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Heat transfer in HTS transformer and current limiter windings

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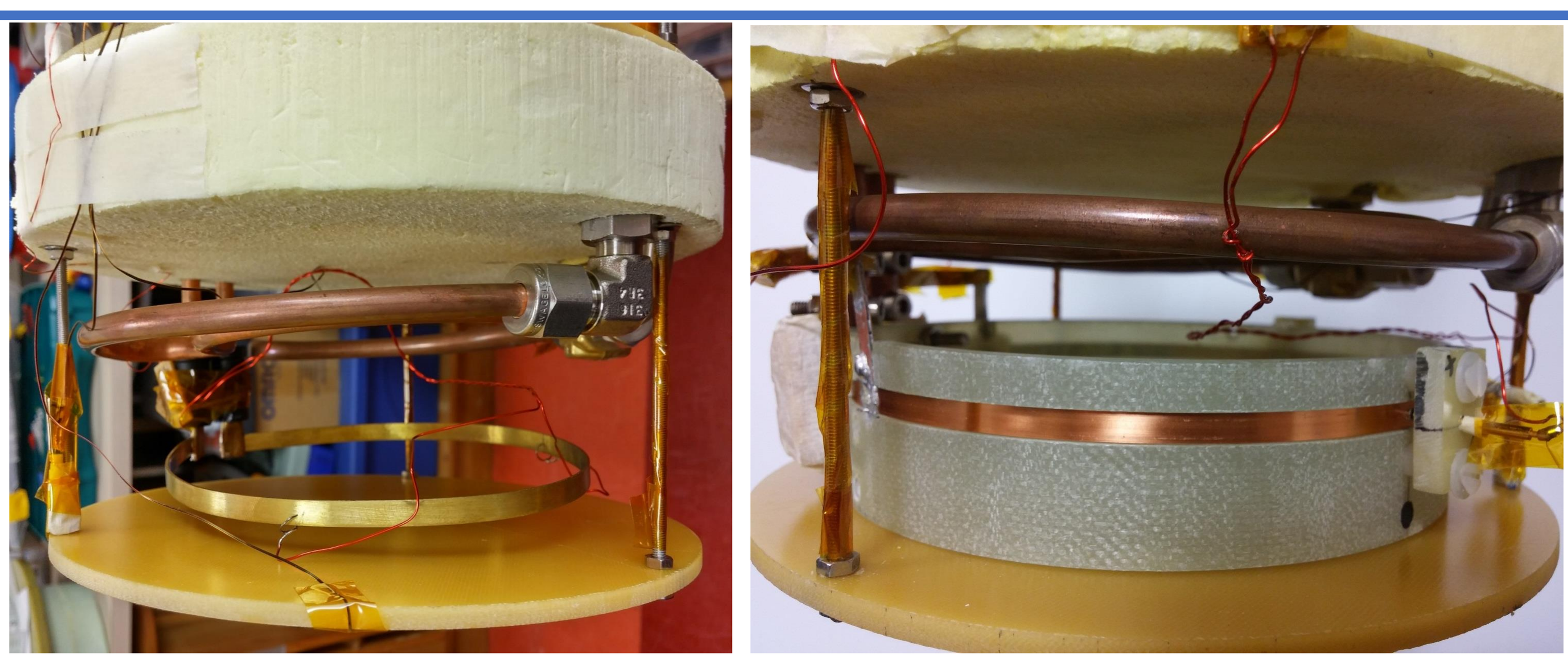
Measurement of heat transfer in metallic and superconducting short samples: Effect of subcooling, surface coatings, mounting on former

***Aim:** to measure heat transfer in conditions relevant for HTS transformer windings cooling down after a fault:*

- *Immersed in sub-cooled LN2, 65 – 67 K at ambient pressure*
- *Wire insulation maximising heat transfer during recovery following a fault: wrapped paper or solid coating*
- *Vertically oriented winding mounted on composite former*

