FCC Week - Amsterdam,
April 9-13, 2018

Overview of Conductor R&D at Fermilab

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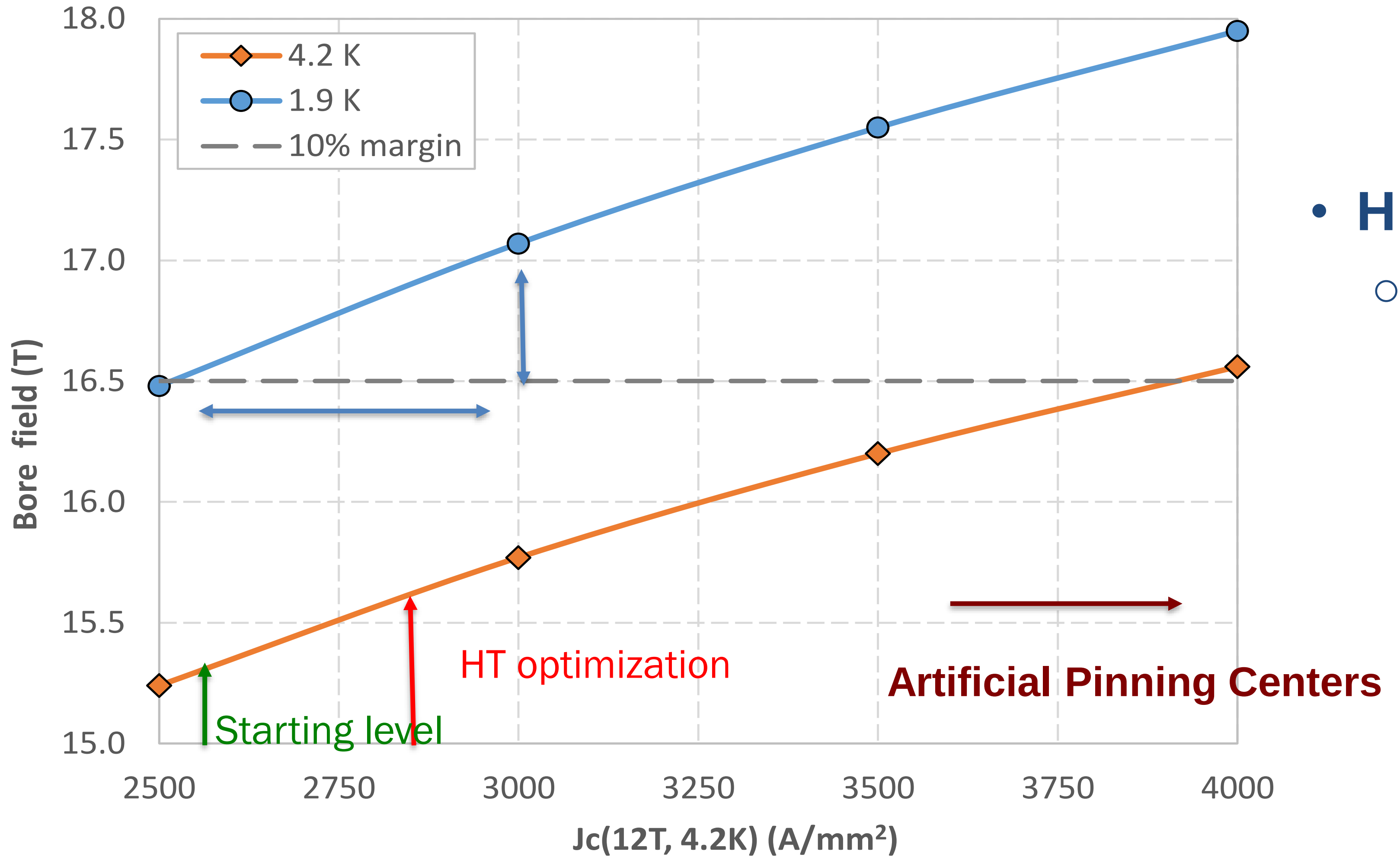
Outline

- **J_c increase:**
  - **Motivation**
  - **Nb_3Sn (traditional) HT optimization**
  - **Artificial Pinning Centers**

- **High-C_p:**
  - **Motivation**
  - **Demonstration (FNAL/Hypertech)**
  - **Industrialization (FNAL/B-OST+B-EAS)**

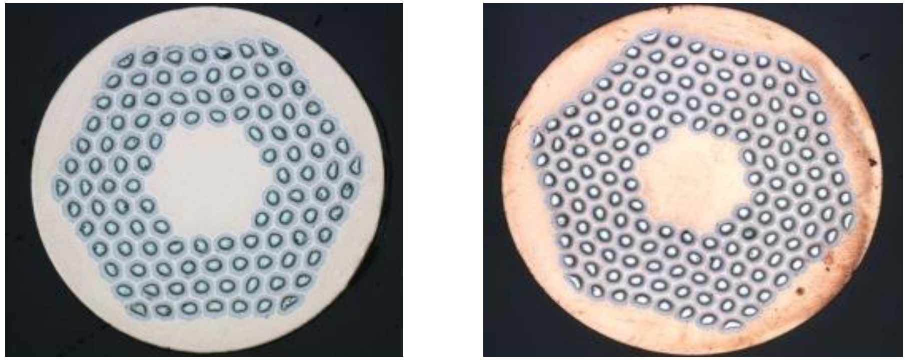
- **Improve I_c retention (stress/strain sensitivity):**
  - **Motivation**
  - **Nb_3Al**
  - **Nb_3Sn**
  - **HTS**

J_c Increase: Motivation

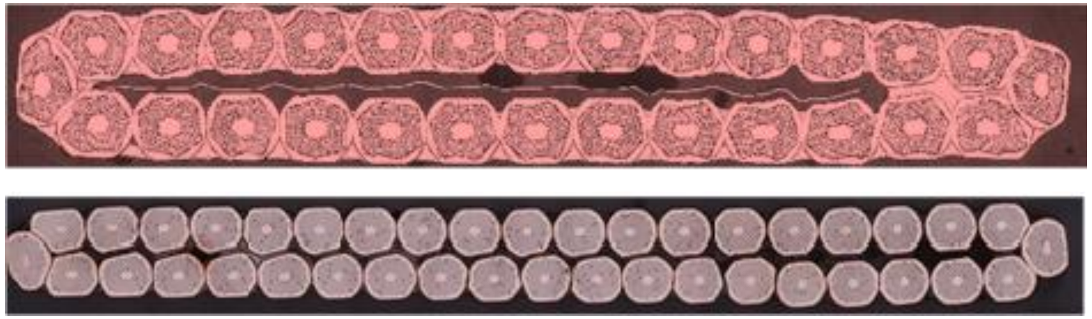


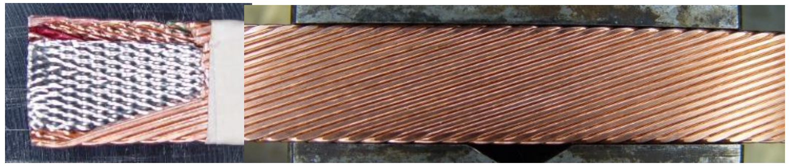
- **High J_c**
  - ○ **More margin and/or Higher field**

15 T Dipole: Wire and Cable Parameters



Strand ID	RRP1	RRP2
Stack design	108/127	150/169
Ternary element	Ti	Ti
Production year	2012	2014
Diameter *d*, mm	0.7	1.0
I_c (4.2K, 12 T), A	451-490	1,052-1,111
J_c (4.2K, 12 T), A/mm^2	2,560-2,722	2,597-2,710
I_c (4.2K, 15 T), A	229-245	566-619
J_c (4.2K, 15 T), A/mm^2	1,289-1,365	1,395-1,502
D_S, µm	41	58
Twist pitch, mm	14-16	23-24
Cu fraction λ, %	53.2-54.4	47.5-48.4
RRR	101-226	343-374
Final HT step	640ºC/50h	665ºC/50h

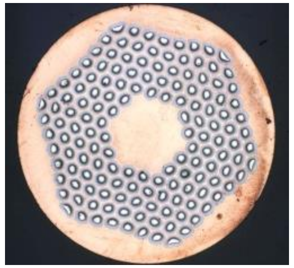


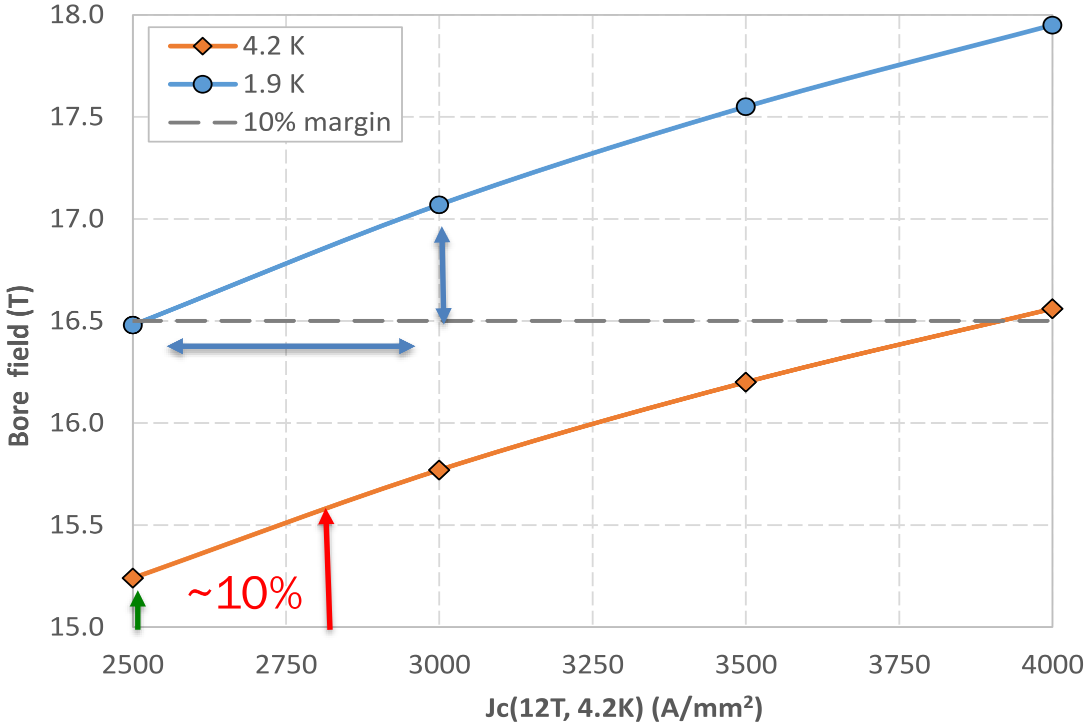


Coil	Cable N x d, mm	RRP® Strand Type	Cable length, m	Cable t_{mid} x w, mm^2	Lay angle, deg.
15 T Dipole Outer Layer	40 x 0.7	RRP1	374	1.251 x 14.71	16.8
15 T Dipole Inner Layer	28 x 1	RRP2	420	1.803 x 14.79	15.5

