# Conductor challenges for FCC-hh

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With grateful acknowledgment as indicated on slides and to:
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**DOE-HEP CPRD**: I Pong (LBNL), M Jewell (UWEC), X Xu (FNAL), D Larbalestier (FSU), V Matias (I-Beam)
**ASC $Nb_3Sn$ group**: C Tarantini, D Larbalestier, P Lee, W Starch, M Mandel*, N Molitor†, A Hoolihan†, J Tietsworth† (now BOST)
**ASC Bi-2212 group**: E Hellstrom, D Larbalestier, F Kametani, J Jiang, U Trociewitz, D Davis, Y Kim, C English, C Brady, G Miller, S Barua*, E Martin*, A Abuzar*, T Shuvo*, C Linville†, A Kunstmann†, I Hudson†
**MagLab HTS R&D and Fusion group**: F Kametani, D Larbalestier, S Hahn (SNU), S Noguchi (Hokudai), D Abraimov, J Jaroszynski, A Polyanskii, J Kvitkovic, J Bang, K Kim, R Ries, G Bradford*, J Lee*, L Schvartsman†, G Murphy, L Louis†, G Watson†, C Irausquin†, N Bishop†, A Almanza-Enriquez†

* PhD and †Undergraduate students

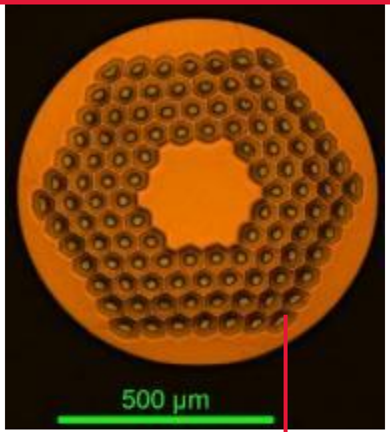
# Main questions

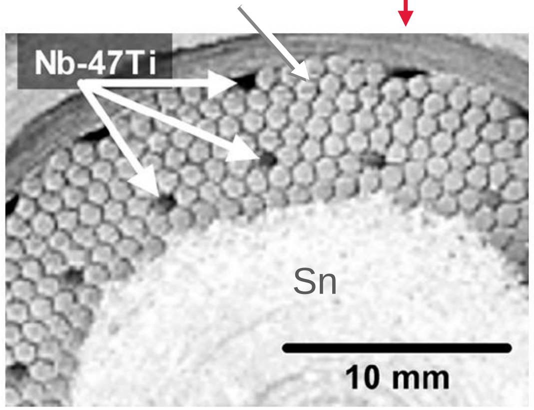
- FCC-hh will require a huge procurement of $Nb_3Sn$ strand
  - What does the scale imply for the present manufacturing base?
    - If 9000 tons, then this is 15 x ITER and 300 x HL-LHC.
  - What parts of the supply chain must evolve to be ready?
  - What is the probable evolution of the present qualified conductor in terms of architecture, properties, manufacturing? What might have to be done to make it ready for FCC-hh?
  - To what extent will advanced ideas (e.g. APC) impact future strand acquisitions? Are things moving fast enough to have significant impact? What can be done if not?
- Will FCC-hh incorporate any amount of HTS conductor?
  - What must be done to advance Bi-2212 conductors to supply 10s to 100s of tons?
  - If REBCO and "sustainable magnets" would displace $Nb_3Sn$, what is the status and what are the plausible development pathways?
- Are test facilities and characterizations adequate? If not, what has to be done?

# Successful mass production of high $J_c$ $Nb_3Sn$ wire for the HL-LHC

- Over 30 tons of high-performance $Nb_3Sn$ strand has been acquired since 2015 for HL-LHC pre-production and production (total of US and CERN).
- Specifications were chosen to be conservative:
  - **<u>This was a first-ever production run!</u>** While the strand was capable of 2,700 to 2,900 A/mm$^2$ at 12 T, 4.2 K in lab studies, the critical current specification was equivalent to 2,450 A/mm$^2$ based on a lack of production information. In the end, virtually all 750 production billets passed.
  - **<u>Piece length</u>** was also of concern. Breakage and cable mapping losses were expected to be 10-15%. In the end, yield was > 95% and average piece was > 3 km long.
    - US HL-LHC AUP: 2,702 km to cable maps out of 2,830 km delivered by end 2023
- Cost at start of procurement (2017): $1750/kg and $8.50/m
  - Production billet mass = 40 kg for a maximum single piece of 9.25 km
  - LHC production billet mass ~400 kg, piece length up to 100 km.

