Superconductor development – update from the 2016 Low Temperature/High Field Superconductor Workshop (LTHFSW2016 – Santa Fe NM February 8-10

David Larbalestier
ASC-NHMFL-FSU

With special thanks to Danko van der Laan (ACT), Yibing Huang and Mike Field (OST), Yifeng Yang and Drew Hazelton (SuperPower), Najib Cheggour (NIST), Carmine Senatore (UniGE) and my colleagues at FSU, especially Eric Hellstrom, Peter Lee, Jianyi Jiang, Fumitake Kametani, Chiara Tarantini, Seungyong Hahn and Ulf Trociewitz, as well as colleagues in CDP and BSCCo, especially Lance Cooley, Dan Dietderich, Arup Ghosh, Ken Marken, and Tengming Shen), and in addition Venkat Selvamanickam (TcSUH)

Other talks by Lance Cooley, Bernardo Bordini, Mike Sumption and Klaus Schlenga to round out my talk – I will not duplicate their points

Sessions on 1. Strategic goals, 2. Magnet drivers for conductor R&D, 3. Nb_3Sn, 4. Bi-2212 and Bi-2223, 5.REBCO, 6. Broad Conductor Issues

LTSW Santa Fe February 8-10, 2016

Key points

- Nb_3Sn issues, concentrating on RRP
  - See also talks by Bernardo Bordini, Lance Cooley, Jeff Parrell and Klaus Schlenga
- Bi-2212 progress
- REBCO progress

Issues for Nb_3Sn

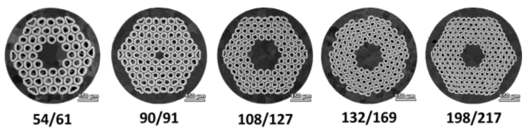
- What is really possible with present RRP (Parrell and Cooley talks) and PIT (Schlenga talk)?
- What can CERN expect and stimulate? (Bordini talk)
- What is the science behind the 20% load line Ic margin desire (de Rijk yesterday)?
  - Is the problem epoxy cracking?
  - Or in the conductor e.g, strain-irreversibility cliff (Cheggour NIST)?
  - Or some combination of factors not yet understood?
- The very best RRP conductors at present made achieve 1650 A/mm^2 at 15 T, 4.2K
  - Control of reaction pathways may be the key to pushing all conductors to this level (ASC focus presented here)
- A new (old) paradigm may be to add new pinning centers (radiation damage – Baumgartner talk) or ZrO_2 pins or grain refiners (Sumption talk)

Restacked-Rod Process® Past, Present and Future

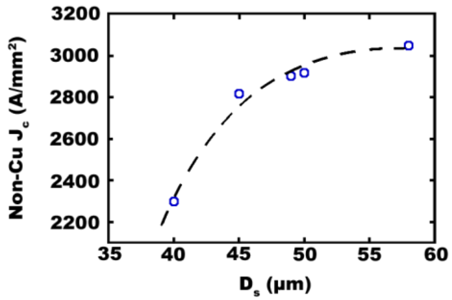
See also Parrell talk this afternoon

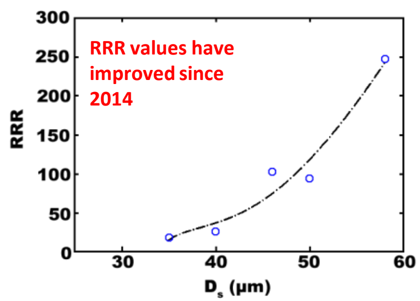
Past

1 Significant processing improvement over the last 10 years.



2 Low RRR and low J_c in small D_s is a long known issue, but has become more pressing as low D_s and high yield billets are demanded.



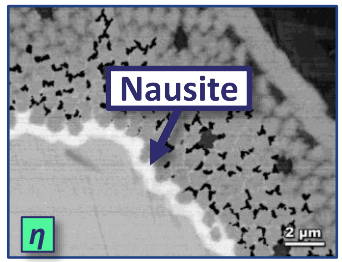


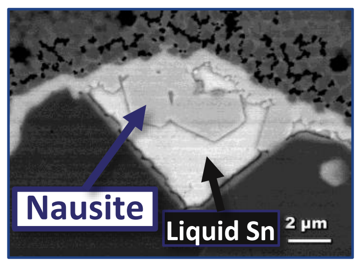
Field *et al. IEEE Trans Appl Supercond* **24,** 1–5 (2014).

Present

1 In 2014 OST found an important source of RRR degradation—RRR was improved about 30%.

2 In collaboration we found that one source of I_c reduction is the excess formation of the ternary Sn-Nb-Cu phase (Nausite):



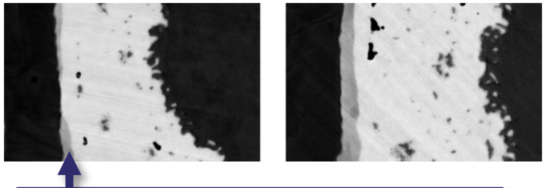


Nausite → $NbSn_2$ → Nb_3Sn

Nb_3Sn formed via this reaction path is often large grained and poorly connected.

Low performing billets are related to excessive production of Nausite.

3 Another limitation of I_c and RRR is the difficulty to control Nb_3Sn reaction as the diffusion distances get smaller.



Dwindling diffusion barrier due to over reaction of barrier at small D_s

Future

1. Our reaction pathways are allowing predictive change of 2 Sn-mixing HT steps. Optimum pathway seems to depend on D_s.
2. Frequent teleconference with LARP and OST tighten the feedback loop and make production changes possible.
3. OST is already working on design alterations and improving their yield and re-stacking capabilities.
4. We believe that >1600 A/mm² (15T) and RRR>100 will be achieved at 40 μm in a couple of years.

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OXFORD INSTRUMENTS *The Business of Science*

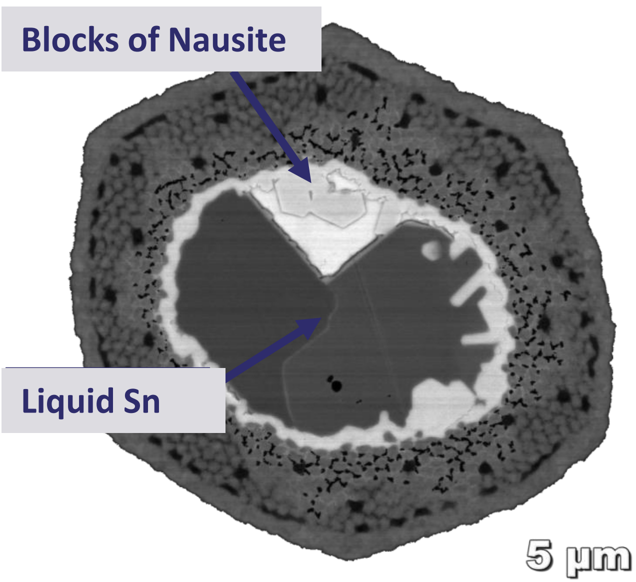
PhD student Sanabria (FSU) with Field (OST) and Ghosh (BNL)

Disconnected A15 wastes J_c - events below 600 °C decide how much disconnected Nb_3Sn occurs in RRP®

- The Sn-Nb-Cu Nausite phase is **responsible** for useless large grain and disconnected Nb_3Sn

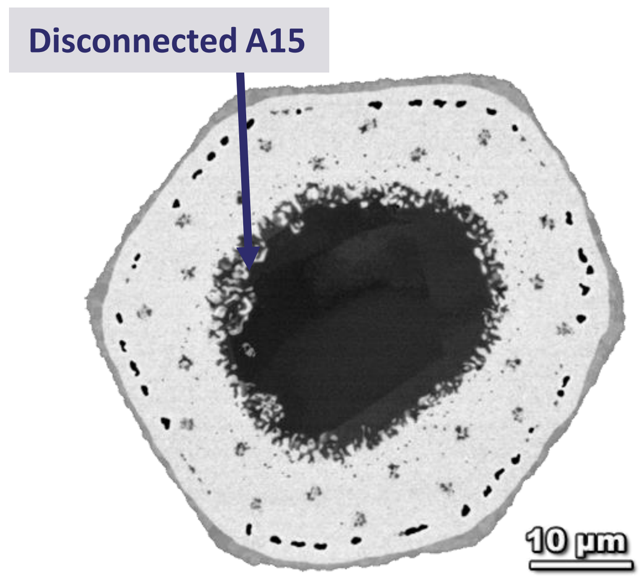
A15 formation

Before

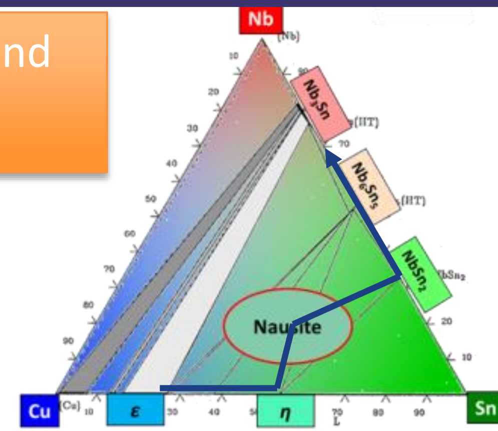


RRP® sub-element quenched from 545°C showing large amounts of Nausite.

After



Fully reacted RRP® filament showing disconnected Nb_3Sn wherever Nausite was present.



Phase diagram adapted from Villars [2], Pong [3] and [1] Scheuerlein

Nausite exists between ~350°C and ~550°C

1) C. Scheuerlein, *et. al.*, *J. Phys.: Conf. Ser.*, vol. 234, no. 2, p. 022032, Jun. 2010.
2) Handbook of Ternary Alloy Phase Diagrams, P. Villars, A. Prince and H Okamoto, eds., ASM International, 9757 (1995).
3) I. Pong, et al. *Supercond. Sci. Technol.*, vol. 26, no. 10, p. 105002, Oct. 2013.

