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Quench behavior and protection of high-field $Bi_2Sr_2CaCu_2O_x$ magnets at 4.2 K

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2014 International Cryogenic Materials Conference

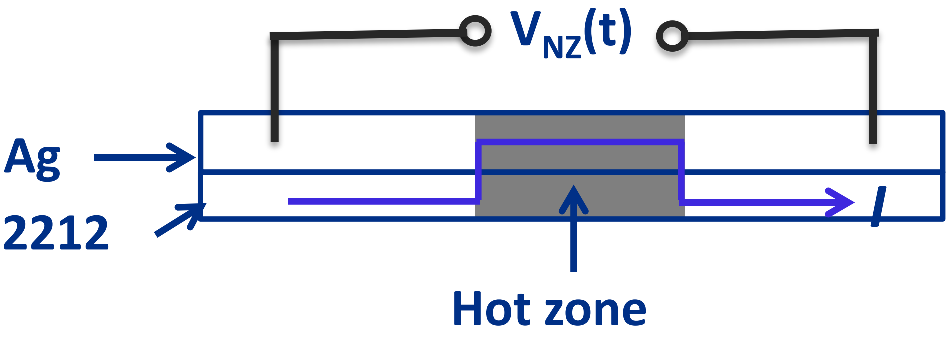
Enschede, the Netherlands, 08 July 2014

Work supported by the U.S. Department of Energy, Office of High Energy Physics

Outline

- 2212 – a multifilamentary HTS round wire with 20-50 T reach at 4.2-15 K
  - 30 T NMR and 20 T dipoles for FCC magnets
  - Overpressure Processing – 20 T (4.2 K) J_E exceeds 700 A/mm^2
- With MQE > 0.1 J and NZPV in several cm/s, neither quench protection nor detection will be easy.
  - First careful measurement of T_{max} v.s. V_{nz}.
  - Measurement of characteristic time for quench detection and quench protection heaters
  - Measurement of quench degradation limits

A race we can't lose: fast temperature rise v.s. detection + protection

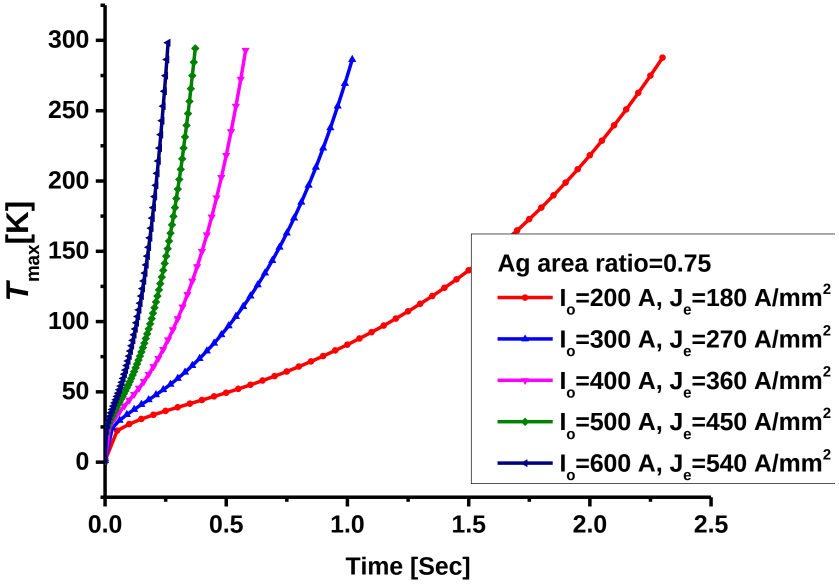


<u>Adiabatic heat balance</u>: $J_m^2 \rho(T)dt = C(T)dT$

MIITs calculation:

Temperature to 300 K within 1 sec if J>400 A/mm²

$$V(t) = I(t) \cdot R_{NZ}(t) = I(t) \cdot \int_{-(L_0+NZPV\cdot t)}^{(L_0+NZPV\cdot t)} \rho(z)/A_m \cdot dz$$



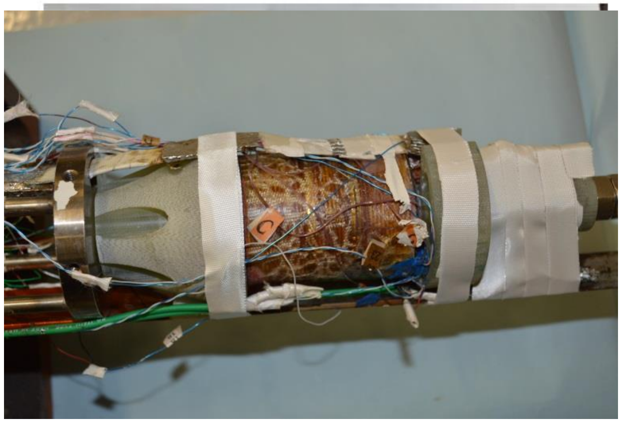
If the initial normal zone ($2xL_0$) is small

