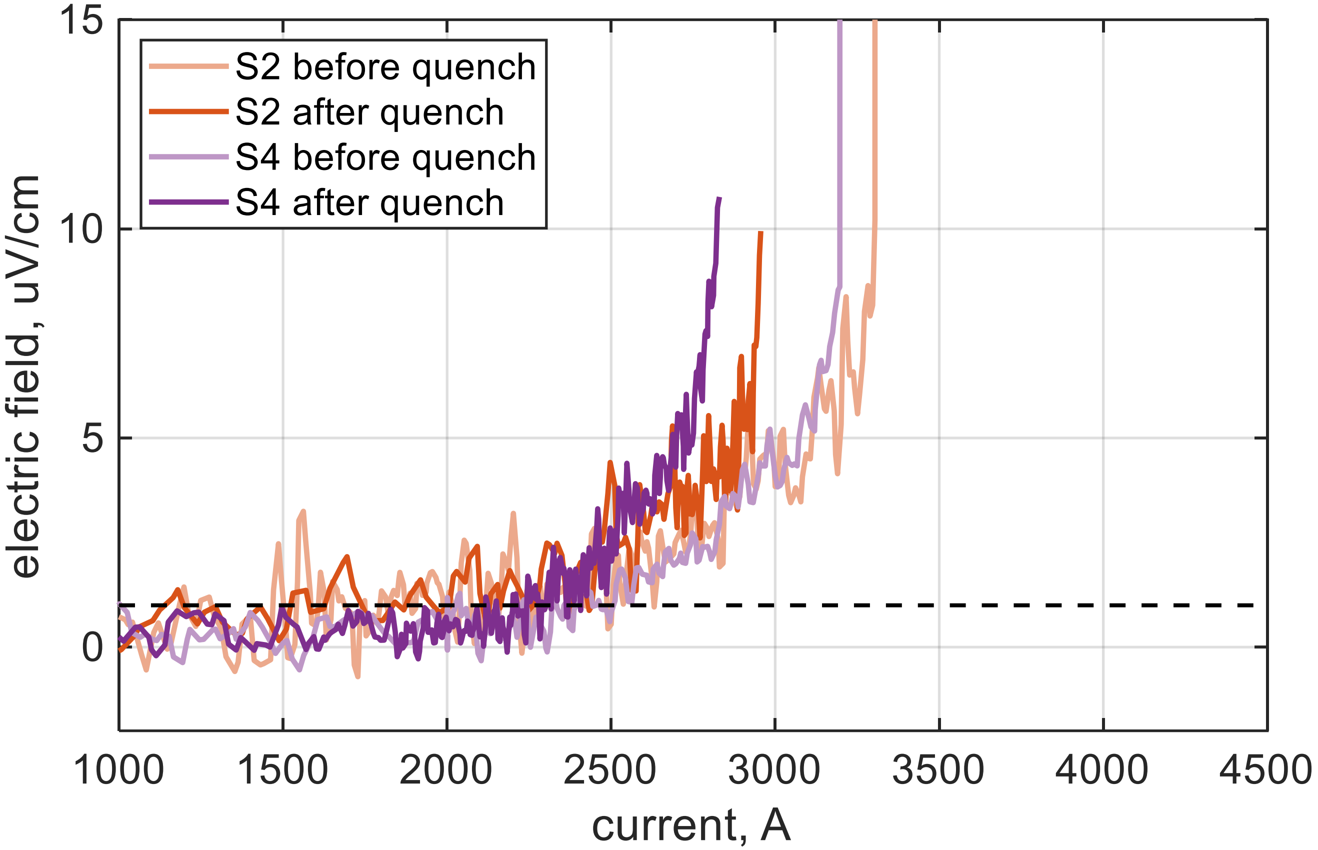

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