Quench behavior of Y-Ba-Cu-O coated conductors

Xiaorong Wang

Florida State University
Department of Electrical and Computer Engineering
and
National High Magnetic Field Laboratory
Applied Superconductivity Center

Presented at the Fermi National Accelerator Laboratory
July 10, 2007

Acknowledgment

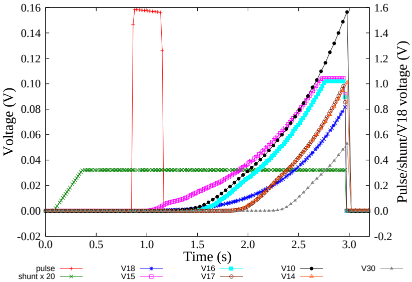
- Work supported by U.S. Air Force Office of Scientific Research and DOE through Center for Advanced Power Systems at Florida State University
- Collaborators
    - Justin Schwartz
    - Ulf P. Trociewitz
    - Sastry V.P.S.S. Pamidi
    - Abdallah L. Mbaruku
    - Honghai Song
    - Timothy Effio
    - Marco Breschi (University of Bologna, Italy)
    - Andreas Heinrich (University of Augsburg, Germany)

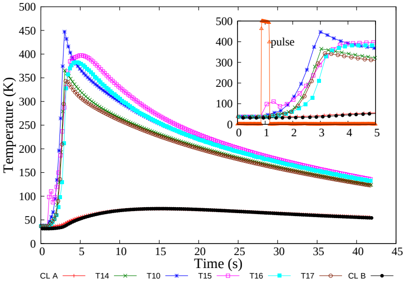
Outline

Contents

What is quench?

- *rapidly, uncontrollably* state change
- most likely cause of death for a superconducting magnet (M.N. Wilson)
- Quench is always possible
- Stability: stable against interruption
- Protection: quickly spread the energy





Specific aims

- High-T_c magnets are more stable
- But protection becomes more stringent
- Vulnerable to overheating

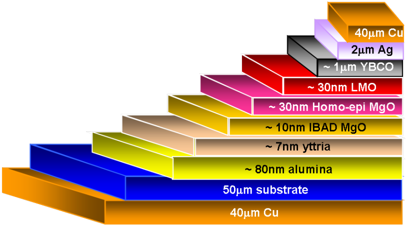
For the emerging and promising 2G YBCO coated conductors, we propose to

- *Experimentally identify their quench behavior*
- *Experimentally identify the critical parameters for them to be degraded*
- *Simulate their behavior during a quench*

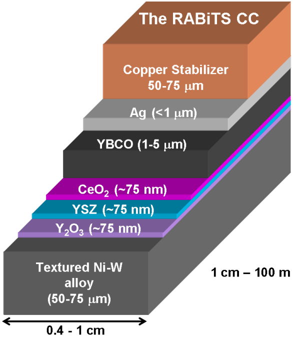
YBCO coated conductors

Two general structures†

IBAD – ion-beam-assisted deposition of the textured template, SuperPower



RABiTS – Rolling assisted bi-axially textured substrates, AMSC



- Brittle YBCO layer sandwiched in a complicated composite.
- Production: 100–500 m length.

† Image courtesy of D. C. Larbalestier

Contents

Quench probe design

A probe that can help us run both I_c and quench tests

1. in nearly adiabatic environment
2. with variable operation temperature (T_{op})
3. and the capability to monitor $V(x, t)$ and $T(x, t)$ during a quench

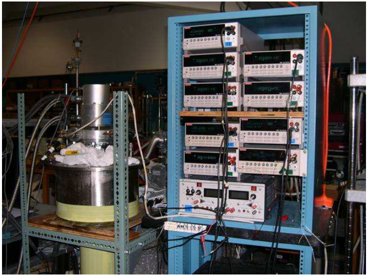
First probe made in 2003[†], but...

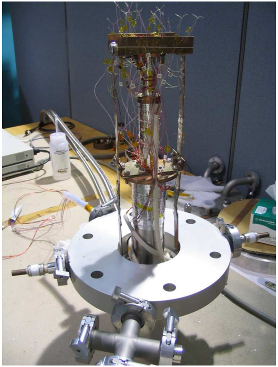
- must bend the samples to mount them (but they are brittle!)
- temperature monitoring capability not fully realized

[†] Trillaud *et al.*, Cryogenics, 43, 271, 2003

Probe overview

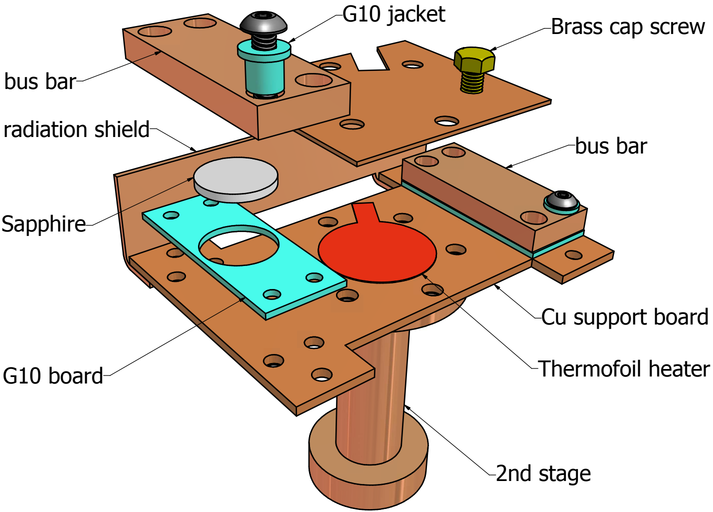
- A 2-stage GM cryocooler and a mushroom cryostat, $T_{\rm op}$: 30 K – 75 K
- Typical pressure by a turbo molecular pump: 10^{-6} – 10^{-7} mbar
- Self-field tests. In-field tests in-progress†.





†See backup slide for the in-field probe

Sample holder – exploded view

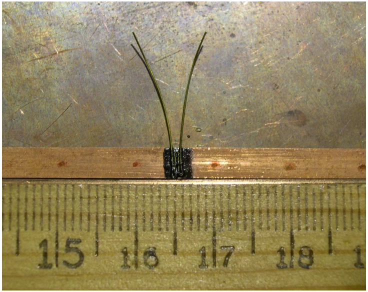


Quench initiation

Several possible methods:

- $T_c \Rightarrow$ heater, induction heating, laser heating, ...
- $I_c \Rightarrow$ over-current pulse, applied field, ...

