U.S. MAGNET DEVELOPMENT PROGRAM

Heat Diffusion Modeling and Data of high-C_p Superconducting Components

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US Magnet Development Program

Outline

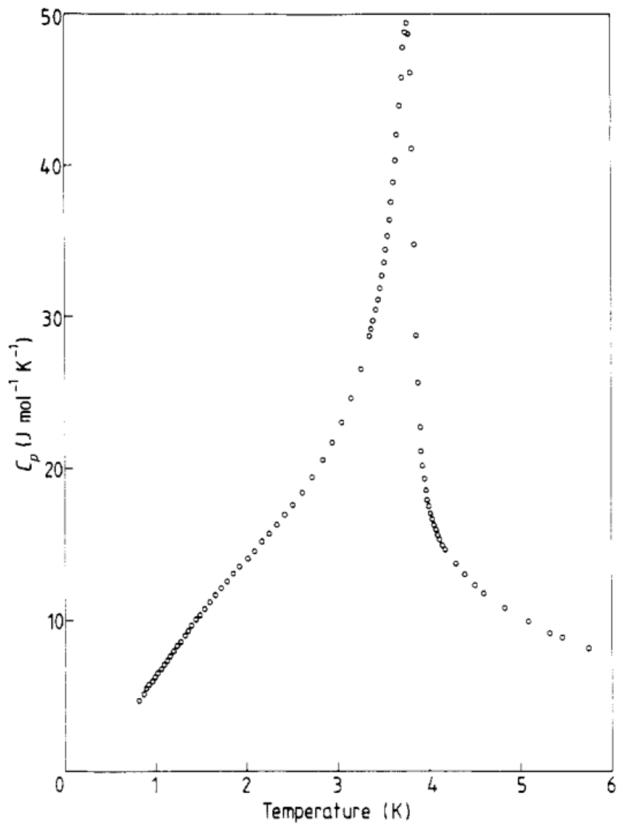
Part I (9 slides). Finite Element Modeling of Heat Diffusion in Standard and High-C_p wires, where some superconducting subelements are replaced with Cu/Gd_2O_3 powders in Cu tubes. Model validation with Minimum Quench Energy (*MQE*) data on standard and high-C_p Hypertech wires.

PUBLISHED AS INVITED PAPER ON INSTRUMENTS SPECIAL ISSUE "Applied Superconductivity for Particle Accelerators": Barzi, E.; Berritta, F.; Turrioni, D.; Zlobin, A.V. "Heat Diffusion in High-C_p Nb_3Sn Composite Superconducting Wires." Instruments 2020, 4, 28.

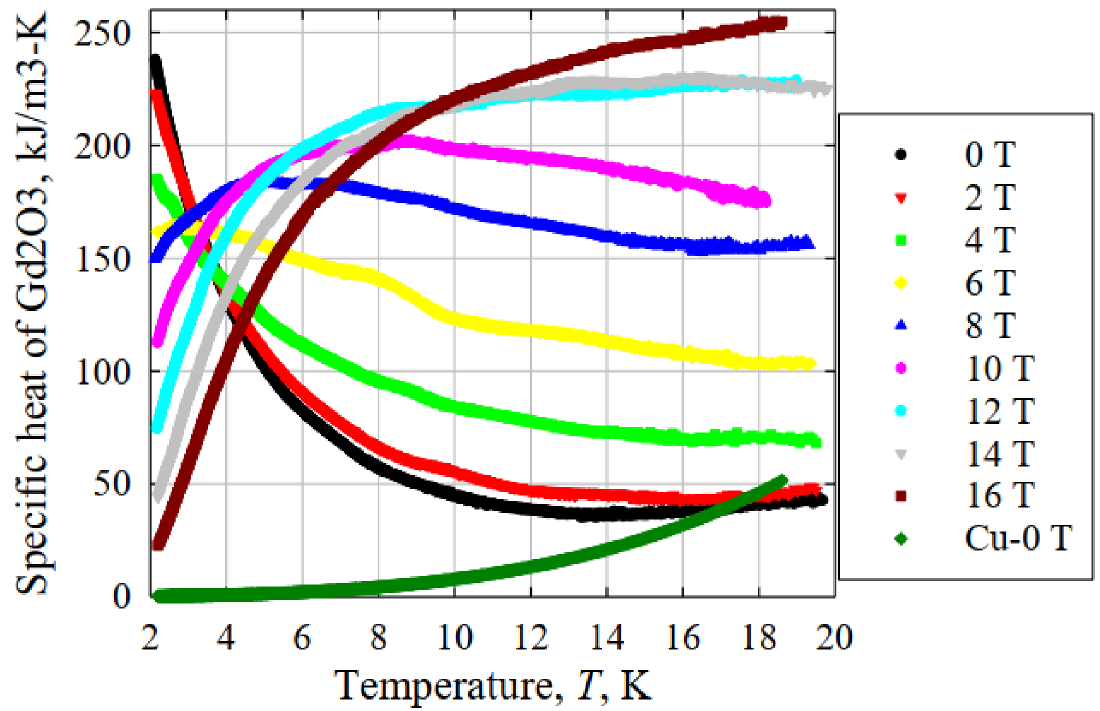
Part II (5 slides). An alternate approach is to introduce high-C_p materials in the Rutherford cable itself, i.e. Hypertech high-C_p ribbon or tape. Samples of this tape of 10 mm width and two different thicknesses 89 μm and 64 μm were used to measure and compare the *MQE* of Nb_3Sn wires, both bare and outfitted with high-C_p tape.

TO BE PUBLISHED: "Test of Superconducting Wires and Rutherford Cables with High Specific Heat," E. Barzi, I. Novitsky, A. Rusy, D. Turrioni, A. V. Zlobin, X. Peng, M. Tomsic.

Heat Capacity of Gd_2O_3



Specific heat of monoclinic Gd_2O_3 R. Hill et al 1983 J. Phys. C: Solid State Phys. 16 2871

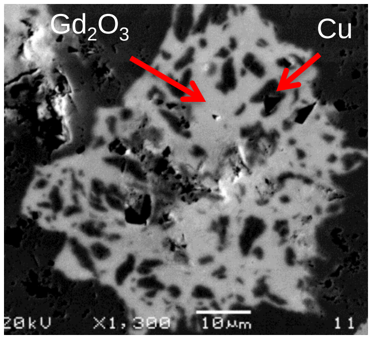


X. Xu, A. V. Zlobin, E. Barzi – Fermilab; C. Buehler, M. Field, B. Sailer, M. Wanior, H. Miao – Bruker EST; C. Tarantini – Florida State University.

