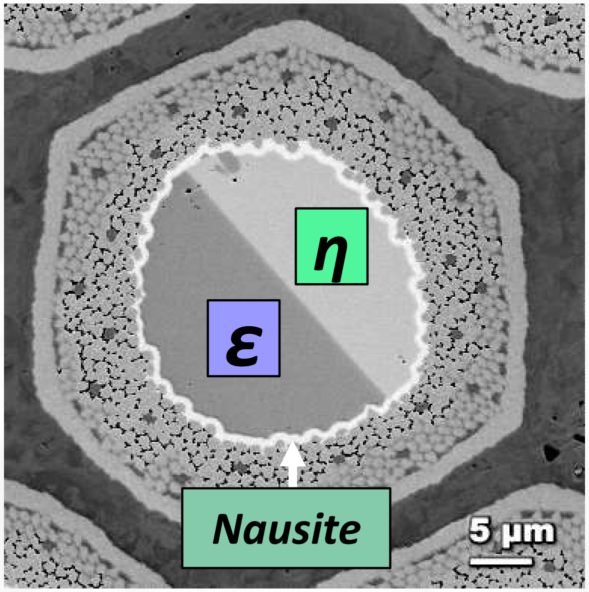
Significant improvement of J_c in small D_s RRP® wires through heat treatment changes and phase control

Using Nausite to our advantage



Charlie Sanabria[1], Michael Field[2], P. J. Lee[1], Hanping Miao[2], D. C. Larbalestier[1] and Jeffrey Parrell[2]

[1] Applied Superconductivity Center, NHMFL, Florida State University, Tallahassee, FL 32310, USA
[2] Oxford Superconducting Technology
600 Milik Street Carteret, NJ
07008, USA

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ASC

September 8th, 2016

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2016.
Presentation of ASC 2016 paper 4MOr2A-04. ASC Victor Keilin Memorial Prize (Materials) Winner.

Outline

- **The 'big picture'**
  - Current RRP® limitations
  - Hi-Lumi and FCC demands
- **Heat Treatment "revelation"**
  - Ian Pong, *et. al.* (2013)
  - The "Nausite mem
  - The Good, the Bad
- **Key Findings**
  - The 215°C dwell is
  - Nausite growth is
  - Cu diffusion is wea
- **Conclusion**
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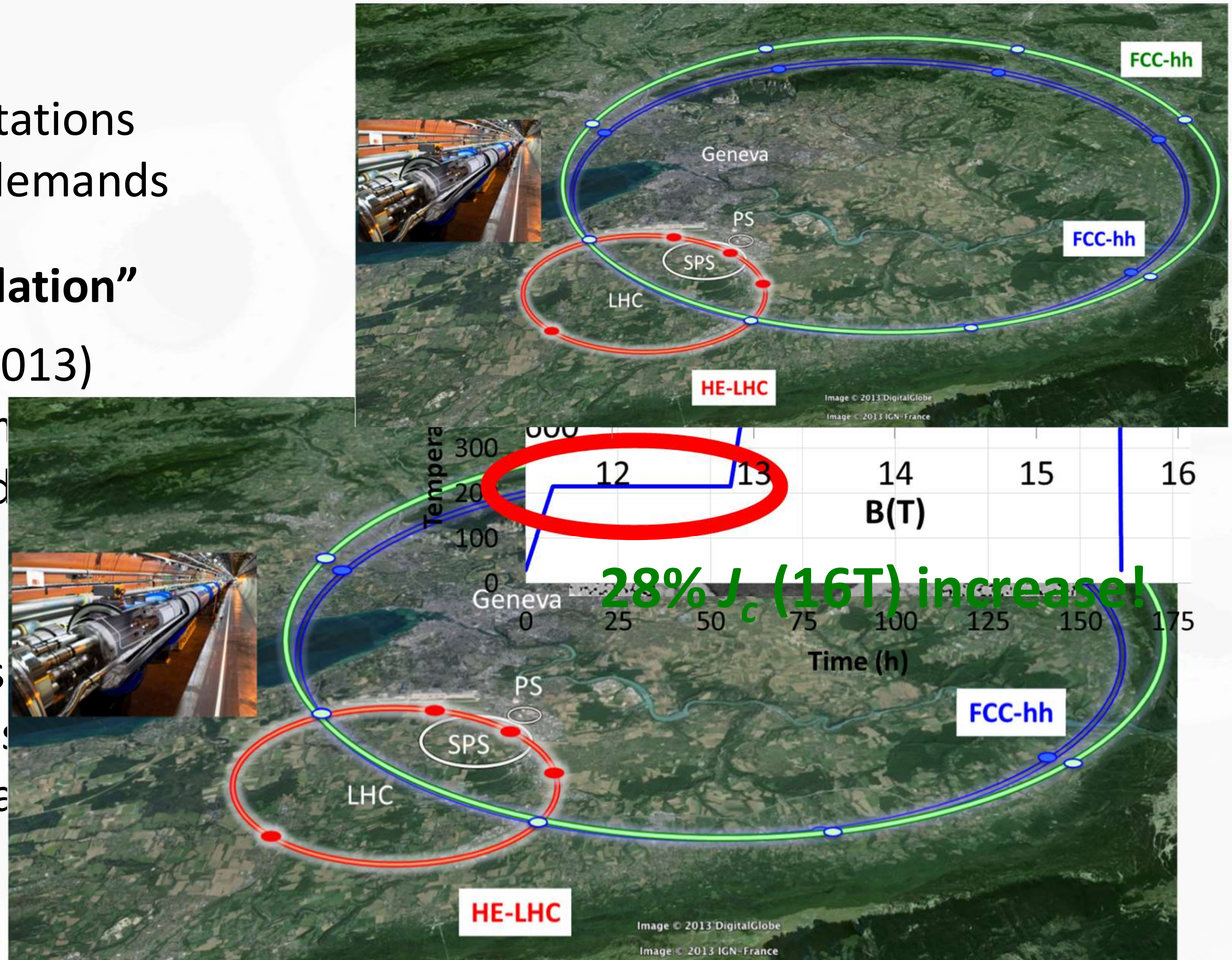
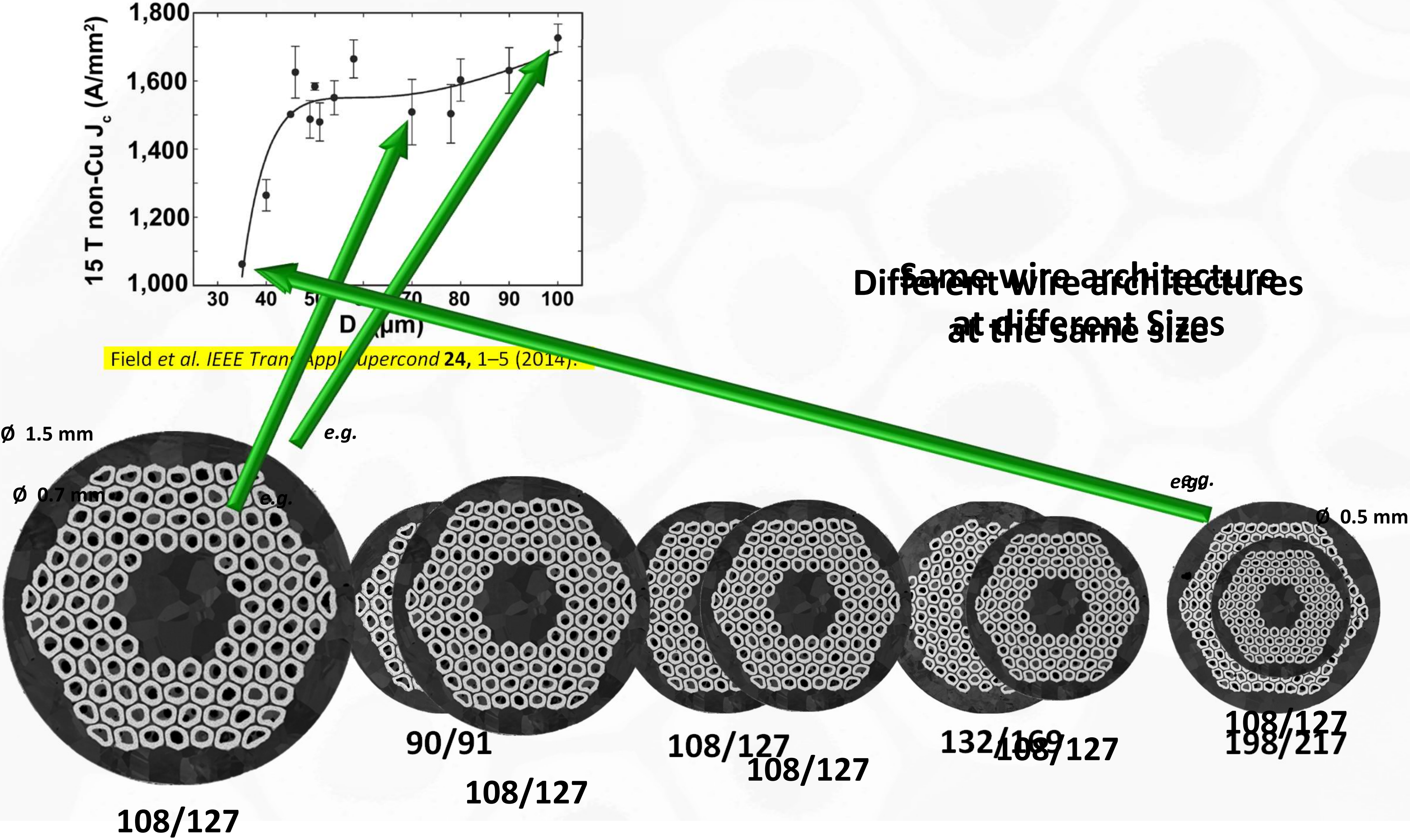


