IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

Challenges and Opportunities to Assure Future Manufacturing of Magnet Conductors

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U.S. DEPARTMENT OF ENERGY | Office of Science | U S MAGNET DEVELOPMENT PROGRAM | CERN | US HL-LHC AUP | HiLumi HL-LHC PROJECT

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

Grateful acknowledgment of supporting agencies

- The U.S. Department of Energy (DOE) Office of Accelerator R&D and Procurement (ARDAP)
- The DOE Office of High Energy Physics (HEP), through the U.S. LHC Accelerator Research Program (LARP) and the U.S. LHC Accelerator Upgrade Project (AUP)
  - Management of conductor procurement and conductor testing at the National High Magnetic Field Laboratory (NHMFL) were supported under sub-contract to AUP from Fermilab
- The High Luminosity LHC project (Hi-Lumi or HL-LHC) at CERN
- The DOE-HEP General Accelerator R&D program, which supports:
  - The U.S. Magnet Development Program (MDP)
  - The Conductor Development Program (CDP, prior to 2015)
  - The Conductor Procurement and R&D Program (CPRD, after 2015)
  - University grants
- Facilities and support for activities at the NHMFL was provided by the National Science Foundation (NSF) and the State of Florida

Grateful acknowledgment of people

- The LARP + CDP conductor teams: A Ghosh, J D'Ambra, E Sperry, A Moodenbaugh (BNL); D Dietderich (LBNL)
- The AUP conductor and cable teams: V Lombardo, D Turrioni (FNAL); I Pong, H Higley, C Sanabria, A Lin, E Lee, M Naus (LBNL)
- The CERN conductor team: B Bordini, C Barth, A Ballarino, S Hopkins
- The AUP and CERN project management: G Apollinari, R Carcagno, G Ambrosio, J Blowers (AUP); E Todesco, A Devred (CERN)
- The Bruker-OST (BOST) manufacturing team: M Field, J Parrell, J Harnanto, J Reineck, M Skibo
- The NHMFL verification team: J Lu, J Levitan, N Cheggour
- The MDP/CPRD team: S Prestemon, S Gourlay, I Pong (LBNL); V Lombardo, X Xu, G Velev, S Zlobin (FNAL); M Jewell (UW-EC); V Mathias (Ionbeam Mat'ls.); D Larbalestier (FSU); K Amm (BNL); K Marken (DOE)
- The ARDAP team: K Amm (BNL); W Hischier (UC Berk.); S Rotkoff (US Army ret.); M Tentnowski, B Vail (FSU)
- The ASC/NHMFL team: D Larbalestier, P Lee, C Linville
- Sponsoring agency input: K Marken, E Colby, B Carlsten, M White, B Strauss, LK Len, D Sutter
- *AND a long list of community stakeholders!*

The story on one slide

Procurement of accelerator-quality Nb_3Sn conductor for Hi-Lumi was a success!

MQXF incl. pre-production:

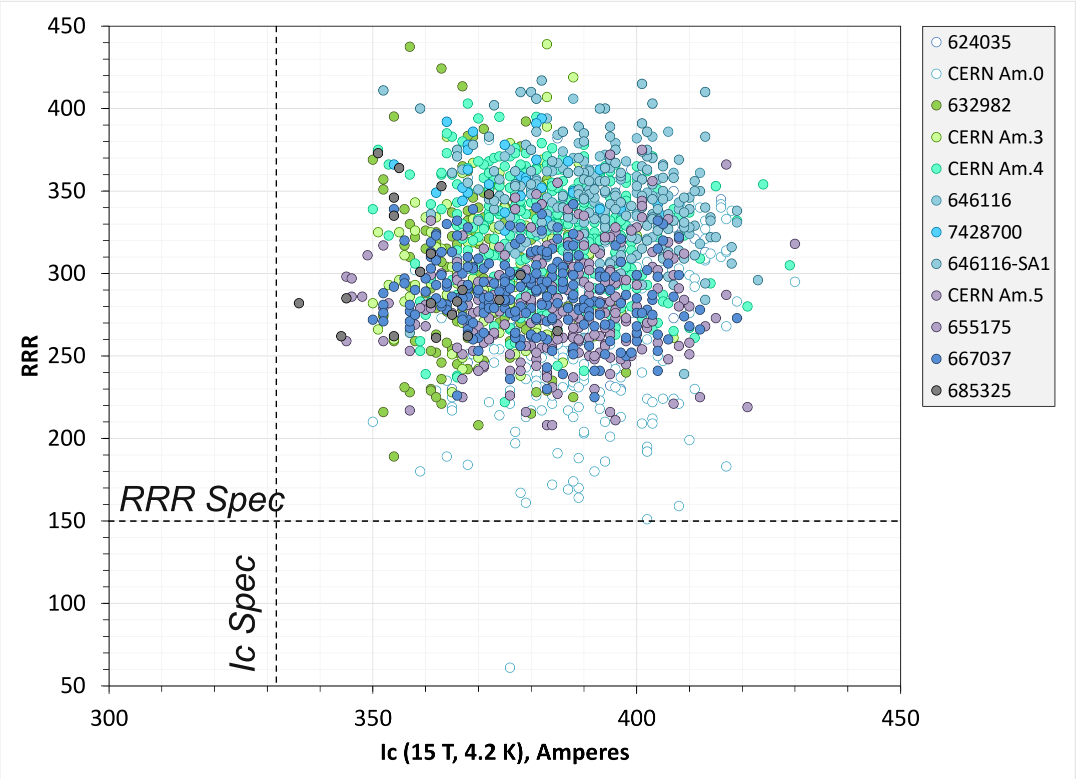
CERN: 2,477 km, 12.2 tons

AUP: 2,715 km, 13.3 tons

How do we keep this manufacturing "warm" for a decade or more, until the next major facility starts a procurement run?

FCC-hh: 10,000 tons of accelerator grade Nb_3Sn by 2050?

RRR vs Ic(15T) for the full production data from 1,760 conductor spools



IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

Table of Contents

IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

A crisis for discovery science realized in 2003

LARP

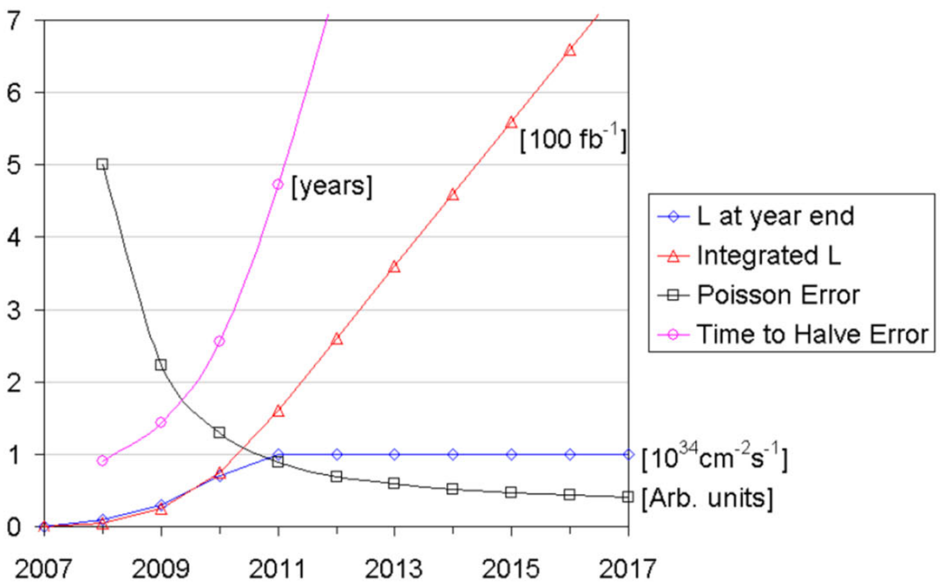


Fig. 3.1-1 Results of a simple model used to estimate the time from LHC start it takes to halve the statistical error in a measurement. Note that after a year of operating at full luminosity, it will take more than seven years to halve the error.

The U.S. LHC Accelerator Research Program:

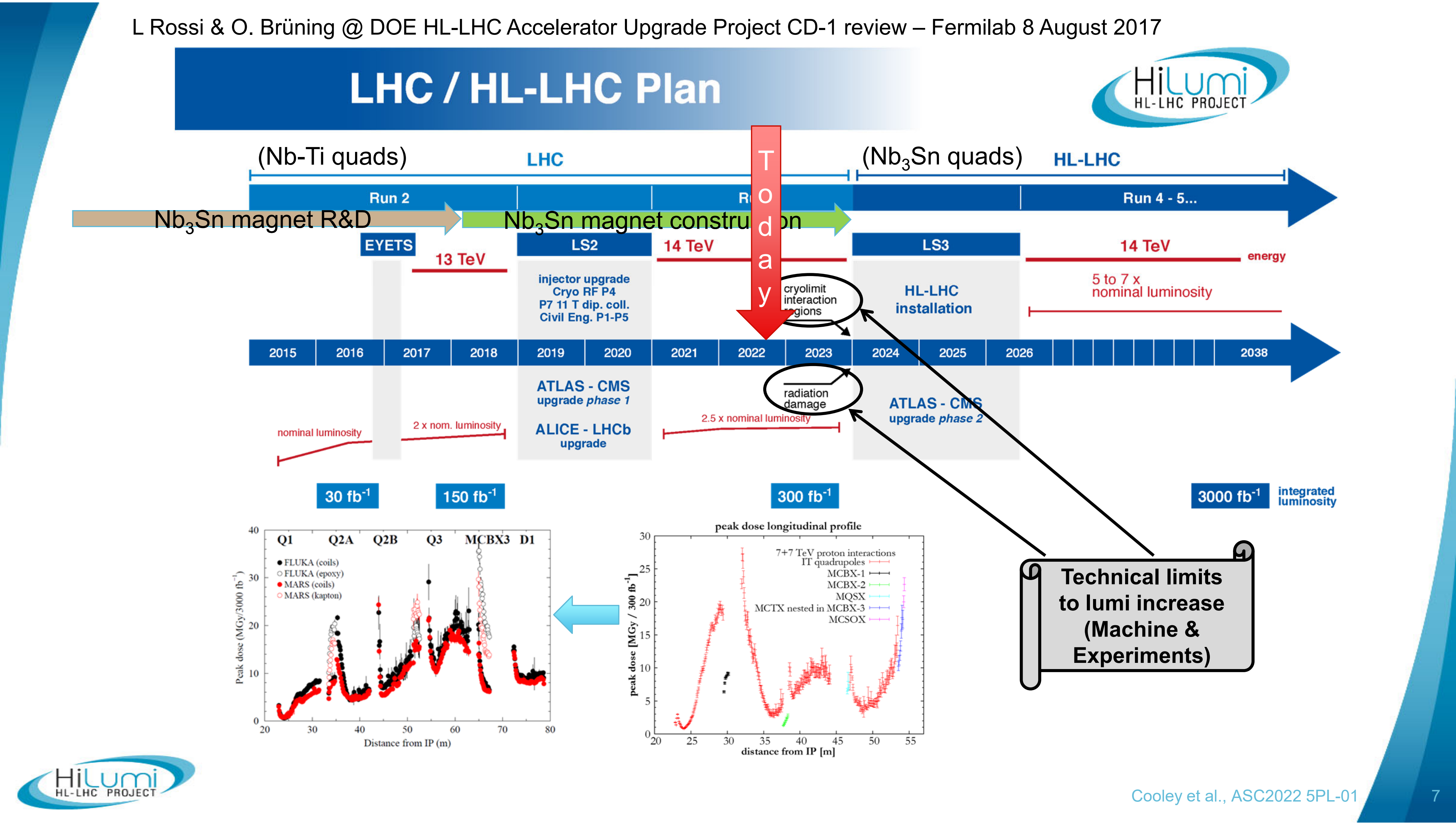
A Proposal

R. Kephart, M.J. Lamm, P. Limon, J. Marriner, T. Sen, J. Strait, A.V. Zlobin
Fermi National Accelerator Laboratory
Batavia, IL 60510

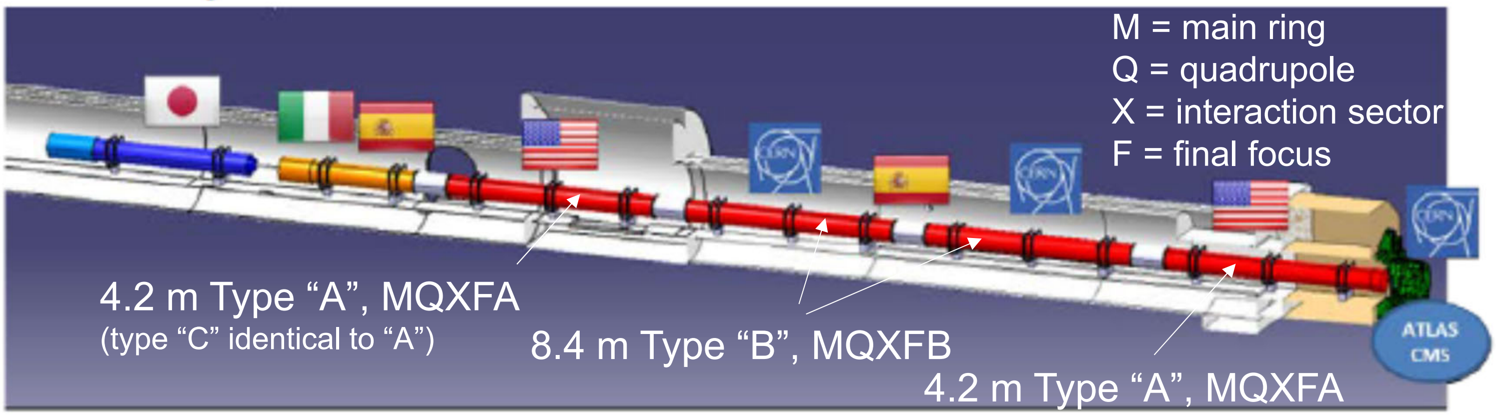
P. Cameron, A. Drees, W. Fischer, R. Gupta, M. Harrison, F. Pilat, S. Peggs
Brookhaven National Laboratory
Upton, NY 11973

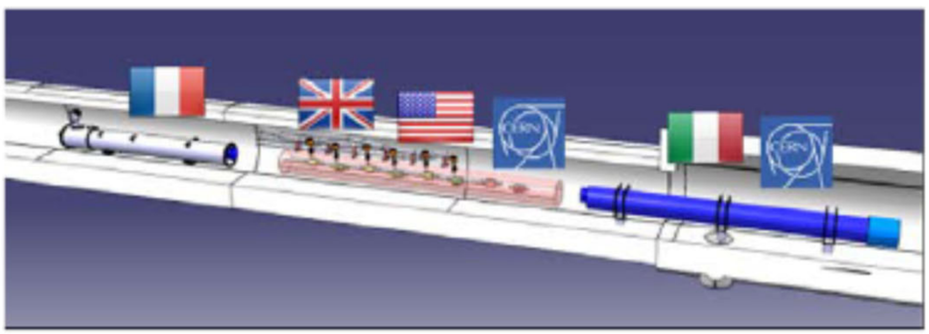
W. Barletta, J. Byrd, P. Denes, M. Furman, S. Gourlay, A. Ratti, W. Turner
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

May 2003


L Rossi & O. Brüning @ DOE HL-LHC Accelerator Upgrade Project CD-1 review – Fermilab 8 August 2017
LHC / HL-LHC Plan
HiLumi HL-LHC PROJECT
(Nb-Ti quads)
LHC
(Nb3Sn quads)
HL-LHC
Run 2
Run 4 - 5...
Nb3Sn magnet R&D
Nb3Sn magnet construction
Today
EYETS
13 TeV
LS2
14 TeV
LS3
14 TeV
energy
injector upgrade
Cryo RF P4
P7 11 T dip. coll.
Civil Eng. P1-P5
cryolimit interaction regions
HL-LHC installation
5 to 7 x nominal luminosity
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
ATLAS - CMS upgrade phase 1
ALICE - LHCb upgrade
radiation damage
ATLAS - CMS upgrade phase 2
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated luminosity
Q1 Q2A Q2B Q3 MCBX3 D1
FLUKA (coils)
FLUKA (epoxy)
MARS (coils)
MARS (kapton)
Peak dose (MGy/3000 fb-1)
Distance from IP (m)
peak dose longitudinal profile
7+7 TeV proton interactions
IT quadrupoles
MCBX-1
MCBX-2
MQSX
MCTX nested in MCBX-3
MCSOX
peak dose [MGy / 300 fb-1]
distance from IP [m]
Technical limits to lumi increase (Machine & Experiments)
HiLumi HL-LHC PROJECT

HL-LHC Accelerator Upgrade Project — Scope
The US is responsible for the outer quadrupole magnets + crab cavities





CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

- 2 interaction regions IR (ATLAS and CMS)
- Q1 and Q3 (identical) cryomodules CM on each side of the IR
- 1 spare each IR
- 2 IR x 2 sides x 2 CM = 8 CM, plus 2 spares = **10 cryomodules**
- 2 magnets per cryomodule x 10 CM = **20 magnets**
- 20 magnets x 4 coils = **80 coils**

B. Alonzo et al., HL-LHC Technical Design Report

Developing conductor for HEP: The Conductor Development Program (CDP)

- Port Jefferson workshop 1998: Push Nb_3Sn to 3,000 A/mm^2 at 12 T, 4.2 K
- MJR stuck at ~2200 A/mm^2
- CDP forms in 1999

2150 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 11, NO. 1, MARCH 2001

Conductor Development for High Energy Physics--Plans and Status of the U.S. Program

Ronald M. Scanlan

Abstract— In order to provide a cost effective high field magnet option for the next generation HEP accelerator, higher performance Nb_3Sn superconductor is required. These requirements have been recognized by the DOE, and a conductor development program has been initiated. The goal is to produce a cost-effective conductor with a Jc(noncopper,12T,4.2K) exceeding 3000 A/mm^2 and an effective filament size of less than 40 micrometers. Although the Nb3Sn conductors manufactured at present have produced Jc values in excess of 2200 A/mm^2, no conductor being manufactured at present can achieve both the aggressive Jc and effective filament size goals. The first phase of the present program is underway, and is focused on improving the understanding of the factors that control Jc. Samples are being manufactured by industry and are being characterized with respect to Jc and magnetization as a function of composition and heat treatment condition. Using this new knowledge as a base, the program will move into a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production size quantities. The status and accomplishments of this program will be reviewed, and the plans

R&D magnets. However, in order to achieve a cost-effective high field dipole for a future high field hadron collider, the Jc must be improved and at the same time, the conductor cost must be reduced. The Advanced Technology Development Program in DOE recognizes this, and is taking an active role in promoting cost-effective high field conductor development in industry. In this paper, we discuss the conductor development goals, the long-term program strategy, and the results of the program to date.

II. Conductor Development Program Goals

The basic outline for this program was developed from discussions at HEP conductor workshops that were held in 1998 and 1999. These goals are derived from the needs presented by the magnet R&D community, the potential performance improvements presented by the wire development groups, and the cost improvements projected by

IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

Developing conductor for HEP: The Conductor Development Program (CDP)

- Port Jefferson workshop 1998: Push Nb_3Sn to 3,000 A/mm^2 at 12 T, 4.2 K
- MJR stuck at ~2200 A/m
- CDP forms in 1999
- Maximize tin activity
- Avoid expensive Nb expanded metal
- Get good bonding for high yield

2150 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 11, NO. 1, MARCH 2001

Conductor Development for High Energy Physics--Plans and Status of the U.S. Program

Ronald M. Scanlan

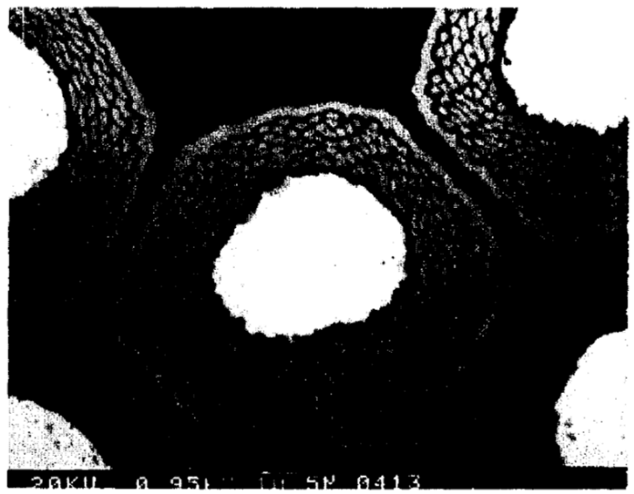


Fig. 1. MJR sub-element showing Sn core, Nb filaments, and Nb diffusion barrier. Sub-element width is 70 microns.

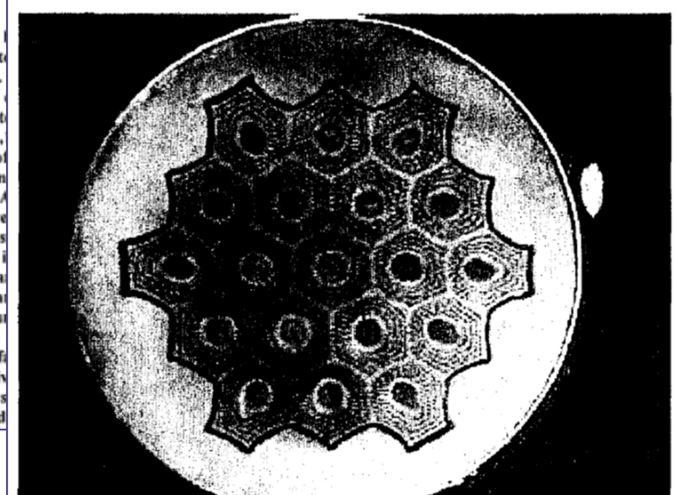


Fig. 2. Hot Extruded Rod Billet with salt packed into the hex-rod centers.

