Stability, quench, and current sharing in Roebel and CORC cables for HEP magnets

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Motivation

- Investigate stability in Roebel and CORC cables at 77 K and 4 K
- YBCO cables are more stable than LTSC – but what are the limits?
- How similar to LTSC are HTSC?
- No insulation is promising – but how will cables respond?

Outline

1. Samples and Experiments
2. Quench character at 77 K – ohmic vs fault
3. Development of stability diagram -- static normal zones
4. Modelling and comparison of 77 K experiment
5. 4 K measurements and modelling

Samples and Instrumentation I: Roebel Cable

Parameter	Specification
Roebel cable manufacturer	Karlsruhe Institute of Technology
ReBCO tape manufacturer	SuperPower Inc.
Type of Roebel cable	9/5.6
Cable Width, W_{Cable} (mm)	11.8
T_{tape} (mm)	0.1
$L_{Transposition}$ (mm)	126
Cross-over angle, ϕ (degrees)	40
$L_{Inter\text{-}strand\ gap}$ (mm)	0.4
$W_{Cross\text{-}over}$ (mm)	5.6

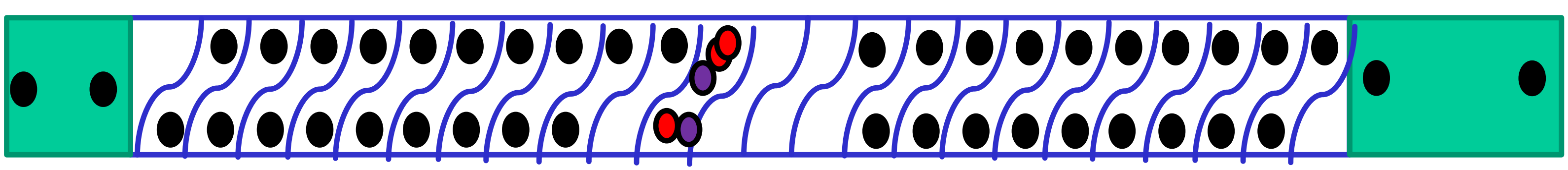
- Length of cable between solder regions: 355 mm
- Individual soldered tapes onto current tap region: 150 mm
- Wood's Metal Solder

● = Voltage Tap

● = Type-E Thermocouple

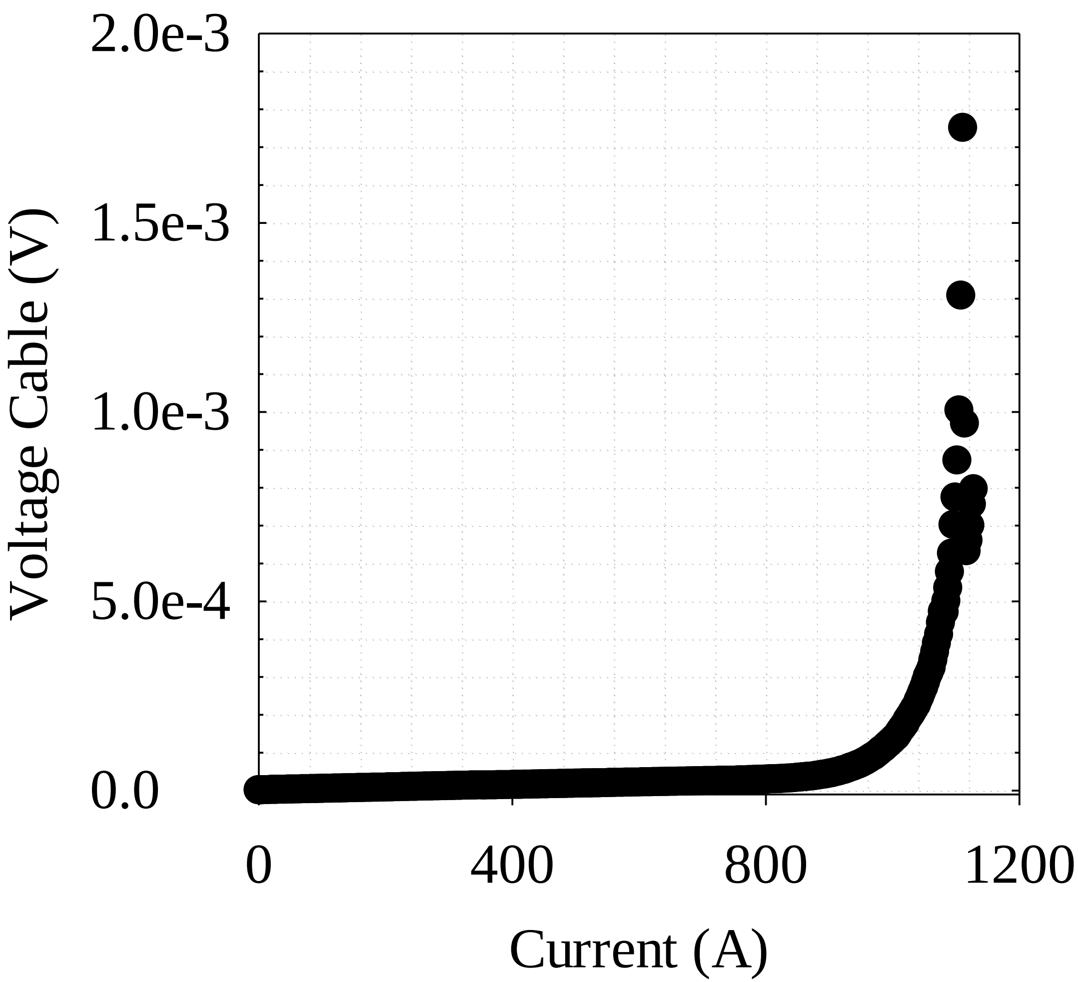
● = 40-Ohm Kapton Heater

▬ = Soldered Current Tap



77 K self field I_c non-epoxy impregnated cable

- No-insulation coils are very promising -But cables are often needed for large magnets
- If cables are used, how will they respond?
- Here Un-impregnated cable with LN_2
- I_c = 1068 A (10 uV/cm), I_q = 1130
- Standing normal-zones created **<u>even at I/I_c very close to 1</u>**
- **<u>Even at I/I_c = 0.98, 8 W was required to slowly quench the cable</u>**