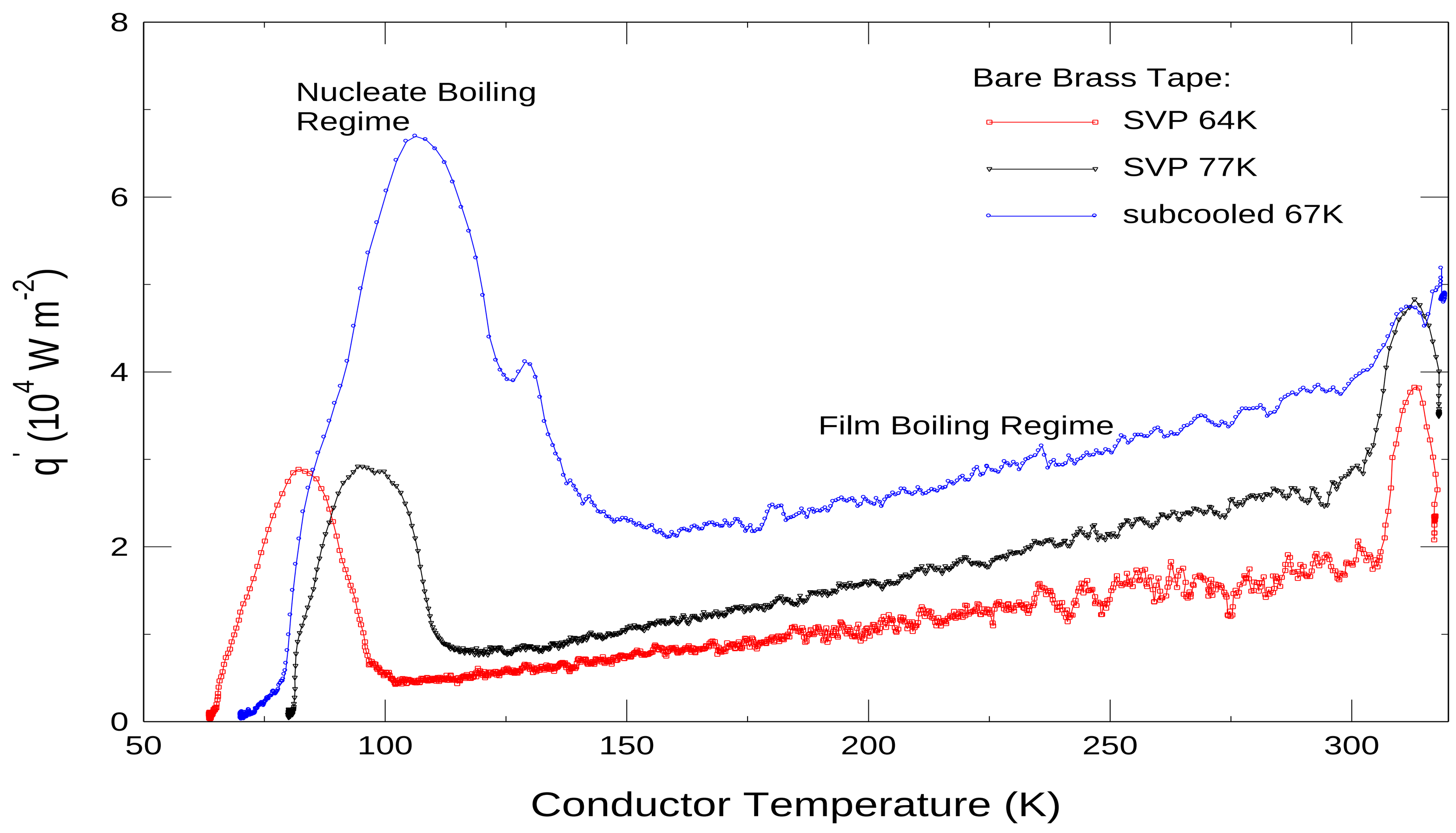


Sample in the experimental system. The sample volume is sub-cooled by pumping on liquid nitrogen fed into the copper tube heat exchanger. On left: free-standing sample; right: mounted in slot on former.

