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

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: \textbf{500 A/mm}\(^2\)


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

<table>
<thead>
<tr>
<th></th>
<th>$T_{op}$ [K]</th>
<th>$\Delta T_{op}(I_{op})$ [K]</th>
<th>$\Delta e_h$ [J/cm³]</th>
<th>$T_{op}$ [K]</th>
<th>$\Delta T_{op}(I_{op})$ [K]</th>
<th>$\Delta e_h$ [J/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LTS</strong></td>
<td>2.5</td>
<td>0.3</td>
<td>$1.2 \times 10^{-4}$</td>
<td>4.2</td>
<td>25</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>0.5</td>
<td>$0.6 \times 10^{-3}$</td>
<td>10</td>
<td>20</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>2</td>
<td>$4.3 \times 10^{-3}$</td>
<td>30</td>
<td>10</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1</td>
<td>$9 \times 10^{-3}$</td>
<td>70</td>
<td>5</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Y. Iwasa, “Case Studies in Superconducting Magnets”
Large temperature margin combined with increase in heat capacity with temperature should guarantee high stability with respect to quenching.

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.

LTS vs HTS conductor

**n value:**

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

“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.

<table>
<thead>
<tr>
<th>LTS</th>
<th>HTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n ~ 50-80</strong></td>
<td><strong>n ~ 15-40</strong></td>
</tr>
</tbody>
</table>

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.

**Uniformity**

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.

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** $(t_d + t_v) \sim 7-15$ ms

- Characteristic extraction time $\tau_e$ depends upon magnet inductance and the sum of magnet and resistance and dump resistance:

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

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 $\sim 100$ m$\Omega$ by the maximal allowable magnet voltage $V_{mag\ max} = (I_{mag} R_{dump}) < 1000$ V. **Typically, for LTS accelerator magnets** $\tau_e \sim 50-200$ ms
Hot spot temperature and time margin

\[
\int_0^{\infty} \frac{c(T)}{\rho(T)} dT = \frac{1 + r}{r} \int_0^{\infty} J^2 dt \quad \text{- adiabatic approximation}
\]


\[d = 0.8 \text{ mm} \quad r = 1.2\]

\[r = \frac{V_{\text{Cu}}}{V_{\text{NbTi}}}\]

\[c(T) = \frac{c_{\text{Cu}}(T)V_{\text{Cu}} + c_{\text{NbTi}}(T)V_{\text{NbTi}}}{V_{\text{Cu}} + V_{\text{NbTi}}}\]

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

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

\[w = 4 \text{ mm} \quad d_{\text{YBCO}} = 1.3 \mu \text{m} \quad d_{\text{Cu}} = 40 \mu \text{m} \quad d_{\text{H}} = 50 \mu \text{m} \quad T_c(15 \text{ T}) = 65 \text{ K} \quad \text{RRR}_{\text{Cu}} = 25 \quad E_0 = 1 \mu \text{V/cm} \quad n = 30\]

\[r = \frac{d_{\text{Cu}}}{d_{\text{YBCO}}} \quad \rho_{\text{St}}(T) = \frac{\rho_{\text{Cu}}(T)\rho_{\text{H}}(T)(d_{\text{H}} + d_{\text{Cu}})}{\rho_{\text{Cu}}(T)d_{\text{H}} + \rho_{\text{H}}(T)d_{\text{Cu}}}\]

\[c(T) = \frac{c_{\text{Cu}}d_{\text{Cu}} + c_{\text{H}}d_{\text{H}}}{d_{\text{Cu}} + d_{\text{H}}} \quad \rho(T) = \frac{\rho_{\text{St}}(T)\rho_{\text{YBCO}}(T)(d_{\text{YBCO}} + d_{\text{St}})}{\rho_{\text{St}}(T)d_{\text{YBCO}} + \rho_{\text{YBCO}}(T)d_{\text{St}}}\]

where: \( \rho_{\text{YBCO}}(T) = \frac{E_0w_{\text{YBCO}}}{I_c(T)} \left( \frac{l}{I_c(T)} \right)^{n-1} \), and \( I_c(T) = I_{c0} \left( 1 - \left( \frac{T}{T_c} \right)^{1.7} \right) \)