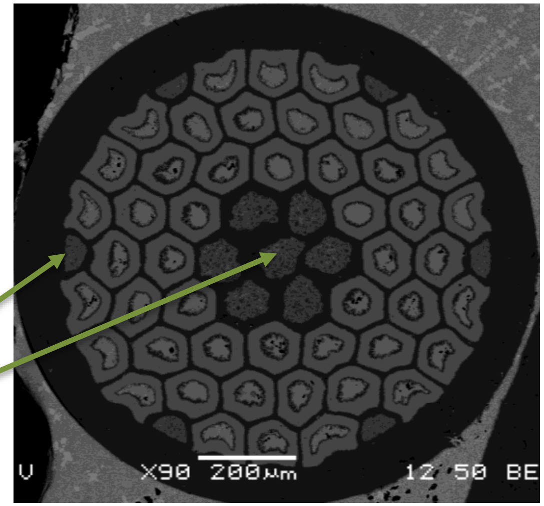
"Enhancing specific heat of Nb_3Sn conductors to improve stability and reduce training. "

Presented at CEC-ICMC 2019

Industry Produced High-C_p Nb_3Sn Wires



Tin in Tube wire

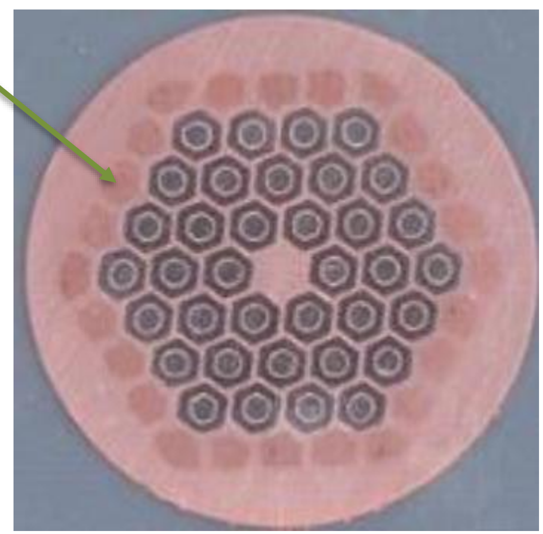


Internally and on Corners

Hypertech

X. Xu, P. Li, A. Zlobin and X. Peng, *IEEE Trans. Appl. Supercond.*, vol. 23, Art. no. 4001605, 2018.

Gd_2O_3/ Cu tubes

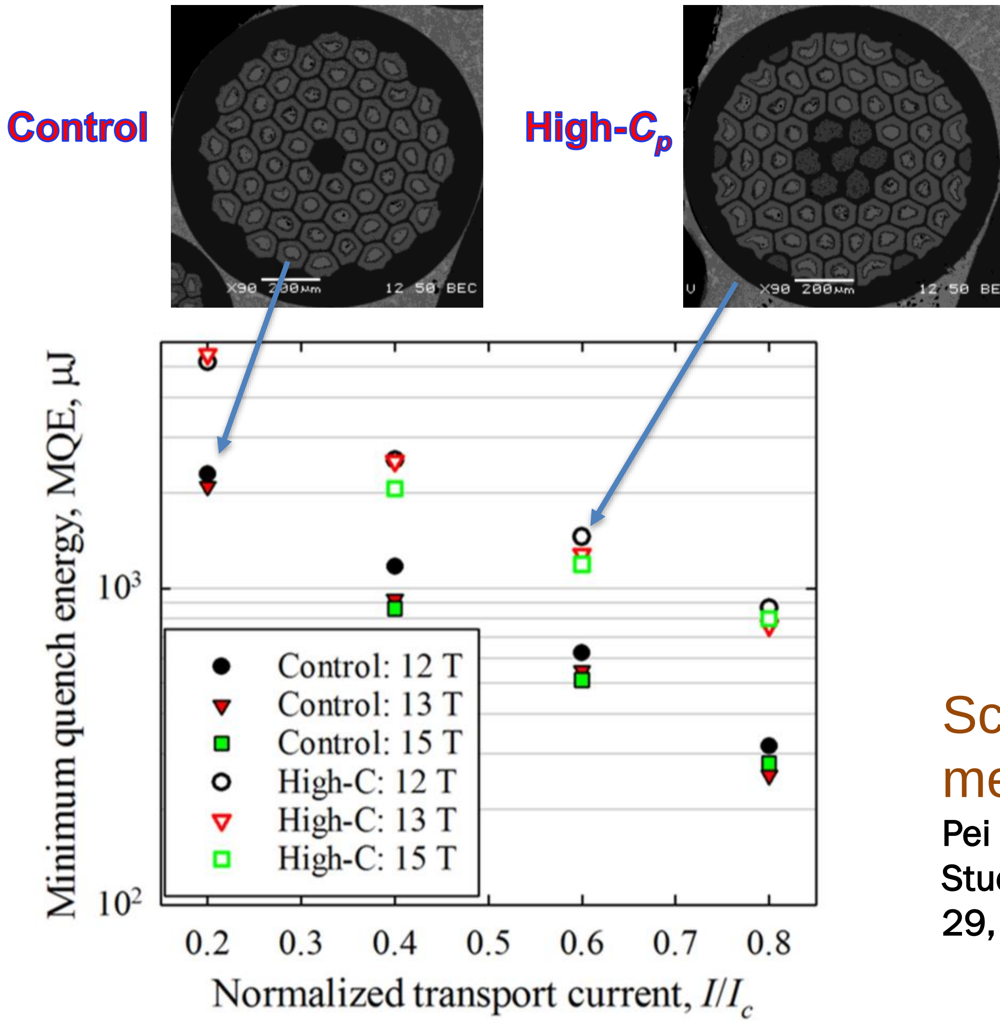


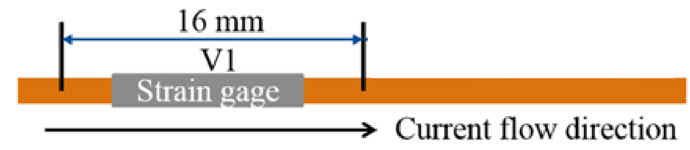
Restacked Rod Process wire

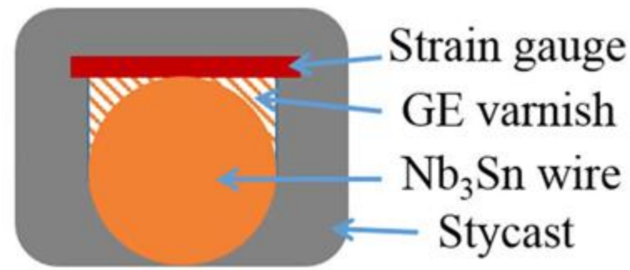