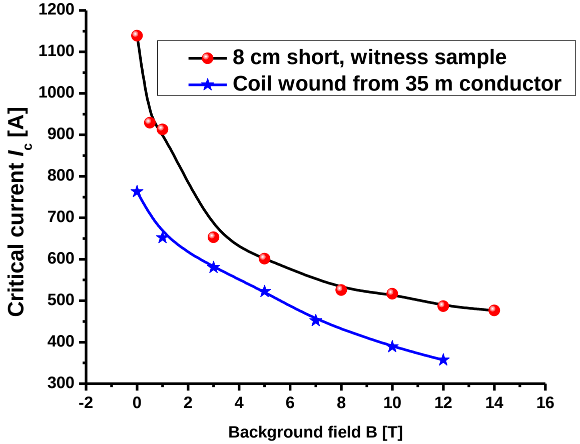
$$\begin{aligned} V_{NZ}(t) &= I(t) \text{ x } R_{NZ}(t) \\ &= I(t) \text{ x } V_{NZPV} \text{ x } t \text{ x } \rho(T_{NZ})/S_m \\ &= J_m \text{ x } \rho(T_{NZ}) \text{ x } NZPV \text{ x } t \end{aligned}$$

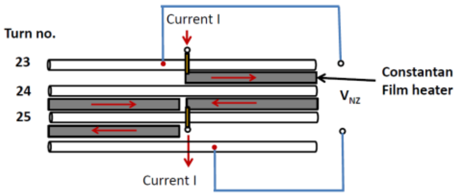
For V_{NZ} to reach 0.1 V, 2212 (HTS) may need >1 s, with temp rise>100 K.

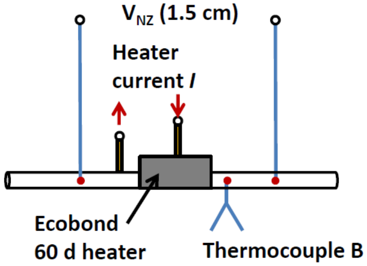
Tool No. I: Experimentally study quench behaviors of small-scale coils and short-samples in background magnetic fields

6-layer, 32 m Ag/Bi-2212 wire,
244.5 turns, ID=33.40 mm, OD=48.1 mm;
Length=57.80 mm





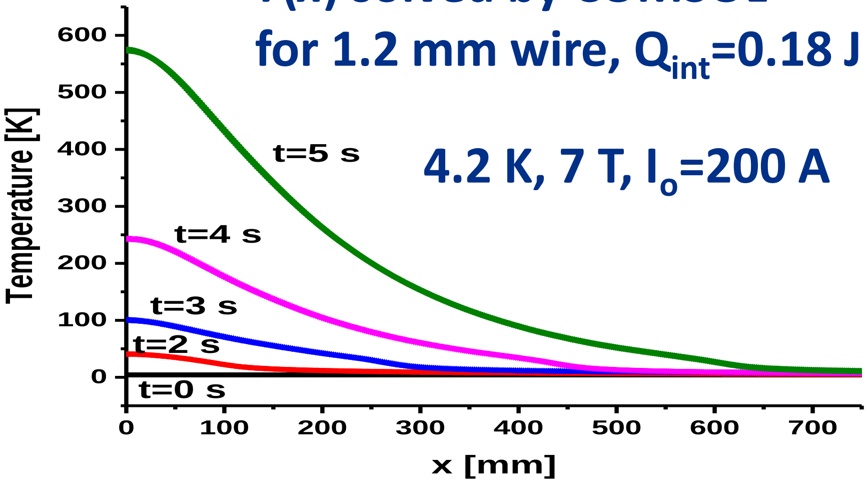

Film heater uses non-inductive winding.



Tool II: The power of computation – 1D adiabatic simulation of quenches

- Solve 1D heat balance equation

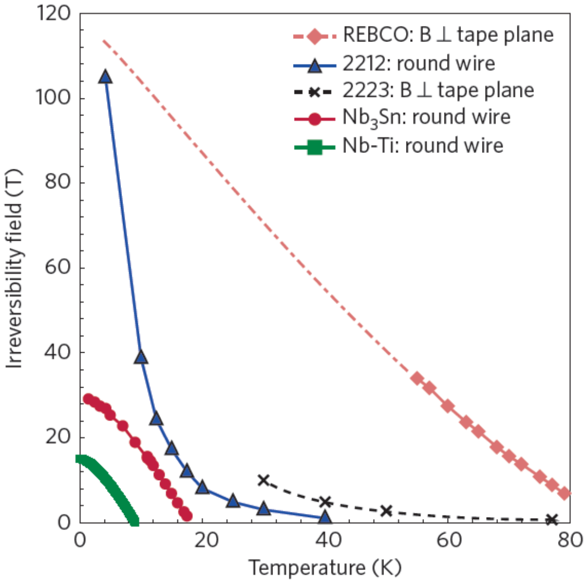
$$C\frac{dT}{dt} = \frac{d}{dx}\left(k\frac{dT}{dx}\right) + \rho J^2 + Q_{int}$$



