Roebel cable industrial optimization - General Cable Superconductors

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Cable attributes for magnet applications

- High current; uniform I_c
- Available in long lengths
- $/kA-m
- Stability (risks of quench, equal current sharing among strands)
- Mechanical behaviour
  - I_c – stress, transverse and longitudinal
  - Bending radii
  - Coil manufacture; potting
- Manageable AC losses

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HTS Roebel cable

- Started R&D at IRL in 2004
- Commercialised through General Cable Superconductors

Goals

- Develop long length Roebel cable manufacture
- Prove applications in high current and/or AC machines
  - 150 MW generator (Siemens)
  - 1 MVA Transformer (Robinson Research Institute (ex IRL))

What is HTS Roebel Cable?

- A high capacity winding cable from coated conductor
- Continuously transposed

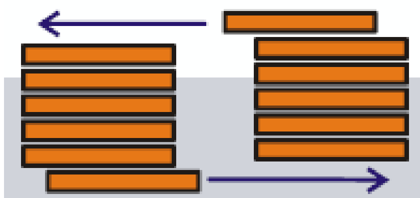

Photo courtesy of Siemens

Cables are labelled (no. of strands) / (strand width)

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Design of strands/cable

- Existing designs are a compromise
  - Use the wire which was available
    - 12 mm SuperPower
    - 10 mm Fujikura and STI (from 2013)
  - Keep tool piece manufacture simple
  - Minimise problems in automated winding
  - Minimise mechanical problems

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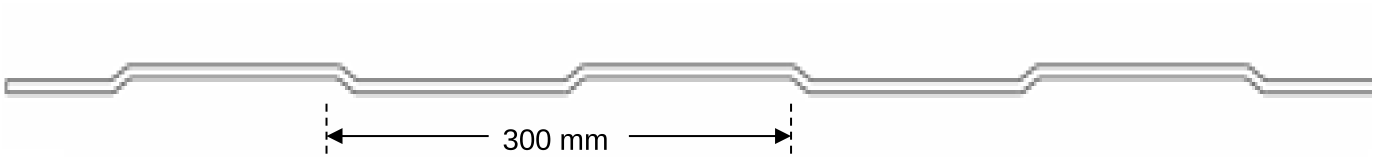
Design of strands

Figure – Roebel strand



“15/5”

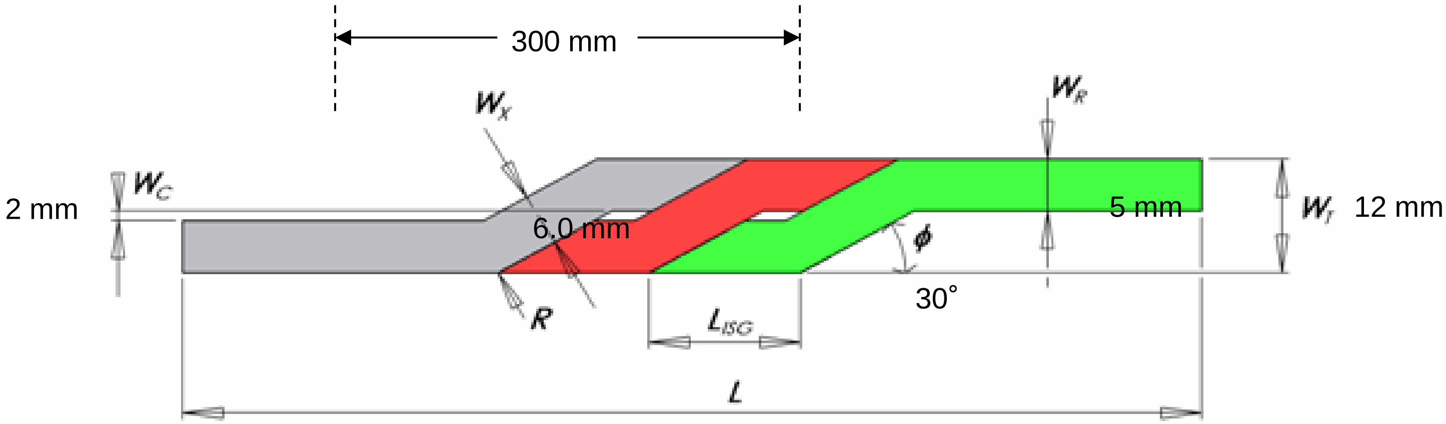


Figure – Strands wound together and geometric parameters

Parameter	Name	2 mm Cable	4.5 mm Cable	5 mm Cable
L_{TRANS} (=2L)	Transposition length	90 mm	300 mm	300 mm
W_R	Strand width	2 mm	4.5 mm	5 mm
W_X	Crossover width	1.7 mm	5.0 mm	6.0 mm