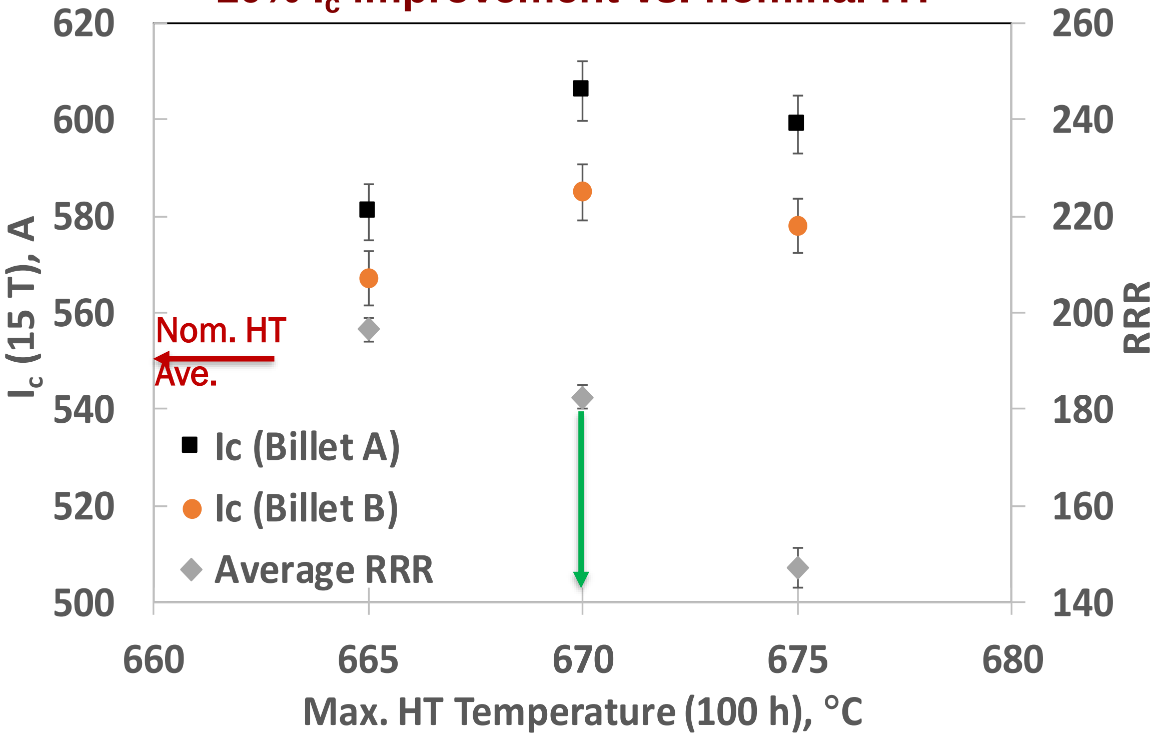
Heat Treatment Optimization for 15 T
Inner Coil

1 mm RRP150/169
28-strand cable with SS core





10% I_c improvement vs. nominal HT



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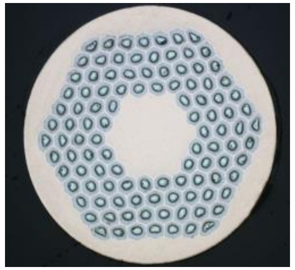
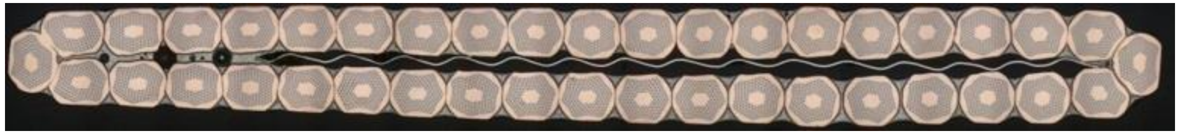
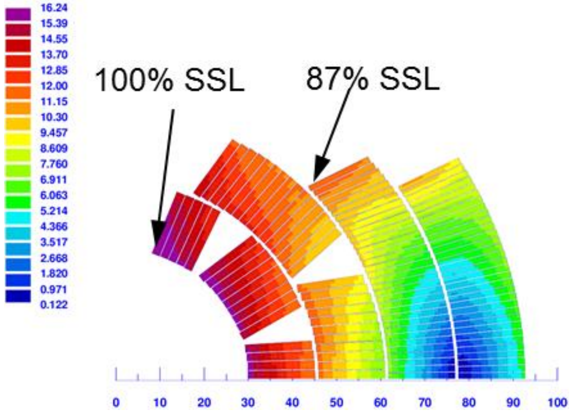
Heat Treatment Optimization for 15 T Outer Coil

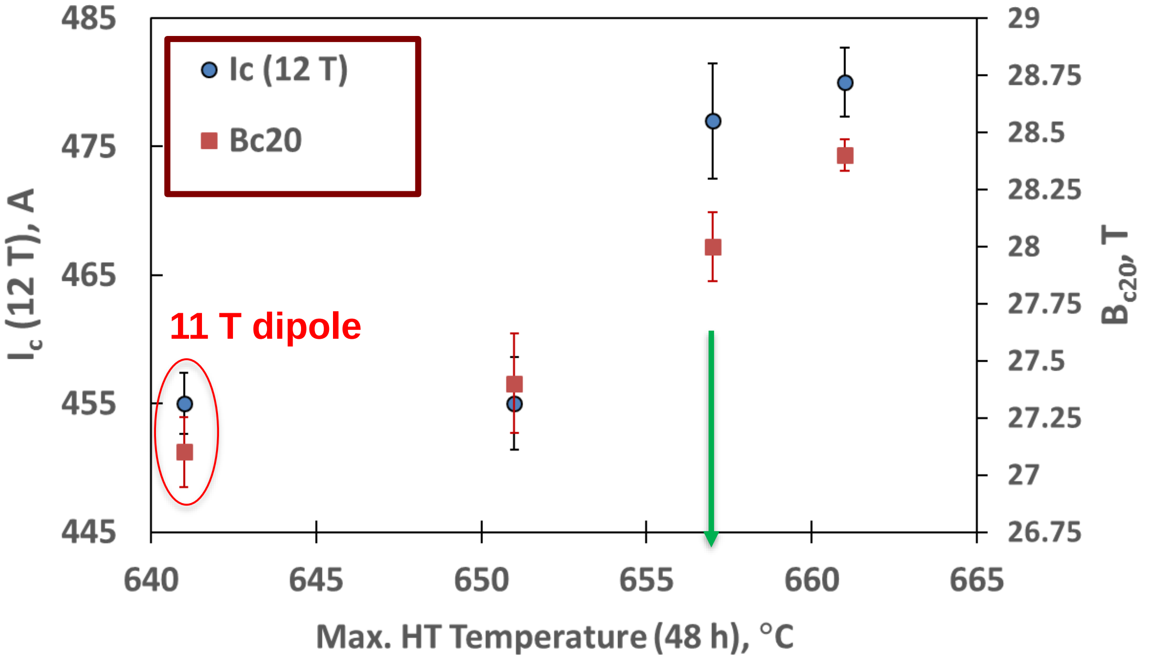


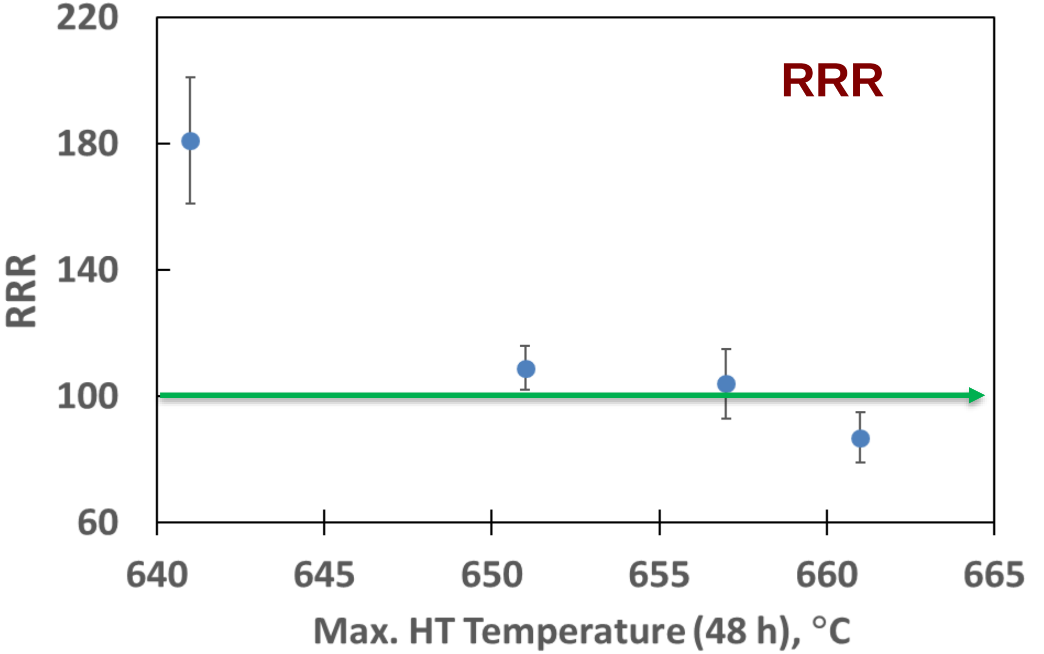
0.7 mm RRP108/127
40-strand cable with SS core