Most of time we use a NiCr heater (34 AWG) to initiate the normal zone.



Temperature sensor

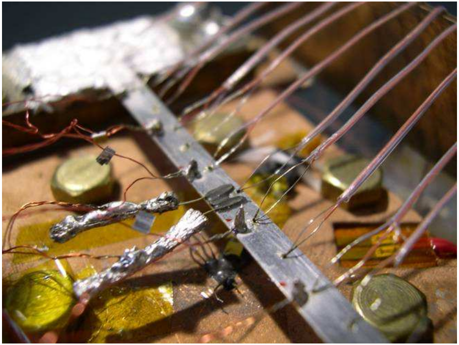
1. Transient event: broad ΔT (4 K – 400 K) in a short time (3 s)
2. Distributed and in-field temperature measurements
3. Limited space (4 mm wide tape)

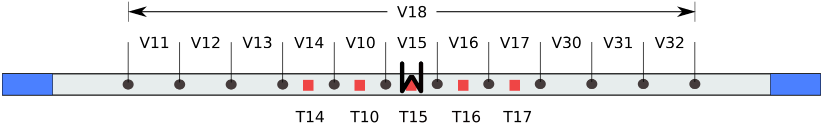
item	Cernox RTD	TC
range (K)	0.1—420	4—1000
small?	yes (bare chip)	yes
measurement speed	slow	fast
price	$100 (uncalib.)	$5/ft
standard curve?	no	yes

Type E TC:

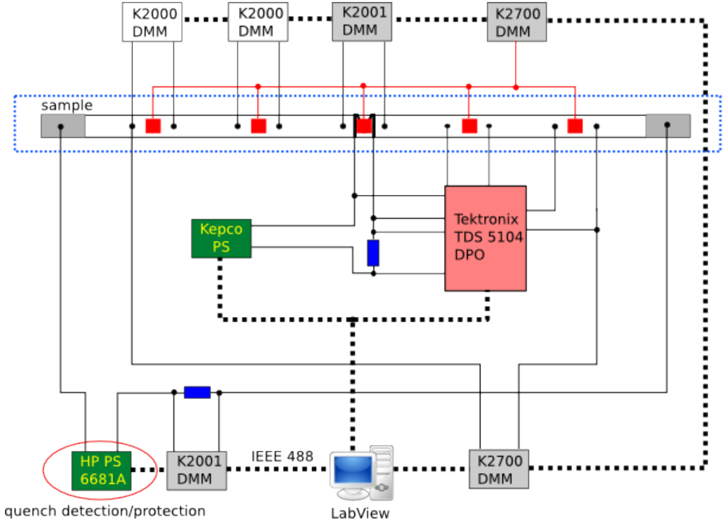
- Sensitivity $> 20\ \mu$V/K for $T > 40$ K, highest for standard TCs
- Calibrated to a Cernox RTD: $\epsilon < 3$ K [RT, 30 K]; $\epsilon \sim 7$ K @ 4.2 K
- Fair in-field performance (7% @ 10 K and 14 T, Lakeshore)

Typical wiring



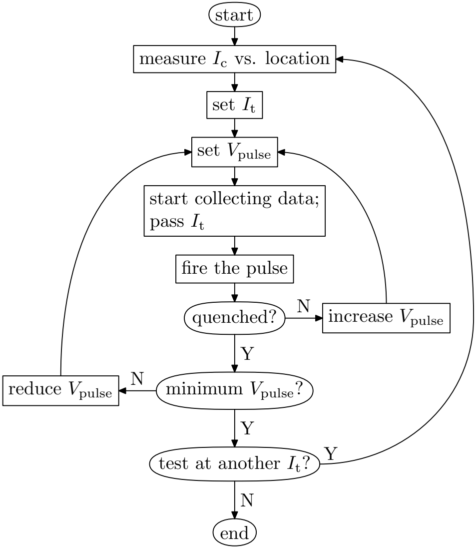


Measurement system



Experimental protocol

- Goal: to find the minimum quench energy (MQE) and the normal zone propagation velocity (NZPV)



Contents

Minimum quench energy (adiabatic condition)

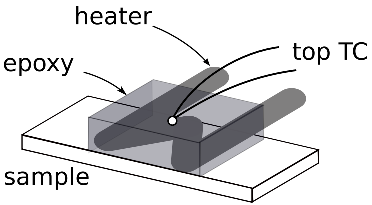
- $MQE = E_{\mathrm{htr}} - E_{\mathrm{epo}}$
- Energy input by the heater

$$E_{\mathrm{htr}} = \int_0^{t_{\mathrm{p}}} V(t)\, I(t)\, \mathrm{d}t$$

- Energy absorbed by the epoxy

$$E_{\mathrm{epo}} = m \int_{T_0}^{T_1} C_{\mathrm{epo}}(T)\, \mathrm{d}T$$

- m : $20 \sim 40$ mg
- $E_{\mathrm{epo}} < 10\%\, E_{\mathrm{htr}}$

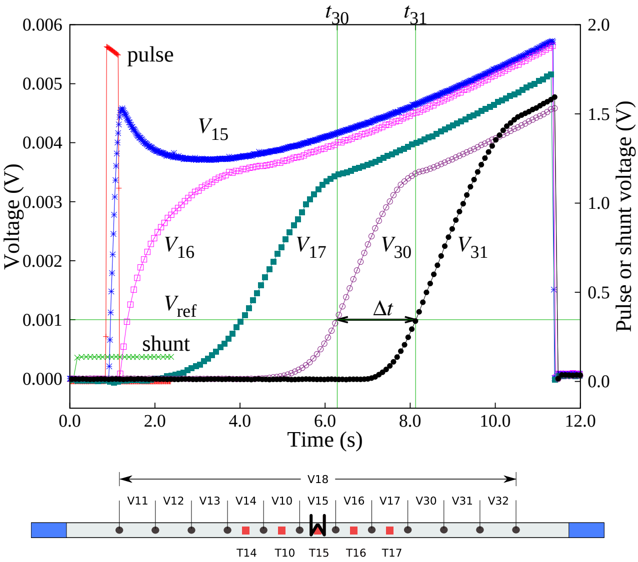


Normal zone propagation velocity

- Voltage criterion

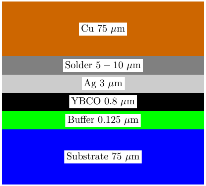
$$v = \frac{d}{\Delta t}$$

- Sections away from the heater
- Example: Voltage traces measured at 70 K with $I_t = 50\% I_c$ (Wang *et al.*, JAP, 2007)

