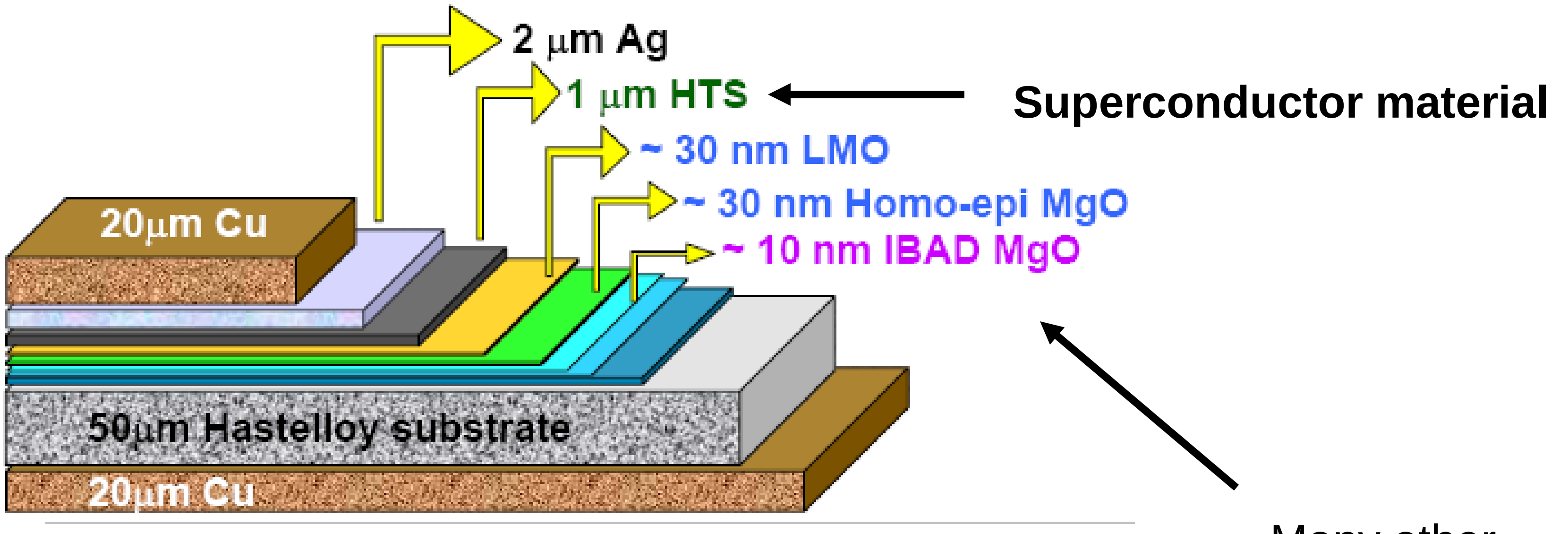
Development of YBCO Roebel cables for high current capacity and management of AC loss

N.J. Long, R.A. Badcock, M. Mulholland, Z. Jiang, S. Lakshmi, A. Wright, and K. Hamilton
Industrial Research Ltd, Lower Hutt, New Zealand
(New Zealand government research institute)
May 2009

Wellington, NZ

State of the art YBCO

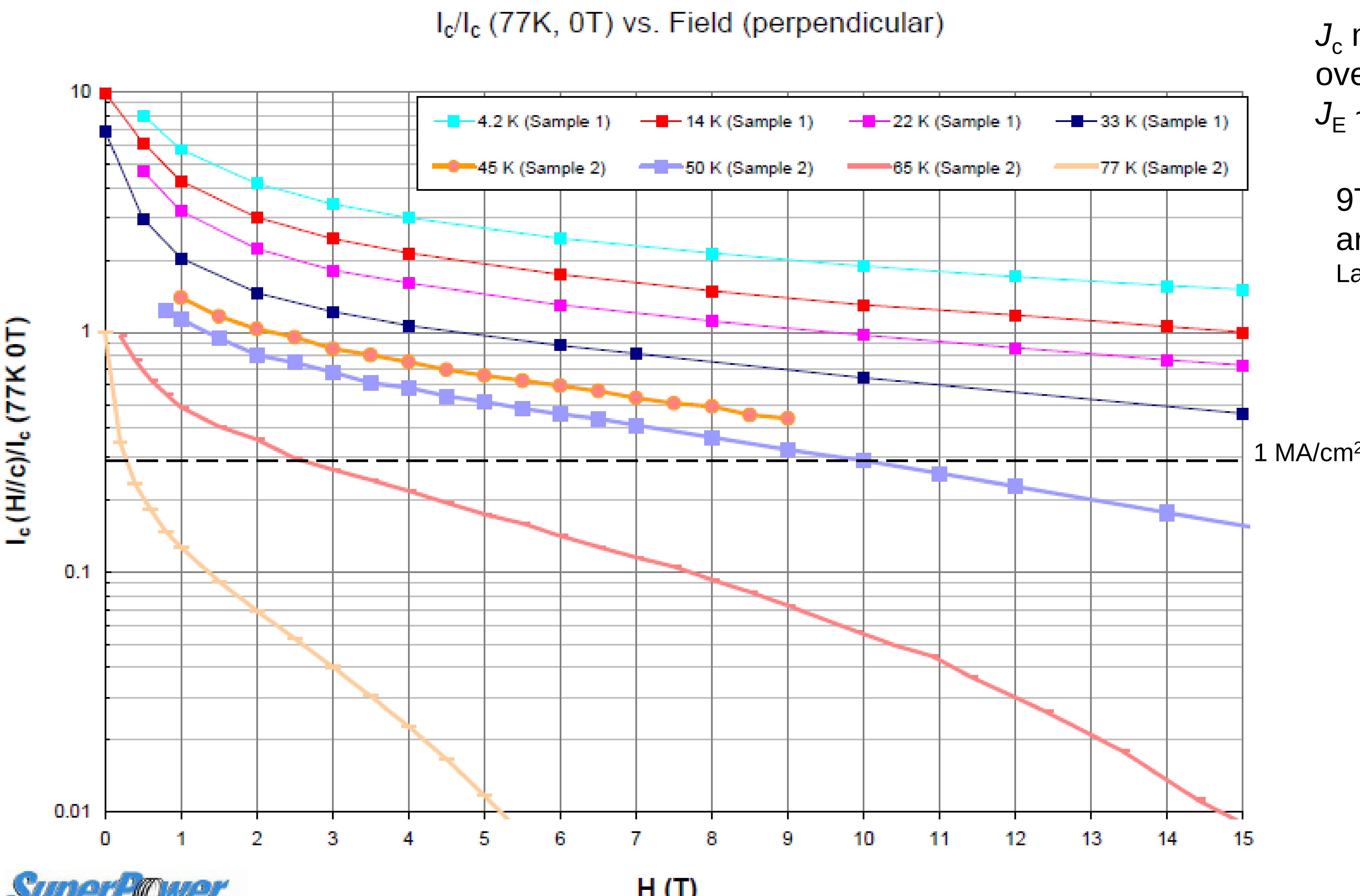
SuperPower architecture



Commercially available wire
Superpower I_c = 250A/cm, 77K,sf

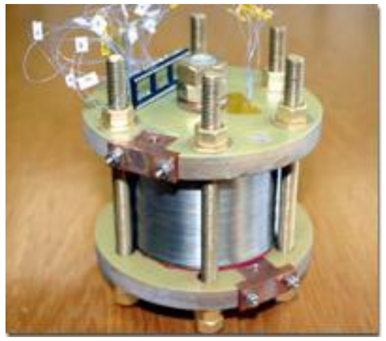
AMSC I_c = 200A/cm, 77K,sf

Field and temperature scaling



J_c more than 1 MA/cm^2 over a very wide range, J_E ~ 1% J_c

9T magnets at 55K are possible ! (D. Larbalestier, NHMFL)



NHMFL YBCO insert coil (2007)
4.2K central field 26.8T in 19T background

SuperPower Inc.

INDUSTRIAL RESEARCH LIMITED

Why YBCO Roebel Cable?

Roebel cable or Continuously Transposed Cable (CTC) is useful for

- Forming a high current capacity conductor
  - 100’s to 1000’s of Amps (maybe even 10,000s?)
- Reducing AC losses
  - rule of thumb – magnetisation losses scale with strand width

General Cable and Industrial Research Ltd have formed a company to commercialise this technology: General Cable Superconductors Ltd.

Designing the Roebel strand

- The strands have a serpentine shape
- YBCO conductor is cut to this shape
- Strand width, transposition length and crossover angle can be chosen to obtain the desired current capacity and mechanical properties

Figure – Roebel strand

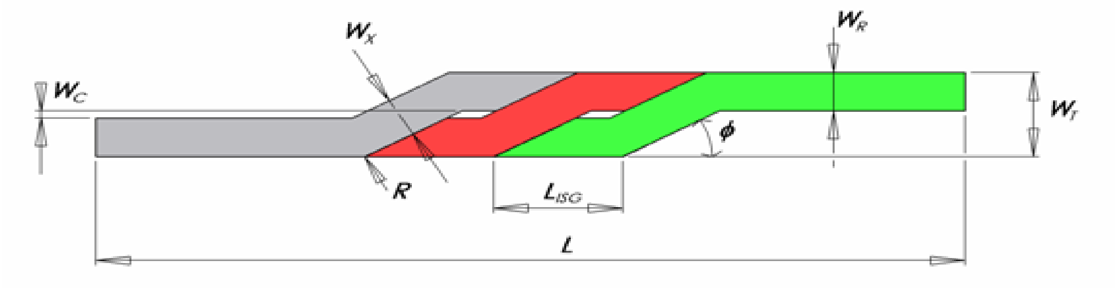


Figure – Strands wound together and geometric parameters

Cables are labelled with the convention

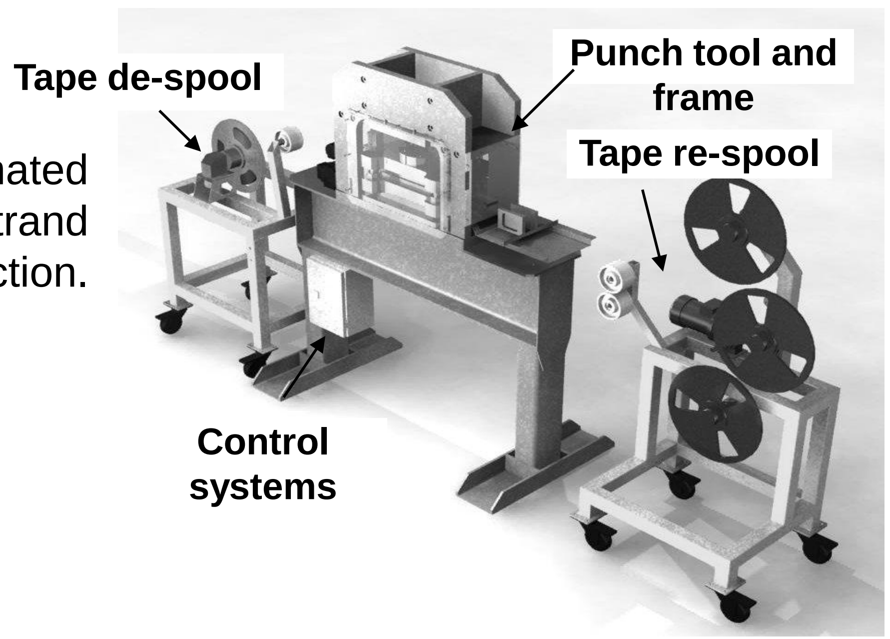
# of strands / strand width

We are making two designs 15/5 and 10/2

Figure 10/2 cable

Cutting the strands

Figure - Set-up for automated multi-strand Roebel strand production.