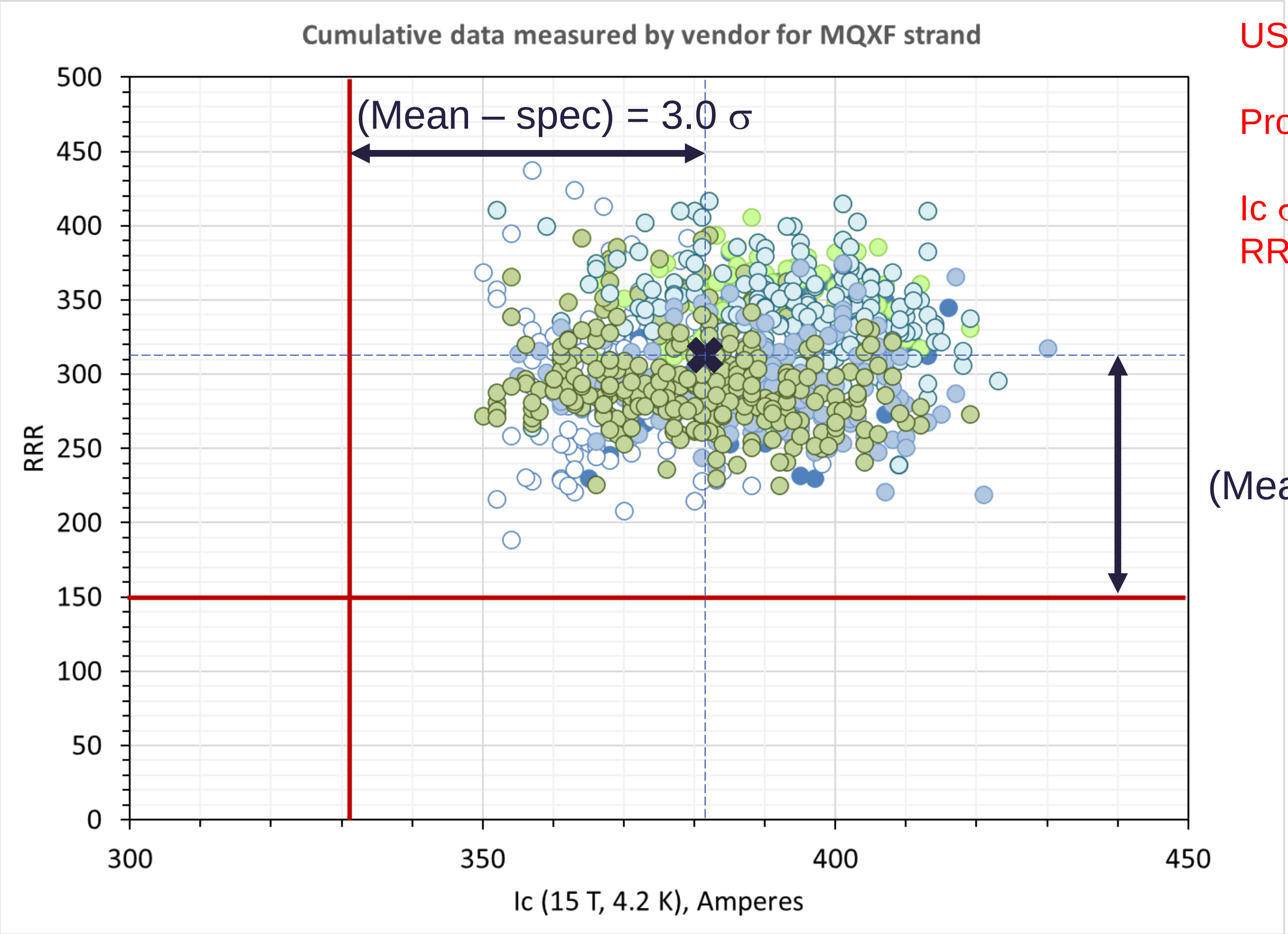
"Restacked Rod Process" (RRP) conductor made by Bruker-OST