Externally

Bruker-OST, 2019

Minimum Quench Energy Measurements



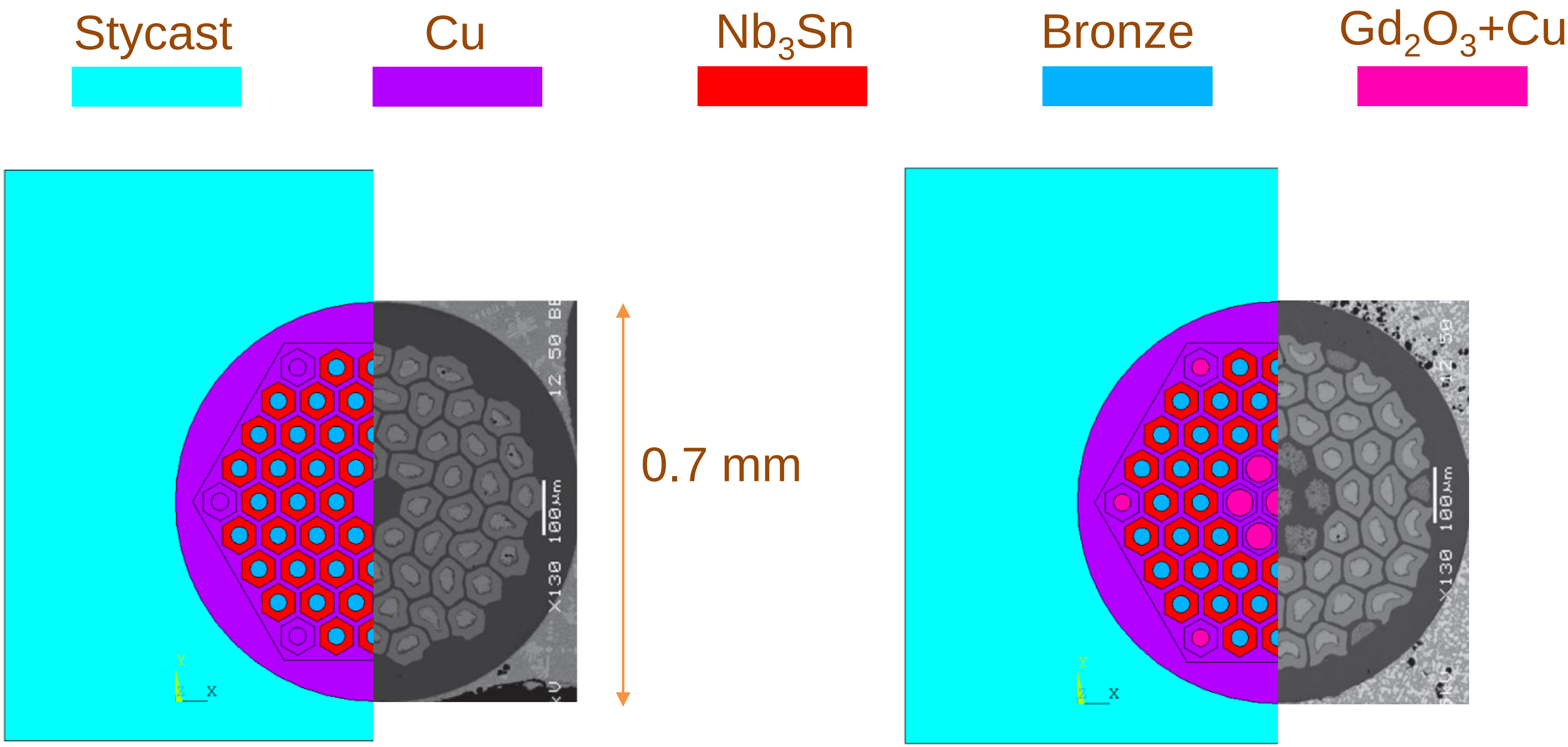




Schematics of the original setup to measure *MQE*.

Pei Li, Xinchen Xu, and A. V. Zlobin, “Development and Study of Nb_3Sn Wires With High Specific Heat.” IEEE, VOL. 29, NO. 5, 2019

ANSYS Thermal APDL Model



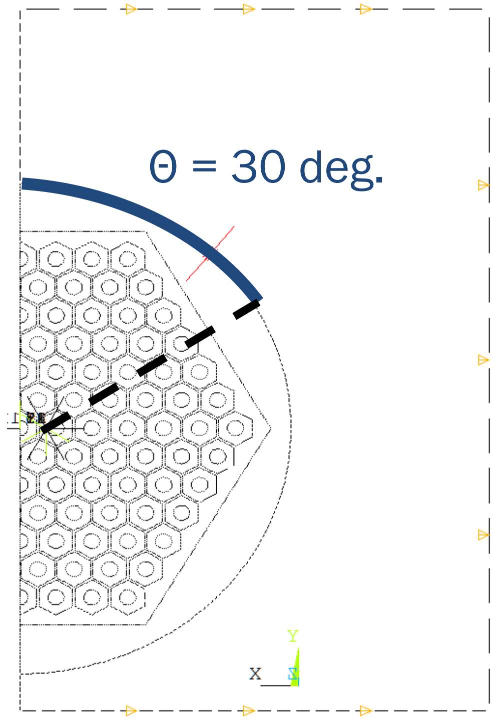
"Measurements and modelling of mechanical properties of Nb_3Sn strands, cables and coils", E. Barzi, et al., IEEE Trans. Appl. Supercond., vol. 29, no. 5, Art. no. 8401808, 2019.

