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# Bi-2212 high-field magnet technology at Fermilab: Prototype overpressure processing coil fabrication and quench protection studies

**Tengming Shen, Fermilab, November 14, 2014**

**With inputs from Pei Li (Fermilab), Liyang Ye (Fermilab & NCSU), Gene Flanagan (Muons Inc.), Lance Cooley (Fermilab), members of BSCCo, and collaborations with Justin Schwartz (NCSU).**

**Work supported by U.S. DOE-OHEP through early career program, SBIR-STTR program and GARD program**

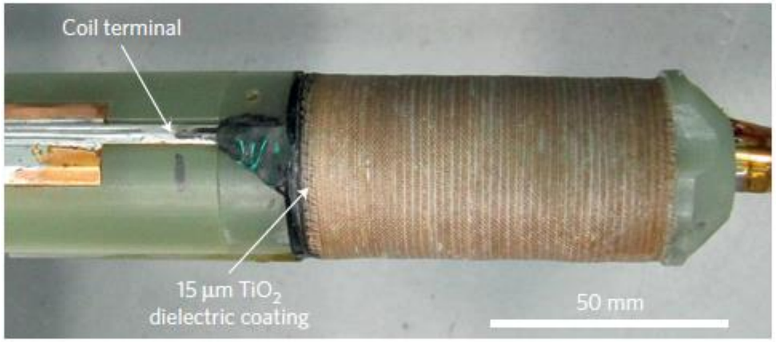
2014 Kyoto
WAMHTS-2

# Big 2212 steps in 2004-2014

- **VHFSMC (ARRA, $4 million, 2009-2011), and BSCCo**
  - **Industry supplied over 7 km of strand**
  - **Good Rutherford cables were made**
  - **Cable-wound racetracks achieving 75% of short sample**
  - **Small solenoids operating at stresses of >100 MPa in fields up to 32 T were made.**
- **Melt processing/wire design/$J_c$ relationships better understood**
  - **Removing gas bubbles leads to high $J_c$.**
  - **Leakage caused by creep rupture of silver driven by internal gases**
- **Better insulation technology available**
- **Breakthrough in $J_c$ – 20 T (4.2 K) $J_E$ exceeds 700 A/mm$^2$**
  - **New paradigm: overpressure processing – heat treat conductor in a high pressure external gas**
  - **used to be 300 A/mm$^2$ in short commercial wire**
  - **used to be 200 A/mm$^2$ in coils**

# Deploying OP 2212 for applications and some driving questions

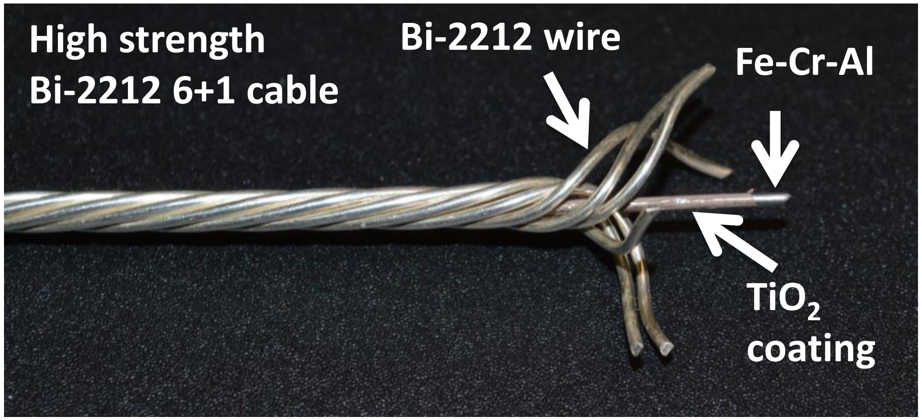
- **Coil fabrication common issues**
  - **What insulation and structural materials to use?**
  - **How to heat treat a coil with +/-2Ccontrol?**
- **Overpressure melt processing coil engineering**
  - **Can the success of overpressure processing be replicated in coils?**
  - **Will OP work well with cables?**
  - **How easy is overpressure melt processing @100 bar with +/-2C control?**




**10 bar OP; $J_E$=252 A/mm$^2$ at 33.8 T (coil quenched). Add 2.6 T to 31.2 T background.**

Larbalestier et al.,
(Nature Materials, 2014)

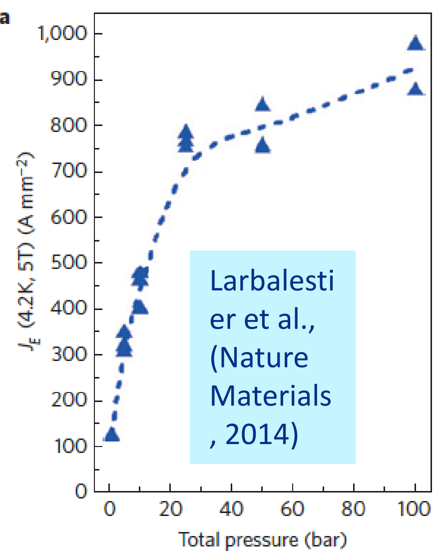
# How does OP work out on cables? – Still effective

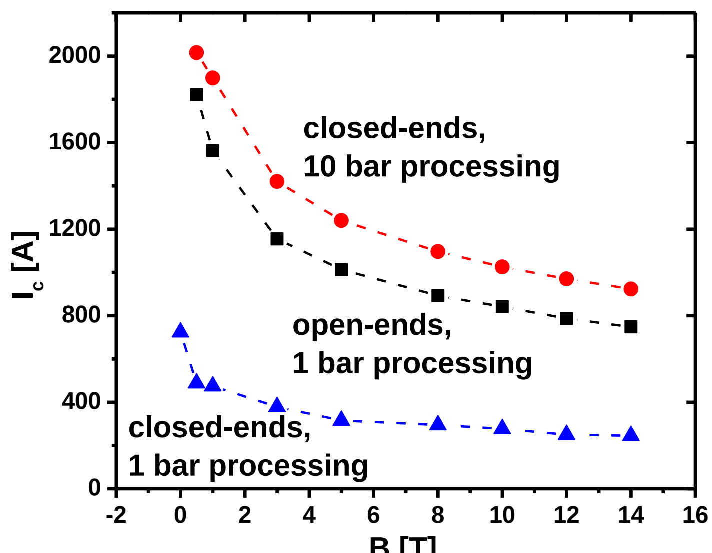



OP by J. Jiang (FSU)

Shen, Jiang et al., to be submitted to SuST and to appear in ArXiV

Single-strand data



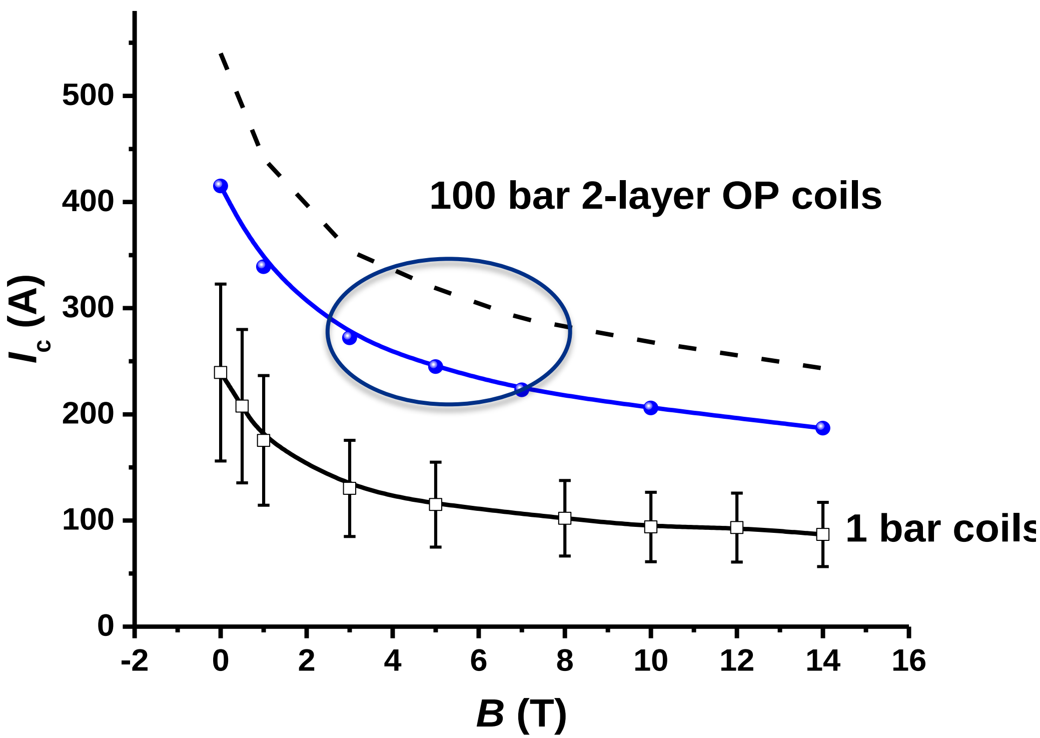




Average $J_e$(strand in 10 bar OP cable )= 415 A/mm$^2$

**Though two 100 bar OP attempts produced $J_e$=500 A/mm$^2$**

# Prototype OP solenoids yielded $I_c$ that is 2-2.6 times that of 1 bar solenoids

- **Muons Inc – Fermilab, U.S. DOE-OHEP STTR project**
- **OP coil $I_c$(5 T)=250-320 A vs. typical 120±40 A in 1 bar coils (0.8 mm strand)**
  - **400 A for the best witness sample ($J_E$=900 A/mm$^2$)**