Picture by Luca Bottura

There is a dramatic drop in J_c as the subelements get smaller



Field *et al. IEEE Trans. Appl. Supercond* **24,** 1–5 (2014).

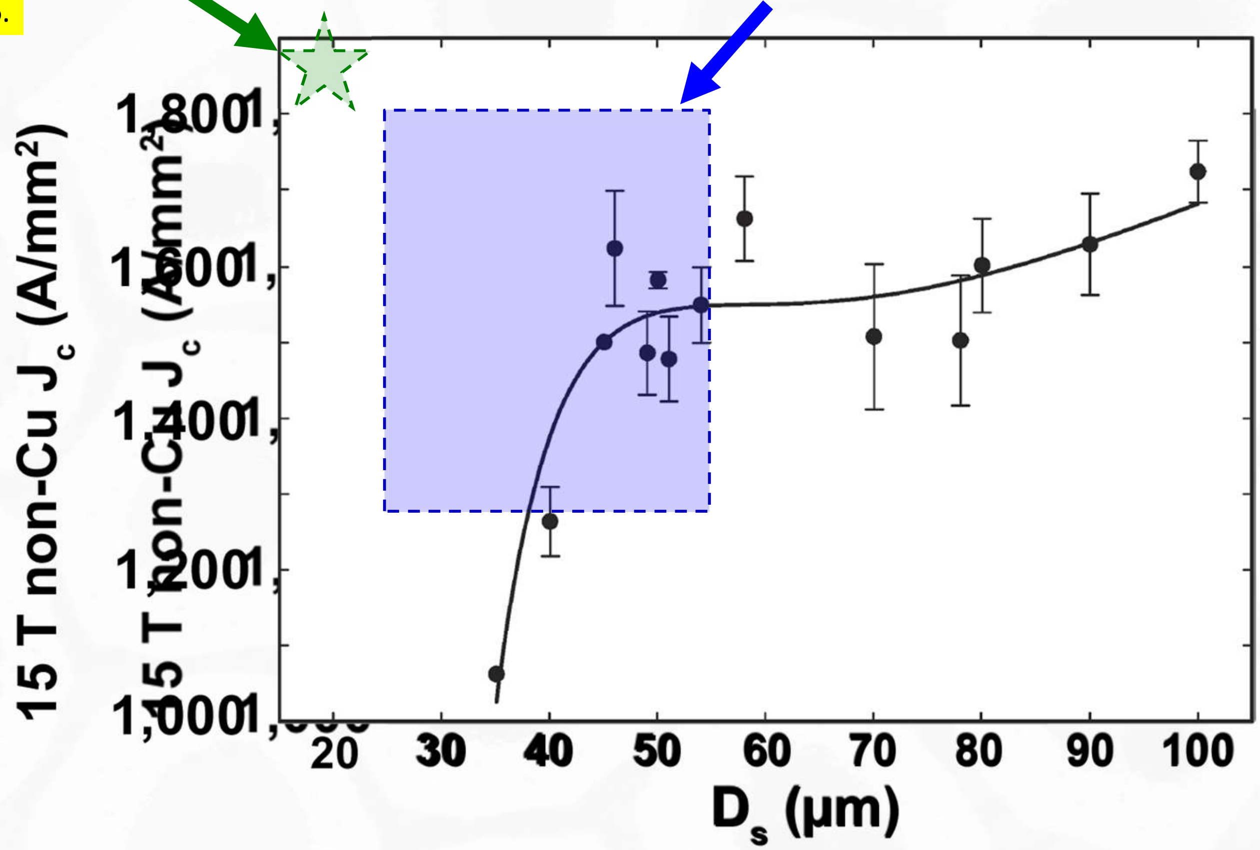
LHC requirements

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



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* **Values presented at 16 T (1500 A/mm²)**
Kramer extrapolation to 15 T = 1865 A/mm²

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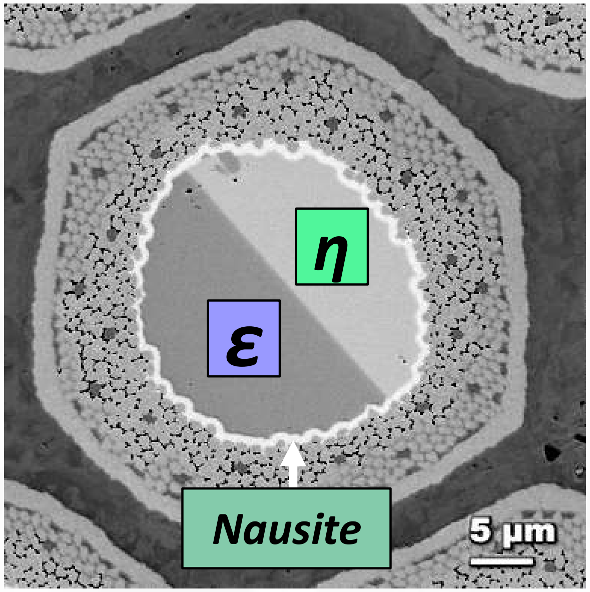