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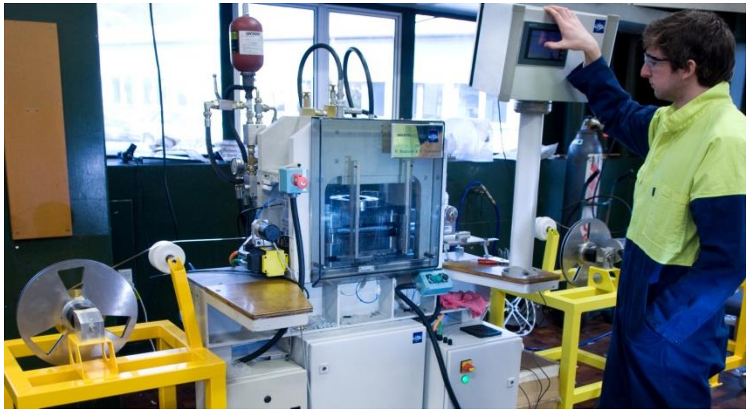
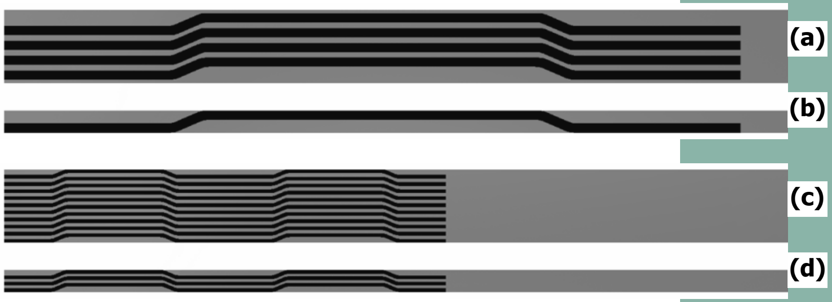
Strand manufacture

Punching



Automated multi-strand production



Formation of Roebel punched strands in 40 mm and 12 mm wide feedstock material.

(a) 4 x 5 mm strands in 40 mm wide material,
(b) 1 x 5 mm wide strand in 12 mm wide material,
(c) 10 x 2 mm strands in 40 mm wide material,
(d) 3 x 2 mm wide strands in 12 mm wide material.

Wire demonstrated: AMSC, SuperPower, Fujikura, STI

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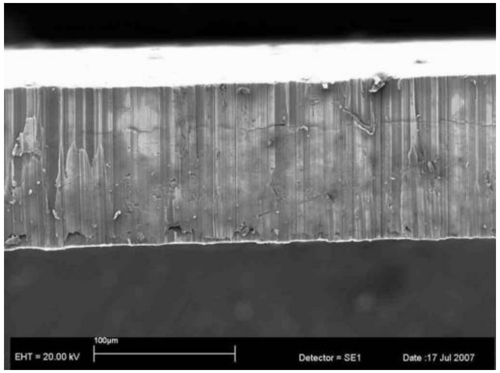
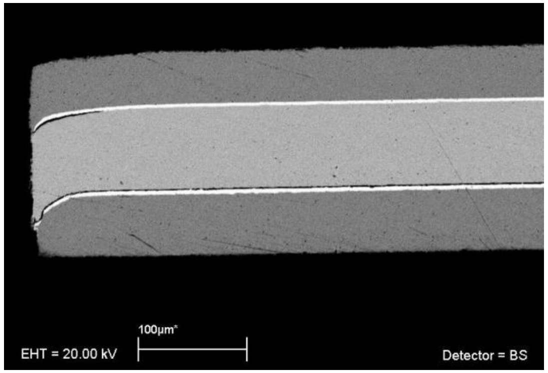
Quality of punching: AMSC wire