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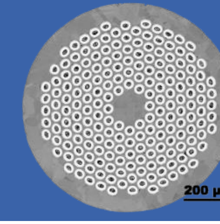
Powder In Tube: Past, Present and Future

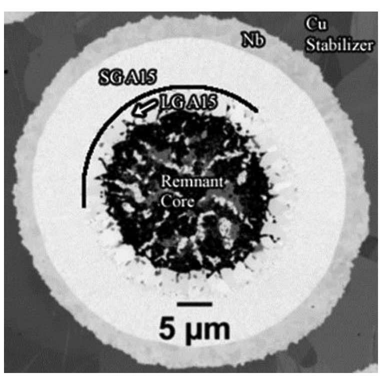


Past

Two major obstacles since the beginning of PIT:

1 The appearance of large A15 grains which do not carry current but take up ~15% of cross section.[1]

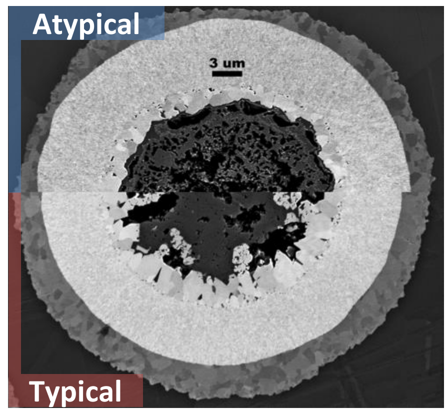
2 25% of the final cross section is residual diffusion barrier (DB)

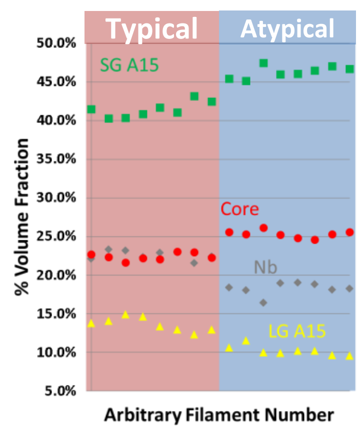


[1]Veringa *et al. IEEE Trans on Magnetics* **19**(1983).

Present & Continuing Work

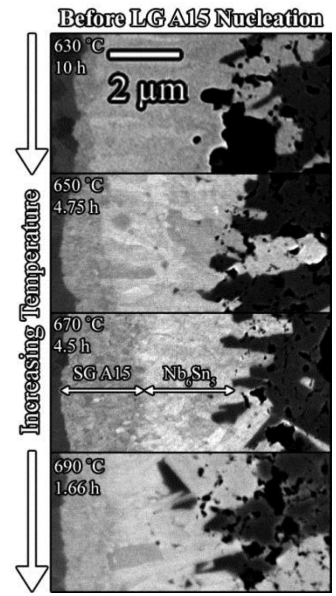
1 In 2014 we found 'atypical' filaments with suppressed LG A15 formation, more SG A15, and more DB was consumed.





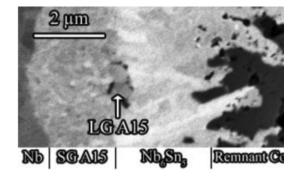
2 Recently we found that the layer thickness of SG A15 which forms before LG A15 can be controlled using multistep heat treatments

<u>Single step HT's</u>



The maximum SG layer which forms before LG's appear is variable with temperature

<u>Multi-step HT</u>



Multiple HT steps early in the reaction allow the SG layer to grow larger before precipitating LG A15

J_c implications now being explored

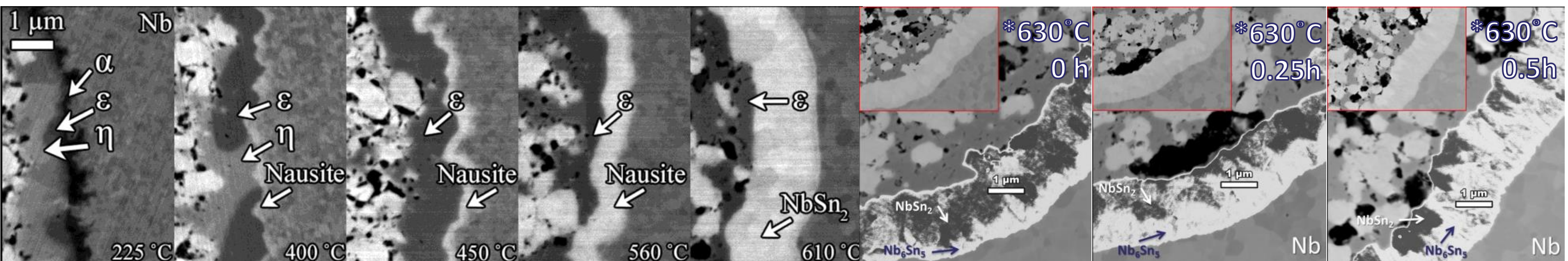
PhD student Segal (FSU) with Sailer (BEAS) and Ballarino (CERN)

LARP CERN BRUKER ASC NATIONAL MAGLAB

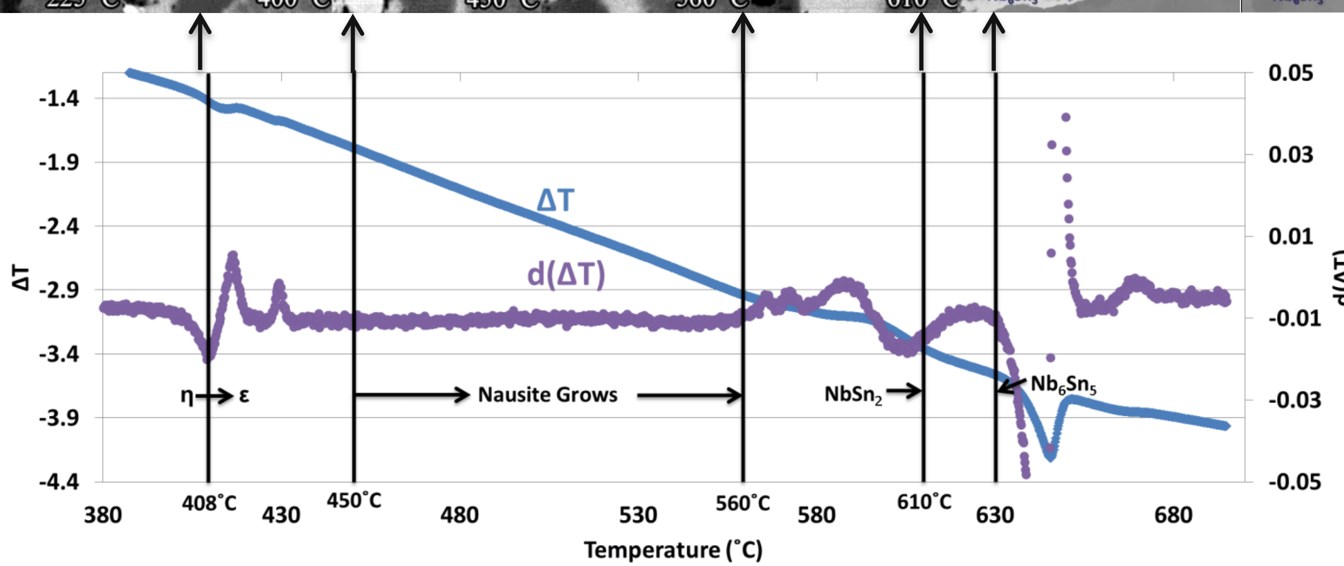
Events below 630 °C determine the conditions of formation for A15 in PIT

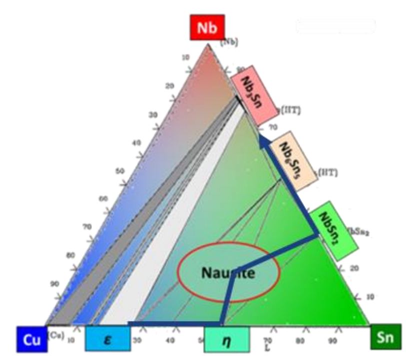
- DTA coupled with microstructure shows the evolution from the Sn rich powder core forming Nausite with tube wall, then $NbSn_2$ and a rapid decomposition into Nb_6Sn_5 at 630 ˚ C

PhD student Segal (FSU) with Sailer (BEAS) and Ballarino (CERN)