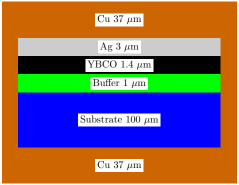


Standard samples

Done:



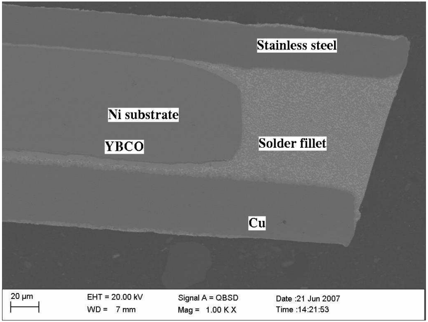
AMSC



SuperPower

Doing:

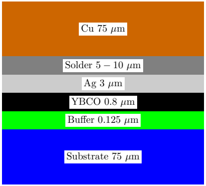
- Quench behavior comparison between three architectures
  1. Cu-Cu stabilizer
  2. Cu-SS stabilizer
  3. SS-SS stabilizer

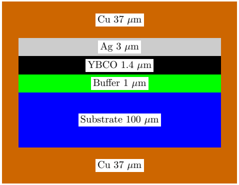


Samples to be shown

For the sake of time, only the following will be covered...

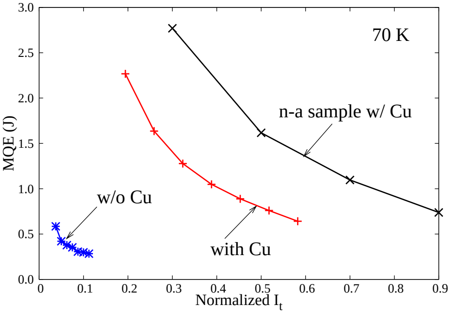
Name	Width (mm)	Length (mm)	comment	circa
AMSC-OR1[†]	10	120	only Ag stabilizer	1/04-5/04
AMSC-OR2	10	120	with Cu stabilizer	1/04-5/04
AMSC-51750	10	180	neutral-axis with Cu layer	5/05
SPI-FSU1	4	180	surrounded Cu stabilizer	7/05

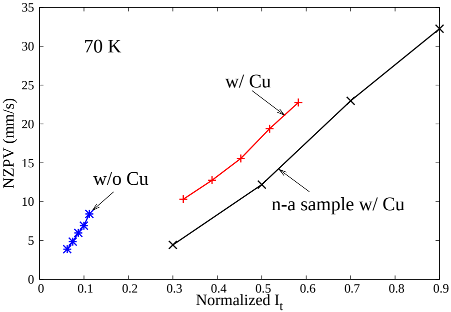




[†] Provided by AMSC through ORNL

Standard samples quench results — AMSC[†]



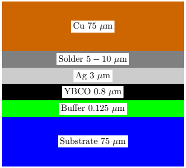


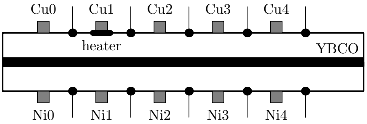
- MQE $\sim$ 1 J, NZPV $\sim$ 10 mm/s
- Additional Cu stabilizer improves stability
- I_c doubled in 1 year

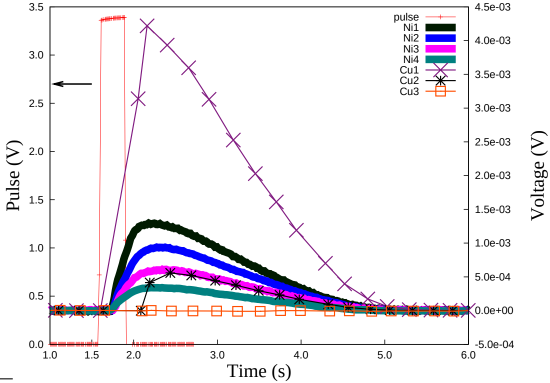
[†] Wang *et al.*, IEEE TAS, 15(2), 2586, 2005

Quench behavior of a specific sample architecture

- Non-equipotential voltage development observed in experiments[†]
- Theoretical investigation: contact resistance[‡]
- Possible usage for quench detection



