Strain control of composite superconductors to prevent degradation of superconducting magnets due to a quench

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With inputs from Liyang Ye (LBNL), Pei Li (FNAL), Justin Schwartz (NCSU), Fermilab summer students, and help from NHMFL DC magnet time staffs, Fermilab and LBNL technical staffs.
Strain budget for quench protection of superconducting magnets – how large should it be?

- How is degradation induced? Is it dominated by strain?
- To what quench degradation limit can superconductors survive?
- At what hot spot temperature can a quench be detected?
- What role stress is going to play to determine the quench degradation limit?
$I_c$-axial strain behavior of Ag/Bi-2212 wires

Established by ten Haken and ten Kate in tapes and early wires, and by Cheggour and Godeke in modern Bi-2212 wires and overpressure processed high current density wires.

- **Tensile strain limit** – 0.4-0.6%
- **Compressive strain** induces irreversible degradation, but widens strain window.
- **Characteristic reversible and irreversible behavior.**
Quench protection is constrained by a limited 'time' budget and slow NZPV

- Time constant in several tenths of a second when $J_o > 300 \, \text{A/mm}^2$.
- Time constant decreases with the decrease of maximum allowable temperature during a quench.

$t_D \propto 1/\text{NZPV}$

$t_p \propto 1/\text{NZPV}$
Quench characteristics of HTS – small normal zone with high temperature gradient propagating at low speeds

- HTS vs LTS at 4.2 K
- NZPV – cm/s vs m/s
- $dT/dx$ – 100s K/cm vs K/cm
- A thermal shock to both – $dT/dt$ up to 100s K/s.
- What controls the quench induced $I_c$ degradation? $T_{\text{max}}$, $dT_{\text{max}}/dt$, or $dT_{\text{max}}/dx$?

Temperature profile of a 2212 wire during a quench at 4.2 K and 15 T, and $J_o=500$ A/mm$^2$. 

T. Shen, L. Ye, D. Turrioni, P. Li, SuST, 28 (2015) 075014
Quench degradation limit \( \approx \) maximum allowable temperature during a quench, at least for Ag/Bi-2212 round wire

- Quench degradation is driven by local straining of 2212 filaments with \( T_{\text{max}} \) limit close to 500 K.
- Irrespective of \( dT_{\text{max}}/dx \), conductor design, heat treatment, porosity levels et al.
- Quenched degraded filaments develop cracks.
- Reversible and irreversible behavior of \( J_c \) dependence on \( T_{\text{max}} \).
Instrumentation setup and a typical behavior: Quench induced $I_c$-degradation is very localized.
Microstructure study supports the strain-driven mechanism

OST 37X18,
Dia=0.8 mm as-drawn
Dia=0.775 mm after 100 Bar OP
95-100% densified Bi2212
No-$I_c$-degradation regions: filaments are dense and crack-free

Sample with no $I_c$ degradation (After Ag etching)
Degraded region contains cracks perpendicular to wire axis

Sample with ~30% $I_c$ degradation (After Ag etching)
Quench-induced $I_c$ degradation shows a characteristic reversible and irreversible behavior

$I_c$-axial strain of Bi-2212 wires (Cheggour, Godeketen, Haken and ten Kate)
Dependence of quench degradation limit of Bi-2212 wires on axial stress up to 160 MPa for high critical current density, overpressure processed Bi-2212 wires*

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What is the role of strain state on determining quench degradation limit – maximum allowable temperature during a quench?

How strongly would quench degradation limit depend on axial stress/strain states of conductor?

Cheggour, IEEE, 2011
$I_c$ measurement using ITER barrels
- results consistent with standard $I_c$ measurement of short straight samples on G-10 sample holders

OP produces high $J_c$

With collaborations with Arup Ghosh@BNL
Ye, Li, Ghosh, Shen, ICMC2015, poster
Determining axial stress limit using ITER barrels

- 5% $I_c$ degradation at 156 MPa @4.2K and 15 T for 25 bar OP PMM101108-2

**Diagram:**

- Force pointing outward
- Hoop stress $\approx BJR$

**Axes:**
- $J_e$ (A/mm$^2$) @4.2 K, 15 T
- Axial stress = hoop stress (MPa)
- $n$-Value @4.2 K, 15 T

**Graph Data Points:**
- Blue dots for 25 bar OP PMM101108-1 @4.2 K, 15 T
Quench experiment under high tensile axial stress, in high field, while transporting high current.
Dependence of quench degradation temperature limit on axial stress up to 145 MPa in a 25 bar OP Bi-2212 wire at 4.2 K in field of 15-30 T

Decreasing from 500 K at zero hoop stress to ~150 K with increasing hoop stress to 146 MPa at 4.2 K and 15 T
High-field Quench Characteristics and Quench Degradation Limit of Bi-2223 and REBCO Conductors

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Bi-2223 and REBCO – some first comments

- The same argument might apply (quench degradation limit $\approx$ maximum allowable temperature during a quench).

- Much different conductor architecture produces much different strain: The degradation might not be first driven by conductor axial stress and strain.

- R&W produces significant strain with small bending and improper handling.
Sumitomo type-H Bi-2223 – its degradation behavior similar to that of Bi-2212, when no bending applied

Test conditions: 77 K, straight sample.

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2212 data: Cheggour, IEEE TAS, 2011
2223 data: ten Haken, IEEE, TAS, 1997
We started to test quench characteristics and quench degradation limit of 2223 with increasing axial stress at 4.2 K and high-field.
Some preliminary data on HT-NX at 15 T and bending diameter=50 mm

- Bending diameter=50 mm.
- Preliminary data.
REBCO – high degradation limit (>600 K) without epoxy, and early degradation below 250 K with epoxy

Tested w/o epoxy impregnation

Tested with epoxy impregnation

Superpower tape

Test conditions: 77 K, straight sample.
Degradation mechanism found so far – delamination, and holes created by thermal shock

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

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

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

- Quench induced critical current degradation is strain driven.

- Quench degradation limit $\approx$ maximum allowable temperature, at least true for Ag/Bi-2212 round wires.

- Quench degradation temperature limit for Bi-2212 wires decreases with tensile axial stress
  - $>500$ K when not stressed, 320 K with 100 MPa axial stress, 250 K with 120 MPa axial stress. Axial stress limit~156 MPa for a high $J_c$ OP wire.

- 2223 – 400 K when not stressed; axial stress has a strong influence.

- REBCO - $>600$ K when not stressed, more limited by delamination than by axial stress.
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