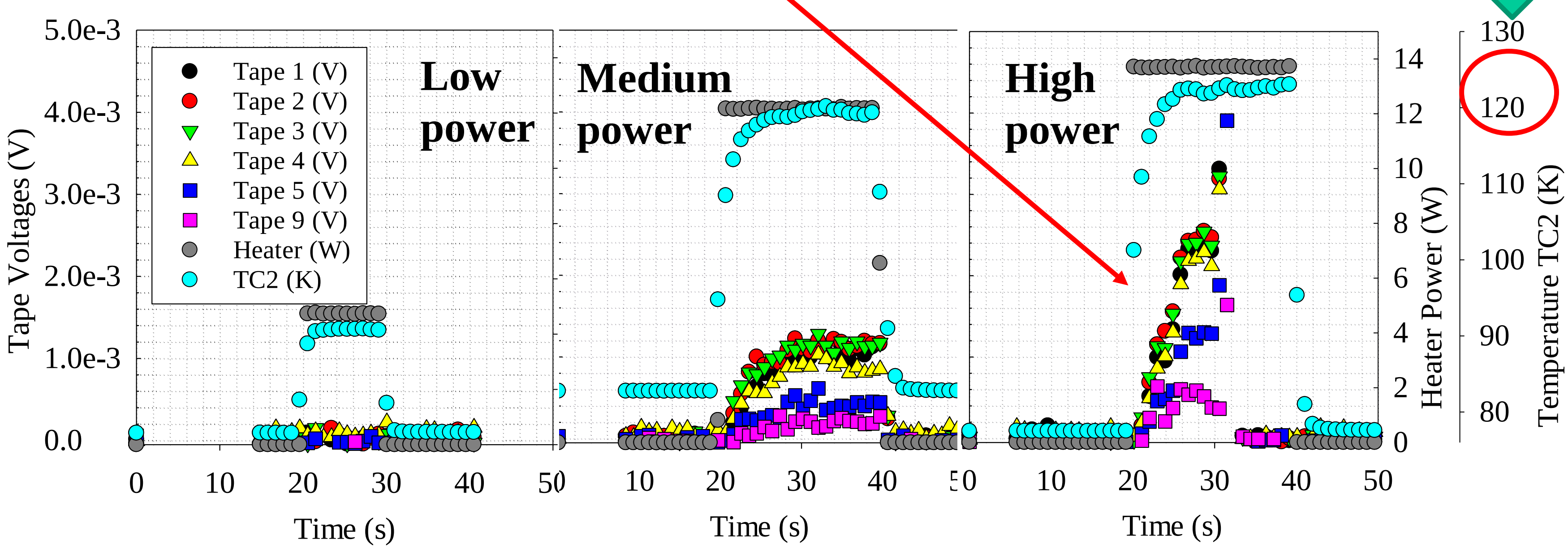


Self-field 77 K Stability

The formation of temperature Plateaus

Larger voltages generated in some, but not all, tapes signifies poor current sharing.

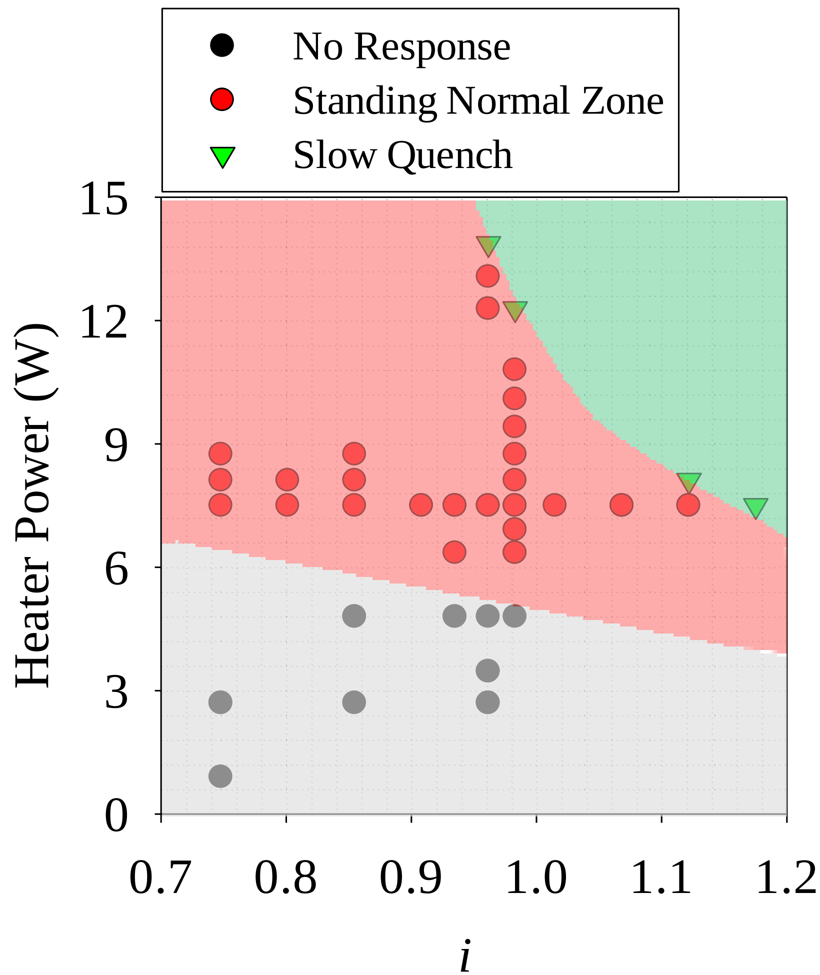
Note T plateaus – we reach ***stable temperatures above Tc***



Current switched off

77 K Stability Map

- For most of our measurements standing normal zones were generated instead of propagating ones.
- At low excitation, no normal zone was seen
- At very high excitation, quench was seen
- But, standing normal zones were seen for a wide range of excitation
- **Notably – the standing normal zones could be both above or below Tc**
- The reason for this is the thermal balance between heat generated from the normal zone and cooling of the sample with the LN_2 – the basic principle of cryostability



Varieties of Excitation

Excitations which:

(1) Increase T slightly, but do not generate a cable voltage (T' is below Tc, below current sharing T)

(2) Increase T enough to cause a voltage (above current sharing T), may be either below or above Tc, but lead to a stable T

For the first two we assume that the current is left on, for the next two, that it is shut off early during quench event

(3) Increase T, but if current is shut off, cable will recover

(4) Increase T, and even if current is shut off, cable will not recover

Modelling quench for HTS – lessons from LTS

- During the 1960s, 1970s, and early 1980s a great deal of attention was given to the cryostability of LTS conductors immersed in pool boiling LHe.
- A starting point was the theory of Stekly, who's $a = G/Q$ described a balance between the ohmic "heat generated", G, by current transferred into the matrix and "cooling", Q, by the boiling cryogen.
- Under the a = l, the system is stable and above a = l the system is unstable and will heat up.
- Cold end cooling (Gauster, Maddok, James) included the effect of axial heat conduction to the part that is still at bath temperature
- Meuris and separately Dresner considered the conditions under which a conductor can remain in stable thermal equilibrium in the presence of a permanent source of extra localized heat generation or disturbance, G_d.
- Transferring the above principals of cryostability from LTS to HTS lead to some surprising results that stem principally from: (i), ***the differences in Cu/SC ratio which in REBCO is typically 40:1 or 60:1, (ii) the higher Tc and Cp***

Nucleate and Film Boiling LN_2

Note: Q_{max} for shifting to film boiling about 200 kW/m^2K

$h = 0.6953 + 0.001079\Delta T^4$

(ΔT = 2-11 K) kW/m^2K (nucleate)