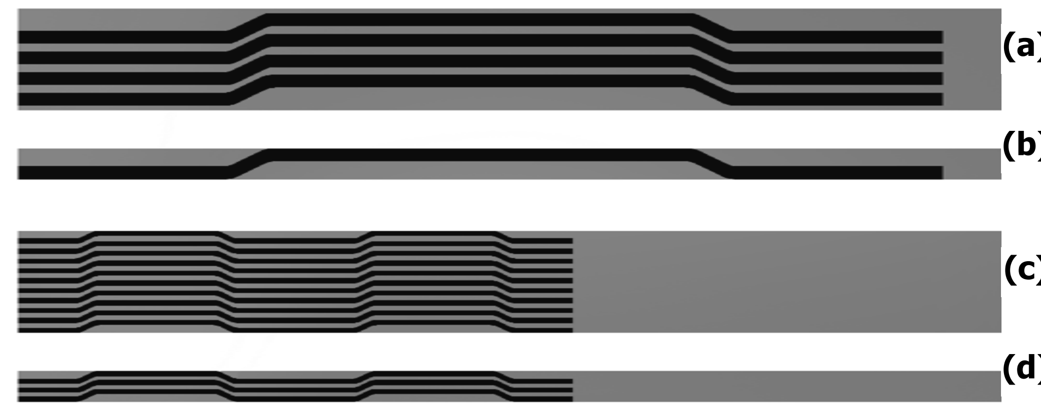


Figure - Formation of Roebel punched strands in 40 mm and 12 mm wide feedstock material.

(a) 4 x 5 mm strands in 40 mm wide material,

(b) 1 x 5 mm wide strand in 12 mm wide material,

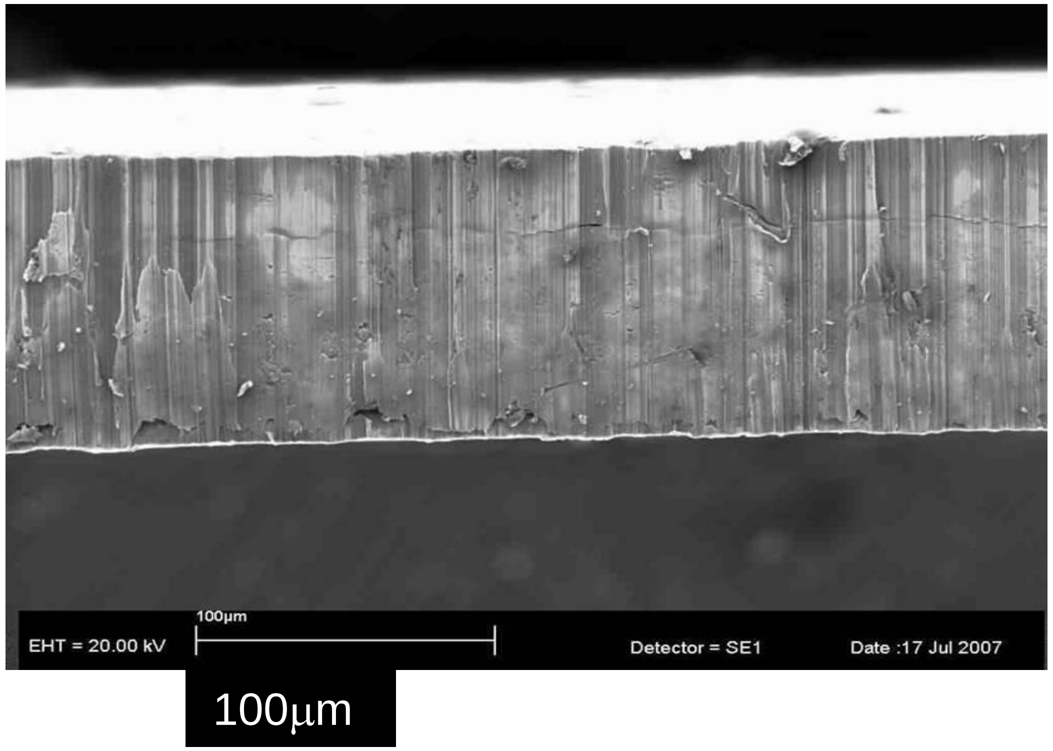
(c) 10 x 2 mm strands in 40 mm wide material,

(d) 3 x 2 mm wide strands in 12 mm wide material.

Figure – Cut strands emerging from the punching tool. Ten 2.0 mm strands are formed by continuous punching of 40 mm wide YBCO conductor.

Cutting HTS Roebel Strands
- Quality of cut surface

- To maximise HTS yield, cut edge must minimise damage to material
- Punch tooling designed provides high quality edge
  - Alternate techniques investigated but not suitable (laser, water and wire cutting)
- Typical strand edge shown



Planetary Winding

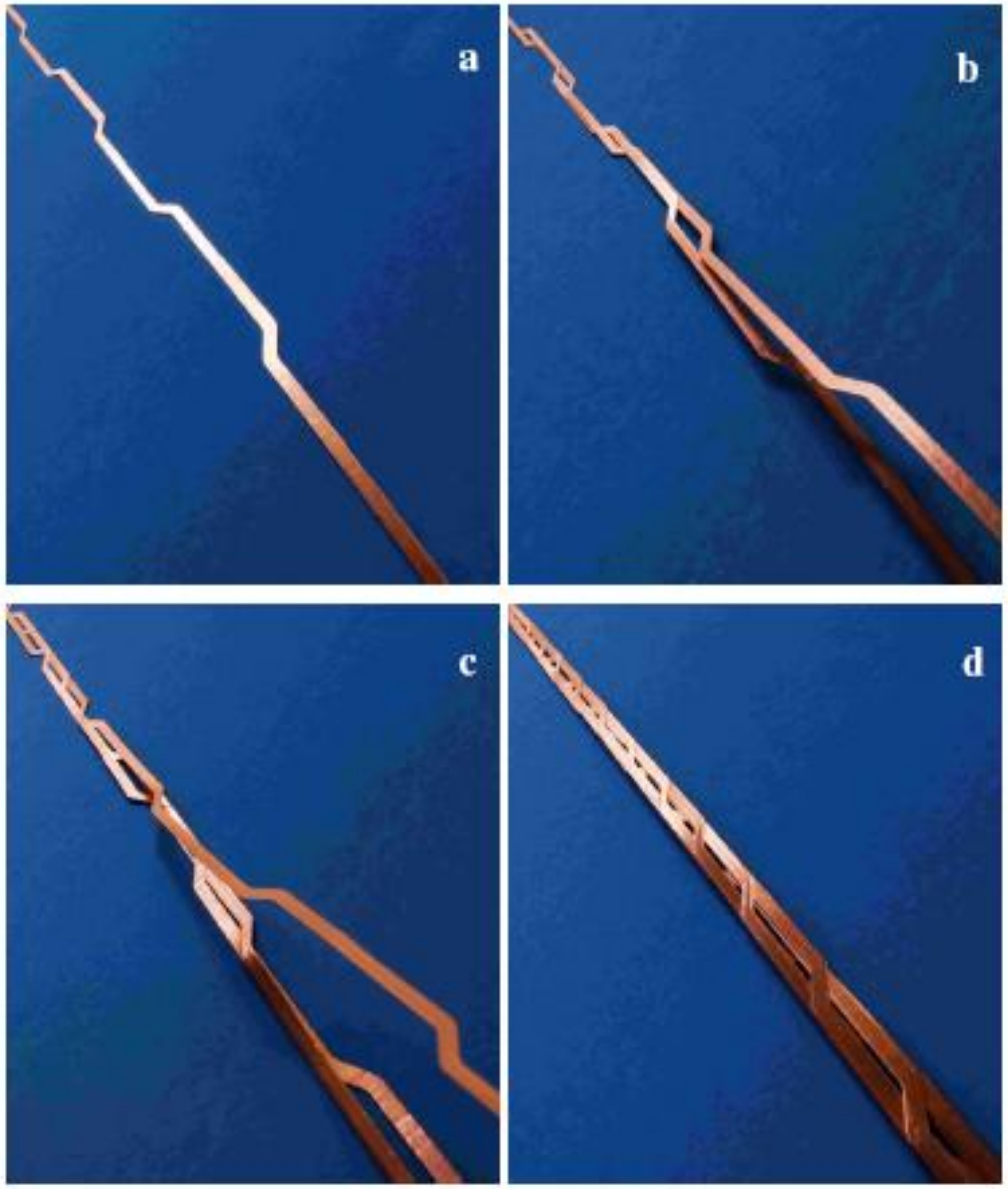
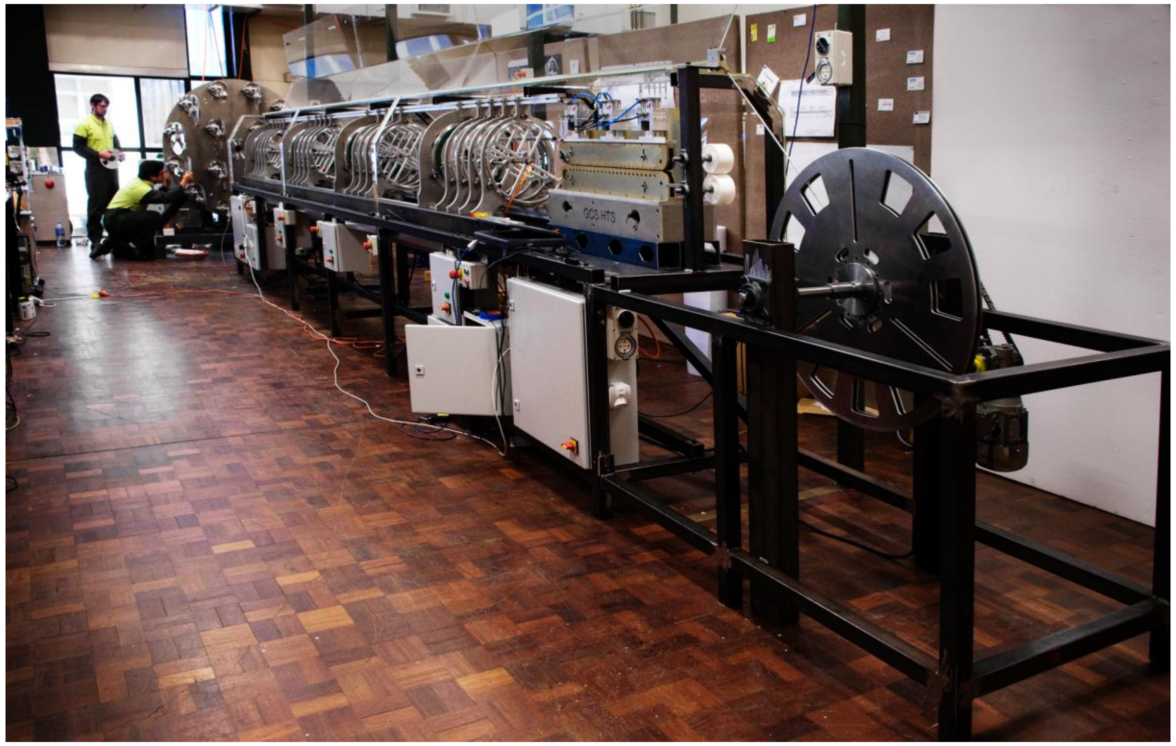


Figure 1: Winding of CTC a) single strand b) winding in second strand c) winding in third strand d) completed cable

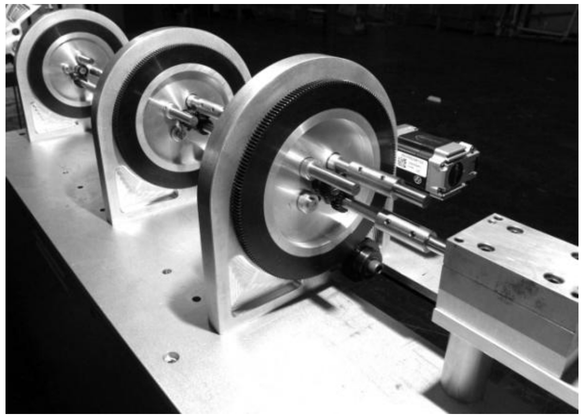
Automated Winding

The cable is wound using an automated planetary wind system.



Winding machine for 15/5 cable

Figure - Geared winding heads allow four strands to be cabled at each stage. The design is scaleable for different strand geometries.



