LARP

BNL -FNAL - LBNL - SLAC

LARP DOE Review
July 09-10, 2012
SLAC

Conductor and Cable

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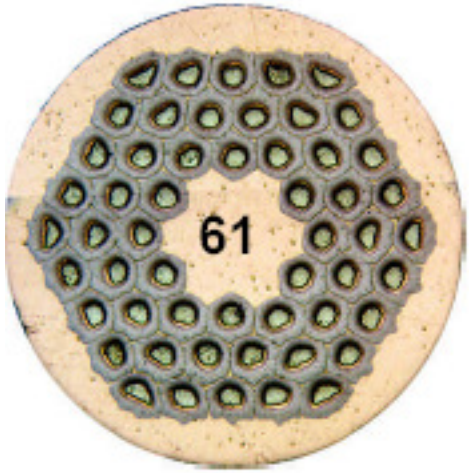
Strand Procurement: *A. Ghosh (BNL), D. Dietderich (LBNL)*

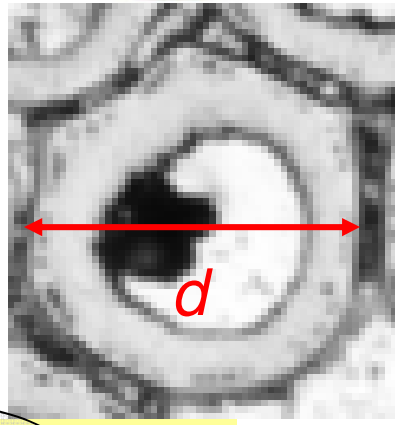
Outline

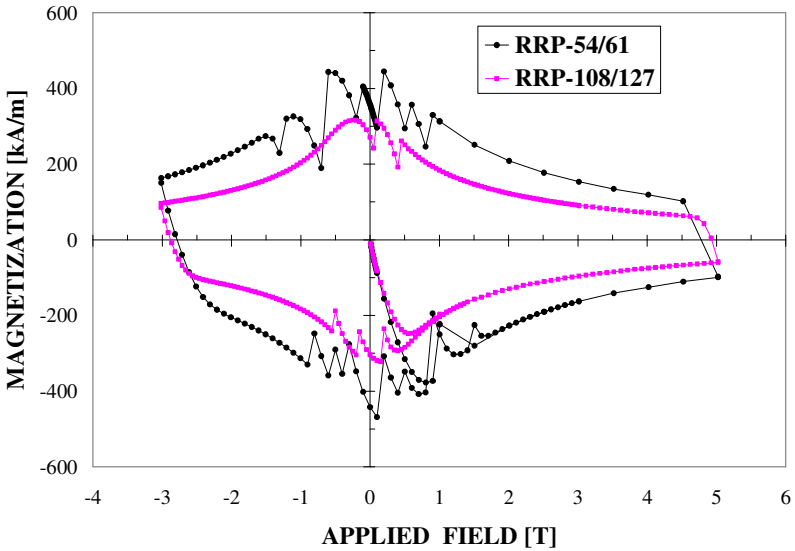
- Introduction
- RRP 108/127 Strand
- OST strand production
- Ti-Ternary Strand
- Cable Development
  - Cored-Cable
  - Cable R&D for 150 mm magnet
- R&D towards smaller filaments
- Procurement Plan for LARP
- Cable Insulation
- Rad-hard Epoxy
- Summary

Introduction

- The long 90 mm quad-magnet LQS01 used 0.7 mm RRP® 54/61 Ta-Ternary strand from Oxford Superconducting Technology
  - ⇨27-strand 10 mm wide cable with 1.0° keystone angle
  - J_c > 2400 A/mm^2 at 12T
  - d ~ 70 μm ➡ Flux-jump instability at low field







$$\beta = \frac{\mu_0 J_c^2 d^2}{4C(T_c - T_{bath})} < 3$$

Tc =Transition Temp.

T_{bath}= Bath Temp

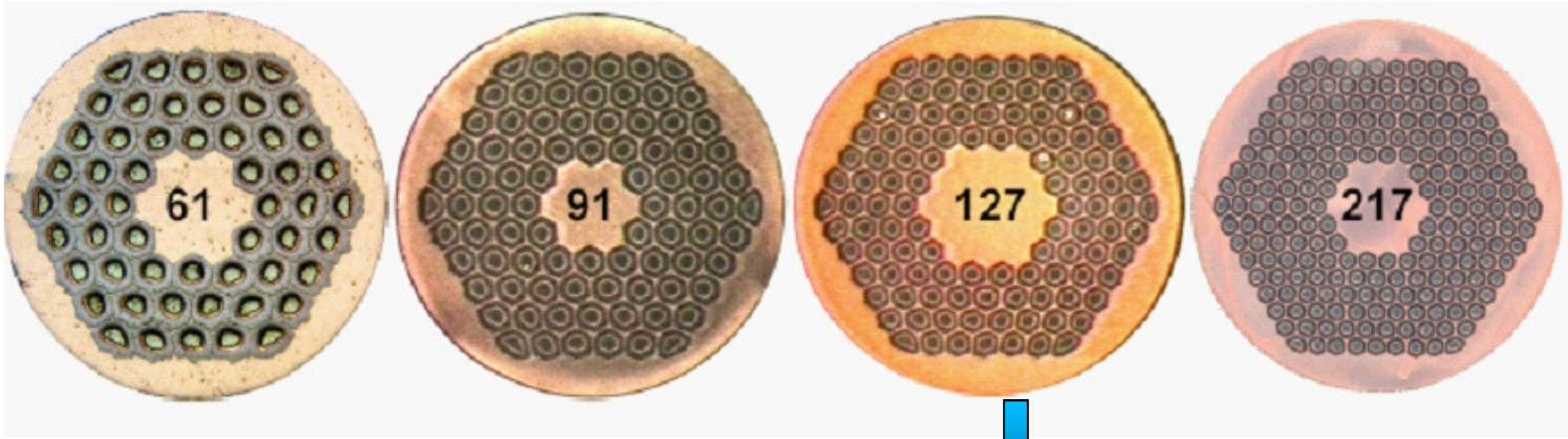
Stability can be improved by reducing filament diameter, *d*

- Smaller sub-elements can minimize flux jumps and improve stability.
- Smaller Filament Magnetization

$$\beta = \frac{\mu_0 J_c^2 d^2}{4C(T_c - T_{bath})} < 3$$

73 μm — 0.8 mm Cu/non-Cu 1.22 — 38 μm

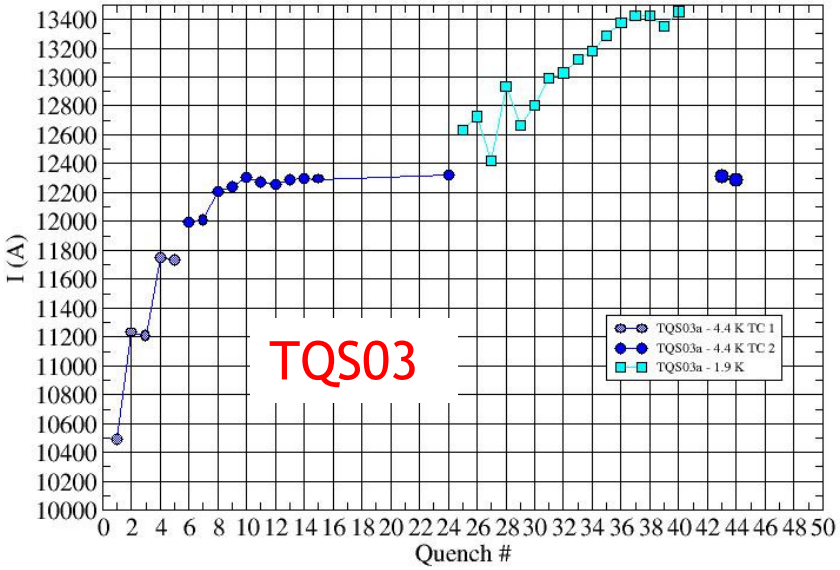
d → Smaller Filament Size



"Baseline" Strand

Development of 108/127-design strand

- In 2008 OST delivered 180 kg of high-Jc strand with the 127-stack design and larger spacing between sub-elements ⇨ *Cu fraction is 53% compared 47% in standard 54/61*
- *This production went well - good piece lengths*
- Used to wind-react four TQ coils (1 m long) ⇨TQS03
- TQS03 (90-mm aperture) magnet tested at CERN
  - Good performance at 4.2 K and at 1.9 K
- In 2010-2011 fabricated 5 coils for LQS03 (3.6 m long)
  - ⇨ Currently awaiting test at FNAL Starting July 23rd



Ta-Ternary 108/127 Production at OST

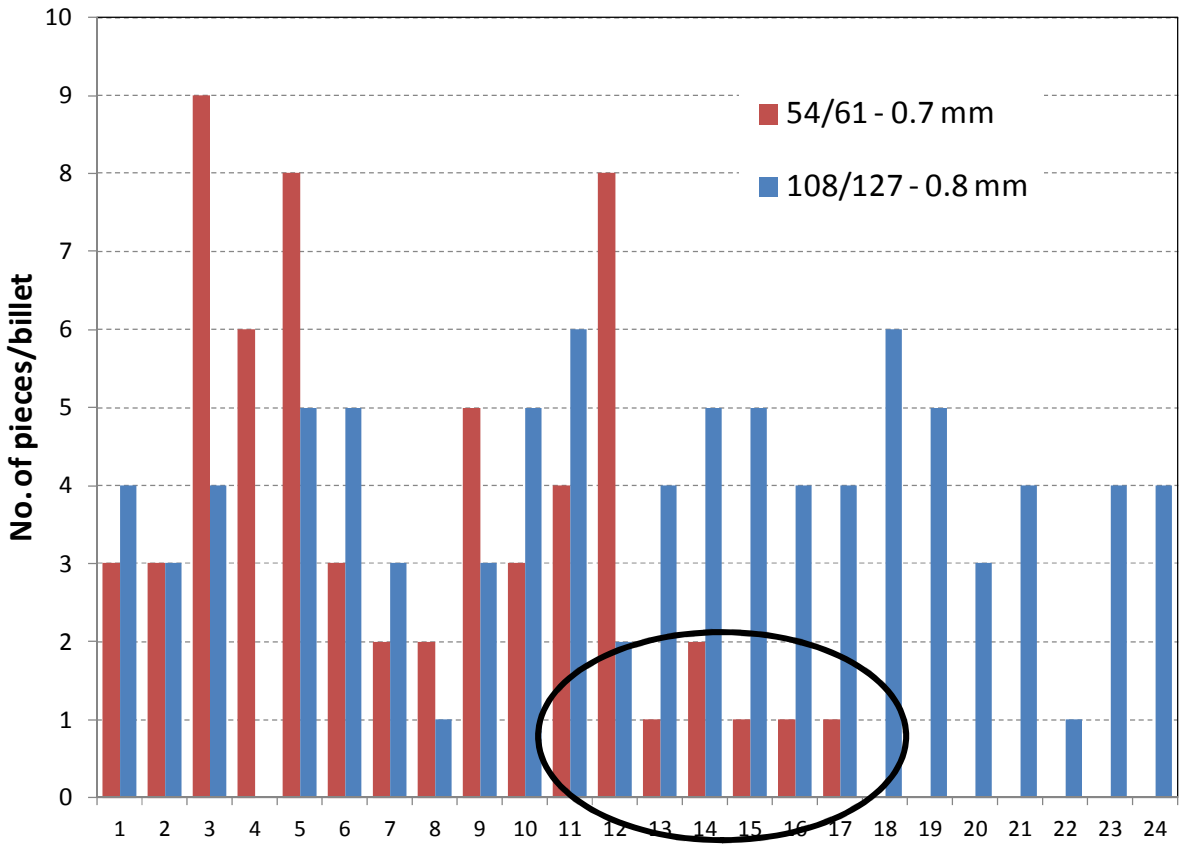
- Typical Billet Yield is 35 kg
  - Plan to increase to 45 and then to 60 kg

Strand Specifications	
Strand Diameter, mm	0.778 ± 0.003
J_c(12 T) at 4.2 K, A/mm2	> 2650
J_c(15 T) at 4.2 K, A/mm2	1400
D_s, μm (nominal)	50
Cu-fraction, %	53 ± 3
RRR (after full reaction)	> 60
Twist Pitch, mm	14 ± 2
Twist Direction	Right-Hand
Minimum Piece length, m	550