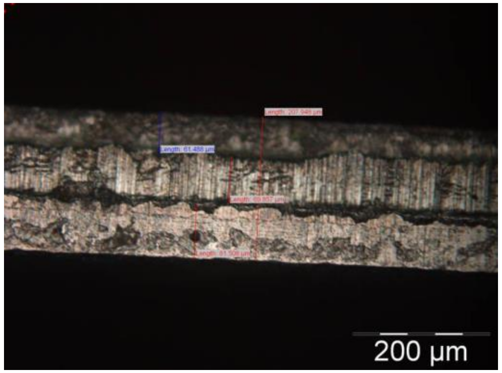
Electroplated copper/NiW



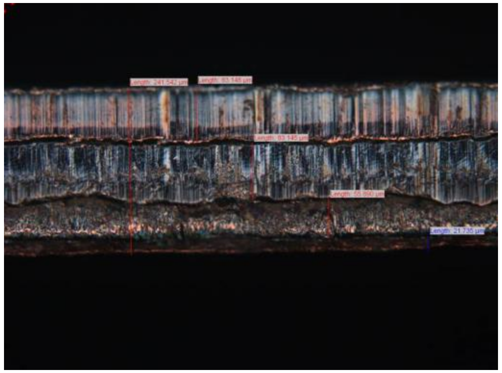
Electroplated copper/NiW



AMSC 3 ply SS/NiW/SS



AMSC 4 ply Cu/2x NiW/Cu



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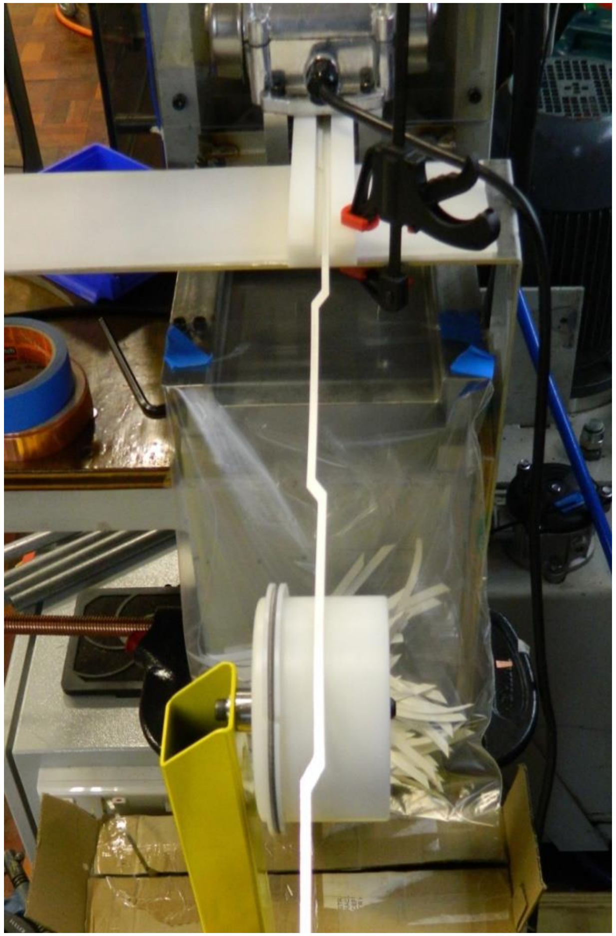
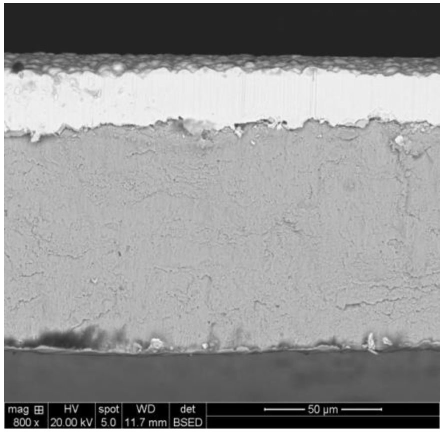
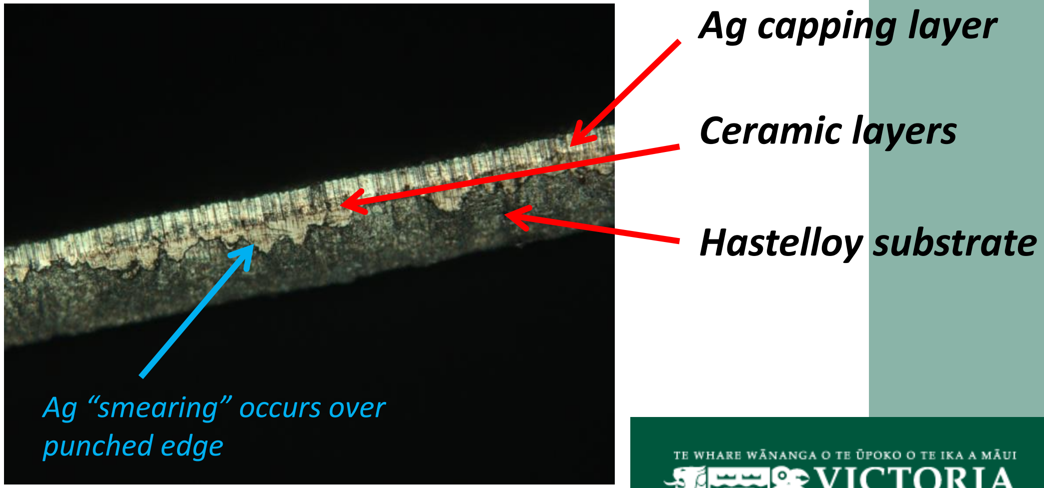
Fujikura: Silver-stabilised punched strand







