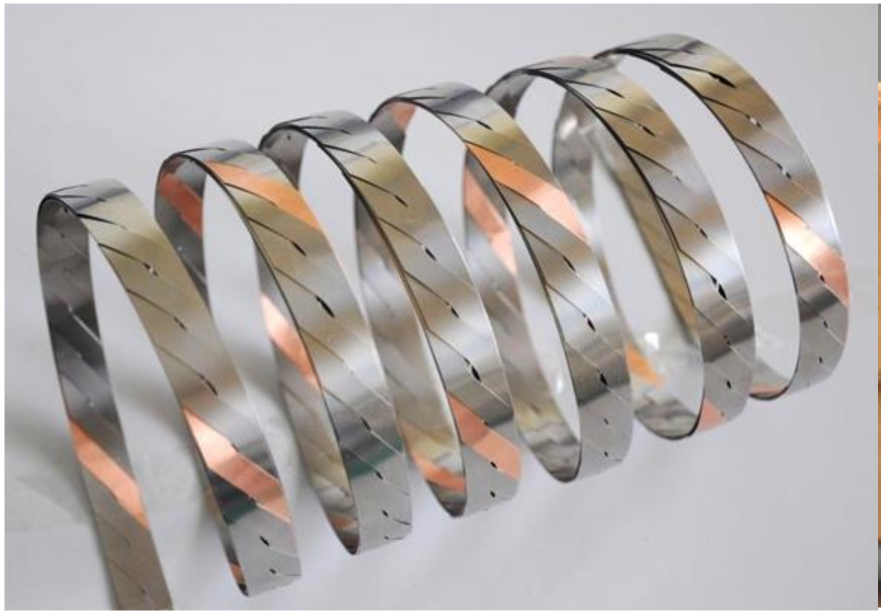
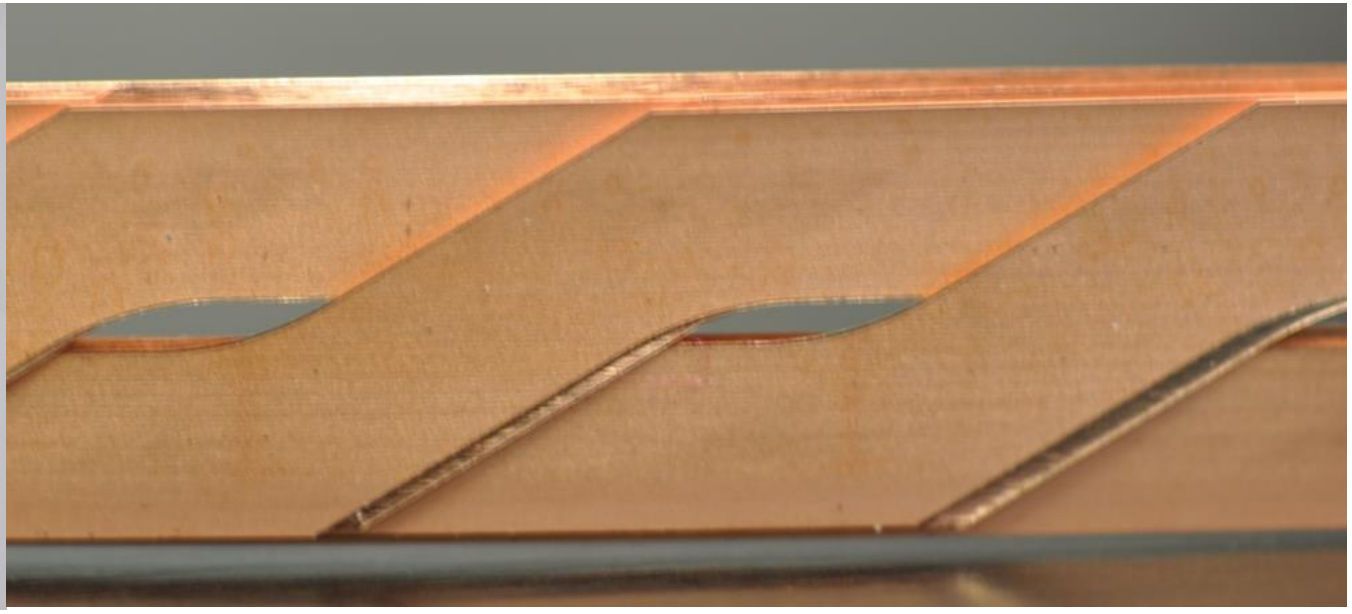
# WAMHTS – Hamburg
# 21 – 23.May 2014

## Properties of HTS-Roebel cables and the approach for EuCARD-2

**W.Goldacker,** A.Kario, R.Nast, A.Jung, A.Kling,
Institute for Technical Physics, ITEP, Karlsruhe Institute of Technology





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- Introductary remarks
- Roadmap of Roebel R&D
- Production methods and overview Roebel cable shown
- Overview industrial Coated Conductors and status of test
- Current anisotropy and aspects for magnet applications
- The current carrying potential
- Application of filaments to CC
- The message of filaments on CC  current homogeneity
- The potential of the concept for magnets

# Roebel Assembled Coated Conductors (RACC)

These cables are developed at KIT for different applications

- Future Fusion magnets with HTS solutions (DEMO ?)
- Transformers, rotating machinery (generators), AC windings
- Dipole magnets within EuCARD-II

Synergy is given for

- Qualification of available CC concepts for Roebel cables
- Qualification of CC performance for cable processing issues
- Technical issues as contacts, stabilisation, impregnation
- Winding process (loops, magnets)