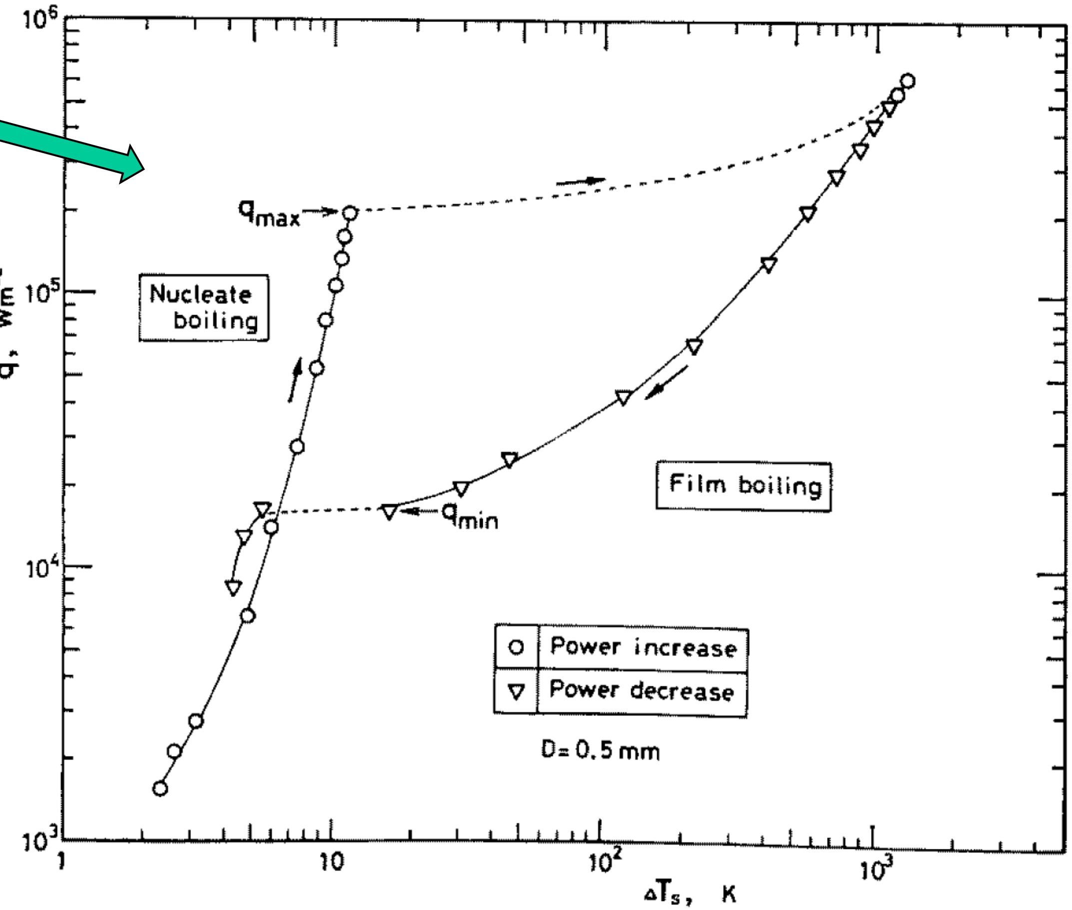
$h = (a+b\Delta T)/(1+c\Delta T)$

(ΔT = 8-300 K) kW/m^2K (film)

with $a = -5.787$

$b = -0.155$

$c = -0.546$



Kida M, Kikuchi Y, Takahashi O, and Michiyoshi I 1981 'Pool-Boiling Heat Transfer in Liquid Nitrogen', *J. Nucl. Sci. Technology*, vol. 18, no. 7, pp. 501-503 (1981)

Simple Stekly Stability Analysis

Modeled non-epoxy impregnated cable as a stack of RECBCO tapes

Thus allow for heat removal from the total tape surface - total tape perimeter in a cross section, *P* = 9 x the tape perimeter (is this correct, or should we use cable? – see below)

Following Stekly's approach we assumed complete current Xfer giving $G = I_c^2R = I_c^2\rho L/A_{Cu}$,

Normalized to unit length and unit total strand-surface area (*PL*) is

$$G = \frac{\rho I_c^2}{PA_{Cu}} = 5.49\ kW/m^2$$

$$Using\ Q_{max} = 200\ \mathrm{kW/m^2} \quad \alpha = G/Q_{max} = 0.027$$

The cable far exceeds the Stekly limit for cryostability.

In equilibrium ($G = Q = h\Delta T$), a complete Xfer of current to the stabilizer would generate 5.49 $\mathrm{kW/m^2}$

ΔT = 4.5 K (T_{stack} = 81.5 K) – the system would recover

From Stekly, the cable would be stable to much higher currents than I_c – and to power densities as high as 194 $\mathrm{kW/m^2}$.

But what about an external heat perturbation, one that might originate from a localized fault?

Adding Heat Generation from a Fault

Adding a fault (per unit length and total tape surface area A_s), the total heat generated per unit length is now

$$G' = \frac{\rho I_c^2}{P A_{Cu}} + G_d$$

Using a more general $Q = h(T-T_b)$, where T_b is the bath temperature and h is the coefficient of surface cooling

$$\alpha' = \frac{\frac{\rho I_c^2}{P A_{Cu}} + G_d}{h(T-T_b)}$$

If $\alpha' < 1$, the sample is always cooling towards the bath temperature. If $\alpha' > 1$, the sample temperature will rise, and if $\alpha'=1$, an equilibrium is established at some $T > T_b$, given by $\Delta T = T - T_b = \frac{\frac{\rho I_c^2}{P A_{Cu}} + G_d}{h}$

A cable with a certain current applied and a certain heat perturbation will increase in temperature until a stable point is reached.

Comments

- Taking a 10 W perturbation, if the power was uniformly applied to all strands the cable stack's local G_d would be $10/A_s$ = 35.27 kW/m^2 (with $G + G_d$ = 40.76 kW/m^2)
- Looking to the cooling curve, we would seem to still be in the nucleate boiling regime, with a ΔT = 8 K
- However, this is not in fact what we see experimentally – we see ΔT = 30 K -- film boiling.
- In order to get to film boiling, we should need about 200 W/cm2. How can it be?
- The reason is a thermal diffusivity limitation. In our case the heater was applied to the top surface of the cable. This mimics a surface fault (different faults might be applied differently)
- Initially only the surface of the top tape under the heater would be active such that $G_d = 10/A_Z$ = 634.9 kW/m^2 and $G + G_d$ = 640.4 kW/m^2. This would put the tape into the film boiling regime where it would remain as the heat fully permeates the whole stack. As heat diffuses the local G_d drops to $10/A_s$ = 35.27 kW/m^2 (with $G + G_d$ = 40.76 kW/m^2)
- Thus, the cable is much less stable to external perturbation than to internal heating, because of the heat distribution – and this kicks the system into film boiling

Comments II

- The previous scenario leads to a developing a ΔT_{film} of 104 K, and a theoretical 181 K normal zone
- This zone would recover to the superconducting state when the heater is switched off
- However, this is now much higher than we measure experimentally.
- There must be an additional cooling
- This cooling is end cooling

Adding Cold End Cooling

Besides direct cooling, heat is also removed by conduction along the cable

$$Q_{ce} = \frac{\kappa A_{Cu} \Delta T}{X_c} 2 \qquad \text{W}$$

Describing heat transport down a temperature gradient $\Delta T/X_c$. (X_c is the distance where cable drop to T_b, and 2X accounts for cooling on both ends

Recognizing that this heat is deposited from both ends of the hot zone into the cryogen bath via pool boiling LN_2 at a rate $Q_{ce} = 2 \times X_c P h(\Delta T/2)$ and equating we find $X_c = \sqrt{(2\kappa A_{Cu}/Ph)}$. Which leads to

$$Q_{ce} = T\sqrt{2\kappa A_{Cu} P h} \qquad \text{W}$$

Normalized to A_s, the surface area of all the tapes in the event zone gives

$$Q_{ce}'' = \Delta T \sqrt{(2\kappa A_{Cu} P h)}/A_s \qquad \text{W/m}^2$$

The total cooling becomes

$$Q'' = \eta h \Delta T + \Delta T \sqrt{(2\kappa A_{Cu} P \eta h)}/A_s) \qquad \text{W/m}^2$$

Here we have introduced an "efficiency factor", η, to recognize that not all the tape surfaces are exposed to the liquid cryogen. The heat-balance equation for cold-end cooling is then

$$1 = (G + G_d)/(\eta h \Delta T + \Delta T \sqrt{(2\kappa A_{Cu} P \eta h)}/A_s)$$

Such that →

$$\Delta T = \frac{\frac{\rho I_c^2}{P A_{Cu}} + G_d}{\eta h + \frac{\sqrt{2\kappa A_{Cu} P \eta h}}{A_s}}$$