$T(x)$ solved by COMSOL for 1.2 mm wire, Q_{int}=0.18 J

4.2 K, 7 T, I_o=200 A

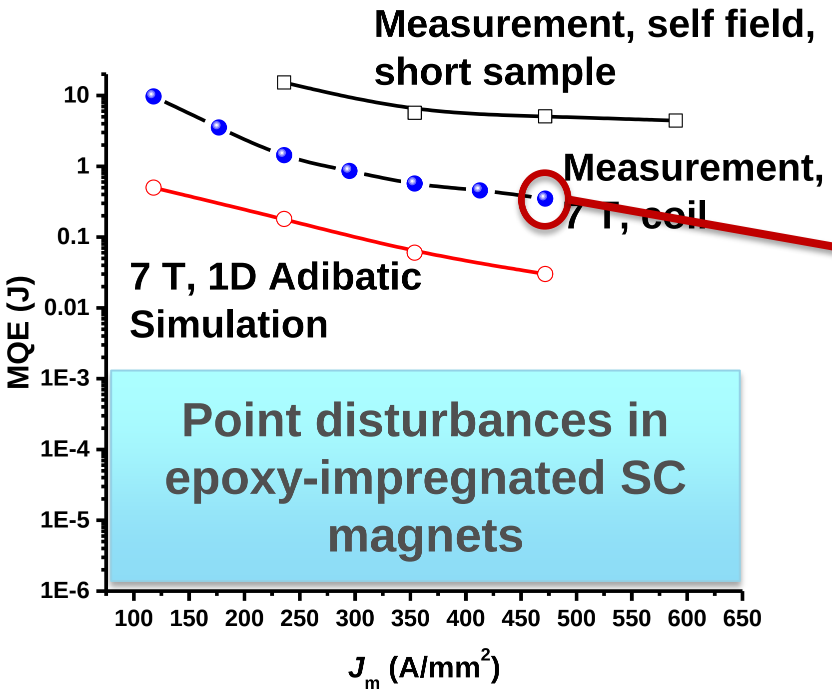
Larbalestier et al, Nature Mateirals, 2014



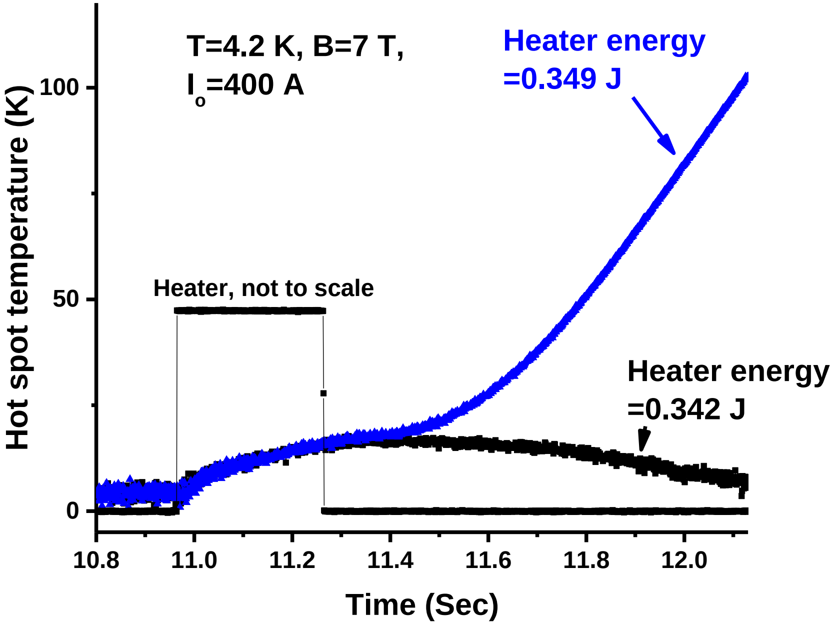
- At a given field, J_c is linear with T.
- Huge H_{irr}(T) when T<20 K.
  - 2212 at zero field has small NZPV, but how about at large fields?
  - H_{irr}(T) is far from being unanimously defined.

The coil is very stable – MQE exceeds 0.1 J at 4.2 K and 7 T

- MQE of Bi-2212 exceeds 0.1 J (experiment) and 0.01 J (simulation)
  - Energy produced by conductor motion and epoxy cracking: <1 mJ
- But Bi2212 coils are not quench-free: coils degraded by quenches (800 kJ SMES coil from 2212 tapes, Tixador et al.)