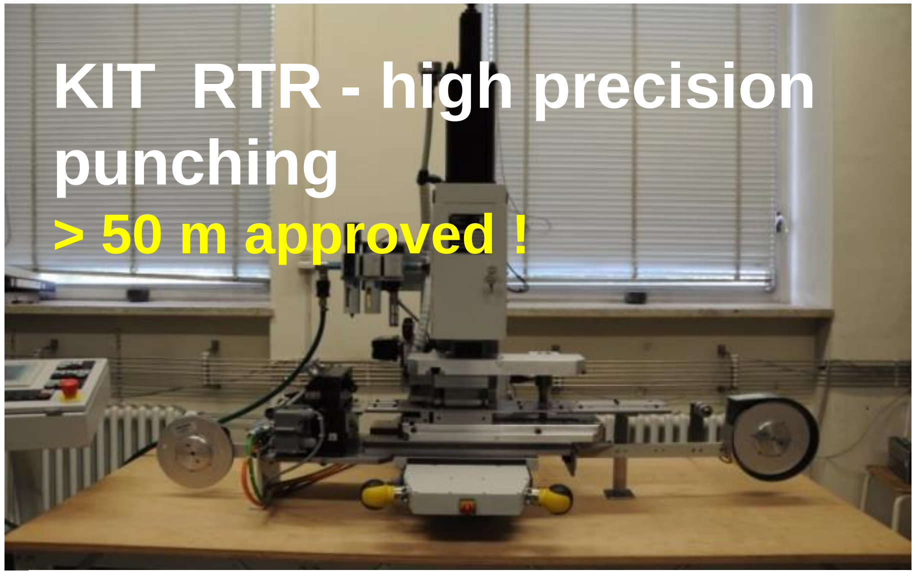
Activity for EuCARD II

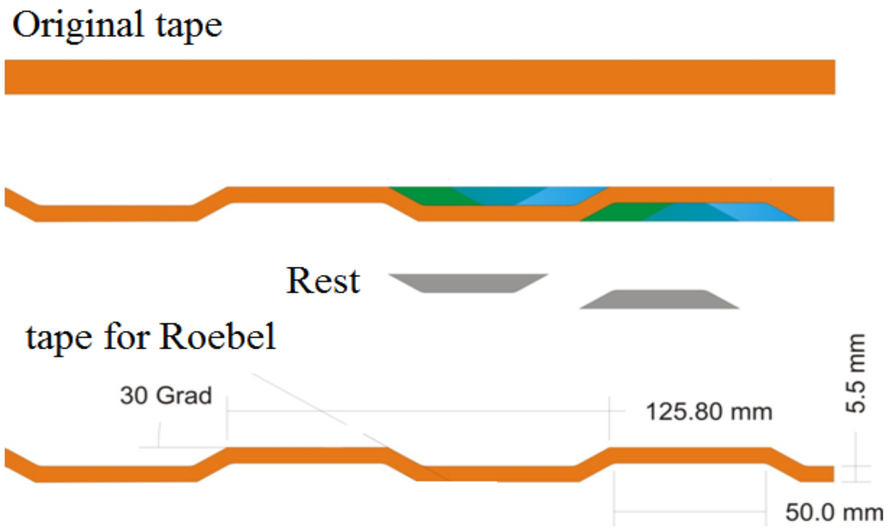
- Qualify available CC for Roebel process, customize & optimize cables
- Produce longer lengths and solve technical demands / options

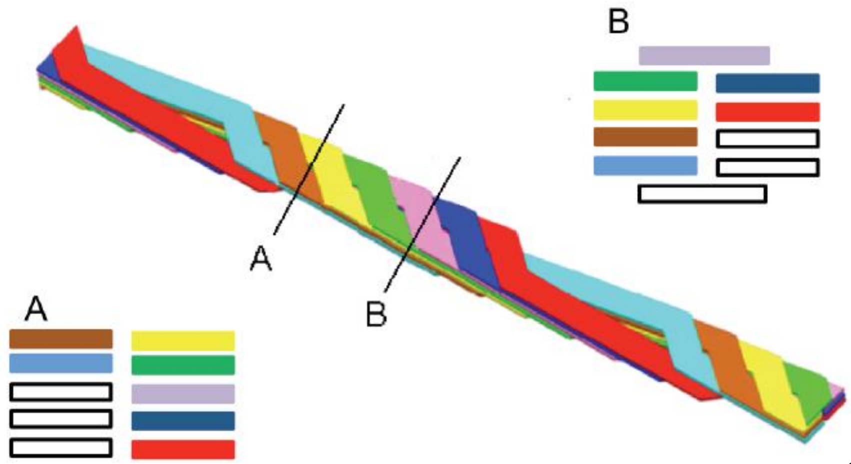
# General KIT R&D Roadmap on Roebel Cables

- **Short sample (<2m): Properties at T = 77 K / self field**
  Cable design / technology, technical features, AC losses
- **Short sample: Properties at T = 4.2 - <77 K / background field**
  $I_c$ with temperature and magnetic field, stabilisation issues, mechanical strength
- **Applications of filaments (striations): AC losses, Homogeneity**
- **Medium Long sample (> 2m): Properties at T = 77 K / self field**
  Cable in Coil arrangement: pancake coil, solenoid with one layer
- **Applications of Conduit/Jacket and Impregnation issues**
- **Long sample (> 5m): Multilayer solenoid at T = 4.2 - 77 K / self field**
- **Long sample (> 5m): Properties at T = 10 - 77 K / B = 0 – 5 T**
  **Quench dynamics on** Solenoid loop with 0.6 m diameter for **KIT – VATESTA facility**
- **Long sample (2 x 3m): Properties at T = 10 - 77 K / B = 0 – 15 T**
  Straight sample for **EDIPO – Test facility at PSI-EPFL**
- **50 m cable for Dipole Insert (CERN – Eucard-II ???) + other devices**

