# Quench detection and protection for HTS accelerator magnets

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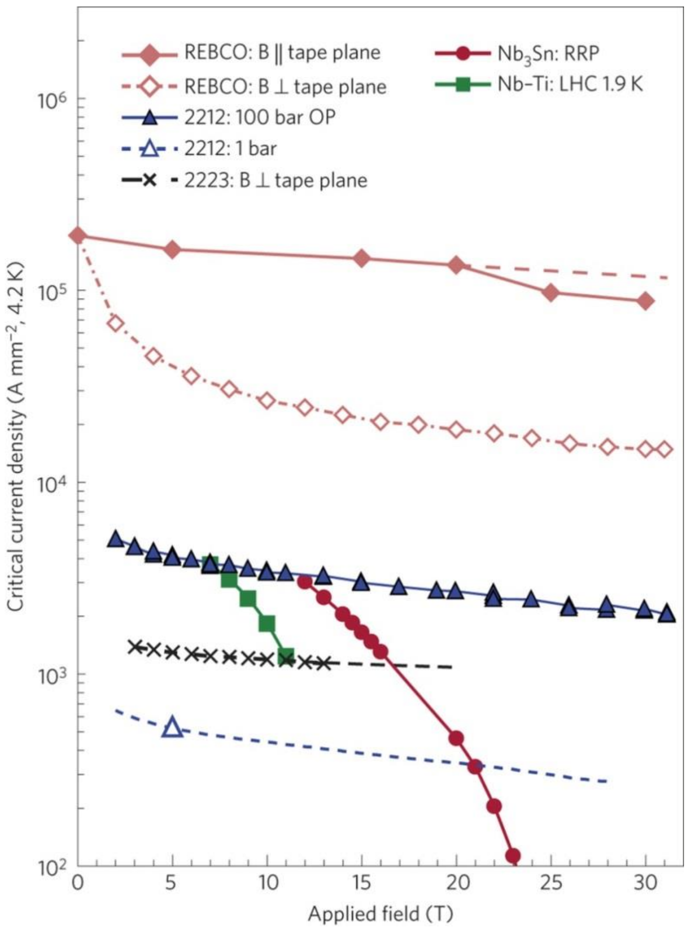
# Outline

- Quench in HTS magnet: the basics
  - Conductor properties: HTS vs LTS
  - Protection time margin
  - Simulation of quenching in HTS under adiabatic conditions and consequences for protection
- Quench protection in HTS: recent activity highlights
  - Conductor modification
  - Detection techniques
  - Protection techniques
- Split conductor for detection and protection

# Magnet prospective using HTS conductor




*D. C. Larbalestier et al., "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T", Nature Materials 13, 375–381 (2014)*

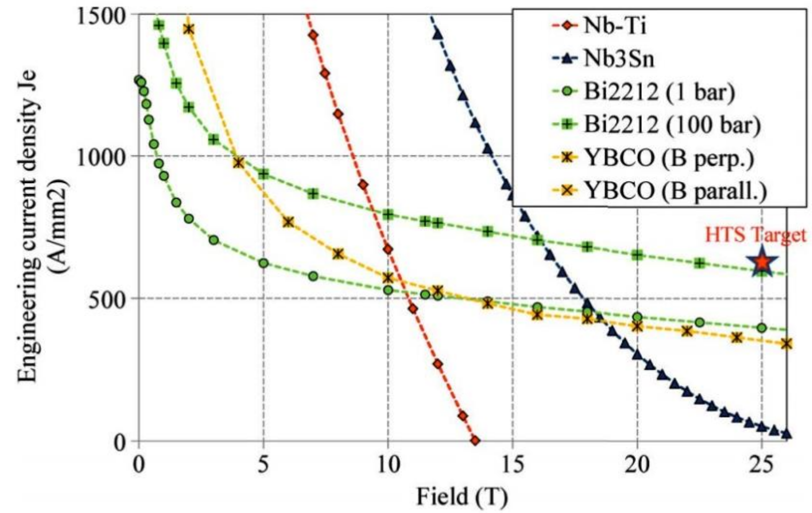


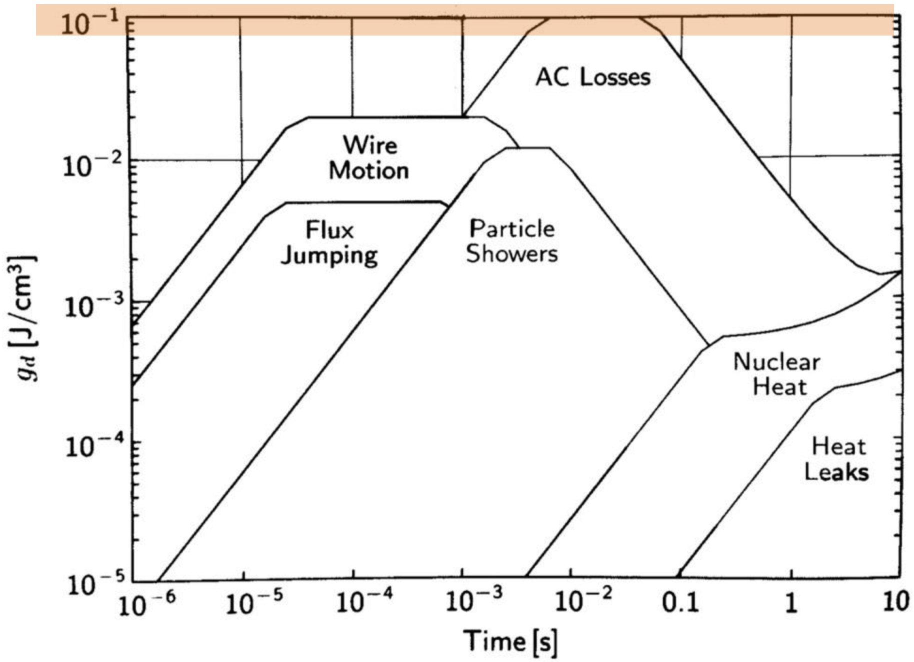

Fig. 1. Critical surface of practical supercondutors for magnets [data from P. Lee, NHFML].

20 T field with 400 A/mm$^2$ overall current density has been considered in "Malta Design" (*E. Todesco, F. Zimmermann, "The High-Energy LHC", CERN Rep. 2011-3, p. 13-16*)

HTS target: **500 A/mm$^2$**

E. Todesco, L. Bottura, G. De Rijk, L. Rossi , *"Dipoles for High-Energy LHC", IEEE Trans. Appl. Supercond.*, 24, 4004306, (2014)

# Disturbance spectra and stability margin




Mechanical events associated with conductor motion and/or impregnation material fracturing – a major source of quenching in LTS accelerator magnets are not likely to cause quenching in HTS.

Minimal quench energies in HTS are 2-3 order of magnitude larger than those in LTS !

Table 6.4: Selected Values of $T_{op}$, $\Delta T_{op}$, and $\Delta e_h$ for LTS and HTS

| *LTS* | | | *HTS* | | |
|---|---|---|---|---|---|
| $T_{op}$ [K] | $[\Delta T_{op}(I_{op})]_{st}$ [K] | $\Delta e_h$ [J/cm$^3$] | $T_{op}$ [K] | $[\Delta T_{op}(I_{op})]_{st}$ [K] | $\Delta e_h$ [J/cm$^3$] |
| 2.5 | 0.3 | $1.2\times10^{-4}$ | 4.2 | 25 | 1.6 |
| 4.2 | 0.5 | $0.6\times10^{-3}$ | 10 | 20 | 1.8 |
| 4.2 | 2 | $4.3\times10^{-3}$ | 30 | 10 | 3.7 |
| 10 | 1 | $9\times10^{-3}$ | 70 | 5 | 8.1 |

*Y. Iwasa, "Case Studies in Superconducting Magnets"*

# Temperature dependence of $J_e$

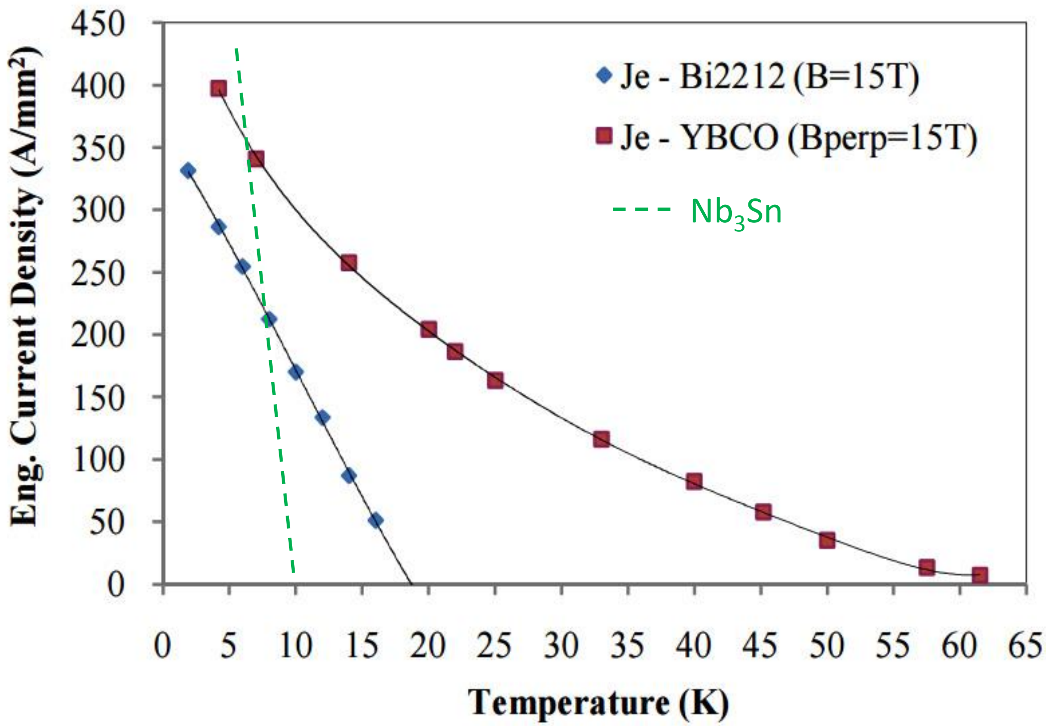



Fig. 12. Bi-2212 and YBCO $J_e$ comparison at the maximum achievable field (15T) as a function of temperature from 1.9 K up to 62 K.

**Large temperature margin combined with increase in heat capacity with temperature should guarantee high stability with respect to quenching**

*V. Lombardo et al., "Critical Currents of $YBa_2CuO_{7\text{-delta}}$ Tapes and $Bi_2Sr_2CaCu_2O_x$ Wires at Different Temperatures and Magnetic Fields" IEEE Trans. Appl. Supercond., 21, pp 3247 – 3250 (2011)*

# LTS vs HTS conductor

**n value:**

$$E = E_0\left(\frac{J}{J_c(T)}\right)^n$$

| LTS | HTS |
|---|---|
| **n ~ 50-80** | **n ~ 15-40** |
| Sharp "on-off" depinning: all current flows in the superconductor at $J<J_c(B, T_{cs})$), and switches fully into a normal metal stabilizer at $J>J_c(B, T_{cs})$, with Ohmic relation between E and J. No "flux-flow" regime! | As transition at $J_c$ is more gradual, superconductor can carry a portion of the current in the resistive (flux-flow) regime, while the rest flows into a stabilizer. Current is thus shared between superconductor and stabilizer over an extended (B,T) interval. |

"True" n-value is related to a thermally-activated flux creep exponent, as $E(j) = E_0(j/j_C)^n$, where $n = U_0/T$ and $U_0$ is the creep activation energy.