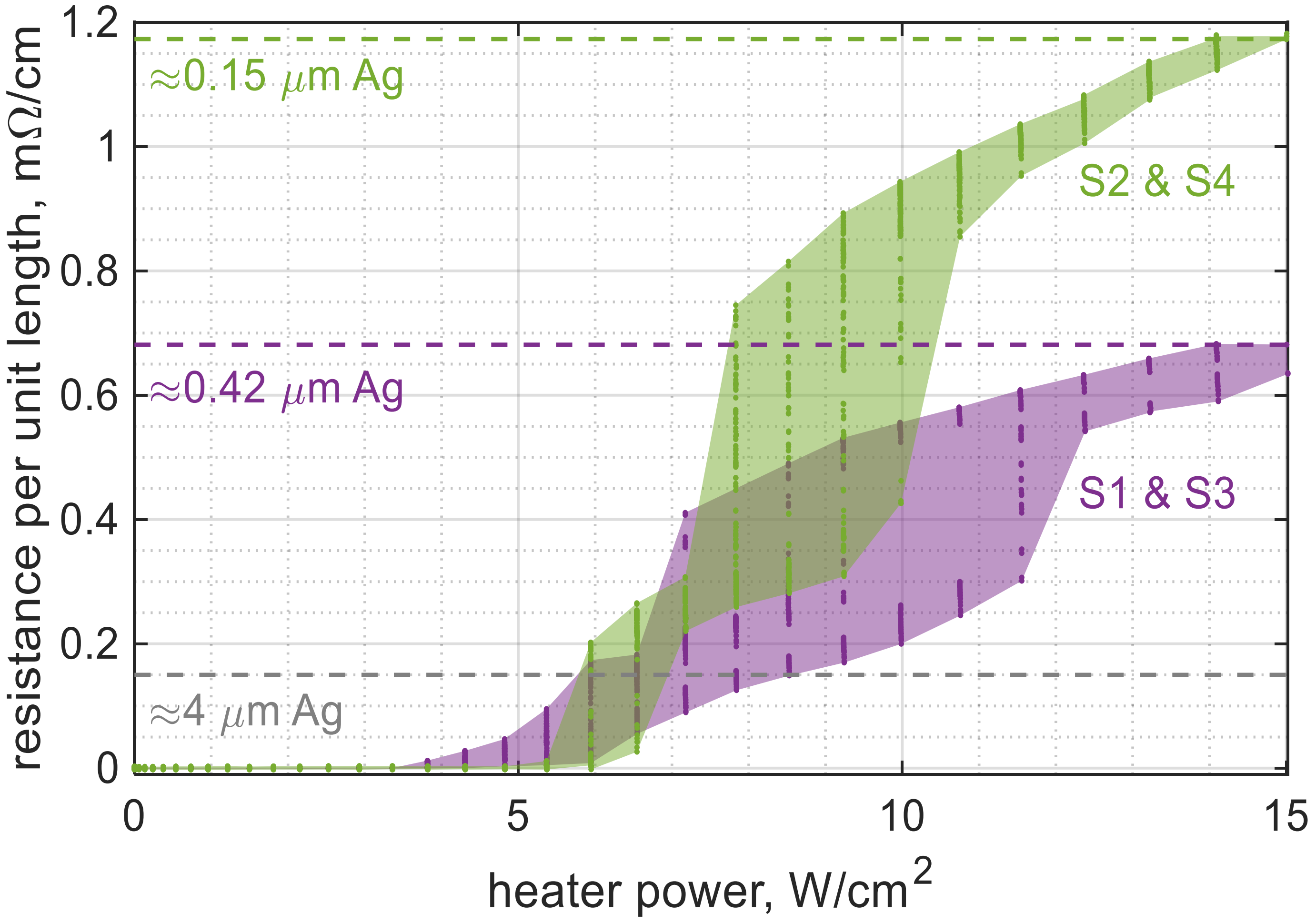
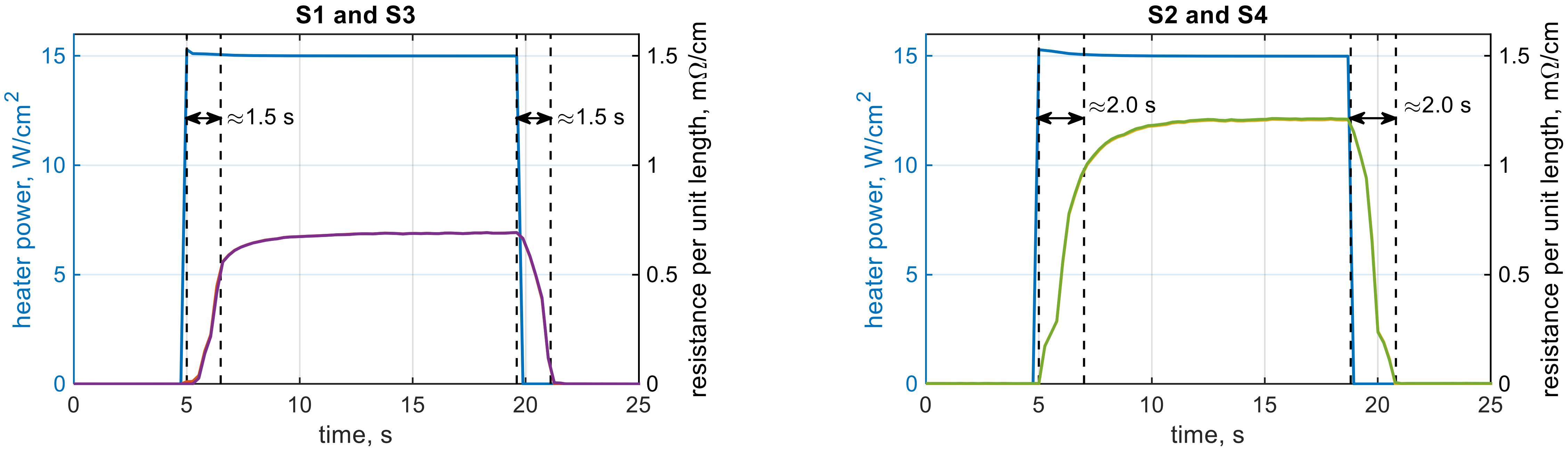
Test in LN2: ‘off’-state resistance