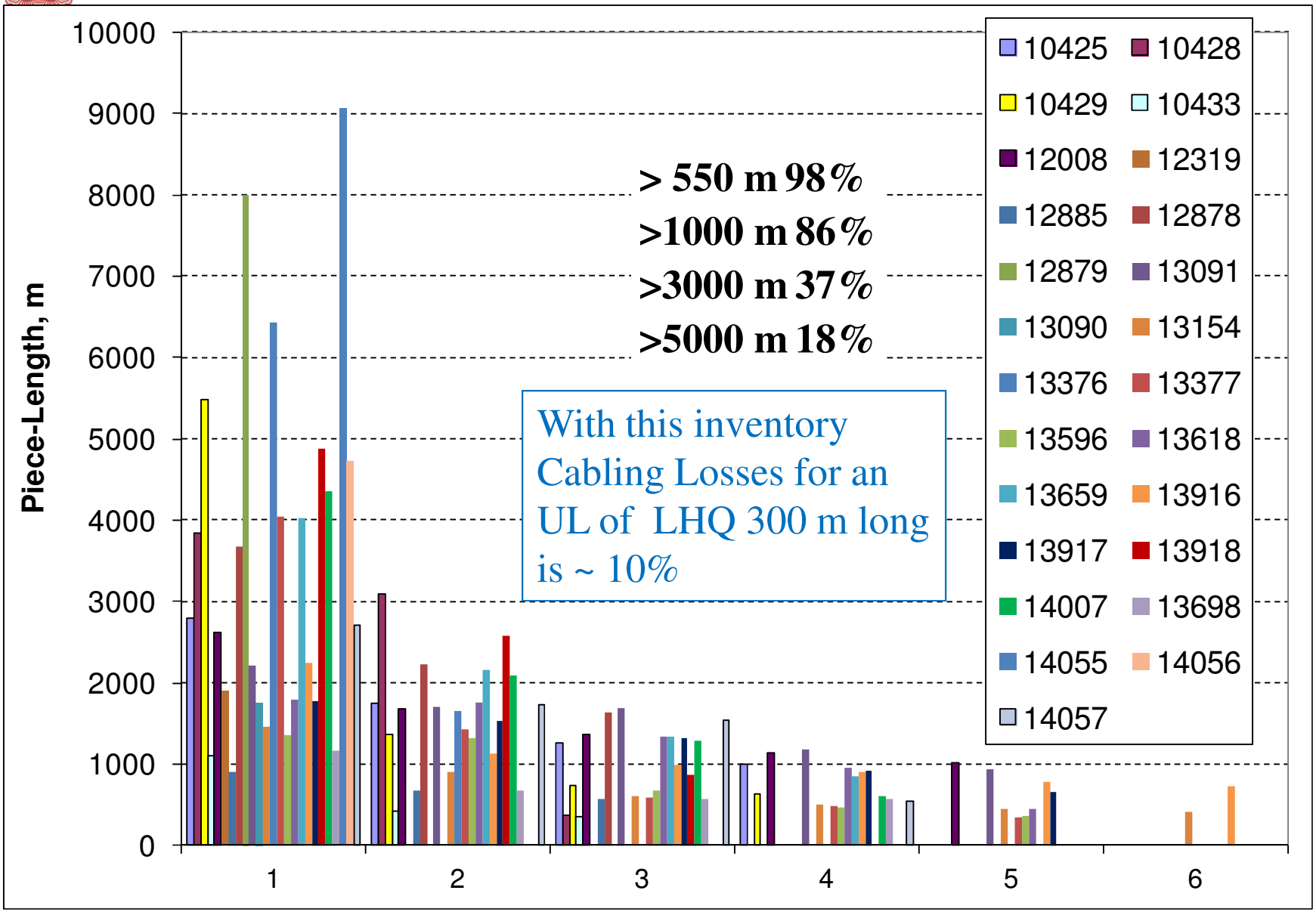
- Samples are reacted using a schedule optimized for the 54/61 stack wire :210C/48h + 400C/48h + 665C/50h

0.8 mm RRP 108/127 Production
No. of pieces/billet

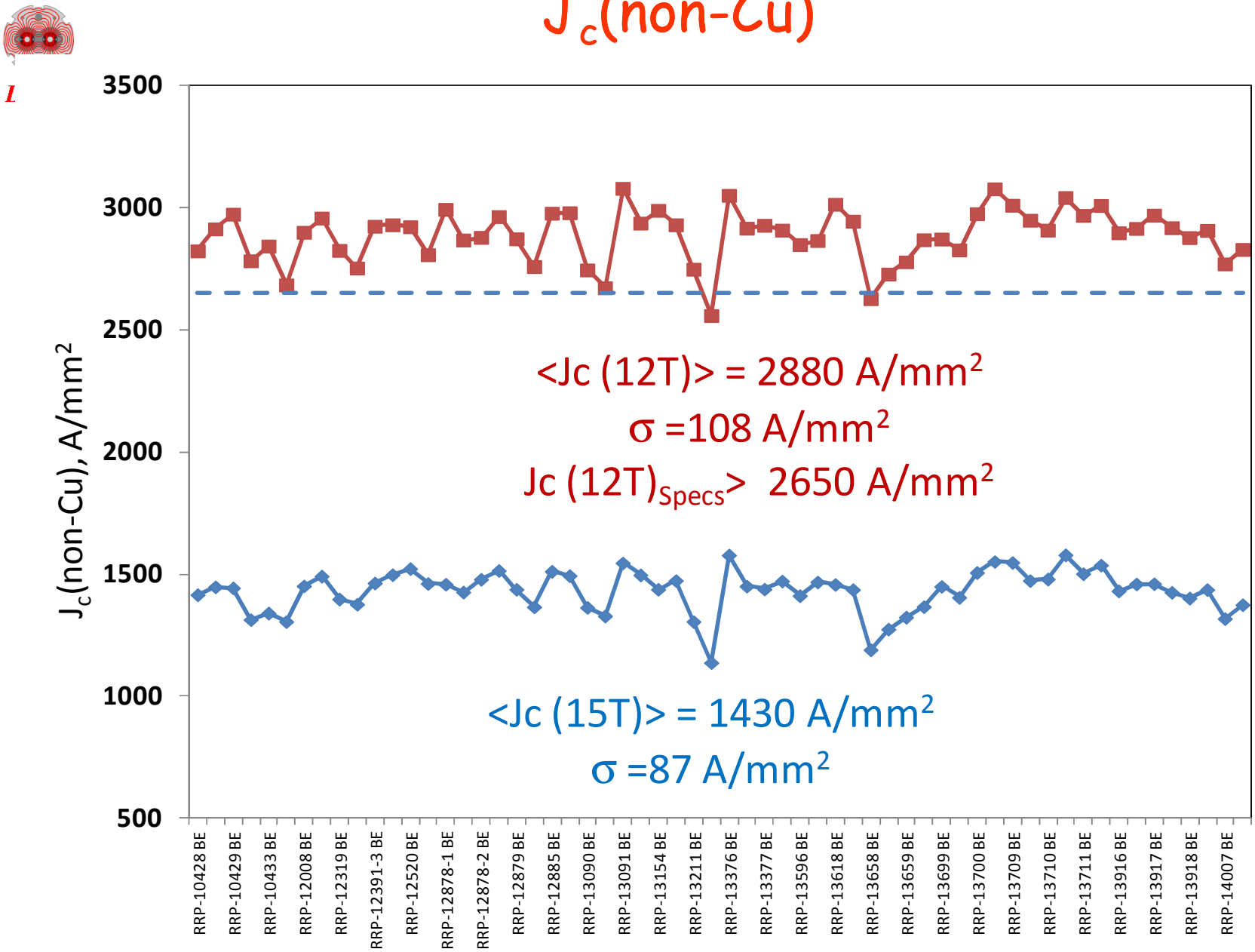
- After sustained production, RRP 54/61 achieved 1-2 pieces per billet (5-10 km range). Wire at 0.7 mm
- RRP 108/127 is averaging 4-5 pieces/billet. Wire at 0.778 and 0.8 mm



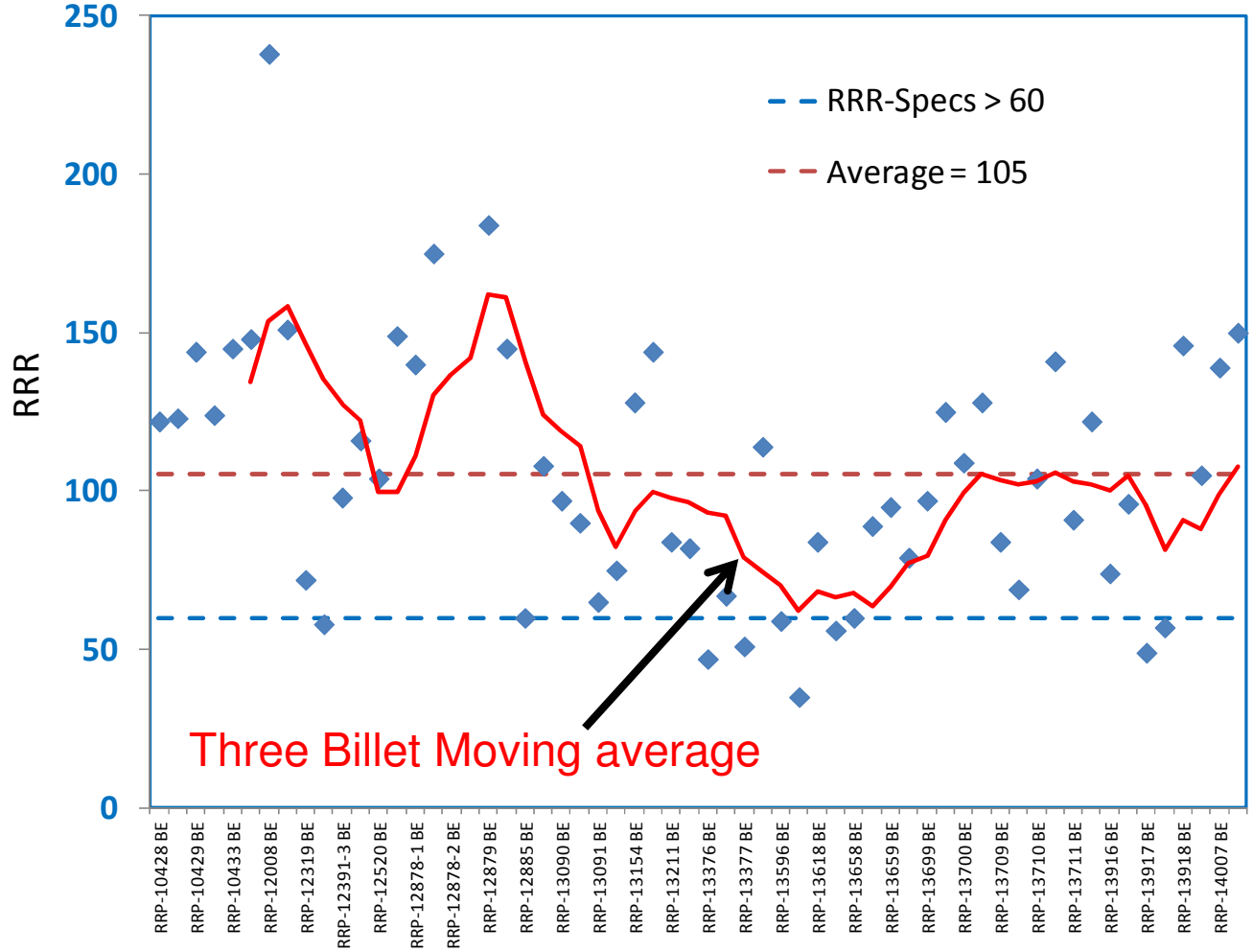
Piece Length, 25 billets



J_c(non-Cu)


3500
3000
2500
2000
1500
1000
500
J_c(non-Cu), A/mm^2
<Jc (12T)> = 2880 A/mm^2
σ =108 A/mm^2
Jc (12T)$_{Specs}$> 2650 A/mm^2
<Jc (15T)> = 1430 A/mm^2
σ =87 A/mm^2
RRP-10428 BE
RRP-10429 BE
RRP-10433 BE
RRP-12008 BE
RRP-12319 BE
RRP-12391-3 BE
RRP-12520 BE
RRP-12878-1 BE
RRP-12878-2 BE
RRP-12879 BE
RRP-12885 BE
RRP-13090 BE
RRP-13091 BE
RRP-13154 BE
RRP-13211 BE
RRP-13376 BE
RRP-13377 BE
RRP-13596 BE
RRP-13618 BE
RRP-13658 BE
RRP-13659 BE
RRP-13699 BE
RRP-13700 BE
RRP-13709 BE
RRP-13710 BE
RRP-13711 BE
RRP-13916 BE
RRP-13917 BE
RRP-13918 BE
RRP-14007 BE