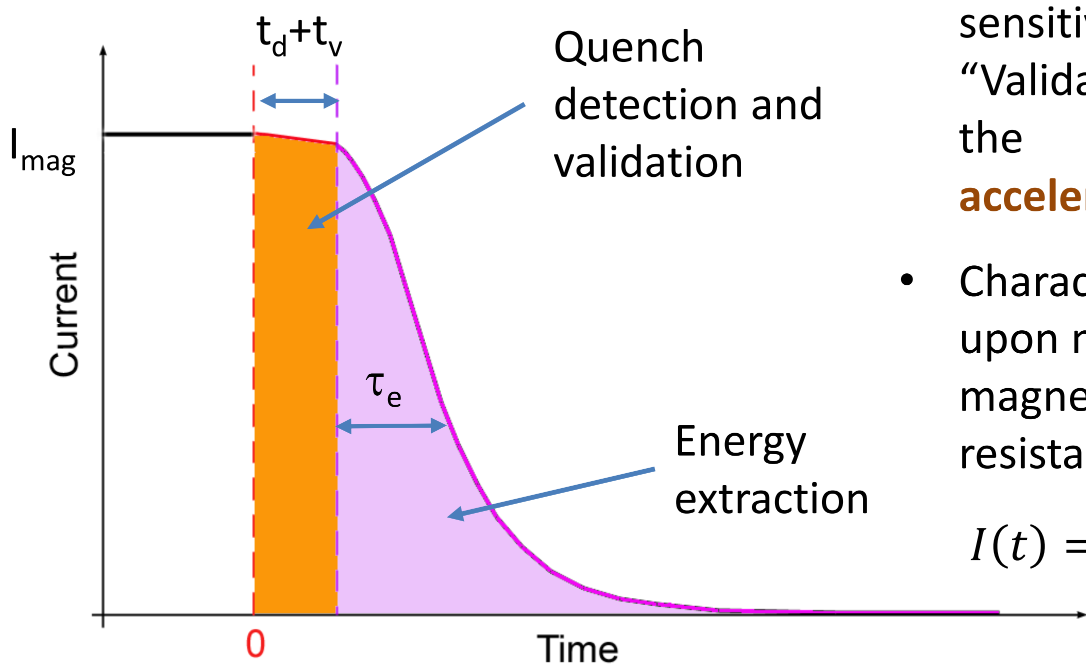
**Uniformity**

| LTS | HTS |
|---|---|
| Uniform $I_c$ of the conductor, modulated with magnetic field profile. Quench locations are usually defined by external factors. | Local $I_c$ variations can be large (10-15%) along the conductor, causing a pre-defined pattern of weak spots.<br>Caveat: low **n** measured in practice in fact result from local $J_c$ degradation along the conductor |

# So why would an HTS magnet quench?

- **Over-heating**: insufficient cooling resulting in a thermal runaway
- **Over-current**: current density goes overcritical, either locally due to:
  - conductor inhomogeneity
  - degradation due to stress (delamination, hairline cracks, edge defects - in REBCO; micro-cracks - in Bi 2212
  - quench in the LTS outsert of a hybrid magnet

# Current decay and energy extraction




- Detection time $t_d$ depends upon sensitivity and thresholds of QDS. "Validation time" $t_v$ is typically defined by the hardware. **Typically, for LTS accelerator magnets ($t_d+t_v$) ~ 7-15 ms**
- Characteristic extraction time $\tau_e$ depends upon magnet inductance and the sum of magnet and resistance and dump resistance:

$$I(t) = I_0 e^{-t/\tau_e} = I_0\ e^{\frac{-t(R_{mag}(t)+R_{dump})}{L}}$$

As magnet inductance *L* scales with magnet size, $\tau_e$ can be reduced by increasing $R_{mag}(t)$ (active protection) or by increasing $R_{dump}$ (passive protection).
In practice $R_{dump}$ is limited under ~100 mΩ by the maximal allowable magnet voltage $V_{mag\ max} = (I_{mag}\ R_{dump})$ < 1000 V. **Typically, for LTS accelerator magnets $\tau_e$ ~ 50-200 ms**

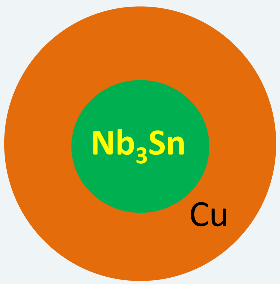
# Hot spot temperature and time margin

$$\int_0^{\text{Hot spot } T} \frac{c(T)}{\rho(T)} \mathrm{dT} = \frac{1+r}{r} \int_0^{\infty} J^2 \, dt$$ - adiabatic approximation

*N.M. Wilson, "Superconducting Magnets", Plenum Press, 1983.*

d = 0.8 mm

r = 1.2

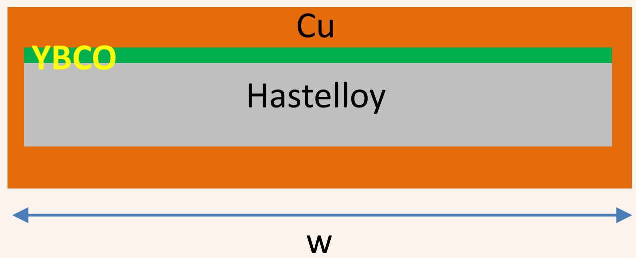



$$r = \frac{V_{Cu}}{V_{NbTi}}$$

$$c(T) = \frac{c_{Cu}(T)V_{Cu} + c_{NbTi}(T)V_{NbTi}}{V_{Cu} + V_{NbTi}}$$

$$\rho(T) = \rho_{Cu}(T)\frac{V_{Cu}+V_{NbTi}}{V_{Cu}} \quad (> T_{cs})$$

- At quench at $T_{cs}=T_c(B)$ all current switches into the stabilizer




w = 4 mm

$d_{YBCO} = 1.3 \ \mu m$

$d_{Cu} = 40 \ \mu m$

$d_H = 50 \ \mu m$

$T_c(15 \ T) = 65 \ K$

$\mathrm{RRR}_{Cu} = 25$

$E_0 = 1 \ \mu\mathrm{V/cm}$

$n = 30$

$$r = \frac{d_{Cu}}{d_{YBCO}} \qquad \rho_{St}(T) = \frac{\rho_{Cu}(T)\rho_H(T)(d_H + d_{Cu})}{\rho_{Cu}(T)d_H + \rho_H(T)d_{Cu}}$$

$$c(T) = \frac{c_{Cu}d_{Cu}+c_H d_H}{d_{Cu}+d_H}, \qquad \rho(T) = \frac{\rho_{St}(T)\rho_{YBCO}(T)(d_{YBCO}+d_{St})}{\rho_{St}(T)d_{YBCO}+\rho_{YBCO}(T)d_{St}}$$

where: $\rho_{YBCO}(T) = \frac{E_0 w d_{YBCO}}{I_c(T)} E_0 \left(\frac{I}{I_c(T)}\right)^{n-1}$, and $I_c(T) = I_{c0}\left(1 - \left(\frac{T}{T_c}\right)^{1.7}\right)$ *

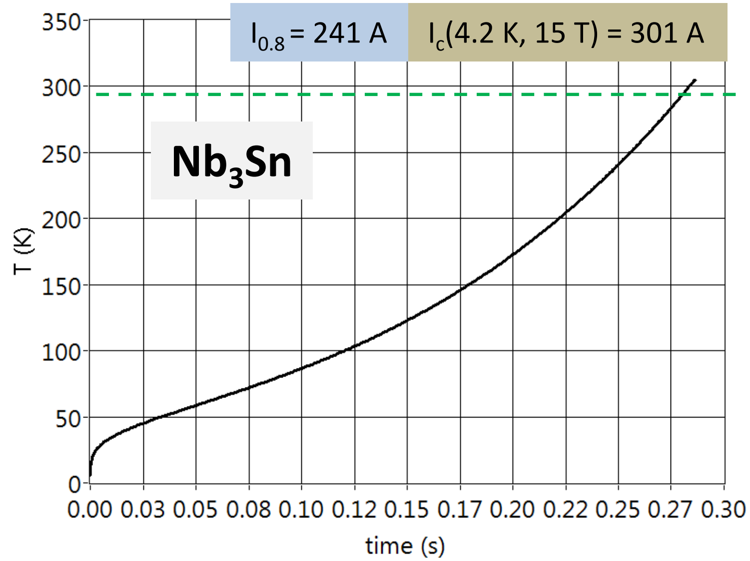
* *A.A.R. Fernades et al., Appl. Phys. Lett 61, 3181 (1992)*

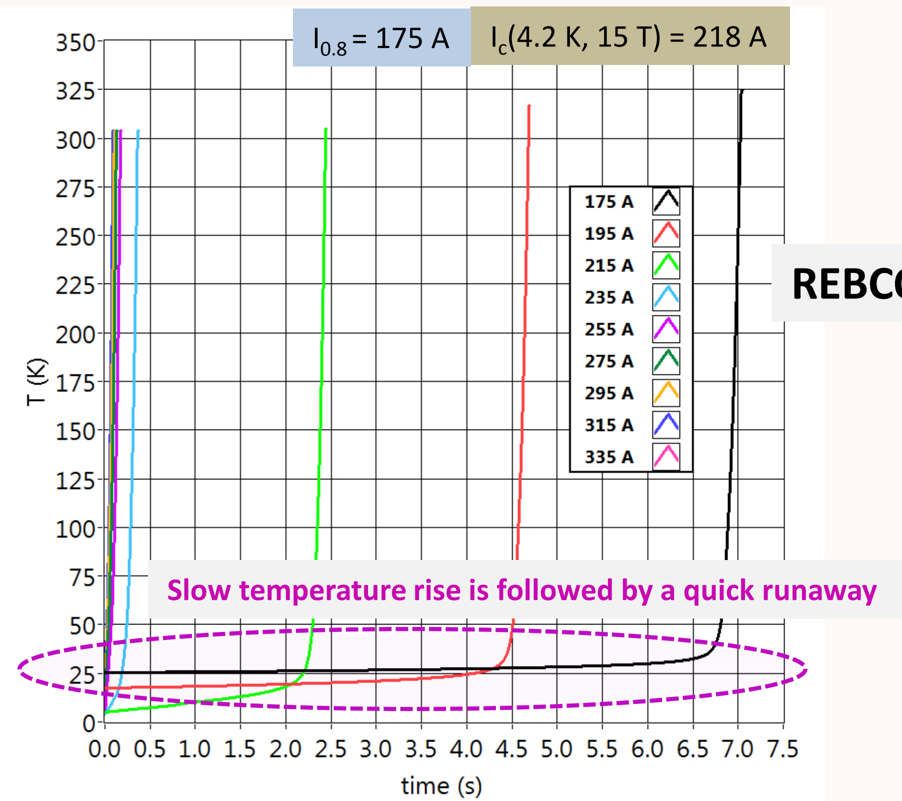
- Current is shared between superconductor and stabilizer (in parallel) across the entire temperature range

