Meeting on 11 T Dipole Conductor

October 4, 2011

Development and Fabrication of Nb_3Sn Cable for 11 T Dipole at Fermilab

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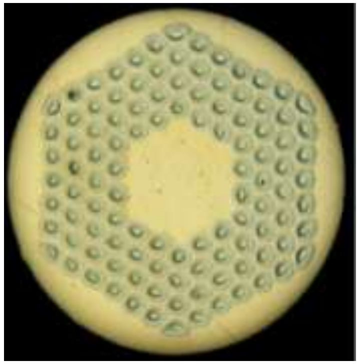
Introduction

The following considerations were used in selecting cable properties:

- **Max. No. of strands ≤ 40 to comply with CERN cabling machine capability**
- **Strand size ≤ 0.7 mm to achieve required magnet transfer function of 11 T at 11.85 kA**
- **Critical current degradation due to cabling < 10%**

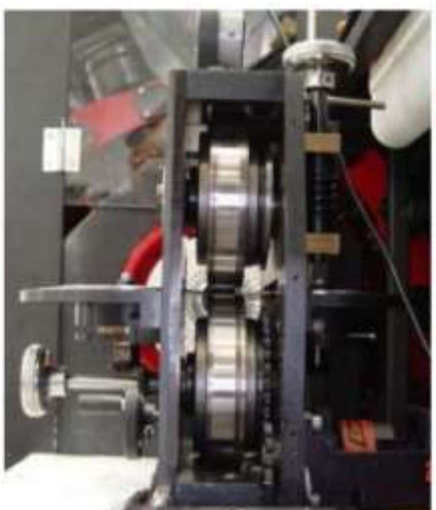
The Nb_3Sn technology to be used for the short models of the 11 T dipoles is the RRP 108/127 by OST:



Parameter	Value
Strand diameter, mm	0.700±0.003
Cu fraction, %	53±3
Effective sub-element diameter, µm	<60
Critical current I_c(12T, 4.2K), A	>450
Critical current density J_c(12T, 4.2K), A/mm^2	>2650
RRR (after heat treatment)	>60
Twist pitch, mm	14±2

FNAL Cable Technology




- **Two steps**
- **Rollers**
- **Mandrels (core, no core)**
- **Size control**
- **Cabling machine picture**
- **Keystoned cable tooling for single pass - in progress.**

Cable Specs Development (1)

- **4 rectangular Cu practice cables:**
  - **Keystoned cables 14.7 mm and 15.1 mm wide, with and without SS core.**
  - **=> 15.1 mm required 41 strand for stability, therefore the 14.7 mm width was chosen.**
- **2 rectangular Nb_3Sn cable short samples at 14.7 mm width, with and without SS core:**
  - **Average I_c (4.2 K, 12 T) degradation was 3.5% for uncored cable and 2% for cored one.**
  - **At 1.9 K, I_c(12T)=602 A and I_s=951 A for uncored cable, and I_c(12T)=592 A and I_s=812 A for cored one.**
  - **=> Feasibility of a cored cable technology to suppress eddy currents.**
- **A 250 m long Cu cable for the first practice coil.**
- **A 250 m long Nb_3Sn keystoned cable for the second practice coil made of RRP 114/127 wire:**
  - **230 m used in the coil were keystoned without annealing,**
  - **15 m were used to study intermediate annealing before keystoning.**

E. Barzi et al., "Nb_3Sn Cable Development for the 11 T Dipole Demonstration Model", accepted for publication in Advances in Cryogenic Engineering (2011).

Cable Specs v.1

Parameter	Value	
	Unreacted	Reacted
Cable unit length, m	210	
Number of strands	40	
Transposition angle, degree	15	
Transposition direction	Left-handed	
Mid-thickness, mm	1.269	1.307
Thin edge, mm	1.167	1.202
Thick edge, mm	1.370	1.411
Width, mm	14.70	14.847
Key-stone angle, degree	0.79	0.81
Insulation thickness, mm	0.150	0.100

The following cable specs v.1 resulted from the first phase of cable development, as well as the addition of an intermediate annealing step to the rectangular cable.