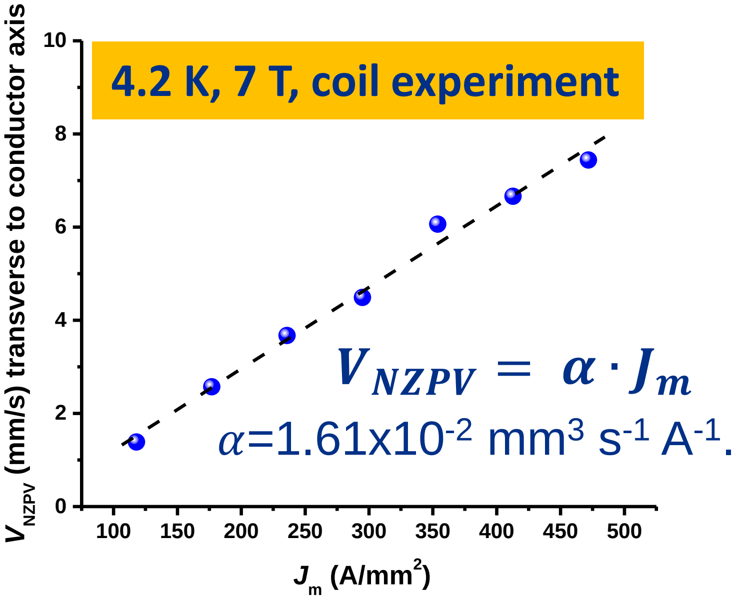


Point disturbances in epoxy-impregnated SC magnets



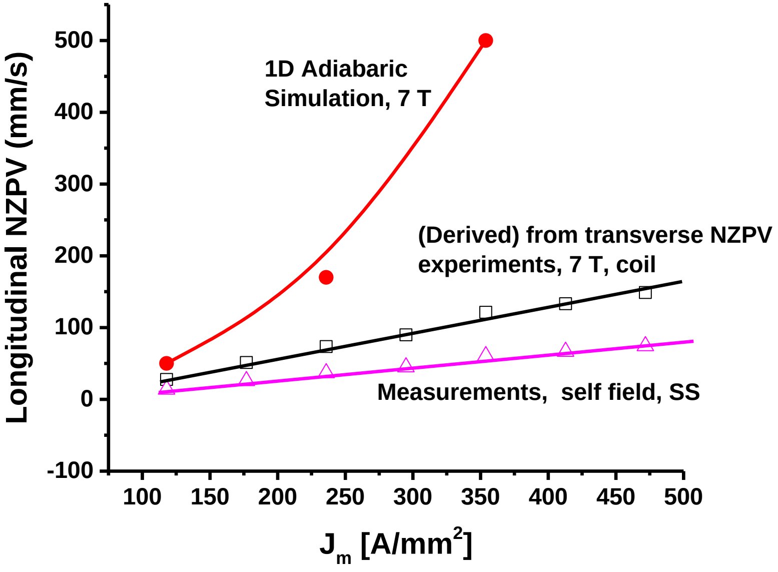
Propagation is slow – longitudinal speed smaller than 15 cm/s at 80% I_c at 7 T

- Experimental: NZPV linear with J_m.
- Simulation: NZPV goes up with J_m^2, exceeding 50 cm/s at 60% I_c at 7 T.



$$V_{NZPV} = \alpha \cdot J_m$$

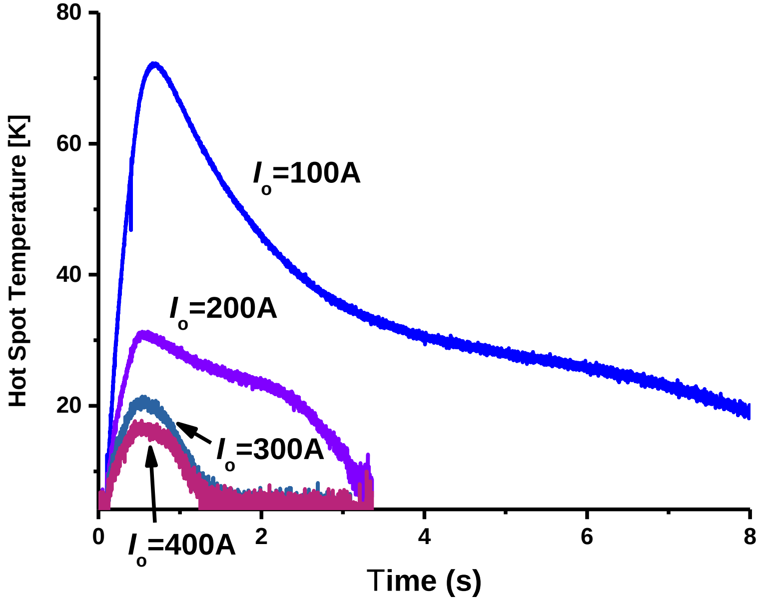
$\alpha = 1.61 \times 10^{-2}$ mm^3 s^{-1} A^{-1}.



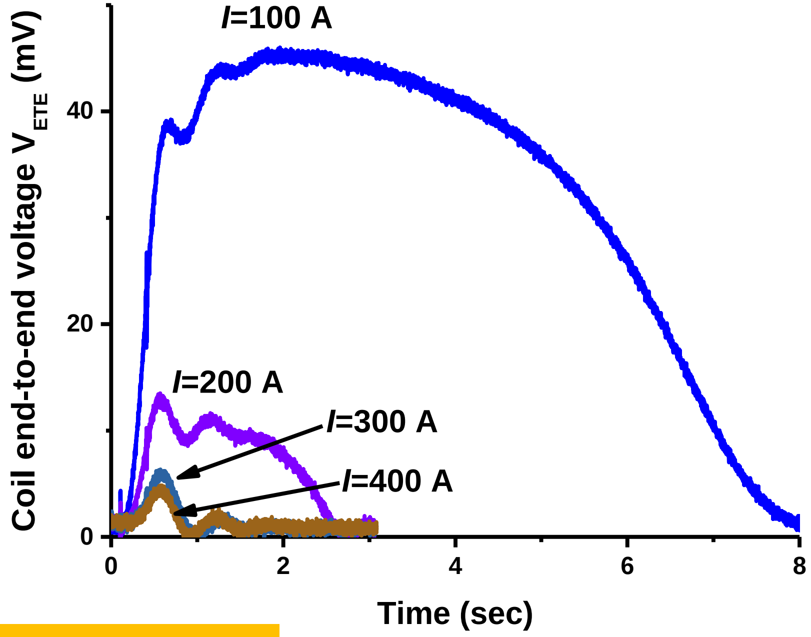
Temperature and voltage growths during recovery: what voltage should be used for reliable quench detection?