Thermal Model Hypotheses

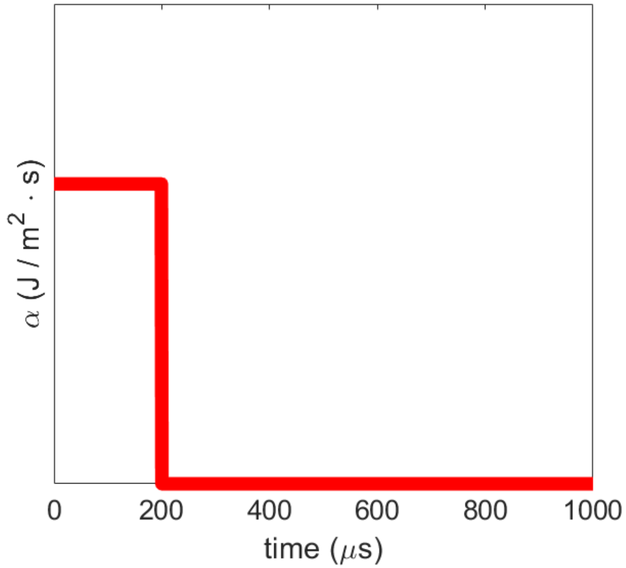
The initial temperature is 4.2 K and it is set as boundary temperature constraints:

- T(**r**,0) = 4.2 K
- T(**r**,t) = 4.2 K @boundary

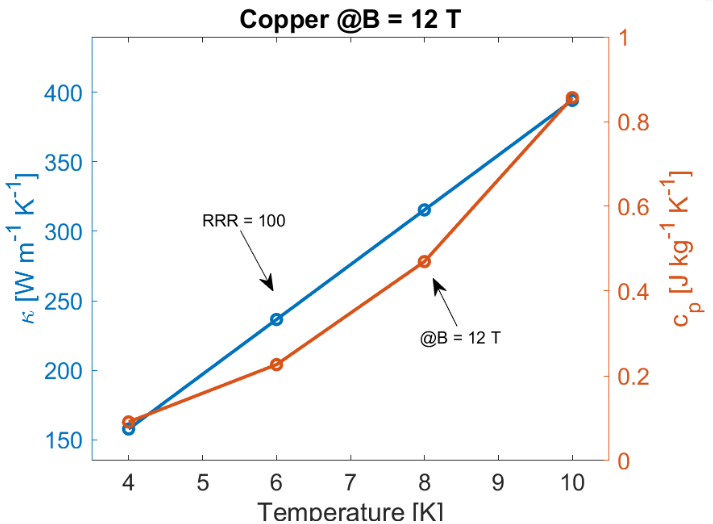
Magnetic Field B=12T

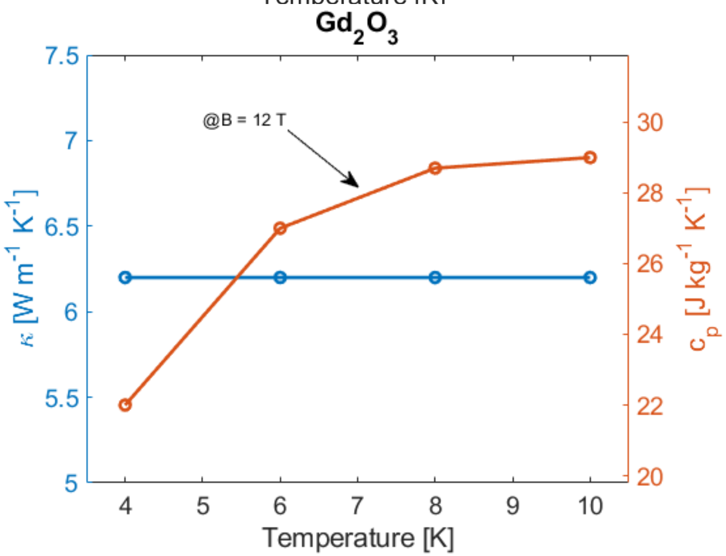


An heat flux pulse of 200 µs is applied on the upper half arc (2D model) with unitary thickness in *z*.



Temperature/Field Dependent Material Properties





By obtaining I_c(12 T, 4.2 K) using parameterization and solving for T_c in I_c(12 T, T_c) :

Current ratio I/I_c @B=12 T	T_c
0.2	6.3 K
0.4	5.3 K
0.6	4.8 K
0.8	4.4 K

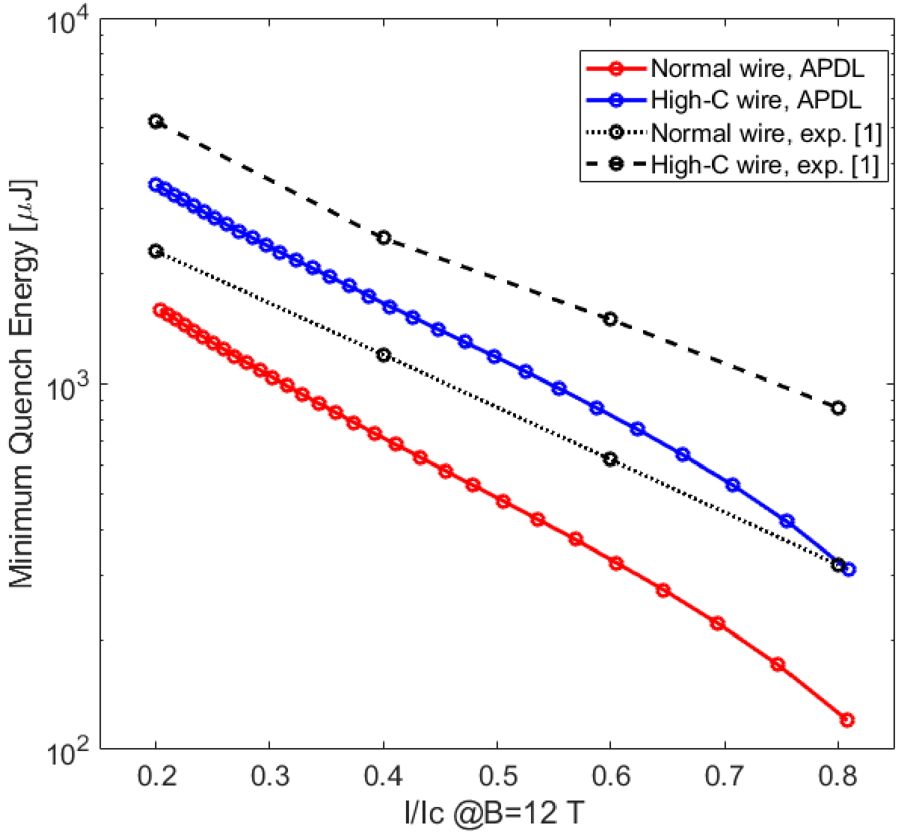
Sensitivity of modelled *MQE* was calculated for thermal conductivity and heat capacity variations of Nb_3Sn, Cu, Gd_2O_3, stycast and bronze, as well as for heater angle amplitude.