J Parrell et al., IEEE Trans. ASC 15 (2005) 1200

# Production was “capable” for round strand at 15 T




US HL-LHC AUP data only

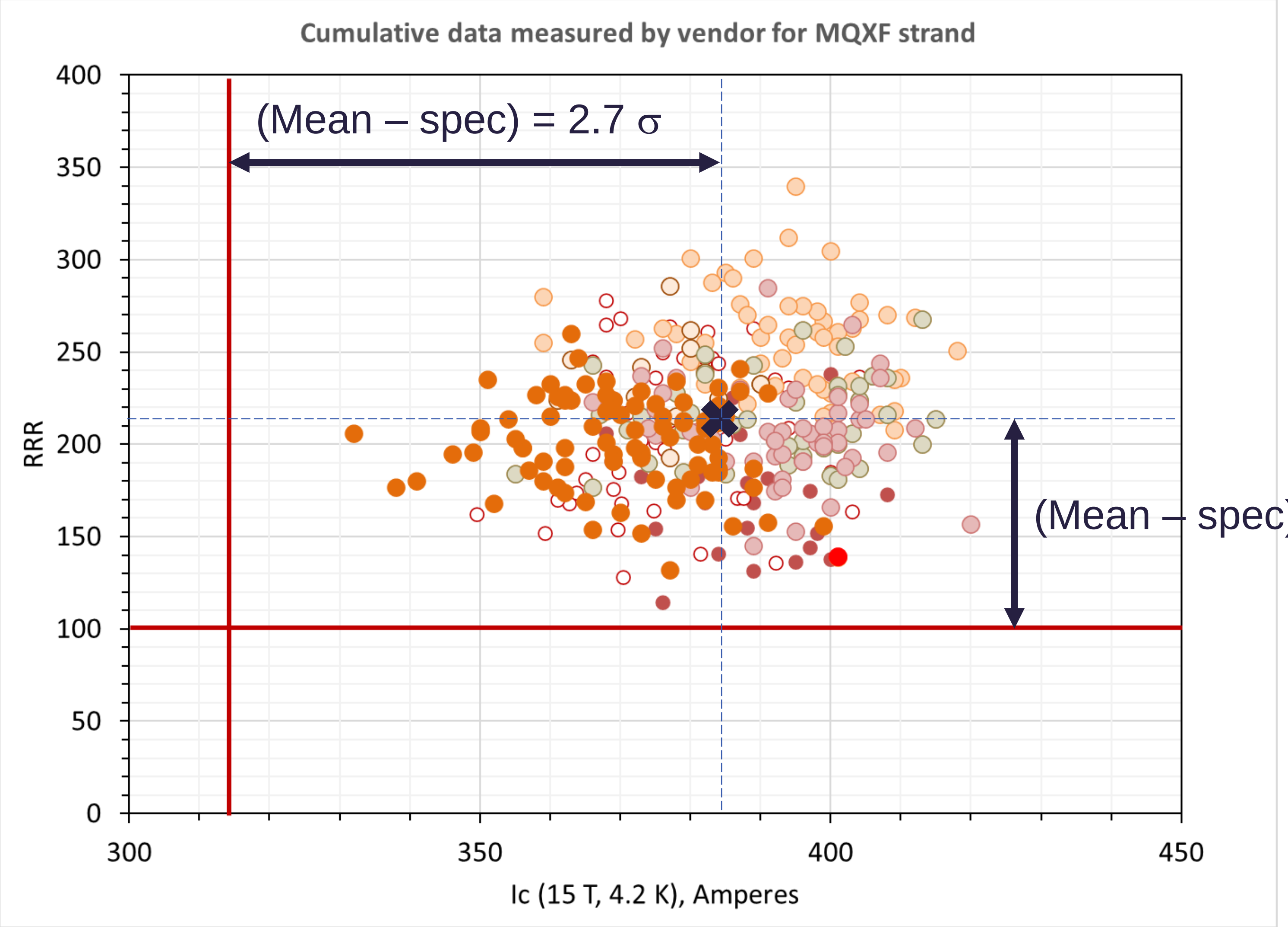
Process controlled at ±3σ

Ic σ / mean = 4.5%

RRR σ / mean = 12.6%

# Production was “barely capable” for *rolled* strand at 15 T

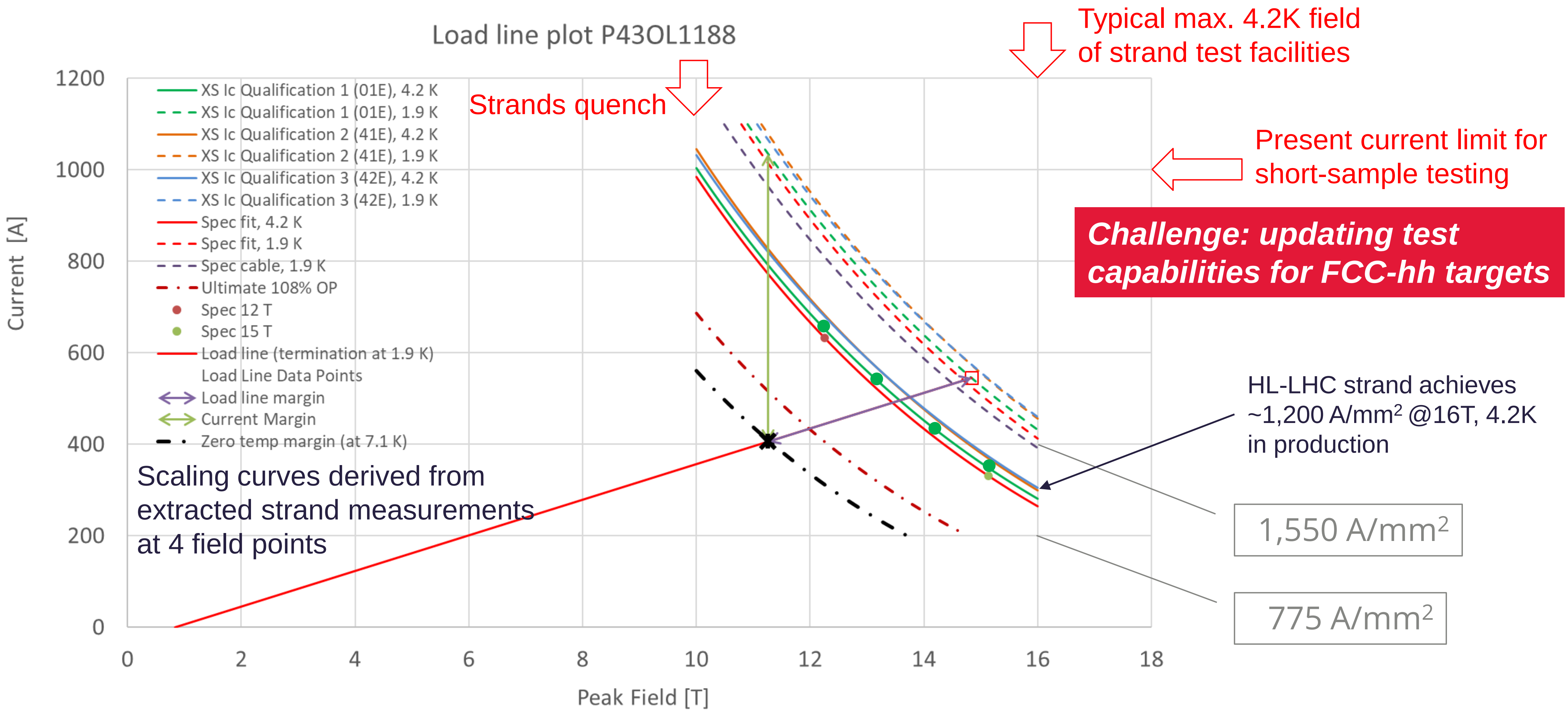
**Rolled strand simulates cable performance very well**