# Roebel cable preparation I

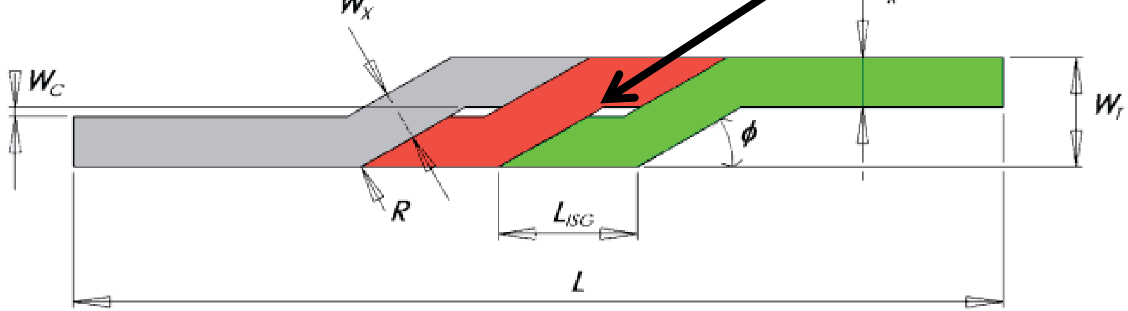



**Inner edge radius: 1-2 mm for wide cables**

**GCS nomencl.**




**Widths: 4, (10), 12 mm, others possible !**

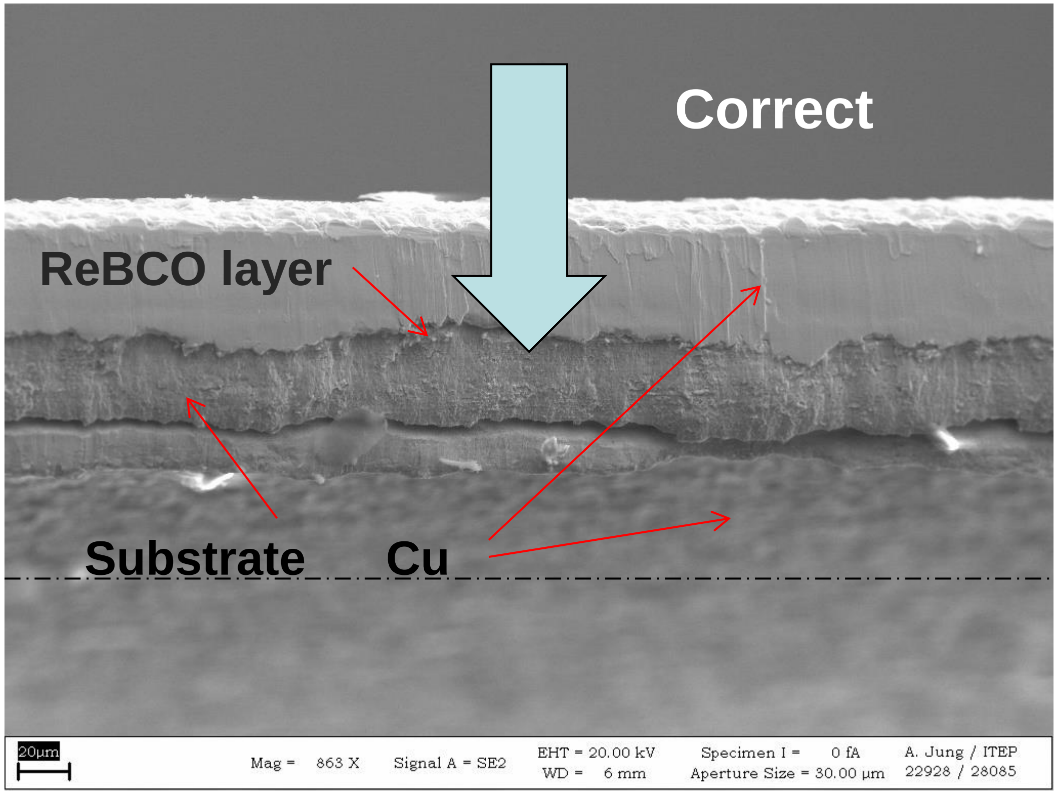
**Transposition (full flexible):**

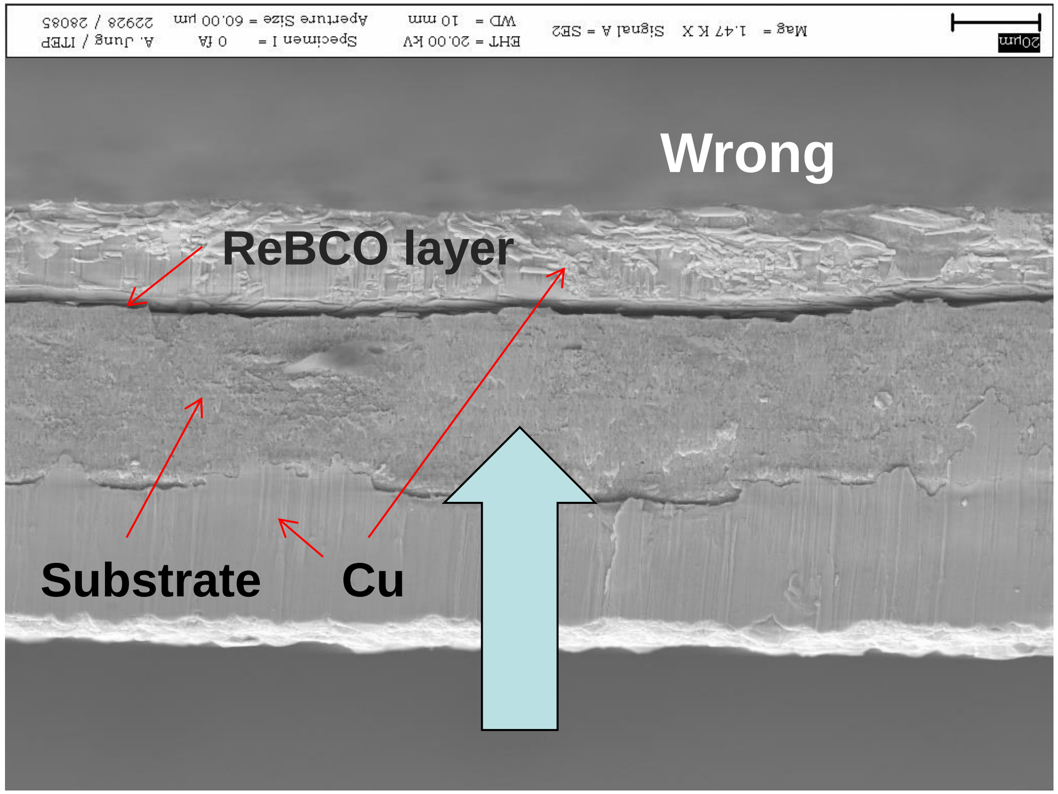
**4 mm cable: 115.7 mm, $W_c$ = 0 – 0.6 mm**

**12 mm cable: 126, 226, 426 mm, $W_c$= 1 mm**

**Punching tool is specified for tolerance, tape material + thickness, shear quality and shape of strand: Punching geometry = fully flexible to each design !**

# Optimized punching avoids delamination / defects




- Punching Tool works with consequeutive punching steps if required
- The material response is important
- Correct conditions = no delamination, no defects !
- The knife is designed to material choice, architecture and tape thickness
- Consequently all the different CC materials need to be tested !

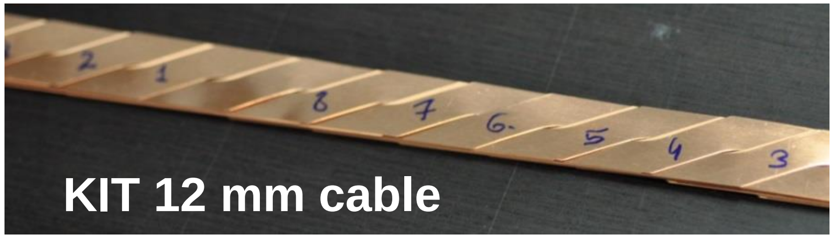
# Roebel cable preparation II

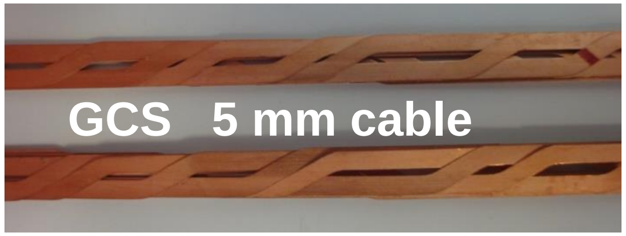
## Assembling technique

- KIT cables = handmade, up to 5 m
- KIT new process for > 5 m and dense packing
- IRL/GCS cables = different machinery used

**Characteristics:**

- KIT Cables are dense packed (transv. stress balance !)
- Geometry very regular (stress distribution, bending) !
- Flexible in geometry, strand arrangement !



