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Improvement of stability of Nb_3Sn superconductors by introducing high specific heat substances

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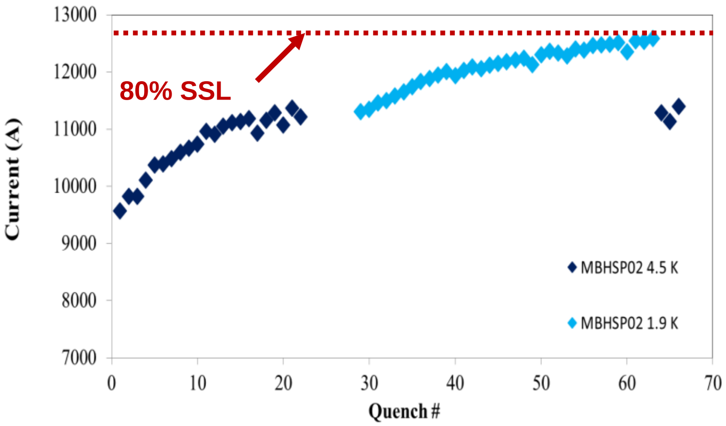
Motivation

Nb_3Sn magnets: slower training rate than NbTi. May be a potential problem for large projects (e.g., FCC: 14% margin, ~5000 dipole magnets).



Slow training because:

- Nb_3Sn is intrinsically less stable than NbTi (larger D_s, higher J_c)
- Epoxy impregnation (poor dynamic stabilization, epoxy cracking)
- Other perturbations

How to solve?

For intrinsic instability: $\frac{\mu_0 J_c^2 d_{eff}^2}{4C(T_c - T_b)} < 3$ (adiabatic), RRR (dynamic)

For external perturbations: try to be less sensitive to them: $\Delta T = Q/C$.

How to increase C of conductors/cables/coils?

Add substances with high C: Gd_2O_3, PrB_6, $CeCu_5$, etc.

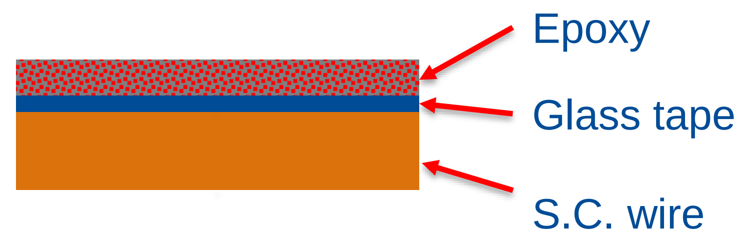
Not a new idea.

The question is, how to do this practically.

How to add high-*C* substances in?

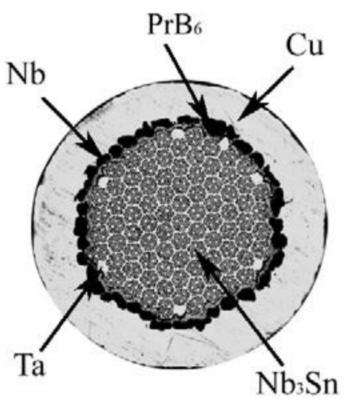
We have considered various ways of applying this idea practically:

1. Add such powders to epoxy: effectiveness



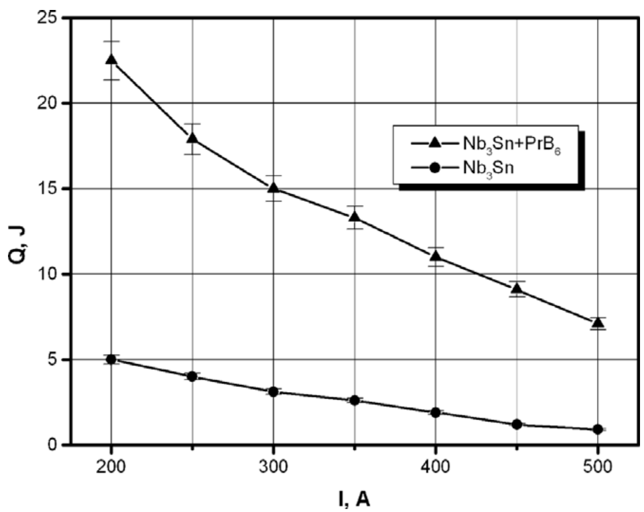
2. Coat such powders onto cables? Cracking during winding?