RRR
Some measurements are <60

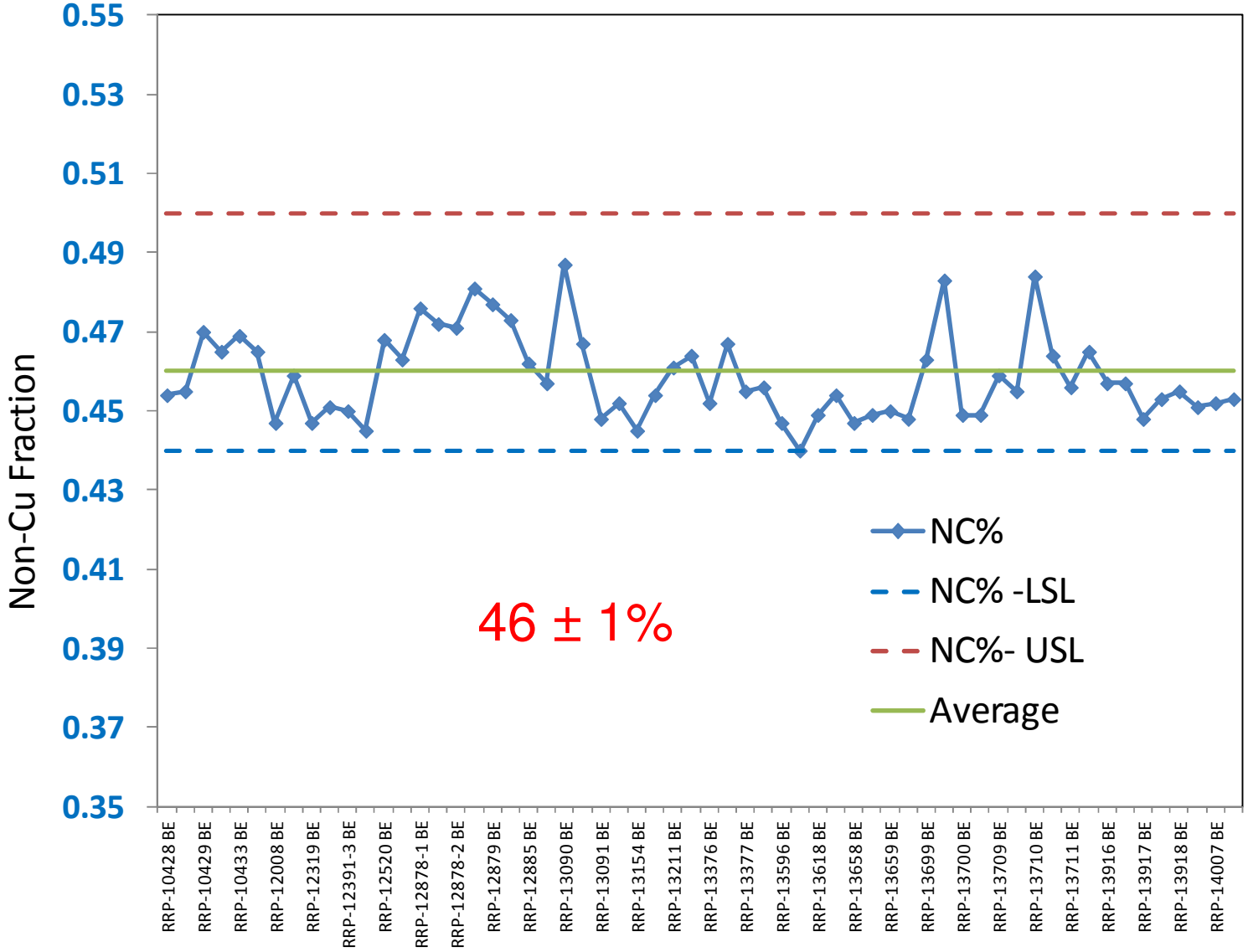


Reaction schedule for HQ coils modified to 650C/48h to increase RRR

$J_c(12T)_{AVG}$ ~ 2750 A/mm^2

~5 % lower J_c

Non-Cu %


Non-Cu Fraction
0.55
0.53
0.51
0.49
0.47
0.45
0.43
0.41
0.39
0.37
0.35
46 ± 1%
NC%
NC% -LSL
NC%- USL
Average
RRP-10428 BE
RRP-10429 BE
RRP-10433 BE
RRP-12008 BE
RRP-12319 BE
RRP-12391-3 BE
RRP-12520 BE
RRP-12878-1 BE
RRP-12878-2 BE
RRP-12879 BE
RRP-12885 BE
RRP-13090 BE
RRP-13091 BE
RRP-13154 BE
RRP-13211 BE
RRP-13376 BE
RRP-13377 BE
RRP-13596 BE
RRP-13618 BE
RRP-13658 BE
RRP-13659 BE
RRP-13699 BE
RRP-13700 BE
RRP-13709 BE
RRP-13710 BE
RRP-13711 BE
RRP-13916 BE
RRP-13917 BE
RRP-13918 BE
RRP-14007 BE

RRP® Ti-Ternary vs. Ta-Ternary

- Advantages of Ti-Ternary:
- *Higher strain tolerance (main reason)*
- Does not require Nb-7.5wt% Ta alloy rods
- Ti content can be tweaked easily to maximize B_{c2}
- *Ti accelerates Nb_3Sn reaction*
- *At 650C/48h, Ti-Ternary has higher J_c(15T) than Ta-Ternary*

Ti-Ternary conductor is being phased into magnet coil fabrication

LARP Cable Production (LBNL)

LARP

Standard 2 Pass Fabrication Procedure

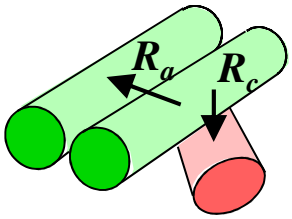
- 1st Pass
  - Fabricate cable slightly over size by 50-100 microns
- Anneal at 200C/4 hrs
  - Softens Cu and cable contracts by ~0.25% in length
  - In addition the width and thickness of the cable increases
- 2nd Pass
  - Re-roll cable to the specification thickness
  - Compacts cable making it more mechanically stable for coil winding

Present Modified Process for HQ and LHQ

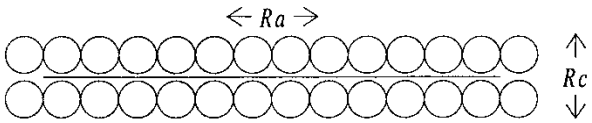
- Anneal strand prior to cabling, no anneal of cable
  - Changes wire deformation behavior
  - Enables the use of metallic cores
- Fabricate cable in 1 Pass to the specification thickness

Suppression of Eddy-Current Magnetization and Losses by increasing R_C

crossover resistance R_C
adjacent resistance R_A



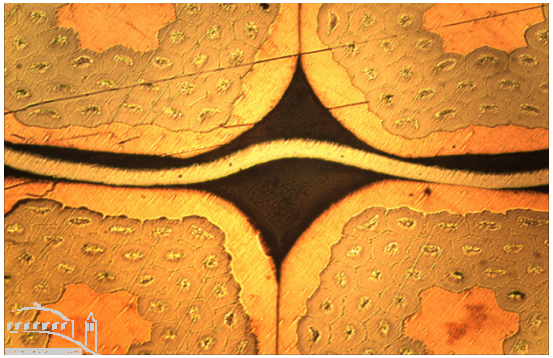
- In a typical cable $R_C \sim R_A$
- In Nb_3Sn cables these resistances are very low as the copper sinters during the reaction
- Resistive coating on strand increases both R_C *and* R_A
  - Chrome plating on ITER strand
- Increase R_c selectively
  - ➢ By using a Resistive core

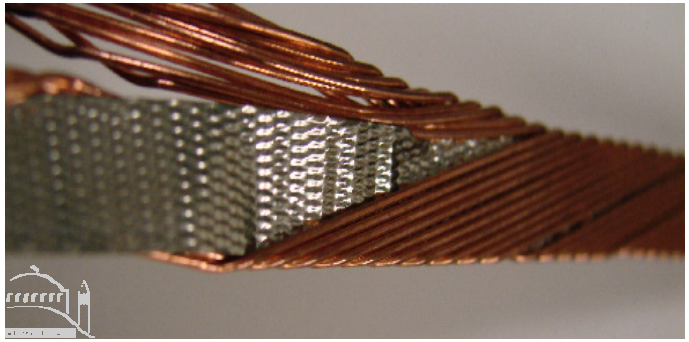


  - Maintain R_A for adequate Current Sharing

15 mm wide HQ-Cables with Core-Development at LBNL

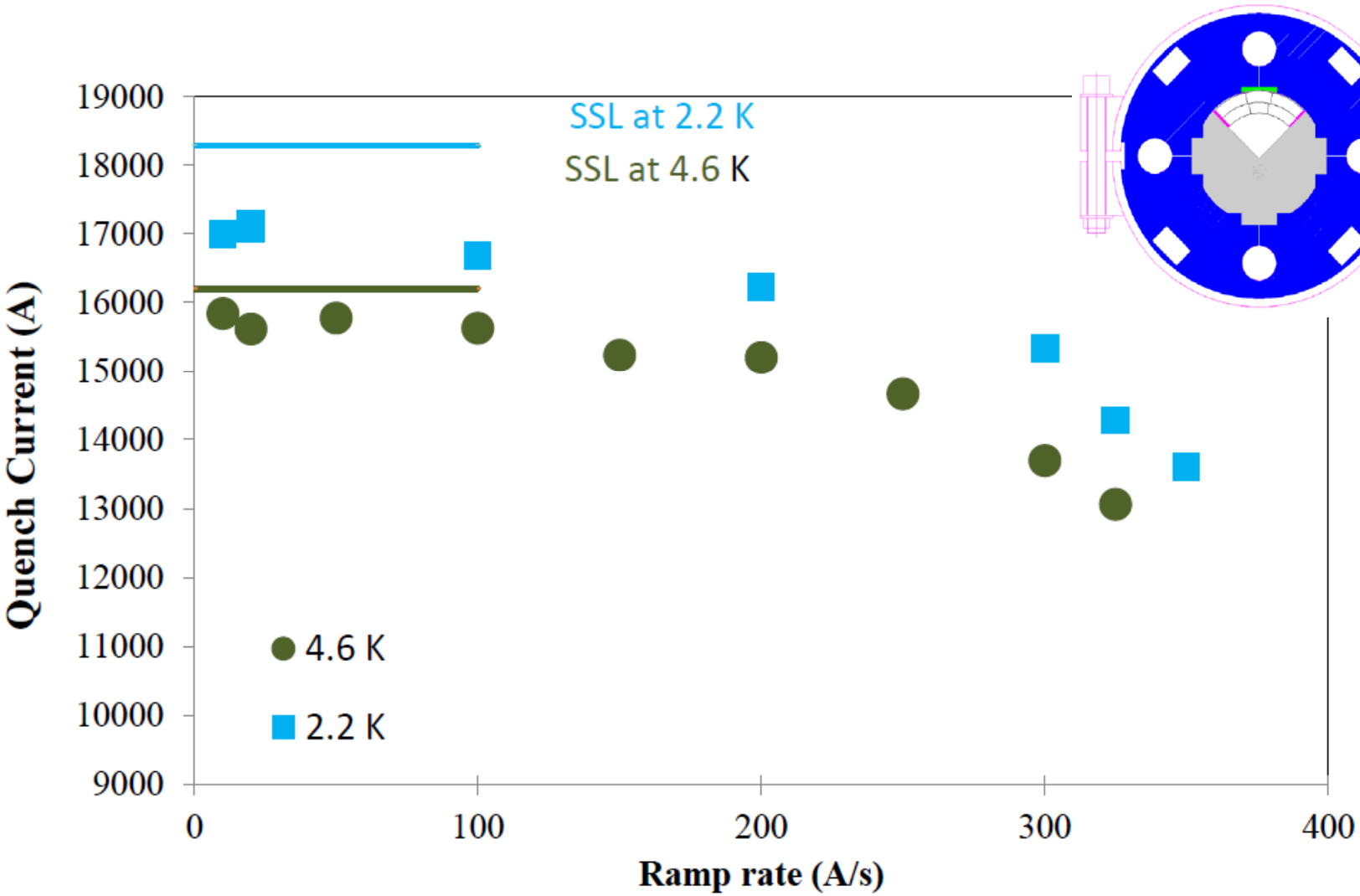
- Annealed Stainless Steel 304 Core
  - Cannot anneal and re-roll cable
    - During anneal cable shrinks whereas the core does not leading to core bunching
  - Anneal strand prior to cabling
    - LBNL has developed HQ cable in one pass using annealed 0.778 mm strand
  - Coil winding and coil performance
    - HQ-Coil 15 wound and tested in mirror configuration HQM04

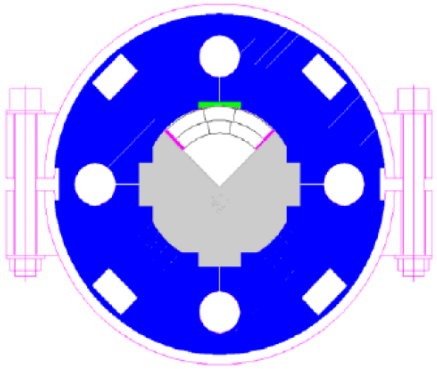




Mandrel with slot

Performance of HQ Coil with SS Core
Single coil Test in Mirror configuration





HQ/LHQ Cable Parameters

Cable Specifications

Strand Diameter	0.778 mm
No. Strands	35
Thickness	1.375 ± 0.01 mm
Width	14.80 ± 0.05 mm
Keystone angle	0.75° ± 0.05
Strand annealed	190 ± 5 C /4 hrs
Core	25 μm Annealed SS tape
Cable Pitch	95 mm

With these parameters the over-compaction of the insulated cable in the coil fabrication/reaction tooling has been eliminated

Cabling Plan for LHQ and beyond

- LHQ
  - Ta-Ternary
    - Fabricate 4 UL's in FY'12
    - 4 UL's in early FY'13
  - Ti-Ternary
    - Fabricate 6 UL's in FY'13
- 150 mm aperture magnet cable
  - Initial design is 40 strand cable using 0.85 mm strand.
  - Plan to hold wire at 1.07 mm pending final design of cable.