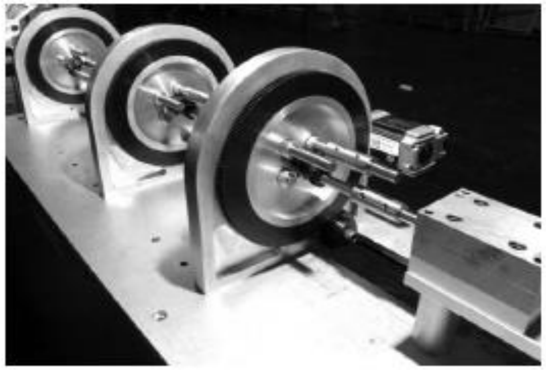




- IRL/GCS cables show larger spacings
- Can be very disordered !

**The assembling process requires a sophisticated tape guide system to avoid plastic deformation/overbending**

**The mechanical strength for bending of the CC and the bonding between the layers in the CC are crucial !**

### IRL/GCS machinery



Winding machine for 10/2 cable

Winding machine for 15/5 cable

**AKAK-method**
**KIT**
**20 m approved**

KIT process for long lengths under optimization (confidential)

# Roebel qualification of Coated Conductors & status

- **Micrograph on conductor cross section, Ag and copper clad quality (bonding, porosity)**
- **Checking transport currents: short sample + > 1 m piece, defect monitoring by MOI**
- **Test of punching process: Conductor dimension, shear edge, delamination issues**
- **Transport currents of strands on several sections (amount of degradation, homogeneity)**
- **R of Cu-stabilisation, Current homogeneity (Hot spots), filament test (if necessary)**
- **Current transfer properties (feed in length) at leads**

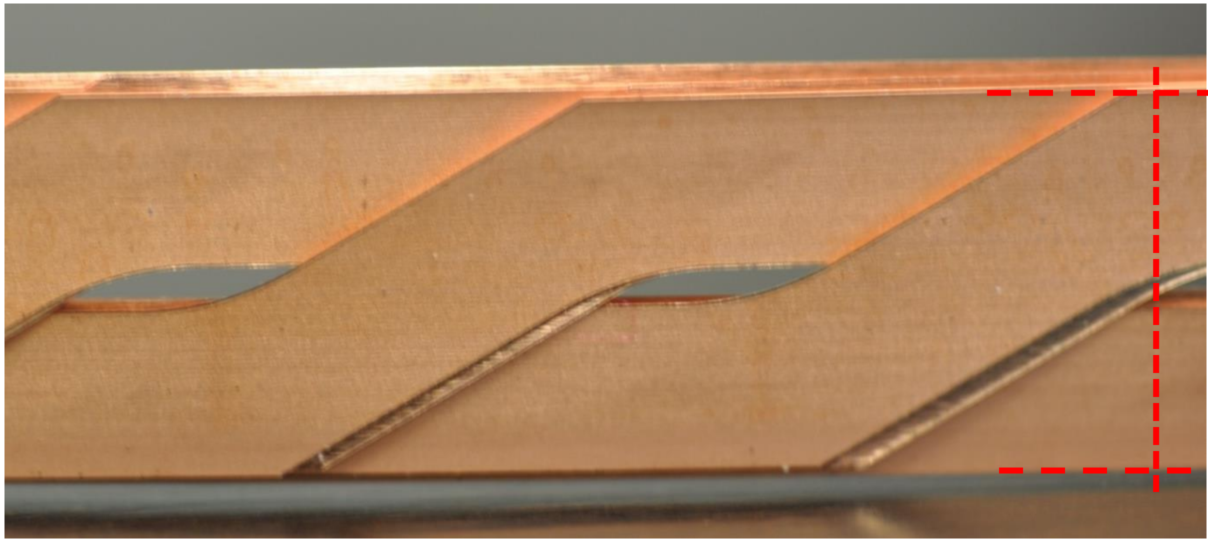
| Origin | Dimension | Cap | Current 77 K Curr.Density | Piece length | Roebel approved |
|---|---|---|---|---|---|
| SuperPower | 94 µm x 12 mm. 75 µm ? | Ag + Cu (40 µm) | 360-420 A 32000 $Acm^{-2}$ | < 200 m | Yes, Standard |
| SuperOx | 105 µm x 12 mm | Ag + Cu (40 µm) | > 300 A 23800 $Acm^{-2}$ | > 50 m (200 m) | In work |
| SuNAM | 150 µm x 12 mm | Ag + Cu (40 µm) | > 600 A 33000 $Acm^{-2}$ | > 100 m | No |
| Fujikura | 150 µm x 10 mm | Ag + Cu (75 µm) | > 500 A 33300 $Acm^{-2}$ | 600 m | No |
| Bruker | 220 µm x ca. 12 | Ag + Cu (120 µm) | 300 A 11400 $Acm^{-2}$ | 1.3 m | In work |

# Current anisotropy and situation in coils

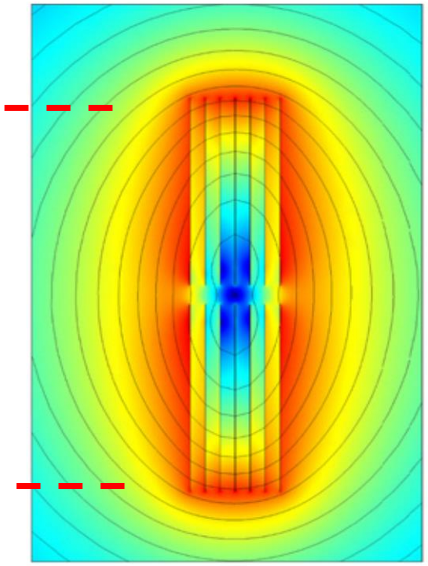
# Short straight single RACC sample in self field