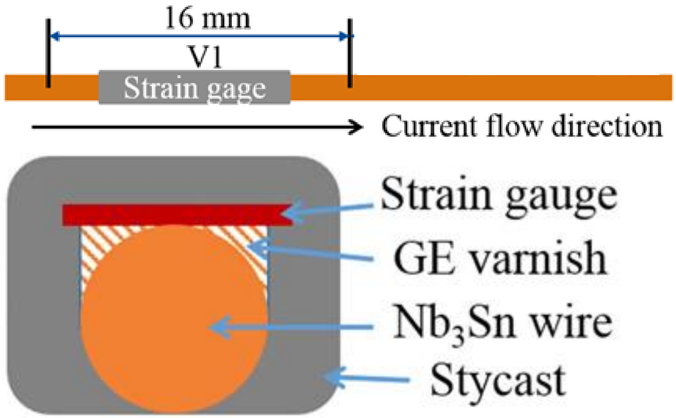
Materials Properties Table

	Nb_3Sn d = 8400 kg m^{-3}		Cu d = 8960 kg m^{-3}		Cu-Sn (Sn wt%=5.46) d = 8850 kg m^{-3}		Stycast d = 2400 kg m^{-3}		Gd_2O_3 d = 7410 kg m^{-3}	
T	κ	C_p	κ	C_p	κ	C_p	κ	C_p	κ	C_p
4 K	174	0.41	158	0.091	1.9	0.129	0.07	0.44	6.2	22
6 K	237	0.94	237	0.226	2.9	0.194	0.11	1.70	6.2	27
8 K	308	1.85	315	0.470	3.9	0.387	0.15	3.70	6.2	29
10K	320	3.27	394	0.856	4.9	0.968	0.19	6.20	6.2	29

T	Thermal Diffusivity a [cm²/s]				
4 K	$0.505\cdot10^{3}$	$1.940\cdot10^{3}$	16.6	0.663	0.380
6 K	$0.300\cdot10^{3}$	$1.170\cdot10^{3}$	16.9	0.270	0.310
8 K	$0.198\cdot10^{3}$	$0.748\cdot10^{3}$	11.4	0.169	0.289
10 K	$0.116\cdot10^{3}$	$0.513\cdot10^{3}$	5.7	0.128	0.289

