BNL -FNAL - LBNL - SLAC

LARP DOE Review
June 19 - 20, 2008

2.4 Materials – Conductor R&D

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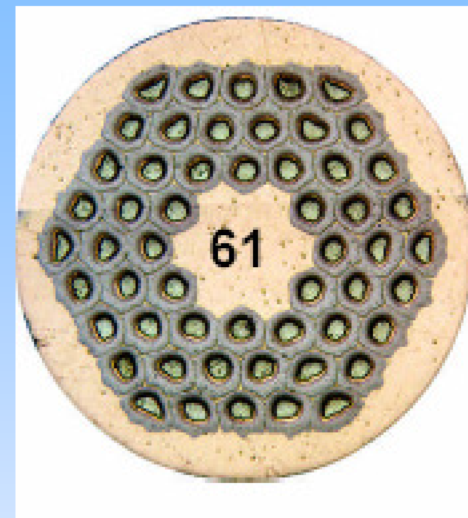
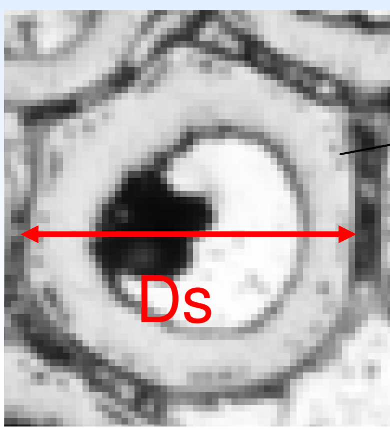
Outline

1. Introduction
2. OST strand production
3. Cable Production and R&D
    1. Extracted strand test
    2. HQ-Cable R&D
4. Roll strain effects on RRP strands
    1. Increased Copper spacing
    2. RRP with larger re-stack elements
5. Electro-mechanical studies – NIST
6. Instability in superfluid helium
7. Production Plan for FY08 and FY09
8. Inventory of strand
9. Summary

1. Introduction

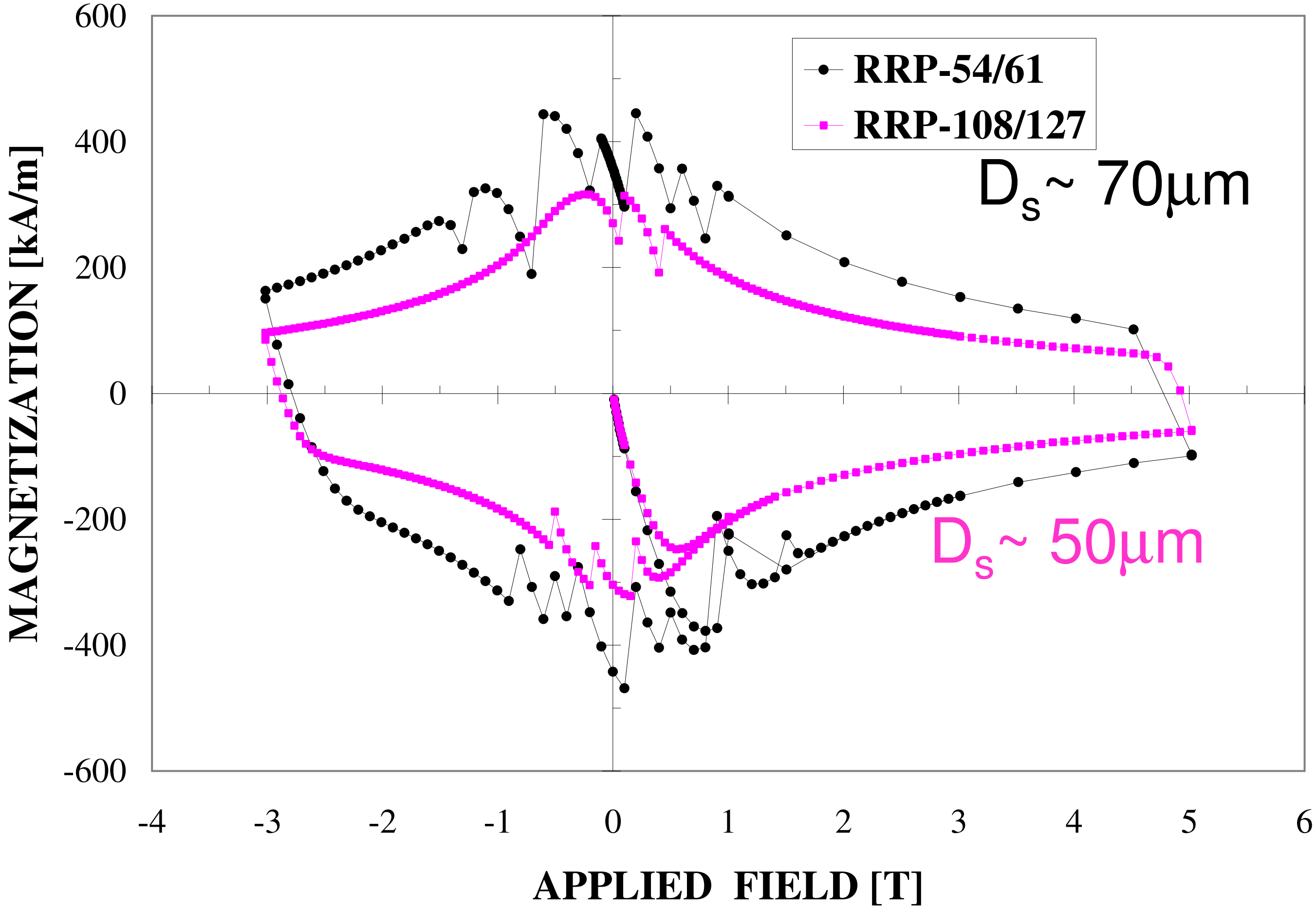
- The 2nd TQ magnets, TQC02 and TQS02 and the first long quad-magnet LQS01 use RRP - 0.7mm strand
  - ⇨27-strand cable with 1.0º keystone angle
  - Strand is of the 54/61 design with large sub-element diameter ~ 70 μm





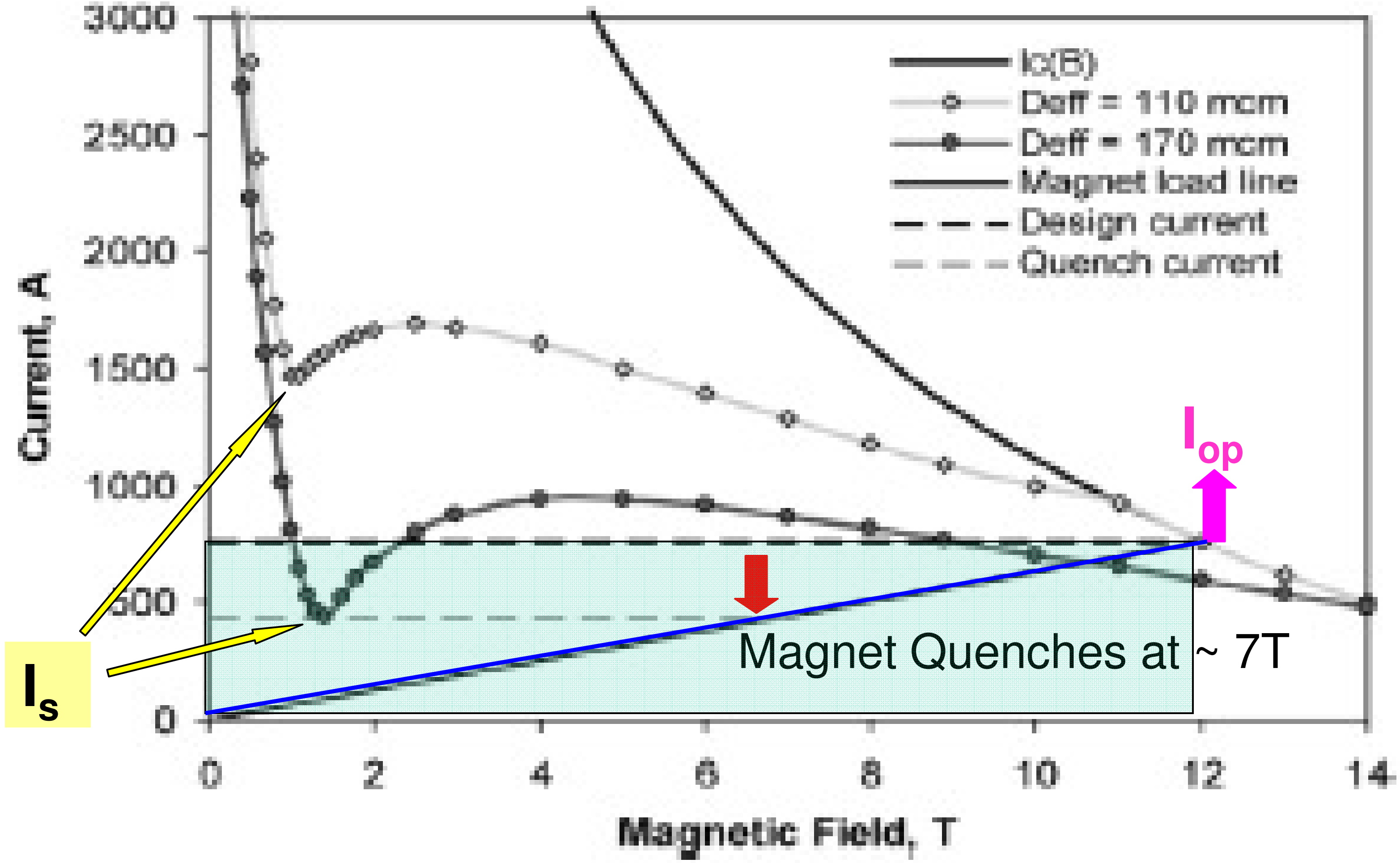
Flux-jump instability

Can be readily seen in Magnetization measurements ⇨ Persistent current collapses periodically at low fields



These Flux-Jumps Impact Magnet performance

Adiabatic Stability-Calculations by Kashikin & Zlobin MT-19 (FNAL)



Low-field instability does not impact magnet performance

Since wires of 0.7 mm with Ds < 35 μm cannot be made at present, flux-jumps are inevitable in low-field regions of magnets.

Will "flux jump" initiate a quench as Magnet approaches I_{op} of 500 A (per strand)?

Not if: local copper stabilizer RRR is "high"

Using an "optimized" heat treatment

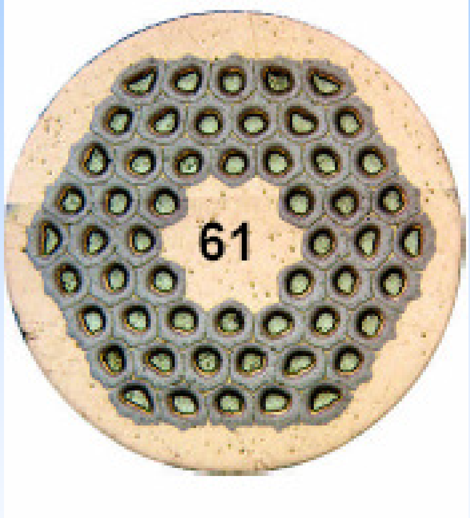
210C/72h + 400C/48h + 640C/48h

- ▸ Jc (12T,4.2K) is > 2400 A/mm^2 , and with **RRR >100** the strand has a stability current I_s >1000A, well above magnet operating current
- Extracted strands from TQ cable also show I_s>I_{op}

2. OST Strand Production

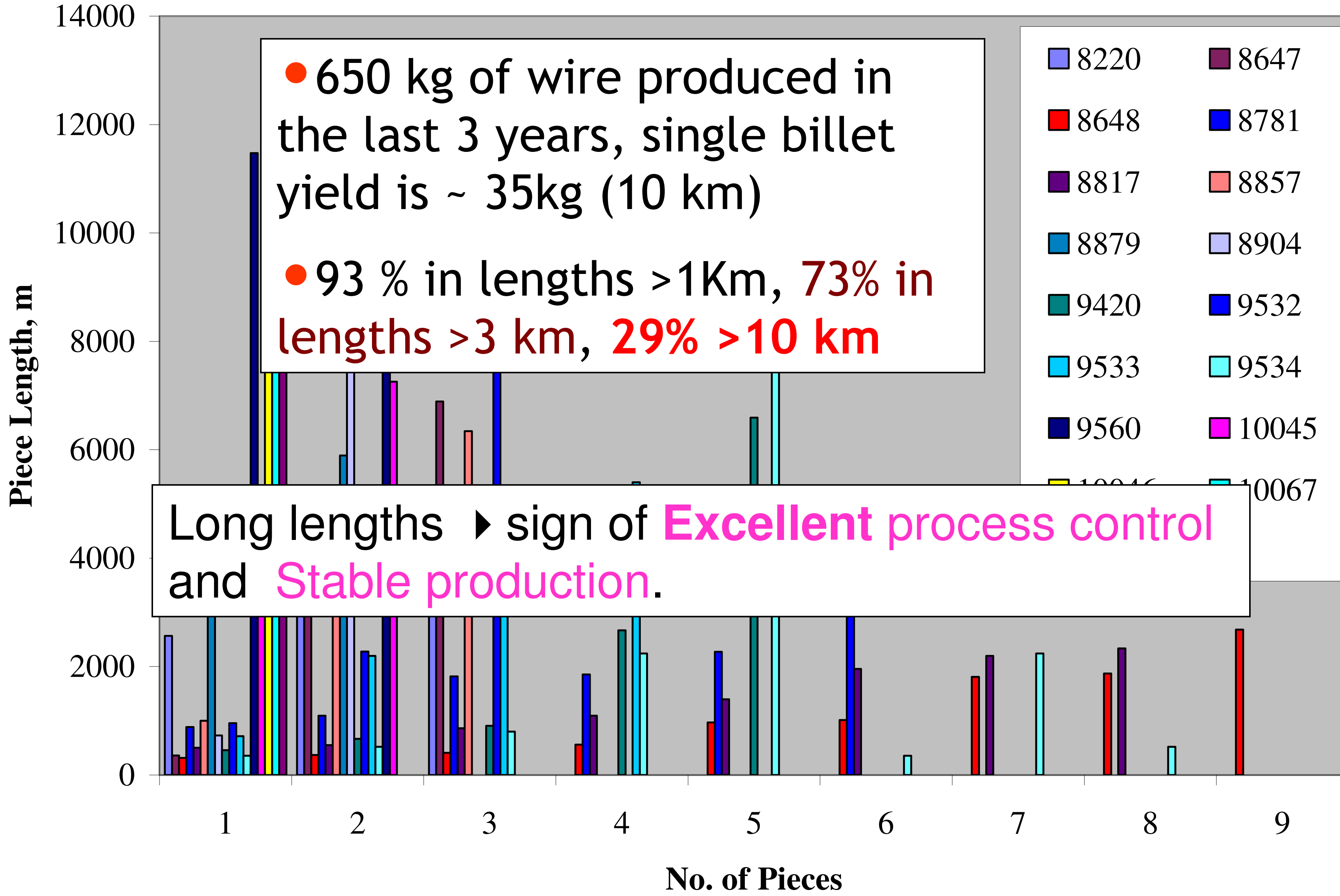
- High J_c production wire from Oxford Superconducting Technology, OST
- **R**od **R**e-Stack **P**rocess, RRP® 54/61 Design

Process	Ternary RRP Nb_3Sn
Strand Diameter, mm	0.7 ± .003
Jc(12 T) at 4.2 K, A/mm^2	≥ 2400
D_s, µm (sub-element diameter)	< 70
I_S, A	> 1000 A
Cu-fraction, %	47 ± 2
RRR (after full reaction)	≥ 100
Twist Pitch, mm	14 ± 2
Twist Direction	right-hand screw
Minimum Piece length, m	350
High temperature HT duration, h	≥ 48

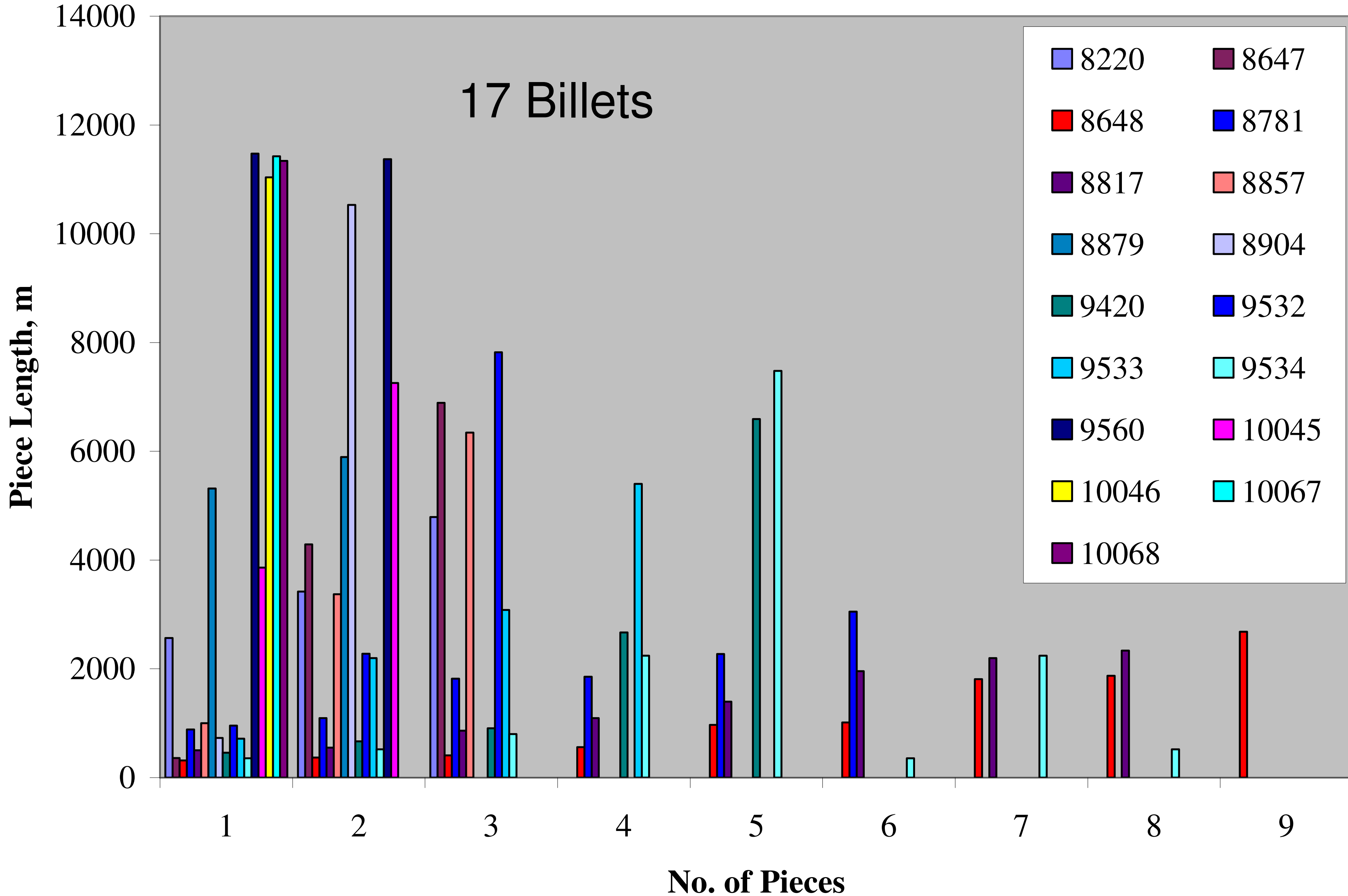


"Baseline Strand"- Specs.

- 650 kg of wire produced in the last 3 years, single billet yield is ~ 35kg (10 km)
- 93 % in lengths >1Km, 73% in lengths >3 km, **29% >10 km**

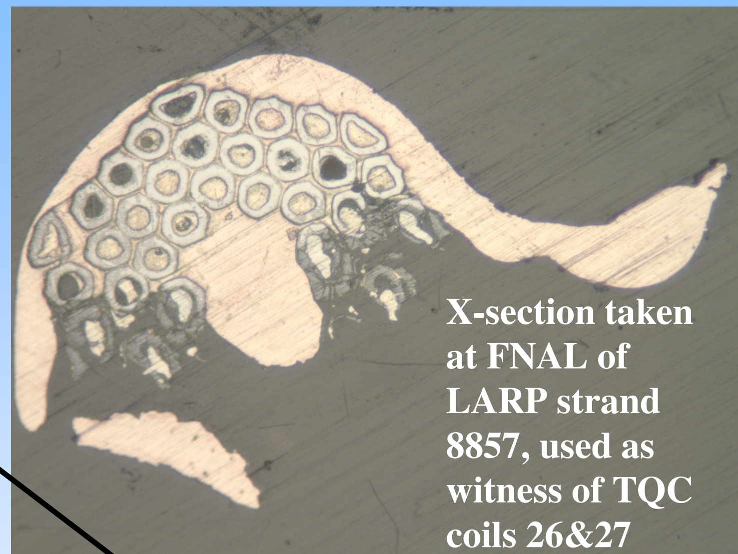


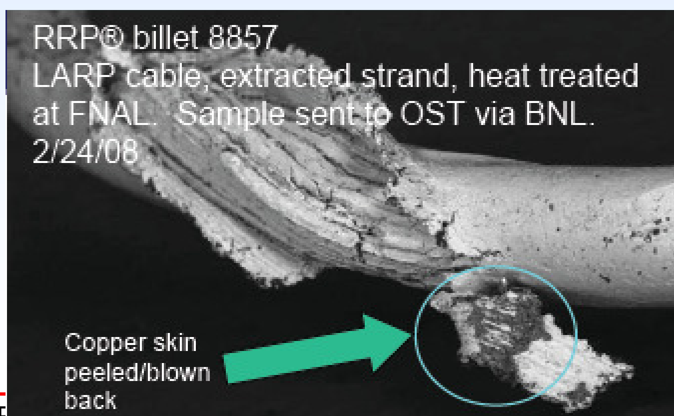
Long lengths ‣ sign of **Excellent** process control and Stable production.

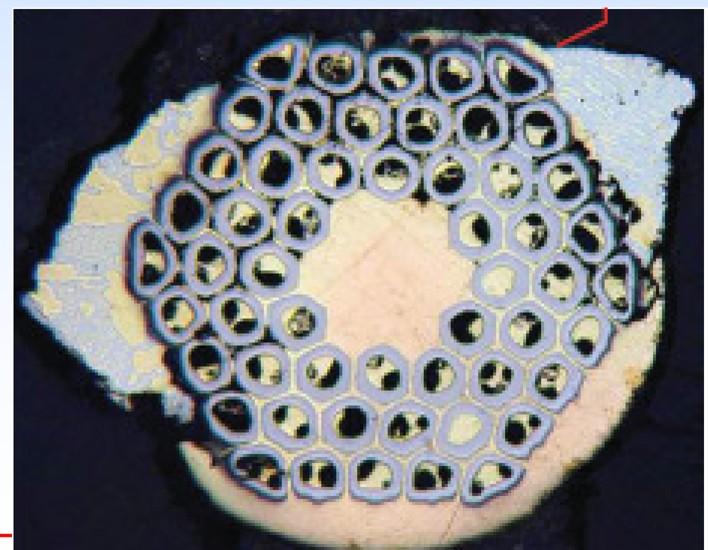

17 Billets
Piece Length, m
14000
12000
10000
8000
6000
4000
2000
0
1
2
3
4
5
6
7
8
9
No. of Pieces
8220
8647
8648
8781
8817
8857
8879
8904
9420
9532
9533
9534
9560
10045
10046
10067
10068

Cu burst observed recently in reacted RRP wire
First documented by E. Barzi (FNAL)

- Wires from LARP billets 8857 (reacted at FNAL) and 8781 (heat treated at the Univ. of Geneva) showed Cu bursts, as well as seen in wires from R&D billets 9272 and 9772 (FNAL)







Pictures from OST

Following a strong collaboration between LARP and OST, the source of the problem was identified to be Al-Si-O particles and fibers that embed into the surface of the wire during wire fabrication

The most likely source is the high-temperature insulation (bricks and fiber-blankets) used in the furnaces for NbTi manufacture

OST has taken several steps to:

- Reduce contamination of wire
  - Increased frequency of machine cleaning
  - Specialized containers to store wire between operations
  - Coil cleaning at ~ 0.3" diameter (acid etch)
  - Improved eddy-current detection
    - May result in wire cuts (shorter piece lengths)

3. Cable Production

LQ Specifications: Same as TQ Cable Specifications

Parameters	Units	TQ Final	Tolerance
Strands in cable	No.	27	NA
Strand diameter	mm	0.7	+/- 0.002
Width	mm	10.077 max.	+0.000, -0.100
Thickness	mm	1.26	+/- 0.010
Keystone angle	deg.	1.0	+/- 0.10

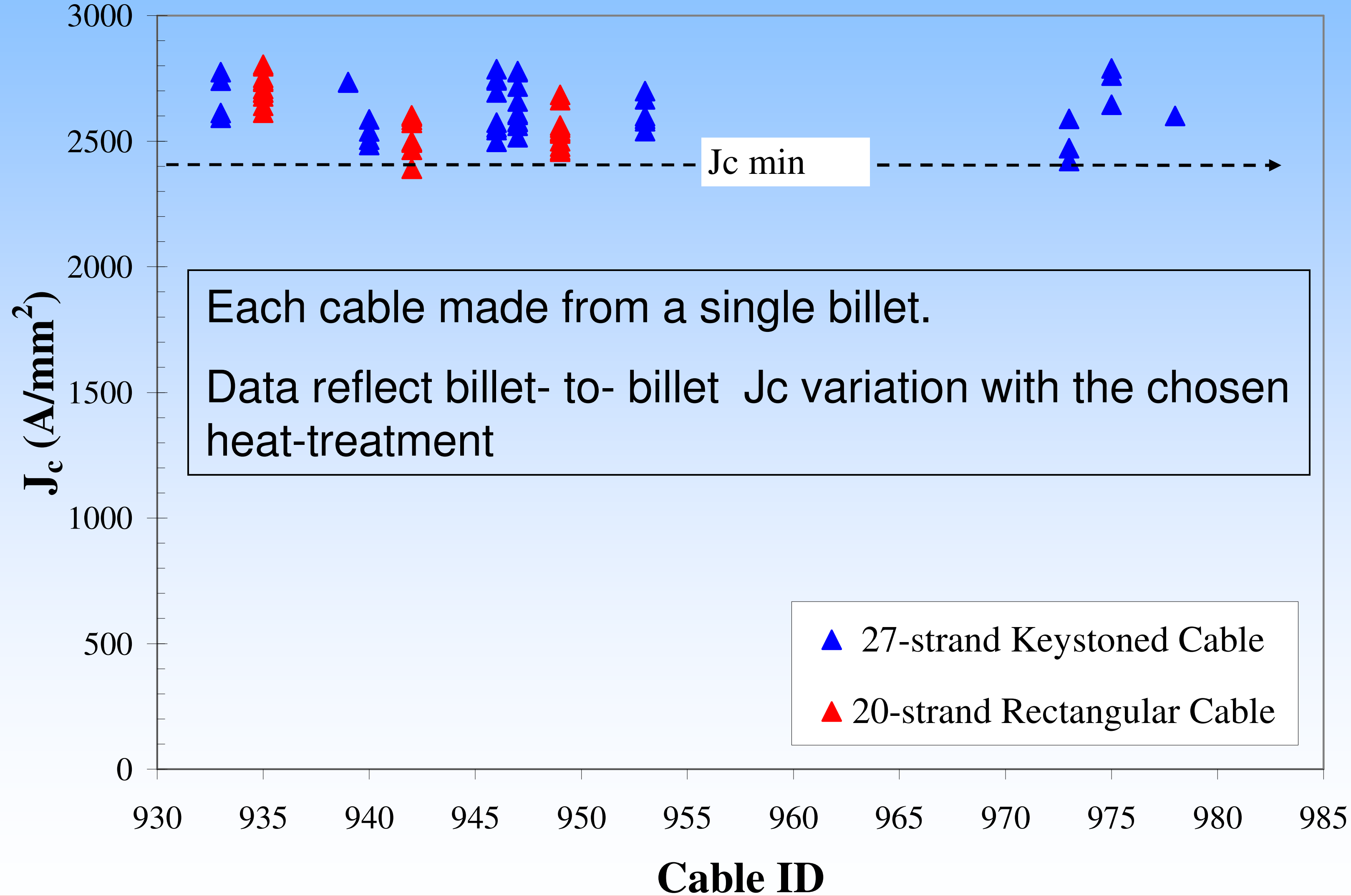
LQ- Cable unit length is 225 m

Six unit lengths have been made in FY08 for LQS01 Magnet

Cable Acceptance

- Optical Microscopy of cable
- React Cable sample and extracted strands using the following heat-treat schedule:
  - ➢ 210^{o}C/72h + 400^{o}C/48h + 638-640^{o}C/48h
- Extracted strand measurements of Ic , Is and RRR
  - –Check for Minimum Ic requirement
  - –Check for strand stability
- Transformer test of cable
  - –Minimum cable stability in Flux-jump regime

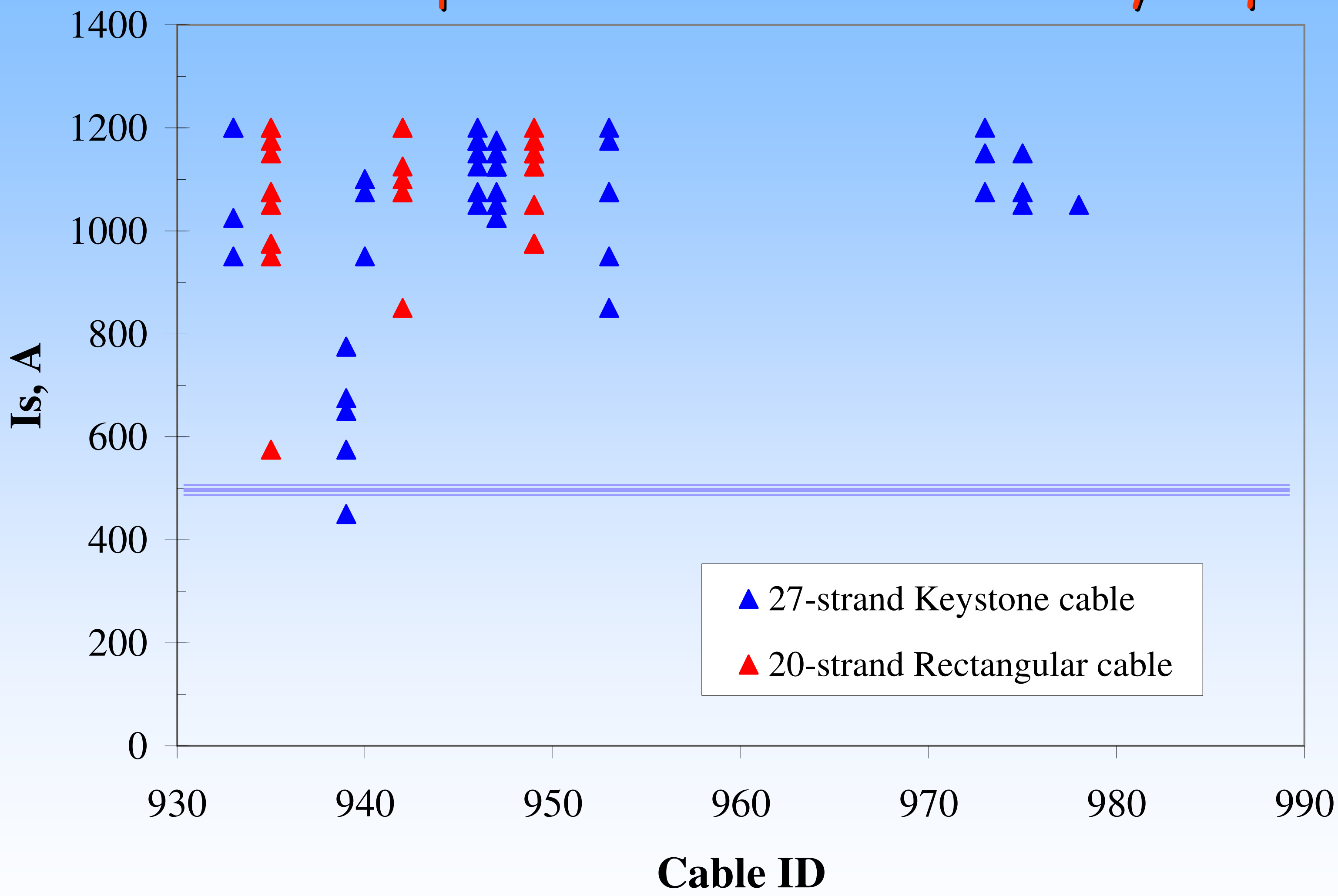
Strands Extracted from Cables meet $J_c(12T, 4.2K)$ requirement >2400 A/mm^2



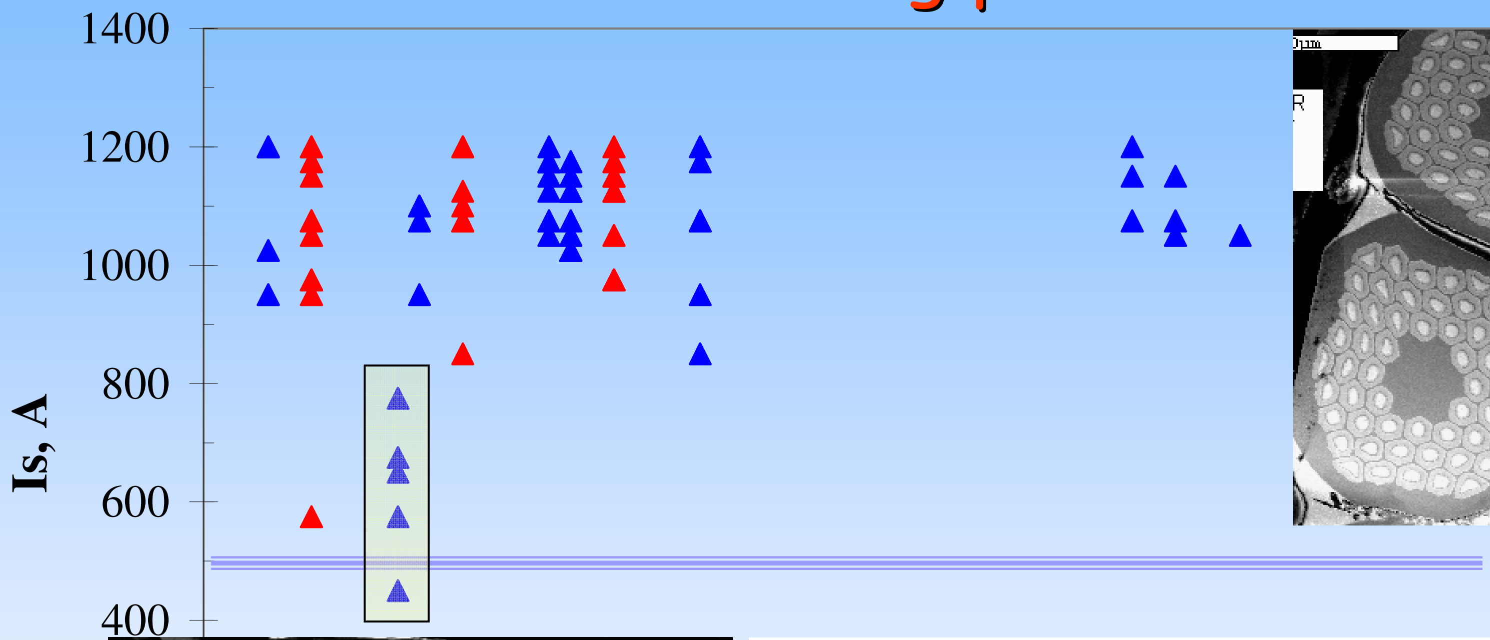
Each cable made from a single billet.

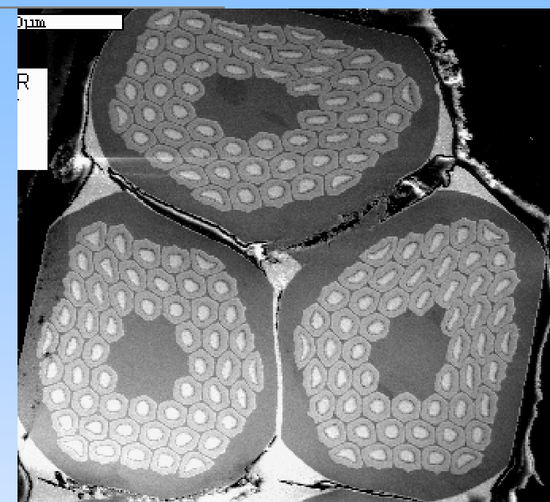
Data reflect billet- to- billet Jc variation with the chosen heat-treatment

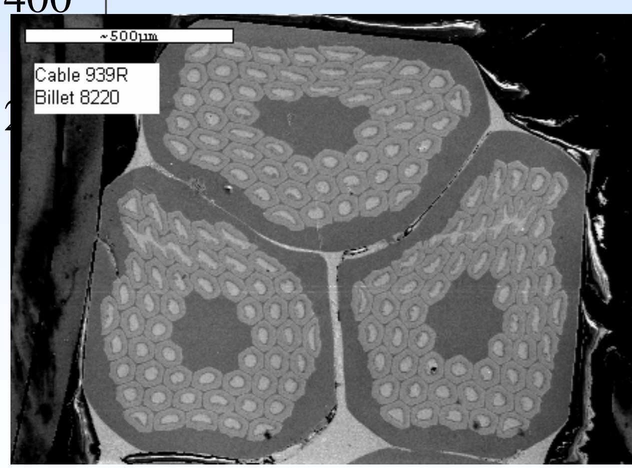
Is of Strands Extracted from Cables,
All except one cable meets stability requirements



Optical microscopy used to detect early cabling problems







- Cable 939 over-compacted during the re-roll operation leading to significant barrier damage.
  - Cabling procedures were modified to avoid this problem.

- LBNL Cable Production of 27-strand Keystone Cable is very stable

3.2 HQ 15 mm wide Cable Development

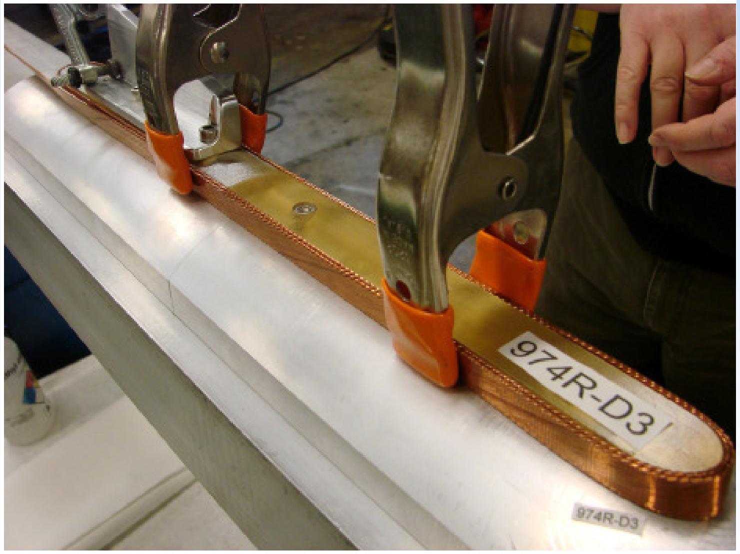
1. Strand Diameter -- Start with 0.80mm
   - LBNL Experience with cables for HD-1 and HD-2
   - Concerns with larger diameter strand
     - Less magnetically stable due to larger sub-elements
     - Thicker cable more difficult to wind a coil

2. HQ first prototype cable parameters (HQ-KC1), Feb. 8, 2008
   - Strand diameter: 0.80 mm
   - No. strands: 35
   - Thickness: 1.41 mm
   - Width: 15.17 mm
   - Keystone angle: 0.75 degrees

HQ Prototype Cable B974R

- 8 cable samples were made from B0974R
- Island and fixture were fabricated for test winding
- Wound with 30 lbs of cable tension
- Two turns were placed on the island
- Mechanical stability of samples was noted
- Samples were rated for winding characteristics

Cable No.	Width (mm)	Thickness (mm)	Keystone (deg.)
974R-A2	15.11	1.432	0.656
974R-B1	15.132	1.401	0.641
974R-B2	15.14	1.431	0.588
974R-C1	15.089	1.428	0.819
974R-C2	15.131	1.407	0.819
974R-D1	15.05	1.428	0.832
974R-D2	15.177	1.386	0.76
974R-D3	15.168	1.407	0.77

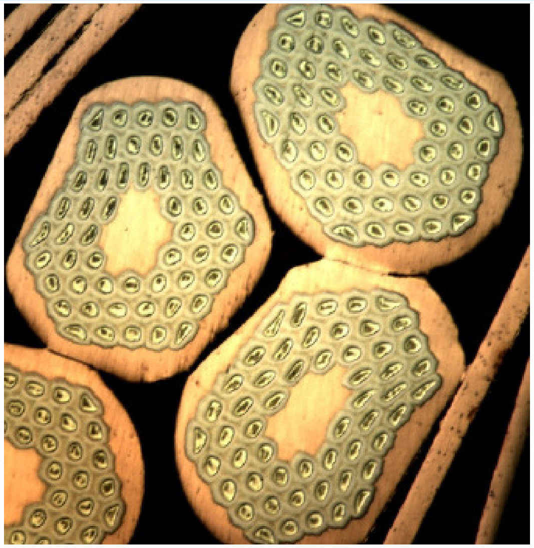


Cable C2 and D3 were judged acceptable

HQ prototype Cable B0977R

- HQ prototype cable parameters (HQ-KC1), Feb. 8, 2008
  - Strand diameter: 0.80 mm
  - Thickness: 1.41 mm
  - Width: 15.17 mm
  - Keystone angle: 0.75 degrees

- Samples of 977R are being heat treated at BNL and LBNL for
  - Critical current and RRR measurements



Parameters similar to 974R-D3

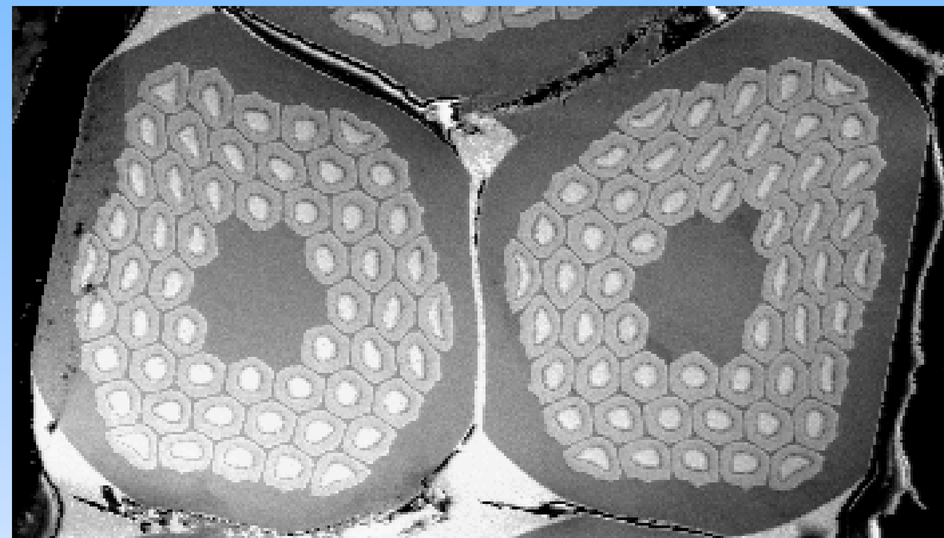
974R-D3	15.168	1.407	0.77

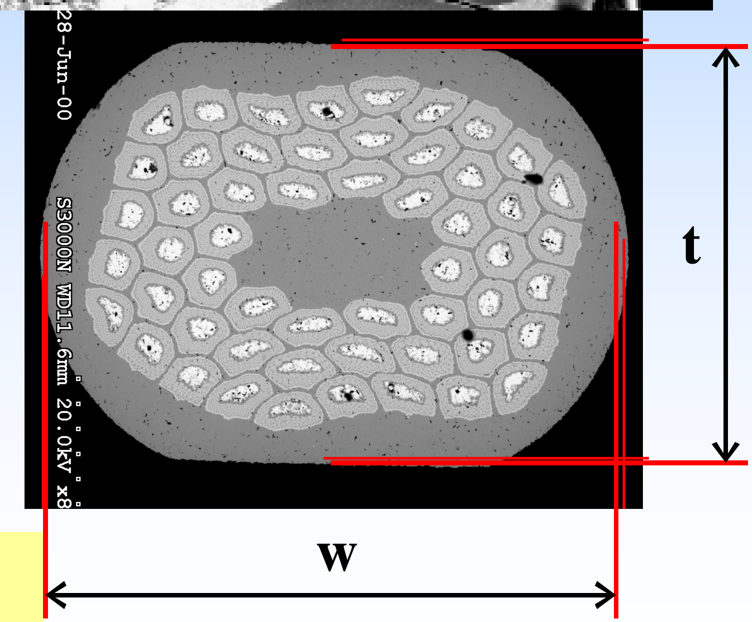
4. Cabling Degradation and Roll Strain

- Strand Deformation at the cable edges
  - Filament Distortion
  - Barrier Rupture
- Study this at the strand level

➢ Simulate by rolling strands and examine

  - Deformation of sub-elements
  - Effect on Ic, RRR, Is and barrier rupture



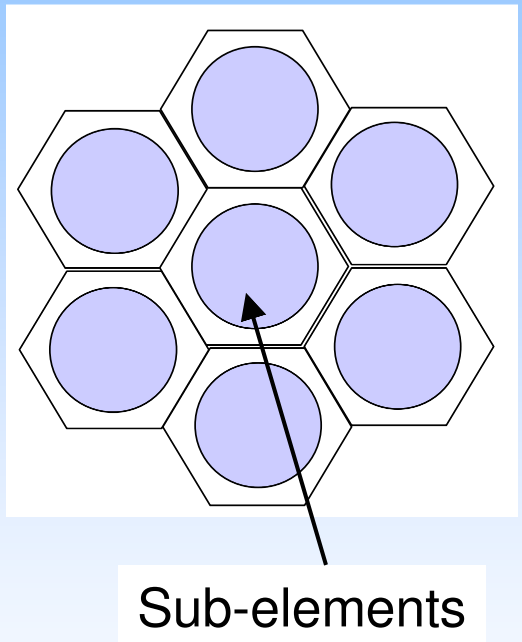


Roll strain=1-(t /d)
d=wire diameter

Rolled strand studies have shown that increasing Cu-spacing between Sub-elements improves the low field stability of deformed strands

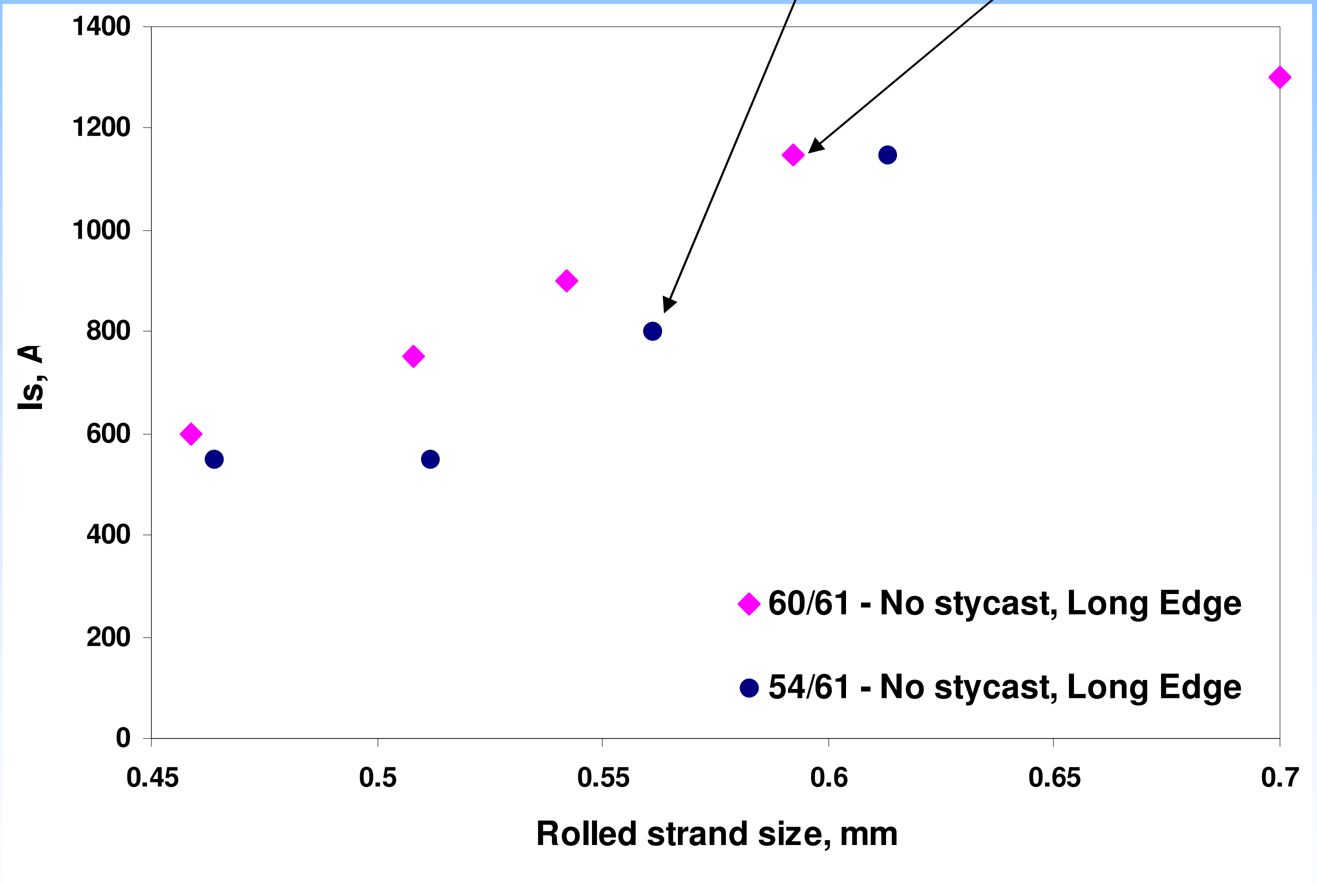
Based on work at FNAL:

- Comparison of rolled strands from a standard 54/61 billet and a 60/61 billet with larger spacing
- Comparison of a 108/127 standard billet with a 114/127 billet with larger spacing
- FEM calculations both at FNAL and CERN show that sub-element *deformation under rolling is reduced by increasing the Cu-spacing and having a large central Cu-core*. Also thicker Nb-barrier is less susceptible to barrier rupture.
- Therefore we have increased the Cu-spacing in our recent orders



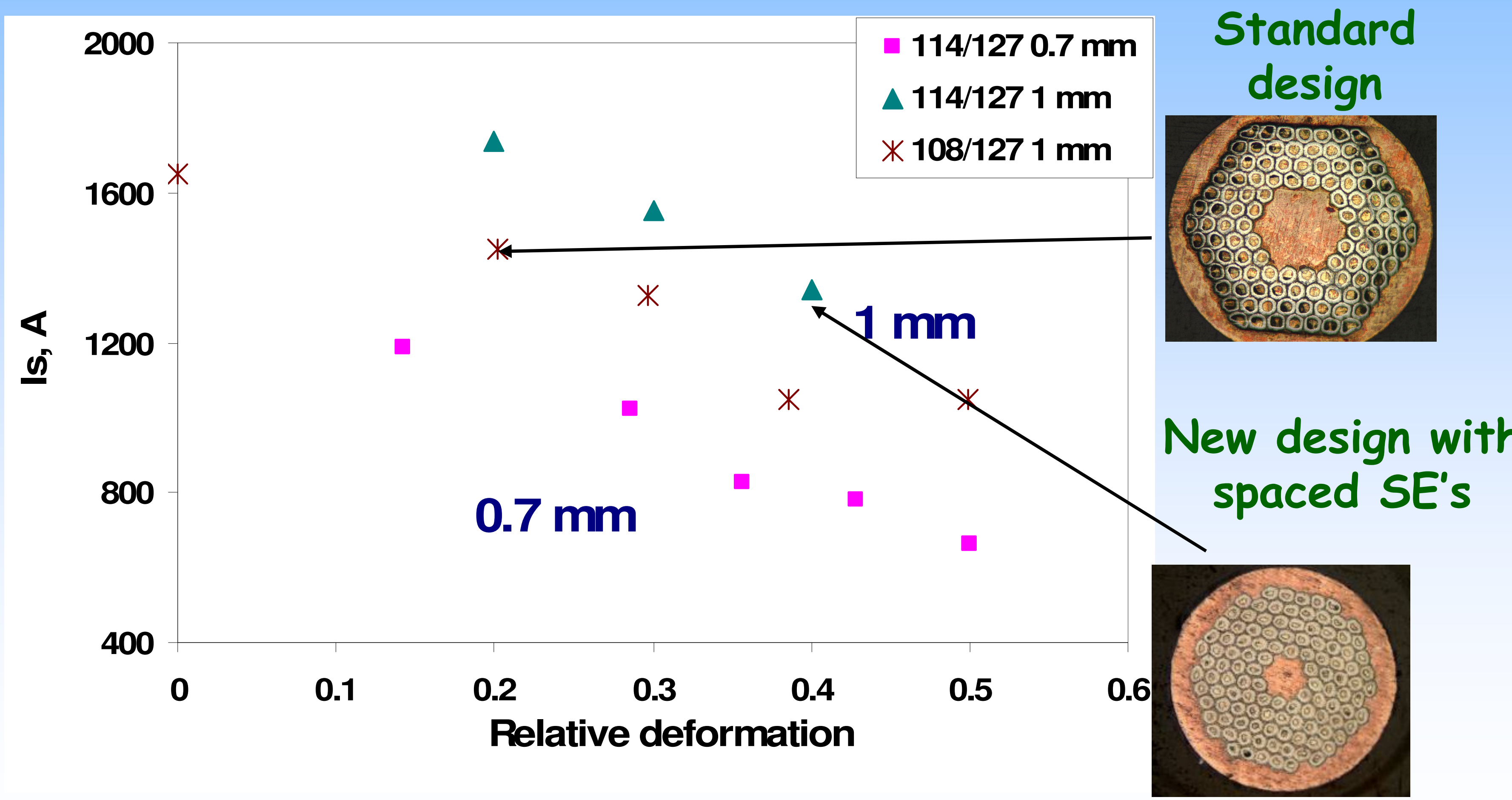
FNAL-Stability data – 54/61 vs. 60/61

Increased spacing ⇨ Higher tolerance to roll deformation



FNAL-Stability data – 108/127 vs. 114/127

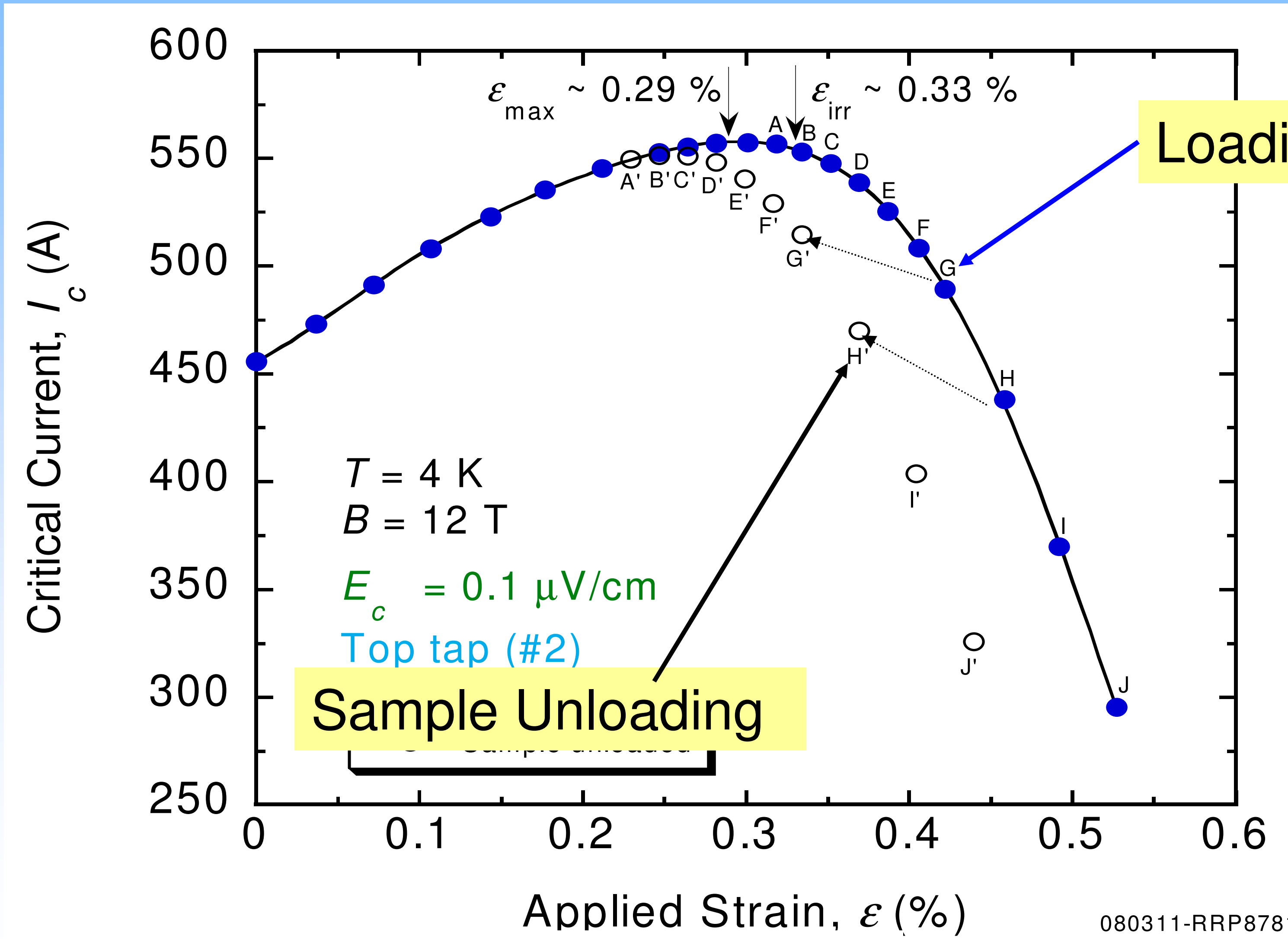
Increased spacing ⇨ Higher tolerance to roll deformation



5. Electro-mechanical Measurements of 0.7 mm RRP 54/61 strand Collaboration with NIST

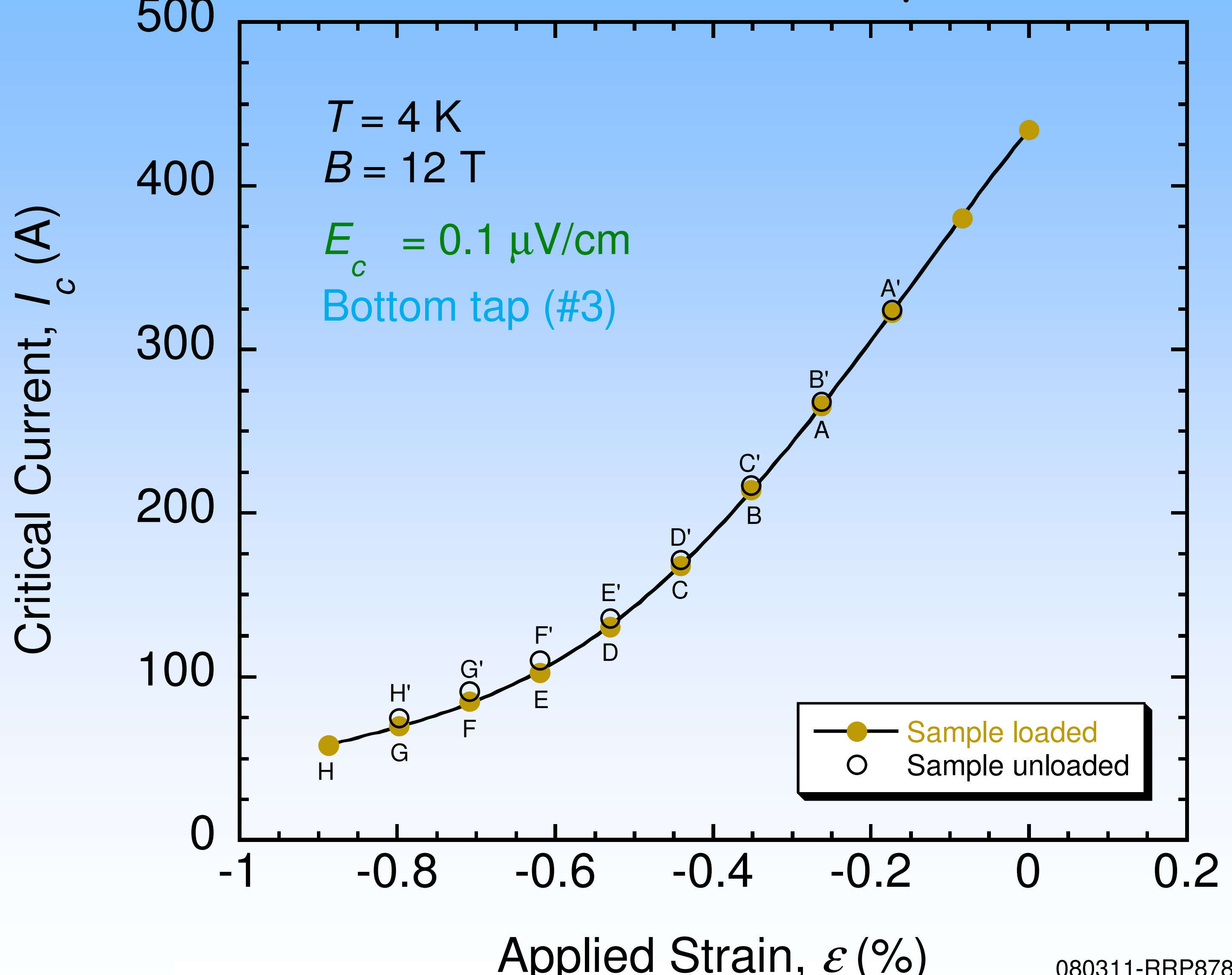
Najib Cheggour

In tension, irreversible damage sets in at a strain just above ε_{max}



Electromagnetics Division
Boulder, Colorado

In compression Ic is reversible-no permanent damage



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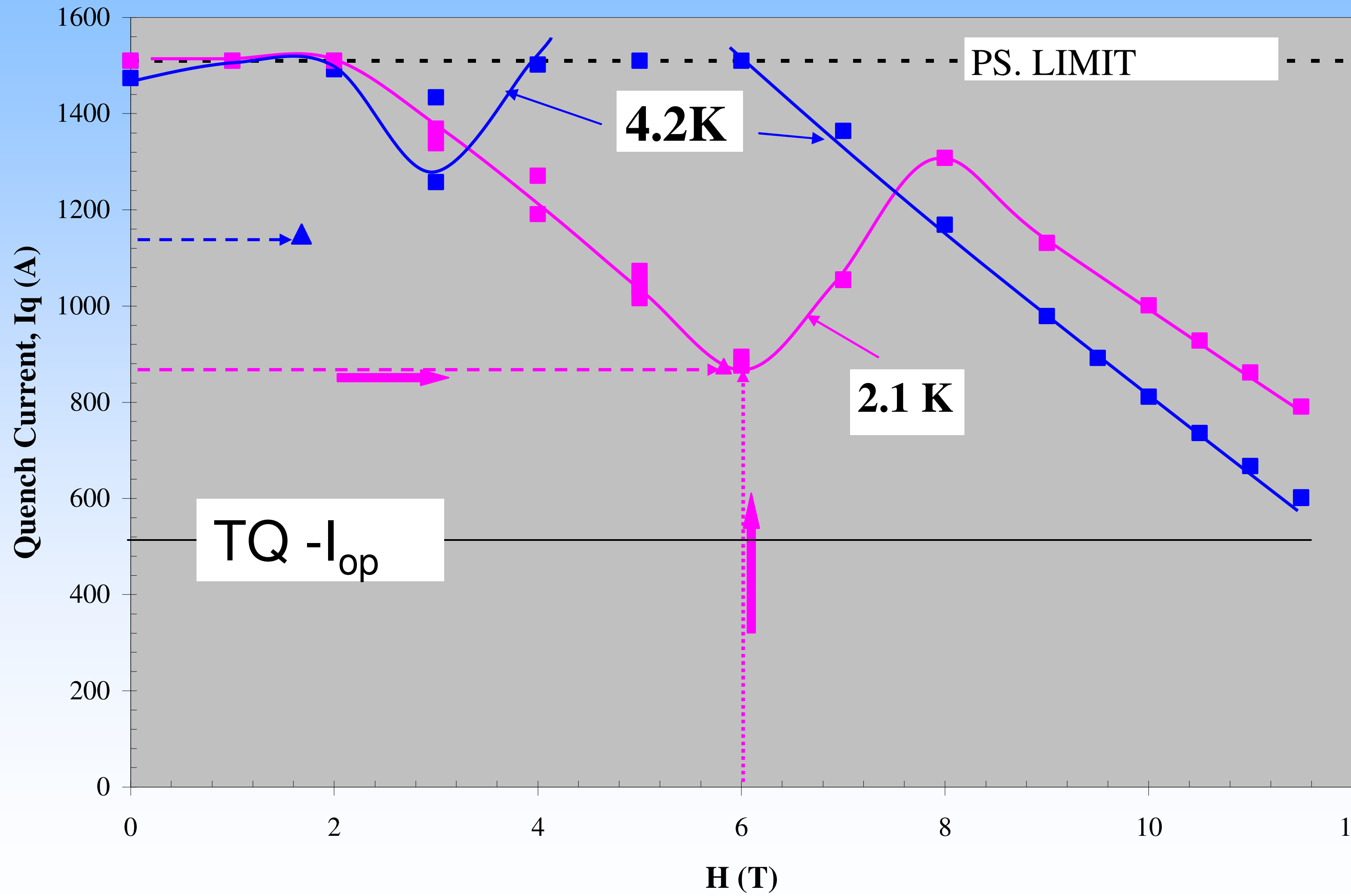
6. Strand Stability at 1.9 K

Driven by the observations of erratic quenching and no increase in quench current of TQ02 magnets in superfluid helium, we have been doing some detailed measurements of the quench performance of LARP strands in superfluid helium.

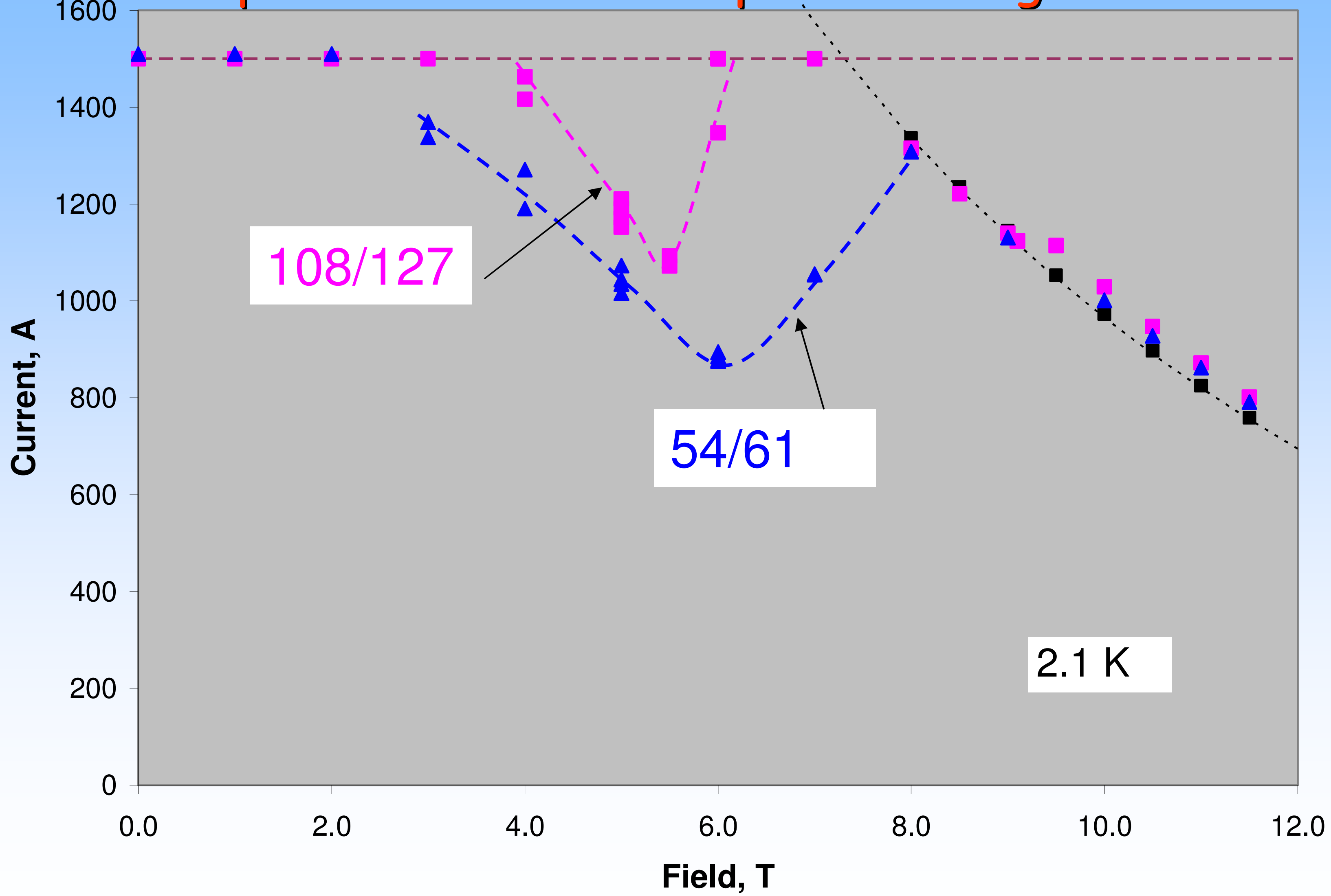
Measurements on RRP 54/61 and 108/127 strand in 4.2 K pool-boiling helium and in sub-pressure superfluid helium at 2K

Besides the "flux-jump" instability mediated by collapsing persistent currents at low fields, strands also exhibit "Self-Field" Instability due to transport current. This is usually established by looking at the quench performance of strands in fixed external fields. i.e. V-I Measurements

RRP 54/61, Jc ~ 2550 A/mm2, RRR ~ 310
In superfluid, stability threshold lower than at 4.2 K



108/127 has higher stability than 54/61 in superfluid helium. Samples have high RRR ~ 300



Strand Stability at 1.9 K

Instability more pronounced in superfluid helium at 2K than at 4.2K

- At 4.2 K strand instability dominated by magnetization flux-jumps at low fields < 3T
- At 1.9-2.1 K , instability is dominated by “self-field” instability at intermediate fields of 5T – 6T. Stability threshold is higher for the smaller sub-element strand (108/127).
- *Minimum quench currents of strand in liquid helium still higher than that observed in magnets*
  - However, effect of heat transfer and Cu-RRR on “self-field” instability needs further measurements

7. Production Plan
RRP 108/127 Strand for LARP

- For FY08 LARP focused on strands with the *127-stack design*
  - *High Jc ~ 3000 A/mm^2 has been achieved*
  - *30% reduction in Ds ☛ Stability improves with decreasing sub-element diameter*
  - *lower magnetization*
  - *Option to increase strand diameter ⇨ wider cable*

➔ *OST accepted a fixed price contract for 180kg of 108/127 strand, S/d~0.13, 0.7mm, Nb-Ta-Sn*

➔ *This production went well - good piece lengths*

Procurement Strategy

•Based on strand/cable characterization, we have selected the 54/61 as the baseline strand for LQ. Accordingly, we show a 54/61 procurement plan that covers the needs of LQ01, LQ02, spare coils, HQ models.

•Although the 54/61 strand is adequate for LQ, a conductor with smaller Deff would be much better for any accelerator magnet RRP 108/127 with increased Cu-spacing is the most promising option.

•Our current plan allows us to further develop and qualify the 127-design strand and, to procure this strand consistently for use in model magnets

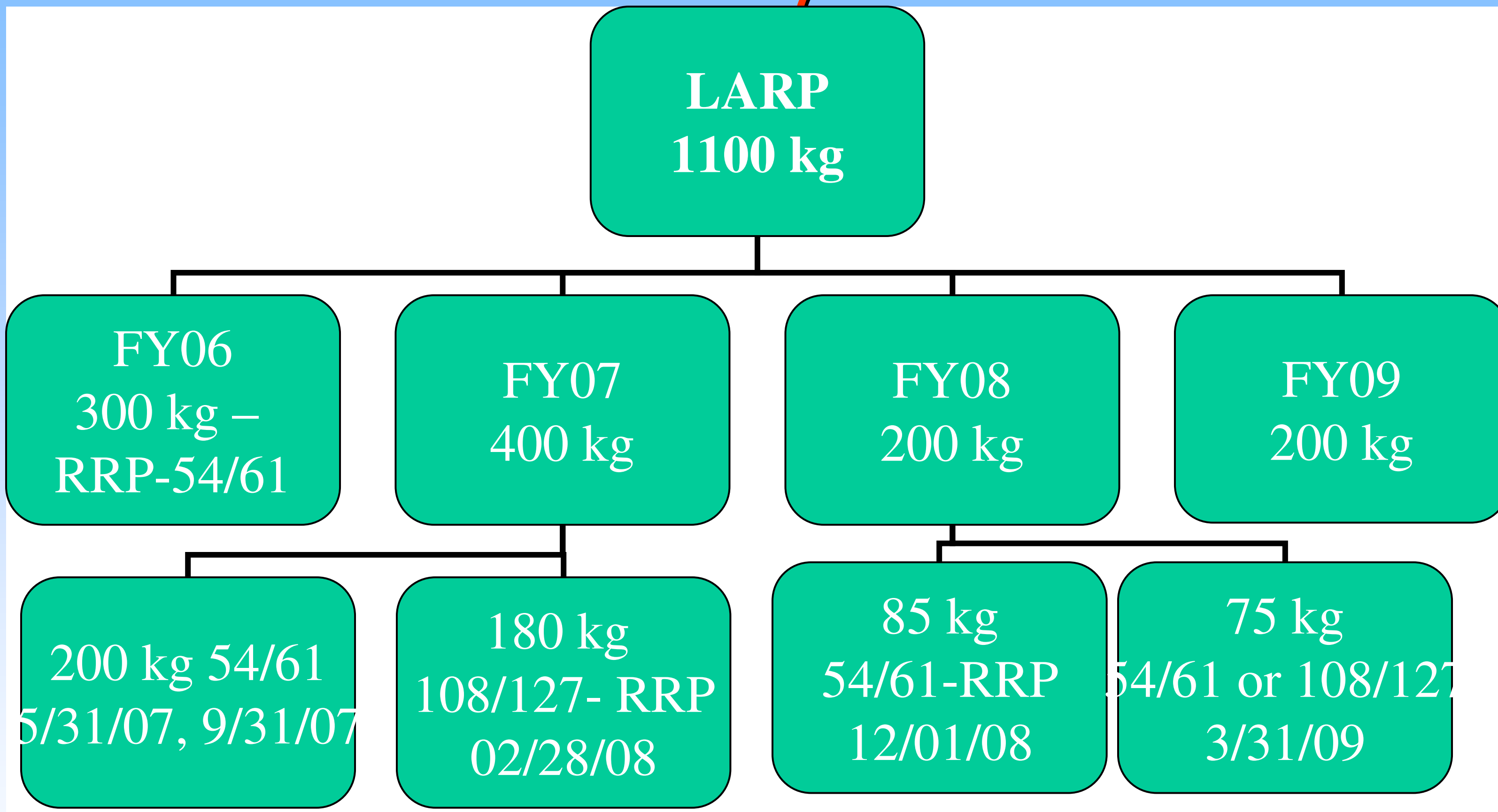
•We can switch to 108/127 starting from LQ02 in case (a) we encounter unexpected problems with 54/61 and/or (b) based on our qualification and procurement efforts, we show that 108/127 offers significant benefits and low risk. It can replace 54/61 as the new “baseline” strand starting from LQ02.

•This strand can also be used for HQ model magnets.

Qualification of 127-design strand

- Repeat Roll strand measurements using "127-strand optimized HT".
- Extracted strands from TQ cable (B0982R)using 108/127 strand
  - In process
- Fabricate TQ coils from B0982R and test in a TQ structure
- Extracted strands from HQ 15 mm wide cable with 0.8° keystone and using 0.8 mm strand

Procurement Plan –Consistent over three years



8. Conductor Procurement Summary

- 26 kg required for UL of LQ
  - 6 UL's have been made
  - Present 54/61 strand inventory is 232 kg
- 60 kg of 54/61- 0.7 mm wire from five billets available for practice coils
- 180 kg of RRP 108/127 (increased spacing)
  - 37 kg at 0.7 mm
  - 30 kg at 0.8 mm
  - 114 kg at 1.07 mm
- 85 kg has been ordered in FY08
  - 54/61 or 108/127 at 0.8 – 1.0 mm
- Another 75 kg order will be placed in Aug'08
  - Strand design 54/61 or 108/127

R&D to address stress-strain and stability issues for cable conductors in magnets

- Collaboration with NIST
  - Measurement of electro-mechanical properties of RRP 54/61 and 108/127 wires
  - Deals only with tensile strain
- Cable tests
  - Effect of transverse pressure on Ic
    - What is the tolerance of the cable in the magnet
    - First series of tests planned for Nov (NHMFL, LBNL)
  - Strand/Cable stability at 4.2K and 1.9K
    - Bridging the understanding from strand to impregnated cable to magnet performance
    - Test at FRESCA facility (CERN) towards the end of CY08
- Resources allocated for FY08 for sample prep, more needed in FY09 for these tests

9. Summary

- The LARP Materials Group has focused on cable production, strand and cable qualification, coil reaction and witness sample testing, and R&D towards developing the "next generation" conductor for high field accelerator magnets.
- Some conductor issues requiring more R&D is in
  - Transverse stress effects in cables
  - Instability in superfluid helium
- The 127-stack design has matured significantly at OST that it is considered a "production" wire
- There is adequate inventory of 54/61 for LQ01 and LQ02 magnets
- Beyond the first LQ and for the HQ magnets LARP can consider the 108/127 strand after completion of strand/cable and TQ magnet evaluation

End of Presentation

Additional Slides

1. Strand stability and RRR
2. Transformer test of cable
3. HQ-Cable Development
4. Strand inventory and usage

1. Flux-Jump Instability

Key concern specific to LARP strand and TQ magnet operating current of 500 A

Since wires of 0.7 mm with d_{eff} < 35 μm cannot be made at present, flux-jumps are inevitable in low-field regions of magnets.

Will "flux jump" initiate a quench ?

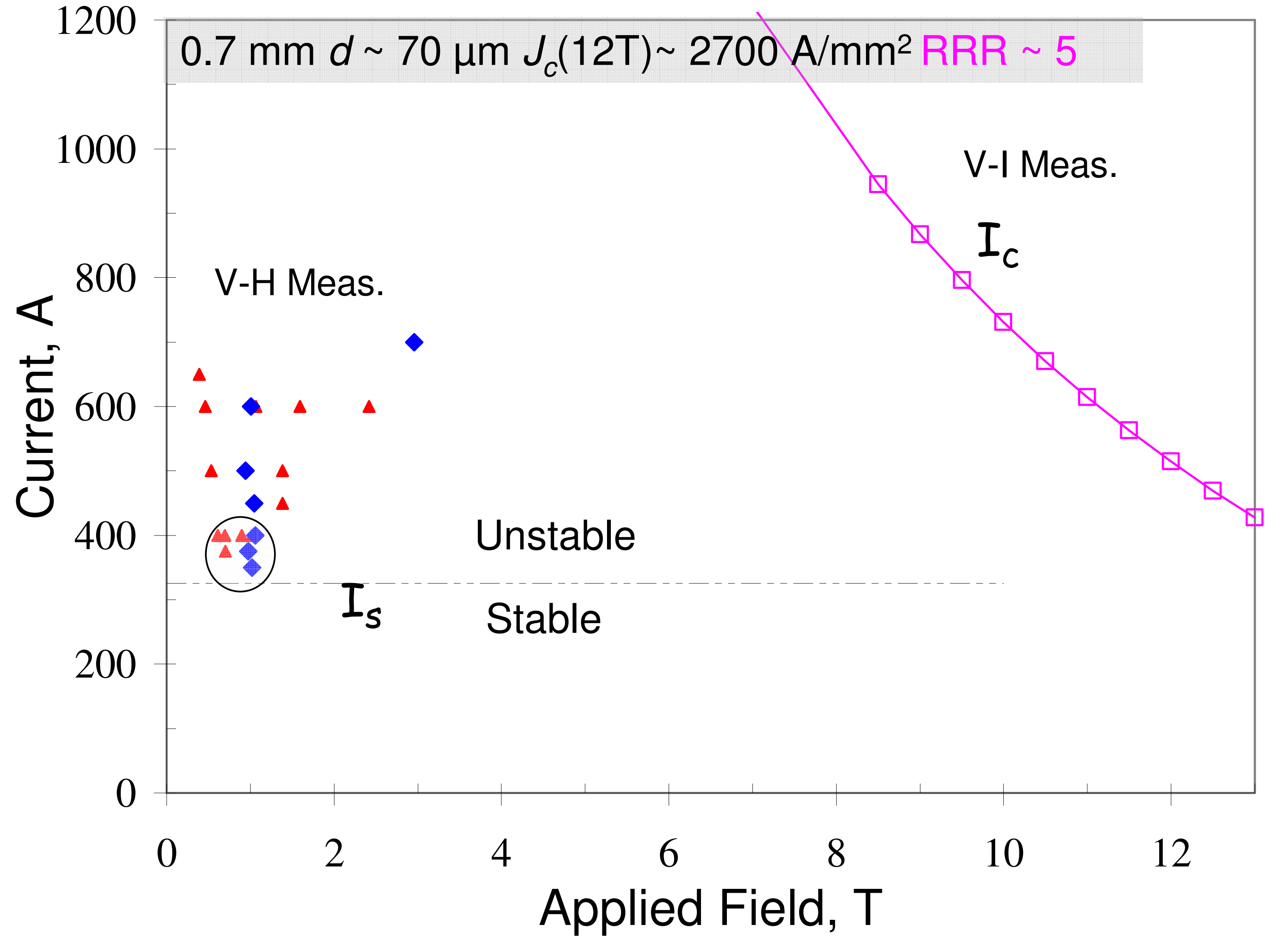
Not if: local copper stabilizer RRR is "high"