## Non-homogeneous distribution of the magnetic self field in Roebel Coated Conductor cable cross section.

12 mm



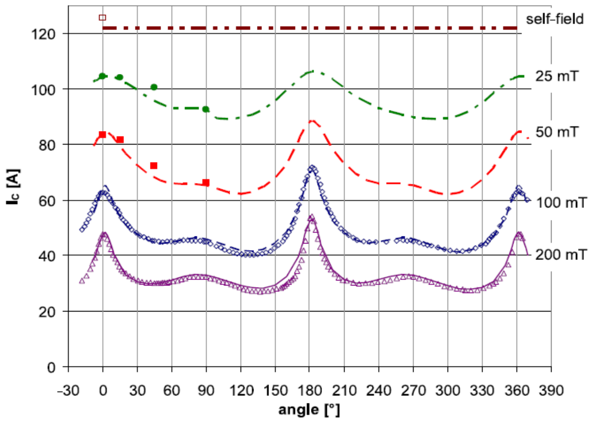
cross section

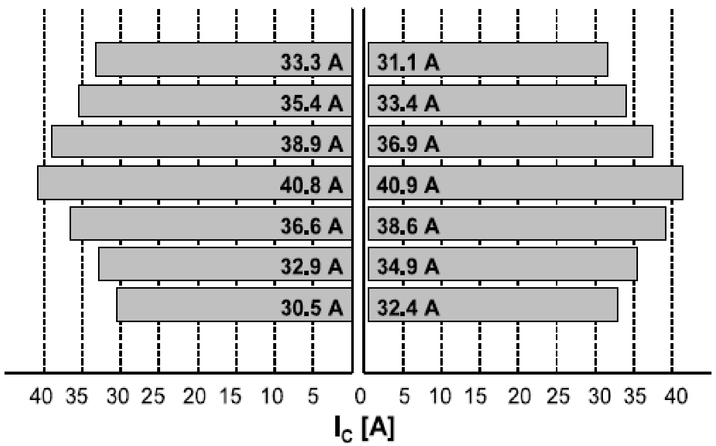



Modeled self field pattern with $I_c$ anisotropy

M.Vojenciak et al. Supercond. Sci. Technol. 24 (2011) 095002

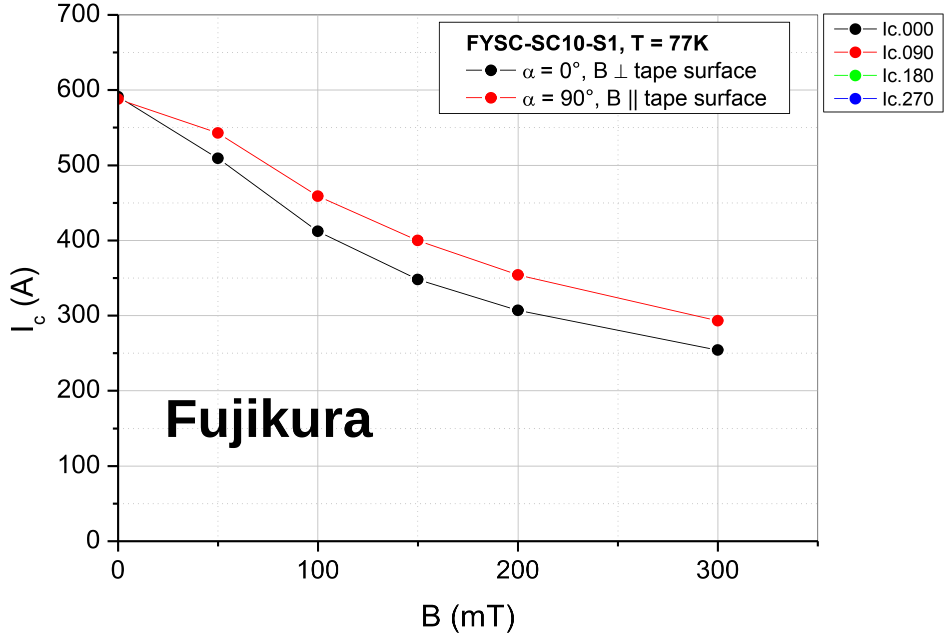
## Current depends on local field and orientation

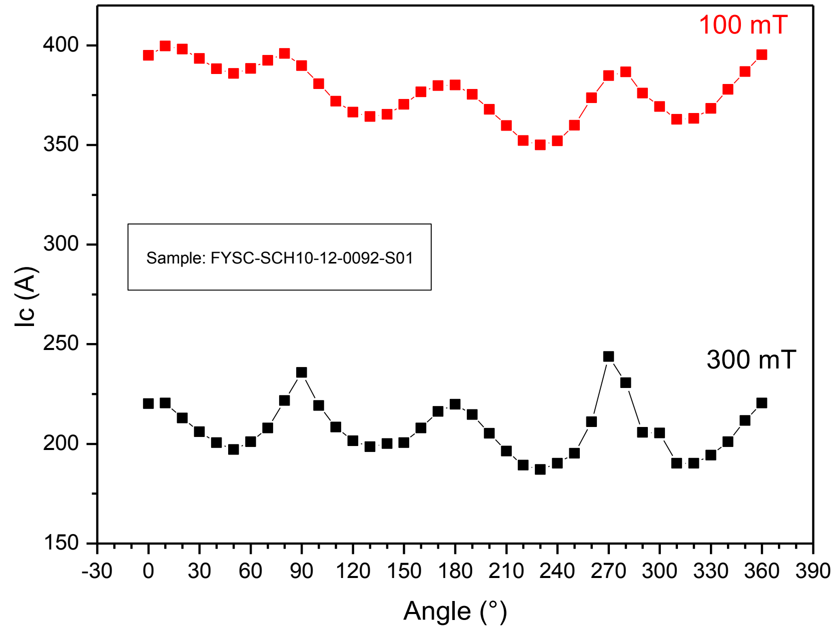



- **Behavior well understood !**
- **Current redistribution effects begin at $I > \frac{1}{2} I_c$**
- **Modelling works well**
- **$I_c$ in s.f. reduced by 40-60%**

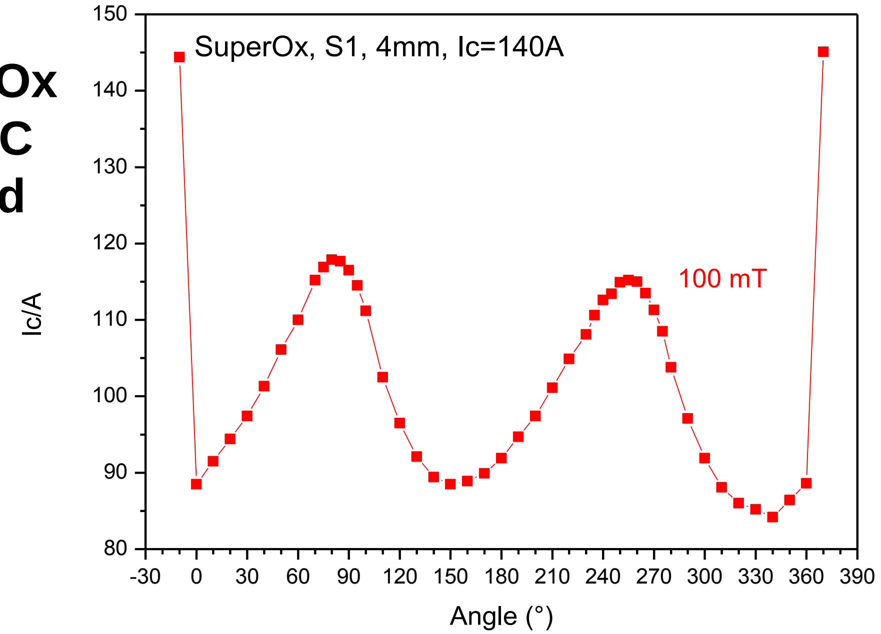
# Current anisotropy in field is conductor specific !