The RRP concept

- CDP contracts Oxford Superconducting Technology (OST)
- RRP c. 2002 at OST
- Jc > 3,000 A/mm^2 achieved by mid 2003
  - Non-copper Jc
- Challenge of D_{eff} also recognized

A NEW GENERATION Nb_3Sn WIRE, AND THE PROSPECTS FOR ITS USE IN PARTICLE ACCELERATORS

R.M.Scanlan[1], D.R. Dietderich[1], and S.A.Gourlay[1]

[1]Lawrence Berkeley National Laboratory
Berkeley, CA, 94720, USA

ABSTRACT

The US DOE has initiated a Conductor Development Program aimed at demonstrating a high current density, cost effective Nb_3Sn conductor for use in accelerator magnets. The first goal, an increase in current density by 50 %, has been achieved in a practical conductor. The program is focused at present on achieving the second goal of reduced losses. The different approaches for achieving these goals will be discussed, and the status will be presented. Magnet technology R&D has been proceeding in parallel with the conductor development efforts, and these two technologies are reaching the level required for the next step--introduction into operating accelerator magnets. An obvious point for introducing this technology is the LHC interaction region magnets, which require large apertures and high fields (or high field gradients). By upgrading the interaction region magnets, machine performance can be enhanced significantly without replacing the arc magnets, which represent most of the cost of an accelerator. Design requirements generated by recent studies and workshops will be reviewed, and a roadmap for the development of the next-generation interaction region magnets will be presented..

INTRODUCTION

The Large Hadron Collider (LHC), under construction at CERN, will be the world's most powerful particle accelerator, with a luminosity of about 2 x 10^{34} $cm^{-1}s^{-1}$, and a proton beam energy of 7 TeV. As construction of this phase is nearing completion, CERN has initiated a task force to study the feasibility of upgrades to the LHC [1]. Two possible upgrade scenarios for LHC are being evaluated--a luminosity upgrade and an energy upgrade. Both upgrades will require higher performance superconducting magnets, beyond the capability of the NbTi superconductor that was used in the LHC. Several luminosity upgrade options are being considered, with the most likely being a replacement

CP711, *Advances in Cryogenic Engineering: Transactions of the International Cryogenic Materials Conference - ICMC, Vol. 50,* edited by U. Balachandran

The RRP concept

- CDP contracts Oxford Superconducting Technology (OST)

A NEW GENERATION Nb_3Sn WIRE, AND THE PROSPECTS FOR ITS USE IN PARTICLE ACCELERATORS

R.M.Scanlan[1], D.R. Dietderich[1], and S.A.Gourlay[1]

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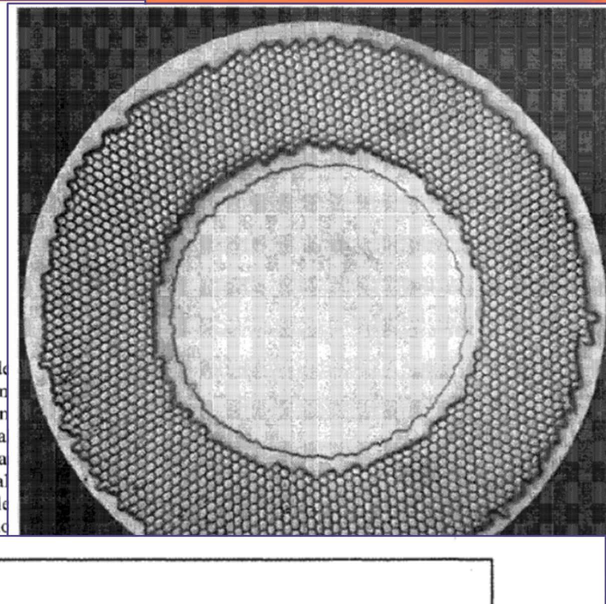


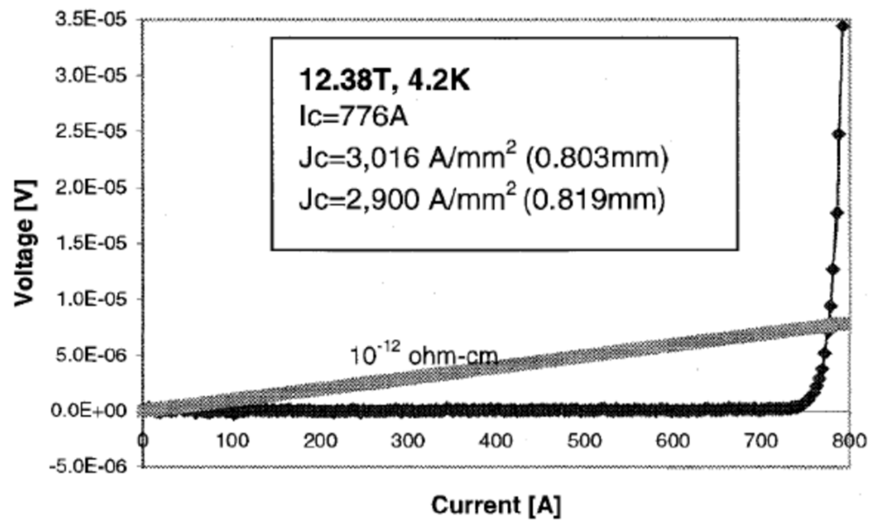


FIGURE 2. Short sample measurement of RRP process wire, showing a J_c value of 3016 A/mm^2 at a field (background + self field) of 12.38 T. The V vs. I curve is stable to a level of 60 microVolts/m.

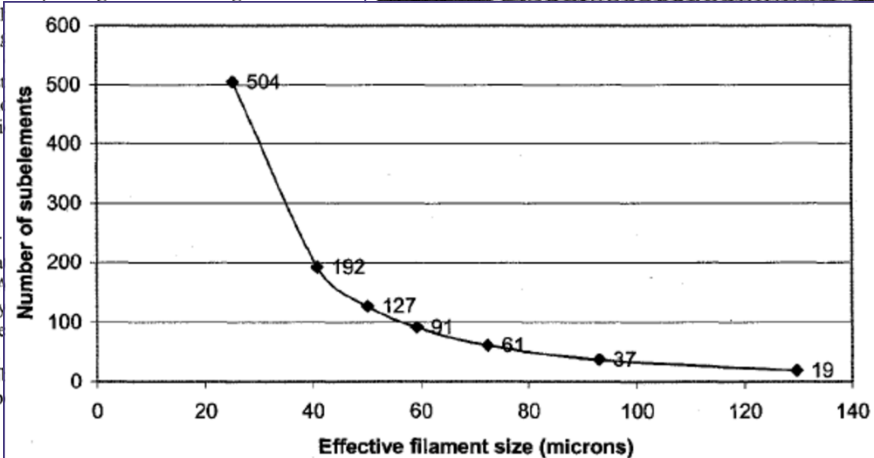


FIGURE 3. Number of subelements required to produce the effective filament size indicated by the abscissa.

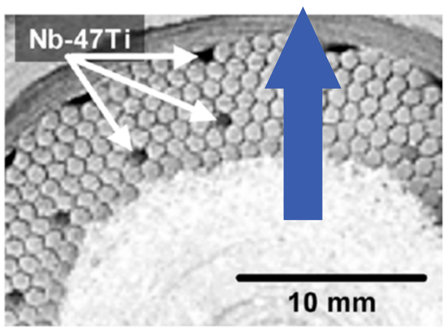
Immediately high Jc was realized

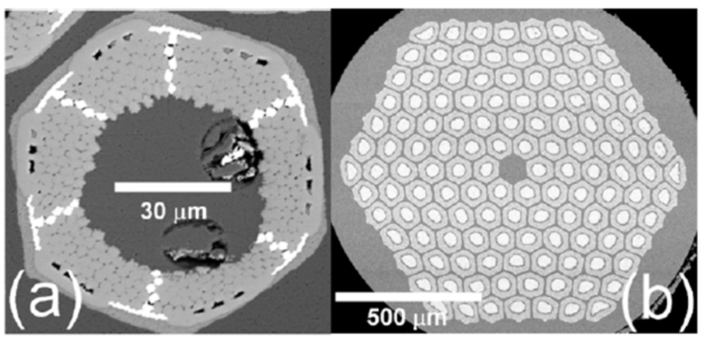
- OST reported at ASC2004 many designs with Jc > 3000 at 12 T
- Advances to decrease D_{eff} were demonstrated as well

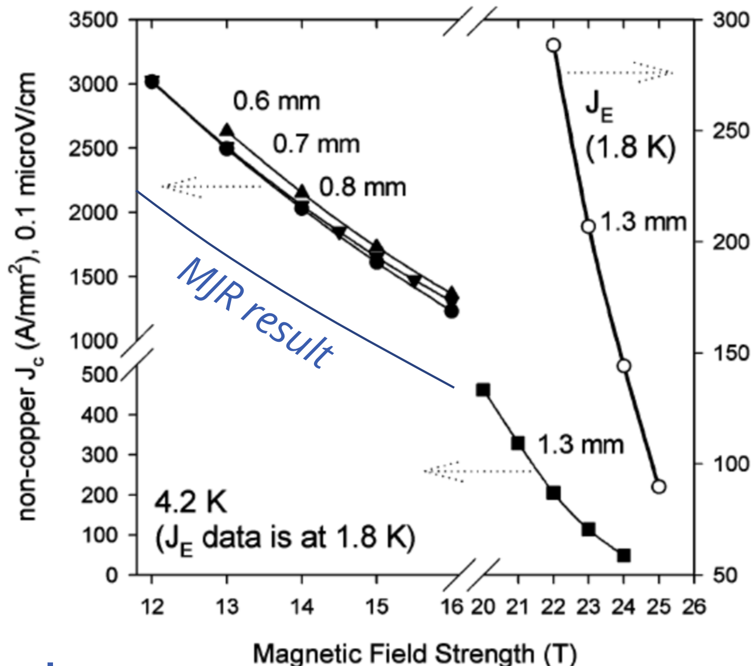
1200 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

Advances in Nb_3Sn Strand for Fusion and Particle Accelerator Applications

Jeffrey A. Parrell, Michael B. Field, Youzhu Zhang, and Seung Hong







Radial tin reaction from core to (and possibly through) diffusion barrier

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Flux jumps: Conductor requires a 2-parameter optimization (Jc & RRR)

- Reactions that drive up Jc also possibly drive Sn through the diffusion barrier → RRR loss
- The entire sub-element behaves like a single filament
  - LARP "baseline" at that time was a 54/61 conductor at 0.8 mm → D_{eff} ~ 80 µm
  - *Adiabatic* stability condition: $J_c^2 D_{eff}^2 / C_p V (T_c - T_{op}) < 1$ is violated for J_c ~ 3000 A/mm^2 and 80 µm
  - *Dynamic* stability: energy released must not exceed heat conduction to LHe
- Flux jumps were causing quenches in test magnets
  - *Why? Heat treatments that maximized J_c also reduced RRR and took away dynamic stability*

Supercond. Sci. Technol. **18** (2005) L5–L8

RAPID COMMUNICATION

Dynamic stability threshold in high-performance internal-tin Nb_3Sn superconductors for high field magnets

A K Ghosh[1], E A Sperry[1], L D Cooley[2], A M Moodenbaugh[2], R L Sabatini[2] and J L Wright[2]

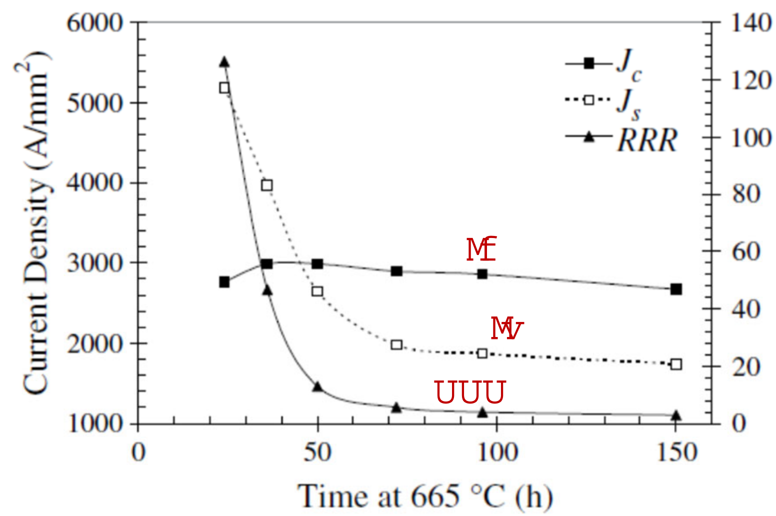

Figure 3. Critical current density, magnetic stability threshold current density, and RRR plotted as a function of final reaction time at 665 °C.

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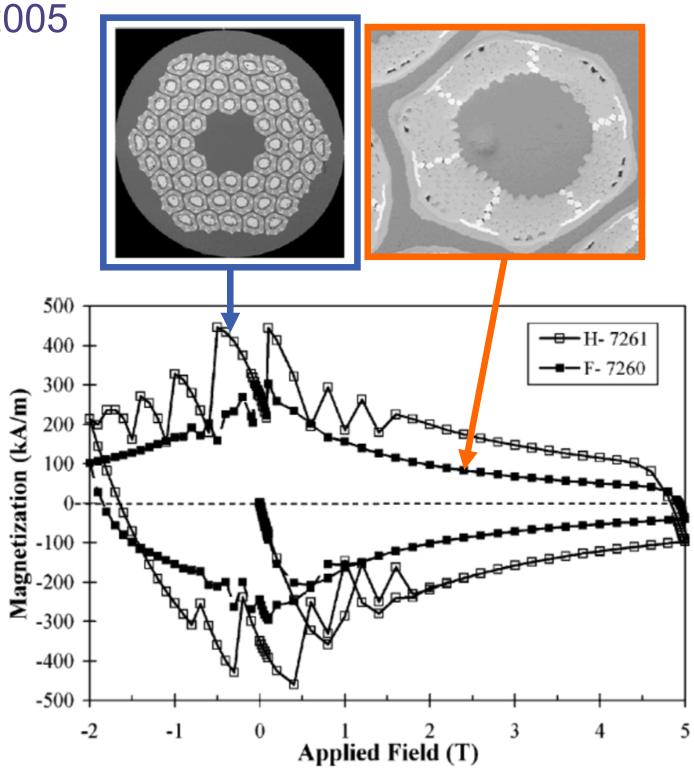
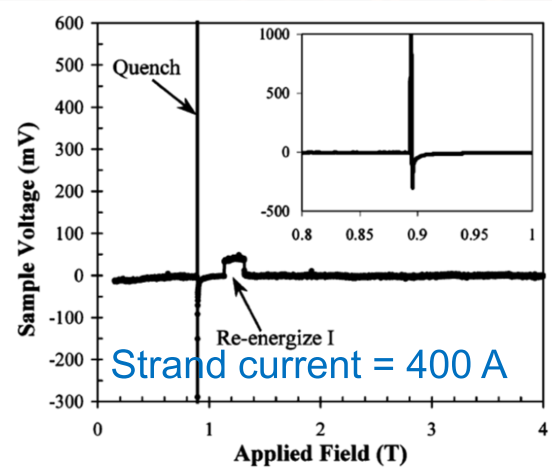
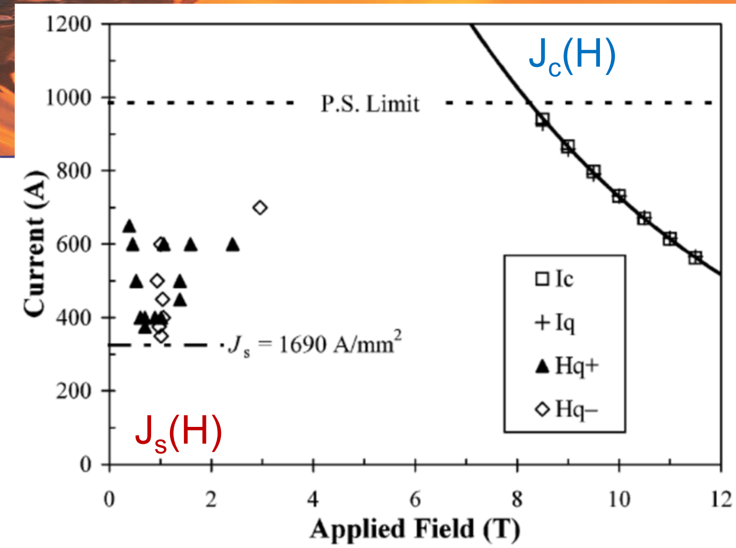
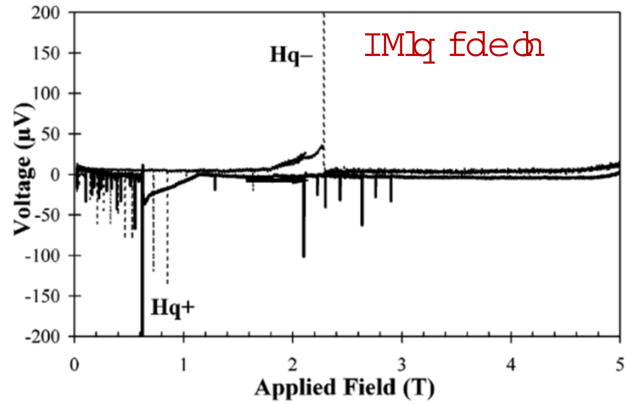
Instabilities are a real challenge for magnets

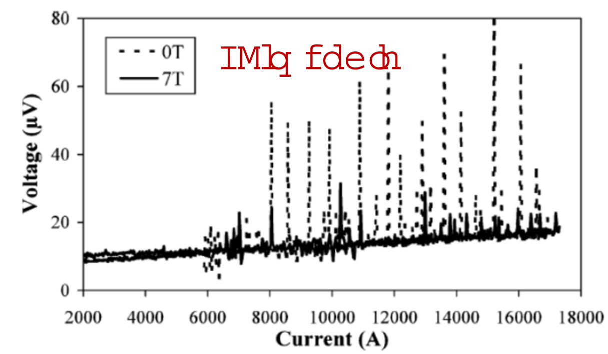
2005









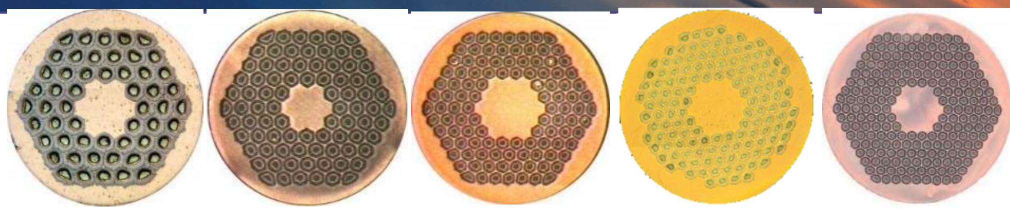


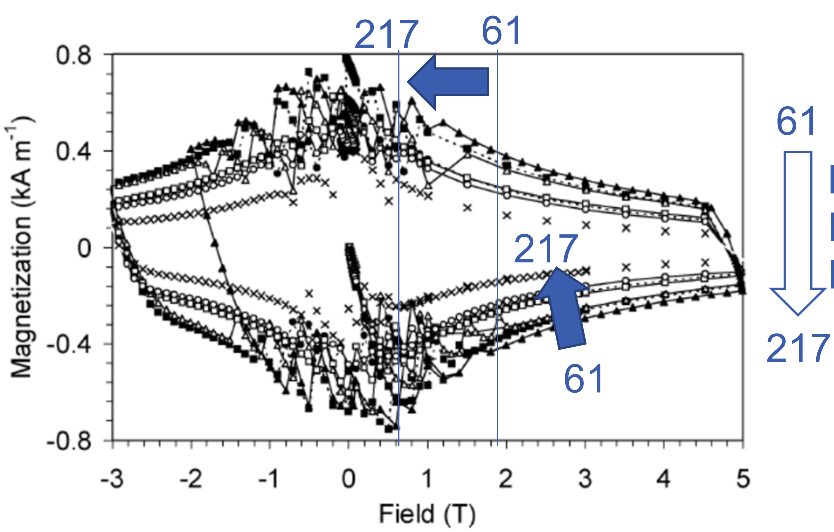
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

Pushing to small D_{eff} and keeping J_c high continues to be a challenge

61 91 127 169 217





Magnetization reduces
FJ onset at lower field
FJ magnitude reduces

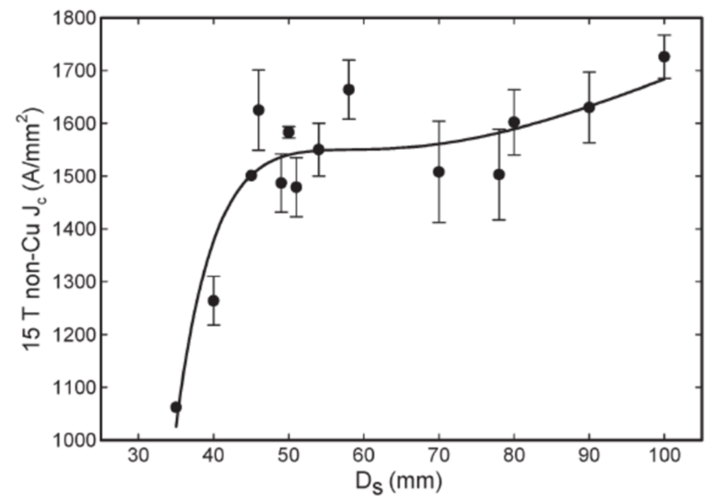
L. D. Cooley, P. S. Chang, and A. K. Ghosh

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 24, NO. 3, JUNE 2014

Optimizing Nb_3Sn Conductors for High Field Applications

Michael B. Field, Youzhu Zhang, Hanping Miao, Michael Gerace, and Jeffery A. Parrell



2014 summary: Critical current always degraded

(and Charlie Sanabria + others identified why – see Sanabria 2018)