# Simulation 1: over-heating

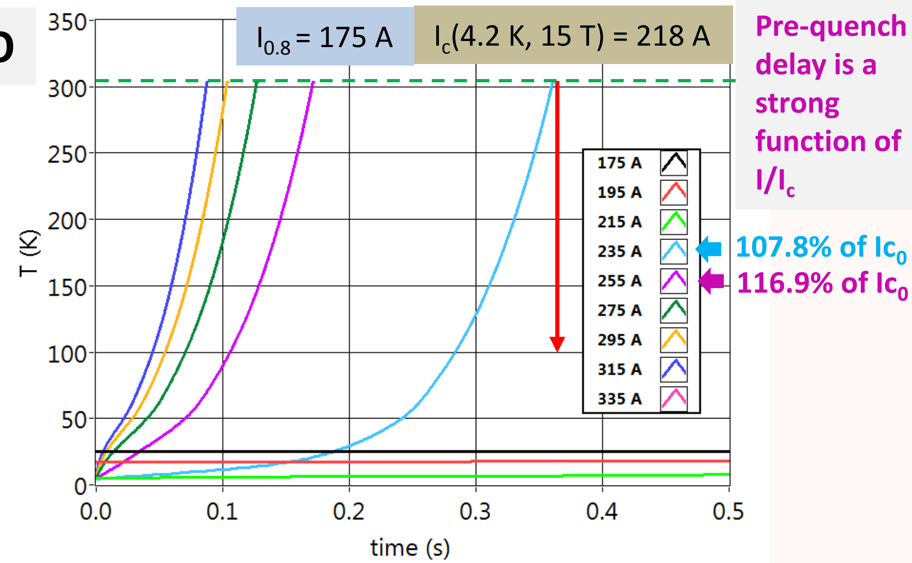
Let us assume that:

- Both conductors have same $J_e$=600 A/mm$^2$ at 4.2 K, 15T
- Both are operated at $I_{0.8}$ = 0.8 $I_c$(4.2 K, 15 T)
- The initial hotspot temperature $T_x$ is such that $I_c(T_x) = I_{0.8}$ resulting in:
  - $T_x$ = 5.63 K for $Nb_3Sn$ => T margin is ~ 1.4 K
  - $T_x$= 25.2 K for REBCO => T margin is ~ 21 K



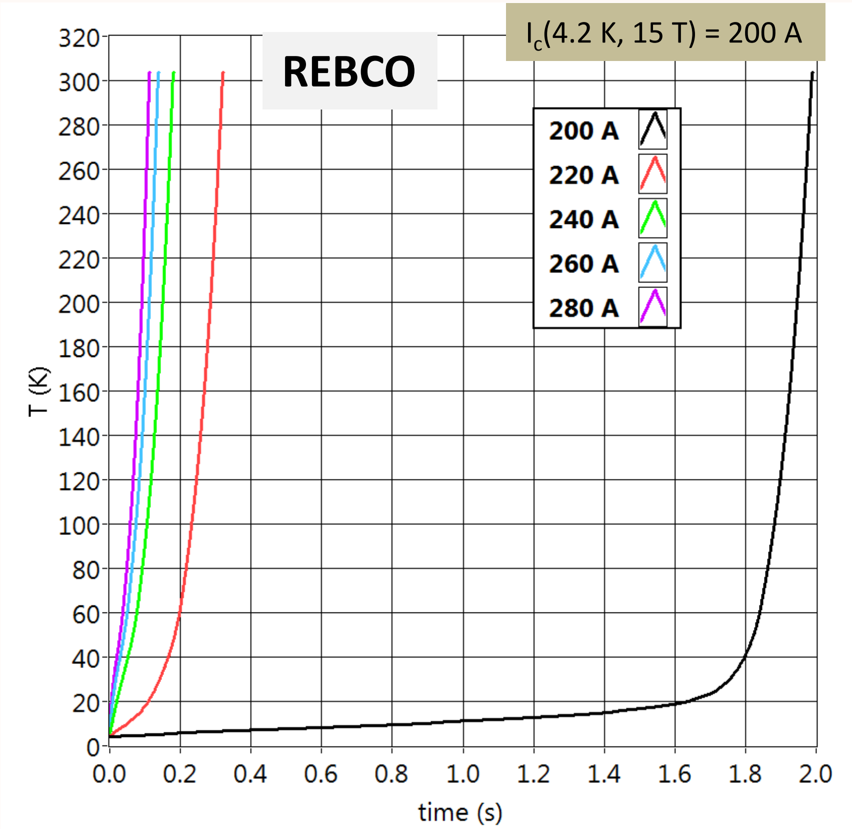



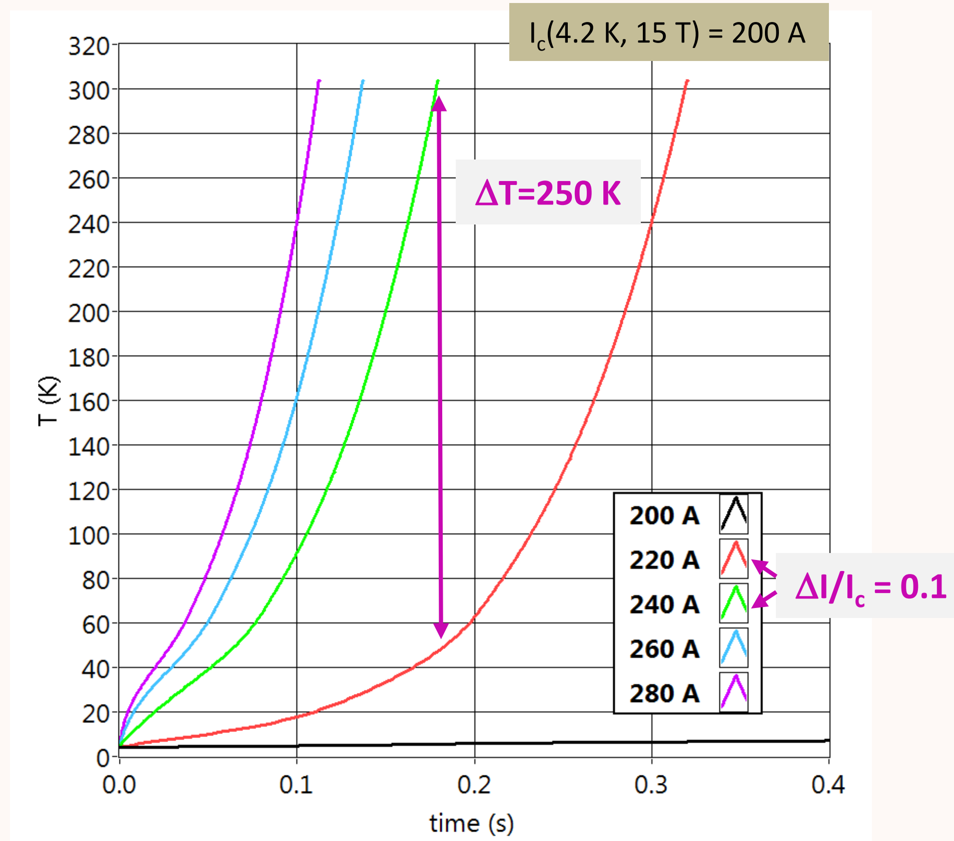

REBCO




Pre-quench delay is a strong function of $I/I_c$

# Simulation 2: over-critical current




**Temperature rise is very sensitive to the over-critical current magnitude.**
**10% difference in current may lead to as much as 250 K temperature variation!**

Same result holds if $I_c$ is varied while transport current is kept constant **=>** **localized hot spots will form** at the limiting points in the conductor, even if $\Delta I/I_c$ variations are just 5-10%...

# Quench propagation studies

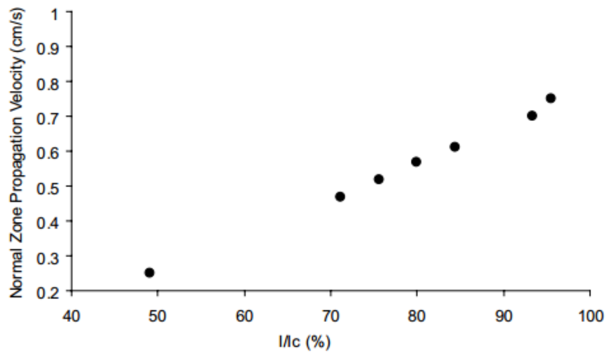
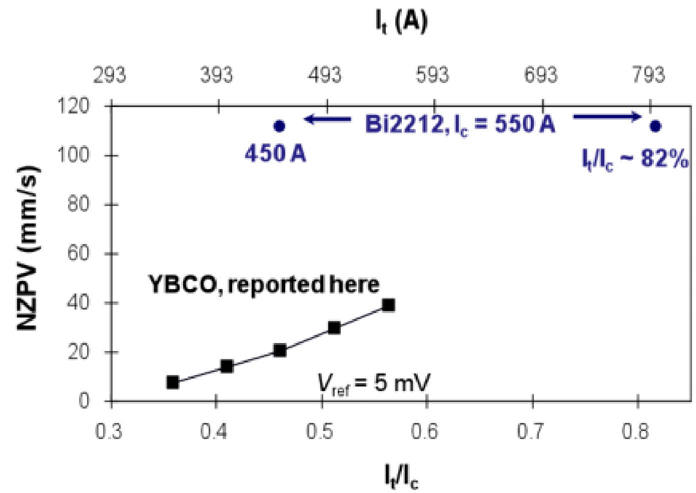
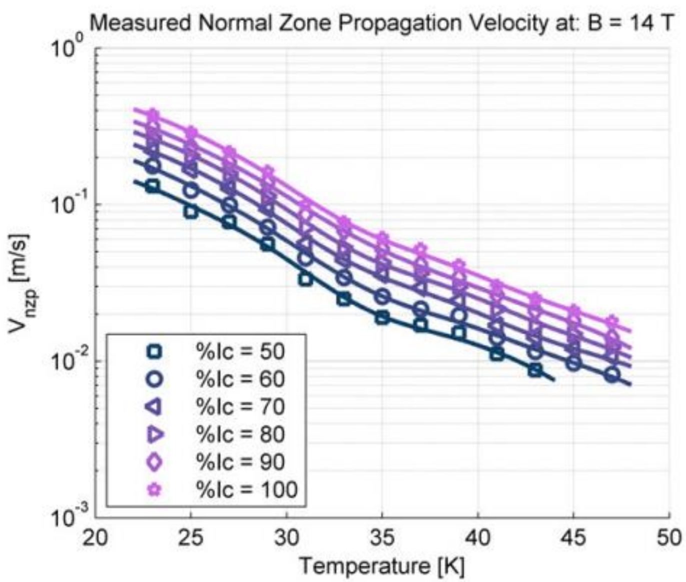



Fig. 13. Normal zone propagation velocity at the minimum energy required to initiate normal zone propagation versus $I/I_c$ for the YBCO coated conductor.