Baseline Cable Parameters for 150 mm aperture quadrupole

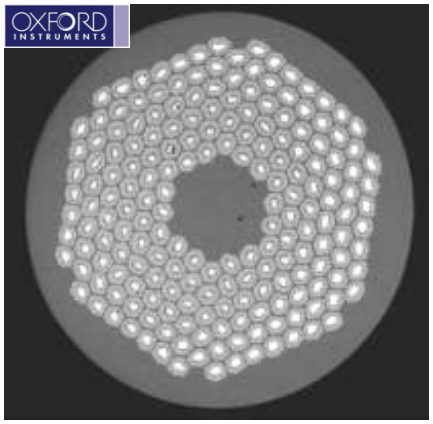
Wire diameter	0.85 mm	increase from 0.778 mm
No. of strands	40	increase from 35
Width:	18.25 mm	increase from 14.8 mm
Thickness:	1.50 mm	increase from 1.38 mm
Keystone angle	0.65 deg	decrease from 0.75 deg

Plan to make 100-150 m of cable in Aug'2012, with the first 35 kg delivery of wire at 0.85 mm

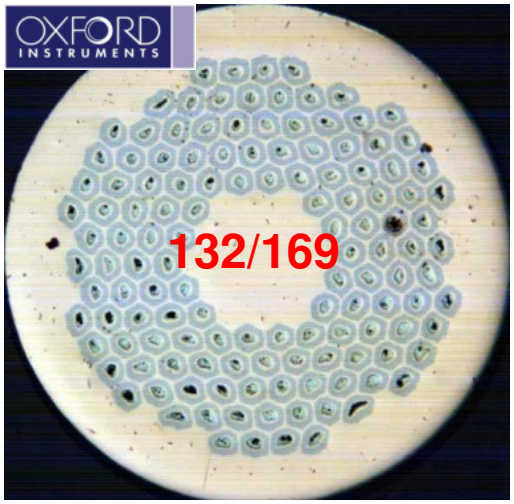
- Check cabling degradation
- winding tests for mechanical integrity

Pathway towards smaller filaments
CDP-Conductor Development – 217 stack

- 192/217 re-stack of 3000 A/mm^2 class sub-elements(high *Nb* and *Sn*-content design used for 54/61 and 108/127) could not be processed to 0.8 mm
- 2400 A/mm^2 class (lower *Nb* and *Sn*-content) processed to 0.8 mm in two long pieces
  - Ti-Ternary
  - For optimized J_c , RRR very low ~ 8.
  - Very difficult to maintain high-J_c and RRR > 50 for smaller filaments
- To increase RRR ⟹ new sub-element design
  - ➢ Increase starting *Nb* filament diameter
  - ➢ Control roundness of *Nb* mono-rods
  - ➢ Increase spacing between *Nb* filaments
  - ➢ Increase barrier thickness
- New 2700 A/mm^2 class conductor being developed. First results Aug-Sep'12 ⟹ Ti-Ternary



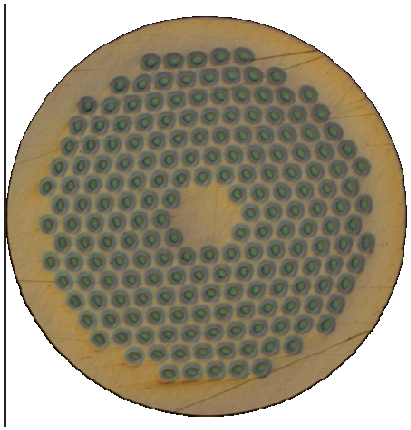
RRP Conductor
Another Option– 169 re-stack

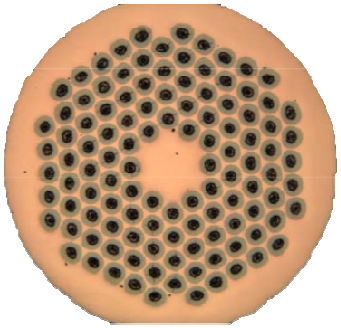


- 10 km delivered to CERN
  - Ti-Ternary, 1.0 mm
  - d ~ 57 μm
  - J_c(12T) ~ 3050 A/mm^2,
  - J_c(15T) ~ 1680 A/mm^2
  - RRR 142 - 201
- 1.0 mm wire when drawn down to 0.8 mm shows very good properties
  - d ~ 46 μm
  - J_c(12T) ~ 3130 A/mm^2
  - J_c(15T) ~ 1630 A/mm^2
  - RRR ~ 100

Secondary source of wire : Powder-in-Tube PIT wire

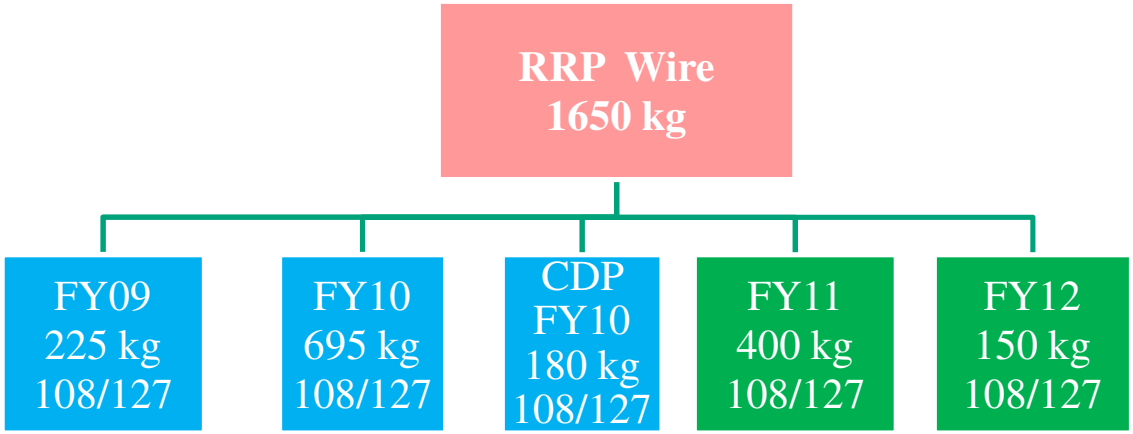
- Development driven by CERN
  - 1.0 mm PIT (FRESCA II Dipole)
    - 192/217 design, d ~ 50 μm
    - 50 km of wire produced
    - Good piece lengths: 500 m to 5 km
    - J_c(12T) > 2500 A/mm^2, RRR >150
  - 0.7 mm PIT (11 T Dipole)
    - 114/127 design Ds ~ 45 μm
    - In-process
    - Specification
      - J_c(12T) > 2500 A/mm^2, RRR >100
  - LARP is acquiring 50 kg of wire at 0.85 mm for cable/coil evaluation





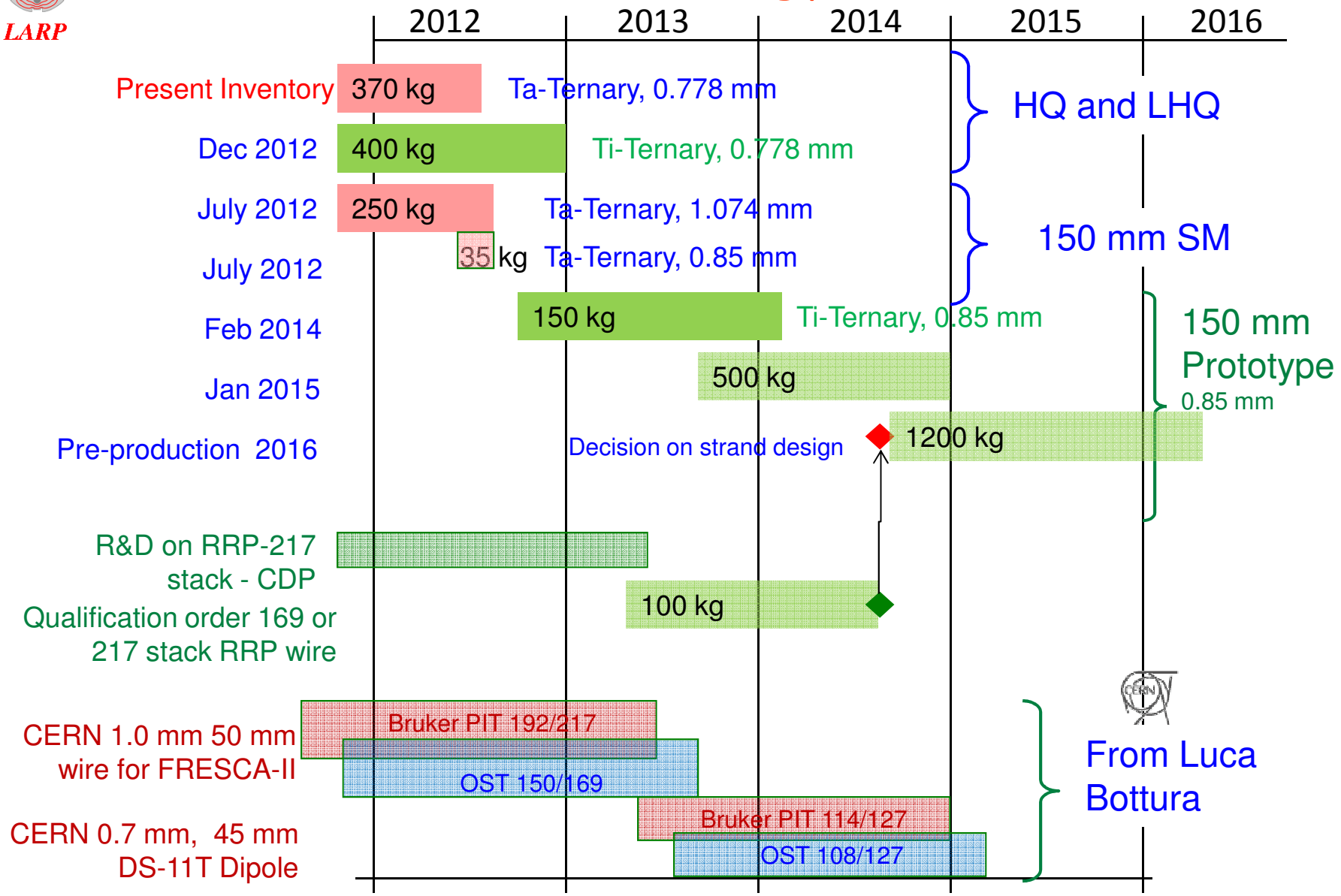
Procurement of RRP- 108/127

Strand lead time is 15 months

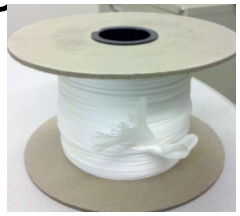


- OST is currently producing ~ 1200 kg/month of Nb_3Sn
- LARP production is in parallel with ITER wire production
- ITER production will continue for the next 12-18 months

Procurement strategy (June 2012)



Cable Insulation



- At present cable is insulated with S2-glass sleeve
  - Limited to cable lengths ~ 250 m
    - Labor intensive
      - Heat-remove 636 sizing, dip coat with palmitic acid, insulate cable like a sock
- Production friendly options
  - Tape wrapped onto cable
    - FNAL has done extensive development to insulate cables.
    - LBNL and BNL also has capability
    - S2 –glass tape too thick, E-glass -thinnest 0.075 μm.
    - Insulation thickness ~ 125 – 150 μm
  - Braiding S2 glass directly on cable
    - Industrial process
    - Development at New England Wire Technology Co (NEWTC).