Winding machine for 10/2 cable

Wire specifications

Wire must have good transverse as well as longitudinal I_c

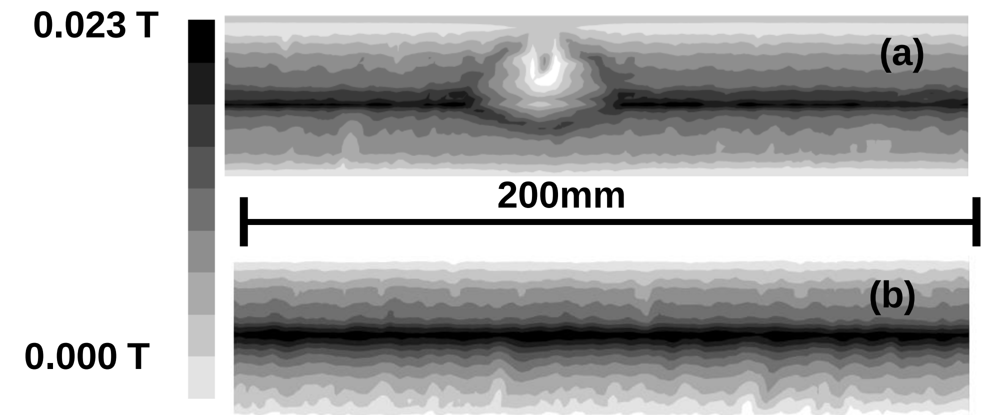
Quantify using statistical correlation with Bean model* profile

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

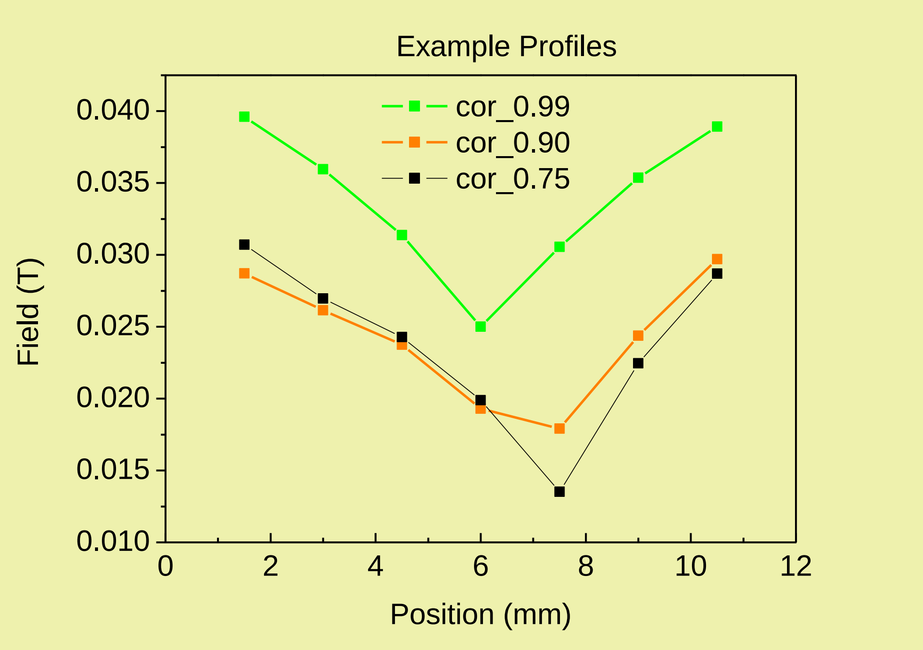
where

X is a dataset representing Bean model

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

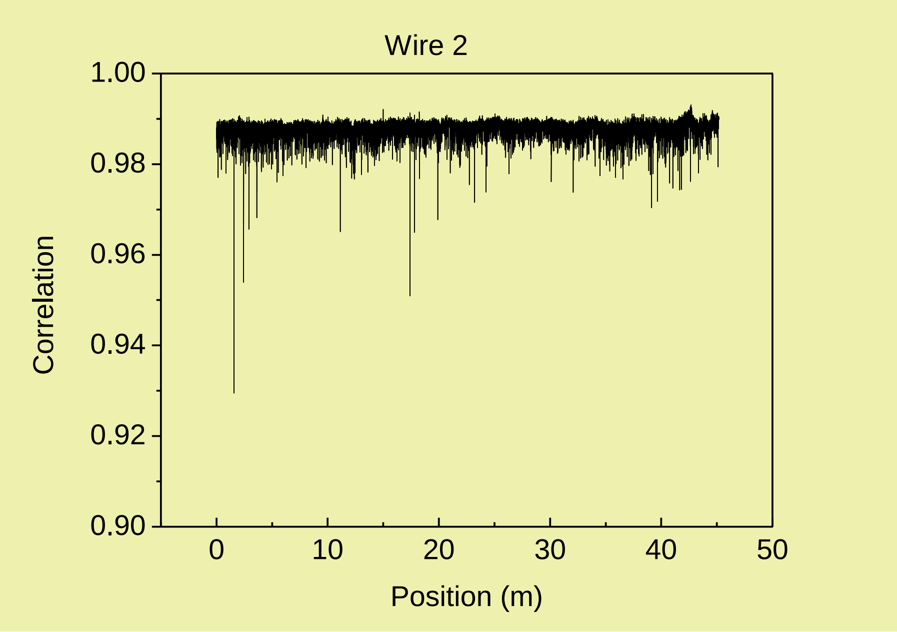


We use continuous scanning of the Remanent magnetic field to assess tape quality (a) tape with a known defect, and (b) tape with only small scale variability.



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

*Use a FEM derived profile for tape with weakly magnetic substrate



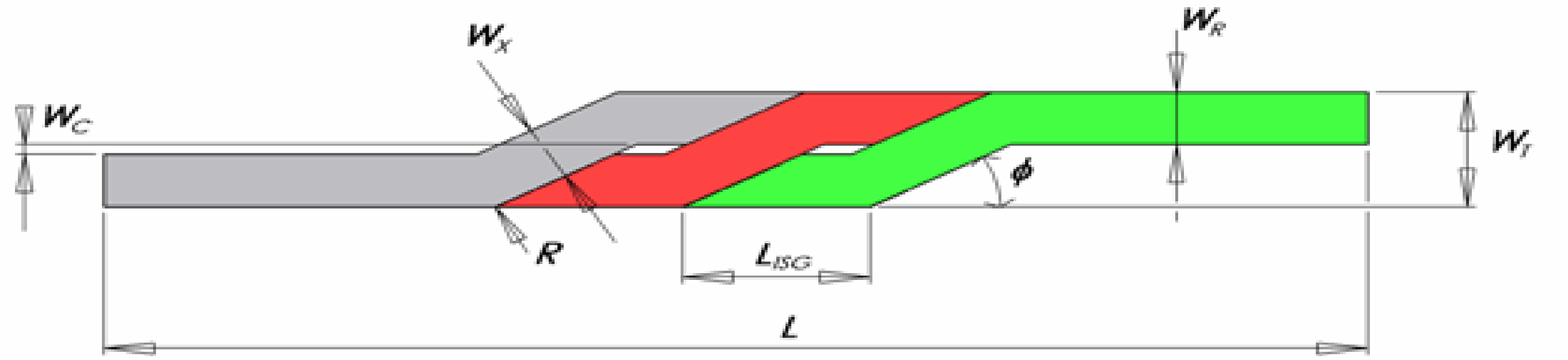
Magnetic imaging "TapeScope"

Uses 4x 7 element Aeropoc Hall sensor array
Can image 12mm or 40mm AMSC tape

2 Cable designs at present

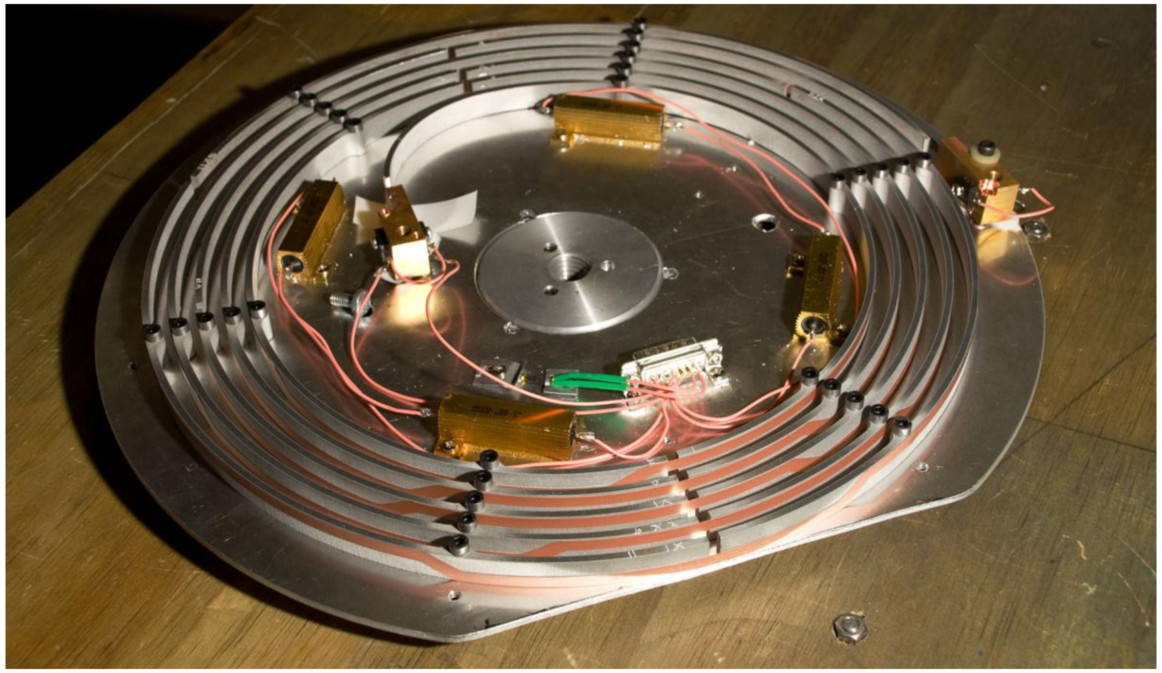
- 15/5 and 10/2 parameters

Parameter	Name	10/2	15/5
L_{TRANS}	Transposition length	90 mm	300 mm
W_R	Strand width	2 mm	5mm
W_X	Crossover width	2 mm	6.0mm
W_C	Strand edge clearance	1.0 mm	2.0mm
W_T	Cable width	5.0 mm	12.0 mm
Φ	Roebel angle	30°	30°
L_{ISG}	Interstrand gap	9 mm (10 strand) 18 mm (5 strand)	30 mm (10 strand) 60 mm (5 strand)
R	Cut-out fillet radius	0.75 mm	3.0mm