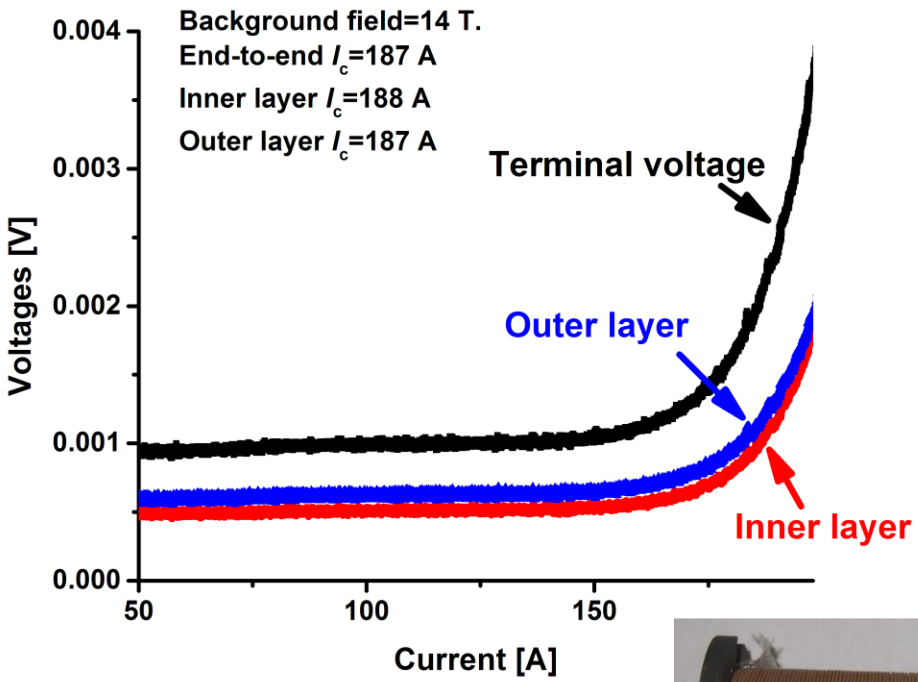


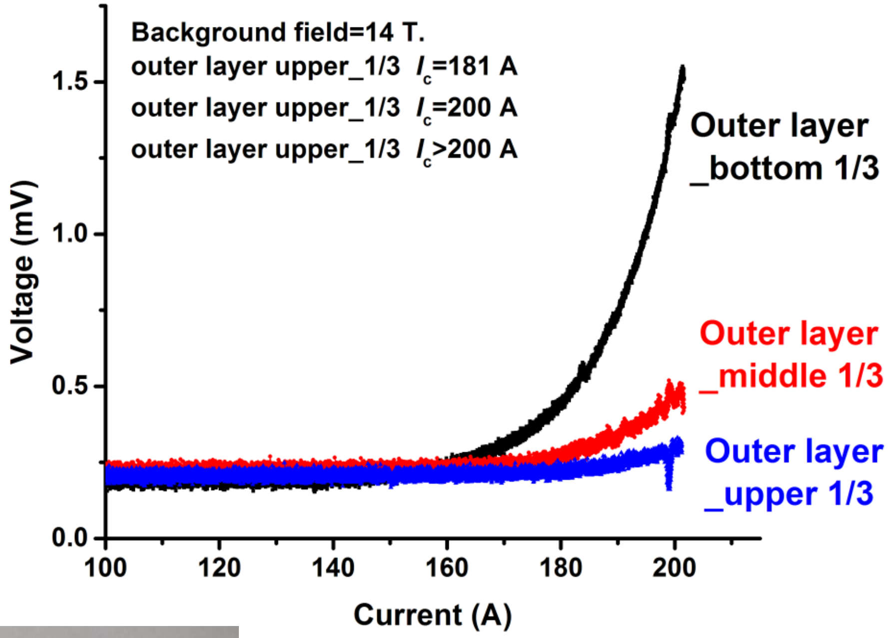

FNAL 100 bar OP system
Hot zone – 16 cm x 50 mm diameter

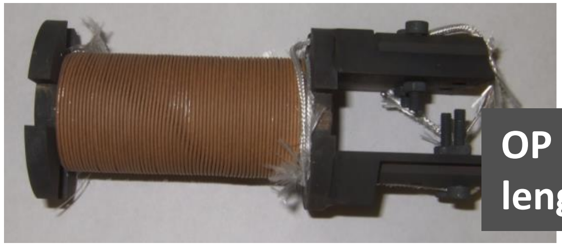

OP 2-layer coil; conductor length=11 m; nGimat insulation

# Good superconducting transition seen, despite that coils were reacted in a temperature gradient; insulation is good as well

- Inner layer $I_c$ ≈ Outer layer $I_c$
- No electrical shorts – nGimat $TiO_2$ insulation works well.
- Non-uniform Coil $I_c$ – coil reacted in a temperature gradient



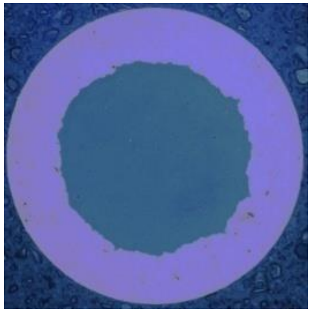



OP 2-layer coil; conductor length=11 m;

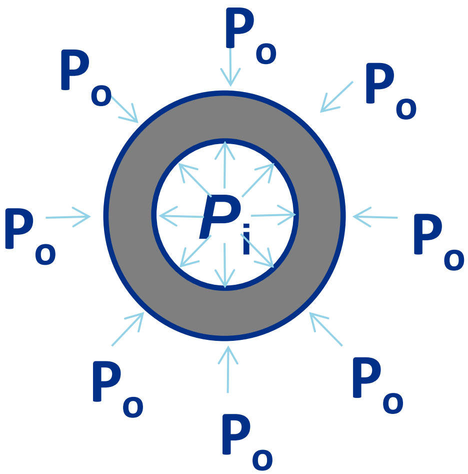
# Coil survived >110 quenches and a hoop stress of 97 Mpa, and comments about OP

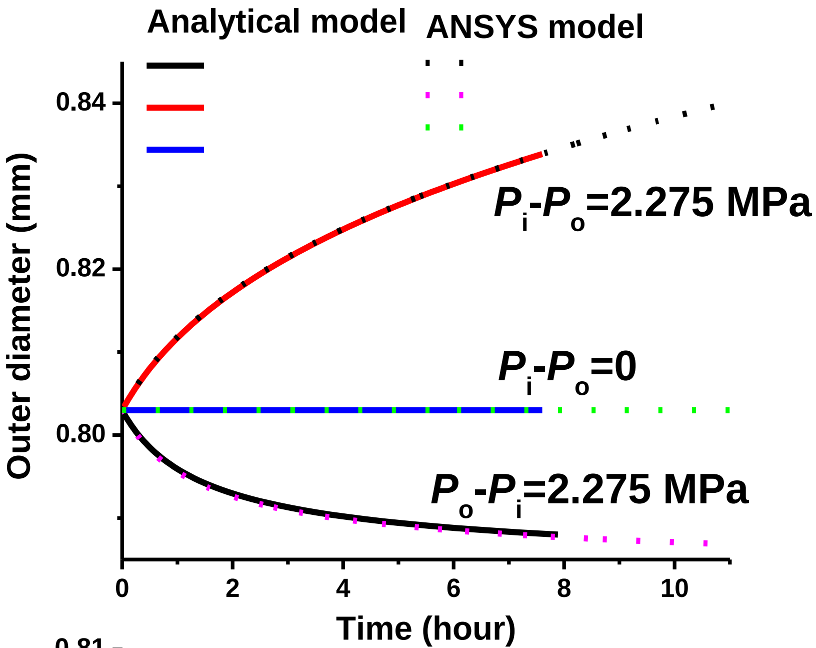
- No degradation
  - after 110 quenches (initiated by a heater) at 7 T, 9 T, and 12 T
    - Maximum temperature reached = 250 K.
  - Hoop stress reached 97 Mpa at 14 T
- OP@100 bar with temperature control in +/- 2C is not easy
  - High thermal conductivity of pressured gas messed up temperature homogeneity.
  - Not-so-easy temperature calibration
- Sumitomo Bi-2223 300 bar OP furnace: +/- 1C in a sample space of 1 m diameter x 1.2 m height
- Can we reduce the OP pressure to 30-50 bar?

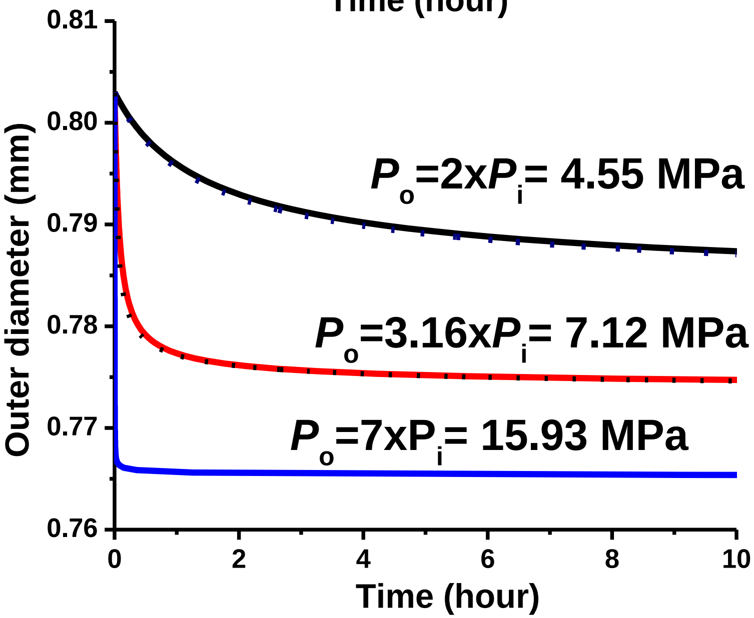
# Model of OP: Under external pressure, Ag creeps inward, producing denser Bi-2212 core and raising $J_c$



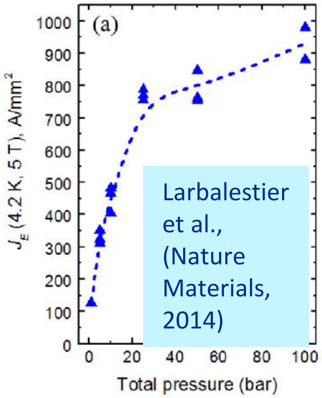
(courtesy of OST)