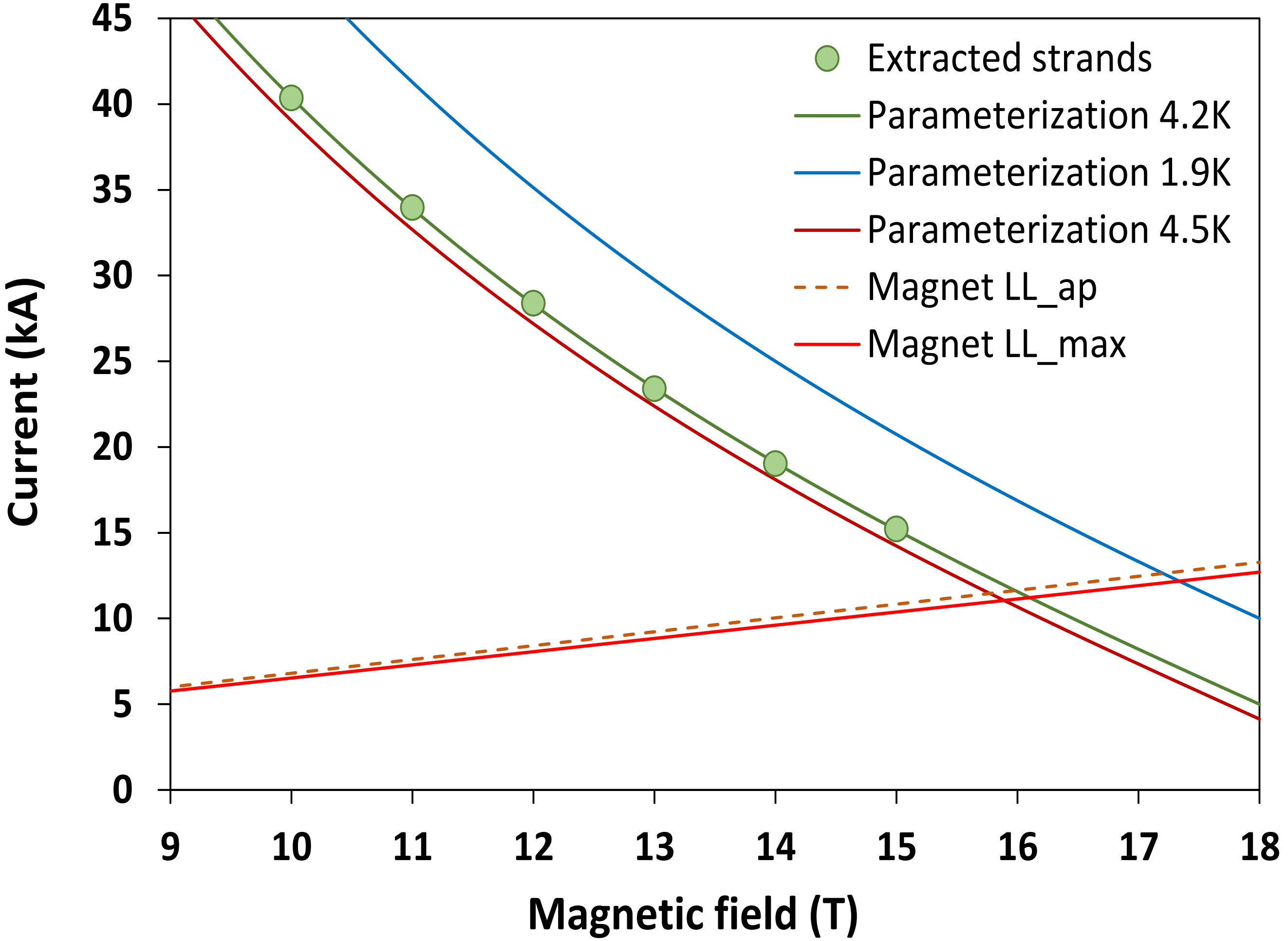
5% I_c improvement vs. nominal HT





15 T Dipole: Short Sample Limit vs. Design Limit

- Magnet short sample limit (SSL) estimated based on extracted strand data:
  - ○ Sample HT: 665ºC/50 hrs (OST)
  - ○ I_{ssl}=11.05 kA (B_0=15.25 T) at 4.5 K
  - ○ I_{ssl}=12.2 kA (B_0=16.65 T) at 1.9 K

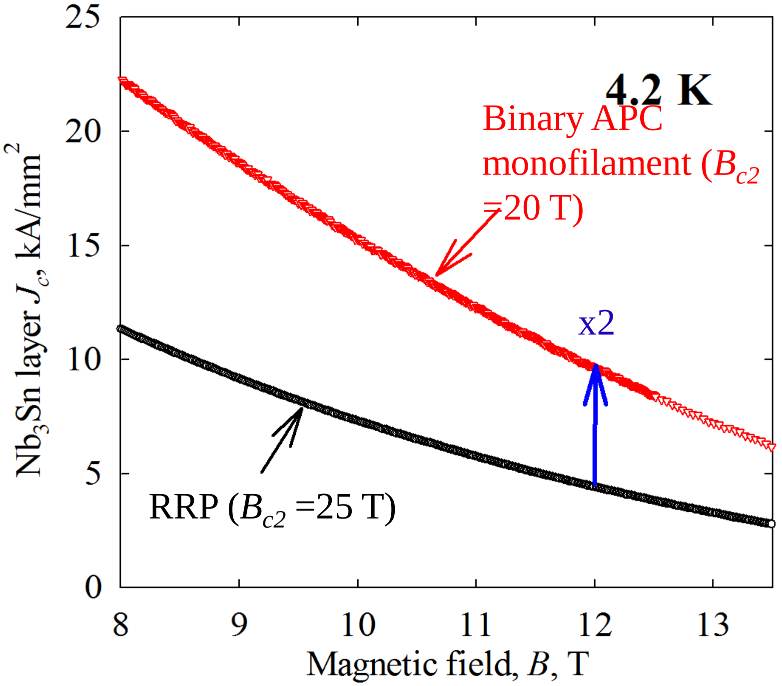


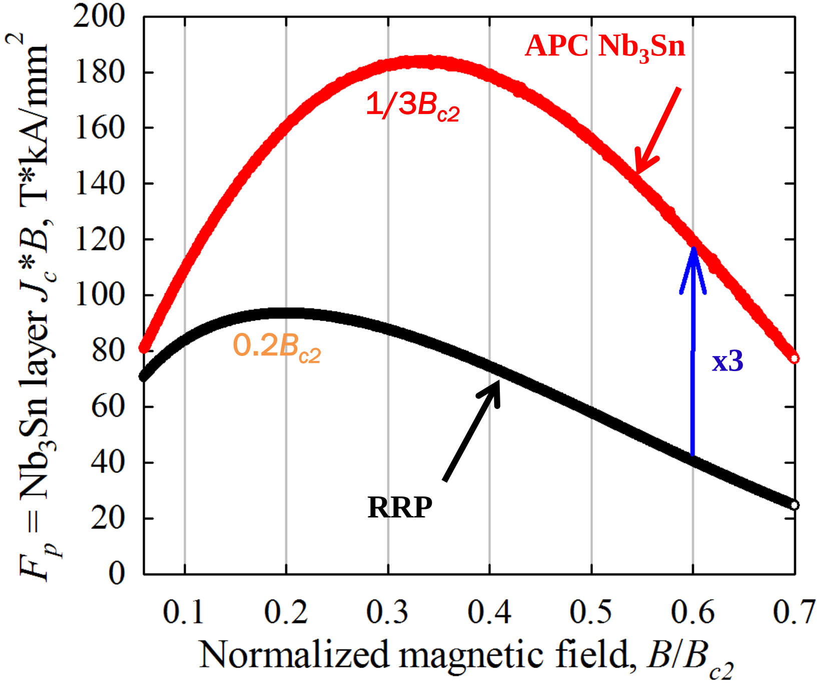
Magnet design limit is determined by mechanical constraints and it is 15 T.

The challenge is pushing the design limit of these magnets to their superconducting potential (or SSL). For a 16 T Nb_3Sn dipole, the design limit needs to be at least 17 T.

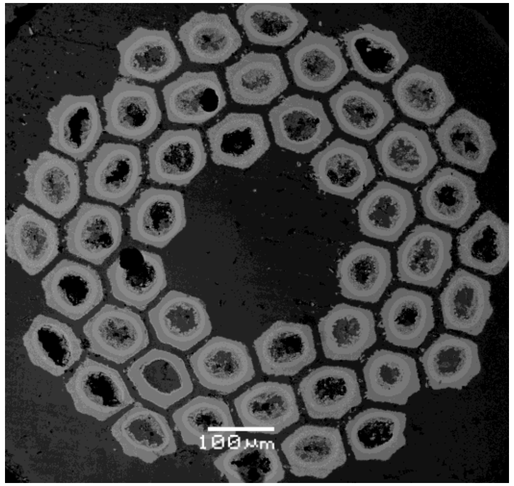
Artificial Pinning Center (APC) Technology with ZrO$_2$ – Xingchen Xu

- **Previously, ZrO$_2$ APC Nb$_3$Sn materials showed grain size refinement** from ~150 nm to < 50 nm **and a doubling of layer J_c at 12 T (50% increase at 15 T) vs. HL-LHC RRP.**
- **ZrO$_2$ is formed by internal oxidation of Nb-Zr tubes.**
- **ZrO$_2$ particles (1-10 nm) can be flux pinning centers themselves, causing point pinning behavior.**
- Due to point pinning, F_p-B curve peak shifts from 0.2B_{c2} to 1/3B_{c2}.

