EUCAS 2017

US HL-LHC AUP

HiLumi HL-LHC PROJECT

U.S. MAGNET DEVELOPMENT PROGRAM

Industrial production of Nb_3Sn conductors for particle accelerator magnets

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Main Points

- Industrial production is starting for ~3000 km of state-of-the-art Nb_3Sn superconductor for HL-LHC projects in the US and Europe
- Statistics so far anticipate a successful production
  - Margins are excellent over the first 300 km
  - Conductor costs are not breaking the project banks
- How was a “production conductor” achieved?
  - CDP (now CPRD) invested in full production-scale billets
  - The university – lab – industry feedback cycle …
    - Evaluated conductor alternatives in cables, coils, and prototype magnets
    - Dissected conductor elements to correct flaws
    - Identified conductor limits and how they might be approached
  - Procurement experience established best value
  - The community, including conductor suppliers, embraced the big science goal and committed to working as a team toward the goal

Grateful acknowledgments

- Arup Ghosh (BNL, retired) — Head, LARP conductor R&D until 2016
  - Now HL-LHC Accelerator Upgrade Project – Cooley
- Dan Dietderich (LBNL, retired) — Head, US Conductor Development Program and LARP cable R&D lead until 2016
  - CPD → Conductor Procurement and R&D program, under Cooley
  - HL-LHC AUP cable lead is Ian Pong
- Mike Field, Jeff Parrell, Hanping Miao, and the team at Bruker-OST
- Dan Turrioni, Al Rusy, Vito Lombardo, Pei Li, Giorgio Apollinari, Giorgio Ambrosio, and the HL-LHC AUP team at Fermilab
- David Larbalestier, Peter Lee, Chiara Tarantini, Charlie Sanabria, and Najib Cheggour at ASC
- Jun Lu and the strand testing team at MagLab

Magnet Functional Requirement Specifications that affect Conductor Specifications

ID	Description
R-T-01	The MQXFA coil aperture requirement is **150 mm**. This aperture is the nominal coil inner diameter at room temperature, excluding ground insulation, inner layer quench heaters, cold bore, and beam screens.
R-T-02	The MQXFA physical outer diameter must not exceed **614 mm**.
R-T-03	The MQXFA magnet must be capable of reaching a gradient of **143.2 T/m** in superfluid helium at **1.9 K** and for the magnetic length specified in R-T-04.
R-T-04	The MQXFA magnetic length requirement is **4.2 m** with a tolerance of ± 5 mm at 1.9 K.
R-T-05	MQXFA magnets must be capable of operation in pressurized static superfluid helium (HeII) bath at **1.3 bar** and at a temperature of **1.9 K**.
R-T-11	The MQXFA magnets must be capable of operating at ±**15 A/s.**
R-T-19	MQXFA magnets must not quench while ramping down at **300 A/s** from the nominal operating current.
R-T-20	The MQXFA quench protection components must be compatible with the CERN-supplied quench protection system and comply with the corresponding interface document specified by CERN [3].
R-O-05	After training and after following a thermal cycle to room temperature, MQXFA magnets should attain the nominal operating current with a target of no more than 1 quench.

Operating point 11.4 T; Ultimate 12.3 T at 1.9 K ➔ Nb_3Sn conductor

Maximum two layers ➔ 16.5 kA Op, 17.8 kA ult. ➔ I_c and #strands per cable

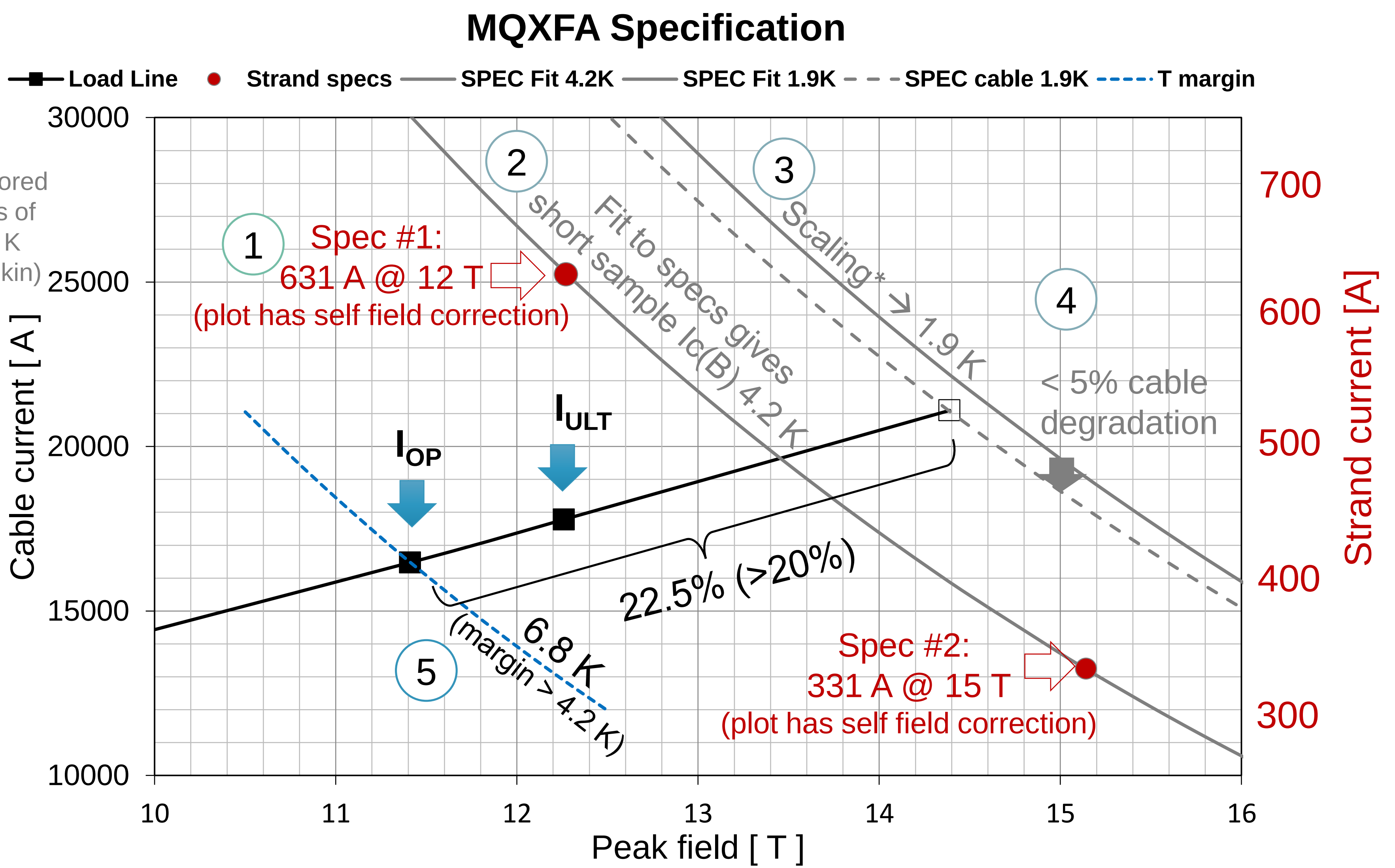
Stability & QP ➔ Cu%, D_{eff}, twist pitch; T_{CS} > 6.1 K, Loadline margin

Control dynamic effects ➔ Cored cable, twisted strand

Magnet length × # of turns ➔ Cable unit length

Translation of magnet spec to conductor spec

*Scaling has been anchored by actual measurements of extracted strands at 1.9 K (see Godeke, Bordini, Ekin)



Solicited procurements of MQXF strand by LARP
August 2015 – completed; May 2017 – in process

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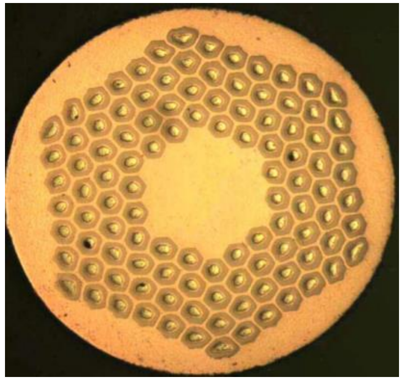
Contracts awarded to Bruker-OST for RRP 108/127



40 strands per cable

Value engineering: AUP Cable unit length (UL) reduced from 550 m to 500 m → 20 km strand per cable

Results of 2015 procurement

Shipment	Ship date	Shipped length	Invoiced length	Spools > 550 m	550 m pieces	200 m pieces
A	20-Nov-15	33015	31700	13	54	10
B	28-Mar-16	57446	55178	30	88	34
C1	22-Nov-16	28390	27500	8	46	11
C2	6-Dec-16	47325	45700	13	74	25
D	20-Mar-17	48796	47950	9	85	6
Grand Total		**214972**	**208028**	**73**	**347**	**86**
					92%	8%