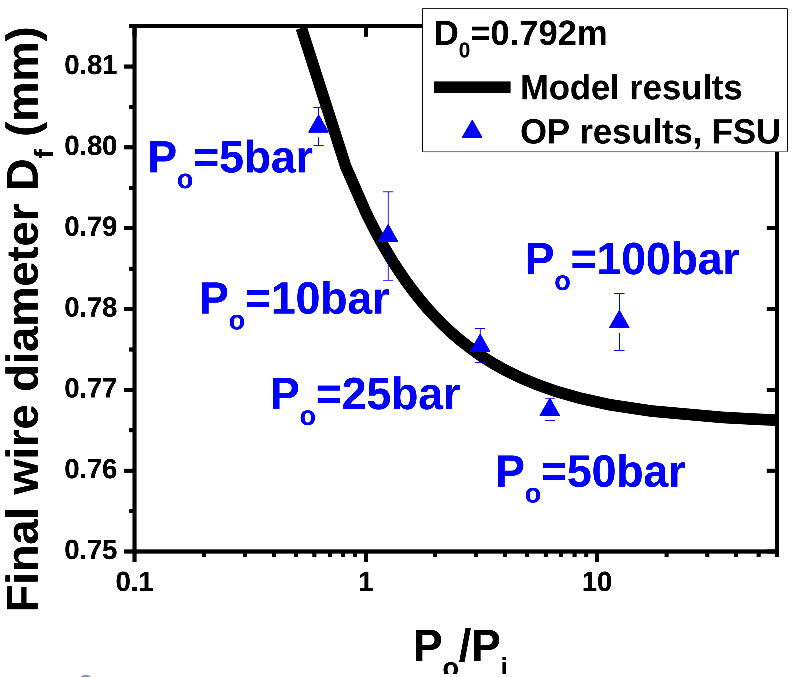



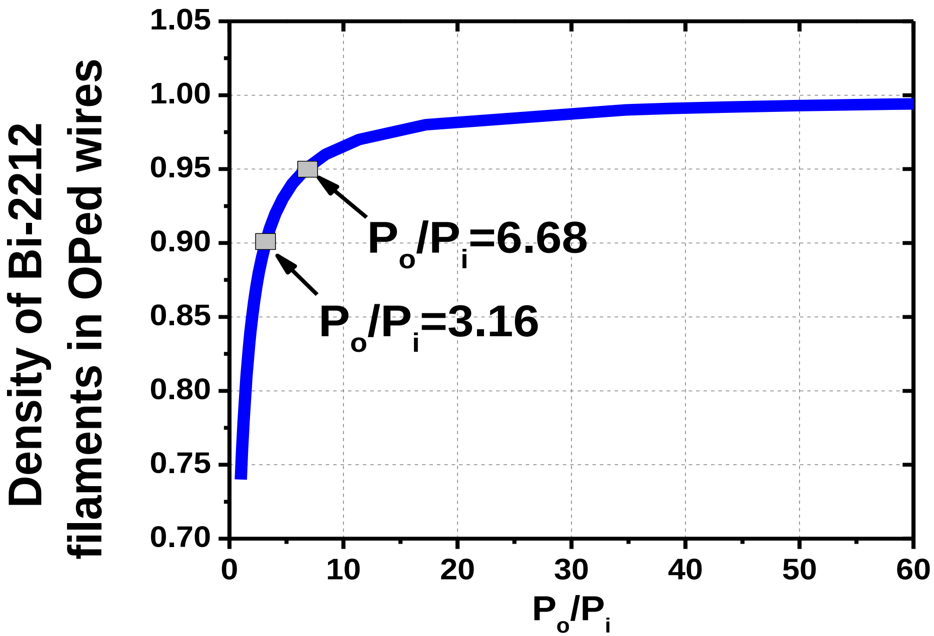
# Model predicts that OP requirement decreases linearly with decreasing internal gas pressure




$P_i$=8 bar now

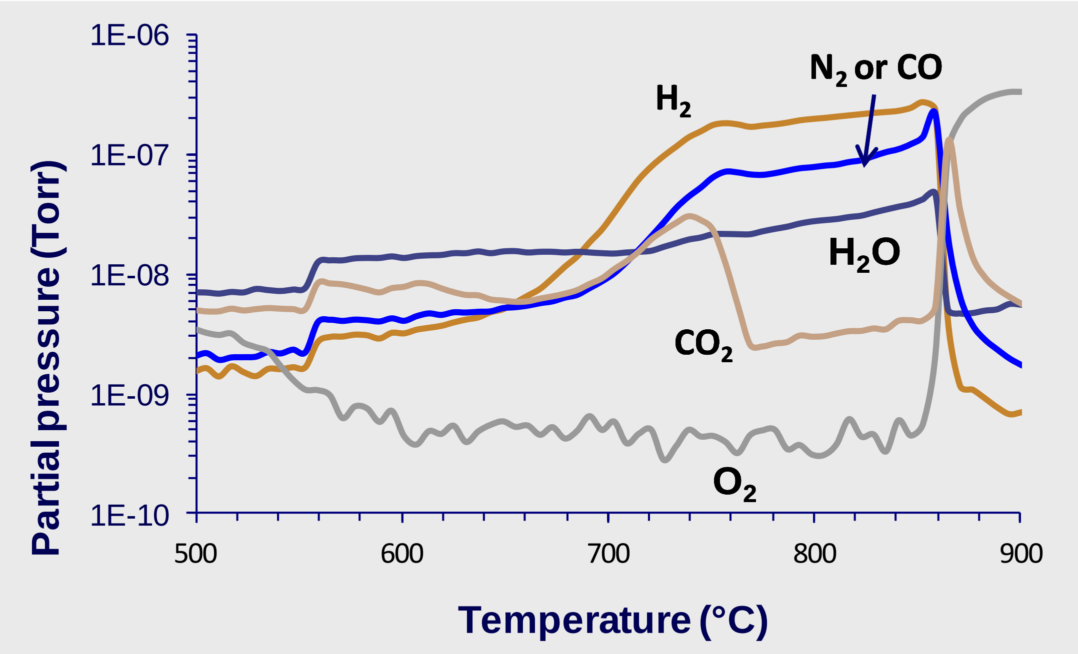
$J_c$ goes up with the filament density.



# Challenges to take on: decreasing the OP requirement from 100 bar to 30-50 bar

- **The model predicts that it is feasible.**
- **Mass spectroscopy indicates that wire releases plenty of gases while being heated up**
- **Need collaboration between powder manufacturer, wire manufacturer, and materials scientists.**



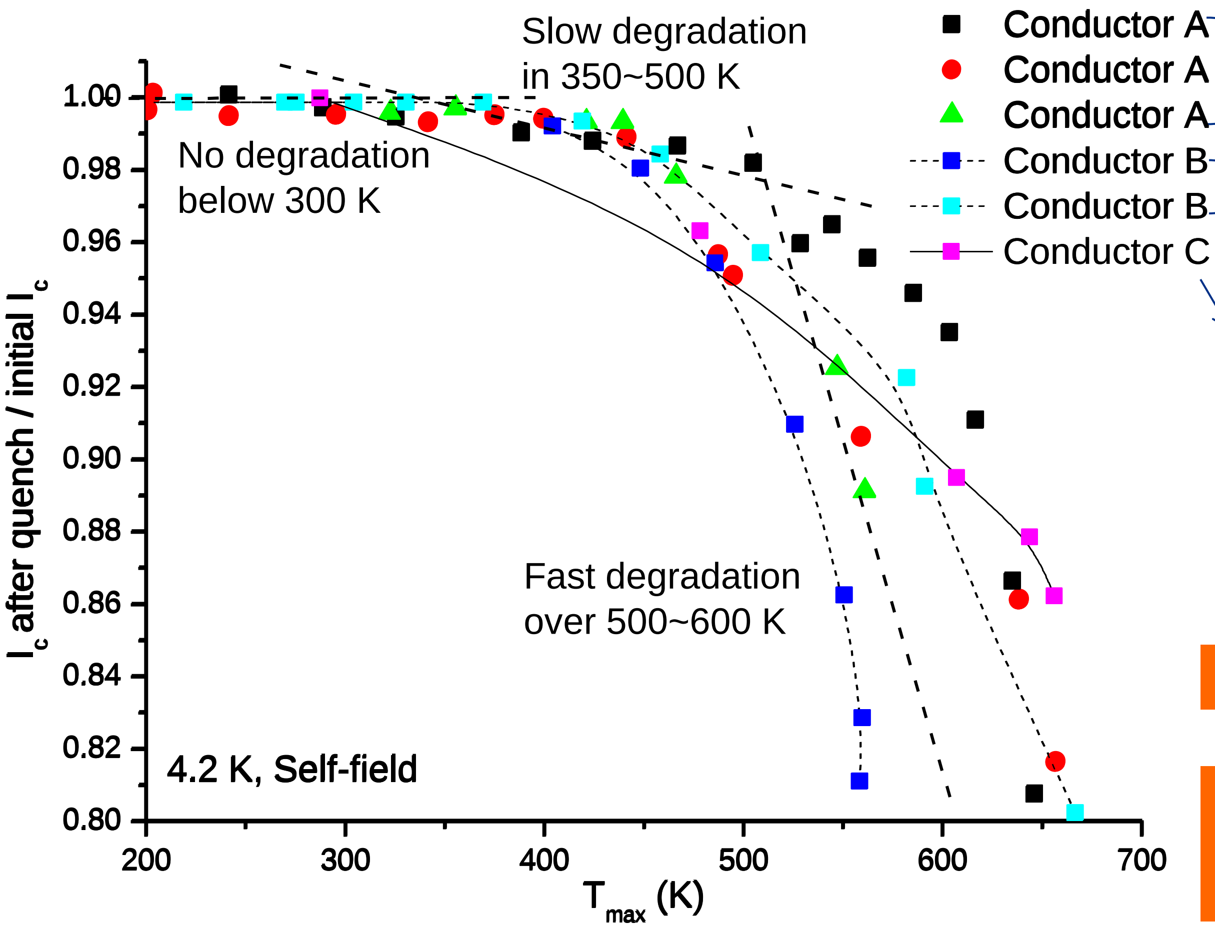

Gas species detected by a residual gas analyzer while heating Bi-2212 wires at 180 ° C/h in vacuum.