Rectangular stage

Keystoned stage

Cable Specs Optimization

The second phase of cable development was based on the important feedback obtained from the cable processing itself, and from the use of such cable in the practice coils:

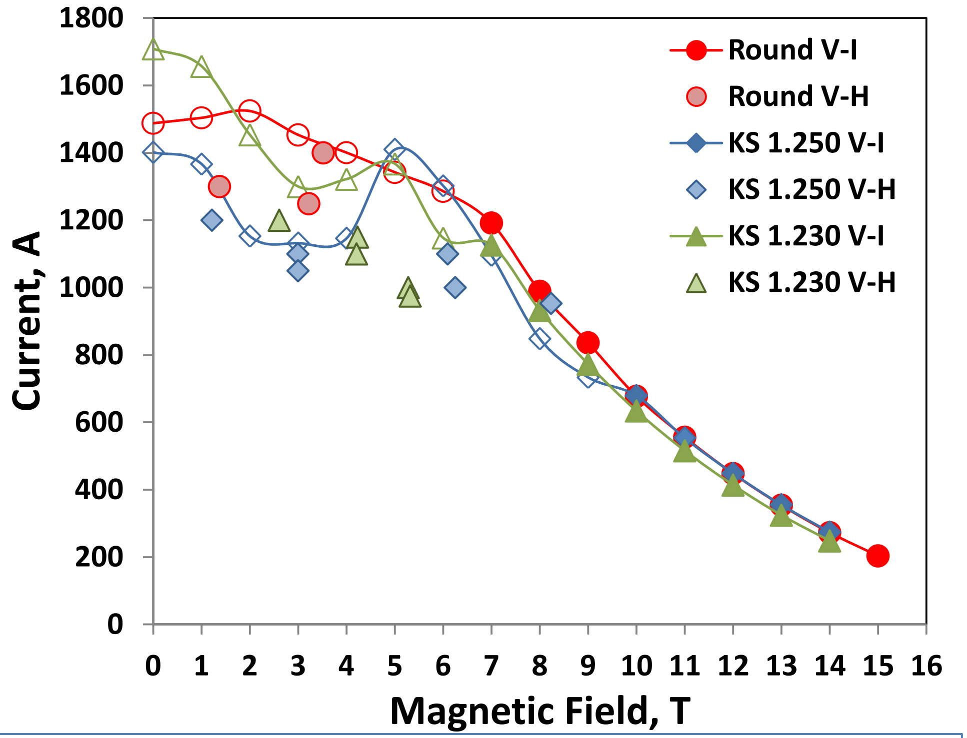
- **The addition of the intermediate annealing step required revisiting the size of the rectangular cable.**
- **In addition, practice coil winding revealed insufficient cable mechanical stability for a production oriented winding process.**

In the following slides, each of the Nb_3Sn cable studies of this phase is described.

Cable Thickness Optimization (1)

First, a number of keystoned short samples of various thicknesses obtained from more compacted rectangular cables were made. This determined the thickness of a more compacted rectangular cable.

Mandrel width, mm	Width before/after keystoning, mm	Mid-thickness before*/after keystoning, mm	Lay angle, °	PF, %
13.90	14.58/14.70	1.30/1.27	15	84.5/85.8
13.90	**14.58/14.70**	**1.30/1.25**	**15**	**84.5/87.2**
13.90	**14.58/14.70**	**1.30/1.23**	**15**	**84.5//88.6**
13.90	14.58/14.70	1.27/1.27	15	86.5/85.8
13.90	14.58/14.70	1.27/1.25	15	86.5/87.2
13.90	14.58/14.70	1.27/1.23	15	86.5/88.6