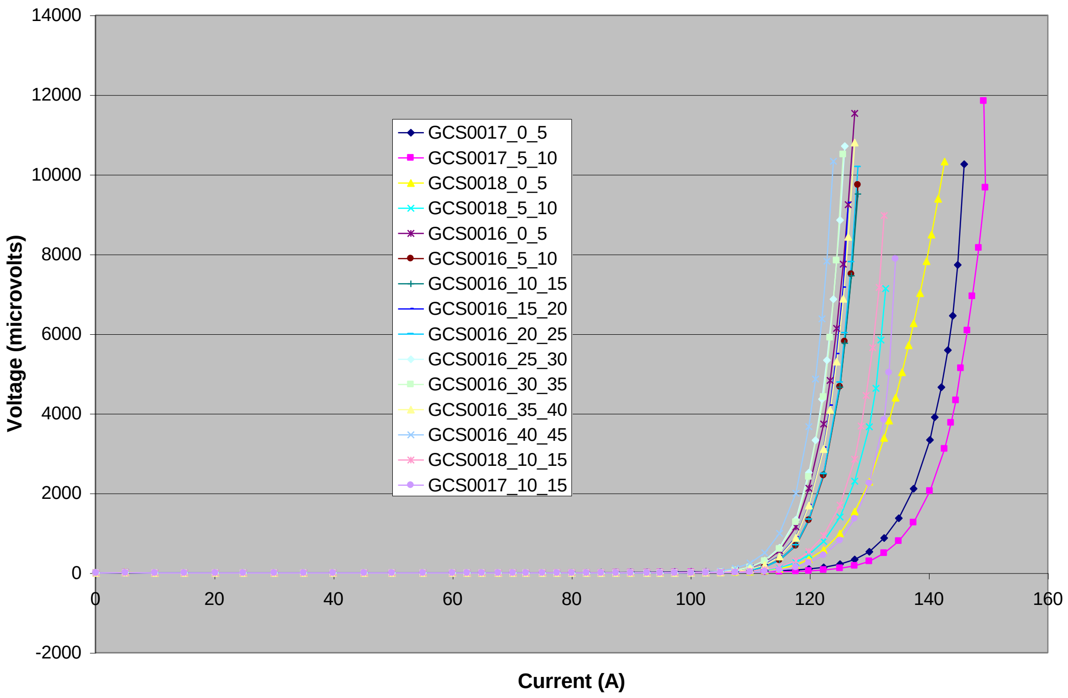


Quality control

Strand I_c's are tested before assembly

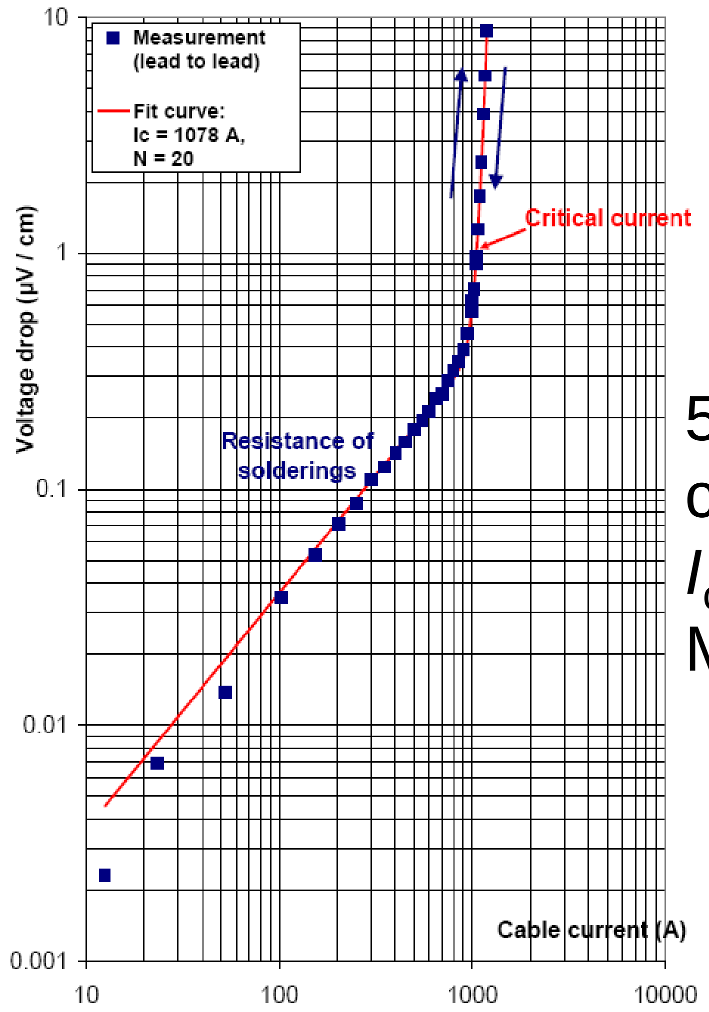


Pancake I_c test assembly for strands gives 97% of self-field I_c

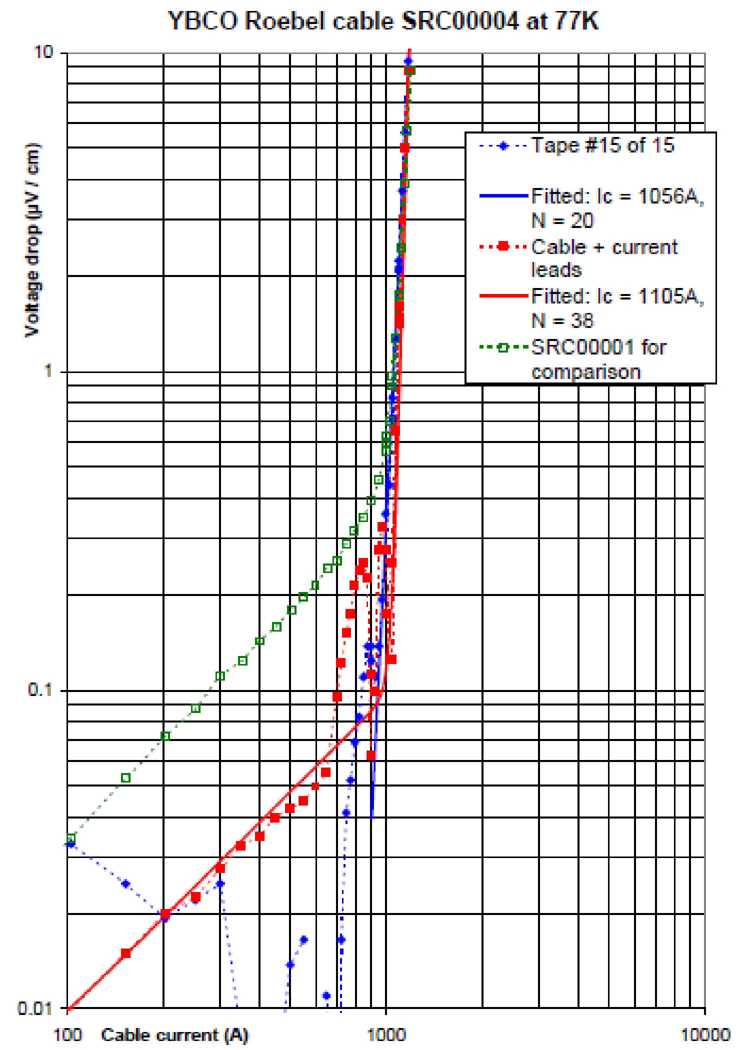


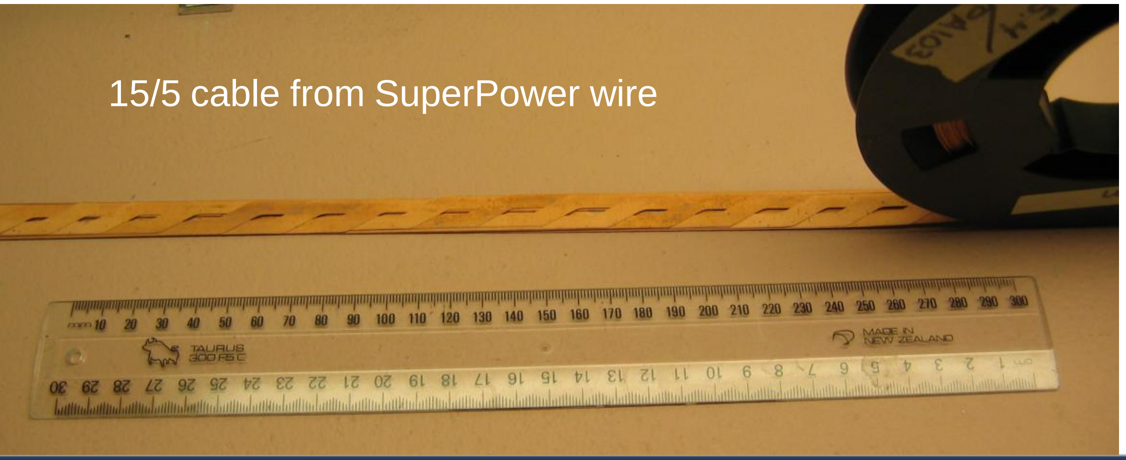
Some results for 5mm strands

I_c measurement of cables



5m length 15/5 Roebel cable.
I_c = 1.1kA, n = 20, @77K
Measurement by Siemens

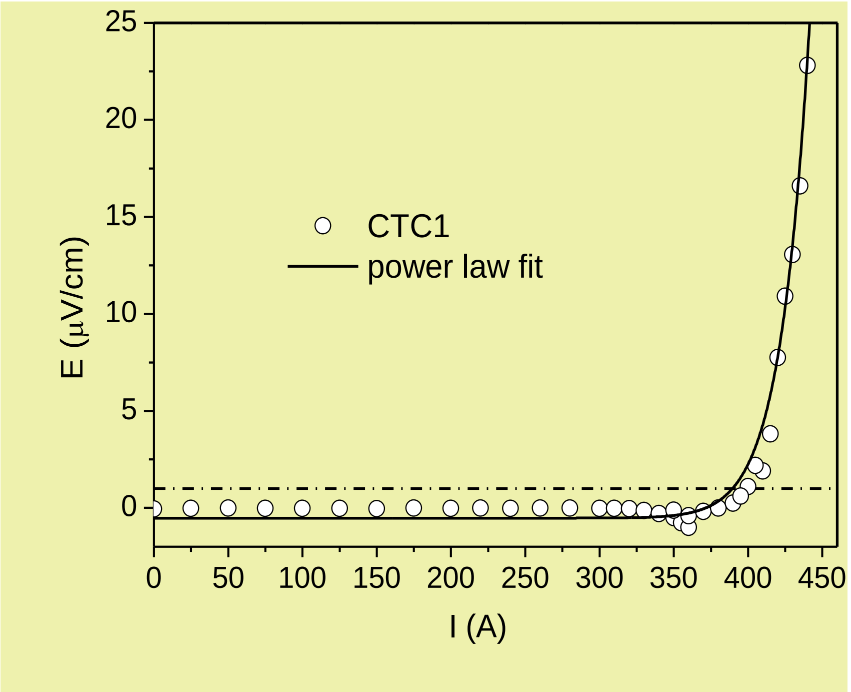




5m length 15/5 Roebel cable.
I_c = 1.1kA, n = 38, @77K
Measurement by Siemens

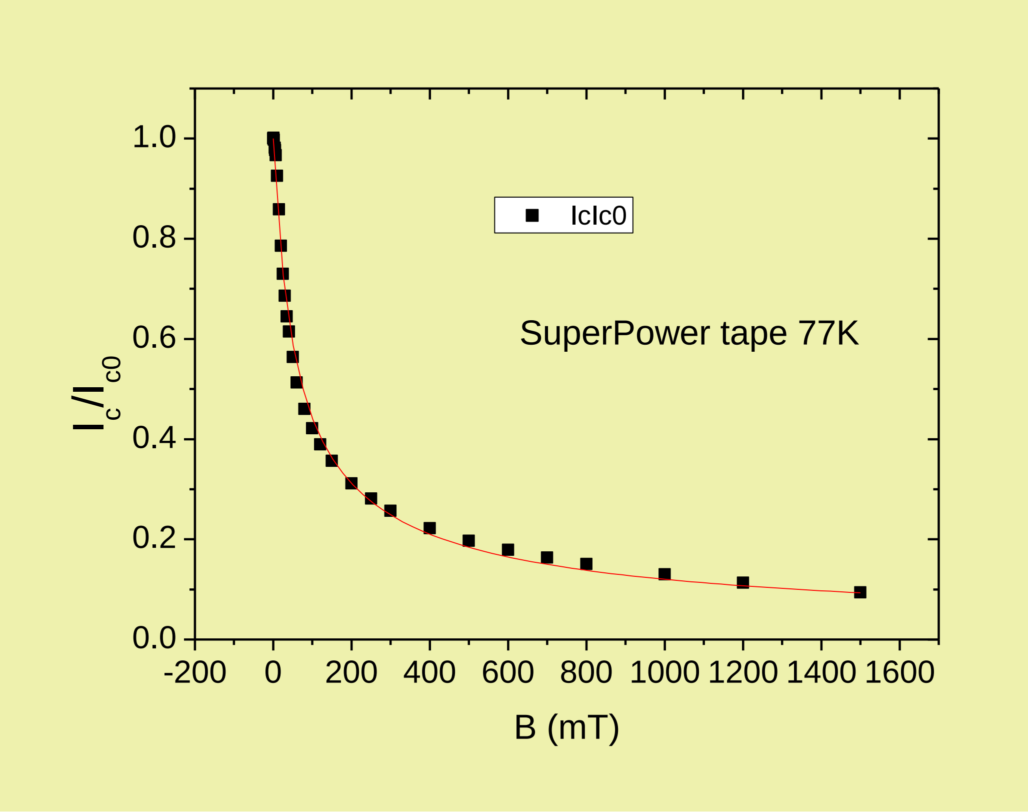
INDUSTRIAL RESEARCH LIMITED

I_c of 10/2 cable (AMSC wire)