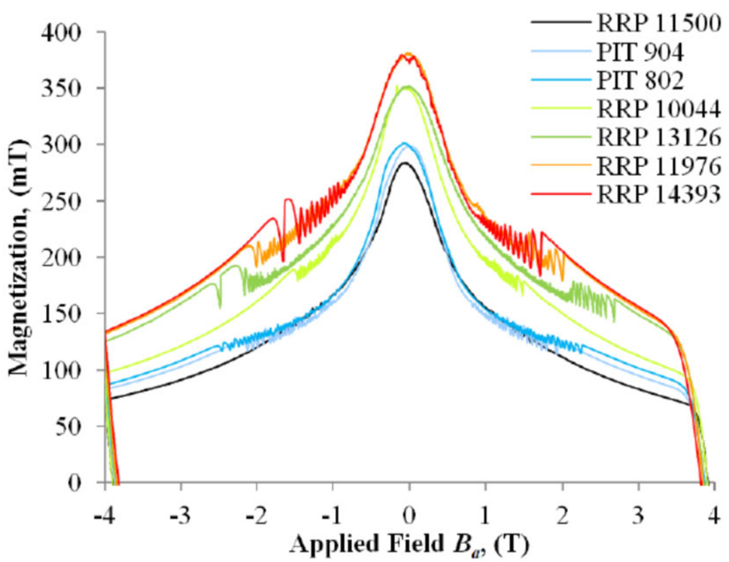
Fortunately, flux-jumps are not as severe at 1.9 K

Magnets could be ramped and protected even with D_{eff} = 70 µm when RRR high

Magnetization Measurements of High-J_c Nb_3Sn Strands

B. Bordini, D. Richter, P. Alknes, A. Ballarino, L. Bottura, and L. Oberli

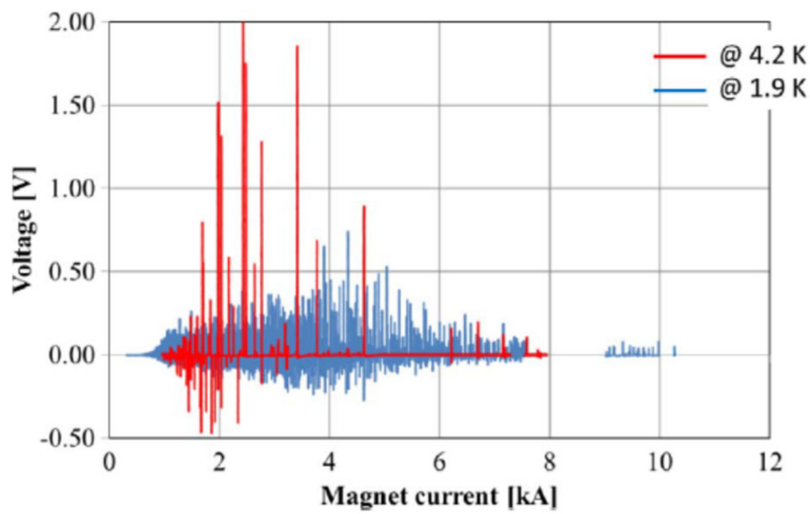
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013



Cold Test Results of the LARP HQ Nb_3Sn Quadrupole Magnet at 1.9 K

H. Bajas, G. Ambrosio, M. Anerella, M. Bajko, R. Bossert, S. Caspi, A. Chiuchiolo, G. Chlachidze, D. Dietderich, O. Dunkel, H. Felice, P. Ferracin, J. Feuvrier, L. Fiscarelli, A. Ghosh, C. Giloux, A. Godeke, A. R. Hafalia, M. Marchevsky, S. Russenschuck, G. L. Sabbi, T. Salmi, J. Schmalzle, E. Todesco, P. Wanderer, X. Wang, and M. Yu

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013



Ti alloying gives rapid reactions at 650-665°C where RRR could be kept high

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 19, NO. 3, JUNE 2009

Systematic Changes of the Nb-Sn Reaction With Time, Temperature, and Alloying in Restacked-Rod-Process (RRP) Nb_3Sn Strands

Arup K. Ghosh, Edward A. Sperry, Joseph D'Ambra, and Lance D. Cooley

- Reaction rate depends on Nb:Sn, time, temperature, D_{sub}, and dopants
- Lots of university work here – tremendous value of the university collaborations!

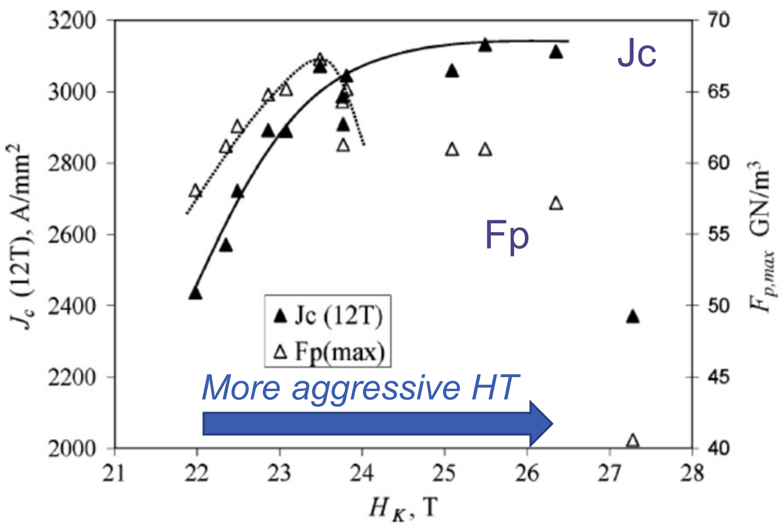


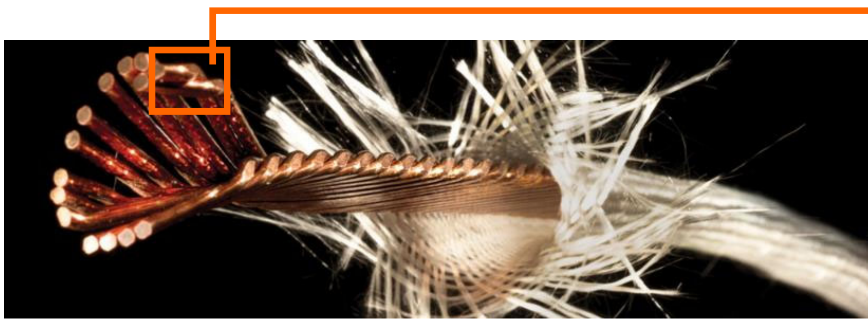
TABLE I
SUMMARY OF REACTION PARAMETERS AND MEASUREMENTS FOR RRP 8220 STRANDS

Temp °C	Time h	J_c(12T) A/mm²	RRR	H_K T	T_c K	ΔT_c	$F_{p,max}$ GN/m³
605	150	2437	411	22.0	16.34	1.10	58.1
620	96	2722	450	22.5	16.53	1.20	62.6
620	192	2892	377	22.9	16.64	1.35	64.8
620	384	2909	74	23.8			61.3
635	48	2571	364	22.4	16.53	1.25	61.2
650	48	2890	305	23.1	16.77	1.03	65.2
650	96	3072	233	23.5	16.92	0.85	67.3
665	50	2987	171	23.8	16.92	0.85	64.3
680	48	3060	109	25.1	17.10	1.13	61.0
695	48	3114	56	26.4	17.32	1.00	57.2
750	96	2371	15	27.3	17.24	1.35	40.6

A sweet spot in parameter space was found

The RRP design is surprisingly resilient to cabling degradation

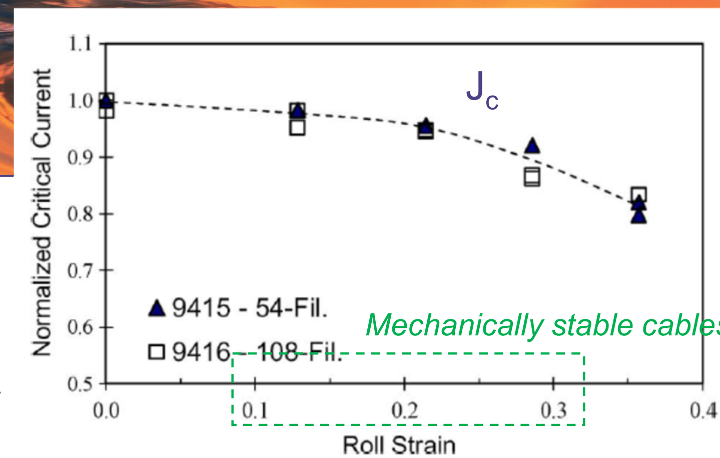
- Magnets need cables for low inductance
  - AUP uses a 40-strand Rutherford cable
- Deformation produces reduction of Jc and especially
  - But the Jc loss was ***modest*** (not so for PIT)

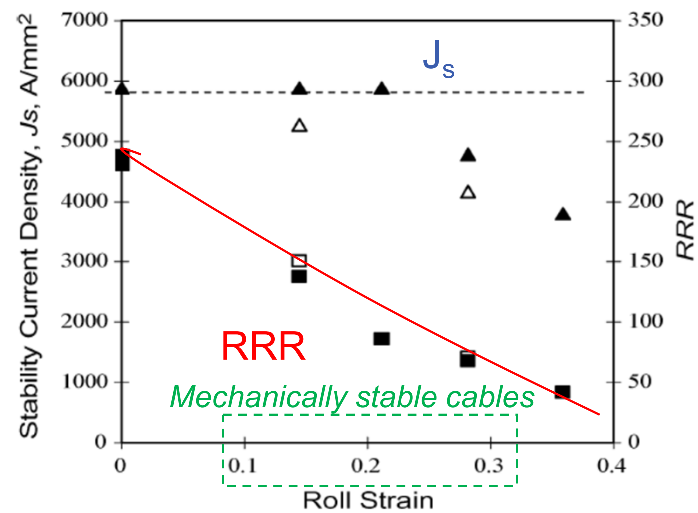


ACCELERATORS | FEATURE

Taming the superconductors of tomorrow

11 May 2020



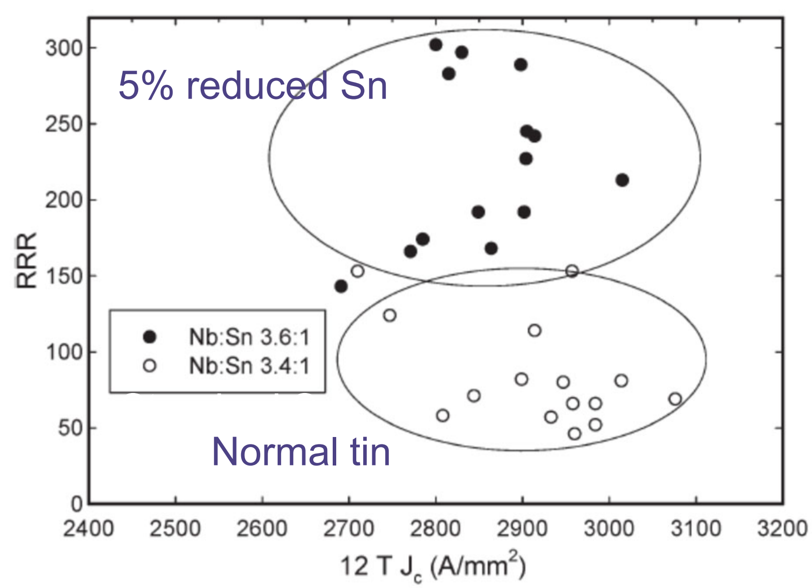


A. K. Ghosh, L. D. Cooley, D. R. Dietderich, and L. Sun

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008

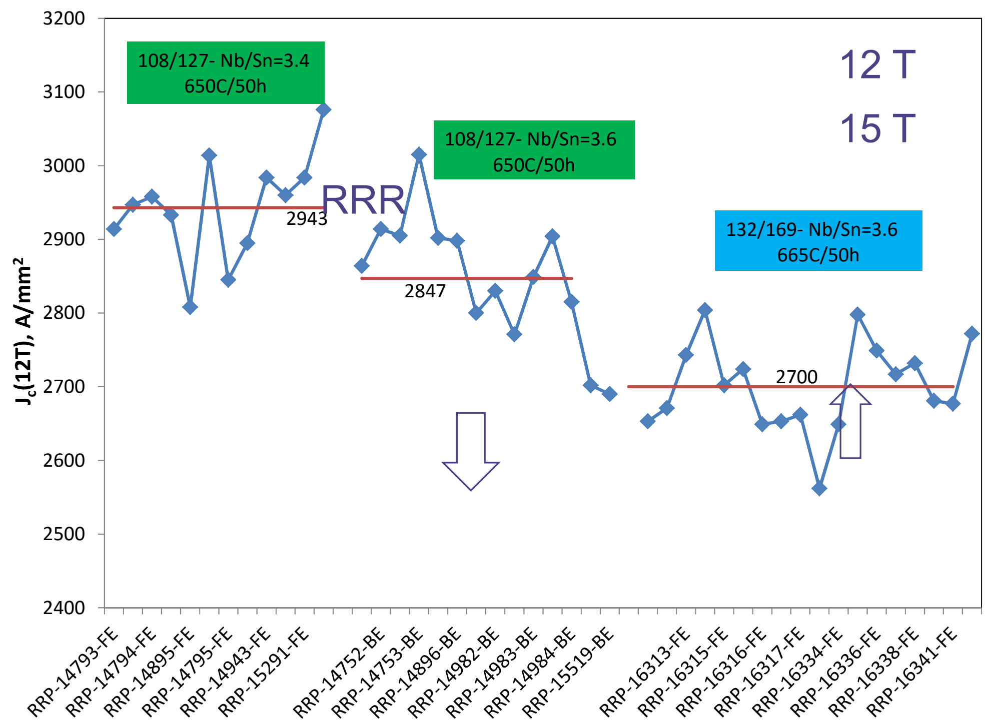
Production readiness: Go with the reduced Sn architecture

Field *et al.* 2014 summary: *Reducing* the amount of tin increases manufacturing margins! Lower tin can be offset by more aggressive reaction HT



"Sweet spot" reaction 665°C / 48 h

Arup Ghosh – 2015 Billet-to-billet variations



IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

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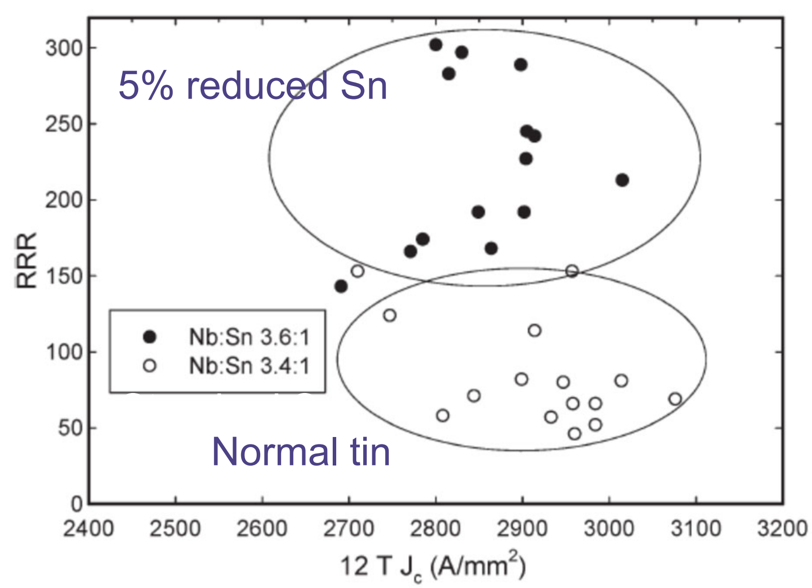

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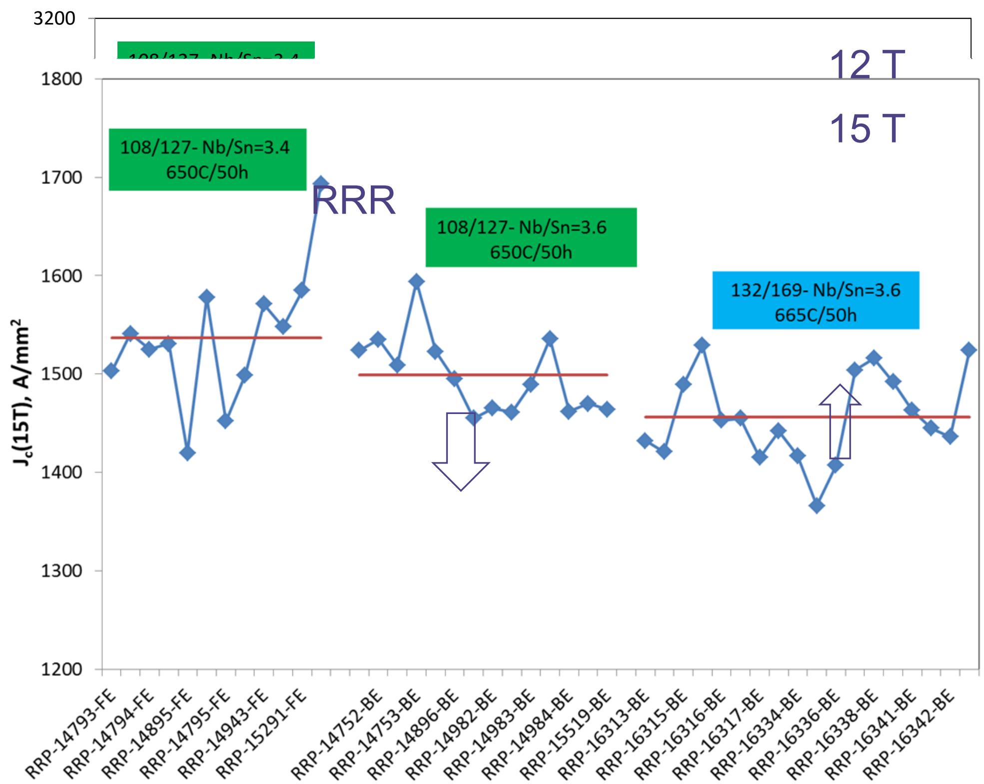

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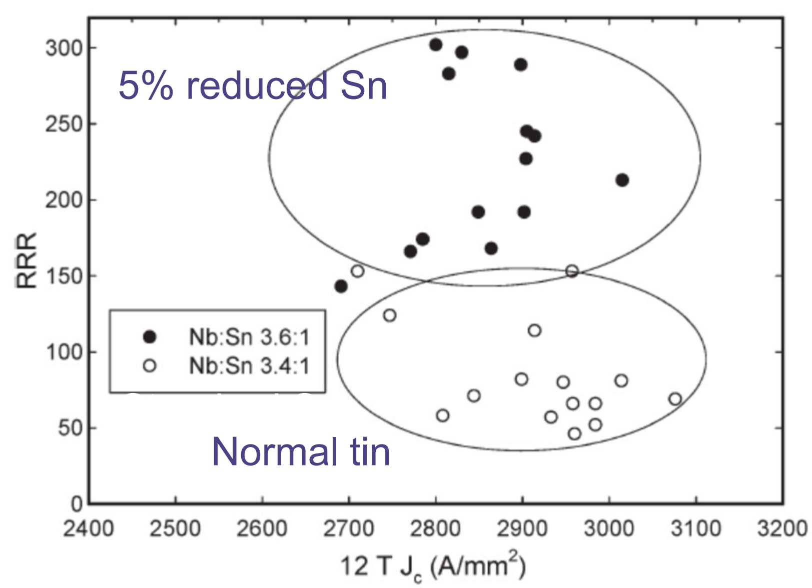

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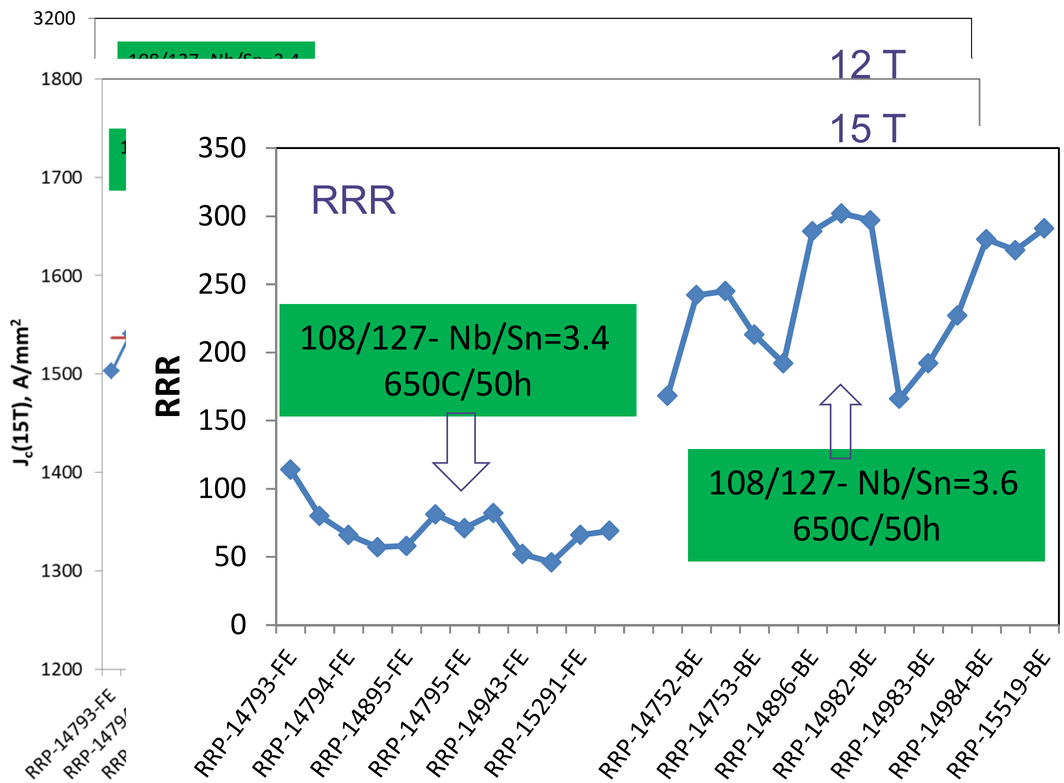