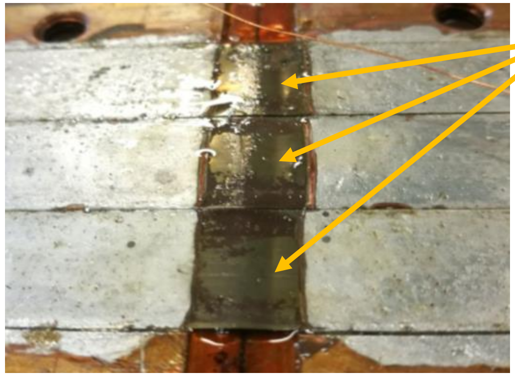
- Resistance of the open switch corresponds to **≈ 0.15 µm** and **≈ 0.42 µm** average remained thickness of Ag and 60 µm Hastelloy layers.
- Switches are activated starting from **5 W/cm²** heater power and turned fully normal at ≈12 W/cm².
- High heater power required is due to **strong cooling** conditions in LN2 bath.

Test in LN2: transition metrics

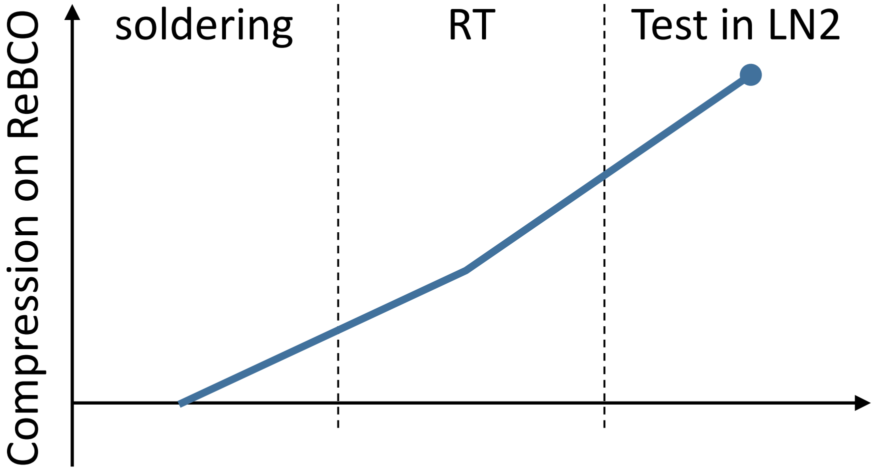


- Rise and fall times of the transitions are around **1.5 s** for S1 & S3 and **2.0 s** for S2 & S4, close to expected values from the thermal simulation model.
- Commutation of the switches can be applied right after these time delays.