Quench detection voltage: how high should it be to not false trigger protection?

Hot spot temperatures during recovery

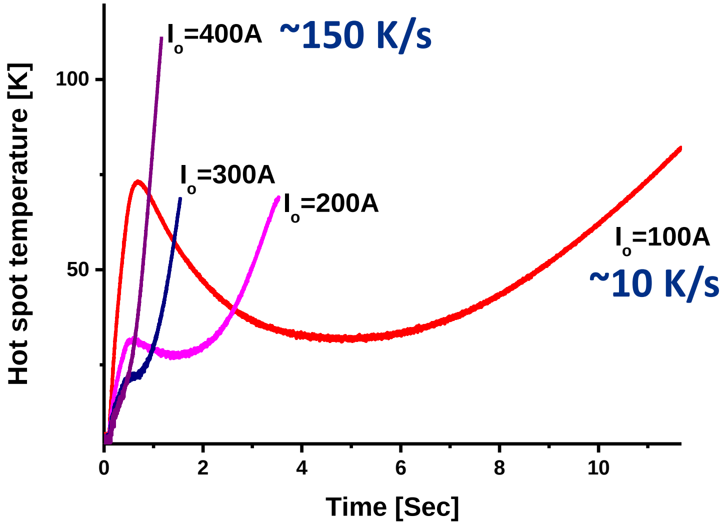


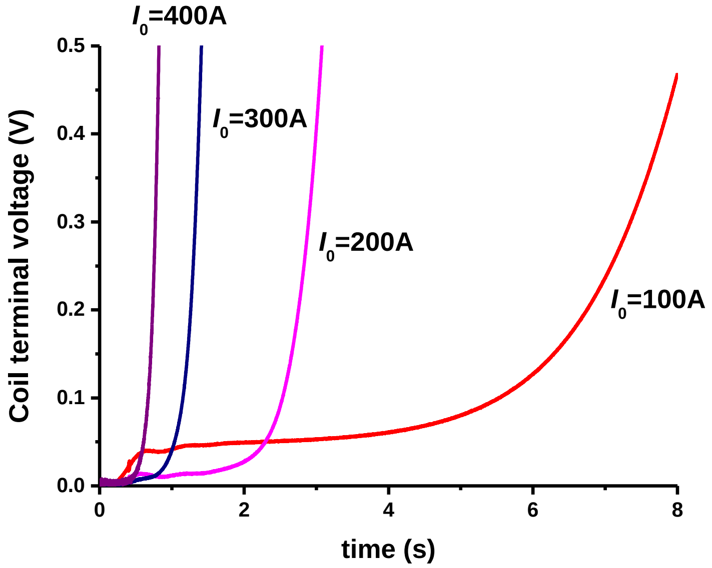
Coil terminal voltage during recovery cases