# Billets	Billet max, m	100% yield, m
25	9250	231250

Longest piece 9900 m

4.8 cable unit lengths (UL) per spool

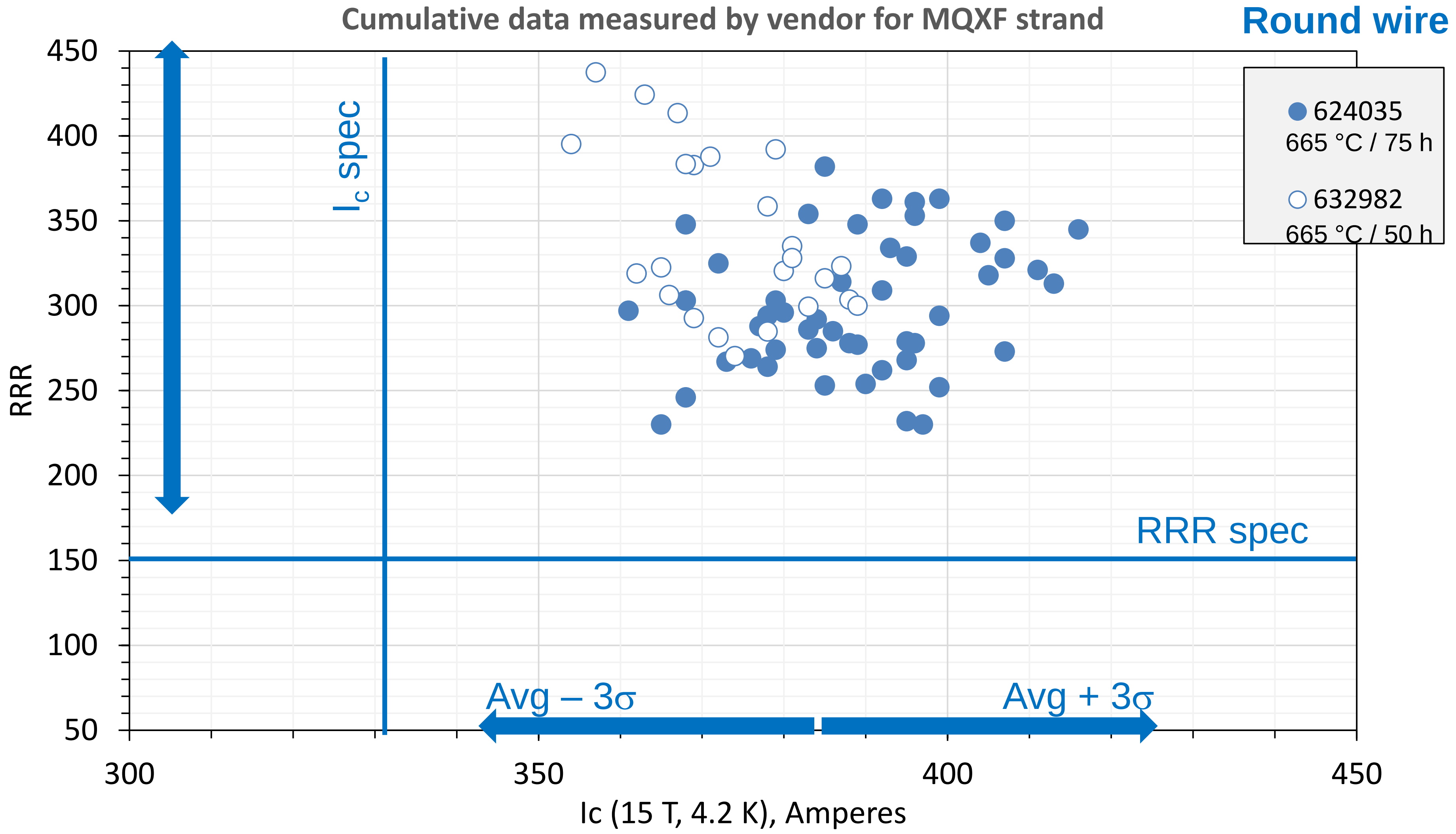
90% Production yield

BRUKER

LARP

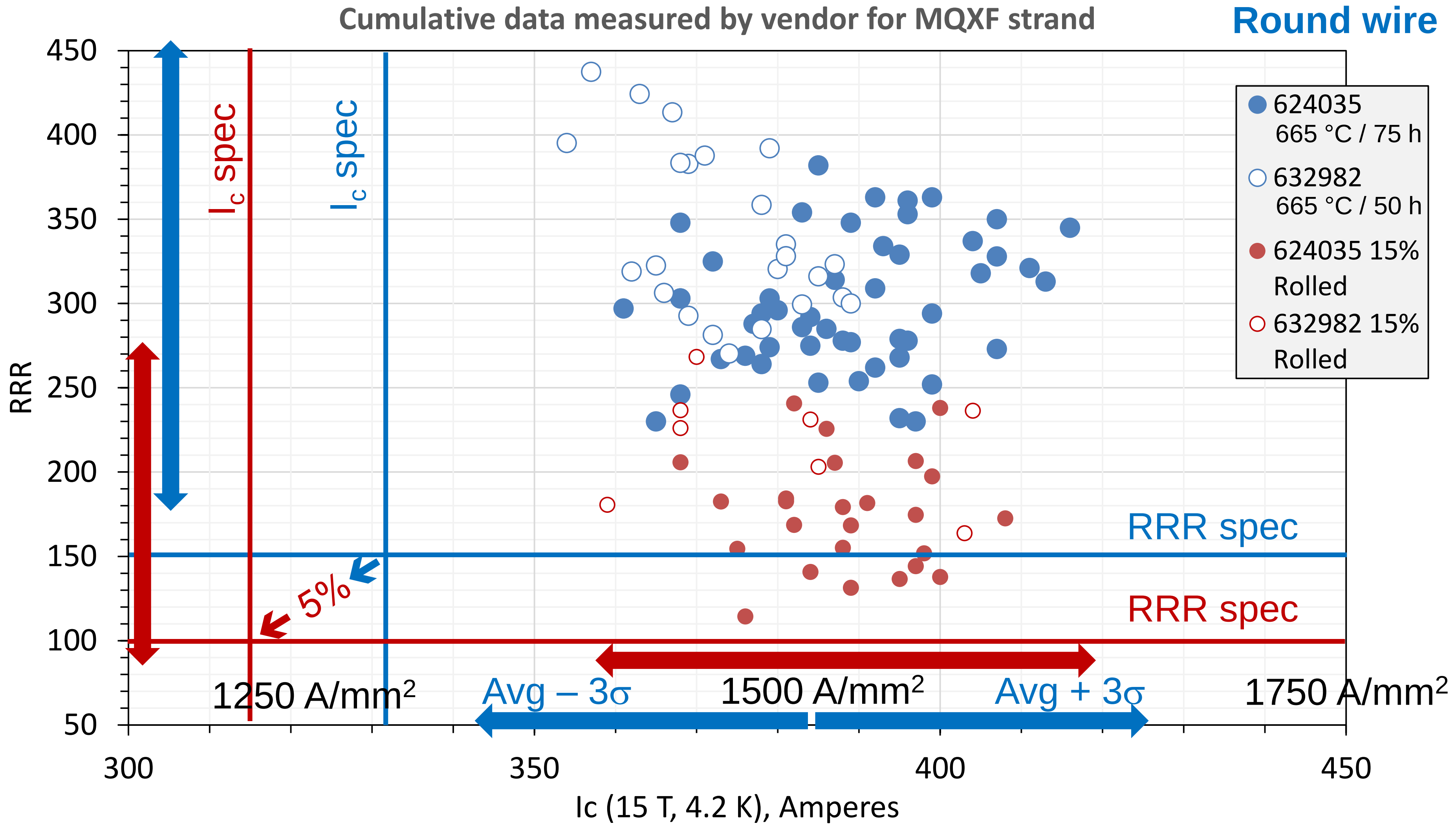
300 km of MQXF strand, RRR vs Ic(15 T)

2015 and 2017 procurements; Measurements by Bruker-OST

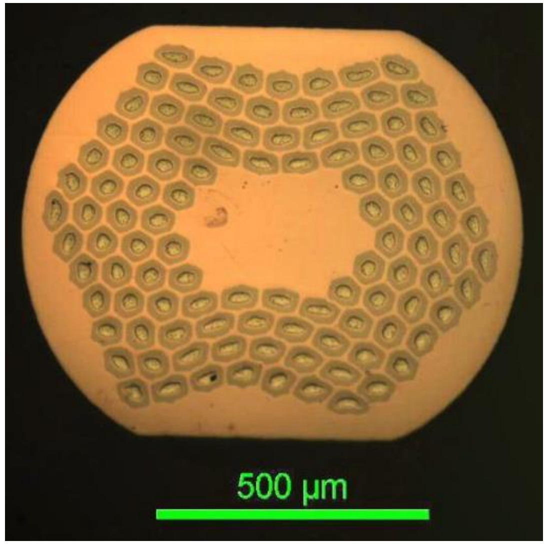


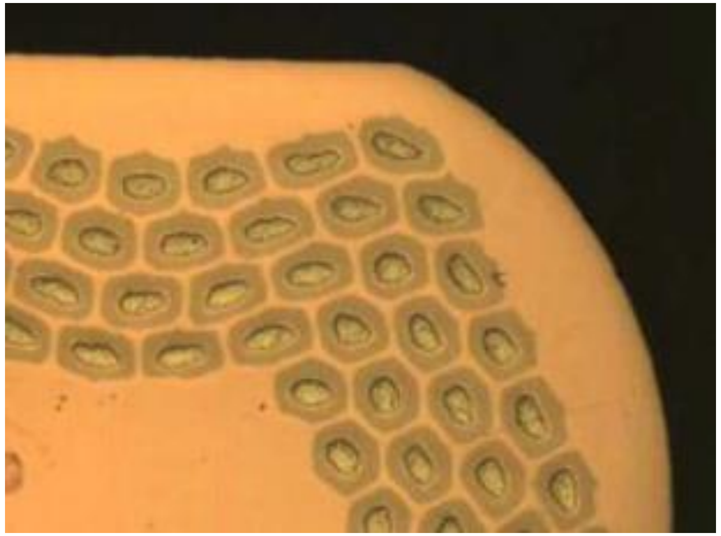
300 km of MQXF strand, RRR vs Ic(15 T)
2015 and 2017 procurements; Measurements by Bruker-OST

Rolled by 15%
Round wire



Rolled strands are predictors of cable performance

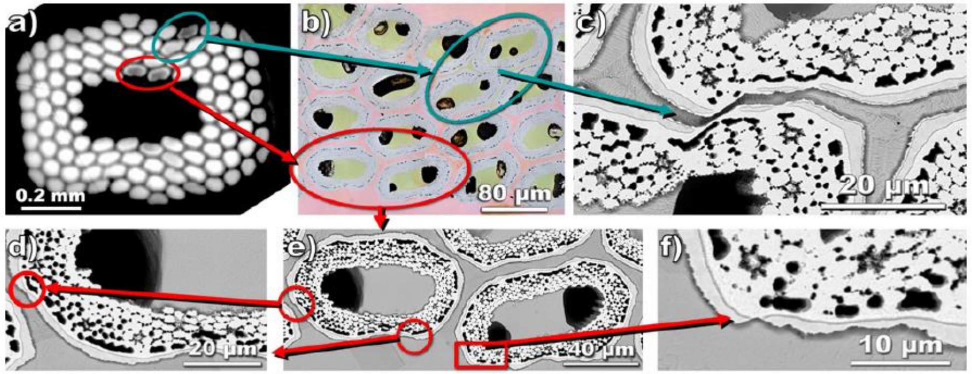




15% Rolled

The count of sheared sub-elements and RRR loss are qualifying controls for cables. (Pong 1LP1-06)

Rolled strands, extracted strands, and tests of cable critical current all showed retention of critical current, even under heavy damage.