US HL-LHC AUP data only

Process controlled at ±3σ

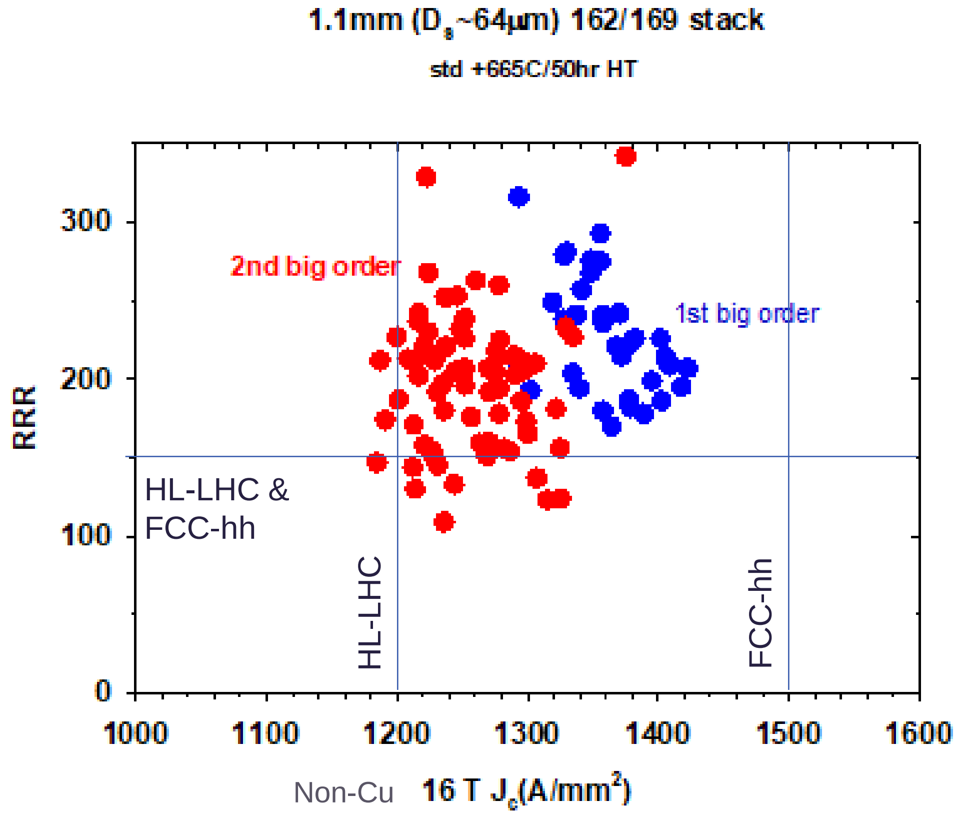
# HL-LHC strand should be capable of 1,200 A/mm² at FCC-hh 16 T, 4.2 K




***Challenge: updating test capabilities for FCC-hh targets***

# How much can the HL-LHC strand art advance to support FCC-hh?

- Very recent strand designs for magnet projects at LBNL and FNAL have advanced by:
  - Adding back tin (HL-LHC Nb:Sn 3.6:1, now 3.4:1)
  - Innovating the reaction sequence (C. Sanabria 2018)
  - Developing 169 sub-element stacks
- Challenge: these are incremental advances
  - *Sustained acquisitions of substantial quantities of the present workhorse magnet conductor could continue to drive beneficial evolution toward FCC-hh*
- Unknown: origins of performance variations
  - Speculation: $J_c$ is connected to grain size in initial Nb melt
    - FCC-hh might catalyze metallurgical investigations into the processing and structure of grade-1 and grade-2 Nb, its forging and annealing, and other factors that affect the downstream microstructure.




Courtesy of Mike Field – Bruker OST

# Challenges in the Nb supply chain

- CBMM: approx. 100 kt / year, > 200 yr reserves
- Challenge: Superconductivity applications are a tiny fraction of the Nb market space
  - Steels: approx. 90%
  - Electronics: approx. 4%
  - Nuclear and Aerospace: approx. 4% (increasing)
  - MRI conductor: < 1 kt of Nb → *Small market player, needs long-range planning and steady demand to hold supply chain interest and capability*
- Challenge: Superconductivity needs *pure* Nb
  - 12-18 month delay right now (in front of 12 month production), continued no-quotes from Nb vendors
  - $Nb_3Sn$ wire: grade-1 and grade-2 Nb (3-4 e-beam remelts)
  - SRF: grade-5 (6-7 remelts)
  - Challenge: e-beam capacity and scheduling, large orders get priority → *Delays triggered by market opportunities, expensive investment for project capacity. Need sustained demand from magnets. Major players such as CBMM are considering addition to capacity.*
    - 1 ingot Nb = about 5 billets = 200 kg $Nb_3Sn$ wire

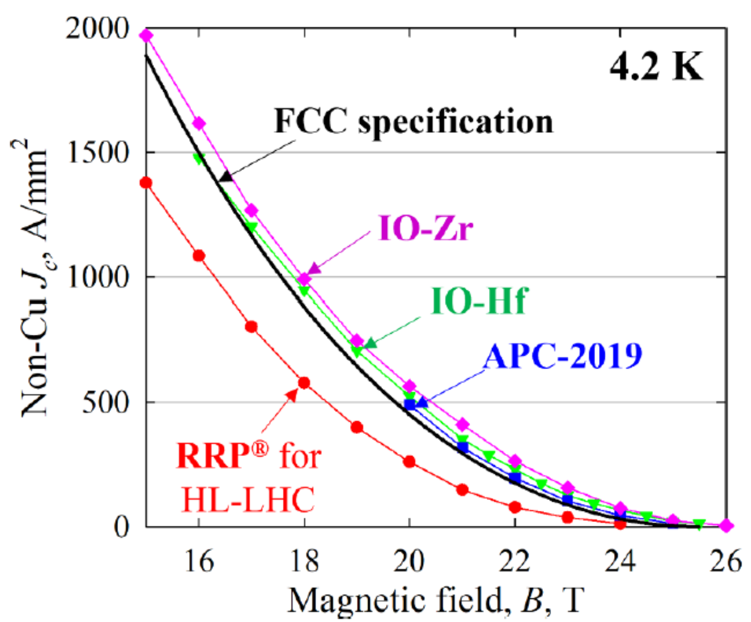
*I am grateful for discussions with and contributions from:*
*Jeff Parrell – Bruker OST, Miles Naughton – ATI Specialty Metals, and Isadora Costa - CBMM*