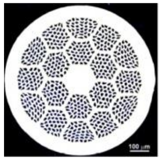
Shen et al., J. Appl. Phys., **113**, 213901 (2013)

# Driving questions for the next section

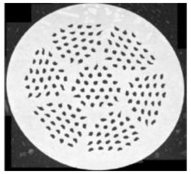
- **Quench detection and protection of Bi-2212 magnets**
  - **What are quench degradation limits and mechanisms?**
  - **How high the hot spot temperature needs to be for the resistive voltage of a normal zone to be detectable?**
  - **At what speed a normal zone propagates and how does this speed depend on operating conditions and conductor processing?**
  - **How can we achieve a quench protection with a time constant $<500$ ms.**

# A large pool of wires, including OP wires, shows a consistent $I_c/I_{co}$-$T_{max}$ behavior

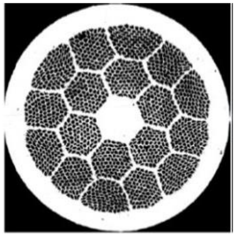


OST 0.8 mm, 37x18
$I_c$(s.f)=450A
Bench marker



OST 1.0 mm, 27x7
$I_c$(s.f)=150A
No Bridging



OST 1.2 mm, 85x18
$I_c$(s.f)=950A

**See Schwartz talk**

**Liyang Ye, PhD thesis work**
**Justin Schwartz, Tengming Shen**

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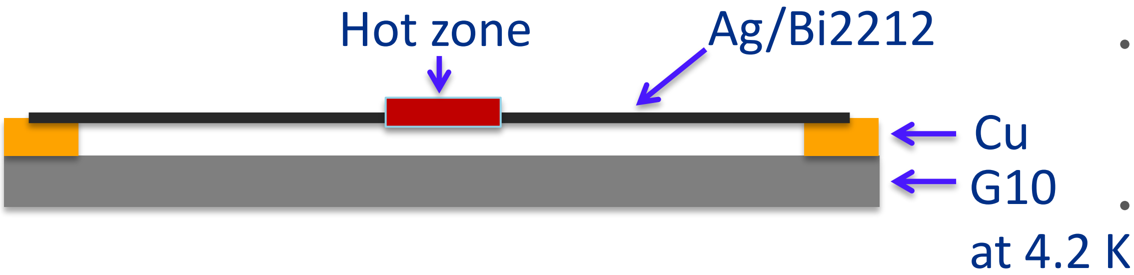
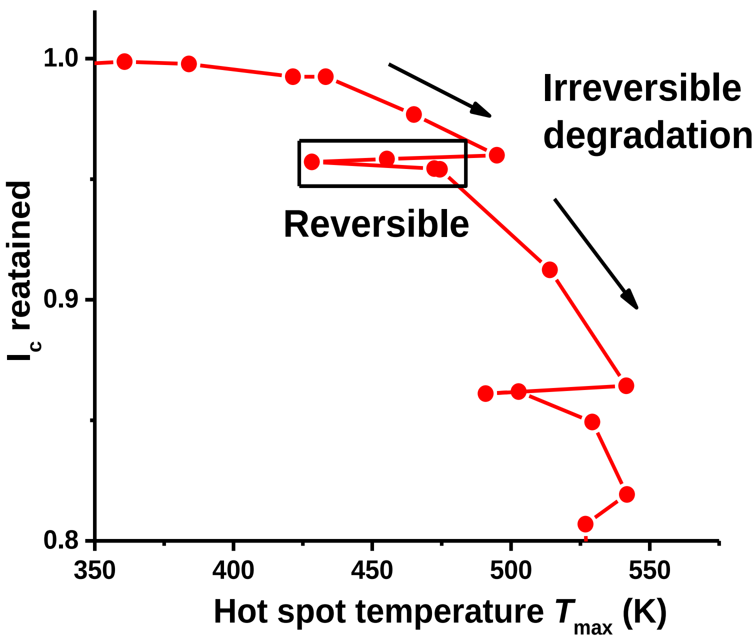
# The observed quench degradation is strain driven - first evidence: irreversible and reversible degradation behavior

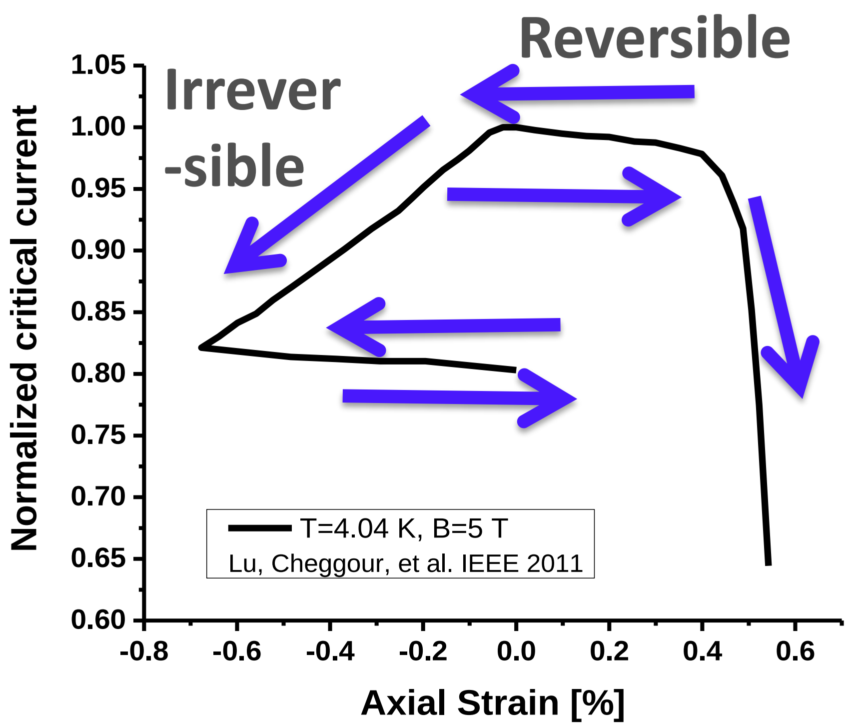



- Wires want to expand but couldn't.
  - Silver buckles under compressive stress.
- Silver and 2212 expand differently.