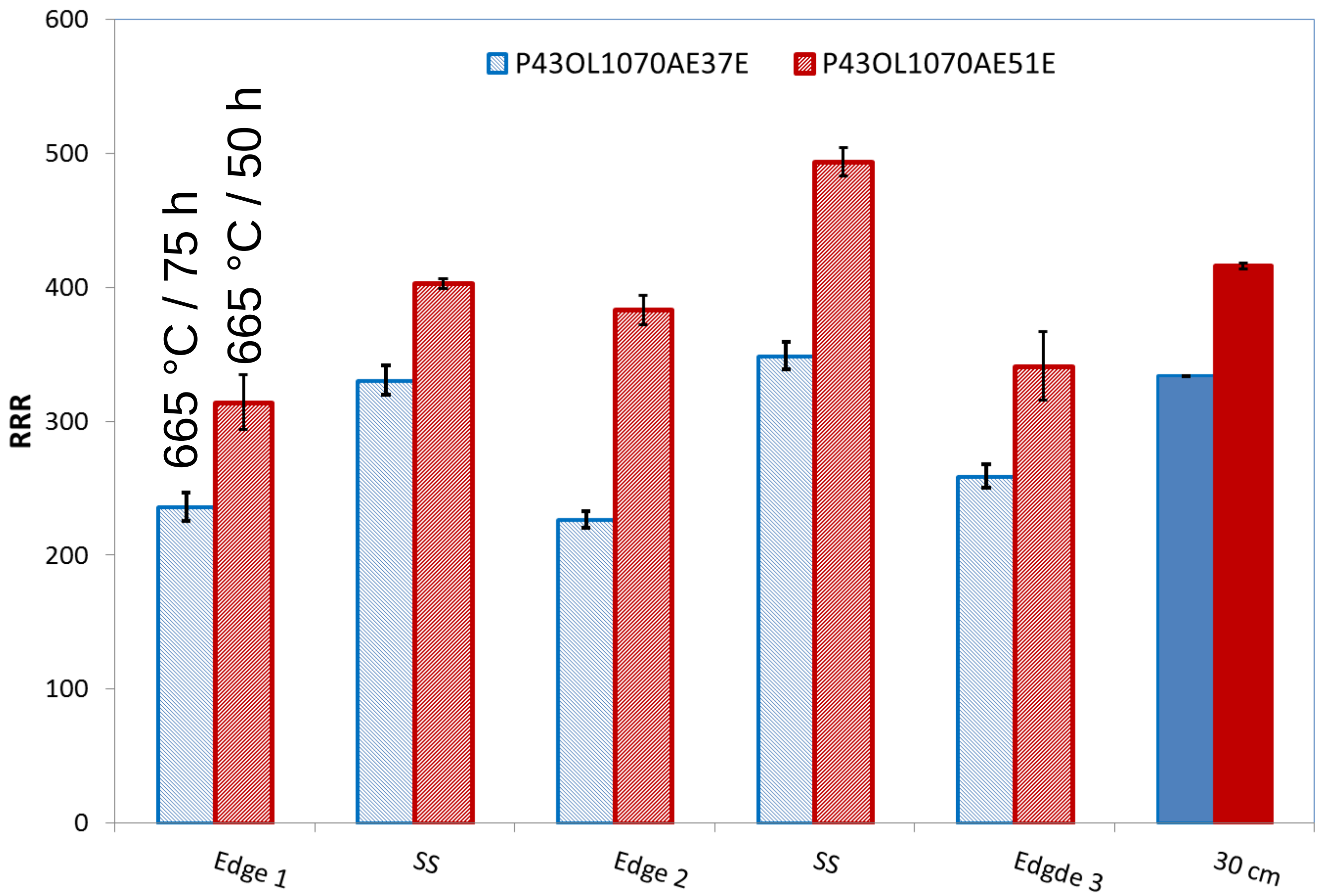
20% rolled

Evidently, tin remains available for Nb → Nb_3Sn reaction even when sub-element is sheared. This might not be true for tube-type strands. (Mike Brown, ASC)

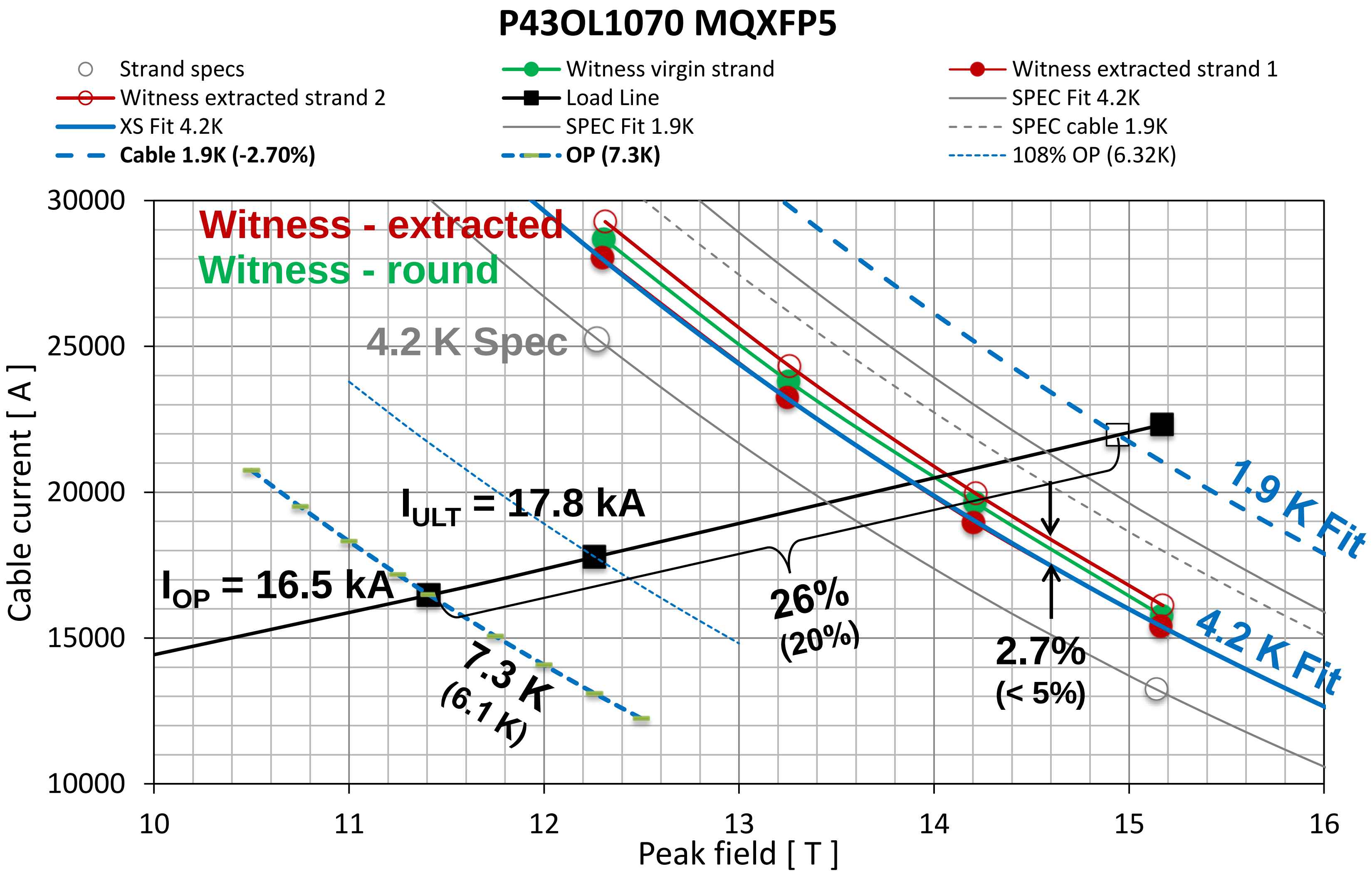
Polyanskii, A. A., Lee, P. J., Jewell, M. C., Barzi, E., Turrioni, D., Zlobin, A. V., & Larbalestier, D. C. (2009). *Superconductor Science and Technology*, *22*(9), 095008.