# Is there time for new $Nb_3Sn$ innovations to help?

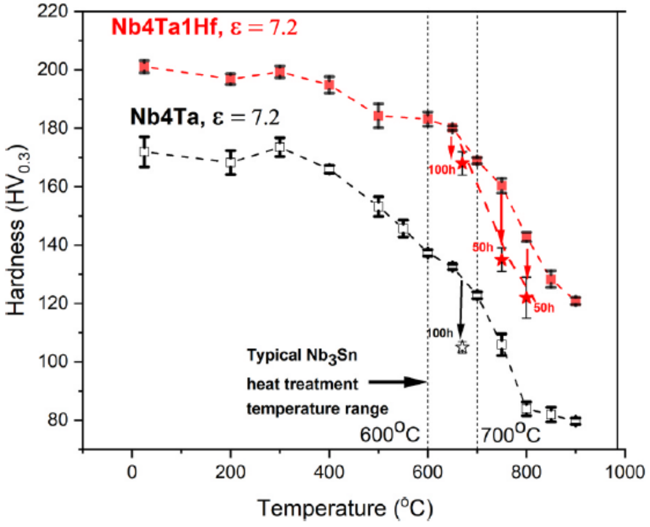
- Nb-Zr-Hf emerged as a potential game-changer c. 2018 and is now the focus of $Nb_3Sn$ R&D
- Two pathways toward meeting the FCC-hh spec:

1. When combined with a tin-oxide source, *internal oxidation* (IO) leads to the formation of tiny precipitates of $ZrO_2$ and $HfO_2$, which increases flux pinning at high fields.

2. The addition of Hf increases the *storage of cold work* during wire drawing and leads to grain refinement. The higher melting point also reduces the tendency to recover cold work in the temperature zone where the $Nb_3Sn$ formation reaction occurs.



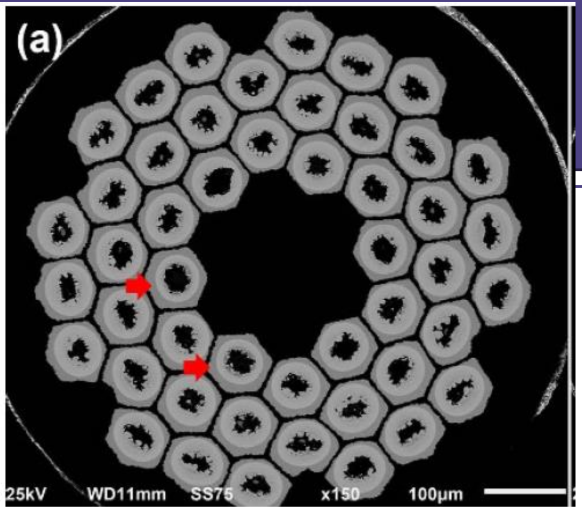

X. Xu *et al.*, *Supercond. Sci. Technol.* 36 (2023) 035012



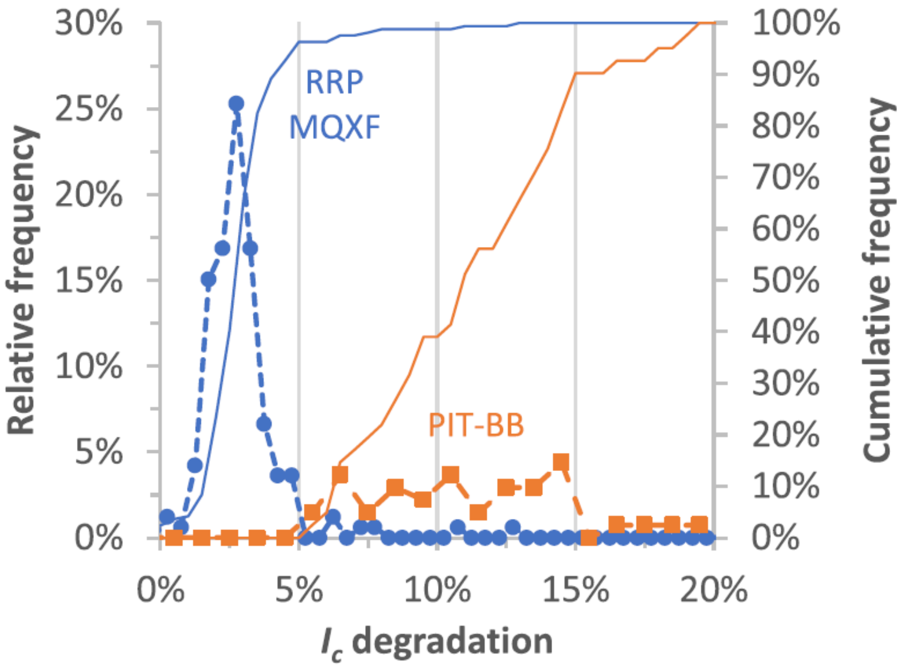

S. Balachandran *et al.*, *J. Alloy Cmpd.* *984* (2024) 173985

# Internal oxidation APC $Nb_3Sn$ favors a powder-in-tube method

- HL-LHC qualified PIT strands made by Bruker-EAS
- Offers opportunities for small $d_{eff}$ and better field uniformity, as well as higher $B_{c2}$ compared to HL-LHC strand
- Status: Conductor manufacturing is scaling from 2 kg research billets toward 10 kg demonstrations and 40 kg production billets. *Needs sustained support.*
- Challenge: Producing uniform reactions across the entire conductor has not been achieved yet.
- Challenge: strands with the PIT architecture typically suffer more performance loss (both $I_c$ and *RRR*) after rolling or cabling than the HL-LHC RRP design.