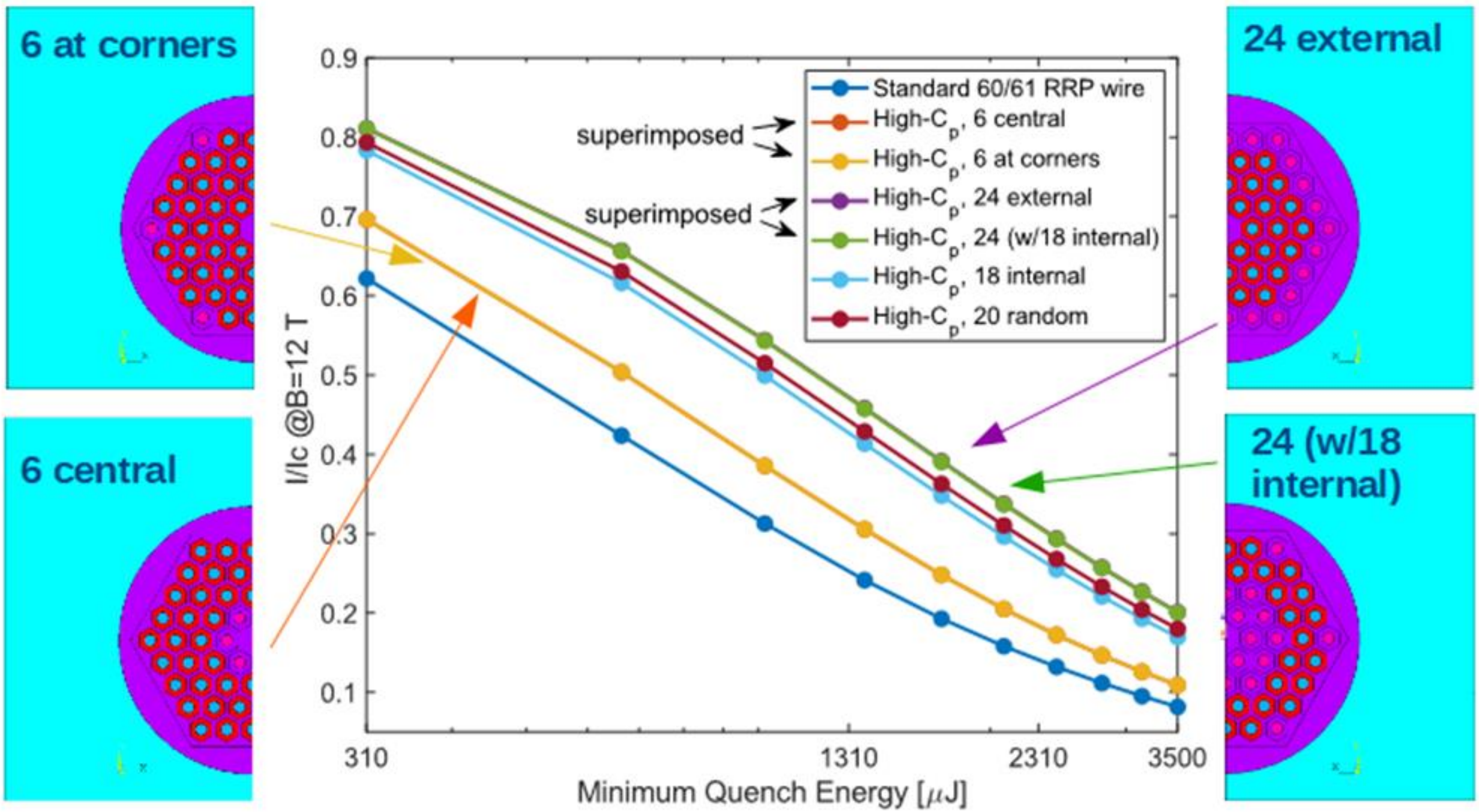
Model versus Experiment





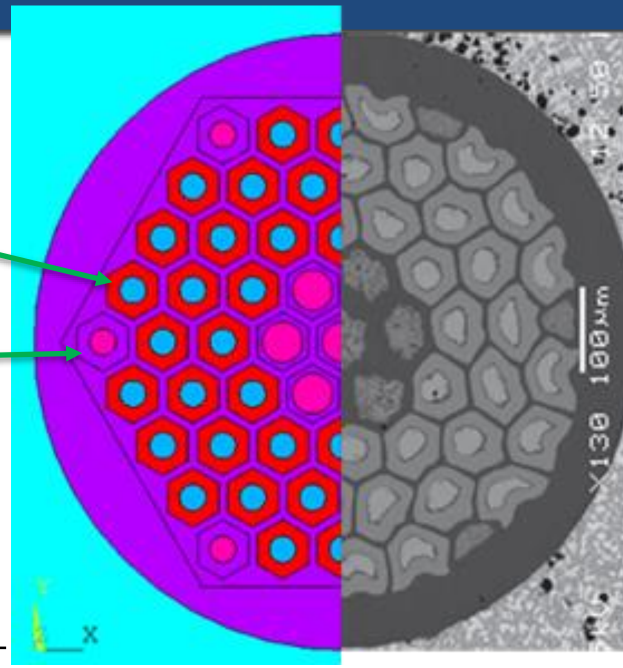
MQE from model is systematically lower than *MQE* from data since in the experiment 100% of the heat from the strain gauge used as heater is assumed to go into the sample.

Is there an optimal thermal location for high-C_p elements?

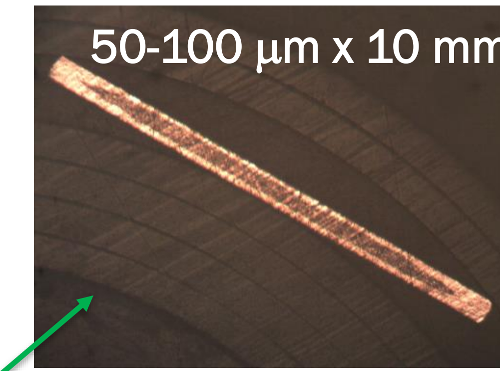


J_e Loss in High-C_p Wire vs. High-C_p Cable

Hypertech Sn-in-Tube Nb_3Sn wire with 48 regular Nb-Sn subelements and 13 high-C_p ones made of Cu/Gd_2O_3



-20% in J_e



Bare Cable C_p ~ 1.5 kJ/(m³K)

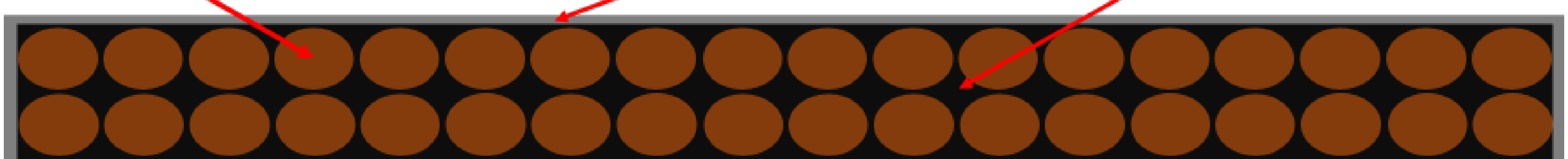
-10% in J_e

C_p of Cable wrapped with High-C_p tape ~ 10 -15 kJ/(m³K)

