LARP DOE Review
June 01-02, 2011
FNAL

Conductor and Cable

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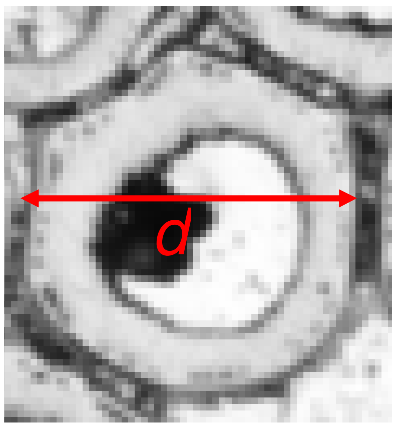
Outline

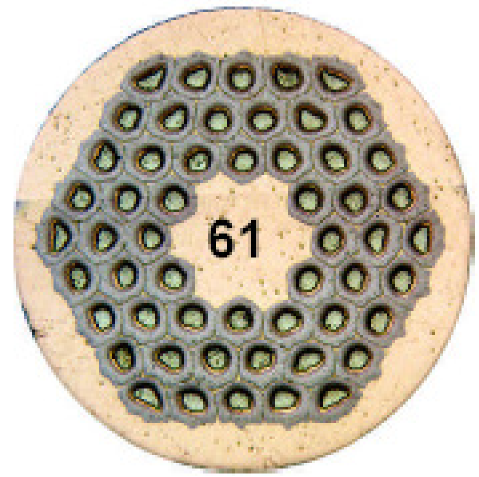
1. Introduction
2. RRP 108/127 Strand
3. OST strand production
4. Cable Production and R&D
    1. HQ Cable
    2. Cored-Cable R&D
5. Ti-Ternary Strand
6. Production Plan for FY10 and FY11
    1. Inventory of strand
7. Cable Insulation
8. Summary

LARP

1. Introduction

- The first long 90 mm quad-magnet LQS01 uses RRP® - 0.7mm strand from Oxford Superconducting Technology





  - ⇨27-strand 10 mm wide cable with 1.0° keystone angle
  - Strand is of the 54/61 design with d ~ 70 µm and Jc >2400 A/mm² at 12T

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

Flux-jump instability at low field

Tc =Transition Temp.

T_{bath}= Bath Temp

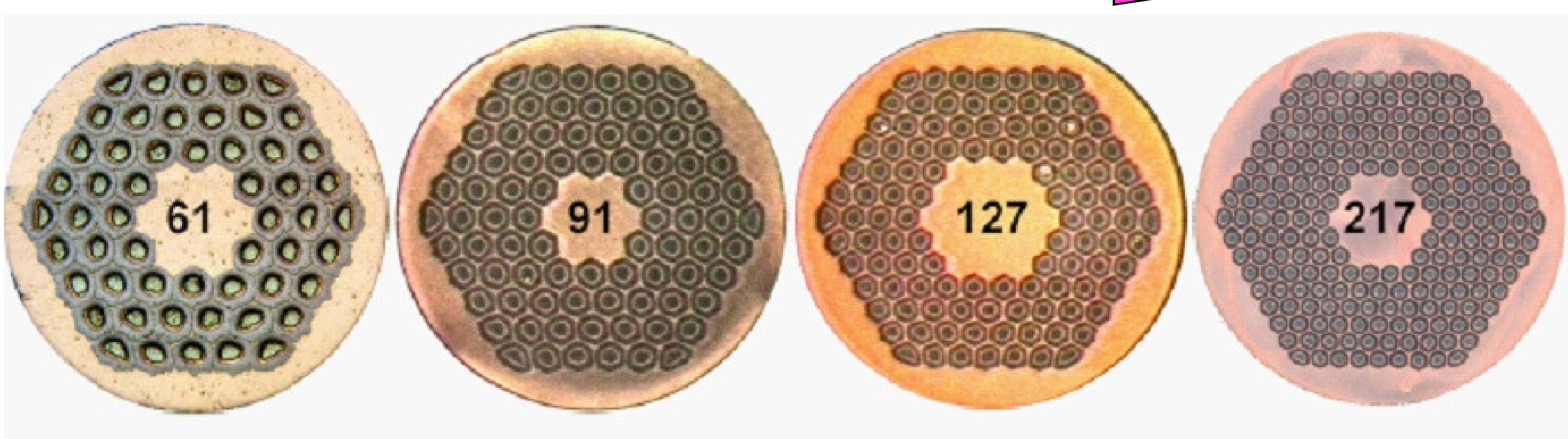
Stability can be improved by reducing filament diameter, *d*

- Smaller sub-elements can minimize flux jumps and improve stability.
- Smaller Filament Magnetization
- Main drivers have been DOE- HEP Conductor Development Program
- And FNAL Magnet R&D Program

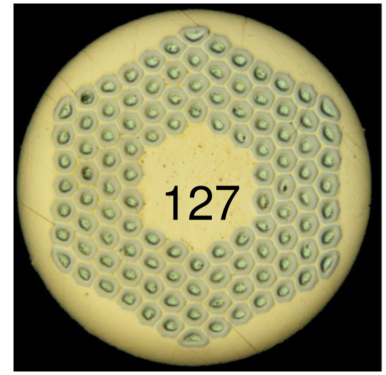
$$\beta = \frac{\mu_0 J_c^2 d^2}{4C(T_c - T_{bath})} < 3$$

73 μm   0.8 mm Cu/non-Cu 1.22   38 μm

d   Smaller Filament Size



2. Development of 108/127-design strand

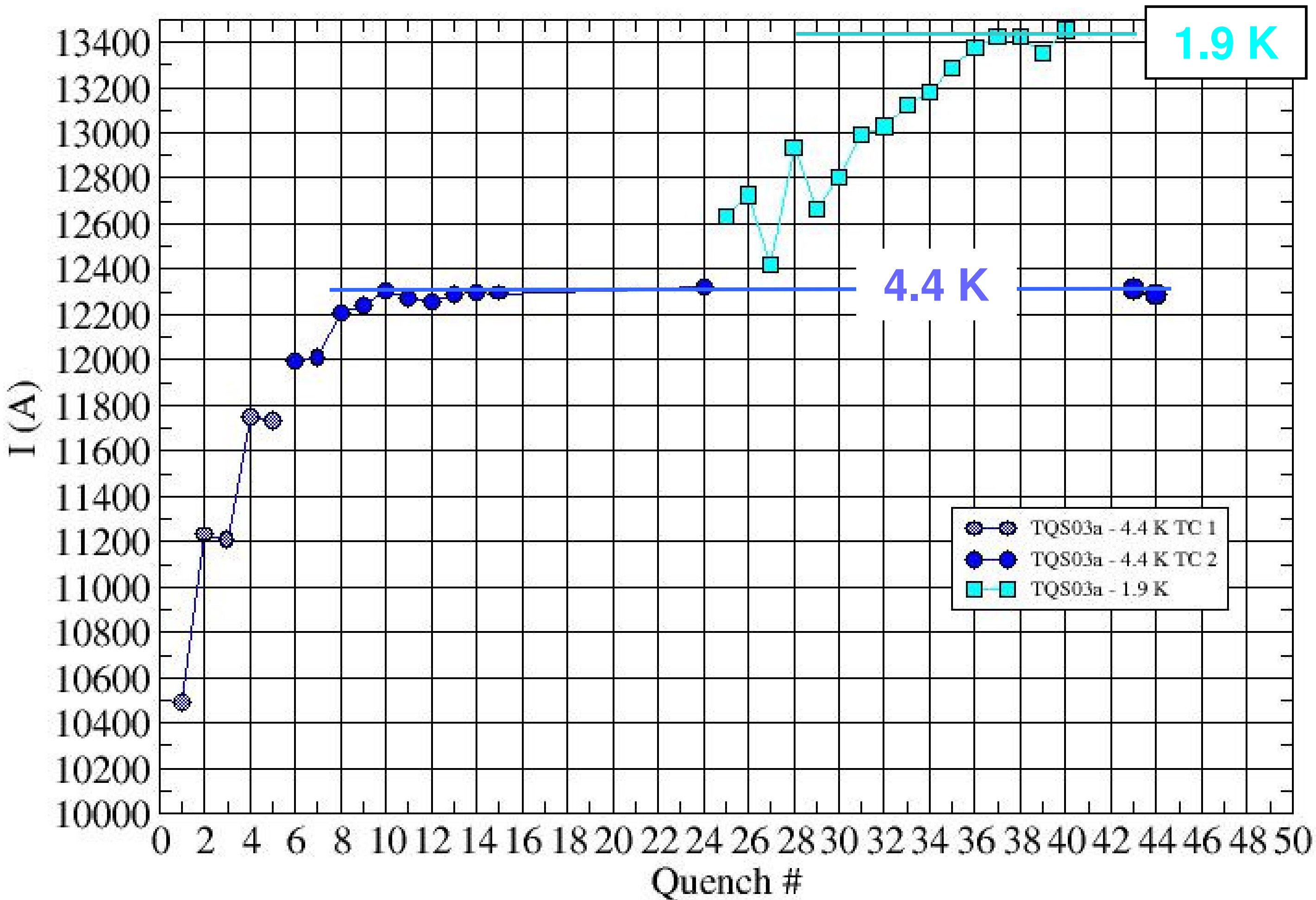


- In FY08 OST delivered 180 kg of high-Jc strand with the 127-stack design and larger spacing between sub-elements ⇨ *Cu fraction is 53% compared 47% in standard 54/61*
- *This production went well - good piece lengths*
- Ic measurements of extracted strands from TQ cable using 108/127 0.7 mm strand show
  - ➢low Ic degradation
- 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
- Extracted strands from a HQ 15 mm wide cable with 0.75° keystone and using 0.8 mm strand show
  - ➢ Low cabling degradation.

⇨ FNAL "core-program" : TQM03 mirror magnet test using 108/127 strand with cable fabricated at FNAL

⇨ Good performance at 4.2 K and at 1.9 K

TQS03a Quench History



S. Caspi LBNL

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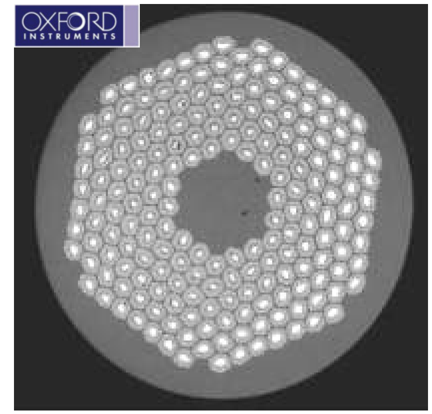
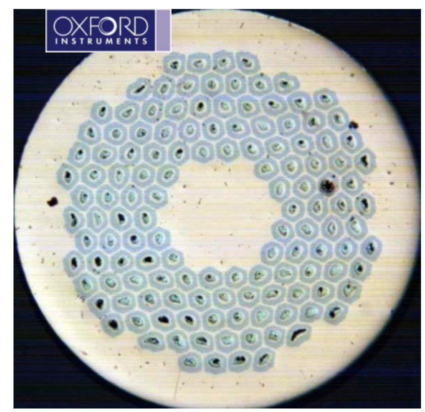
Pathway to smaller filament diameter

- So far OST has not been successful in producing a high-Jc 217 stack wire under the CDP program. Last year they made a lower Jc ~2400 A/mm^2-class Ti-Ternary 192/217 wire – RRP11500. Drew down in one piece to 1.1 mm. A high-Jc version billet broke up at large wire size. However, barrier integrity for 11500 was poor as RRR dropped to < 10 for the 665C reaction.
  - Very difficult to maintain High-Jc and RRR > 50 for smaller filaments