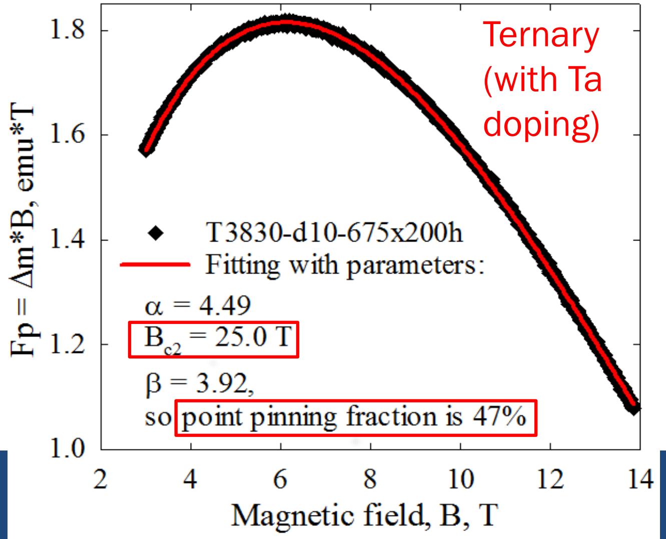


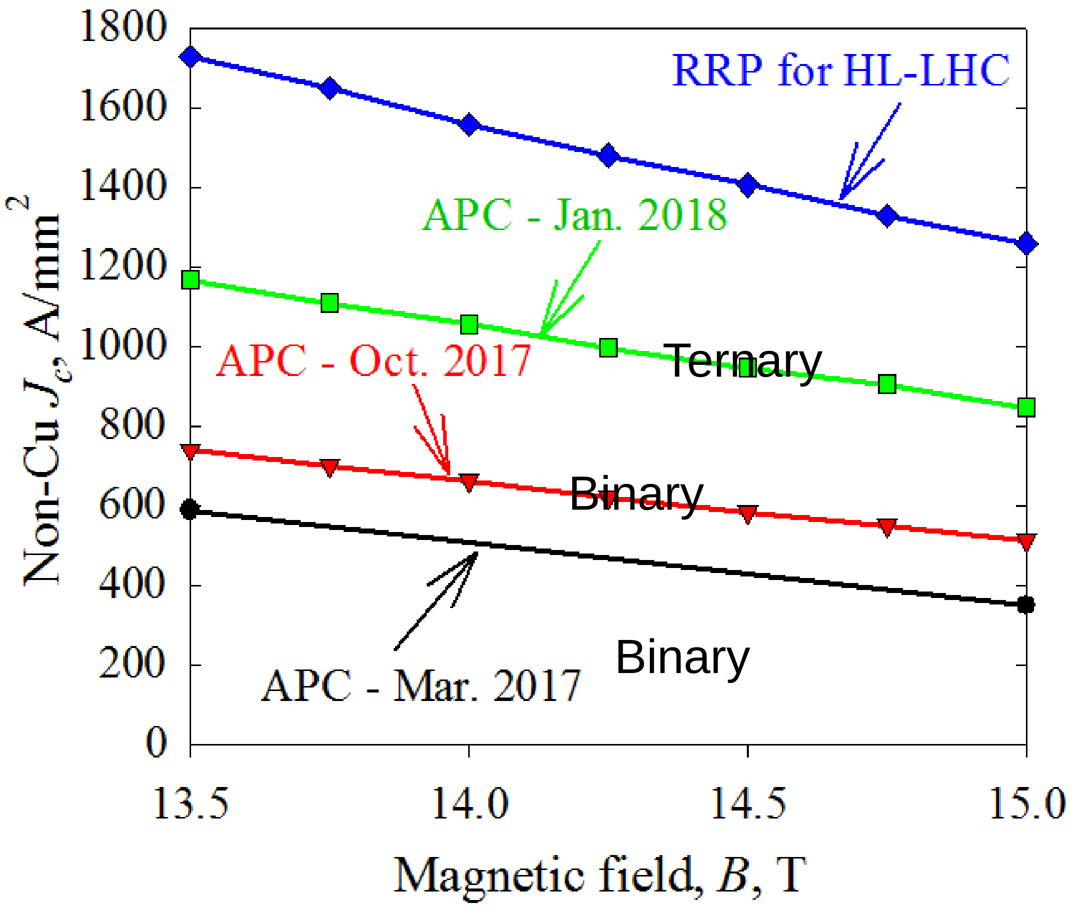


Artificial Pinning Center (APC) Technology with ZrO_2: New Results – Xingchen Xu



48/61 Powder-in-Tube Tube wire





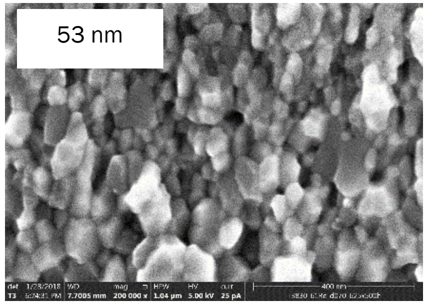
Results for binary and ternary multifilamentary wires (with Nb_3Sn fraction in non-Cu ~ 15%)

NEXT STEPS

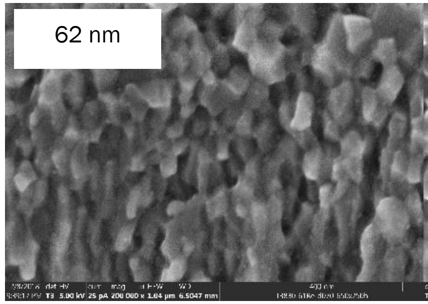
- **Optimize powder mixing/filling to push the Nb_3Sn fraction in the non-Cu up to 40%.**
- **Optimize selection of precursors and their ratios (*e.g.*, Sn/Cu/oxide), I.D./O.D. of Nb-Zr tubes, powder packing density, etc.**

Demonstration of Enhanced B_{c2} and Refined Grain Size in Ta-doped APC Nb_3Sn Wires - **J. Rochester, X. Peng, M. Tomsic, X. Xu, E.W. Collings, C. Kovacs, and M.D. Sumption**

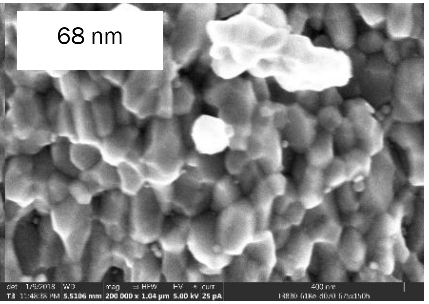
- Prototype multifilament PIT strand with incorporation of ternary Ta element:
    - Oxide induced grain refinement simultaneously with Ta incorporation;
    - Kramer field (B_k) enhanced beyond 25 T, as expected for ternary wire.



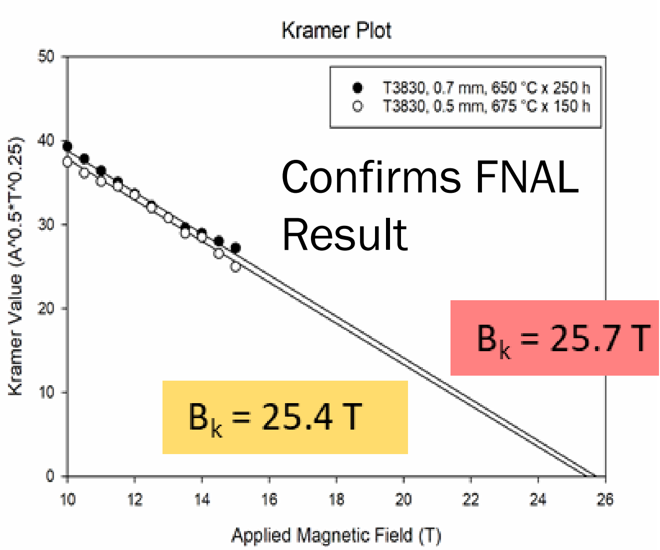
T3830, 625 °C x 500 h



T3830, 650 °C x 250 h



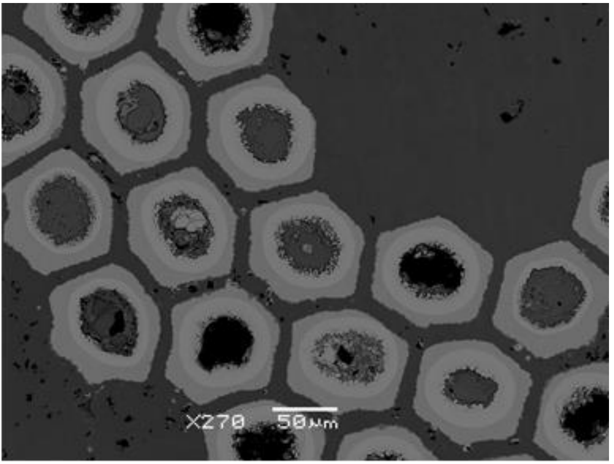
T3830, 675 °C x 150 h



Confirms FNAL Result

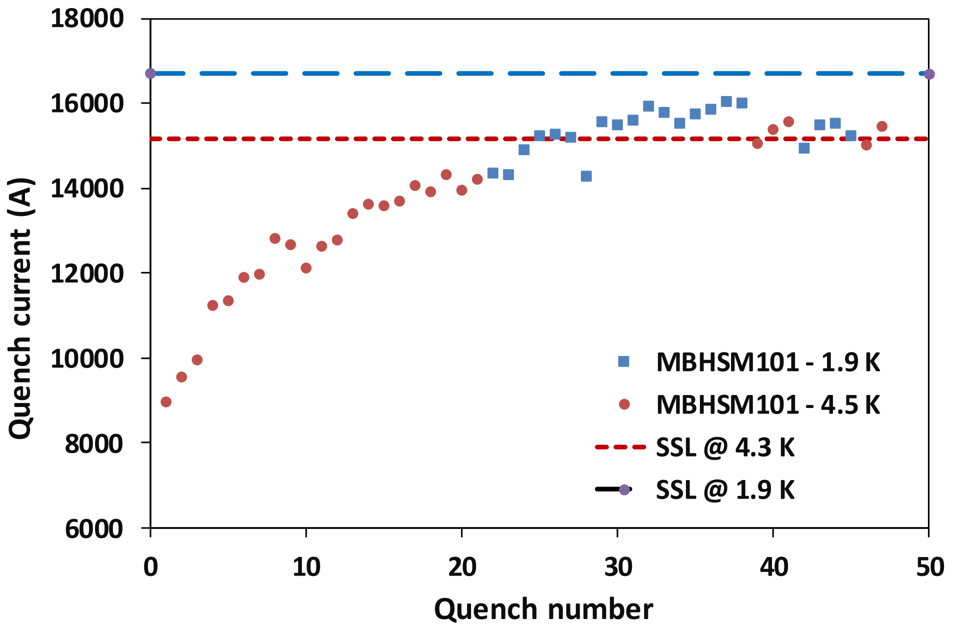
B_k = 25.7 T

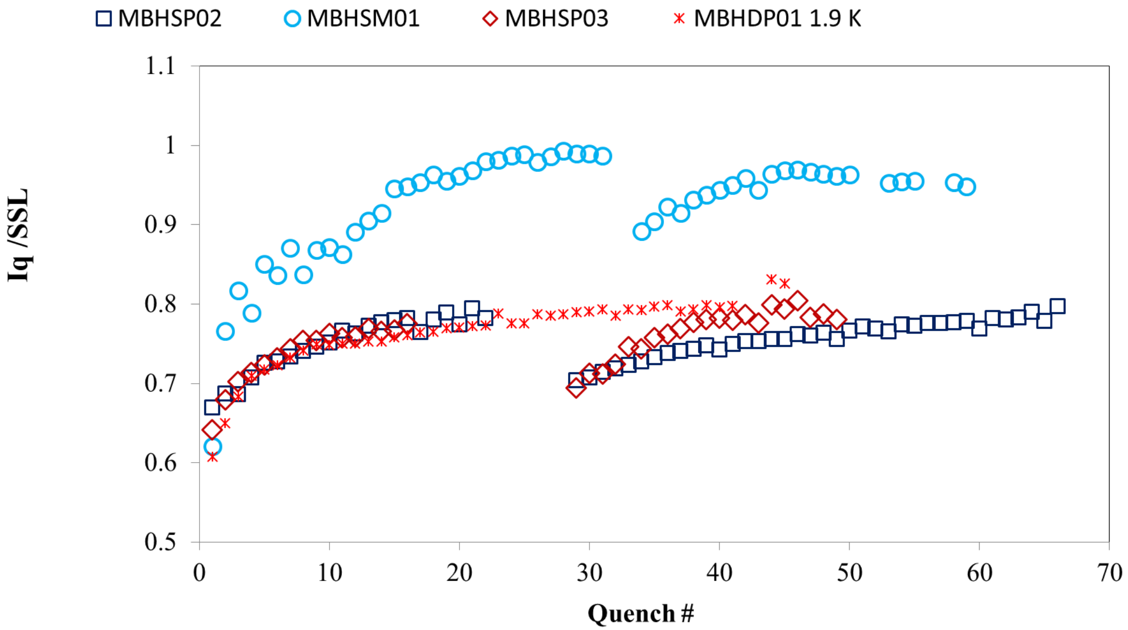
B_k = 25.4 T



BSE-SEM of T3830, 675 °C x 190 h

C_p Increase: Motivation





We know that Nb_3Sn magnet training is very long.