Experimental

Samples are metal or superconductor tapes 4 to 5 mm wide and 400 mm long, heated with DC currents to reproduce the power dissipation in HTS transformer windings during a fault and subsequent recovery under load. We measure current and voltage over a 120 mm length at the centre and determine the average conductor temperature T_w from the resistance. Heat transfer $\dot{Q}$ is calculated from the input electrical power P_{el} and rate of temperature change: $\dot{Q} = P_{el} - mC_p \frac{dT_w}{dt}$

Effect of subcooled operation on heat transfer during cooling



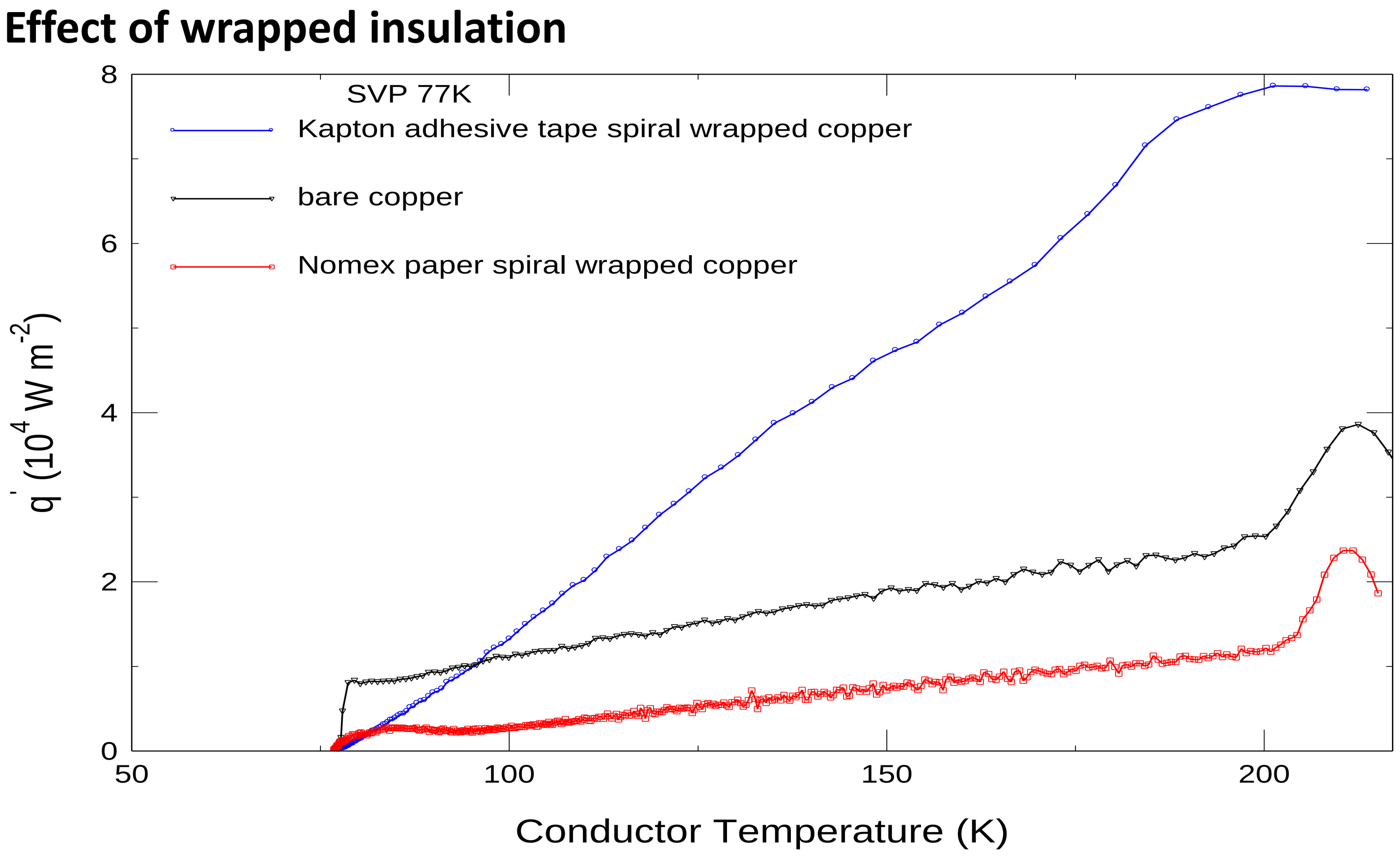
Two regimes of boiling heat transfer:

- Nucleate Boiling - reaches a maximum, the Critical Heat Flux, beyond which liquid access to the surface is blocked by streams of escaping vapour leading to dry-out and transition to film boiling.
- Film Boiling - heat transfer is reduced because a layer of vapour insulates the hot surface from the liquid coolant.

The effect of subcooling: Vapour condenses in the surrounding subcooled liquid, and so reduces the effectiveness of the insulating vapour film in Film Boiling, and also reduces the volume of the vapour plumes in Nucleate Boiling - and so delays dry-out and increases the Critical Heating Flux.

Result: Heat transfer is enhanced in subcooled liquid nitrogen compared to cooling at Saturated Vapour Pressure (SVP) at 77 K

Effect of wrapped insulation



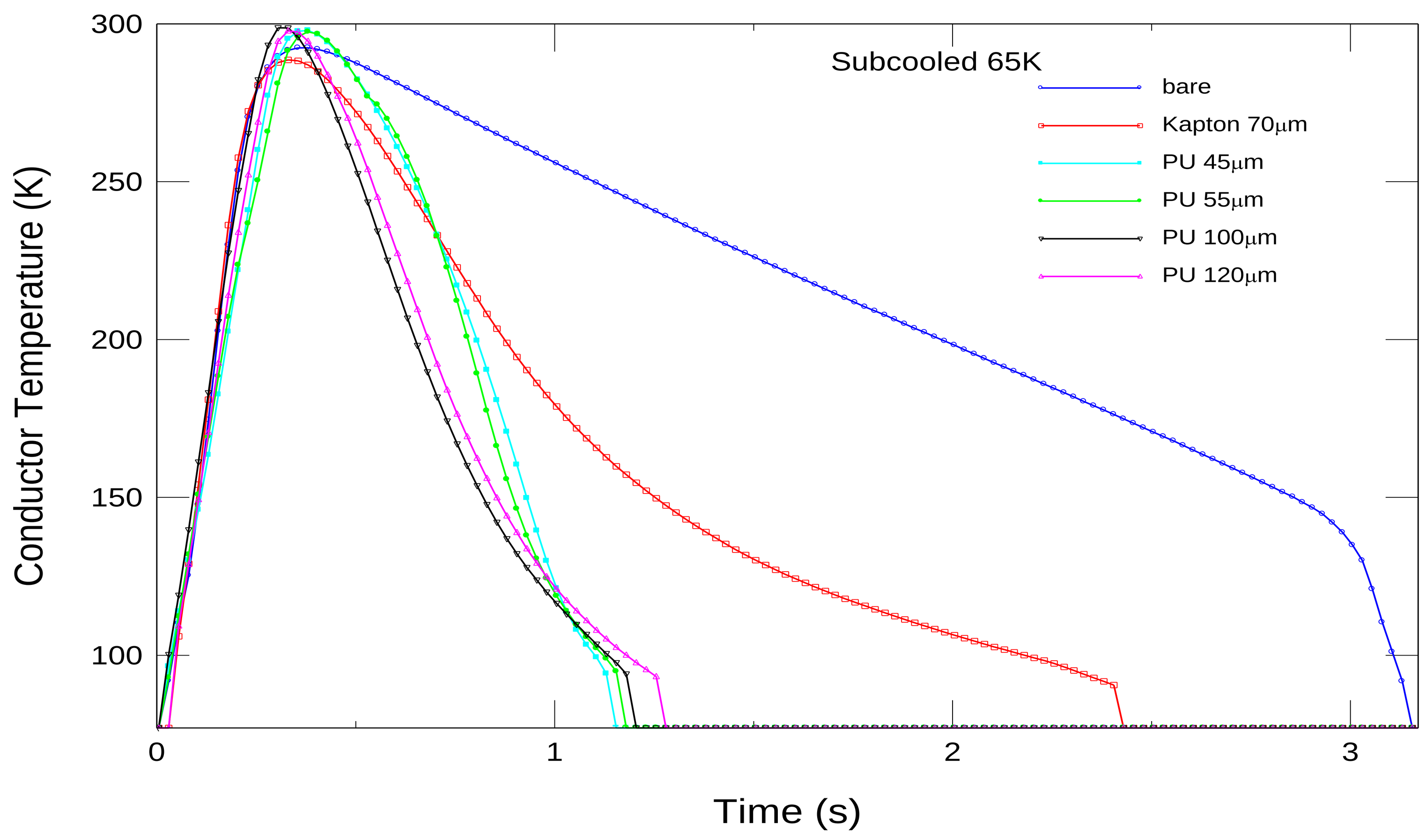
Wrapping with adhesive kapton tape (spiral wound, 50% lap) increases boiling heat transfer compared to a bare surface. Non-adhesive Nomex paper reduces heat transfer.