F. Trillaud et al., “Normal zone propagation experiments on HTS composite conductors”, Cryogenics 43 271–279, (2003)

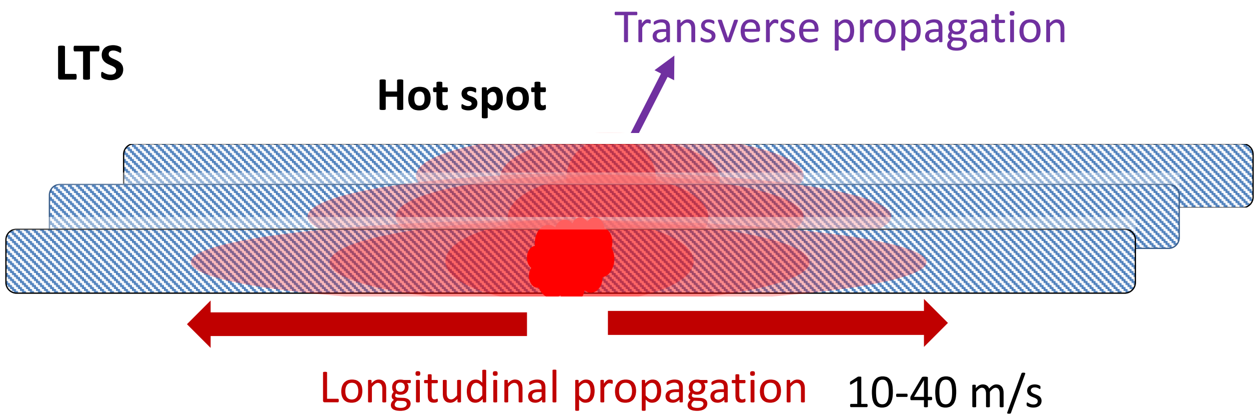



*H. H. Song and J. Schwartz, "Stability and Quench Behavior of YBa2Cu3O7-x Coated Conductor at 4.2 K, Self-Field," IEEE Trans. Appl. Supercond., 19, pp. 3735-3743, (2009).*

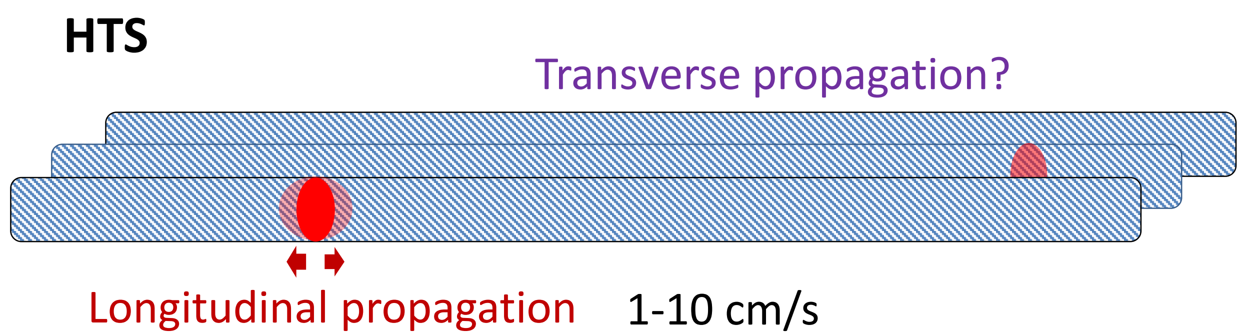



J. van Nugteren, “Normal Zone Propagation in a YBCO Superconducting Tape” MSc Thesis, Univ. of Twente, 2012

# Quench propagation: LTS vs HTS



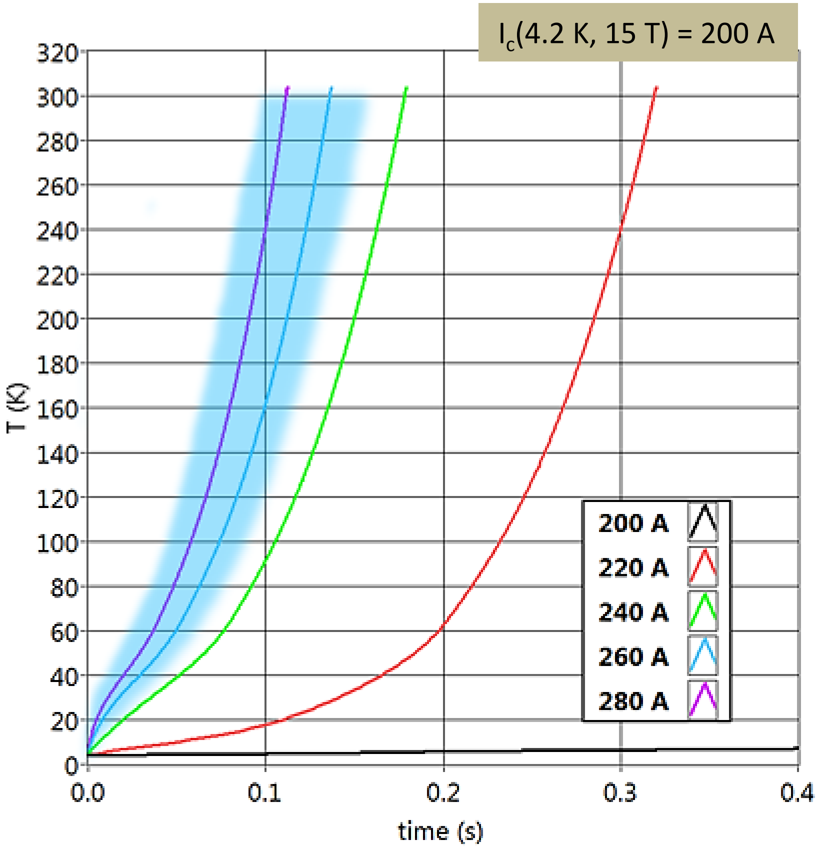

Resistance develops mainly due to quench propagation: **normal zone grows in size**




Resistance develops mainly due to heating of a hot spot: **normal zone heats up**

NZPV is 2-3 orders of magnitude lower in HTS compared to LTS (even in high fields!).
Isolated hot spots may be generated around various local conductor defects

# Do we have enough sensitivity to detect a quench?




$$E = E_0 \left( \frac{I}{I_c(T)} \right)^n$$

$$E_0 = 10^{-6}\ V/cm$$

Assuming there is only one hot spot in the coil, and quench propagation velocity is 1-10 cm/s, voltage of $\sim 10^{-6}\ V$ will develop at $I_c$. But it will be nearly impossible to detect 1 μV across a magnet coil of realistic size (due inductive voltage, PS noise, etc…). Typical voltages detected by QDS in LTS magnets are in range of 50-500 mV.

Suppose we can detect 1 mV (still very difficult), and n=30. Then we "over-shoot" $I_c$ by at least $(1000)^{1/30}$ = 1.26, i.e. by **26%** before detecting a quench.

And if we can only detect 100 mV (realistic), we "over-shoot" $I_c$ by $(100000)^{1/30}$ = 1.46, i.e. by **46%** !

**This leaves a very narrow time margin of ~100 ms.**
**A limiting factor for building large HTS magnets…**

**Detection is a key to protection**!

# So, what can be done?

**Modify the conductor:**

- Increase amount / conductivity of the stabilizer
- Improve heat transfer
- Increase interfacial resistance

**Alternative detection techniques:**

- optical (interferometric, Rayleigh scattering, FBG)
- acoustic (passive and active)

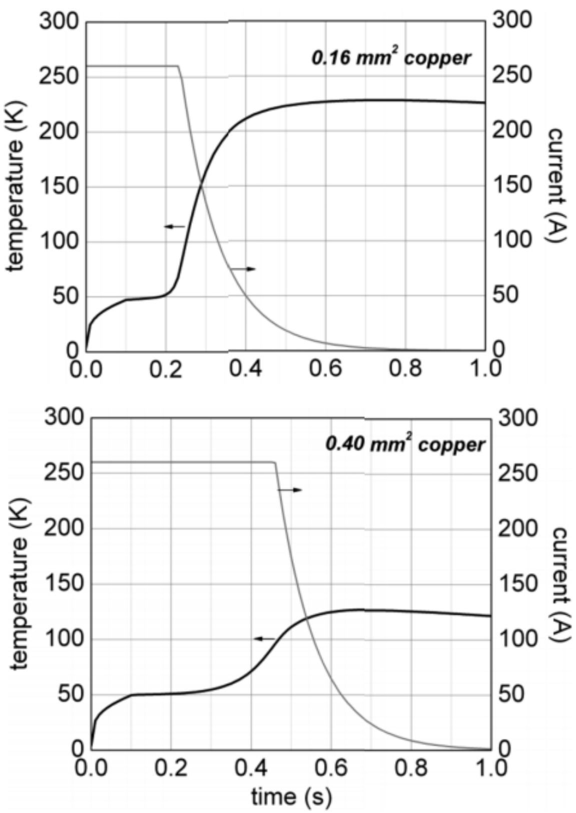
**New / improved protection techniques:**

- Passive protection: use non-insulated conductor
- Active protection
  - heaters to create a larger normal zone
  - coupling loss-induced bulk heating (CLIQ)
  - ac loss (hysteretic + eddy current) heating

# Conductor modification

# Adding thicker (or different) stabilizer

**Increased thickness of the stabilizer helps to reduce quench temperature…**



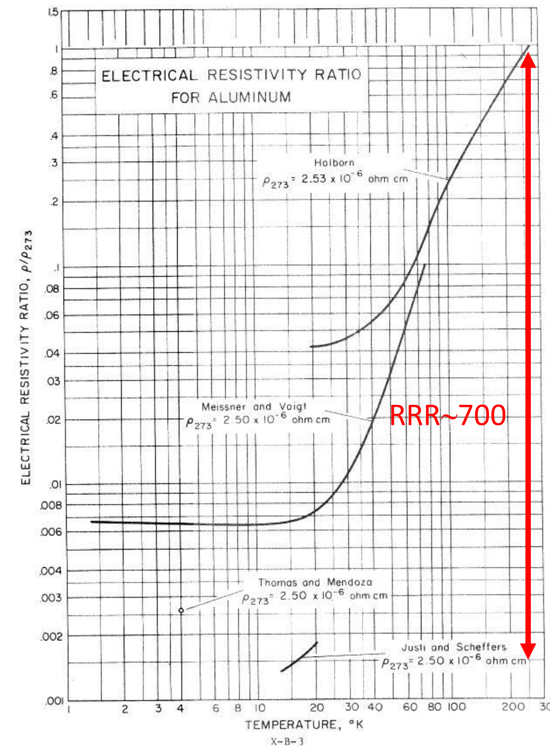

Evolution of YBCO tape temperature and current during the entire quench. Current dump started when the voltage drop reached 100 mV

*D. Uglietti and C. Marinucci, "Design of a Quench Protection System for a Coated Conductor Insert Coil", IEEE Trans. Appl. Supercond., 22, 4702704 (2012)*

**…but also reduces $J_e$**

**Alternative approach: use a stabilizer material with higher RRR.**

- High-purity Al can reach RRR of > 1000
- 3 mm of 99.999% Al is equivalent by resistivity to 40 mm of electroplated Cu at T<20 K




- If anodized, Al can also provide an efficient electrical insulation of the conductor.