**Irreversible and reversible degradation behaviors**

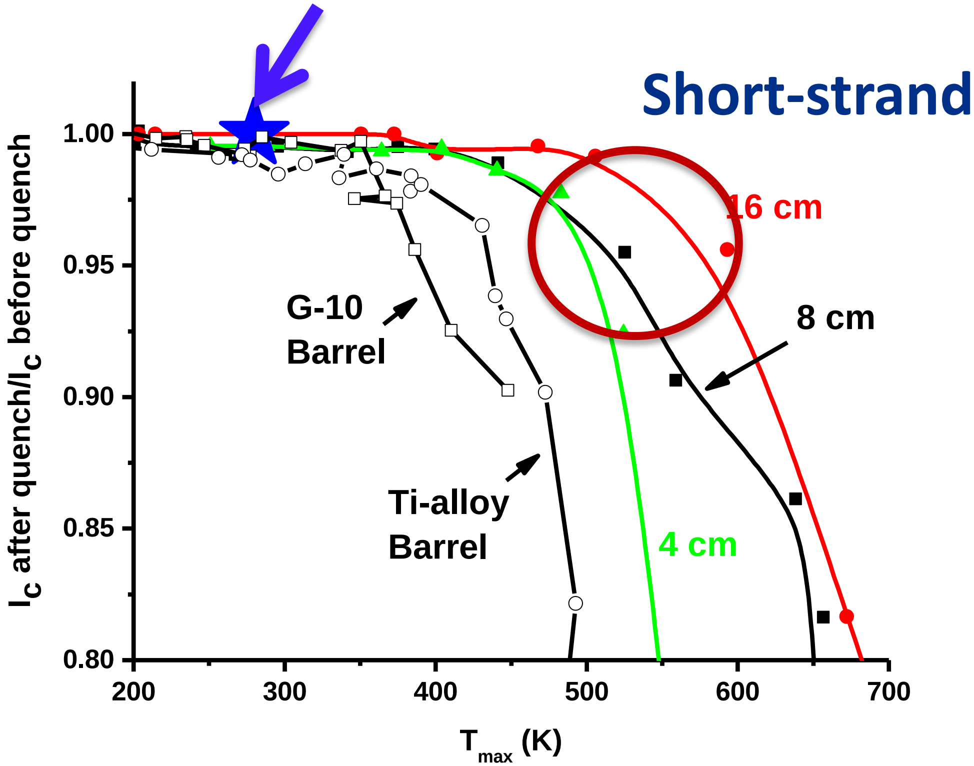



**$J_c$-Strain for Ag/2212 wire**

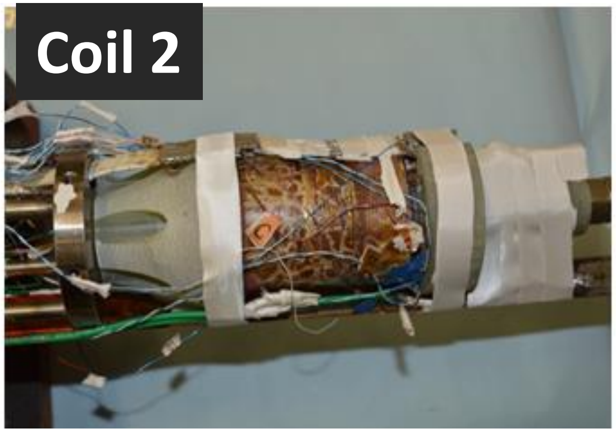


# 300 K seems safe – even for coils under good electromagnetic stresses

## Coil 2 at 7 T, stress=60 MPa






Liyang Ye, PhD thesis work
Justin Schwartz, Tengming Shen

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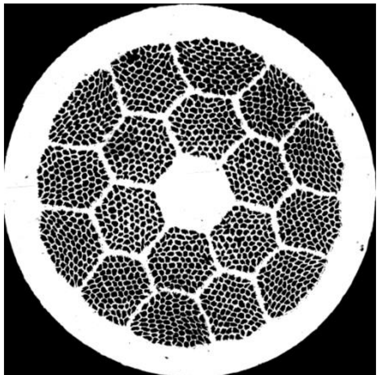
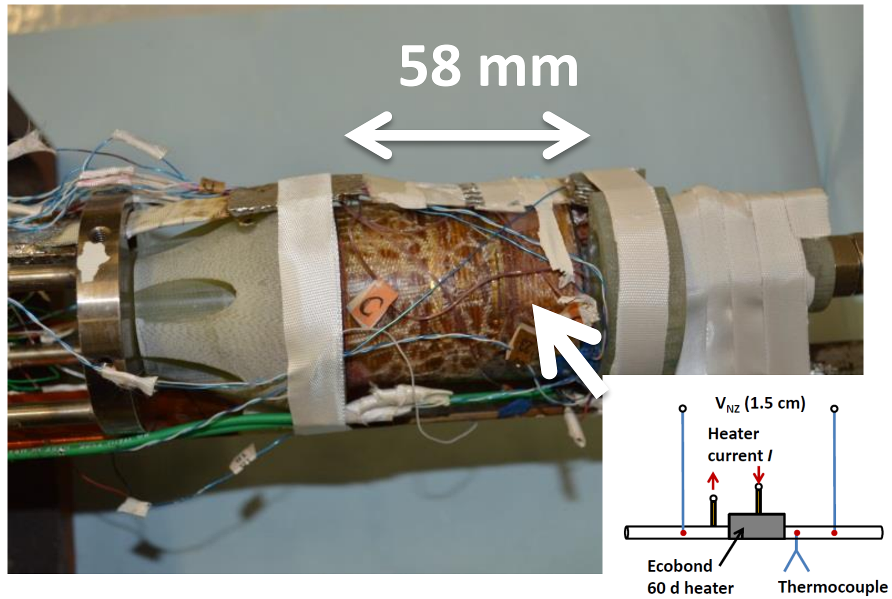
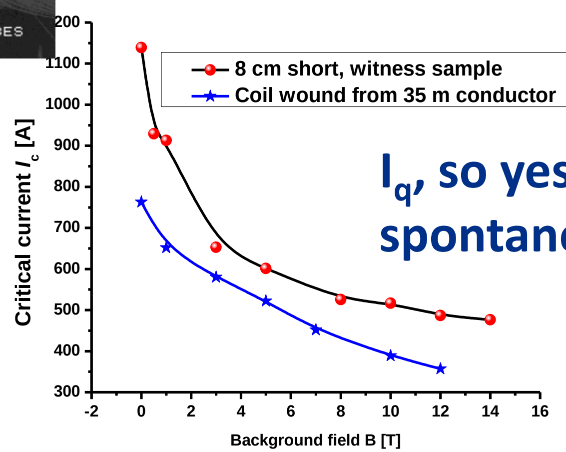
# A 1 bar processed coil and heater-induced quench experiments