Shorter HT improves RRR at cable edges

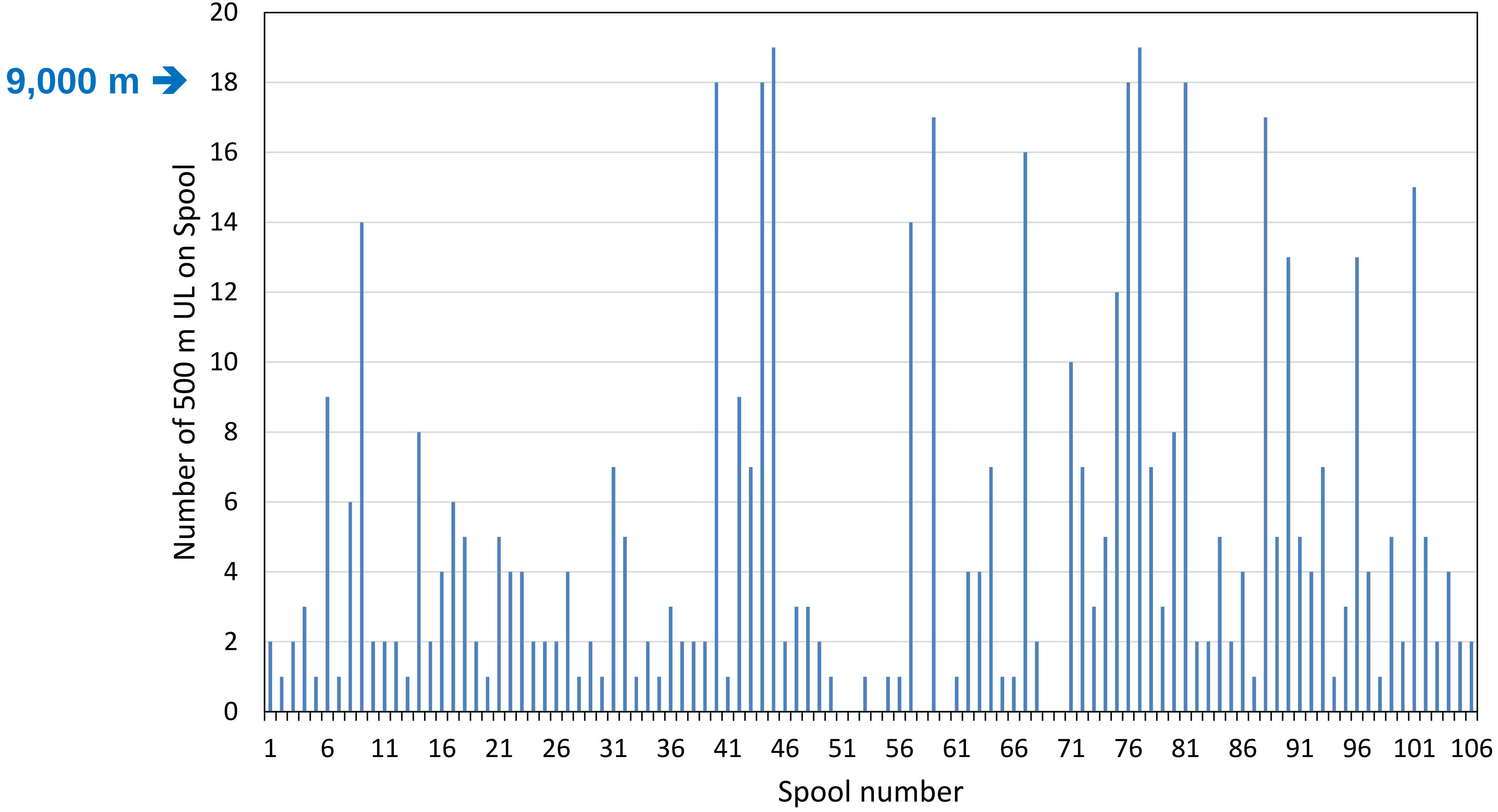
Arup Ghosh and Bruker-OST comparing extracted strands from same cable