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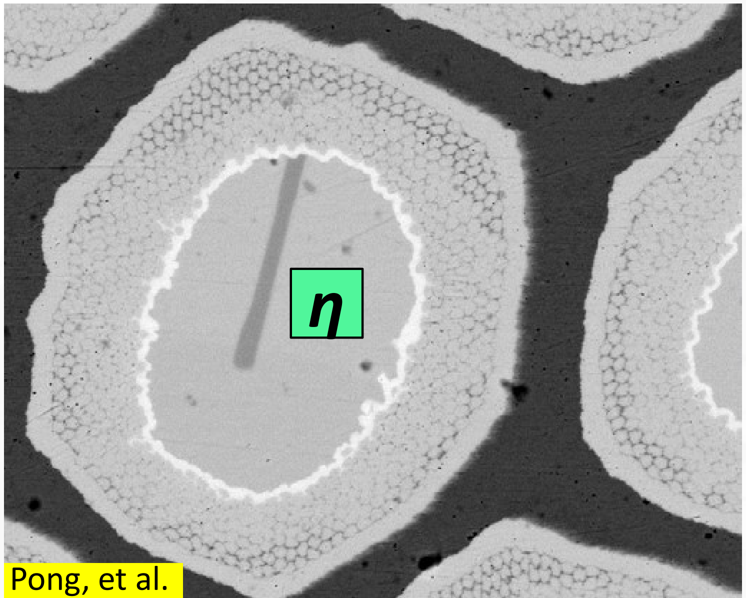
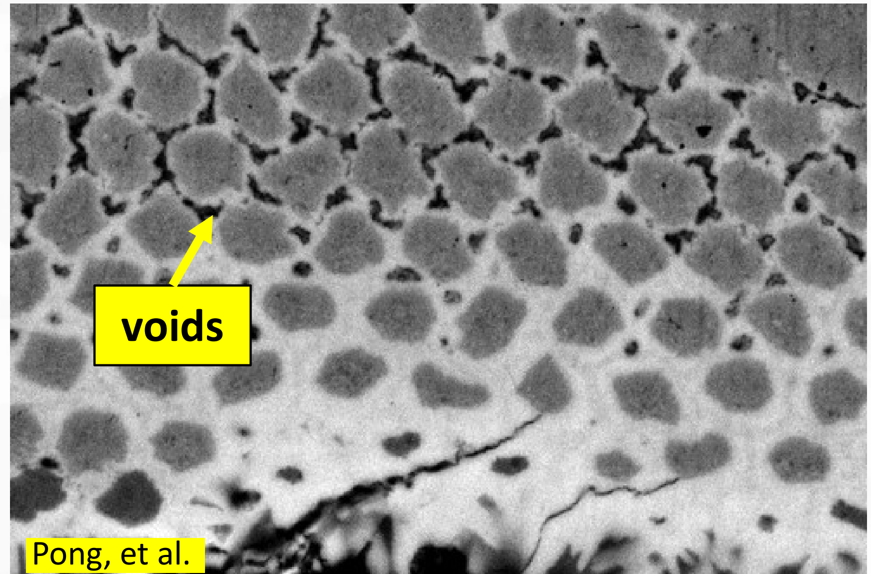
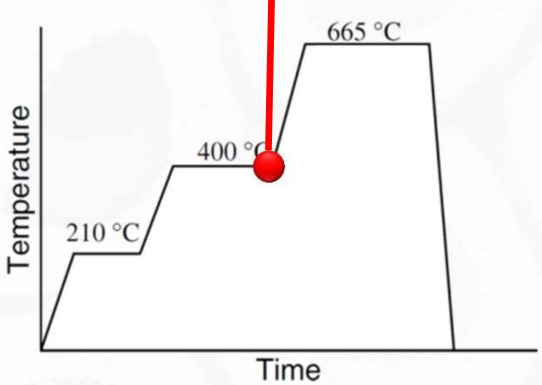
“There is limited Sn diffusion outwards” during the 400°C dwell – Pong, *et. al.* (2013)

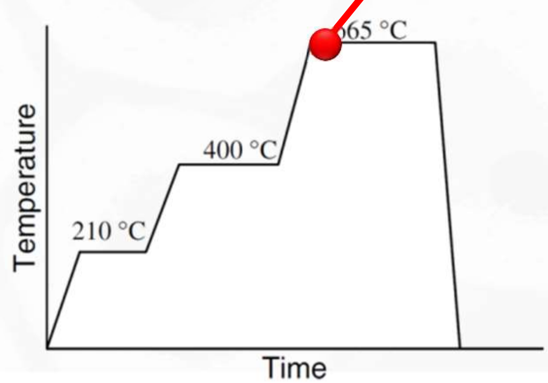




“**There is limited Sn diffusion outwards**” during the 400°C dwell due to a barrier of the so-called Nausite (Sn-Nb-Cu phase)

“**Pores are mostly observed above 415°C in the filamentary region**”

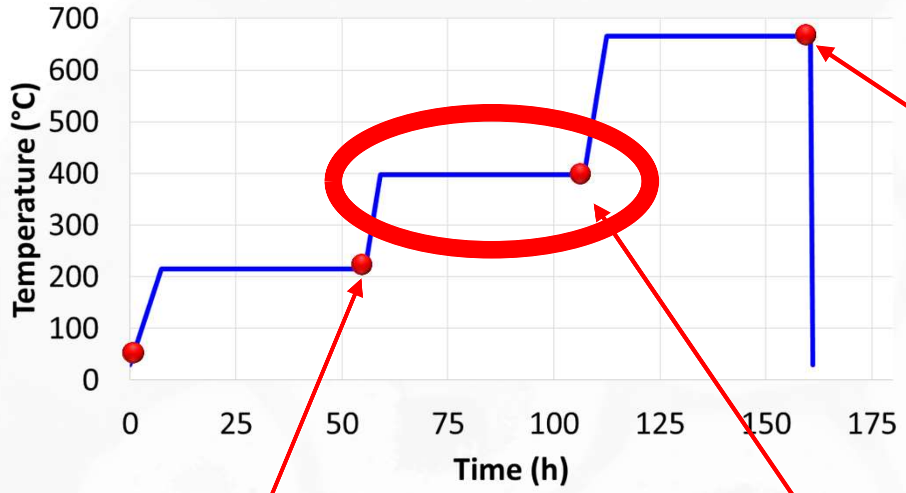


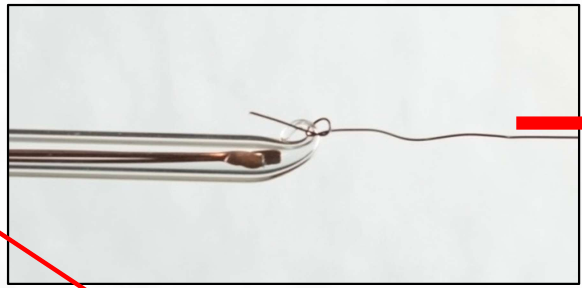


I. Pong, et al. *Supercond. Sci. Technol.*, **26** (10) Oct. 2013

The 400°C dwell is where all of the interesting kinetics happens

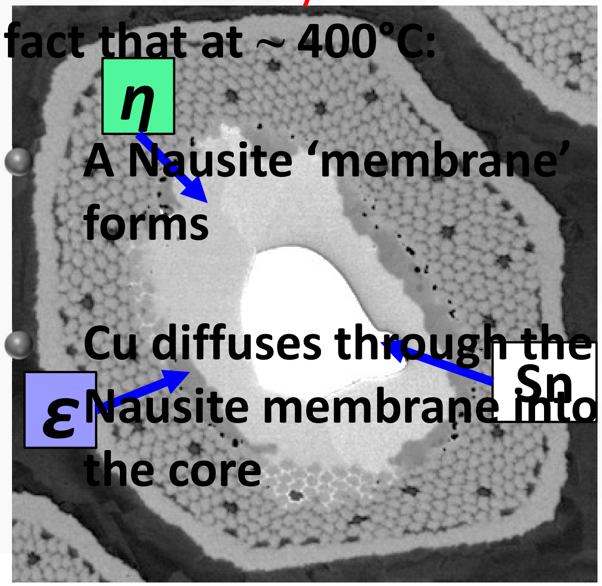
- Quartz tubes
- Argon gas
- ~13 cm long pieces