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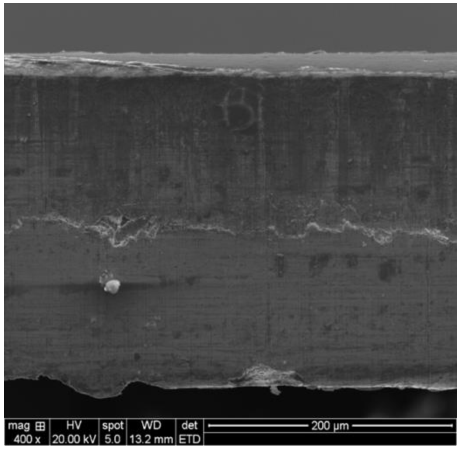
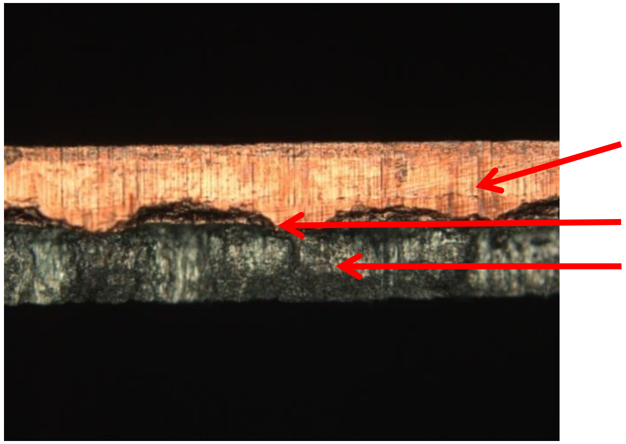
Fujikura Cu-laminated wire – punched strand