Conductor margins vs. magnet requirements

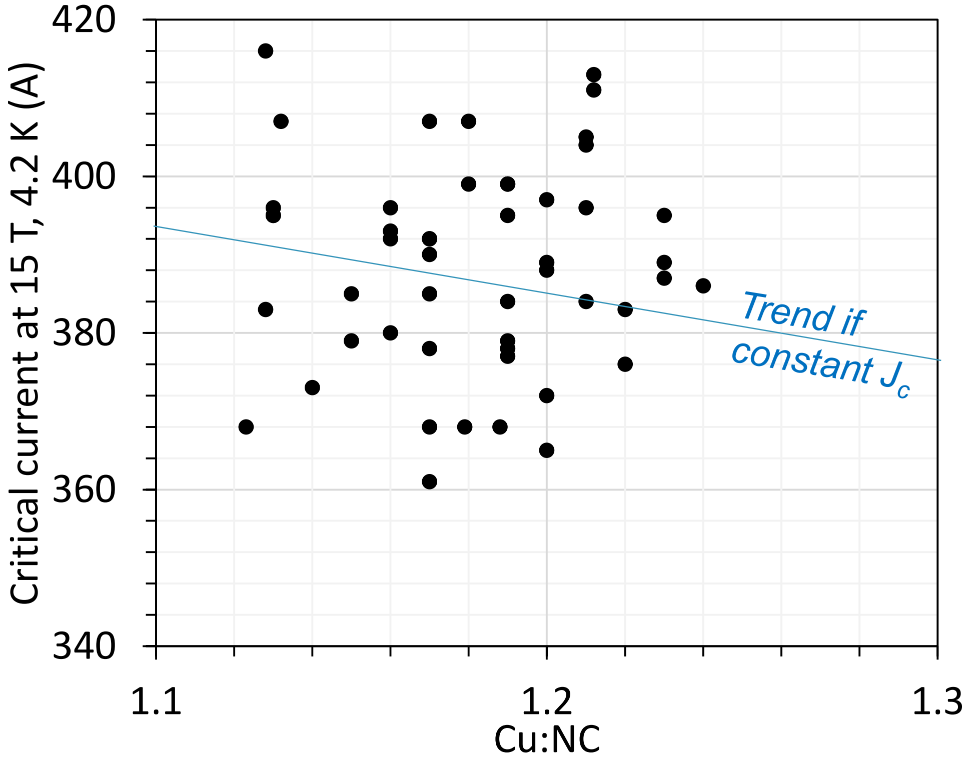


Long pieces in recent production

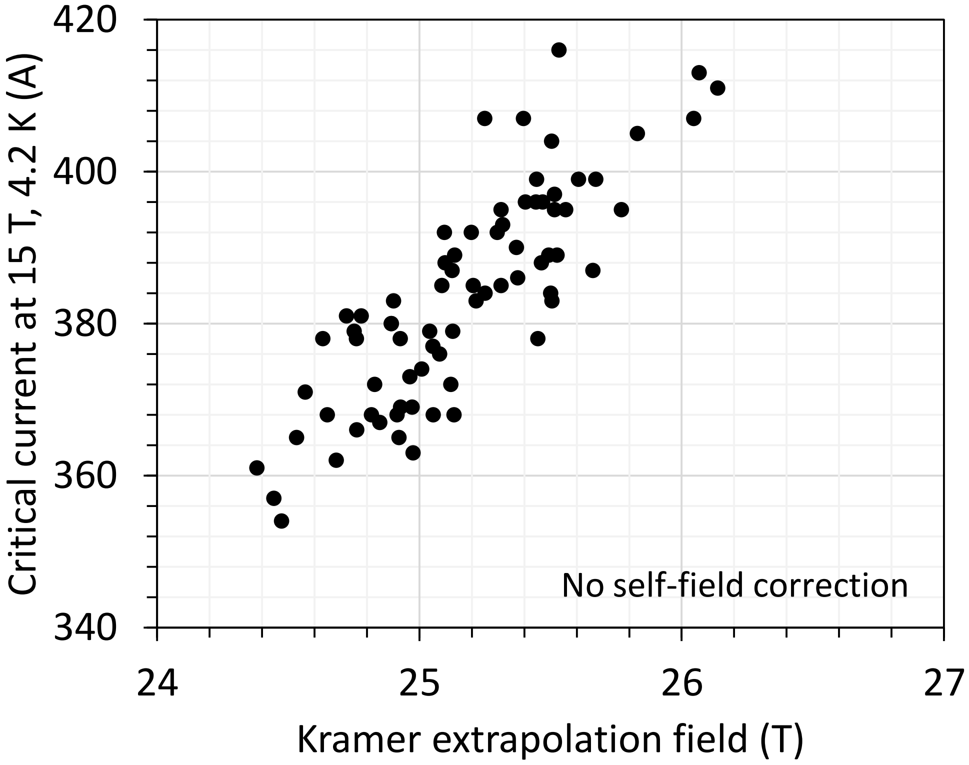


Data trends are interesting

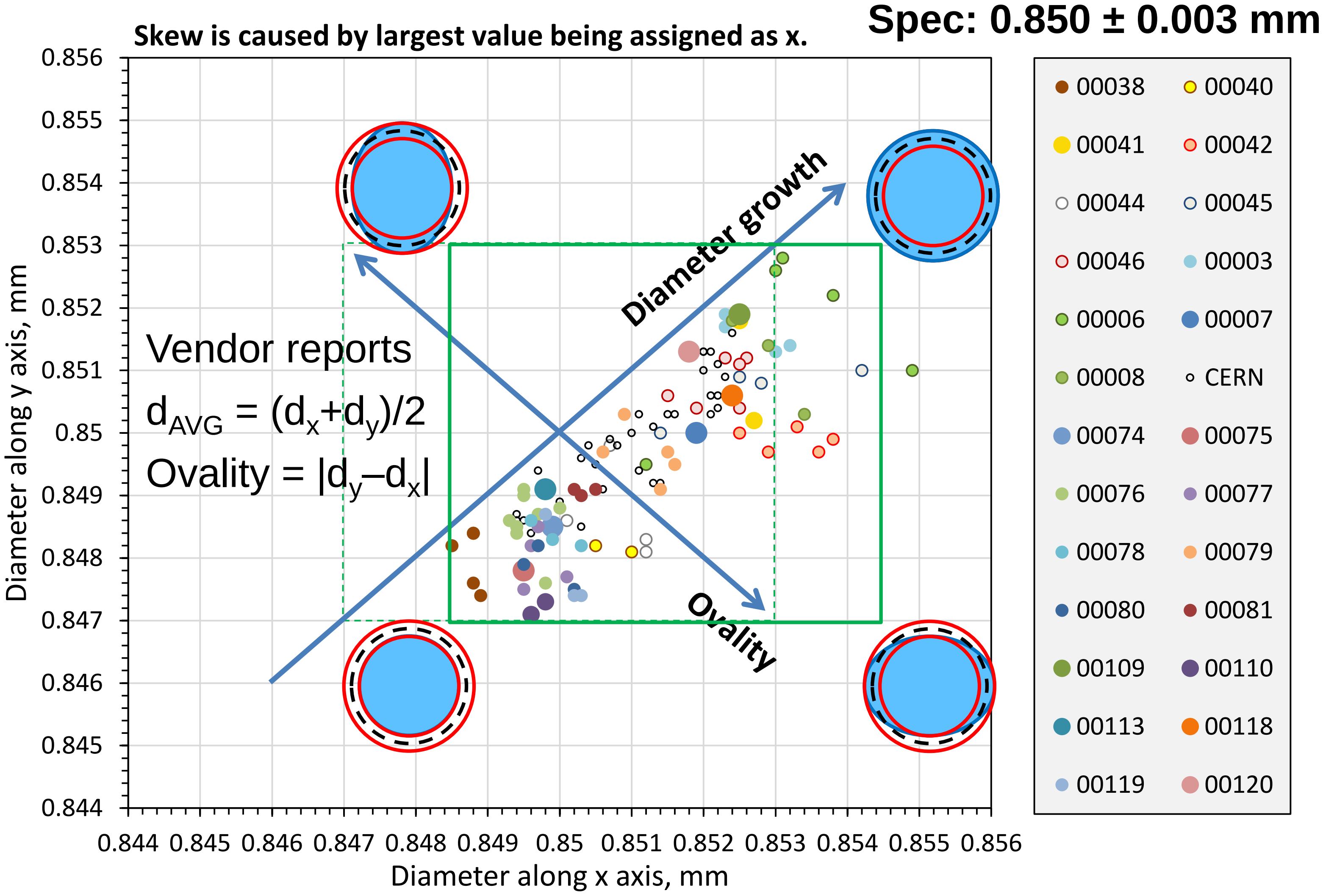
No apparent correlation between I_c at 15 T and the Cu:NC → slightly smaller sub-elements have slightly higher J_c

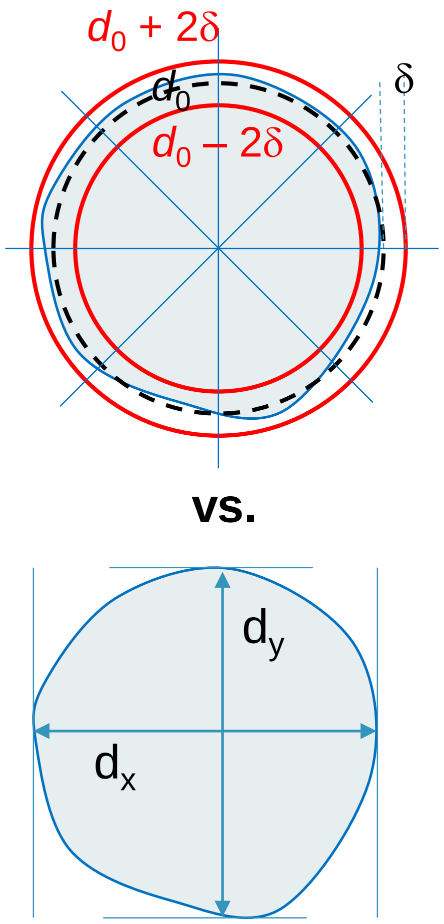


Strong correlation between I_c at 15 T and the Kramer extrapolation → tin-rich regions are important



Process control – wire diameter
Data marker is larger for longer pieces

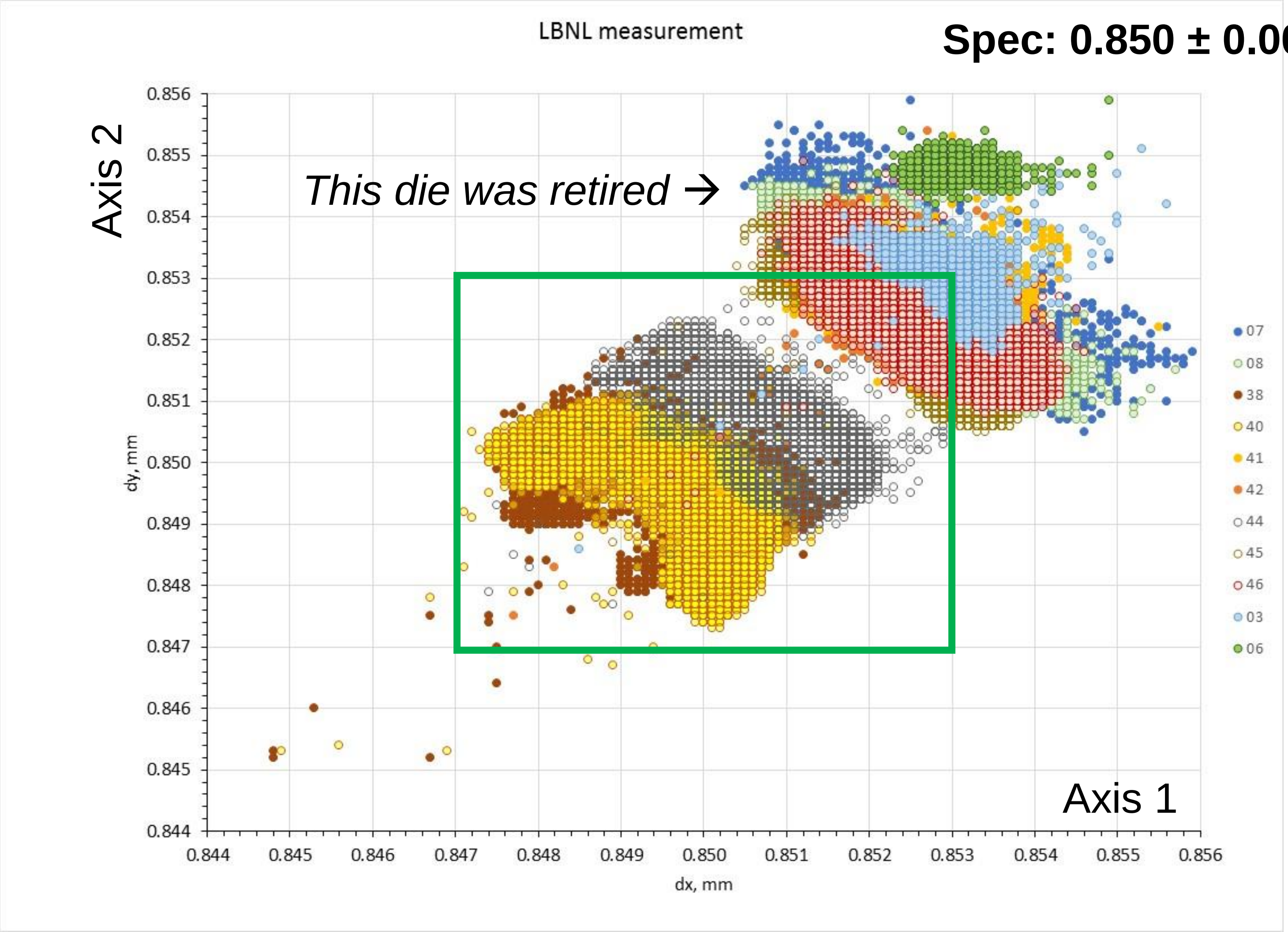




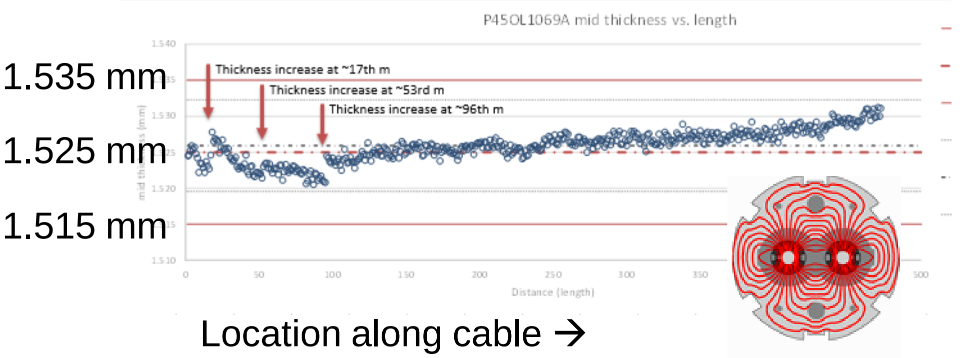
LBNL data – sampling every 2 meters during re-spooling