3. Add such powders directly to Nb_3Sn wires? Need to find a proper wire design.



Problems:

1. Difficult to do
2. Difficult to draw



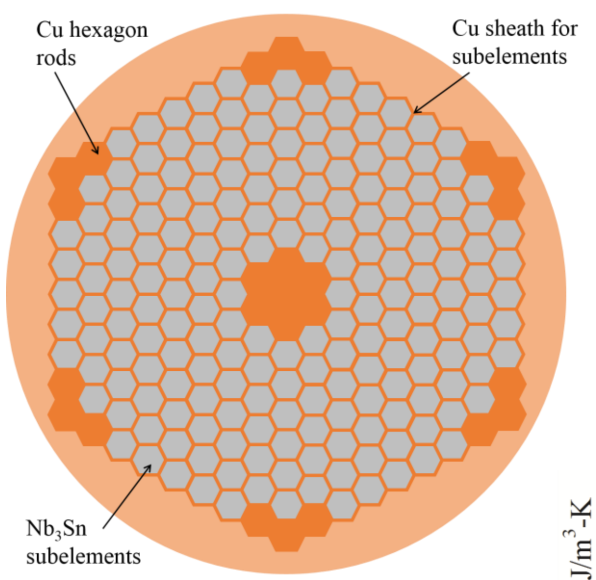
Increasing *C* is a correct direction to go, but the key issue lies in how to do it practically.

Keilin V E et al. 2009 *Supercond. Sci. Technol.* **22**, 085007

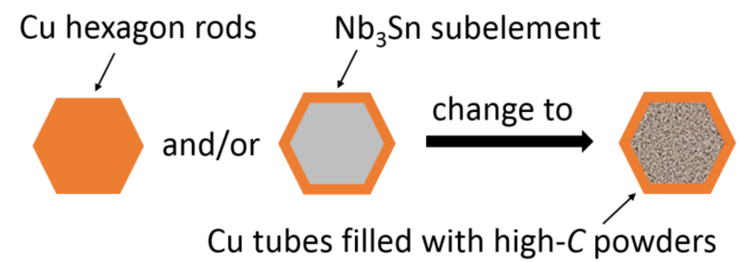
Our scheme

We decided to add high-*C* materials directly into Nb_3Sn wires.
… and, thanks to the design of modern high-J_c Nb_3Sn wires:

Distributed-barrier Nb_3Sn wires:



Our scheme:

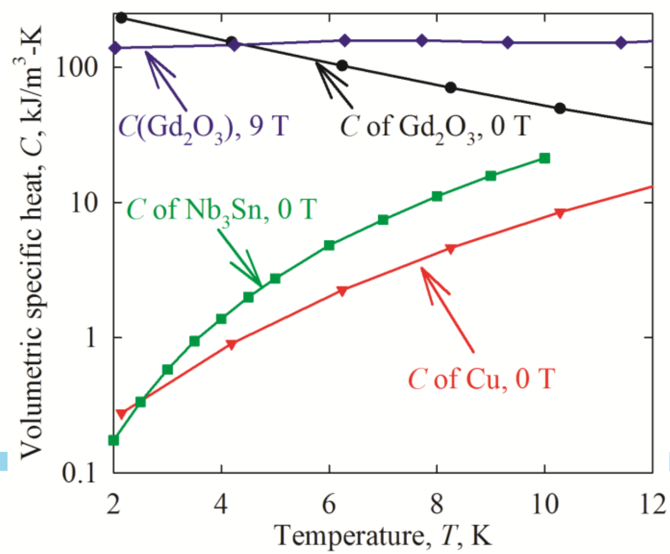


We use mixture of Cu & high-*C* powders instead of pure high-*C* powders.
This modification brings two advantages:
(1) Enhance thermal conduction
(2) Draw better

At 4 K, 0 T	Cu	Gd_2O_3
α, m^2/s	1	$< 10^{-9}$

We use Gd_2O_3 due to its availability and high *C*:

- 2 K: $C(Gd_2O_3)/C(Cu)=1000$
- 4.2 K: $C(Gd_2O_3)/C(Cu)=170$
- 9 T does not suppress its *C*



There are other high-*C* substances.