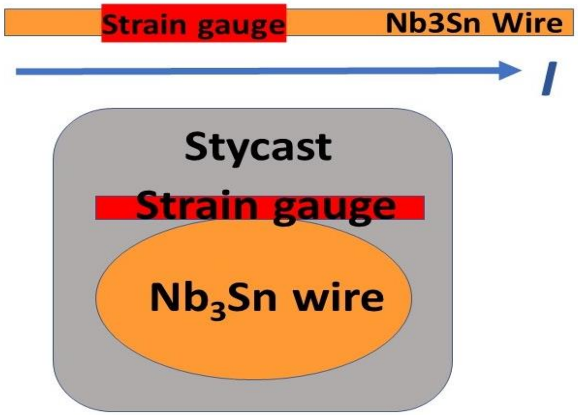
Strand

Cu/Gd_2O_3 tape

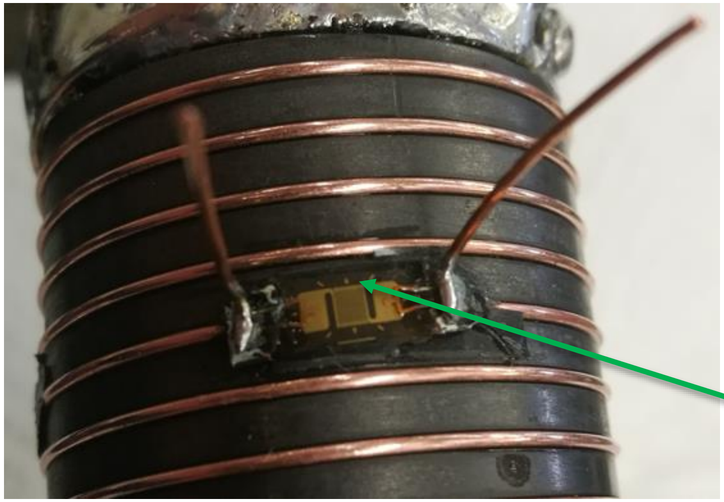
Epoxy



MQE Measurement Procedure for Wires

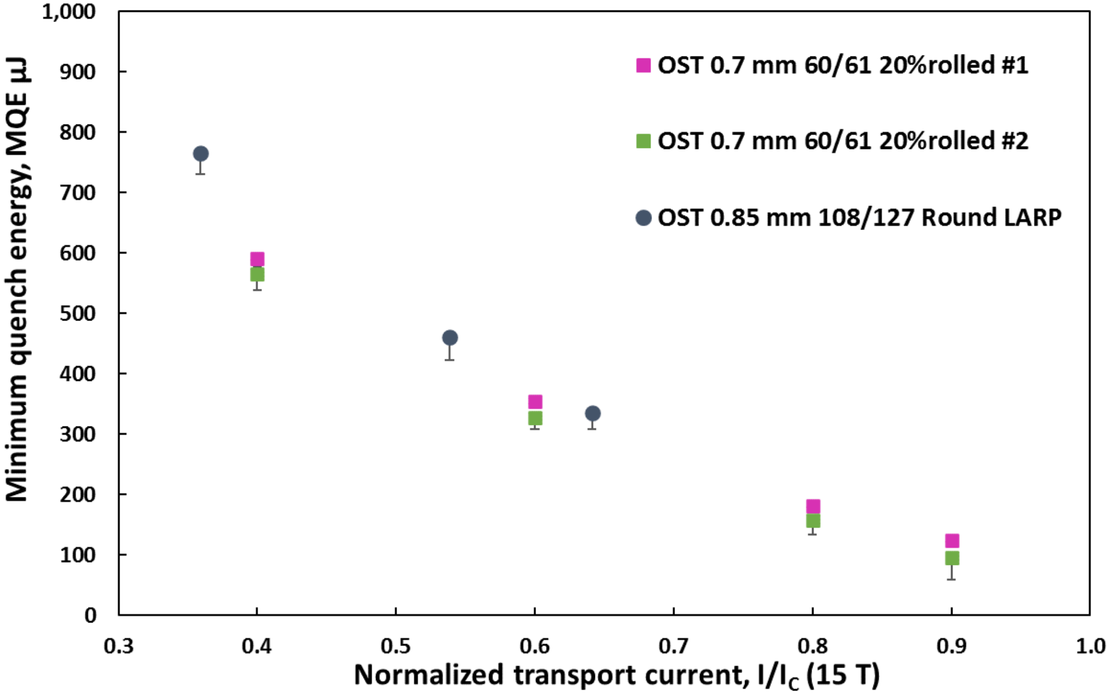


EXPERIMENTAL SETUP



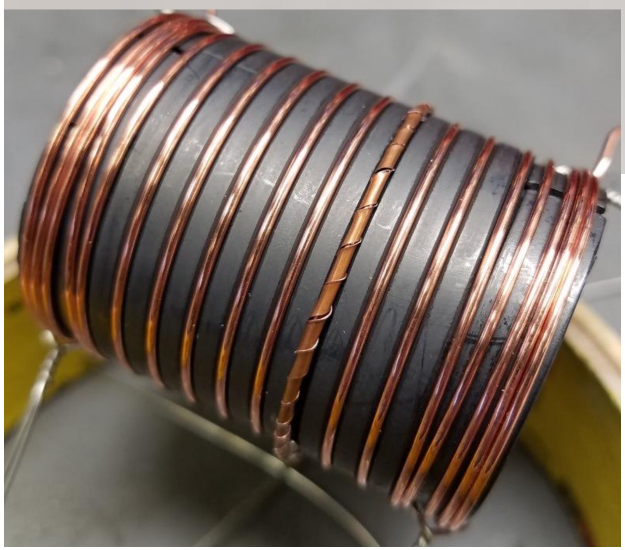
WK-09-125BT-350 Micro-Measurements strain gauge (4 mm x 1.5 m) as heater

REPRODUCIBILITY AND MEASUREMENT ERRORS

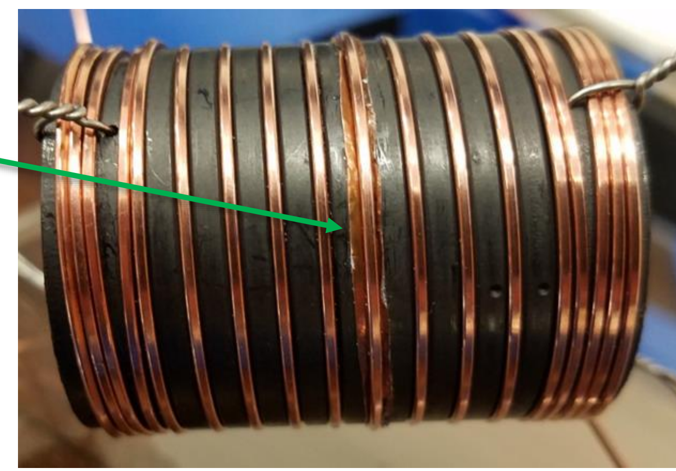


Geometrical Configurations of Nb_3Sn wire and High-C_p Tape

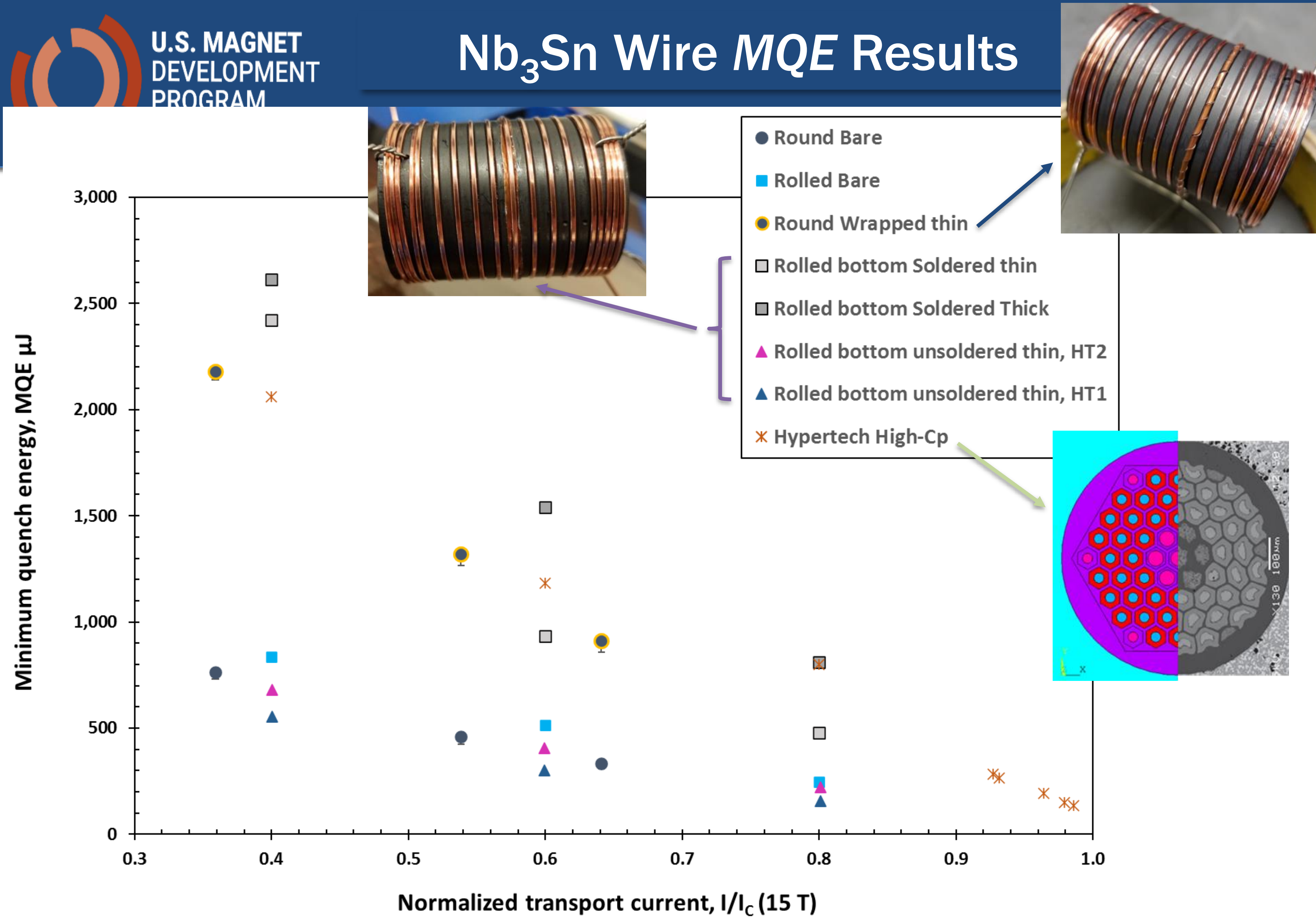
OPTION A – Tape wrapped around wire before heat treatment