Braided Insulation

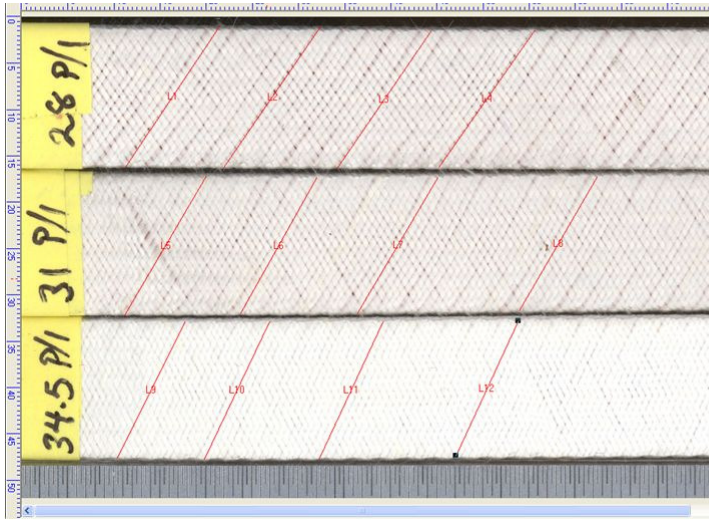
- Braided Insulation at NEWTC
  - Initial development : 10 mm wide LQ cable using S-2 glass with 636 sizing (starch binder)
    - Reaction at 640C leaves a lot of carbon residue
  - Recent trials used S-2 glass with 933 Silane sizing
    - Product literature: 933 sizing is stable at processing of temperature of 670°F and above
    - Trials at LBNL show that 2% by weight is lost by heat treating at 665C
    - CERN is also experimenting with braiding similar yarn.
    - Tests at CERN to 650C show no decomposition of the sizing.

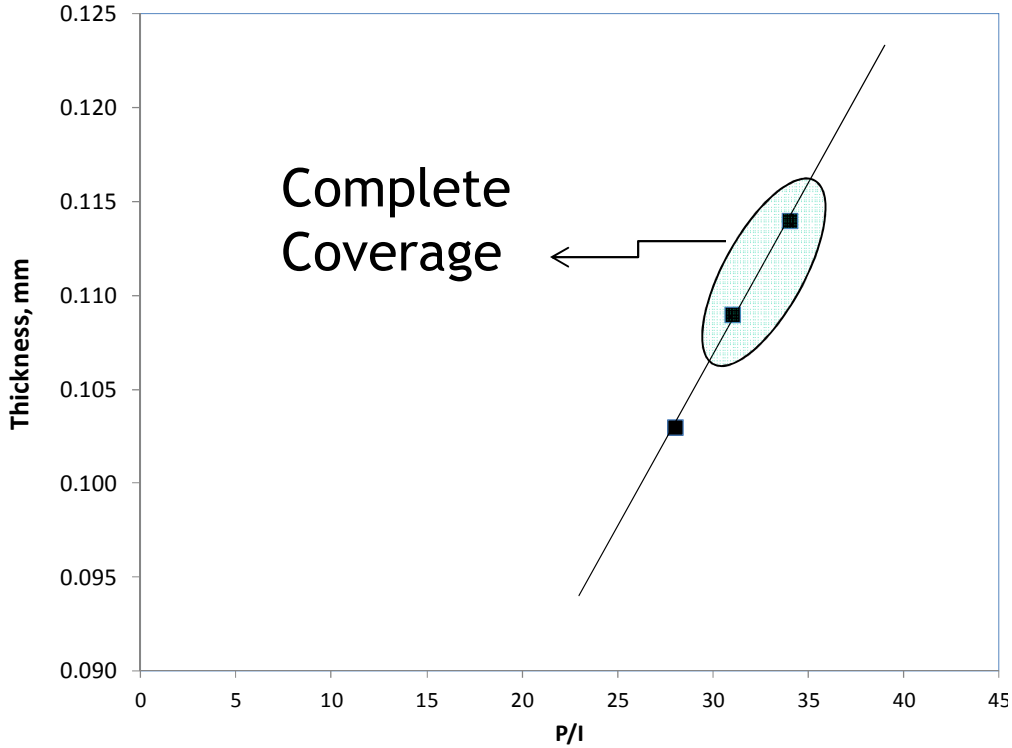
S-2 glass with 933 sizing

agy

High Temperature
933 S-2 Glass® Yarn

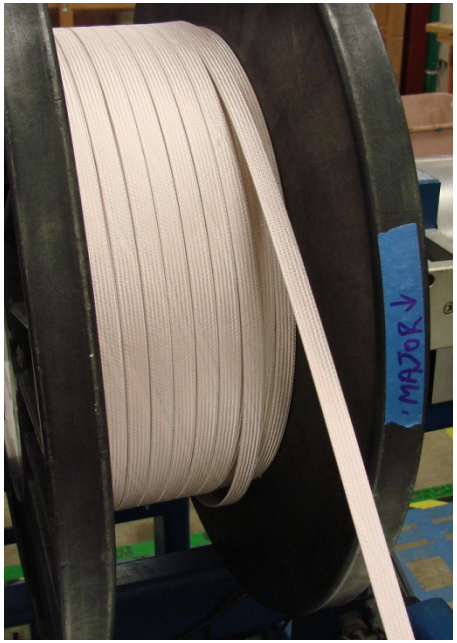
- 1st Trial ~ 30 m of 15 mm wide cable using three different lay pitch
- Thickness measured at LBNL, using dry 10-stacks

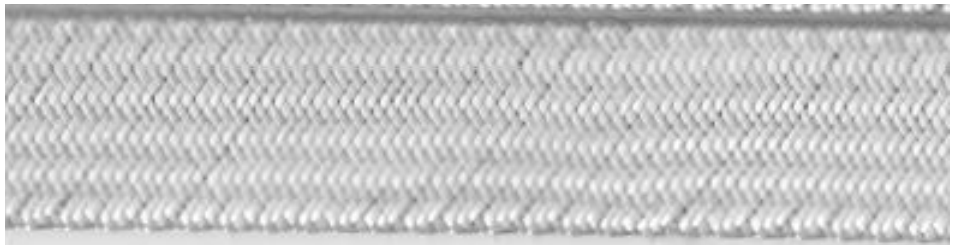




Braided Insulation- 2nd Trial

- 2nd trial : 100 m of HQ 15 mm wide cable
  - Using braiding parameters to yield 100 μm thickness
  - 10-stack measurements at 6 MPa 103 μm
  - Cable used to wind coil HQ-C17 . Coil was reacted and is now being impregnated





- Plan is to insulate another HQ unit length and 2 unit lengths of cable for the first two practice coils for LHQ, cable unit length ~ 320 m.
  - Capture braiding process and QA checks at vendor to ensure a good and reproducible product.

Plans for insulation development

- Insulation for LHQ cable
  - Plan is to braid insulation on the cable using S-2 glass with 933 sizing with insulation thickness of 100 mm
  - Reliability of process at vendor (NEWTC) is being established
- Insulation for the 150 mm magnet cable
  - Discussion on-going with CERN and the design group to settle on the ideal thickness based on voltage stand-off requirements
  - For insulation thickness of 125 μm, both Braiding and Tape wrapping processes are viable
    - Tape will require use of E-glass tape – this has radiation concern due to the presence of Boron

Rad-Hard Epoxy

- Some options:
  - Cyanate Ester (CTD-403)
  - Cyanate Ester / Epoxy Blend (CTD-425)
    - This is being used by ITER
  - Matrimid 5292
- New materials need to be qualified:
  - Make and test 10-stacks.
  - Compare with current epoxy - CTD-101K:
    - Electrical
    - Mechanical
    - Cryogenic

Rad-Hard Epoxy

- Matrimid has issues with temperature / viscosity
  - High working temperature – 125 C/ short pot life ~ 60 min
  - High cure temperature – 225 C
  - Lines need to be actively heated to prevent solidification / blocked lines.
- CTD-425 – Epoxy/Cyanate Ester Blend (60/40).
  - Mixing / Processing Temperature 45-60 C, long pot life
  - Cure: Slow ramps, 22 hours at 100 C, 24 hours at 170 C.
  - Cyanate Ester/Blends have safety issues with possible exothermic reaction.
    - Requires precise control of epoxy temperature from mixing through impregnation.
    - Need ability to cool epoxy pot.
    - May need ability to cool impregnation fixture.

Matrimid Investigation at FNAL

- Building on previous experience at FNAL
- Developed tooling to impregnate 36” coil stacks
- Successful impregnation of 36” cable stacks
- Followed-up with impregnating a 1-m TQ Coil

Steve Krave,
Rodger Bossert
Marianne Bossert

- On-going activity
  - 10-stack for material characterizations at room temp and 77K (or 4.2K)
    - TQ cable with Cyanate Ester-425, Matrimid and CTD-101K
    - HQ 15 mm wide cable
    - 11 T 16 mm wide cable

Plans for Epoxy development

- BNL developing impregnation tooling to use both Matrimid and Cyanate Ester CTD-425
  - First pass to impregnate an HQ coil with Matrimid
- FNAL developing short sample characterization
- Opened a dialogue with people working within the EuCARD program WP7 (CERN and RAL) to collaborate on comparing these epoxies with those being developed under EuCARD, including radiation damage studies.

Summary

- Production of Ta-ternary 0.8 mm RRP 108/127 strand has been good
  - Piece lengths are reasonable but needs improvement
  - J_c(12T) > 2800 A/mm^2 , J_c (15T) ~ 1400 A/mm^2
  - Some billets show RRR < 60
- HQ/LHQ cable parameters revised to reduce over-compaction of the insulated cable in the coil fabrication tooling
- Cabling procedures revised to enable cable that can be made with a core.
- Cored-cable in magnet coil has been demonstrated
- Procurement of strand in line with LHQ and HQ magnet schedule
- Ti-Ternary strand has been phased into strand procurement
- Conductor procurement strategy has been developed to enable 150 mm model coil program and the long prototype IR magnet

LARP

End of Presentation

Additional Slides

1. Nomenclature
2. Conductor PL histogram
3. Ti-Ternary vs. Ta-Ternary (3 slides)
4. Strand Inventory and Usage
5. Impact of higher copper content on HQ Short sample Limit
6. TQM03 Test at FNAL
7. Magnetization of 54/61 and 108/127
8. Low-field Instability
9. Insulation thickness comparison