Test in LN2: effect of thermal contraction



Damaged after testing



Material		Thermal expansion, % @ 220 C	Thermal expansion, % @ 77 K
Copper		0.34	-0.30
Hastelloy		0.23	-0.20
G10	//	0.25	-0.21
	⊥	0.82	-0.64

- Etched section more sensitive to mechanical strain and mismatch in **thermal shrinkage** of copper and Hastelloy might be at the origin of the damage.

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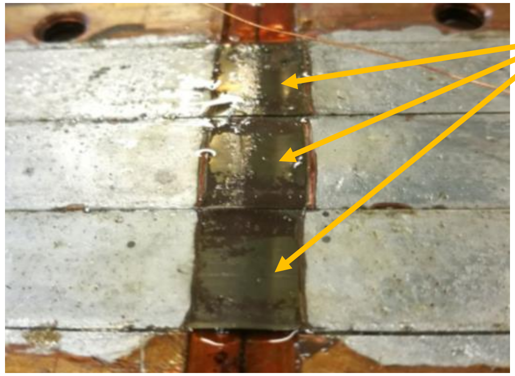

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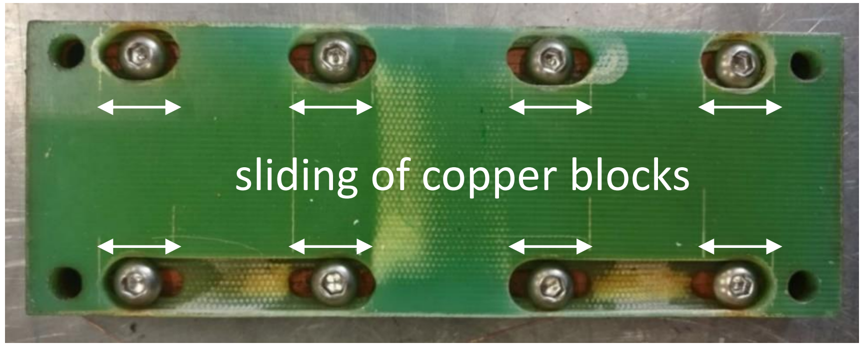

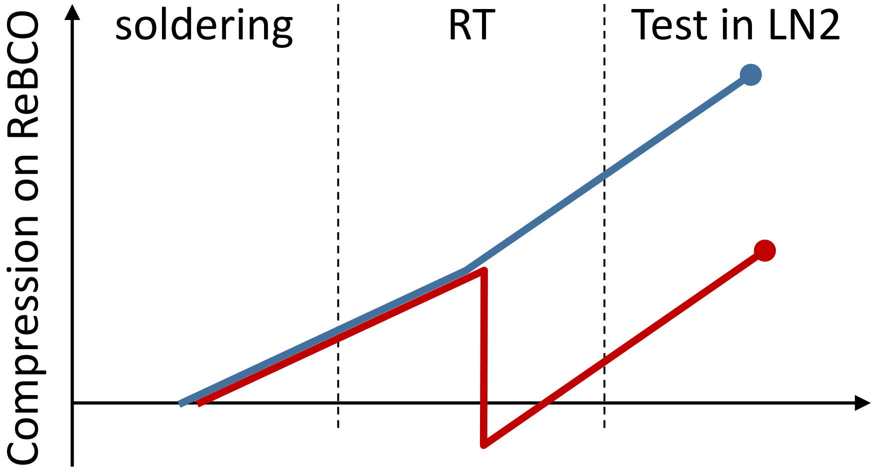

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- Tapes can be tensioned after soldering to release exceeding compression on *Re*BCO.

Conclusion

- The bridge type switch layout based on etched *Re*BCO tapes is proposed for charging high current magnets using a super-conducting rectifier type flux pump.
- The construction is performed using 12 mm wide, pre-tinned SuperOx tapes and components of a simple block geometry.
- OFF-state resistance and transition time delay measured at 77 K follow the values from the dedicated simulation model.
- Some loss of current capacity after full assembly to be addressed by pre-tensioning of tapes.
- Operation in 50 to 60 K temperature range using cryocoolers is foreseen for the next models.