Data courtesy of Ian Pong

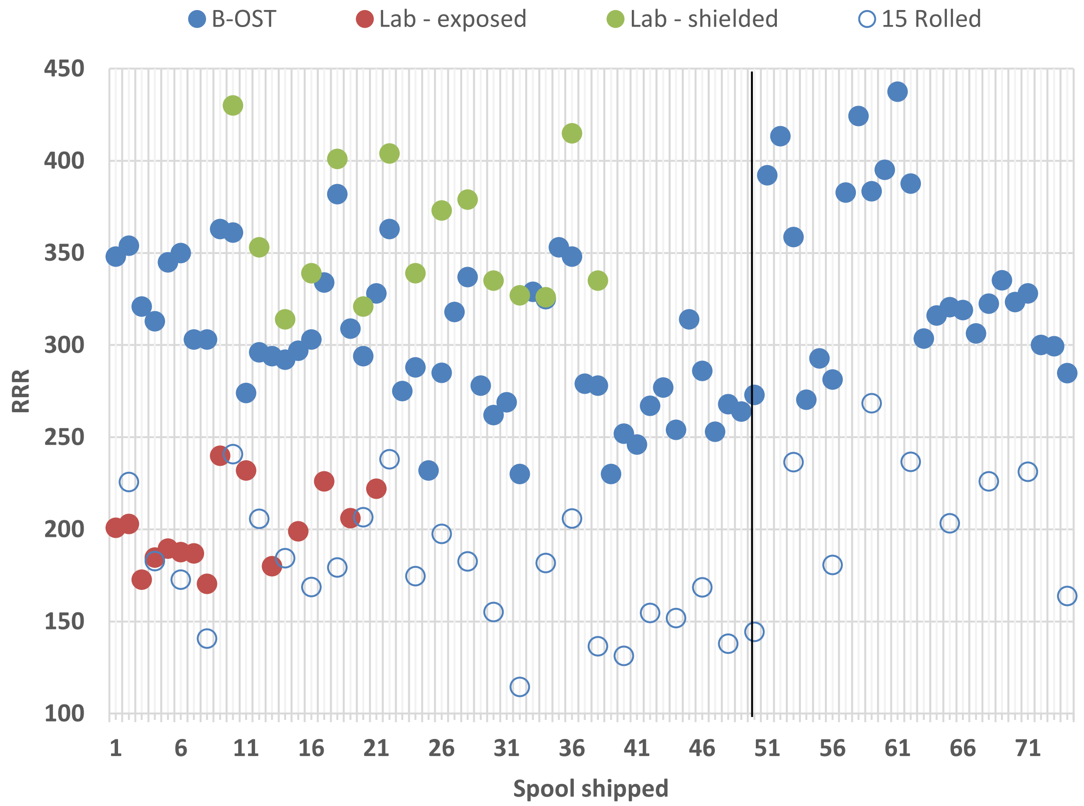
Spec: 0.850 ± 0.003 mm



During cabling, a dimensional change of 3 μm may cause concern / correction.



RRR as a process control



EXPOSED: Strand was secured to a stainless steel rod with copper wire ties. Strand ends were pinched flat.

PROTECTED: Strand length inserted in a close-fitting quartz tube and the tube ends were wrapped with Cu foil. Strand ends were pinched flat.

Spools 36-51: consecutive points below mean

Inquiry → correction → new control

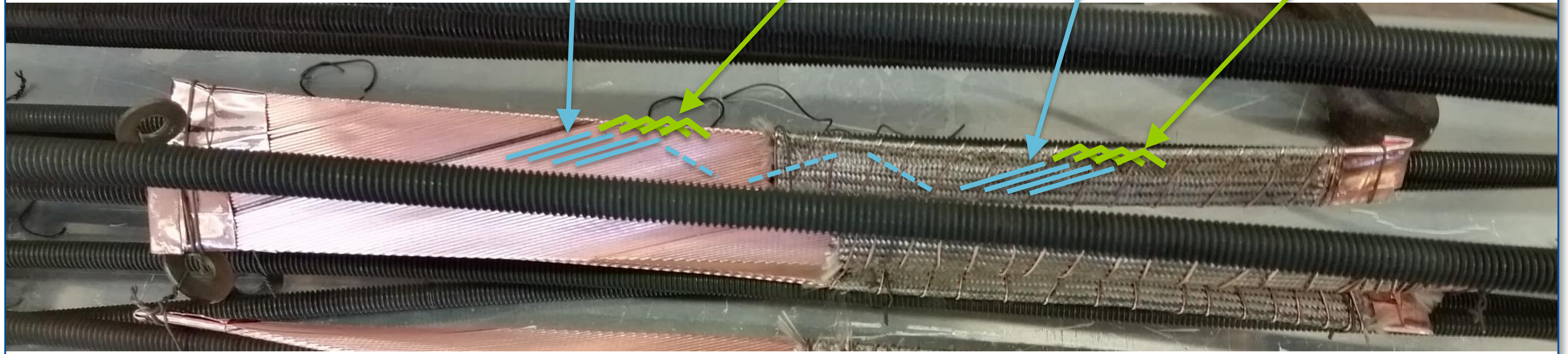
Measurement discrepancy → Reaction conditions affect RRR

Quartz and S-glass appear to protect strands
Exposure to "impurities" seems to assist tin contamination of copper

Cable samples were reacted, with part of the sample covered by insulation.
Specimens for RRR measurement were then cut out of the reacted samples.

RRR = 223, 223, 210, 224 | 223, 259, 247, 247

207, 151, 143, 170 | 226, 235, 224, 242



Pei Li, Fermilab

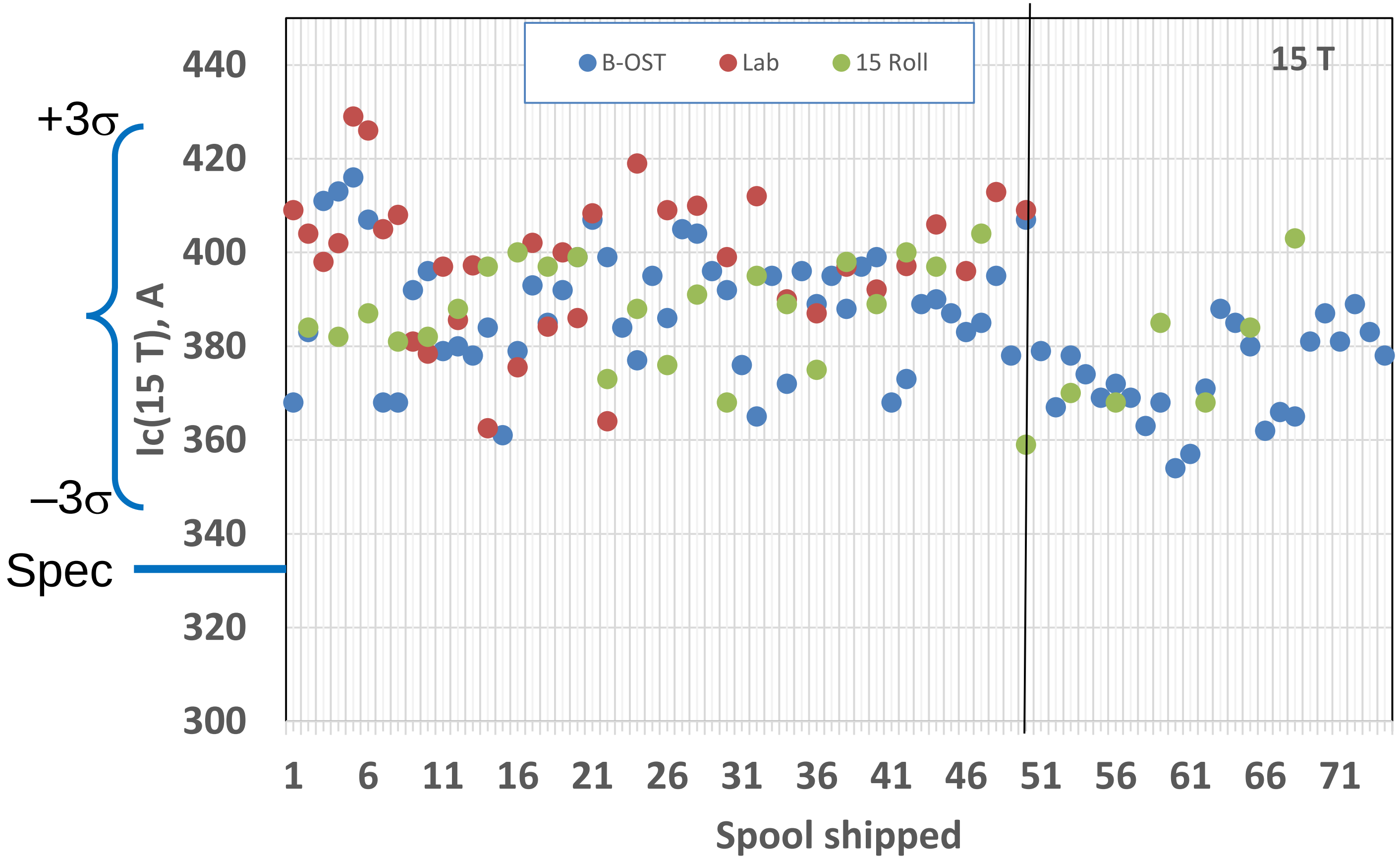
Also Dan Turrioni and Al Rusy
SIMS data from Yulia Trenikhina

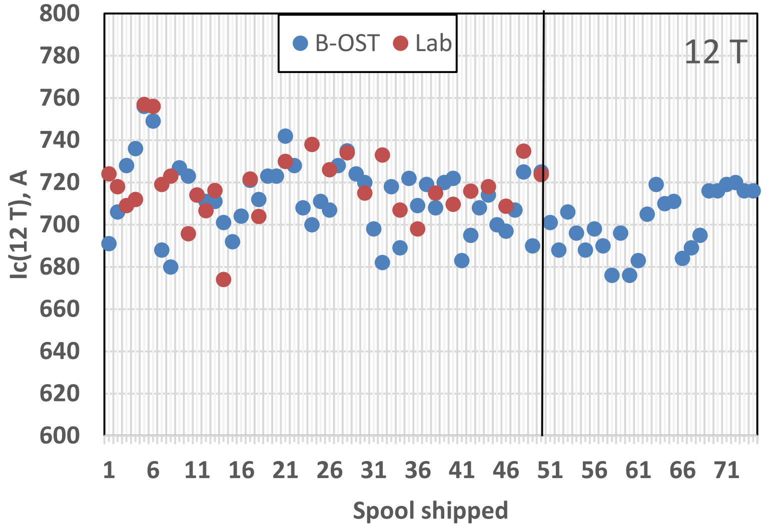
Round wire: RRR = 173, 185, 186, 171 in BNL furnace (exposed)
RRR = 321, 313, 303, 303 in OST furnace (protected)

15% rolled wire: RRR = 141, 183 in OST furnace

Critical current as a process control

HT was changed for 2017 contract





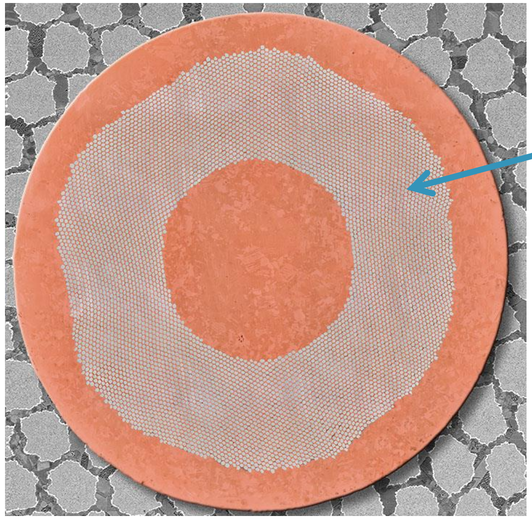
What led to the present manufacturing maturity?

