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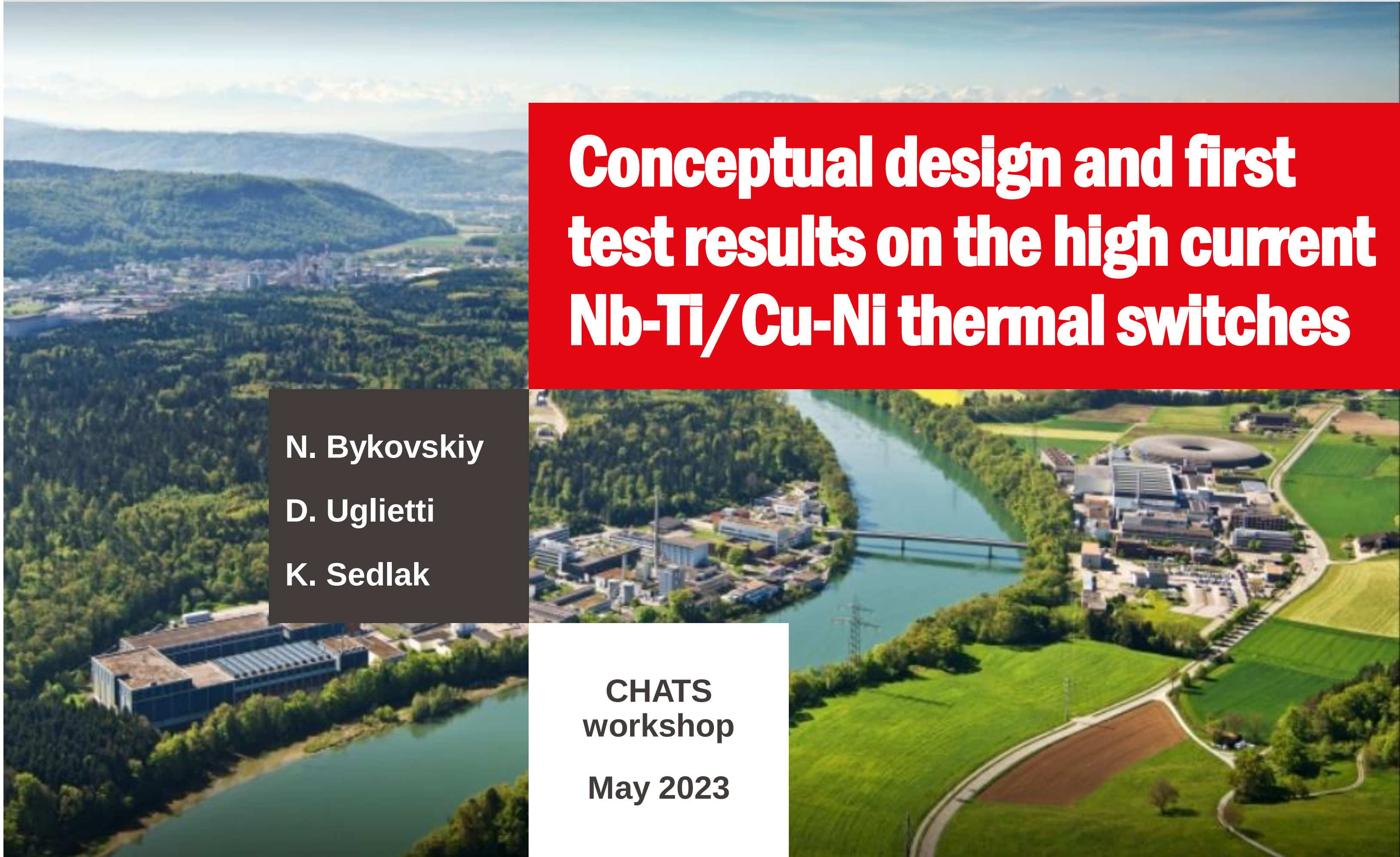

Conceptual design and first test results on the high current Nb-Ti/Cu-Ni thermal switches

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CHATS workshop

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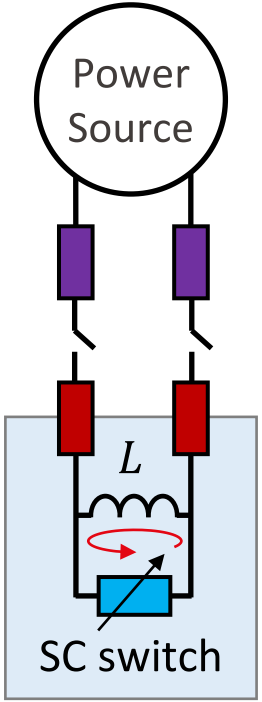
SWISS
PLASMA
CENTER

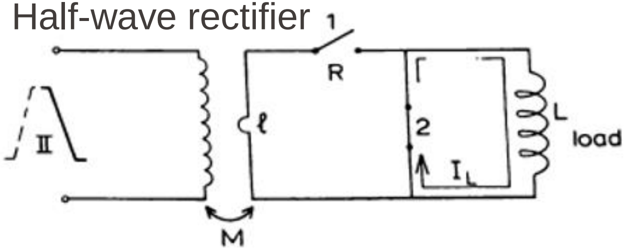
Outline

1. Need for high-current superconducting switches
2. Material candidates
3. Measurements on Nb-Ti/Cu-Ni wires at CERN
4. High current switch concept
   a) 1 kA / 2 Ohm sample
   b) 6 kA / 0.5 Ohm sample
5. Heat loads of safety leads
6. Summary

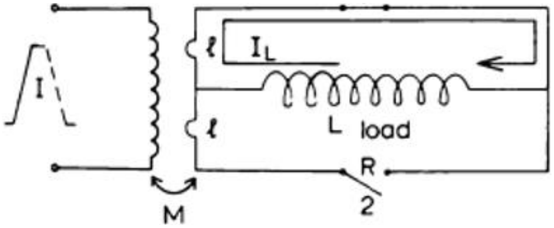
Background on high current sc switches



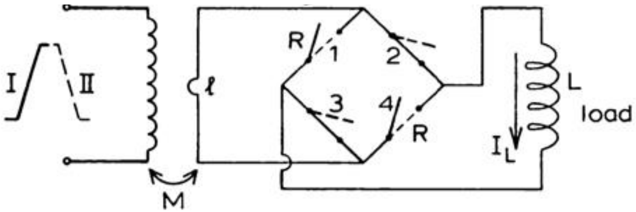
Half-wave rectifier



Full-wave rectifier



Full-wave bridge rectifier



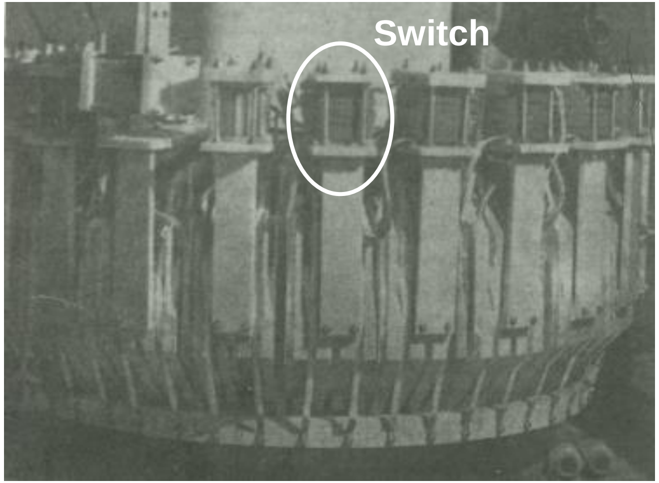
- Persistent mode operation enables low ppm current stabilization and reduced power consumption (essential for cryocooler-based magnets)
- Same for high current rectifiers → need for practical and reliable superconducting switches

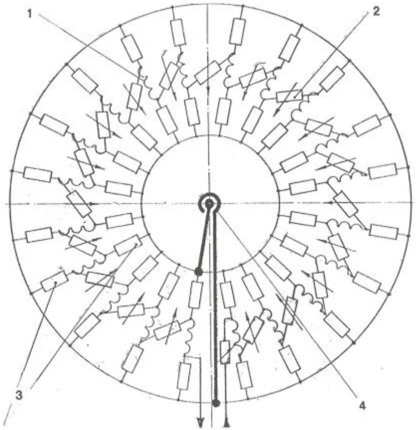
1981 https://doi.org/10.1016/0011-2275(81)90195-8

Background on high current sc switches

SMES magnet

1999 https://dx.doi.org/10.1109/PPC.1999.823720





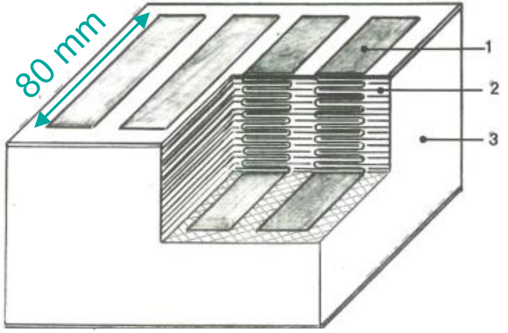
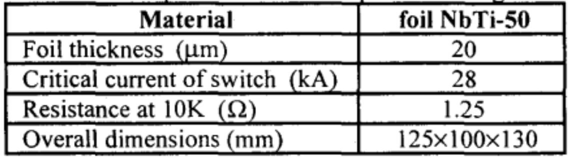