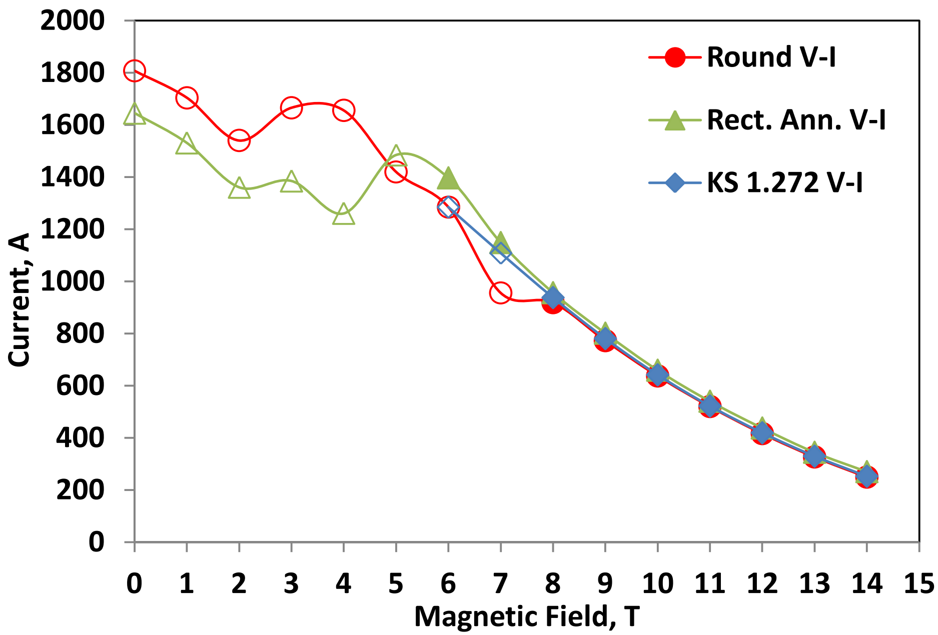


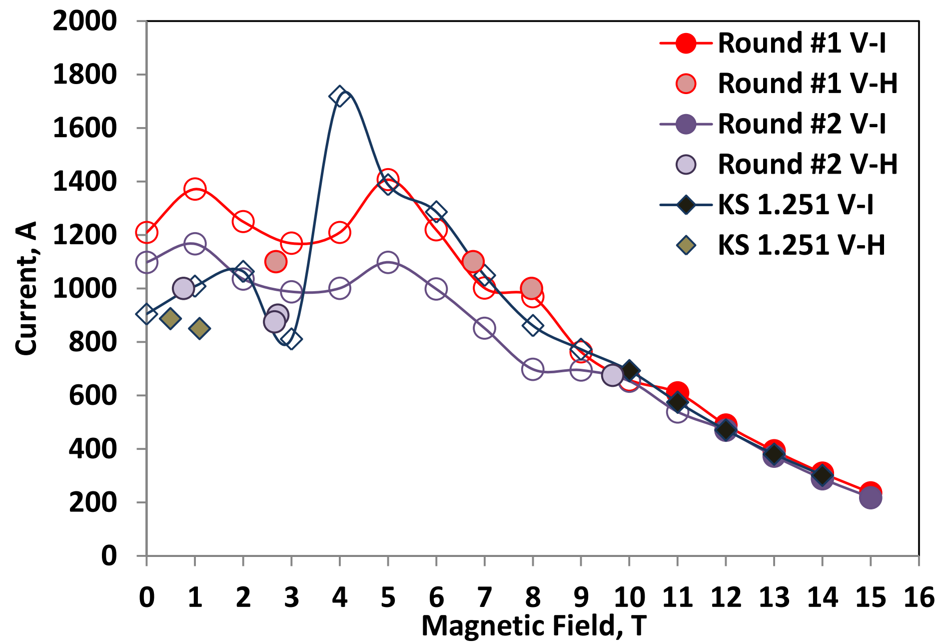
The I_c (4.2 K, 12 T) degradation of a keystoned cable sample with 1.25 mm mid-thickness obtained from a rectangular cable 1.30 mm thick was ~0%. I_c degradation at 1.23 mm was 7.6%.

Cable Thickness Optimization (2)

Then, keystoned short samples of two different thicknesses obtained from the more compacted rectangular cable were made. This determined the mid-thickness of a more compacted keystoned cable.

Mandrel width, mm	Width before/after keystoning, mm	Mid-thickness before/after keystoning, mm	Lay angle, °	PF, %
13.90	14.57/14.95	1.297/1.272	15	84.8/84.2
13.90	14.57/14.95	1.297/1.251	15	84.8/85.7