Opinions of the speaker…

- B-OST saw benefit in being part of a Big-Science achievement
  - Big Science advanced the state of their product, which awarded prestige and changed the non-Big-Science marketplace
    - Added value beyond the direct procurement contract
  - Like an oligopsony, Big Science controls the technology standard and acquires all of the highest-tech product produced.
    - Oligopsony = marketplace with few buyers that purchase all of the industry output.
    - Medical magnets is an example…
- Meetings such as LTSW, which “opened the technical books”, maintained connections, and established a spirit of collaboration and commitment
  - Candid discussion of flaws and failures, enthusiastic support for ideas to improve
  - Many stakeholders share viewpoints, e.g., B-OST principals previously made wire under DOE-HEP university programs
  - Reinforcement of agency, mission, and technical needs → eyes on goal
  - Exploration of potential limits, uncovering of fundamental details

What led to the present manufacturing maturity?
Opinions of the speaker…

- Investments in metal-working
  - Niobium in RRP receives more strain than given to Nb47Ti in LHC strand
  - Attention was given to aspects such as Nb hardening rate, grain size, etc.



Peter Lee's image of the LHC Nb47Ti reference strand

6 µm Nb47Ti filaments

3 mm dia. at re-stack and anneal.

Strain $\varepsilon = 2\ln(d_0/d_F)$ *~12*

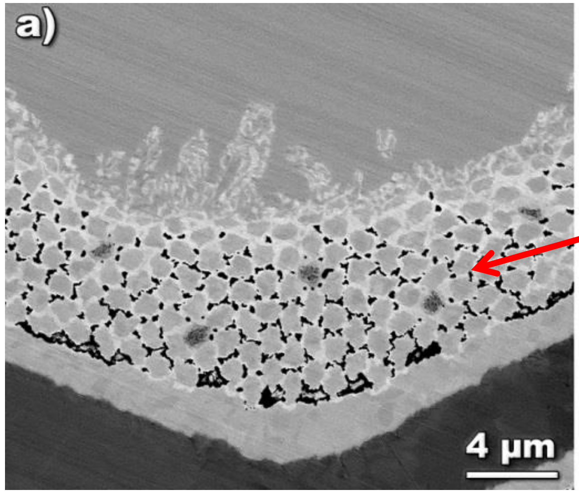


Photo 45 from Charles Sanabria PhD Thesis: **A new understanding of the heat treatment of Nb_3Sn superconducting wires**

1 µm Nb filaments

Strain ε *~16 if same diameter (3 mm) at re-stack as for Nb47Ti strand*

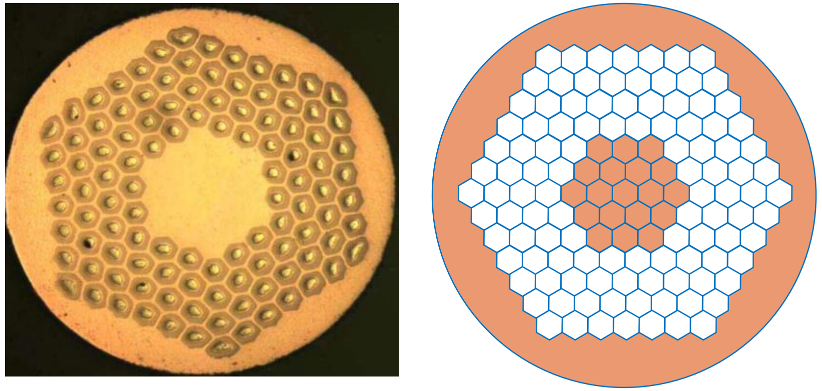
What led to the present manufacturing maturity?
Opinions of the speaker…

- Sustained procurements of production-level billets that tested ideas and pushed technology forward
  - US Conductor Development Program and LARP purchased 300 kg per year
- LARP evaluation of conductor, cables, coils, and magnets justified the selection of the MQXF specification among alternatives:
  - Ti alloying instead of Ta
  - 2-parameter optimization (RRR and critical current) led to selection of 3.6:1 ratio of Nb:Sn and 665 °C reaction temperature
    - We were lucky: the "strain cliff" was avoided (N Cheggour, in preparation)
  - 55 µm sub-element diameter based on value engineering and test results
    - 108/127 design at 0.85 mm instead of 169-element restacks

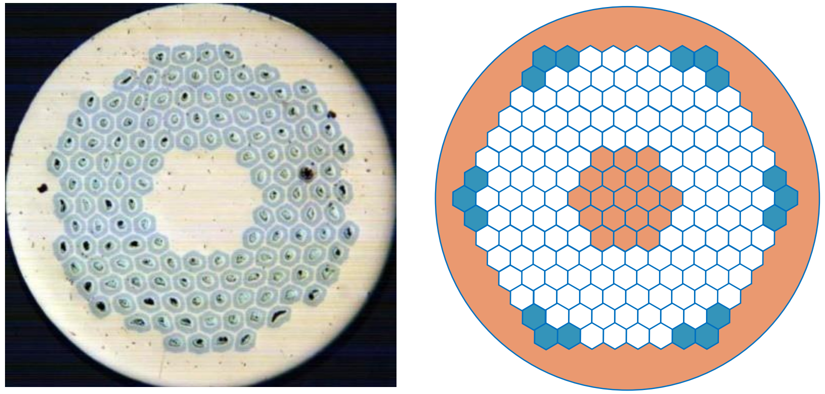
HL-LHC strand selection from available alternatives

- LARP and CDP explored several alternative designs 2003–2015
  - Specs LARP-MAG-M-8004.A through 8004.D
  - HL-LHC-AUP Spec.
- Bruker-OST was only vendor to consistently respond and work with LARP and CDP
- Bruker-OST's RRP strand fully meets the AUP spec.
  - Bruker-EAS's PIT strand does not meet the 12 T Ic spec, but does meet other needs
  - Tube-type strands also had difficulty meeting rolled strand / cabling degradation specs.