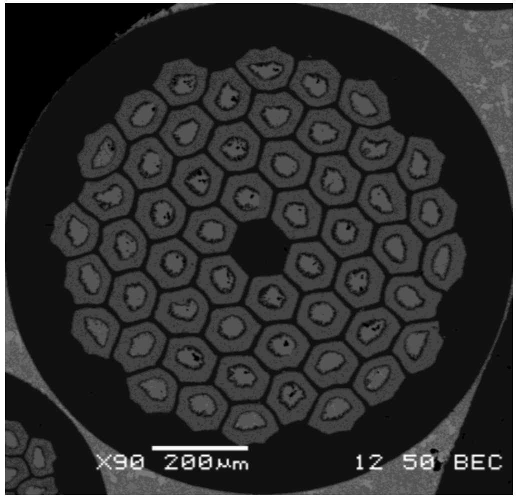
- Additional design margin => magnet cost increase.
- Then how to reduce training?
  - Understand origins of quenches (e.g., perturbations) and provide solutions.
  - Increase enthalpy margin of conductors by introducing rare earths oxides in the Nb_3Sn billet: a new technique to increase specific heat.
- dT~dQ/Cp => high C_p increases conductor stability to perturbations:

- Better magnet training;

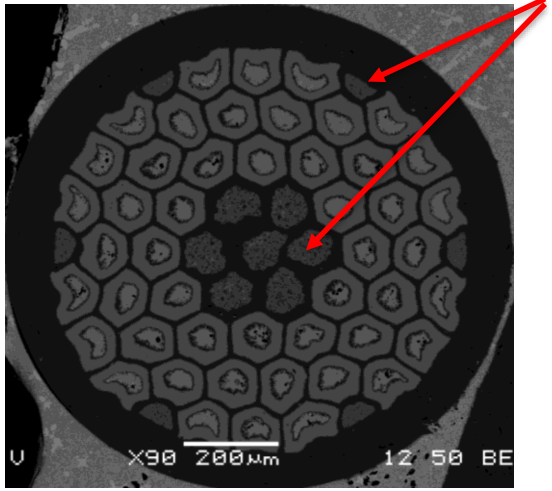
- Better energy margin.

High-C_p Nb_3Sn Conductors: Demonstration (Hypertech)

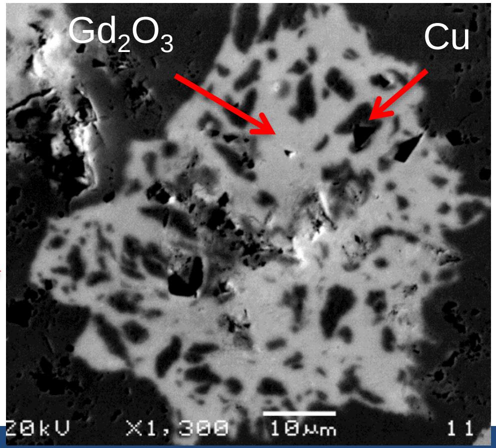
- **At 2 K: $C(Gd_2O_3)/C(Cu)=1000$ ➔ Adding 2 vol.% of Gd_2O_3 improves C by 20 times (2 K).**
- **Gd_2O_3 powder (99.9%, 10-100 nm) is <\$1000/kg ➔ To add 2 vol.% Gd_2O_3, 1 kg Nb_3Sn wire needs 17 g Gd_2O_3: <\$17.**



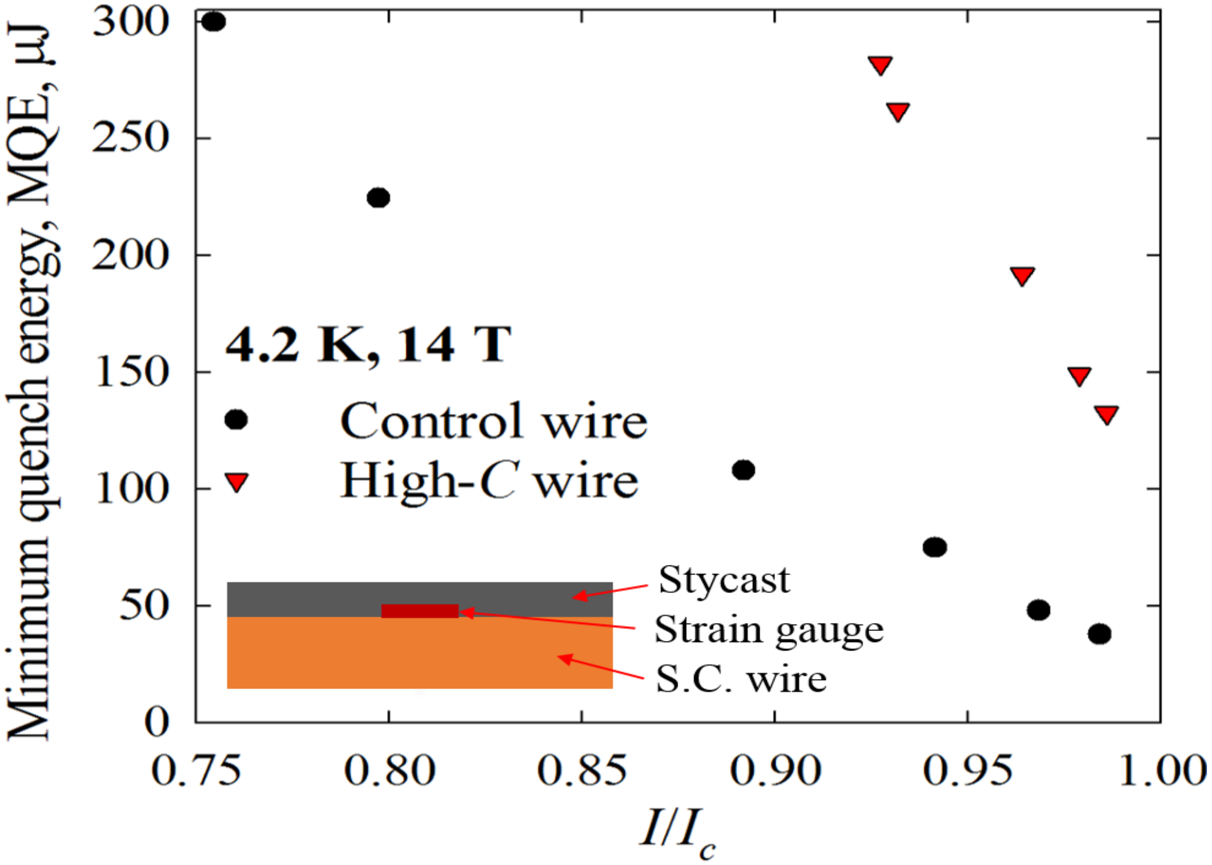
Tin in Tube wire



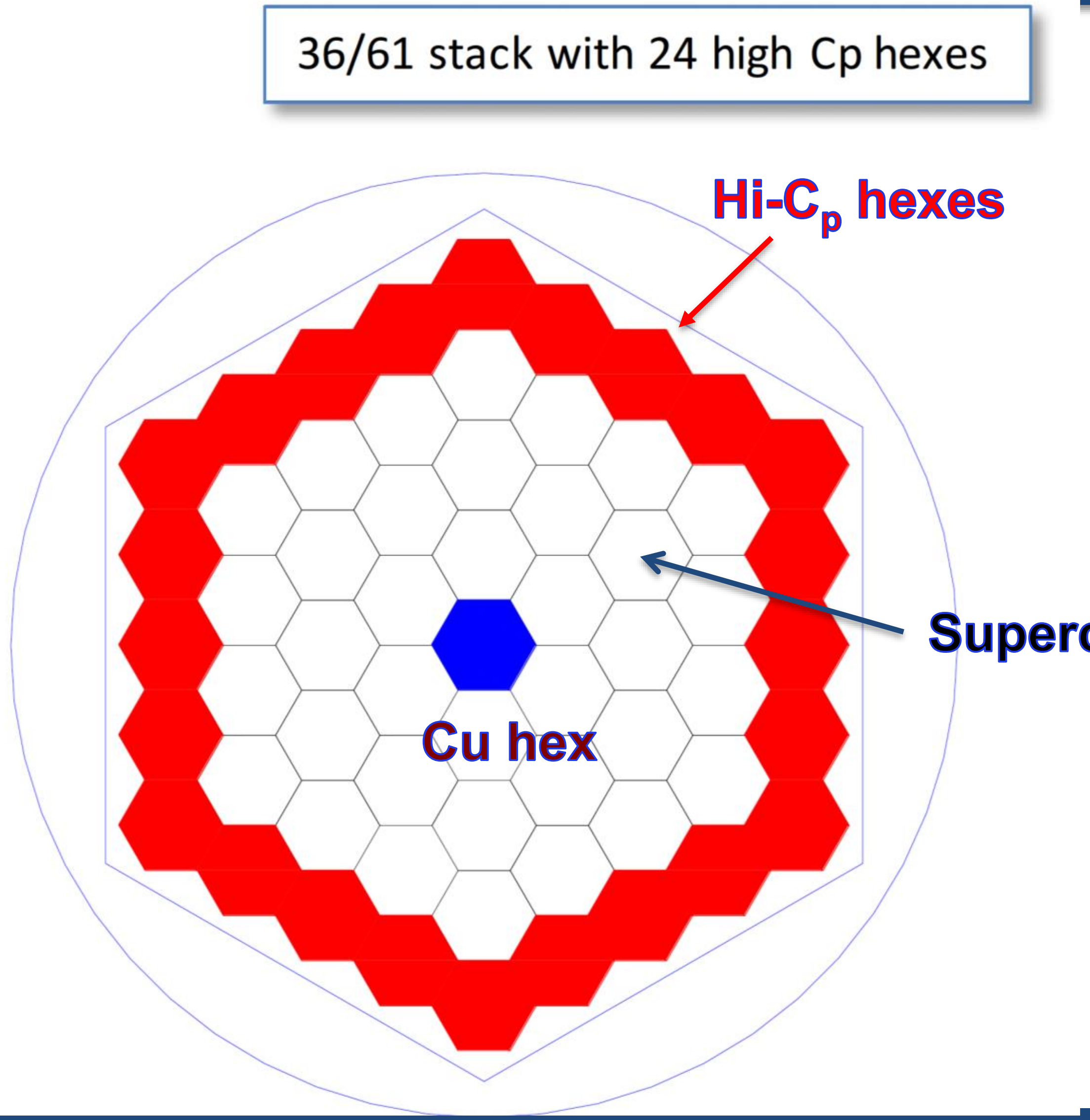
Hi-C_p hexes (corners and center)



Mixture of Cu & high-C powders provides Cu thermal conduction and better drawability.



High-C_p Nb_3Sn: Industrialization with B-OST+B-EAS



Superconducting subelements

- Optimize powder packing density, Cu/Gd_2O_3 ratios and Cu wall thickness.
- Fabricate ~20 kg of wire.