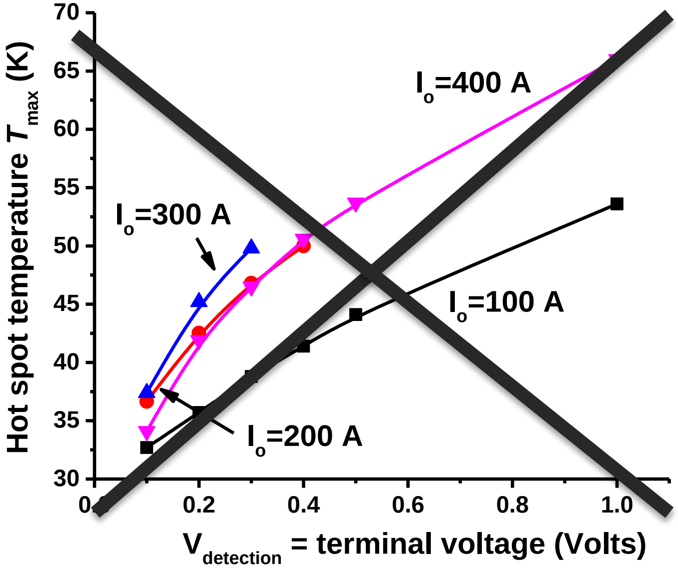
4.2 K, 7 T, coil experiment

Temperature and voltage growths during quenches : T_{max} vs. $V_{detection}$



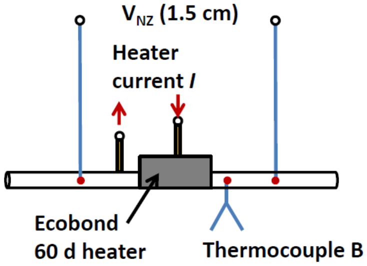


- TC underestimates temperature rise
- Response time of E-type TC: ~100 ms

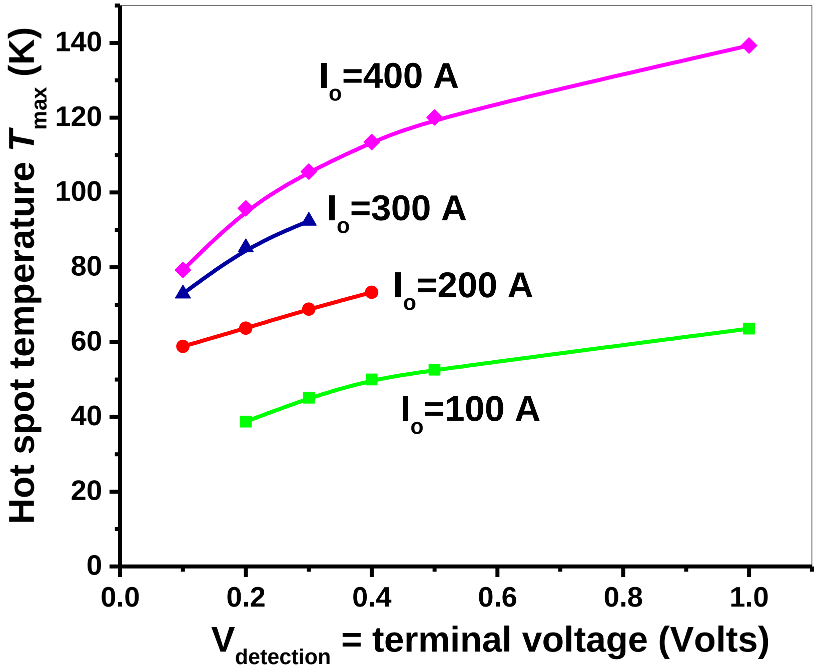


4.2 K, 7 T, coil experiment

Hot spot temperature v.s. resistivity voltage across normal zone: voltage->temperature results



Temperatures derived from voltages across the 1.5 cm hot zone:



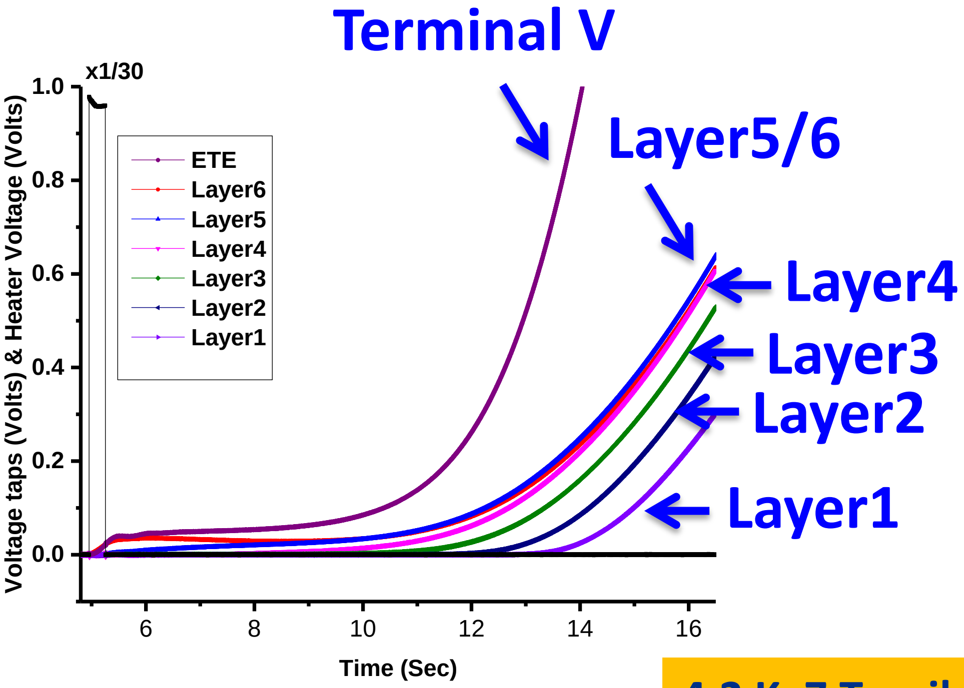
- At a given V_d, hot spot temperature rises with I_o.
  - At I_o=400 A, T_{max}=79 K for V_d to reach 0.1 V
- T($V_{detection}$=1.0 V) - T($V_{detection}$=1.0 V) increased with I_o.
  - 40 K for I_o=400 A vs. 25 K for I_o=100 A

4.2 K, 7 T, coil experiment

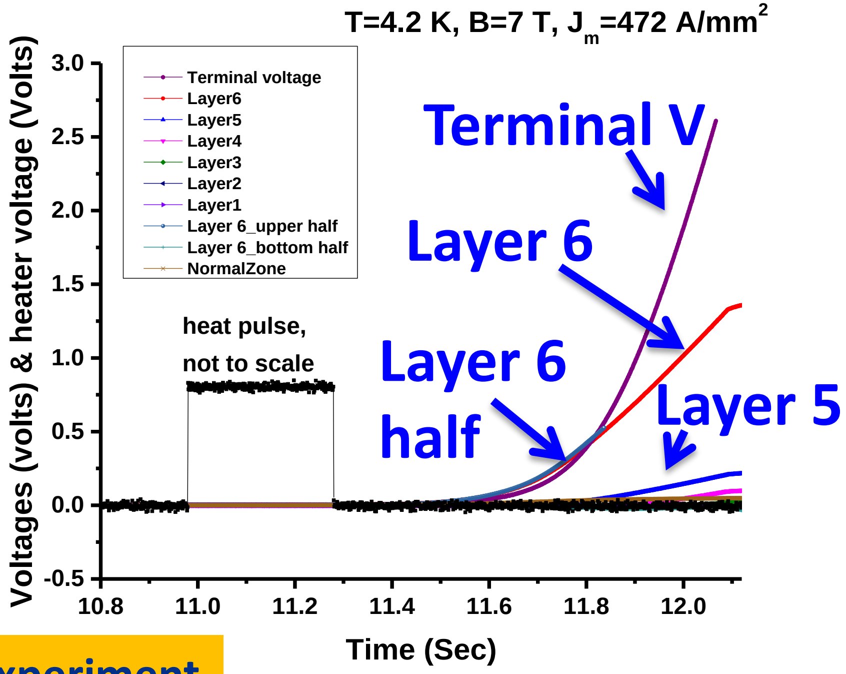
The staggering hot zone and difficult quench protection at high I_o