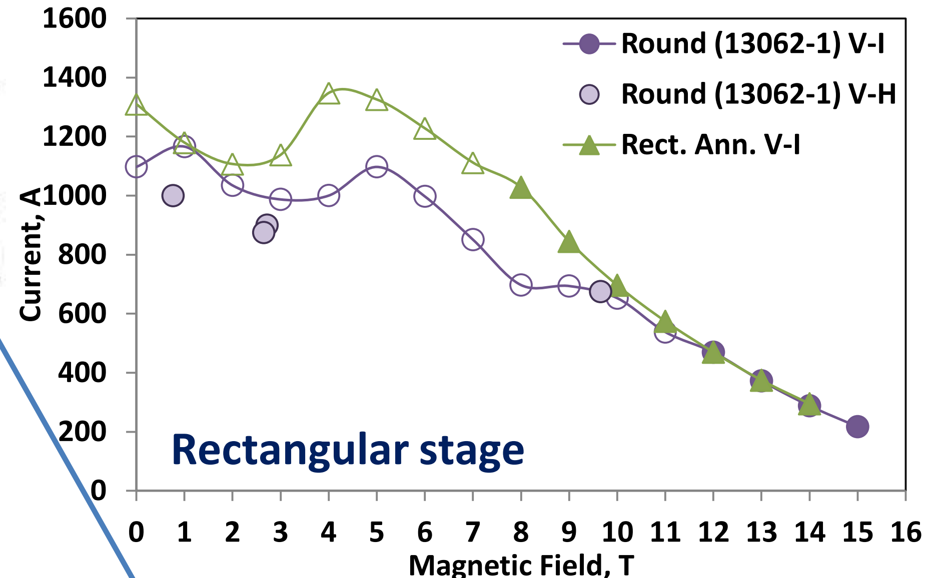


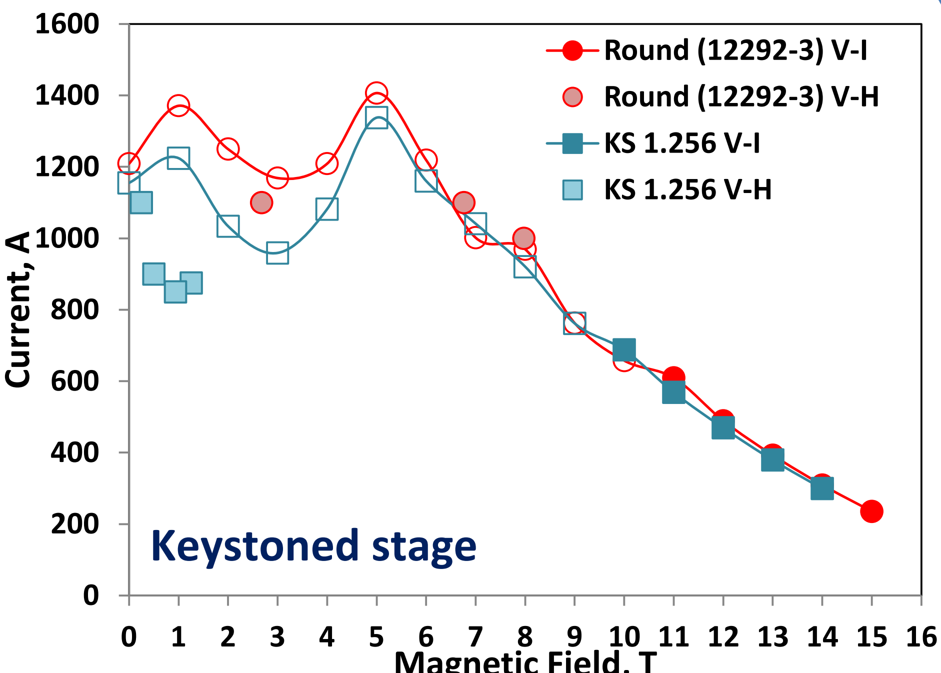
The I_c (4.2 K, 12 T) degradation of the keystoned cable sample with 1.272 mm mid-thickness was ~0%. I_c degradation at 1.251 mm was between 0 and 4%.

Cable Width Optimization

Finally, a long length sample of more compacted keystoned cable obtained from a more compact and also narrower rectangular cable to allow for any width expansion due to spring back and annealing was made. This determined the narrower width to use in the rectangular stage.