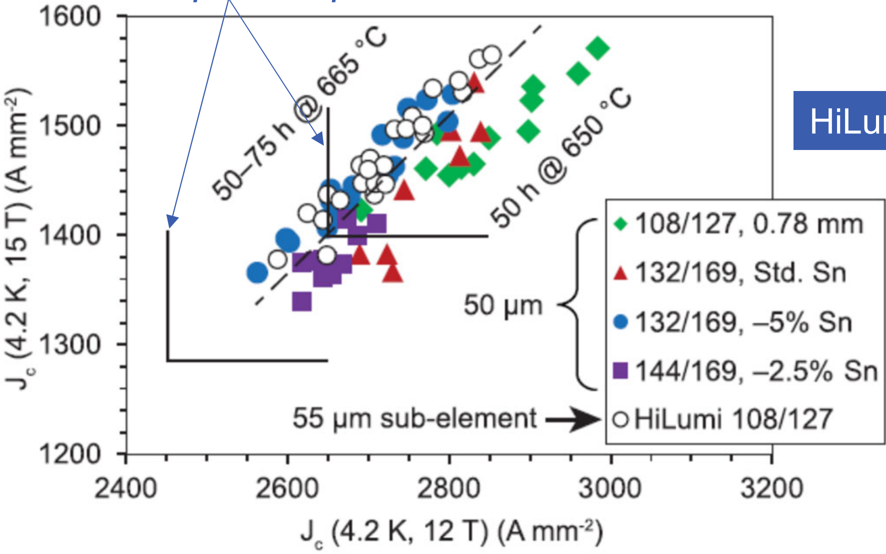
Production readiness: High performance, high yield with 108/127

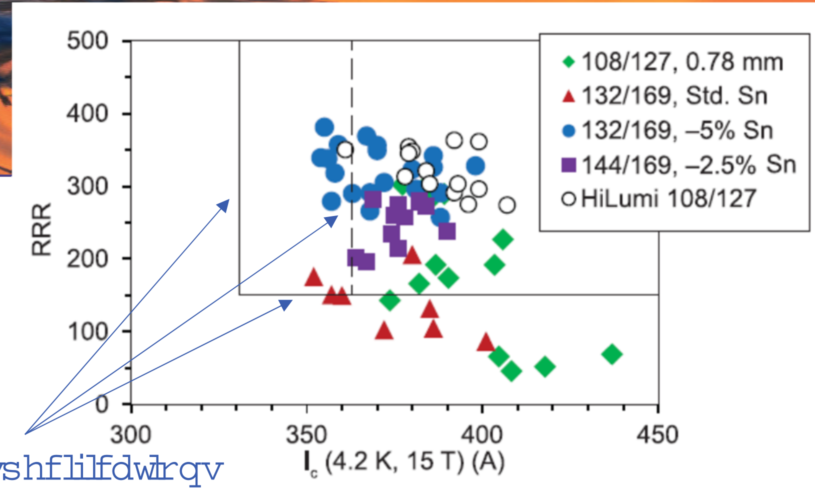
Conductor Specification and Validation for High-Luminosity LHC Quadrupole Magnets

L. D. Cooley, *Senior Member, IEEE*, A. K Ghosh, D. R. Dietderich, and I. Pong

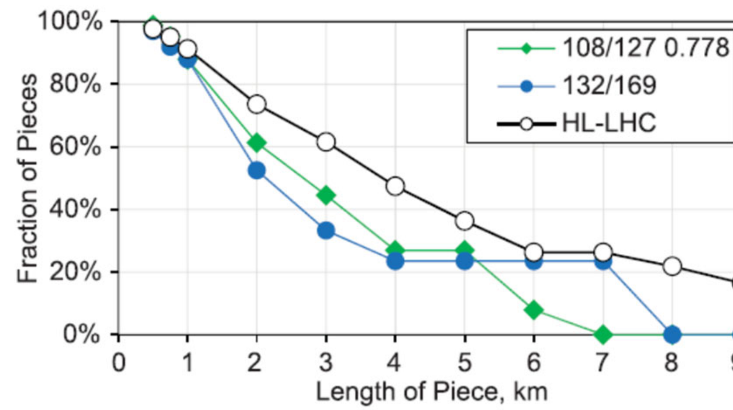
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017

Proposed specifications





HiLumi QXF strand is RRP 108/127 at 0.85 mm, -5% Sn



An unknown that could have dealt the Hi-Lumi project a severe blow

SCIENTIFIC REPORTS

Corrected: Publisher Correction

OPEN

Implications of the strain irreversibility cliff on the fabrication of particle-accelerator magnets made of restacked-rod-process Nb_3Sn wires

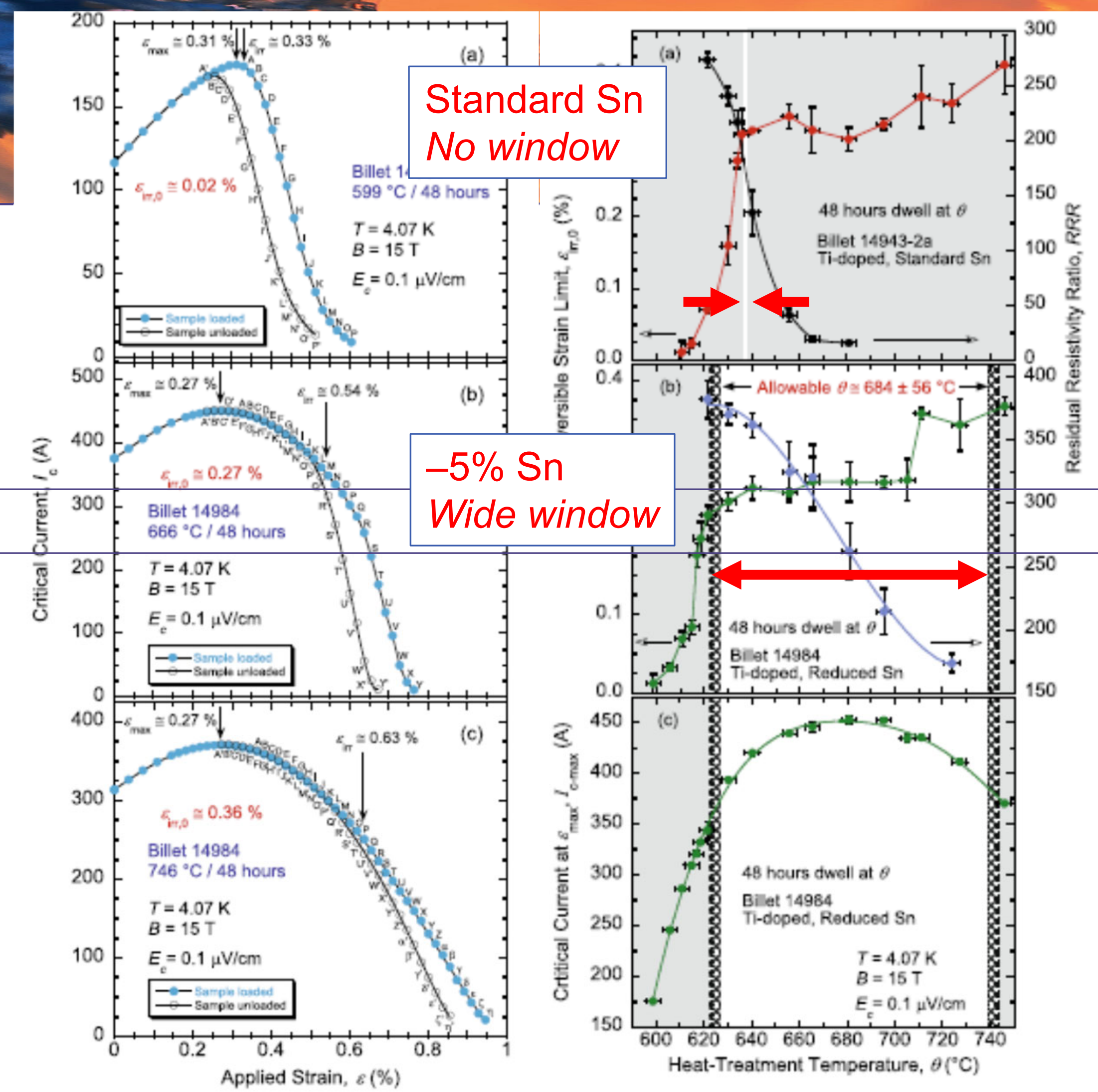
Received: 24 September 2018
Accepted: 18 March 2019
Published online: 2 April 2019

Najib Cheggour[1,2,3], Theodore C. Stauffer[3], William Starch[3], Loren F. Goodrich[1,2] & Jolene D. Splett[4]

A threat imposed by the strain irreversibility cliff was not revealed until well into the Hi-Lumi procurement

A "window" of reaction temperature occurs between a point of vulnerability to strain at 620–640°C and loss of RRR for higher temp.

Fortunately, the reaction strategies to simultaneously optimize Jc and RRR using –5% Sn architecture and the selection of Ti-alloyed material avoided this risk.



2017: CERN and AUP* update the 2015 drafts to form a common specification and quality plan for QXF conductor

- Nb_3Sn strand, Ti-alloyed, 5% reduced Sn, 108 sub-elements
- Diameter 0.850 ± 0.003 mm
  - 2-axis laser micrometer
- Cu:NC 1.2 ± 0.1 (52.3–56.5% Cu)
  - IEC 61788-12: *Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires*
- Twist pitch 16 mm < *p* < 19 mm, right-handed
- Pass 6 sharp bends, 720° springback
- Photomicrographs
- *"The strand surface at the final diameter shall be free of any surface defects, slivers, folds, laminations, or inclusions, and shall not have any component other than the copper stabilizer material visible."*

- At 4.2K: Ic(12T) > 632 A, Ic(15T) > 331 A
  - Ic(13T), Ic(14T) measured for information
  - FYI Jc(12T) > 2450 A/mm^2, Jc(15T) > 1284 A/mm^2
  - IEC 61788-2: *DC critical current of Nb_3Sn composite superconductors*
- 15% rolled: Ic(12T) > 600 A, Ic(15T) > 314 A
- RRR > 150, 15% rolled RRR > 100
  - IEC 61788-11: *Residual resistance ratio of Nb3Sn composite superconductors*
- N-value at 15 T > 30
- Not specified: Magnetization at 3 T
  - Expensive QC test for little gain in assurance

*** AUP = High-Luminosity LHC Accelerator Upgrade Project in the US DOE**

IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

Why specify critical current at two fields and 4.2 K instead of 1.9 K?

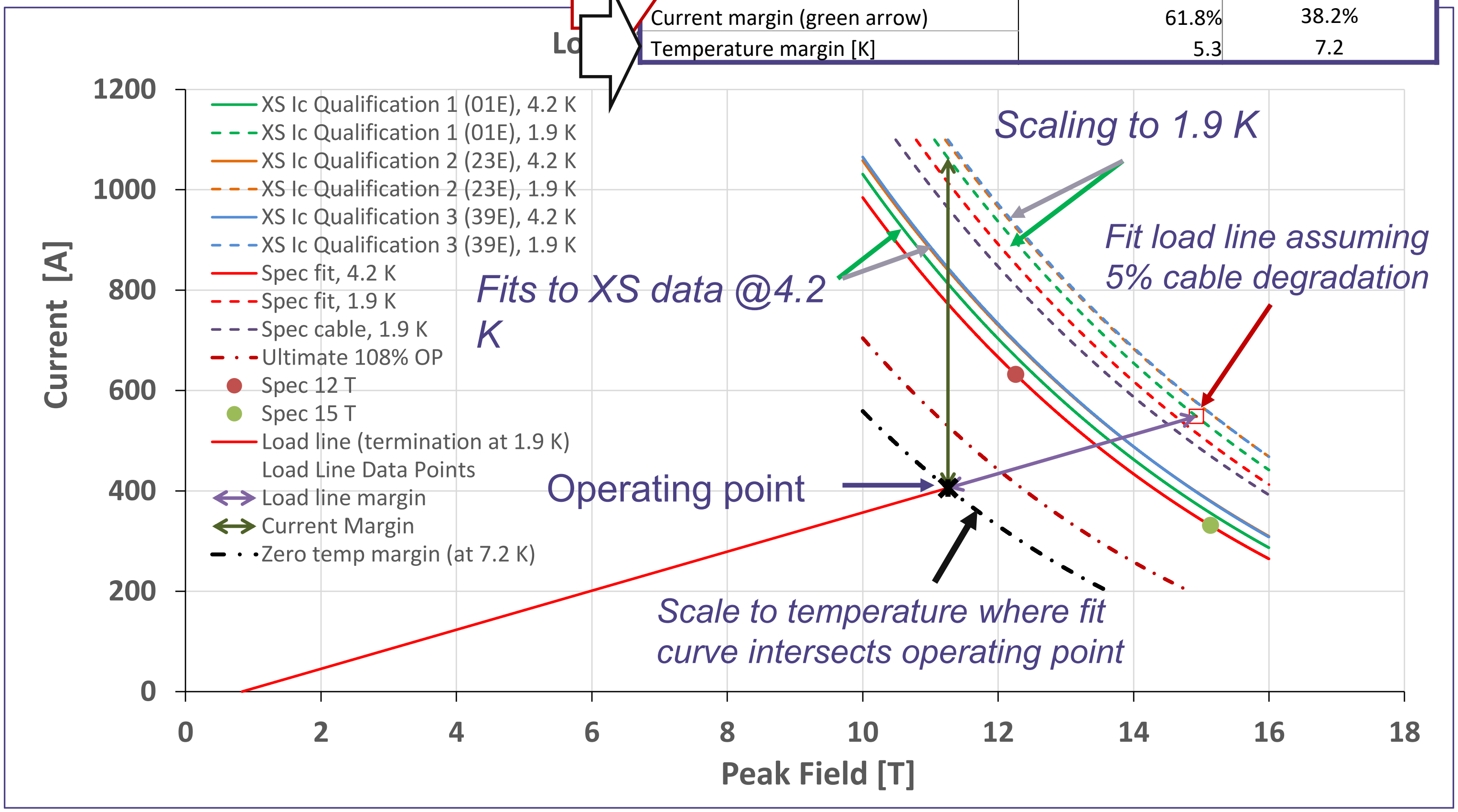
I [A] to calculate margin at	405.75	
Corresponding load line B [T]	11.26	
SS curve to calculate margin from	XS Ic Qualification 1 (01E), 1.9 K	
Margins	*Margin*	*Operating Point* (**X**)
Load line margin (purple arrow)	26.0%	74.0%
Current margin (green arrow)	61.8%	38.2%
Temperature margin [K]	5.3	7.2

Magnet margins must be determined by fitting and using scaling relationships

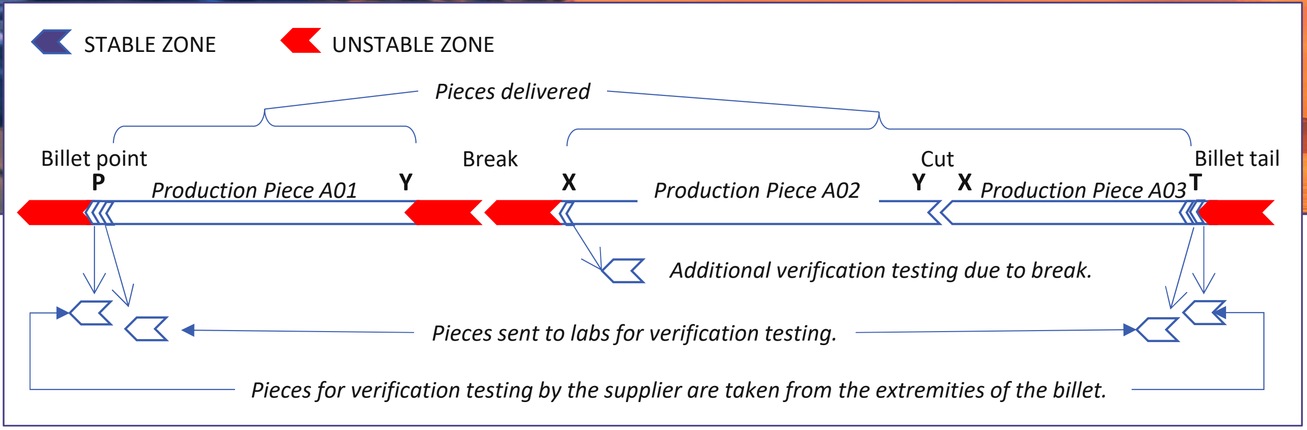
- Extracted strands (XS) from cables and a reference wire as witness make up plot data
- Measurements at 1.9 K would be very expensive to the project

Much credit is owed to Jack Ekin for this "ESE" scaling workbook!

I Pong, B Bordini, A Ghosh, others have also contributed

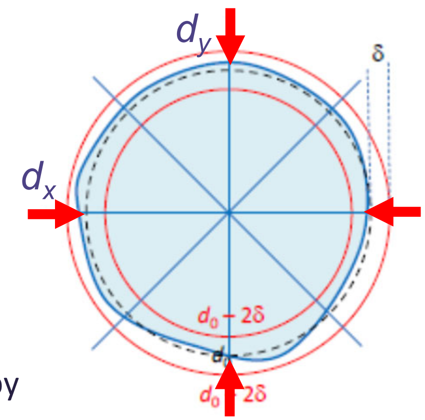


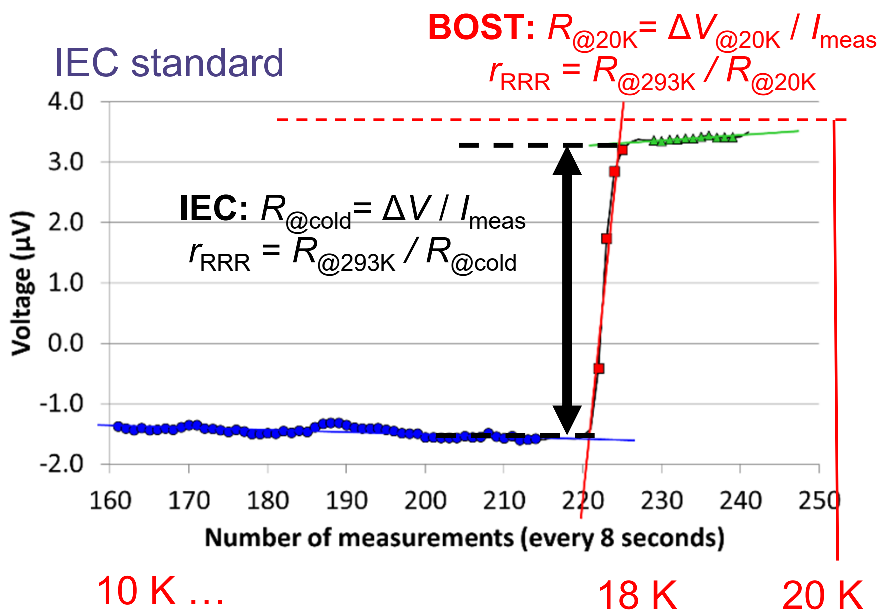
Quality plan



Generally:

- 3 measurements of Ic, RRR
  - Point, Tail, and first break or cut
  - Performance incentive: reduced QC test frequency if Ic(15) > 360 and RRR > 200
- Diameter measurements per meter: 1.3 (2016-2018), 13.4 (2018-2022)
- Exception: RRR uses R(20K) at supplier, R(IEC) at lab
  - Consistent 15% difference validated by inter-laboratory comparison
  - Supplier's method is *conservative*





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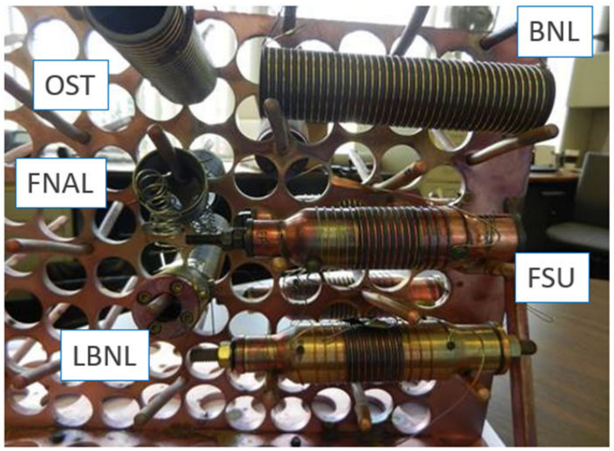
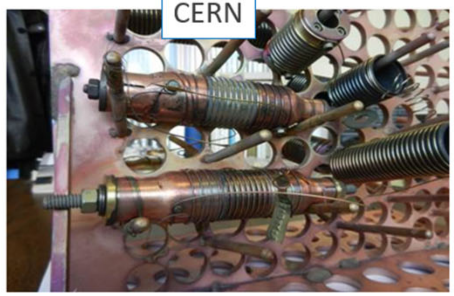
Benchmarking and inter-laboratory comparison

LARP

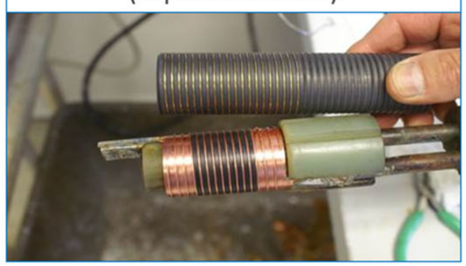
Benchmarking
Photos of the reaction barrels - OST

High Luminosity LHC





OST's reaction barrel and test probe (copied from BNL)



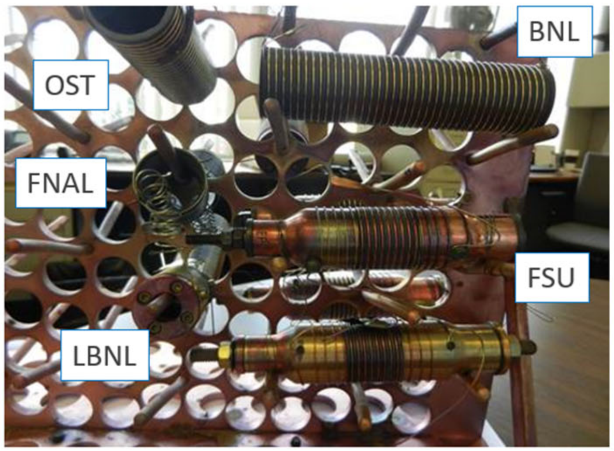
One spool of wire was used to distribute test lengths to each lab. Reaction barrels were wound at labs and returned to OST for reaction at same time in same furnace. Reacted samples were returned to labs for individual tests. (True round-robin testing is not possible due to differences in probes and magnets.)