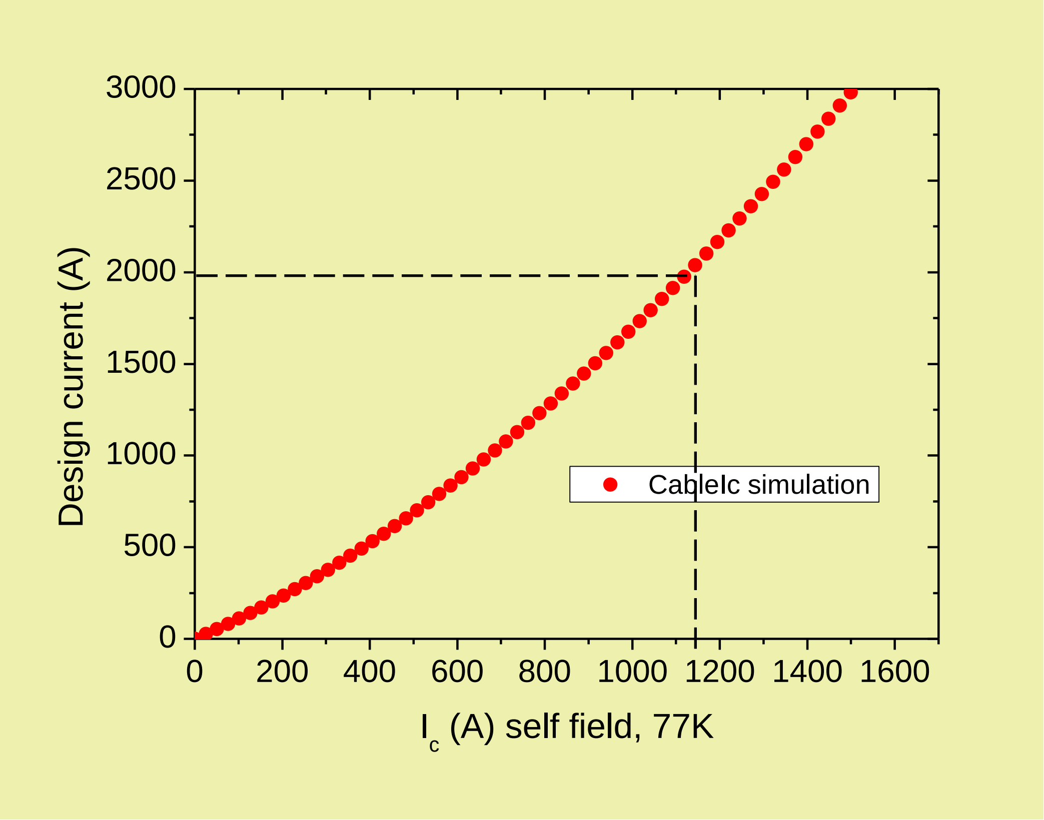


10/2 Roebel cable
I_c = 407 A, n = 40, @77K

Self field effects



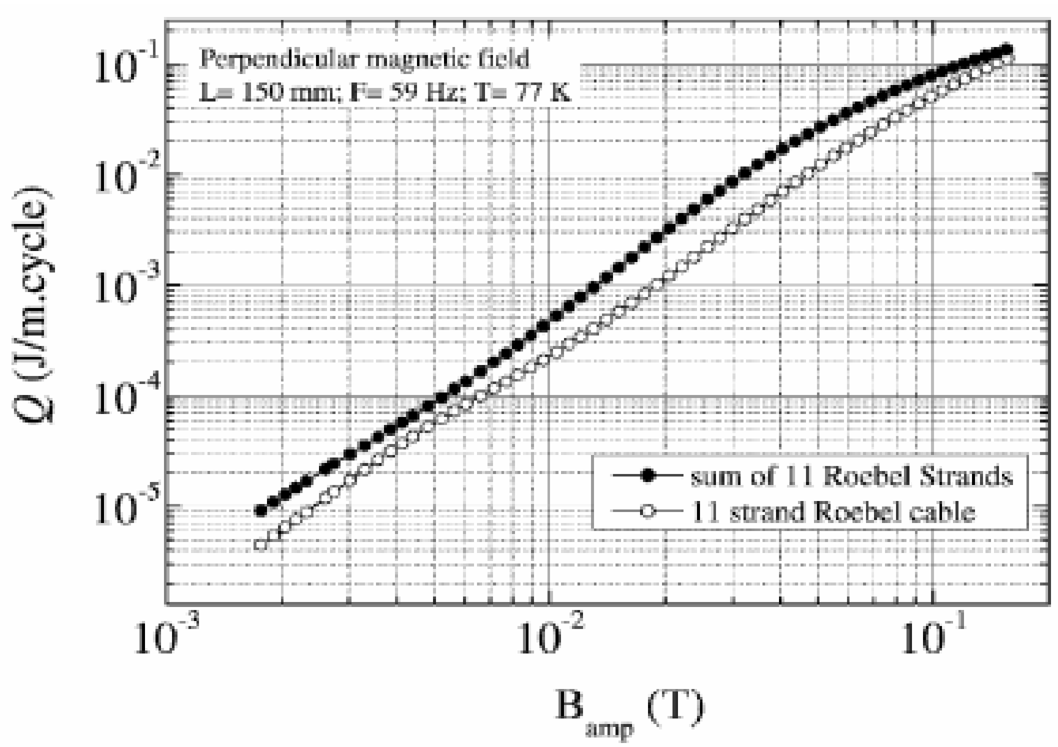
Scaling of SuperPower tape in perperdicular field



Estimated scaling for a 15/5 cable:
15 strands x 5mm wide at 130A,
design I_c = 1950A and I_c(sf) =1130A.

Based on modelling by FZK

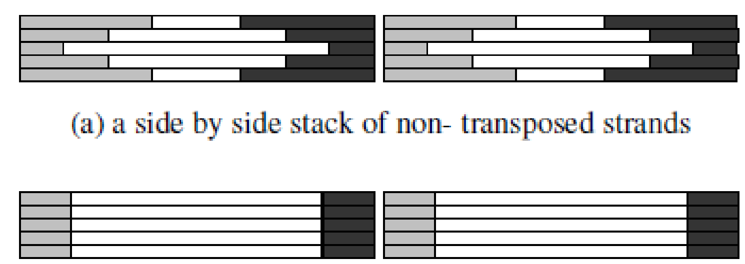
AC loss - Magnetisation



11/2 cable (AMSC wire)

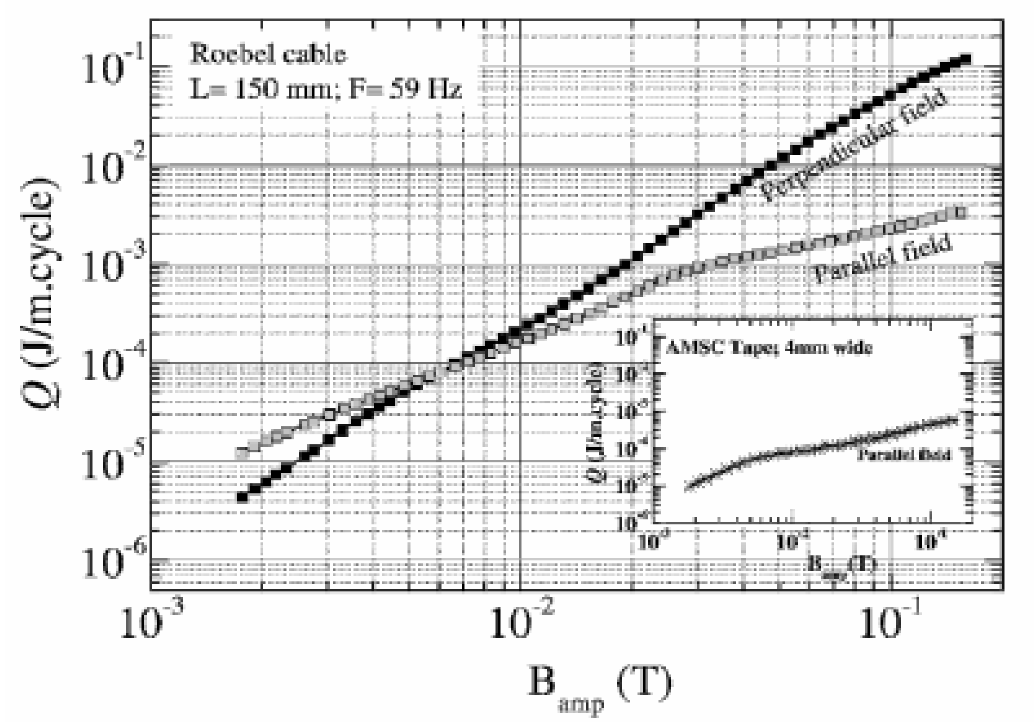
- Cable I_c ~ 430A
- At high field strands are all fully penetrated
- Loss equals sum of strands
- At low field cable loss is lower due to shielding effects
- Low field loss is dominated by substrate

Current distributions



(a) a side by side stack of non- transposed strands

(b) transposed strands of a Roebel cable

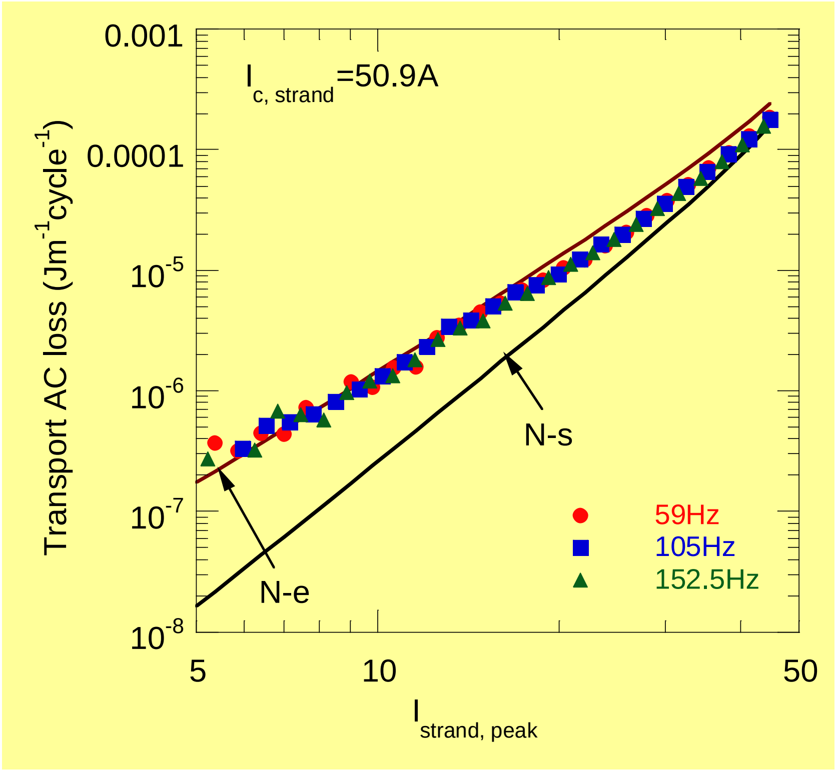


11/2 cable (AMSC wire)