## 6-layer, 245 turns, epoxy impregnated Bi-2212 solenoid

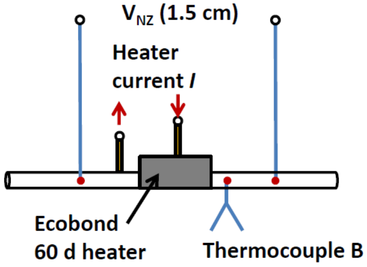


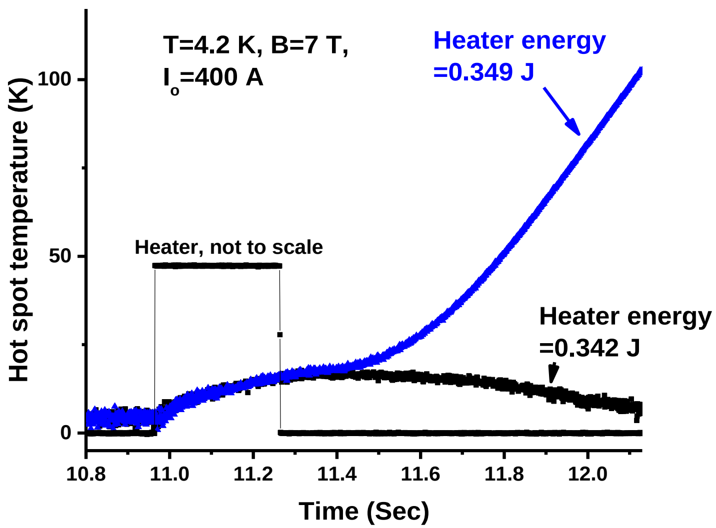



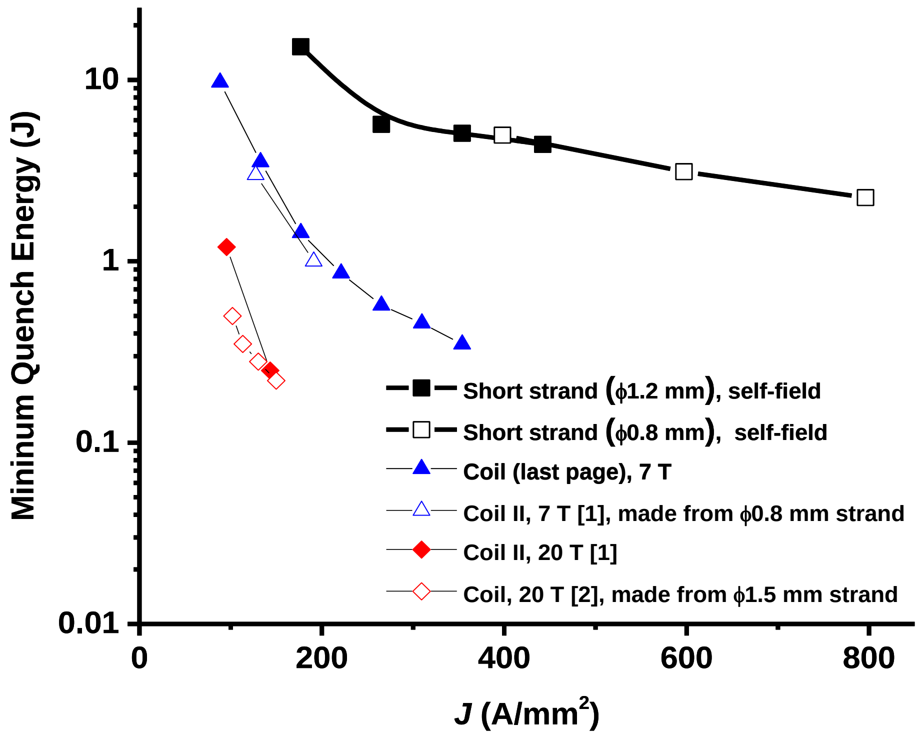




## $I_q$, so yes, 2212 coil can quench spontaneously

# MQE determined from heater-induced quench experiments: a master plot



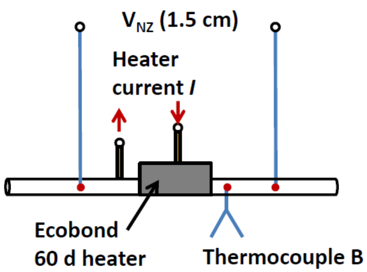



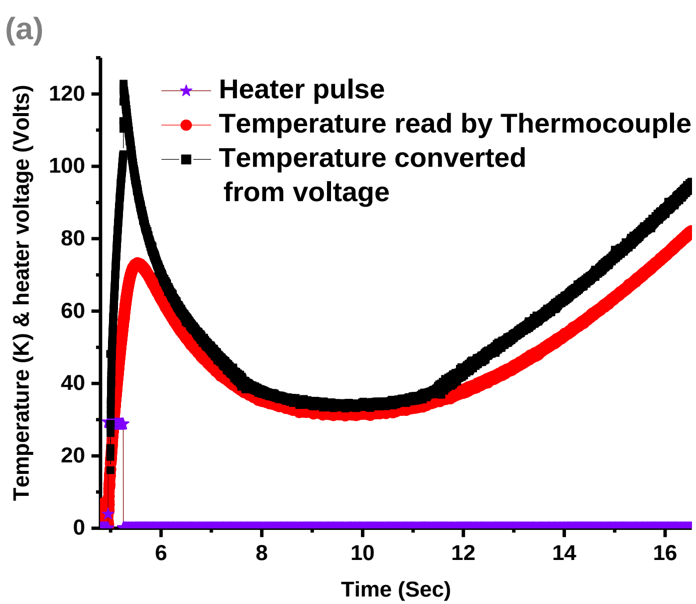



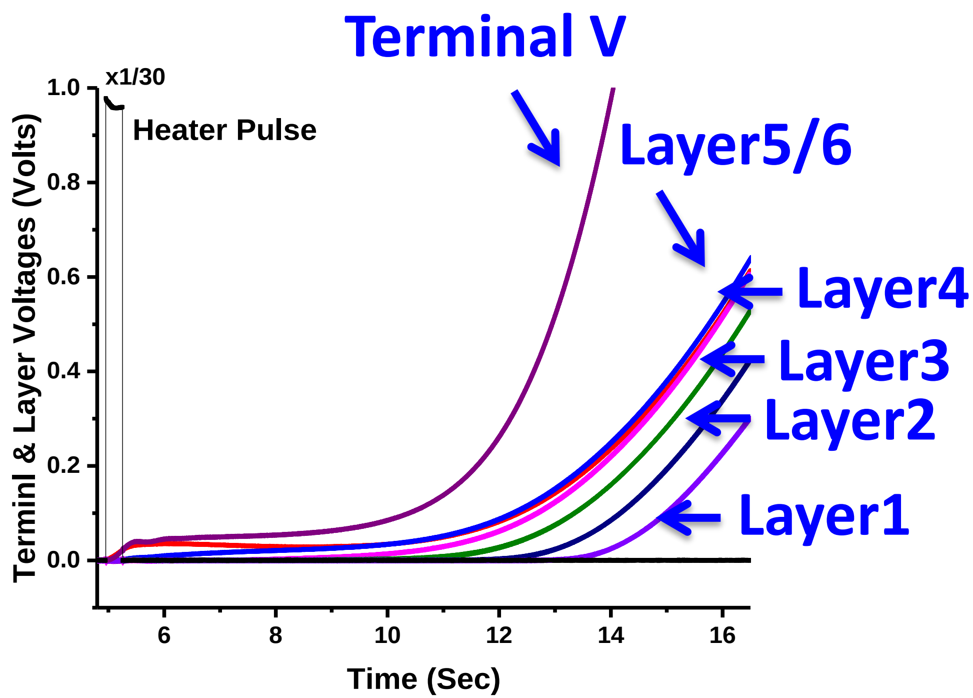

Shen, Ye et al., to be submitted and to appear in ArXiV


[1] Ye et al., SuST, 2013
[2] Yang et al., IEEE, 2012

# T=4.2 K, B=7 T, $I_o$=100 A – Quench propagation and temperature rise at *J*=88 A/mm$^2$

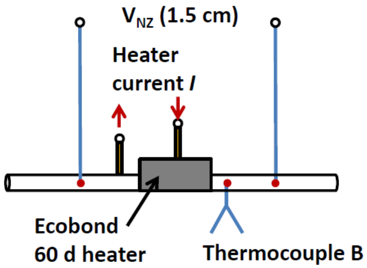


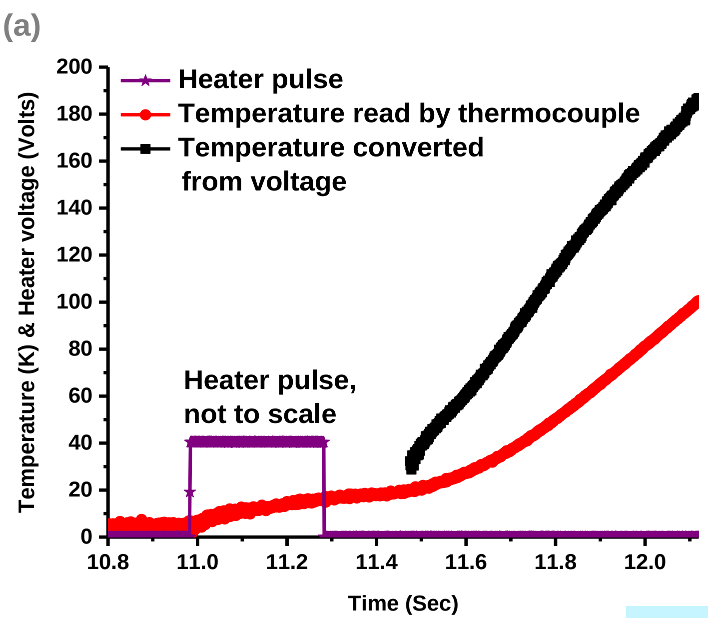



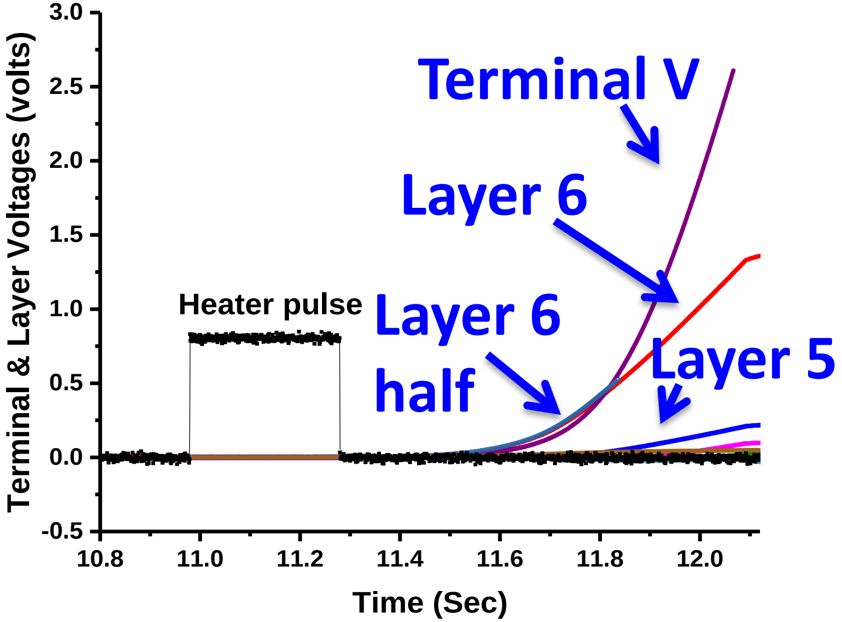




Shen, Ye et al., to be submitted and to appear in ArXiV

# T=4.2 K, B=7 T, $I_o$=400 A – Quench propagation and temperature rise at *J*=354 A/mm$^2$

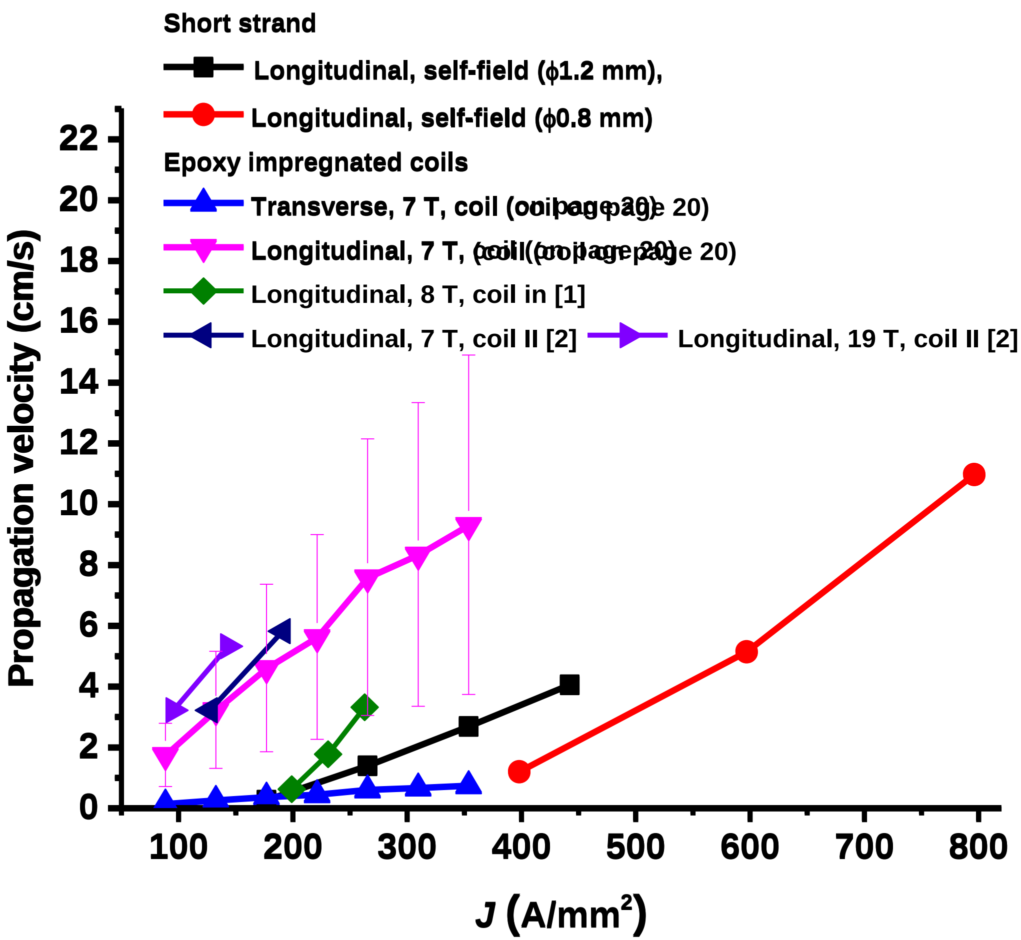



Shen, Ye et al., to be submitted and to appear in ArXiV

# NZPV determined from heater-induced quench experiments: a master plot

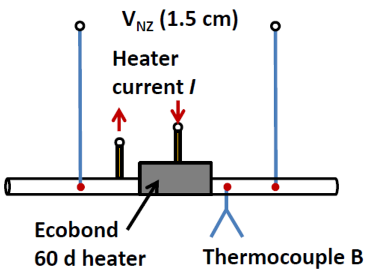



[1] Trociewitz, SuST, 2008
[2] Ye et al., SuST, 2013

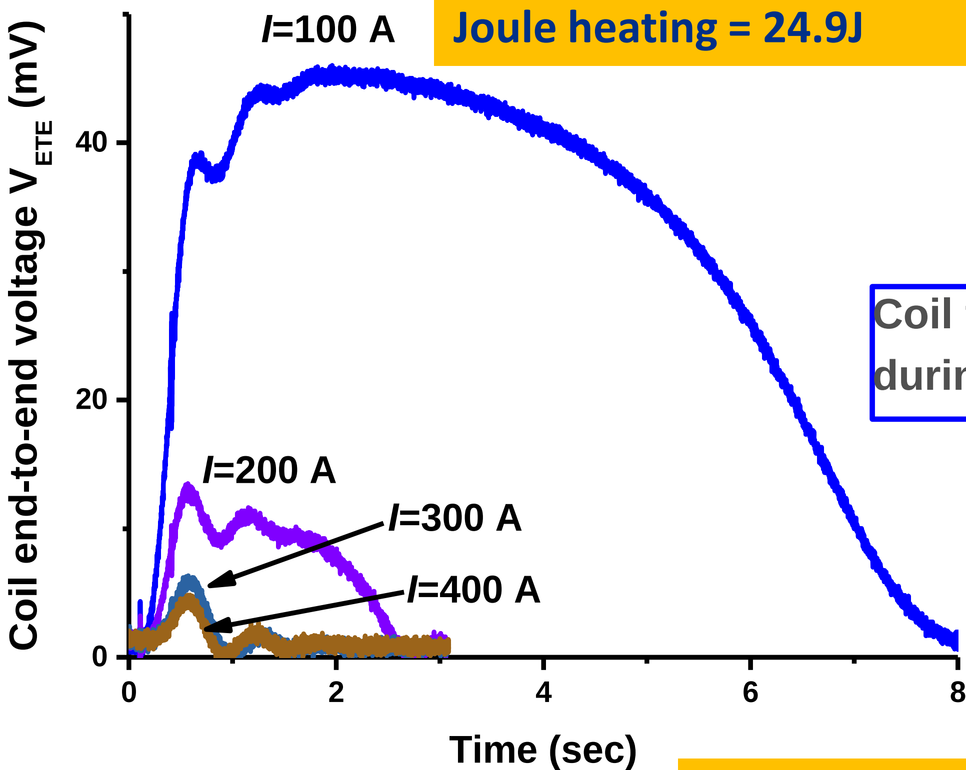
Shen, Ye et al., to be submitted and to appear in ArXiV

# Quench detection – Terminal voltage that coil sustains without a quench varies with transport current

Should a dynamic quench detection threshold used?