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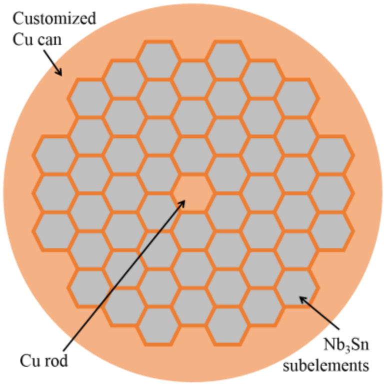
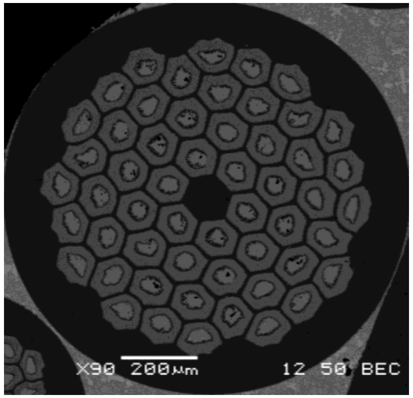
Wires fabricated

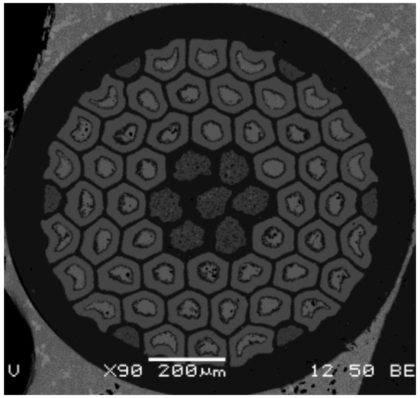
Wires were fabricated by Hyper Tech.

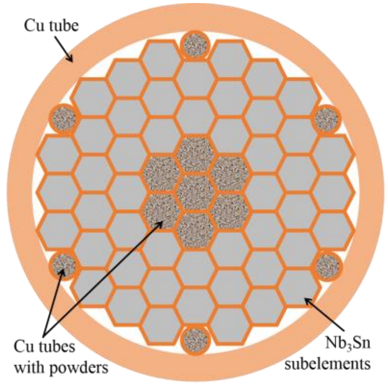
The control wire without Gd_2O_3:

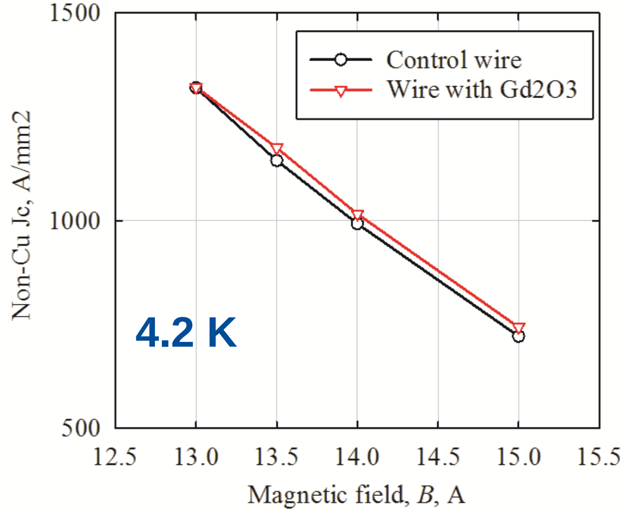




The wire with Gd_2O_3 powder ($Cu/Gd_2O_3 = 0.5$):

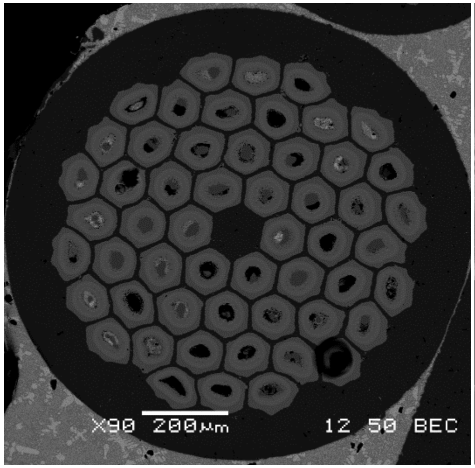


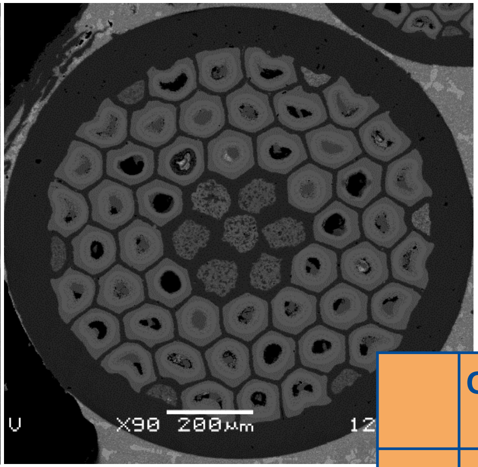




Wires drawn to 1.0 and 0.7 mm without any issues.