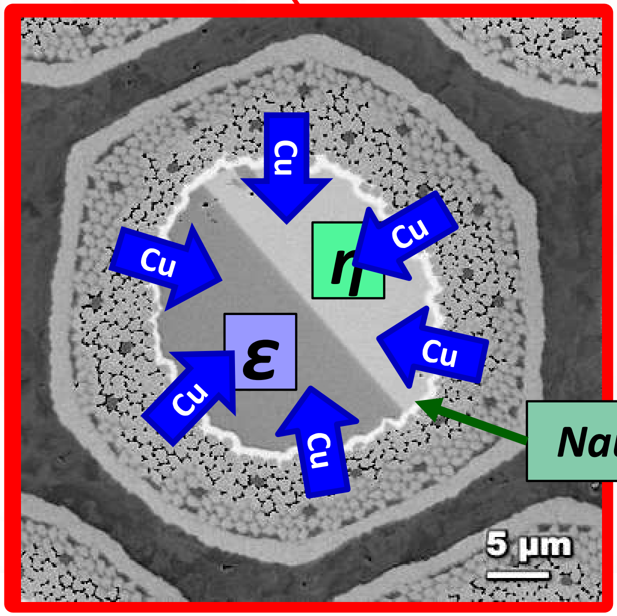


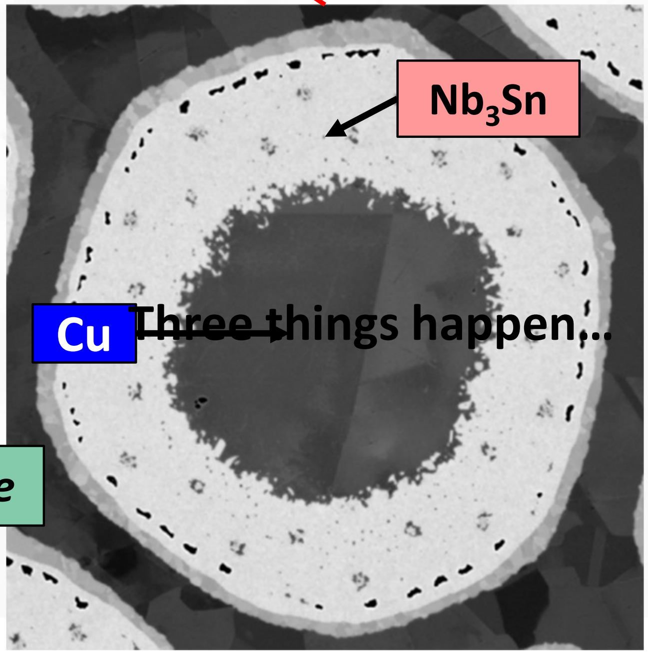


This talk will focus on the fact that at ~ 400°C:

- A Nausite 'membrane' forms
- Cu diffuses through the Nausite membrane into the core







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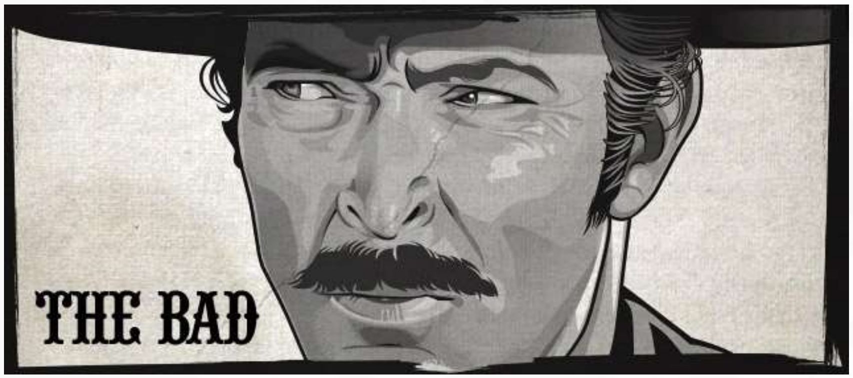
The Good, the Bad and the Ugly

Cu diffusion into the core



Nausite growth

Liquefaction of η

The Good, the Bad and the Ugly

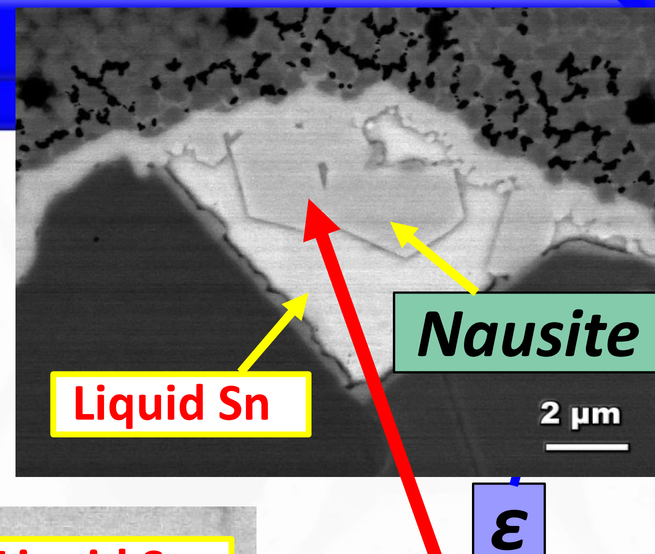
…membrane)

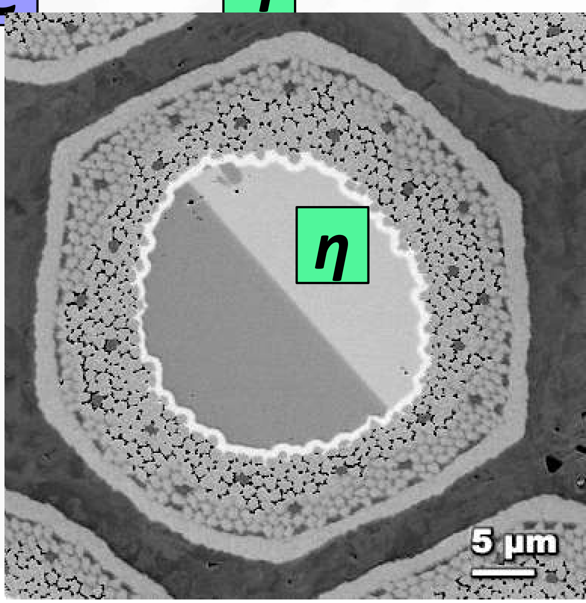
…phase η

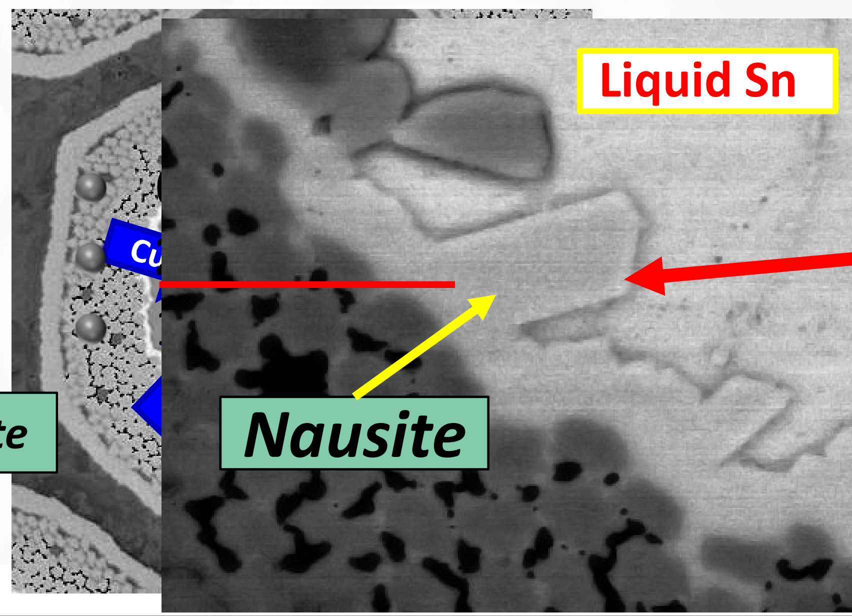
Time

How do we rescue this Nb???