- For I_o=400 A, hot zone length – 7-14 cm when V_d=0.1 V.
  - Only 1-D propagation contributes till V_d=0.1 V.

T=4.2 K, B=7 T, I_o=100 A



T=4.2 K, B=7 T, I_o=400 A



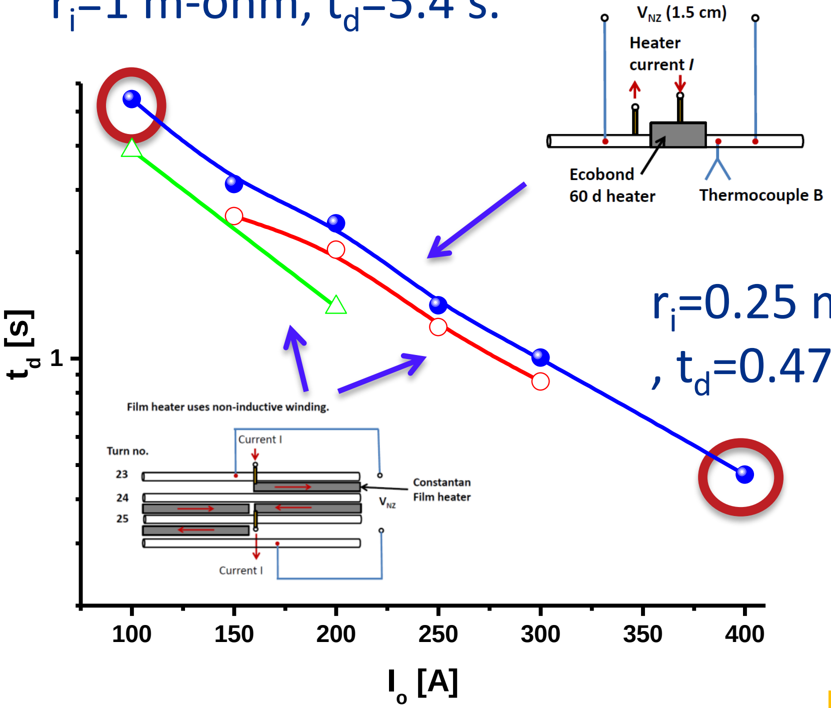
4.2 K, 7 T, coil experiment

Characteristic time for quench detection and quench protection heaters

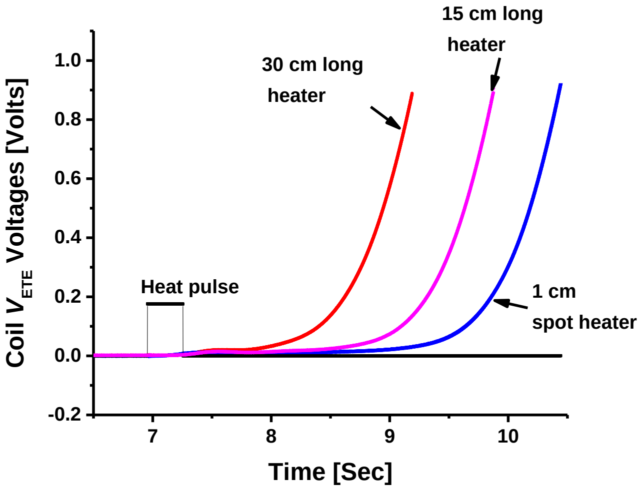
- **With $U_{NZ}(t)=J_m \times \rho(T_{NZ}) \times NZPV \times t_d$**
  - **t_d (**time elapsed from current sharing to V_d=0.1 V**) should decrease with I_o.**
- **Easier detection needs larger t_d**
  - **t_d proportional to MQE.**

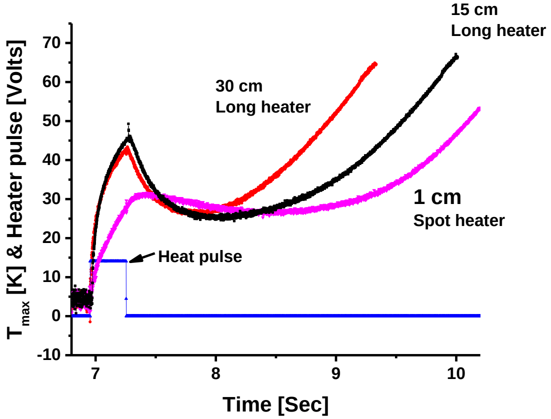
4.2 K, 7 T, I_o=200 A

r_i=1 m-ohm, t_d=5.4 s.



