Status of MQXF Conductor
LARP Update

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LARP/HiLumi Collaboration Meeting CM-24

FNAL

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Outline

- Introduction
- RRP® 108/127 Strand
  - OST strand production
- RRR Control
- Recent MQXF strand RRP® 132/169 and 144/169
- Strand Procurement Plan
- Cable
- Insulation
- Summary

Introduction

- The 150 mm aperture MQXF magnet program in LARP is presently using the RRP 108/127 Ti-Ternary strand.
- Strand specification
  - Strand Diameter, mm — 0.85
  - J_c(12 T) at 4.2 K, A/mm^2 — > 2650
    - I_c, A — > 684
  - J_c(15 T) at 4.2 K, A/mm^2 — > 1400
    - I_c, A — > 361
  - d_s, μm (nominal) — < 60
  - Cu-fraction, % — > 53
    - Cu/non-Cu — > 1.13
  - RRR — > 150
  - Piece length — > 750 m

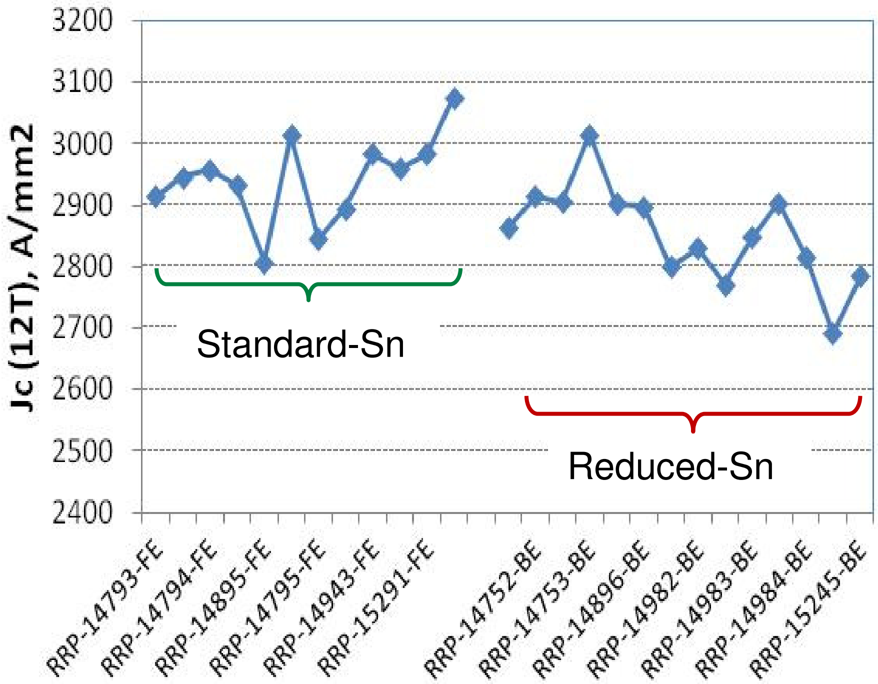
Ti-Ternary RRP® 108/127 Wire

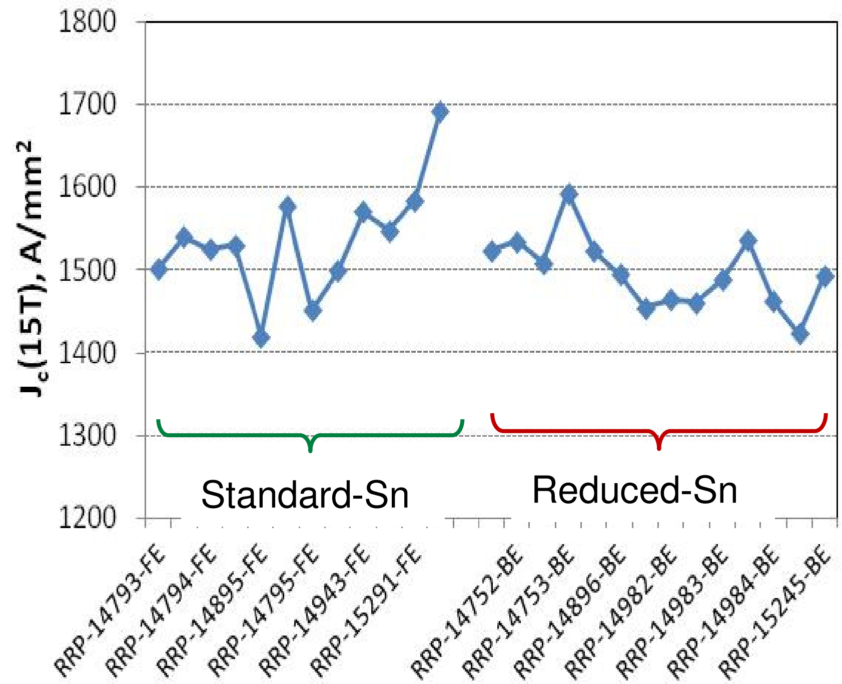
- Oxford Superconducting Technology delivered 400 kg of wire ~ 13 billets (2012-2013)
  - Vendor Data provided at 0.778 mm
  - Wire initially held at 1.04 mm
  - Final wire delivered at 0.85 mm
  - Two types of billets
    - Standard Sn content : Nb/Sn=3.4, 6 billets
    - 5% lower Sn content : Nb/Sn=3.6, 7 billets