h vs ΔT

After inserting the physicals for our cable we get

$\Delta T = 40.76\text{x}10^3/(\eta h + 72.06\sqrt{(\eta h)})$

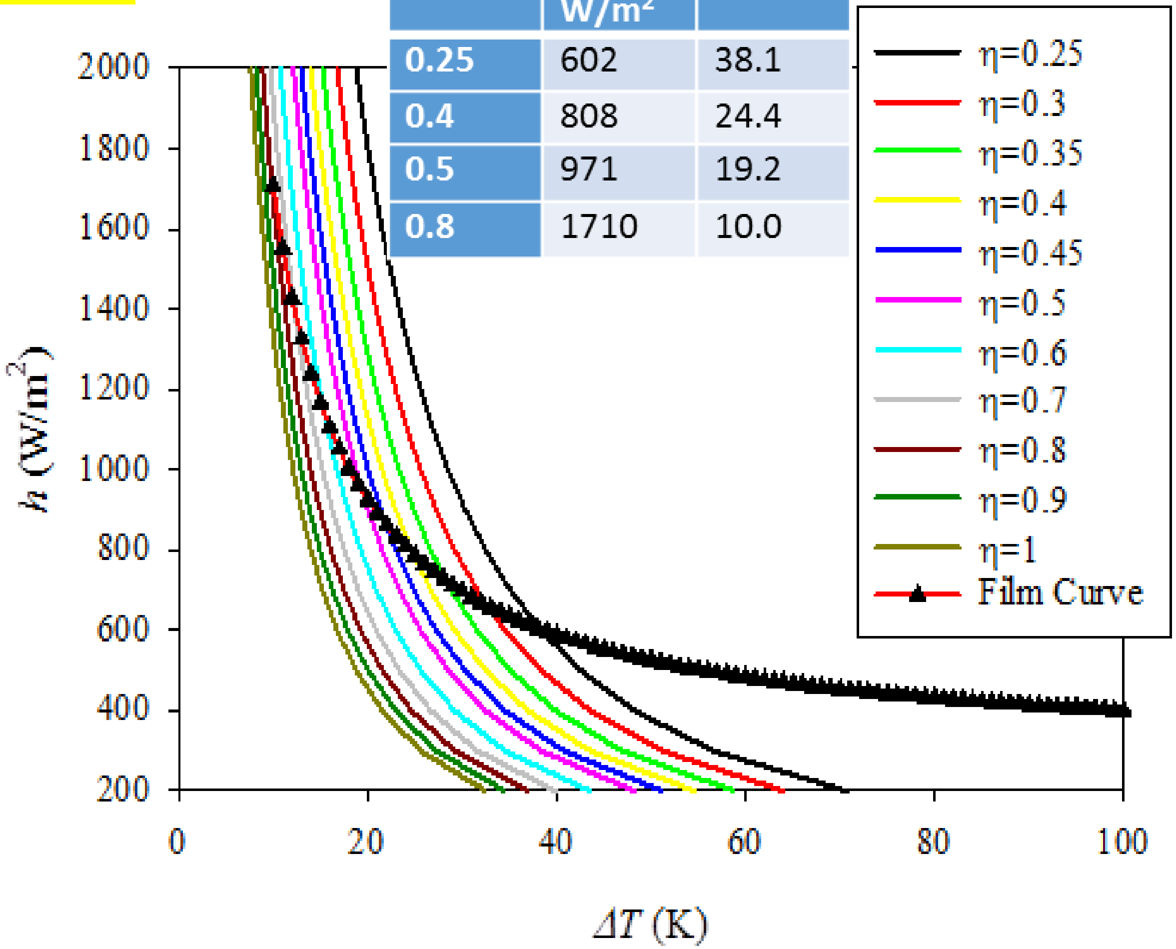
This can be viewed as h vs ΔT for a set of η-values which range from 0.25 (low cooling efficiency) to 1 (in which all tape surfaces receive cooling).

h versus ΔT must also satisfy the basic film boiling curve

Various points of intersection of these two curves, for various η, are shown at right

Experimentally we measured a ΔT of 31 K giving a cooling efficiency of η = 0.31.

η	h, W/m²	ΔT, K
0.25	602	38.1
0.4	808	24.4
0.5	971	19.2
0.8	1710	10.0



Comparison to experiment 77 K

At right is ΔT versus G_d for two ratios I/Ic

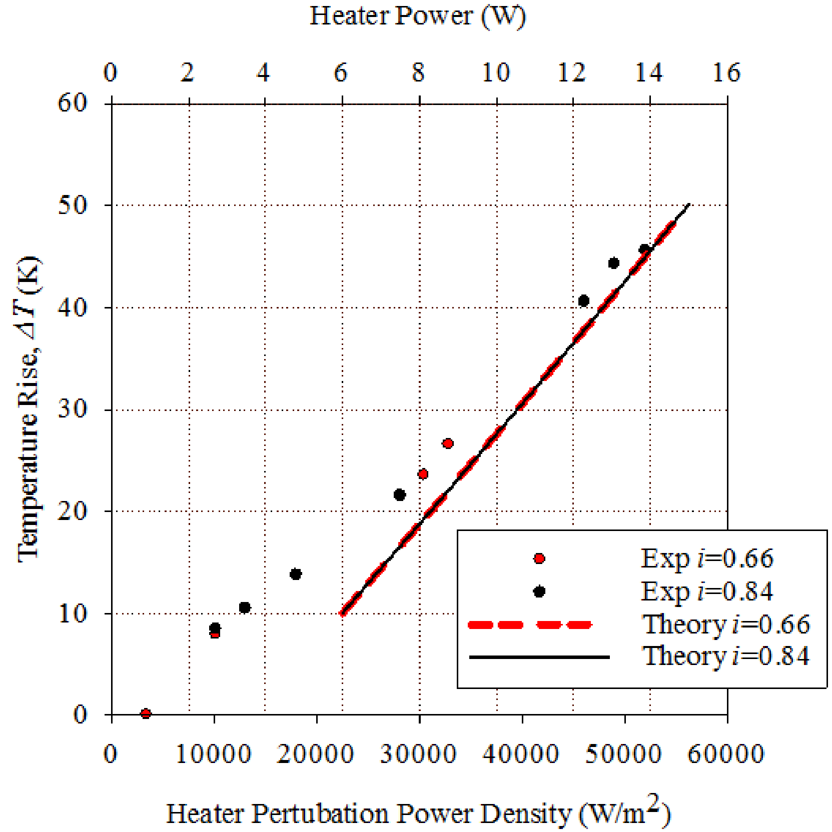
We used

$$I_c\,(T < T_c) = I_c(77\text{ K})(T_c - T)/(T_c - 77)$$

$$\rho\,(T) = \rho\,(273.25\text{ K}) - 7\text{x}10^{-11}(273.25 - T)$$

We also replace I_c by $(I - I_c)$.

The analytical predictions are compared with the experimental results at right



Discussion

Stability was measured for a 9/5.6 ReBCO Roebel cable at 77 K/self-field to create stability phase diagrams

Three distinct types of stability behaviors were created: no response, standing normal zone, and slow quench.

This was described using a heat balance equation (I^2R vs direct cryogen cooling) with fault current and cold end cooling included

A Stekly parameter $a = G/Q \ll 1$ and a heat generation margin of ~ 190 kW/m^2 show the present Roebel REBCO cable to be ultra-cryostable with respect to internally generated transport current overload

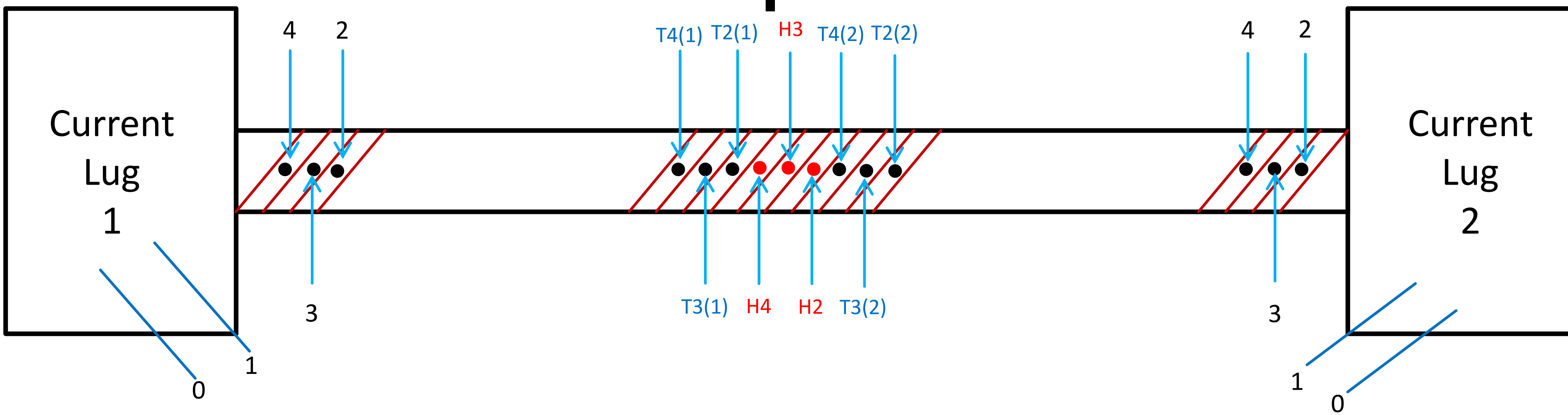
Not so to an externally applied disturbance, G_d. Locally applied heat of only 35 kW/m^2 was found sufficient to drive the cryogen into film boiling and to raise a normal zone's temperature to 181 K.