Strand Stability

↓

Evaluated by measuring I_s

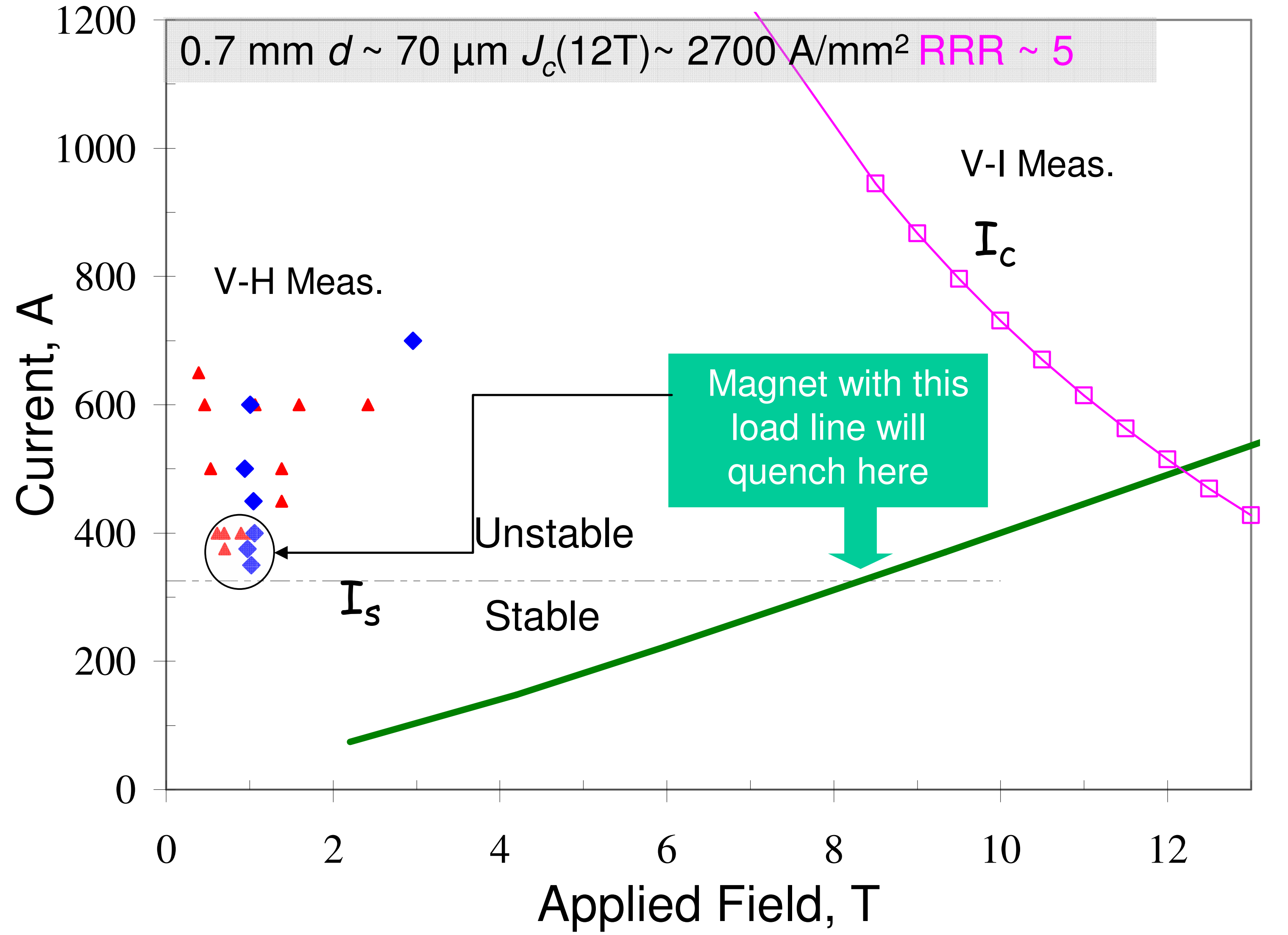
Stability Current Is



Unstable

Stable

Stability Current Is



Unstable

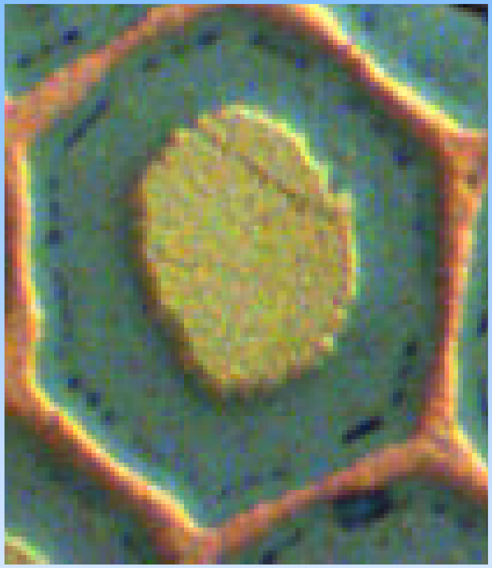
Stable

Why is RRR low ?

- High Jc is achieved by reacting the most Nb area, including the Nb diffusion barrier.

However

- Reactions: to get high Jc allow tin (Sn) to react through the Nb-barrier and poison the surrounding copper.



Sn Leakage leads to low copper RRR

Instability Management

- Tin leakage into copper destroys "*dynamic stability*" by increasing its resistivity ρ which also reduces thermal conductivity k_{TH} *(which affects heat transfer within the strand and to the coolant)*

- Copper RRR reduces from 300 to 7 for as little as 0.1% Sn

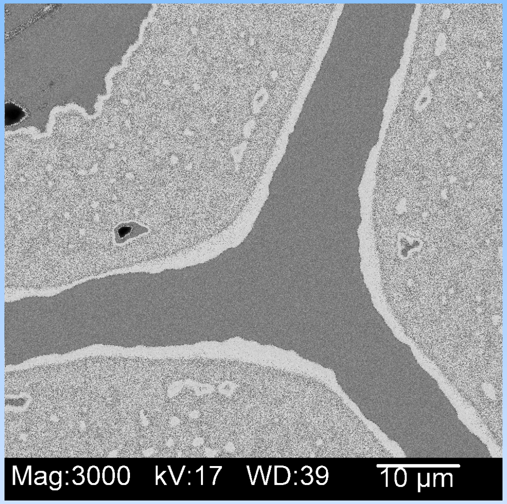
- Measurements show that RRR (~ 1/ρ) of the copper stabilizer influences I_s
  - I_s increases with increasing RRR

Manage Instability by HT Optimization – Trade some J_c for high RRR in strand

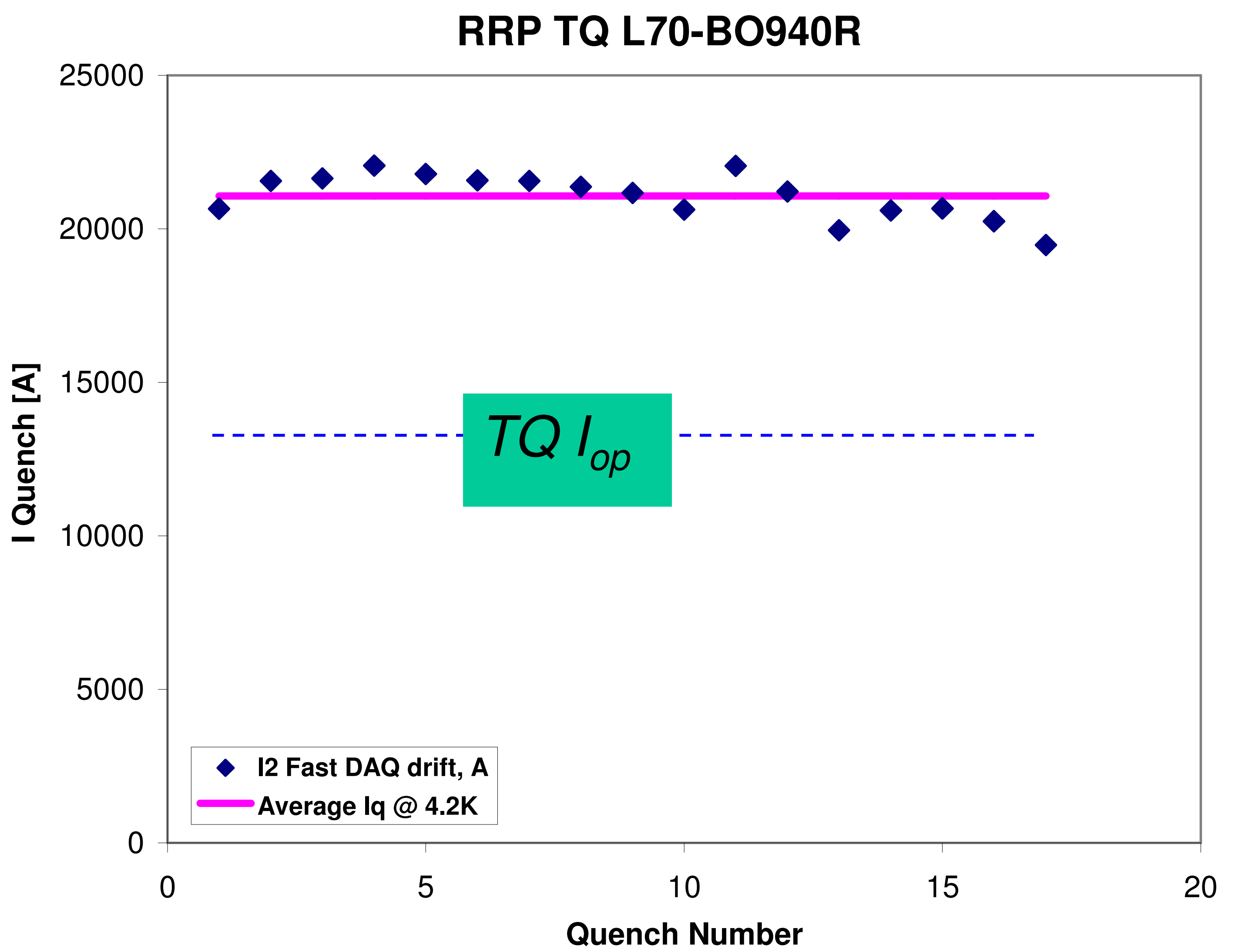
Minimize Sn-Leakage into stabilizer

Even for moderate reactions Sn leakage can still occur due to

- Diffusion barrier thins or tears during the wire fabrication process.
  - ⇨ *Measure Is for round strands*
- Strand deformation (e.g. cabling) distorts sub-elements and diffusion barrier.
  - ⇨ Adjust cabling parameters and procedures to minimize filament distortion
  - ⇨ *Measure Is for extracted strands*
  - ⇨ *Measure Is for cables*



2. Low field quench test for stability



3. HQ Prototype Cable B974R

CABLE	WINDABILITY	RATING	NOTES
974R-B1	Poor	8	Cable did not feel stable under tension. De-cabling on every turn. The strands would not stay in place after putting it together.
974R-B2	Poor	7	Cable felt fairly unstable under tension. De-cabling on every turn. Most of the popped strands would not go back in and hold.
974R-A2	Poor	6	Cable felt kind of loose and unstable under tension. There was de-cabling on the first turns and popped strands on al the turns. Even when put back, they still popped out.
974R-D2	Fair	5	Feels fairly stable under tension. Popped strands when winding. Put back in place and most seemed to stay in place.
974R-D3	Good	1	Cable feels fairly stable under tension. Only very slight de-cabling when winding around the pole turns. Strands stayed in place when put back.
974R-C2	Good	2	Cable feels fairly stable under tension. Slight de-cabling when winding. Strands stayed in place when seated back.
974R-C1	Fair	3	Cable feels slightly irregular under tension. Light de-cabling around poles. Cable seems to hold when the strands are seated back in place.
974R-D1	Fair	4	Cable feels kind of loose under tension. Popped strands when winding around the poles. Strands are slightly out still when put back together.

3. HQ Prototype Cable B977R

- First Pass Rolls P29 & 30

	Roll Angle	Cable Width mm	Cable Thickness mm	Cable Keystone Deg.	Cable Length m
HQ-RRP-B0977	0.85	15.061	1.4969	0.834	19

- Cable Anneal: 205c / 12 hrs

- Second Pass R Rolls P23 & 24

	Roll Angle	Width mm	Thickness mm	Keystone Deg.	Length m
HQ-RRP-B0977R	0.75	15.128	1.402	0.749	16

- Winding tests:
  - Sample of cable 977R showed no tendency to pop strands going around the first turn on either side of the pole.
  - Seemed much better than all of the samples of 974R

4. Strand inventory and Usage

	54/61 kg	MAGNET	Strand Req. kg	Inventory of 54/61 kg		54/61 kg	108/127 kg	MAGNET	Strand Req. kg	Inventory of 54/61 kg	Inventory of 108/127 kg
Oct-05	33	SR01	7	26	Oct-07					386	0
Nov-05	70			96	Nov-07			LQ01-C03-PC	28	359	0
Dec-05				96	Dec-07					359	0
Jan-06				96	Jan-08			LQ01-C04	26	333	0
Feb-06				96	Feb-08		180	LQ01-C06/C07	51	282	180
Mar-06	90	TQC02	40	146	Mar-08					282	180
Apr-06		LRS01-C01	27	119	Apr-08					282	180
May-06	90	TQC02-R	35	174	May-08			LQ01-C08/C09	51	231	180
Jun-06		TQS02	35	139	Jun-08			TQS03	35	231	145
Jul-06				139	Jul-08					231	145
Aug-06				139	Aug-08					231	145
Sep-06		LRS01-C02, SQ	36	103	Sep-08					231	145
Oct-06				103	Oct-08					231	145
Nov-06				103	Nov-08					231	145
Dec-06	30	LQ01-C05	37	96	Dec-08	85				316	145
Jan-07	90			186	Jan-09					316	145
Feb-07	30			216	Feb-09					316	145
Mar-07				216	Mar-09	75				391	145
Apr-07	50	LRS01-C03	30	236	Apr-09					391	145
May-07				236	May-09					391	145
Jun-07		SQ03		236	Jun-09					391	145
Jul-07				236	Jul-09					391	145
Aug-07		PCX01	0	236	Aug-09					391	145
Sep-07	150			386	Sep-09		200			391	345
Oct-07				386	Oct-09					391	345

60kg R&D Stock, only used for practice coils.
PC: Practice coil for LQ coil winding