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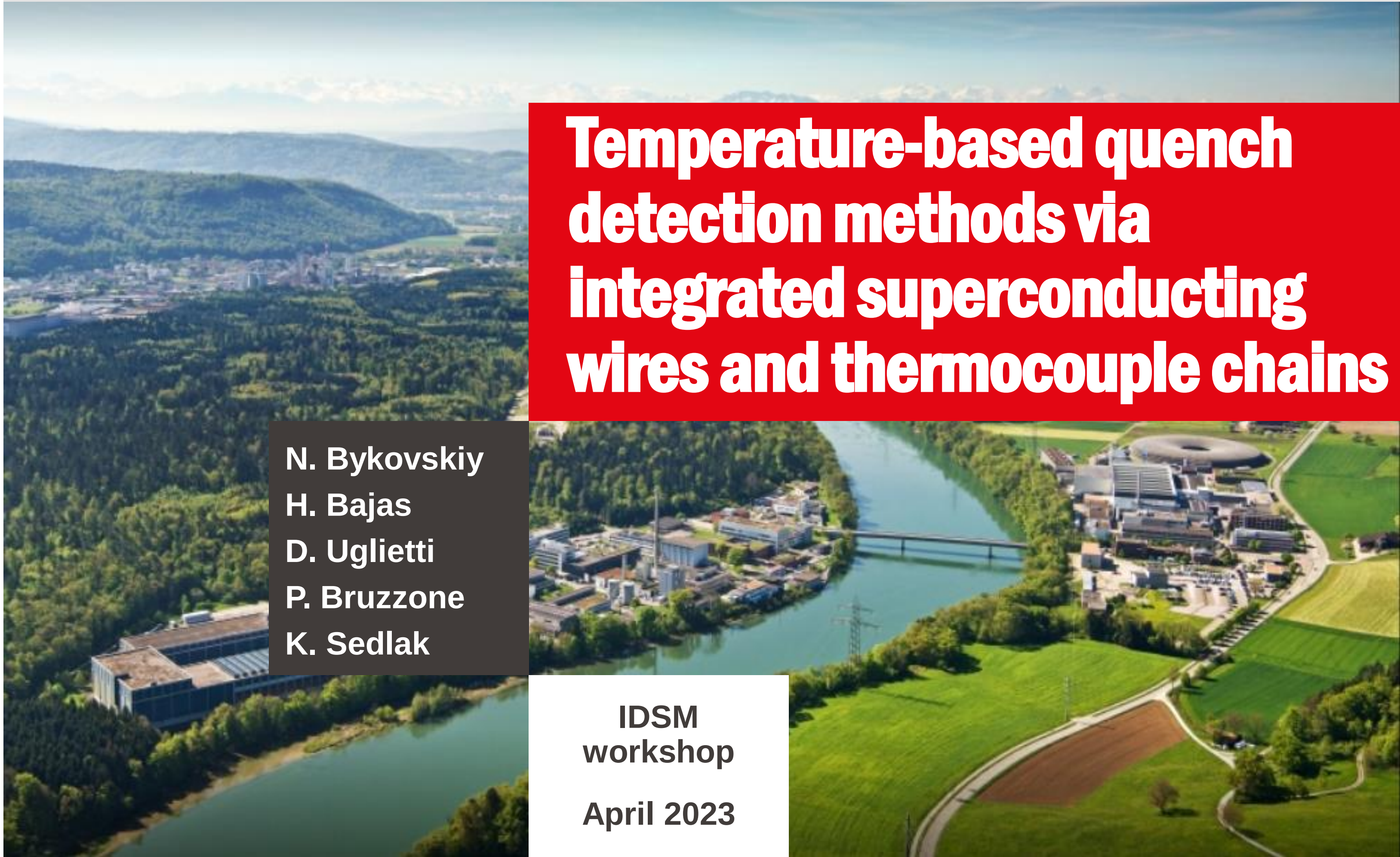

Temperature-based quench detection methods via integrated superconducting wires and thermocouple chains