Upon liquefaction…







Sequestered Nb, bound to form disconnected Nb_3Sn

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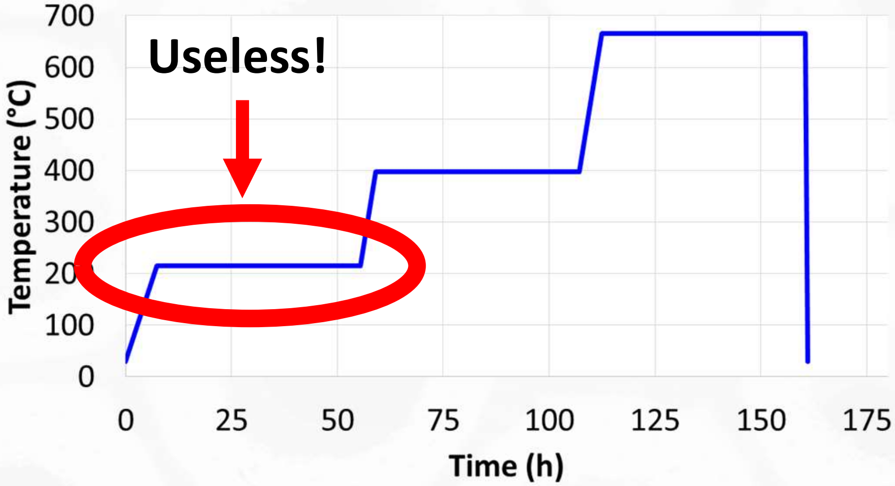

- **Key Findings**
  - The 215°C dwell is useless
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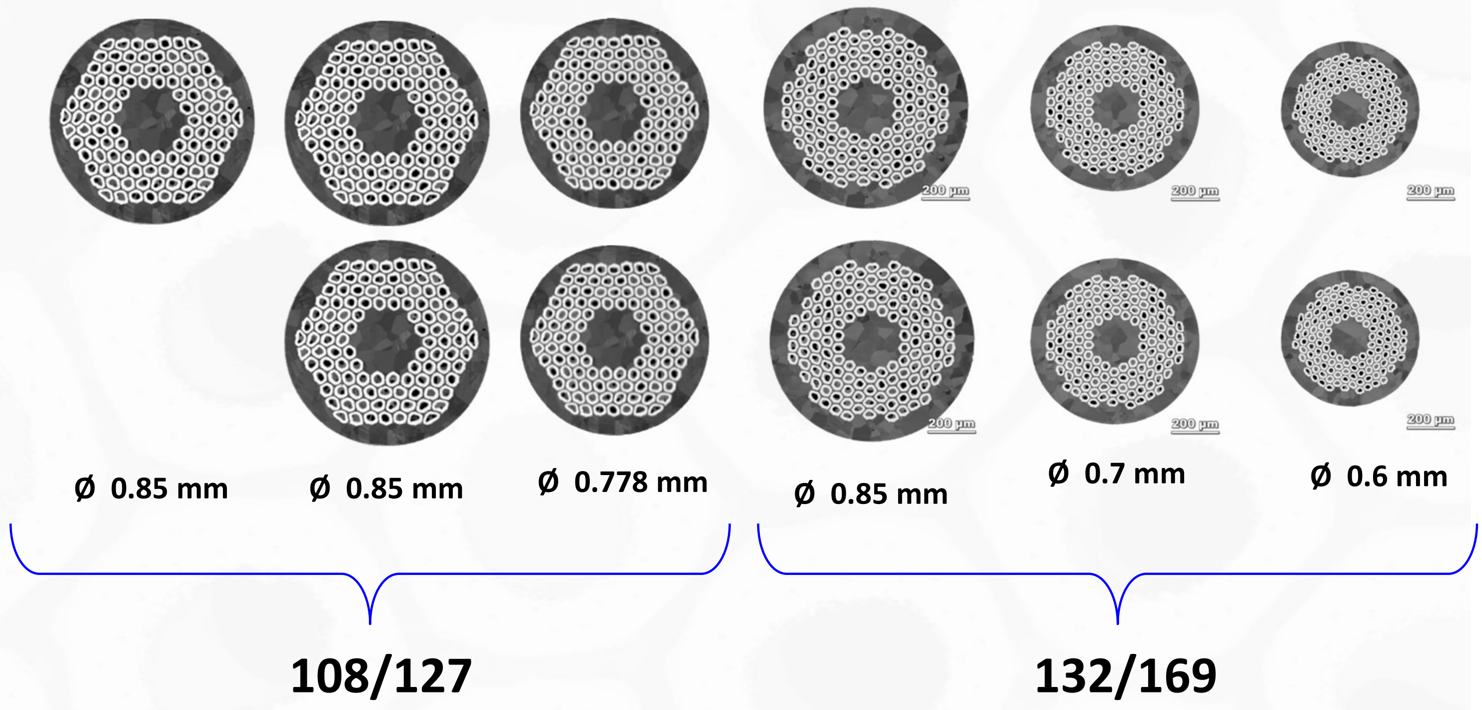
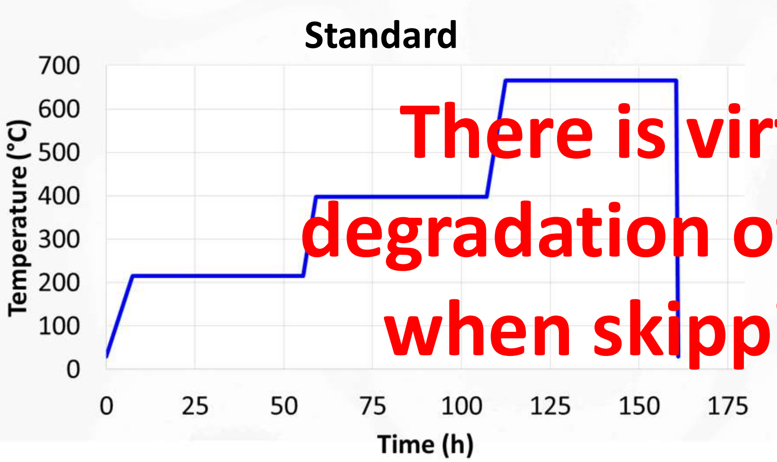
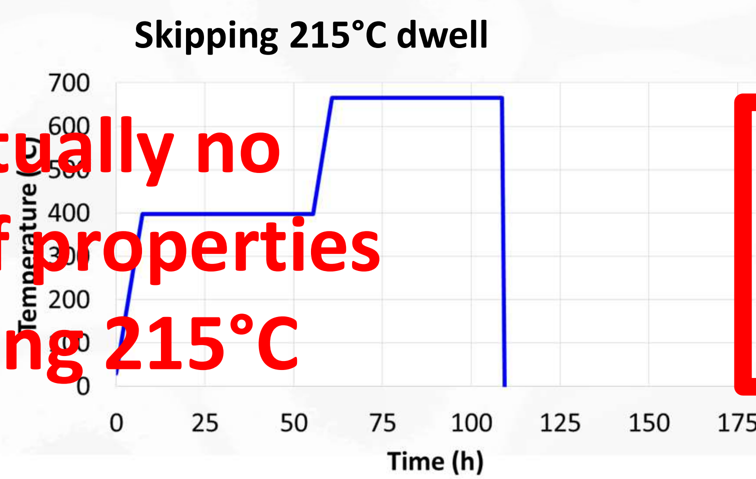
The 215°C dwell is useless, and it can be skipped without affecting strand properties