Table 1. Basic performances of superconducting switches



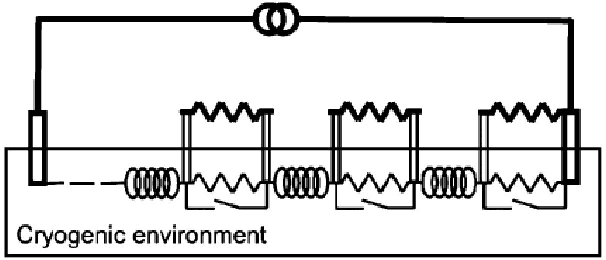
Material	foil NbTi-50
Foil thickness (µm)	20
Critical current of switch (kA)	28
Resistance at 10K (Ω)	1.25
Overall dimensions (mm)	125×100×130

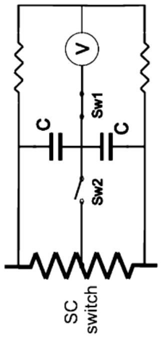
- Toroidal coils charged in series (switches on), discharged in parallel (switches off)
- High current switches by 4 parallel Nb-Ti folded tapes (80 mm width, 20 µm thick)
- Stand-by operation up to 7 kA demonstrated
- Output current up to 115 kA within ~1 ms (Bdot ~ 1000 T/s)

→ Research on Nb-Ti foils is still active: manufacturing at Wigner group and thesis on E-M properties

Background on high current sc switches

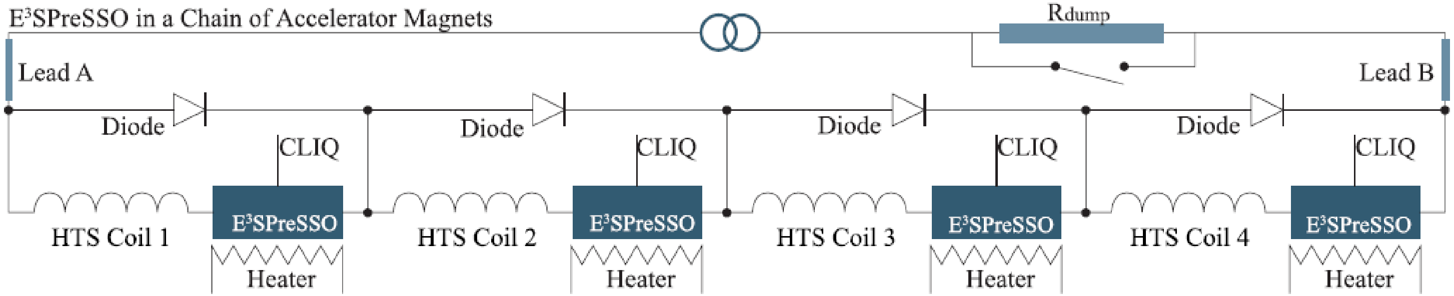
Accelerator magnets





- Switching by heaters and current pulse
- Reduced cryogenic consumption
- Faster protection for HTS – energy dump right after the switch is off

2010 https://doi.org/10.1109/TASC.2010.2042044

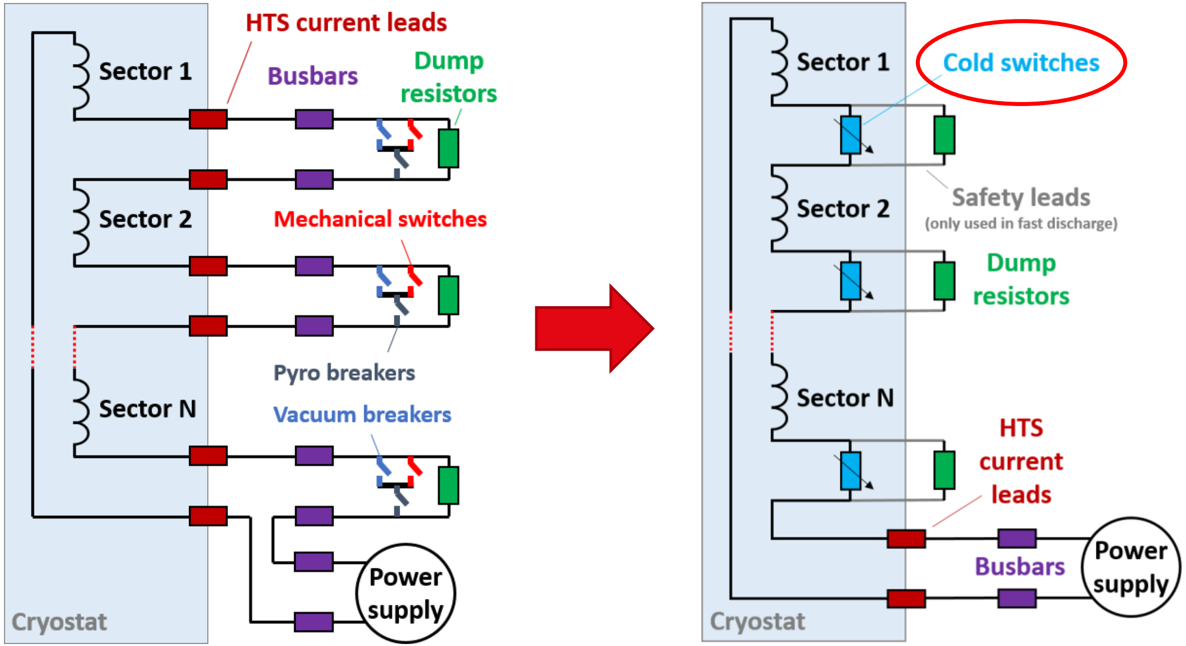


2018 https://doi.org/10.1109/TASC.2018.2848229

High current sc switches for TF coils

Design issues of baseline option for Toroidal Field magnet system:

- Complex and expensive dump units (dump resistor + mechanical switch + vacuum and pyro breakers)
- Power loss on long RT busbars (up to few MW)
- Need of few dozens HTS current leads
- Risk of electrical arcing



The proposed circuit layout should address the main baseline issues + potential for sub-sectioning.

The challenge is to demonstrate the reliability of high current / high voltage operation of SC switches.

1995 https://doi.org/10.1109/77.402530 2021 https://dx.doi.org/10.1088/1361-6668/ac0992

Material candidates for SC switches

Estimate for the case of ITER: I = 68 kA, U = 10 kV, E = 4.5 GJ, Tmax = 200 K

	Nb-Ti 0.8 mm wire	**ReBCO 12 mm x 30 µm tape**	
Material	0.20 mm^2 NbTi 0.30 mm^2 CuNi	1 µm ReBCO 30 µm Hastelloy **0.1 µm Ag, 0 µm Cu (?)**	
Operating temperature	4 K	4 K	50 K
# of wires or tapes	60*	7	48
Length of sub-cables	0.5 km	1.4 km	0.6 km
Energy to reach normal state	0.2 kJ	300 kJ	650 kJ
Length of material	30 km	10 km	27 km
Material cost	≈80 k$	≈600 k$	≈1600 k$

* early optimism

Key design aspects:

Material: absence of low resistivity protection metal.

Winding: Low inductance bifilar layout.

Energy dump: 98% – dump resistor, 0.1% – switch winding, 2% – heat sink.

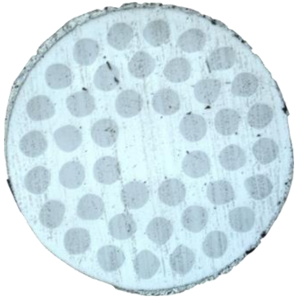
Quench: switch protection by the same system used for the main winding.

Reliability:** too low MQE using Nb-Ti?

Switching:** too high MQE using ReBCO to achieve fast switching?

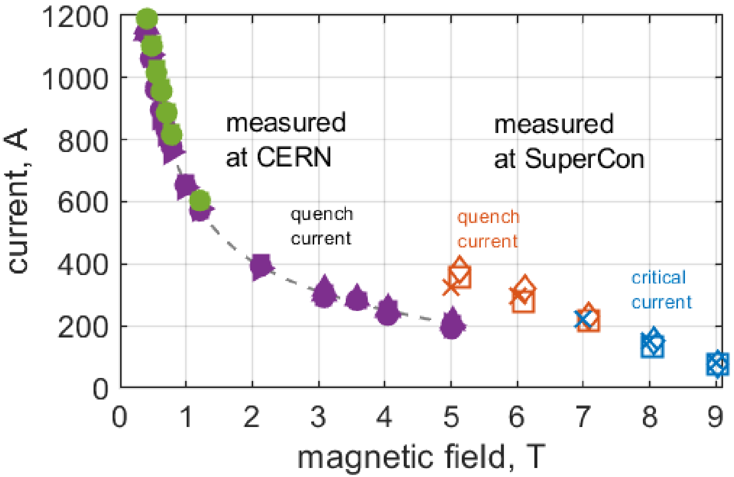
** optimal use for MgB$_2$?