- Another option is 169-restack
  - First billets fabricated for FNAL, 2400A/mm^2 class 142/169 design
  - Two billets are being fabricated for CERN
  - Jc (12T) > 2500 A/mm^2, RRR >50
- Future Steps: Make test cables and coils with either the 217 or the 169 stack wire delivered under CDP



Nb_3Sn HQ-Strand Specification
LARP-Mag-M-8002 Rev. E

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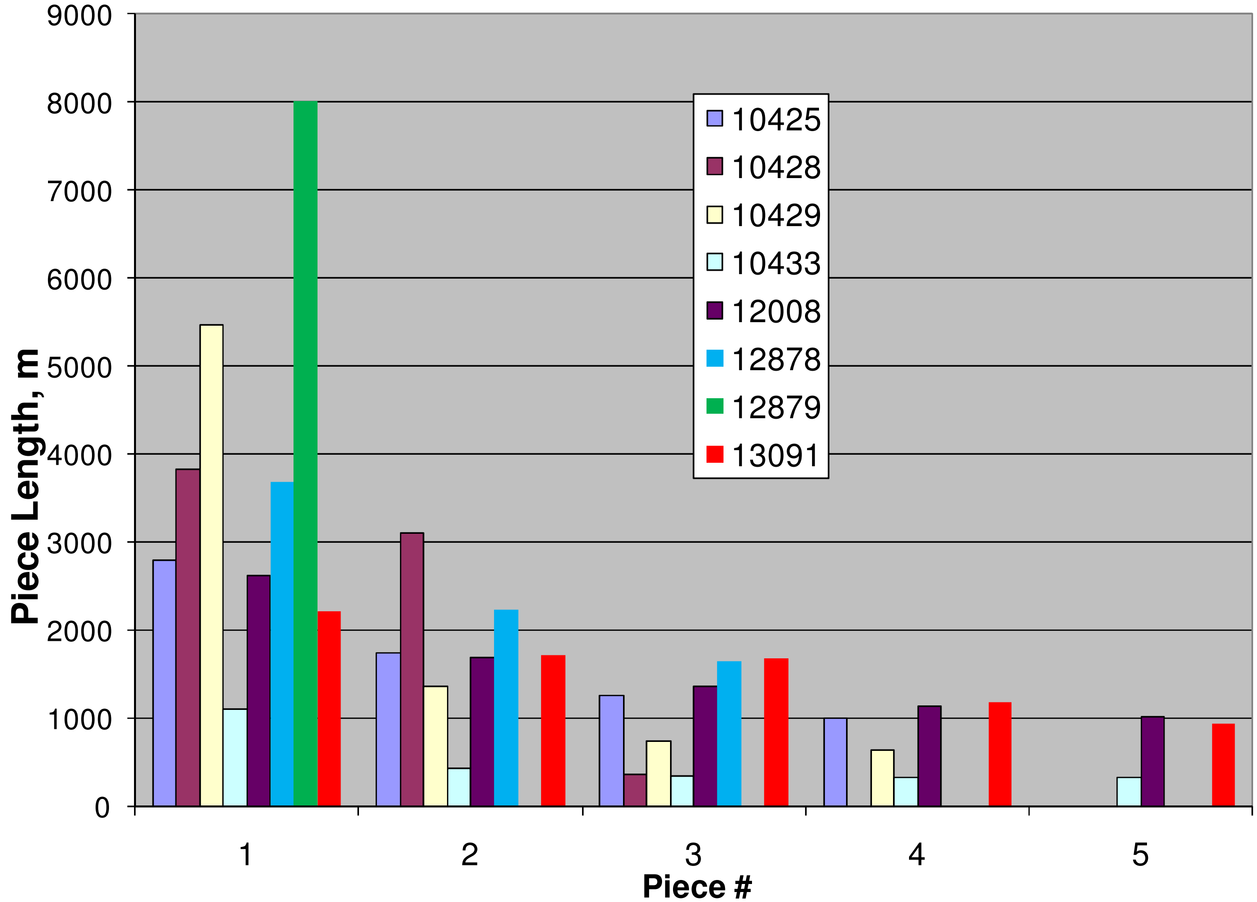
RRP 108/127 with increased Copper Spacing

Process	Ternary RRP Nb_3Sn
Strand Diameter, mm	0.7 – 0.8 ± .003
Jc(12 T) at 4.2 K, A/mm^2	≥ 2650
Jc(15 T) at 4.2 K, A/mm^2	>1400
D_s, µm (subelement diameter)	< 60
J_s, A/mm^2	>3000
Cu-fraction, %	53 ± 3
RRR (after full reaction)	≥ 60
Twist Pitch, mm	14 ± 2
Twist Direction	right-hand screw
Minimum Piece length, m	550
High temperature HT duration, h	≥ 48

3. 0.8 mm RRP 108/127 Production



Good Piece Length

Cable-Map losses for 4 m LHQ-Coils requiring 360 m cable lengths is expected to be ~10-12%

- 267 kg of wire produced so far from 8 billets,
- single billet yield is ~ 35kg (~8 km)

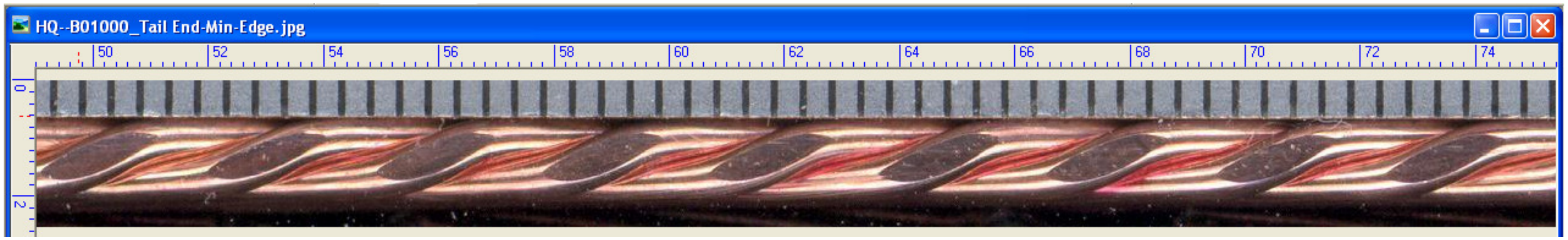
4. LARP Cable Production
Standard 2 Pass Fabrication Procedure (LBNL)

- 1st Pass
  - Fabricate cable slightly over size by 50-100 microns
  - Stop run at 5m and inspect cable
    - Inspect cross-sectional images for strand deformation
    - Measure facet size at the edge of the cable and correlate it to the cable pitch length.

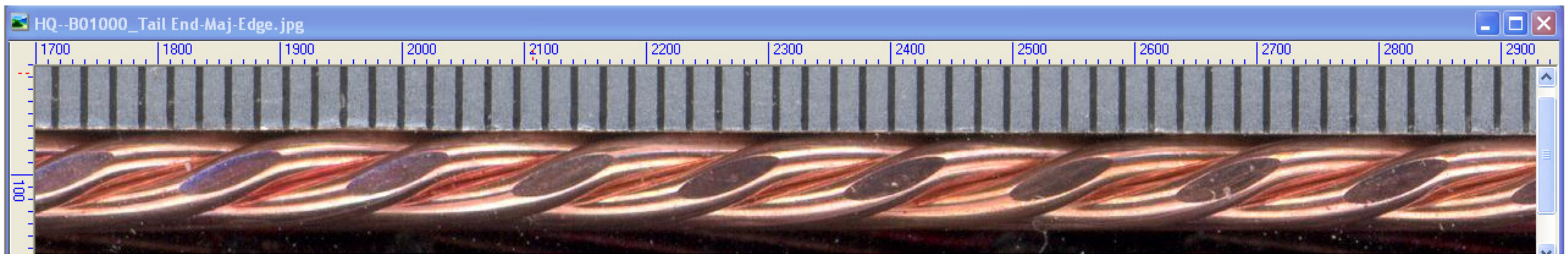
- Anneal at 200C/4 hrs
    - Softens Cu and cable contracts by ~0.25% in length
    - In addition the width and thickness of the cable increases
- 2nd Pass
  - Re-roll cable to the specification thickness: LQ ~ 1.26 mm, HQ ~ 1.44 mm
    - Compacts cable making it more mechanically stable for coil winding
  - Stop run at 5m and inspect cable
  - Check facet size

Cable Edge Facets
Early detection of cabling problems

Minor edge



Major edge



"Original" HQ Cable Parameters

Strand Diameter	0.8mm
No. Strands	35
Thickness	1.44 mm
Width	5.15 mm
Keystone angle	0.75°

- 7 unit lengths of HQ cable made from 54/61 strand
  - C01, C02, C08, C09, C10, C12, C13
- 6 unit lengths made from 108/127 strand
  - C03, C04, C05, C06, C07, C11

210C/72h + 400C/48h + 665C/48h

$J_c(12T) > 2900\ A/mm^2$

RRR>100

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4. Cable R&D

1. Narrower, Thinner Cable Development
   - Explore HQ-cabling parameter space
   - Use smaller diameter strand
2. Core-Cable Development
   - Reduce Eddy Current Coupling
     - Makes Quench Current in magnets insensitive to ramp rates

HQ Cable R&D Objective – Narrower, Thinner Cable

- To use existing HQ tooling
  - Provide more space azimuthally (i.e. thinner cable)
  - Perhaps more radial space (i.e. narrower cable)
- Cable R&D targets :
  - Reduce cable thickness 60-100 microns
    - To 1.38 mm - 1.34 mm
  - Reduce cable width < 15mm (14.7mm -15mm)
    - Accommodates dimensional changes of cable during reaction
    - Thicker insulation or more insulation between layers and tooling

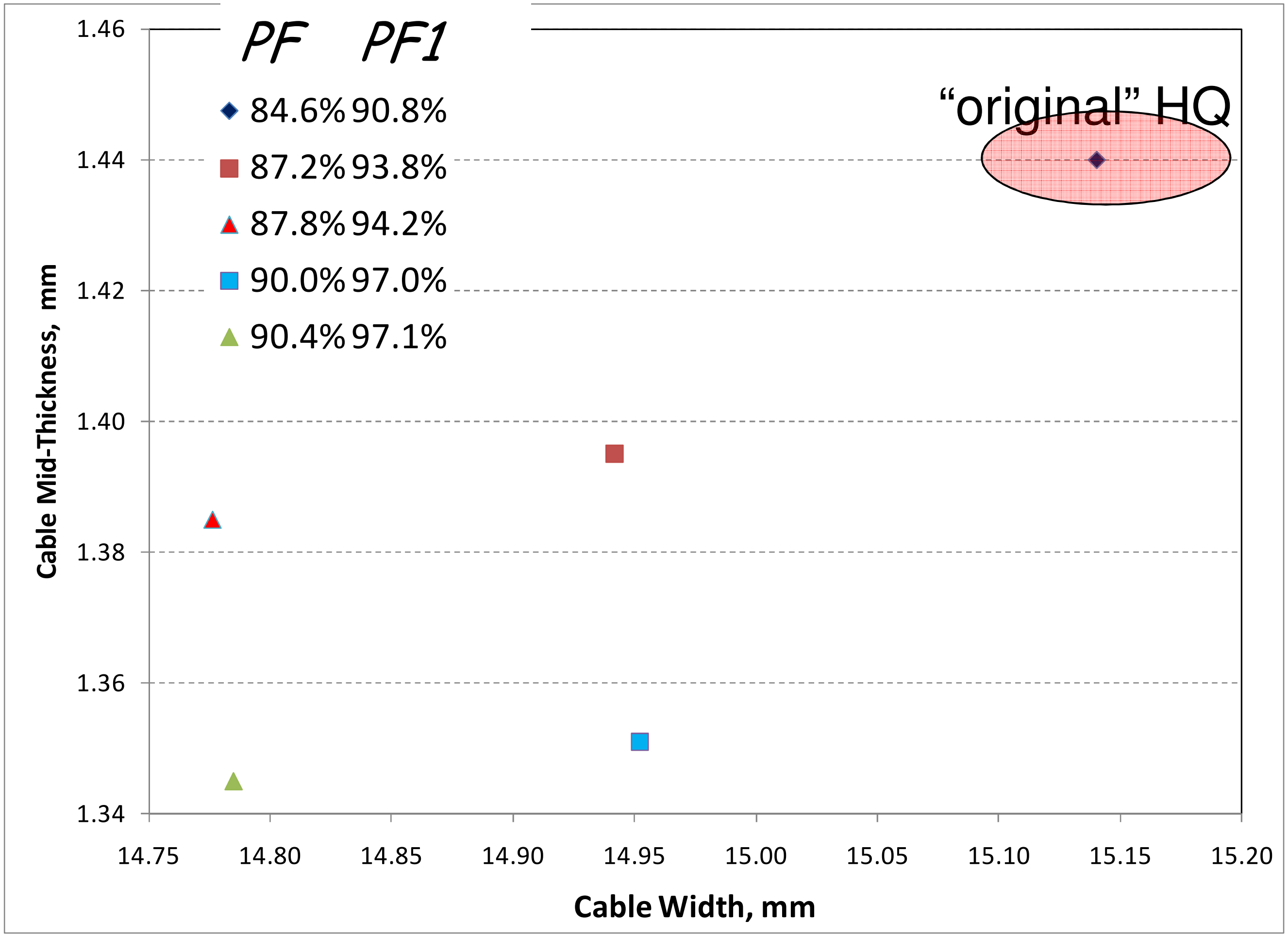
Changes from Standard HQ Process for R&D

