BNL -FNAL - LBNL - SLAC

2.4.1 Materials – Conductor Support

Arup K. Ghosh

Introduction

Strand Stability

Strand Procurement

Future LARP Strand

Strand R&D

Cable R&D

Summary

Materials Group

- E. Barzi 2.4.1.1 Strand R&D
  - Strand Characterization
    - Ic, Is, RRR, M
    - Heat-treatment optimization
    - Extracted strand test
    - Rolled strand test
- D. Dietderich 2.4.1.2 Cable R&D
  - Cable Fabrication
    - Prototype Cable using new strand
    - Production Cable for Magnets
    - Cable Test
- A. Ghosh 2.4.2 Conductor Procurement

Main Goals

Two goals for the Materials group

- Provide "baseline" material for magnet program
- Support R&D program for development of future LARP material
  - (augmented with significant core program support)

Nb_3Sn Strand

Magnets for LARP are designed to use high J_c (> 2000 A/mm2 at 12T) Nb_3Sn wires.

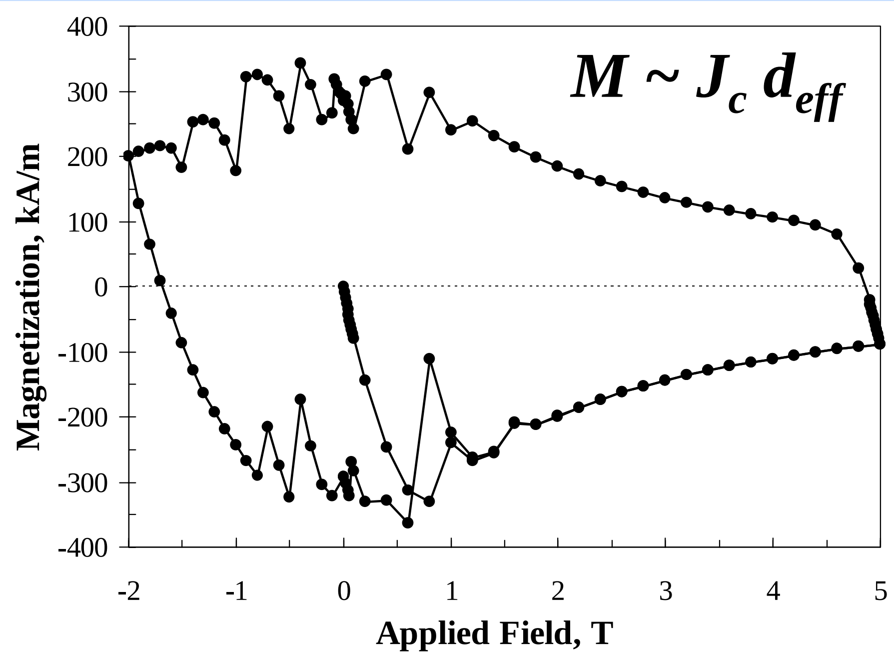
- Current Strand Options
  - MJR (Modified Jelly Roll) – OST has discontinued this wire
  - RRP (Re-Stack Rod Process) – OST production wire (commercial applications, US magnet programs)
  - PIT (Powder-in-Tube)– unreliable delivery, high cost
- One US vendor capable of furnishing LARP conductor (Oxford Superconducting Technology, OST)
  - Future Strand Development
    - DOE SBIR program
    - DOE Conductor Development Program
    - Core program (FNAL procurement of PIT)
    - Conductor Development under NED

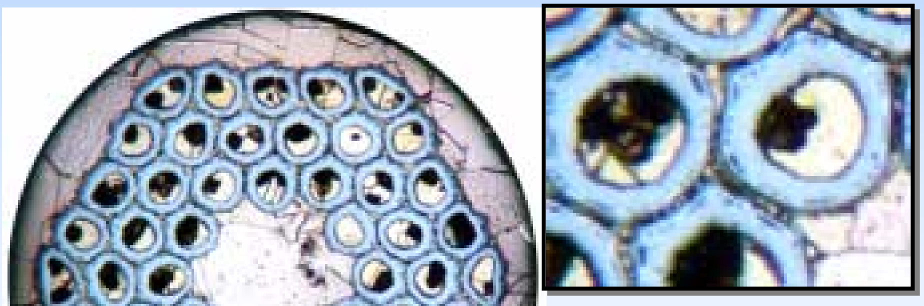
Strand Stability

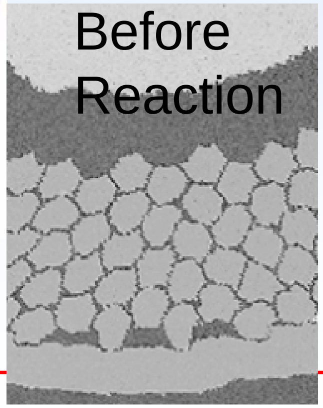
Key issues for both MJR and RRP

1. Lack of "Adiabatic" stability in currently available strands (RRP design)

Filaments merge into a solid mass after reaction, so sub-element diameter is often the effective filament diameter ➢ d_{eff}. Large filament diameter produces flux jumps at low fields.







Flux-Jump Instability

- The combination of high *Jc* and large *d* results in the loss of “adiabatic” stability

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

- Restore “adiabatic” stability
  - reduce ***d to less than 40μm*** ➢ increase number of filaments

Key concern: Since wires with d_{eff} < 40 μm cannot be made at present, flux-jumps are inevitable in low-field regions of magnets.

Will “flux jump” initiate a quench ?

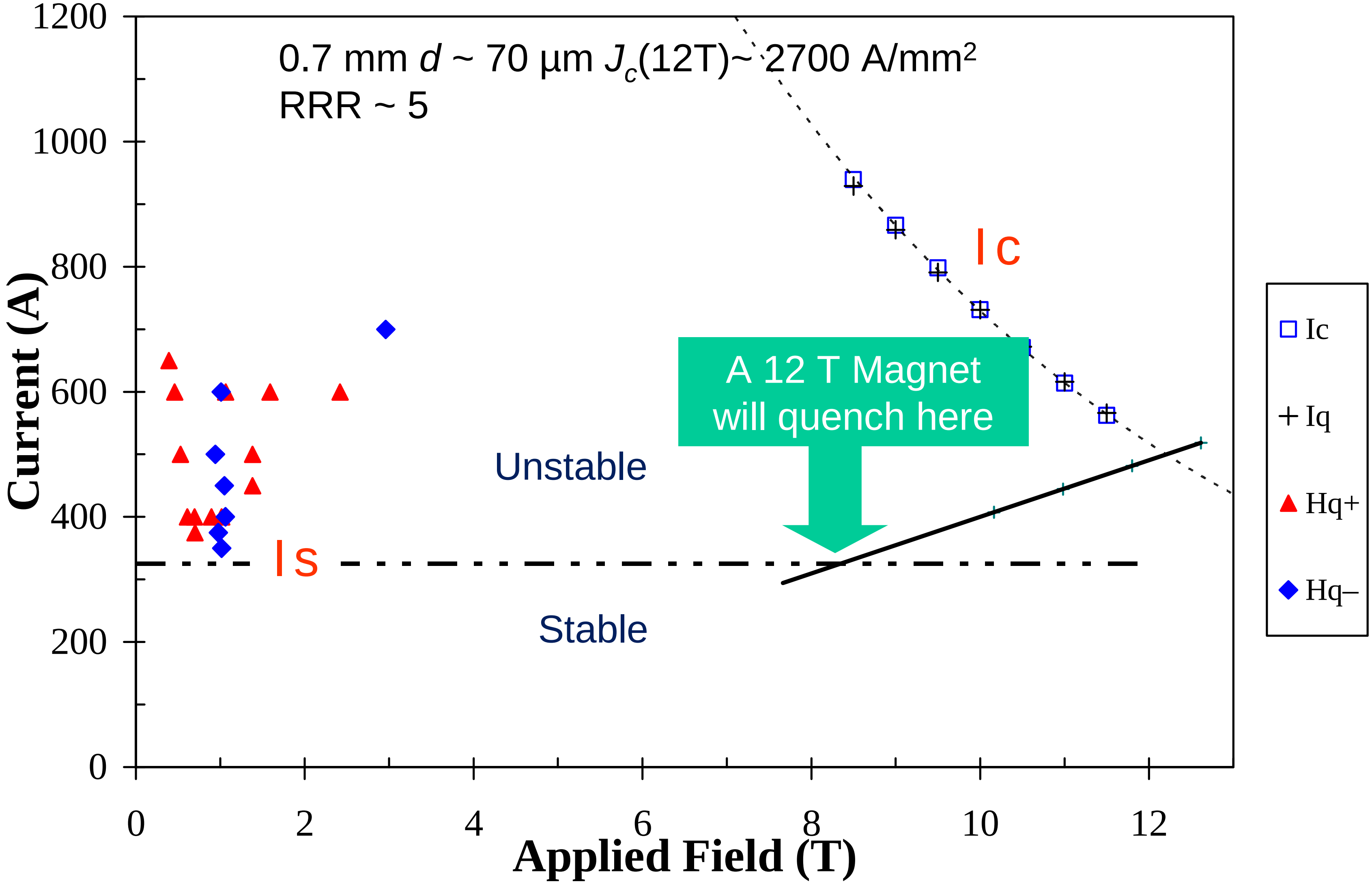
Not if: local copper stabilizer RRR is “high”

Strand Stability

↓

Evaluated by measuring I_s

Stability Current Is



Sn-Leakage into stabilizer

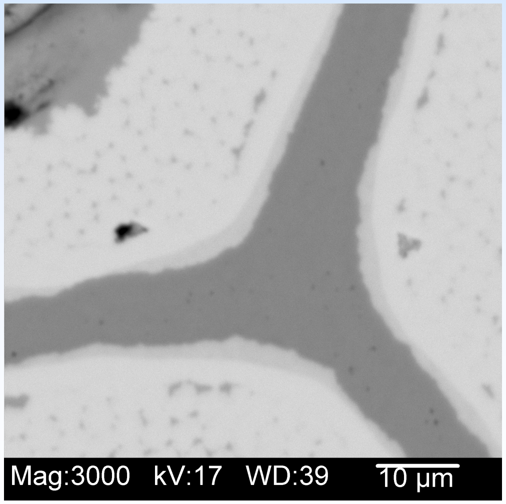
- High Jc is achieved by reacting the most Nb area, including the Nb diffusion barrier.

However

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

Even for moderate reactions Sn leakage can still occur due to

- Diffusion barrier thins or tears during the wire fabrication process.
- Strand deformation (e.g. cabling) distorts sub-elements and diffusion barrier.