Nb-Ti/Cu-Ni wire



	Nb-Ti/Cu-Ni strand
Diameter	0.8 mm
SC ratio	40%
Number of filaments	42
Effective filament diameter	77 µm
Twist-pitch	18 mm

Measured at CERN Cryolab in 2020



Single wire maximum current (data fit):

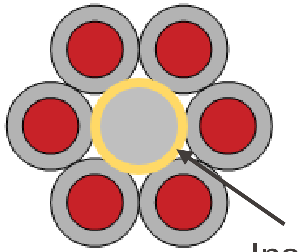
$$I_{max}(B, 4.2\ \mathrm{K}) = 1346\ e^{-B/0.5} + 586\ e^{-B/4.7}$$

→ Reproducible performance at low field, but smooth transition is not observed below 7 T

Nb-Ti/Cu-Ni 6-around-1 cable

Measured at CERN
Cryolab in 2020

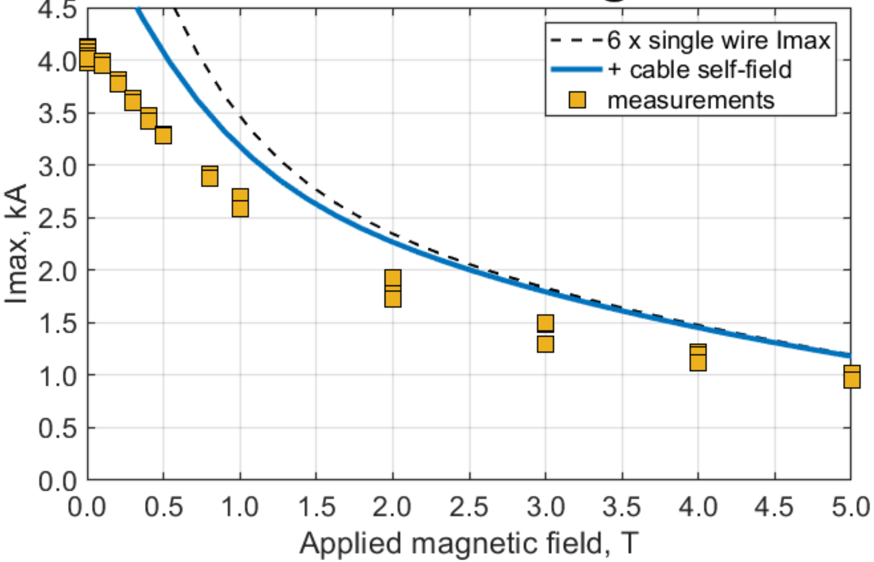
6-around-1 sub-cable



Insulated Cu-Ni wire
as embedded heater

	Nb-Ti/Cu-Ni 6-around-1 sub-cable
Diameter	~2.4 mm
Twist-pitch	~25 mm

6-around-1 switch cable @4.2 K

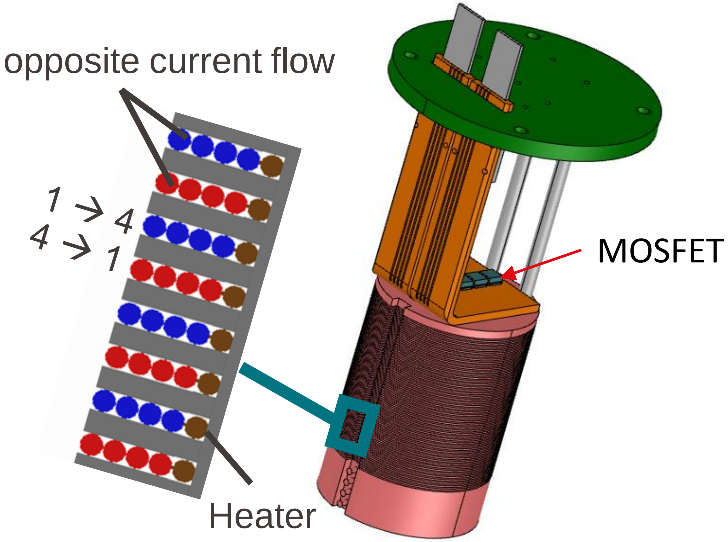


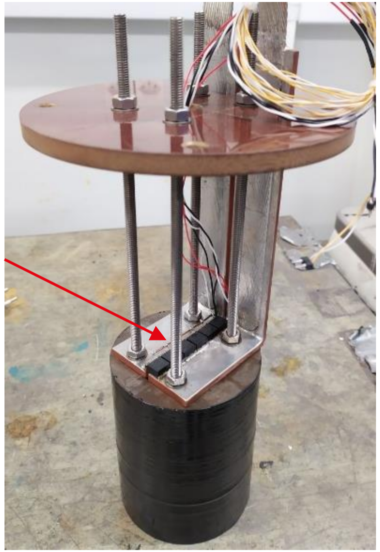
→ Again, reproducible performance but transition is abrupt at a quench current

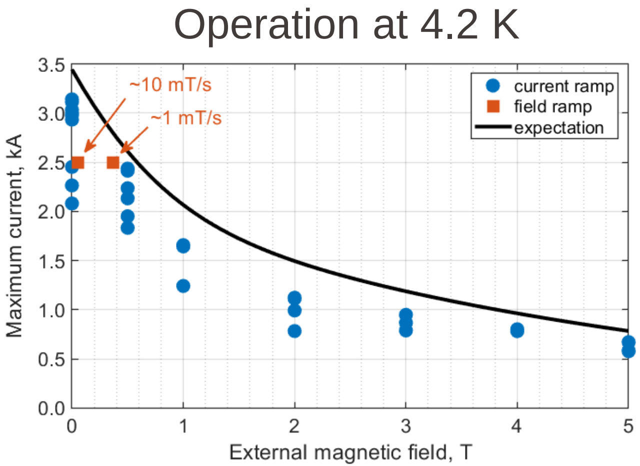
→ 120 m long sub-cable procured from **SuperCon**

Nb-Ti/Cu-Ni 4-wire bifilar winding

Measured at CERN Cryolab in 2020





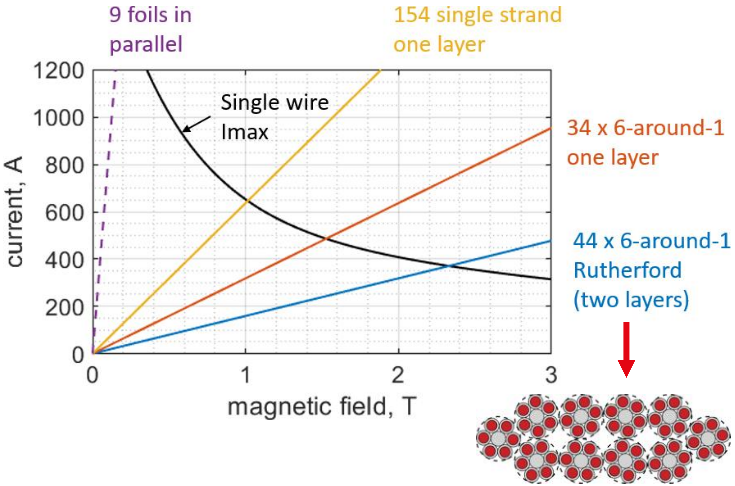


Reliability test @0 T:

I, kA	Duration, min	
2.5	63	No quench
2.8	10	
2.9	2	
3.0	0.93	Spontaneous quench
3.0	0.96	
3.0	0.92	
3.0	1.06	

- 4 parallel 14-m long wires, 3 Ω total resistance, wet wound using STYCAST
- Sample protected by MOSFET @Vgs=10 V using 6 units in parallel: ~0.1 V over quenched sample at any operating current
- Measured sample inductance ~2 μH by 1 kA/s ramp

Baseline switch concept

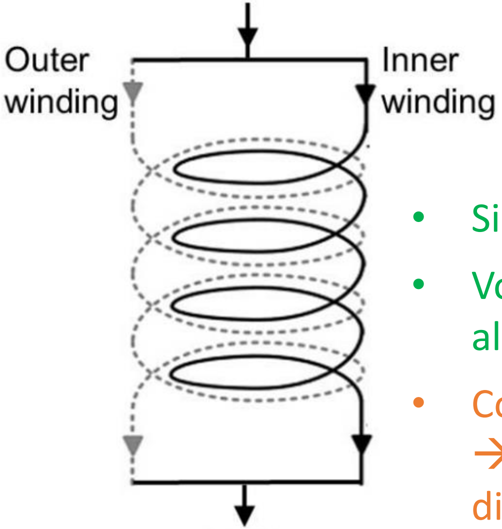


Using two-layer conductor: mostly outsourced activity, lower material performance, cabling and winding are complex and expensive