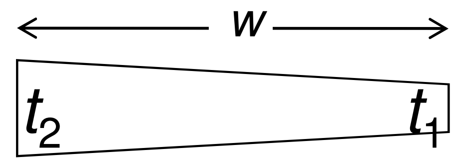
- *Anneal strand prior to cabling*, no cable anneal
  - Changes wire deformation behavior
  - Enables the use of metallic cores
- Fabricate cable in 1 Pass
- Increase keystone angle on rolls from 0.75^o to 0.8^o
  - Thin edge is thinner than standard HQ
- Shortened pitch length of cable
  - From 102mm to 85mm and 95 mm
  - Improves mechanical stability of cable

HQ Cable 1014 R&D

- 0.80 mm diameter strand
- Narrower rolls with widths of 14.7 mm and 14.9 mm.
- Roll keystone angle increased from 0.75° to 0.8°
- Drop one strand: from 35 to 34 strands
- Cables mid-thickness of 1.35mm - 1.40mm

Cable -B1014





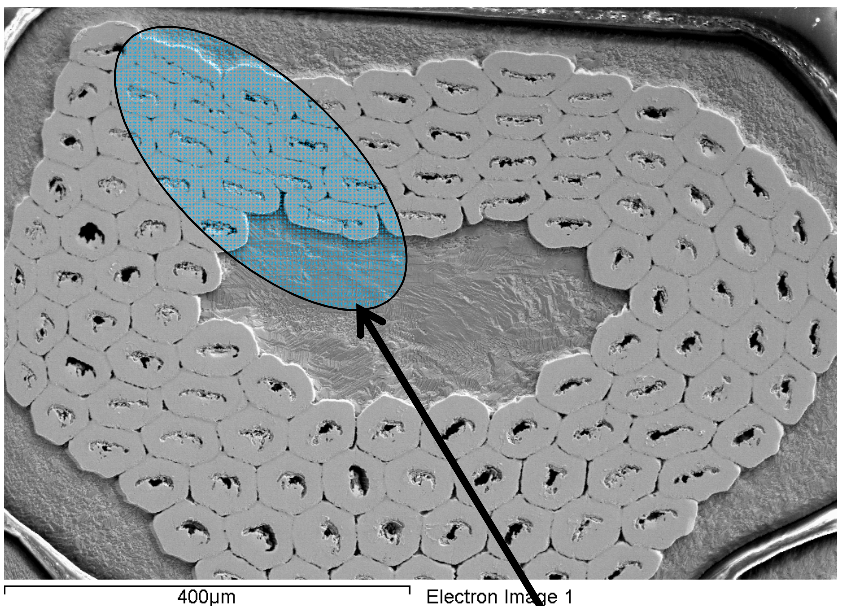
$$PF = \frac{n\pi d^2}{2w(t_1 + t_2)\cos\theta}$$

$$PF1 = \frac{\pi d}{2t_1}$$

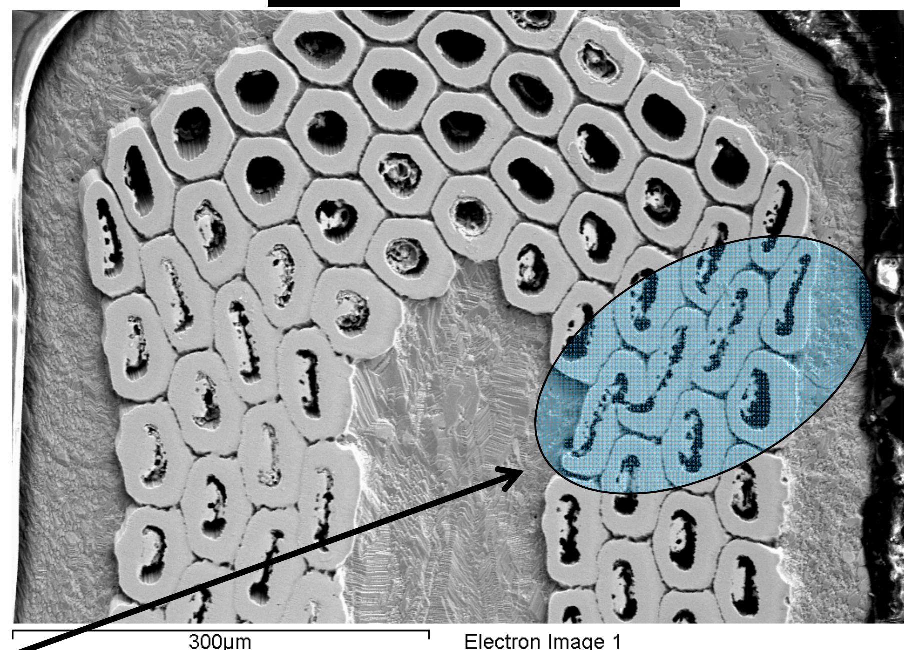
For NbTi LHC 15 mm wide cable
PF= 90%, PF1= 98%

Cable -B1014

PF	PF1
87.2%	93.8%



PF	PF1
87.8%	94.2%



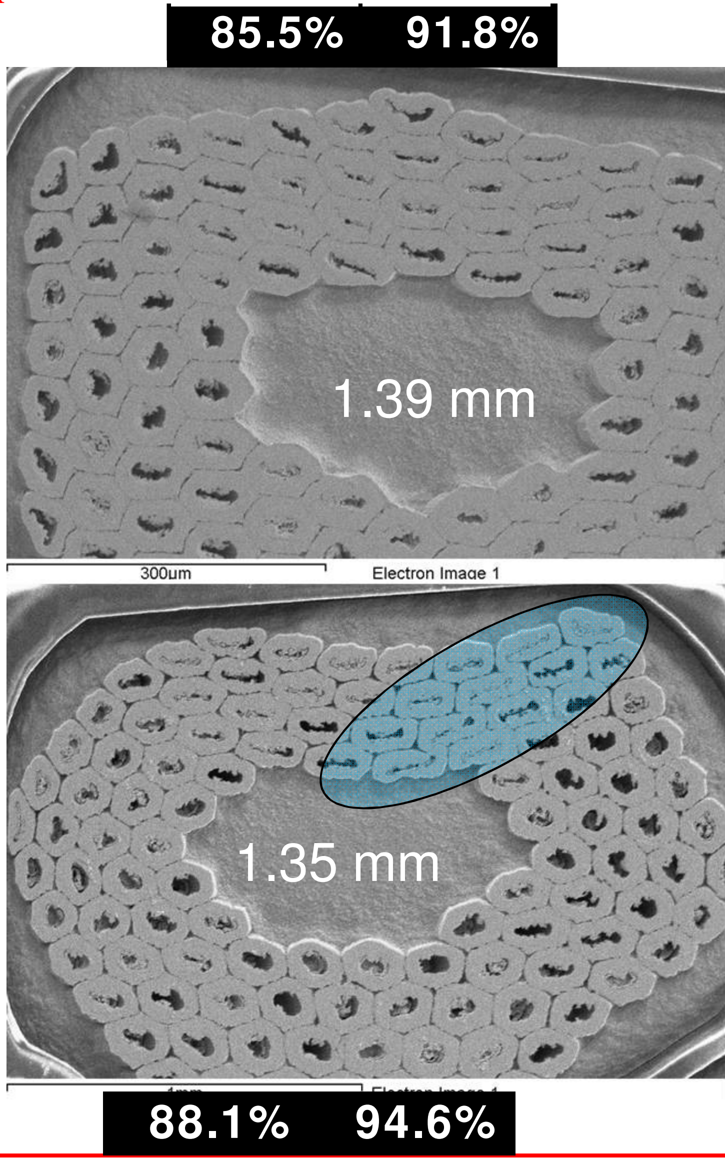
Sub-element shearing and barrier breakage at the minor edge. Leads to Sn-leakage. Some degradation of Jc (extracted strand measurements). Significant impact on local RRR.

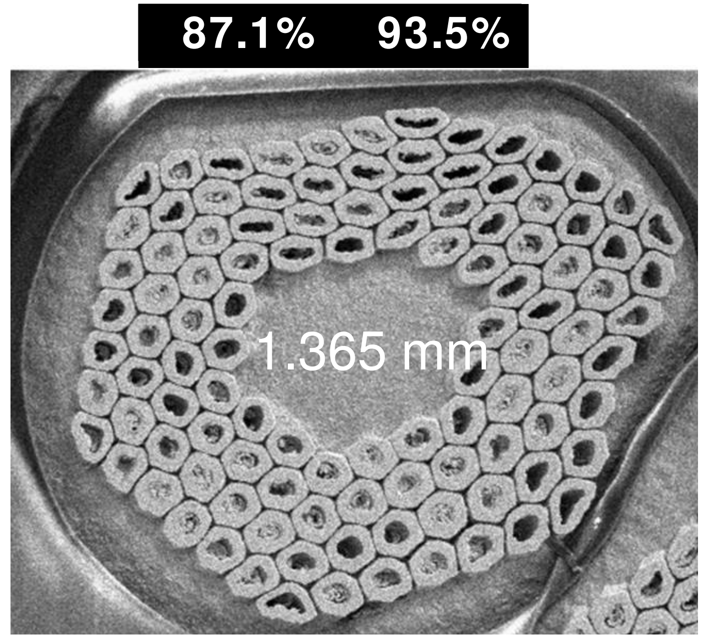
Smaller Diameter 0.778 mm Strand – Cable 1015

- R&D objectives
- Target cable width < 15mm
- 35 strands
- Cable thickness range 1.385 mm – 1.340 mm, (Cable 0.055 – 0.100 mm thinner than standard HQ cable)

- Made several sections with the following parameters:
- 85 and 95 mm Pitch Length and width 14.77 and 14.97 mm
- Thicknesses of ~1.38 mm - 1.32 mm,

Cable B1015





Sub- element shearing observed for PF1 > 94 %
Minimal Ic degradation for mid-thickness ~ 1.37 mm

Conclusions from B1014 and B1015 R&D

- 0.778 mm strand better for Narrower and Thinner cable.
- "New" HQ Cable Specifications

Strand Diameter	0.778 mm		
No. Strands	35		
Thickness	1.375 ± 0.01 mm	PF	PF1
Width	14.80 ± 0.05 mm	**86.3%**	**92.9%**
Keystone angle	0.75^o		
Strand annealed	190 ± 5 C /4 hrs		

•First UL (unit length) of cable ~ 100 m is being fabricated
•Cable will be qualified by microscopy and by testing a minimum of 3 extracted strands and one round strand at two labs
- •Samples reacted using standard HQ reaction schedule.