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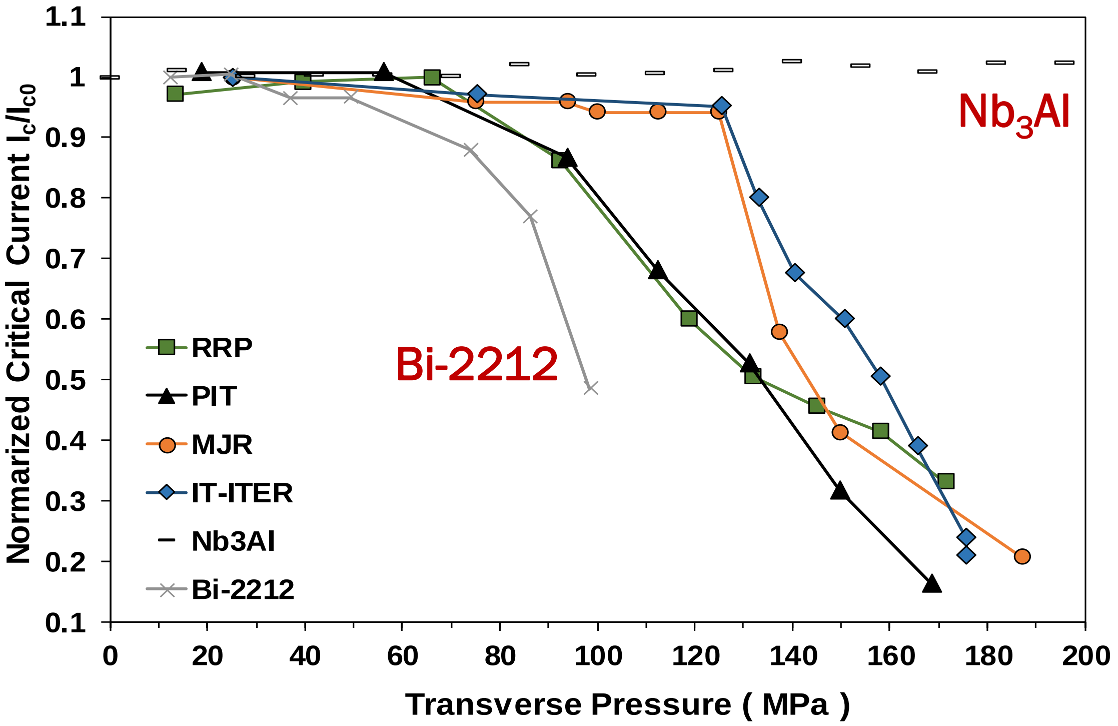
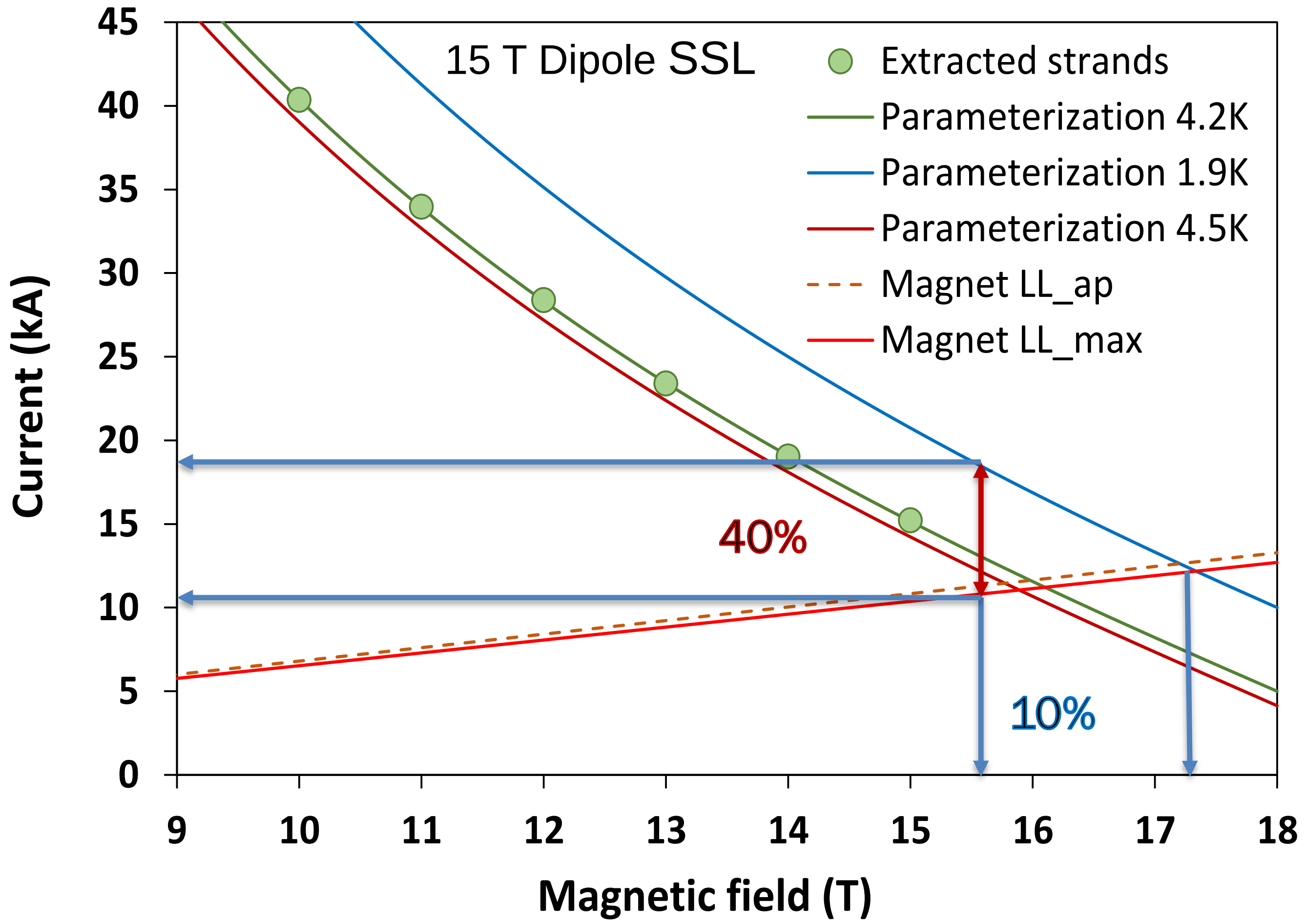
Improve I_c Retention: Motivation

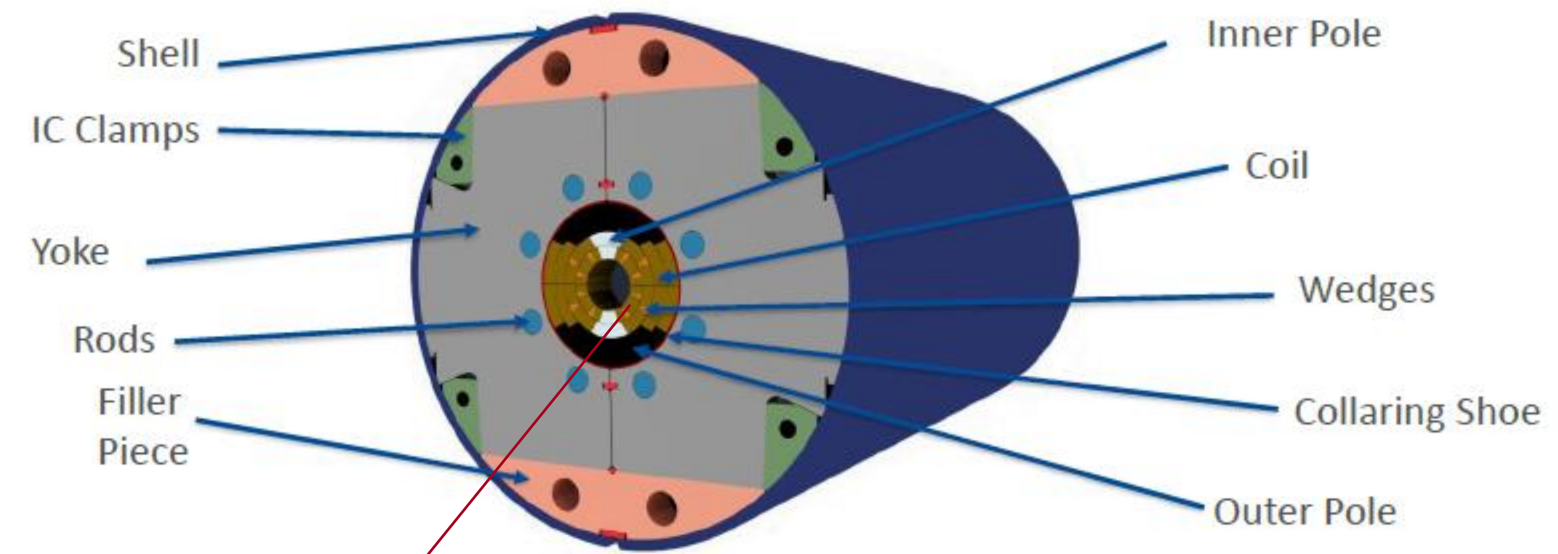
Why Nb_3Sn accelerator magnets typically reach at best 90% of SSL (corresponding to ~60% of I_c) ?

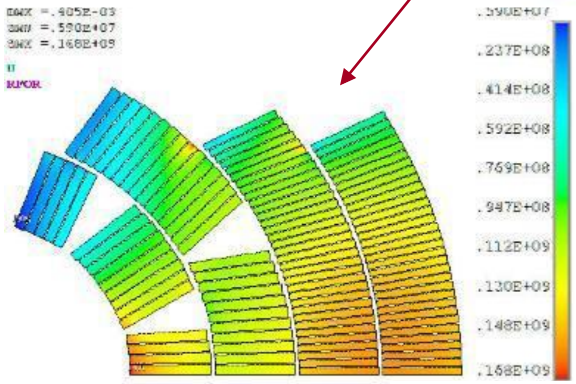


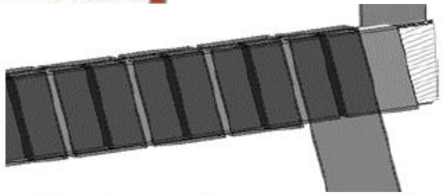
<u>Relative</u> performance under transverse pressure as measured in FNAL setup.