Using one-layer conductor: possible R&D on demonstrator windings, improved material performance, simplified coil winding

→ Selected layout:
parallel solenoid windings each made of parallel 6-around-1 sub-cables

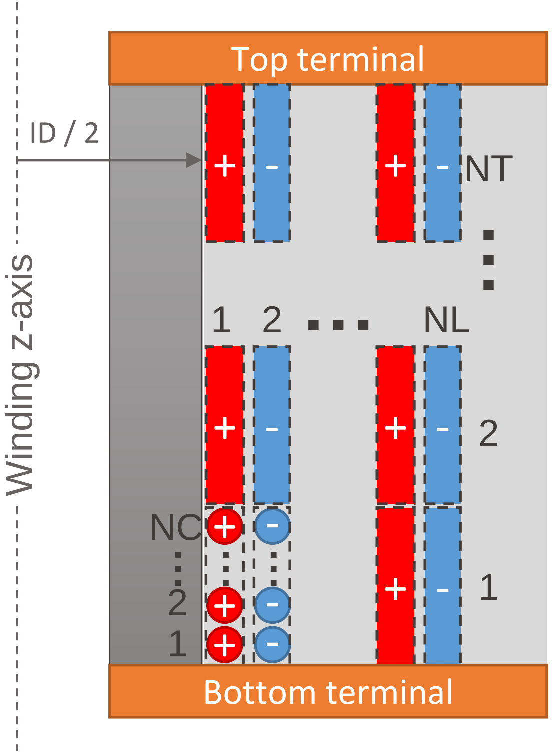
aka ‘Ayrton–Perry winding’



- Simple winding
- Voltage increasing gradually along the winding length
- Conductors not transposed → non-uniform current distribution?

Inductance analysis

Switch winding pack



Current distribution among the layers can be balanced by adjusting the number of conductors in each layer.

For example, NC = 2 conductors per layer, NL = 4 layers, NT = 60, then the layer inductances in µH for ID 50 mm:

29.3	-24.9	25.0	-24.5
sym	35.6	-30.7	30.7
sym	sym	42.4	-37.1
sym	sym	sym	49.8

Total inductance = 1.9 µH

Mode	Current distribution			
Inductive	0.93	-1.26	1.14	-0.68
Resistive	1	-1	1	-1

→ 30% mismatch

Instead of [2,2,2,2], let us see the [3, 2, 2, 4] configuration:

13.1	-16.6	16.7	-8.1
sym	35.6	-30.7	15.4
sym	sym	42.4	-18.5
sym	sym	sym	12.6

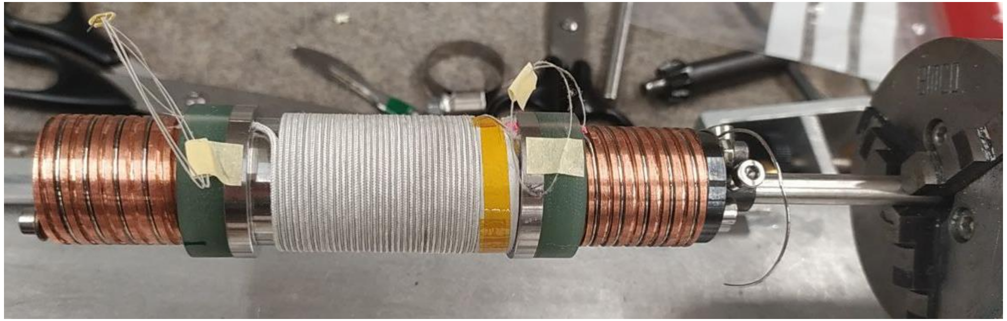
Total inductance = 1.2 µH

Mode	Current distribution			
Inductive	1.02	-1.06	1.10	-0.91
Resistive	1	-1	1	-1

→ 10% mismatch

1 kA/2 Ohm switch

1st layer + heater wire…

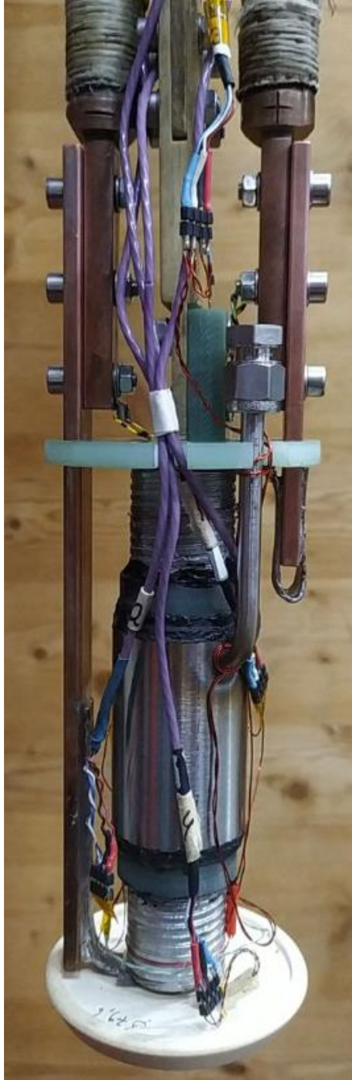


… + 2nd layer + T sensors + V taps + soldered terminals…

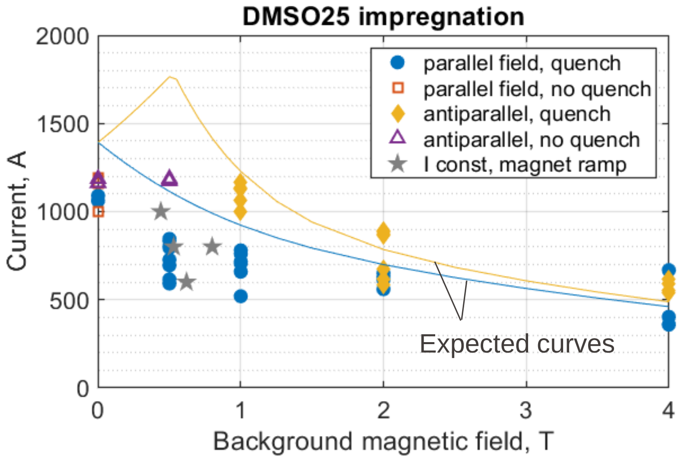
… + impregnation: 1st test – DMSO25%, 2nd – dry, 3rd – wax

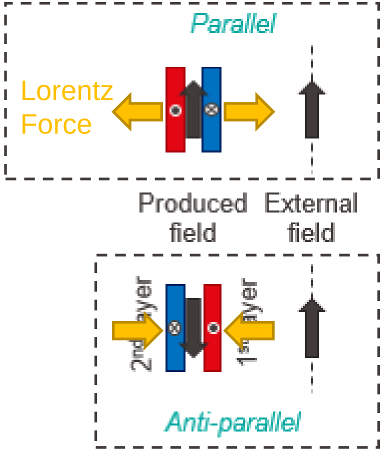
Switch insert for LHe test in 15 T magnet:

- Voltage taps: inner & outer layers, top & bottom terminals, total voltage
- Co-wound heater between the layers
- Temperature sensors on the wire (thermocouple & CERNOX)
- Hall probe at the center of the switch
- AC current heating



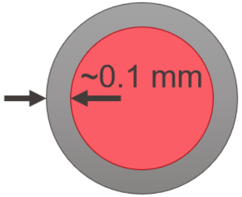
Test results: DC performance





‘Parallel’ – self-field and background field added up, repulsive force on the two layers

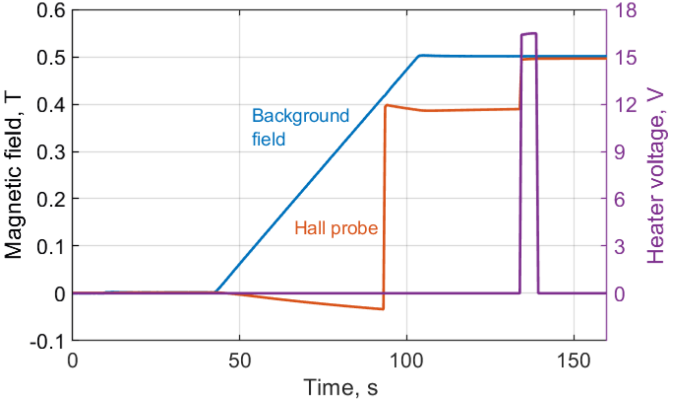
‘Anti-parallel’ – subtracted field contributions, attractive force when background field is dominant



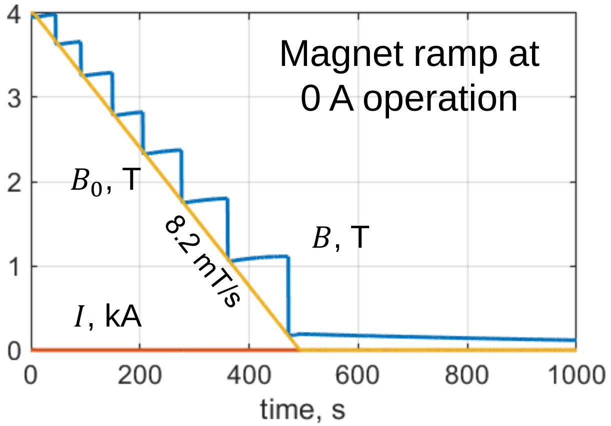
Terminal resistance:

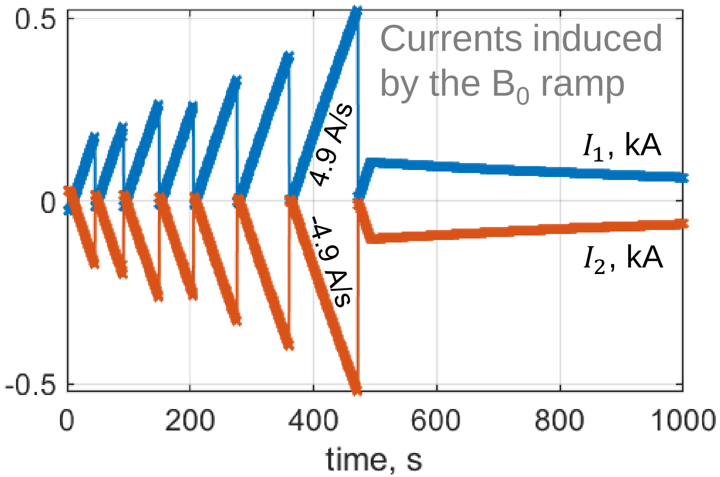
- measured 20 nΩ top, 50 nΩ bottom
- expected wire specific resistance 15 nΩ.m (assuming 0.1 mm thick Cu30Ni cladding), thus 19 nΩ per terminal for the two 40 cm-long wires

Q: Malfunctioning Hall probe?



Current distribution by Hall probe





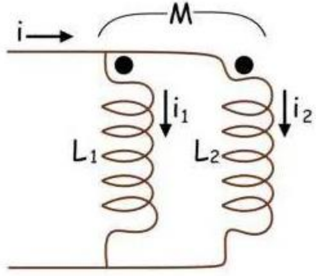
A: No, screening effect!

$$B = B_0 + c_1 I_1 + c_2 I_2$$
$$I = I_1 + I_2$$

$$I_1 = (B - B_0 - c_2 I)/(c_1 - c_2)$$
$$I_2 = (B_0 - B + c_1 I)/(c_1 - c_2)$$

B total magnetic field
B_0 background field
I transport current
I_1 current in layer 1
I_2 current in layer 2
c_1 =±0.91 T/kA at center
c_2 =±0.89 T/kA at center

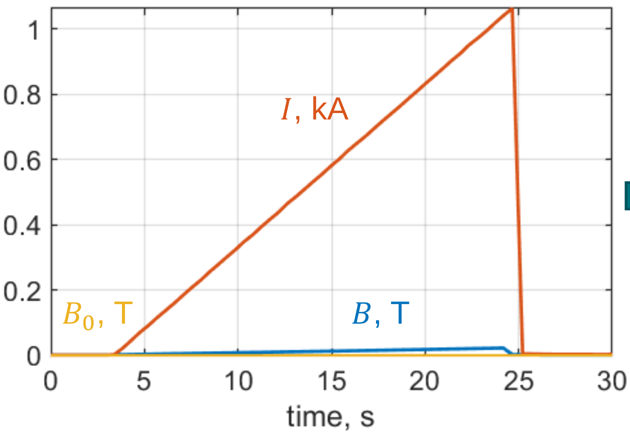
- 2 layers in series (B_0 ramp):
  Idot=4.9 A/s → L serial = 87 µH
  Estimated 90.3 µH
  Note: $L_s = L_1 + L_2 + 2(-M)$
- 2 layers in parallel (Iop ramp):
  measured ~ 1.9 µH ± 0.4 µH
  Estimated 1.9 µH
  Note: $L_p = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M}$