Wire Reaction schedule

210 ^{o}C/48h + 400 ^{o}C/48h + 650 ^{o}C/50h

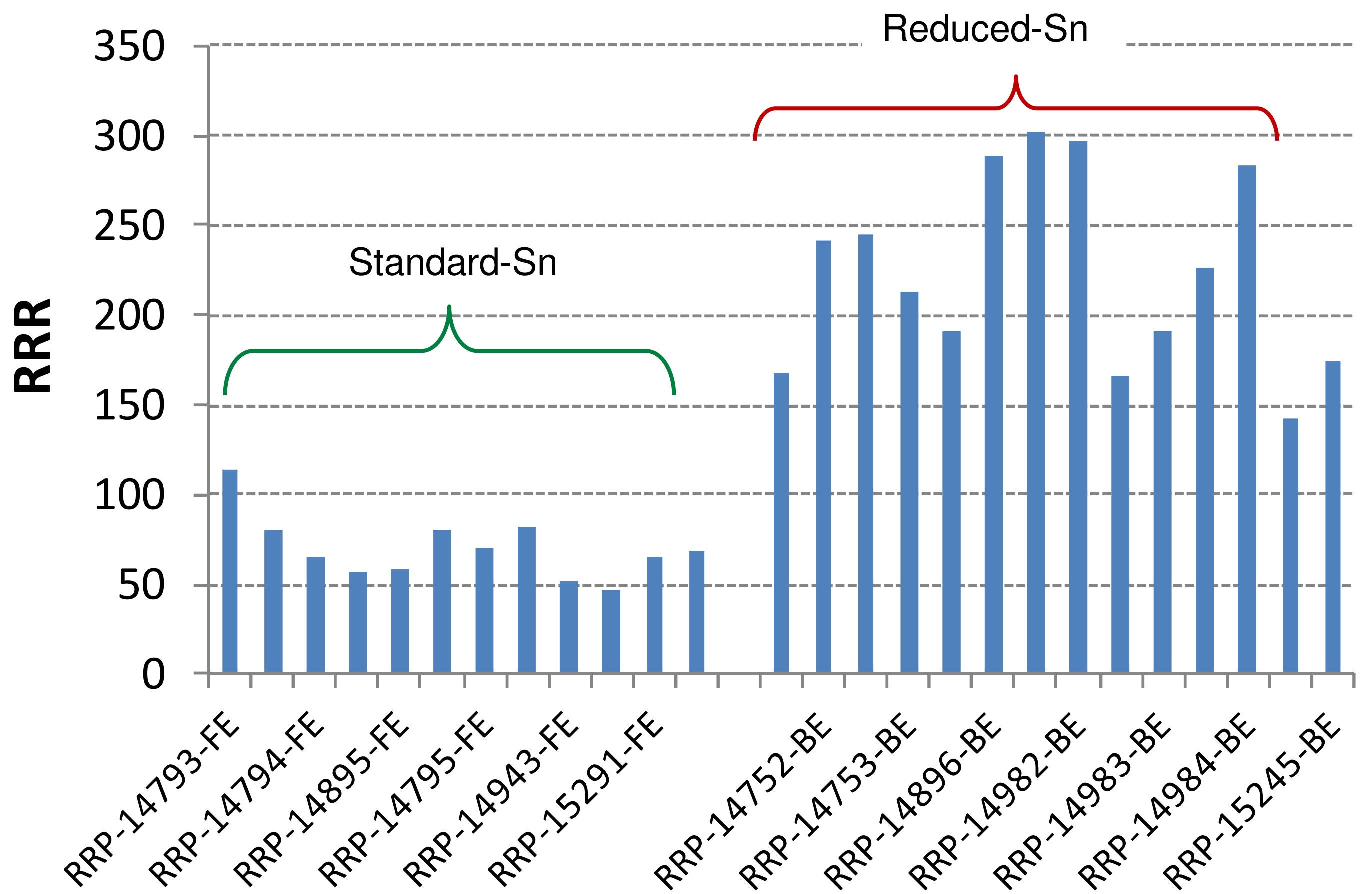
J_c of 108/127 wire - 13 billets





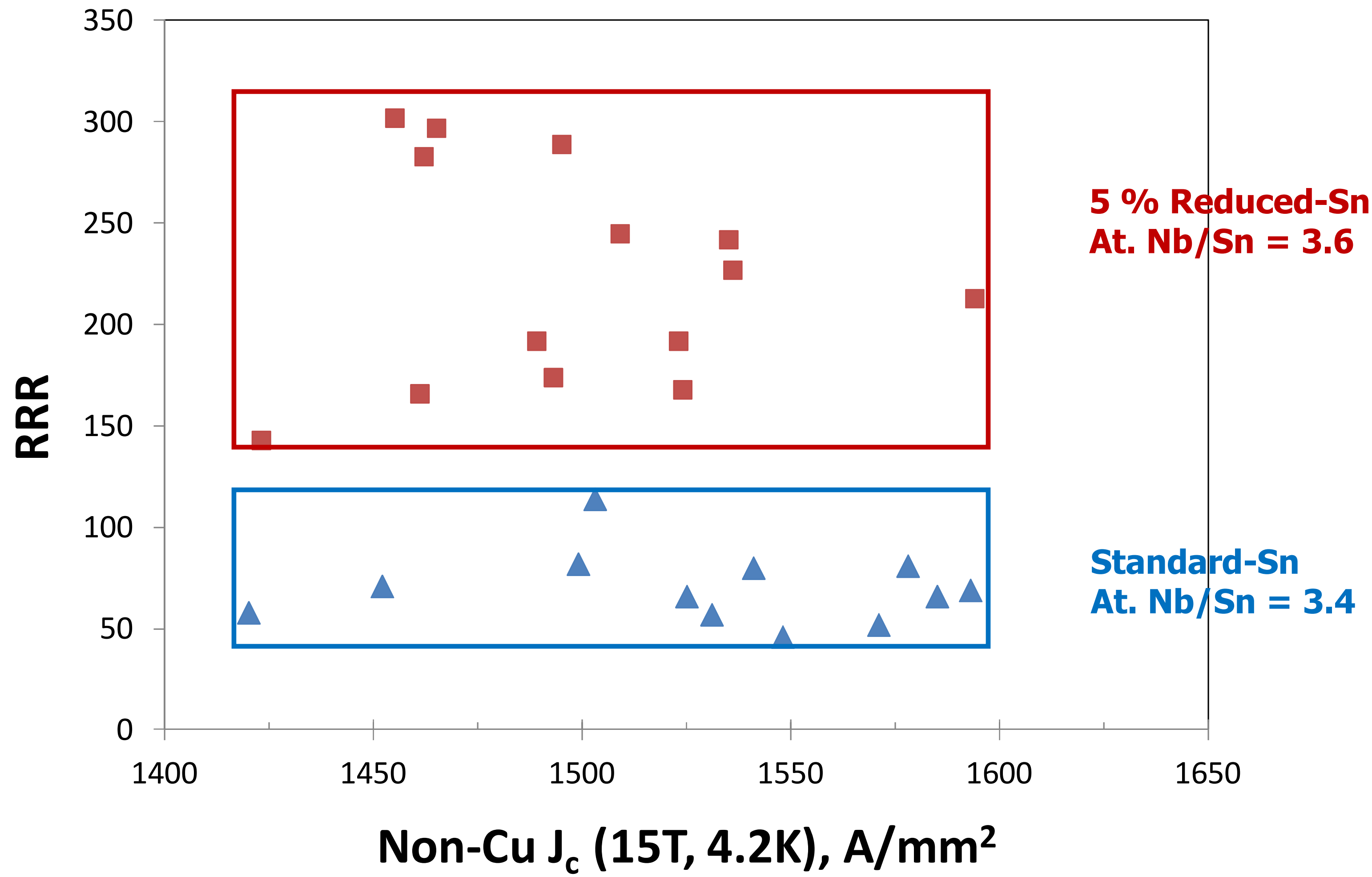
J_c of "reduced-Sn" billets are somewhat lower than the standard-Sn billets