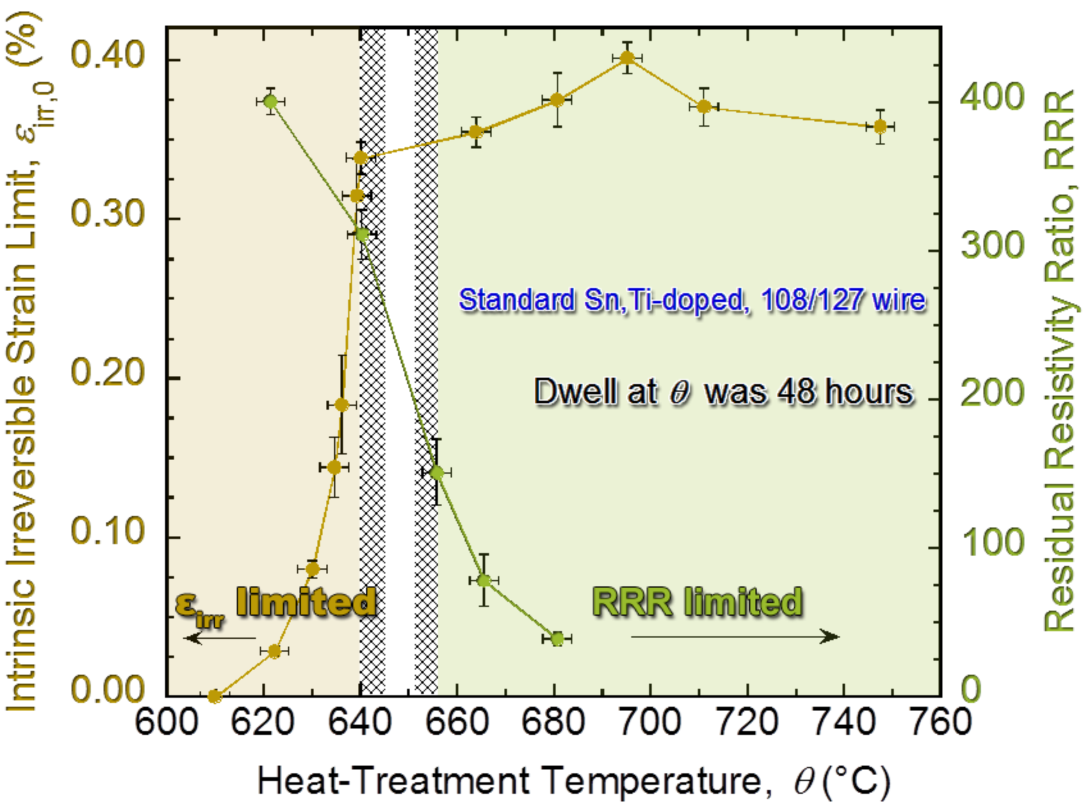
*A filter has been applied to these images to better distinguish phases. Original image provided as inset





The irreversibility cliff of Cheggour and the RRR (round wire) constraint are closely coupled

- Epoxy impregnated solenoids work reliably up to 23 T at 1.8 K in 1 GHz NMR machines
  - ΔT values are >4 K in magnets weighing 2 T and storing 5-10 MJ
- Dipoles have less symmetric stresses and are also impregnated
  - Is the problem in the epoxy or the conductor?
- Two potential conductor problems
  - Low RRR material at the cable edges hugely reduces the stability (Bordini/CERN)
  - The strain irreversibility cliff of low ε_{irr} appears below about 640 C, precisely the temperature range at which reaction is trying to be limited

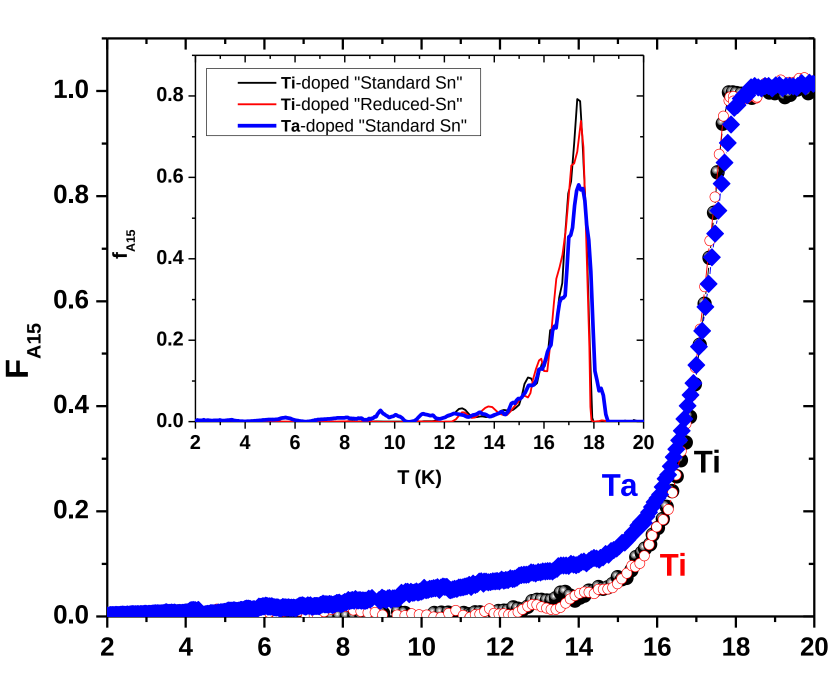


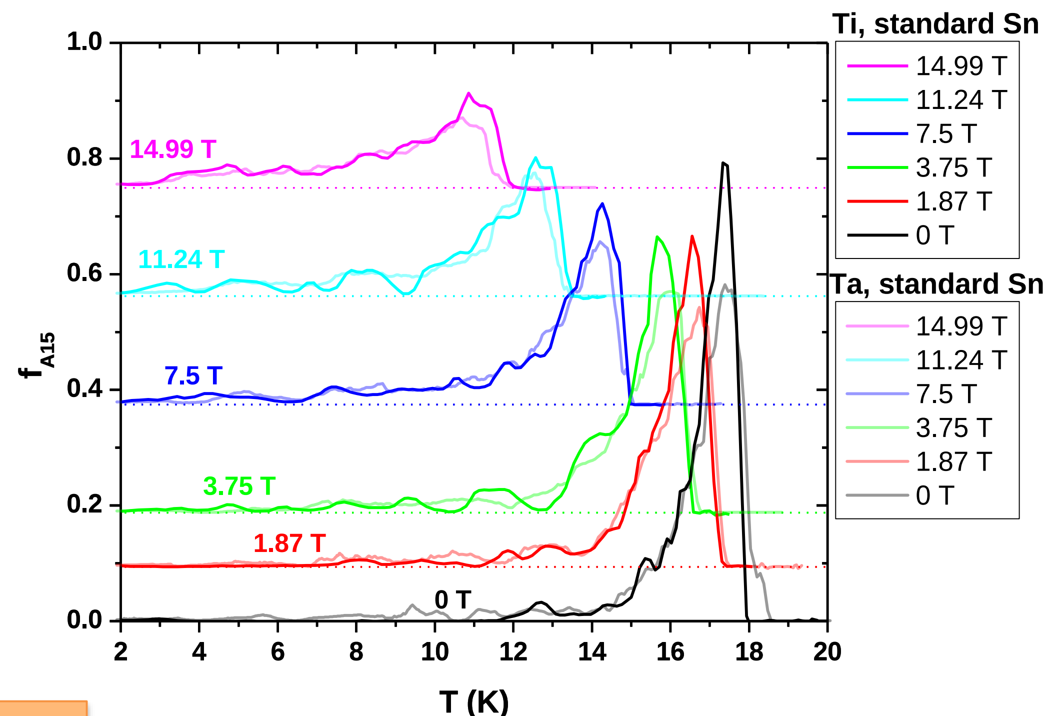
Cheggour (NIST), Ghosh (BNL), Lee (FSU) collaboration

Is this just a curious conductor level issue – or a serious magnet-level issue?

Ti-doping increases phase homogeneity, even in reduced Sn ratio conductors

RRP 108/127, 0.778mm diam., Ta or Ti doped, standard or reduced Sn





- **Ti-doping**

  No A15 phase with T_c below ~12 K
- **Ta-doping**

  A15 phase with T_c down to ~5-6 K

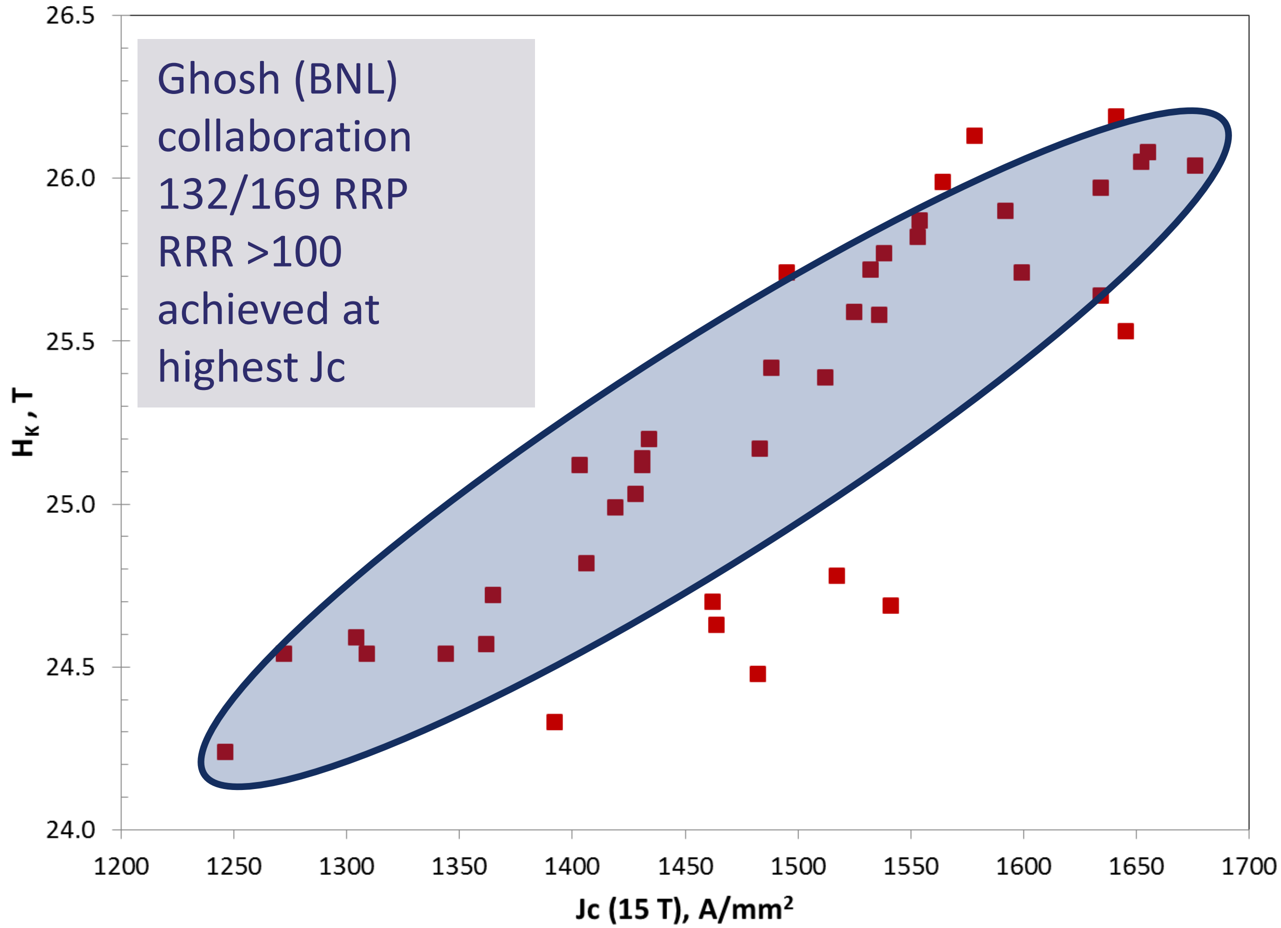
More uniform in-field behavior for Ti-doped wires:

2 Tesla larger H_{c2}

C. Tarantini *et al.*, Appl. Phys. Lett. 108, 042603 (2016)

Maximizing the J_c in present RRP

- Many recent optimizations carried out by Ghosh on recent RRP show:
- Strong correlation of Jc (15T) and H_K
- Jc (15T) of almost 1700 A/mm^2 at best – but 1250 A/mm^2 at worst



Reaction path (Nausite) and A15 homogeneity all play into the upper and lower bounds – Ti in RRP definitely better than Ta doping

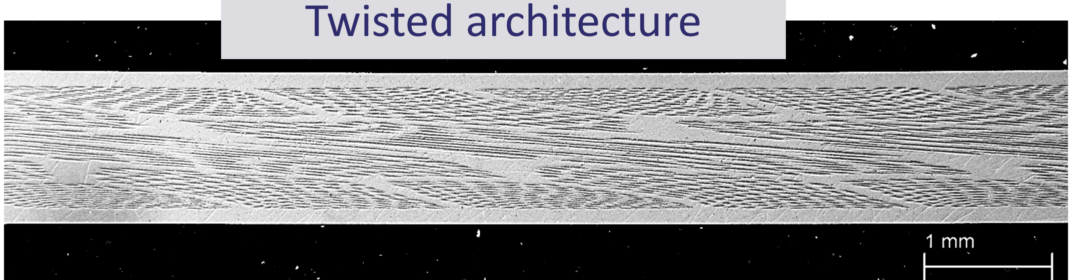
The ASC-FSU view of Nb_3Sn

- **Still work to do** – even though HiLumi performance seems to be converging on a good upper limit of Jc
  - Today's action is on manufacturing variables – they are forcing all to confront what we do not yet understand
    - They are also the route to lower $/kA.m
  - The reaction pathway(s) are still not fully understood (And offer the pathway to higher yield and perhaps greater stability margin)
  - A new POP of small grain size and oxide pinning has been provided by OSU (Xu and Sumption) and SupraMagnetics
    - Potential for 6x increase of Jc at 15 T
    - But is it fabricable in Filamentary form? Recent SBIR work is interesting .

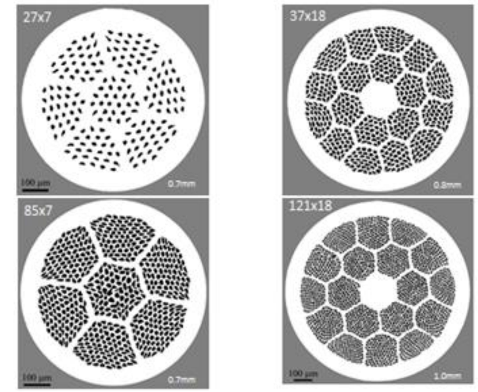
Bi-2212 – key positives

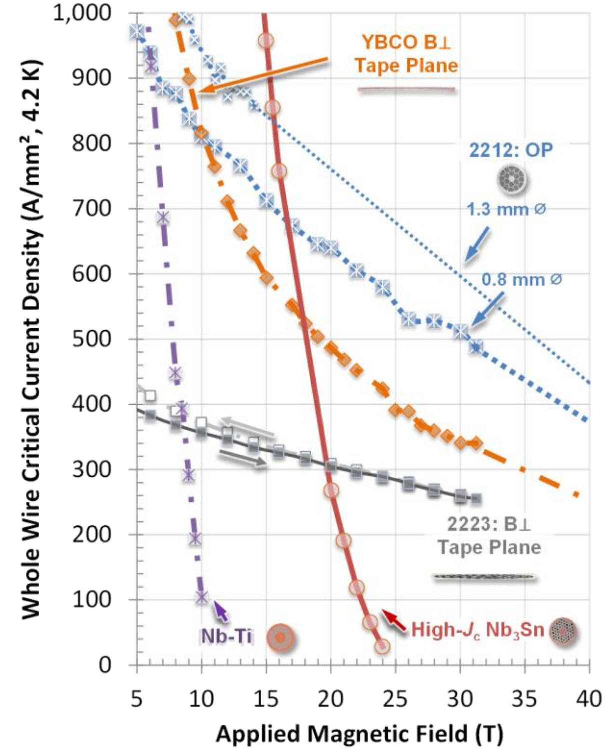
- Round, fine filament (~15 μm), twisted
- Available in multiple architectures
- Made on the same fabrication lines as Nb-Ti and Nb_3Sn
- OST is making single billet piece lengths in multiple architectures at 10 kg scale (2 km at 0.8 mm)
- Does not depend (like REBCO and Bi-2223) on electric utility demand
- US SBIR companies appear able to supply equal or better powder to Nexans
- Has the highest J_E of any HTS conductor and crosses over with Nb_3Sn at ~ 16 T (but with much bigger temperature margin)
- Small coils being fabricated at FSU and LBL

Twisted architecture



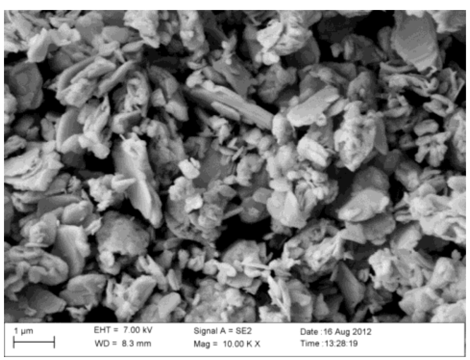
Unreacted Wire Cross Sections



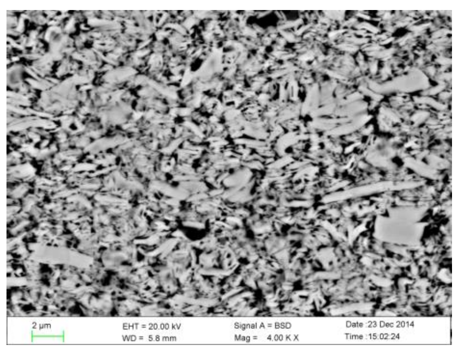


Bi-2212 – key challenges

- 50-100 bar overpressure required (now) for optimum properties (swaging (OST), square rolling (SPIN) potential partial alternatives)
- Ag has low E (70GPa) and conductors have low filament fracture stress (~160 MPa)
- Powder supply has been a challenge – but 2 US vendors are active (MetaMateria, nGimat) – best equals long-time supplier Nexans



Nexans granulate



MetaMateria

The MagLab 100 bar OP furnace with 6 zone, 14 cm dia x 50 cm high uniform hot zone – open for collaborative reactions

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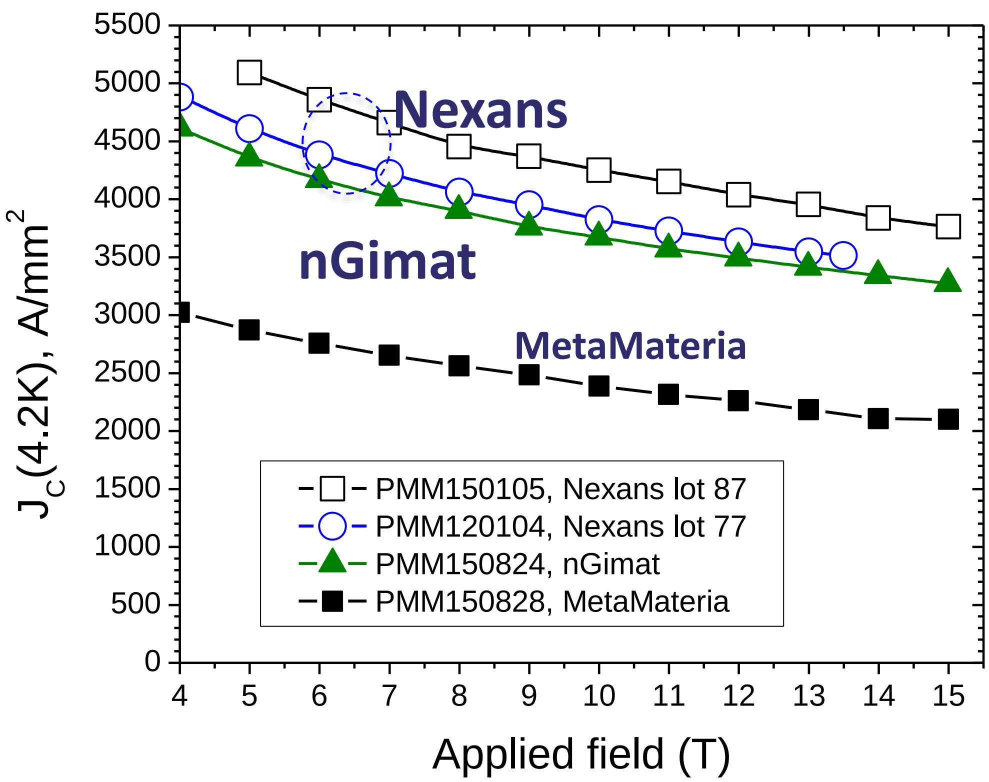
MetaMateria, nGimat powders close to very best Nexans performance