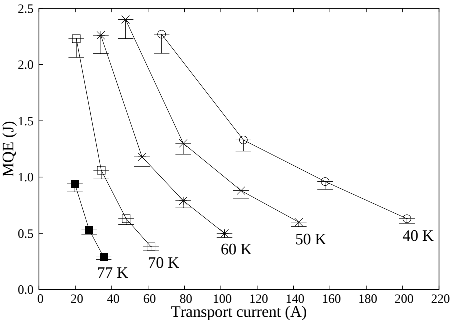


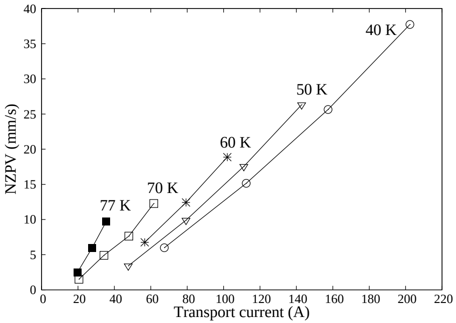


[†] Wang *et al.*, IEEE TAS, 2005

[‡] Breschi *et al.*, SuST, 2007; Levin *et al.* preprint, ArXiv:0706.4040

Standard samples quench results — SuperPower†

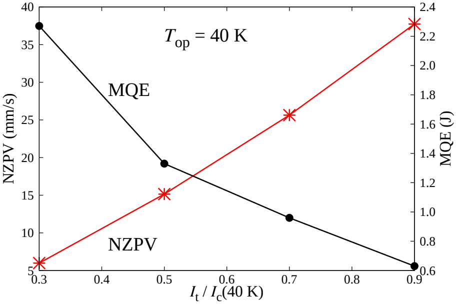


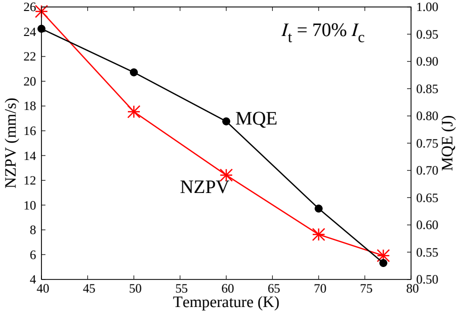


- Measured at 40 K, 50 K, 60 K, 70 K, and 77 K
- MQE $\sim$ 1 J, NZPV $\sim$ 10 mm/s $\Rightarrow$ Samples by different vendors have similar quench performance
- Compared to $v = \frac{J_\mathrm{m}}{C}\sqrt{\frac{\kappa_\mathrm{m}\rho_\mathrm{m}}{T_\mathrm{t}-T_\mathrm{op}}}$

†Wang *et al.*, JAP, 101, 053904, 2007

Indications of single conductor quench behavior†

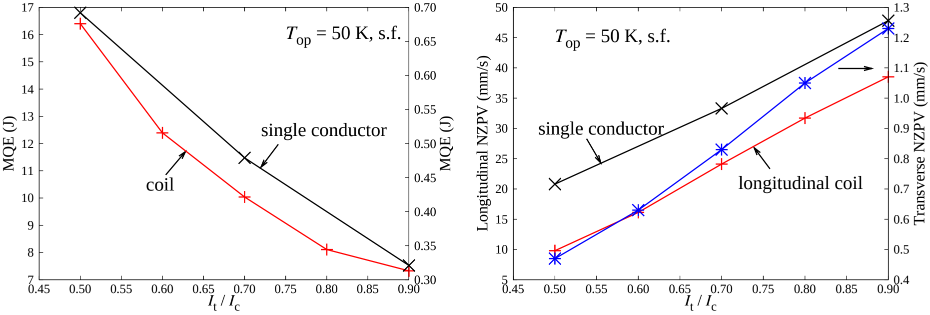




- Trade-off: stability (high MQE) and protection (high NZPV).
- $T_{\mathrm{op}} \Downarrow$ improves I_{c}, stability and quench behavior
- NZPV still low (layer-layer velocity one order lower!) $\Rightarrow$ innovative detection and protection technique

†Wang *et al.*, JAP, 101, 053904, 2007

Quench behavior of an AMSC pancake coil



- cryocooled @ 50 K, s.f. Ni-alloy heater embedded.
- MQE $\sim$ 10 J
- Transverse velocity <u>one order lower</u> than the longitudinal velocity
- Longitudinal velocity: coil $<$ single conductor

Contents

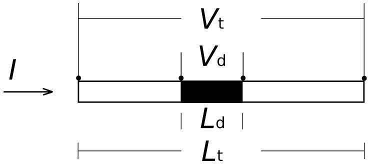
Introduction

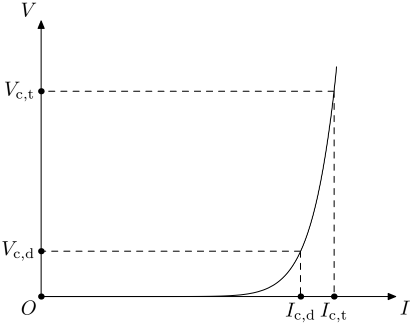
- Uniform I_c for long length conductor may be difficult.
- Will the non-uniformity in $I_c(x)$ profile affect the stability of the conductor? Or to what extent can we tolerate in terms of stability?

- The relationship between the end-to-end and the defect's I_c
- Use a sample with well-characterized defects to find the minimum quench current

A superconductor with a defective section

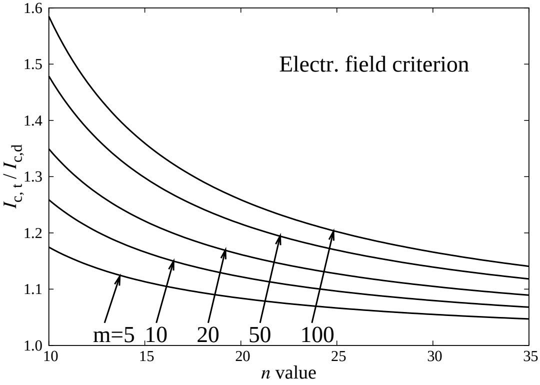
- Defective section: dark area. Length ratio: $\frac{L_t}{L_d} = m \geq 1$
- Measure $I_{c,t}$ with transport. Power law: $V = c\, I^n$
- $I_{c,t} = I_{c,d}$?





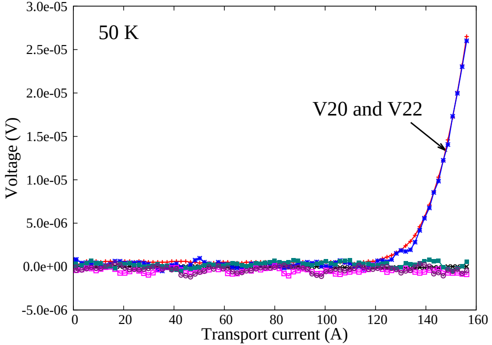
$I_{\mathrm{c,t}}$ *vs.* $I_{\mathrm{c,d}}$

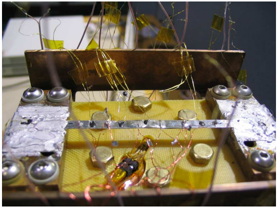
- Electric-field criterion: $\Rightarrow \frac{I_{\mathrm{c,t}}}{I_{\mathrm{c,d}}} = \sqrt[n]{m}$ (see backup slide for proof)
- $I_{\mathrm{c,t}} \geq I_{\mathrm{c,d}}$. Larger m, smaller $n \Rightarrow$ more overestimation. In industry, $m = 100$ and $n \sim 25$, $I_{\mathrm{c,t}}$ 20% higher than $I_{\mathrm{c,d}}$ possible.
- Is the $I_{\mathrm{c,d}}$ the minimum quench current?