108/127 HL-LHC MQXF conductor

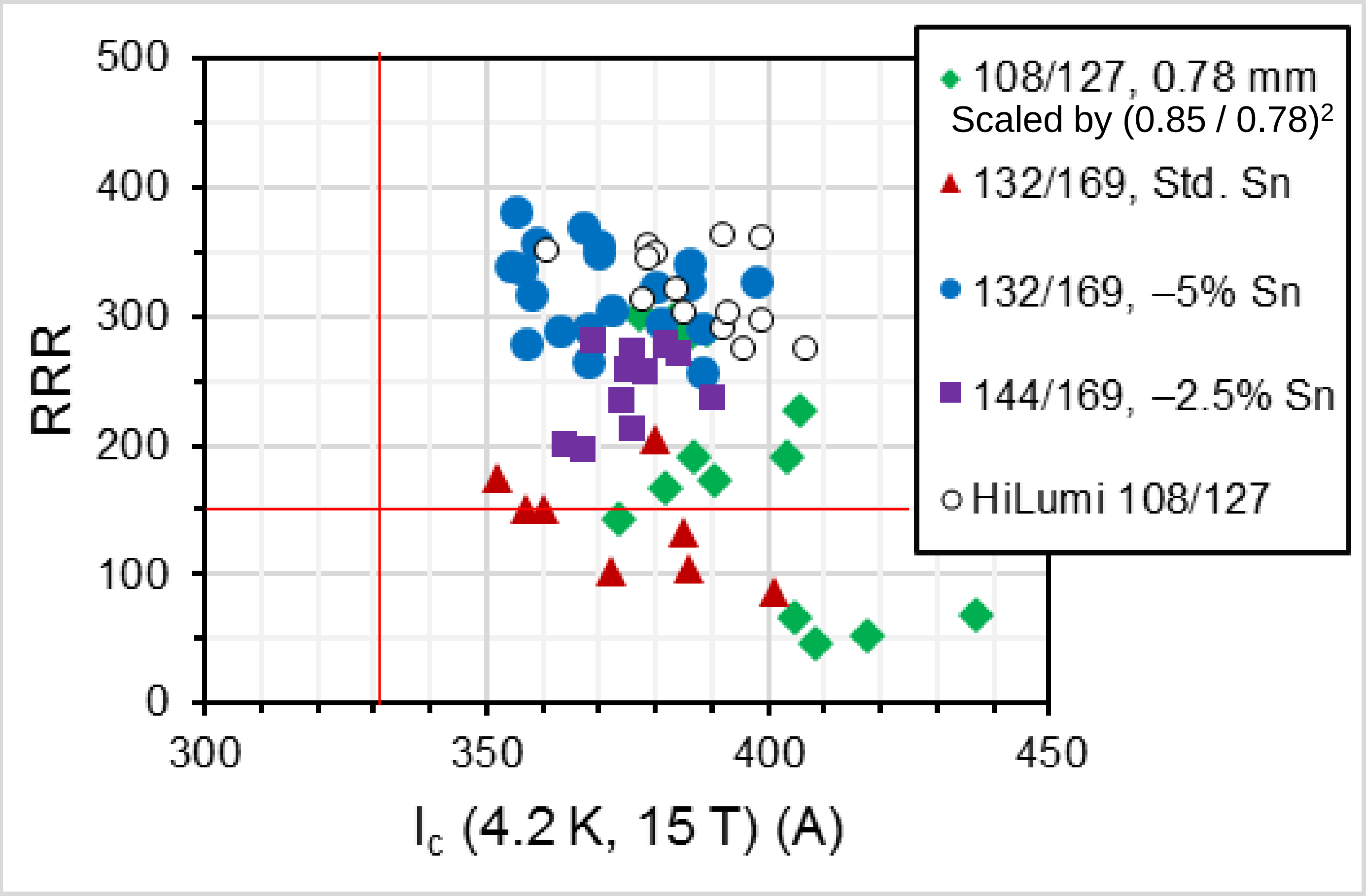


RRP 132/169 LARP QXF conductor



CDP and LARP efforts to zero in on the best design

Plot compares ~90 kg batches for each design, at 0.85 mm unless noted



3.4 and 3.6 Nb : 1.0 Sn

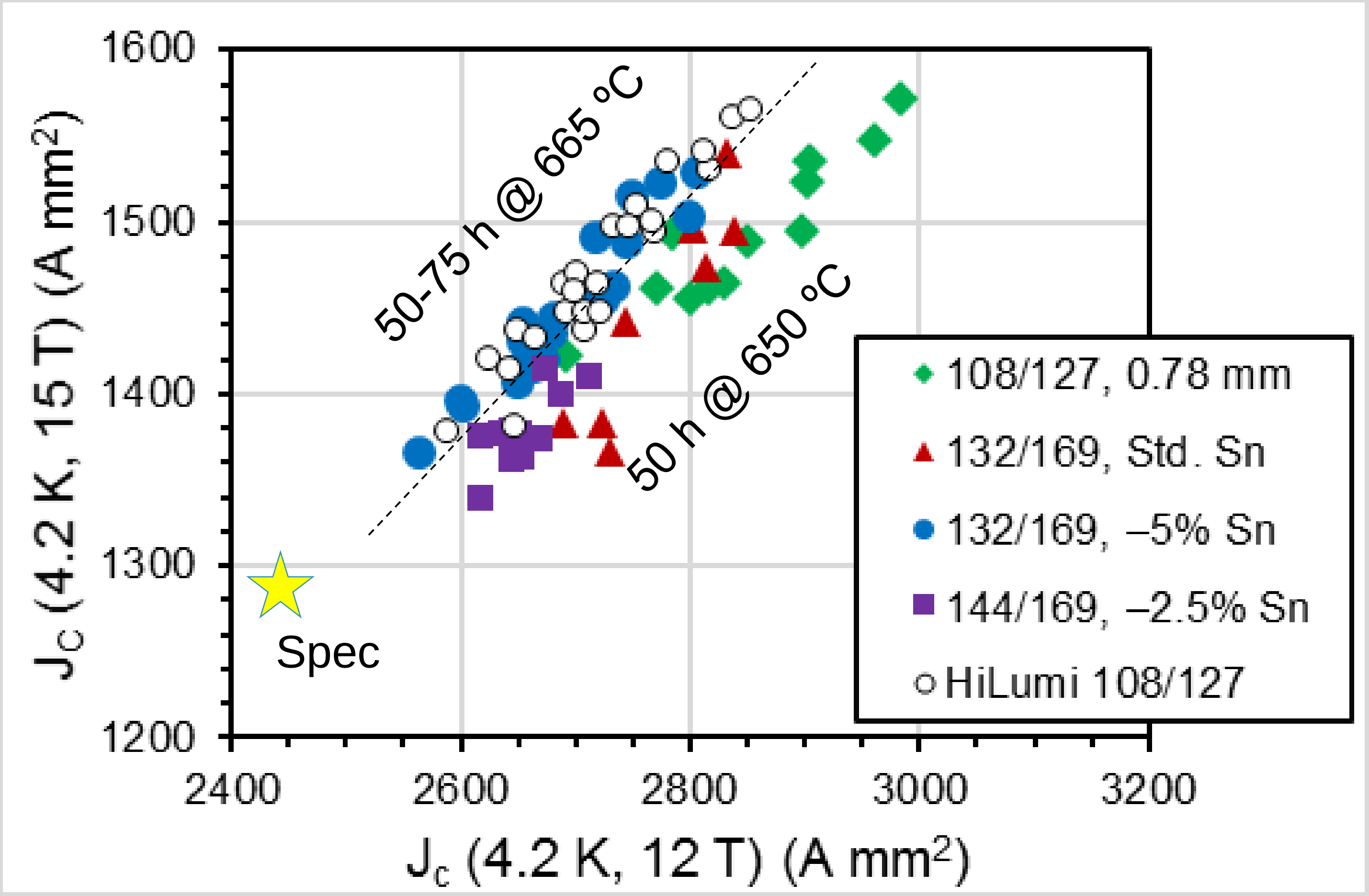
3.4 Nb : 1.0 Sn

3.6 Nb : 1.0 Sn

3.5 Nb : 1.0 Sn

3.6 Nb : 1.0 Sn

High temperature reactions made a crucial difference

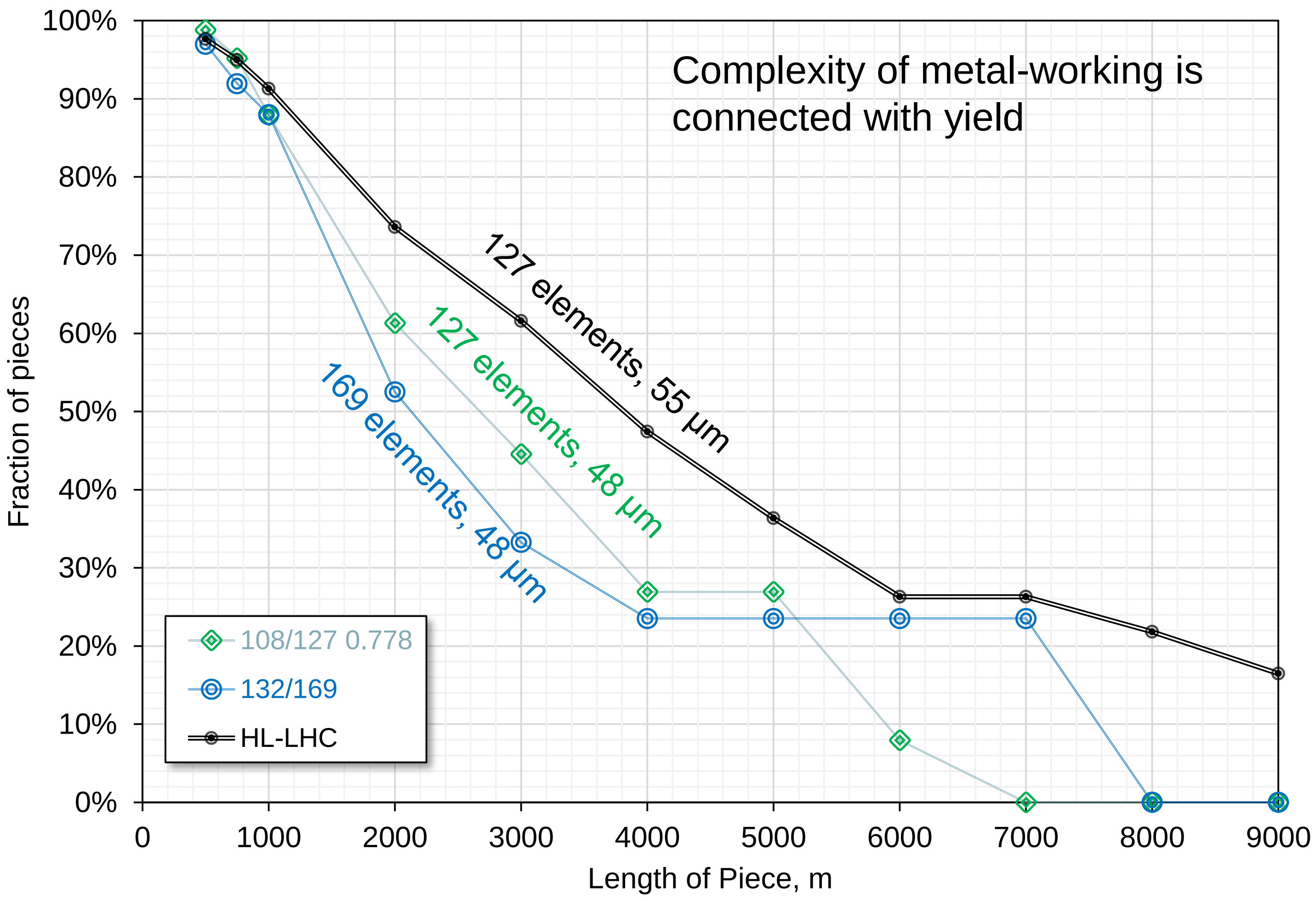


This result may be counter-intuitive:

Reduce the availability of tin to allow access to high-temperature reactions without penalty to RRR.

Prior work sought to increase availability of tin to reduce gradients in composition.

Value engineering: longer pieces



Practically every spool will have a remnant → Longer pieces over the course of production will result in fewer remnants.

The cost of remnants may be included in the price offered by the supplier → Longer pieces results in lower conductor cost for the project

Summary – looking forward

- The HL-LHC Accelerator Upgrade Project is cruising forward, and we are hopeful for a successful procurement
  - Clouds on the horizon, while potentially capable of a depression, do not appear to be heading toward Category 0 = storm level
- The next cycle of innovation is already underway
  - New reactions → 1400 A/mm^2 at 16 T, 4.2 K (C. Sanabria *et al.*)
  - APC and other ideas
- The industrial component may be less certain, however
  - Profits from medical magnets are less able to cover R&D (Prause MT-25)
  - Budget uncertainty makes Big Science a fickle customer
- Are partnerships a worthwhile solution in this new context?
  - Center at university or lab to reduce cost-share burden on industry
  - Billet-scale, should dove-tail with existing processes and enhance markets while also pushing toward the technology horizon for Big Science