Benchmarking and inter-laboratory comparison

LARP

Benchmarking
Photos of the reaction barrels - OST

High



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LARP

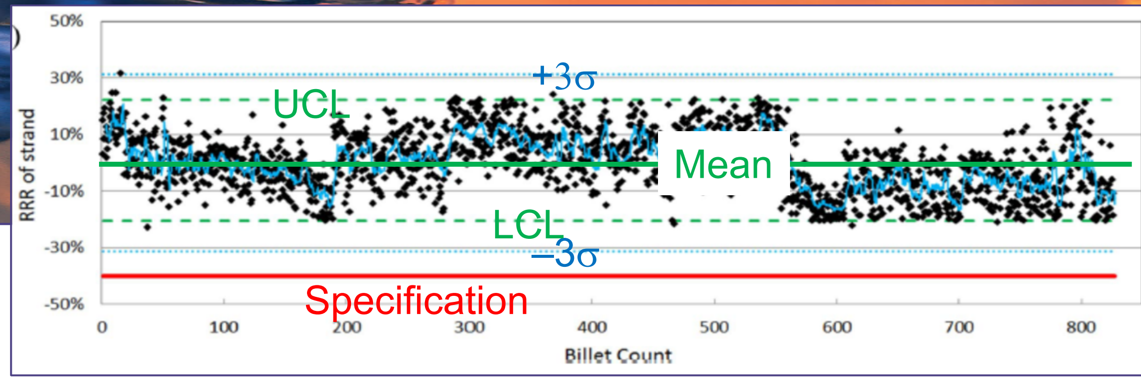
Critical current benchmarking results

High Luminosity LHC

Lab / sample	Ic(15T) – 331 A	Ic(14T)	Ic(13T)	Ic(12T) – 632 A
BNL 1, 2	410, 413	501, 504	605, 609	722, 726
CERN 1, 2	395, 400, 406	487, 497	590, 600	708, 711, 723
FNAL 1, 2	401, 395*, 414†	493, 487*, 510†	598, 590*, 617†	717, 708*, 739†
FSU 1, 2	396, 399	487, 488	591, 591	709, 708
LBNL 1, 2	401, 404	492, 496	596, 599	714, 718
OST 1, 2	411, 402	502, 497	611, 604	728, 724
AVERAGE	403	495	600	718
STDEV	6.6	7.3	8.8	9.3
COV	1.6%	1.5%	1.5%	1.3%

5 test labs plus one supplier are qualified to perform this QC test

Statistical process controls: A lesson from ITER

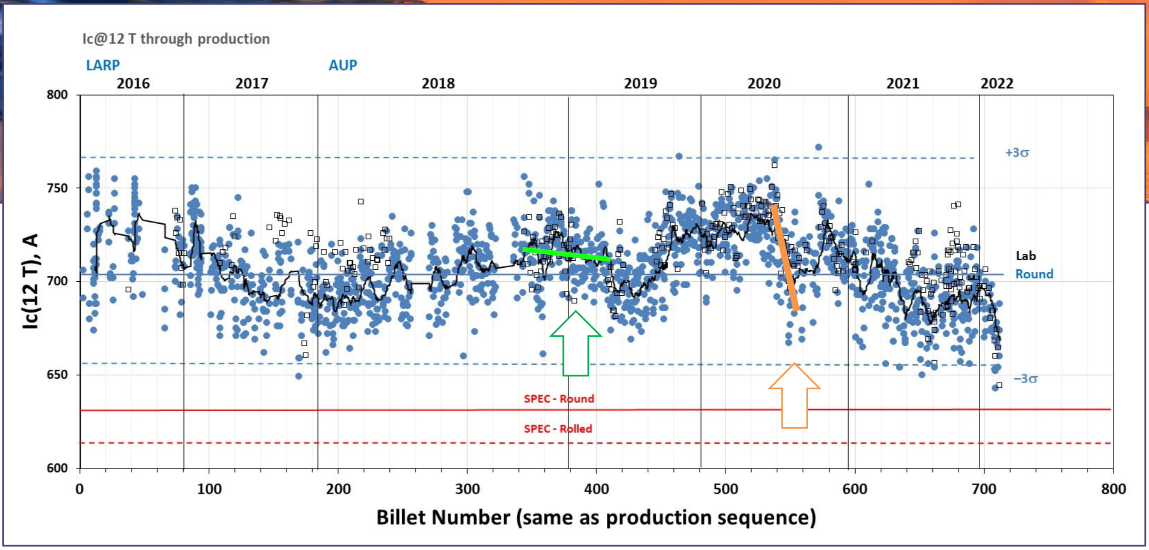


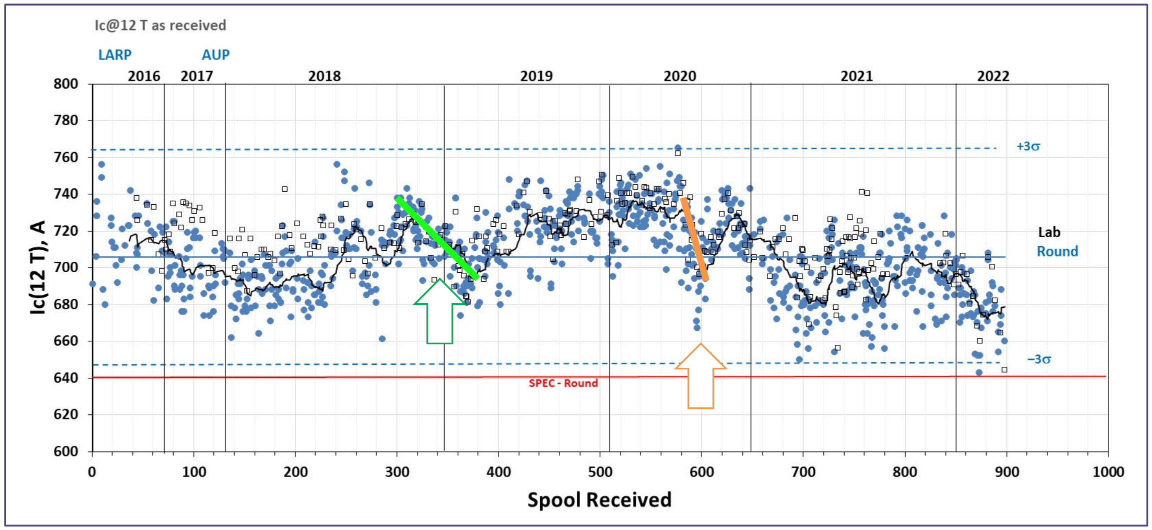
Vostner et al., *Supercond. Sci. Technol.* **30** (2017) 045004

- We took the attitude that this procurement cannot fail!
  - It is the first large procurement of this type of wire
  - The magnets are beyond state of the art → unknowns are certain to be revealed
  - We wanted to develop a spirit of *trust*, instead of mistrust, with the suppliers
- We needed to be able to spot process shifts to work with suppliers to implement corrective and preventative actions (CAPAs) as soon as possible
  - Isolated deviations: individual inquiries without impact on overall production (common sources)
  - Process shift: Inquiry, possible production audit (special sources)
    - Nelson rules: 9+ points on one side of mean = bias, 6+ points up or down = trend, 14+ points alternate around mean = oscillation, 5+ points at $\pm 2\sigma$ = control shift
  - Loss of process control: Possible audit and halt, with requalification on restart

SPC as production comes in

- Data came in batches, and did not include data that went elsewhere
- Communication was needed to signal problems
  - 2018-2019 event: AUP data indicated a downward trend, but overall data did not verify a trend.
  - Mid-2020 event: Both AUP data and overall data correlated to an event → production inquiry was called

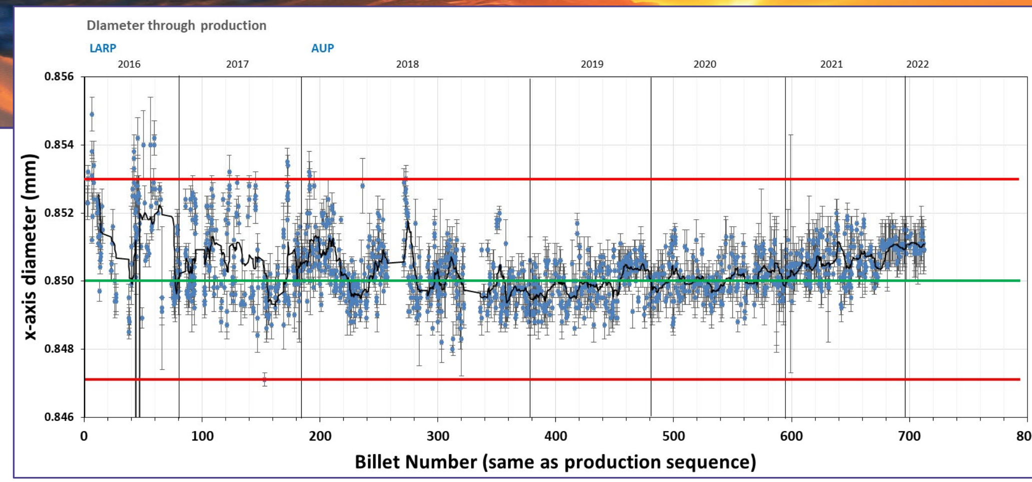


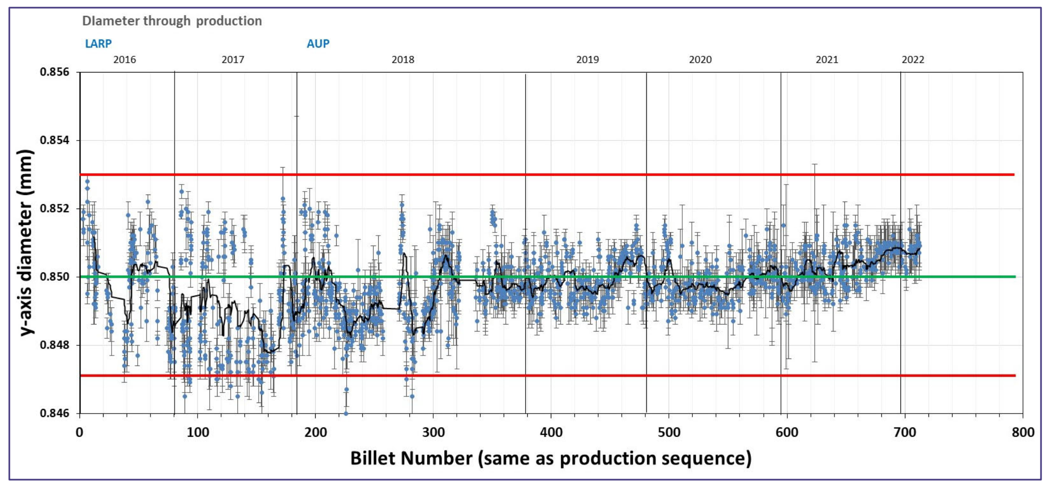


IEEE-CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), March 2023. Plenary presentation 5PL1A-01 was given at Applied Superconductivity Conference, Honolulu, HI, USA, October 28, 2022.

An early test of SPC was diameter control

- Prior to 2018, supplier's equipment reported a diameter and an ovality
  - While 2 axes were measured, the larger of the two was arbitrarily assigned to dx, with dy = dx - ovality
  - This led to skew in monitoring diameter.
- CAPAs:
  - New 2-axis laser-mic same as labs
  - Prevent strand vibration at the laser-mic
  - Improved die cleaning and retiring
- After 2018, a 2 µm tolerance was kept





IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 29, NO. 5, AUGUST 2019 6001505

Diameter Quality Control of Nb_3Sn Wires for MQXF Cables in the USA

Ian Pong, *Senior Member, IEEE*, Lance D. Cooley, *Senior Member, IEEE*, Andy Lin, Hugh C. Higley, and Charlie Sanabria

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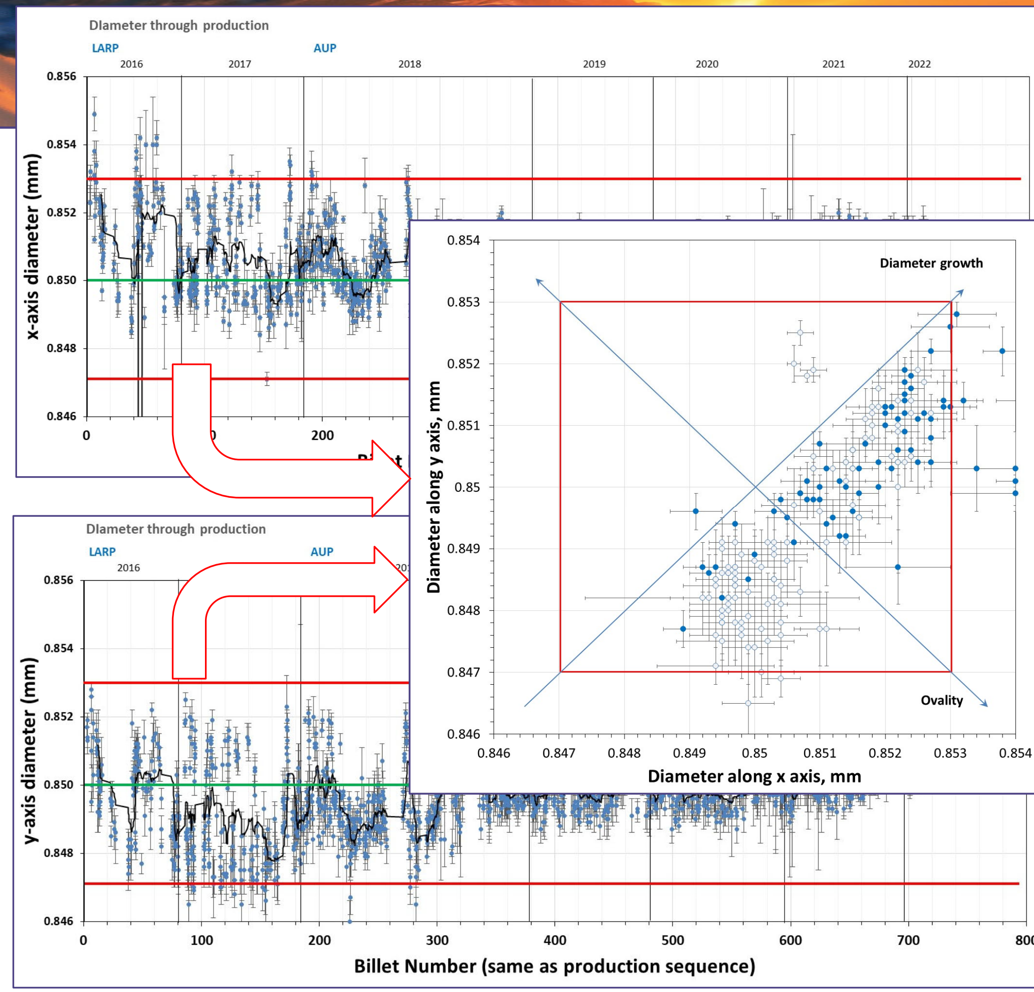

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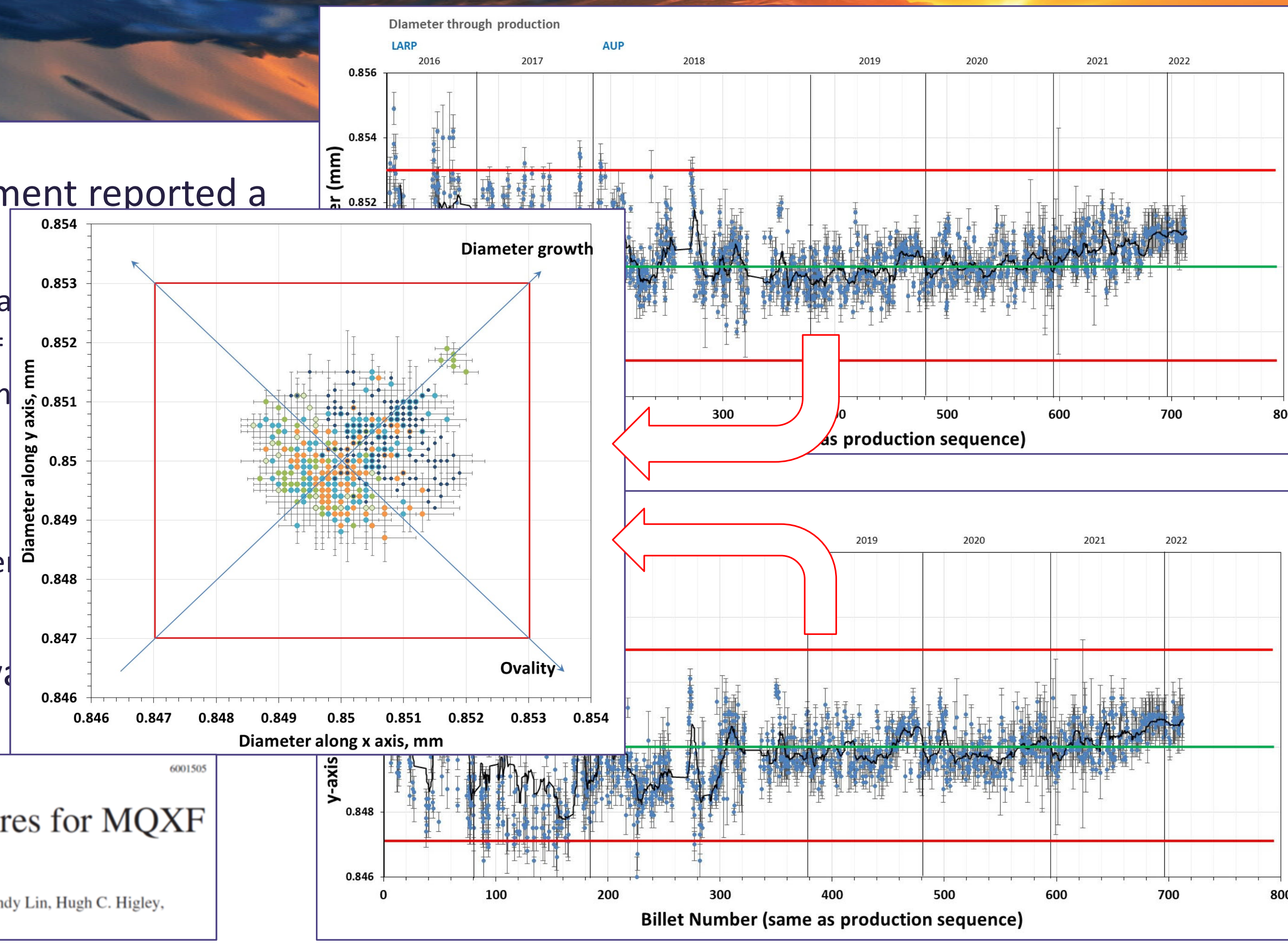

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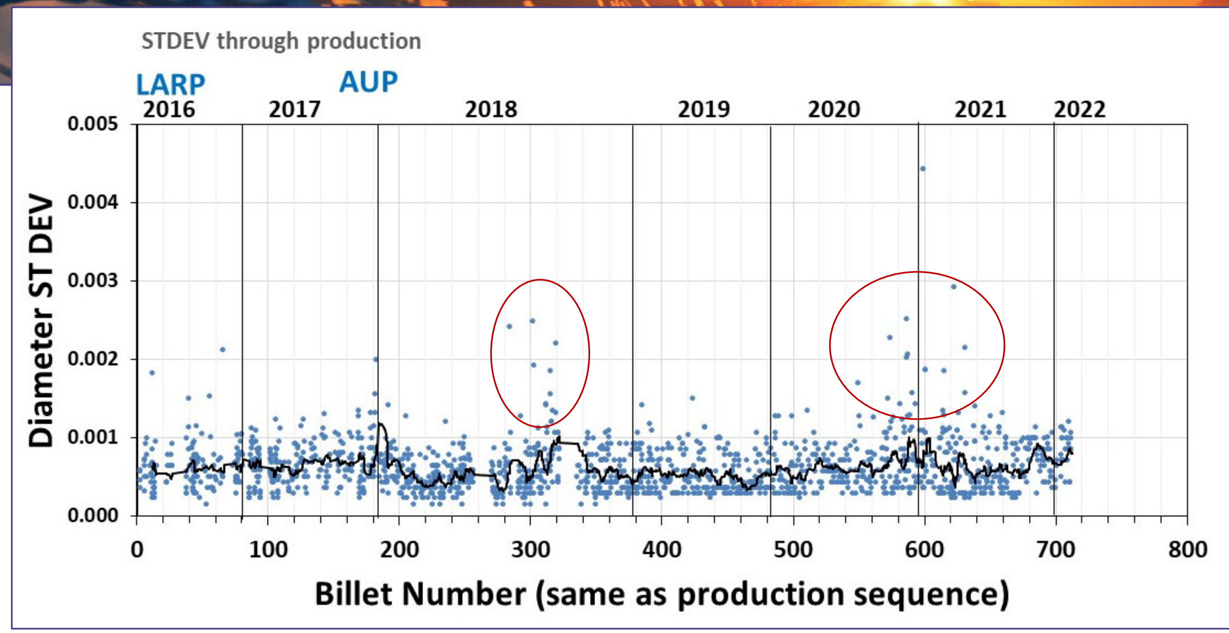
Diameter statistics were sensitive enough to pick up surface quality issues

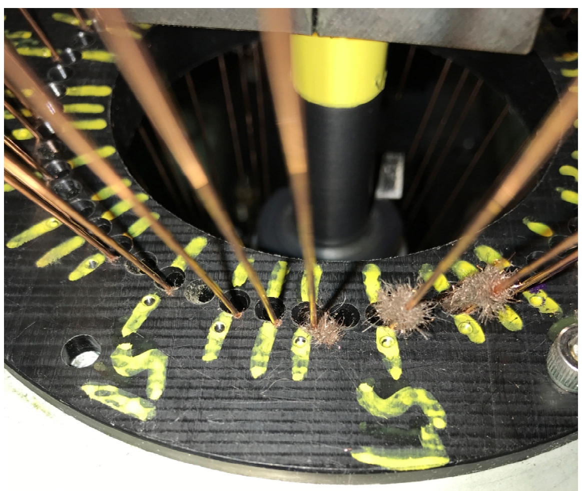
Incident: Conductor with surface scratches cut into cable guides upstream of turkshead