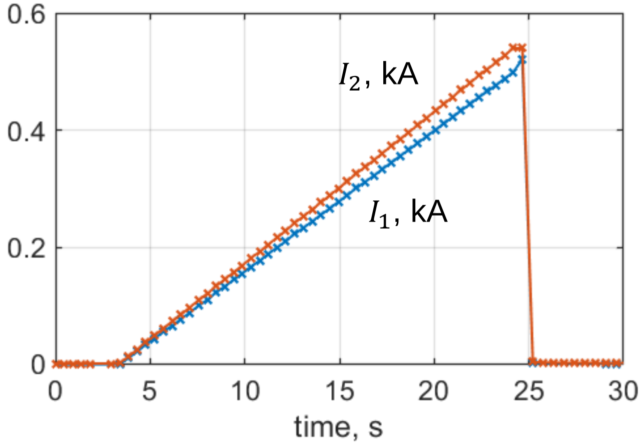


23.2	-20.7
-20.7	25.7

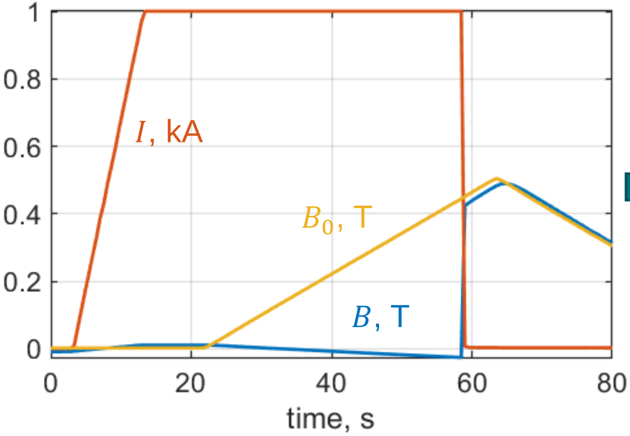
Current distribution by Hall probe

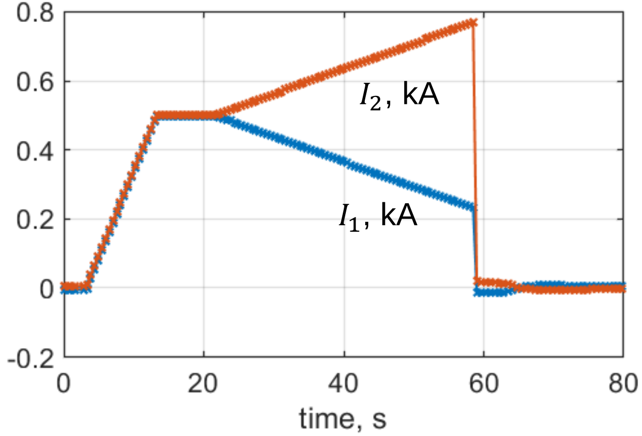
Current ramp at
zero field



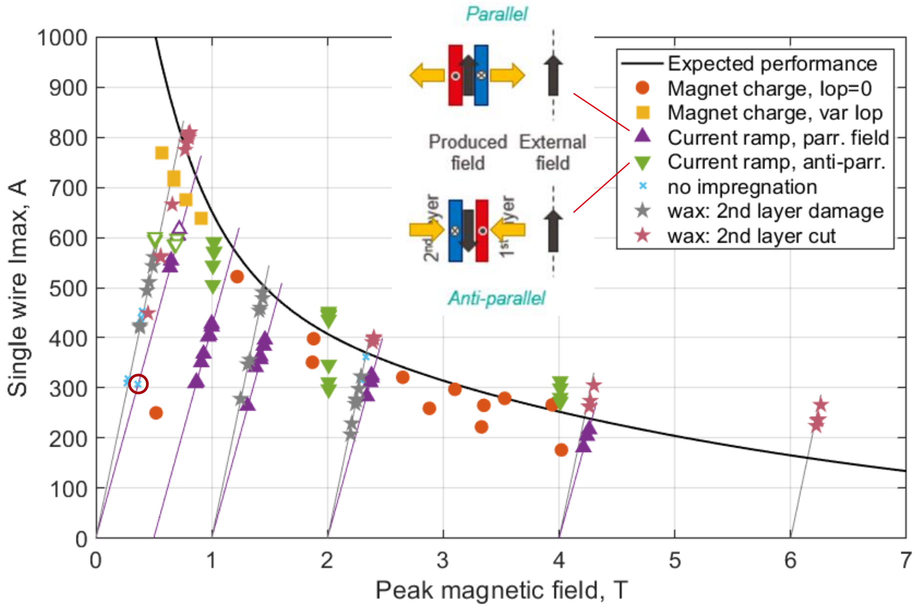


Magnet ramp at
1 kA operation





Performance comparison

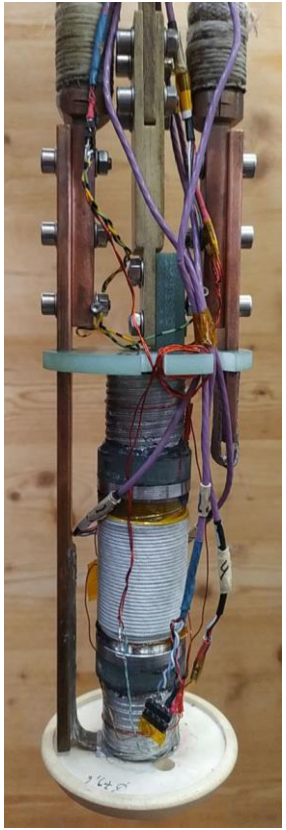


Impregnation trials:
DMSO25% → no impregnation → wax

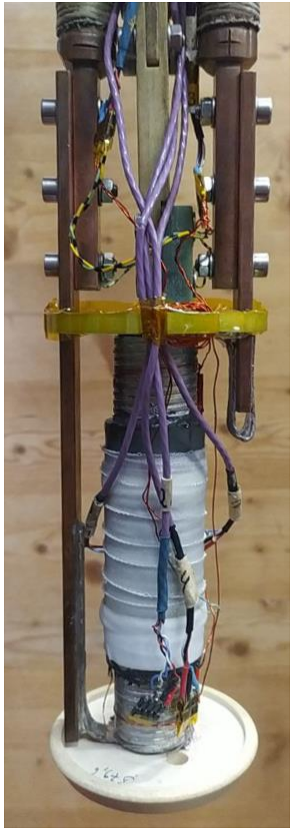
Switch damaged by quench at ~600 A, self-field:

- no more screening effects
- switch inductance increased from ~2 µH to ~50 µH

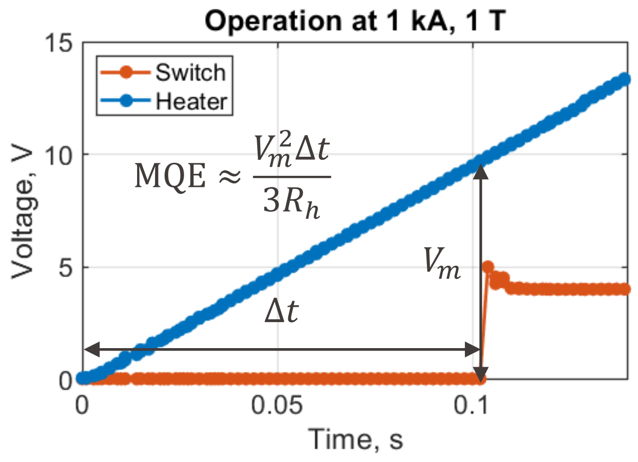
No impregnation



Wrapped in wax-impregnated fiberglass cloth

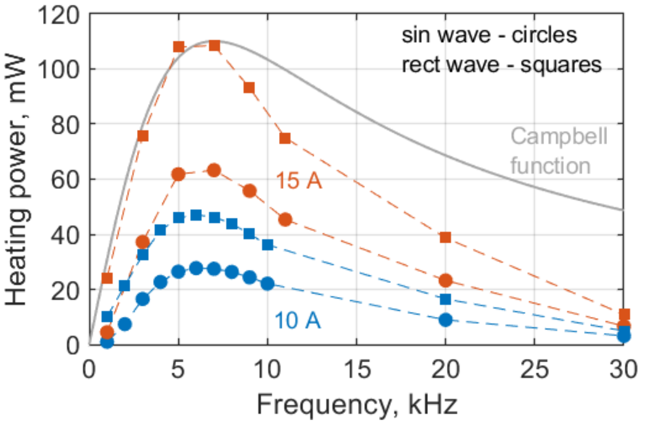


Transition metrics



Co-wound heater:

- switching delay ~0.1 s (limited by the heater power source providing ~100 V/s ramp)
- MQE ~ 0.1 – 0.5 J depending on current and magnetic field

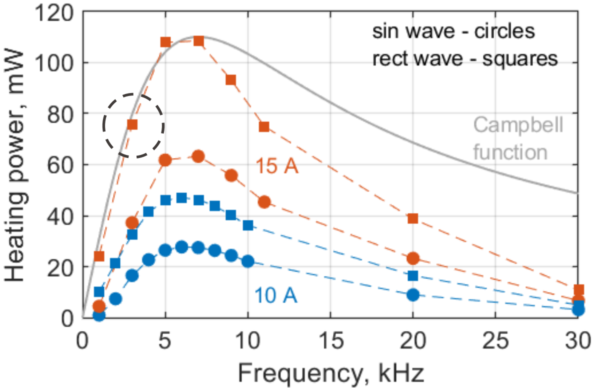


AC current heating: $I = I_0 + A\sin 2\pi\nu t \rightarrow B = \mu_0 I/d,\ P = \dot{B}^2 n\tau S/\mu_0$?

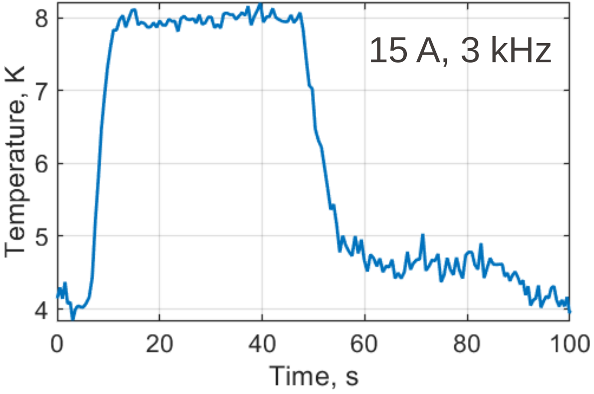
- Heating power scales as A^2, but Campbell function is not reproduced
- Measured: $\tau \approx 1/(2\pi\nu_{peak}) \approx 23 - 32\ \mu\mathrm{s}$ (e.g. $\rho \approx 20\ \mu\Omega\cdot\mathrm{m}$)

  Expected: $L = 18\ \mathrm{mm},\ \rho \approx 30 - 35\ \mu\Omega\cdot\mathrm{m},\ \tau = \frac{\mu_0}{2\rho}\left(\frac{L}{2\pi}\right)^2 \approx 16\ \mu s$
- Absolute values ~500 times lower than expected for the sin wave, but still possible to turn the switch off at low MQE operation

AC current heating

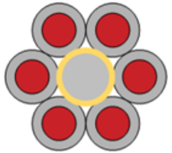


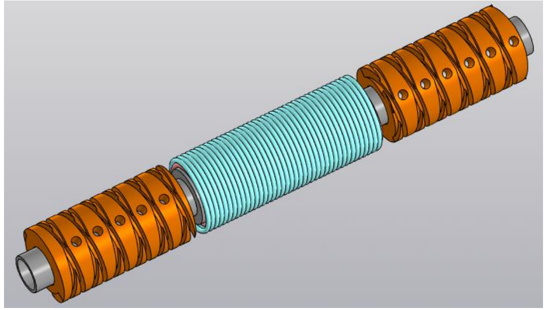
Thermocouple signal
(low precision at helium temperatures)

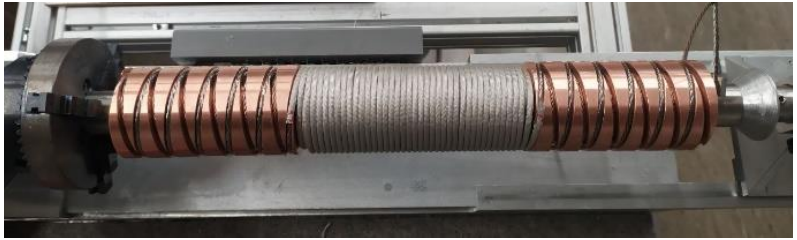


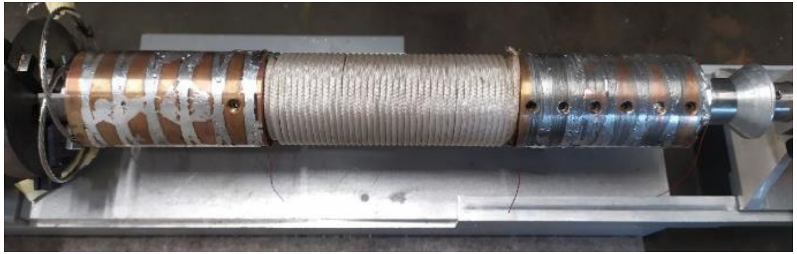
- In the first test with two layers, the AC current heating is ~500 times lower than expected.
- However, after cutting the 2nd layer, its efficiency drastically improved: for example, 15 A, 3 kHz operation lead to ~4 K increase, ~2 W heating power (initially: ~0.2 K, ~80 mW)
- In this case, AC current can be used instead of co-wound heater for thermal switching
- The screening mechanism is not yet understood

6 kA/0.5 Ohm switch: 2 layers, 6 wires/layer









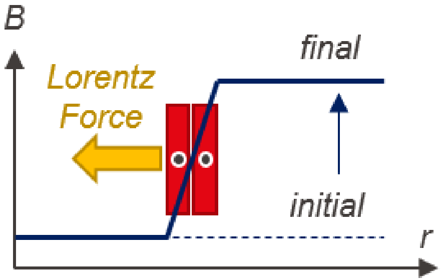
Sample features:

- 6-around-1 cable in fiberglass sleeve, 2-layer winding on a steel tube with OD 36 mm, ID 20 mm
- 40 turns / layer, inductance matrix (in µH):

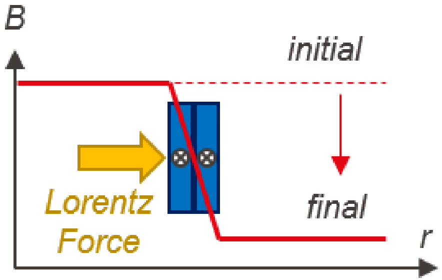
20.9	-16.5
-16.5	26.6

- ~11 m total cable length
- Copper terminals with two crossing helical grooves to keep conductor tension during winding and avoid cable cut between the two layers

→ **1st test** – DMSO 25% impregnation, inductive charging in 15 T magnet, i.e.