- Filament quality is clearly an important variable for high Jc
- Avoid hard particles that disrupt filament pack
- Heat treatment becoming much better understood
- OP HT enforces essentially 95% density
- Melt process and slow cool enforces biaxial texture with no observable grain boundary weak links (unlike Bi-2223)



Very best Nb-Ti – 3000 A/mm2 at 5 T
Very best Nb_3Sn – 3000 A/mm2 at 12 T, 1500 A/mm^2 at 15 T

Jianyi Jiang (FSU) in collaboration with Yibing Huang (OST) and their powder suppliers at Nexans and MetaMateria

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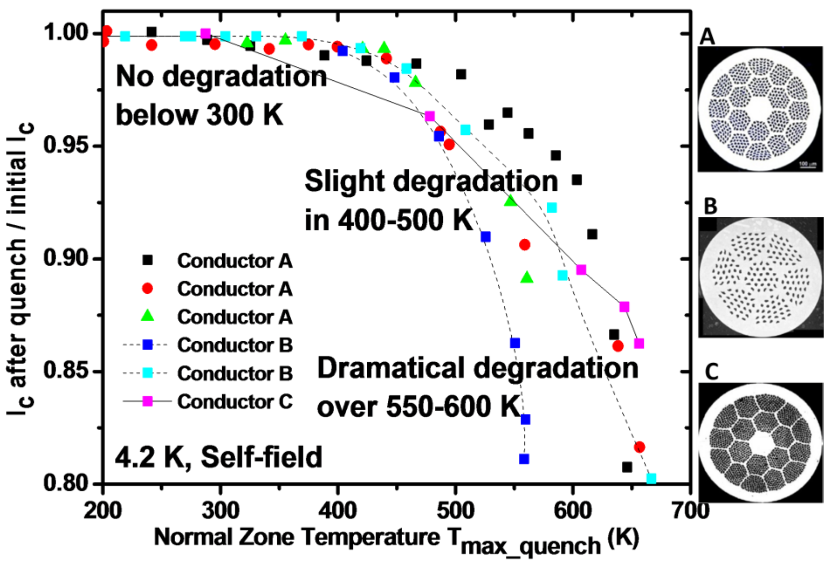
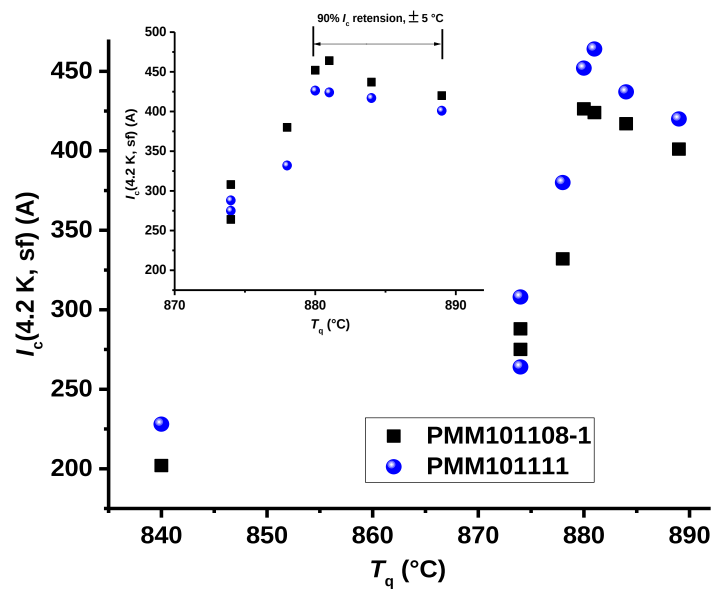
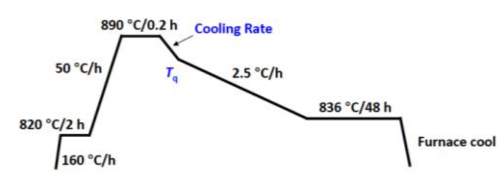
Quench/strain studies, heat treatment studies - Shen

Quench studies on various conductor architectures



Heat treatment studies



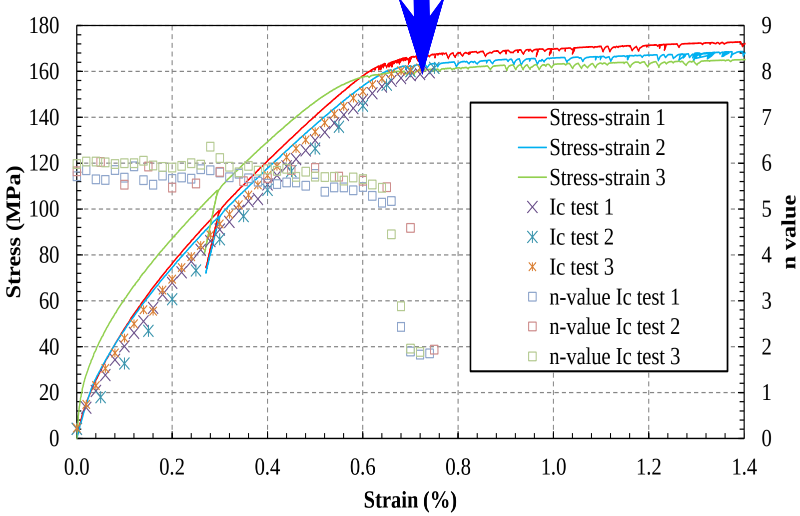


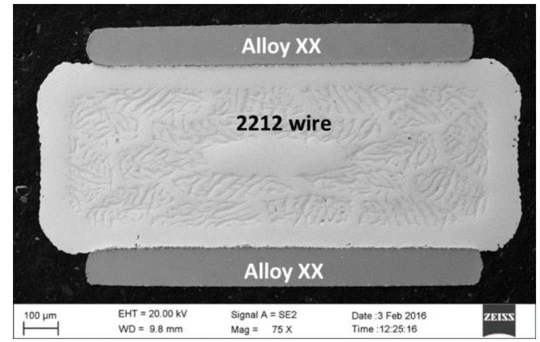
Onset of irreversible damage occurs progressively and with some sensitivity to stress state at quench

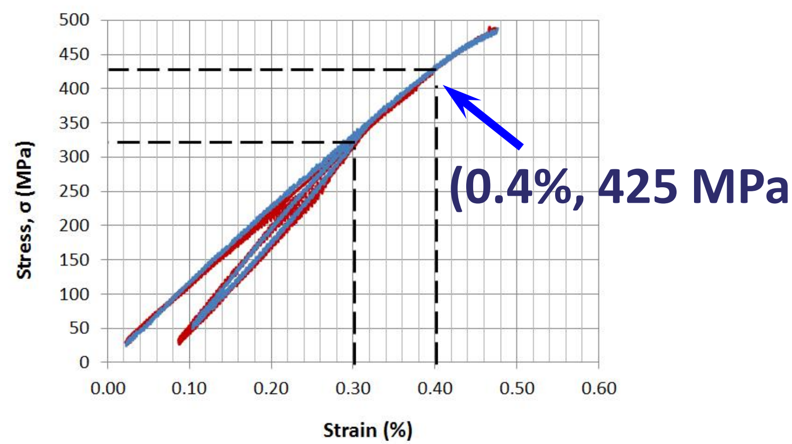
Shen and Ye

Mechanical properties of plain and strengthened wires

I_c degradation of 5% is at $\varepsilon_{irr-5\%}$ = 0.60% (σ = 160 MPa)







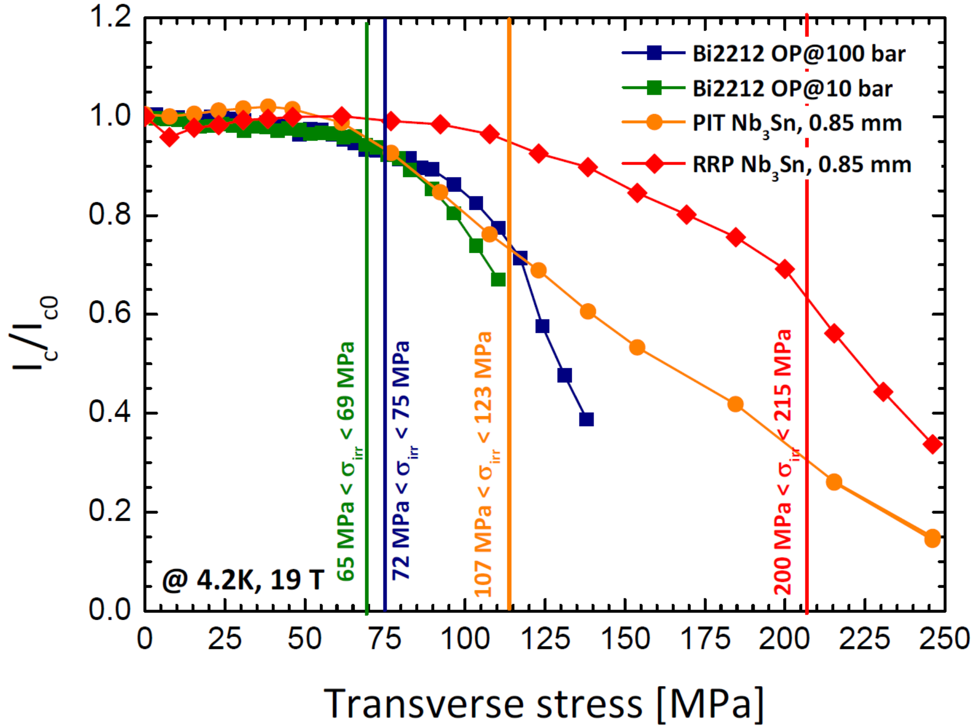
Tested at 77 K
OP-HTed Wire: pmm130723-2, 37x18, 0.8 mm