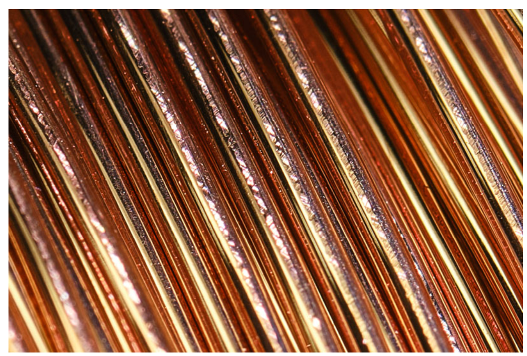
Threat: crossover and failed cable

Causes: wire not following guides, leading to scrapes; final scan trigger points not sensitive to problem

CAPA: improved wire paths and pathway locks; revision to final scan settings







Critical current at 15 T is most sensitive to process variations

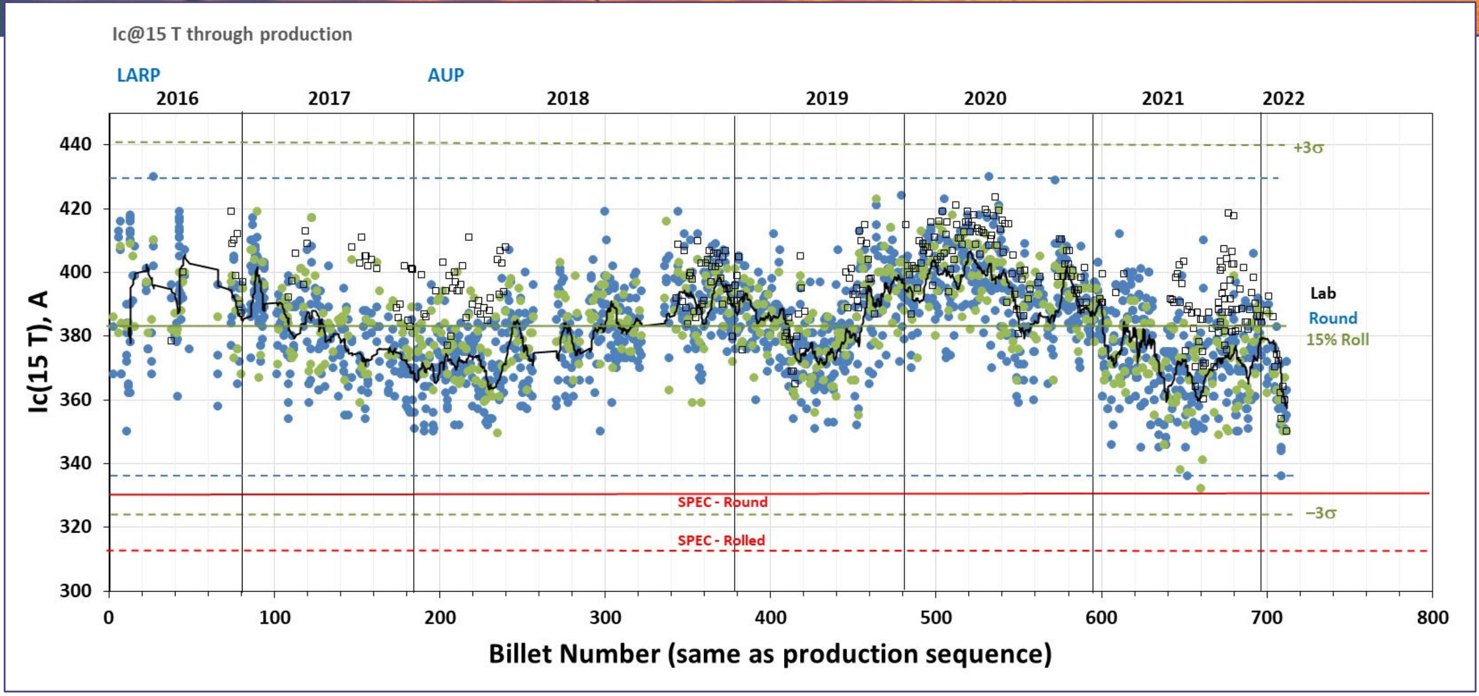
The robustness of the RRP strand after rolling is clearly demonstrated here

1,751 measurements
Average = 381.7 A
S.D. = 15.1 A (3.9% of mean)
Process capability C_{pk} = 1.10 (round) and 1.15 (rolled)

C_{pk} = (mean – spec) / 3σ

A value between 1.0 and 1.25 for a one-sided spec is "barely capable"

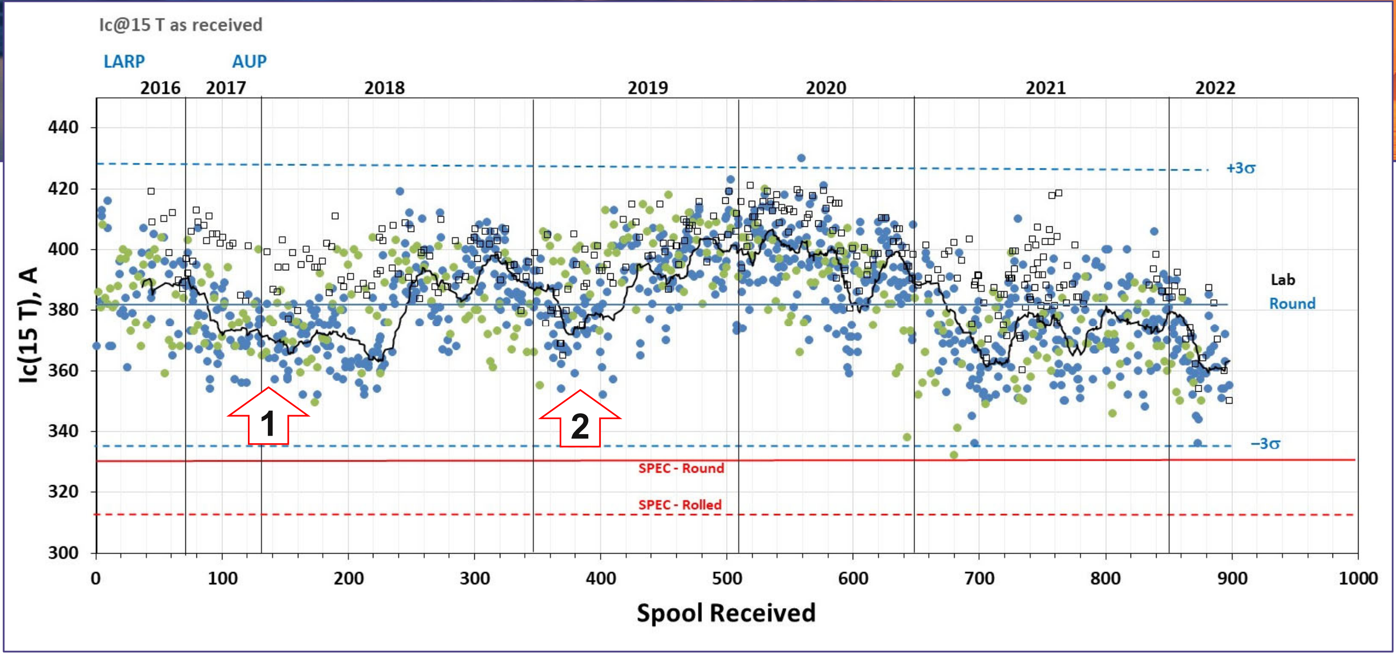
The process is "capable" for Ic(15T) specified at 324 A.



Process tweaks from Ic(15T) data

1 – Verification lab did not implement new HT schedule (665°C/50h) in quality plan, kept old HT (665°C/75h)

2 – Process inquiry related to performance drop. Possible natural variation due to raw material.



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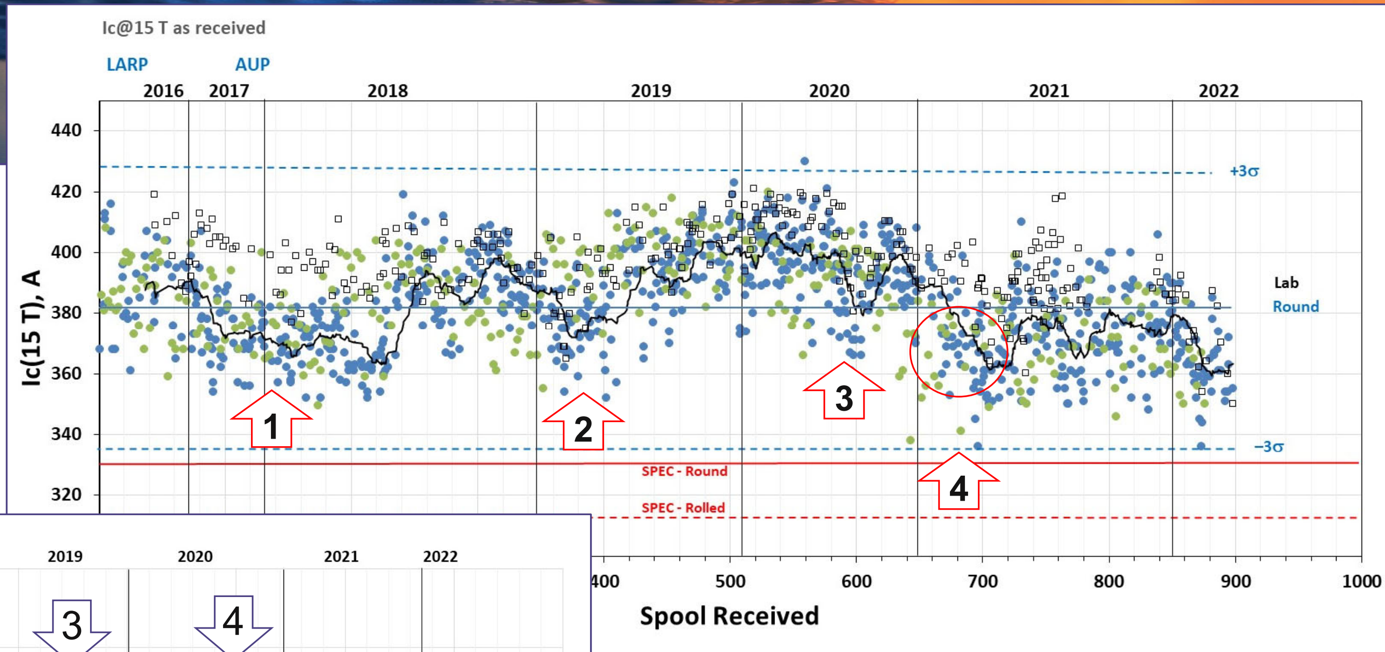
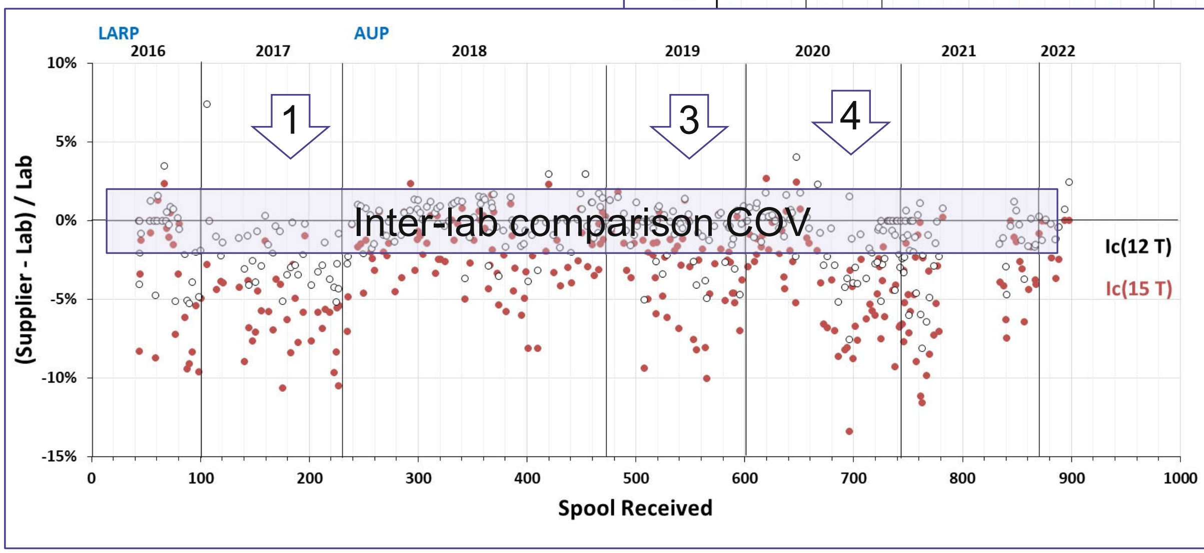




3,4 – Loss of reliability of QC measurement, supplier 5% low or more. Possible Covid-19 contribution.

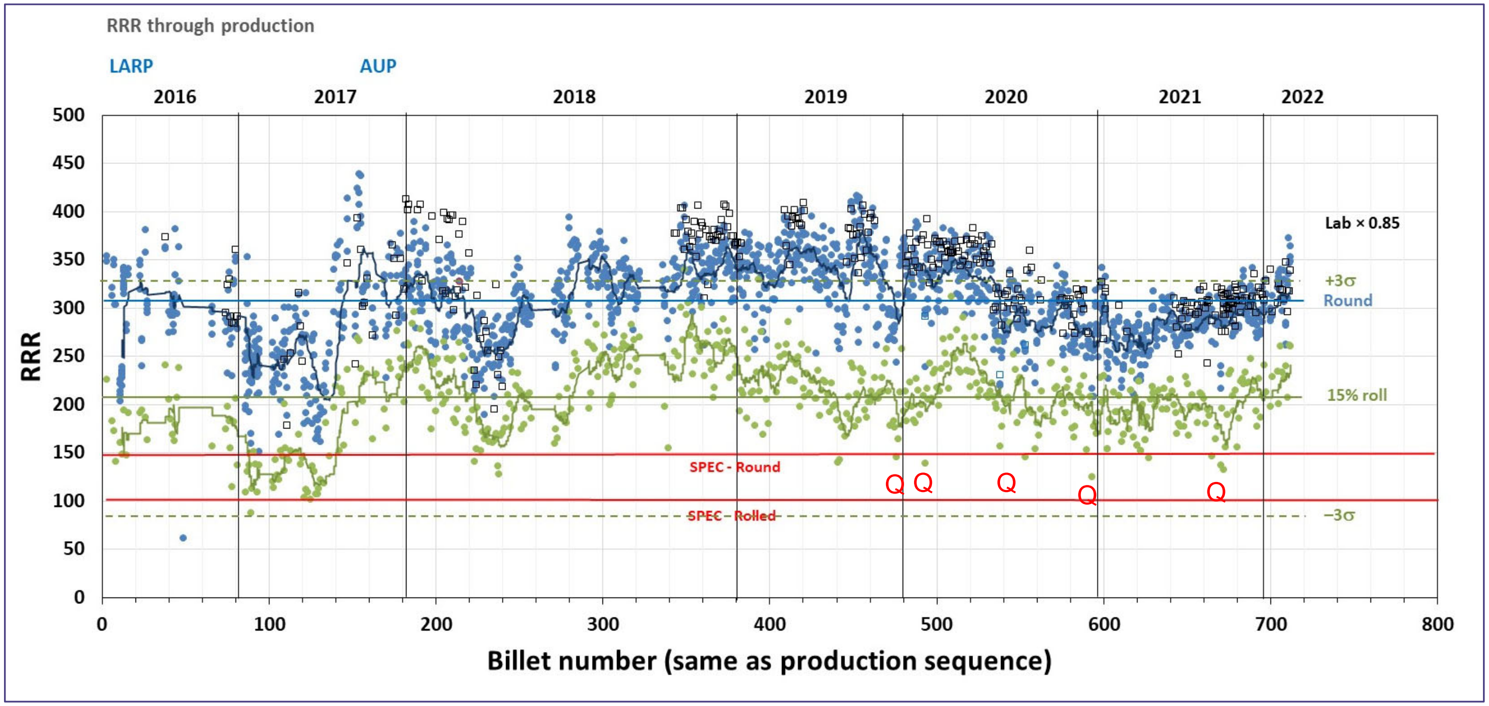
Production audit – CAPA: (a) 100% lab testing until recovery; (b) review of procedure suggested higher strain from mounting procedure; (c) P/M of supplier furnaces, thermocouple recalibration, other steps.

RRR: Rolled strand must withstand ~30% degradation

Rolling the strand simulates cabling degradation. Sub-elements shear, creating regions where tin can leak into the copper.

Round: average RRR = 308.2
S.D. = 42.5 (13.8% of mean)
C_{pk} = 1.24 (“capable”)

Rolled: average RRR = 211.0
S.D. = 38.2 (18.1%)
C_{pk} = 0.97 (“barely capable”)



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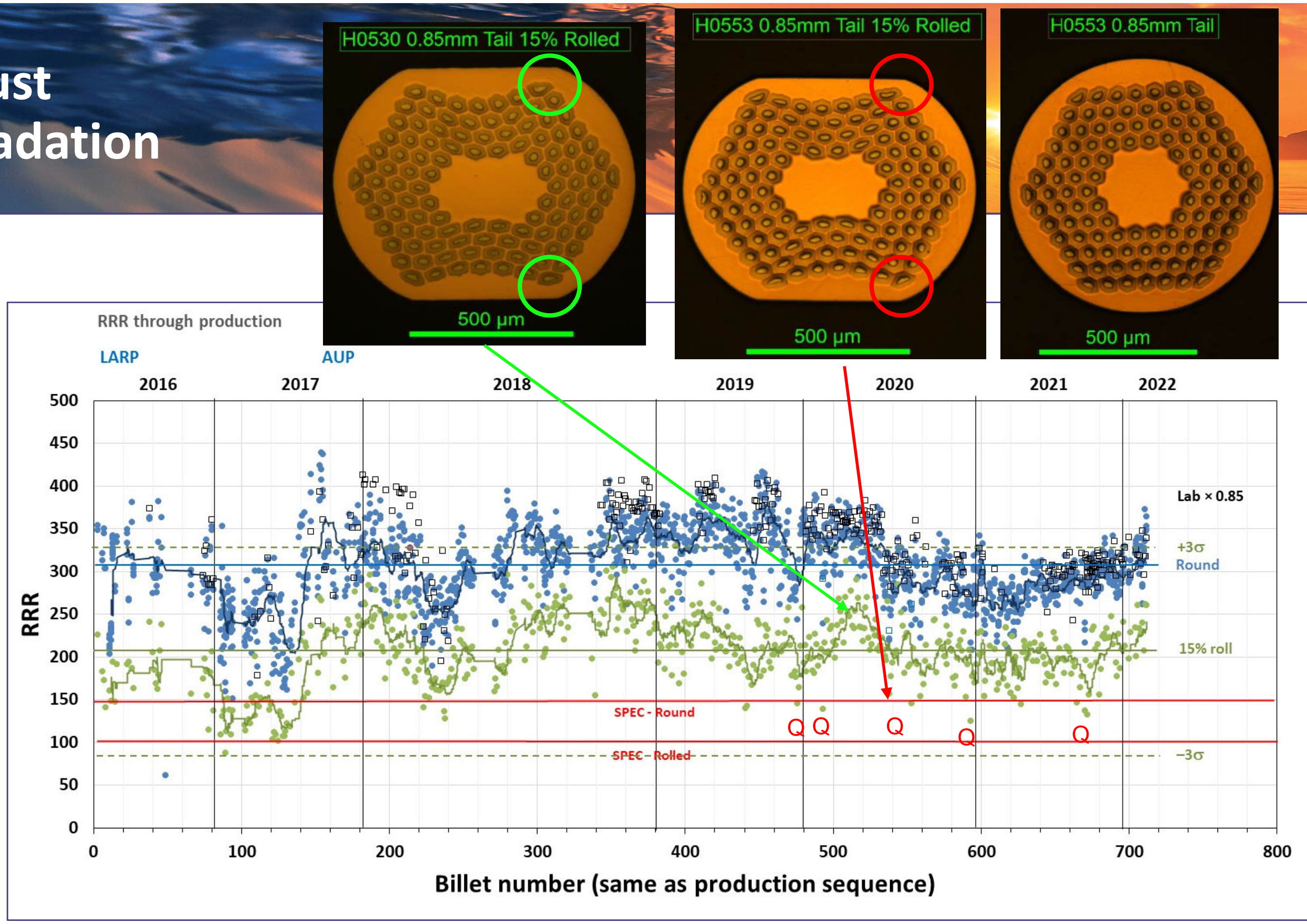
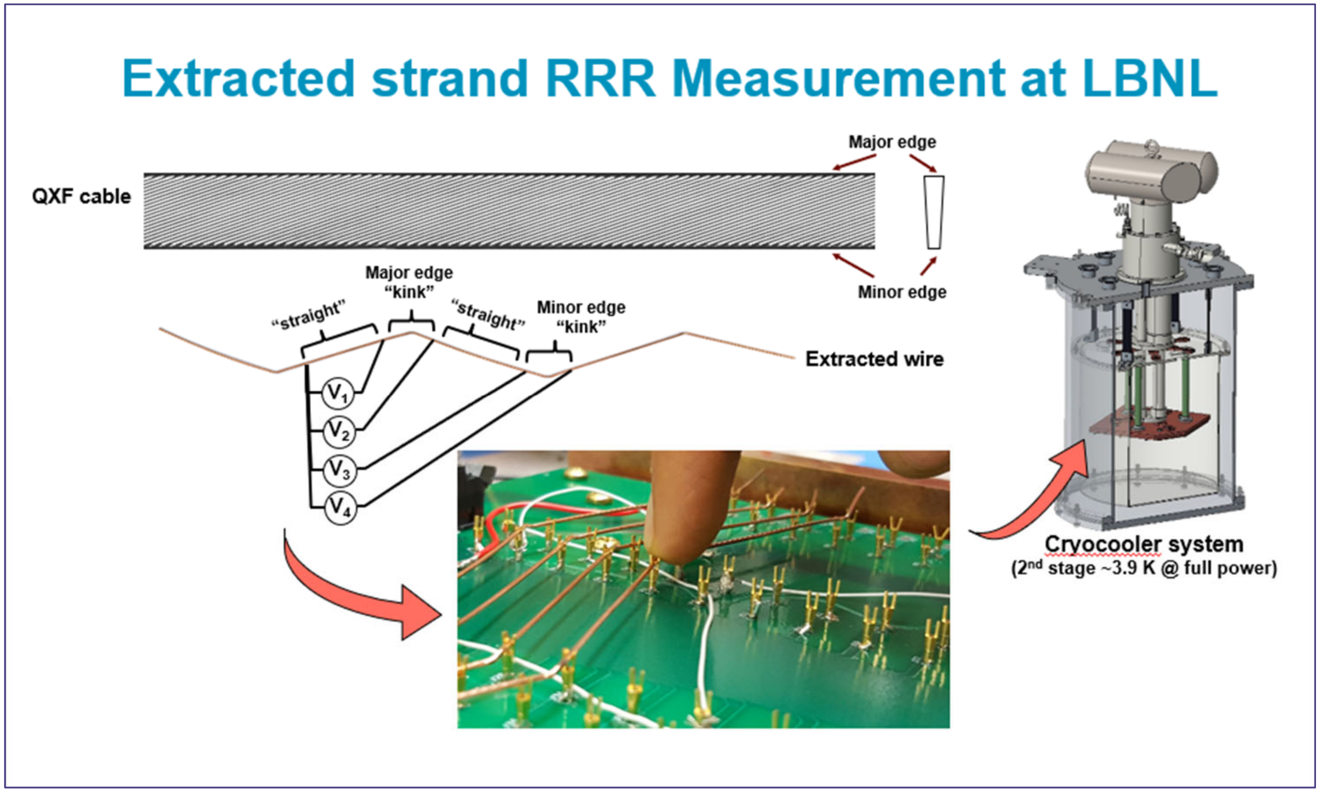