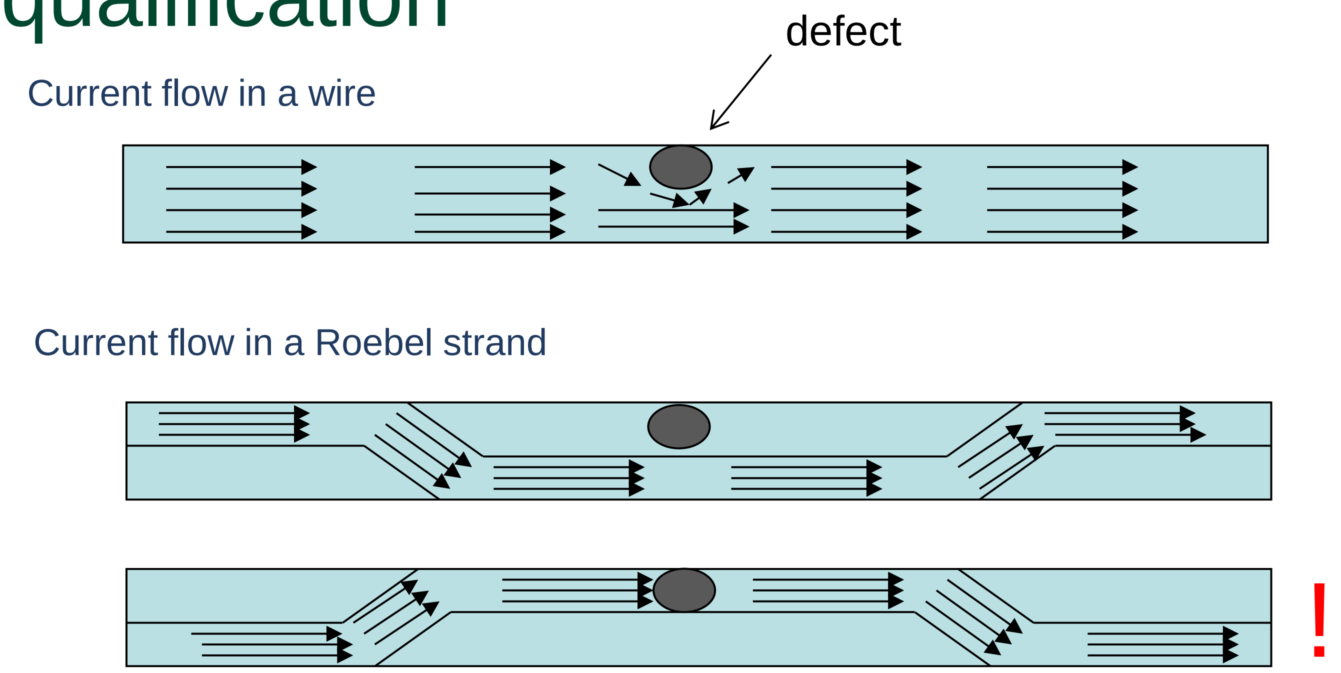


Cross section of punched edge from Cu-laminate stabilised wire *(GCS00048)*:



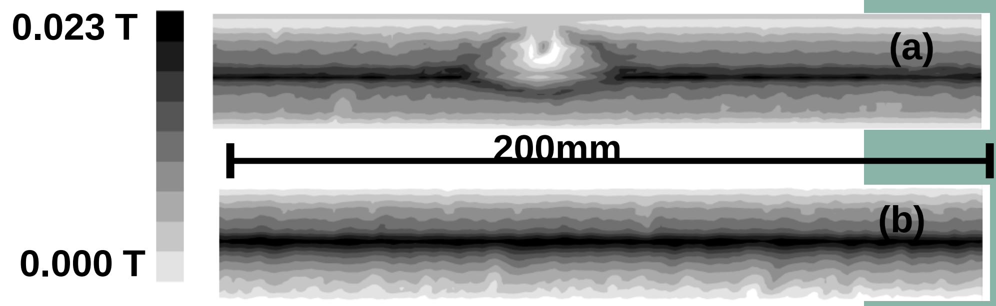
Total thickness: ~200μm

Wire qualification



Wire qualification

- Scan wire magnetically (penetrated or remanent field)
- Quantify uniformity using statistical correlation with an ideal magnetic profile



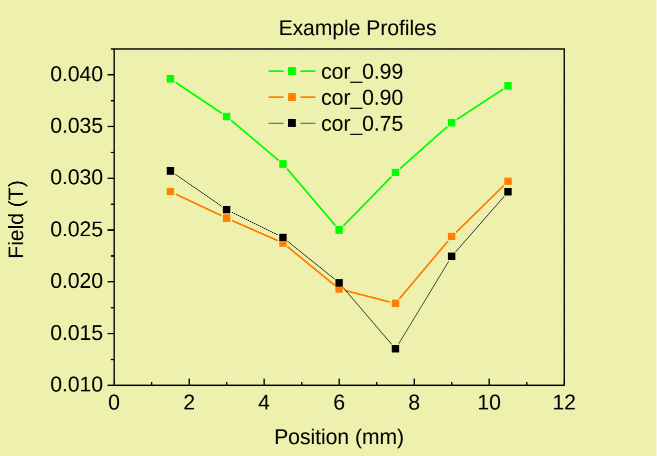
We use continuous scanning of the Remanent magnetic field to assess tape quality (a) tape with a known defect, and (b) tape with only small scale variability.