Strengthened wire made by Alex Otto at ASC and SMS

R. Bjoerstad, and C. Scheuerlein, ***et al. SuST. (2015)***

My take on Bi-2212 – strong momentum

- VHFSMC, now BSCCo, CDP and the SBIR program are doing well in driving the technology synergistically
- First coils have taught a lot (Tengming Shen FNAL, now LBL on quench especially) – CCT coil now being readied for reaction at FSU (Tengming Shen)
- Costs are high but no higher than coated conductor – but scale up from present 9 kg billets is quite feasible and can follow RRP scale up – Lance Cooley talk on Thursday) Transverse (U. of Geneva (strand) and U. of Twente for cables) and longitudinal (NIST and UWEC and FSU) testing on OP samples made at FSU is underway at multiple labs

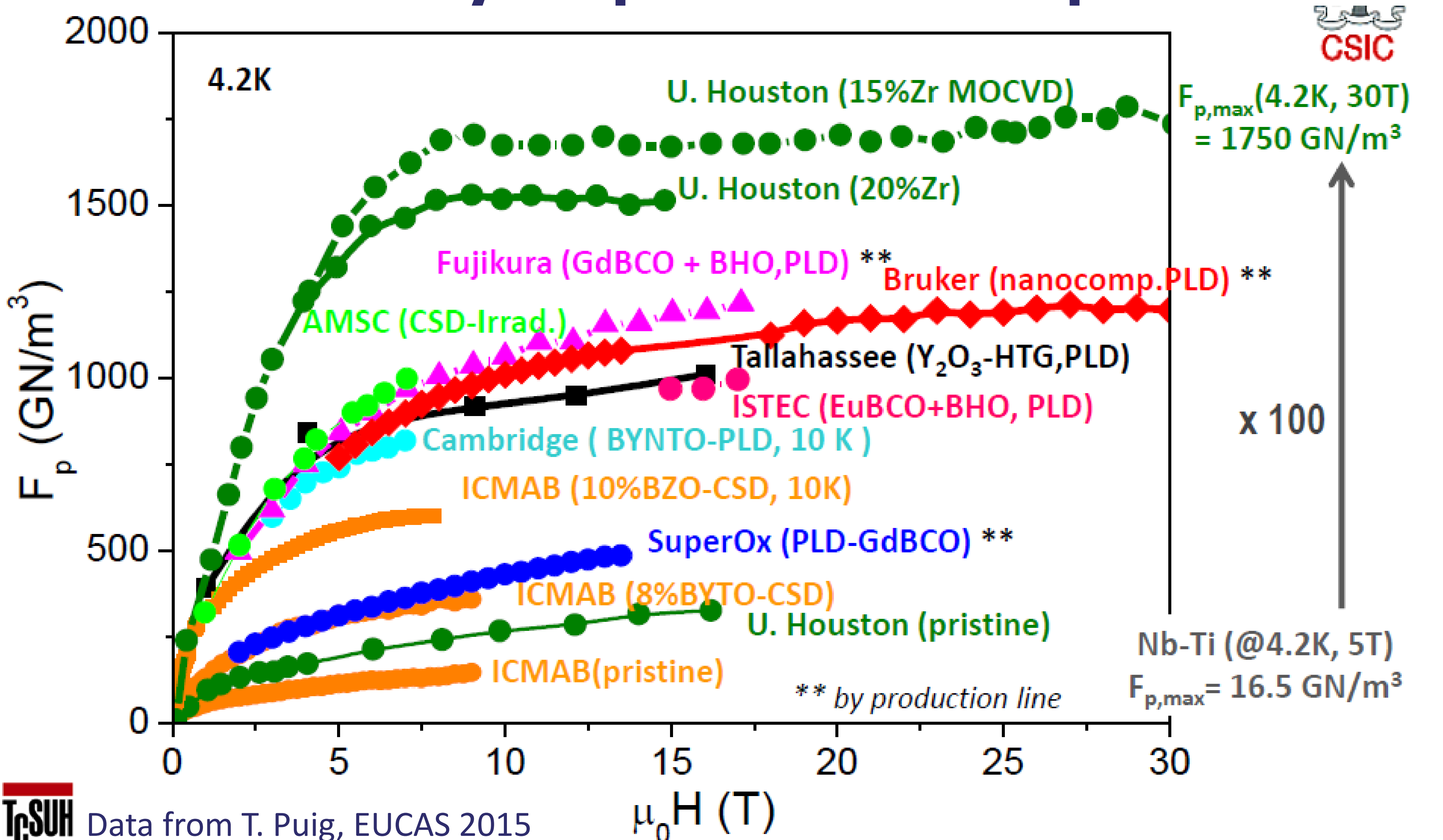


Transverse stress – Ic measurements at 19 T, 4.2 K by Senatore group at U. of Geneva on OST 37 x 18 wires OP at ASC-FSU

REBCO for HEP

- The highest margin of any conductor and 2 major coil successes recently:
  - The SuNAM/MIT/NHMFL no insulation (NI) 26.4 T magnet – no quenches so far – now at FSU for test
  - The 32 T prototype with 1/6th of the full insert generated 12 T inside 15 T for 27 T total
  - But these are single strand tapes with large magnetizations
- HEP use favors cables (Roebel – EUCARD2) and CORC (Danko van der Laan in collaboration with SuperPower)
  - CORC provides a multifilamentary, twisted, high current cable

100 times high flux pinning force in heavily-doped REBCO tapes



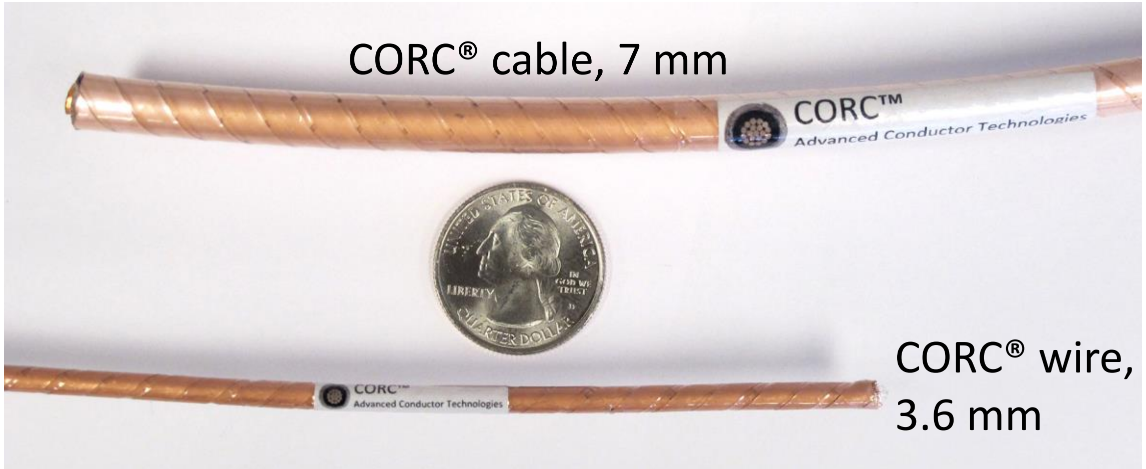
TcSUH Data from T. Puig, EUCAS 2015

Summary (Selva LTSW 2016)

- 3X improvement in performance of REBCO tapes by heavy doping
- Additional 2X improvement with thicker films: HTS is still only 2 – 3% of total conductor
- **At 4.2 K, 21 T, I_c = 663 A/4mm, J_e = 1658 A/mm^2** in thick film tapes made with heavy doping
- Even at today's REBCO tape $/m, price of this tape based on 4.2 K, 21 T performance = **$ 60/kA-m** → compare with $ 100 – 150/kA-m projections for Bi-2212 in 2030
- Yet another 2X improvement in J_e feasible using ultrathin REBCO tapes → 3000 A/mm^2 at 4.2 K, 20 T possible!
- Ultrathin tapes provide capability to make round, filamentized, transposed small-diameter REBCO wires

HEP community is encouraged to seriously consider REBCO as an option

CORC® cables and wires compared



CORC® cables
- tapes with 50 μm substrate
- O.D.: 5 – 10 mm
- tapes of 3 mm and 4 mm width

CORC® wires
- tapes with 30 μm substrate
- O.D.: 2.5 – 5 mm
- tapes of 2 mm and 3 mm width

First round, isotropic YBCO wire!