Rolled strand is a good predictor of cable performance

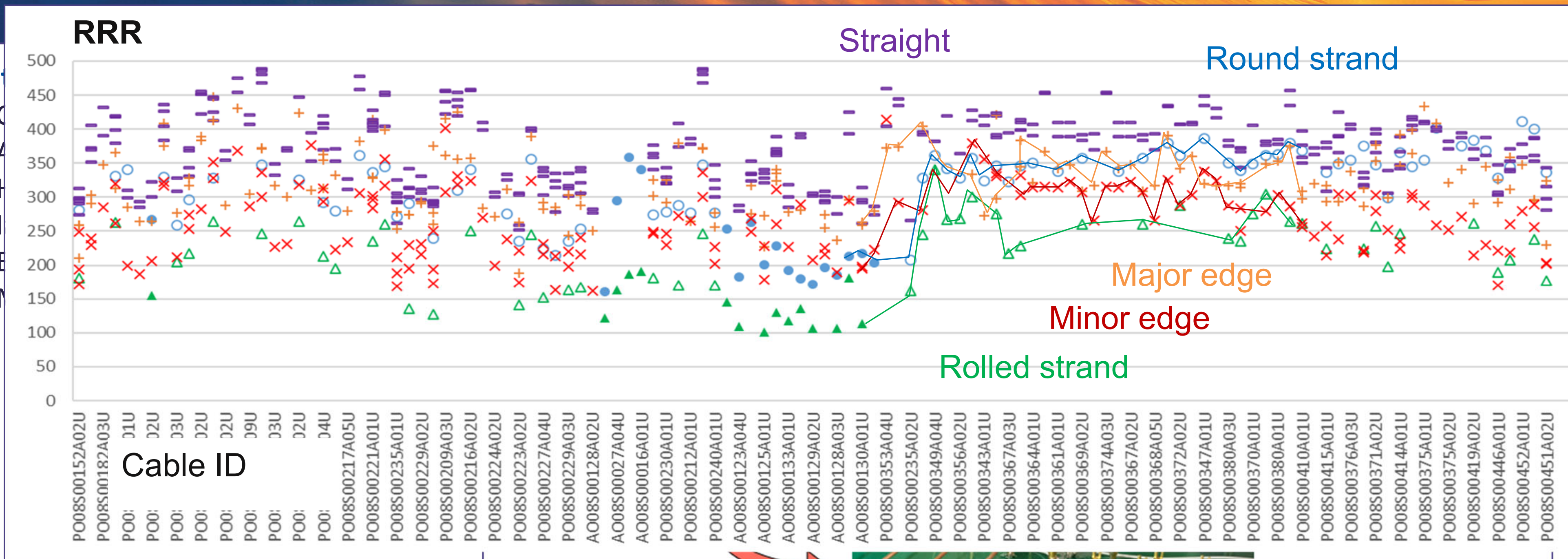
Credit to the innovative team at LBNL:

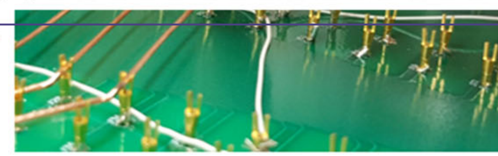
Charlie Sanabria (then postdoc)
Andy Lin
Hugh Higley
Ian Pong
Elizabeth Lee
Mike Naus



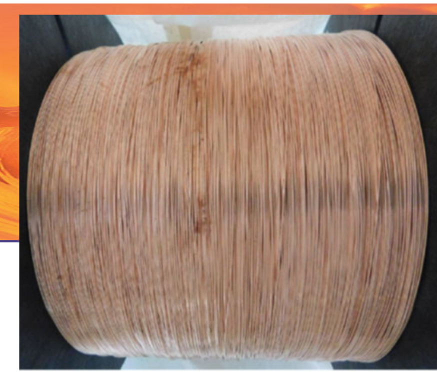
Rolled strand is a good predictor of cable performance

Credi



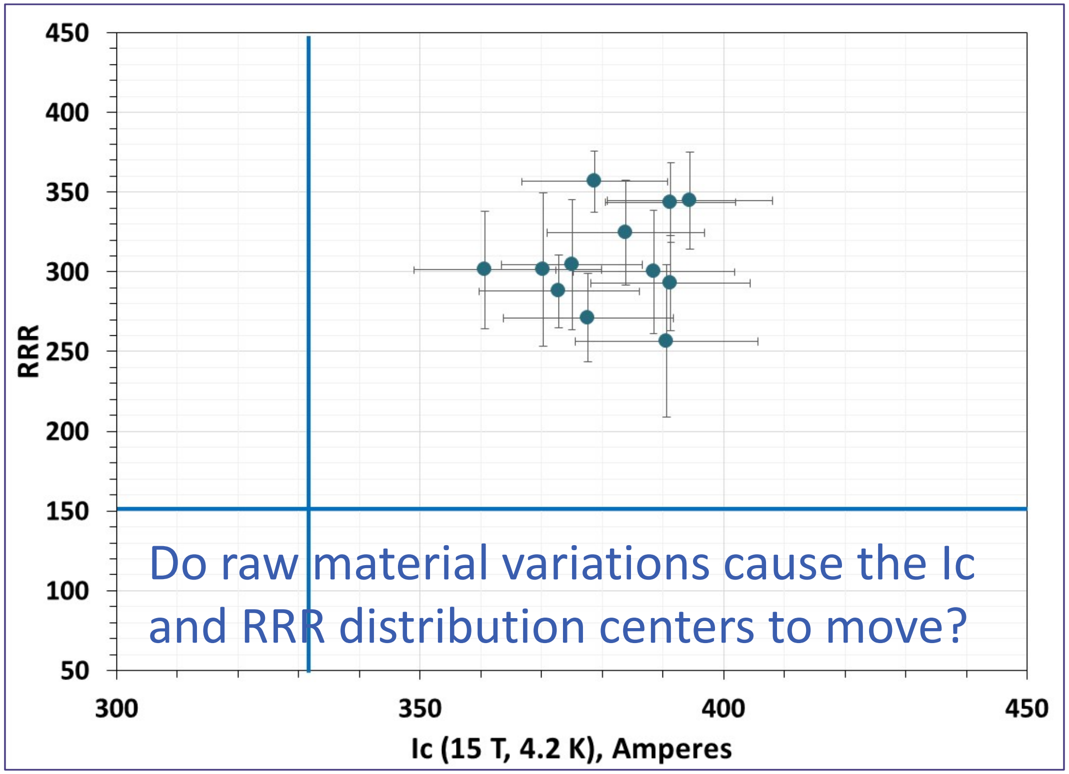


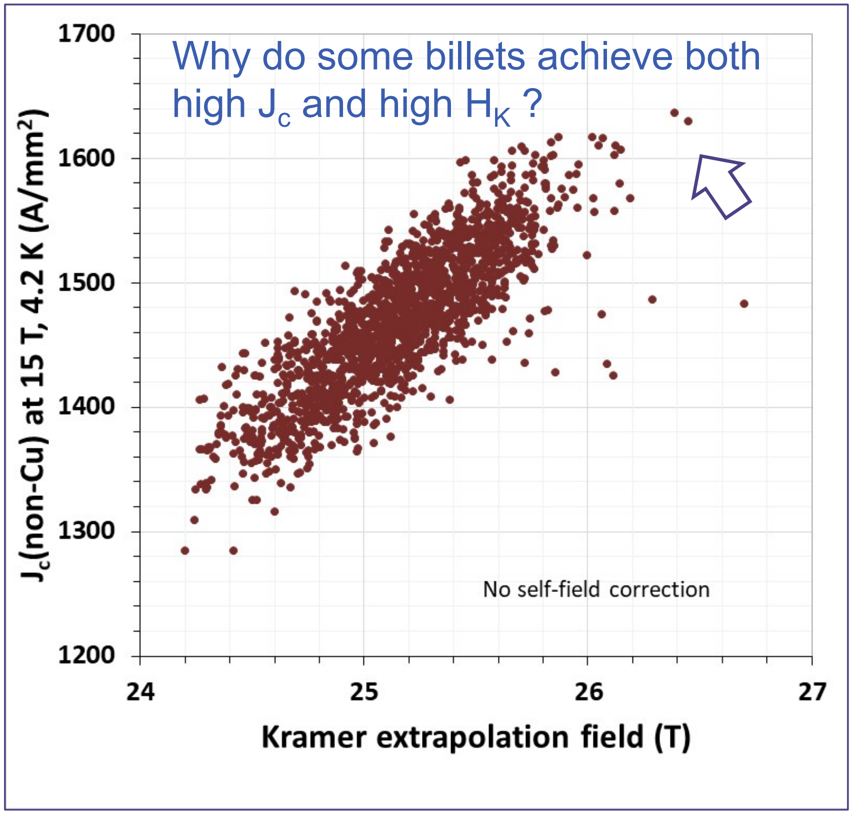
Excess lubrication: a risk not known prior to the project



- Lubrication is necessary at all wire drawing steps, including final inspection
  - The final die size or a guide die is required to maintain tension and suppress vibration at the laser mic
- Residual lubrication is not captured in the specification
  - Too little → strand is not adequately protected from environmental effects
  - Too much → possible lost cables and coils
    - Strand slips along length counter upon respooling for cable run → mapping loss
    - Cables suffer more strand popping, possible crossovers and stress concentration in coils
- CAPA: (1) revised procedures at inspection; (2) wiping on respool line before cabling; (3) various cleaning steps were successful

Other characterizations now ripe for data mining

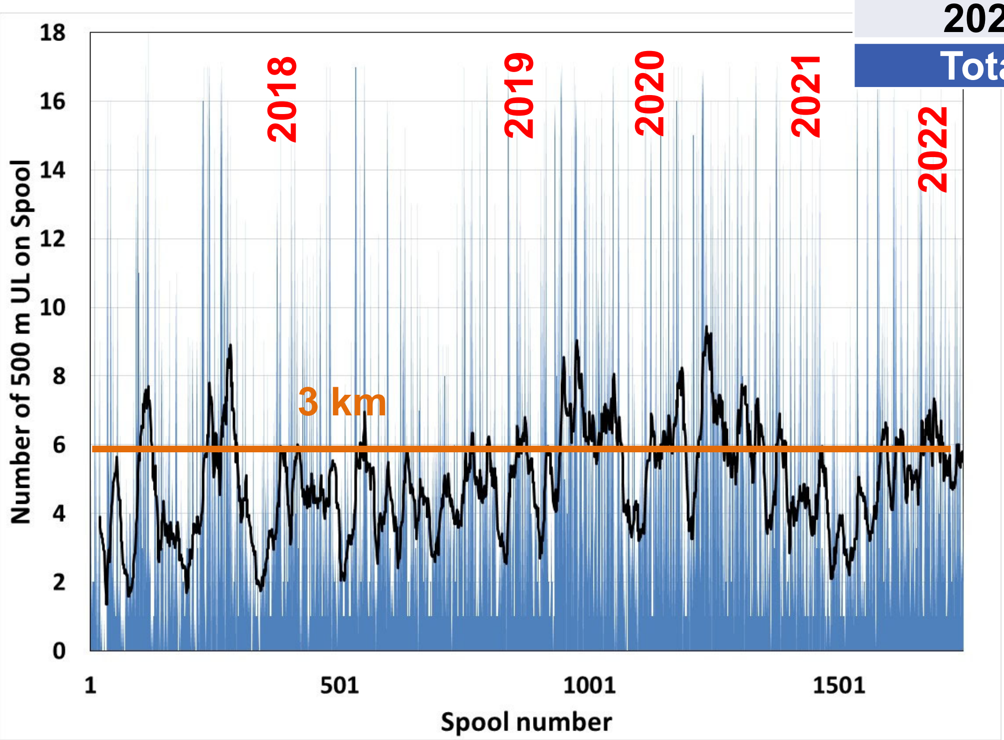


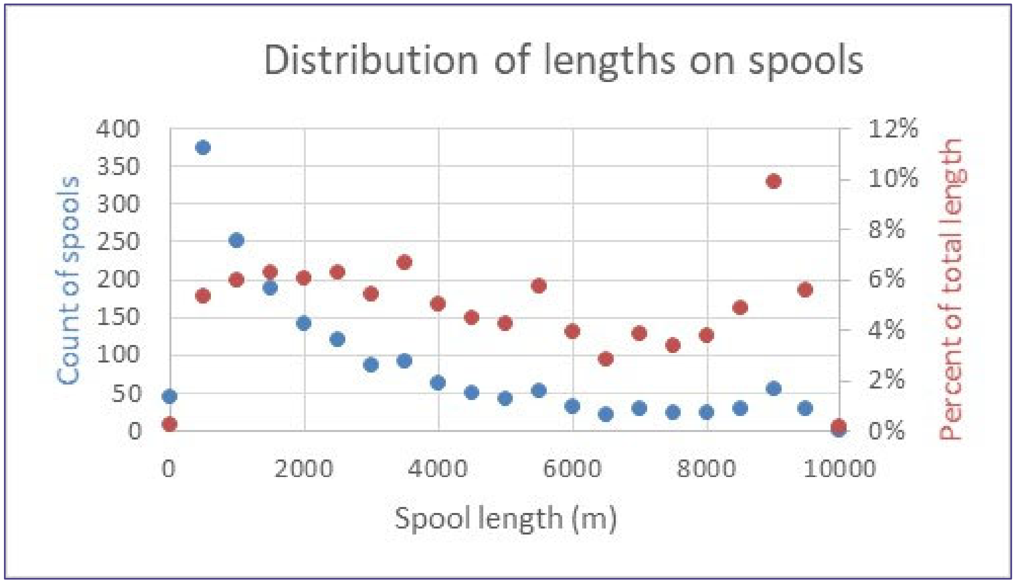


Production length statistics

Year	Spools	Length (m)	Invoiced	Max (m)	Avg (m)
2016	144	366,363	349,938	9,900	2,544
2017	270	742,394	702,030	9,570	2,750
2018	467	1,252,695	1,189,360	9,696	2,682
2019	265	913,683	878,560	9,783	3,448
2020	270	990,467	954,200	9,800	3,668
2021	284	772,098	733,460	9,717	2,719
2022	50	154,297	146,460	9,767	3,086
Total	1,750	5,191,997	4,954,008	9,900	2,967

1 billet drawn in 1 piece = 9,250 m





Production summary

Overall manufacturing yield was 97%

Total length delivered / total possible length

High yield was due to complementary unit lengths for cables

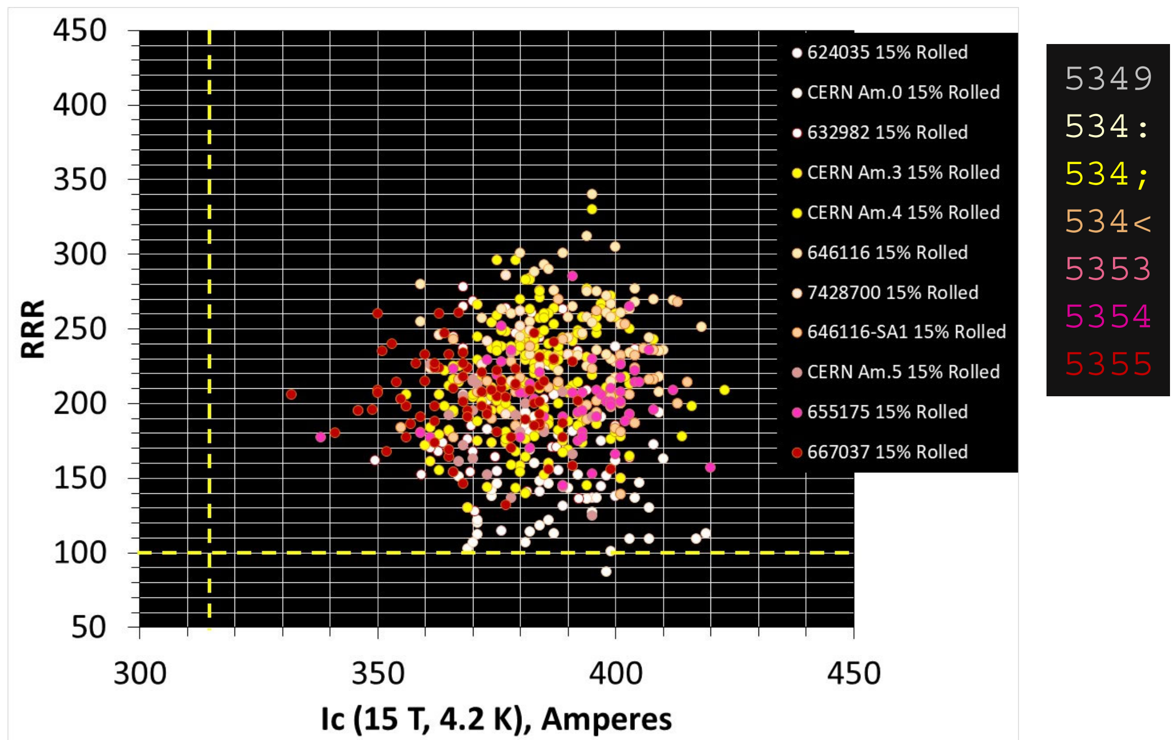
AUP 500 m, CERN 840 m

Spool remnants were exchanged to minimize mapping loss

Typical spool length was 3 km

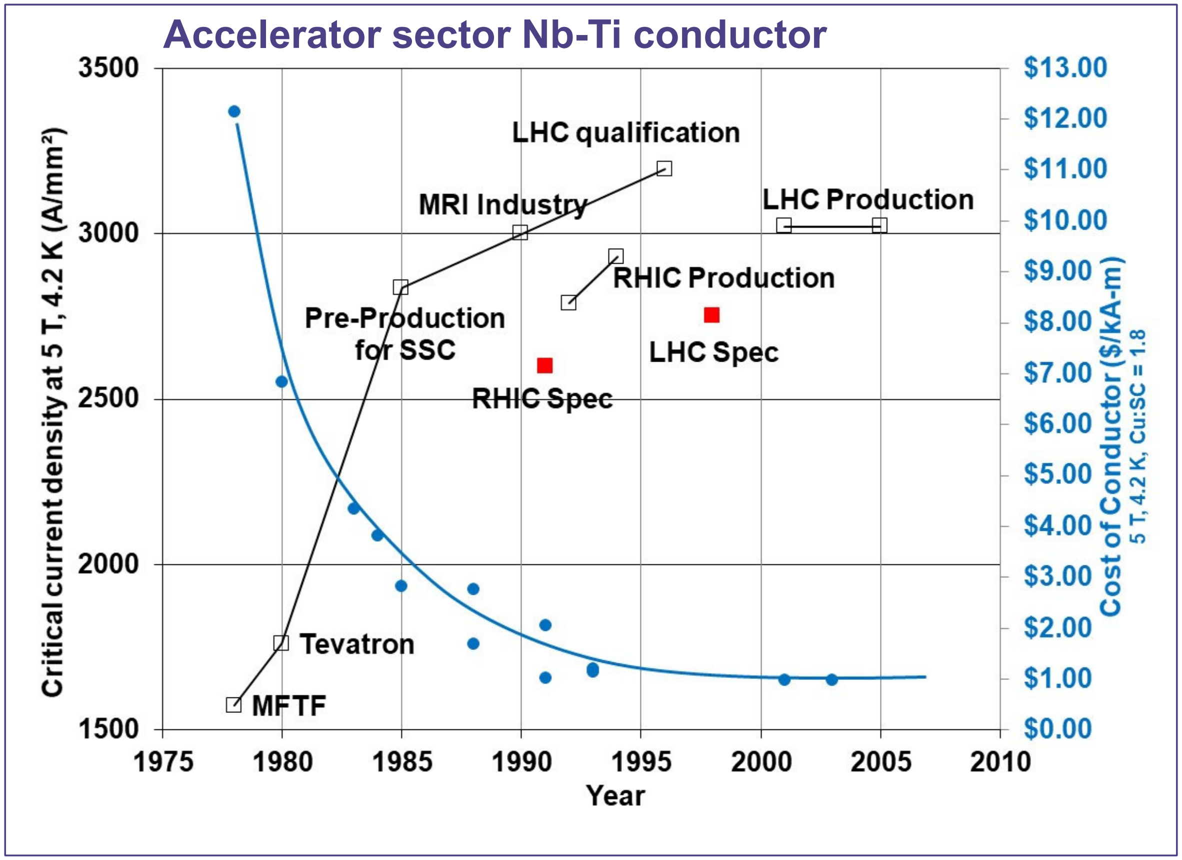
Also seen for ITER manufacturing for some internal-tin suppliers

15% rolled strand data cloud



What happens now that the HL-LHC production run is over?