Cold end cooling lowered the zone temperature

Our modelling generated a set of curves (77 K + ΔT) as a function of cryogenic cooling efficiency. Comparing this to our experimental results (31 K for a 10 W surface disturbance) led to the determination of an efficiency factor of 0.31

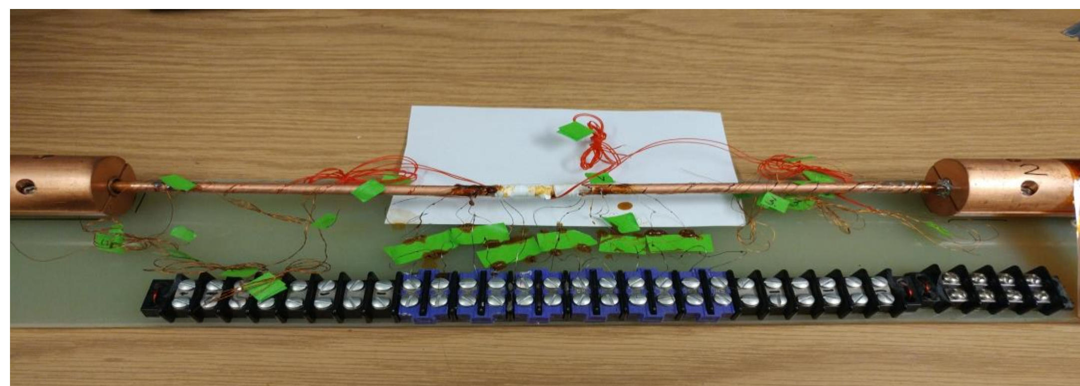
The model now calibrated by cooling efficiently described the stable zone temperature well

CORC with kapton insulation

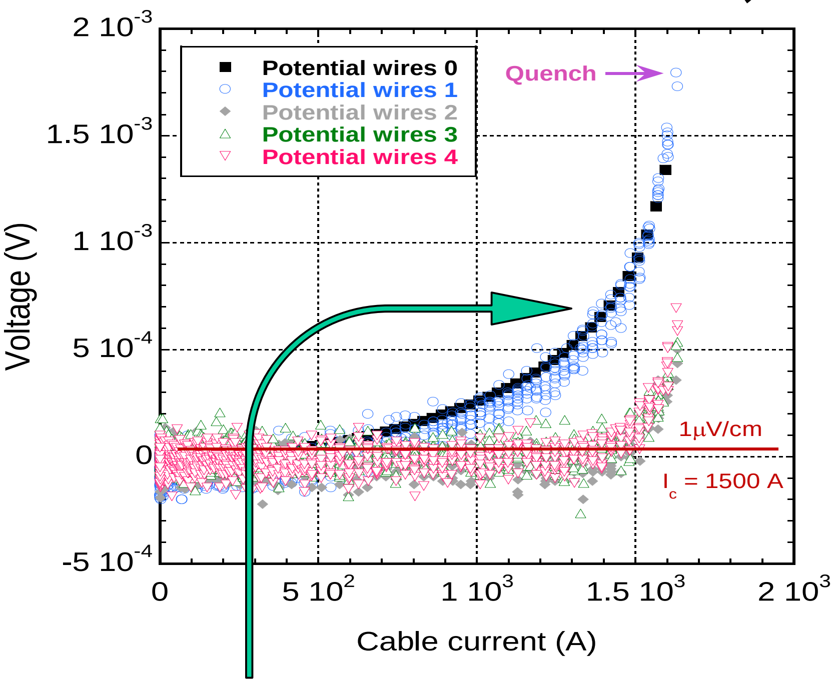


CORC Cable
15 tapes, wound into 5 layers
Each layer contained 3 tapes (4 mm wide)

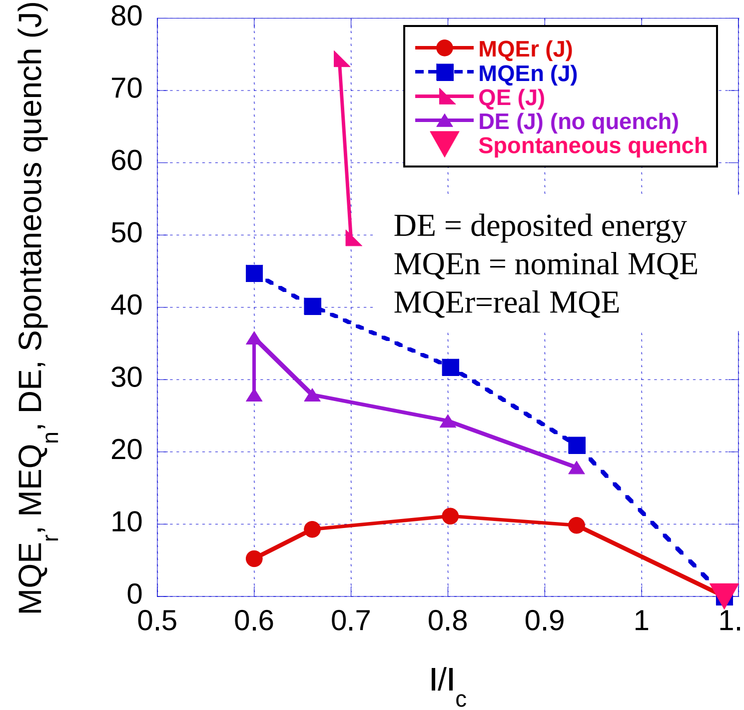
Cable former 5.8 mm OD (solid copper rod + 3 layers of copper tapes)
Cable OD = 6.5 mm.