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

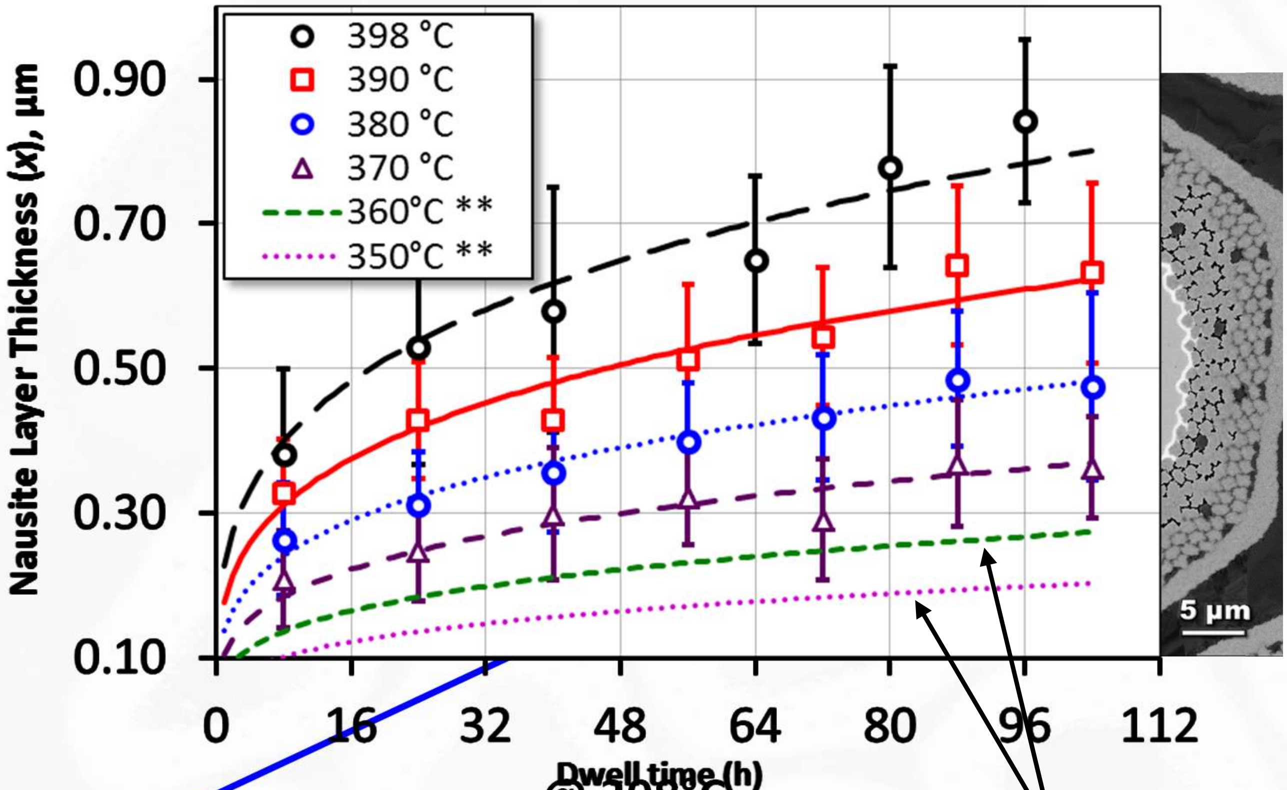
$\Delta H_k \approx 0.06$ T

ΔJ_c (12 T) ≈ -38 A/mm^2

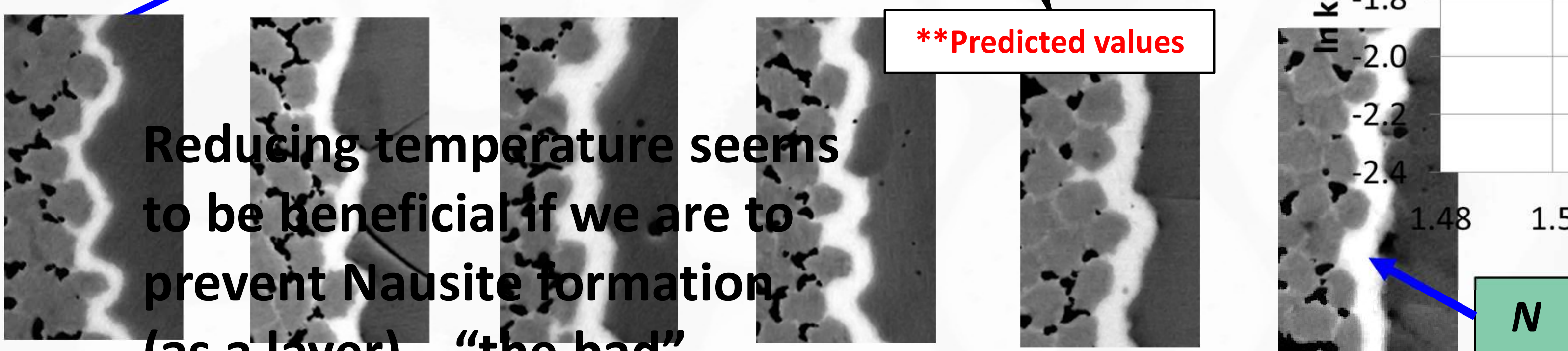
Δ n-value ≈ 0.04

(when skipping 215°C dwell)

Nausite growth is strongly dependent on temperature



@ 398°C



**Predicted values

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

8 hours 16 hours 24 hours 32 hours 40 hours 48 hours

Power law growth

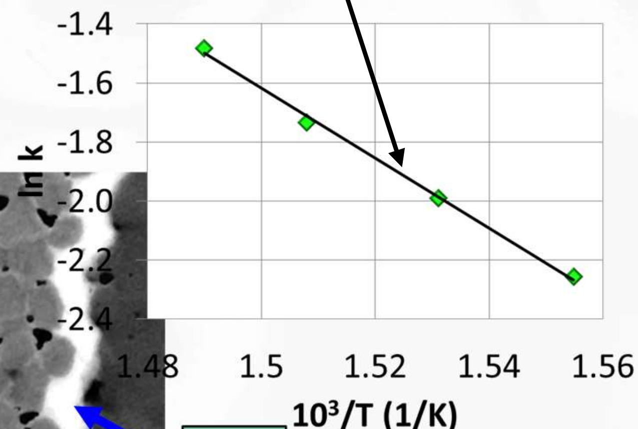
$$x(T,t) = kt^{0.27}$$

Arrhenius

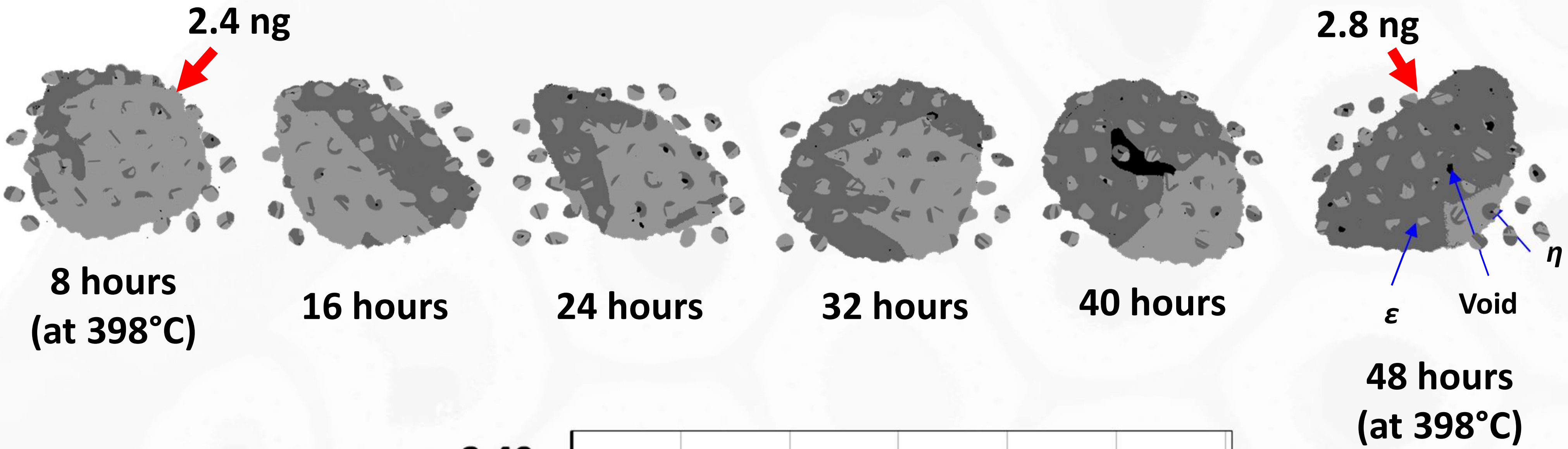
$$k = k^0 \, e^{\left(-\frac{Q_g}{RT}\right)}$$