RRR of 108/127 wire



- Reduced-Sn billets show marked increase in RRR

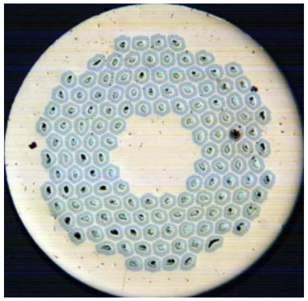
OST Data for 0. 778 mm wire Jc (4.2 K, 15T) vs. RRR



210 °C/48h + 400 °C/48h + 650 °C/50h

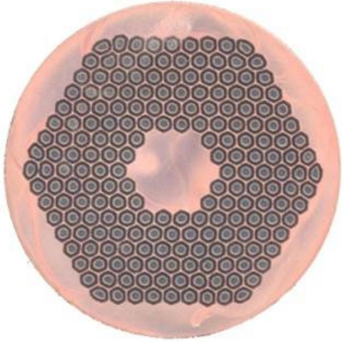
Ti-Ternary RRP® Wire

- More recently, Oxford Superconducting Technology has also delivered
- 55 Km (380 Kg) of 0.85 mm wire ⇨ 9 billets
  - Design 132/169
  - "5% Reduced-Sn" : Nb/Sn=3.6
  - Exception taken to Ic(15 T) specification ➢ Ic (15 T) > 350 A

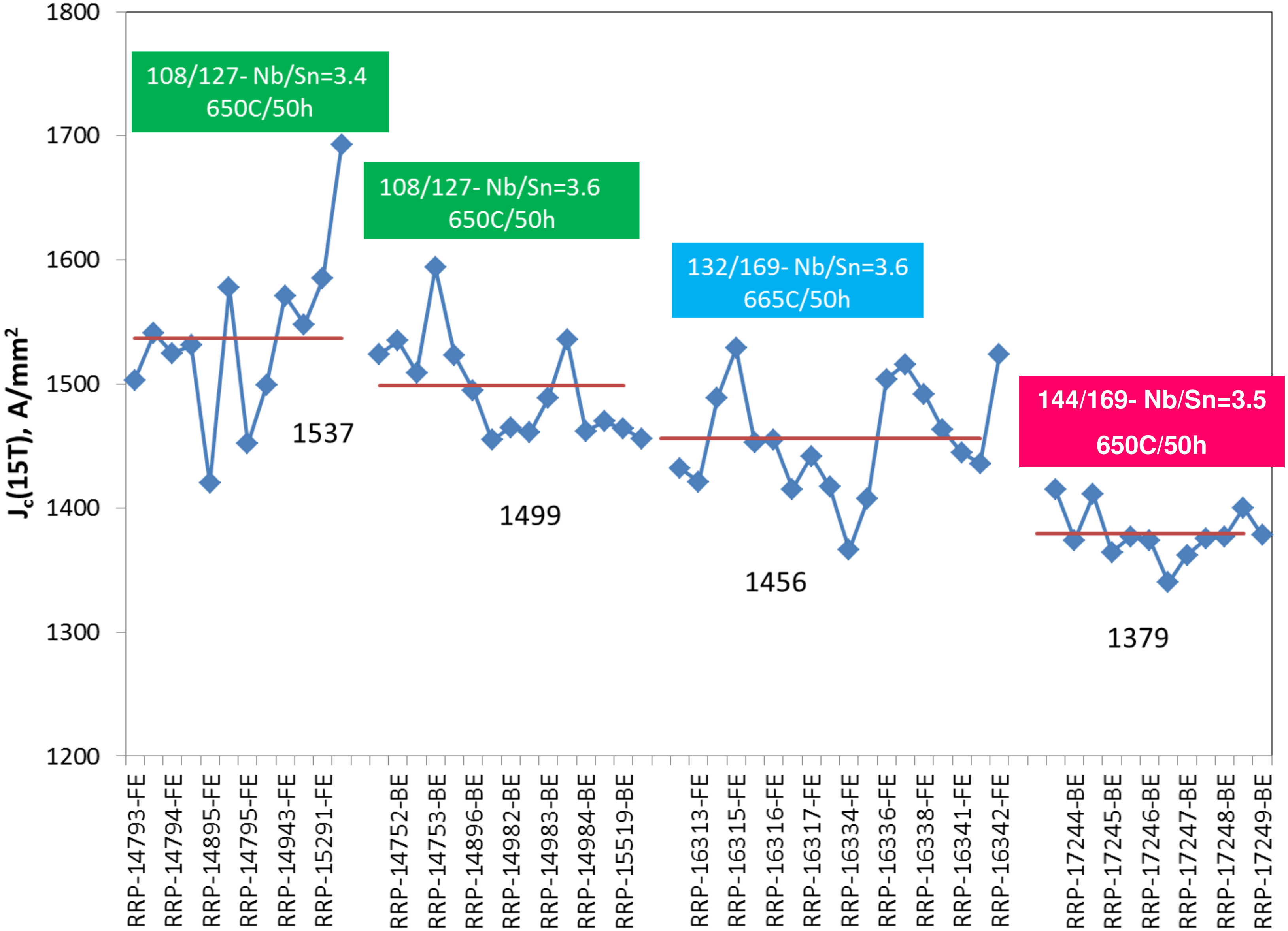


- 38 Km (185 Kg) of 0.85 mm wire ⇨ 6 billets
  - 20 Km (LARP), 18 Km (CDP: Conductor Development Program)
  - Design 144/169
  - "2.5% Reduced-Sn": Nb/Sn=3.5
  - Exception taken to Cu/Non-Cu ratio
    - set to 1.05 ± 0.10
  - All wire qualified using the wire reaction schedule