X. Xu *et al.*, *Supercond. Sci. Technol.* 36 (2023) 035012



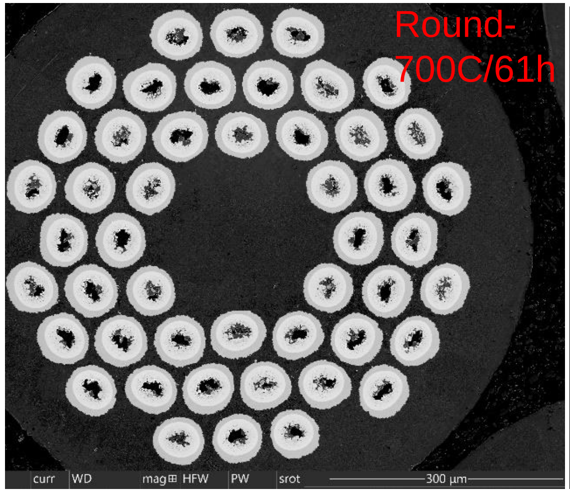

S. Hopkins *et al.*, *IEEE Trans. ASC* 34 (2024) 6001308

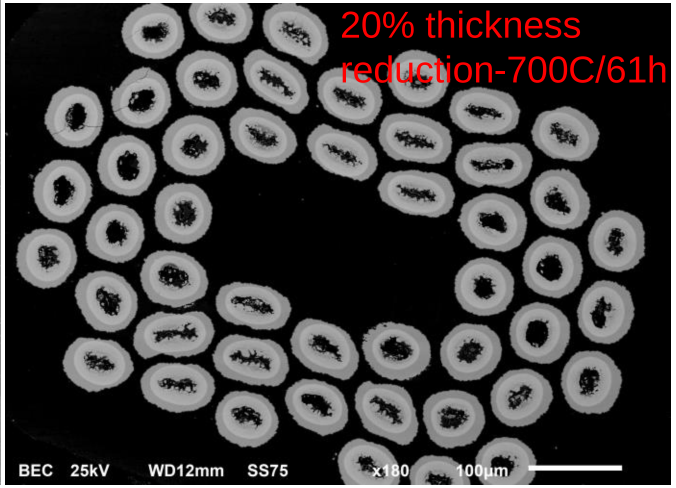
# APC wires after rolling

**Slide from Xingchen Xu, Fermilab**

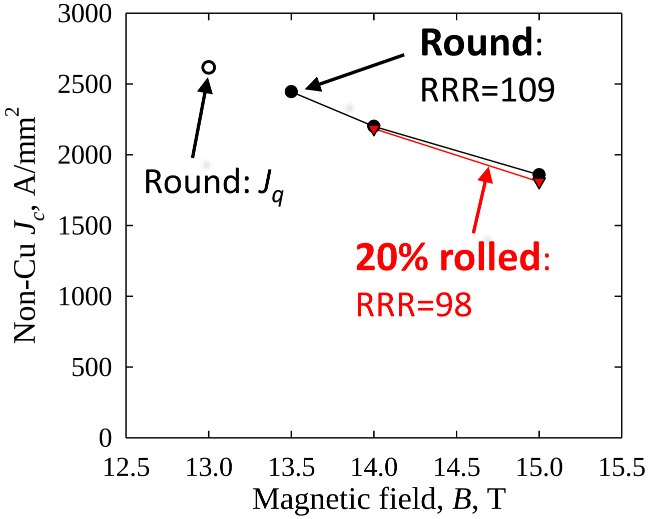
Optimize the wire design to reduce rolling degradation:

- Increase filament spacing.
- Change filament shape from hexagonal to round.




Tests of short samples:

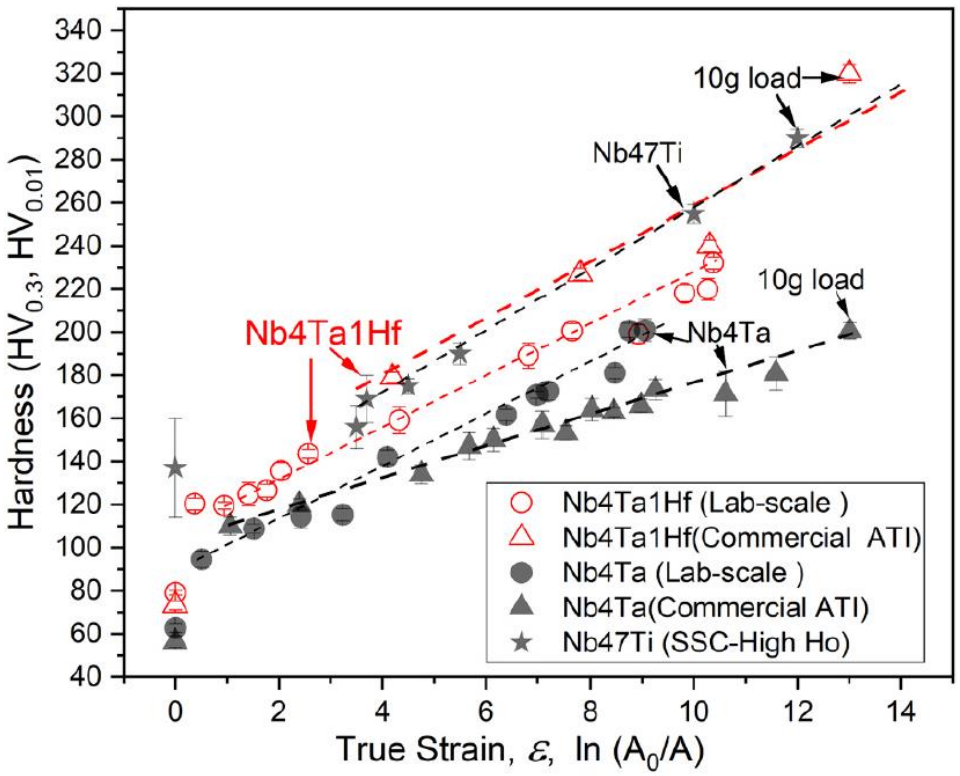



Recent tests on ITER barrels showed much better stability than the tests of short samples.