I=100 A, $V_{ETE}$=45 mV. $R_{nz}$=0.45 m-ohm
Joule heating = 24.9J



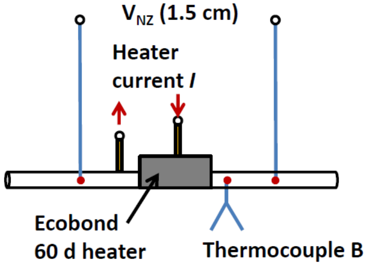

Coil terminal voltage during recovery cases

Shen, Ye et al., to be submitted and to appear in ArXiV

4.2 K, 7 T, coil experiment

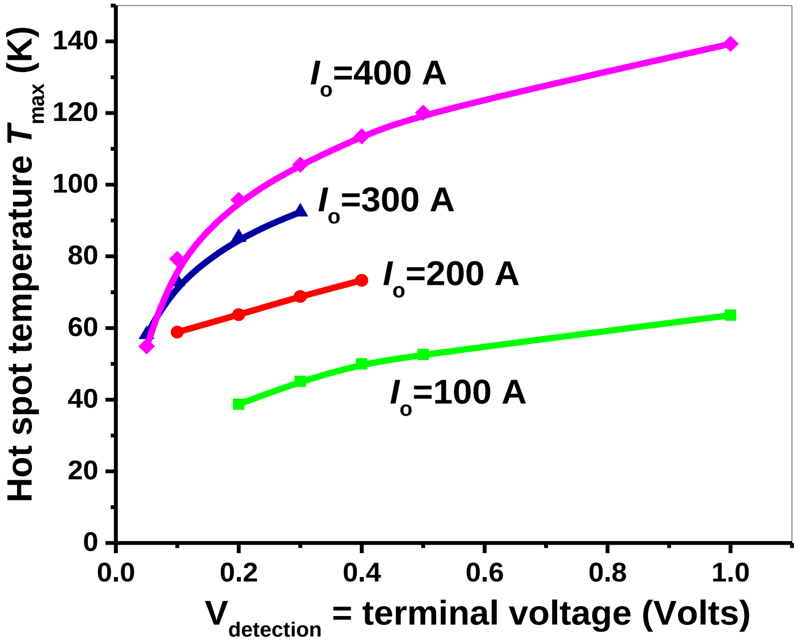
I=400 A, $V_{ETE}$= 4.26 mV. $R_{nz}$=10.6 $\mu$-ohm
Joule heating = 1.18J

# Hot spot temperature v.s. resistivity voltage across normal zone: quench detection is demanding; $V_d$=50-200 mV is preferred




**Note: Temperature from voltage measurement, not from TCs. TCs tend to underestimate $T_{max}$ when dT/dt>10 K/s.**

**Temperatures derived from voltages across the 1.5 cm hot zone:**

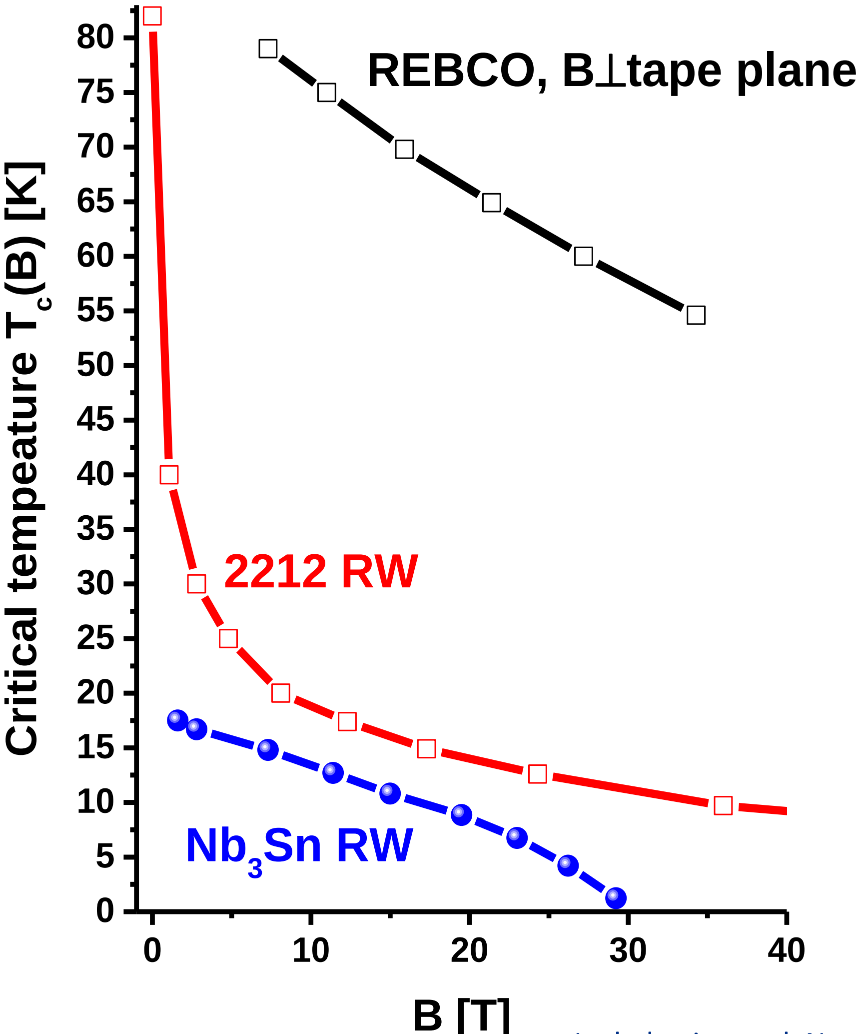



- **100 A-> 400 A, quench detection becomes more difficult.**
- **Beyond 400 A, quench detection should becomes easier (prediction)**
- **Not wise to increase $V_{detection}$ beyond 1 V**

Shen, Ye et al., to be submitted and to appear in ArXiV

**4.2 K, 7 T, coil experiment**

# When B> 5 T, NZPV of 2212 is still in cm/s – but it should be in tens of cm/s or even m/s considering its small temperature margin



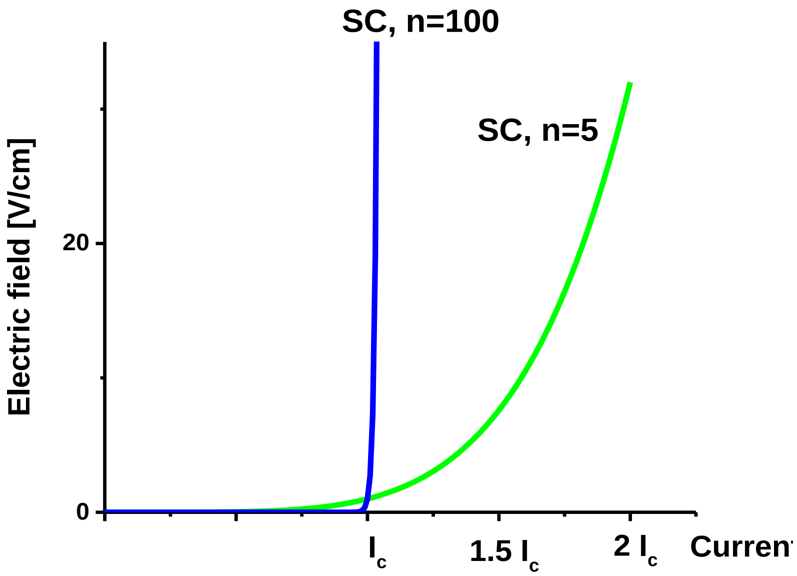

Larbalestier et al, Nature Materials, 2014

- $T_c$ (2212) drops to 25 K when B>5 T
  - B=0: typical HTS, NZPV in cm/s
  - B>5 T: somewhat LTS, NZPV should be in m/s but actually in cm/s
- A big reason is low n-value in Bi-2212
  - Typical n-value for 1 bar coils: 5-12
  - Typical n-value for OP coils: 12-20