$$Correl(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

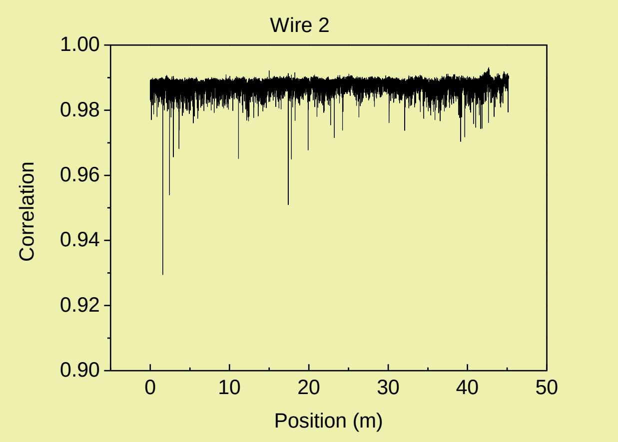
Where $|Correl| \leq 1$ X is a dataset representing calculated field

$Y\{y_1 \ldots y_j\}$ is magnetic data across tape

Some wire is extremely good !



Correlation along a length of YBCO wire, a minimum *Correl* can be specified for input wire



I_c measurement of strands

Spiral racetrack former for testing strands up to length 30 m.

- Punched strands are moisture sensitive
- Heat in dry nitrogen only

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Table 1. Example performance of selected wire and 5mm strands

Sample #	Length (m)	Tape transport I_c (A/cm)	Min{Correl}	Strand transport I_c (A/cm)
1	27	248	0.98	232
2	27	213	0.89	200
3	27	213	0.85	239
4*	27	265	0.94	191
5	27	263	0.9	236
6	27	329	0.88	310
7	27	215	0.9	243
8	27	322	0.9	309
9	27	363	0.94	334
10*	27	400	0.78	307

Summary of strand performance

- **(J_e strand) / (J_e wire) ~ 90-95%**
- **High minimum value of *Correl* is necessary but not sufficient condition**
  - **→ ΔI_c also needs to be considered**
  - **→ Length of defect important**
  - **→ Scaling to low T, defects look like a cross sectional loss of conductor**
- **Can we mitigate low *Correl* values?**
  - **Probably not!**

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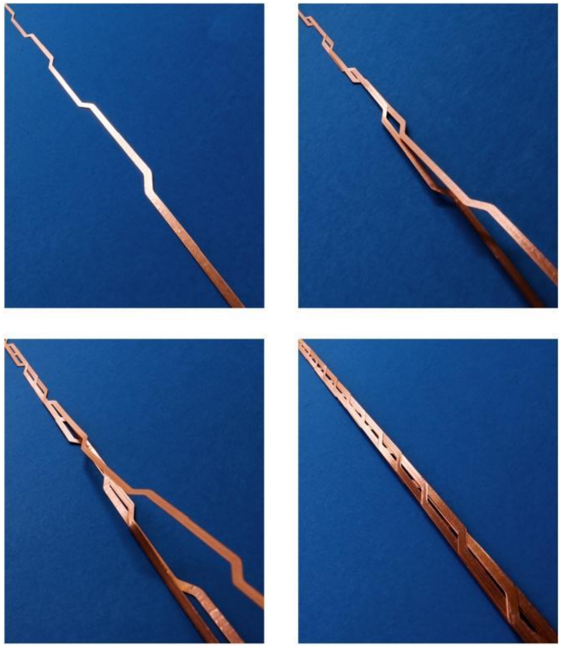
Cable assembly

Illustration of the assembly process



Automated planetary wind system for 15/5 cable

Assembly issues

- Long length registration of crossovers
  - Need high precision for each transposition length in the punching process
  - Need tension control on strands in winding
  - Difficult to simulate (relevantly) with low cost dummy cables
    - Mechanical properties
    - Camber