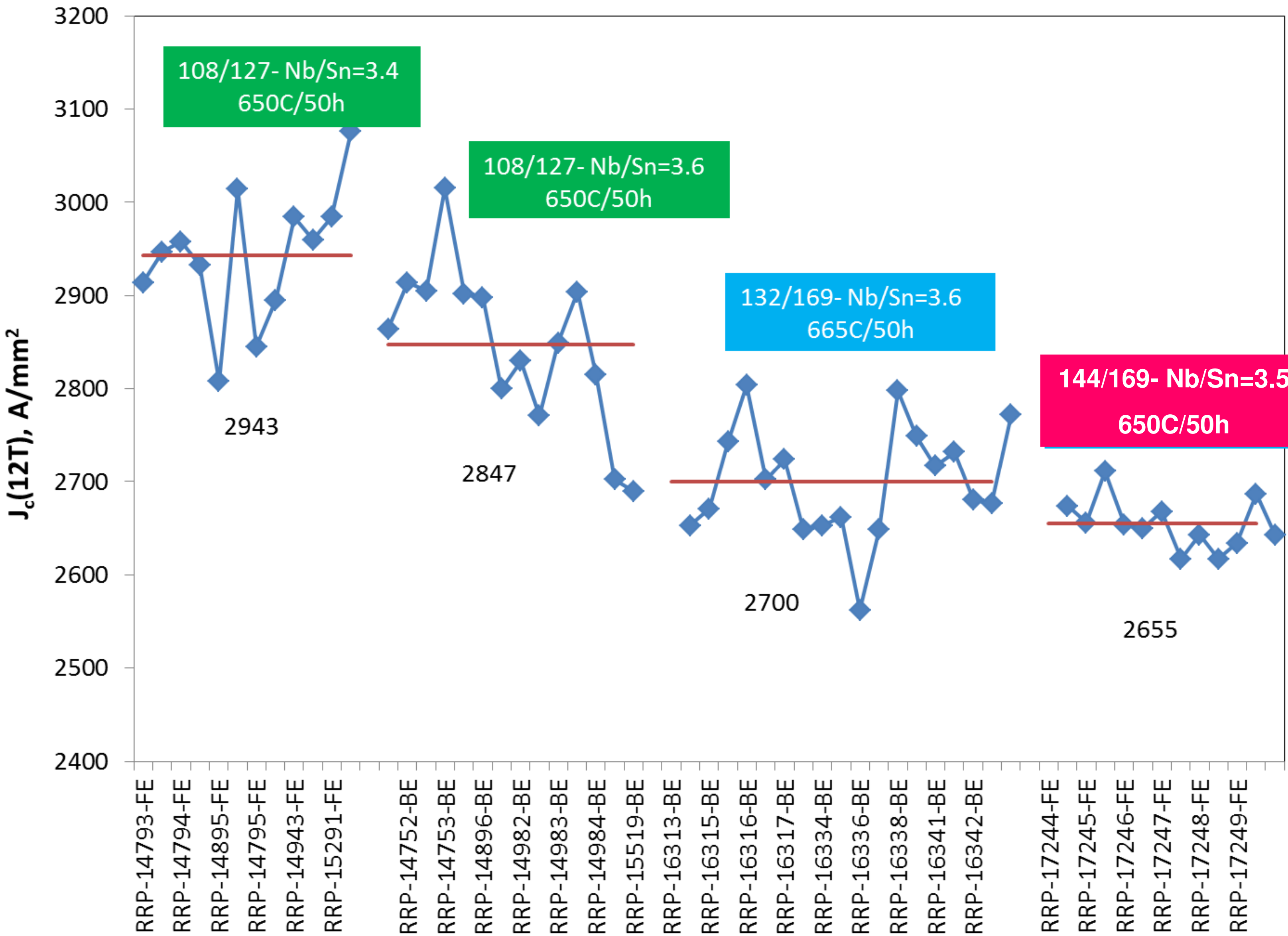
    210 ^{o}C/48h + 400 ^{o}C/48h + 650 ^{o}C/50h