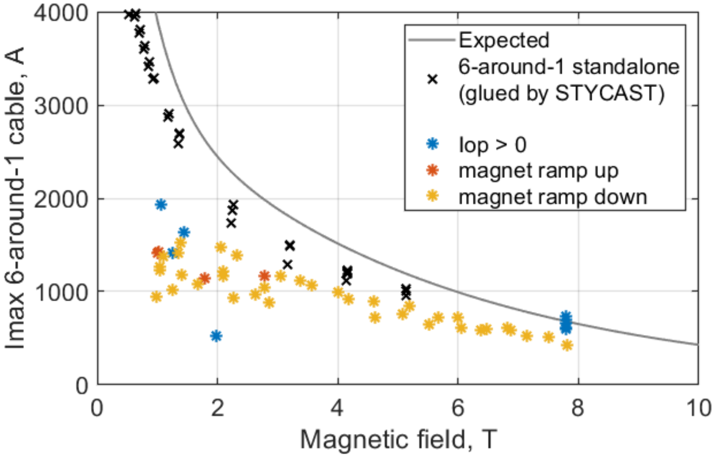


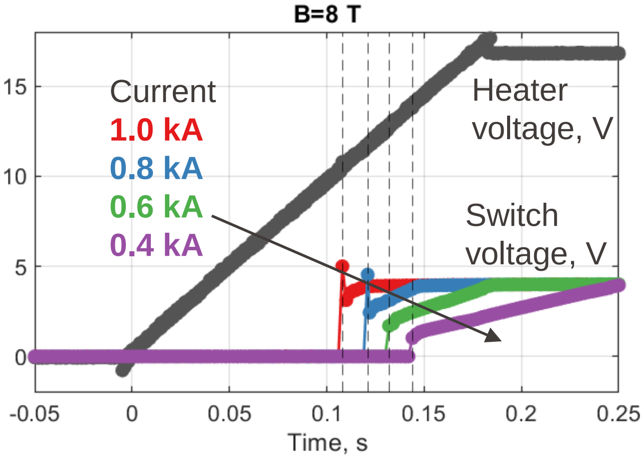
External field ramp up



External field ramp down

First results





DC performance:

Imax lower than expected at low fields

Resistance: winding ~0.3 – 0.4 Ohm at ~10 K, terminals: 0 nΩ at bottom (sc), ~1 nΩ at top

MQE ~10 J at 0 T, 1 kA and ~0.5 J at 8 T, 1 kA, max AC heating at 15 A, 7 kHz rect wave (T~4.4 K)

Switch inductance:

Parallel: expected 3.5 uH, measured ~0.2 – 0.5 uH (geometry issue?)

Serial: expected 81 uH, measured ~80 uH (~18 A/s current ramp by 12 mT/s magnet charge)

Further test plans

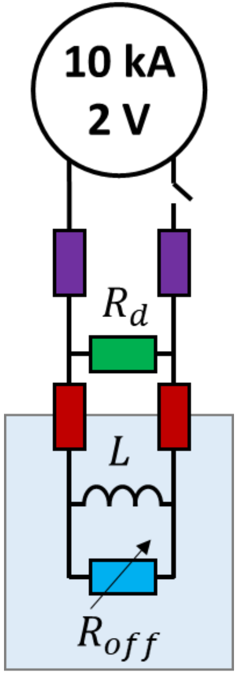
→ **2nd test** – direct current operation in JORDI stand (operation up to 10 kA, supercritical He cooling)

High current load coil is needed for a high voltage test.

For example, quench in a persistent mode operation at I = 6 kA and L = 1 mH (stored energy $E = 20$ kJ):

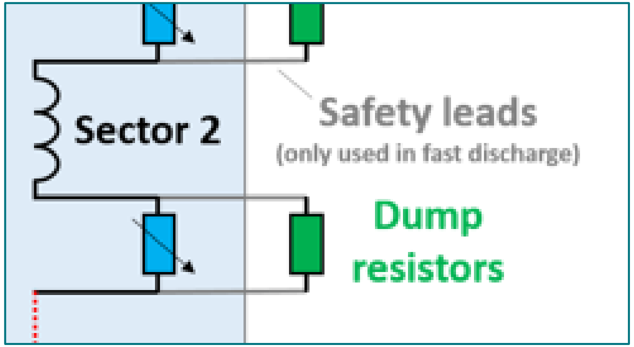
- Switch resistance $R_{off} = 0.4\ \Omega$, total resistance R
- Energy released in the switch $E_s = ER/R_{off}$
- Energy absorbed in the switch $Q_s = \int_{T_0}^{T_{max}} c_{eff}(T)dT$, where c_{eff} includes winding, impregnation and steel
- Adiabatic process $E_s = Q_s \rightarrow T_{max}$ results:

R_d	0.01 Ω	0.1 Ω	1 Ω	Inf
V_d	60 V	0.5 kV	1.8 kV	2.5 kV
T_{max}	~30 K	~60 K	~90 K	~100 K
τ	~100 ms	~12 ms	~3 ms	~2 ms



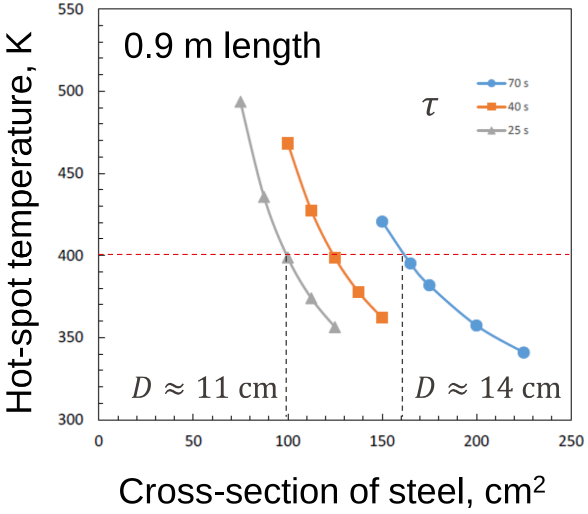
JORDI test stand

Safety leads (analysis by Rainer Wesche)



$$\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{I^2\rho(T)}{A^2}=C_c(T)\,v\frac{\partial T}{\partial t}$$

- 1-D thermal model, only conduction cooling (4.5 K cold end, 293 K warm end)
- No current through the safety leads in normal operation
- In case of quench, 68 kA operating current decays exponentially with the time constant τ



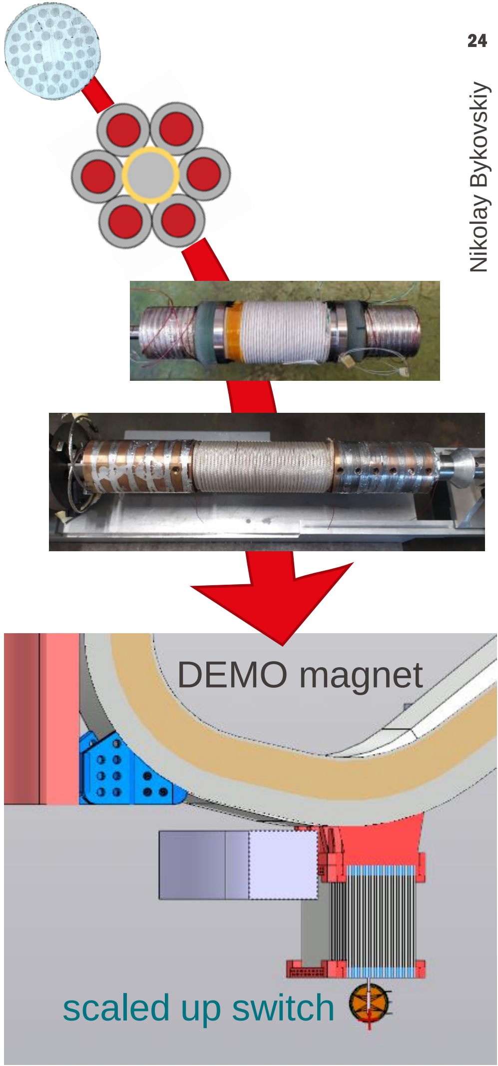
Steel cross-section	**Heat load in normal operation**	**Refrigerator input power compared to ITER leads @68 kA**
100 mm^2	33 W	26%
165 mm^2	54 W	46%*

i.e.: 54 W * 0.2 kW/W for safety lead vs
10 W * 0.2 kW/W + 4.5 kJ/g * 5 g/s for ITER lead