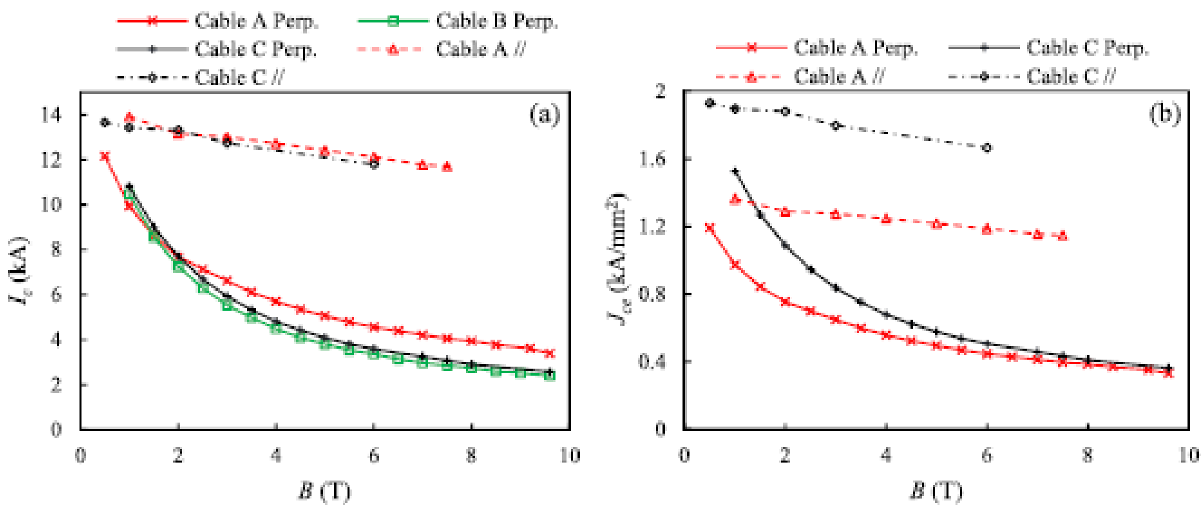
I_c measurement of cables @ 77 K

Cable details	Cable I_c (A)		
	Design I_c	Measured	Computed
5/2	252	203	220.1
9/2	426	318.8	339.1
9/2	426	341.9	359.1
15/5	1454	1100	1033
15/5 SRC0024	1616	1010	1109
15/5 SRC0027	2093	1410	1372

RRI – 1 MVA Transformer

- Measured I_c has been close to expected I_c
- For short length cables accurate I_c measurement is difficult
- At 77 K there are strong self-field effects

I_c measurement of cables @ 4.2 K



J. Fleiter *et al*, Supercond. Sci. Technol. 26 (2013) 065014

Figure 5. (a) Critical current measured on RACC cables (markers) as a function of applied field. The I_c was measured using the 0.2 μV cm^{-1} criterion. (b) J_{ce} of cable A and C in parallel and perpendicular field.

From manufacturing perspective cables work as advertised

- Measured I_c close to expected I_c (taking into account self-field)
- These cables used both 'CF' (Cable A) and 'AP' (B + C) Superpower wire
- Actual strand I_c @ 4 K values were not measured

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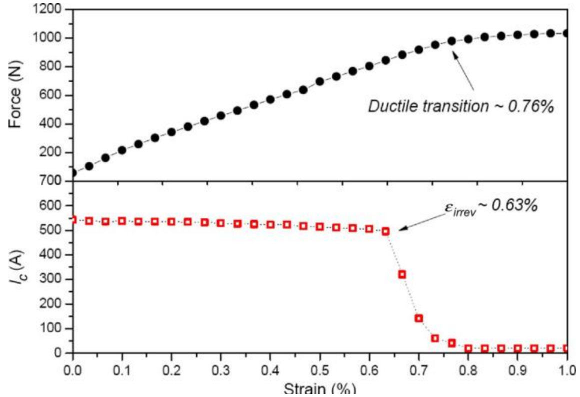
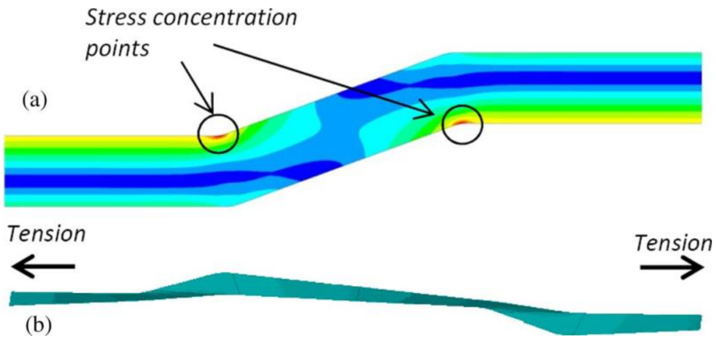
Mechanical properties – longitudinal stress-strain

