Characteristics, degradation limits, and failure mechanisms of REBCO coated conductors during a quench

Tengming Shen, Liyang Ye
Lawrence Berkeley National Laboratory
Coated Conductors for Applications, Aspen, Colorado
Sept 11-14, 2016

Acknowledgements: Justin Schwartz (NCSU), Pei Li, Mattia Duranti, Jason Wu (FNAL), David Larbalestier, Arno Godeke, Jan Jaroszynski, and Scott Marshall (NHMFL), Hugh Higley and Xiaorong Wang (LBNL)
Opening questions and comments

• How do superconductors fail during a quench?
• To what stress can your superconducting magnets/devices be designed to work?

• **Good news**: The temperature margin to degradation due to a quench is quantitatively predictable for Bi-2223, Bi-2212, MgB₂, and Nb₃Sn, and highly depends on the conductor strain state.
• **Bad + good news**: It is not much the case for REBCO, though the margin seems quite high.
Does the tensile test tell us the real axial tensile stress limit for composite superconductors?

Sumitomo DI-BSCCO Type HT-NX, >400 Mpa axial stress limit

(From internet)

(courtesy of NHMFL)
A simple technique tells us that the axial tensile stress limit is bending dependent.

Irreversible degradation starts. 160 Mpa

4.2 K, 15 T, B // Tape
Sumitomo DI-BSCCO
Type HT-NX.
Bending diameter = 50 mm

5% degradation, 185 Mpa,
What is the practical axial stress limit of a superconductor if potential damages from quenches are also considered?

Sumitomo DI-BSCCO
Type HT-NX.
Bending diameter = 50 mm
What is going on? – For Bi-2223, quench induced $I_c$ degradation is *mostly* (axial) strain driven event.

- $I_c$ degradation due to a quench is (axial) strain driven.
- Strain caused by a quench is localized, associated with $T_{\text{max}}$ only, not $dT_{\text{max}}/dx$ or $dT_{\text{max}}/dt$.

Thermal strain – thermal strain due to quench
$T_{\text{allowalbe}}(\sigma_a, r_b)$ is predictable, and it sets the practical practical axial stress limit for 2223-NX.
What about REBCO coated conductors? – Winding strain is small or even can be advantageous

- Axial tensile strain limit is 0.7%, instead of 0.5% for 2223/NX.
- Smaller bending strain, or better, compressive bending strain.

Sumitomo 2223 and Superpower SCSxx50
Axial strain effects during a quench on maximum working stress – some ballpark analysis

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    height=\textwidth,
    xlabel={Strain ($\%$)},
    ylabel={Stress (MPa)},
    xmin=0, xmax=1.4,
    ymin=0, ymax=900,
    xtick={0,0.2,0.4,0.6,0.8,1,1.2,1.4},
    ytick={0,100,200,300,400,500,600,700,800,900},
    legend entries={SCxx50-40Cu, SCxx50-100Cu, NHMFL 32 T},
    legend pos=north east,
]
\addplot coordinates{(0,0) (0.4,400) (1,900)}; \addlegendentry{SCxx50-40Cu}
\addplot coordinates{(0,0) (0.4,300) (1,700)}; \addlegendentry{SCxx50-100Cu}
\addplot coordinates{(0,0) (0.4,200) (1,600)}; \addlegendentry{NHMFL 32 T}
\end{axis}
\end{tikzpicture}
\end{center}

Working zone with $T_{\text{allowable}} > 300 \text{ K}$.
1. $< 600 \text{ Mpa}$ for SCxx50-40Cu
2. $< 480 \text{ Mpa}$ for SCxx50-100Cu

Bending diameter=50 mm and tensile winding strain assumed.

Data from Yifei Zhang (Superpower) MEM2016
Temperature rise in the multilayered thin films also gives rise to shear stress and peeling stress.


Shear stress \( \tau_{\text{max}} = -kE_f^0 h_f \Delta \alpha \Delta T \)

Peeling stress \( p_{\text{max}} = -\frac{1}{2} kh_f \tau_{\text{max}} \)

Both of them and axial strain rise up with \( \Delta \alpha \Delta T \).

Peeling stress maximizes at the edge.
REBCO – high degradation limit (>600 K) without epoxy, and early degradation below 250 K with epoxy

Test conditions: 77 K, straight sample.

Axial strain not large enough to cause irreversible damages.
Early degradation in the epoxy impregnated samples, likely associated with epoxy impregnation, is rather localized.
Quench induced $I_c$ degradation is rather localized – sample 1
Quench induced $I_c$ degradation is rather localized – sample 2
Degradation mechanism expected: Delamination due to peeling stress developed in multi-layer films with a temperature rise

Sample 2 (with epoxy)
- $T_{\text{max}} \sim 750 \text{K}$
Final Quench
Delamination of Cu-Ag layer from REBCO layer

Sample 3 (w/o epoxy) – $T_{\text{max}} \sim 900 \text{ K}$
Degradation mechanism **unexpected**: Holes created by thermal shock – perhaps with local temperature exceeding 1000°C

Hole on hastelloy side - Sample 1 (Final Quench - $T_{\text{max}} \sim 450\text{K}$)

Hole on REBCO side - Sample 1 (Final Quench - $T_{\text{max}} \sim 450\text{K}$)
Concluding remarks

• For multifilamentary wires including Nb$_3$Sn, Bi-2212, MgB$_2$, and Bi-2223, quench induced $I_c$ degradation is axial strain driven.
  • Their temperature margin to degradation, as measured by $T_{allowable}$, can be quantitatively predicted as a function of bending and axial stress $\sigma_a$ on wire, using strain models.
  • $T_{allowable}(\sigma_a, r_b)$ sets the practical stress limit that superconducting magnets can be designed to.
  • CT-OP Bi-2223/NX given as an example.

• REBCO coated conductor – Its quench degradation is NOT axial strain driven, and mostly triggered by conductor delamination. Its degradation limit therefore varies with conductor delamination resistance, and is expected to be highly variable.