Enhancement of boiling heat transfer by insulating coatings was reported long ago [1, 2]. A layer of appropriate thermal resistance keeps the surface cold enough to avoid film boiling and stay in the nucleate boiling regime.

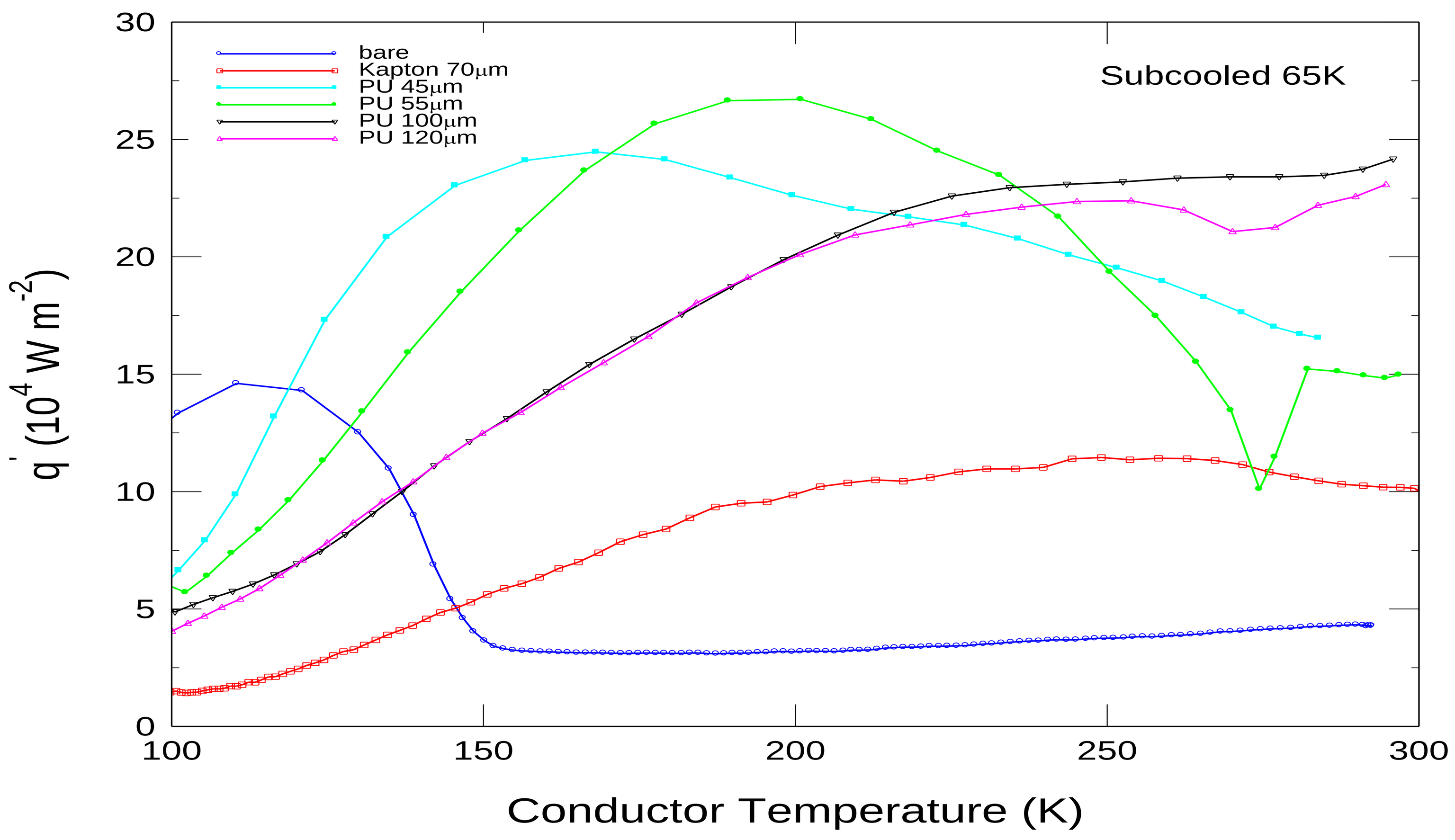
Wrapped Nomex paper, on the other hand, allows liquid to contact the conductor and appears to trap a vapour film under the paper so the boiling heat transfer is less than for a bare surface.

Optimizing heat transfer by varying the coating thickness

We measured samples of AMSC type 8700 brass laminated ReBCO wire with various surface coatings: Kapton adhesive film, UV-cured polyurethane (PU) of varying thickness, and bare wire.