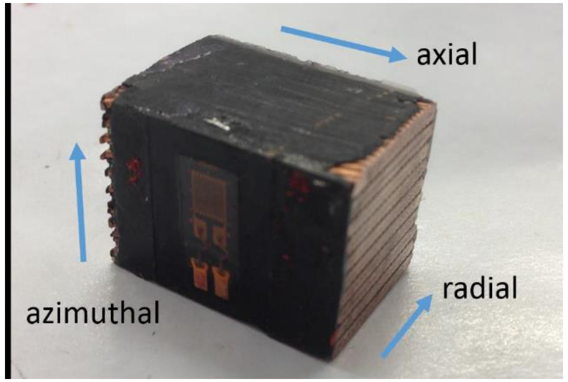


Sub-Modelling vs. Homogenous Models



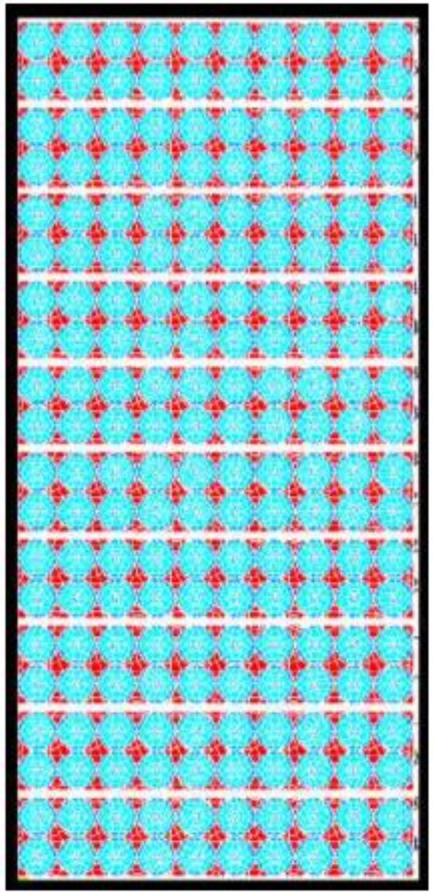






10-STACK SAMPLE

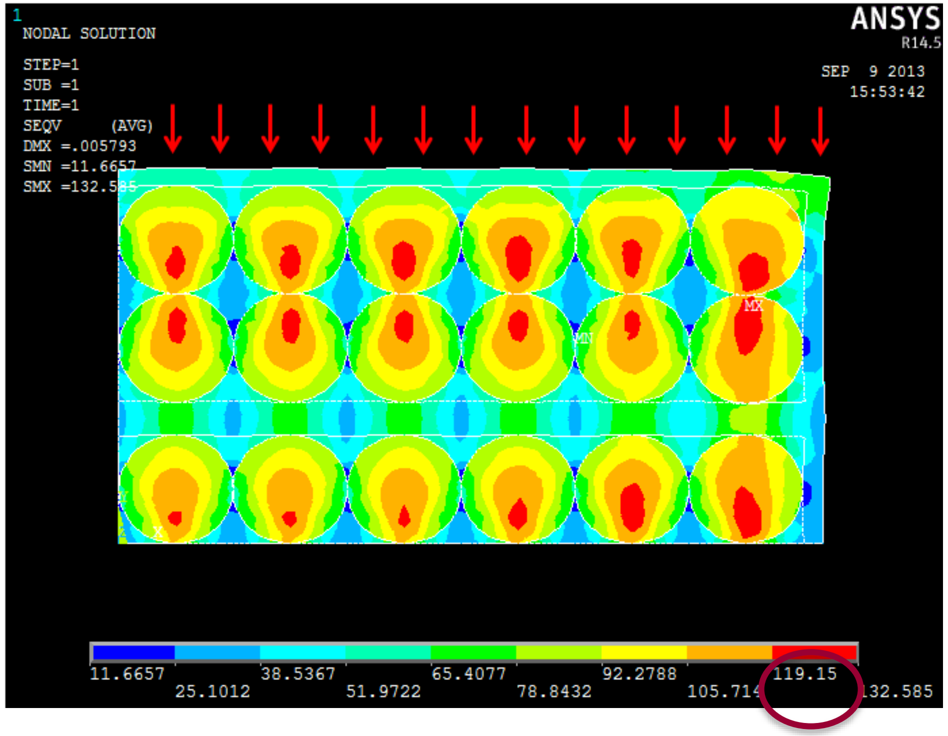
STATIC LOAD IN ELASTO-PLASTIC REGIME



Simple FEM sub-model of Transverse Pressure Tests shows Stress Concentrations

Unconstrained sample

$$\sigma_{\theta\theta} = 80\ \text{MPa},\ \sigma_{rr} = 0$$



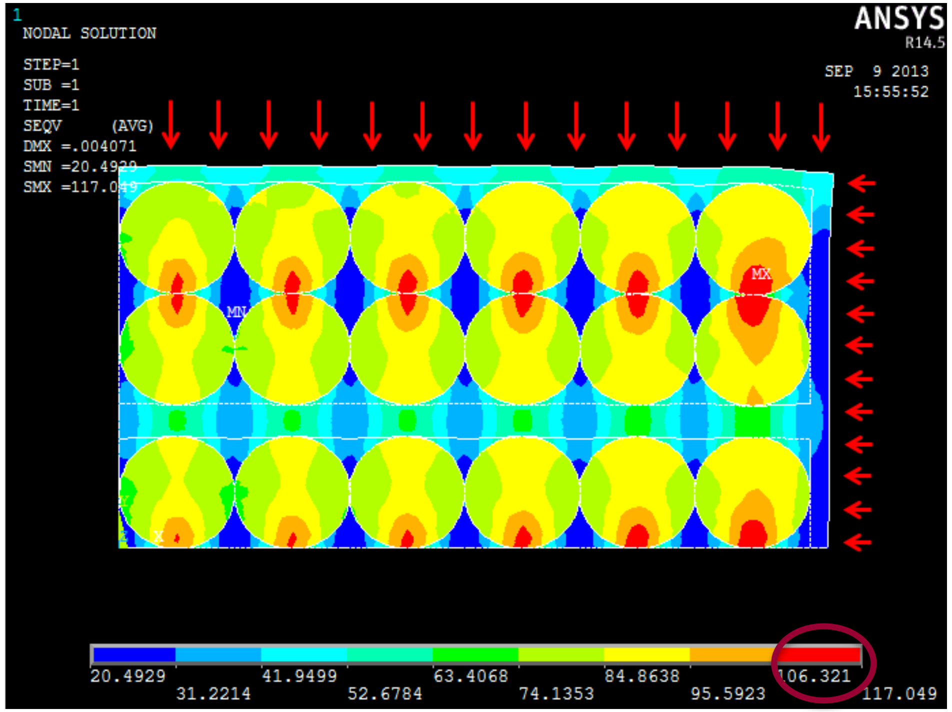
```
1
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
SEQV       (AVG)
DMX =.005793
SMN =11.6657
SMX =132.585
```

Max. Von Mises Stress 132 MPa

Constrained sample

$$\sigma_{\theta\theta} = 80\ \text{MPa},\ \sigma_{rr} = 40\ \text{MPa}$$



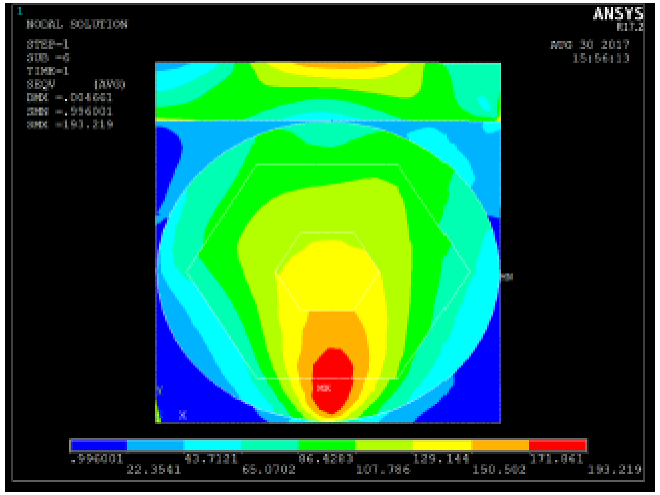
```
1
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
SEQV       (AVG)
DMX =.004071
SMN =20.4929
SMX =117.049
```

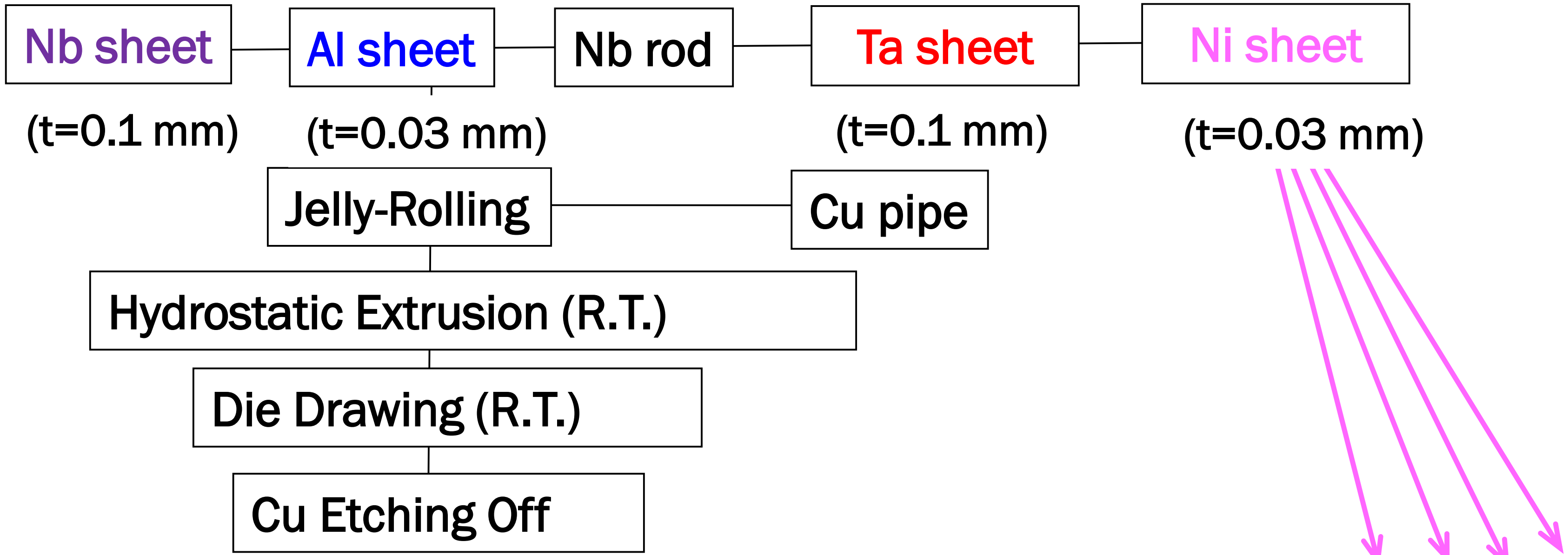
Max. Von Mises Stress 117 MPa

Study Stress and Strain Concentration

Understand how stresses and strains are distributed inside the conductor ➔ Apply strain and stress management techniques.