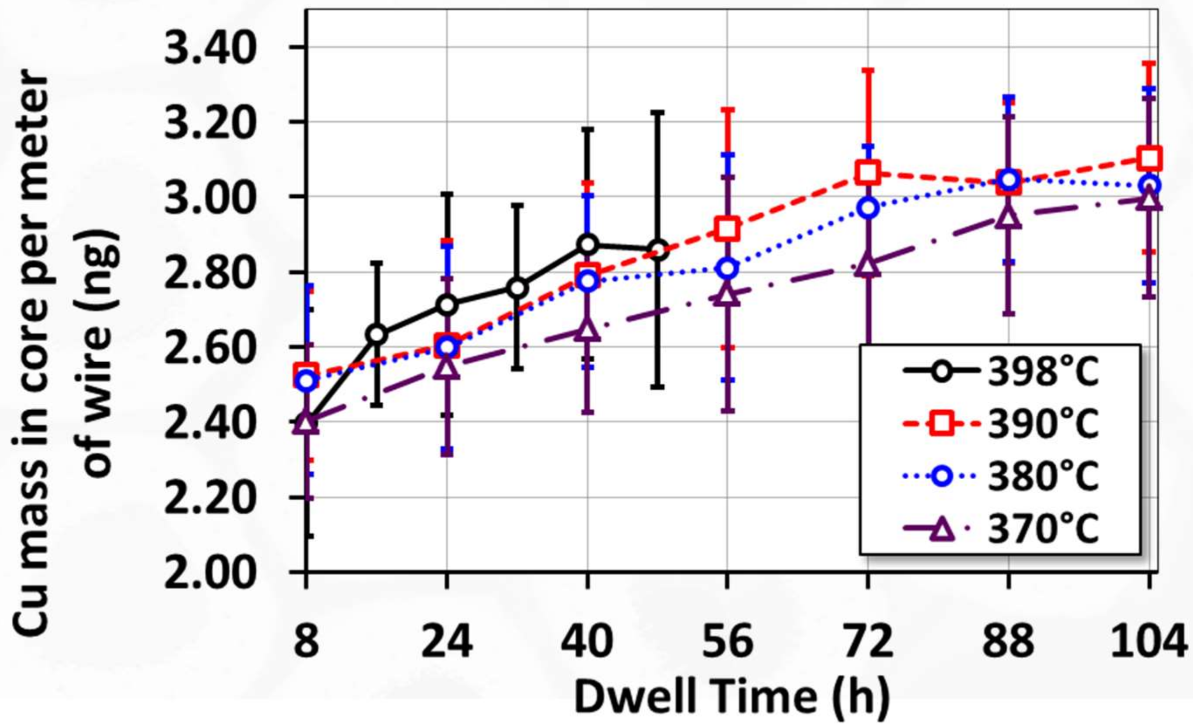
Activation energy

$$Q_g = -98.274 \text{ kJ/mol}$$



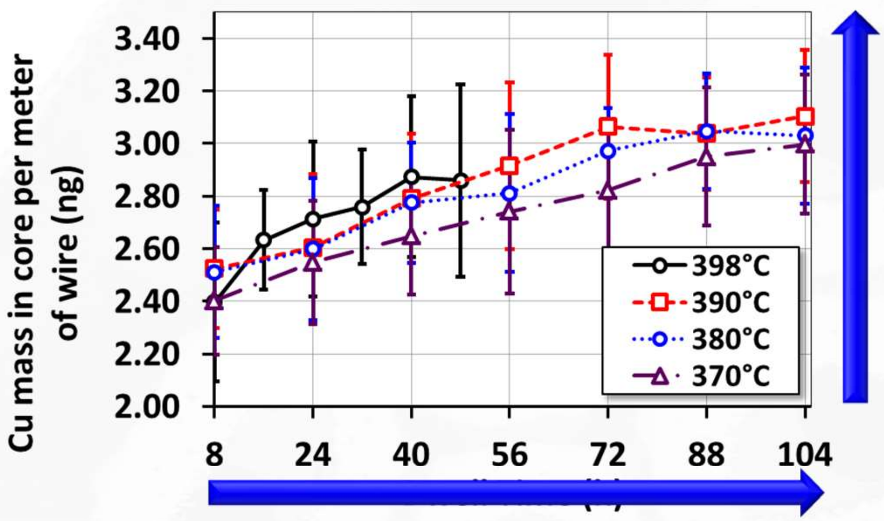
Cu diffusion to the core is weakly dependent on temperature



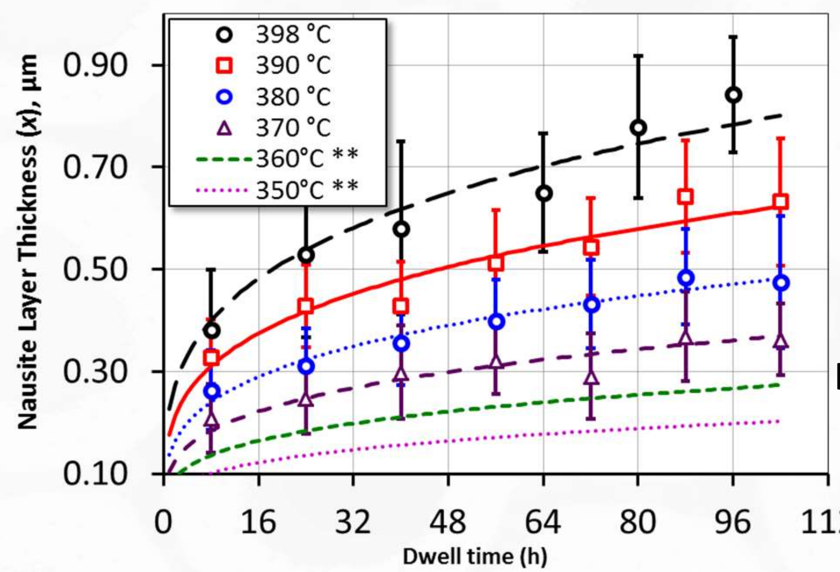


Longer heat treatments at lower temperatures draw more Cu in and inhibit Nausite Growth

"The Good" is not affected by lower temperatures



"The Bad" is slowed down significantly by lower temperatures



From previous slide

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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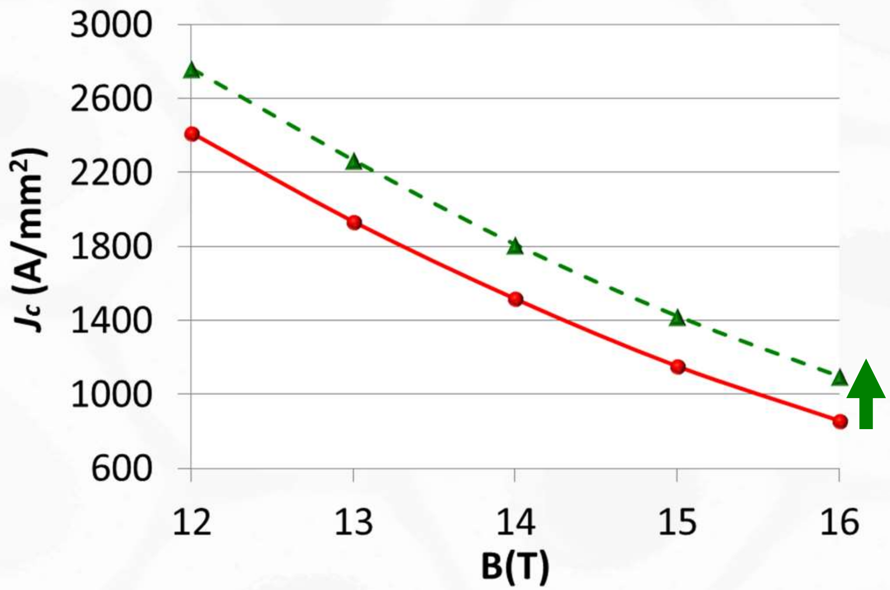
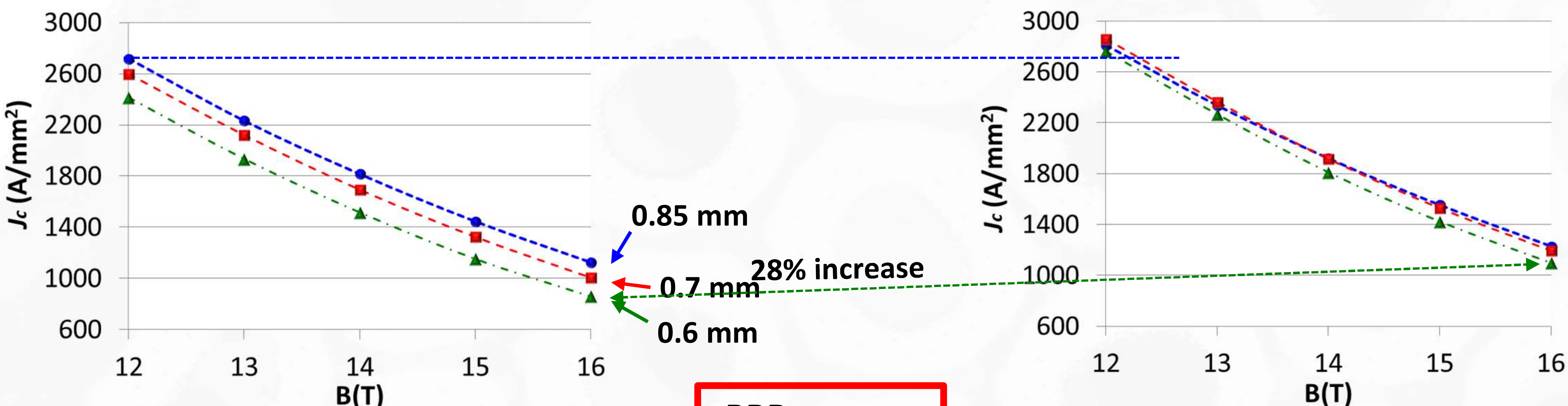