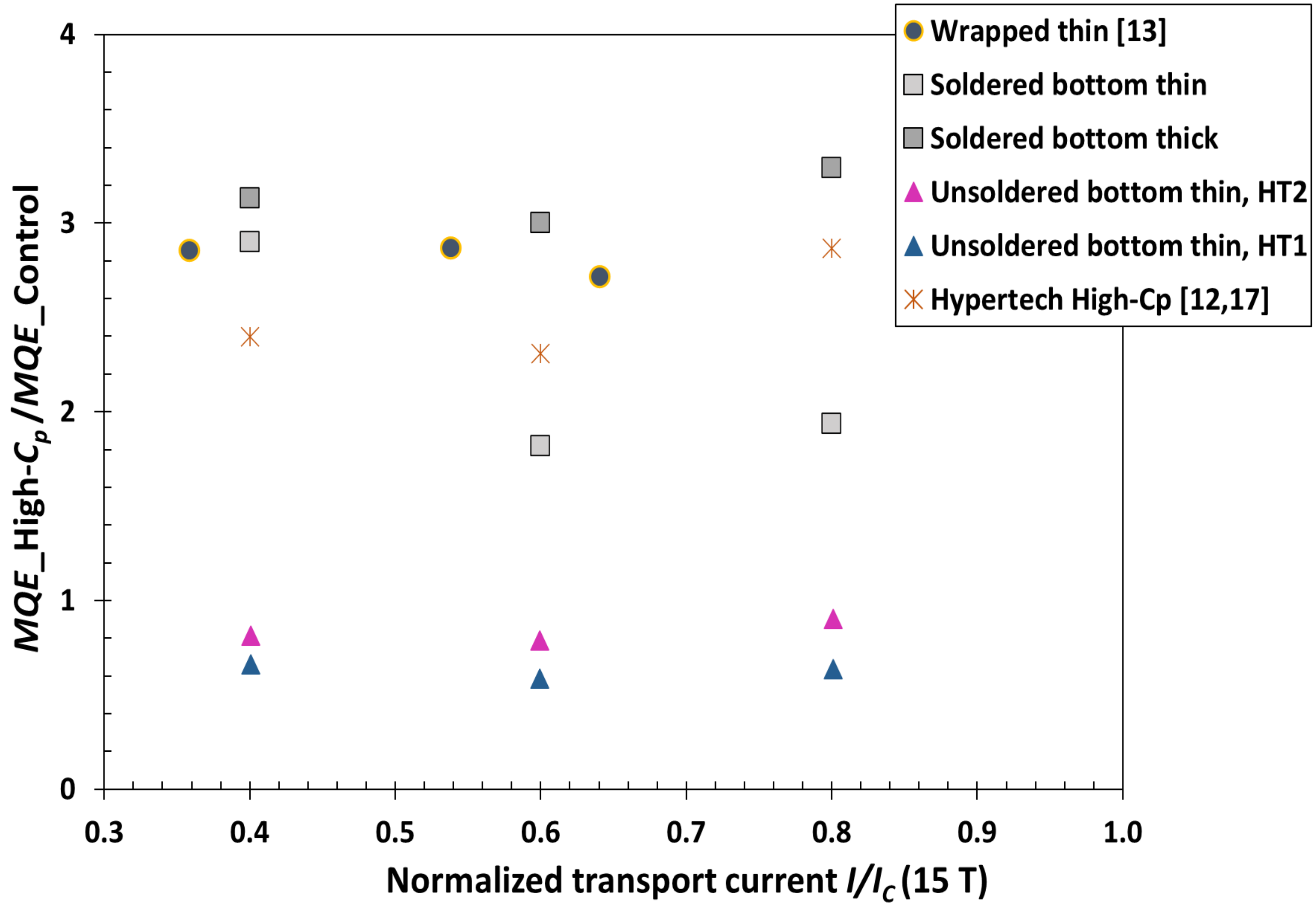
OPTION B – Tape placed **underneath** wire, and either soldered or not after heat treatment.



Nb_3Sn Wire *MQE* Results



Nb_3Sn Wire Normalized *MQE* Results



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Summary

A major focus of Nb_3Sn accelerator magnets is on significantly reducing or eliminating training. Increasing the conductor specific heat will lead to shorter training with substantial savings in machines commissioning costs.

PART I: **- The FEM thermal model accurately reproduces relative behavior in Minimum Quench Energy (*MQE*) between standard and high-C_p wires.**

- The model was also very useful in contrasting the intuitive thought that for maximum thermal efficiency the Gd_2O_3 tubes have to be external to the superconducting elements.

- This is good news since on the contrary there are indications that placing the Gd_2O_3 tubes externally is an obstacle to drawing.

PART II: **- Samples of an Hypertech high-C_p Cu/Gd_2O_3 tape 10 mm wide and two different thicknesses 89 μm and 64 μm were used to measure and compare the *MQE* of bare Nb_3Sn wires and wires outfitted with this tape.**

NEXT

Measure and compare at various magnetic fields the *MQE* of standard NbTi and Nb_3Sn Rutherford cables and cables outfitted with high-C_p tape, and look for relative correlations between wire and cable tests.

NEXT – NbTi and Nb_3Sn CABLE *MQE* TESTS