- Anisotropy depends on pinning centers, the APC approach, the nature of pinning centers, the orientation in the REBCO layer, the processing method
- The anisotropy is crucial for the end sections of dipole windings

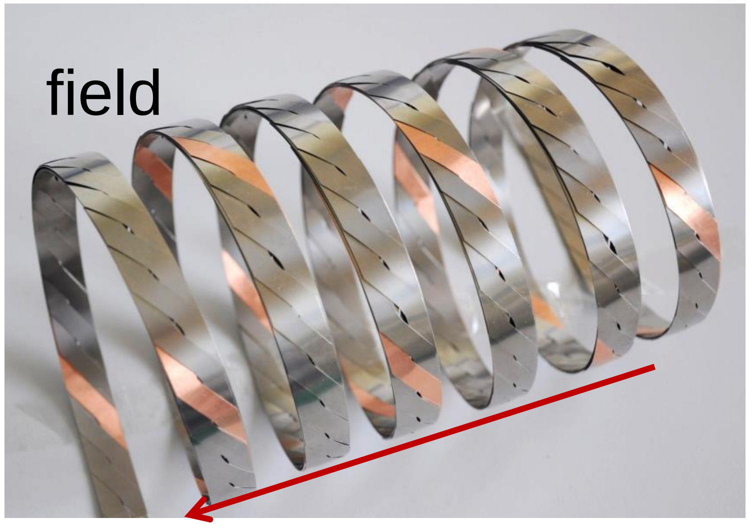
**SuperOx No APC applied**

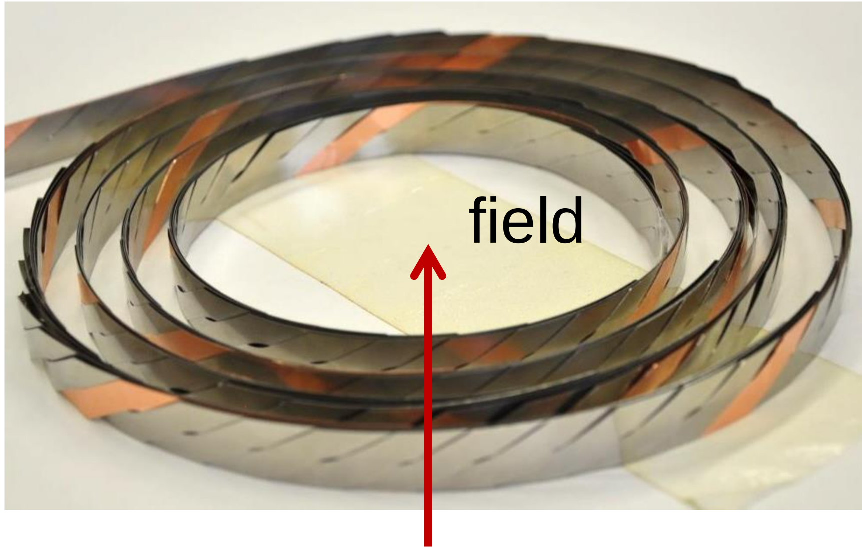



**Measured at ITEP, T=77K**

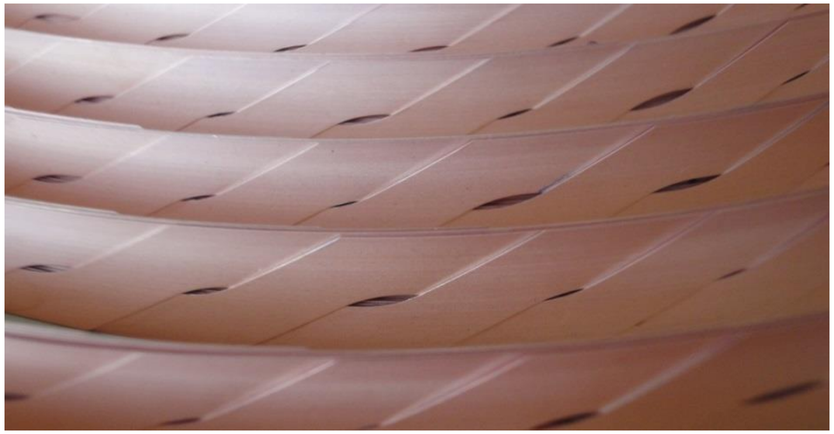
# Test of windings ( > 2 m) at 77 K in self field

- 5 m sample, investigations in 2  coil arrangements:  **solenoid or pancake** .




Roebel dummy sample for illustration using SS + Cu



**Multiple use of one sample**

**Investigations of coils:**

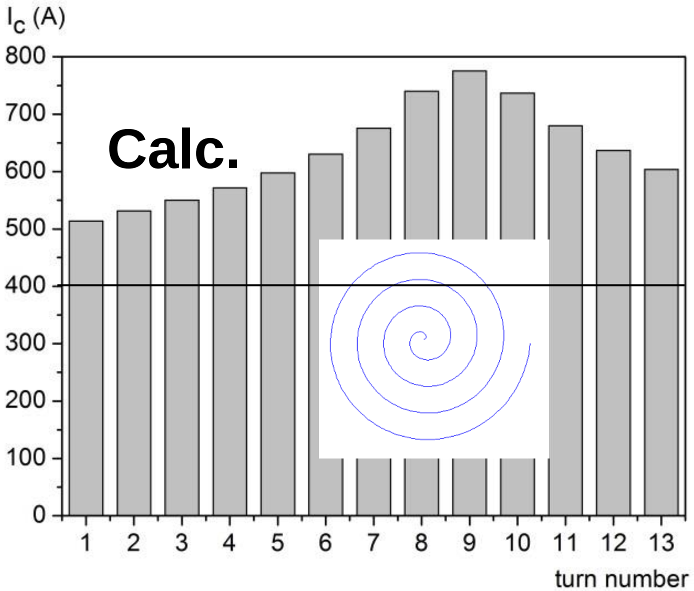
- DC performance measured and modeled
- AC losses by transport measurements
- Self field effect of the coil

# Roebel (RACC) cable as pancake and layered coil (1 piece used)

5 m sample

### Sample data

- SuperPower CC
- Length 5 m, width 12 mm
- Strand width 5.5 mm
- 10 strands
- Transposition 126 mm