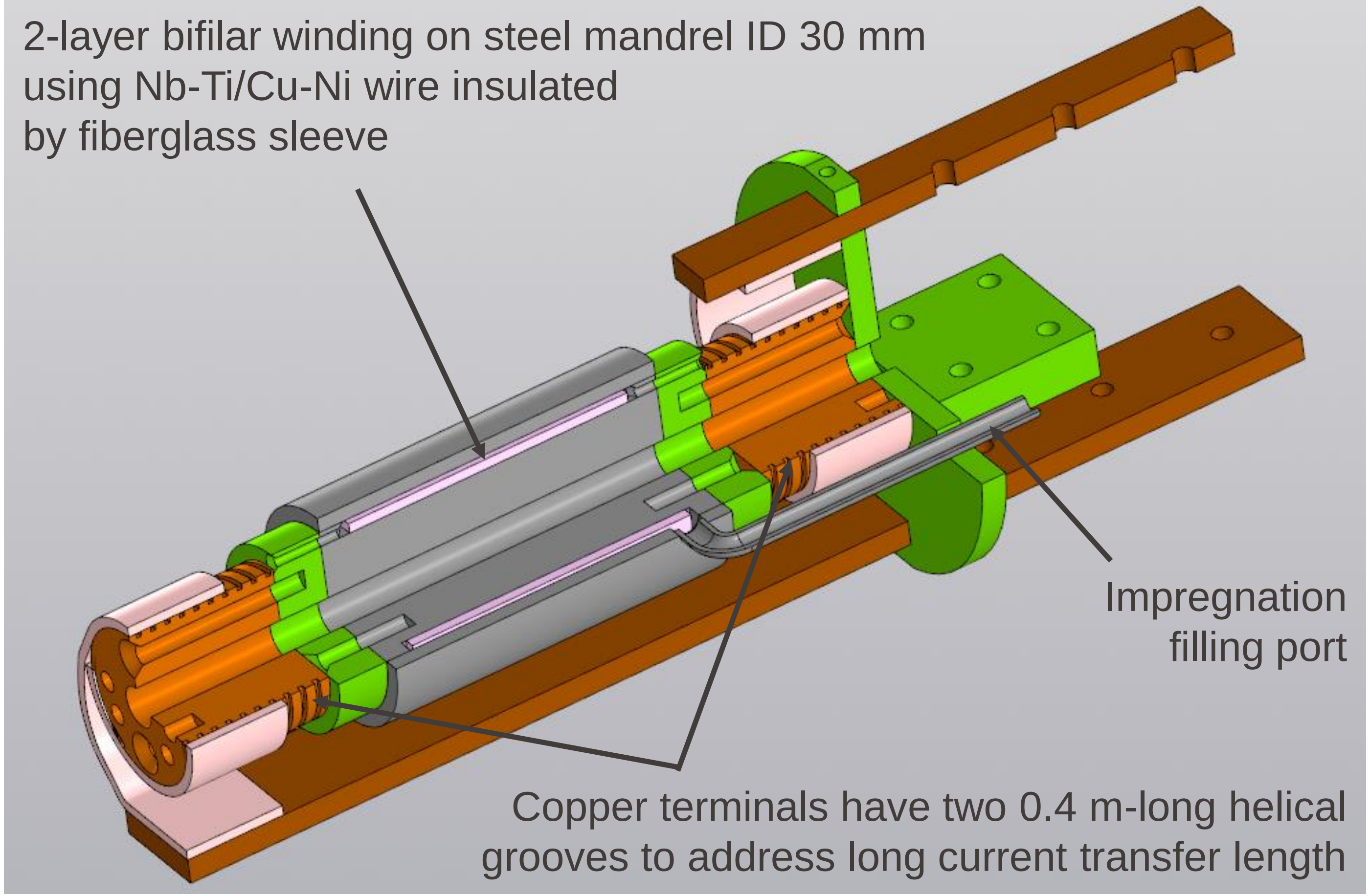
Conclusion

- High-current superconducting switches can provide various advantages for quench management in large magnet systems, SMES operation, conduction cooled magnets, etc.
- Two switches made of layer-wound solenoids are constructed using single wire and 6-around-1 cable. The 2 Ω switch was tested with transport (layers in parallel) and induced (layers in series) current, while the 0.5 Ω switch only with induced current → in preparation for the direct drive operation.
- Reliability of the low MQE operation for the Nb-Ti/Cu-Ni switches is currently the main concern → aim at optimal impregnation? MgB_2 might be considered as an alternative option.
- Steel safety leads can reduce refrigerator input power in normal operation by a factor ~3 compared to vapor cooled HTS current leads.

THANK YOU FOR YOUR ATTENTION!



1 kA/2 Ohm switch layout



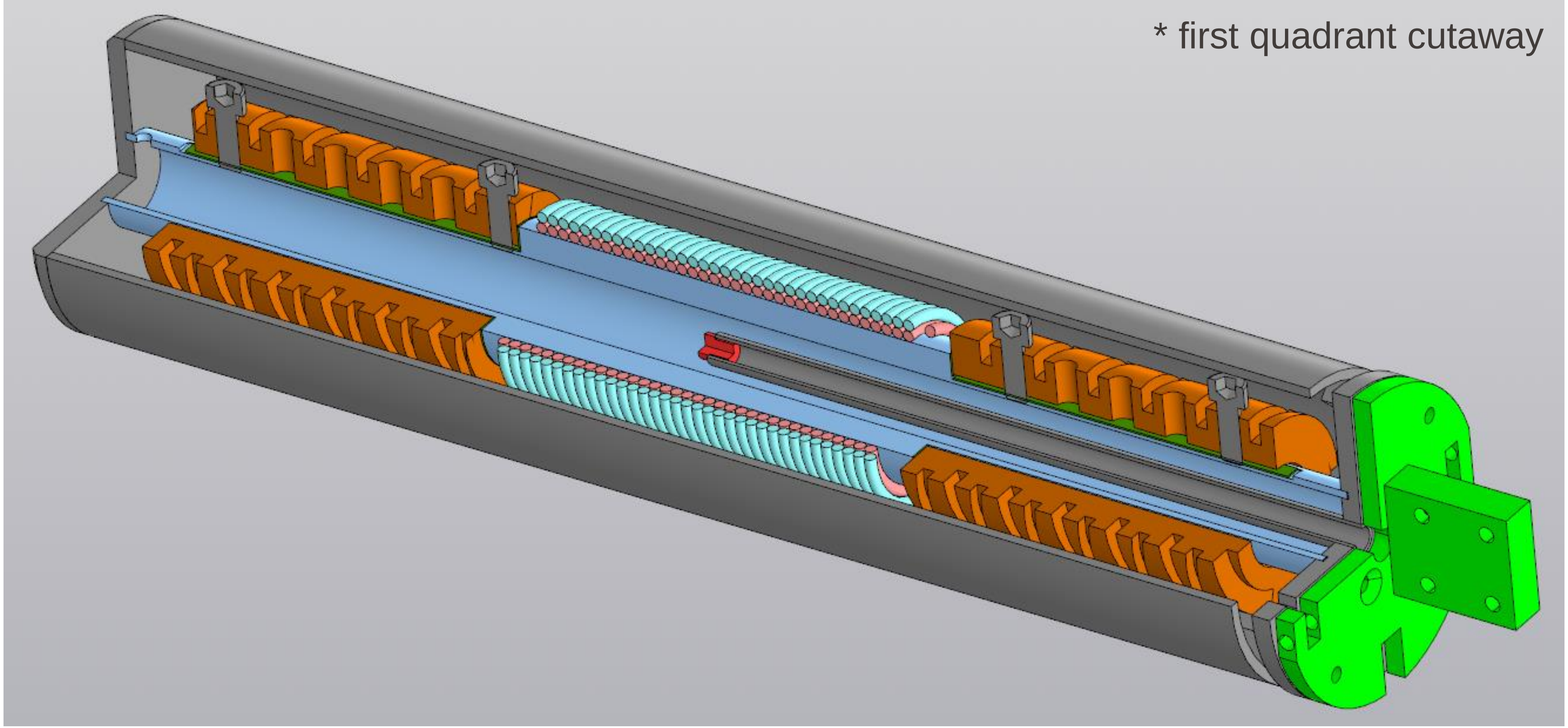
2-layer bifilar winding on steel mandrel ID 30 mm using Nb-Ti/Cu-Ni wire insulated by fiberglass sleeve

Impregnation filling port

Copper terminals have two 0.4 m-long helical grooves to address long current transfer length

* first quadrant cutaway

6 kA/0.5 Ohm switch layout



* first quadrant cutaway