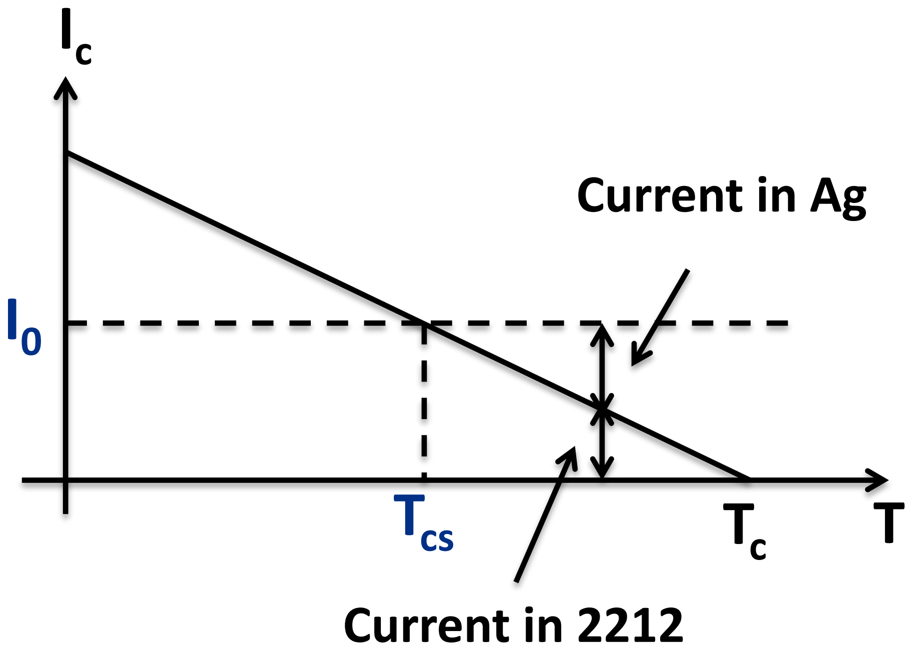
# Summary

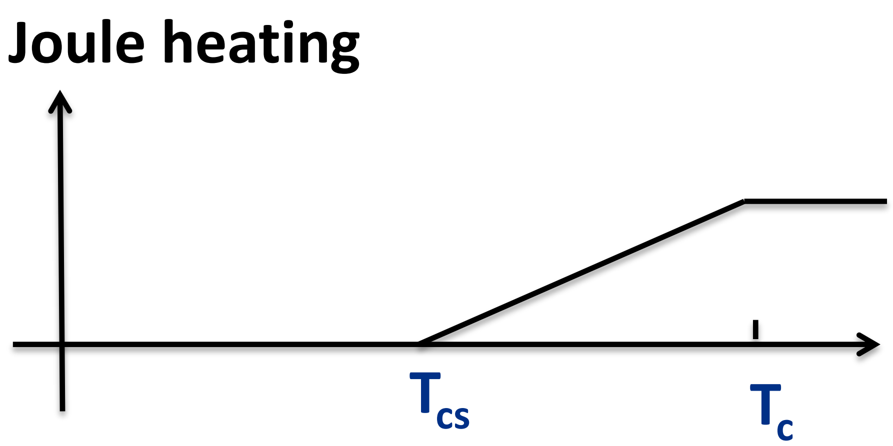
- **Overpressure processing, though not easy, is fundamentally sound**
  - **Good OP cables and coils made and tested**
- **Found a consistent quench degradation behavior in a large spool of wires**
- **Deeper understanding of quenches**
  - **Measure MQE vs. J and B, and NZPV vs. J and B**
  - **First careful measurement of $T_{max}$ v.s. $V_d$**
  - **Strong effects of n-values on quench propagation and detection revealed**
- **Project pull:**
  - **28-30 T all SC solenoid – NHMFL NMR and DOE SIBR/STTR**
  - **The world's first cosine-theta Bi-2212 dipole**
  - **The world's first canted-cosine-theta Bi-2212 dipole**

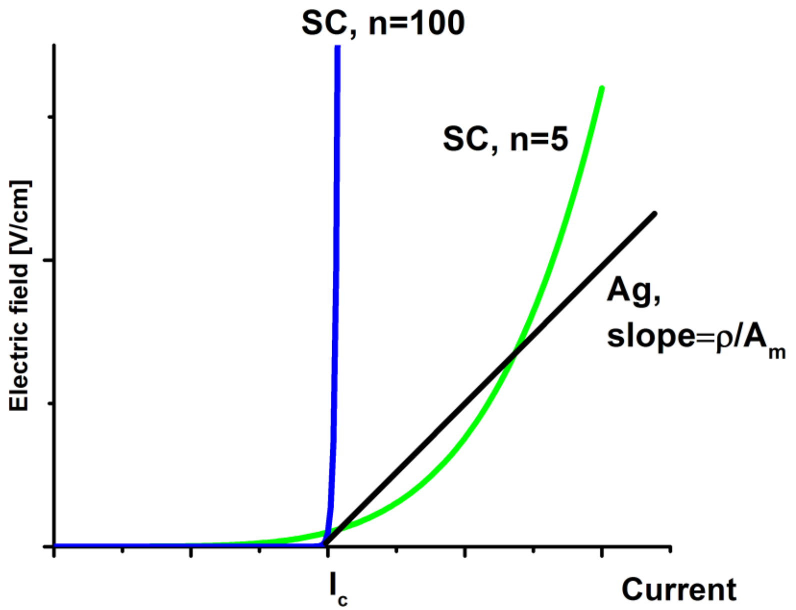
# Slow propagation of normal zones in Bi-2212 magnets: Effects of conductor E-J characteristics



## The joule power model that describes Nb-Ti and $Nb_3Sn$ well is not suitable for 2212 because 2212 has a small n-value (5-15 in fields)

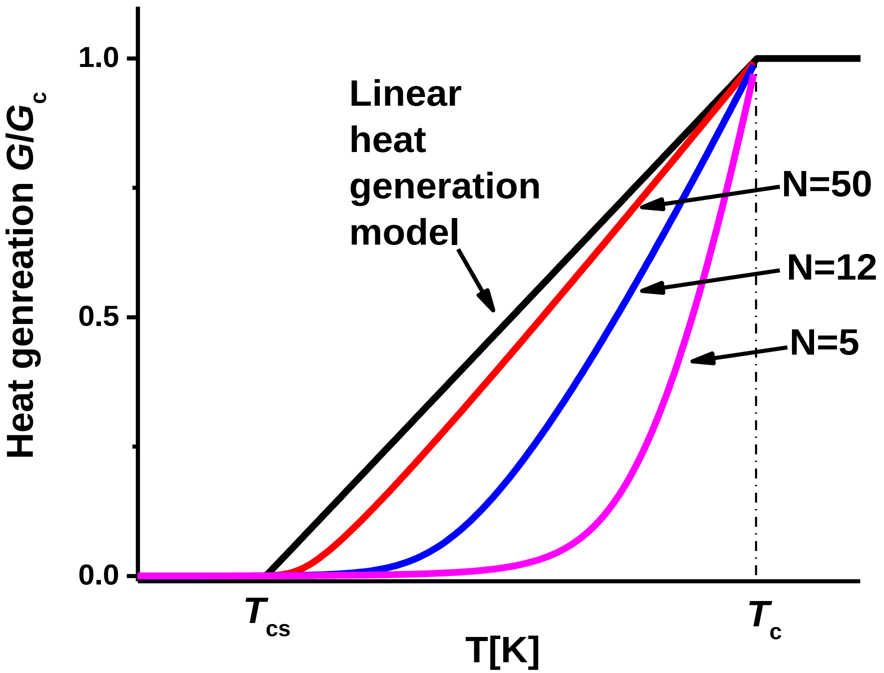


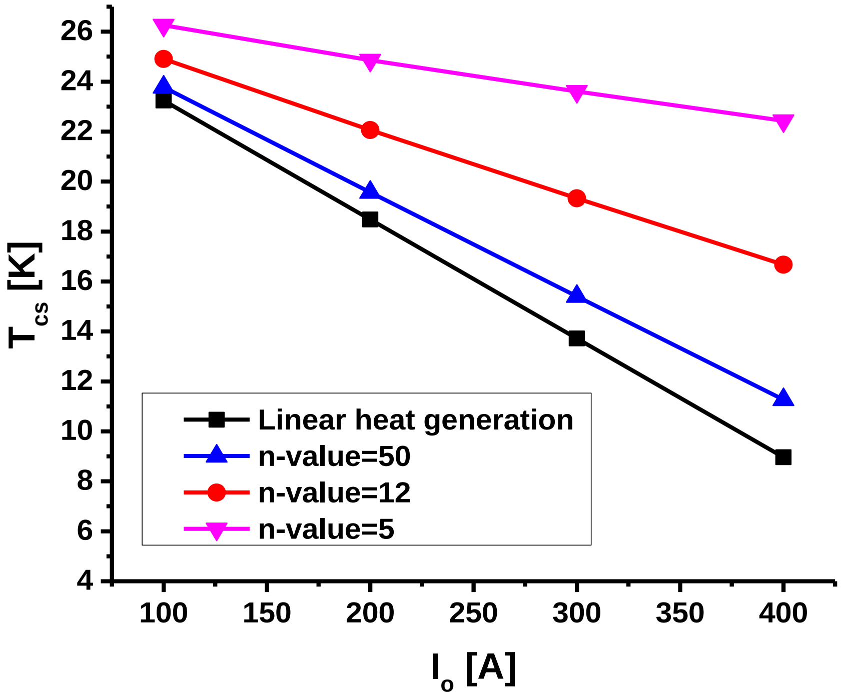



# New nonlinear current-transfer model: Smaller N-value -> more difficult to drive formation of normal zones

- Low N-values, in combination with small RRR, increase $T_{cs}$.
  - More pronounced at high $I_o/I_c$ and at high magnetic fields.



# N-values ⬇: conductor stability ⬆, normal zone propagation speed ⬇

- **Low NZPV in 2212 at B > 5 T is largely caused by low n-values.**
- **Increase the N-value -> In-field NZPV in m/s (though sacrificing some stability)**