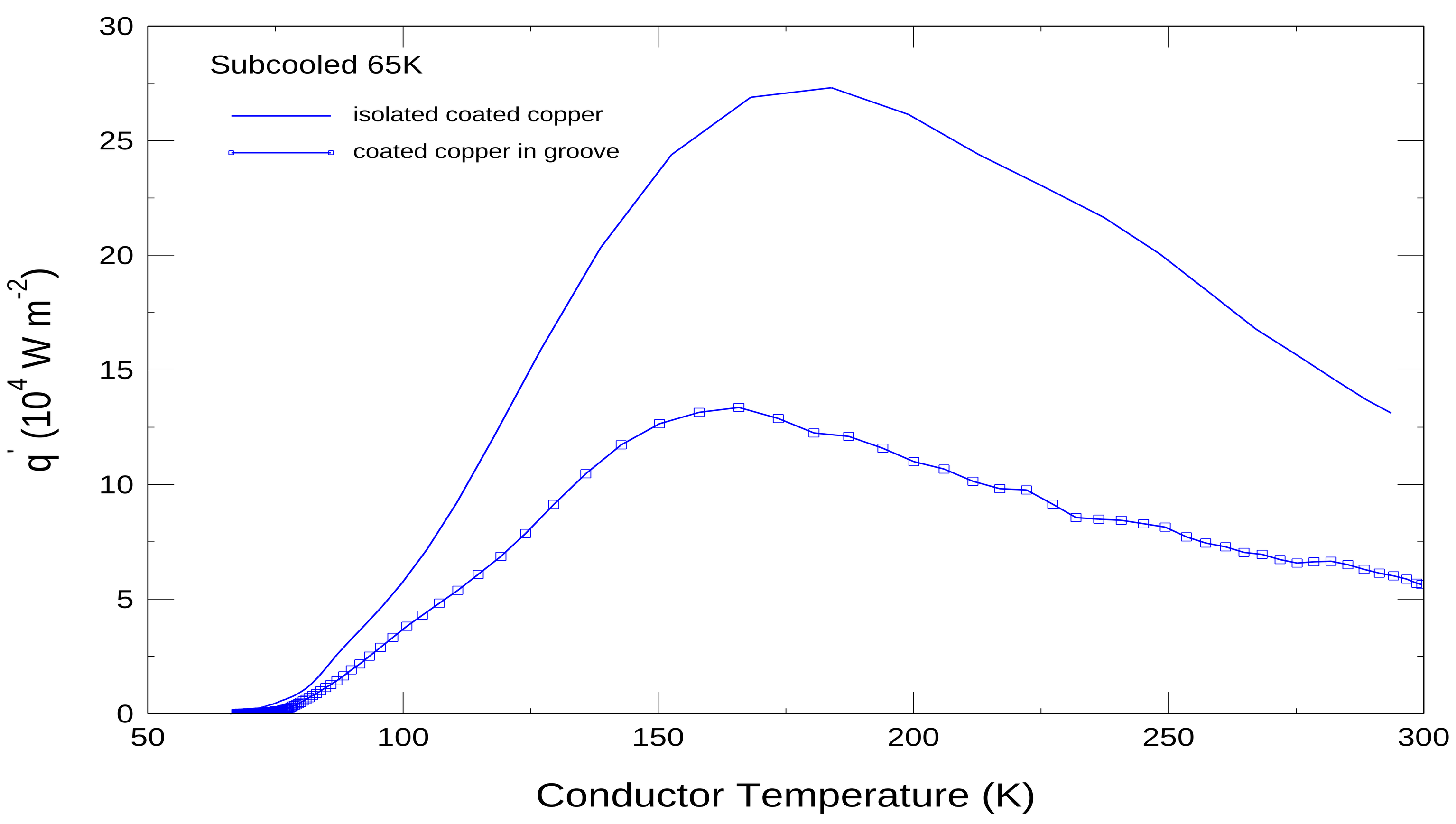
The recovery time (carrying a current of just 10 A) is reduced from 2.8 s for the bare wire to 0.7 s for polyurethane-coated wire



The 55 μm polyurethane coating produced peak heat transfer of $27{\cdot}10^4$ Wm^{-2} at wire temperature ~200 K, around 9x the cooling power of liquid nitrogen in contact with the bare wire.

Mounting wire in a groove on a composite former

In an actual transformer winding, heat transfer will be affected by proximity to formers and spacers. We tested the effect of mounting a 0.3 mm copper sample with 55 μm PU coating in a 1.5 mm deep slot machined in a glass-epoxy former.



Boiling heat transfer in subcooled liquid nitrogen is approximately halved by mounting the wire in the groove.

SUMMARY

- Heat transfer in subcooled liquid nitrogen at 67 K is around 45% more than at SVP at 77K
- Compared to bare wire:
  - Wrapped Nomex paper insulation significantly reduces boiling heat transfer
  - Solid insulation coating with optimized thermal resistance increases boiling heat transfer as much as 9x
- Heat transfer in subcooled liquid nitrogen roughly halved by mounting on a former

References

[1] Cowley, C. W., Timson, W. J., and Sawdye, J. A., 1962. A method for improving heat transfer to a cryogenic fluid., Advances in Cryogenic Engineering, vol. 7, pp. 385–390.
[2] Barron R. F., Nellis G. F., 2016, Cryogenic Heat Transfer 2nd Ed, Ch. 3.5, CRC Press, ISBN-13: 978-1-4822-2745-1