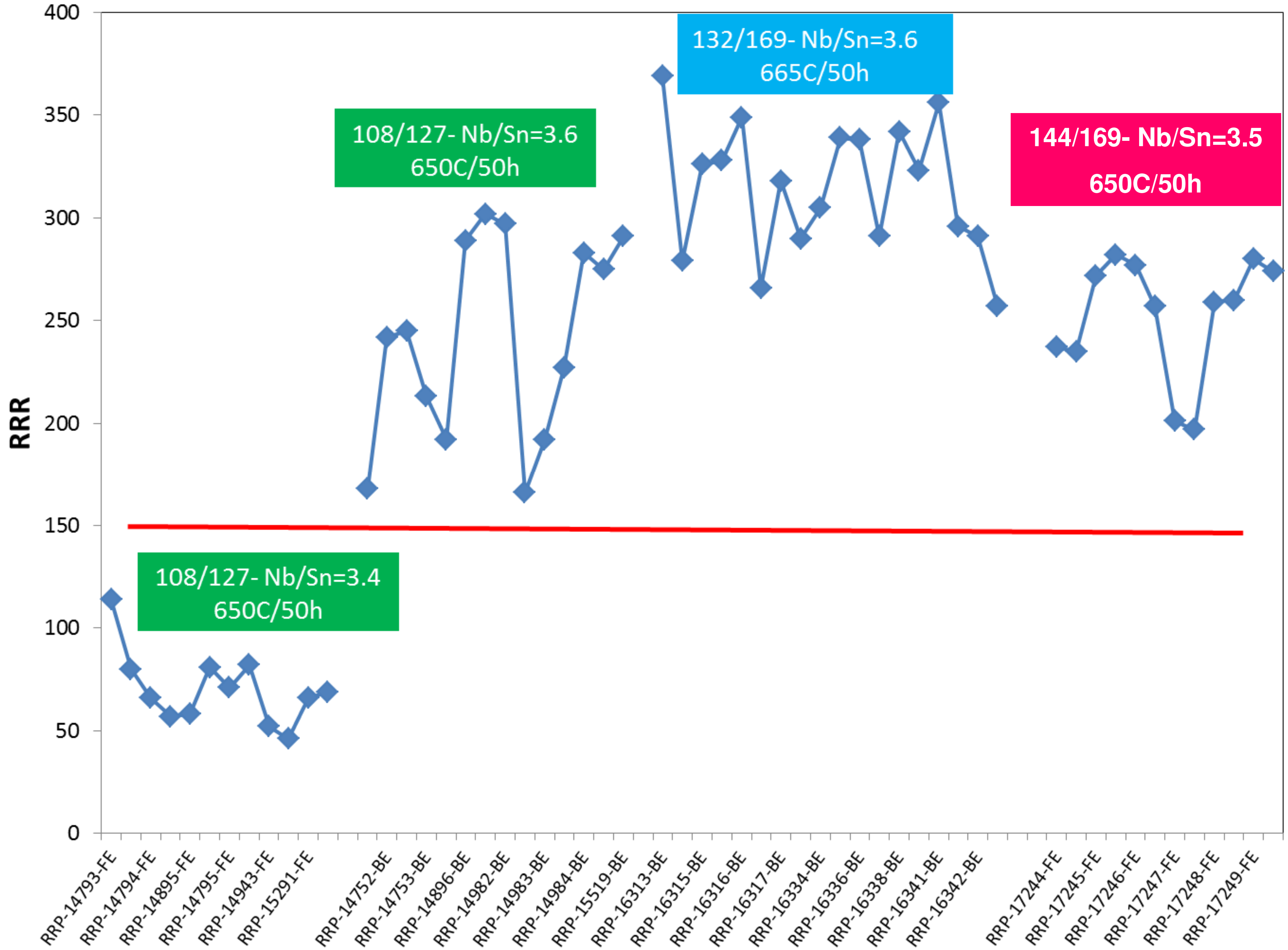
Jc (15 T) - A comparison



Jc (12 T) - A comparison



RRR– A comparison



Statistics for 108/127, 132/169 and 144/169

7 Billets	Ic(12T)	Ic(15T)	Jc(12T)	Jc(15T)	Non_Cu %	RRR	Cu/Non_Cu	Cu%
AVG	743	390	2853	1497	0.459	224	1.179	0.541
σ	20	10	80	44	0.006	54	0.027	0.006
MIN	707	374	2691	1423	0.447	143	1.141	0.533
MAX	775	409	3015	1594	0.467	302	1.237	0.553
AVG-3σ	682	358	2615	1366	0.442	62	1.098	0.524

9 Billets	Ic(12T)	Ic(15T)	Jc(12T)	Jc(15T)	Non_Cu %	RRR	Cu/Non_Cu	Cu%
AVG	691	372	2692	1452	0.452	312	1.214	0.548
σ	19	13	65	49	0.007	29	0.033	0.007
MIN	664	354	2562	1366	0.444	257	1.151	0.535
MAX	730	388	2798	1524	0.465	356	1.252	0.556
AVG-3σ	634	334	2497	1306	0.431	226	1.114	0.528

7 Billets	Ic(12T)	Ic(15T)	Jc(12T)	Jc(15T)	Non_Cu %	RRR	Cu/Non_Cu	Cu%
AVG	724	376	2655	1379	0.481	253	1.078	0.519
σ	10	7	28	21	0.004	29	0.017	0.004
MIN	711	364	2617	1340	0.475	197	1.045	0.511
MAX	738	390	2711	1415	0.489	282	1.105	0.525
AVG-3σ	693	354	2572	1316	0.470	165	1.029	0.507

I_c Statistics for 108/127, 132/169 and 144/169

7 Billets	Ic(12T)	Ic(15T)
AVG	743	390
σ	20	10

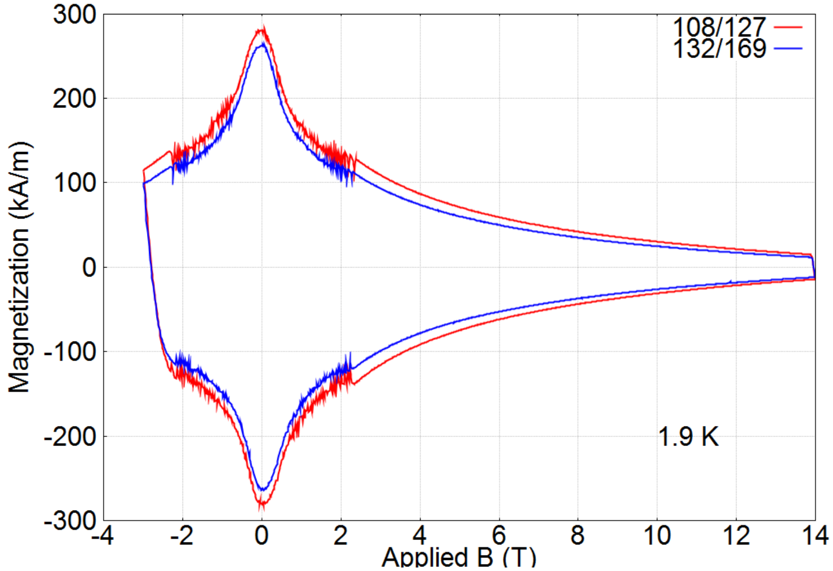
9 Billets	Ic(12T)	Ic(15T)
AVG	691	372
σ	19	13

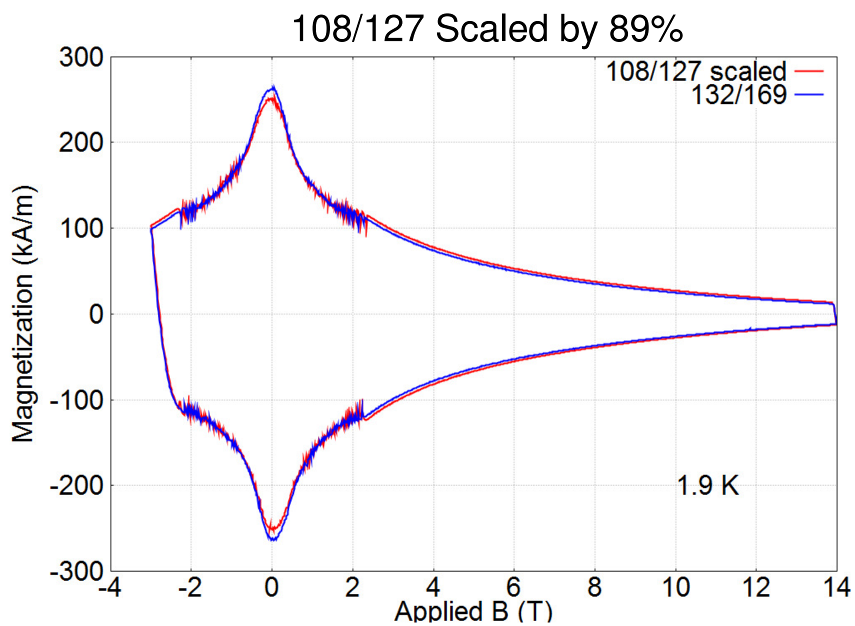
7 Billets	Ic(12T)	Ic(15T)
AVG	724	376
σ	10	7

Production should be within ± 3 σ

108/127 Min Ic (15 T) = 358 A
132/169 Min Ic (15 T) = 334 A
144/169 Min Ic (15 T) = 354 A

Magnetization of 0.85 mm, 108/127 and 132/169 at 1.9 K
Strands have same Jc and Cu/Sc ratio





X. Wang

Measurements performed at OSU
By M. Sumption and X. Xu

- Magnetization scales with filament diameter

RRP strand for MQXF coils

- Present inventory of wire at LARP is the following:
  - 38 Km of 144/169
  - 43 Km of 132/169
  - 11 Km of 108/127
- This wire will be used to fabricate cables for 3 short coils and 3 long coils.
- Unit length of a short coil is 170 m and that for the long coil is 450 m.