Flexibility now allows for accelerator magnets

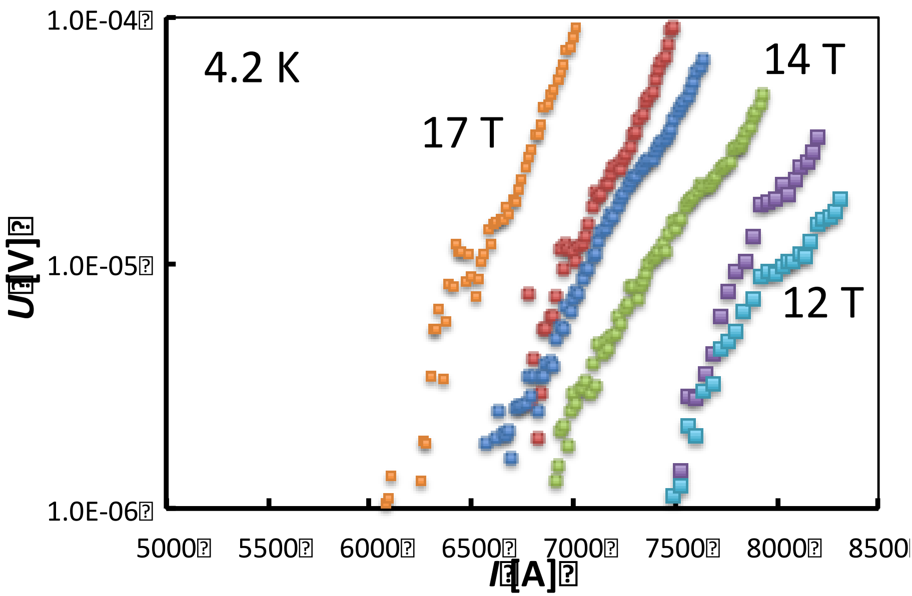
Advanced Conductor Technologies LLC
www.advancedconductor.com

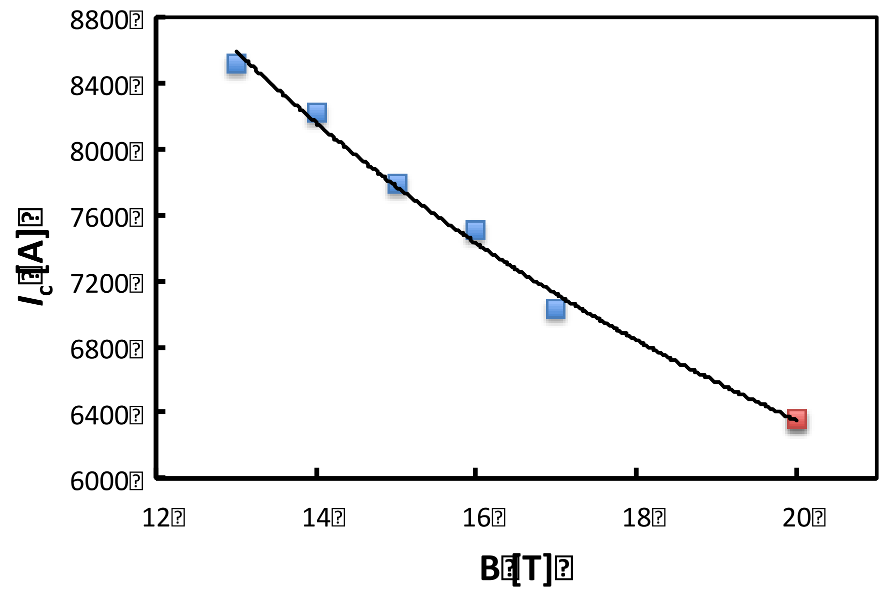
DOE-High Energy Physics Award DE-SC0009545

J_e in CORC® cables with 30 μm substrate

CORC® cable

- 50 tapes with **30 μm substrate**
- 7.5 % Zr doping
- 3 mm wide tape I_c (77 K) = 99 A
- cable outer **diameter 5.1 mm**





Extrapolated I_c (4.2 K, 20 T) = 6,354 A

October 2015

Extrapolated J_e (4.2 K, 20 T) = 309 A/mm^2

New record!

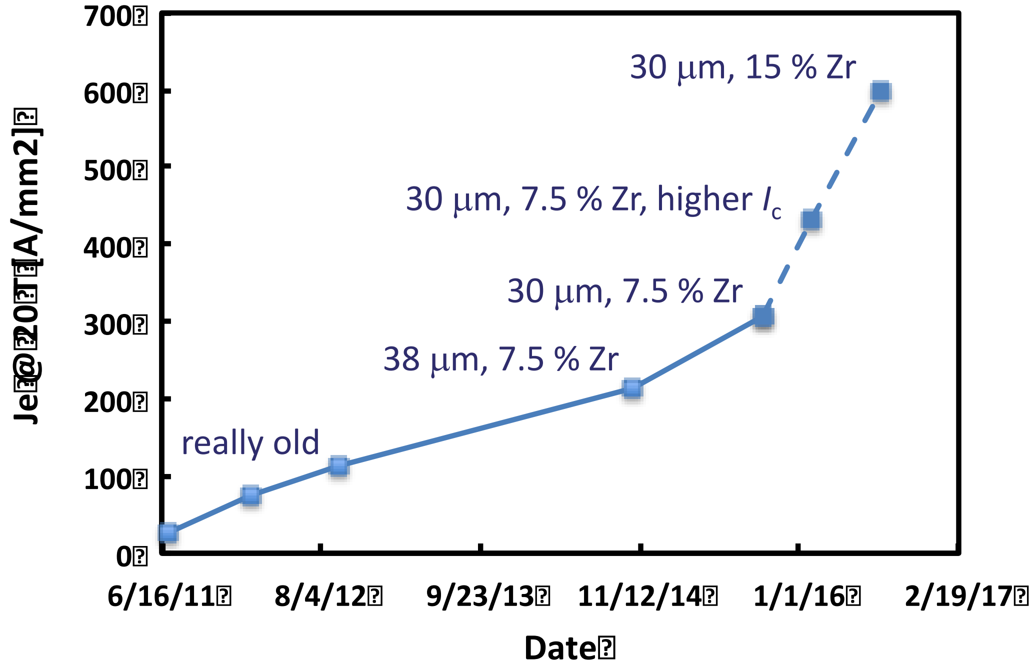
Advanced Conductor Technologies LLC
www.advancedconductor.com

DOE-High Energy Physics
Awards DE-SC0009545, DE-SC0014006

J_e in CORC® accelerator cables: current and future

CORC® cable J_e on track to 600 A/mm² at 20 T

- J_e of 309 A/mm² at 20 T achieved
- J_e of 450 A/mm² possible with higher I_c tapes (currently in hand)
- Transition from 7.5 % Zr to 15 % Zr will result in J_e(20 T) 600 A/mm²

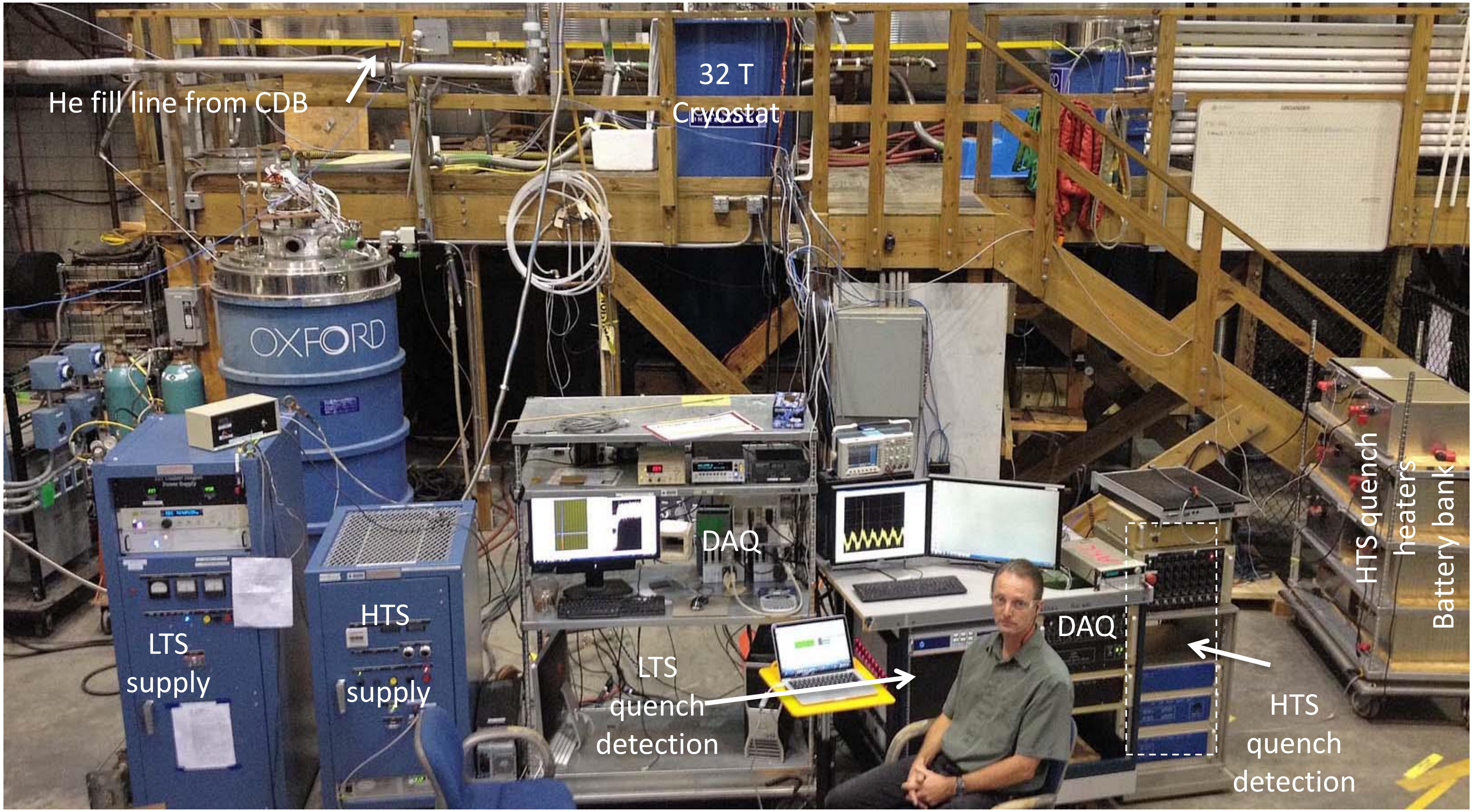


J_e in CORC® cables has exceeded the threshold for accelerator magnets

Advanced Conductor Technologies LLC
www.advancedconductor.com

Danko van der Laan – see SuST 29 055009 (2016)