*J. H. Bae et al., Thermal Characteristics of 2G HTS Tape With Anodized Aluminum Stabilizer for Cryogen-Free 2G HTS Magnet", IEEE Trans. Appl. Supercond.,25, 6605704 (2015)*

# Improving heat transfer

## Coating the conductor with a high thermal diffusivity compound

*S. Ishmael et al., "Enhanced Quench Propagation in $Bi_2Sr_2CaCu_2Ox$ and $YBa_2Cu_3O_{7-x}$ Coils via a Nanoscale Doped-Titania-Based Thermally Conducting Electrical Insulator", IEEE Trans Appl. Supercond. 23, 7201311, (2013)*

TABLE IV
TRANSVERSE (TURN-TO-TURN) NORMAL ZONE PROPAGATION VELOCITIES AT 77 K, SELF-FIELD, FOR YBCO PANCAKE COILS WITH KAPTON AND DOPED-TITANIA INSULATION COATINGS (TRANSPORT CURRENT = 60 A)

| Sections | Kapton insulated | Doped-titania insulated (large nanoparticles) | Doped-titania insulated (small nanoparticles) |
|---|---|---|---|
| Y1→Y2 | 5.15 layers/s (0.194 s/layer) | 12.82 layers/s (0.078 s/layer) | 15.63 layers/s (0.064 s/layer) |
| Y2→Y3 | 4.50 layers/s (0.222 s/layer) | 13.70 layers/s (0.073 s/layer) | 12.34 layers/s (0.081 s/layer) |
| Y3→Y4 | 4.12 layers/s (0.243 s/layer) | 12.66 layers/s (0.079 s/layer) | 13.33 layers/s (0.075 s/layer) |
| Average | 4.59 layers/s (0.219 s/layers) | 13.06 layers/s (0.077 s/layers) | 13.76 layers/s (0.073 s/layers) |

TABLE V
TRANSVERSE (TURN-TO-TURN) NORMAL ZONE PROPAGATION VELOCITIES AT 4.2 K AND 5 T FOR YBCO PANCAKE COILS WITH KAPTON AND DOPED-TITANIA INSULATION COATINGS

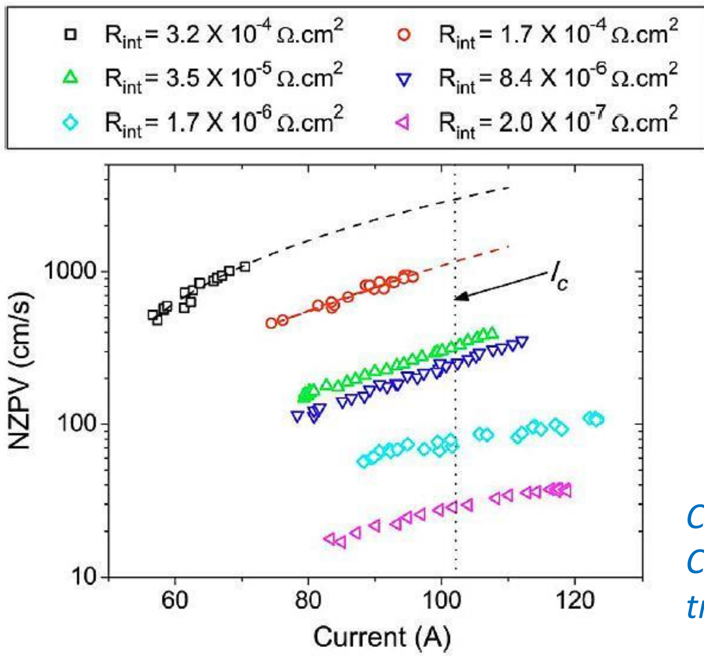
| Sections | $I_t = 150$ A | | $I_t = 250$ A | |
|---|---|---|---|---|
| | Kapton insulated | Doped-titania insulated | Kapton insulated | Doped-titania insulated |
| Y1→Y2 | 6.71 layer/s (0.149 s/layer) | 13.70 layer/s (0.073 s/layer) | 11.11 layer/s (0.09 s/layer) | 27.03 layer/s (0.037 s/layer) |
| Y2→Y3 | 6.02 layer/s (0.166 s/layer) | 14.29 layer/s (0.070 s/layer) | 10.10 layer/s (0.099 s/layer) | 26.32 layer/s (0.038 s/layer) |
| Y3→Y4 | 7.52 layer/s (0.133 s/layer) | 14.49 layer/s (0.069 s/layer) | 10.31 layer/s (0.097 s/layer) | 25.00 layer/s (0.040 s/layer) |
| Average | 6.75 layer/s (0.149 s/layer) | 14.16 layer/s (0.071 s/layer) | 10.51 layer/s (0.095 s/layer) | 26.11 layer/s (0.038 s/layer) |

- **Pro**: somewhat improved NZPV (several times). Can actually induce inter-layer propagation within the acceptable time margin
- **Con**: may be still insufficient for convention style quench protection relying on normal zone propagation

# Interfacial resistance

**Increase interfacial resistance between superconductor and stabilizer** (*G.A. Levin et al., "The effects of superconductor–stabilizer interfacial resistance on the quench of a current-carrying coated conductor", Supercond. Sci. Technol. 23 014021, (2010)*)

**"What is the advantage of having coated conductor with high stability margins?... Reduction of the stability margins in coated conductors accompanied by increasing NZP speed increases their value from the applications point of view…"**




The current diffusion length: $L = \sqrt{R_{int} d_n / \rho_n}$ (where $R_{int}$ is interfacial resistance, and $d_n$ and $\rho_n$ are stabilizer thickness and resistivity respectively) replaces thermal diffusion length in heat transfer equation, leading to a faster quench propagation.

*C. Lacroix et al., "Normal Zone Propagation Velocity in 2G HTS Coated Conductor With High Interfacial Resistance", IEEE trans. Appl. Supercond., 23, 4701605 (2013)*

- **Pro**: quench propagates at velocities comparable to those of LTS => all conventional quench protection schemes can be applied
- **Con**: reduces stability. This may in fact be OK… provided superconductor layer is fairly uniform

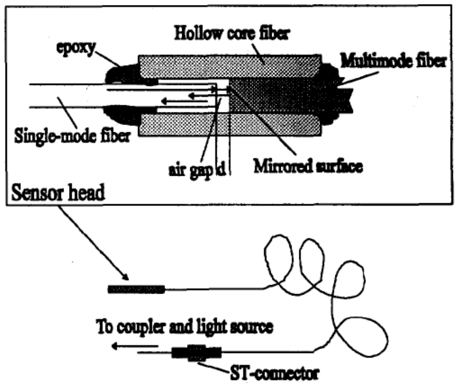
***Needs further studies!***

# New detection techniques

# Optical techniques

## Optical sensing: based on detecting local stresses generated by a hot spot

### Fiber-optic interferometer




J.M. van Oort, R.M. Scanlan and H.H.J ten Kate., *"A Fiber-optic Strain Measurement and Quench Localization System for Use in Superconducting Accelerator Dipole Magnets", IEEE Trans. Appl. Supercond. 5, 882 (1995)*

**The sensitivity of the fiber optic sensors for absolute readout is in the order of 50-100 nm, which yields a strain resolution of the order of $10x10^{-6}$ in the longitudinal and radial direction. The pressure resolution in the transverse direction is in the order of *5* MPa.**

### Rayleigh scattering

W.K. Chan, G. Flanagan and J. Schwartz, *"Spatial and temporal resolution requirements for quench detection in (RE)$Ba_2Cu_3O_x$ magnets using Rayleigh-scattering-based fiber optic distributed sensing",* Supercond. Sci. Technol. 26 105015 (2013).

### Fiber Bragg gratings (FBG)

F. Hunte et al., "Fiber Bragg optical sensors for YBCO applications", Proceedings of PAC09, Vancouver, BC, Canada

**Pro**: immune to EM interference. High sensitivity. Proven to work on small coils.
**Con**: requires co-winding optical fiber with the conductor + an increasingly powerful data processing for detecting quenches in long coils. Detection time is ~1s.

# Passive acoustic sensing

**Acoustic emissions (AE) in magnets appear due to epoxy cracking, delamination, slippages, or rapid heating of the normal zone volume (quench). When quench is triggered by a conductor motion (LTS), AE is always a precursor.**

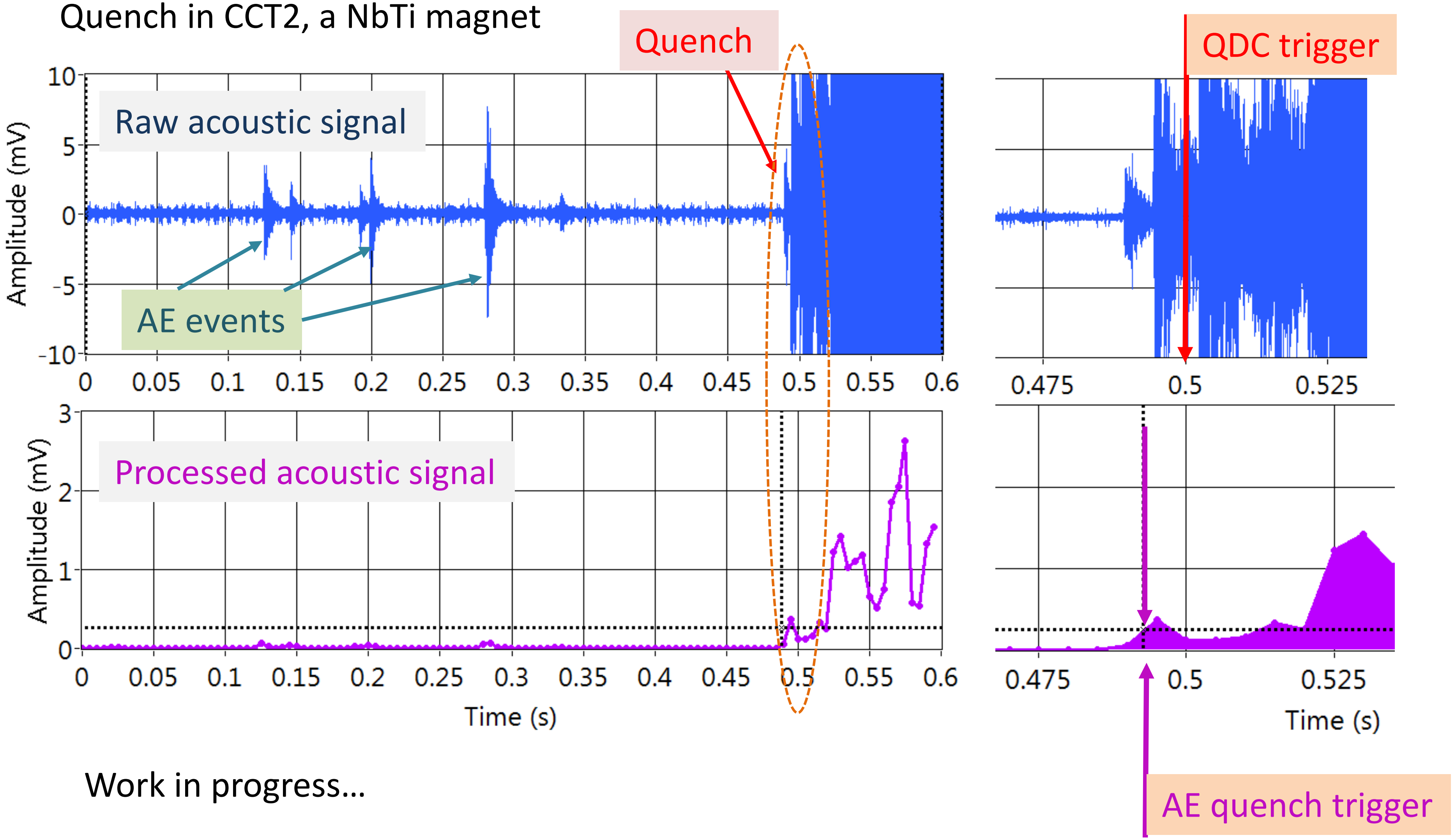
- *O. Tsukamoto, J.F. Maguire, E.S. Bobrov, and Y. Iwasa, Identification of quench origins in a superconductor with acoustic emission and voltage measurements", Appl. Phys. Lett. 39, 172 (1981)*
- *O. Tsukamoto and Y. Iwasa, "Sources of acoustic emission in superconducting magnets", J. Appl. Phys. 54, 997 (1983).*
- *"Acoustic emission triangulation of disturbances and quenches in a superconductor and a superconducting magnet", Appl. Phys. Lett. 40, 538 (1992)*
- *Y. Iwasa, "Mechanical Disturbances in Superconducting Magnets-A Review", IEEE Trans on Magn., 28 113 (1992)*
- *H. Lee et al., "Detection of 'Hot Spots' in HTS Coils and Test Samples With Acoustic Emission Signals", IEEE Trans. Appl. Supercond. 14, 1298 (2004)*
- *M. Marchevsky, G. Sabbi, H. Bajas, S. Gourlay, "Acoustic emission during quench training of superconducting accelerator magnets", Cryogenics 69, 550-57, (2015)*