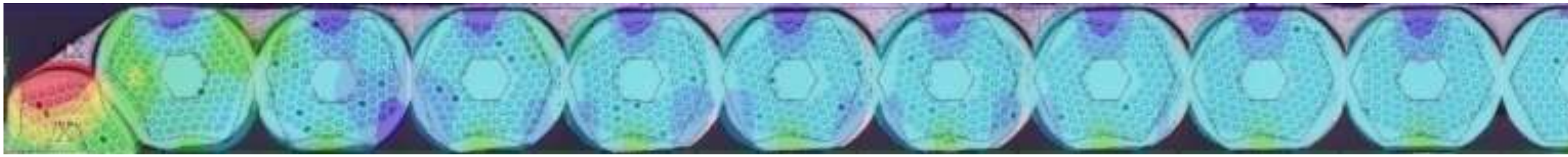
Mandrel width, mm	Width before/after keystoning, mm	Mid-thickness before/after keystoning, mm	Lay angle, °	PF, %
13.81	14.48/14.71	1.294/1.256	15	85.5/86.7
13.74	14.49/14.70	1.294/1.254	15	85.4/86.9



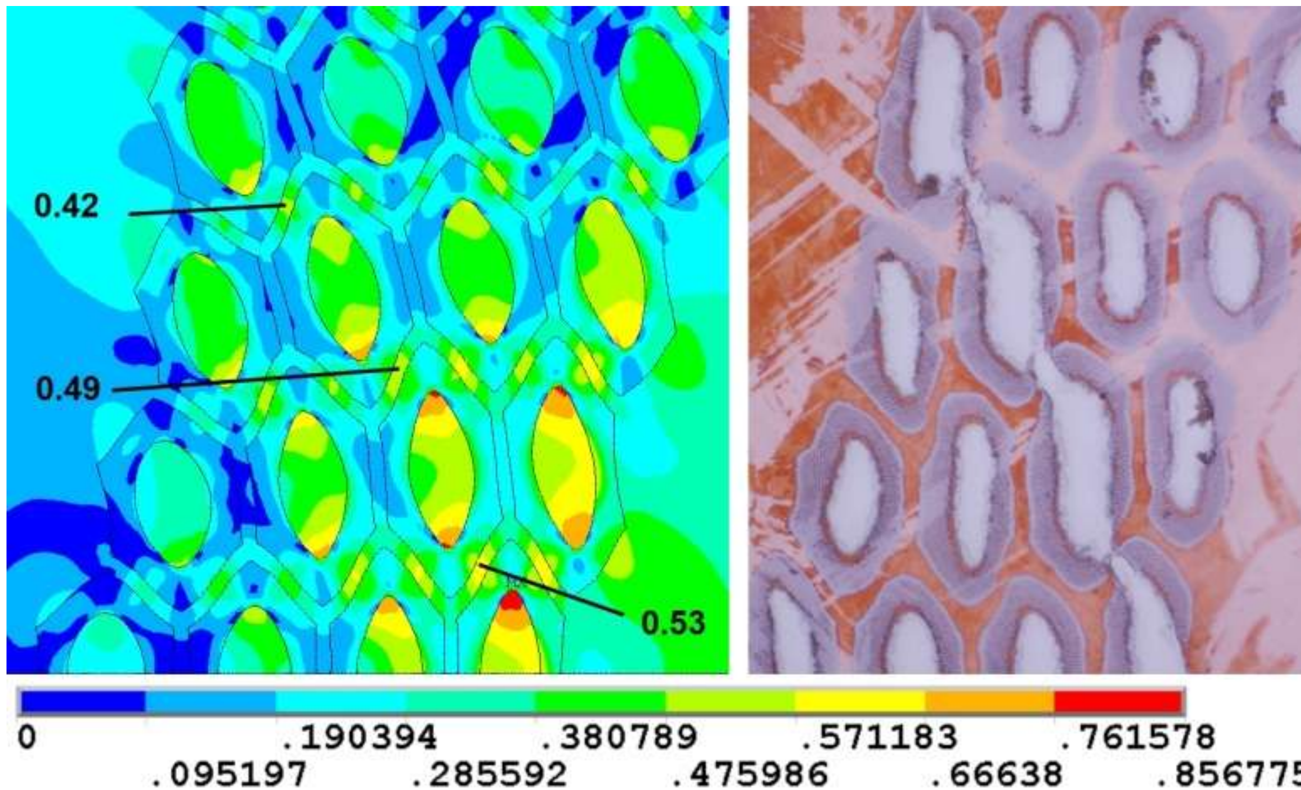


The I_c (4.2 K, 12 T) degradation of the narrower rectangular cable was ~0%. The I_c degradation of the keystoned cable with 1.256 mm mid-thickness was ~4%.
The single 440 m long piece for two unit lengths for the coils was made using the same cable geometry.

Damage Analysis and Modeling



Values shown are of the principal tensile strain in the most critical Cu channels of the strand at cable edge.