Strand Specification for the HiLumi Project

- Very recently within a Conductor Working Group with members from CERN and LARP we agreed on a set of requirements for the strand and cable
- Within LARP the strand Specification is being released under the following document:

  "U.S. HiLumi Project

  SPECIFICATION FOR QUADRUPOLE MAGNET CONDUCTOR

  US-HiLumi-doc.40

  Rev. No. Original Release

  Date: 05-May-2015"

Specification for MQXF Strand

Parameter or characteristic	Value	Unit
Superconductor composition	Ti-alloyed Nb_3Sn	
Strand Diameter	0.850 ± 0.003	mm
Critical current at 4.2 K and 12 T	> 632	A
Critical current at 4.2 K and 15 T	> 331	A
n-value at 15 T	> 30	
Count of sub-elements (Equivalent sub-element diameter)	≥ 108 (≤ 55)	 (μm)
Cu : Non-Cu volume Ratio Variation around mean	≥ 1.2 ± 0.1	
Residual Resistance Ratio *RRR* for reacted final-size strand	≥ 150	
Magnetization* at 3 T, 4.2 K	< 256 (< 320)	kA m^{-1} (mT)
Twist Pitch	19.0 ± 3.0	mm
Twist Direction	Right-hand screw	
Strand Spring Back	< 720	arc degrees
Minimum piece length	550	m
High temperature HT duration	≥ 40	Hours
Total heat treatment duration from start of ramp to power off and furnace cool	≤ 240	Hours
Heat treatment heating ramp rate	≤ 50	°C per hour
Rolled strand (0.765 mm thk.) critical current at 4.2 K and 12 T	> 600	A
Rolled strand critical current at 4.2 K and 15 T	> 314	A
Rolled strand *RRR* after reaction	> 100	

0.85 mm Ti-Ternary

I_c (12 T)>632 A, J_c(12 T)> 2450 A/mm²

I_c (15 T)>331 A, J_c(15 T)> 1250 A/mm²

108/127

Cu % > 53 %

RRR >150   Nb/Sn > 3.5

Procurement Plan for MQXF magnets

MQXFS and MQXFL

- Require ~ 300 Km of wire to complete the short model program (4 additional coils) and fabricate 12 long coils for the long prototype program.
- Place an order for 70 km in FY'15 and 130 Km in FY'16
- 100 Km will be made available from CERN in CY16 to help the MQXFL magnet schedule of the LARP program.

MQXF Production for Q1/Q3

- Require 90 coils with each coil using ~ 20 Km of wire.
- Total procurement is for ~ 1,800 Km (9 tonnes)
- The procurement plan is incorporated in US-HiLumi doc-37 V.5

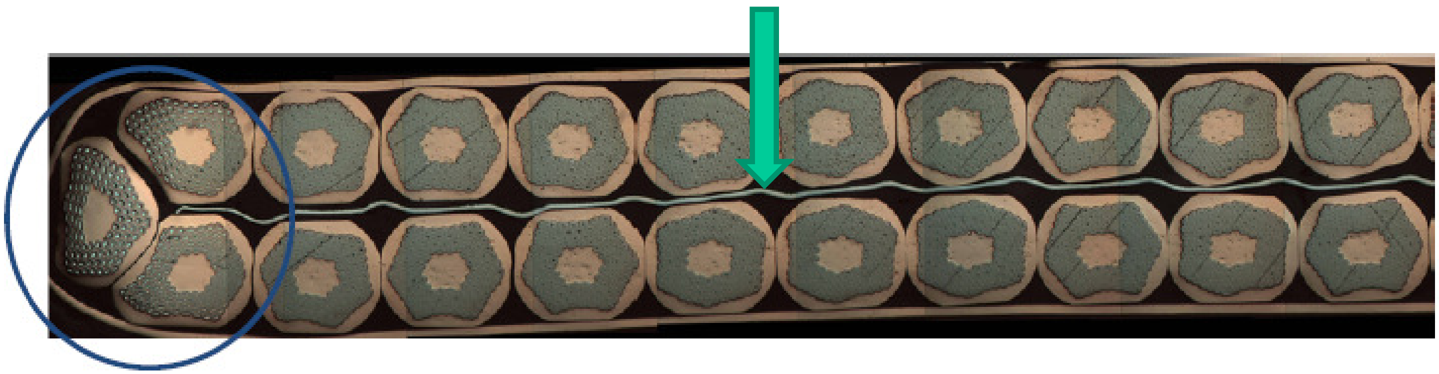
"Advanced Acquisition Plan for Quadrupole Magnet conductor"