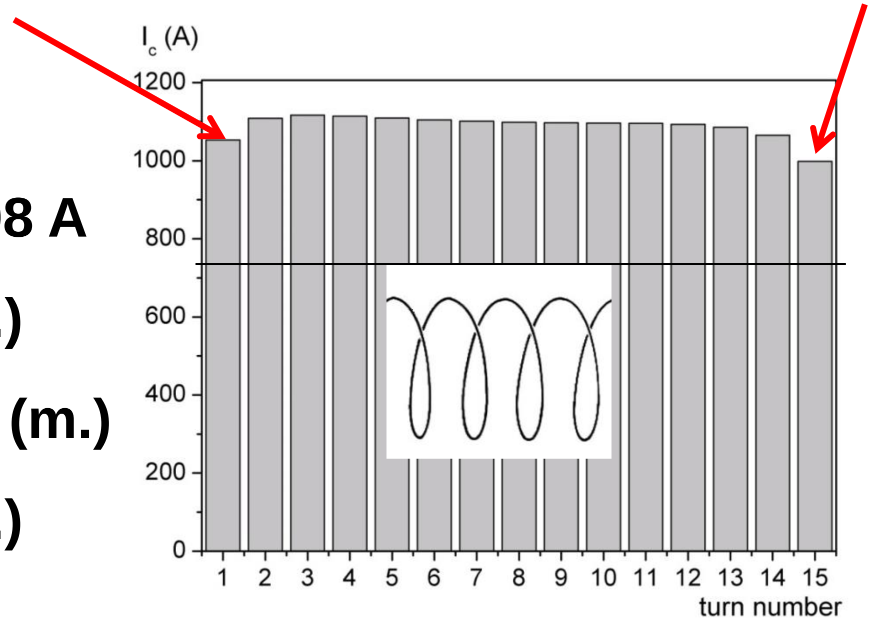

**Design value 1512 A**

**Model with sharing 1108 A**

**Straight cable 936 A (m.)**

**Solenoid coil 750 A (m.)**

**Pancake coil 460 A (m.)**

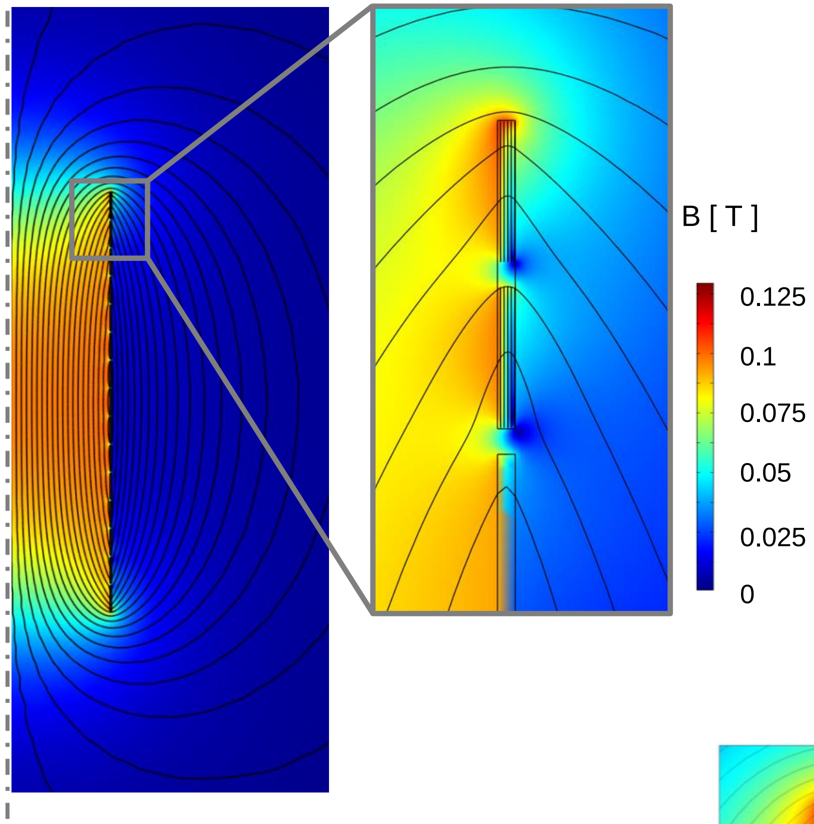



**Bending is excellent, Parallel and perp. field components play important role measured current smaller than expected !**

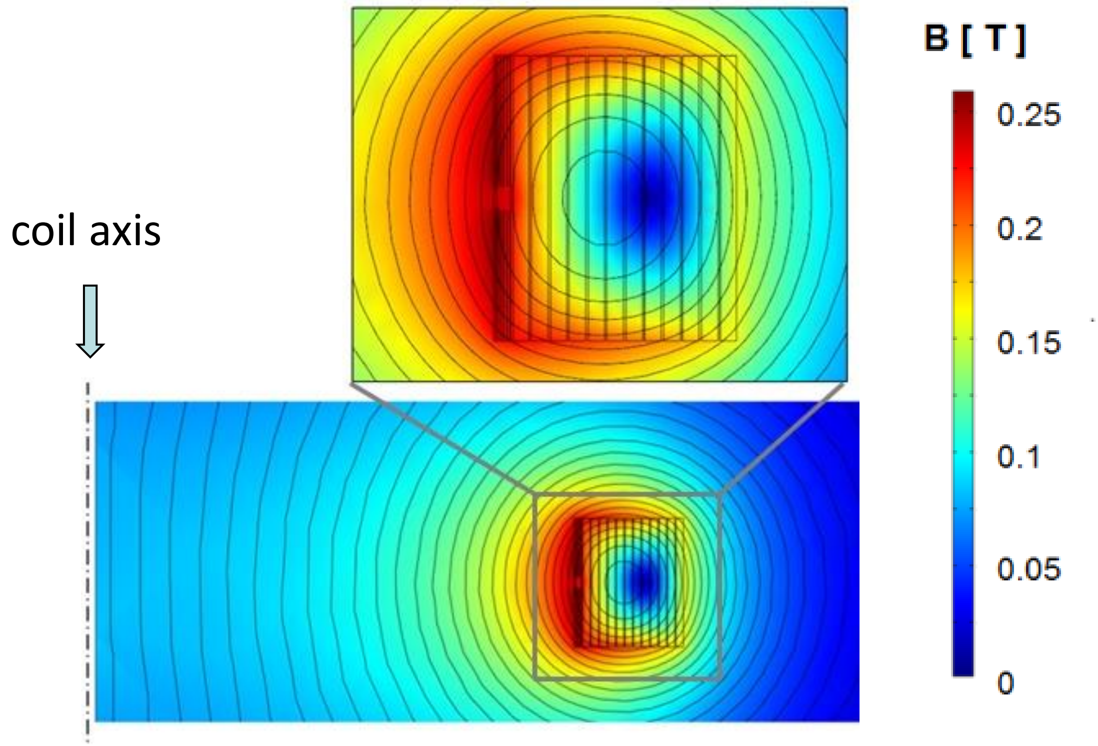
# Modeling of self field in the coil arrangements