CORC Results, 77 K

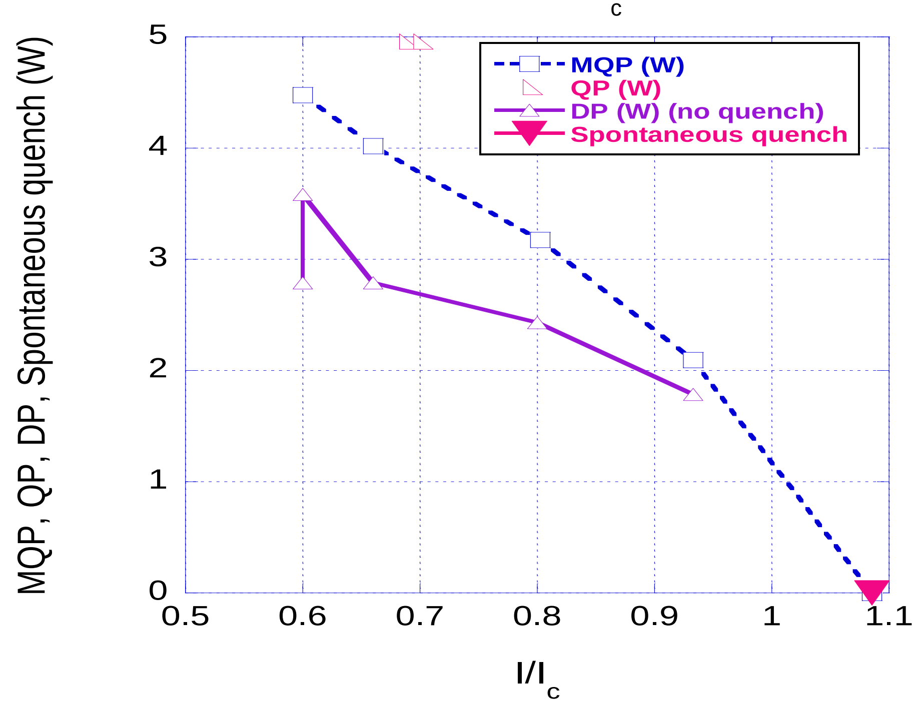


Taps on current Lugs

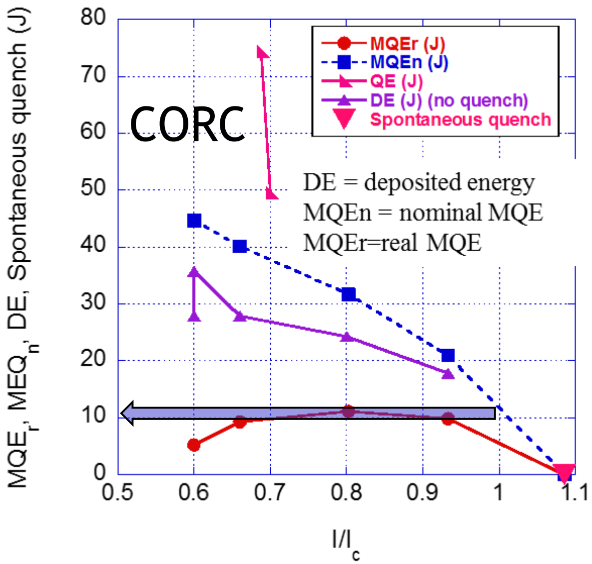


MQE values ranged up to 10 J for the cable with I/I_c from 0.6 to 1

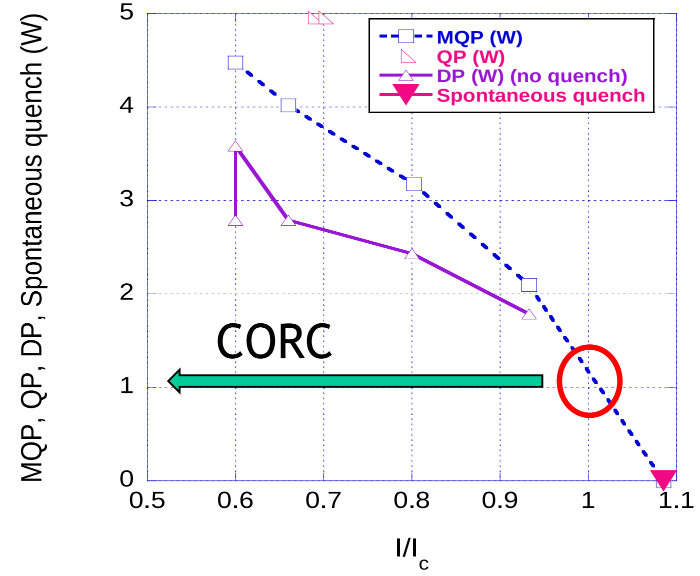
For this cable immersed in liquid nitrogen, the MQP ranged from 4.5 W to 0, with I/I_c from 0.6 to 1

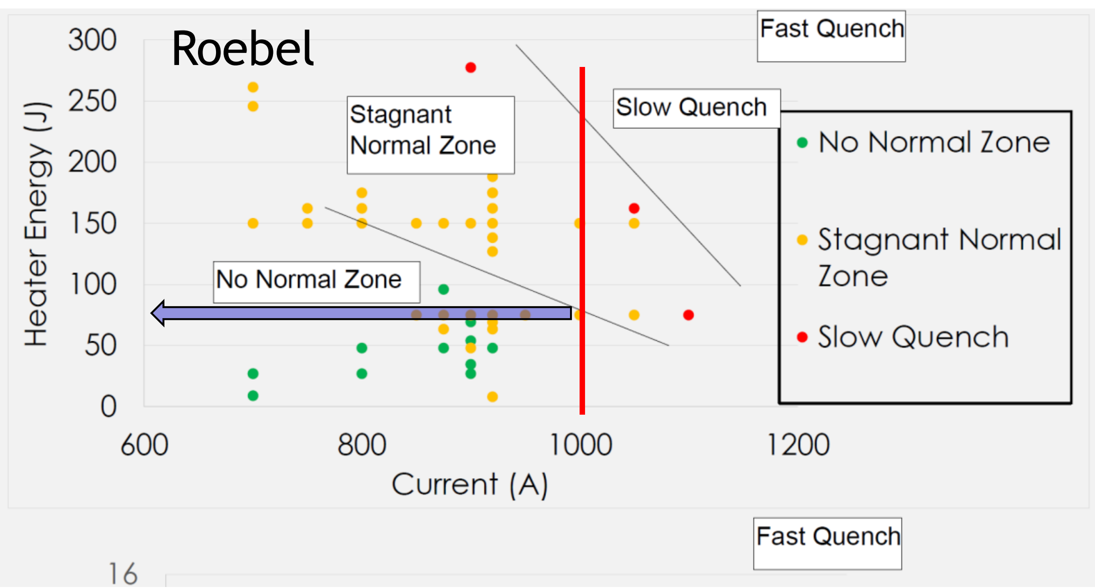


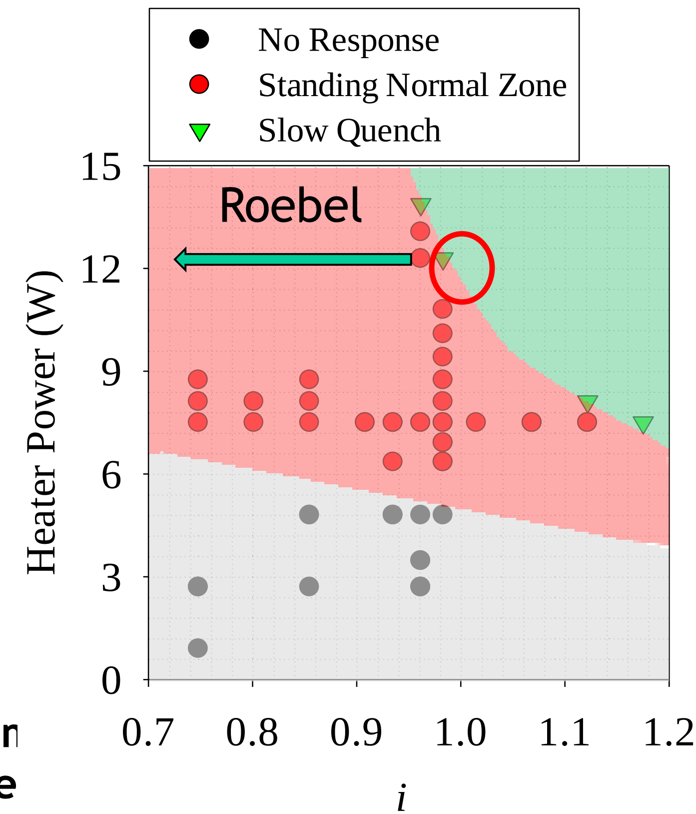
Roebel/CORC



Roebel MQE = 70 J
CORC MQE = 10 J
Roebel MQP = 12 W
CORC MQP = 1 W
Why: Cooling efficiency – note CORC is insulation wrapped







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Science

Discussion II: CORC, Roebel, influence of insulation, epoxy, and cooling efficiency

As tested, our Roebel cable showed a wide range where a constant disturbance would lead to a fixed stable temperature (with current left on)