See also "FEM Analysis of Nb-Sn Rutherford-type Cables", 3IP3-10, MT-22.

Cable Specs v.2

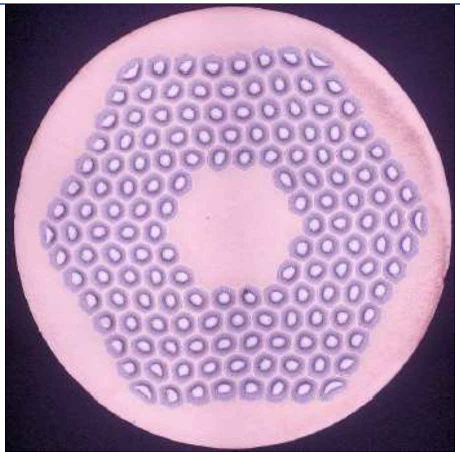
Parameter	Value	
	Unreacted	Reacted
Cable unit length, m	210	
Number of strands	40	
Transposition angle, degree	15	
Transposition direction	Left-handed	
Mid-thickness, mm	> 1.23 ~~1.269~~	~~1.307~~ > 1.267
Thin edge, mm	1.167	1.202
Thick edge, mm	1.370	1.411
Width, mm	14.70	14.847
Key-stone angle, degree	0.79	0.81
Insulation thickness, mm	0.150	0.100

Cable production (Specs v.2)

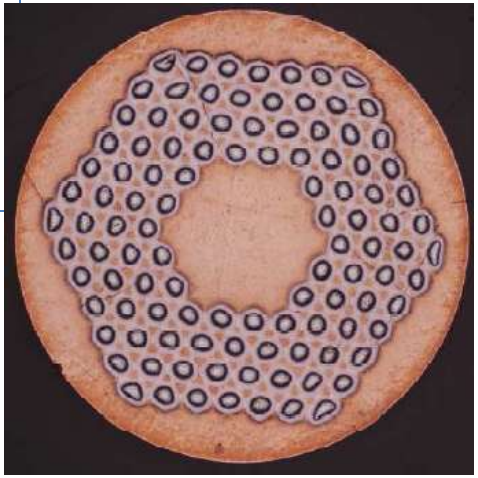
- **234 m piece (RRP-108/127) – practice cable (wide width)**
- **167 m piece (RRP-108/127) – practice cable**
- **440 m piece (RRP-108/127)**
  - Two ~210 m long unit lengths for demonstrator model
  - ~20 m for short sample studies.

RRP Wires for 11T dipole

- The goal is to provide stability margin, which is needed to account for the subelement merging that occurs in cables.
- Design of new wire is at developmental stage, production foreseen by Jeff Parrell at OST within 12 months.