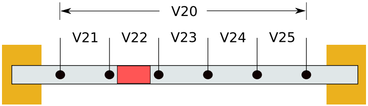


Experimental: a defective sample

- AMSC 344 coated conductor
- Non-uniform I_c profile: V22 lower than others. $n = 15$ and $m = 5$.

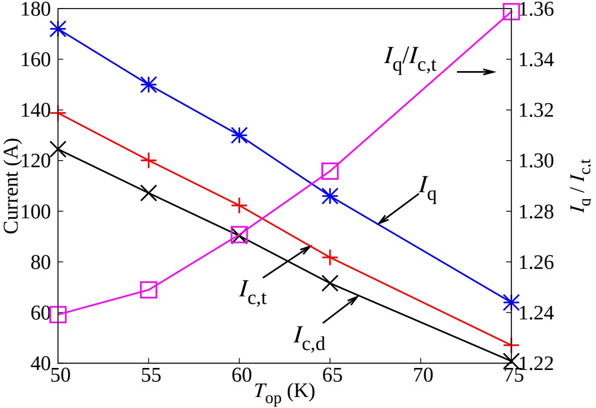






Over-time quench tests

- Constant I_t from below the $I_\mathrm{c,d}$. Test up to 15 minutes, if not quenched, increase I_t. T_op from 50 K to 75 K.
- $I_\mathrm{c,t}/I_\mathrm{c,d}$ as predicted within 0.5%. $I_\mathrm{q}/I_\mathrm{c,t}$: 1.3 $\rightarrow$ 1.2 as T_op $\Downarrow$. Longer test duration, effect of stabilizer, cooling?



Contents

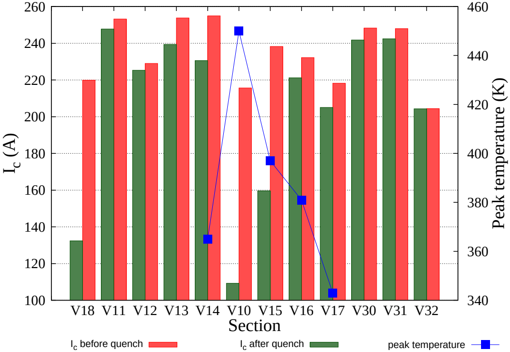
Introduction

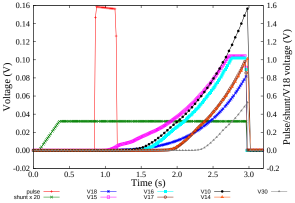
- Superconducting magnets are not like electric bulbs. (Y. Iwasa)
- Low NZPV $\Rightarrow$ HTS magnets are not self-protective.
- Understand how they fail may help us to protect them.
- Work on $\mathrm{Nb_3Sn}$ cables and magnets†
  - cable: T_{peak} 420 K fine in a straight sample.
  - subscale magnet: 430 K fine, 450 K $\Rightarrow$ detraining effects, 580 K $\Rightarrow$ irreversible degradation
  - simulation limits: 400 K
- Any quench-induced degradation in HTS conductors? Why? And what's the operational limits?
- Just show the scenario as the investigation is underway.

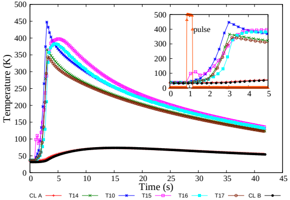
† Imbasciati, PhD thesis and e.g., SuST 17, S389, 2004

Quench-induced degradation in single coated conductors

- $I_t = 160$ A ($70\% I_c$), 37 K
- In only 2 s, $T_{\text{peak}} = 450$ K
- 50% of critical current decrease
- Recently, quench degraded a pancake coil (I_c 233 A $\rightarrow$ 152 A, 35%$\Downarrow$)







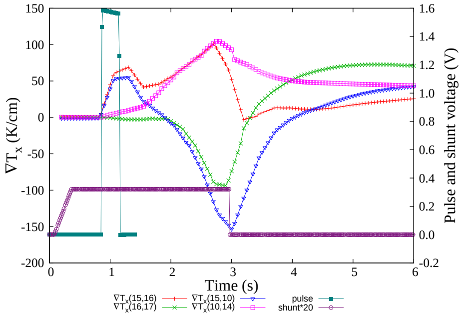
Spatial and temporal temperature gradients

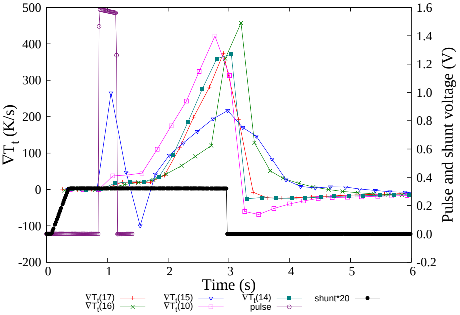
Spatial (K/cm):

$$\nabla T_x(i,j) = \frac{T_i - T_j}{D_{ij}}$$

Temporal (K/s):

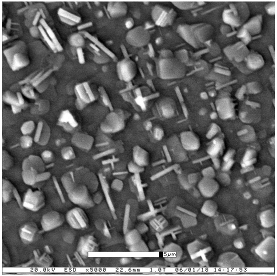
$$\nabla T_t(i, t_{n+1}) = \frac{T_i(t_{n+1}) - T_i(t_n)}{t_{n+1} - t_n}$$





What happened in a degraded sample?[†]

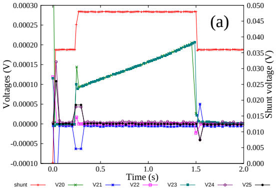
- No crack found in the quench-degraded sample seen in the ESEM
- T_{c} not changed (Dr. Trociewitz) $\Rightarrow$ no chemical change
- Now checked in the magneto-optical imaging (Dr. Heinrich) and SEM
- ϵ_{c} (95% I_{c}): 0.43% $\rightarrow$ 0.33%