The CORC cable did not show this

The MQE and MQP for Roebel was substantially higher

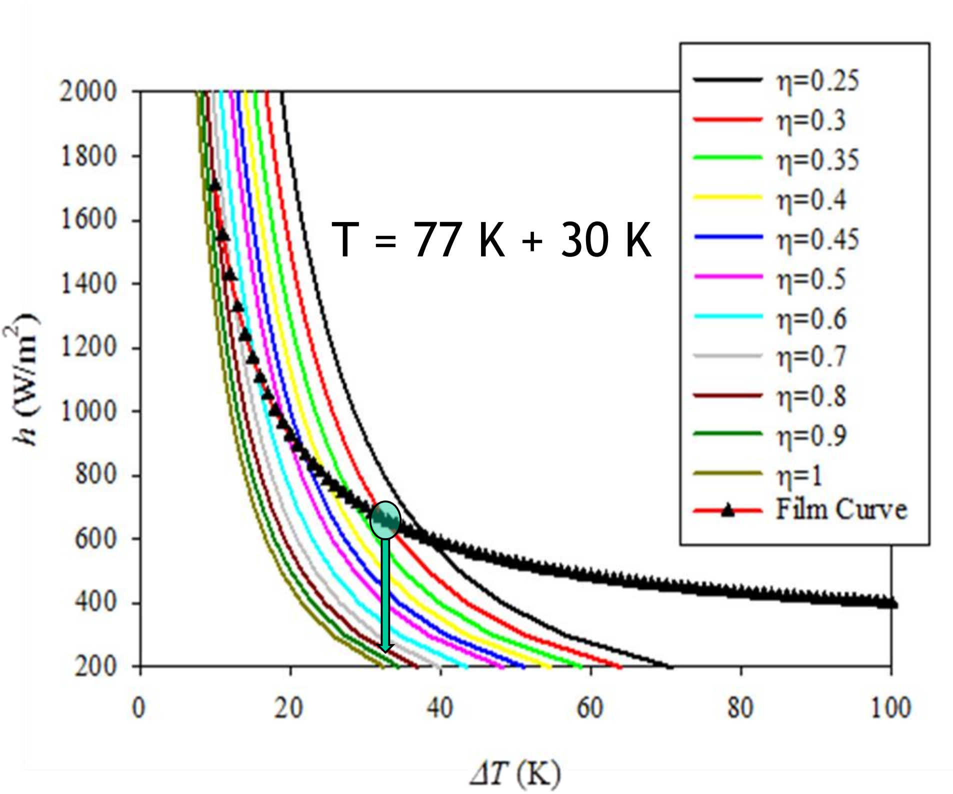
Roebel MQE = 70 J
CORC MQE = 10 J
Roebel MQP = 12 W
CORC MQP = 1 W

Why: We think it is not intrinsic to the cable type - more related to the cooling efficiency dictated by the fact that the CORC we received had an outer kapton wrap, while the Roebel did not. This would significantly reduce the cooling efficiency

So, we next plan to compare wrapped Roebel and unwrapped CORC

On the other hand, if both cable were epoxy impregnated, then both would have much lower MQP and MQE. We next set out to test this with Roebel - and at 4 K and 12 T

Projections LHe vs LN2



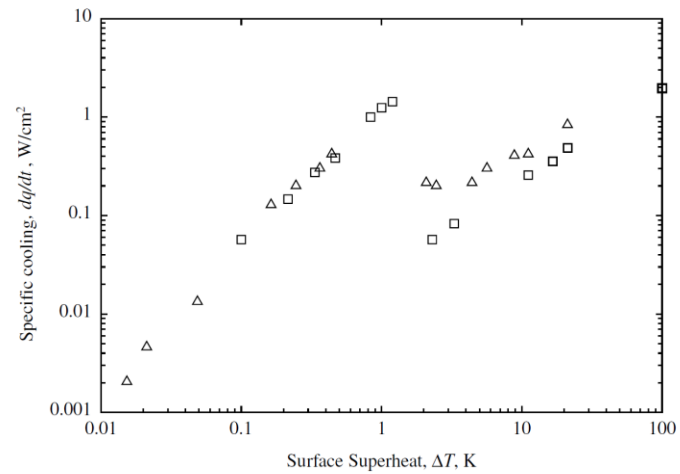
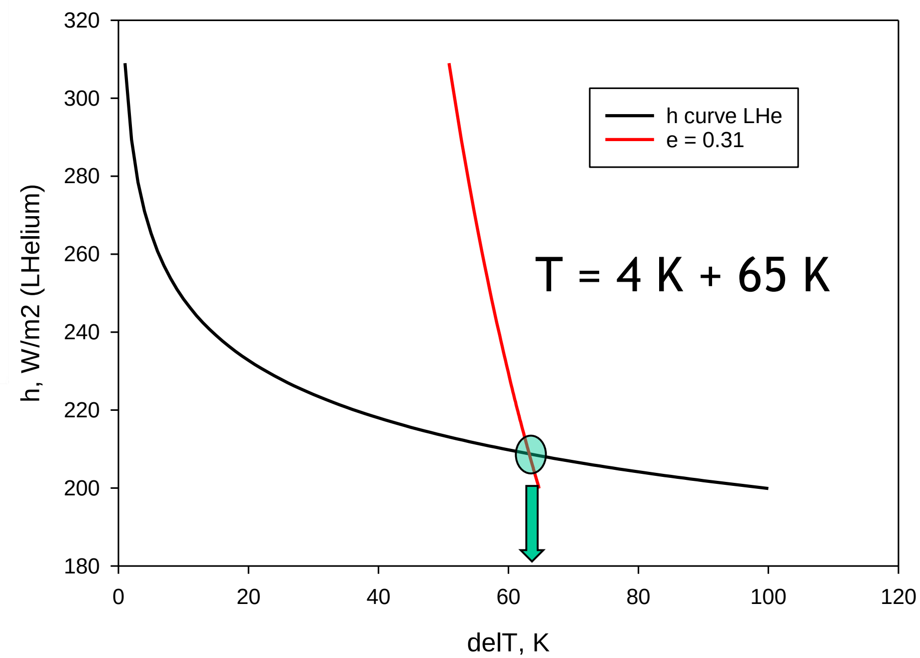


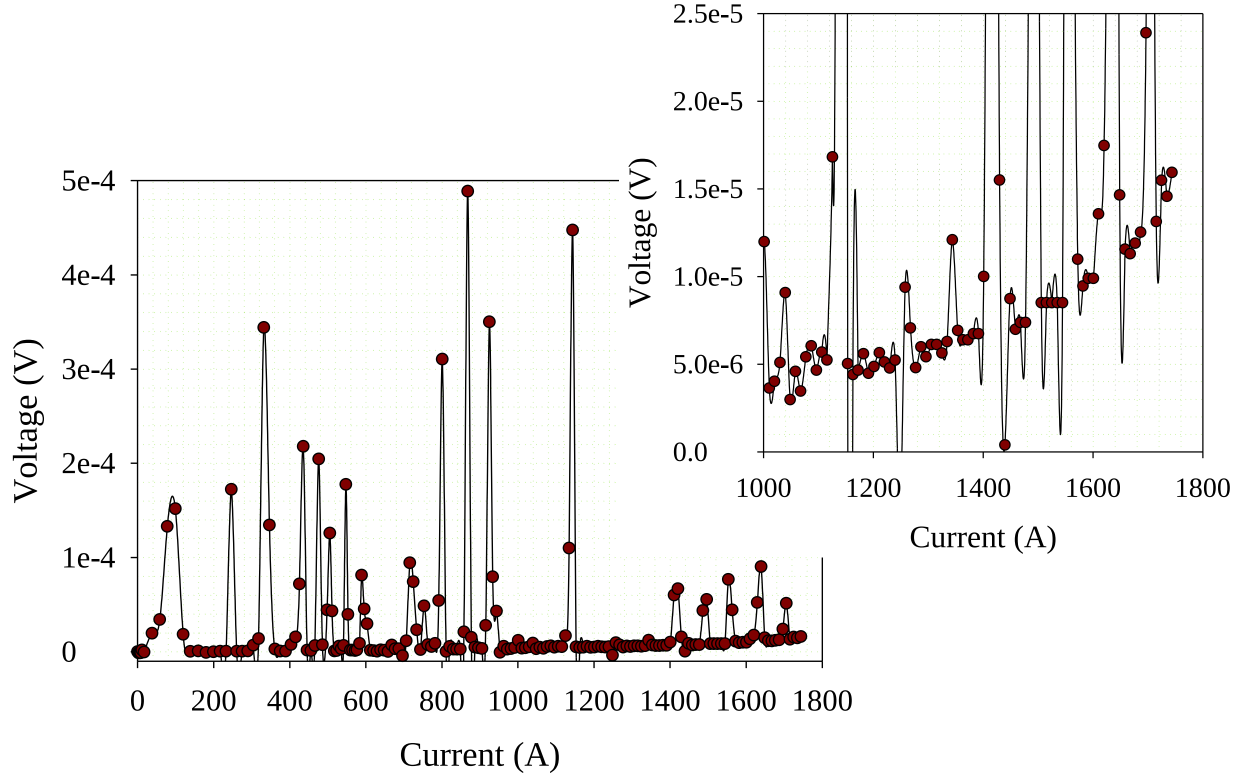
Fig. 1. Heat dissipation by pool-boiling liquid helium—Iwasa [1].