# The higher cold-work path is compatible with the RRP design

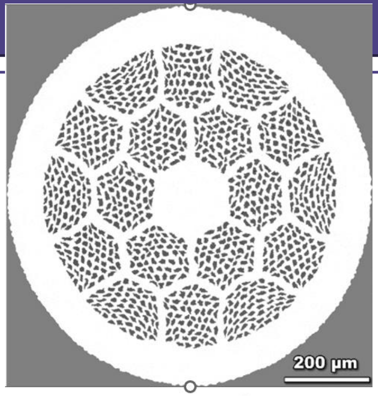
- It may be possible to "retrofit" the RRP design with Nb4Ta1Hf alloy filaments
  - Ongoing research supported by DOE-HEP and its Conductor Procurement and R&D program

- Challenge: The work hardening rate of the new alloys has to be compatible with the RRP manufacturing process to facilitate high yield and optimum reactions
  - Filaments must not only draw well, they must also stay round to let Sn diffuse between them




S. Balachandran *et al., J. Alloy Cmpd. 984* (2024) 173985

# What about HTS? – Bi-2212 status

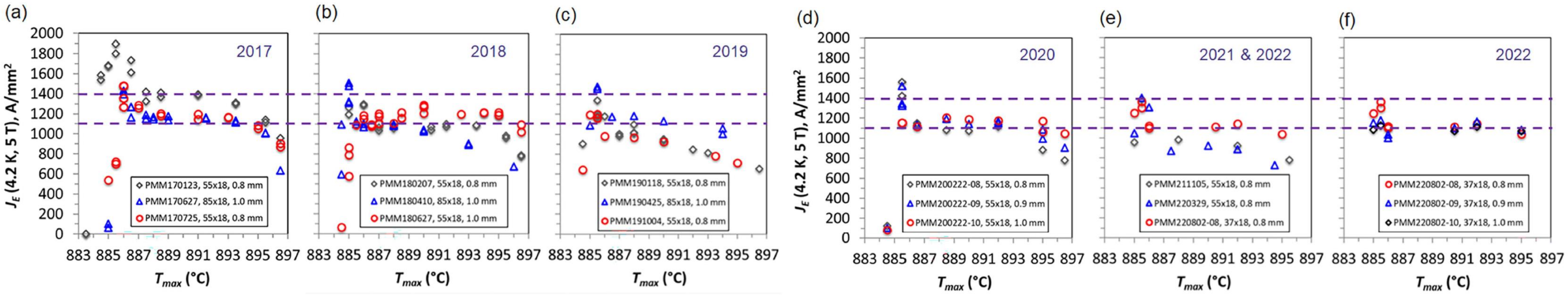



55×18

- Bi-2212 is a "simple" multifilamentary powder-in-tube wire:
  - Bi-2212 powder, silver (or Ag-Mg) tubes
  - 55 x 18 or 37 x 18 restacked architecture → 15 µm nominal filaments at 0.8-1.2 mm dia.
  - Presently delivered in pieces often 1–2 km long, 10 kg billets
    - Present demand is being met at this scale, no push for scale-up yet
  - Challenge: Price is quite high, but also artificial to support PhDs and research lines at present scale. Price is not truly driven by magnet pull.
- Requirements for magnet technology:
  - 2011: over-pressure (50 bar, 2% $O_2$ in Ar) needed to densify and suppress bubbles
  - 2015: melt (at 885-890°C) and slow re-solidification allows $CuO_2$ planes to align parallel to wire axis and provide high $J_c$
  - 2020: insulation schemes to prevent reactions between silica and Bi-2212 (causes "leakage")
    - $TiO_2$ paint under an alumina-silica insulation braid (often scraped off by cabling)
    - Alumina-only insulation braid (compatible with cabling)

F. Kametani *et al.*, *Supercond. Sci. Technol.* 24(2011) 075009
F. Kametani *et al.*, *Sci. Rpts. (Nature)* 5 (2015) 8285
T. Shen *et al.*, *PRSTAB* 25 (2022) 122401

# Bi-2212 supply chain: kg-scale powder manufacturers, sufficient consistency to build magnets but not sufficient to assure make-to-spec repeatability




J. Jiang *et al.*, *IEEE Trans. ASC* 33 (2023) 6400105

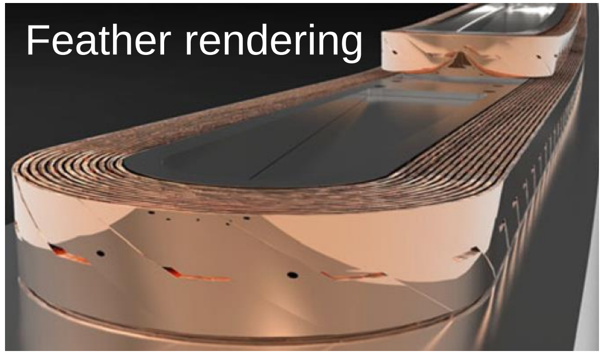
- The powder is made with composition not exactly 2:2:1:2
  - What is the optimum composition and why? Are there opportunities to add flux pinning? → *Ongoing research supported by DOE-HEP*
  - Challenge: The impact of a process change cannot be determined until after a wire is made. Variables in wire manufacturing compound variables in powder production in ways that are not easy to separate. *A new program supported by DOE-ARDAP addresses this challenge.*
  - Challenge: It has not been possible to replicate performance from batch to batch, although overall batches have retained consistency within about a 30% performance band. *New powder manufacturers and new equipment in university labs is coming to bear on this topic more broadly.*

# Overpressure infrastructure for magnets

- Renegade v.2 is in final assembly now and will undergo qualification testing in July-August.
  - Renegade v.1 revealed insulation U-Us that triggered a re-design
  - 150 mm dia., 1 m long Bi-2212 inserts for 20 T “hybrid” dipole
- Challenge: Longer accelerator magnets will need horizontal high-pressure furnaces
  - Challenge: there is no application data and limited design and engineering experience. Industrial partnerships may be possible but also expensive.

