Significant improvement of $J_c$ in small $D_s$ RRP® wires through heat treatment changes and phase control

*Using Nausite to our advantage*

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Outline

The ‘big picture’
- Current RRP® limitations
- Hi-Lumi and FCC demands

Heat Treatment “revelation”
- Ian Pong, et. al. (2013)
- The “Nausite membrane”
- The Good, the Bad

Key Findings
- The 215°C dwell is useless
- Nausite growth is strongly dependent on temperature
- Cu diffusion is weakly dependent on temperature

Conclusion
- Promoting Cu diffusion while inhibiting Nausite growth can increase $J_c$
- Our new heat treatment improved $J_c$ (16 T) in small $D_s$ wires by 28% (preserving RRR)
There is a dramatic drop in $J_c$ as the subelements get smaller.

LHC requirements

**Final Targets for FCC Conductor**

A. Ballarino, presented at the FCC week 2016.

**Current Hi-Lumi LHC requirements for LARP Quadrupoles**

S-HiLumi-doc.40; Rev. No.: Original Release; Date: 05-May-2015


* Values presented at 16 T (1500 A/mm²)
* Kramer extrapolation to 15 T = 1865 A/mm²
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“There is limited Sn diffusion outwards” during the 400°C dwell – Pong, *et. al.* (2013)


“There is limited Sn diffusion outwards” during the 400°C dwell due to a barrier of the so-called Nausite (Sn-Nb-Cu phase)

“Pores are mostly observed above 415°C in the filamentary region”
The $400^\circ C$ dwell is where all of the interesting kinetics happens

- Quartz tubes
- Argon gas
- $\sim 13$ cm long pieces

This talk will focus on the fact that at $\sim 400^\circ C$:

- A Nausite ‘membrane’ forms
- Cu diffuses through the Nausite membrane into the core

Three things happen...
The Good, the Bad and the Ugly

Cu diffusion into the core

Nausite growth

Liquefaction of $\eta$

Drawings: © Orlando Aquije 2008
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The Good, the Bad and the Ugly

**The Good:** The Cu diffusion (facilitated by the membrane) consumes the low melting point phase \( \eta \).

**The Bad:** The Nausite membrane grows with time.

**The Ugly:** Any remaining \( \eta \) will liquefy and produce large amounts of Nausite.

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**How do we rescue this Nb??**

Upon liquefaction...

Sequestered Nb, bound to form disconnected Nb\(_3\)Sn.
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Conclusion
- Promoting Cu diffusion while inhibiting Nausite growth can increase $J_c$
- Our new heat treatment improved $J_c (16\, T)$ in small $D_s$ wires by 28% (preserving RRR)
The 215°C dwell is useless, and it can be skipped without affecting strand properties.

There is virtually no degradation of properties when skipping 215°C.

\[ \Delta H_k \approx 0.06 \, \text{T} \]
\[ \Delta J_c (12 \, \text{T}) \approx -38 \, \text{A/mm}^2 \]
\[ \Delta n\text{-value} \approx 0.04 \]

(when skipping 215°C dwell)
Nausite growth is strongly dependent on temperature.

Power law growth:

\[ x(T, t) = kt^{0.27} \]

Arrhenius:

\[ k = k^0 e^{-\frac{Q_g}{RT}} \]

Activation energy:

\[ Q_g = -98.274 \text{ kJ/mol} \]

Reducing temperature seems to be beneficial if we are to prevent Nausite formation (as a layer)—“the bad”

**Predicted values**

8 hours 16 hours 24 hours 32 hours 40 hours 48 hours
Cu diffusion to the core is weakly dependent on temperature.

- 2.4 ng after 8 hours (at 398°C)
- 2.8 ng after 48 hours (at 398°C)

Graph showing Cu mass in core per meter of wire (ng) vs. Dwell Time (h) at different temperatures:
- 398°C
- 390°C
- 380°C
- 370°C
Longer heat treatments at lower temperatures draw more Cu in and inhibit Nausite Growth

“The Good” is not affected by lower temperatures

“The Bad” is slowed down significantly by lower temperatures

All we have to do to take care of “The Ugly” is let this run for a long time...

...so more Cu gets drawn in
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**Key Findings**
- The 200°C dwell is useless
- Nausite growth is strongly dependent on temperature
- Cu diffusion is weakly dependent on temperature

**Conclusion**
- Promoting Cu diffusion while inhibiting Nausite growth can increase $J_c$
- Our new heat treatment improved $J_c$ (16 T) in small $D_s$ wires by 28% (preserving RRR)
Promoting Cu diffusion while inhibiting Nausite growth can increase $J_c$

- **Standard Heat Treatment**
  - Roughly the same length
  - Same A15 reaction $T$
  - RRR was not affected

- **1st attempt to control Nausite**
  - Roughly the same length

Graphs showing $J_c$ vs. $B(T)$ for different thicknesses (0.6 mm, 0.7 mm, 0.85 mm) and indicating a 28% increase.
Back to the (sobering) ‘big picture’

There are two kinds of heat treatments in this world my friends, those who use Nausite to their advantage, and those who waste Nb.

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 Plenty of work ahead of us!

Current Hi-Lumi LHC requirements

Kramer extrapolation to 15 T = 1865 A/mm²

1st attempt to control Nausite

The Good

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Kramer extrapolation to 15 T = 1865 A/mm²

Thank you

Special thanks to **Arup Ghosh** (BNK), **Ian Pong** (LBNL), **Dan Dietderich** (LBNL), and **Lance Cooley** (Fermi Lab) for fruitful discussions.

This work was funded by the **Department of Energy** under grant: DE-FOA-0001604

The National High Magnetic Field Laboratory where the experiments were performed is supported by the **National Science Foundation** Cooperative Agreement DMR-1157490 and by the State of Florida.

Some of the wires used in this study were made under the **US Conductor Development Program**.