**But is there a *criterion* that would allows differentiating AE of quenches from other events?**

**Yes, we believe such criterion exists.**

# Example of passive AE quench detection

Quench in CCT2, a NbTi magnet




Work in progress…

# Active (heat-specific) acoustic detection

**Monitoring changes in acoustic transfer function and structural resonances due to a local heating within the windings**

- O. Tsukamoto and Y. Iwasa, "*Correlation of acoustic emission with normal zone occurrence in epoxy impregnated windings: An application of acoustic emission diagnostic technique to pulse superconducting magnets*", Appl. Phys. Lett. 44, 922-924 (1984)
- T. Ishigohka et al., "*Method to detect a temperature rise in superconducting coils with piezoelectric sensors*", Appl. Phys. Lett. 43 (3), pp. 317-318 (1983)
- A. Ninomiya et al., "*Quench detection of superconducting magnets using ultrasonic wave*", IEEE Trans. Magn. 25, v2 pp 1520-1523 (1989)

- *T. Ishigohka et al., "Method to detect a temperature rise in superconducting coils with piezoelectric sensors", Appl. Phys. Lett.43, 317 (1983)*
- A. Ninomiya et al., "*Monitoring of a superconducting magnet using an ultrasonic technique*", Fusion Eng. Design 20, 305-309, (1993)

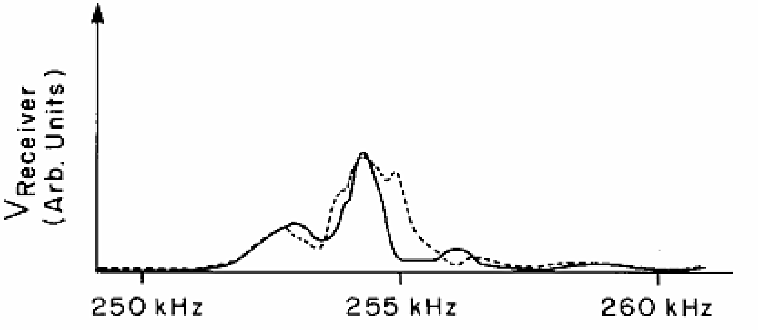
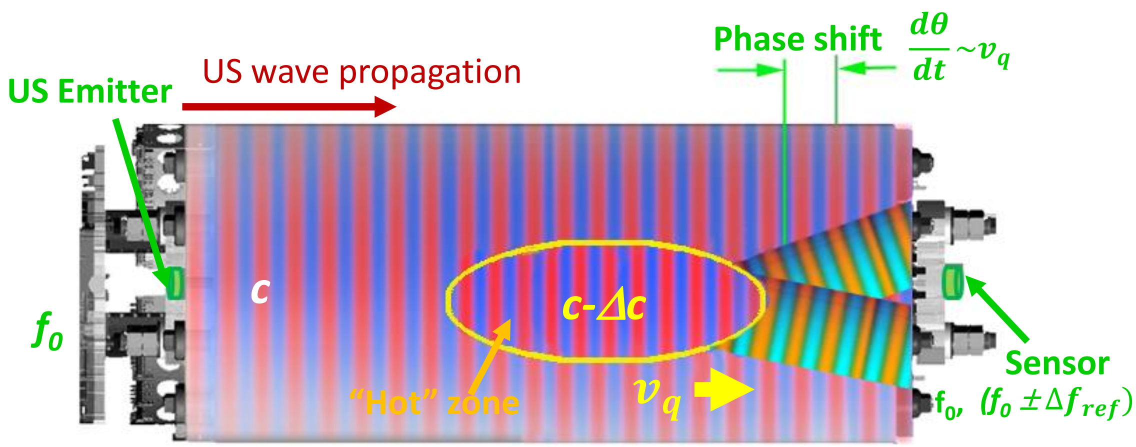


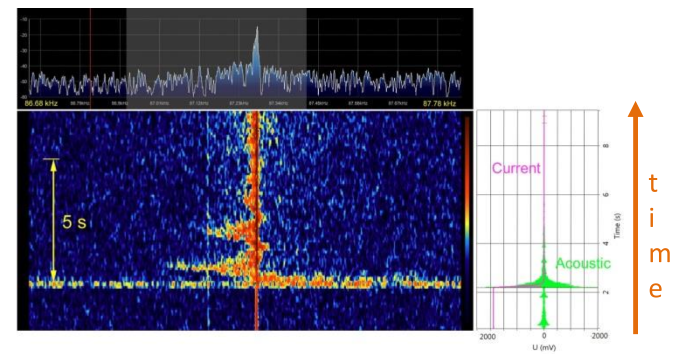

FIG. 3. Frequency spectra for the test coil immersed in a bath of liquid helium, with heater current zero (solid curve) and with heater current at 0.3 A (dotted curve).

**To be usable for quench detection, these techniques require mechanical modeling of the coil eigenfrequencies and transfer function that are experimentally validated prior to actual QD.**

# Acoustic detection of a propagating hot zone using "Doppler" effect

*MM, "Active ultrasonic quench diagnostics for the superconducting magnets", ASC 2014*




Heating will cause a local variation of the sound velocity, and some amount of acoustic energy will be scattered back from the hot zone. If the hot zone is expanding with radial velocity v, the associated frequency shift of the scattered wave is $\frac{\Delta f_{ref}}{f_0} = \frac{v_q}{c} \sim 10^{-5}$ (Doppler effect). However, since $\Delta c/c \sim 4.35 \times 10^{-3}$ per $\Delta T=100$ K, the amount of scatted energy will be very small… Still, it is clearly detectable when a large portion of the winding heats up.

# Protection methods

# Passive protection: non-insulated coils

Non-insulated coils can be a viable option for protection:

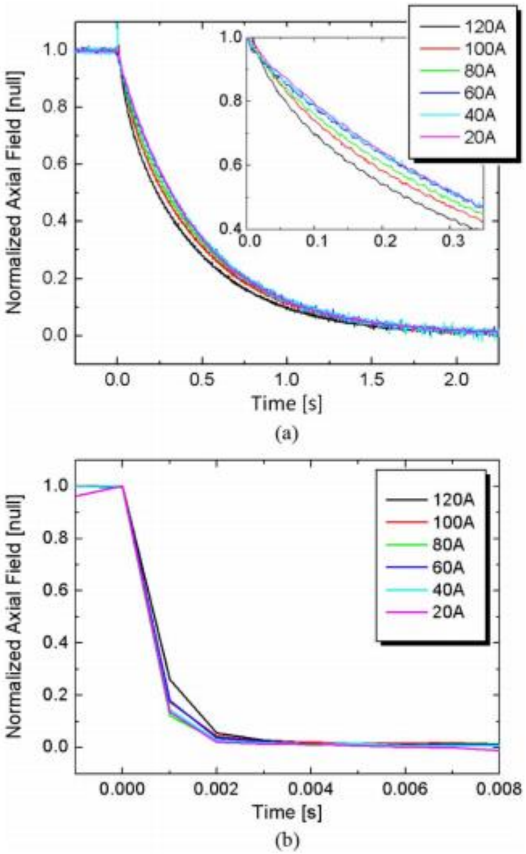
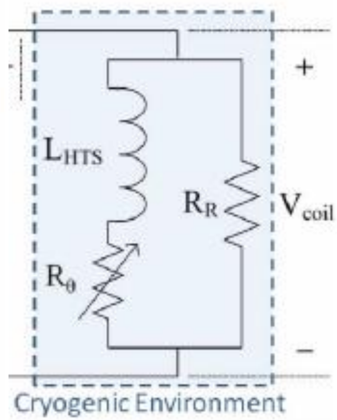



Fig. 6. Normalized field time functions from sudden discharge tests: (a) Bare; (b) Hastelloy. Time reference of each graph was adjusted for easy comparison.



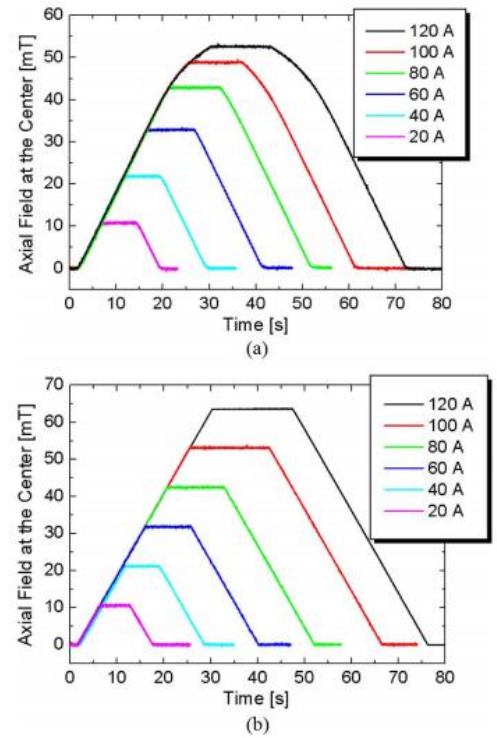
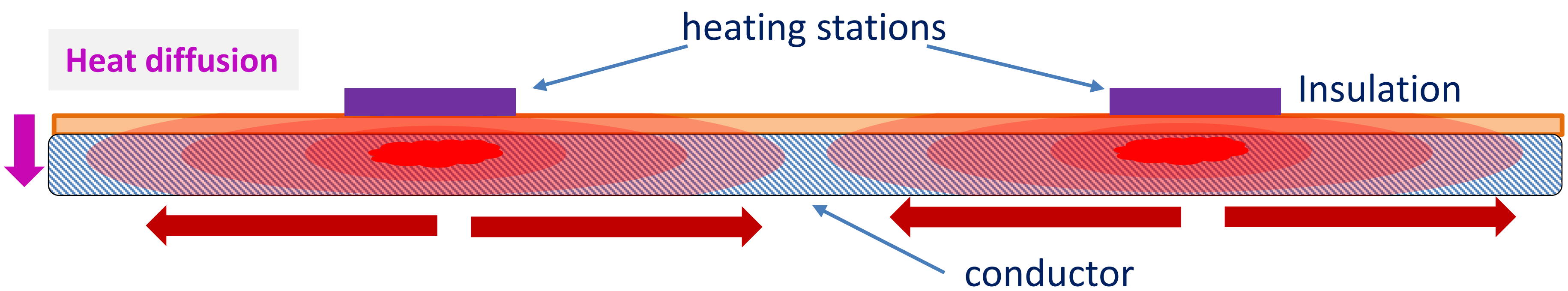




Fig. 4. Axial center field time functions: (a) Bare; and (b) Hastelloy.

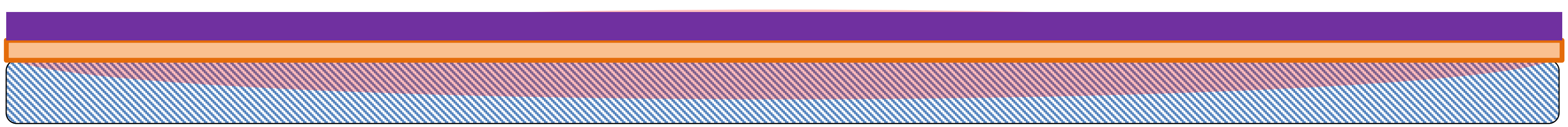
*S. Hanh et al., "HTS pancake coil without turn-to-turn insulation", IEEE Trans Appl. Supercond., 21 1592 (2011)*

- The NI coil was shown to carry 2.7 $I_c$ without burning
- Fast current decay for over-critical currents

# Active protection: surface heaters



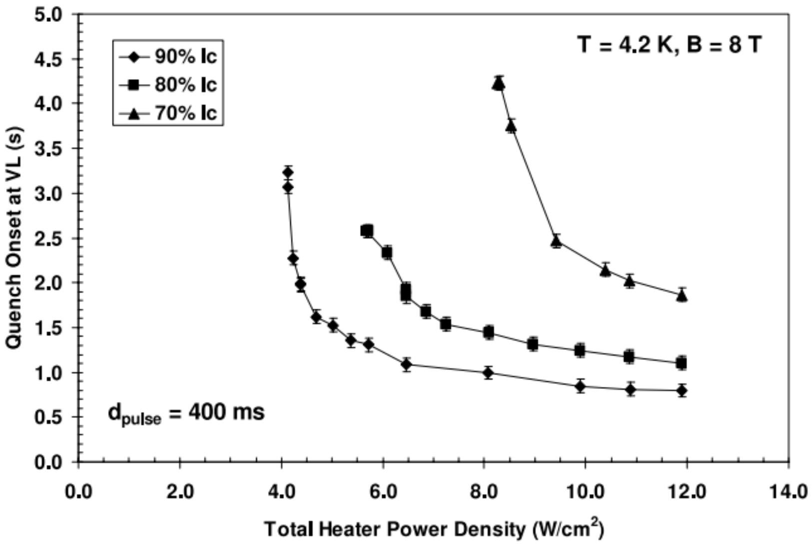

Duet to a very low NZVP in HTS, one can not rely on quench propagation between heating stations (unless they are just a few cm apart)



Continuous heater coverage is possible (and was demonstrated for small coils). But covering the **entire** conductor length is not very practical (unless maybe it is co-wound with the conductor, which will reduce $J_e$).

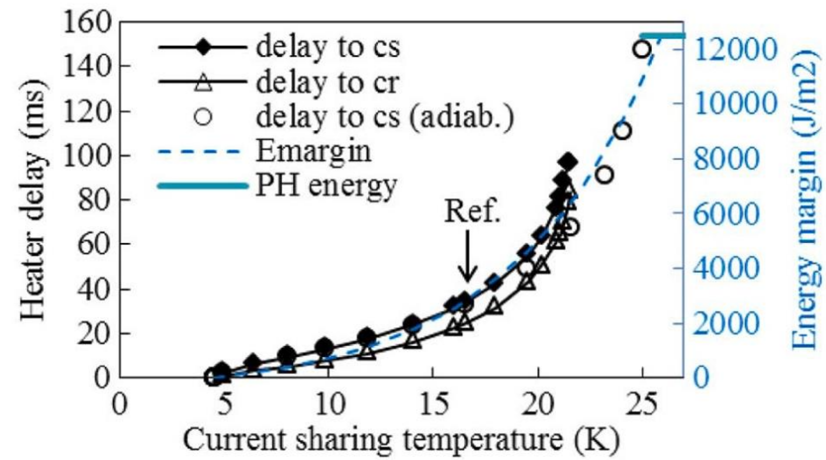
*P.D. Noyes et al, "Protection heater development for REBCO coils", IEEE Trans. Appl. Supercond.* 22 4704204, (2012)

# Heater delay vs current and temperature margin




U. P. Trociewitz et al., “*Quench studies on a layer-wound $Bi_2Sr_2CaCu_2O_x/Ag_X$ coil at 4.2 K*”, Supercond. Sci. Technol. 21 025015, (2008)

**Coil can be quenched with low heater power, but the delay times are long…**




PARAMETERS REFERENCE VALUES AND THE RANGE OF VARIATION IN THE PARAMETRIC ANALYSIS OF HEATER DELAYS

| Parameter | Reference | Variation range |
|---|---|---|
| Magnetic field (T) | 20 | 6.5 - 50 |
| Current sharing temperature (K) | 16.5 | 4.9 - 26.6 |
| Heater power (W/cm$^2$) | 50 | 20 - 200 |
| Heater insulation (mm) | 0.050 | 0.001 - 0.15 |
| Heater coverage (mm) | 100% | 10-100 (period 120) |
| Heater thickness (mm) | 0.025 | 0.025 or 0.050 |

*T. Salmi and A. Stenvall, “Modeling Quench Protection Heater Delays in an HTS Coil, IEEE Trans. Appl, Supercond., 25, 0500205, (2014)*

**Heater delay increases with quench margin. Use of heaters becomes increasingly problematic at low (< 15 T) fields.**

# Active protection: bulk heating using coupling losses (CLIQ)

**Coupling loss induced quenching (CLIQ) heats up the conductor in the bulk, and therefore is superior to the surface heating technique. It has been very successful in application to LARP magnets, and is to be used for protection of the future MQXF quadrupole at LHC**

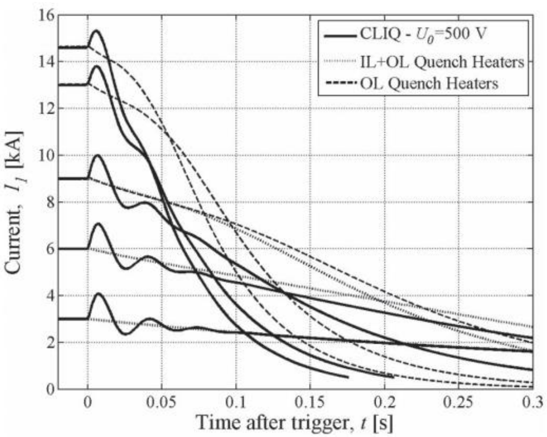



Fig. 2. Comparison between the measured magnet current after triggering quench heaters or CLIQ at current levels ranging from 3 to $I_{nom}$ = 14.6 kA.

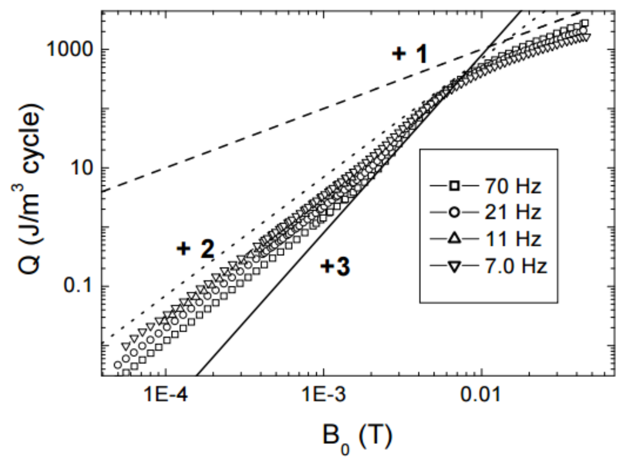
*E. Ravaioli et al., "Protecting a Full-Scale $Nb_3Sn$ magnet with CLIQ, the New Coupling-loss Induced Quench System, IEEE Trans. Appl. Supercond., 25, 4001305 (2015)*

- Are coupling losses in round or striated HTS conductors sufficient to realize CLIQ given the large temperature margin?
- Time margin?
- Optimization in frequency and amplitude?

*E. Ravaioli (next talk)*

Coupling losses in a BSCCO tape conductor.

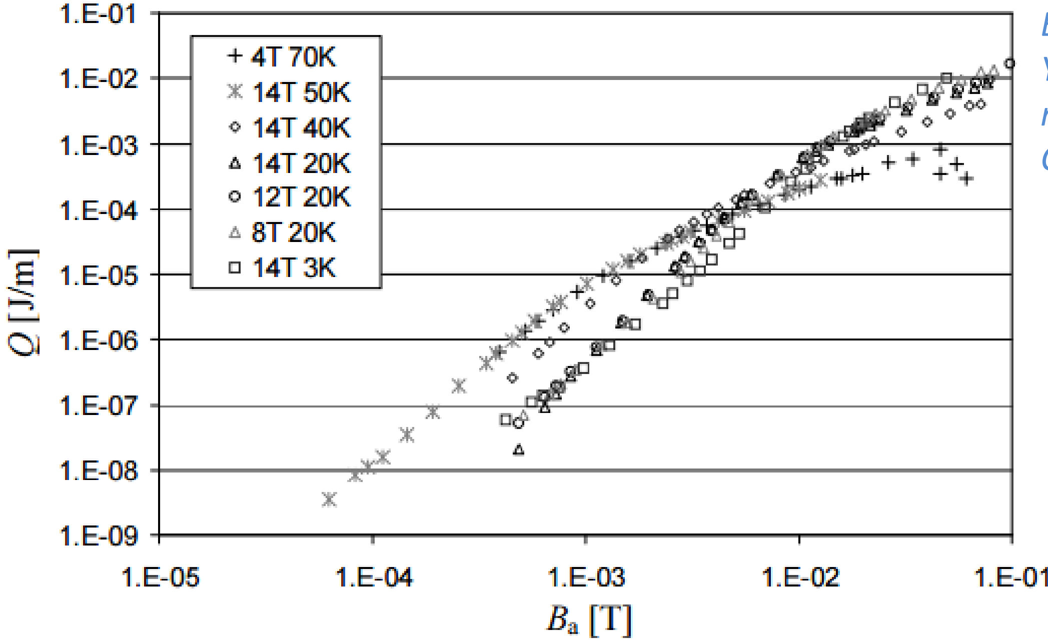
| | |
|---|---|
| matrix | Ag |
| External sheath | Ag |
| fill factor ($\eta$) | 32 % |
| width ($w$) | 3.3 mm |
| thickness ($t$) | 0.25 mm |
| initial length ($\ell$) | 61.7 mm |
| critical current ($I_c$) | 23.5 A |
| c. c. density ($J_c$) | 9653 A/cm$^2$ |
| exponent ($n$) | 15 |




*D Zola, "A study of coupling loss on bi-columnar BSCCO/Ag tapes through ac susceptibility measurements", Supercond. Sci. Technol., 17, 501 (2004).*

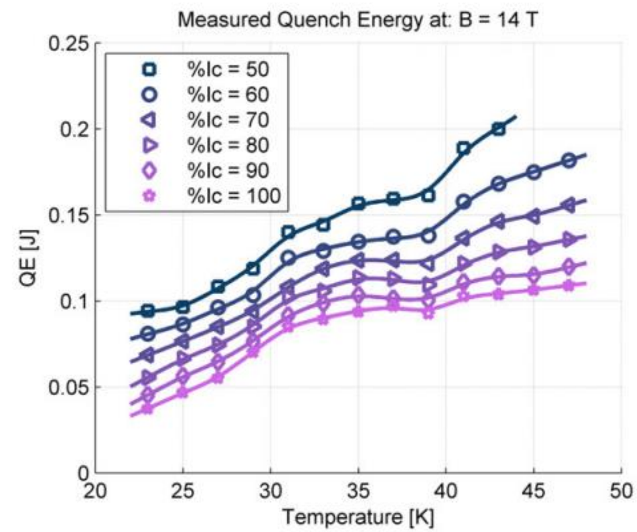
# AC loss in REBCO tape and protection?

AC field normal to the tape surface:




*E. Seiler and L. Frolek , "AC loss of the YBCO coated conductor in high magnetic fields", Journal of Physics: Conference Series 97 , 012028, (2008)*

AC losses per meter of the coated conductor (per cycle) in dependence on the AC magnetic field amplitude $B_a$ measured at different temperatures and superimposed DC magnetic fields.



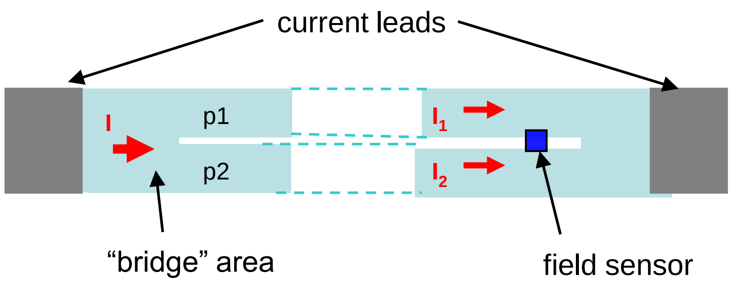

J. van Nugteren, "Normal Zone Propagation in a YBCO Superconducting Tape" MSc Thesis, Univ. of Twente, 2012

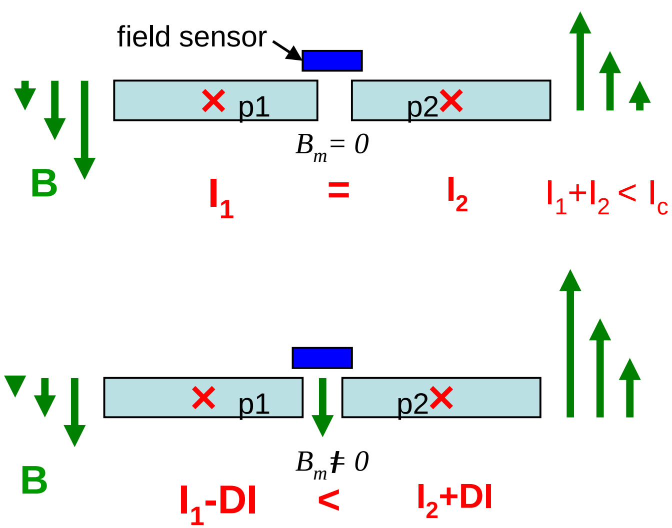
**Assuming protection operates at ~ 100 Hz, ac loss heating is about 1 W/m, or ~2.5 W/cm$^3$ when re-calculated with tape dimensions.**

**In the same range as typical MQEs!**

# Detection + protection using split conductor

# Split conductor for detection…




*M. Marchevsky et al. "Quench detection method for 2G HTS wire", Supercond. Sci. Technol. 23 034016 (2010)*

Quench detection using split wire or otherwise two conductors following same geometrical path and electrically separated from each other except at the ends.

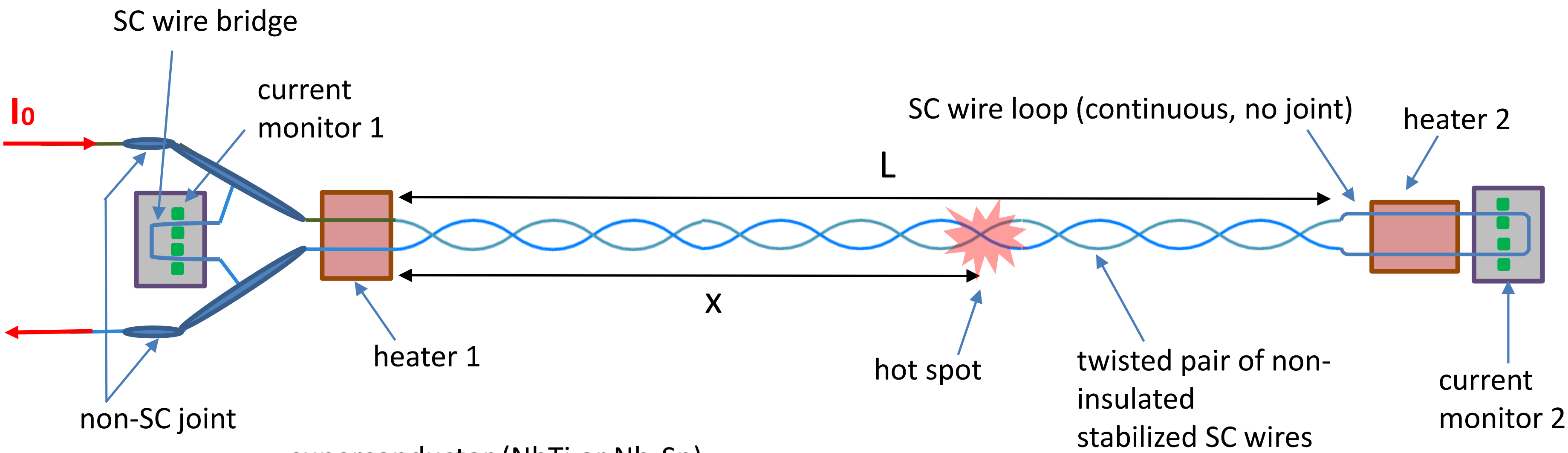
**Pro**:

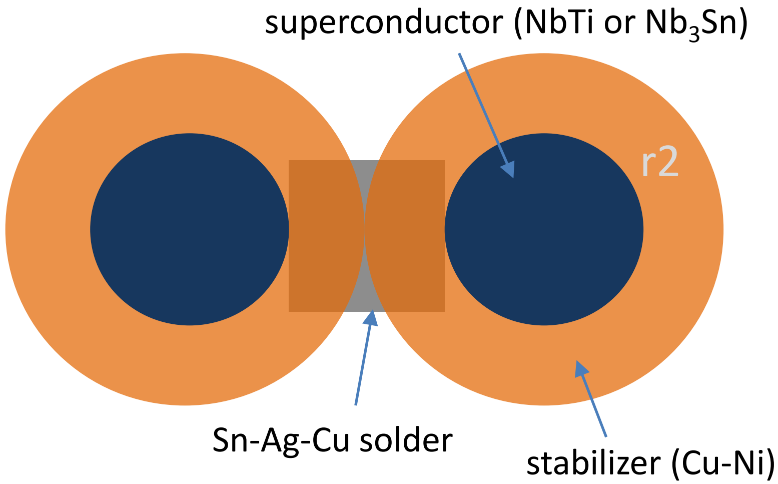
- **Sensitivity is in $10^{-12}$ Ohm range** for superconducting end joints, and ~$10^{-8}$-$10^{-9}$ Ohm for non-superconducting joints - way superior to voltage detection!
- The technique **can sense heating at $I \ll I_c$ (!)** - through increased *flux creep rate* in the conductor leading to a change in the current balance
- Fast and **applicable to long magnets**, as inductance of the coil is (almost) cancelled out

**Con**:

- Field sensors must be placed well away from the magnet bore
- Imbalance due to ac losses (ramp-rate dependent) is possible

# …quench location sensor…



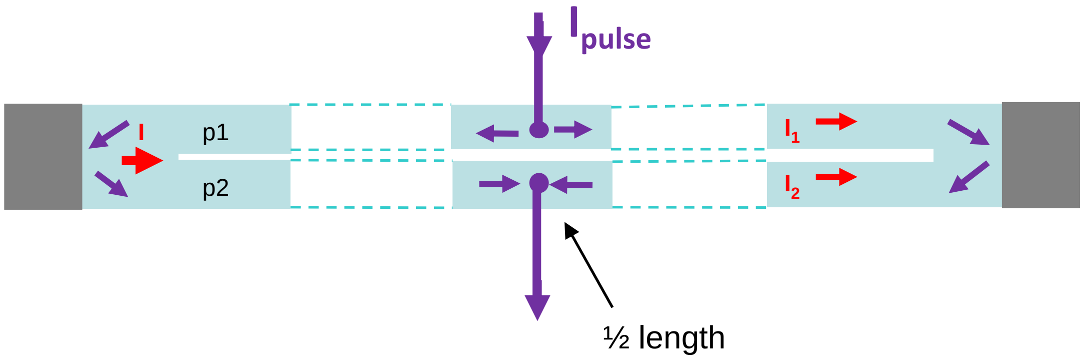




- No low-level voltage measurements are necessary
- Inter-core resistance is measured through a current balance against a fixed resistance formed by the two normal joints connecting a superconducting wire bridge. Length of the joints is tuned to provide for a resistance of ~10x-30x of the core-to core resistance of the twisted pair from end to end.

*M. Marchevsky et al. "Linear quench localization sensor", to be published.*

# …and protection

Same conductor configuration was proposed for magnet protection!




Upon detecting a quench, a current pulse (in excess of $I_c$) is applied to the central taps connected to the branches of a split conductor.

*T. Wakuda et al. "A Novel Quench Protection technique for HTS Coils", IEEE Trans. Appl. Supercond. 22, 4703404 (2012)*

**Inductance in cancelled out along the conductor path => applicable to long magnets**

The principle can be realized in various configurations, such as:

- REBCO ROEBEL cable with half of its strands electrically insulated from another half
- Two electrically insulated tape stacks
- Pair of insulated and twisted multi-filamentary Bi 2212 wires

**Compensated inductance enables use of high-frequency currents for coil protection. This can potentially enable novel protection mechanisms ("ac shaking", eddy currents, etc…) that are presently incompatible with long magnets due to their inductive impedance.**

# Thank you!