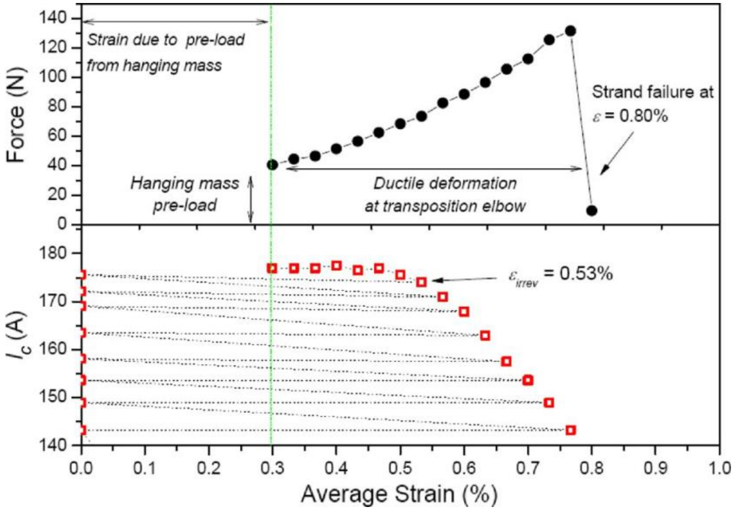


SuperPower 12 mm wire

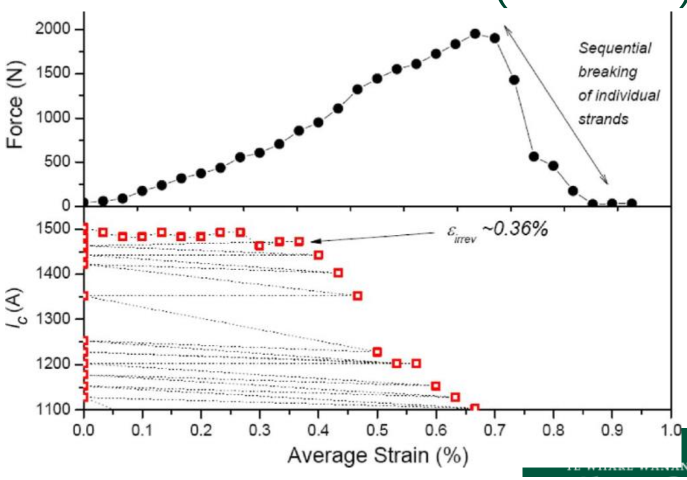
Irreversible change @ 840 N (700 MPa).



Von Mises stress @ 0.4% strain



Roebel 5 mm strand (146 MPa)



15/5 Roebel cable

Irreversible change @ 850 N (113 MPa).

Mechanical properties

- Roebel shape weakens structure
  - 1/6 reversible strain limit of straight wire
- Mitigate through
  - Potting
  - Reinforcement and wrapping
- Transverse stress effects
  - Again get stress concentration
  - Up to 45 MPa without I_c degradation (15/5 cable - CERN)
  - Degradation at 10 MPa, (10/2 cable with insulated strands - EPFL)

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Wrapped insulation

- Nomex wrapped 12 mm wide cable
- Need to include a reinforcing Hastelloy or stainless steel tape
- Nomex adds 200 microns total thickness

Roebel cable ready for testing at Siemens Corporate Technology, Germany.

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Winding and Potting coils

- Strands need to move during coil winding
  - Tight insulation wrapping not advisable
- Coated conductor has known interfacial mechanical weakness which can cause problems in potting
  - This applies to Roebel as well
  - We have damaged cable by using Stycast
- Getting complete void filling needs consideration for large coils

Conclusions

- Manufacturing procedures in place for long lengths
- I_c performance
  - Cables preserve tape performance (~90%)
- Quality control
  - Measuring magnetic *Correl* is relatively easy
  - Measuring strand I_c is time consuming and adds risk
- Cables up to 25 m (15/5 cables) delivered to customers
  - We have wound up to 40 m length
- Cost ultimately dominated by wire cost
- AC loss well characterised (not discussed here)

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Thank you for your attention!