625C/ 250h:



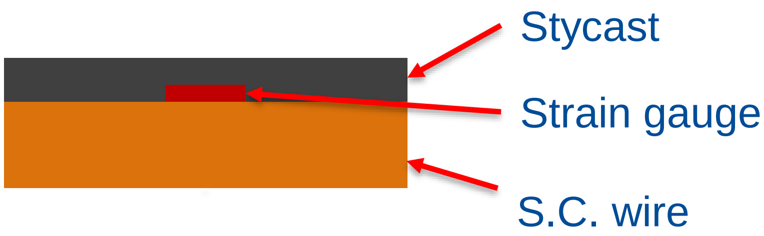


	Control wire: 1.0mm	High-*C* wire: 1.0 mm	Control wire: 0.7 mm	High-*C* wire: 0.7 mm
RRR	107	271	23	34

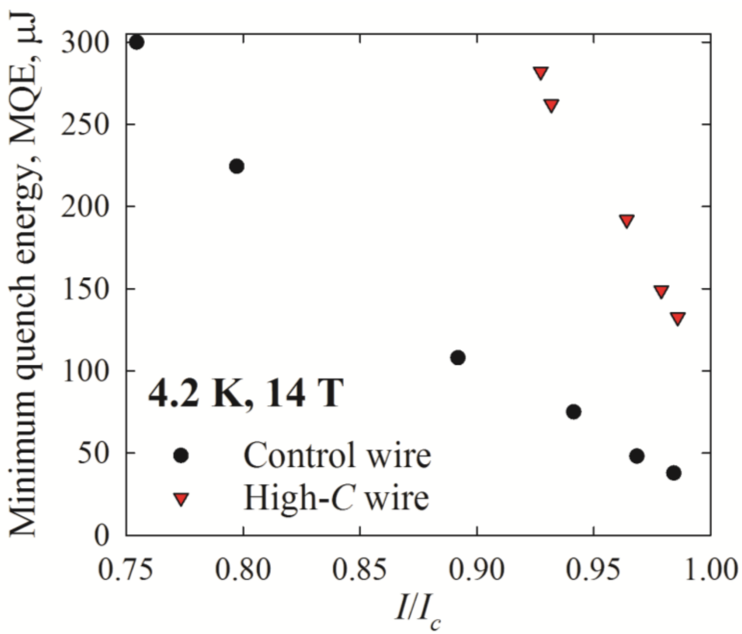
Measurements of stability

Minimum quench energy (MQE) measurements:

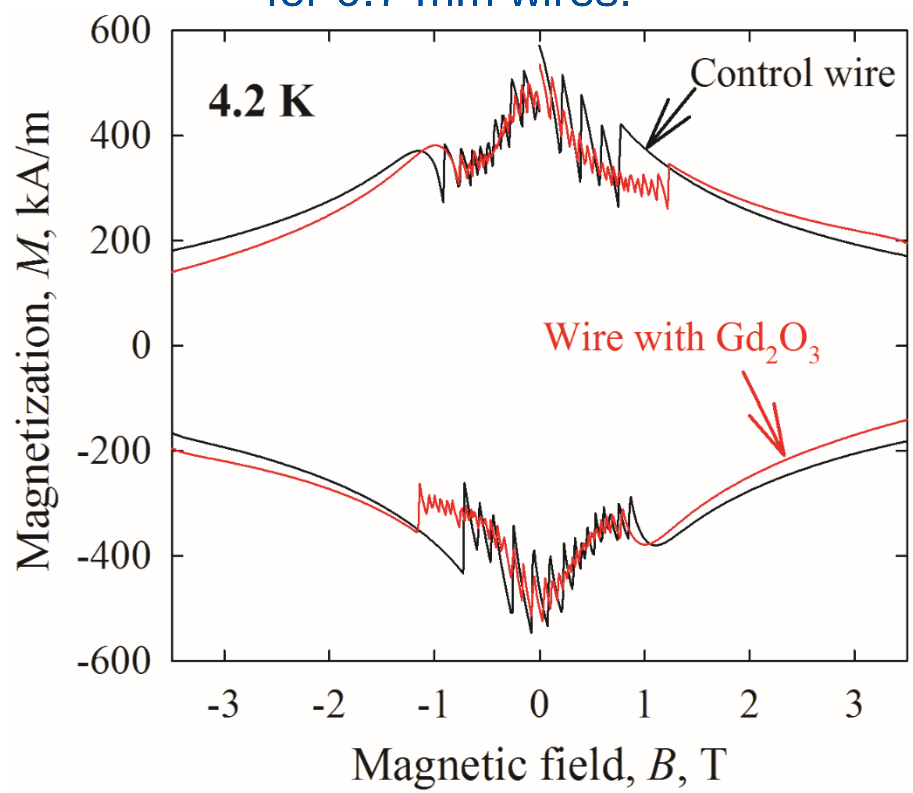
640°C/200h, non-Cu J_cs at 4.2 K, 14 T: 1220 and 1310 A/mm^2 for control and high-C wire.