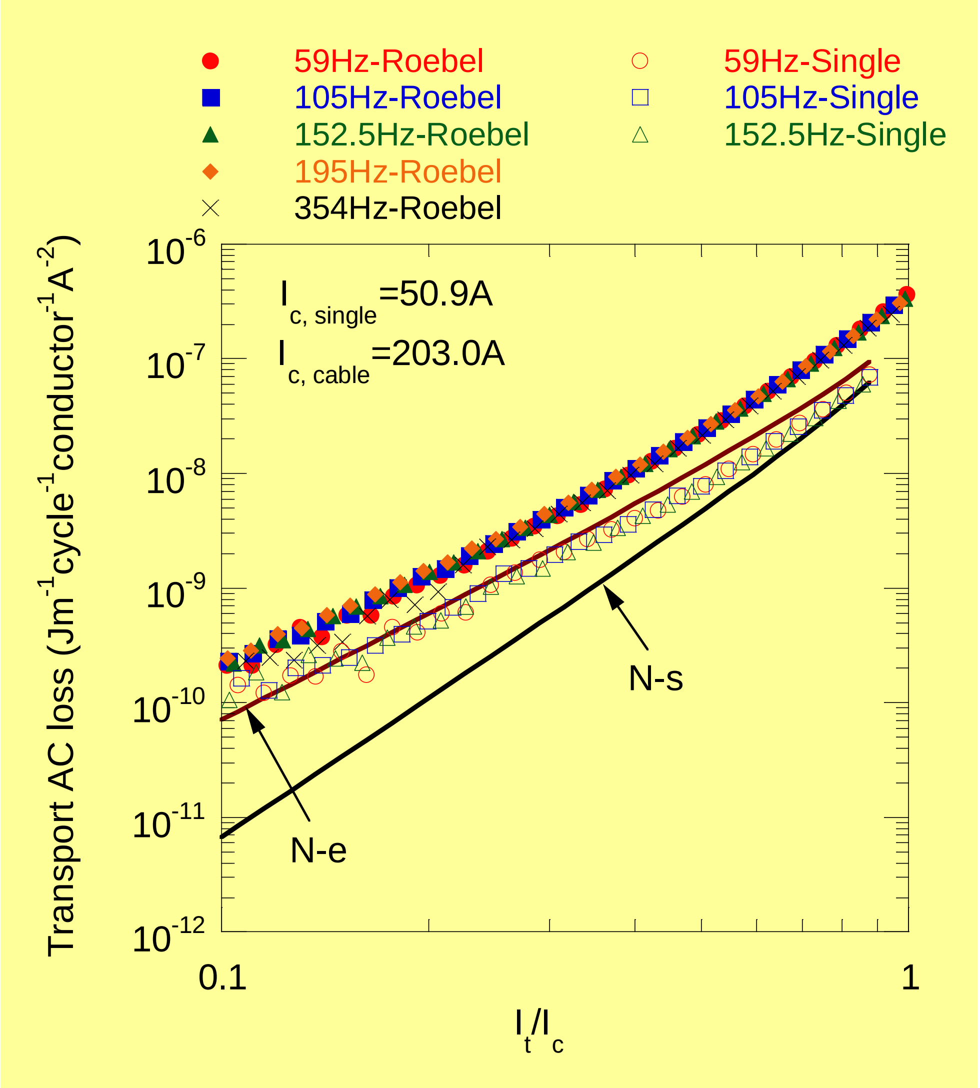
- Parallel field accentuates losses in weakly ferromagnetic substrate at low field.
- For non-magnetic substrate parallel field losses are unmeasurable

AC loss - transport

5/2 Cable made from SuperPower wire



Measured transport AC loss in single strand.



Comparison of normalized AC losses in Roebel cable and single strand.

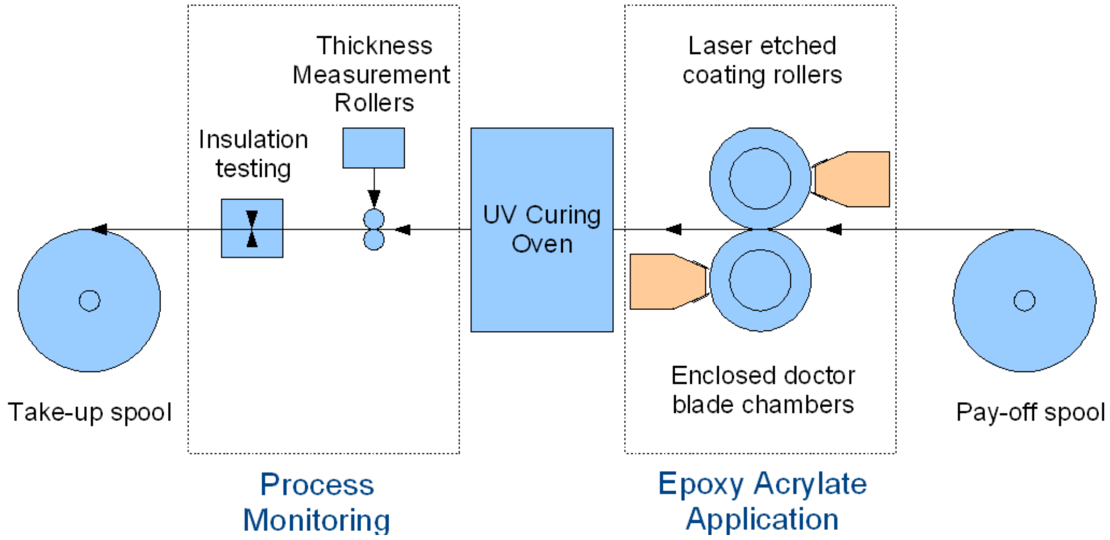
Transport loss 5/2 cable

- Cable I_c ~ 200A
- Transport AC loss in the 5/2 Roebel cable is much larger than in a single strand.
- Hysteresis loss dominates the transport AC loss in the cable.
- At I_t/I_c = 0.85, the normalized AC losses in the Roebel cable were ~ 2.9 times of those in a single strand compared to 5 times predicted for a configuration of stacked conductors with small separation.

Strand Insulation

- Individual strands can be insulated to prevent current sharing
- Low voltage only

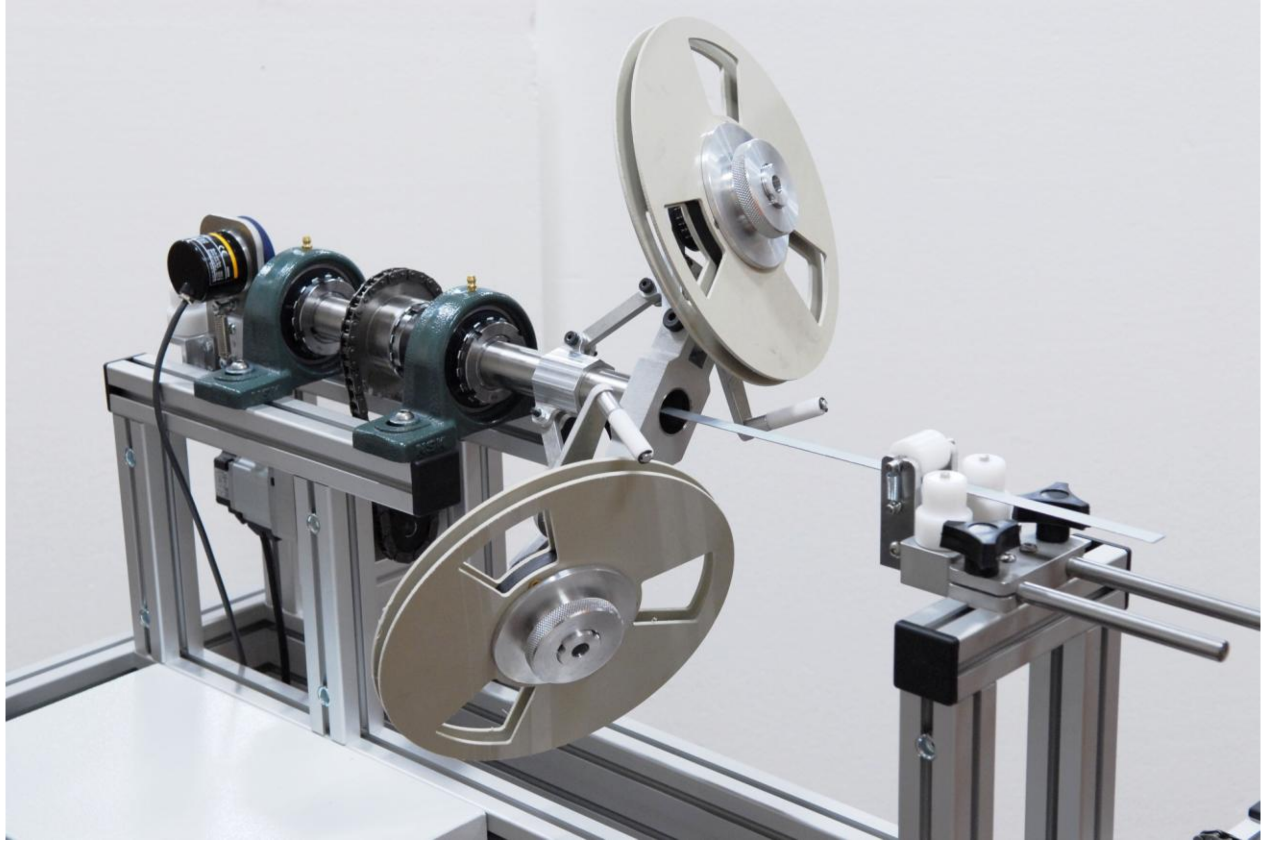
Roll coater to insulate strands



Cable insulation

Extrusion coating: fluorinated polymer

Wrapping: kapton, nomex paper



No in situ processing of wire → flexible insulation options

Manufacturing Plans

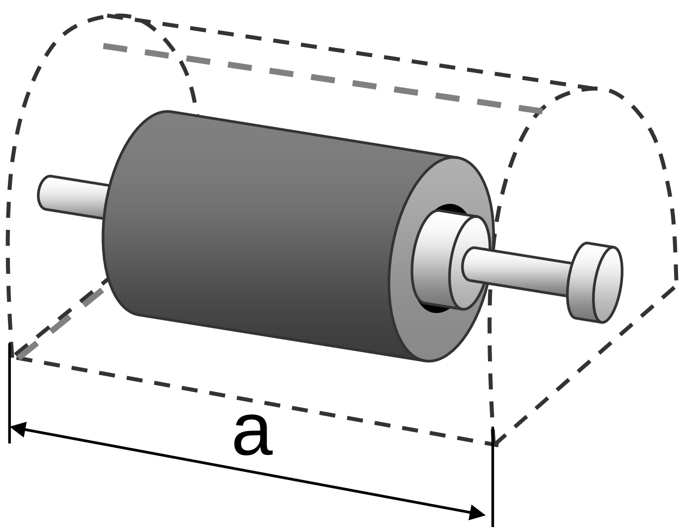
- Establish pilot plant facility with automated production of 10/2 and 15/5 cable
- Incorporate cable wrapping and extruded insulation coating
- Strand insulation available
- In long term use multiple wire suppliers, e.g SuperPower, AMSC and others?