Dynamic Stability

- Tin leakage into copper destroys "dynamic" stability ($\alpha > 1$) by increasing ρ which also reduces thermal conductivity k_{TH}

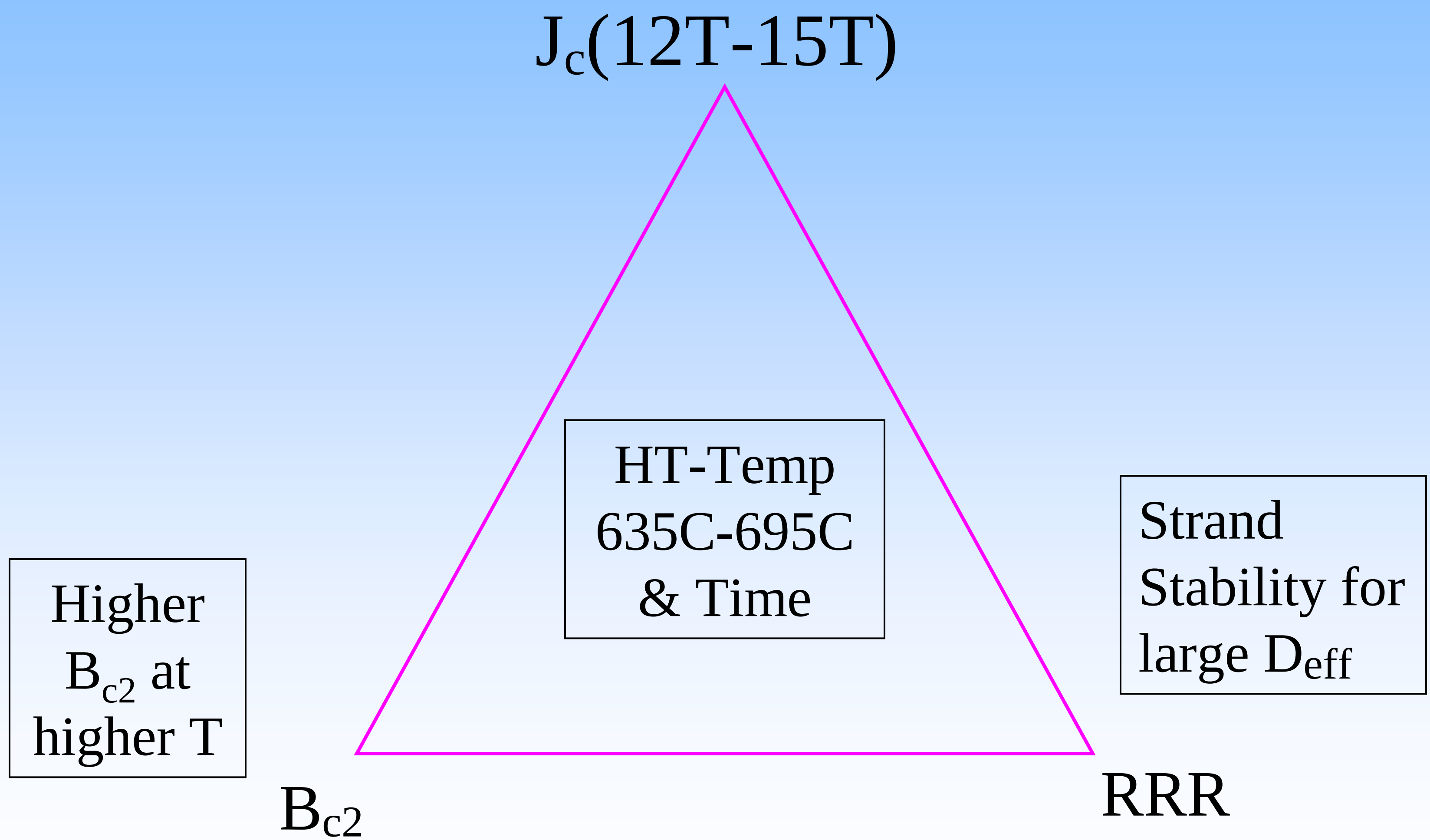
$$\alpha = \frac{\rho J^2}{K_{TH}\left(T_c - T_{bath}\right)}\left(\frac{A}{P}\right) < 1$$

- Fickett(1982 data on Cu-Sn alloys): Copper RRR reduces from 300 to 7 for as little as 0.1% Sn (which is below the resolution of Energy Dispersive X-ray spectroscopy SEM-EDX ~ 0.5%)

- Measurements show that RRR of the copper stabilizer influences Is
  - "Dynamic" stabilization can increase Is

HT Optimization – Trade Jc for RRR

Heat-Treat Optimization



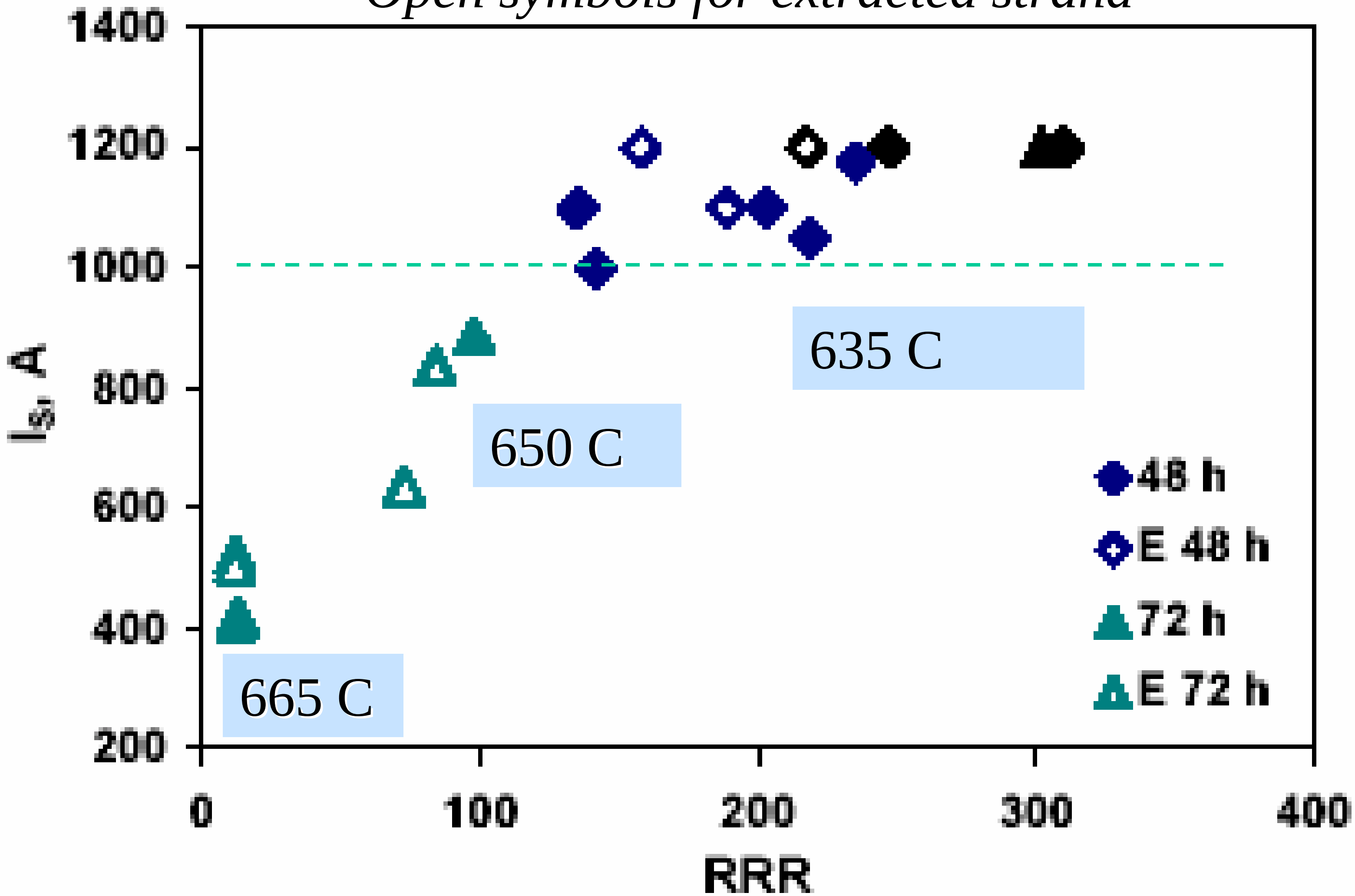
Example of HT Optimization

For 0.7mm MJR round and extracted strands from TQ cable

- By changing Reaction from 675C/72H to 635C/48H
  - Jc(12T) decreased 8%
  - Increased RRR from 10 to > 200
  - Increased Stability Threshold Current, Is
    - From 500 A to >1200 A

Is for MJR wire as a function of RRR

Open symbols for extracted strand



Conductor Procurement

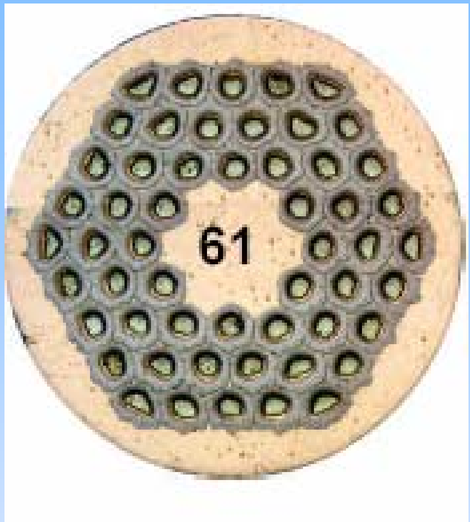
Conductor Procurement Strategy

Have a plan for conductor that ensures that there is sufficient material in the pipeline from OST for all the magnets to be fabricated in FY06 and FY07.

Take advantage of the Conductor Development Program to advance the higher risk strand from being an R&D conductor to a "production" strand.

"Baseline Strand"

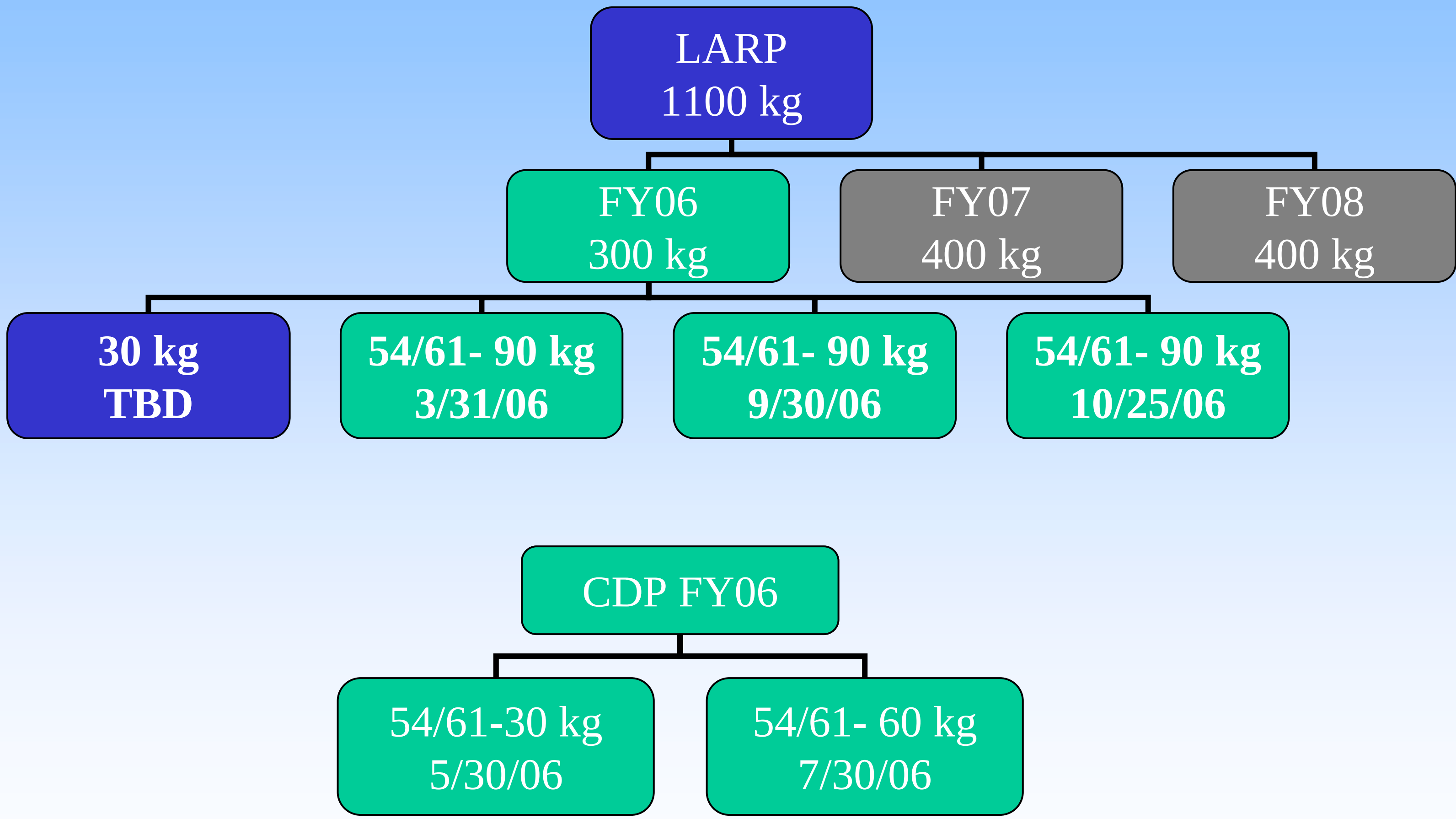
- **R**od **R**e-Stack **P**rocess, RRP 54/61 Design
  - 0.7mm diameter
  - Filament diameter ~ 70 μm
  - Jc > 2400A/mm^2 at 12T
  - Ic > 500 A at 12T
  - Copper Fraction 47%
  - RRR of stabilizer Cu > 100
  - stability current I_s ~ 1000 A
- Magnet Operating Current ~ 500 A



Target Program

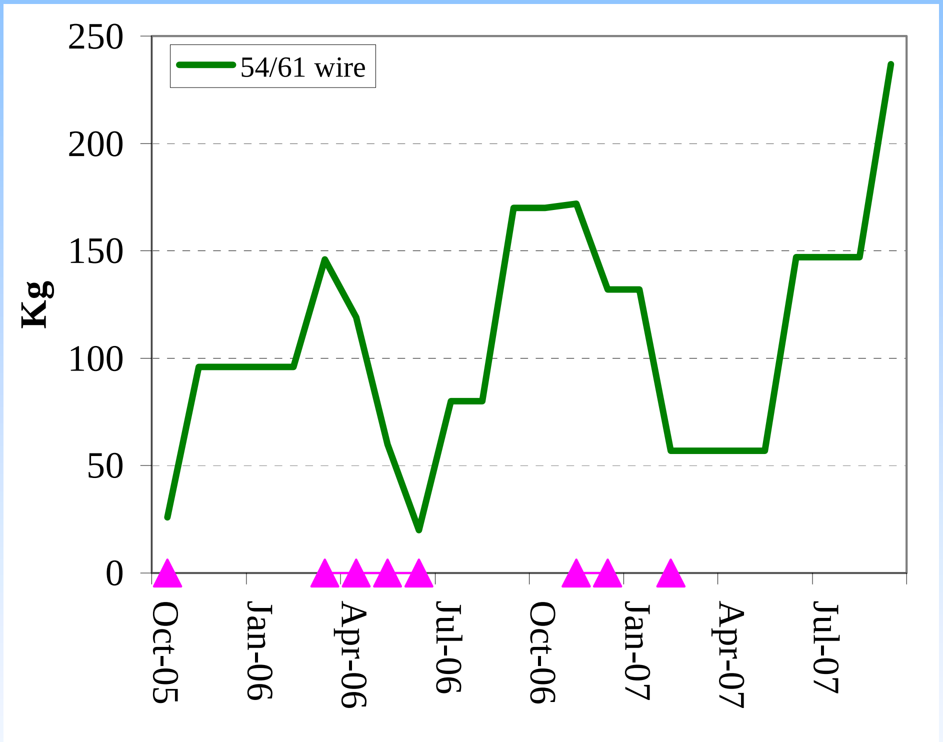
Model Magnets		Type	Length (m)	Gradient (T/m)	Aperture (mm)	FY05	FY06	FY07	FY08	FY09
Series	Description									
TQ	**Technology Quad**	Cos-2theta	1	> 200	90		$\mathbf{3}_N + 1_R$	$\mathbf{2}_N + 1_R$		
LQ	**Long Quad**	Cos-2theta	4	> 200	90				$\mathbf{1}_N$	$\mathbf{1}_N$
HQ	**High Gradient Quad**	Cos-2theta	1	> 250	90					$\mathbf{2}_N$
Supporting R&D		**Type**	**Length (m)**	**Peak Field (T)**	**Aperture (mm)**	**FY05**	**FY06**	**FY07**	**FY08**	**FY09**
Series	Description									
SQ	**Sub-scale**	block	0.3	10 – 11	110	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N + 1_R$	$\mathbf{1}_N$	
SR	**Short Racetrack**	block	0.3	10 – 12	N/A		$\mathbf{1}_N$	$\mathbf{1}_N$	$\mathbf{1}_N$	
LR	**Long Racetrack**	block	4	10 - 12	N/A			$\mathbf{2}_N$		
N = New Magnet										
R = Revised Magnet using existing coils										

Procurement Status
3-30-06



Projected Inventory

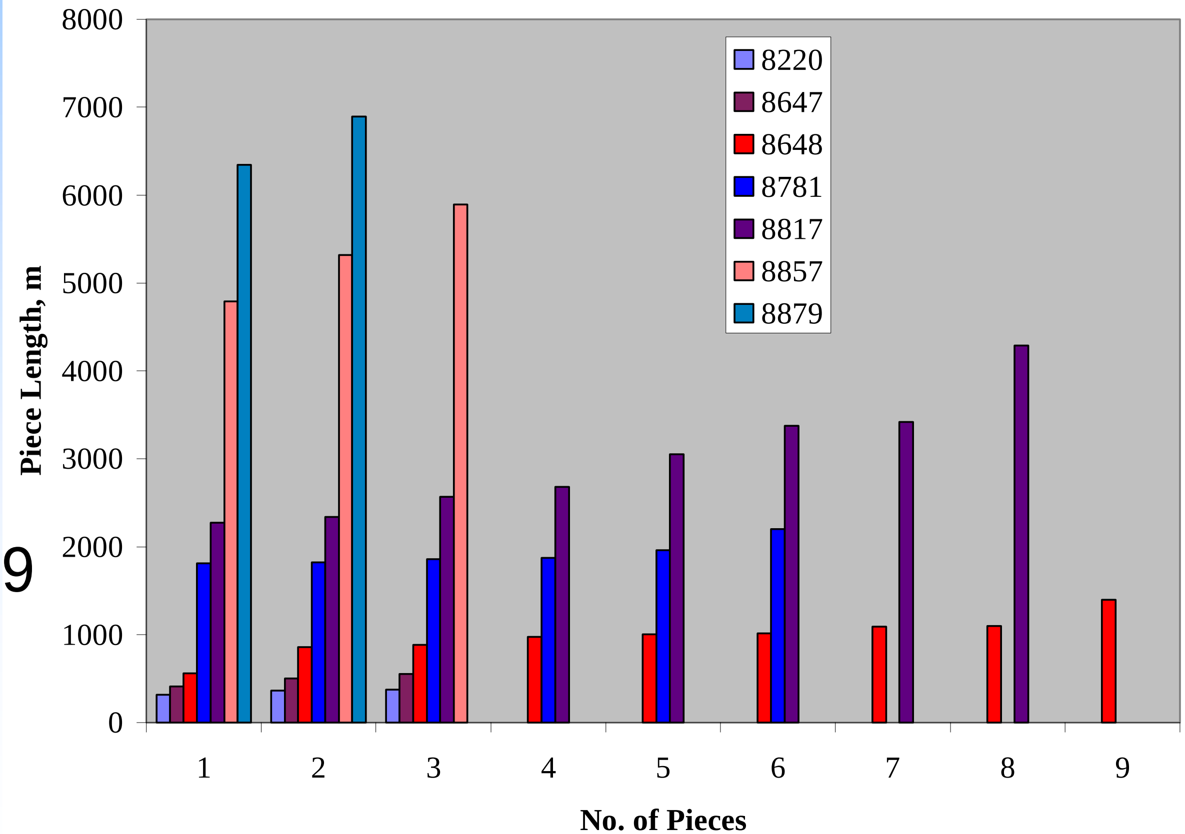
	CDP	LARP	Magnet	Strand Req.	Inventory of strand
Oct-05	33		SR01	7	26
Nov-05	70				96
Dec-05					96
Jan-06					96
Feb-06					96
Mar-06		90	TQC02	40	146
Apr-06			LR01	27	119
May-06	30		LR01, TQC02-R	89	60
Jun-06			TQS02	40	20
Jul-06	60				80
Aug-06					80
Sep-06		90			170
Oct-06					170
Nov-06		90	SRS02, LR02	88	172
Dec-06			PCX01	40	132
Jan-07					132
Feb-07		90	LQX01	165	57
Mar-07					57
Apr-07					57
May-07					57
Jun-07		90			147
Jul-07					147
Aug-07					147
Sep-07		90			237



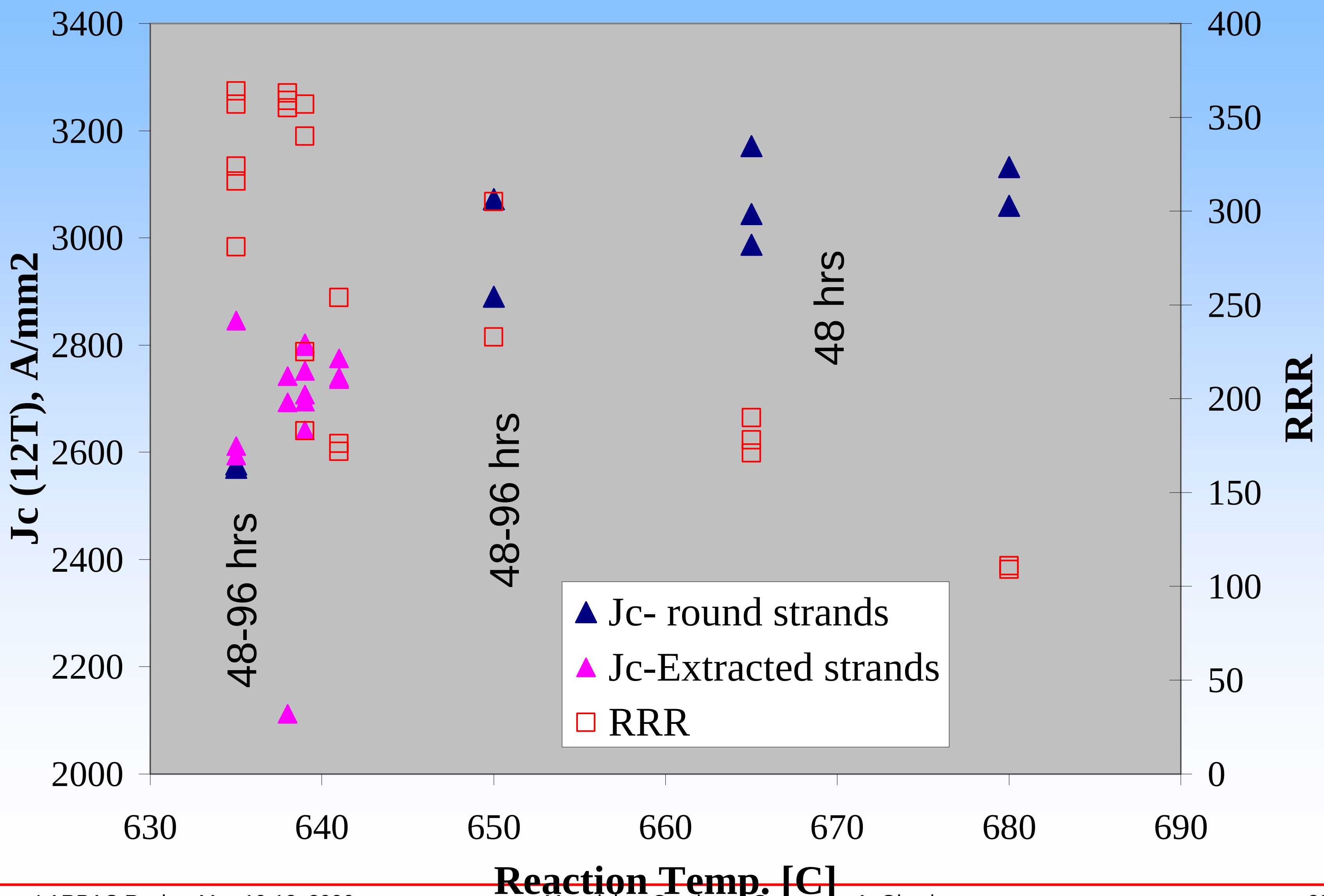
RRP 54/61 –Piece Length

- 250 kg of wire produced for LARP and CDP in the last 12 months, single billet yield is ~ 35kg
- 93 % in lengths >1Km, 57% in lengths >3 km

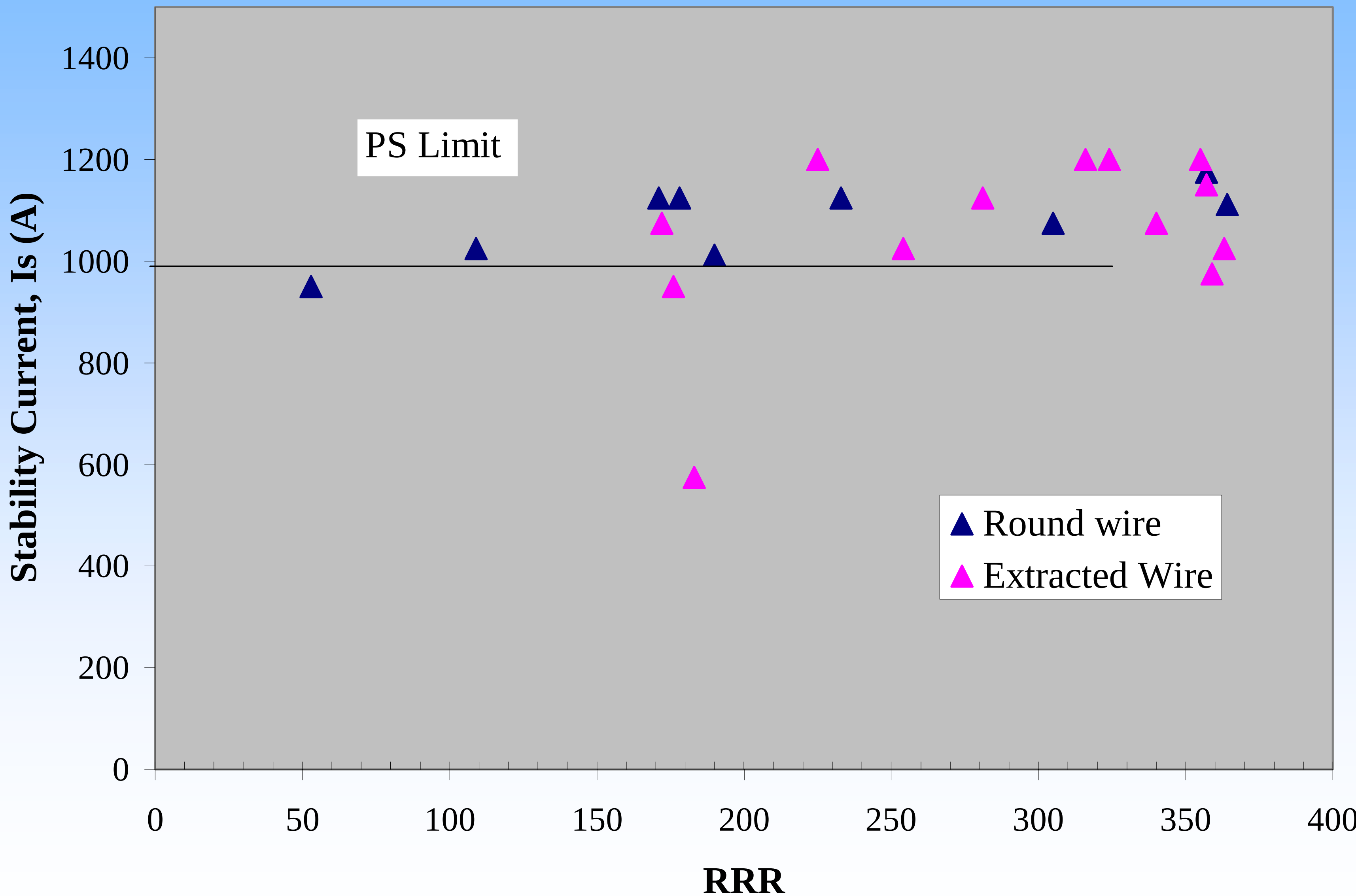
- With the following HT 665C/50 hrs
- Average J_c(12T)=2880 A/mm^2
- Average RRR= 189



Jc and RRR – Billet 8220 Strand



Stability Current of Billet 8220 strand

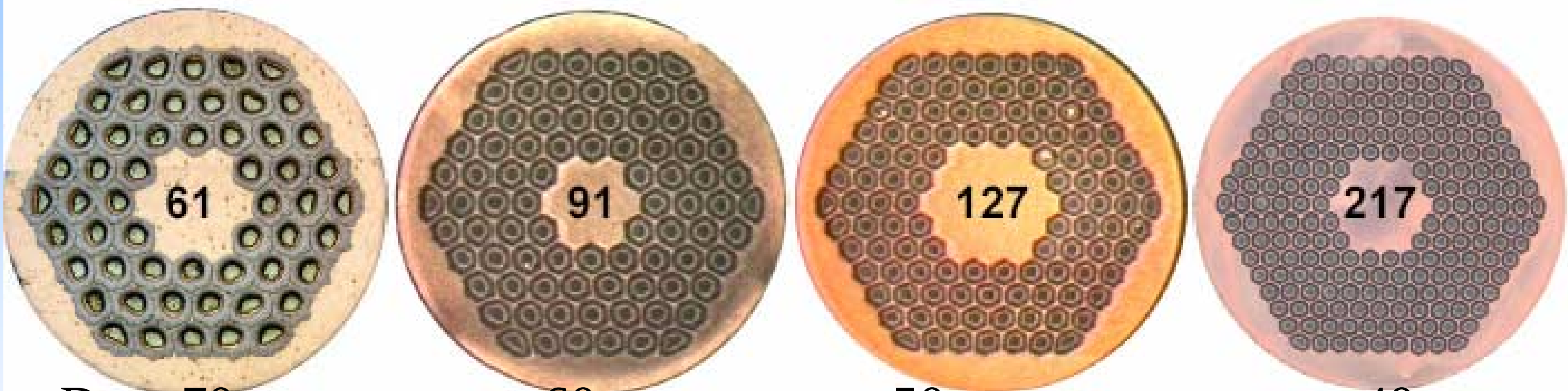


Future LARP Strand

- Conductor Development Program (CDP) has been the main driver in high-Jc strand R&D at OST
  - It continues to fund this development in FY06
  - Main Goal ▸ reduce D_{eff},
  - Other objectives
    - billet “scale-up”, cost reduction
    - $(NbTi)_3Sn$ Ternary

CDP- Reducing Filament Diameter FY05

- For the RRP strand
  - Effective Filament Diameter D_{eff}~ Sub-element Diameter
    - – D_{eff} scales inversely with increasing number of Sub-elements
    - – Strand Stability increases with decreasing D_{eff}



D_{eff} ~70µm 60 µm 50 µm 40 µm

  - Increasing number of filament
    - – Increases difficulty of wire processing
    - – Packing difficulty, increased cold work of non-Sn components
    - – Bonding issues ➢wire yield

91-127-217 series made with Nb-Ta for CDP R&D

High Jc design (3000 A/mm^2):

Objective was to only vary the sub-element size

- same sub element billet for all restacks
- all restacks ~53% non-Cu, 0.7 mm strand

Significant wire breakage for all, 217-stack the worst

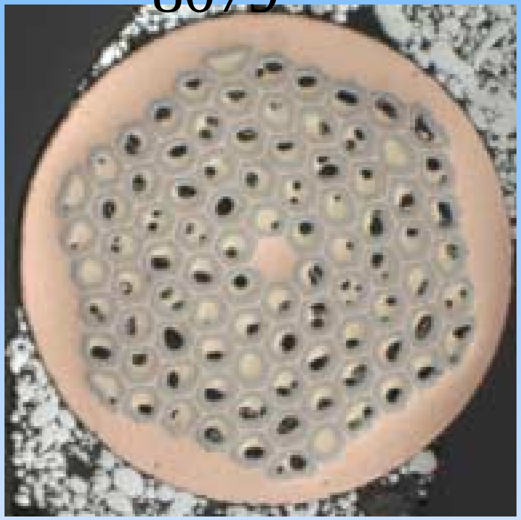
For a reaction at 665 C/50hrs

	(Jc,	RRR)
91-stack	2920,	134
127-stack	2720,	110
217-stack	2660,	7 (Many broken barriers)

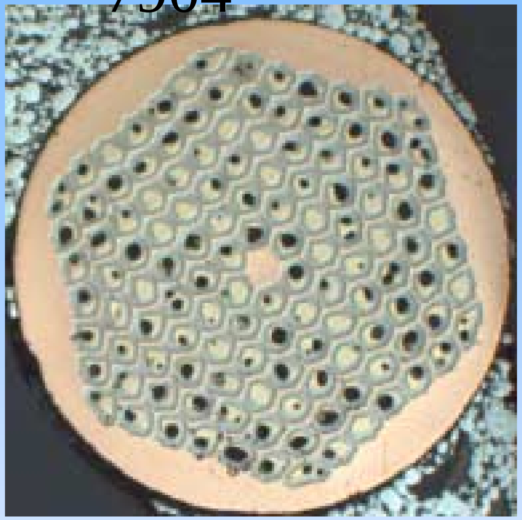
Suggests there is some size effect controlling the maximum Jc

Future RRP Strand

8079



7904



At present the lower Jc (> 2000 A/mm^2) 91-design billet is moving into production ➢ EFDA Dipole order of 400 kg

Under CDP R&D this year, a high Jc 127-design billet is being processed (Nov-06)

Under FNAL core program a R&D billet using 120/127 design with increased sub-element spacing is being fabricated (Dec-06)

Strand R&D

Strand R&D
Main Objectives

In the near term:

- Predict the performance of TQ magnets
- Evaluate the effect of cabling
  - measuring strands extracted from the cables
  - Rolled strands
- Heat treatment optimization
  - Ic , RRR and Js

- Long-term :

  Activities closely tied to strand development and cabling R&D
  - Strand stability
  - Effect of cabling on Ic degradation

Strand Test –Facility Resources

FOR STRAND Ic TESTS

(MAX FIELD 4.2K/1.9K ,POWER SUPPLY MAX CURRENT)

FNAL: 15/17 T, 1800 A; 14/16 T (large bore), 1000 A

LBNL: 15 T, 2000 A

BNL: 11.5/12 T, 1500 A

At present most of the strand testing is being done at BNL and FNAL. LBNL test station is being upgraded.

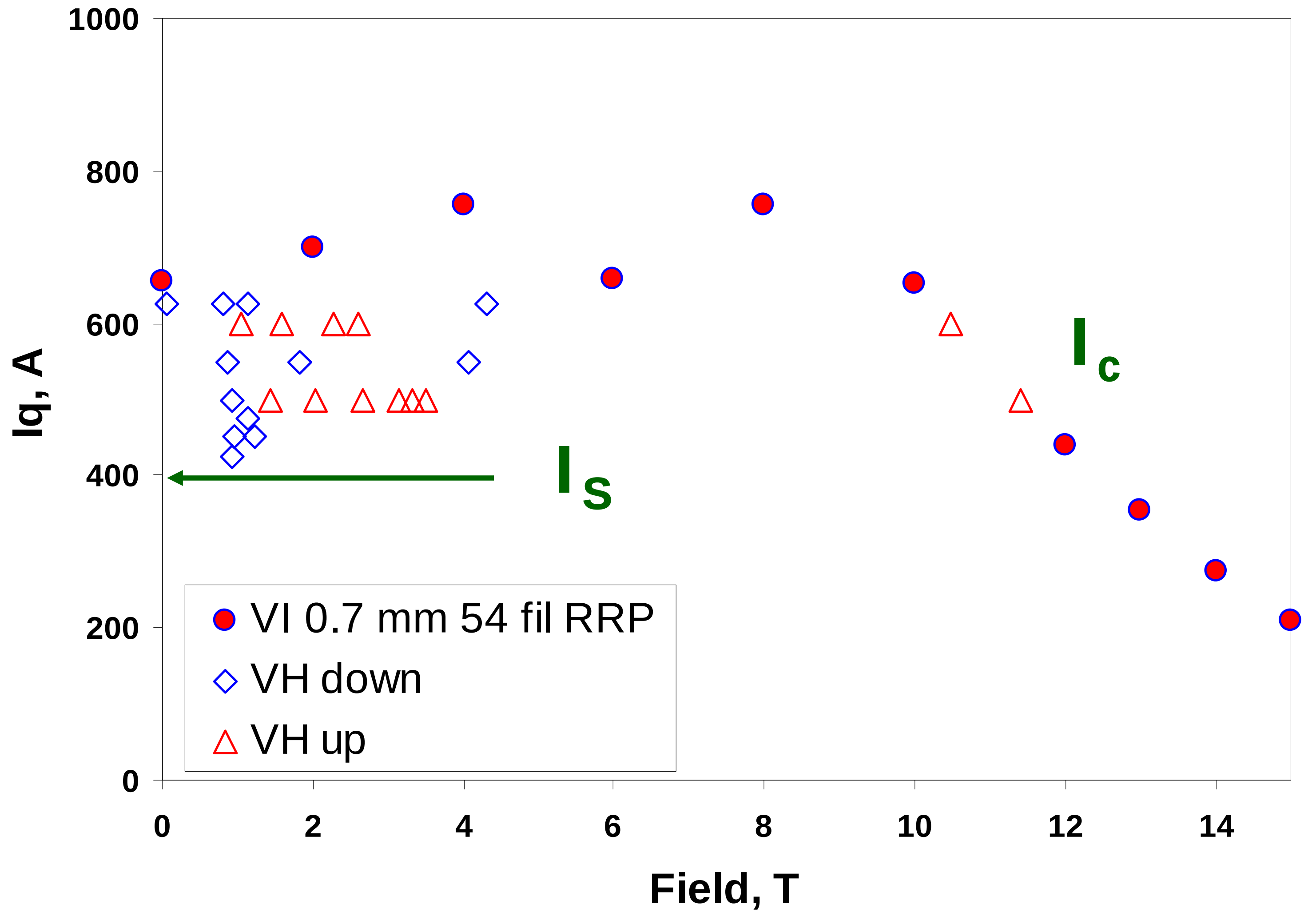
Round Robin BNL-FNAL

2 samples measured at FNAL and two at BNL. All samples reacted at BNL.

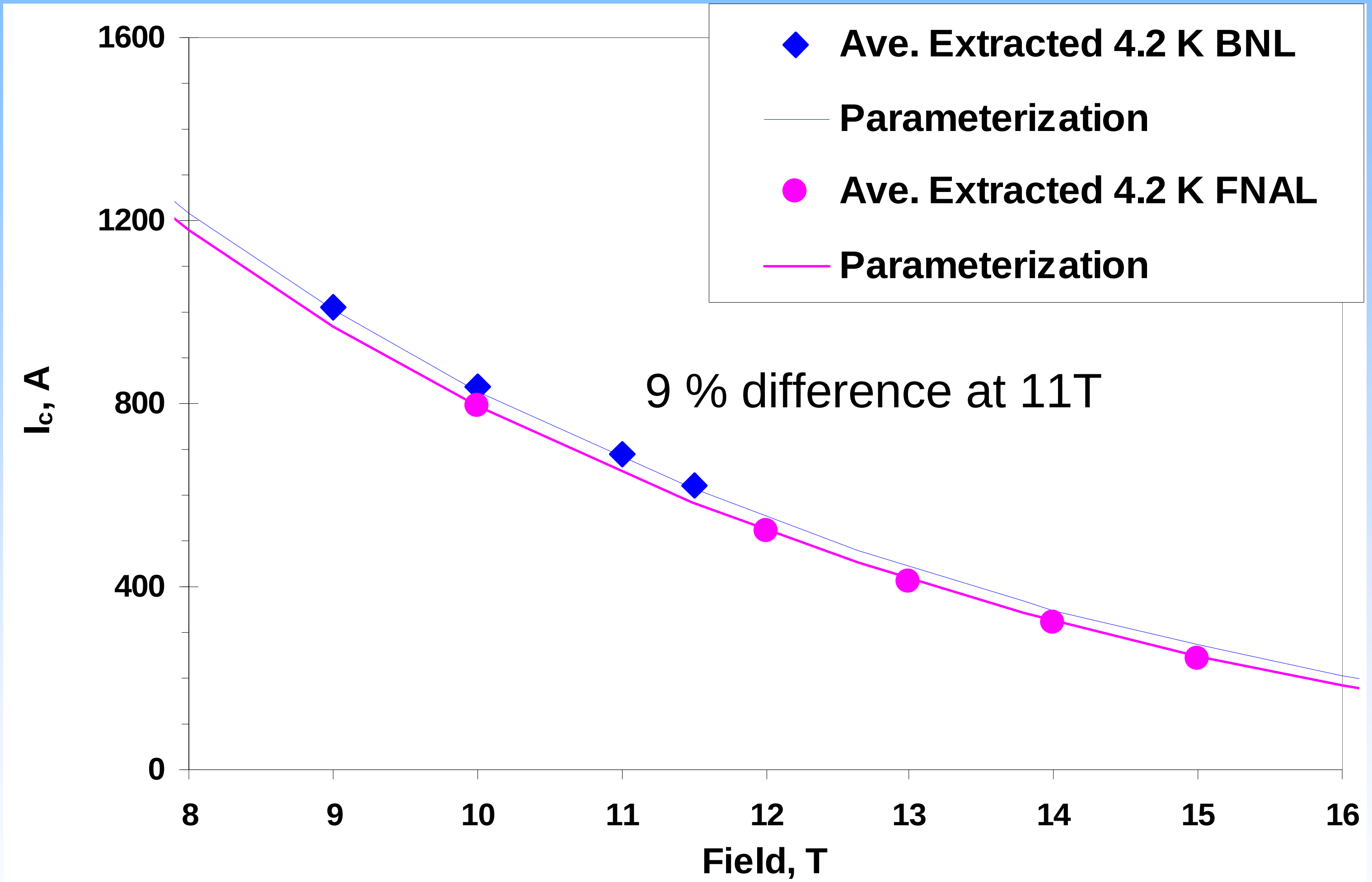
Strand ID I_c, A at	14 T	13 T	12 T [a]	10 T	8 T	Is, A	RRR
FNAL	245±2	317±2	402±1	612±2		980±170	211±11
FNAL w/sty	252±3	320±2	406	616	911	975±110	
BNL			[415]±7	621±8	905±9	1100±140	189±66
BNL w/sty			[421]±1	629±3	909	1100	

I_c at 12 T is within 3%, at 8T it is < 1%

Billet Characterization- Ic , Is and RRR measurements



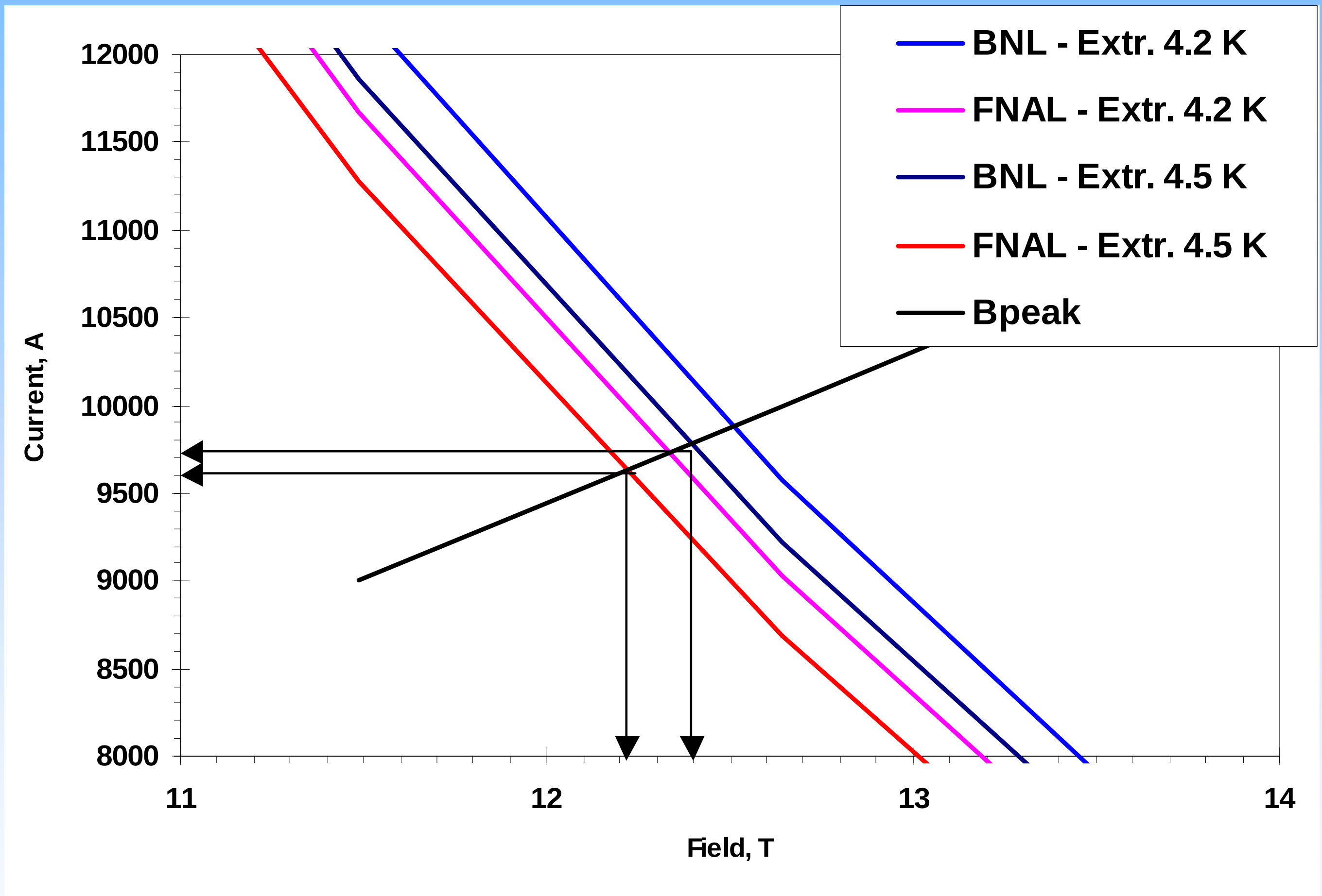
Prediction of Short Sample Limits



SRS01

High Field Short Sample Limits

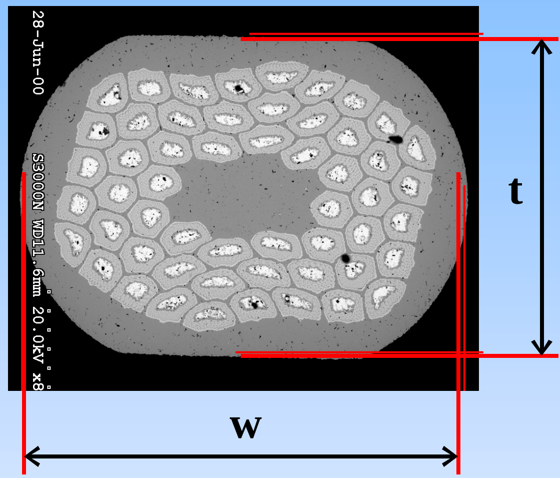
SRS01



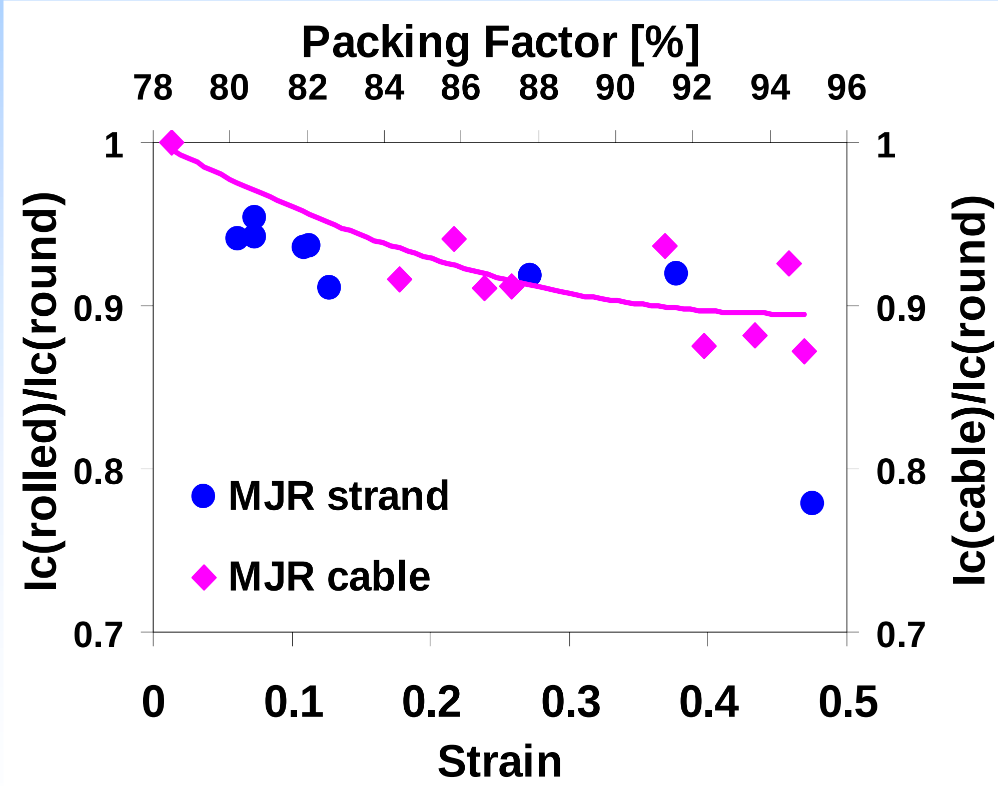
BNL: Imax = 9780 A (490 A/strand) Bpeak = 12.4 T

FNAL: Imax = 9630 A (480 A/strand) Bpeak = 12.2 T

Rolled Strand Measurements at FNAL



Rolled down strand
Strain=(d-t)/d

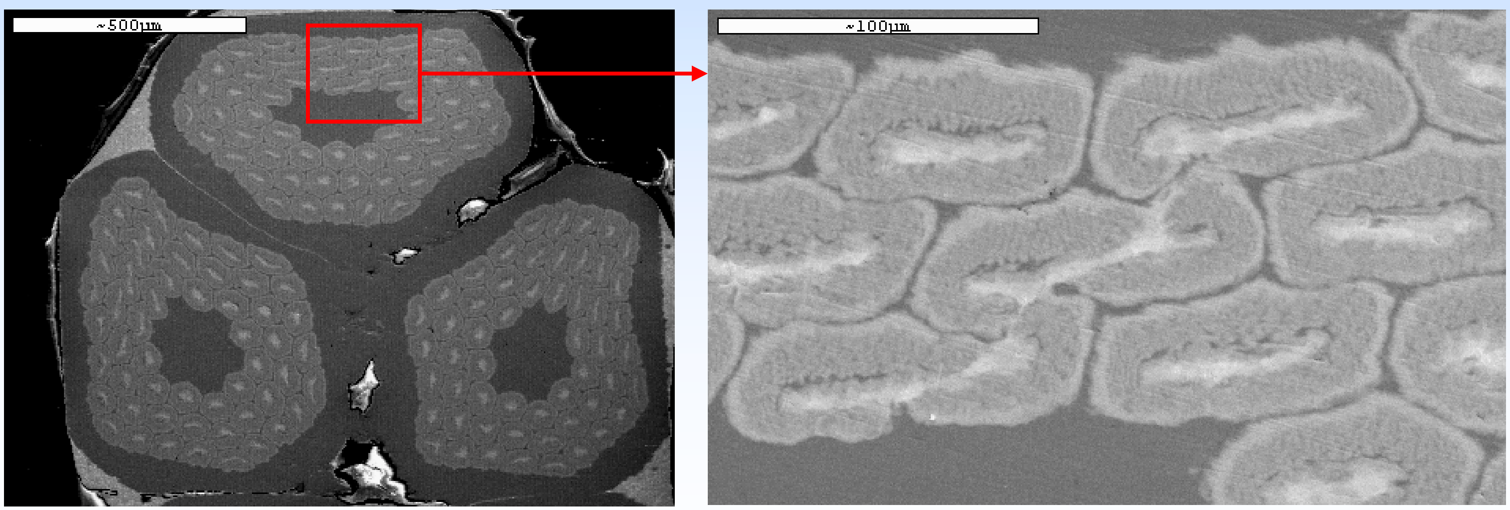


One can find a range of strain where there is a good correlation of I_c degradation between extracted and rolled strands

Cable R&D

Cable R&D

- Primary task is Cable Manufacture for LARP magnets
  - –Optimize cabling parameters to minimize distortion of strand internal structure
    - ➢ reduce critical current degradation at the edges



Cabling Machines

- 64-strand cabling machine at LBNL
  - Versatile machine for cable development.
  - Sufficient to meet the conductor needs of the LARP magnets
- 42-strand cabling machine at FNAL
  - Being used for making LARP prototype and other cables for FNAL core program

Cabling Procedure

Present Nb_3Sn cabling procedure at LBNL

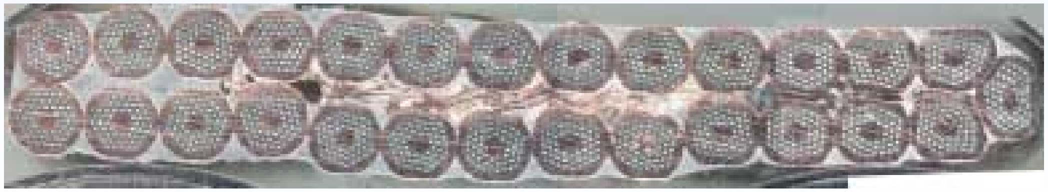
- Fabricate cable
  - Slightly over size
  - Anneal at 200C/2-4 hrs
    - Softens Cu and cable contracts by ~0.25% in length
    - May harden Sn core
- Re-roll to decrease thickness by 25-50 μm.
  - Compacts cable making it mechanically stable

TQ Cable

- As a first task determined final parameters of the cable (using MJR strand) for the first series of TQ quad magnets
- 16 UL's of cable fabricated in FY05 for TQC01, TQS01 and practice coils

Parameters	Units	TQ	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

9.977 min



Cabling Activity in FY06

All Nb_3Sn strands are RRP-54/61

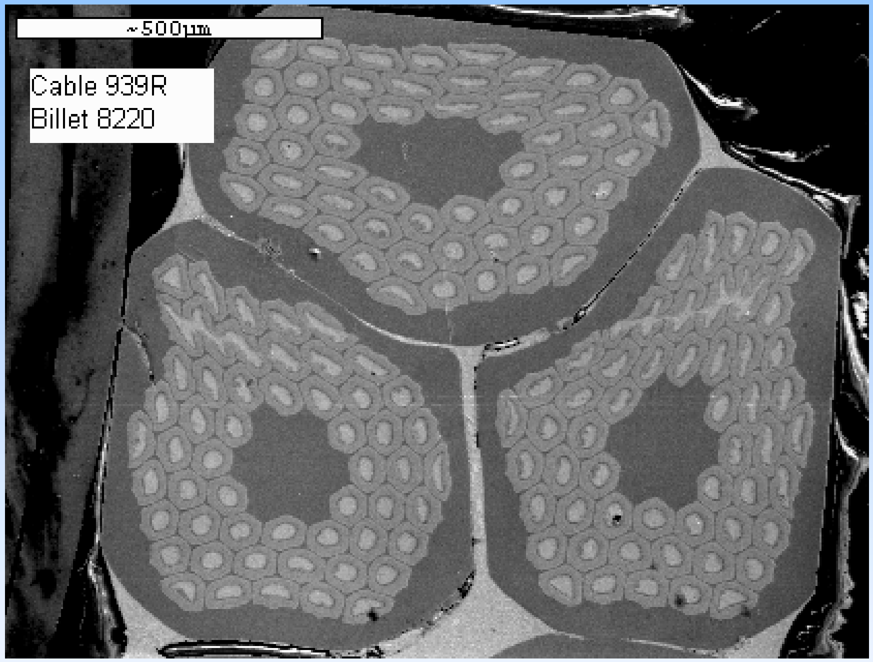
Cable TYPE	CABLE ID	STRAND	MAGNET	Cable Designation	Date / Manufacture
L7O	B0933	RRP	TQ	Prototype	10/5/2005
S3O	B0935	RRP	SRS01	Production	10/28/2005
L7O	B0936	RRP	TQ	Prototype	11/10/2005
L7O	B0939	RRP	TQC02	Production	3/9/2006
L7O	B0940	RRP	TQ	Production	3/20/2006
S3O	B0941	Cu	LR01	Practice	4/3/2006
S3O	B0942	RRP	LR01	Production	4/26/2006

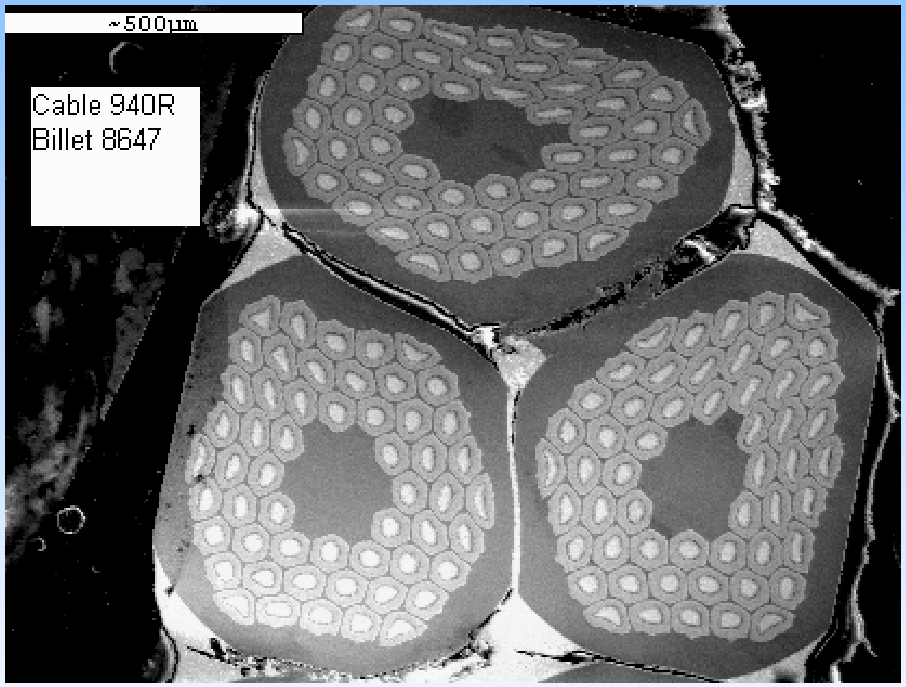
L70 -27 strand ,10mm wide, 1 deg keystone, 70mm pitch

S30 – 20 strand, 8mm wide, rectangular, 30mm pitch

Cabling Degradation
Minor Edge of 939R & 940R

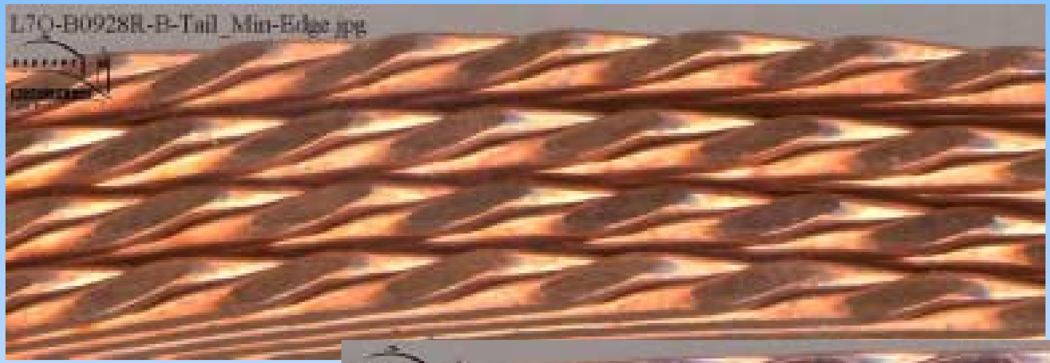
Two cables are in specification of thickness, width, and keystone angle



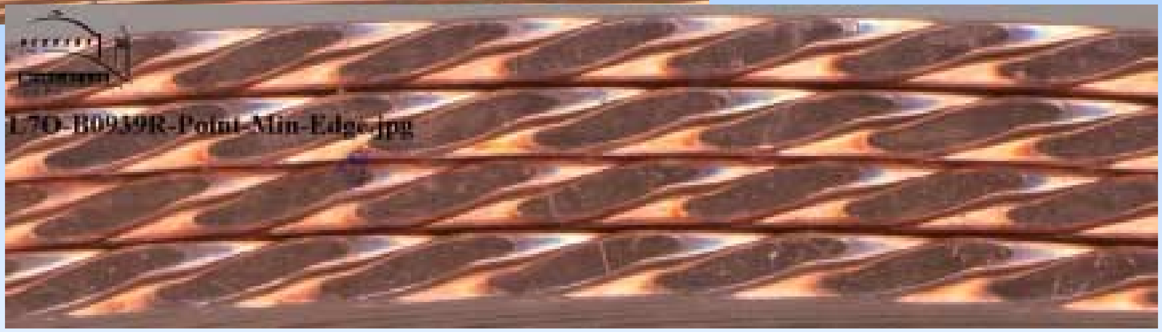


- Cable 939 over-compacted during the re-roll operation leading to significant barrier damage.
  - Cabling procedures being refined to avoid this problem.

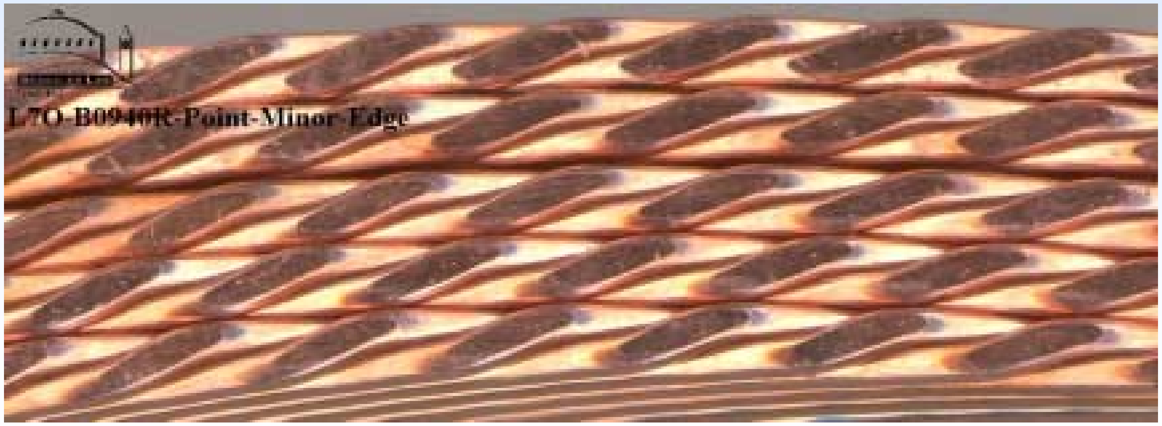
Minor Edge of 3 TQ Cables



928R



939R

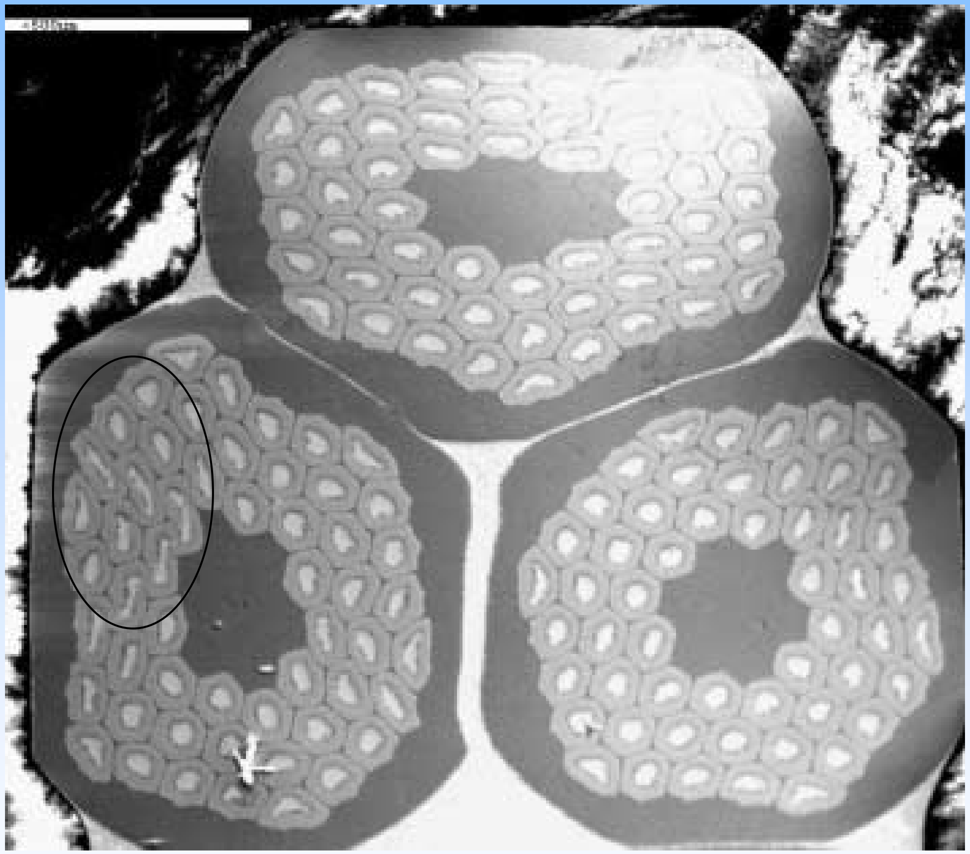


940R

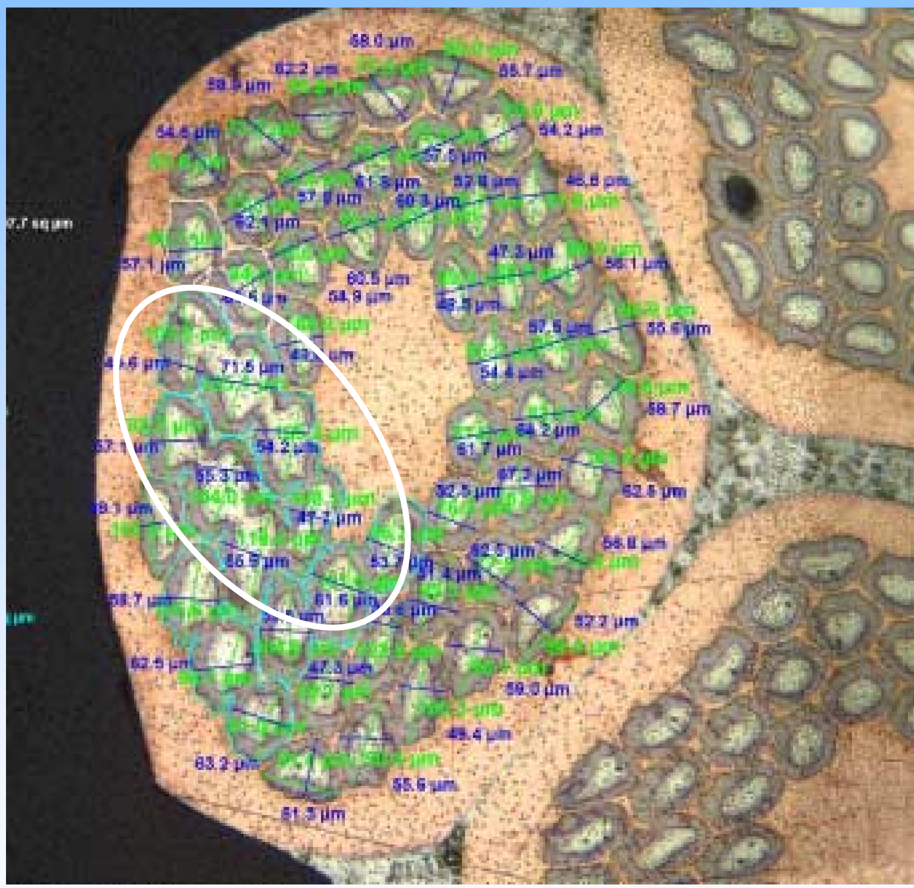
Large edge facets on cable 939R

Cabling Degradation

- Strand Deformation at the cable edges
  - Filament Distortion
- Simulate by rolling strands
  - E. Barzi (FNAL)
  - Filament Merging
  - Microscopy, Ic and Is measurements



Filament Merging study at FNAL



Merging cannot be seen through magnetization of an extracted strand because it is a local effect

Higher local magnetization can lower strand stability at the minor edge.

RRP Cable cross section

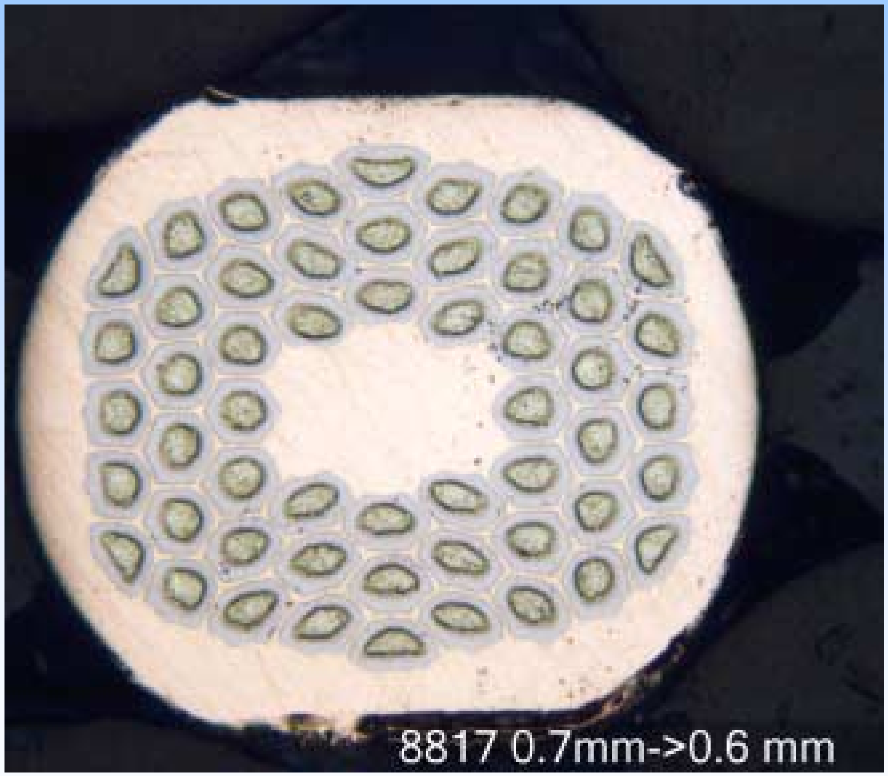
Rolled Strands

RRP 54/61

Def=14%

For the TQ cable Def ~ 18%

Def=28%



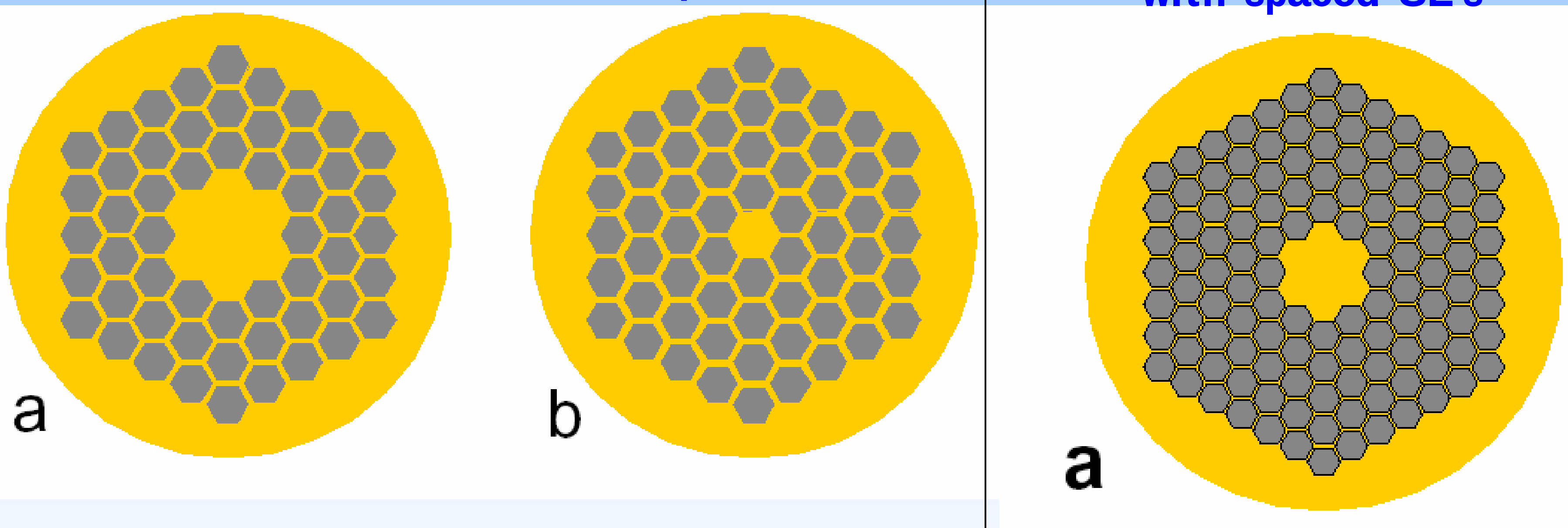
New R&D Design by OST
FNAL Core program

Previous design | **New design ('05)** | **Newer design ('06)**

54/61 restack

60/61 restack with spaced SE's

120/127 restack with spaced SE's

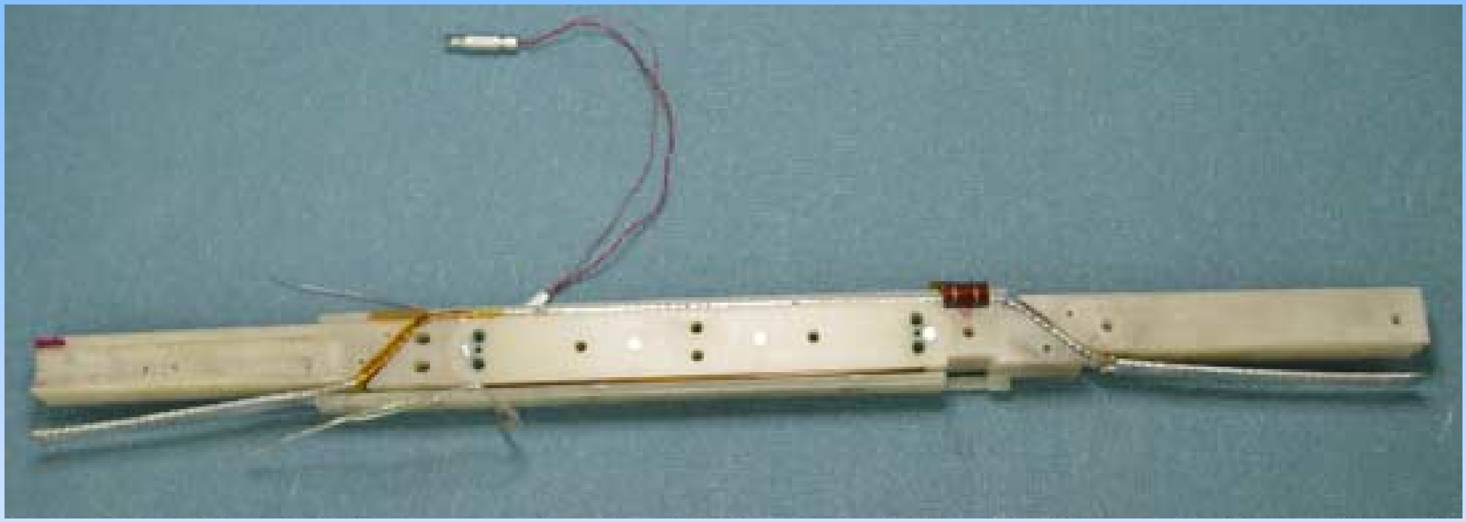


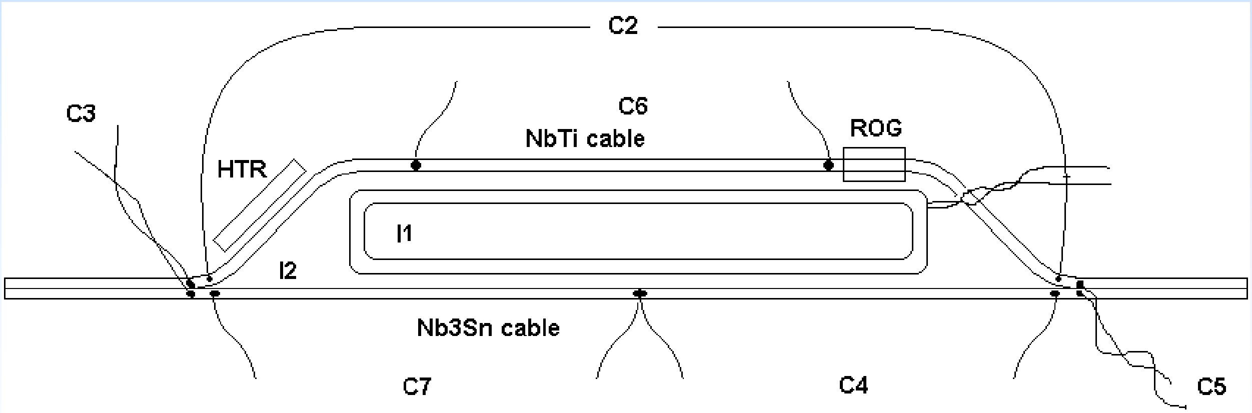
The new design has increased Cu thickness between sub-elements to reduce cabling impact on sub-element merging.

Cable Testing

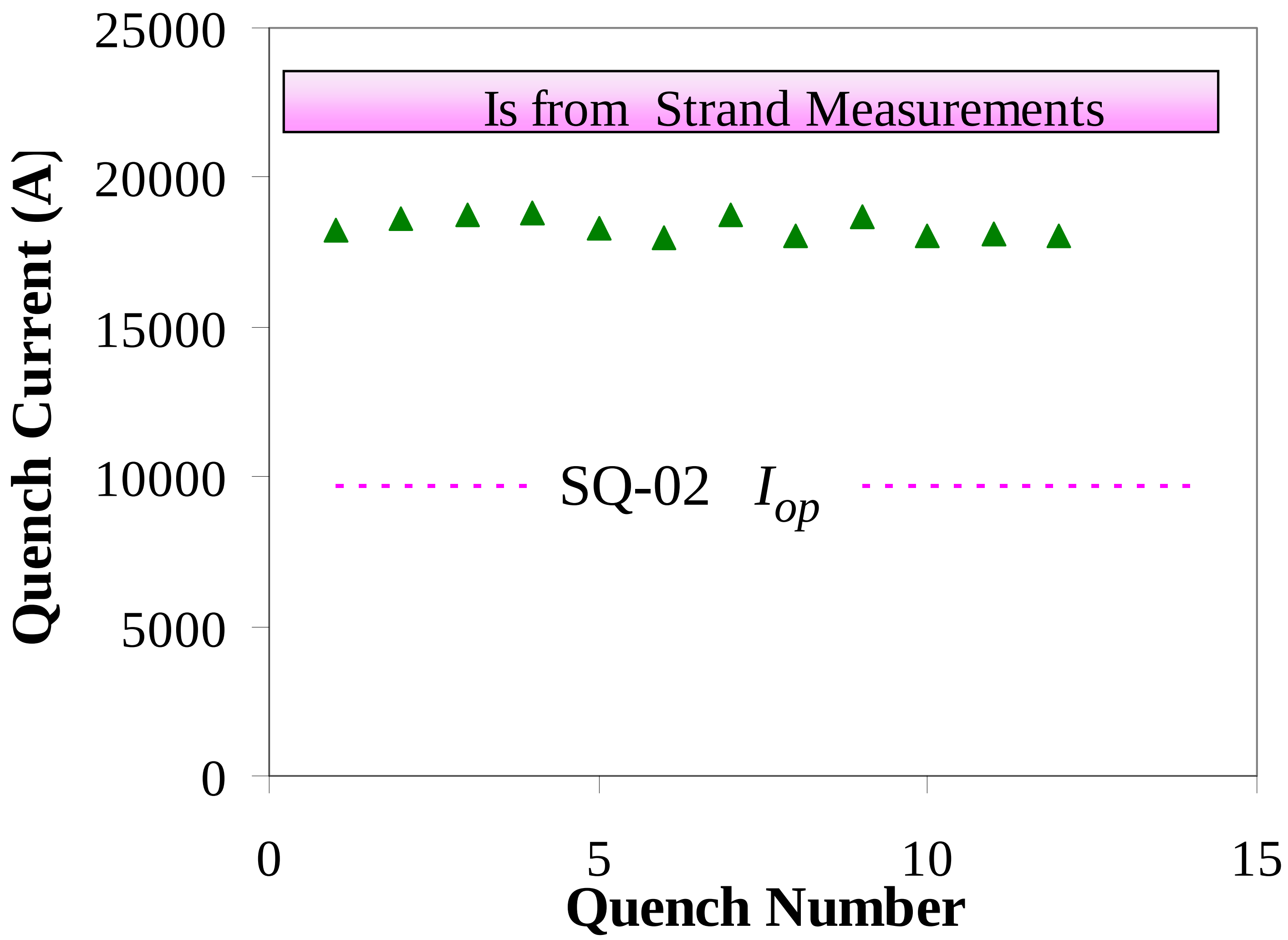
- FNAL
  - –28 kA SC transformer with fast (200kHz, 8-channel DAQ) for tests at self-field (1.8T)
    - Used to determine low field stability current
- No facility at the three labs to test cable samples at high fields 10-12 T.
  - –Options being explored
    - Test at FRESCA facility at CERN, background field 10T, at 4.2 and 1.9K. Cable samples pre-stressed at room temperature.
    - Test at NHMFL in split-pair magnet, 11T, transverse stress applied at 4.2K
- At present cable is qualified based on transformer test and on extracted strand tests.

SC Transformer Test





Transformer Test SQ-02 Witness Cable



Summary

- Strand procurement of RRP 54/61 is proceeding on schedule.
- There is sufficient conductor on hand for fabricating cable for the magnets. This strand is quite uniform.
- Round and extracted strand testing is well established to qualify strand and cable
- Test data on round strands from the three labs are quite consistent
  - That for extracted strands is being evaluated.
- Heat treatment optimization studies used to improve strand stability at the expense of Jc
- Minimize Cabling Degradation at minor edge for keystone cables
  - Optimization of cabling parameters and procedures
  - Optimization of strand design
    - Increase filament spacing ? (FNAL has already ordered a 60/61 billet with larger Cu-spacing, evaluation in progress)
  - Rolled strand studies have been initiated for the new generation RRP conductor to study effect of roll deformation on Ic, Is.

End of Presentation