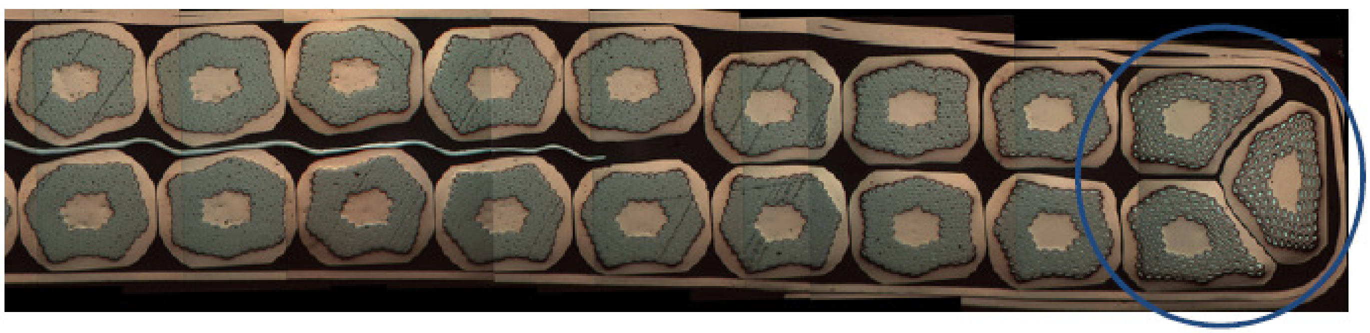
- by Lance Cooley

18 mm wide 40 strand QXF cable
- An example of a developmental cable

SS Core to reduce Eddy Current losses

Thick edge





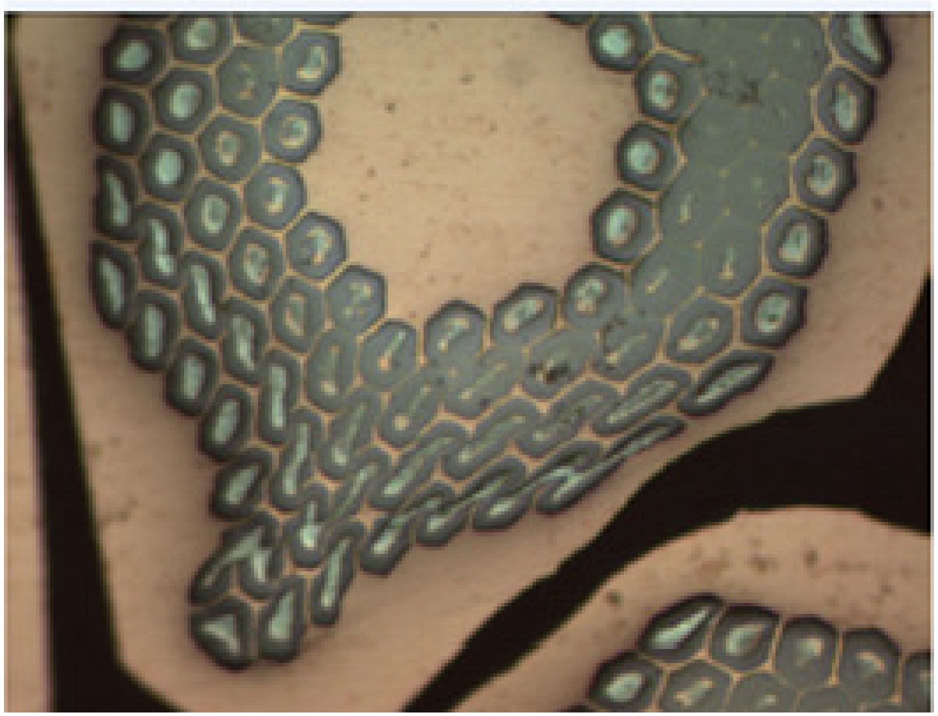
Thin Edge

Width = 17.95 mm

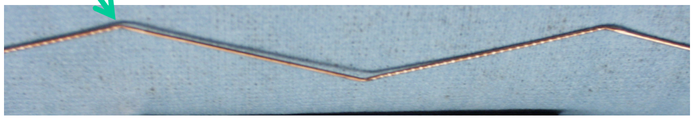
Thickness = 1.50 mm

Keystone Angle = 0.62 Deg.

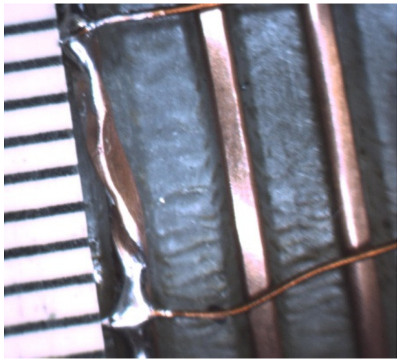
Example of sub-element shearing and barrier rupture



These damage lead to mostly RRR degradation of the copper stabilizer at the edges of the cable. Low RRR can lead to conductor instability due to "magnetization" and "self-field" effects. Target is to maintain RRR > 100 at the "kinks" – cable edges.



V-tap configuration to measure RRR at edges



Wire ID	RRR
B1042Z-11-ES-3-Minor	**68**
B1042Z-11-ES-3-Major	**91**
B1042Z-11-ES-3-Minor	**80**
B1042Z-11-ES-3-Major	**92**
B1042Z-11-ES-3-Minor	**62**
B1042Z-11-ES-3-SS	**166**

Cabling Trade-offs

- Minimize the amount of strand damage
  - Less compaction
  - Can lead to mechanically unstable cable for coil winding
- Increase mechanical stability of cable
  - More compaction and deformation of strands
  - More strand damage - Reduced critical current and RRR (Sub-element shear leading to barrier thinning and barrier breakage causing Sn leak into copper and reducing RRR)
  - To reduce cabling damage, the keystone angle has been reduced from 0.55 to 0.4 degrees

Specification for MQXF Cable 2nd Generation

Number of strands	40
Mid-thickness	1.525 mm +/- 0.010 mm
Width	18.15 mm +/- 0.050 mm
K.S. angle	0.40 deg. +/- 0.10 deg.
Pitch Length	109 mm +/- 3 mm
Core Material	Annealed 316L SS
Core Width	12 mm (biased to major edge)
Core thickness	0.025 mm

The only change made from the 1st generation cable design is to reduce the Keystone angle from 0.55 to 0.40 deg.

1st and 2nd Gen cable using the same Cable Map

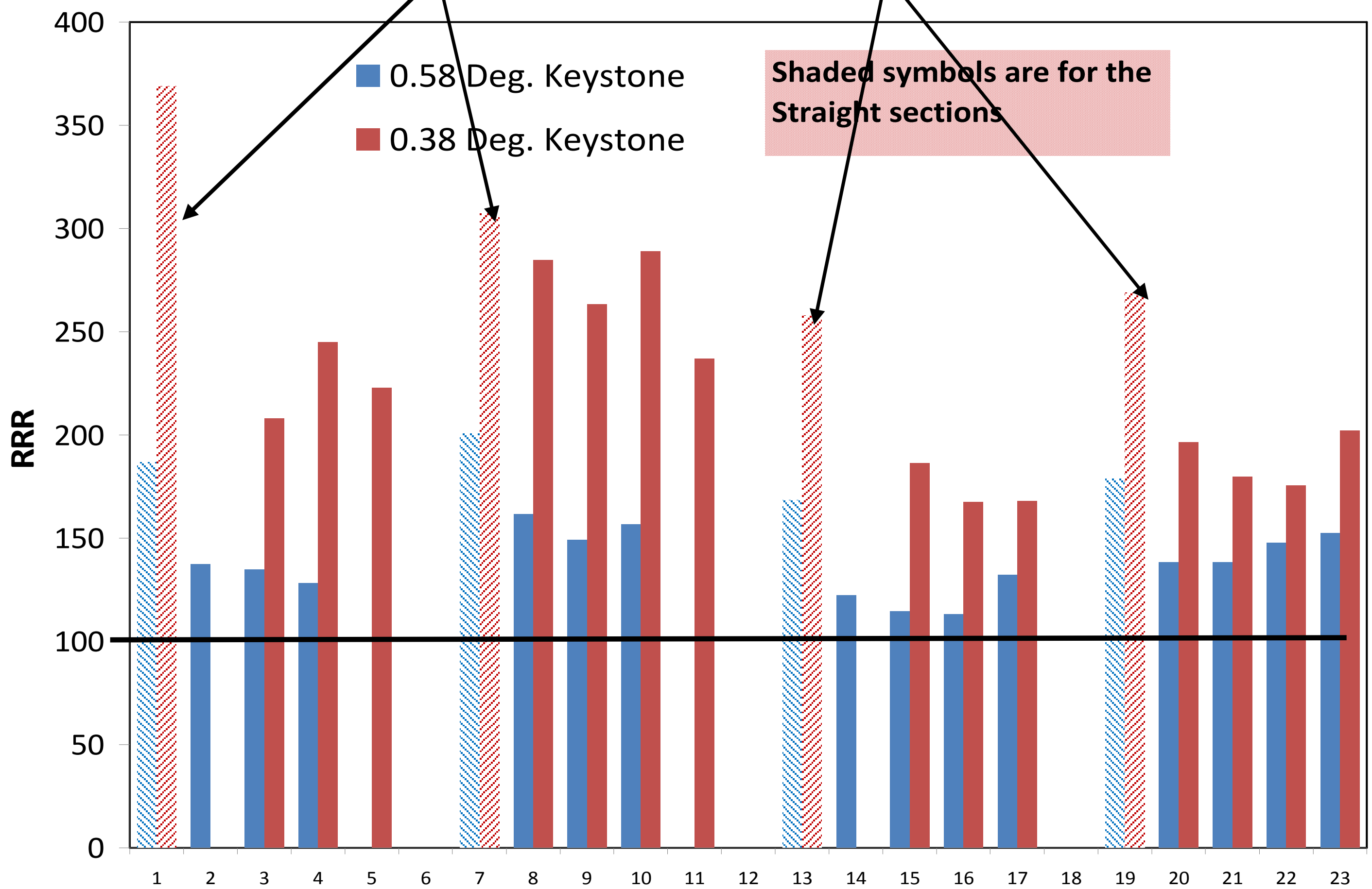
Cable	1056-A 1st Gen.	1056-7 2nd Gen.
Avg. THICKNESS mm	1.524	1.522
Avg. WIDTH mm	18.14	18.19
Avg. ANGLE deg.	0.58	0.38