Cable manufacture equipment at IRL site

Application in generators

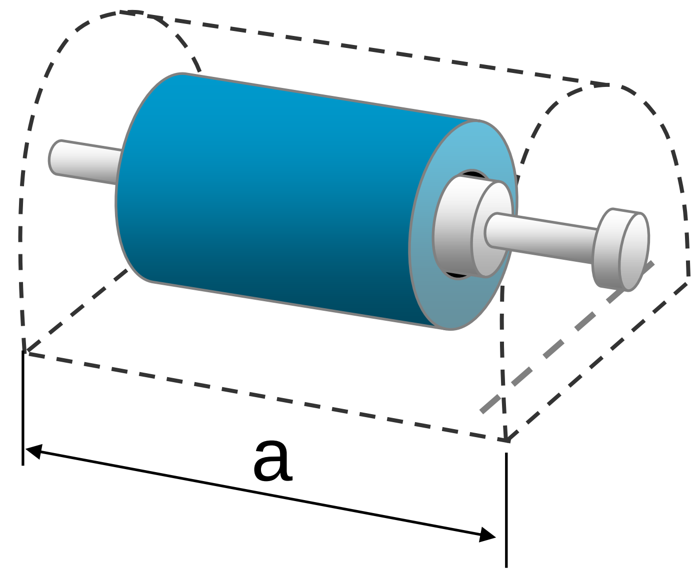
- 15/5 to be used in Siemens 150MVA prototype

• Conventional Generator



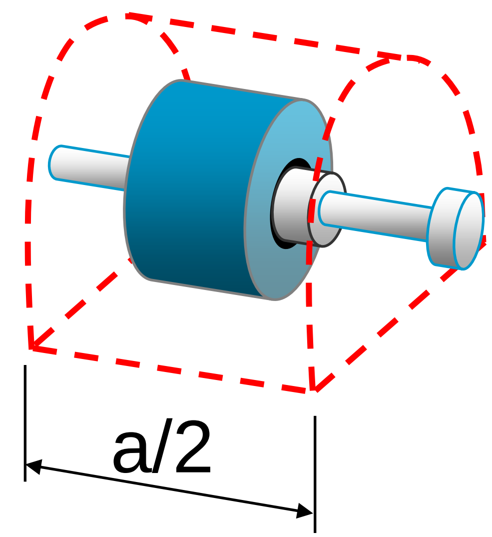
- Power rating 100%
- Ageing rotor winding
- Limited power diagram

• HTS Rotor with conventional Stator (Retrofit)



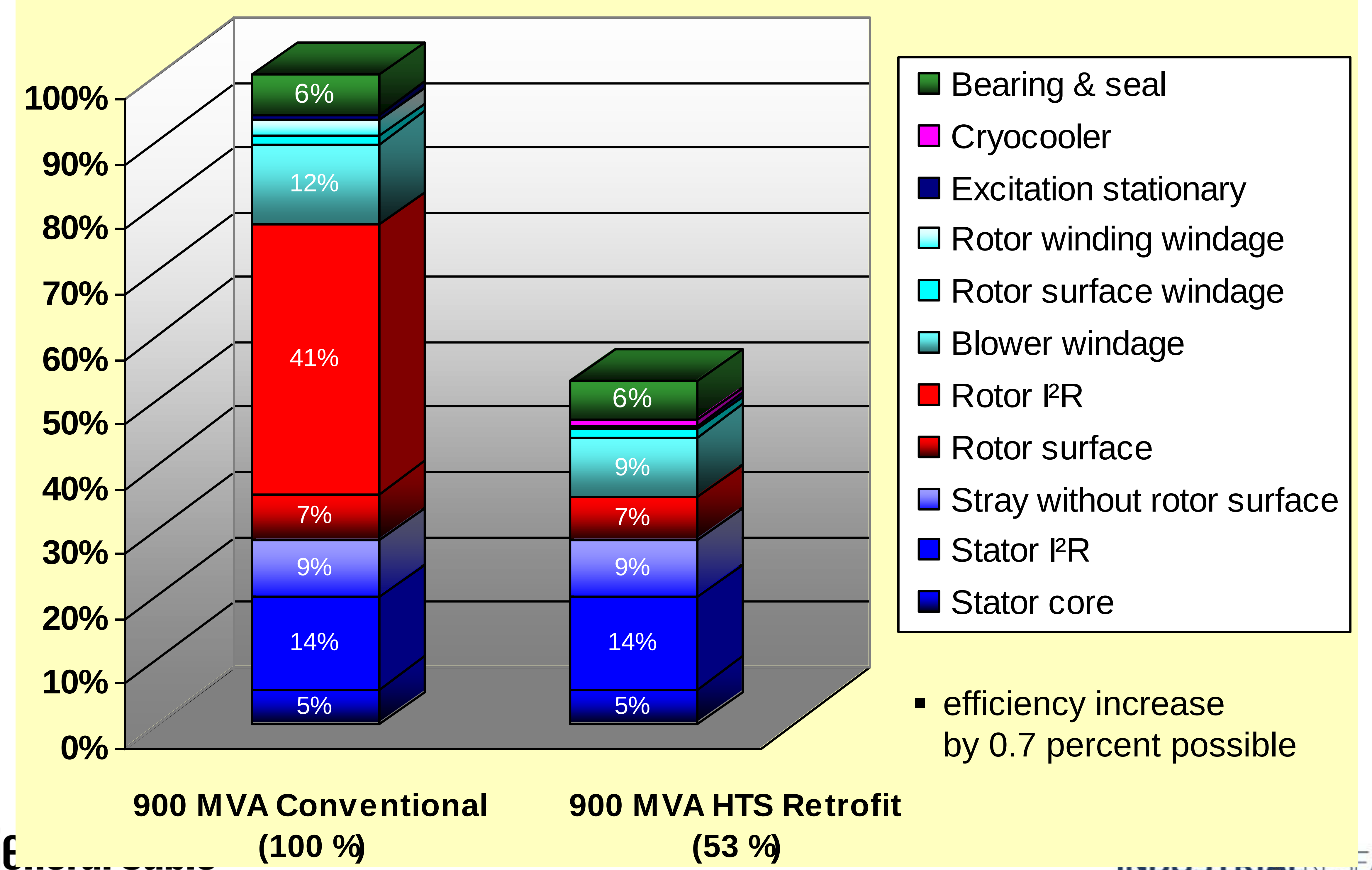
- For new apparatus or rotor retrofit
- Power rating 115%
- No ageing in the rotor
- Less limited power diagram
- Little more investment

• HTS Rotor with air-gap winding stator (High power density)



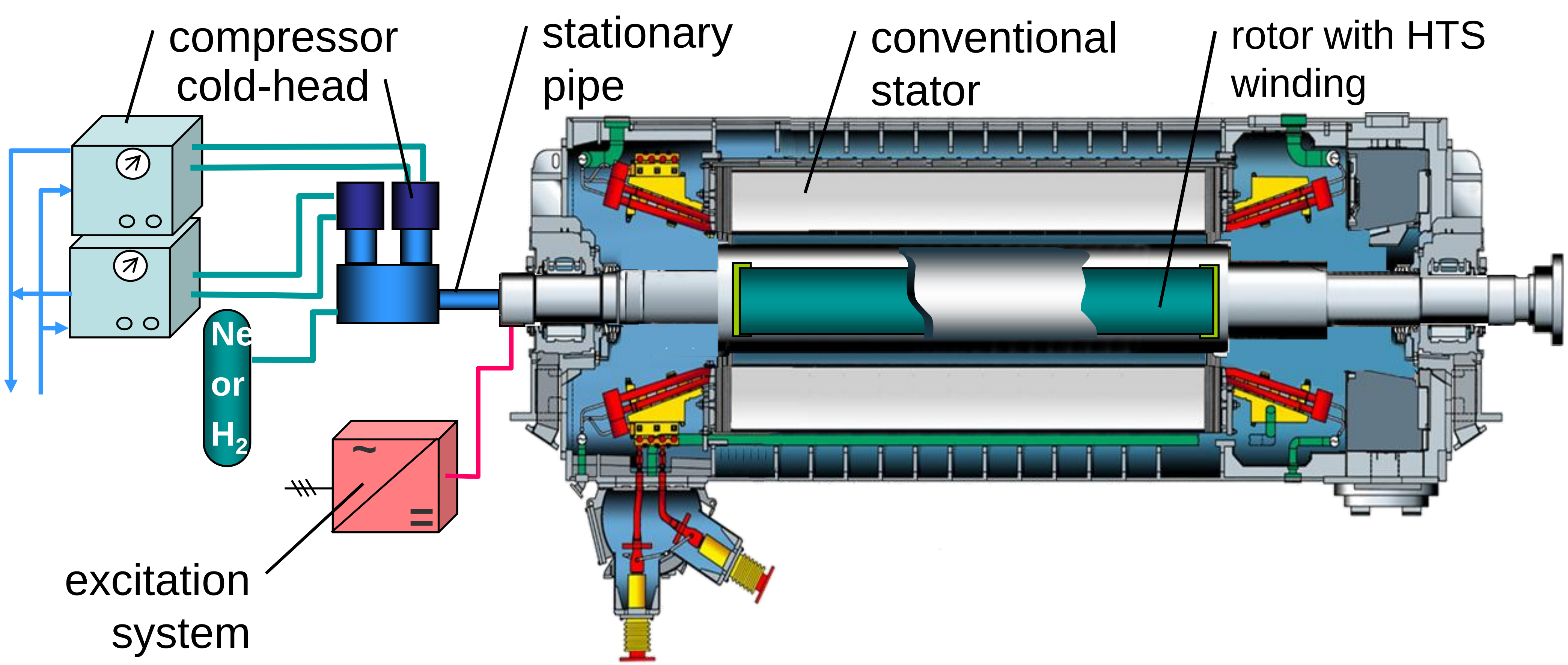
- Totally integrated design applying all benefits
- Power rating 115%
- No ageing in the rotor
- No limits in power diagram
- Improved electrical stability
- More investment

Comparison of generator losses



- efficiency increase by 0.7 percent possible

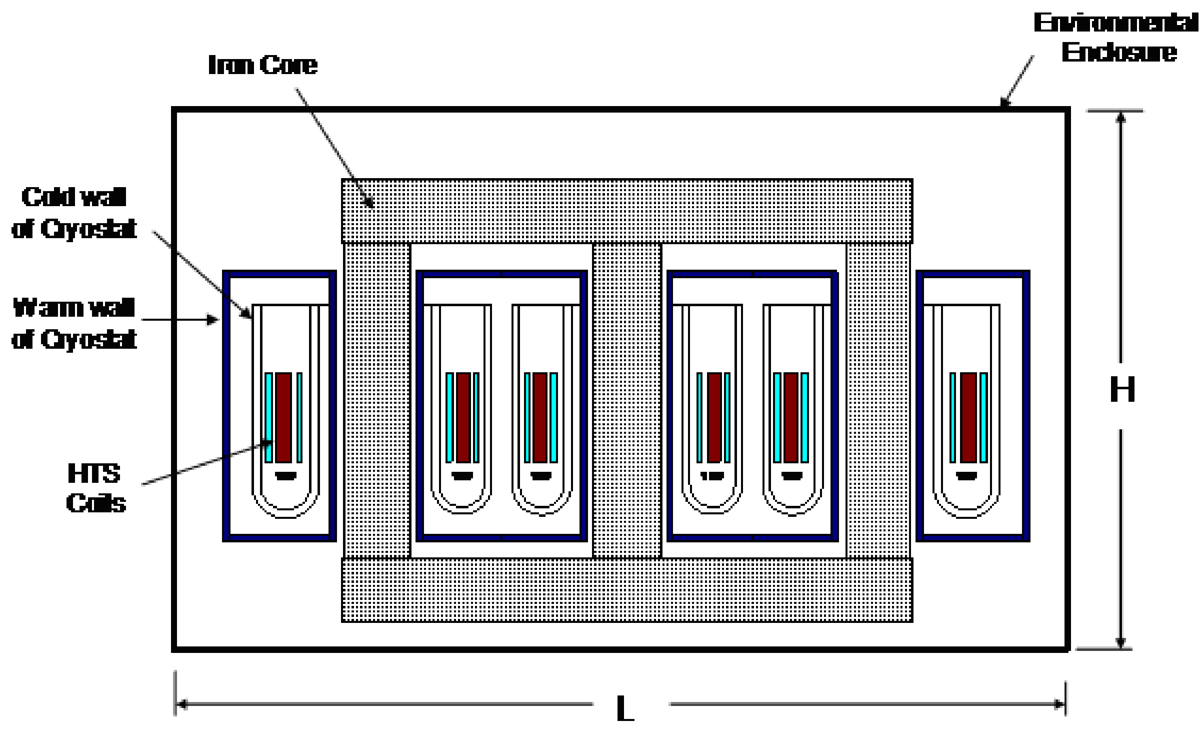
Approach: Design of a Retrofit HTS Rotor