•Following that, plan to fabricate 4 UL's of cable within two months
- ➢Strand is being drawn down to 0.778 mm at OST

4.2 Eddy-Current Coupling in Rutherford cables

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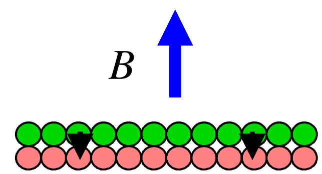
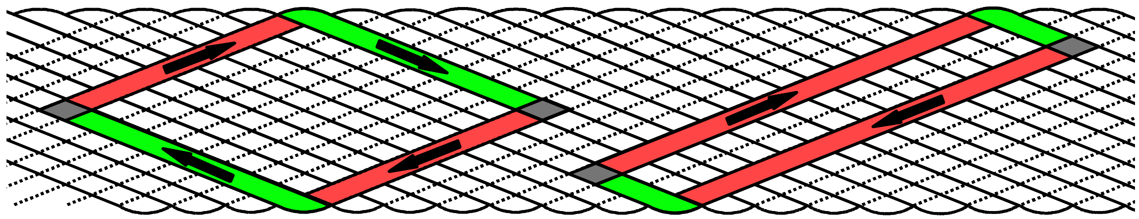
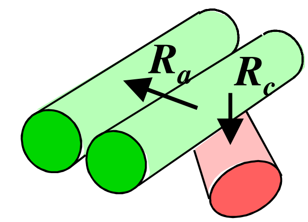
Field transverse coupling via crossover resistance R_C

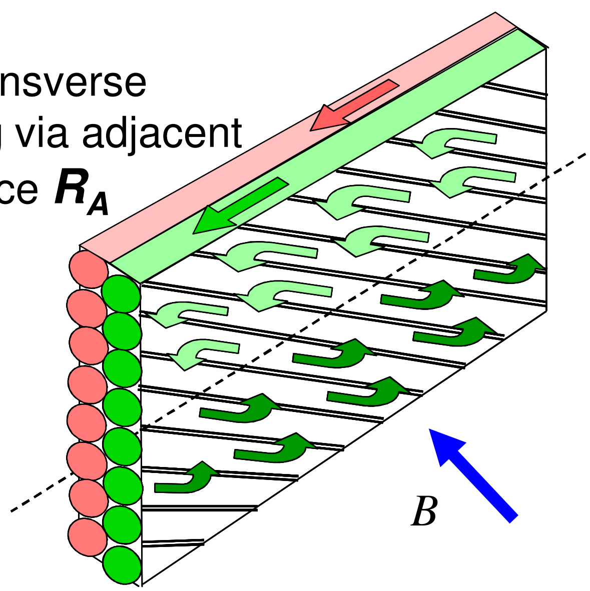


crossover resistance R_C
adjacent resistance R_A

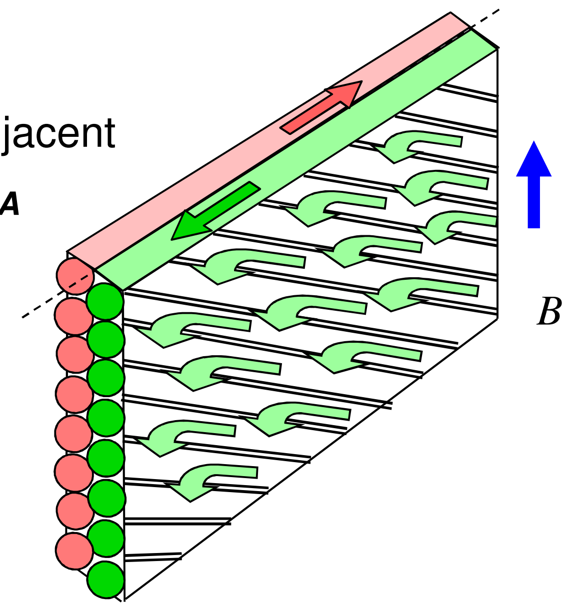




Field transverse coupling via adjacent resistance R_A

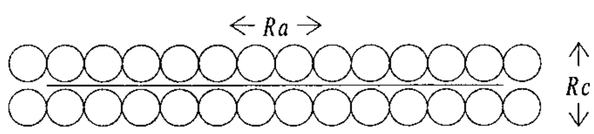


Field parallel coupling via adjacent resistance R_A



Suppression of Eddy-Current Magnetization and Losses by increasing R_C

- 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
- Reduce R_c Loss
  - By using a Resistive core

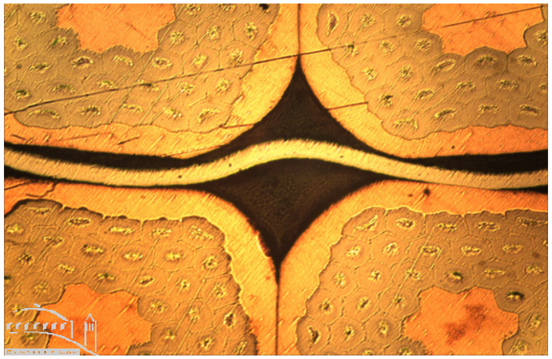


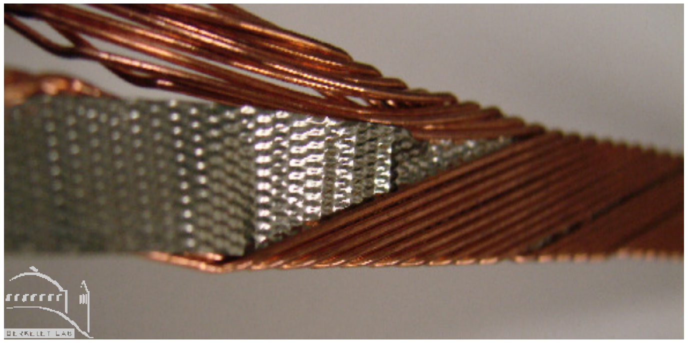
  - Maintain R_A for adequate Current Sharing

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

- Stainless Steel Core
  - Can not anneal and re-roll cable
    - During anneal cable shrinks whereas the core does not leading to core bunching
  - Need to anneal strand
    - LBNL has recently made a HQ cable in one pass using annealed 0.8 mm strand
  - Coil winding and coil performance
    - HQ-Coil 12 wound and tested in mirror configuration HQM01

Mandrel with slot





Ramp rate dependence: 120 mm aperture HQM01 – mirror magnet with core cable vs. HQ01- with non-core cable

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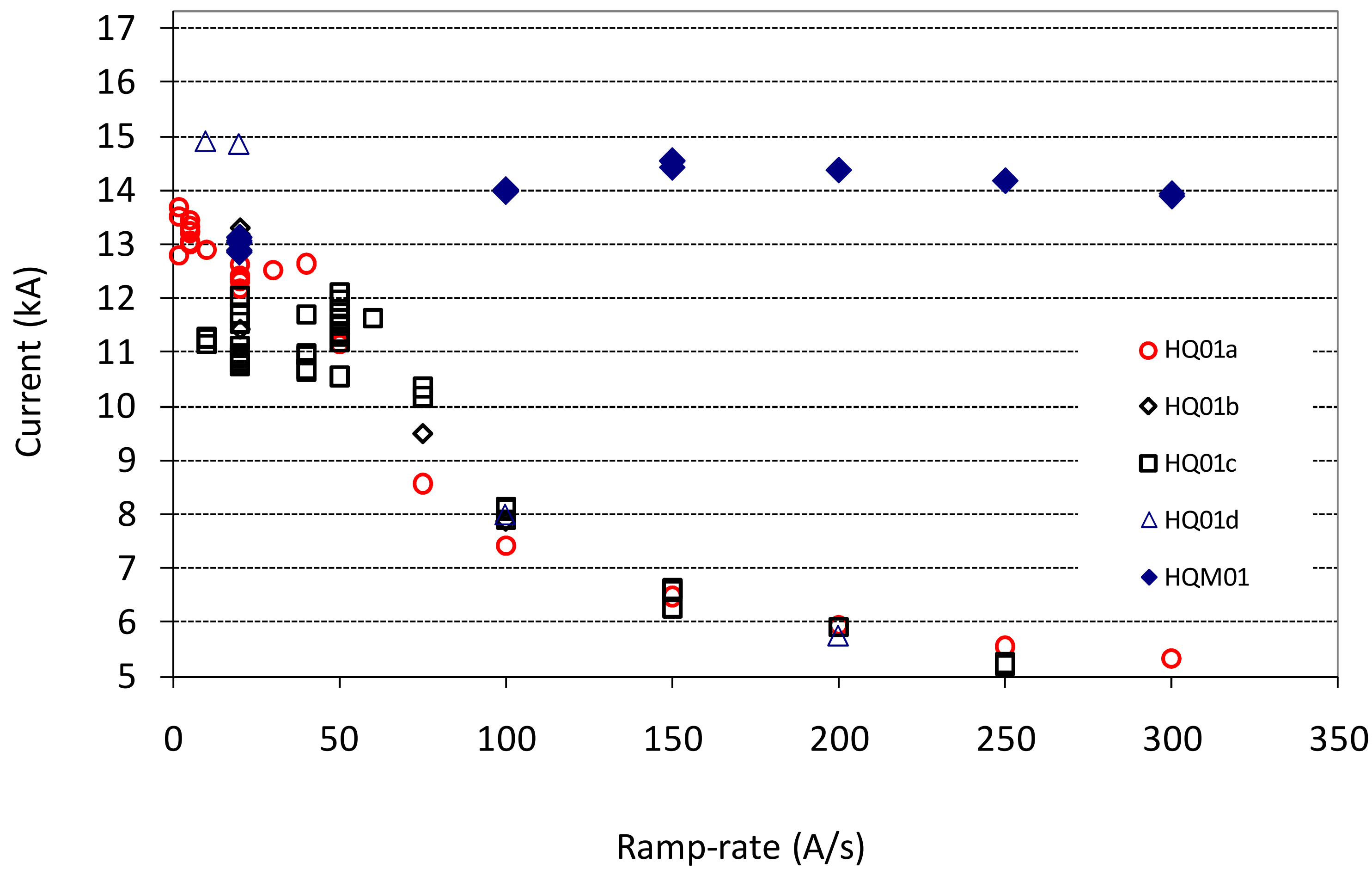


- Coil using cable with SS core shows very low ramp rate dependence ⇨ High R_c

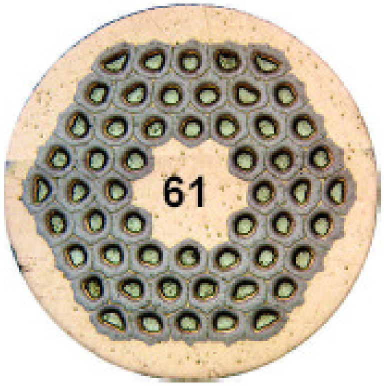
5. Ti-Ternary RRP Strand

Excerpt from 2010 review about conductor for LARP

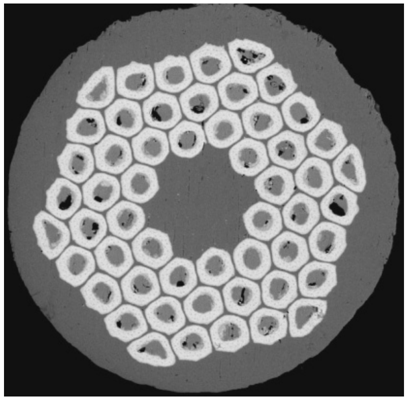
“The reviewers also suggested testing and potential phase-in of the Titanium Doped Superconductor.”