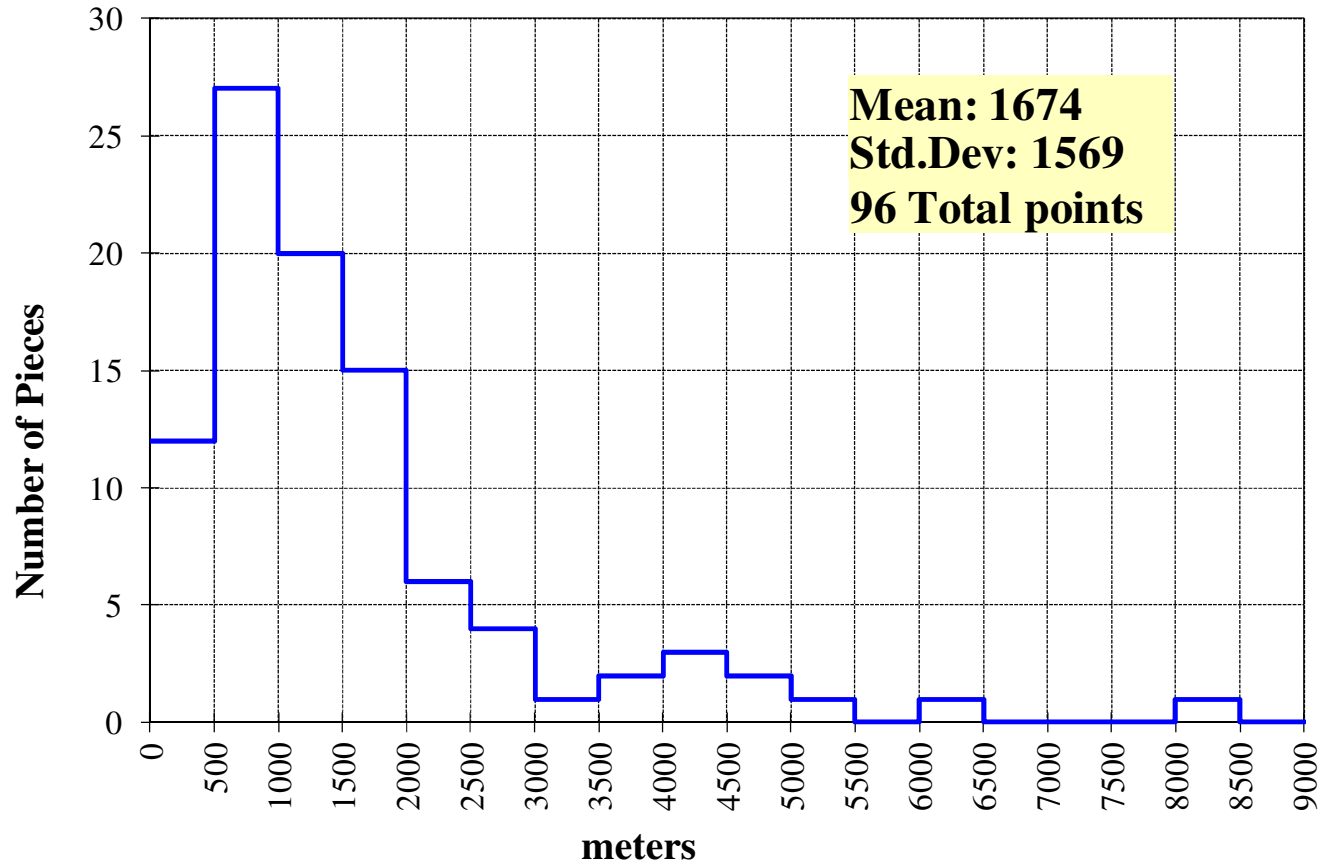
Nomenclature

- RRP® Re-Stack Rod Process
- Ic Critical current usually quoted at 12 T, 4.2 K, A
- Jc Critical current density over the non-Cu area, A/mm^2
- Is, Js Low-field Stability current, current density, A, A/mm^2
- d filament diameter ~ sub-element diameter, μm
- RRR Residual Resistance Ratio of the Cu-matrix R(295K)/R(18K)
- Iq Quench current , can be > = or < than Ic, A
- C Volumetric Heat Capacity , J/m^3-K
- V-I Set field then ramp current till wire quenches
- V-H Set current at zero field then ramp field
- UL Length of cable required for a magnet coil
- ε_{max} applied strain for maximum Ic in Ic-strain measurements
- ε_{irr} applied strain when Ic degrades irreversibly
- PF, PF1 Overall packing factor , minor edge packing factor

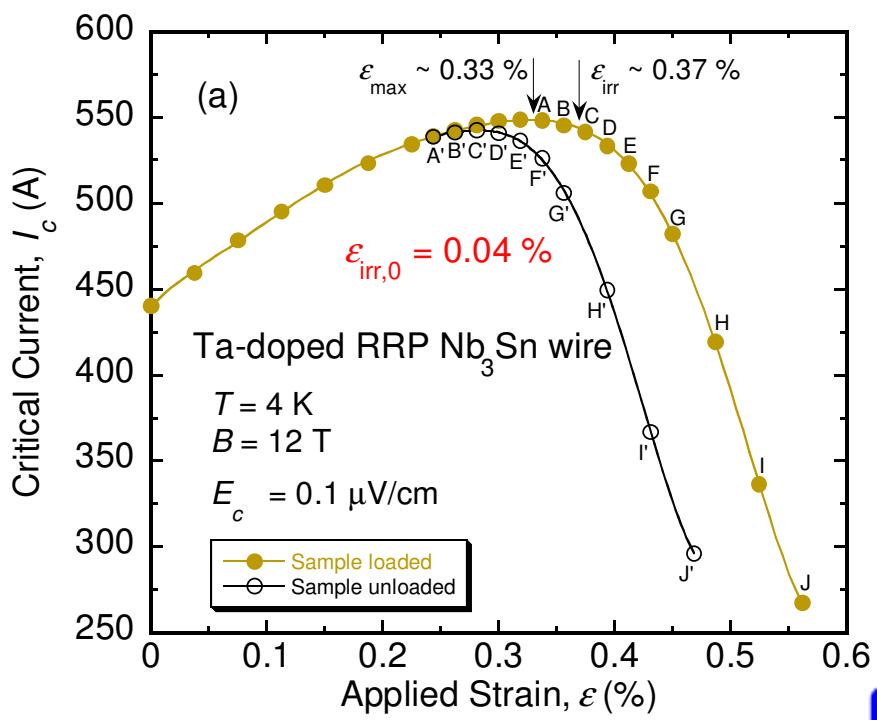
Conductor Piece Length distribution RRP-108/127

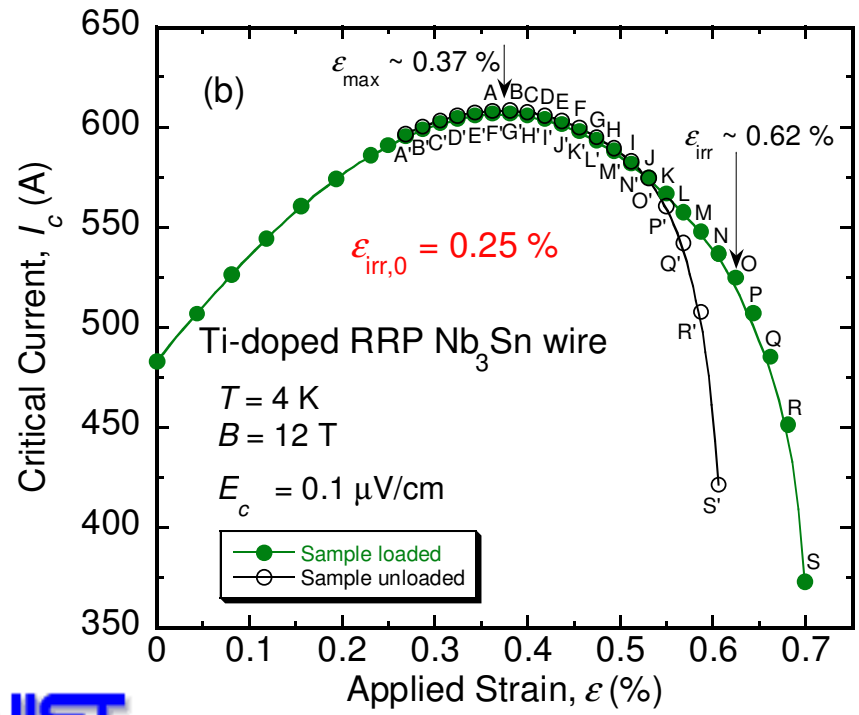
158 km of wire

> 550 m 98%
>1000 m 86%
>3000 m 37%
>5000 m 18%



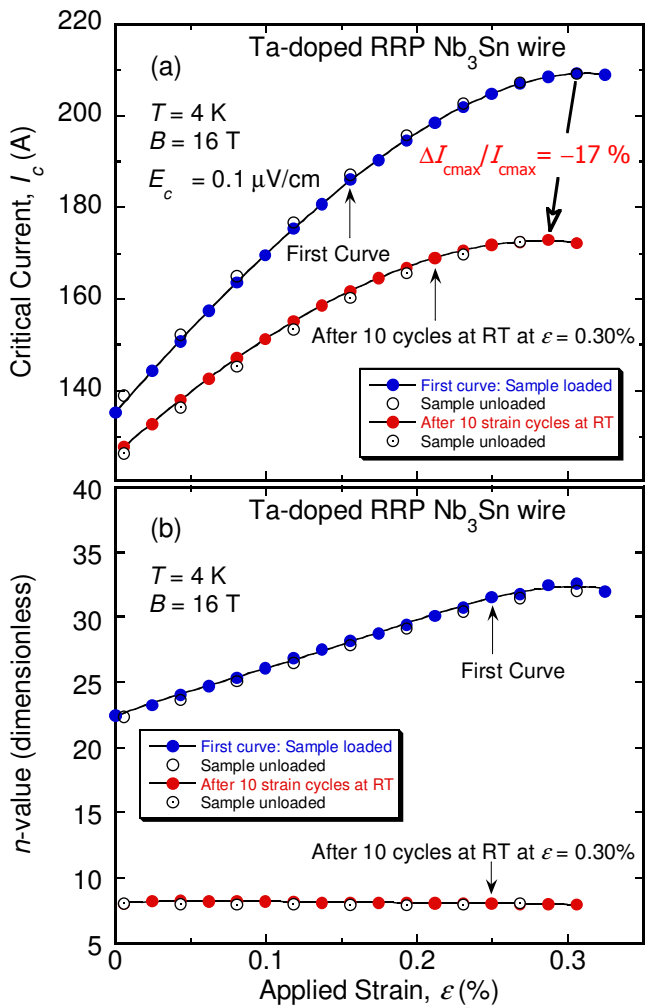
Ti-Ternary vs. Ta-Ternary





In tension, Ti-doped Nb_3Sn wire more strain tolerant than Ta-doped

Strain Cycling: Ta-Ternary



Strain cycling at room temperature at a strain of 0.3 % (~ ε_{max} at 4 K) causes

(a) a noticeable degradation of I_c ~ 17% (with a small shift of ε_{max}),

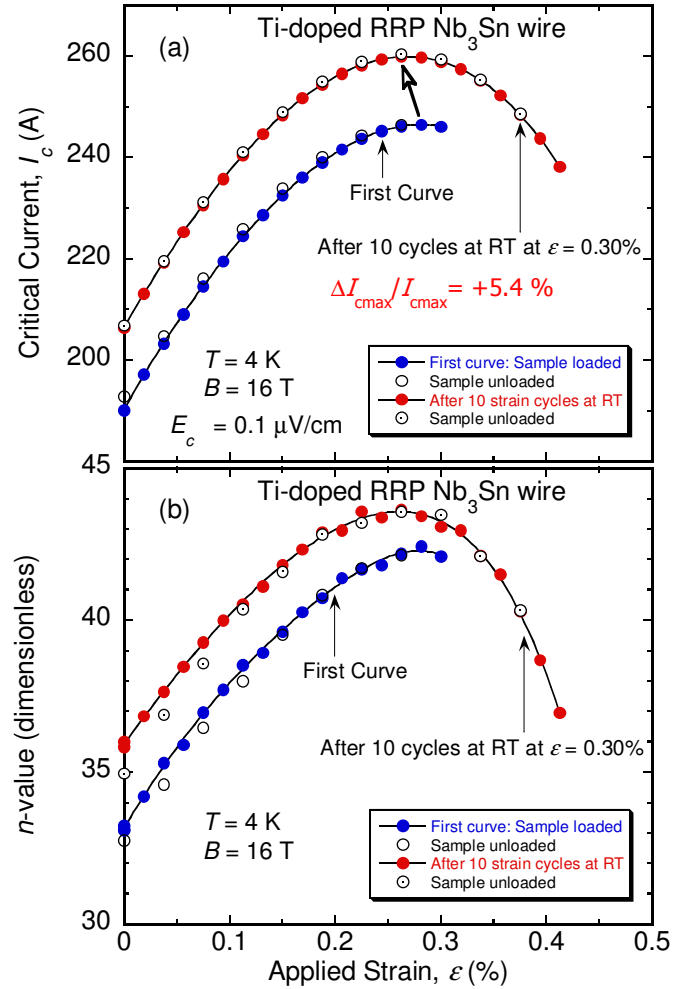
(b) a drastic depression of the *n*-value in the Ta-doped RRP wire.

Strain Cycling: Ti-Ternary

Room-temperature *strain cycling* of the Ti-doped wire at a strain of 0.3 % (~ ε_{max} at 4 K) *was not only safe, but caused an increase in*

(a) I_c ~ 5.4% (with a small shift of ε_{max})

(b) *n*-value.