32 T prototype integration test with OI 15 T/250 mm bore outsert – June 5, 2015



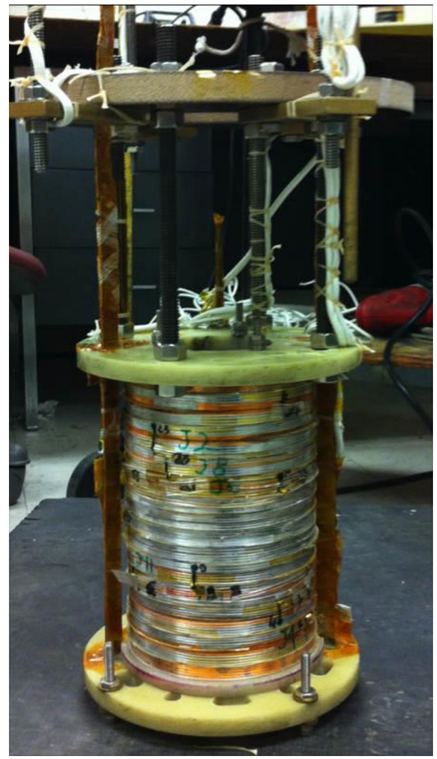
32T project manager Huub Weijers seated at the test station during successful testing of insert coil and outsert coil quenches – extensive tests of operation of LTS and HTS quench performance and cyclic testing achieved 27 T after multiple quenches

Very compact, very high field (26 T) NI (No Insulation) REBCO magnets at NHMFL

New faculty ME-NHMFL Seungyong Hahn formerly of Iwasa group at MIT

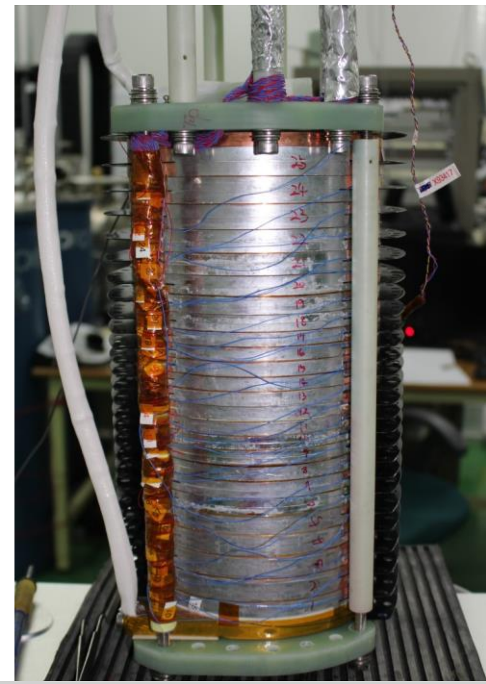
- Pros of NI magnets
  - Self-protecting by turn-to-turn “bypass” of quench current
  - Strong: >50 % enhanced winding mechanical strength
  - Compact: 3x J_W means 1/3 coil radial build
- Cons
  - Charging delay: 0.5-hour for 9 T/78-mm; 3-hour for 26T/35-mm
  - Limited operational experience so far
- Challenges
  - Charging delay may be improved by Partial-Insulation (PI)
  - Unbalanced forces during a quench at high fields

9 T/78-mm REBCO (2014, MIT-FBML)



- Coil OD: 101 mm
- Self-protecting at J_e of 870 A/mm^2

26 T/35-mm REBCO (2015, SuNAM/MIT/FSU)

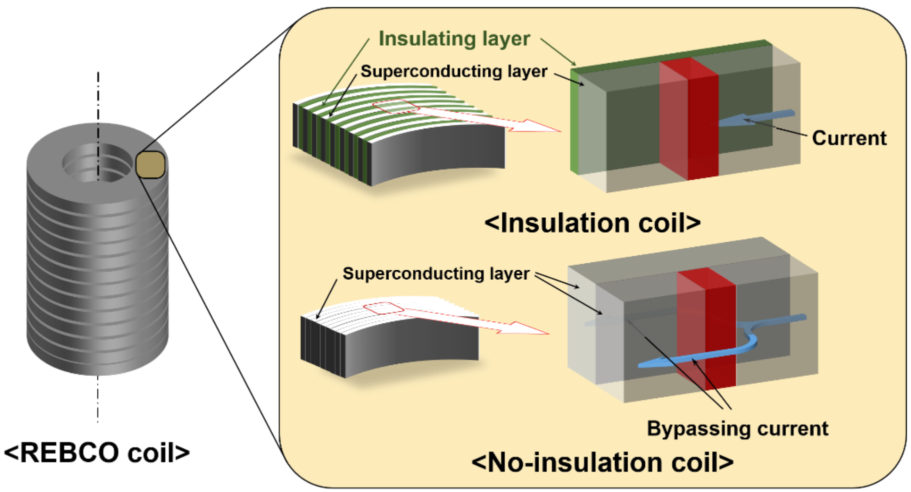


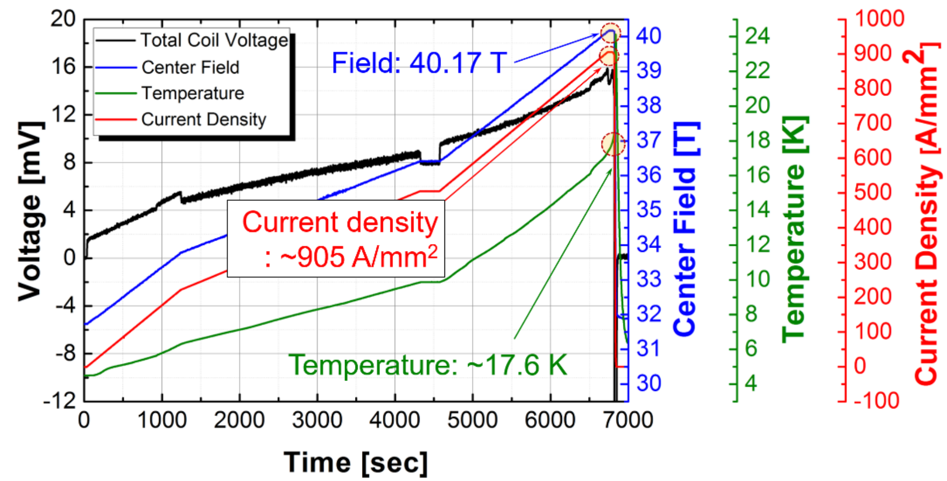
Design by Hahn, mfr by SuNAM

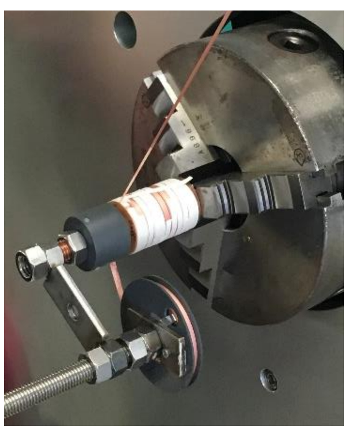
- Coil OD: 172 mm
- World record all-REBCO magnet

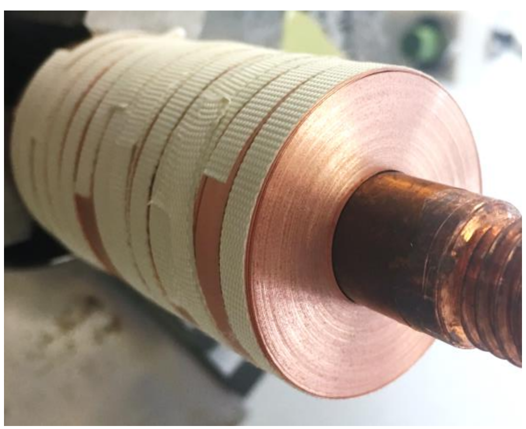
FSU ASC NATIONAL MAGLAB

NI REBCO with SuperPower 30 μm substrate: 40 T!









- 240 m of 7.5Zr tape in 12 single pancakes (14 ID/34 OD/53mm long)
- Large helium bubble due to gas produced by joints
- Safe quench at 18 K
- Total field >40 T
- Test done April 7, data still under review

Hahn *et al*. : https://nationalmaglab.org/news-events/news/new-approach-to-building-magnets-yields-new-world-record

Summary thoughts

- RRP and PIT Nb_3Sn are in large scale production
  - They share some key reaction path issues and gaining better uniformity will be valuable
- Bi-2212 (though a complex technology) demonstrates superior performance as a twisted, multifilament, very high J_c conductor
  - Getting it into insulated coils is the next challenge
- Huge vortex pinning potential of REBCO is still being explored
  - CORC (ACT/SP collaboration) with 30 μm substrates is showing new record J_E values in an isotropic, twisted, multifilament form
- The highest fields – now 40 T – are being attained with REBCO coated conductors