Extracted Strand Tests from a trial run of 2nd Gen

Cable Description	Ic (12 T) Degradation	Ic (15 T) Degradation	RRR Extr.
1st Gen. Cable	2.6%	3.4%	250
2nd Gen Cable	2.2%	2.7%	234

RRR at the edges of the cable V_{tap} ~ 10 mm Comparison of 0.38 and 0.58 Deg. Keystone

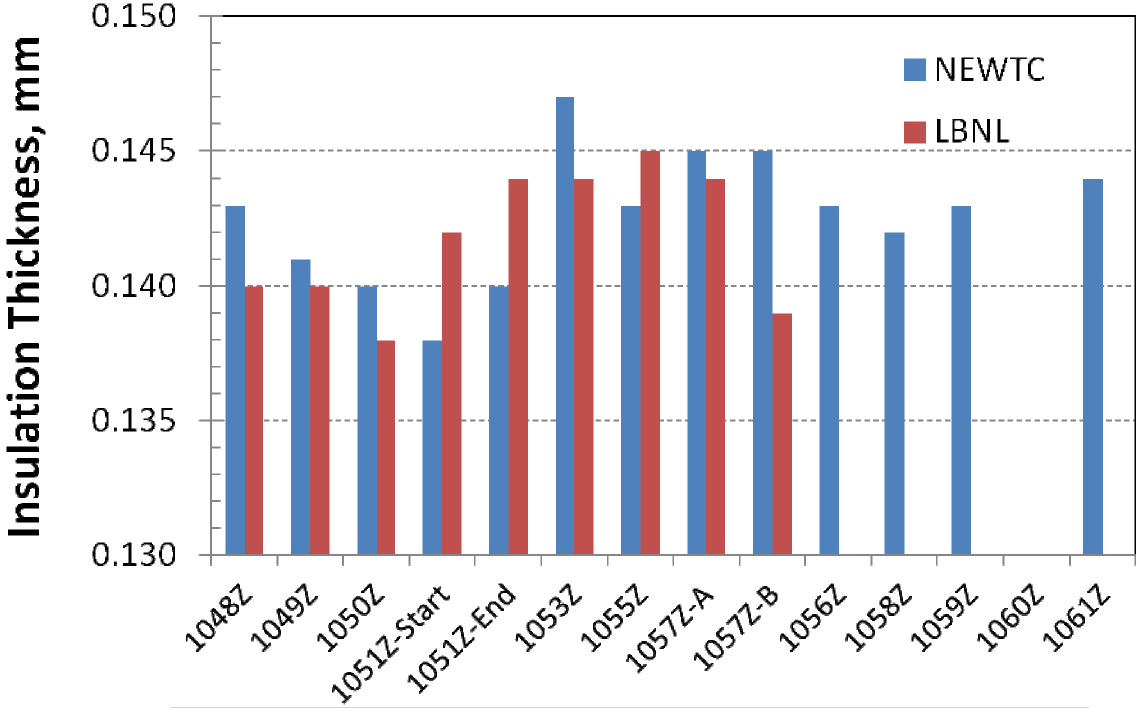
Wires are from two billets 15950 and 15953 with round wire RRR of 307 (15950) and 205 (15953)



Cable Insulation

- Insulation is braided directly on cable
  - New England Wire Technology (NEWT)
- Using S-2® glass (from AGY) with 933 Silane sizing
  - 2 ply yarn
- Several lengths of QXF cable has been insulated
  - Using braiding parameters to yield target specification of 0.145 ± 0.005 mm thickness
  - 10-stack measurements at 5 MPa are used to determine insulation thickness
  - Thickness can be readily adjusted to meet any change to present specification.

Cable Insulation



	Measurement at 5 Mpa mm		
	Ist Cycle	2nd Cycle	3rd Cycle
Average	0.146	0.144	0.143
s	0.003	0.003	0.002
MIN	0.142	0.140	0.138
MAX	0.154	0.149	0.147

Summary

- The "reduced-Sn" design change increases RRR control with minimal loss of J_c.
  - Implemented for all billets in process and future procurements.
- RRP® 108/127 is going to used for all future procurements
  - There is sufficient manufacturing margin in I_c in the specification. RRR margin is ensured by proper control of Nb/Sn content of the sub-element. However, production uniformity has to be emphasized in the control of "raw" materials, and in ensuring proper QA/QC procedures in wire fabrication and in the testing at the vendor.
- Strand procurement has been planned to meet cable manufacture and coil winding schedule.
- We have a 2nd iteration of the cable parameters which reduces the keystone angle and thereby the possibility of sub-element shear in the wire at the cable edges
- Specification and Production QA plan is being finalized this fiscal year for strand, cable and insulation

End of Presentation

Work supported by the US LHC Accelerator Research Program (LARP) through US Department of Energy