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IDSM workshop

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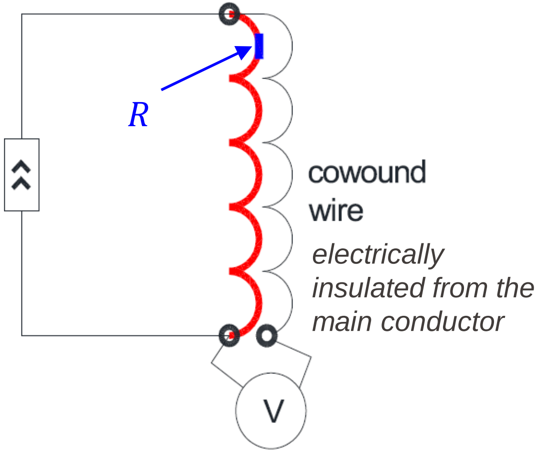
SWISS PLASMA CENTER

Outline

1. Superconducting quench detection wires (SQD)
    - State of the art
    - Candidate materials
    - Experimental demonstration in SULTAN
    - Further development
2. Thermocouple chain
    - Detection concept
    - First test results
3. Summary

Superconducting quench detection wires (SQD)

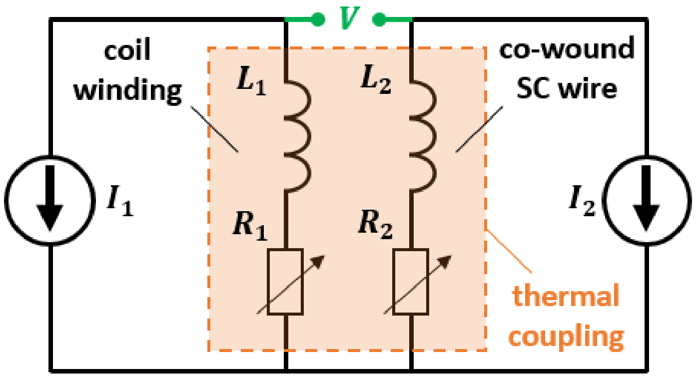
https://doi.org/10.1109/TPS.2022.3212554



$$V = V_R + V_{L_2} - V_{L_1} \approx V_R$$

- Inductive compensation is not perfect
- Slow rise of resistive component in HTS

→ How to improve detection sensitivity?



- Electrically insulated from the main conductor, thus operated independently at current I_2,
- In thermal contact with the main conductor: $T_1(x) \approx T_2(x)$

$V = V_{R_2} - V_{R_1} + V_{L_2} - V_{L_1} \approx \boldsymbol{V_{R_2}} (\gg V_{R_1})$, assuming

- ❖ $T_c(B_{max})$ of detection wire > T quench,
- ❖ High voltage along normal zone of the wire due to the absence of low resistivity protection material (copper or silver), and eventually higher operating current (I_2).

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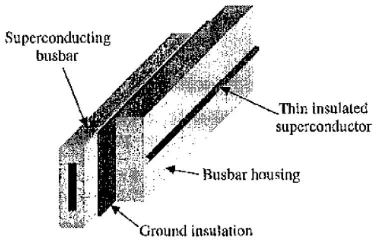
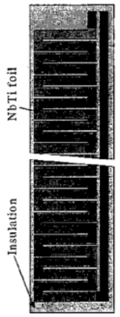
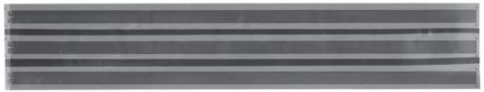
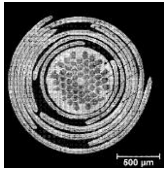
Background

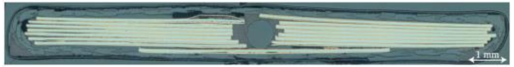
Year	Application	SQD type
2000, 2014 10.1109/77.828253 10.1109/TASC.2013.2286813	Detector magnets	Nb-Ti wire or foil
2016, 2021 https://cds.cern.ch/record/2228249/files/CERN-THESIS-2016-142.pdf https://patents.google.com/patent/WO2021173216A1	HTS cables	LTS wires
2019 10.1109/TASC.2019.2900633	HTS pancakes	Nb-Ti wire
2021 10.1109/TASC.2021.3059602	CCT coils	Nb_3Sn wire
2022 https://doi.org/10.1109/TASC.2022.3171185	General	LTS wires
2022, 2023 (this work) https://doi.org/10.1109/TASC.2022.3140706 https://iopscience.iop.org/article/10.1088/1361-6668/acb17b	Fusion conductors	Nb_3Sn, MgB_2, IBS wires