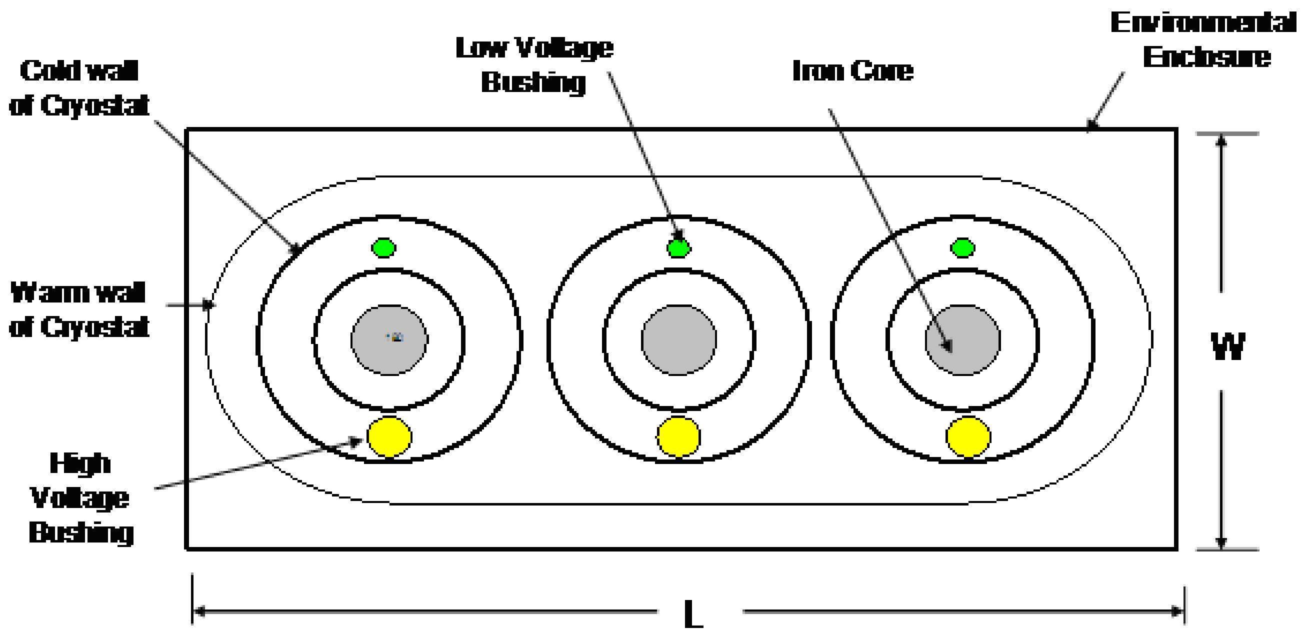
- Roebel cable with operating current ~2kA
- Simplifies rotor manufacturing

Transformers

50MVA conceptual design
Operating at 77K or 65K
-S. Kalsi



Elevation view



Plan view

Transformer benefits

- 50MVA design study shows
  - Smaller size (50MVA transformer is 1/3rd weight, 1/4th foot-print and 1/5th volumetric size of a conventional transformer)
  - Efficiency (similar to conventional)
  - No fire hazard
  - Low leakage reactance (7%) which allows serving loads with minimal voltage regulation.
  - Can carry up to 100% over-load indefinitely (without loss of life) if operated at 66K.
  - Use of CTC simplifies winding, manages AC losses

Fault Current Limiter

13.8kV conceptual design
Operating T=72K
-S. Kalsi

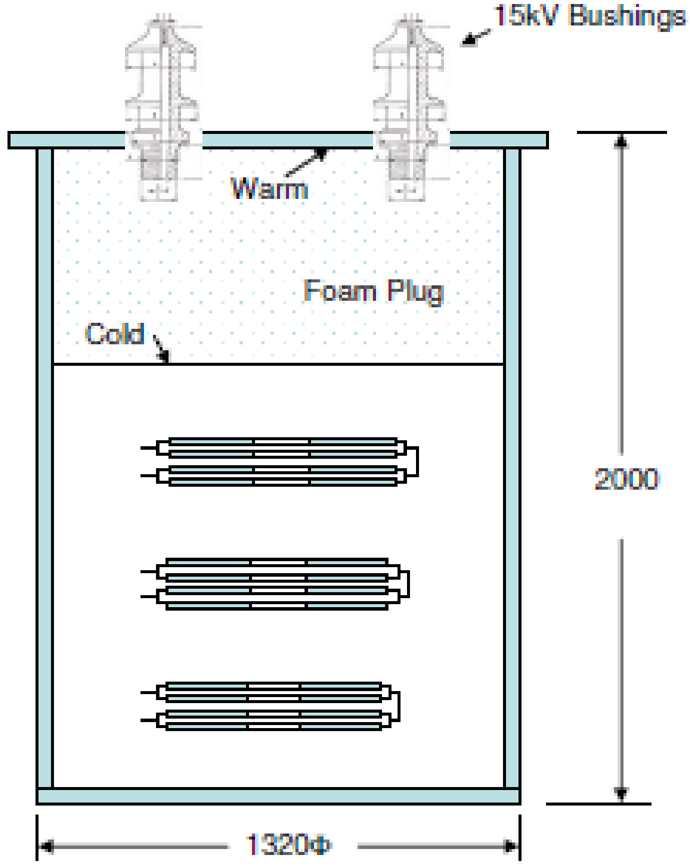


Figure 3: HTS FCL Assembly

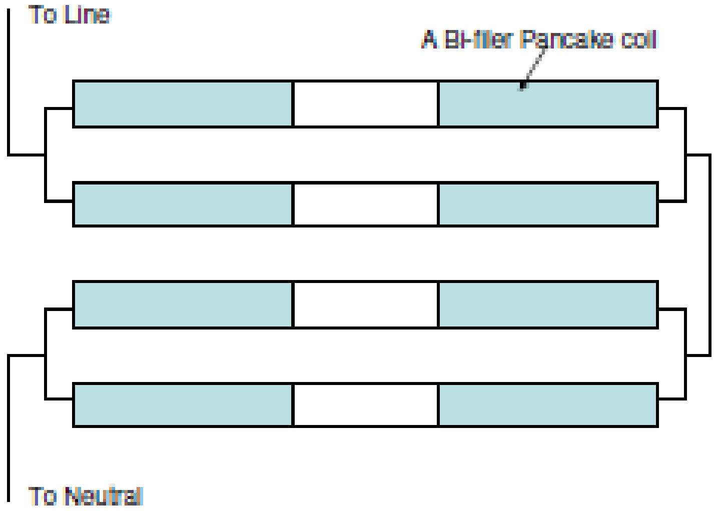


Figure 4: FCL HTS coil assembly for one phase

Table 1: Specifications for a 13.8kV, 3kA Fault Current Limiter

Parameter	*Value*
Rating, MVA	72
Line voltage, kV	13.8
Line current, kA	3
Unlimited fault current, kA	40
Limited fault current, kA	30
Fault hold time, s	0.1
Conductor type	CTC
- Number of strands	17
- Strand width, mm	5

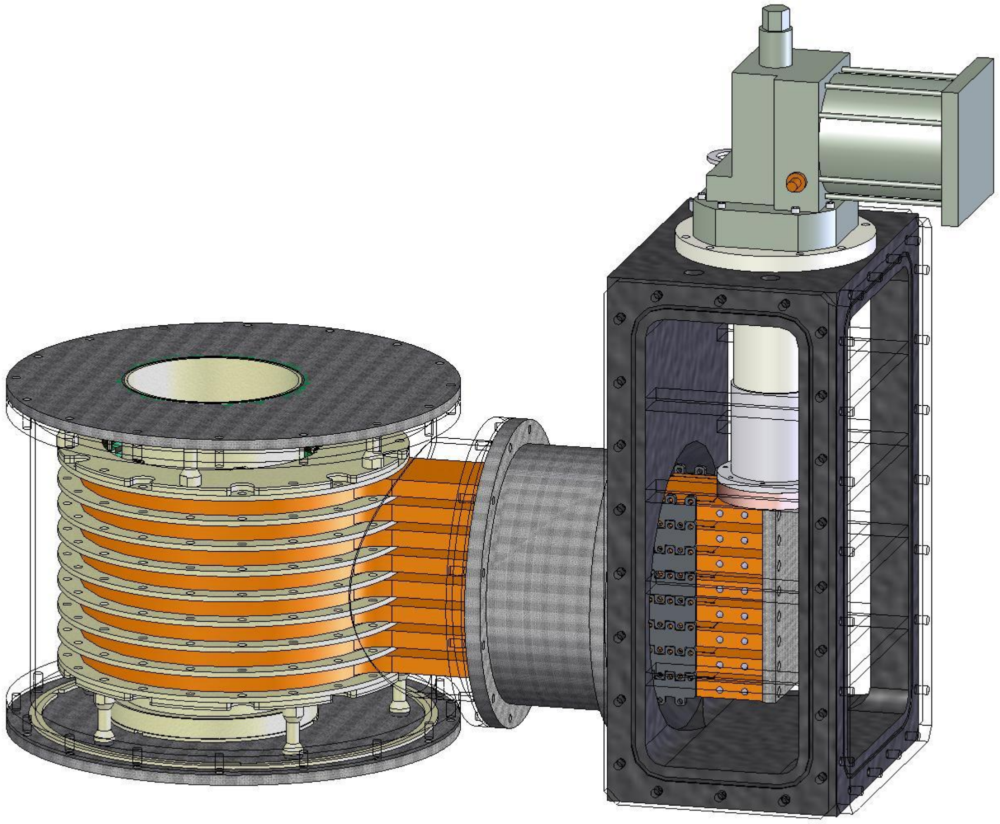
General Cable SUPERCONDUCTORS Limited

Fault current limiters

- CTC simplifies the construction of the FCL system
- Reduces overall size
- Application most attractive at sub-transmission and transmission levels

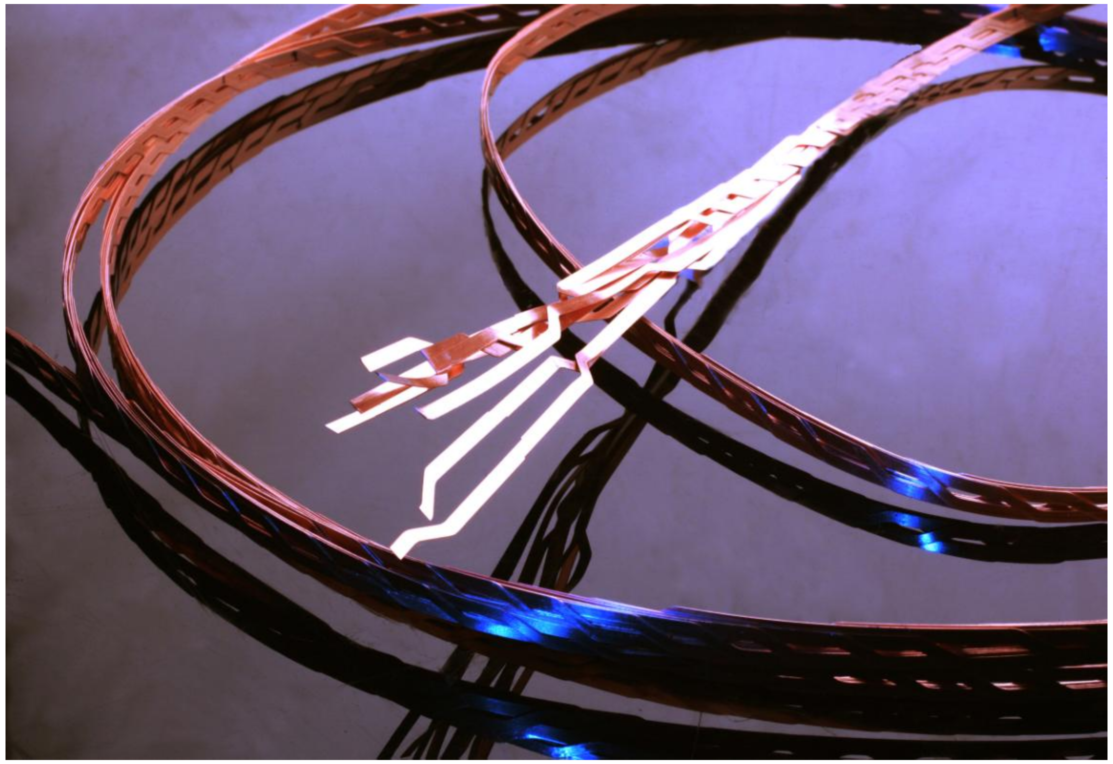
AC magnets

- Beam scanning magnet (HTS-110, www.hts110.co.nz)
  - Require <1T field at 100 Hz
  - Testing 5/2 Roebel cable



Conclusions

We believe YBCO Roebel cables have a future in enabling new applications for superconductivity



We're interested in your ideas
n.long@irl.cri.nz
info@GCSuperconductors.com