The business model we want is not the one we have, unfortunately.



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What happens now that the HL-LHC production run is over?

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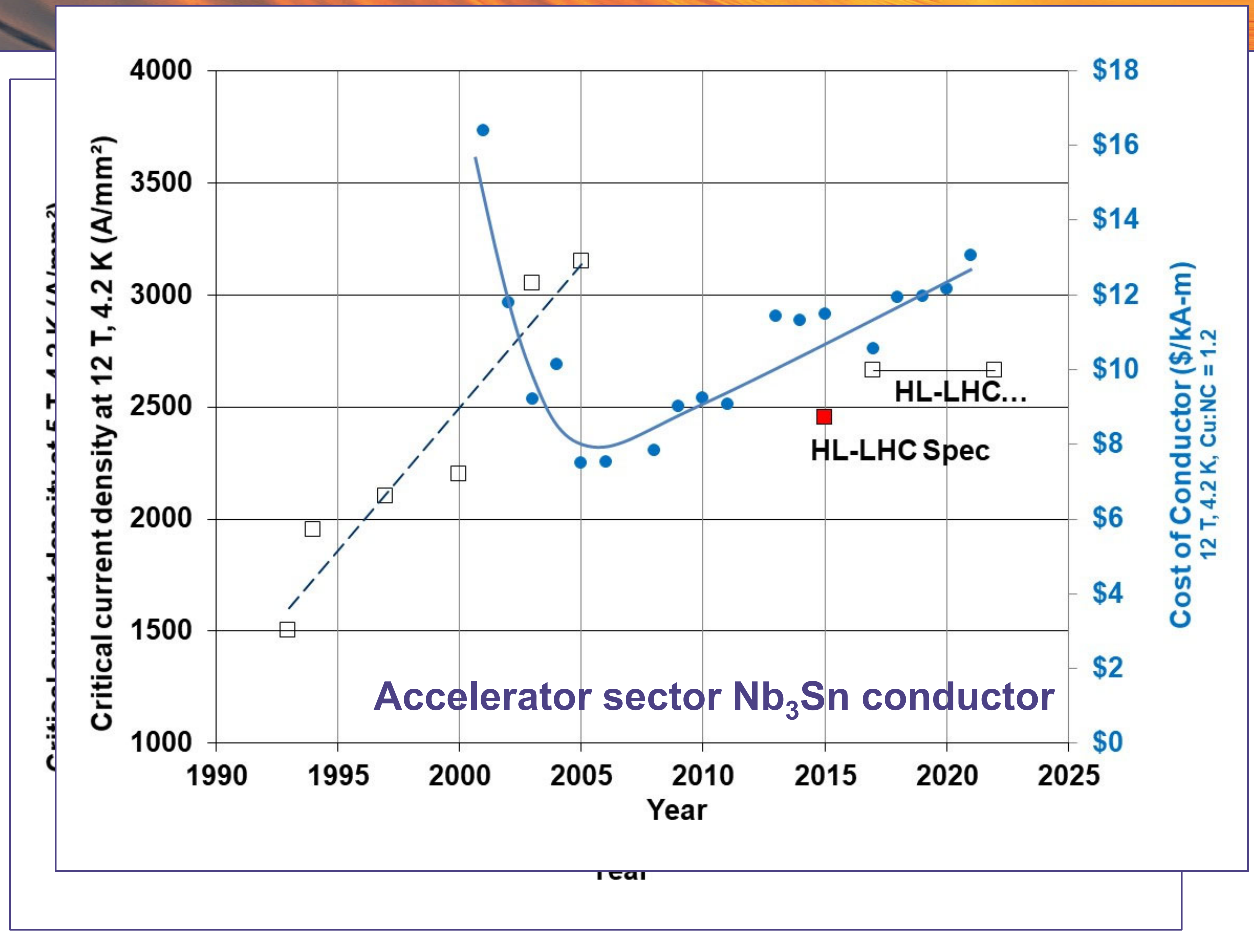
The accelerator sector cannot keep manufacturing "warm" by itself.

How might the accelerator sector engage more broadly with the commercial ecosystem to achieve scaling necessary for a large facility in the future?



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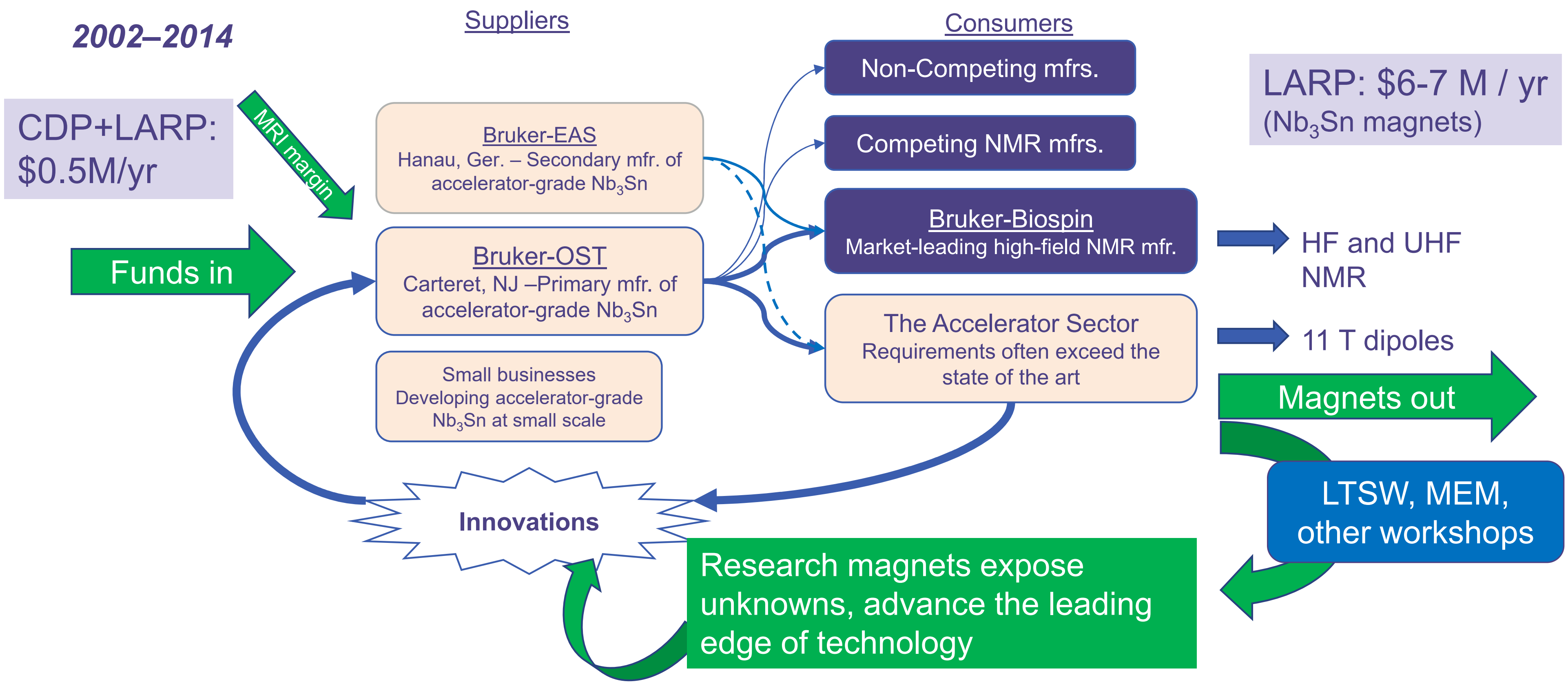
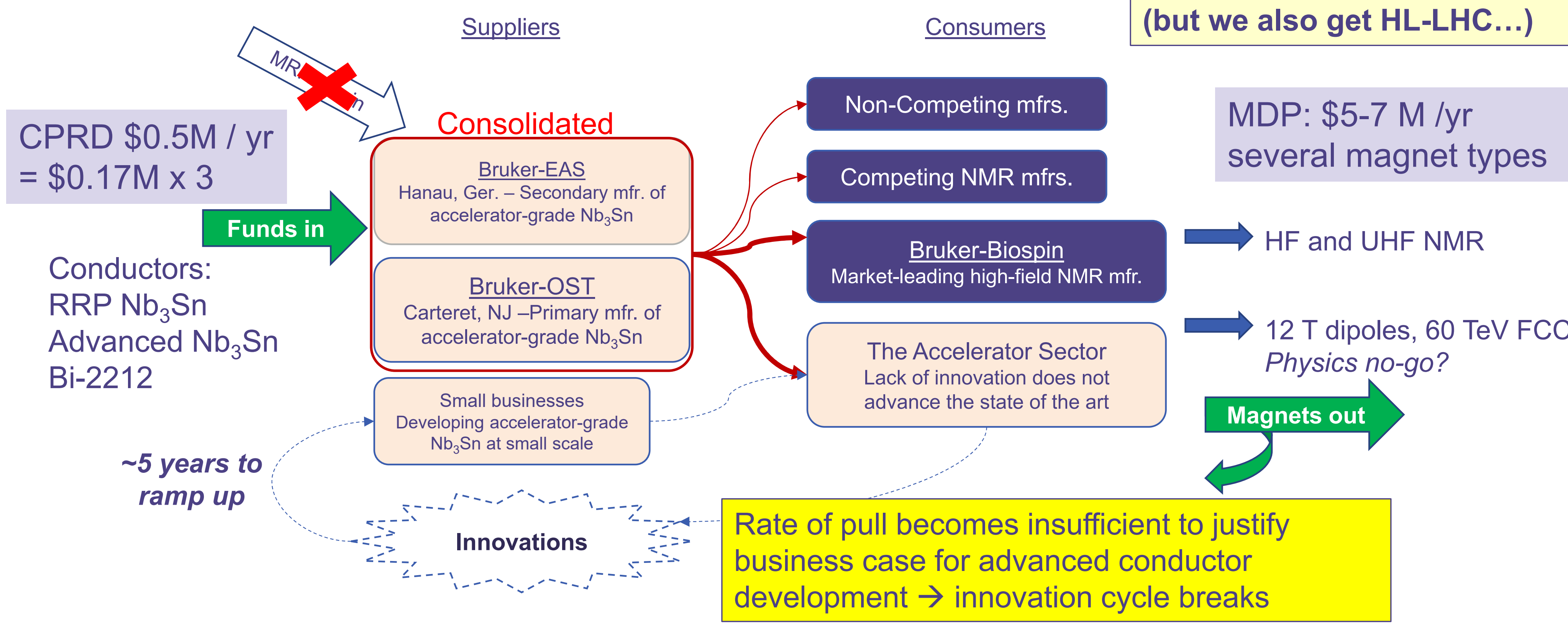
We know how to do this: A healthy public-private partnership advanced conductors and magnet technology for HL-LHC



Threat: Market forces compel consolidation by suppliers, innovation cycle breaks

P5 (2013): more projects, less R&D → MDP, CPRD funded below LARP and CPD

(but we also get HL-LHC…)



Stewardship of the Accelerator Sector by the DOE Office of Accelerator R&D and Production (ARDAP)

ARDAP Workshop on the Development of Business Models for Superconductors in the Accelerator Sector Supply Chain

13-14 March 2022

Tufts University

US Army Col. (ret.) Steven Rotkoff
Advisor to the Joint Chiefs
Co-founder Red Teaming School

Prof. Whitney Hischier
Haas School of Business
Univ. California - Berkeley

Themes from stakeholder interviews prior to workshop:

- Distinguish *products* from development *projects*. Workforce for production is different than workforce for development.
- Distinguish *systems* from *components*. A magnet is often a component of a larger system.
- Critical shortages in talent exist, as well as needs for re-training and retaining existing talent.
- Critical supply chain challenges exist in materials and manufacturing.
- Timeline to get out of the business is as short as 18 months for some businesses.
- There are no feasible near term new commercial applications (for accelerator-grade Nb_3Sn conductor).
- Market forces are the single most important component to manage superconductor manufacturing.
- Must provide actionable items to DOE.

Chief workshop outcomes

- The accelerator sector (AS) drives technology forward, more so than any other sector.
- The AS must embrace the fact that it is wedded to an industry ecosystem, and therefore the AS should take actions that also serve the ecosystem.
  - For example, improve industry access to facilities at national laboratories and universities
- Funds into a public-private partnership need to triple or more. Upcoming P5 and National Academies panels should be given justification for emphasizing this message.
  - Magnet pull is the single strongest driver to keep manufacturing warm. Invest in magnet R&D.
  - A conductor stockpile or repository could help sustain demand, ameliorate supply chain risk, and possibly facilitate valley-of-death bridges for emerging commercial applications.
- Universities, who supply the talent pipeline, should also take on traineeship roles and connect with trade schools.
- Communications and marketing are essential to make careers in the accelerator sector attractive. Make superconductors sexy again!

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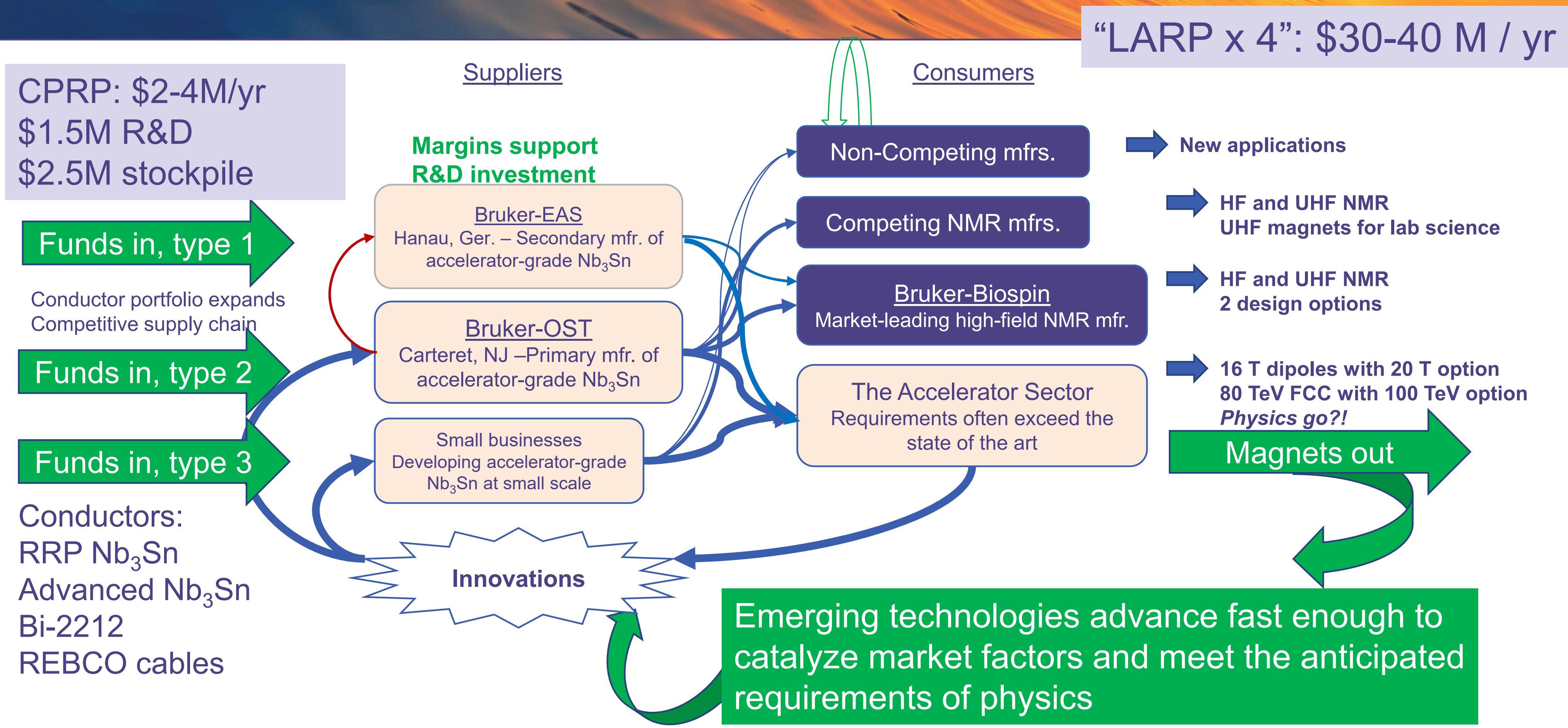
A desired scenario for a public-private partnership that addresses many workshop recommendations



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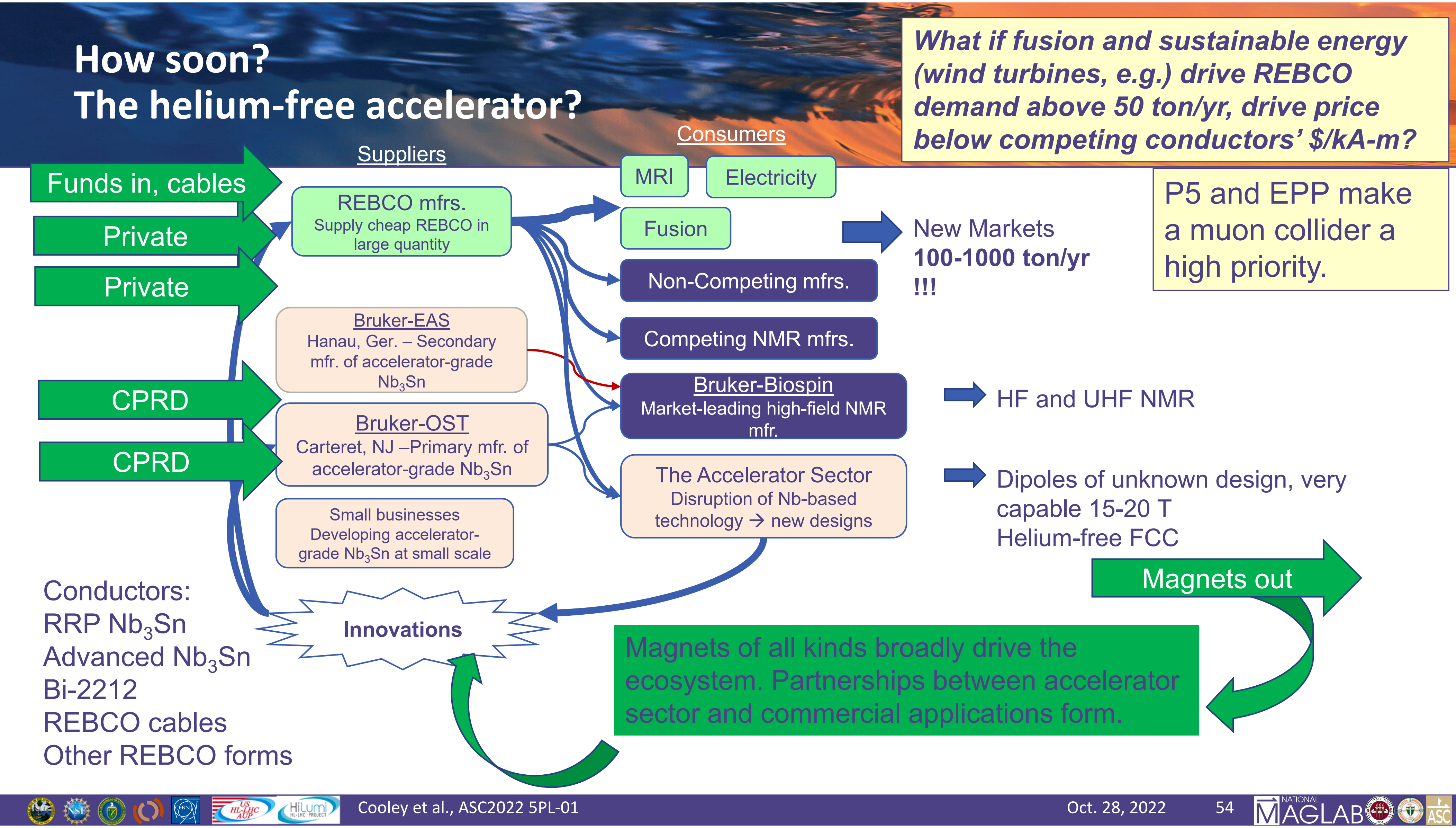

Discussion and Summary

- The ARDAP workshop motived the stakeholders to think more broadly in terms of the return on investment to the nation (or the world) for enhancing public-private partnerships in the accelerator sector. **We need to keep improving the message!**
  - **The Accelerator Sector must embrace and improve its relationship with the commercial magnet sector.**
  - **Ziad Melhem and the SC Future consortium have picked this up in a big way!**
- Magnet builds are the currency unit of the technology advancement cycle.
- While a potential 10,000-ton Nb_3Sn procurement for a future collider is not yet certain, Nb_3Sn will continue to be the conductor of choice for at least the next decade. We must continue to be stewards of this vital resource for magnet technology.
- Accelerator magnets (and NMR magnets) need homogeneous fields. Round-wire multifilamentary conductors (e.g. Bi-2212) have advantages.
  - Much credit to Bruker Biospin for proving REBCO NMR magnets at 1.2 GHz and 28.3 T! Will REBCO work in accelerator magnets?
- 1,000-ton/yr production of REBCO is like printing newspaper. How are we going to do this?

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Thank you

White paper on conductors in the accelerator sector:

Challenges and opportunities to assure future manufacturing of magnet conductors for the accelerator sector

Cooley, D Larbalestier, K Amm - arXiv preprint arXiv:2208.12379, 2022 - arxiv.org

The ARDAP workshop final report will be posted on OSTI.gov and ArXiv.org in ~1 month.

U.S. DEPARTMENT OF ENERGY | Office of Science | US MAGNET DEVELOPMENT PROGRAM | CERN | US HL-LHC AUP | HiLumi HL-LHC PROJECT

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY