Development of High Current Nb_3Sn Rutherford Cables for NED and LARP

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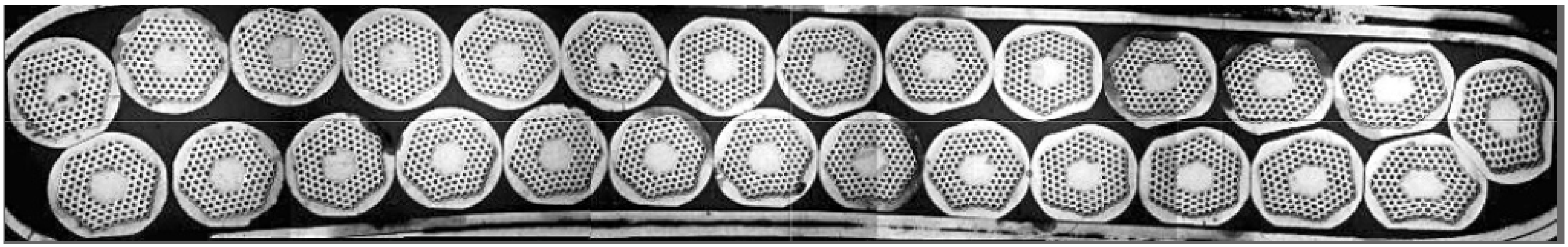
Outline

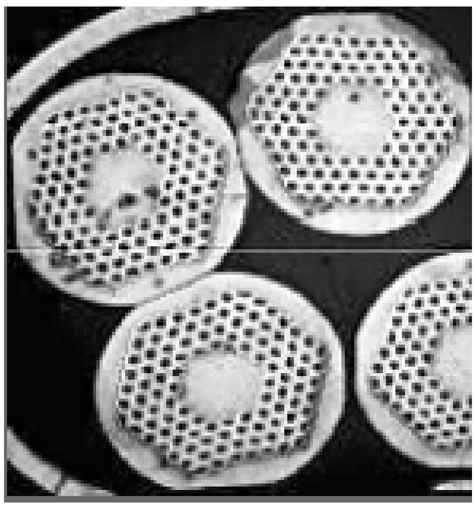
- Rutherford cables
- Cabling objective:
  - Damage free strand
  - Mechanically stable for winding a magnet
- Review cabling history for LBNL
  - Dipole D-20 (13.5/14.5T)
  - Recent rectangular cable fabrication for LBNL magnets
    - RD-3 series (14.7 T)
    - HD-1 series (16 T)
- Cables for LARP Technology Quadrupoles (TQ)
- Proto-type cables for Next European Dipole (NED)

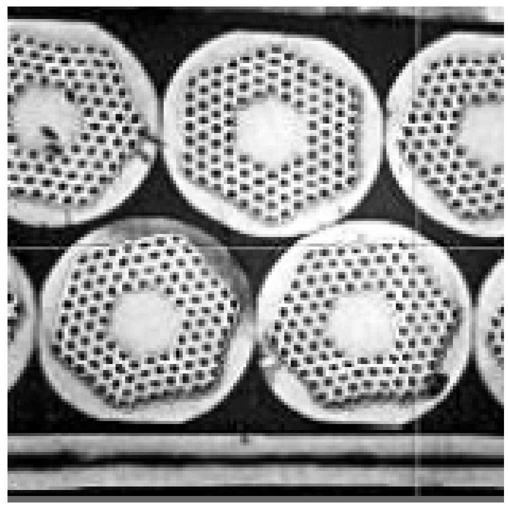
60 Strand Machine for Fabricating Rutherford Cables

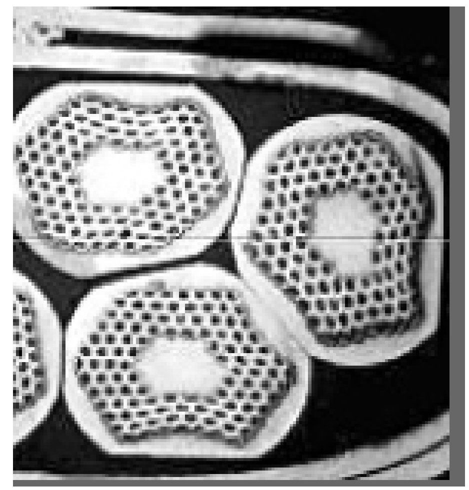
Typical Rutherford Cable

Cable 961





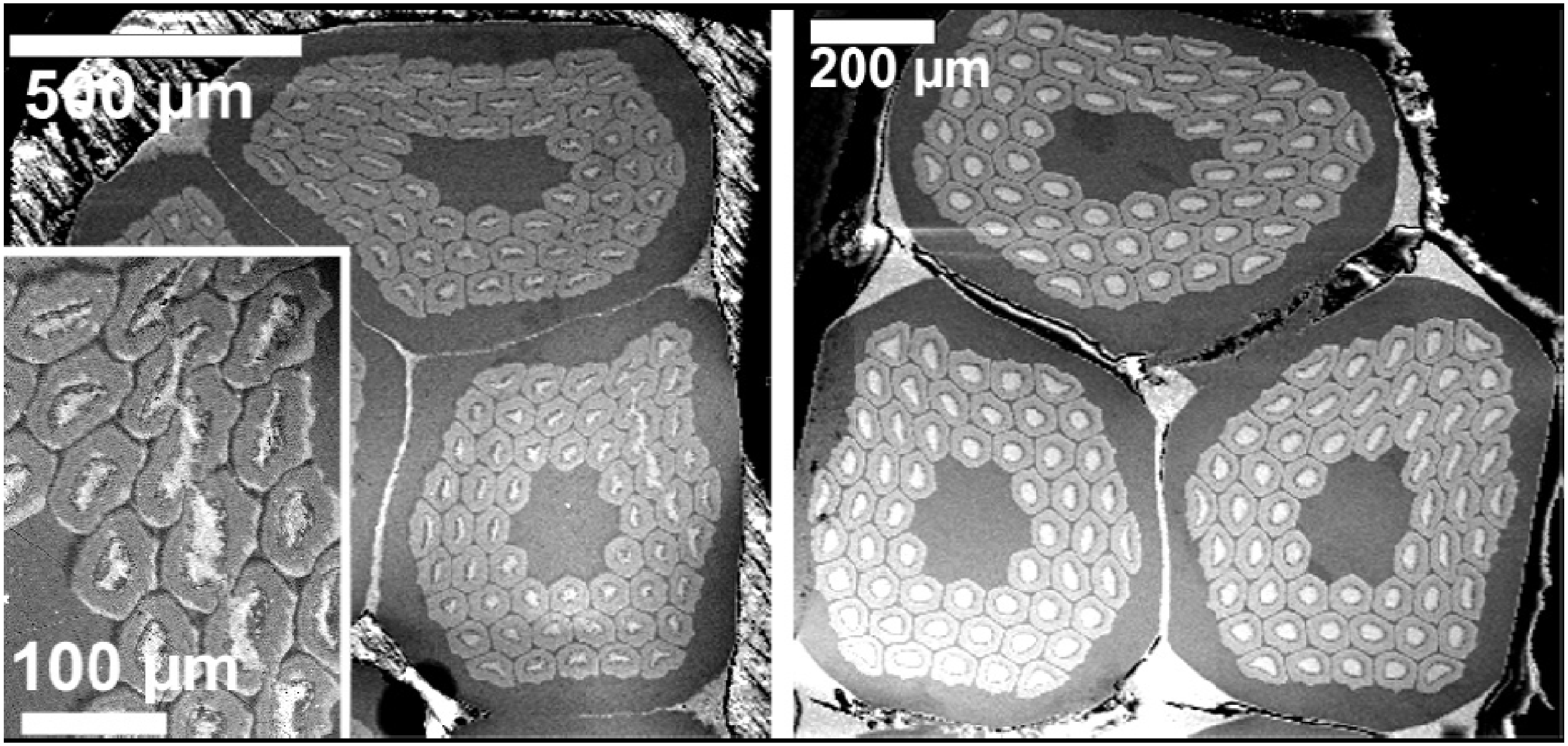




Edge deformations are important

Good and bad cable edge deformation

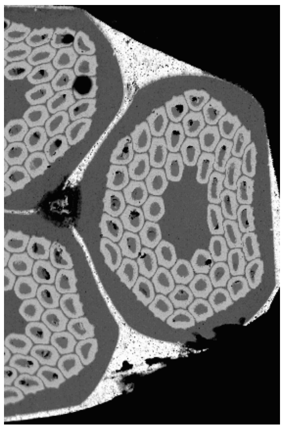
- Bad
- Good



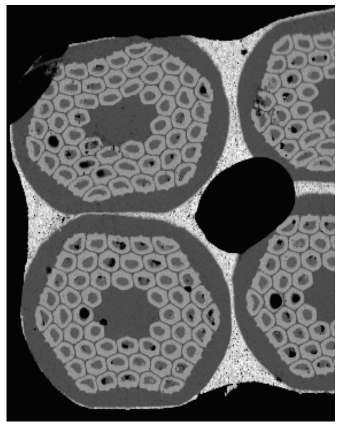
Main difference is different width of the cable

Managing edge deformation

Decoupling of Thickness & Width
as opposed to Packing Factor



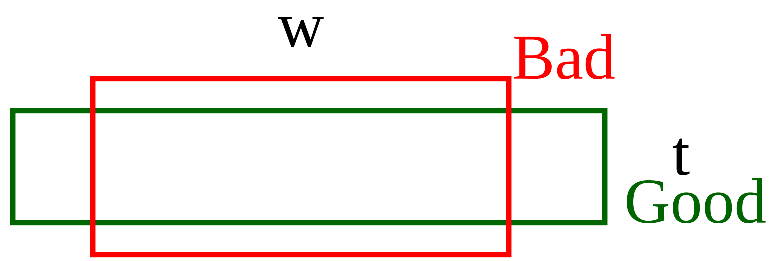
Design for this strand configuration at edge of cable



NOT this strand Configuration

0.8 mm strand diameter
40 Strand cable
Cable Area = 24.40 mm^2
87% Packing Factor

Problem with Packing Factor
Two Cables have equal area but are NOT the same



2 Cables: Same compaction or Packing Factor

17.4 mm x 1.400 mm = 24.4 mm^2

17.0 mm x 1.435 mm = 24.4 mm^2

0.4 is mm half a strand diameter
This difference can be fatal

Deformation Parameters t and w

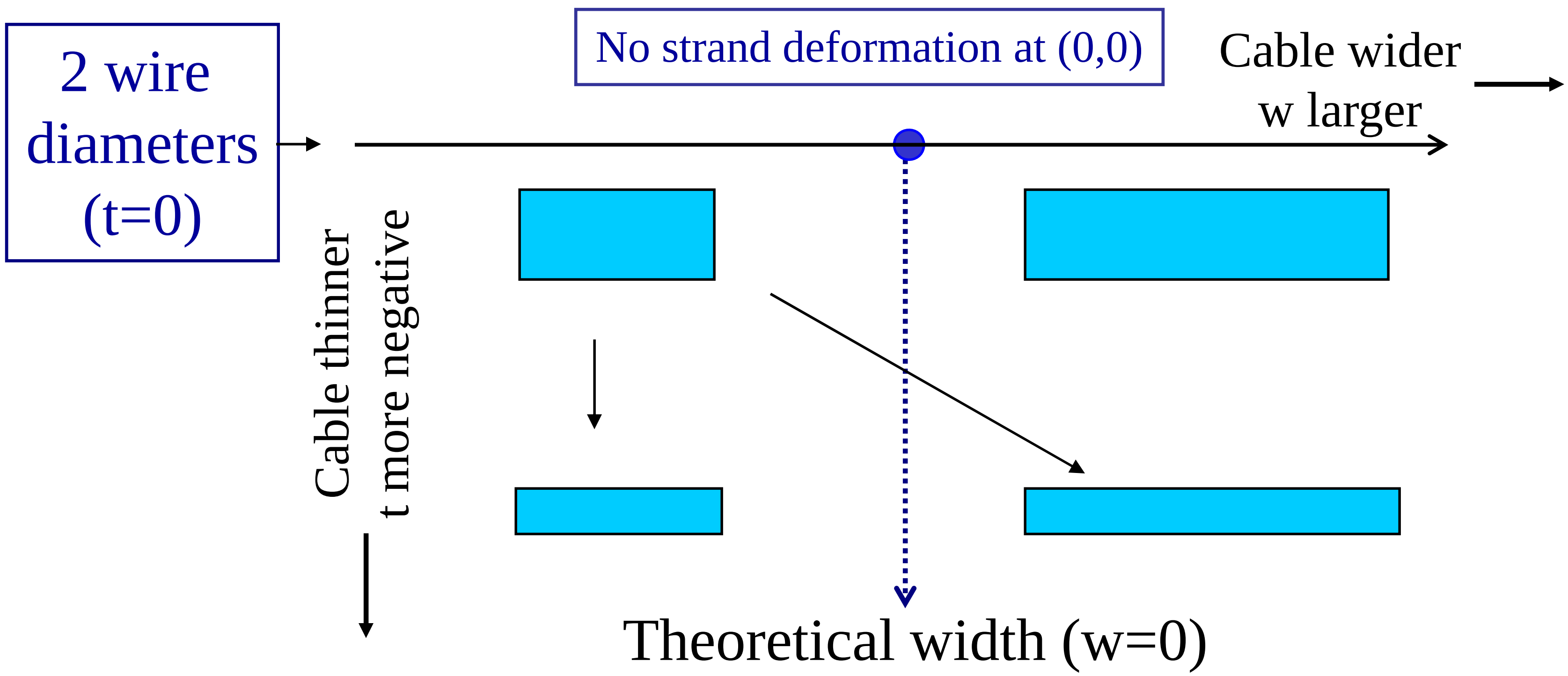
- Thickness deformation t (~strain)
  t = (cable thickness/2x strand diameter) -1
- Width deformation w (~strain)
  w = (cable width – theoretical width)/(th. width)

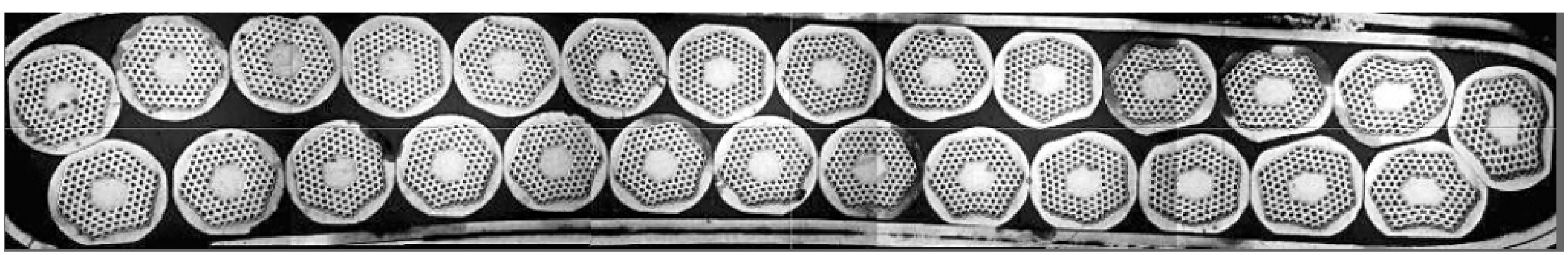
Theoretical width = $\dfrac{Nd}{2\cos(PA)} + 0.72d$

PA = Cable pitch angle

(factor 0.72 d not included in plots in this presentation)

Rutherford Cable Parameter Space

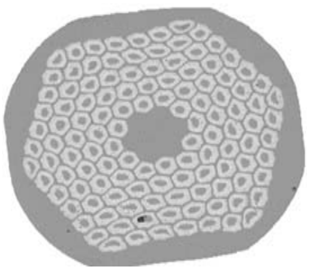




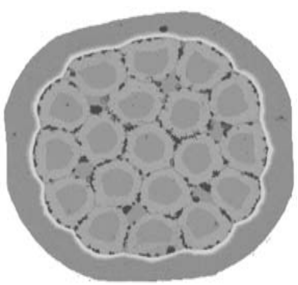
Parameter space cables for D-20, RD-3, and HD-1

D-20 is Cosine Theta Dipole (14.7T), RD-3 is Racetrack Dipole, and HD-1 is High Field Dipole (16T)

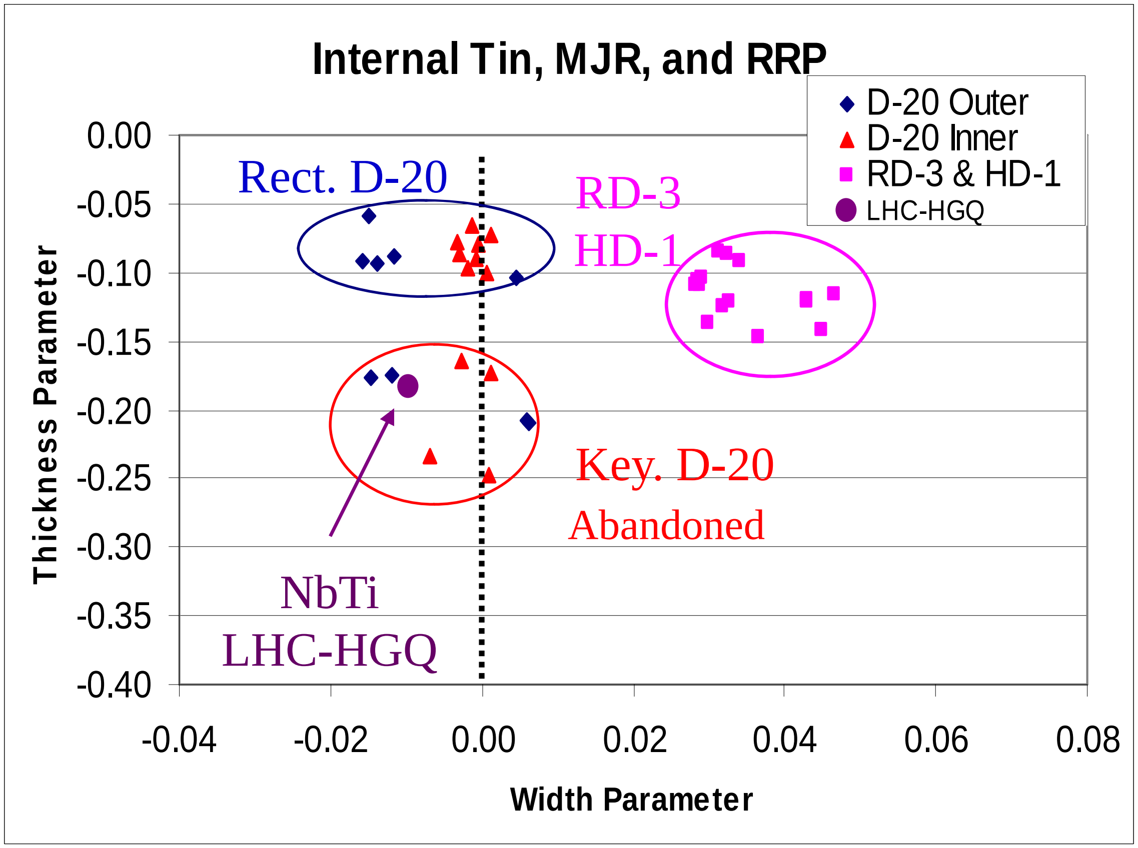
D-20



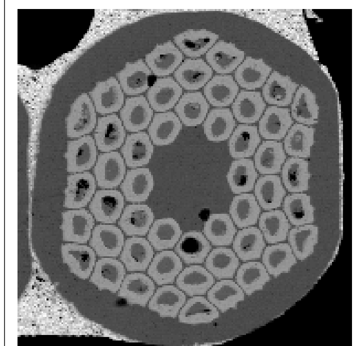
LBL Cable # 523
MJR-TWCA



LBL Cable # 522
IGC-Int. Tin



RD-3



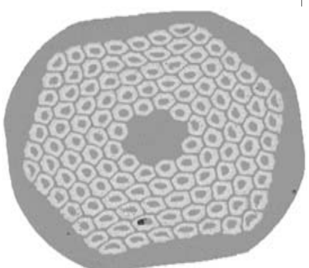
LBL Cable # 805R
Oxford-ORe

Keystoned D20 cables had ~20% loss in Ic and were more sensitive to transverse stress

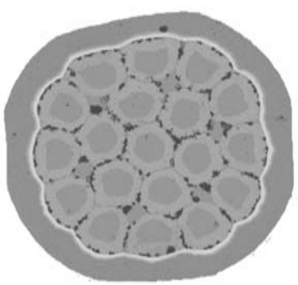
Zones of interest from cables for D-20, RD-3, and HD-1

D-20 is Cosine Theta Dipole (14.7T), RD-3 is Racetrack Dipole, and HD-1 is High Field Dipole (16T)

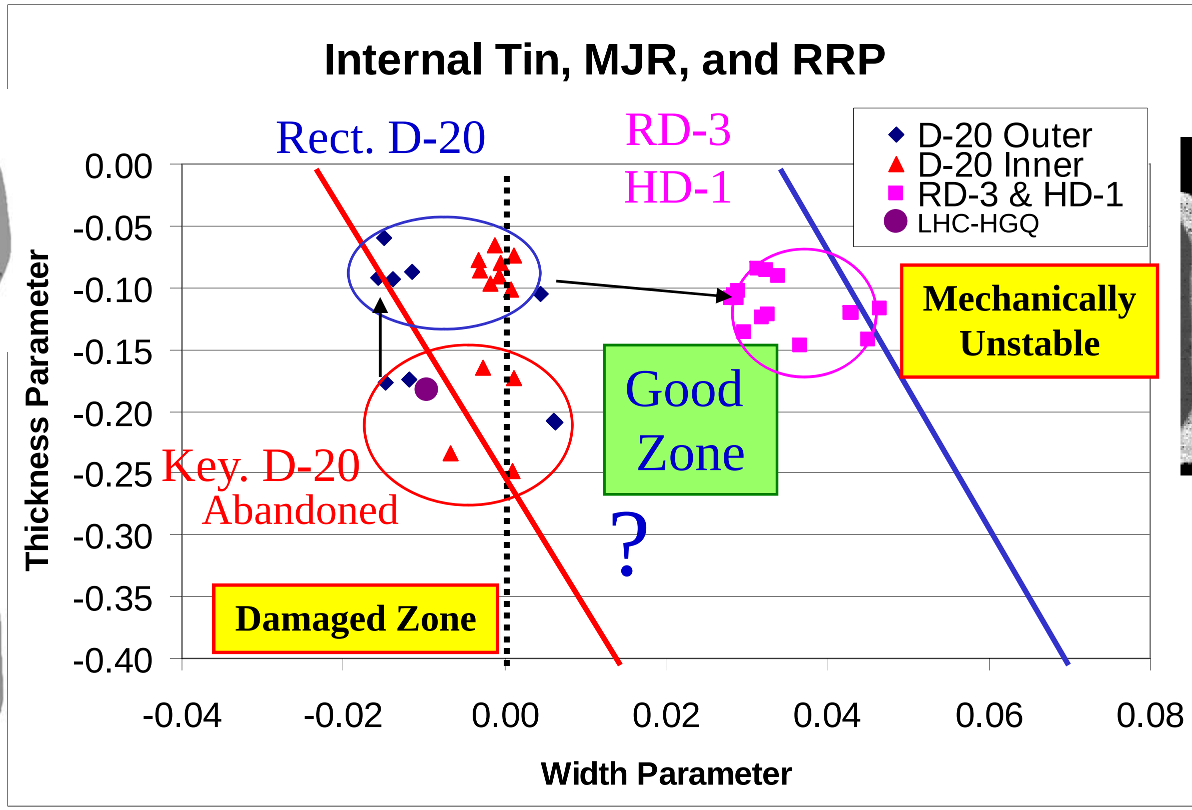
D-20



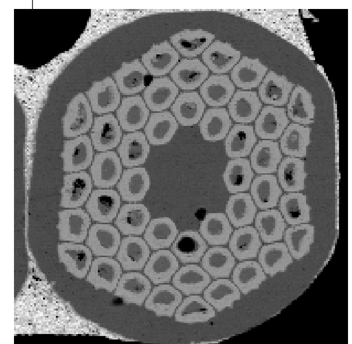
LBL Cable # 523
MJR-TWCA



LBL Cable # 522
IGC-Int. Tin



RD-3



LBL Cable # 805R
Oxford-ORe

Technology Quad (TQ) – Cable Specifications & Production

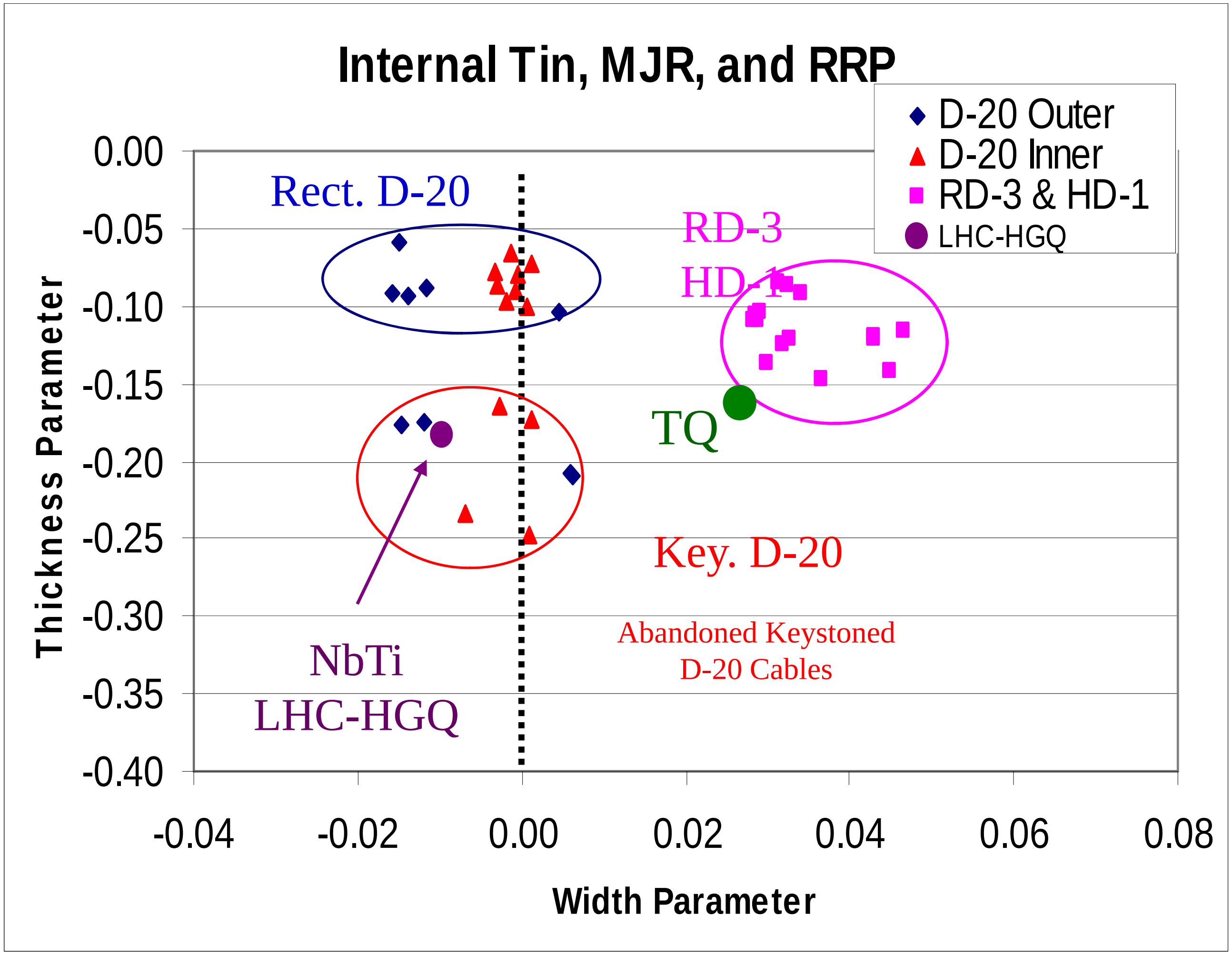
- Spec

Parameters	Units	TQ Cable	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

- Made

Cable No.	Billet No.	Strand Dia. (mm)	Thick. (mm)	Width (mm)	P.L. (mm)	K.A. (deg.)
928R	205, 206, & 208	0.703	1.264	10.056	78.0	1.05
933R	8220	0.703	1.267	10.042	78.7	1.09
939R	8220	0.703	1.262	9.993	80.5	1.04
940R	8647	0.704	1.264	10.026	80.5	0.98
946R	8781	0.705	1.266	10.062	79.5	1.00

TQ cable compared to past cables

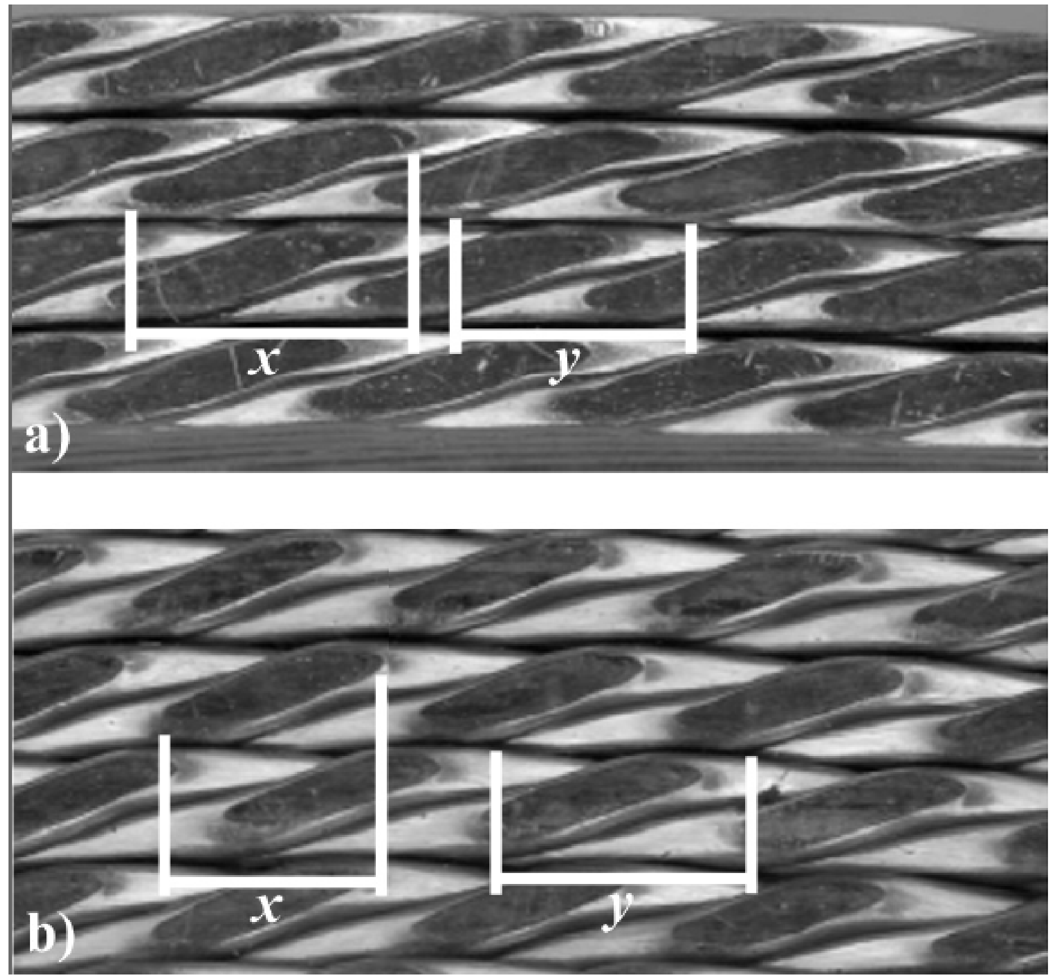


Facet size as online probe

Bad

- Facet length (x) should be less than Pitch Length/strand (y)
  - Minor axis

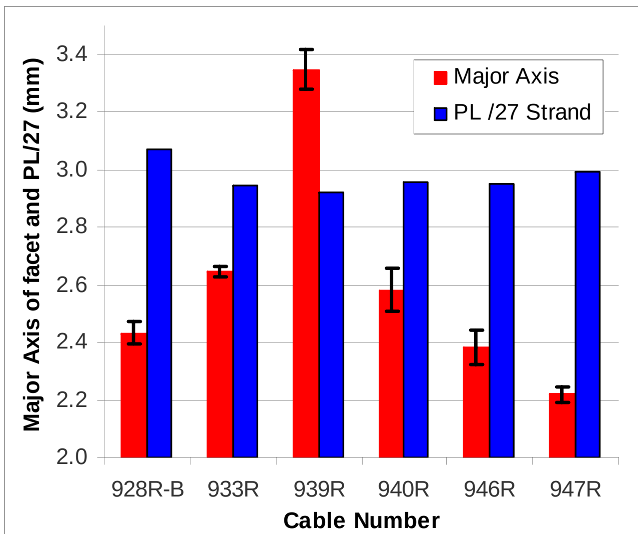
Good

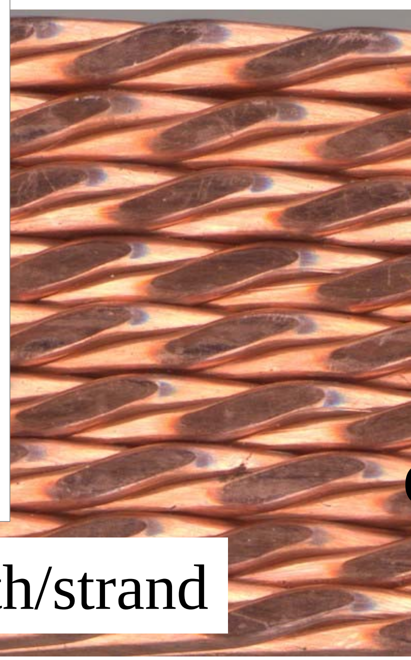


Thin edge of cables as online probe

Facets at cable edge

Facets > Pitch length/strand

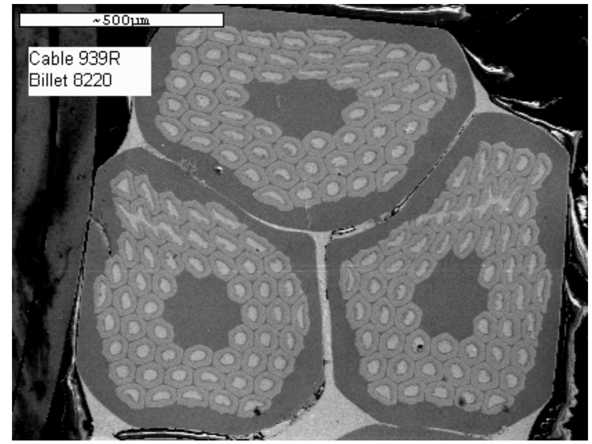




Facets < Pitch length/strand

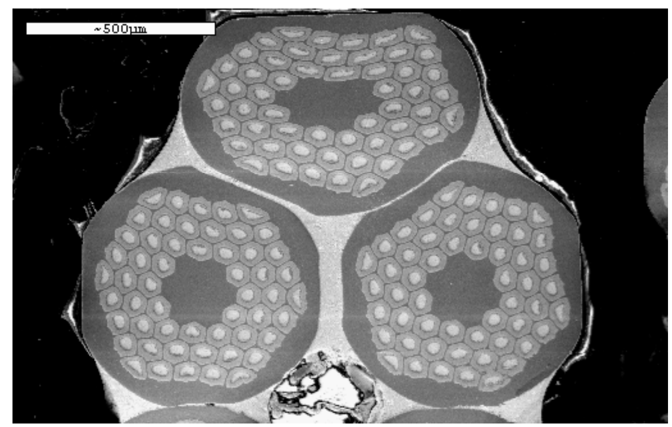
SEM Images of Cross Section

939R



Bad

946R

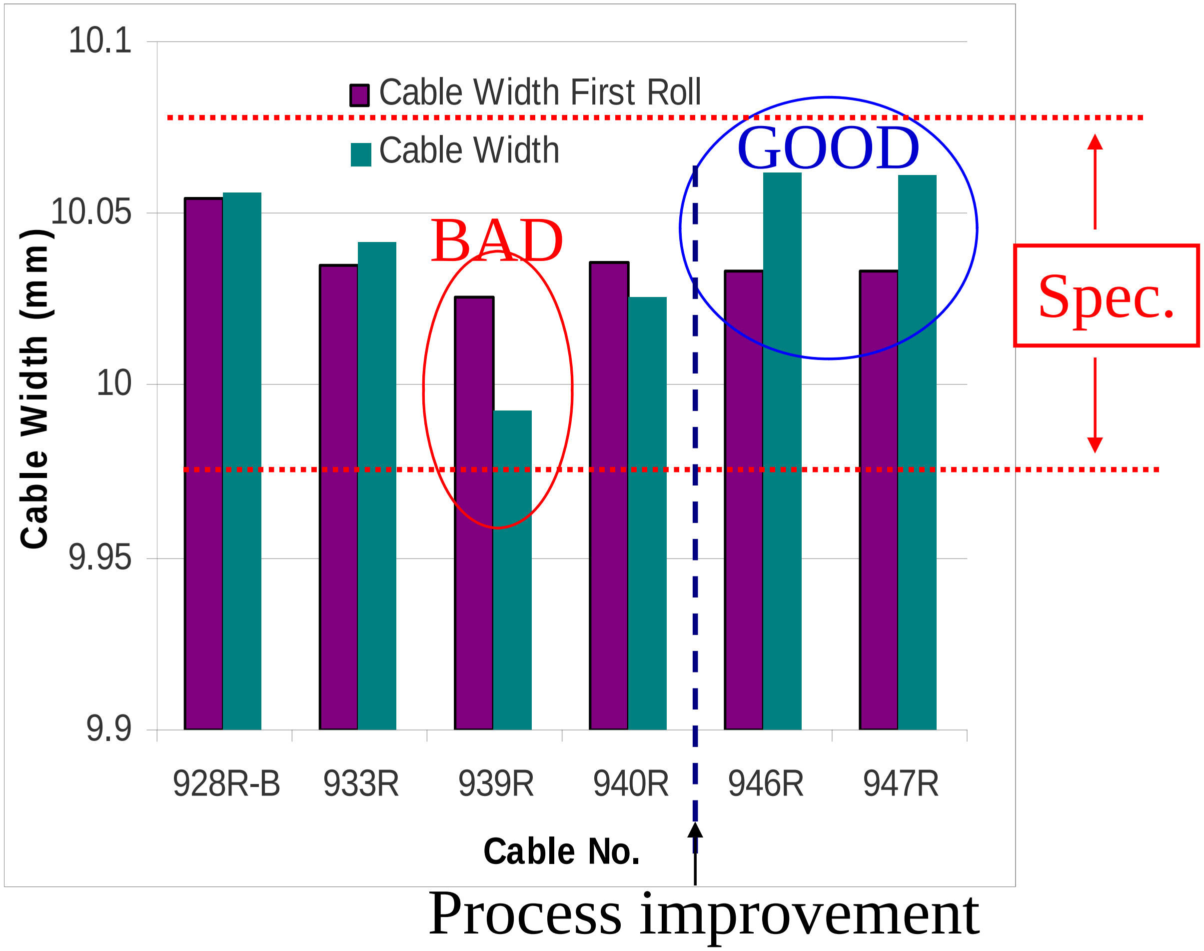


Good

TQ cable widths after re-rolling

- Do NOT re-roll cable to a smaller width
  - **Fabrication (first rolling)**
  - **Anneal cable 200C for 4-6 h**
  - **Re-roll (second rolling) – final cable**

Re-rolling after anneal is used to provide final shape



After cable 940R the processing was changed
From one set of rolls
To 2 sets of rolls,
One for the fabrication
and one for re-rolling
~ 50 micrometer wider

Summary of Critical and Stability Currents for TQ Cables

- All cables but 939R:
  - Reduced J_c(12T,4.2K) by about **0-3%**
  - Reduced stability current (I_s) by **~10%**
- Cable 939R (bad example with sheared sub-elements):
  - Reduced J_c (12T,4.2K) by about **~5% (Only)**
  - Reduced stability current (I_s) **by ~50% (RRR loss?)**

- Concern – Past Jc measurements on cables with edge damage has shown them to be more sensitive to transverse stress.

NED Cable Parameters

No. of Strands =	40	Width > =	26.91		
Strand DIA. =	1.25	Cable MID Thk. =	2.5		
Pitch Angle =	16				
CALC Compacted Cable RESET		Pitch length =	181.398		
		PF @ Max Width =	0.7591		
		PF @ Min Width =	0.78539816		
Module: [B]		COMPACTED CABLE			
	INPUT B				
Cable Width Max. =	26.91		MIN.	MID	MAJ.
Cable Mid Thk. =	2.275				
Keystone angle. =	0.44	Cable Thickness =	2.17167	2.275	2.37833
Pitch length =	181.398	Packing Factor =	0.87586	0.83608	0.79976

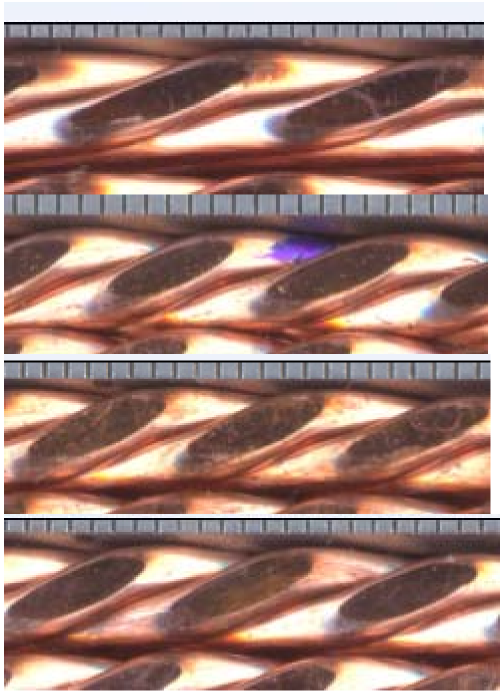
- LBNL Cable-CALC
  - Should increase the width from 26 mm to 26.9 mm.
  - Note: Removal of 1 strand is only 2.5% Ic reduction but provides significantly more width margin

NED Cable Prototype Fabrication

- LBNL cabling machine was pushed to its limits due to the:
  - Large strand diameter
  - High stiffness of the strand
- Higher tension on the strands should make the cabling process easier.
  - It should permit fabrication of cables with a lower pitch angle (~16^{o})
  - Plus reduce the gaps between strands

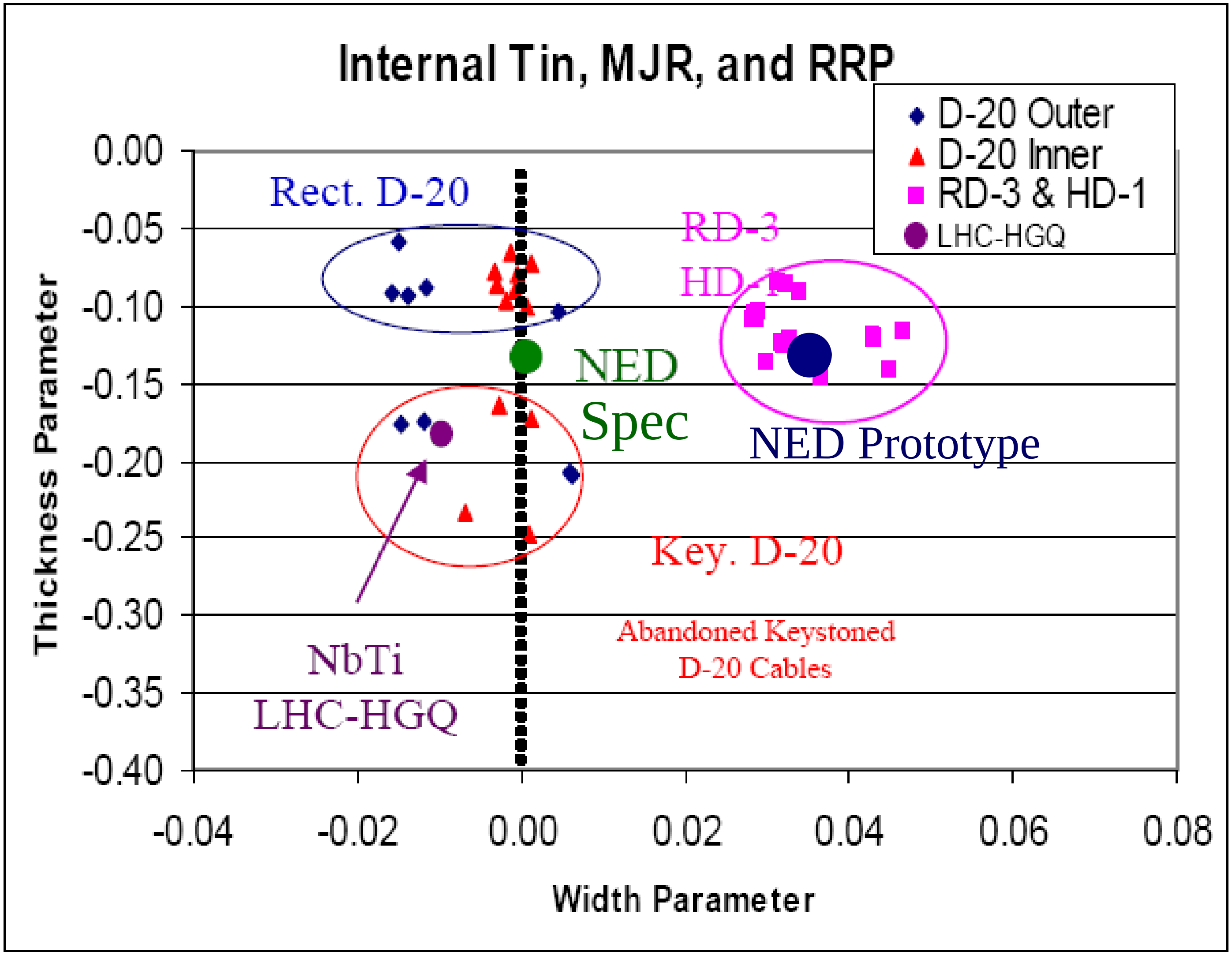
NED cable edge facet summary
Four short prototype cable sections made

	Facet Length mm	Pitch Length mm	Facet/Pitch	Cable Pitch Length mm
965-A-Min	4.26	4.76	0.89	190.7
965-A-Maj	4.11	4.83	0.85	193.1
965-C-Min	3.17	3.76	0.84	150.5
965-C-Maj	3.45	3.76	0.92	150.5
965-D-Min	3.34	3.74	0.89	149.6
965-D-Maj	3.65	3.79	0.96	151.5
965-E-Min	3.33	3.75	0.89	150.1
965-E-Maj	3.57	3.77	0.95	150.9