150/169
New Wire



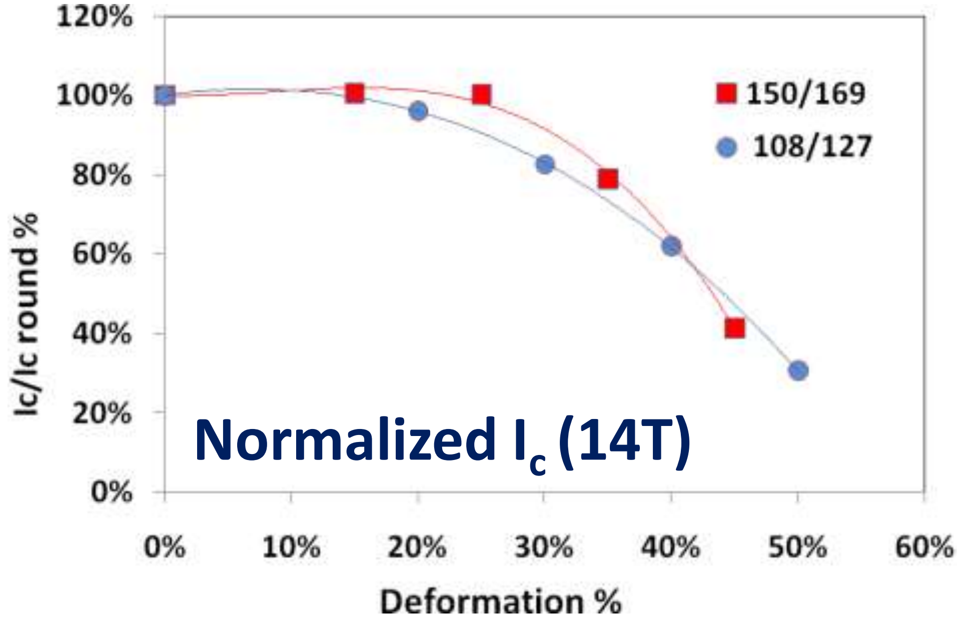
108/127 Present Baseline Conductor

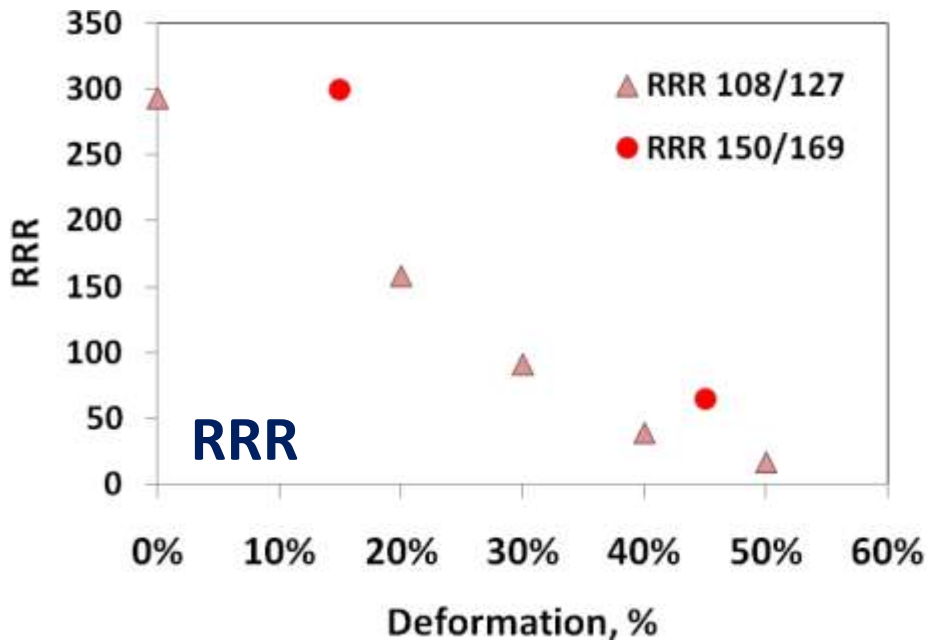
Strand ID	RRP1	RRP2
Stack design	150/169	108/127
Strand diameters, mm	0.7, 0.8, 0.9, 1.0	0.7, 1.0
J_c(4.2K, 12 T), A/mm^2	2,500	2,650
I_c(4.2K, 12 T) for 0.7 mm, A	470	470
Max subelement size, µm	36-52	52-75
Twist pitch, mm	14	12
Cu fraction, %	51	54

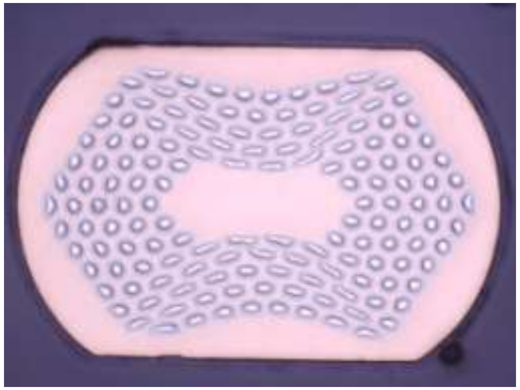
RRP 150/169 Production

- Pure Nb-Ti rods technology was used
- Volume of 60 kg in 0.7 mm, 0.8 mm, 0.9 mm and 1.0 mm sizes
- 58 kg of 0.7 mm wire was produced in 16 pieces: longest was 4.3 km
- J_c(4.2 K, 12 T) was 2500 A/mm^2 for 0.7 mm wire and 2650 A/mm^2 for 1.0 mm wire

Transport Properties at 4.2 K







1 mm original size

Up to 40% deformation the I_c(14 T) degrades similarly or less under increasing deformation in the 150/169 design.
This is consistent with previous findings that smaller subelements are less sensitive to I_c degradation.