New Nb_3Al Jelly-Rolled Subelement - Akihiro Kikuchi, NIMS



Nb sheet (t=0.1 mm)

Al sheet (t=0.03 mm)

Nb rod

Ta sheet (t=0.1 mm)

Ni sheet (t=0.03 mm)

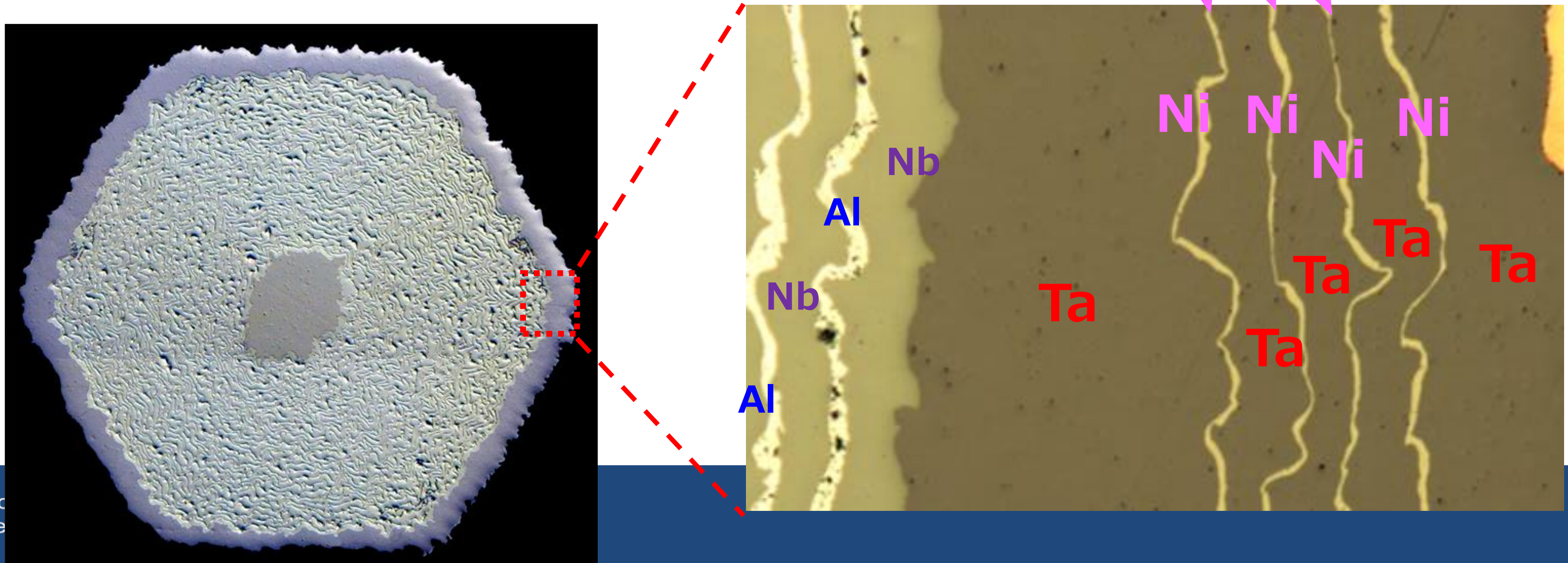
Jelly-Rolling

Cu pipe

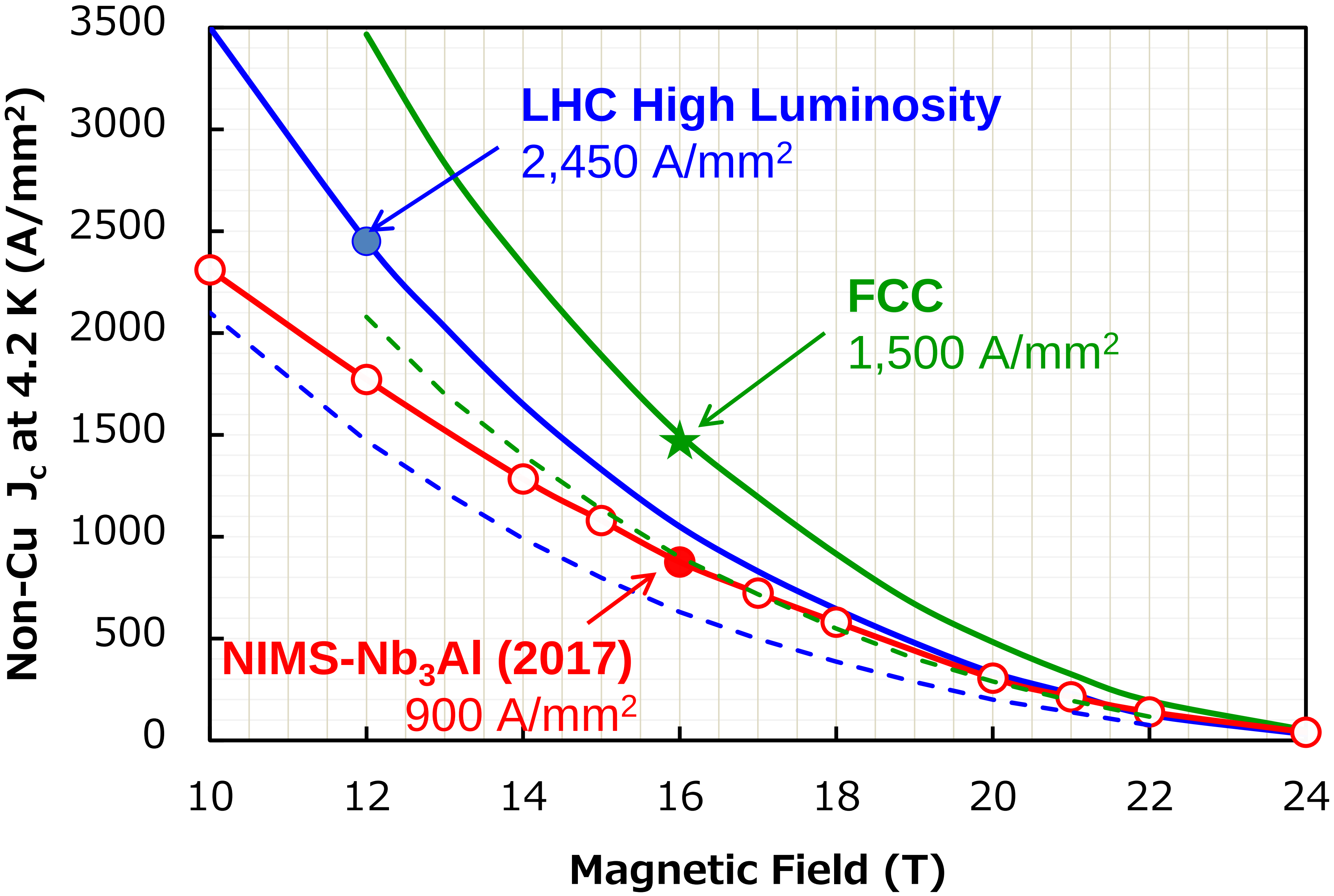
Hydrostatic Extrusion (R.T.)

Die Drawing (R.T.)

Cu Etching Off



Jelly Roll Nb_3Al Performance vs HL-LHC and FCC Specs



Conclusions

- **SC wire and cable R&D for the 15 T Dipole demonstrator:**
  - **Cables were designed and optimized based on the properties of present Nb_3Sn wires.**
  - **Sensitivities studies to heat treatment were performed to push performance to nominal required.**
  - **Next: Sub-modelling studies to identify stress and strain concentration areas.**

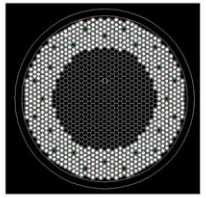
- **R&D on next generation Nb_3Sn wires with high J_c and high C_p for accelerator magnets is a must:**
  - **Improving J_c using Artificial Pinning Centers supported by several sources**
  - **Improving C_p by adding high-C_p substances supported by FNAL GARD.**

- **Support of strain resistant Nb_3Al by NIMS would reduce risk in case strain management solutions fail.**

RRP Strand Optimization (with B-OST)

- Goal:
  - Increase J_c(15T) with an ultimate target of 2000 A/mm^2 for a 169 stack strand at 1.0 mm (D_s~58 µm)
- Approach:
  - Modifications to the subelement designs
- Chemical optimization
  - Produce a half height high-J_c subelement billet with Nb and Nb-Ti filaments with a Nb-Ta diffusion barrier
  - Deliver ~45 kg of 1 mm wire
- Local Area Ratio (LAR) optimization
  - Produce two half height high-J_c subelement billets having Nb and Nb-Ti filaments with variable LAR from annulus to barrier
  - Deliver ~90 kg of 1 mm wire
- 0.8, 0.9, 1.0, 1.1 and 1.2 mm wire sample
- HT optimization
  - The present subelement design - average J_c(15T)~1650 A/mm^2

Ta diffusion barrier for Ti doped strand
Ti doped strand reacts faster at lower temperatures than Ta doped – if diffusion barrier is Ta doped and the filaments are Ti doped, will it be possible to react at a low temperature and obtain a more effective (slower reacting) diffusion barrier?



LAR adjustment for smaller Ds strand
Present LAR (~0.2) works well for D_s>50 microns. For D_s<50 microns, it is possible that a slightly larger LAR will be more effective in terms of J_c?

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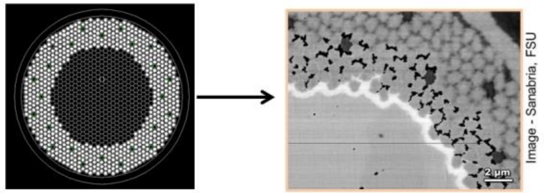

Graded LAR in a Subelement
Standard subelement – There is a complex interaction between the nausite layer and effect on tin diffusion and large Nb_3Sn grain formation on inner ring. For small D_s strand, we are trying a new subelement with graded LAR to alter nausite formation on inner ring and add additional effective barrier thickness to OD.

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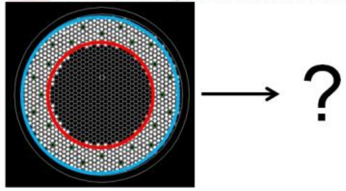

18099 – Ti doped Nb filaments with larger LAR

D_s (calculated)	650/50hrs.	665/50hrs.	665/100hrs.	680/50hrs.
69µm (1.2mm 169 stack)	1570 A/mm^2 164 (25.5T)	1659 A/mm^2 121 (27.2T)	X	X
64µm (1.1mm 169 stack)	1568 A/mm^2 150 (25.4T)	1652 A/mm^2 90 (26.6T)	X	X
58µm (1.0mm 169 stack)	1605 A/mm^2 123 (25.5T)	1679 A/mm^2 60 (26.5T)	X	1684 A/mm^2 30 (27.0T)
52µm (0.9mm 169 stack)	1588 A/mm^2 90 (25.5T)	1633 A/mm^2 36 (26.2T)	X	X
46µm (0.8mm 169 stack)	1578 A/mm^2 48 (25.3T)	1622 A/mm^2 19 (25.9T)	X	1690 A/mm^2 12 (26.7T)