Ta- Ternary vs. Ti-Ternary

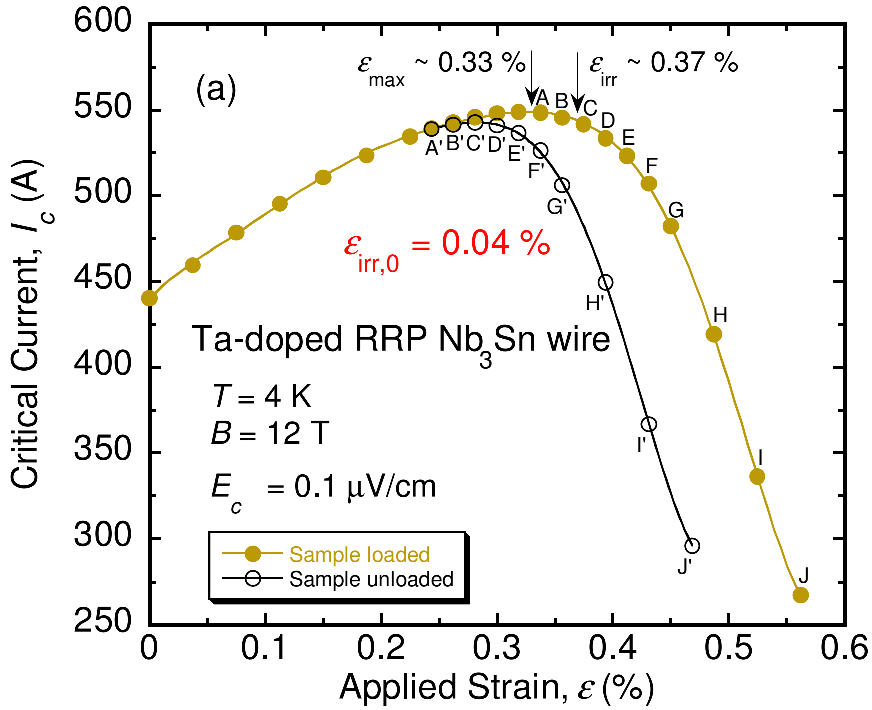
- **Ta-doped RRP-54/61** Nb-7.5wt%Ta-Sn
  - ➢ (Nb-4.0at%Ta)$_3$Sn

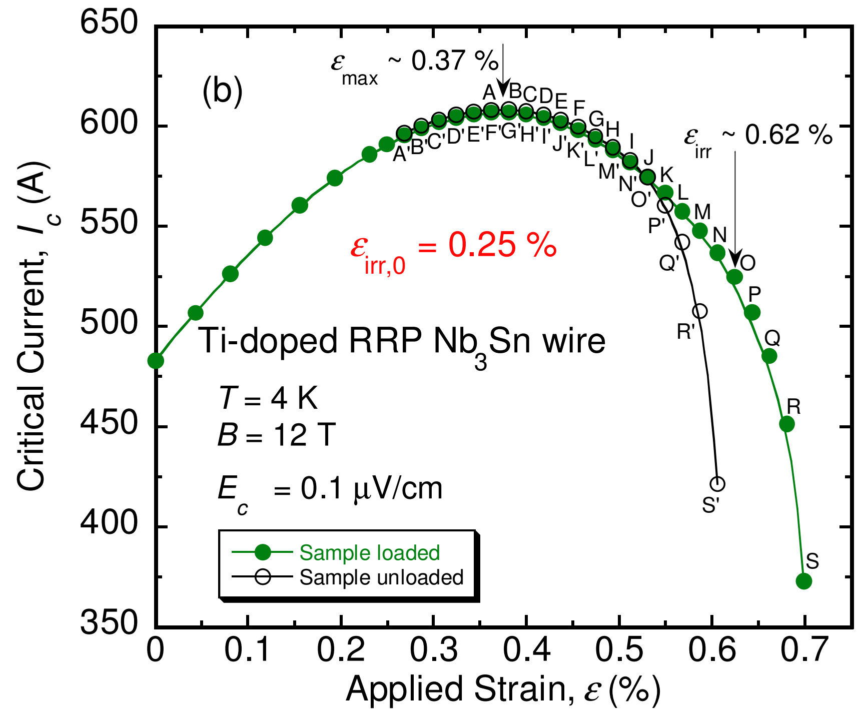


- **Ti-doped RRP-54/61**
- **(Nb-2.0at%Ti)$_3$Sn**
- Ti introduced by distributed Nb-47Ti rods in the Nb-Cu matrix



Ta-Ternary vs. Ti-Ternary 0.7 mm strand





Ti-doped Nb_3Sn wire more strain tolerant than Ta-doped

More recently, this has been confirmed for 0.8 mm $(Nb\text{-}1.5wt\ \%\ Ti)_3\text{-}Sn$ strand ε_{irr} = 0.32-0.35 %

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)

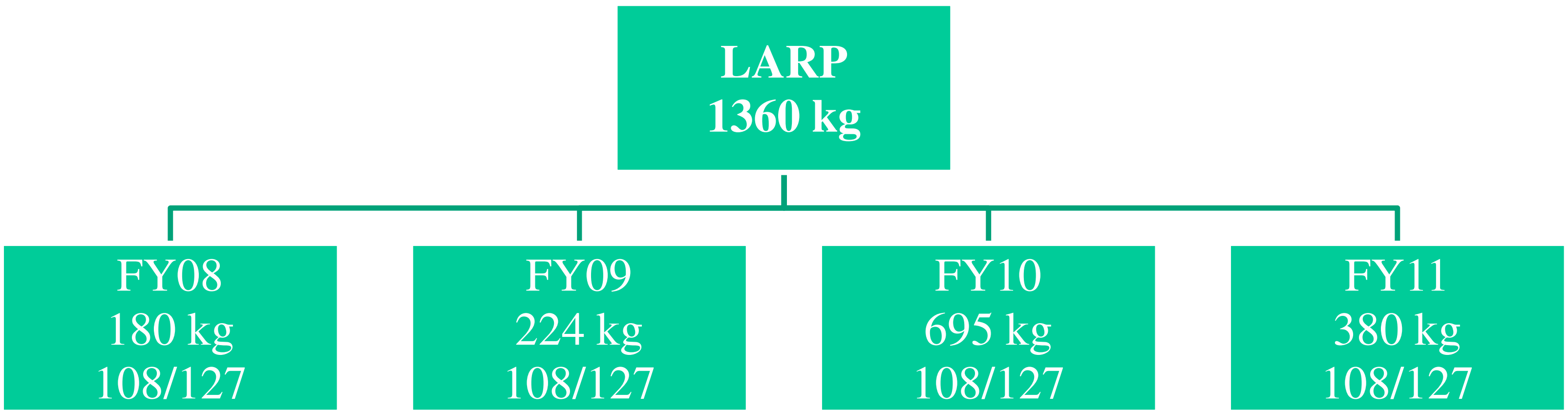
Ti-Ternary 108/127 RRP Strand
CDP program

- In FY 2010 OST delivered two billets at 0.8 mm
  - 28 kg of 2.0 wt.% Ti (RRP12099)
    - Jc(12 T)~ 2700 A/mm^2, Jc(15 T) > 1500 A/mm^2, RRR > 60
    - Cable B1010R HQ-C11
  - 22 kg (one piece) of 1.5 wt.% Ti (RRP11976)
    - Jc(12 T) > 2900 A/mm^2, Jc(15 T) > 1500 A/mm^2, RRR > 60

- In FY 2011
  - 90 kg of 1.5 wt% Ti
  - Three billets, very good piece lengths
    - Meets HQ - specification
    - Jc (12T) > 2850 A/mm2, Jc(15T) > 1500 A/mm2, RRR >60

6. Procurement – Planning for Long HQ

Strand Lead time is 12-15 months



- OST is currently producing ~ 1200 kg/month of Nb_3Sn
- LARP production is parallel to ITER wire production
- ITER production ends Aug-2011. There may be additional ITER orders

Conductor Inventory June-01-2011

- 34 kg of 54/61 - 0.7 mm
- 17 kg of RRP 108/127 - 0.7 mm

- RRP 108/127 Ta-Ternary
  - 27 kg at 0.8 mm (some in short lengths)
  - 35 kg at 0.8 mm (in one piece)

- RRP 108/127 Ti-Ternary (from CDP)
  - 90 kg at 0.8 mm

Strand Production Status

- In CY 2011, OST is producing ~ 785 kg of 108/127 strand wire
  - LARP- MAG-M-8002 Rev. E
    - Minimum Length 550 m

Delivery Schedule of RRP 108/127 for HQ

- 267 kg at OST at 0.84 mm
- 125 kg in Sep'11
- 132 kg in Oct'11
- 194 kg in Dec'11

} 718 kg

Future Planned Deliver of Ti-Ternary 108/127 in CY12

- 200 kg in Sep'12
- 180 kg in Dec'12
  - LARP- MAG-M-8002 Rev. F

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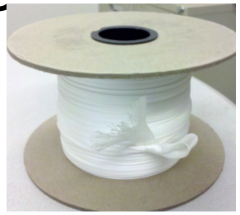
Strand inventory and usage

Month	Wire Delivery, kg	Coil ID	Cable ID	Strand Req. kg	Cable Unit Lengths	108/127 0.8 mm kg	108/127 0.778mm kg	Ti-108/127 0.8 mm kg
Aug-10	68					63		
Sep-10						63		
Oct-10			B1014	36		27		
Nov-10						27		
Dec-10	42					27	42	
Jan-11						27	42	
Feb-11						27	42	
Mar-11	130	HQ1 C14	B1015	42	1	157	0	90
Apr-11	115					272		90
May-11	57					329		90
Jun-11		HQ1 C15	B1016	18	1	311		90
Jul-11		HQ1 C16-C17	B1017	36	2	275		90
Aug-11		HQ1-C18-21	B1018	72	4	203		18
Sep-11	125					328		18
Oct-11	132	LHQ-C01		72	1	388		18
Nov-11						388		18
Dec-11	194	LHQ-C02		72	1	510		18
Jan-12		LHQ-C03		72	1	438		18
Feb-12		LHQ-C04		72	1	366		18
Mar-12		LHQ-C05		72	1	294		18
Apr-12		LHQ-C06		72	1	222		18
May-12		LHQ-C07		72	1	150		18
Jun-12		LHQ-C08		72	1	78		18
Jul-12						78		18
Aug-12						78		18
Sep-12	200					78		218
Oct-12						78		218
Nov-12						78		218
Dec-12	180	LHQ-C09		72		78		326
Jan-13		LHQ-C10		72		78		254
Feb-13		LHQ-C11		72		78		182
Mar-13		LHQ-C12		72		78		110
Apr-13						78		110
May-13						78		110
Jun-13						78		110

- By the end of CY2011 there will be sufficient strand for 8 coils of LHQ
- By the end of CY2012 there will be sufficient Ti-ternary strand for 5 coils of LHQ
- In FY2012, plan to purchase 400-600 kg of conductor
- HQ1: 1 m HQ,
- LHQ4 : 4 m
- 1 UL of HQ1 requires 18 kg
- 1 UL of LHQ: 72 kg

Cable Insulation

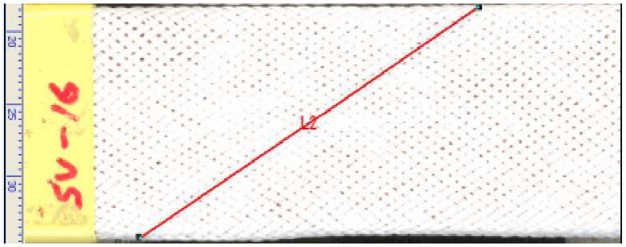
- At present cable is insulated with S2-glass sleeve
  - EDO Fiber Innovations has been the supplier
  - Since they exited the business, LBL has been looking at options for the short term



1. Sleeve options (LBL)

   Nitivy (Japan)– Style SV-16-F2/96

   70% Al_2O_3, 30% SiO_2 (Mullite)



   Revolution Composites , A&P Technologies – Style 272

   S2-glass with 636 sizing, plan to try Silane coated fibers

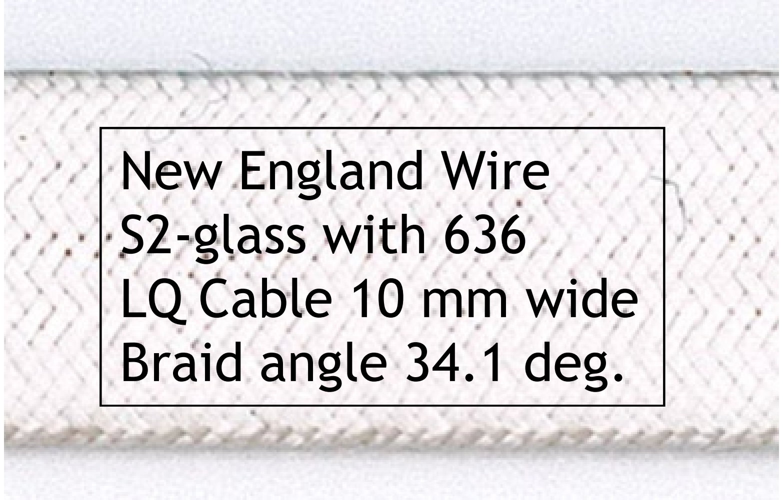
2. Tape wrapped onto cable

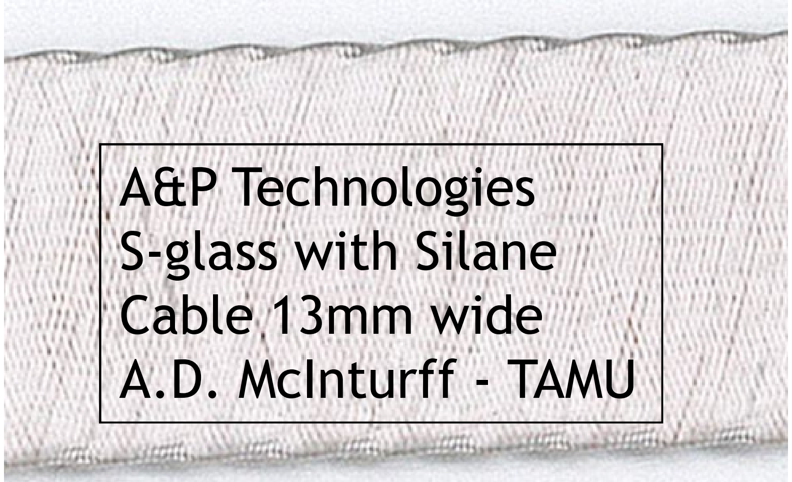
   FNAL has developed technique to insulate cables.

   S2 –glass too thick, E-glass -thinnest 0.075 mm.

Insulation Options

- Braided insulation onto cable
  1. New England Wire (BNL)
     - S2-glass with 636 sizing, (insulated ~80m, 0.100 mm thick)
     - S2-glass with Silane 933 sizing is underway
  2. Revolution Composites (LBL)
     - New company with staff from EDO Fiber Innovations
  3. A&P Technologies





Summary

- Production of Ta-ternary 0.8 mm RRP 108/127 strand has been very good
  - Long piece lengths
  - Jc(12T) > 2800 A/mm^2 , Jc (15T) > 1400 A/mm^2
- HQ 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 if required.
- Cored-cable in magnet coil has been demonstrated
- Procurement of strand in line with LHQ magnet schedule
  - FY2011 purchase was delayed due to CR
- Ti-Ternary strand has been phased into strand procurement
  - Enabled by production of 3 billets under the CDP program

LARP

End of Presentation

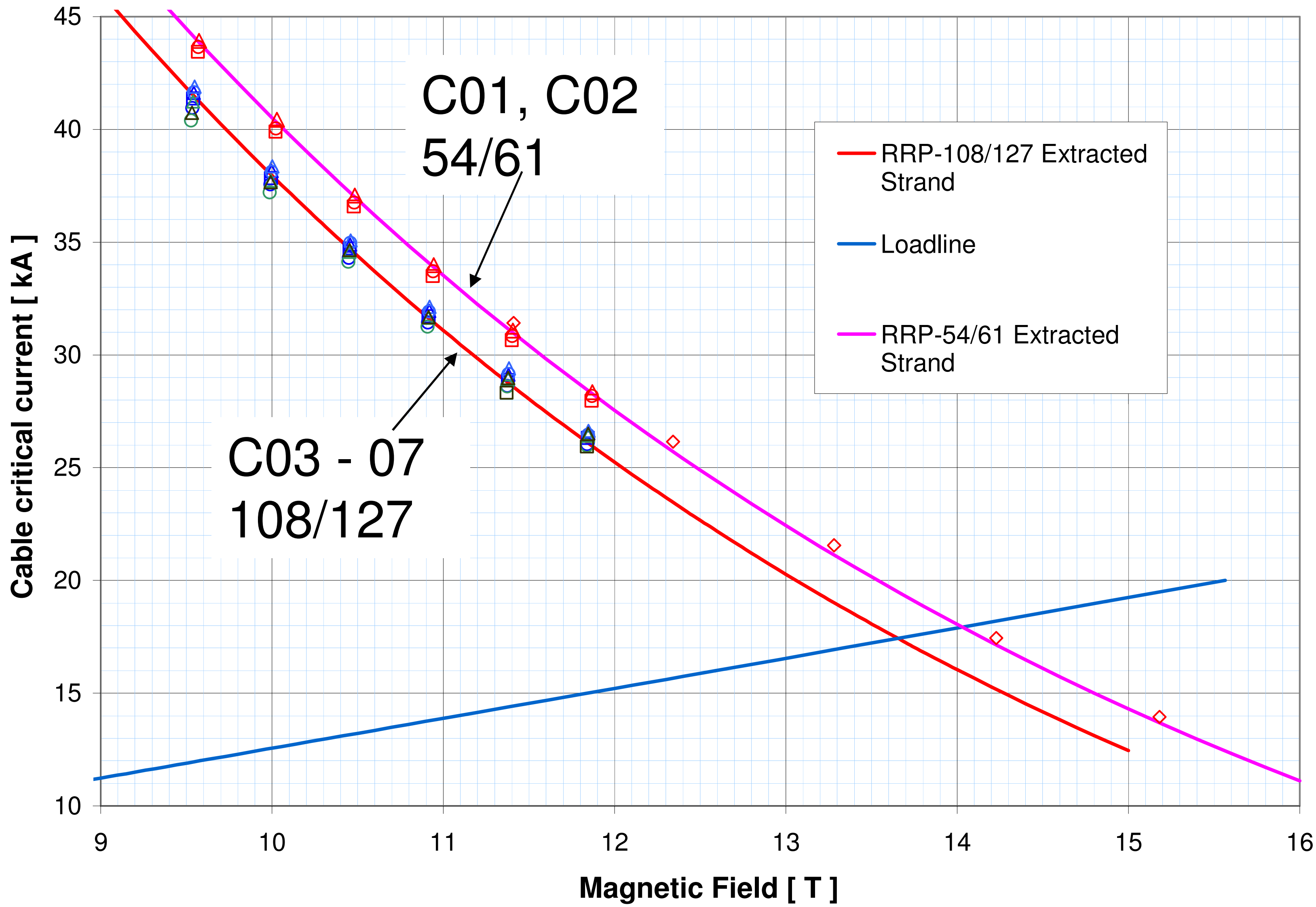
Additional Slides

1. Nomenclature
2. Impact of higher content on HQ
3. TQM03 Test at FNAL
4. Magnetization of 54/61 and 108/127
5. Low-field Instability
6. FNAL coil test with SS-core
7. Insulation comparison

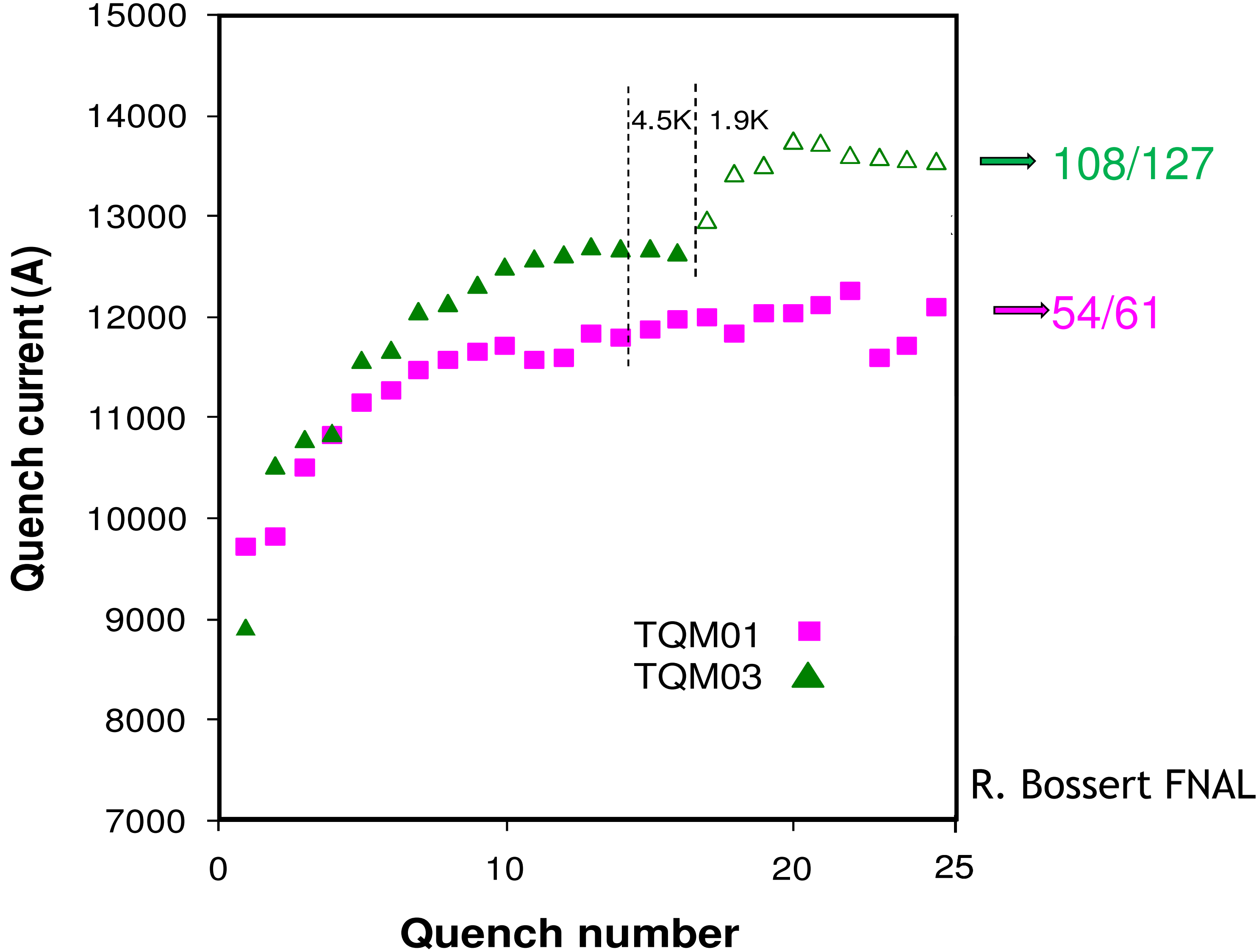
Nomenclature

- 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

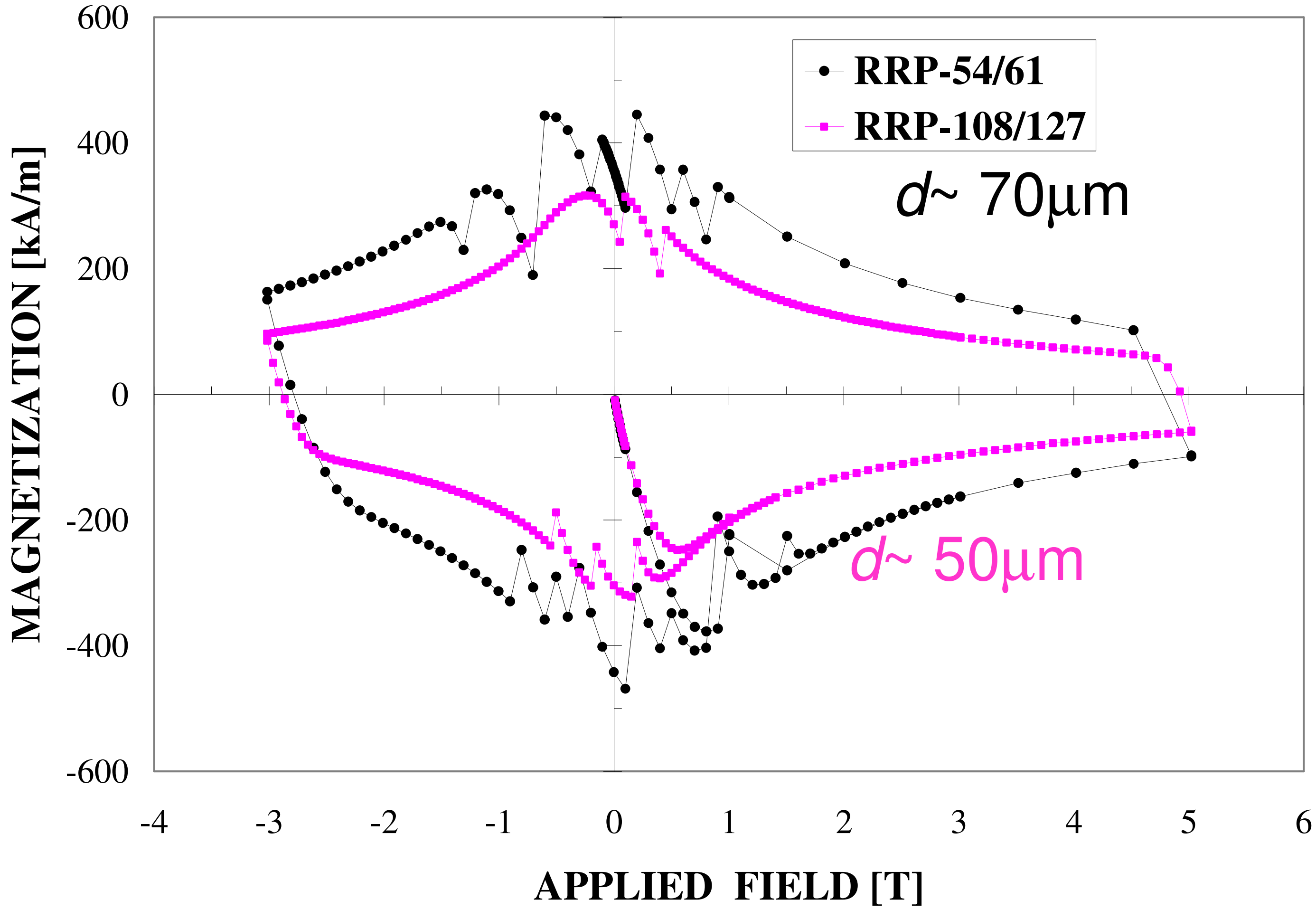
Impact on Magnet SSL
HQS01a



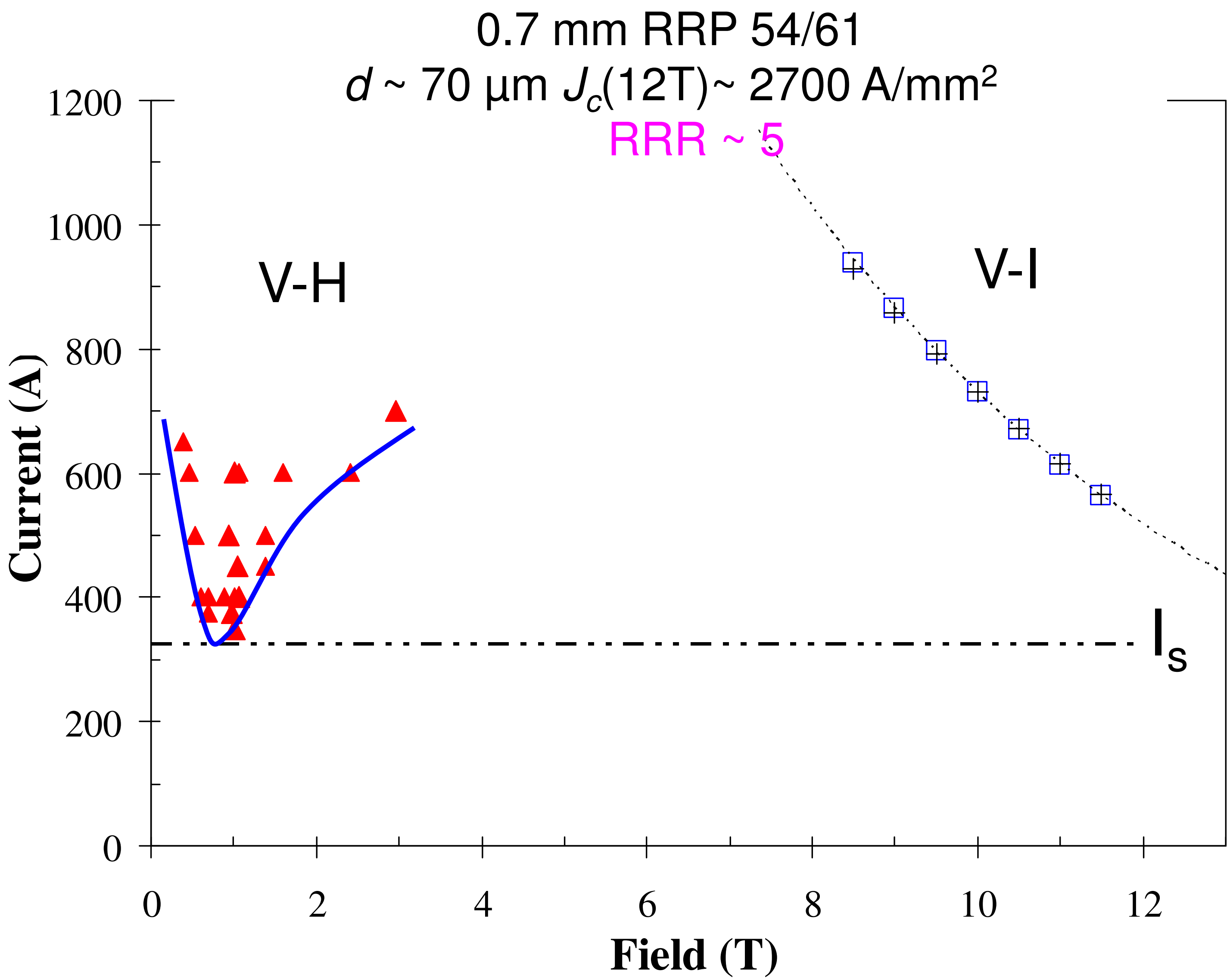
TQM03 Quench History



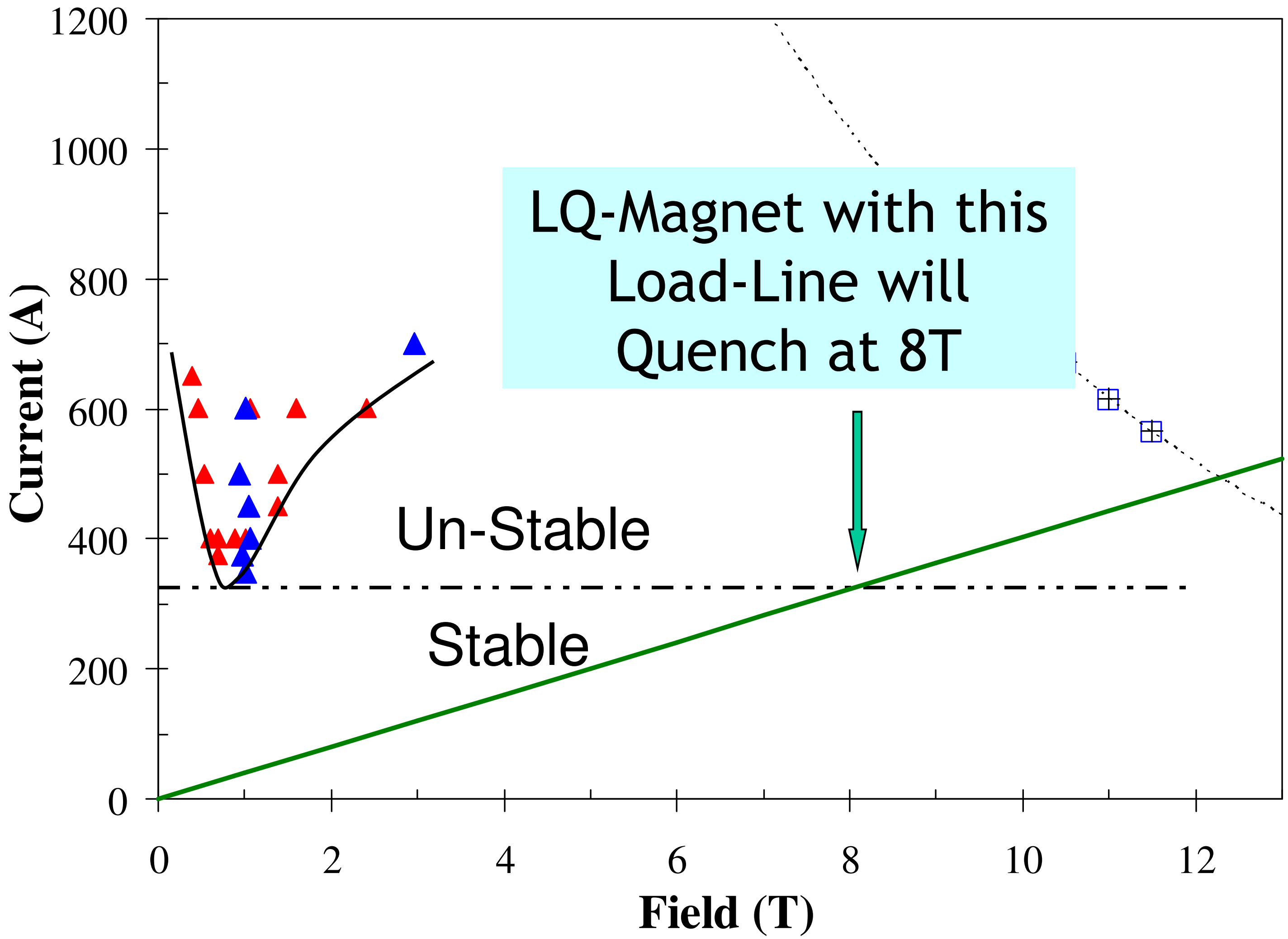
Observed in Magnetization measurements ⇨ Persistent current collapses periodically at low fields



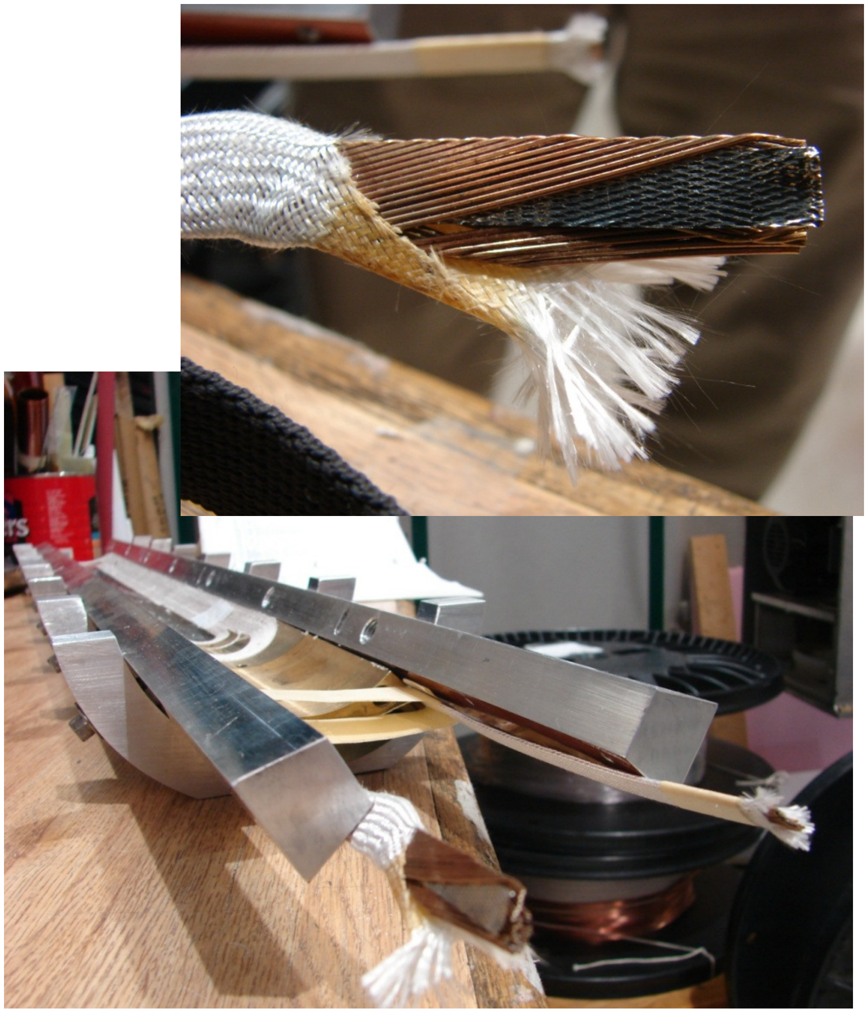
Magnetization Instability at Low Fields ⇨ Is



Impact on LQ Magnet Performance



Cored-Cable development at FNAL
Coils #34 and 35 in TQM structure



Coil #35:

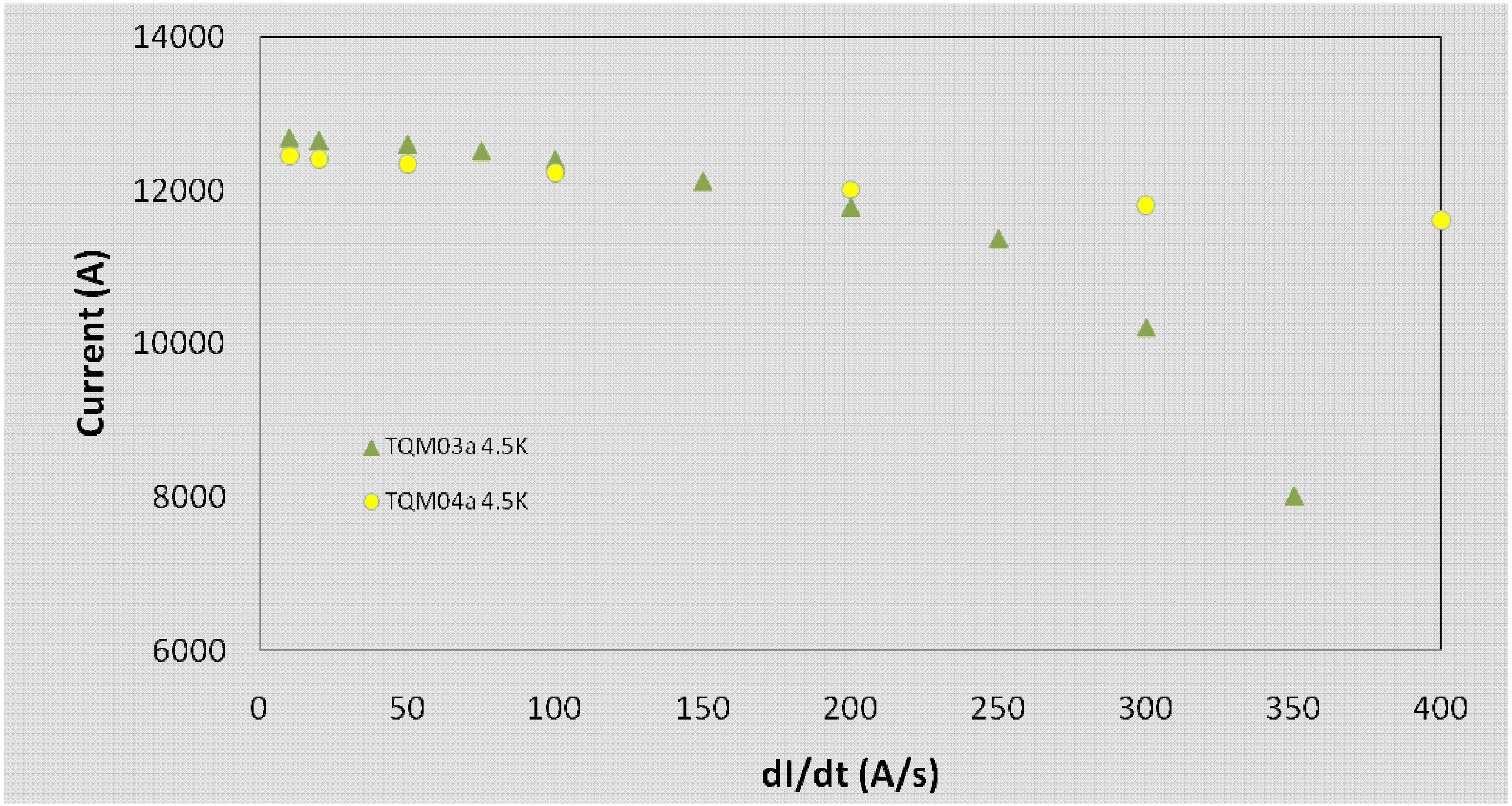
- Coil: standard TQ coil
- Strand: RRP108/127
- Cable: TQ with 25 μm SS core
- Cable insulation: S2-glass sleeve

Coil #34:

- Coil: standard TQ coil
- Strand: RRP108/127
- Cable: regular TQ without SS core
- Cable insulation: E-glass tape

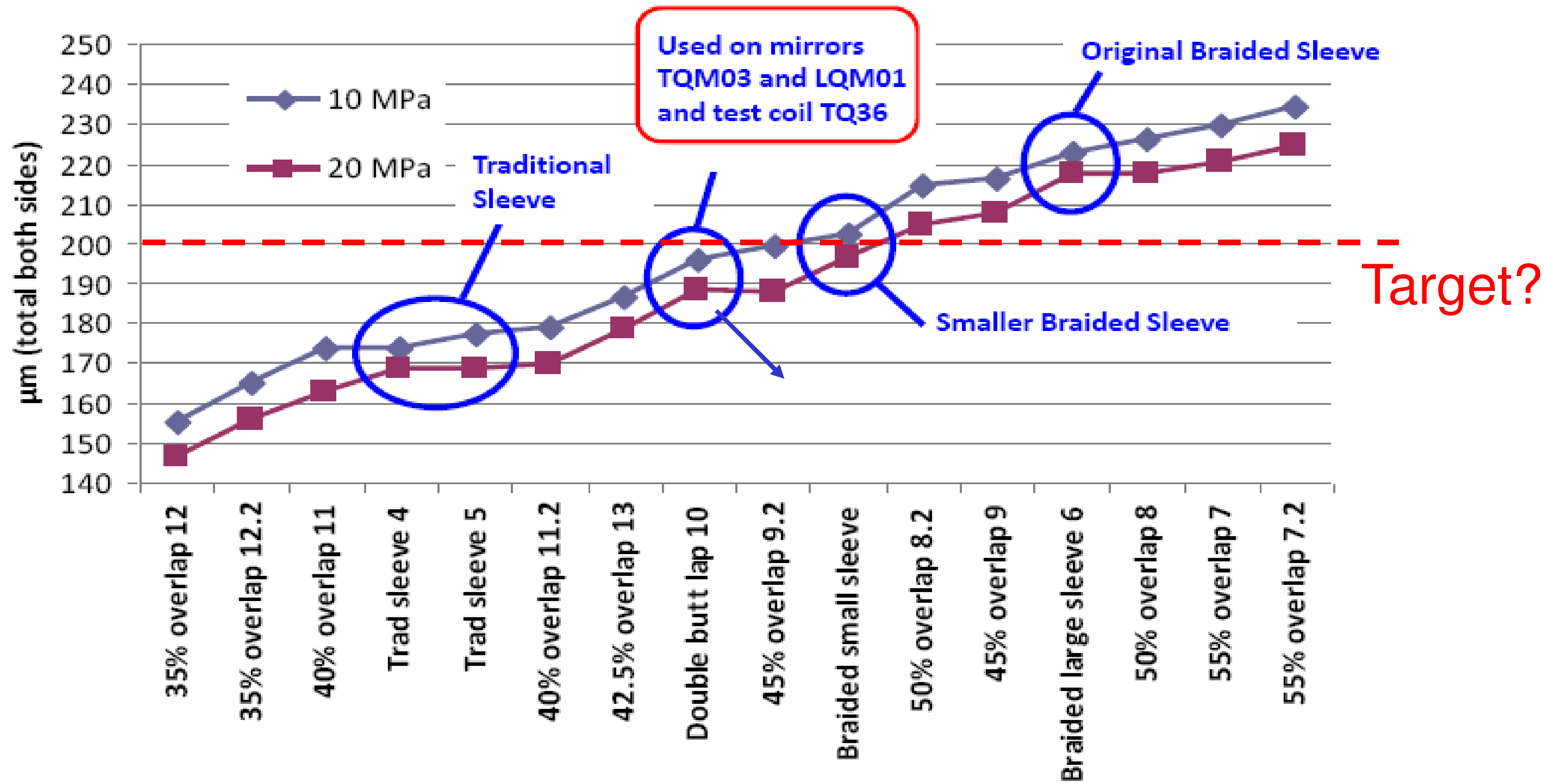
TQM04 test results

Ramp rate dependence at 4.5 K



- TQM04a – coil#35 with SS core shows very low ramp rate dependence ⇨ High R_c

FNAL Insulation Thickness Data - Cured 10-Stacks



Meas. by R.Bossert