28% J_c (16T) increase!

Promoting Cu diffusion while inhibiting Nausite growth can increase J_c

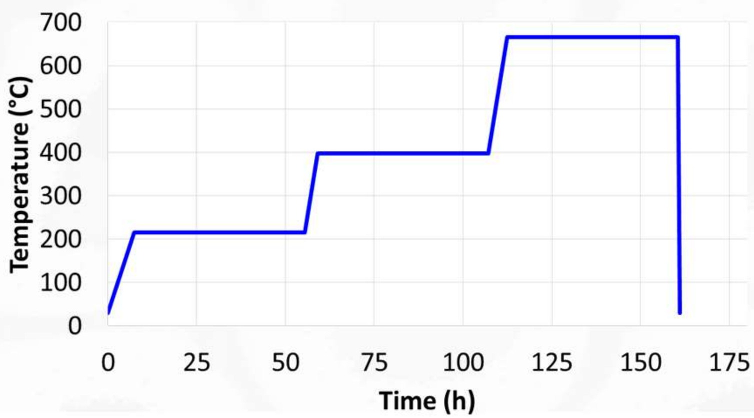
Standard Heat Treatment

1st attempt to control Nausite



RRR was not affected

Standard Heat Treatment



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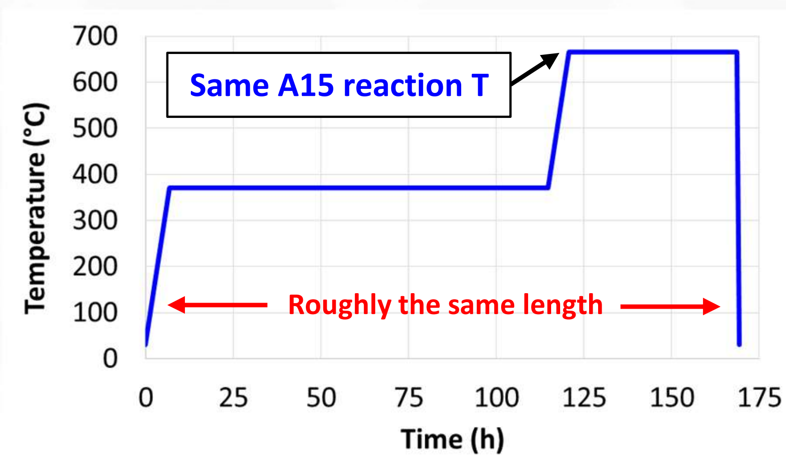


Back to the (sobering) 'big picture'

Final Targets for FCC Conductor*

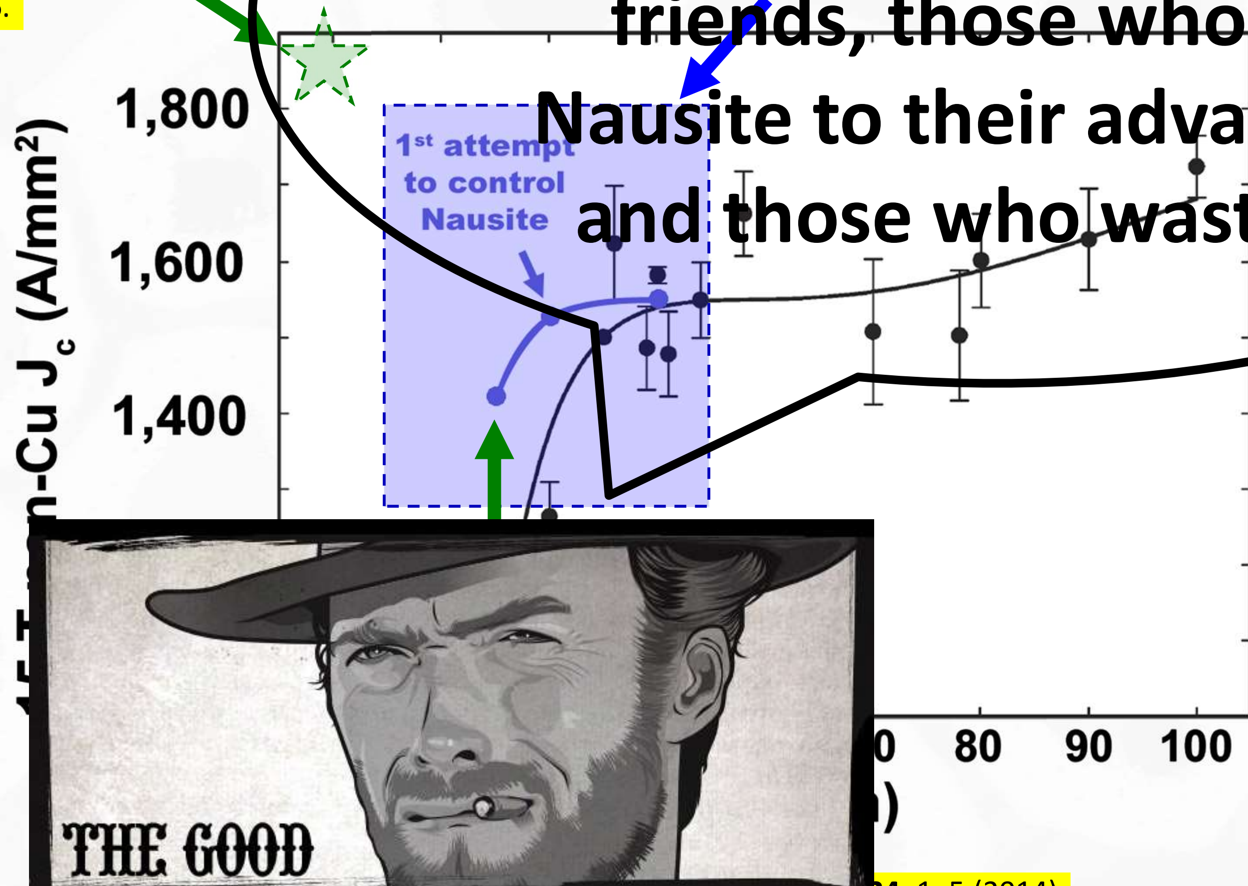
A. Ballarino, presented at the FCC week 2016.

Plenty of work ahead of us!

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

Current Hi-Lumi LHC requirements for LARP Quadrupoles

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



ield et al. IEEE Trans Appl Supercond **24,** 1–5 (2014).

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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.

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