Influence of Ta and Ti doping on the irreversible strain limit of ternary Nb3Sn superconducting wires made with restacked-rod process*
N. Cheggour, L. F. Goodrich, T. C. Stauffer , J. D. Splett , and X.F. Lu, A. K. Ghosh, G. Ambrosio
Supercond. Sci. and Tech., 20, (2010)

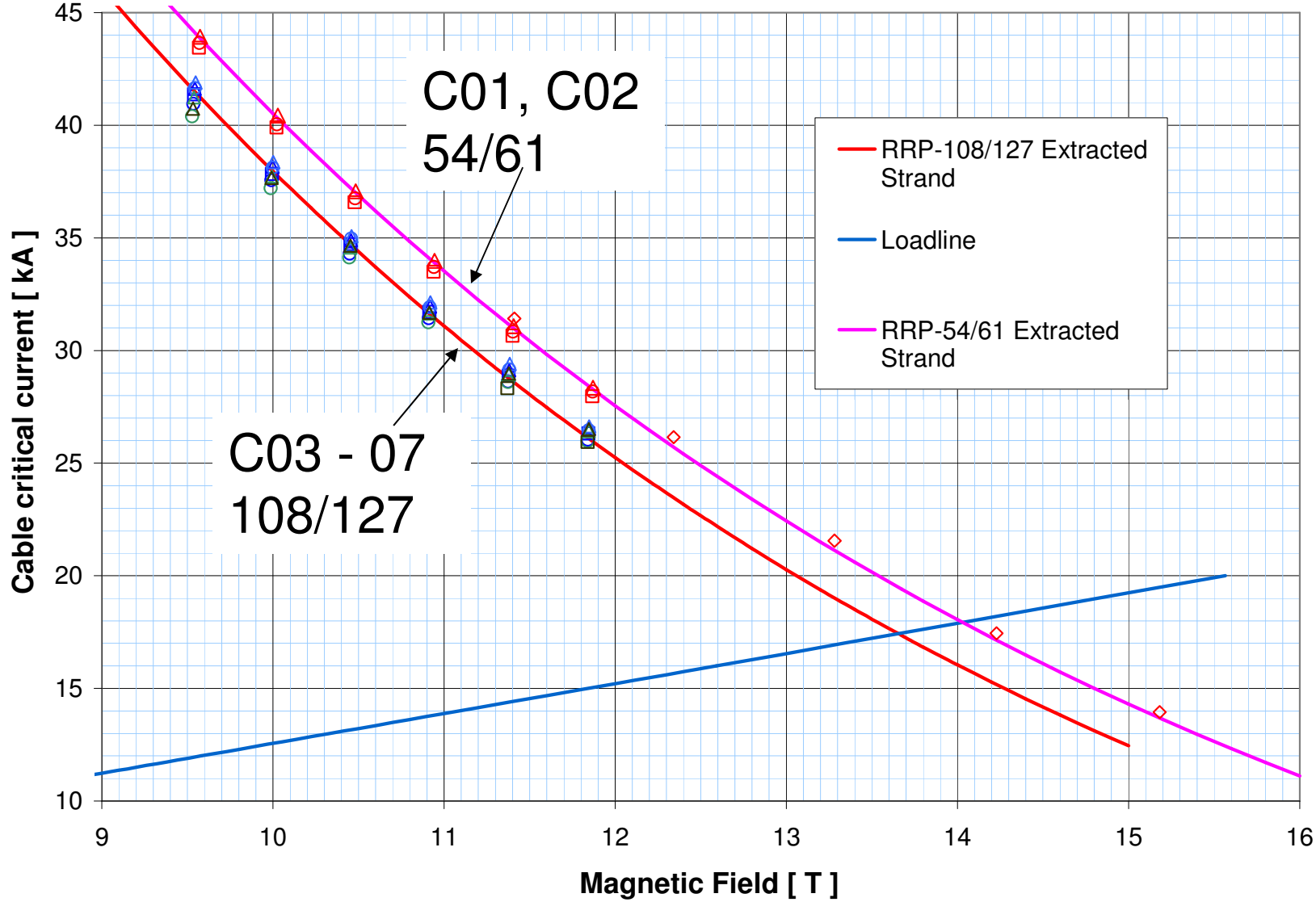
Under Cyclic strain at RT., Ti-doped Nb_3Sn wire more robust than Ta-doped

Strand inventory and usage

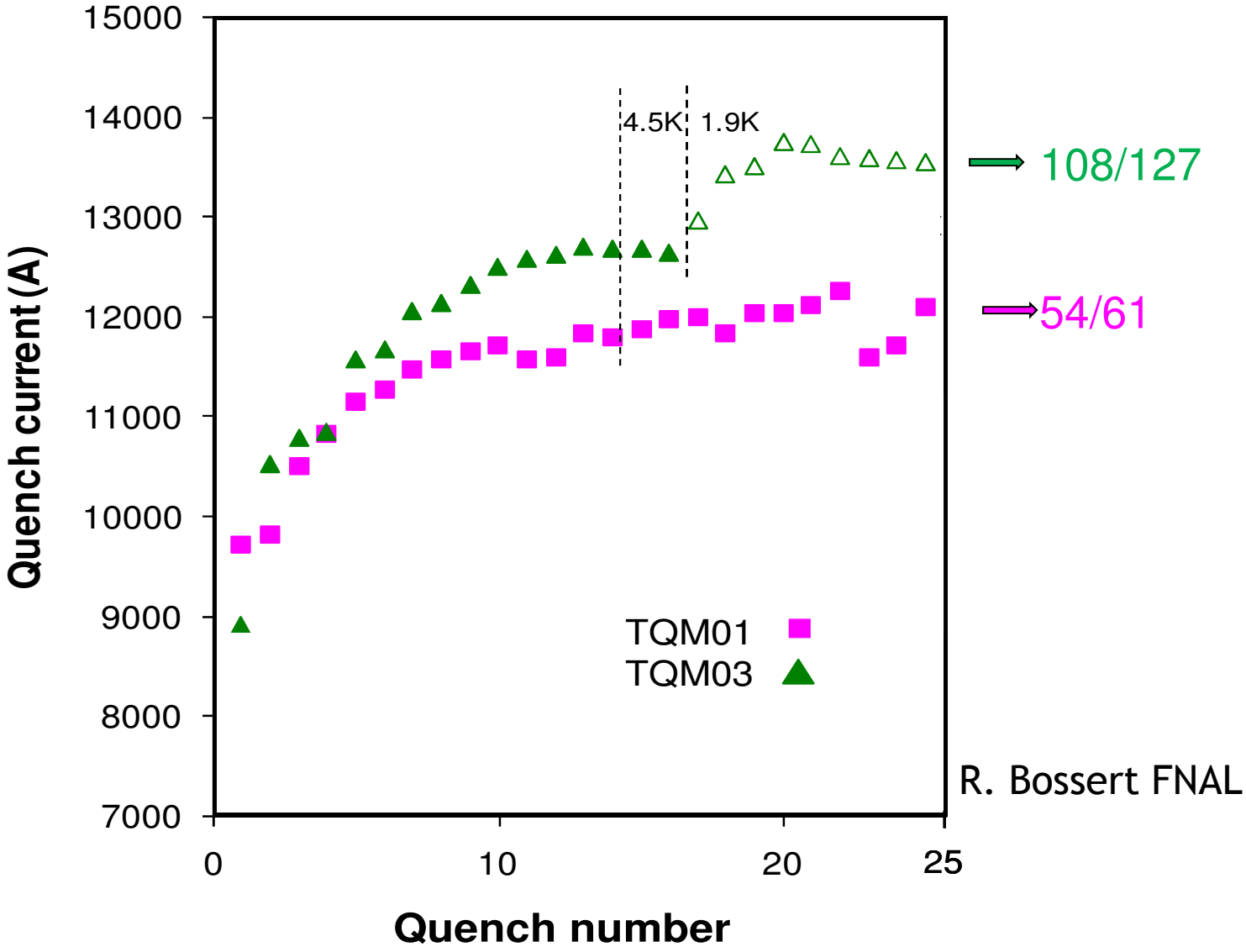
Month	108/127 Delivery, kg	Coil ID	Cable ID	Strand Req. kg	Cable Unit Lengths	108/127 0.778mm kg	Ti-108/127 0.778 mm kg	108/127 1.074 mm kg
Jun-11						130	90	
Jul-11						130	90	
Aug-11		HQ1 C15-C16	B1020Z	80	4	50	90	
Sep-11	115					165	90	
Oct-11						165	90	
Nov-11		HQ1 C17, C19, C20	B1021Z	89	5	76	90	
Dec-11						76	90	
Jan-12						76	90	
Feb-12	125	HQ1-C18	B1024Z	90	5	201	0	
Mar-12	132	LHQ-PC01	B1025Z	60	1	273	0	
Apr-12	57					330	0	
May-12		LHQ-PC02	B1032Z	60	1	270	0	
Jun-12	100					370	0	80
Jul-12	25	LHQ-PC03		60	1	335	0	249
Aug-12		LHQ-PC04		60	2	275	0	249
Sep-12		LHQ-C05/06		120	2	155	0	249
Oct-12	280	LHQ-C07/08		120	2	35	280	
Nov-12						35	280	
Dec-12	120	LHQ-C09/C10		120	2	35	280	
Jan-13						35	280	
Feb-13		LHQ-C11/C12		120	2	35	160	
Mar-13		LHQ-C15/C16		120	2	35	40	
Apr-13						35	40	
May-13						35	40	
Jun-13						35	40	
Jul-13								
Aug-13								
Sep-13								

- There is sufficient Ta-ternary strand for 8 coils of LHQ
- By the end of CY2012 there will be sufficient Ti-ternary strand for 6 coils of LHQ
- HQ1: 1 m HQ,
- LHQ : 3.6 m
- 1 UL of HQ1 requires 18 kg
- 1 UL of LHQ: 60 kg
- 1 UL of 150 mm short model : 26 kg
- 1 UL of MQXF 4 m prototype : 110 kg

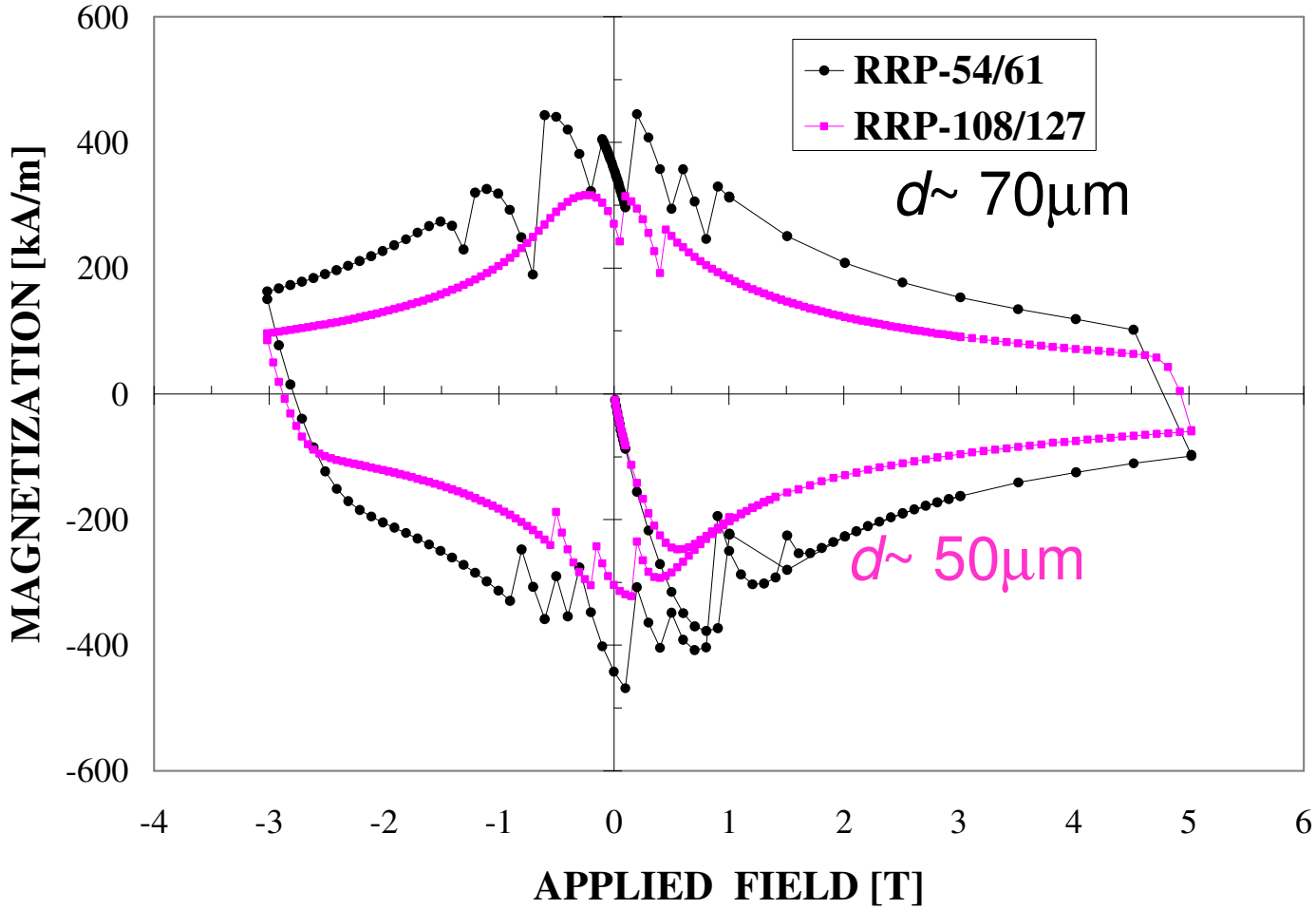
Impact of non-Cu fraction on Magnet SSL HQS01a