We choose to epoxy impregnate sample and to also put an insulating "cap" on – to mimic an epoxy filled winding at 4 K

Roebel Cable Stability at 12 T/4 K for epoxy impregnated cables

- Given the huge role of epoxy impregnation, cooling ingress, and cooling efficiency ----
- Sample was epoxy impregnated (Stycast 1266 w/ 50% weight Silica particles) and measured in a LHe bath at 12 T.
- Ic near 1200, but broad



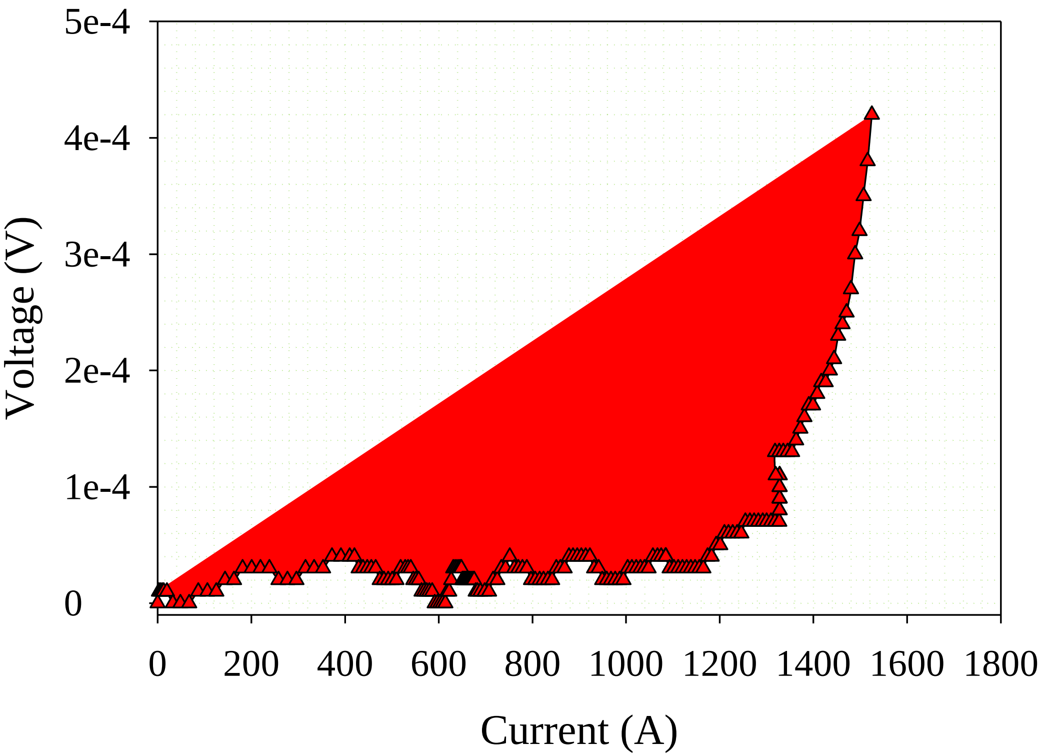
Impregnated 12 T in Lhe, Thermal Cap

In order to test in more realistic conditions where the cable might be imbedded in a magnet, the choice was made to add a thermal cap to mimic limited heat conduction at a magnet core

The same impregnated sample had a foam cap sealed with silicone adhesive.

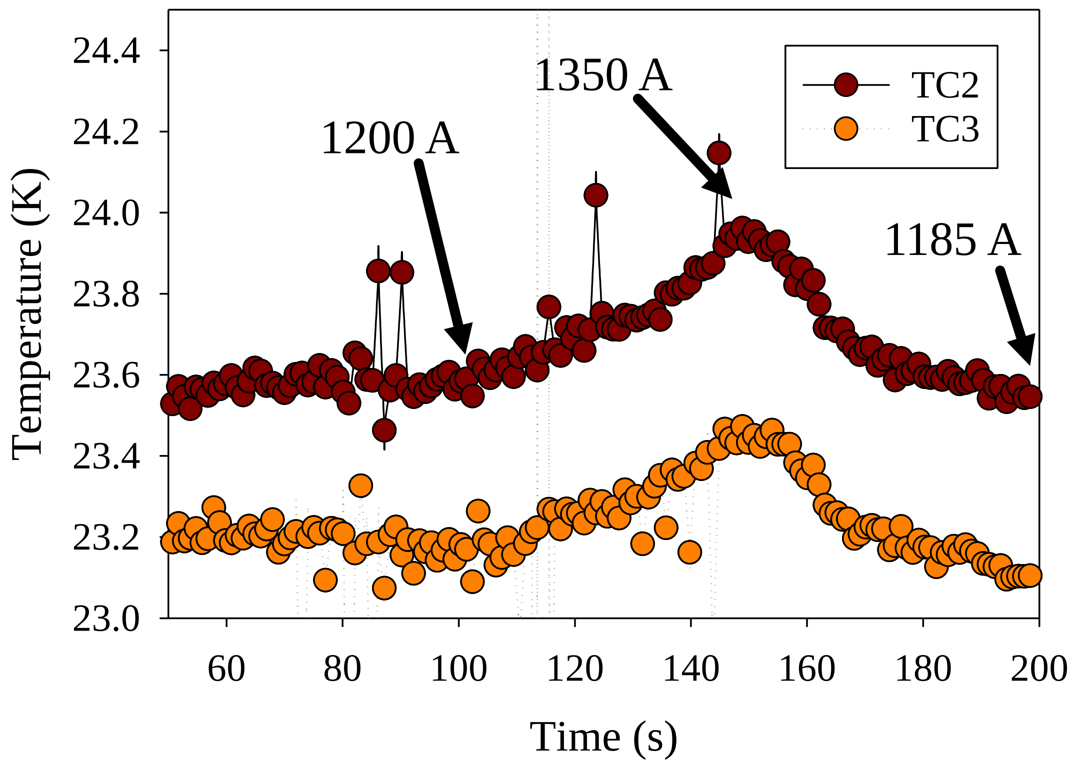
I_c of 1510 A, an I_q of 1530 A

Sample burnt out with 20 mV quench limit (usually safe for our LTS samples)



Why the Difference? Unimpreg vs Impreg

- Temperature increase was seen for impreg sample above 1200 A.
- Current decreased to 1185 A and 10 second heat perturbations , up to 8W, performed.
- No voltage signals detected during HPs.



Conclusions

- For YBCO cables, at least CORC and Roebel Type, cooling efficiency has a very strong influence on stability
- **Two factors which strongly influence this are (i) epoxy impregnation, or, even (ii) simple kapton wrapping for samples in bath cooled cryogen**
- Model development can take a lot from LTS for quench – but a major different is the **low fill factor of YBCO and the high Tc**. The former tends to suppress the ohmic heating component and the latter increase the cooling
- A **simple** model was developed which fit the data well and could be used predictively
- As in LTS, HTS with high levels of cooling and **a heat disturbance are better described in terms of MQP rather than MQE**
- **HTS cables can be much less stable against external perturbations than internal ones** because of a thermal diffusion time between the tapes leading to a premature excursion to film boiling