- Facet/Pitch on the minor edge are similar
  - Section C has the smallest ratio
  - Section C has 4-8% Ic reduction (T. Boutboul, EUCAS-07)

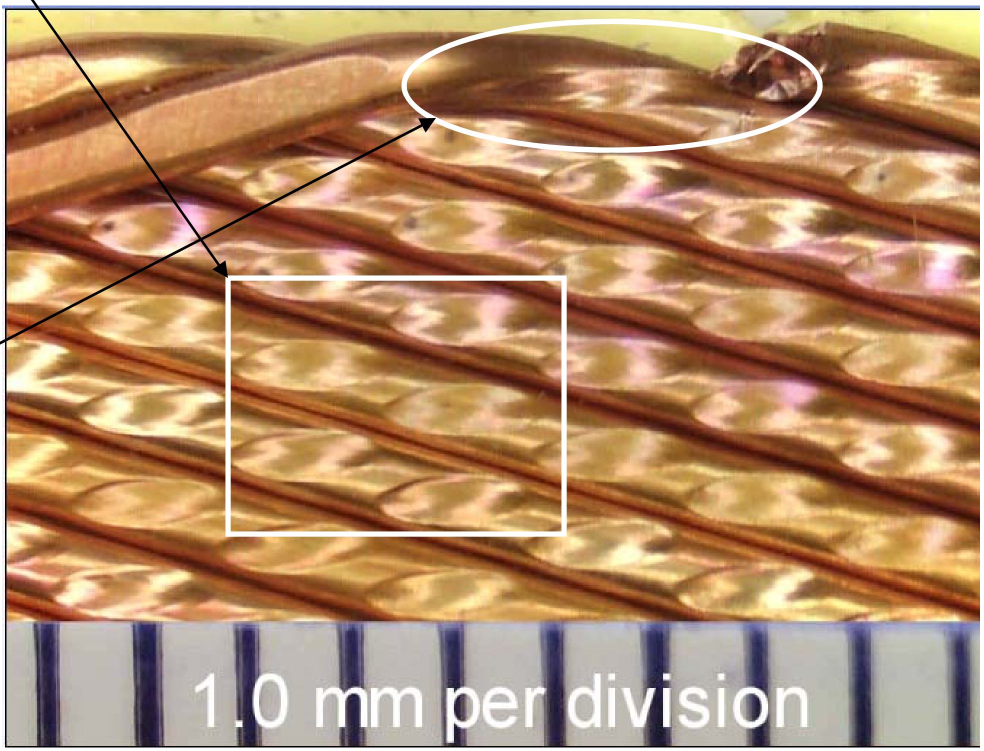
NED spec and prototype



Strand deformation inside a cable

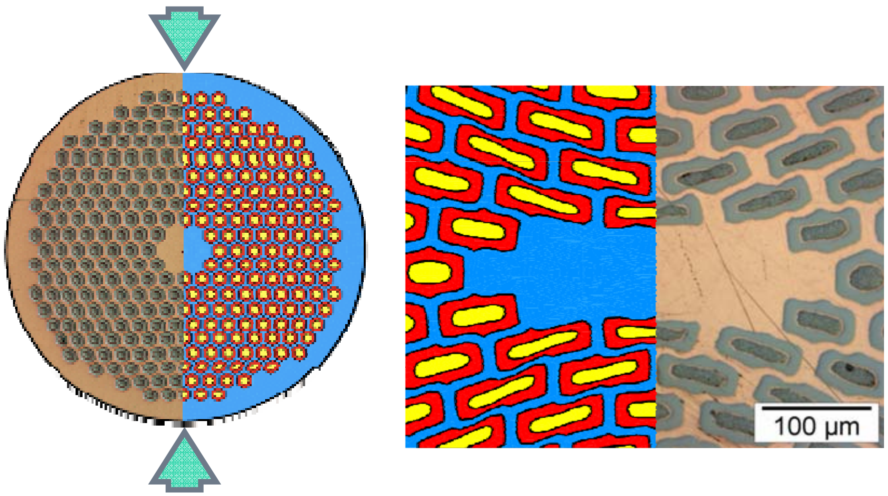
- Dimples at strand cross over points (box)
  - Deformation not uniform along a strand
  - Making cables thinner has shown no significant impact on performance
  - Perhaps cables can be made thinner
- Strand deformation as it goes from the top of cable to bottom (oval)
  - Limits cable performance
- Need 3D modeling to understand strand deformation at the cable edge

Cable 784R



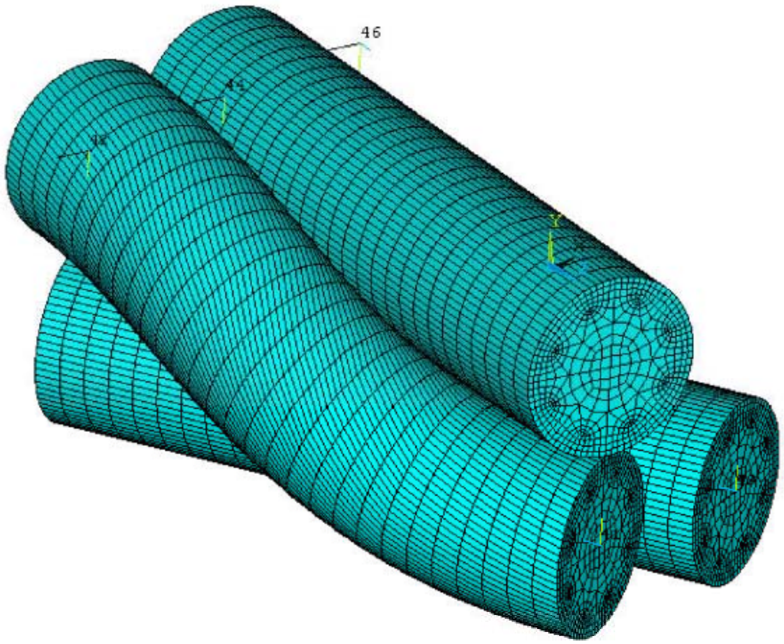
Modeling 2D and 3D

2D Strand Modeling



- *S. Farinon, Presented at CHATS-AS 2006*

3D Modeling of Strand



Marco La China

Summary

- The facet size on the edge of the cable provides a direct measure of the amount of strand deformation.
  - Indicates the amount of sub-element distortion inside the strand.

- This work shows that a nearly damage-free mechanically-stable cable can be produced from:
  - MJR and RRP strands with reduction of only 0-3% J_c (12T,4.2K).
  - PIT strand with reduction of 4-8% Jc (12, 4.2K)

- Cabling damage (i.e. sheared sub-elements) had minimal effect on J_c but it has a significant impact on strand stability.
  - The stability current (Is) drops by ~50% in a strand with only a ~5% drop in Jc at 12T and 4.2K