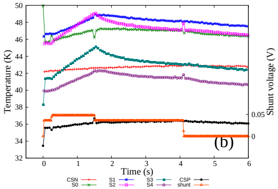


[†] Mbaruku *et al.* IEEE TAS, in press

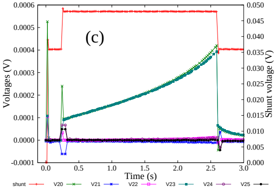
Another example – sensitivity to the detection time

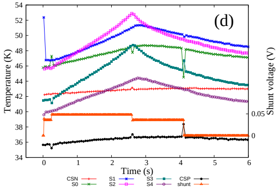
D_{p} = 1.2 s. Recovery, $V_{\max}$ = 2 mV, ΔT = 3 K



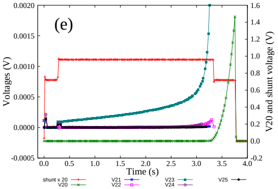


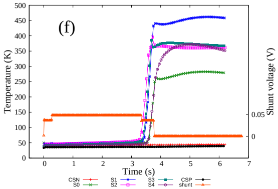
D_{p} = 2.3 s. Normal zone propagates, $V_{\max}$ = 4 mV, ΔT = 7 K





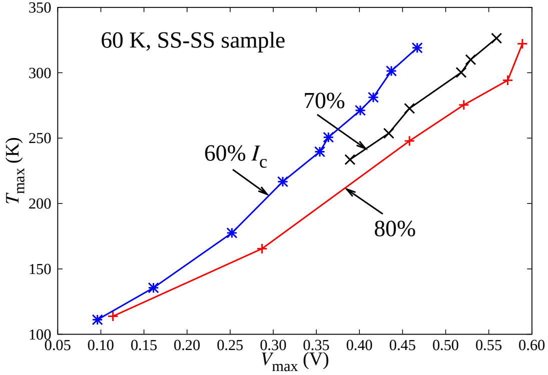
D_{p} = 3 s. Quench, $V_{\max}$ = 1400 mV, ΔT = 400 K! Tape burn out...





Peak temperature *vs.* peak voltage

- The $T_{\max}$ corresponding to the $V_{\max}$ during a quench
- Relationship recorded for a SS-SS sample @ 60 K
- When $T_{\max} = 200$ K, $V_{\max} = 0.3 \sim 0.35$ V
- Quench may be detected before it's getting too hot.



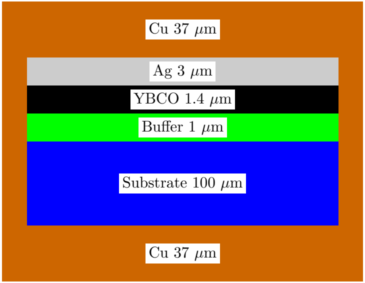
Contents

Introduction

- Better understanding the quench behavior
- Focus on the 1D finite-difference model
- ANSYS coupled-field work in-progress

1D model — assumptions

- Sample SPI-FSU1, surrounded Cu stabilizer
- $I_c \propto T_{op}$
- C and κ volume-averaged. No thermal and electrical contact resistance considered. Buffer layer neglected.
- $R_{nm} = \frac{1}{\sum_{i=1}^{n} \frac{1}{R_i}}$

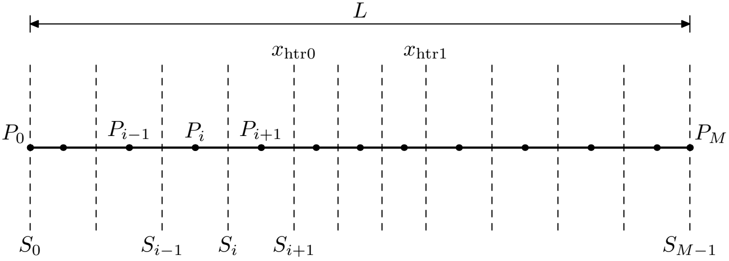


Heat balance equation

The partial differential equation is

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\kappa \frac{\partial T}{\partial x}) + f,$$

solved by finite difference method based on the control volume method†.



† S. V. Patankar. *Numerical Heat Transfer and Fluid Flow*, Hemisphere, 1980

Solving the model — the scheme

For $n = 0$, initial condition,

$$T_i^0 = T(x_i, 0) \quad i = 0, 1, \ldots, M. \tag{1}$$

For $n \geq 1$, boundary condition,

$$T_0^n = T(0, t^n), \tag{2a}$$
$$T_M^n = T(L, t^n). \tag{2b}$$

For $n \geq 1$ and $i = 1, \ldots, M - 1$, we have

$$-a_{\mathrm{E}i} T_{i+1}^n + \alpha_i T_i^n - a_{\mathrm{W}i} T_{i-1}^n = \gamma_i T_i^{n-1} + f(x_i, t^n)\Delta x, \tag{3}$$

Coded in FORTRAN. Implicit scheme used to guarantee the stability.

Material properties

- Temperature dependent material properties
- No effect of magnetic field
- Given fitted function or fitted by polynomial up to 6 order

Material	ρ	C	κ	R
Cu(100)	s1	4–300 K, s2	4–300 K, s2	20–300 K, s1
Ag(30)	s1	20–300 K, s1	20–300 K, s1	20–300 K, s1
YBCO	s1	20–300 K, s1	20–300 K, s1	20–300 K, s1
H C276	s3	55–302 K, s2	20–811 K, s3	$>> R_{\mathrm{Cu}}$
Stycast	s4	4–302 K, s5	4.2–300 K, s6	n/a

s1: Cryocomp, s2: NIST website, s3: Haynes website, s4: Emmerson-Cumming website, s5: literature, s6: Lakeshore website.

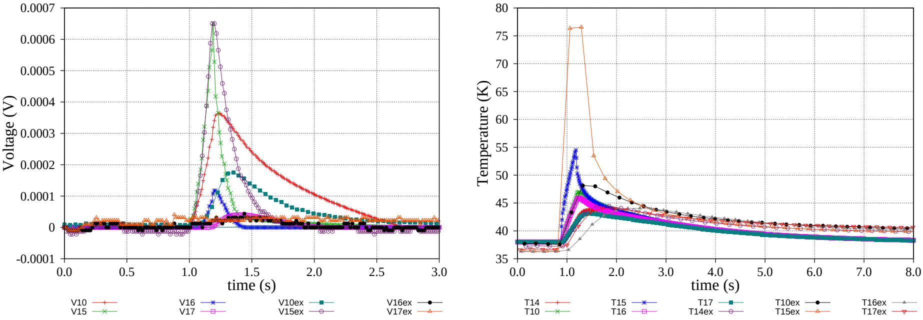
- Heater: $R(T)$ measured and fitted; C and κ neglected.

Results

- Model results compared to 2 experiments — 1 recovery and 1 quench
- ξ adjusted to fit V15 to the measured value
- Agreement between calculation and experiments not good

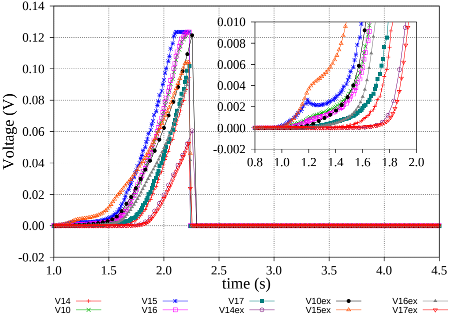
Comparison 1 — Experiment #6, recovery

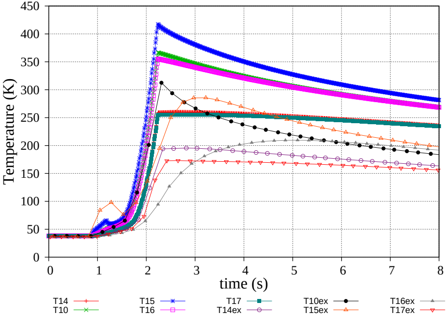
$I_\mathrm{t} = 199$ A (90% of I_c), $V_\mathrm{p} = 1.13$ V, $\xi = 2.8$.



Comparison 2 — Experiment #9, quench

$I_t = 199$ A (90% of I_c), $V_p = 1.35$ V, $\xi = 2.8$.





Contents

Quench experiment variation

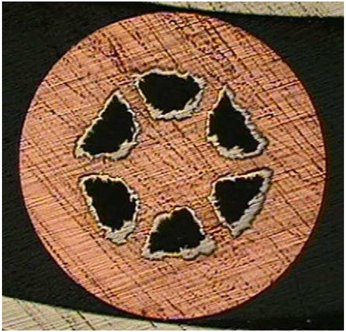
$\mathrm{MgB_2}$ is an interesting emerging conductors.

- Potential cost $\sim$ NbTi with much higher field
- Conductor form can be isotropic wire in long length
- Potential application of $\mathrm{MgB_2}$ for accelerator magnets[†]

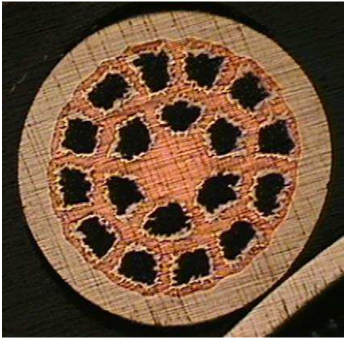
[†] Cooley *et al.*, Proceedings of PAC 2001, Chicago

Samples

- Two kinds of wires provided by HyperTech through CAPS
- ϕ 0.83 mm, 20 cm long, s/c $\sim$ 16%



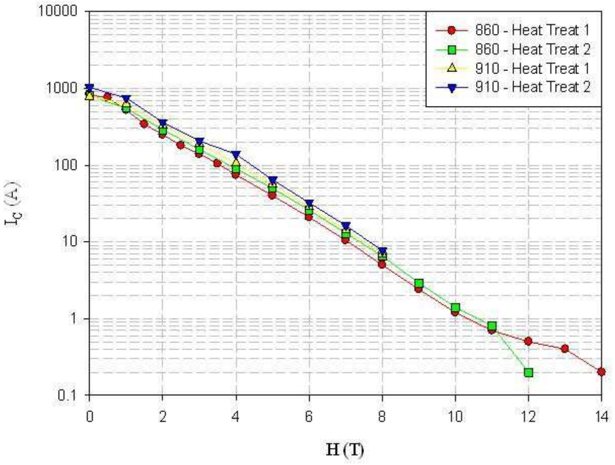
glid Cu sheathed, 6 filaments



CuNi sheathed (Monel), 16 filaments

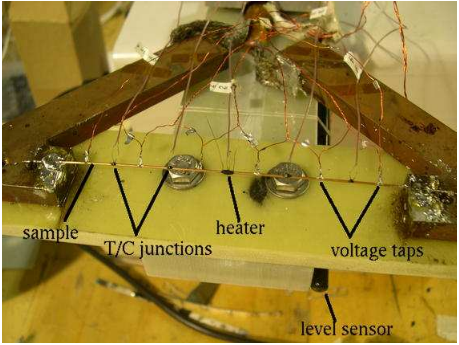
I_c *vs.* field

Measured with ITER barrel by HyperTech Research.

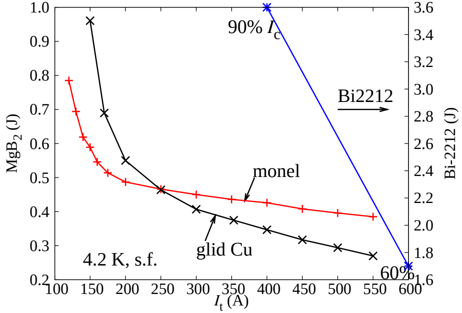


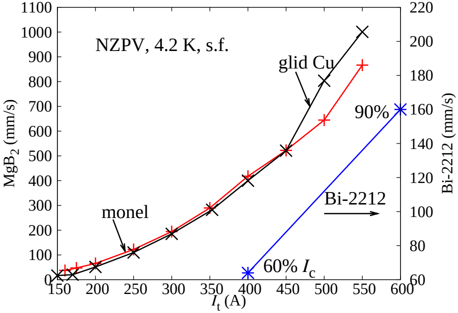
Experimental setup

- Tested in liquid helium, self field
- Normal zone initiated by NiCr heater wound around the sample
- $V(x,t)$ and $T(x,t)$ monitored



MQE and NZPV results





- MQE $\sim$ 1 J, NZPV $\sim$ 1 m/s
- $\sim$ 11% MQE of Bi-2212 round wire†; $\sim$ 1250% NZPV of Bi-2212

† Bi-2212 data by Timothy Effio

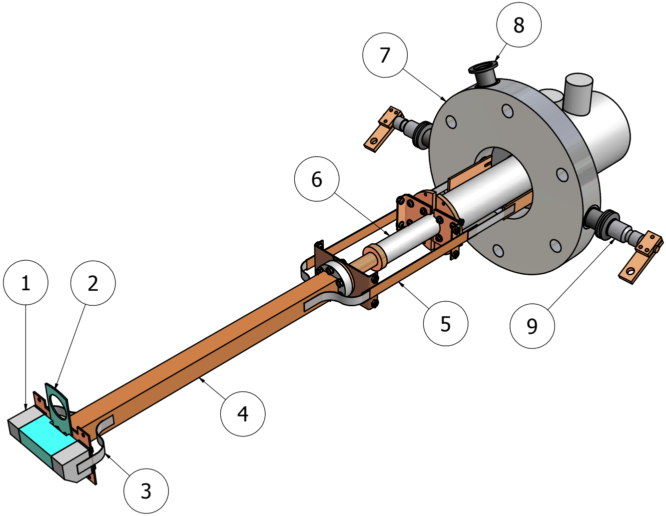
Contents

Summary and conclusion

- Quench behavior of single YBCO coated conductors of different architectures are studied
- Samples are cryocooled and tested in self field
- MQE $\sim$ 1 J; NZPV $\sim$ 10 mm/s
- Severe quench does degrade conductors catastrophically; conductors sensitive to the detection/protection time
- We should look for innovative quench detection and protection techniques for future HTS magnets

Contents

In-field quench probe



1, sample holder; 2, FGRP tension relief board; 3, Cu braids; 4, Cu extension rod; 5, HTS current leads; 6, cold head; 7, top flange; 8, instrumentation port; 9, power feedthrough

Source term — applied heat (backup)

The source term is

$$f(x,t) = f_{\mathrm{appl}}(x,t) + f_{\mathrm{self}}(x,t).$$

The heat generated by the heater is

$$f_{\mathrm{appl}}(x,t) \cdot U_{\mathrm{htr}} = \begin{cases} \frac{V^2}{R(T)} & x \in [x_{\mathrm{htr0}}, x_{\mathrm{htr1}}] \text{ and } t \in [t_{\mathrm{s}}, t_{\mathrm{e}}] \\ 0 & \text{otherwise.} \end{cases}$$

The volume, U_{htr}, is a constant and expressed by

$$U_{\mathrm{htr}} = w_{\mathrm{tape}}\, l_{\mathrm{htr}}\, (\xi\, t_{\mathrm{tape}}),$$

$$1 < \xi \leq \frac{t_{\mathrm{tape}} + t_{\mathrm{sty}}}{t_{\mathrm{tape}}}.$$

Source term — self generation (backup)

The self generation is

$$f_{\mathrm{self}}(x,t)\cdot U(x) = \begin{cases} I_{\mathrm{t}}^2 R_{\mathrm{nm}} & T_i \geq T_{\mathrm{c}} \\ I_{\mathrm{nm}}^2 R_{\mathrm{nm}} + (I_{\mathrm{nm}} R_{\mathrm{nm}}) I_{\mathrm{sc}} & T_i < T_{\mathrm{c}} \text{ and } I_{\mathrm{t}} > I_{\mathrm{sc}} \\ 0 & T_i < T_{\mathrm{c}} \text{ and } I_{\mathrm{t}} \leq I_{\mathrm{sc}}, \end{cases}$$

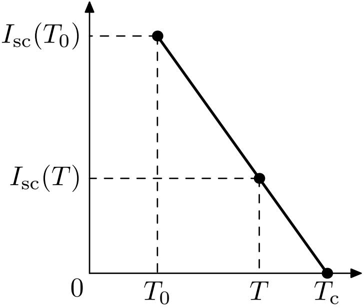
where the current conservation applies,

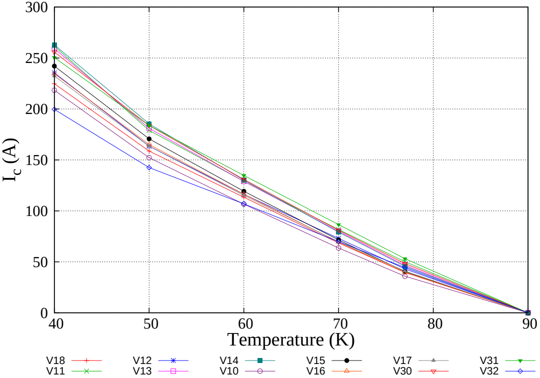
$$I_{\mathrm{nm}} + I_{\mathrm{sc}} = I_{\mathrm{t}}.$$

Source term — self generation (cont.)

Assumption 1,

$$I_{\rm sc}(T) = \frac{T_{\rm c} - T}{T_{\rm c} - T_0}\, I_{\rm sc}(T_0),$$





$I_{\mathrm{c,t}}/I_{\mathrm{c,d}}$ derivation

Three criterions: electric field, resistivity, and offset.[†] For electric field and offset criterions:

$$V_{\mathrm{c,t}} = c\, I_{\mathrm{c,t}}^{n}, \tag{4a}$$

$$V_{\mathrm{c,d}} = c\, I_{\mathrm{c,d}}^{n}, \tag{4b}$$

Since the same criterion is used, so we have

$$\frac{V_{\mathrm{c,t}}}{V_{\mathrm{c,d}}} = \frac{L_{\mathrm{t}}}{L_{\mathrm{d}}} = m. \tag{5}$$

Divide Eq. (4a) by Eq. (4b) and substitute Eq. (5), we have

$$\frac{I_{\mathrm{c,t}}}{I_{\mathrm{c,d}}} = \sqrt[n]{m}. \tag{6}$$

For resistivity criterion:

$$\frac{I_{\mathrm{c,t}}}{I_{\mathrm{c,d}}} = \sqrt[n-1]{m}$$

[†] Ekin, *Experimental techniques for low-temperature measurements*, OUP, 2007