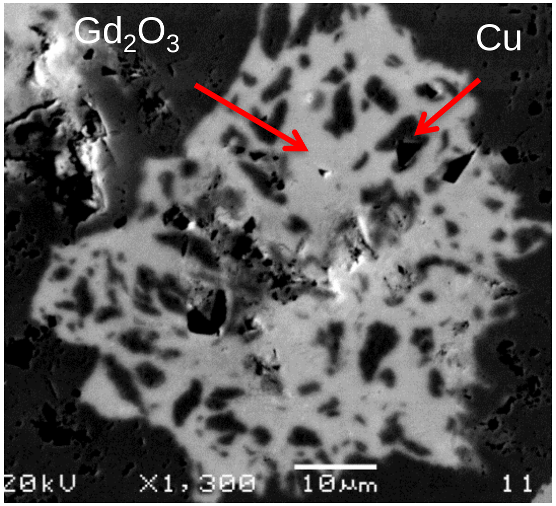
Heat pulse: 100 μs



M-B loop measurements for 0.7 mm wires:



Further optimizations



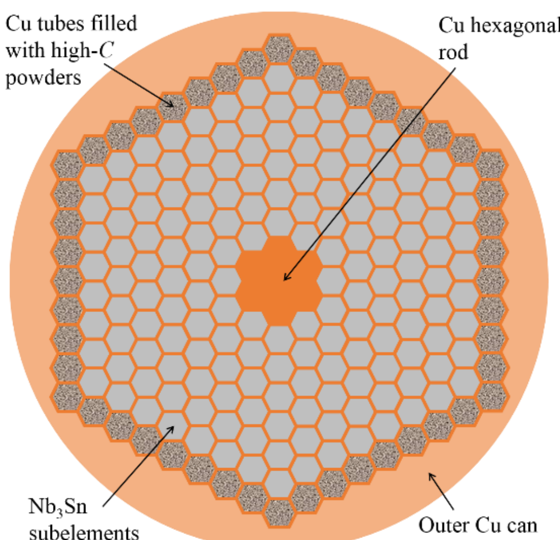
Cu/Gd_2O_3=0.5. Cu forms isolated islands in Gd_2O_3: only a surface layer can absorb heat.

Optimization 1: Cu/Gd_2O_3 ratio & mixing

- Ideal structure: Cu forms a continuous network, dividing Gd_2O_3 into small islands (sub-micron scale).
- Will try different Cu/Gd_2O_3 ratios.
- This could make the stabilization effects more significant.

Optimization 2: wire design

Most effective design:



For this 271-Re design, the fractions are:

- Nb_3Sn subelements: ~43% of the wire;
- Gd_2O_3: ~2% (by assuming Cu/Gd_2O_3=3)

2 vol.% Gd_2O_3 improves *C* of a Nb_3Sn wire by 20 times at 2 K; by 4 times at 4.2 K.

Price? 1 kg Nb_3Sn wire needs 17 g Gd_2O_3. Gd_2O_3 powder (99.9%, 10-100 nm) is <$800/kg, half of Nb_3Sn wires ($1700/kg).

Summary

1. The goal of this project is to combat instability and slow training rate of Nb_3Sn magnets.

2. The method is to increase the specific heat capacity, which not only makes superconductors intrinsically more stable, but also makes them less sensitive to external perturbations (i.e., improvement of energy margin against quenches).

3. A method is put forward to add high-*C* substances to Nb_3Sn wires, which:

   - Adds minimum difficulty to wire fabrication and drawing
   - Does not harm RRR or non-Cu J_c
   - Reduces flux jump amplitudes
   - Improves MQE values significantly

4. Further optimization can lead to more significant stabilization.

5. We have started a contract with Bruker EAS and OST to make long wires.