# Sustainable accelerators? REBCO cables and cryocooling?

- Opportunity: REBCO is now a "tonnage" conductor thanks to private investment in fusion
  - 1,000 km of 4 mm wide tape, 50 µm Hastelloy + 40 µm Cu, weighs about 3 tons
  - Commonwealth Fusion Systems TFMC: 270 km of REBCO (4 mm wide x 60 µm thick)
  - MagLab 32T magnet: 9.7 km, MagLab 40T magnet: ~14 km
- Accelerators will require cables, which imposes constraints
  - ROEBEL cables (as used in CERN's Feather project): wide tape stamped into pattern, challenges for managing integrated tolerances
  - Round cores (CORC®, STAR) or tubes (TORT): thin tapes to minimize wrapping diameter and bend radius while maximizing current density
  - Fusion cables, e.g. Pit Viper® from CFS: can tolerate wide range of tape sources, but not compatible with bends in dipoles




G. Kirby *et al.*, *IEEE Trans. ASC* 27 (2017) 4003307

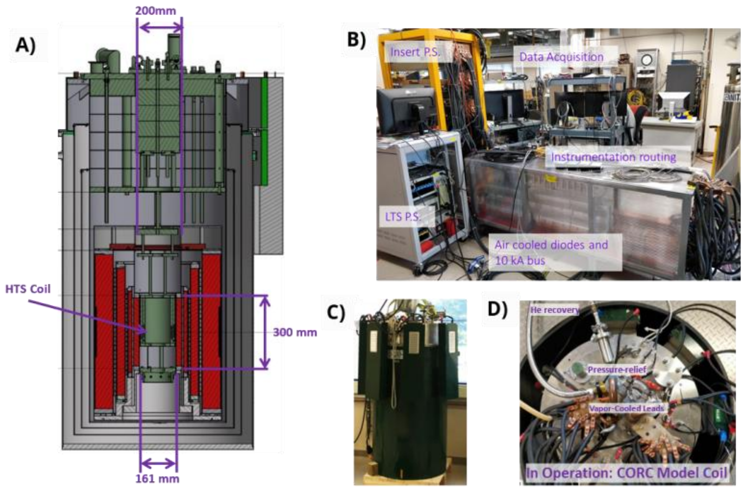

Dan Davis, Ulf Trociewitz, David Larbalestier – ASC/NHMFL
Yuhu Zhai – PPPL, Danko Van der Laan & Jeremy Weiss - ACT

# Challenges in the REBCO conductor supply chain for cables

- ASC has measured conductors from all manufacturers, some of which are being put into test coils for the 40T magnet project and "little big coils" aiming for 50T in 31T resistive
- Challenge: Short pieces, which forces cables to use splices
- Challenge: end-to-end variation of $I_c$ can be as high as spool-to-spool variation
  - 20-40% at 4.2K, 14T, 18° → processes are not under control → Implementation of process controls and measurements for process feedback is a positive outcome of INFUSE funding
- Challenge: Few suppliers make REBCO on 30 μm Hastelloy → Change in supply chain used for CORC cable has been positive
- Challenge: Roughness, dimensional variations work against lubricants to cause property degradation after bending → Some manufacturers have provided sufficient dimensional tolerance to satisfy cable bends for CCT inserts with improved cable lubricant

# Test Facilities

- Challenge: Expansion and upgrade of strand test facilities to >20 T with 1 kA at 4.2 K is essential to continue characterization activities for FCC-hh conductors and other stakeholders
  - Scaling relationships for $Nb_3Sn$ have limited use for extrapolating to high field
- Challenge: REBCO tape manufacturers do not presently have capabilities to characterize their product at the field and temperature where their customers use it.
  - MagLab and other groups (RRI, U Genève) have been successful at high field, variable temperature, and variable field angle measurements, including development of new techniques and probes.
- Challenge: Cable test facilities that “torture” R&D cables and validate production cables
  - ASC operates a 12 T, 160 mm, 10 kA facility
  - Under construction: Fermilab Test Facility Dipole
  - Planned: Large bore resistive magnet at NHMFL



# Summary of challenges for FCC-hh conductors

$Nb_3Sn$

- Need sustained acquisitions of sufficient scale (400 kg annual orders) to maintain supply chain & workforce
- Cost reduction via scale-up without a large market pull
- Accelerating the development of advanced $Nb_3Sn$ with Nb-Ta-Zr or Nb-Ta-Hf

Bi-2212

- Making a real market for Bi-2212: 25T lab magnets, 30T NMR
- Growing a multi-vendor Bi-2212 powder supply base and increasing scale
- Reducing variations in powder and wire
- Optimizing alumina braid insulation
- Over-pressure facilities for long dipoles

REBCO

- Getting enough REBCO into publicly funded magnets to expose weaknesses and drive the innovation cycle
- Reducing variations by introducing process feedback and controls
- Sustaining REBCO on 30µm Hastelloy as a product cable supply chain
- Building QC relevant to magnets at vendors
- Longer pieces, efficient cable mapping without lots of splices

Test facilities

- Strands in the 16-20+ T range @ 4.2K
- Variable $B$, $T$, $\theta$ for REBCO
- Cable test facilities (partnership with fusion)

# Thank you

*LDCOOLEY@ASC.MAGNET.FSU.EDU*

# Backup slide

# Drive costs down by funding frequent magnet builds (1/month?) and by engaging with the surrounding commercial ecosystem

- ARDAP report → Get industry persons within the lab programs (and vice versa?)