Conclusions

- **Reducing rectangular cable thickness from 1.32 mm to 1.3 mm and cable width from 14.6 to 14.5 mm increase cable mechanical stability and reduce the risk of cable collapse during fabrication without increasing cable I_c degradation.**
- **Intermediate annealing improves rectangular cable mechanical properties and slightly reduces keystoned cable I_c degradation.**
- **Reducing keystoned cable thickness from 1.27 mm to 1.25 mm improves cable mechanical stability with small I_c degradation. This study will continue.**
- **The development of tooling to make keystone cable in single pass is in progress.**
- **The new RRP 150/169 is an option for the 11T dipole program. It performs as well as the 108/127 baseline design, is more stable and has a larger RRR, providing stability margin.**

Coil Winding Experience (MBH01 & 02)

Fred Nobrega

Coil Winding → Cable Insulation

- 75 micron thick E-glass
- 2 layers, each half lap

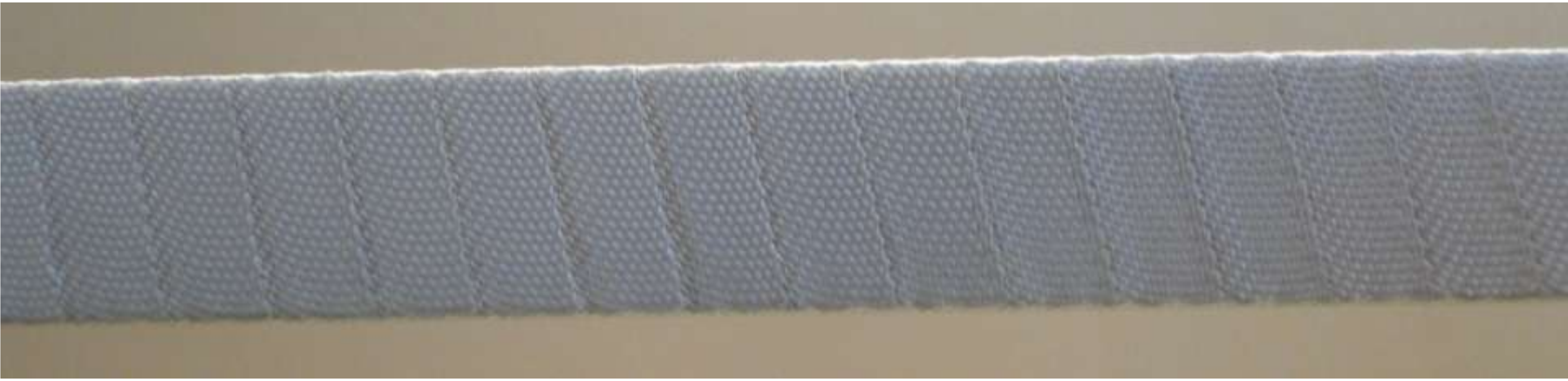


Photo of MBH02 layer one cable insulation.

Coil Winding → Out of lay strands

- PC01
  - Cable: 14.71 mm wide, mid-thickness 1.27 mm, 15.45°, packing factor = 84%
  - Popped strands in all turns
- MBH01
  - Cable: 14.93 mm wide, mid-thickness 1.25 mm, 15°, packing factor = 85.8%
  - 133 N (30 lbf) winding cable tension
  - Used ceramic binder in the cable ends to hold strands in position
  - Many popped strands in a turn
- MBH02
  - Cable: 14.71 mm wide, mid-thickness 1.25 mm, 15.1°, packing factor = 87%
  - 156 N (35 lbf) winding cable tension (design value)
  - Used ceramic binder in cable ends to hole strands in position
  - One popped strand in a turn

Popped Strand Location

PC01 Turn Number	LE Popped Strands	RE Popped Strands
Every turn (22N)	several	several

MBH01 Turn Number	LE Popped Strands	RE Popped Strands
1 (158 N)	0	1
3 (158 N)	0	1
5 (158 N)	Several strands	0
6 (133 N)	Several strands	Several strands
7 (133 N)	0	Several strands

MBH02 Turn Number	LE Popped Strands	RE Popped Strands
1 (158 N)	0	1
2 (158 N)	1	0

Summary

- Reduction in popped strand during winding:
  - Cable improvement
  - End part improvement design iteration
  - Insulation change from double layer butt-lap to double layer half-lap
  - Binder on each turn around end parts