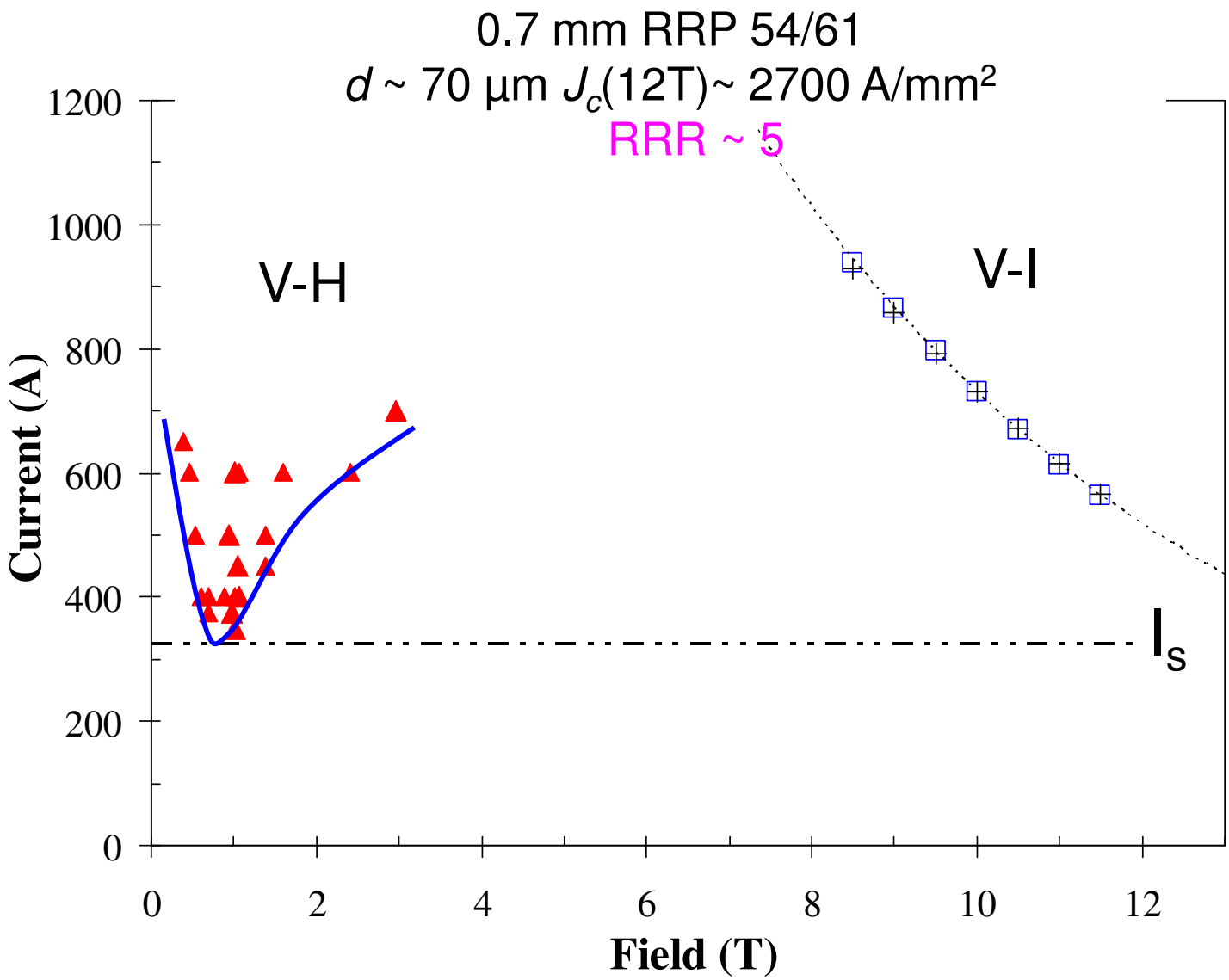
TQM03 Quench History



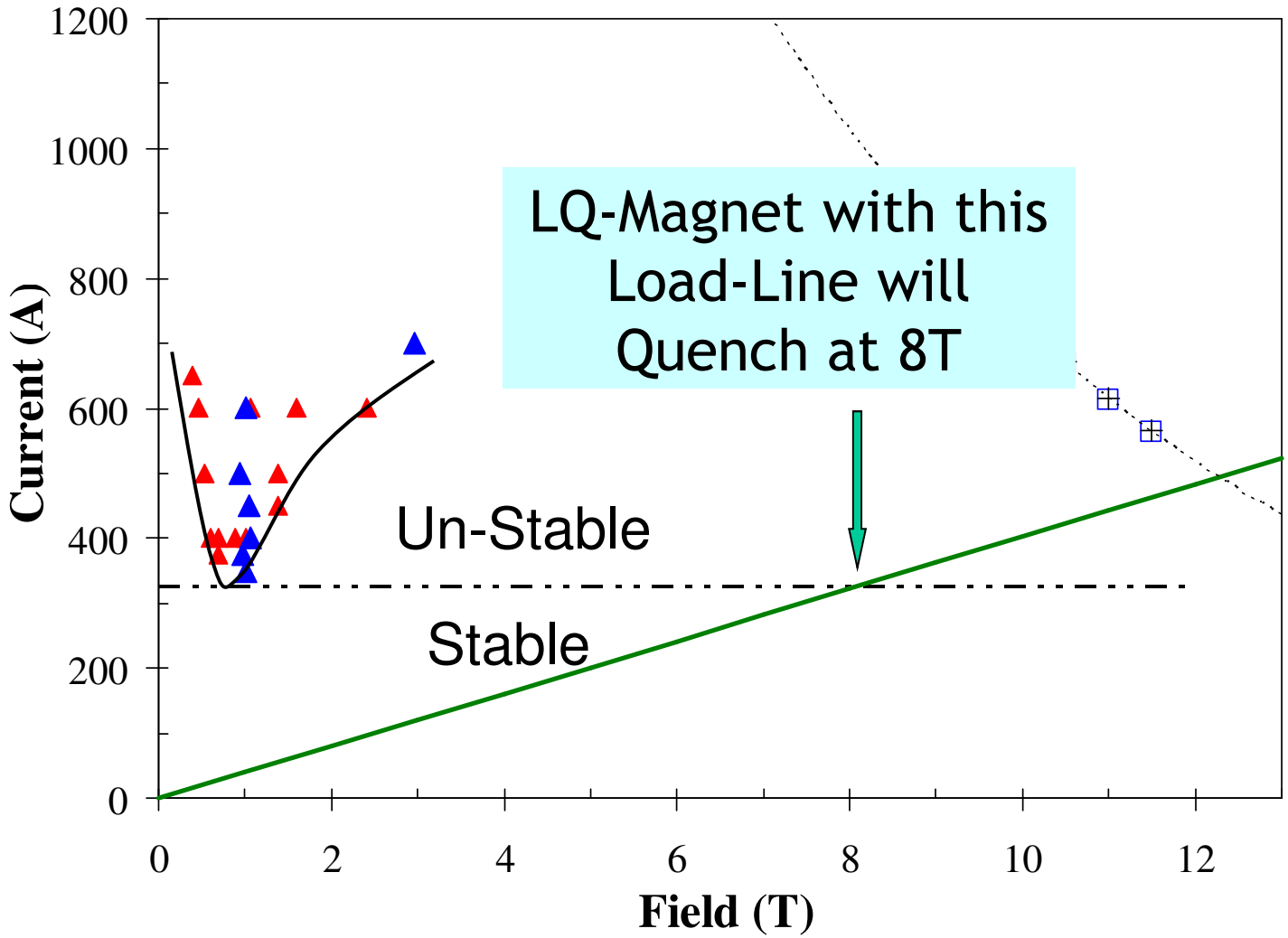
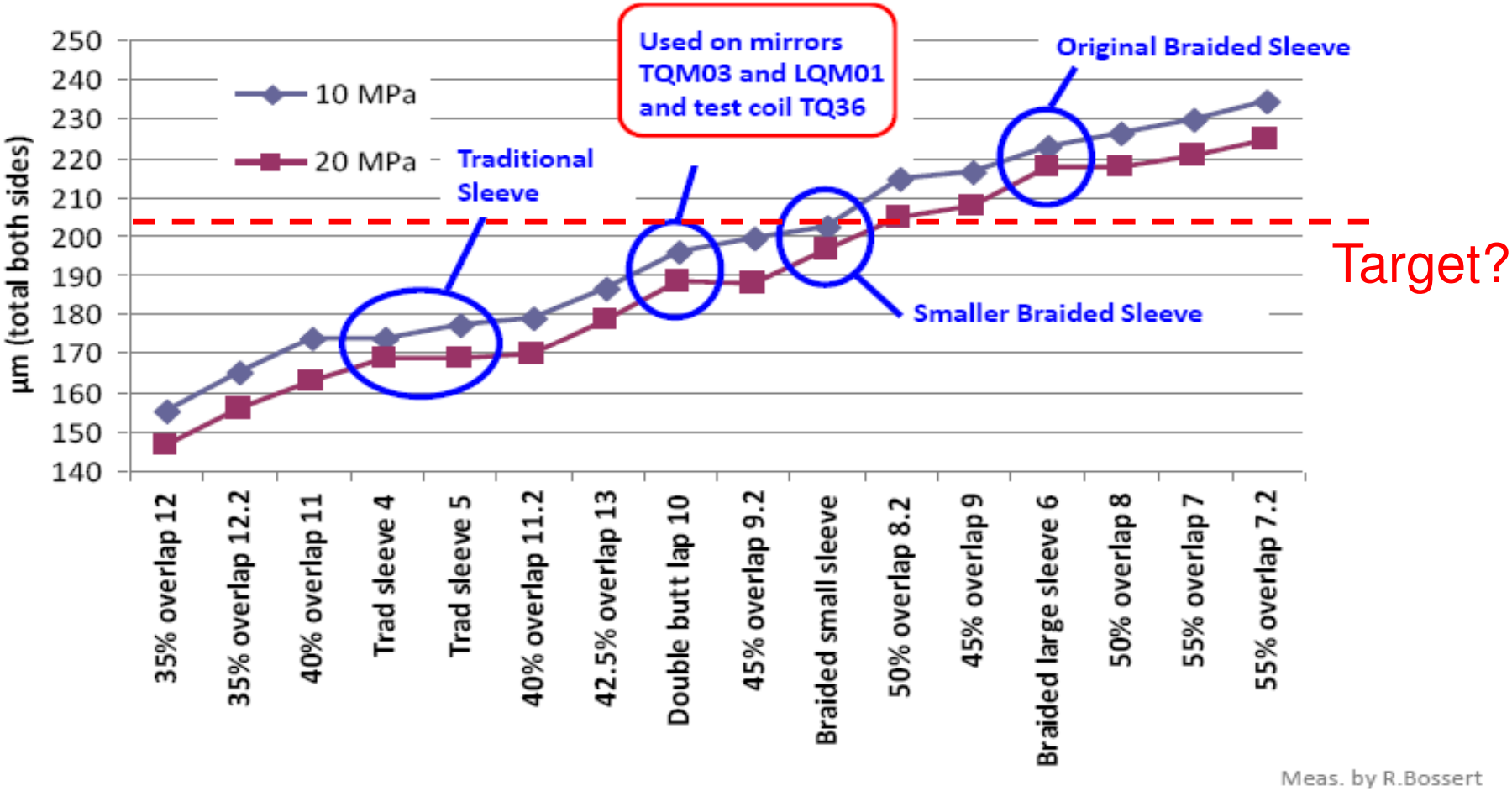
Observed in Magnetization measurements ⇨ Persistent current collapses periodically at low fields



Magnetization Instability at Low Fields ⇨ Is



Impact on LQ Magnet Performance



FNAL Insulation Thickness Data – Cured 10-Stacks