- Current is shared between superconductor and stabilizer (in parallel) across the entire temperature range
Let us assume that:
- Both conductors have same $J_e = 600 \text{ A/mm}^2$ at 4.2 K, 15T
- Both are operated at $I_{0.8} = 0.8 I_c(4.2 \text{ K, 15 T})$
- 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$_3$Sn => T margin is $\sim 1.4$ K
  - $T_x = 25.2$ K for REBCO => T margin is $\sim 21$ K

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

Slow temperature rise is followed by a quick runaway
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


J. van Nugteren, “Normal Zone Propagation in a YBCO Superconducting Tape” MSc Thesis, Univ. of Twente, 2012
Quench propagation: LTS vs HTS

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?

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 $\mu$V 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 $\sim$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...

- 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.

Alternative approach: use a stabilizer material with higher RRR.


M. Marchevsky
Improving heat transfer

Coating the conductor with a high thermal diffusivity compound


**TABLE IV**

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

**TABLE V**

<table>
<thead>
<tr>
<th>Sections</th>
<th>$I_t = 150$ A</th>
<th>$I_t = 250$ A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kapton insulated</td>
<td>Doped-titania insulated</td>
</tr>
<tr>
<td>Y1→Y2</td>
<td>6.71 layer/s (0.149 s/layer)</td>
<td>13.70 layer/s (0.073 s/layer)</td>
</tr>
<tr>
<td>Y2→Y3</td>
<td>6.02 layer/s (0.166 s/layer)</td>
<td>14.29 layer/s (0.070 s/layer)</td>
</tr>
<tr>
<td>Y3→Y4</td>
<td>7.52 layer/s (0.133 s/layer)</td>
<td>14.49 layer/s (0.069 s/layer)</td>
</tr>
<tr>
<td>Average</td>
<td>6.75 layer/s (0.149 s/layer)</td>
<td>14.16 layer/s (0.071 s/layer)</td>
</tr>
</tbody>
</table>

- **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**


"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: \( L = \sqrt{\frac{R_{\text{int}} d_n}{\rho_n}} \) (where \( R_{\text{int}} \) 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.

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**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!*

M. Marchevsky
New detection techniques
Optical techniques

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

Fiber-optic interferometer


- 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 $10 \times 10^{-6}$ in the longitudinal and radial direction. The pressure resolution in the transverse direction is in the order of 5 MPa.

Rayleigh scattering


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.


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

![Diagram showing raw and processed acoustic signals with AE events and quench trigger points.]

- Raw acoustic signal
- Processed acoustic signal
- AE events
- Quench
- QDC trigger
- AE quench trigger

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


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

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 scattered 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:

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

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 $J_e$).

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

U. P. Trociwitz et al., “Quench studies on a layer-wound $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x/\text{Ag}_x$ coil at 4.2 K”, Supercond. Sci. Technol. 21 025015, (2008)

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.


- 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)
AC loss in REBCO tape and protection?

AC field normal to the tape surface:

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!


J. van Nugteren, “Normal Zone Propagation in a YBCO Superconducting Tape” MSc Thesis, Univ. of Twente, 2012
Detection + protection using split conductor
Split conductor for detection...

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 $\sim 10^{-8}-10^{-9}$ Ohm for non-superconducting joints - way superior to voltage detection!
- The technique can sense heating at $I \ll I_c (!)$ through increased \textit{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.

\begin{align*}
I_1 &= I_2, \quad I_1 + I_2 < I_c \\
B_{m} &= 0 \\
B_{m} &\neq 0
\end{align*}

...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 $\sim10x-30x$ 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.


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!