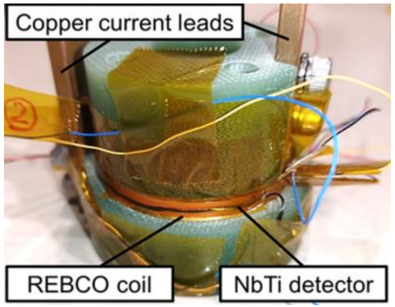


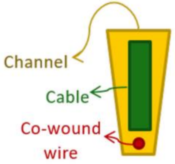


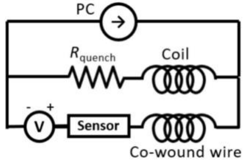


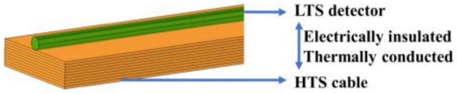


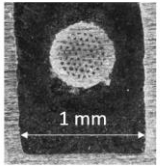


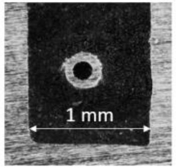


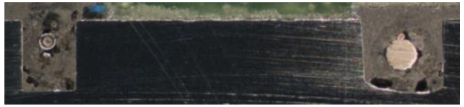


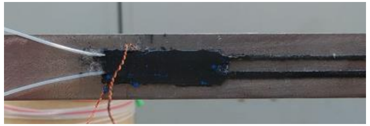


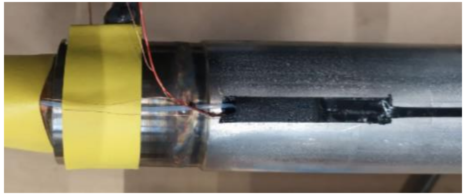












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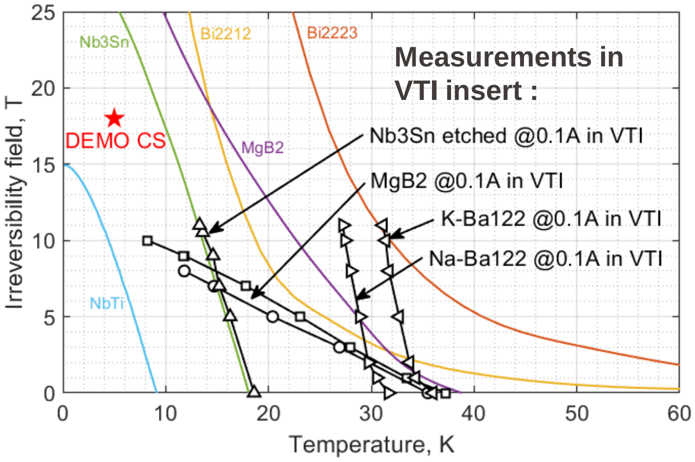
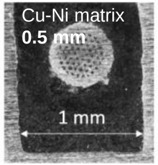
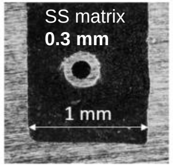
SQD wires: material selection for fusion conductors



MgB2 wires (<u>not doped</u>)

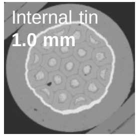


~2 Ω/m

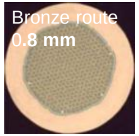


~14 Ω/m

Nb3Sn wires



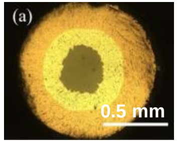
~0.5 Ω/m



~0.3 Ω/m

(after etching)

Iron-based SC wires



~< mΩ/m
(Ag and Cu)

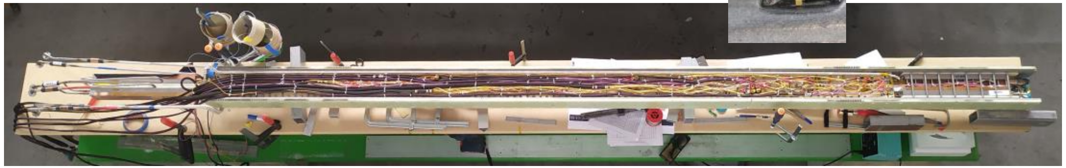
- T quench ~15 to 25 K for HTS fusion conductors, thus broad, but still limited choice to fulfill the $T_c(B_{max})$ target
- V sqd ~ 1 V/m in order to ensure superior performance

→ New tool – ‘quench experiment’ in the SULTAN test facility, i.e.

- Direct current drive up to 15 kA / 10 V
- Temperature from ~5 K up to ~300 K
- Helium cooling 1 – 10 g/s at ~10 bar
- A pair of 3.6 m-long straight conductors:

internal CERNOX

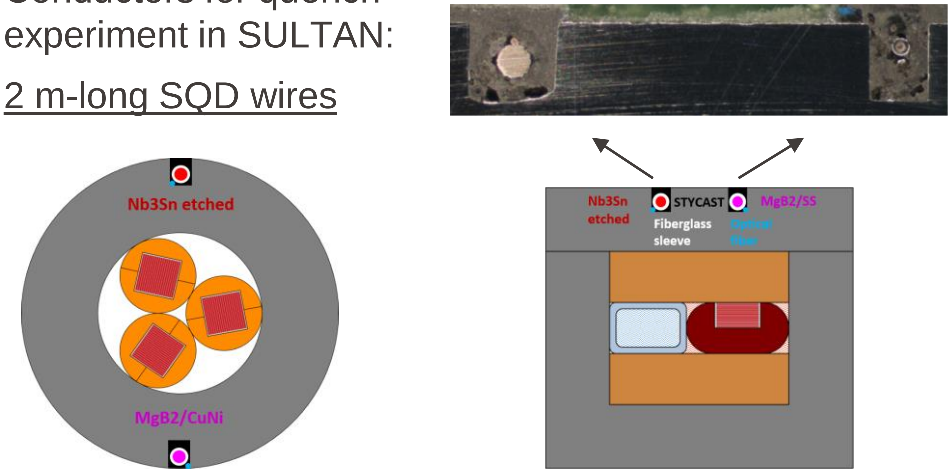
https://doi.org/10.1109/TASC.2021.3063997

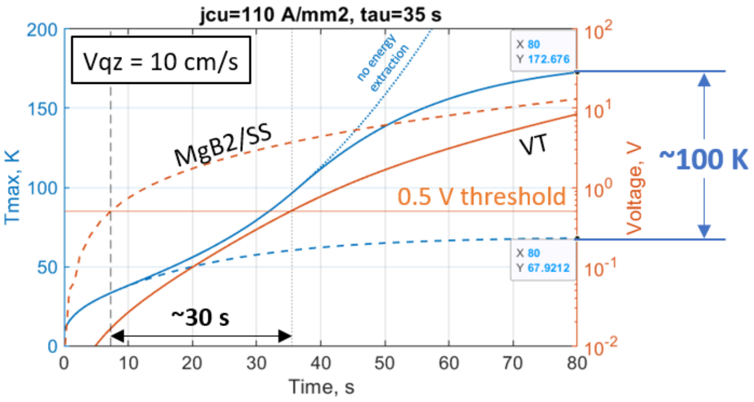


SQD wires: expected & measured performance

Conductors for quench experiment in SULTAN:

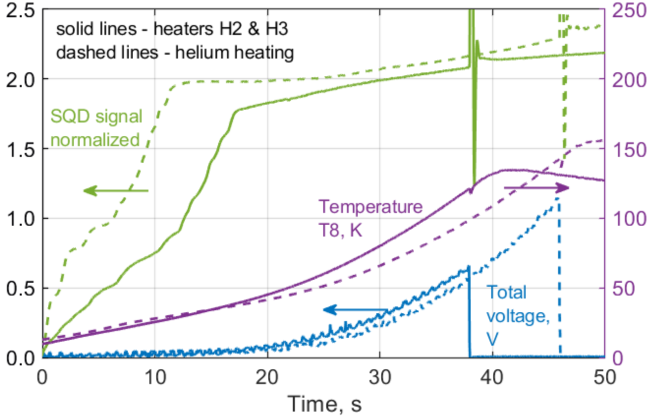
2 m-long SQD wires

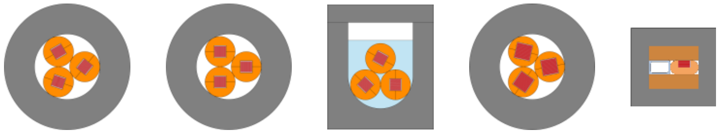




SQD integration in the conductor jacket → simple, robust and eventually sufficiently sensitive for the SQD operation at 0.1 A

ASTRA2 @12 kA, 10.9 T





https://doi.org/10.1088/1361-6668/acb17b

→ Summary on conductor stability and quench propagation

Quench experiment on long lengths

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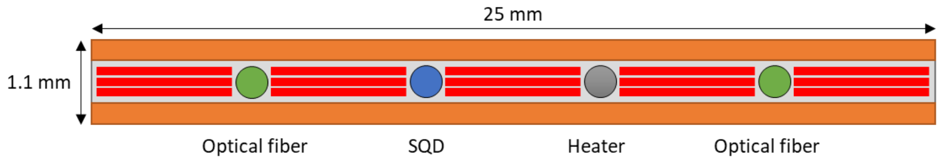
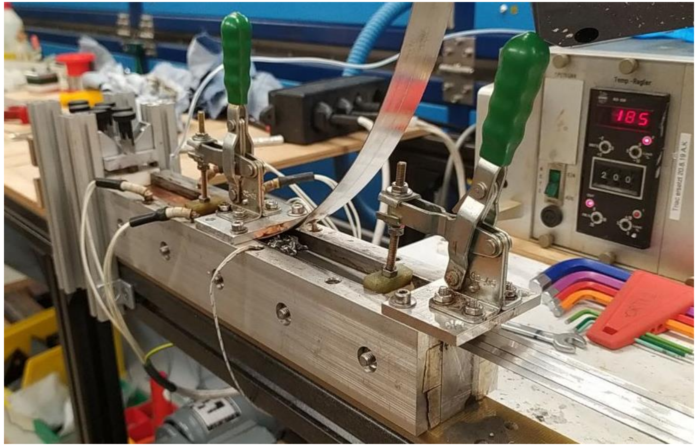
Task challenges:

- HTS conductor development
- Ultra-thin SQD wires
- Embedded optical fibers

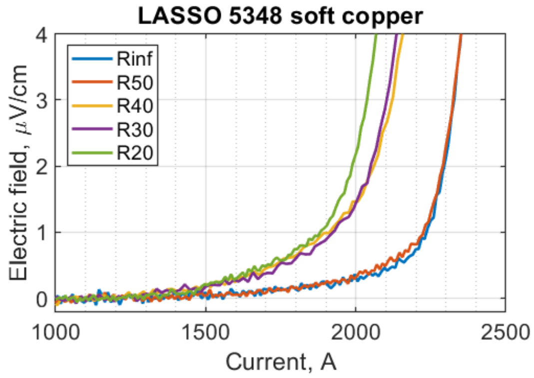
Laminated stacked-tape soldered conductor (LASSO)

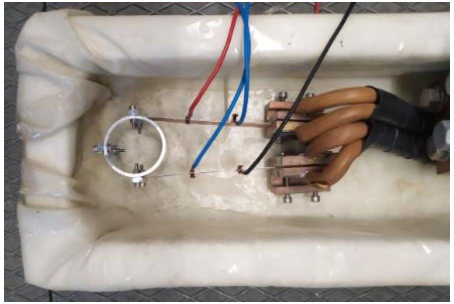


Copper pre-tinning & Cable soldering



Ic bending test at 77 K, self-field





- Initial Ic reduction ~12% due to self-field effect
- By mistake, hard-way deformation at R40 → 15% Ic drop
- Annealed copper to reduce shear stress on ReBCO

Quench experiment on long lengths

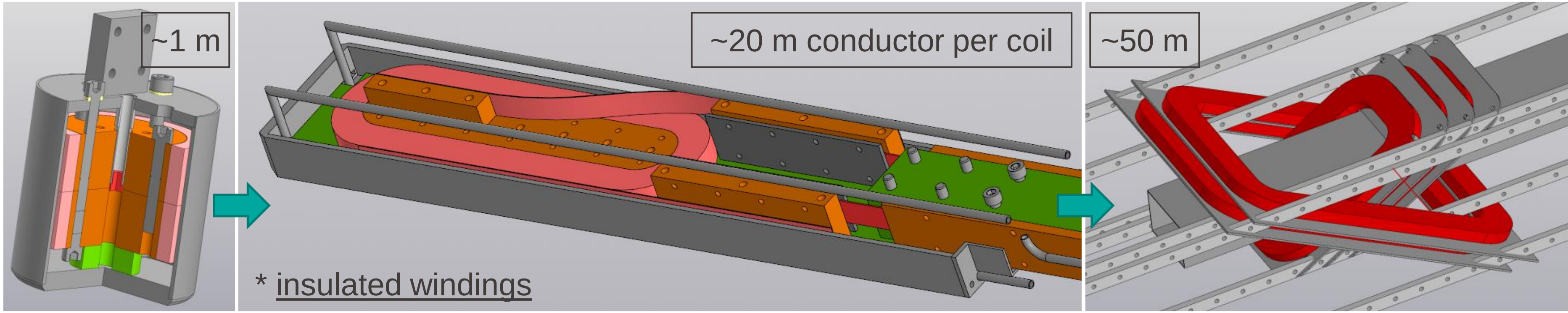
Ultra-thin Nb_3Sn SQD wires:

a) Bronze-route '1st stack' (19 Nb rods in bronze matrix) OD 3.6 mm by **JASTEC**
   → Wire drawing down to OD 0.2 mm by external company and also at EPFL-SPC

b) Internal-tin etched wire (3000 filaments) OD 0.25 – 0.30 mm by **WST**

Embedded optical fibers…

15 T insert | SULTAN QE insert: pancake coils | JORDI stand: x-coil dipole



Detection by a twisted pair

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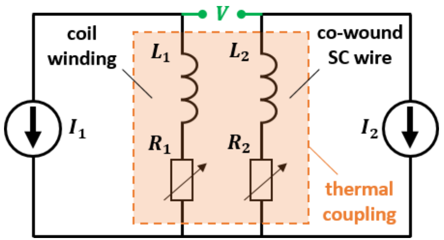
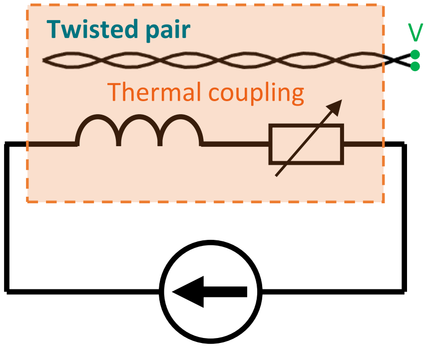




- <u>Twisted-pair</u> SQD wires in order to enhance cancellation of inductive signal + **complete electrical insulation**
- **As an alternative, twisted-pair made of distributed thermocouples?**

Conventional thermocouple:
response on ΔT **only at the ends**

→ Multiple TC connected in series:
response on ΔT **along the length**

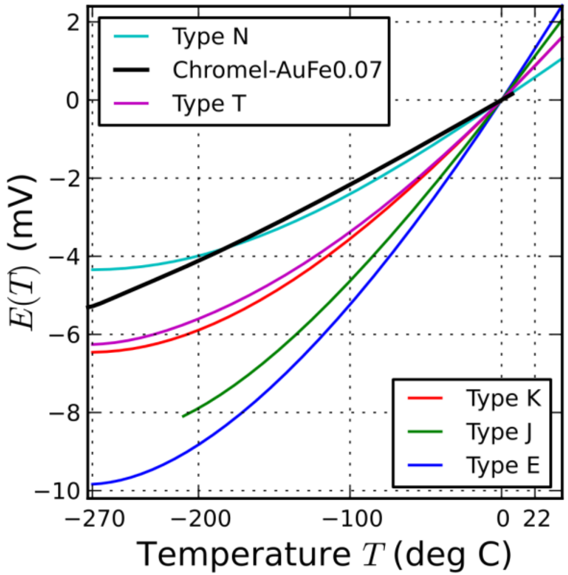
- Welded or soldered joints
- Continuous response on temperature rise, but discrete sensing locations (i.e. opposite to SQD with continuous spatial sensing at a certain T threshold)

Thermocouple materials

ANSI Code	ANSI MC 96.1 Color Coding Thermocouple	ANSI MC 96.1 Color Coding Extension	Alloy Combination + Lead	Alloy Combination - Lead	Maximum T/C Grande temp. range	EMF(mv)Over Max.temp.range	IEC 584-3 Color Coding	IEC Code
K			NICKEL-CHROMIUM Ni-Cr	NICKEL-ALUMINUM Ni-Al	-270 to 1372℃ -454 to 2501°F	-6.458 to 54.886		K
J			IRON Fe (magnetic)	CONTANTAN COOPER-NICKEL Cu-Ni	-210 to 1200℃ -346 to 2193°F	-8.095 to 69.553		J
T			COPPER Cu	CONTANTAN COOPER-NICKEL Cu-Ni	-270 to 400℃ -454 to 752°F	-6.258 to 20.872		T
E			NICKEL-CHROMIUM Ni-Cr	CONTANTAN COOPER-NICKEL Cu-Ni	-270 to 1000℃ -454 to 1832°F	-9.835 to 76.373		E
N			NICROSIL Ni-Cr-Si	NISIL Ni-Si-Mg	-270 to 1300℃ -450 to 2372°F	-4.345 to 47.513		N
S	NONE ESTABLISHED		PLATINUM-10% RHODIUM Pt-10%Rh	PLATINUM Pt	-50 to 1768℃ -58 to 3214°F	-0.236 to 18.693		S
R	NONE ESTABLISHED		PLATINUM-13% RHODIUM Pt-13%Rh	PLATINUM Pt	-50 to 1768℃ -58 to 3214°F	-0.226 to 21.101		R
B	NONE ESTABLISHED		PLATINUM-30% RHODIUM Pt-30%Rh	PLATINUM-6% RHODIUM Pt-6%Rh	0 to 1820℃ 32 to 3308°F	0 to 13.820		B

https://en.wikipedia.org/wiki/Thermocouple

$$V = E(T_{\text{sense}}) - E(T_{\text{ref}})$$



Type K further studied:

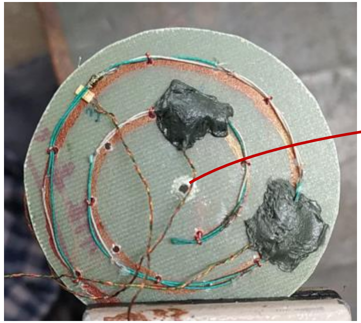
+ Chromel $Ni_{90}Cr_{10}$
– Alumel $Ni_{95}Al_2Mn_2Si_1$

→ OD 0.2 mm, 20 m length procured (10 $/m by a Swiss company, but down to ~0.1 $/m for a km-long order in China)

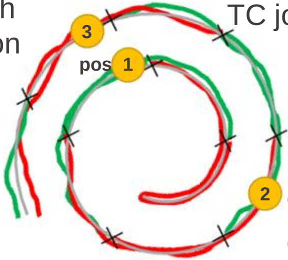
Test samples

Sample 1:

- Manual wire twisting
- 9 TC joints at ~2.5 cm distance, ~25 cm length in spiral shape
- Heaters and temperature sensors at 3 locations along the length



Heater + CERNOX at each position

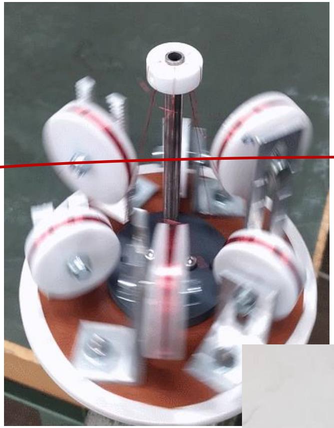


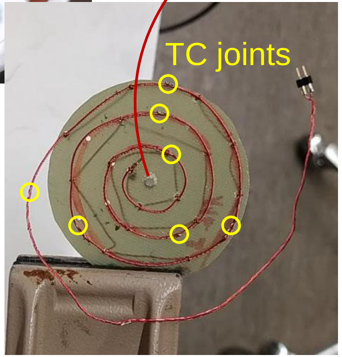
TC joints

'blind spot' ? (by symmetry)

Sample 2:

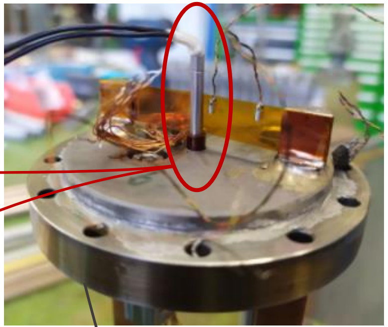
- 6-around-1 return wire wrapping (semi-automated)
- 7 TC joints at 5 cm distance, ~40 cm length in spiral shape





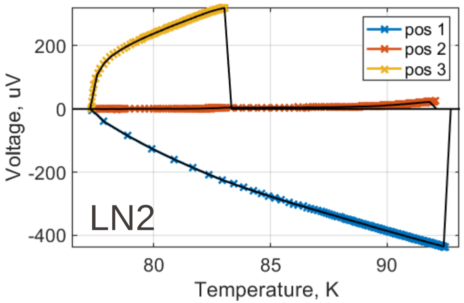
Test insert:

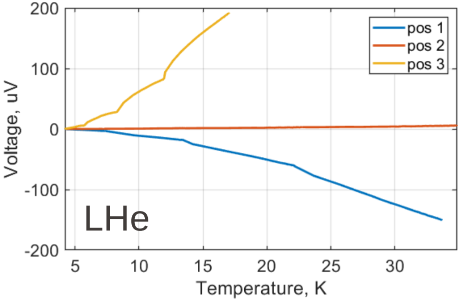
- Central cartridge heater
- Impregnation by 62% aqueous glycerol in a steel container



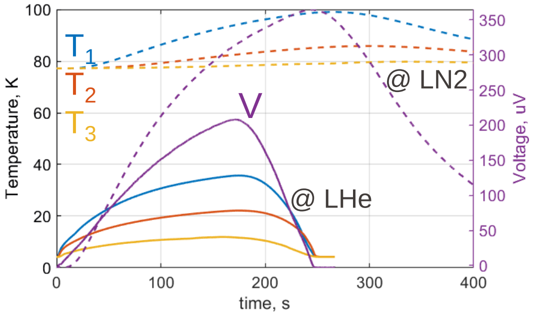
Voltage response at 77 K and 4.2 K

Local heaters on S1 (fired separately)

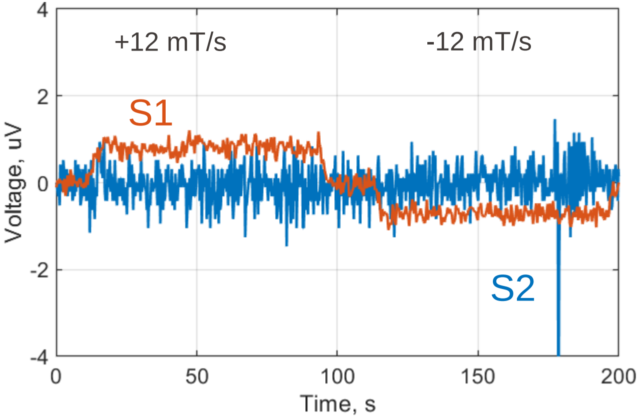




Central heater on S1



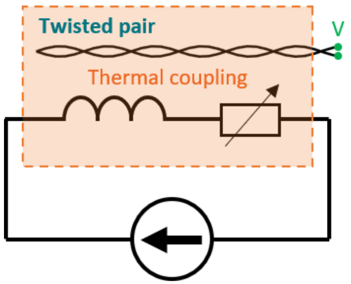
Magnet ramp, operation at 4.2 K

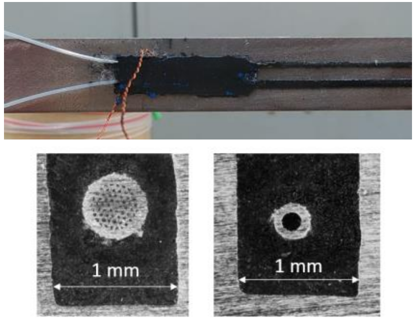


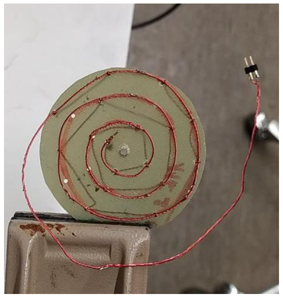
- Voltage response rate (V/K) varies along the length periodically with altering polarity.
- Symmetric temperature distribution centered at a blind spot of a symmetric thermocouple chain cannot be detected.
  In real cases, detection signal is determined by the hottest joint (e.g. see response on the central heater).
- Inductive voltage not observed on S2 at ~12 mT/s also using longer integration time (0.1 uV voltage resolution).
  Assuming negligible inductive contribution, absolute response can be arbitrarily amplified for the desired sensitivity.

Summary

- Temperature-based quench detection, nearly immune to mechanical strain and EM noise, is being developed at SPC using superconducting wires and thermocouple chains.
- SQD wires can be tuned to a large extent for specific application requirements. Ultimately, one can always use the same sc material for SQD as in the main winding and increase the voltage response by higher current and elimination of low resistivity protection material.
- Thermocouple chains offer continuous response on temperature, but long-length manufacturing of a short-segment chain of joints requires further development.
- Both can be used in a twisted-pair configuration to exclude electrical contact with the main winding, enhance noise cancellation and allow signal amplification.







THANK YOU FOR YOUR ATTENTION!