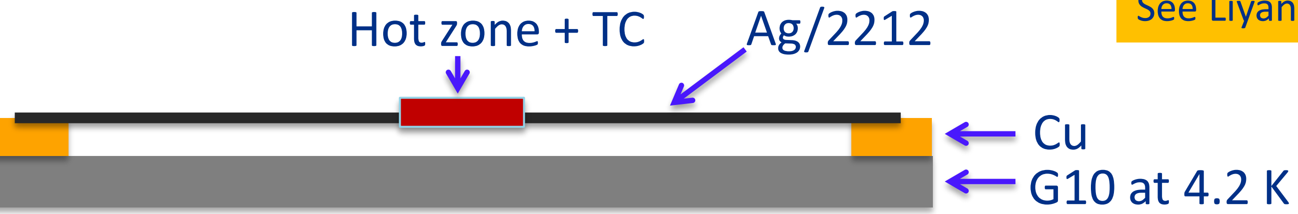
r_i=0.25 m-ohm , t_d=0.47 s





4.2 K, 7 T, coil experiment

What is 2212's quench degradation limit?

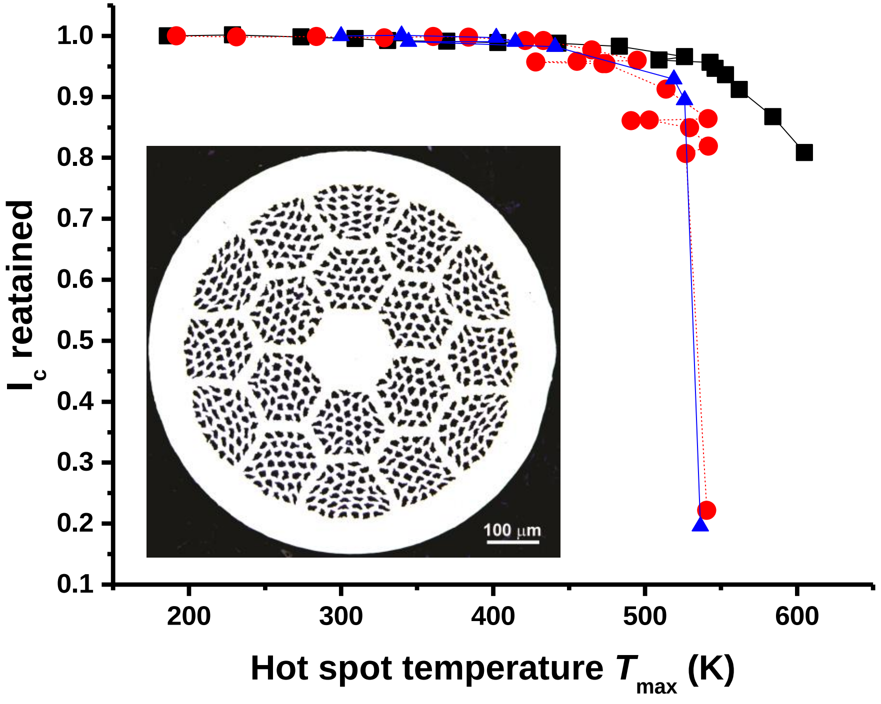


See Liyang Ye talk at 2014ASC: 1MOr3A-04

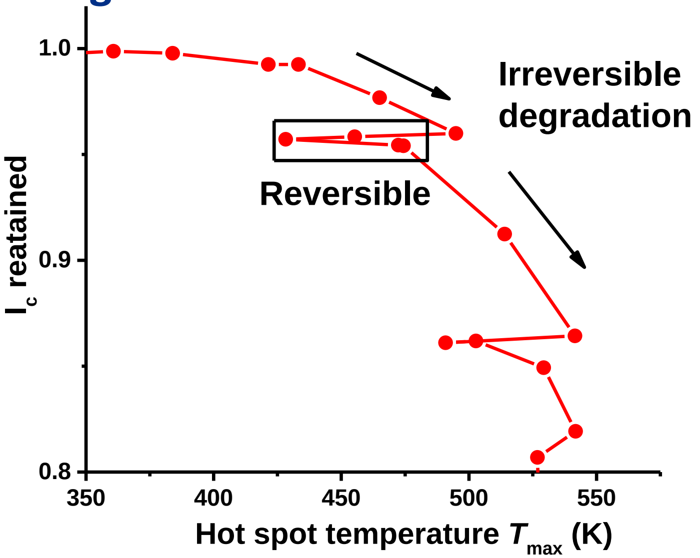
4.2 K, self field, short-sample experiment

- Depends on conductor architecture, processing, and strain state.
- 500 K for this setup, perhaps limited by compressive strain damages.

I_c after quench vs. T_{max}



Irreversible and reversible degradation behaviors shown



Concluding remarks

- Experimentally determined quench behaviors of 2212 wires and coils in magnetic fields and cross-examined with numerical simulations
  - At 4.2 K and 7 T, MQE > 0.1 J and NZPV < 15 cm/s.
- First careful measurements of T_{max} v.s. V_{nz}
  - $V_{nz} < 0.1$ V till T_{max} reaches 80 K for $I_o > 400$ A at 7 T
  - Highlighting the difficulty with quench detection of 2212 (HTS) magnets
- t_d and its dependence on I_o and heater design.
- Quench limit - ~500 K limited by compressive strains.