- **FEM Modeling confirms influence on transport currents**
- **Stronger self-field interaction occurs between turns in a pancake coil.**

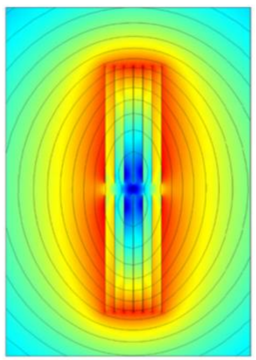
coil axis **Effect at the coil ends**




- Solenoid with cable monolayer
- 1 mm turn distance



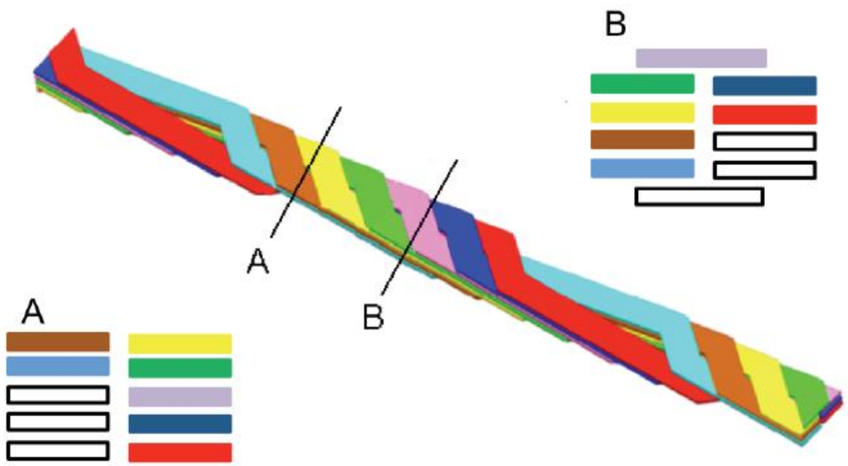

- Dense packed pancake version shown
- 0.1 mm turn distance



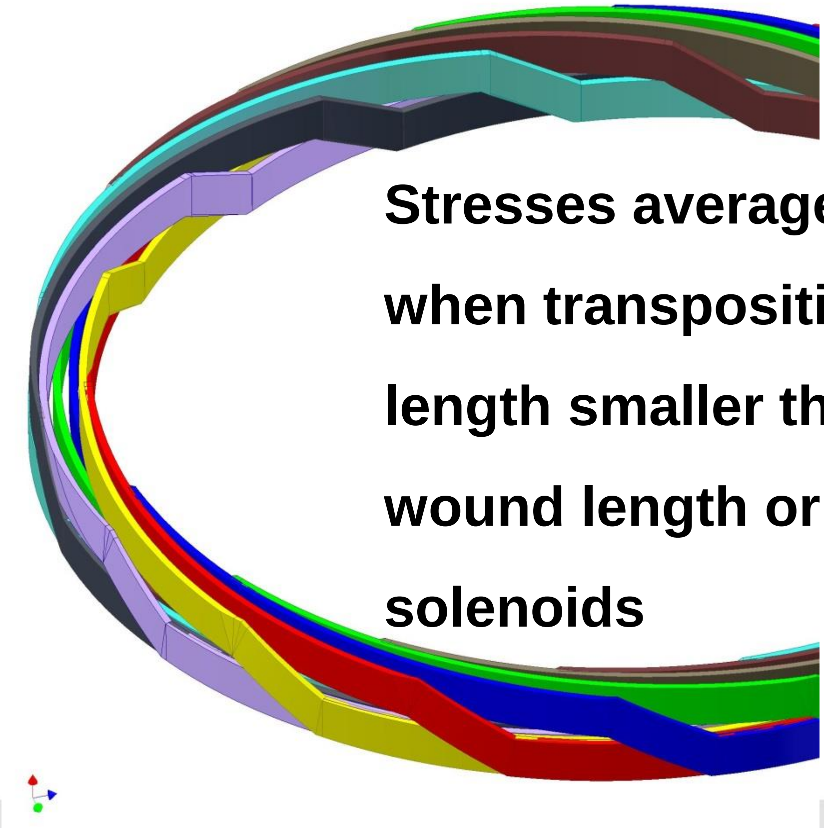
Reference straight cable

**Modeling:**
**M.Vojenciak, F. Grilli et al.**

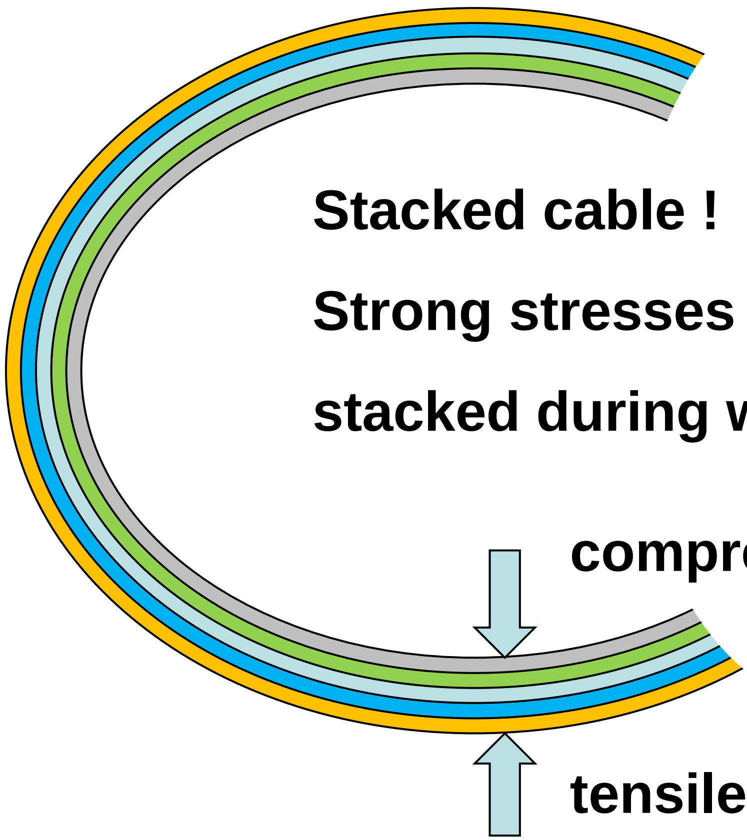
# Bending and influence of transposition in coils
# Comparison stacked CC & Roebel cables




- **Strands in the Roebel cable go through all positions**
- **The bending properties are similar to the single strand or CC**



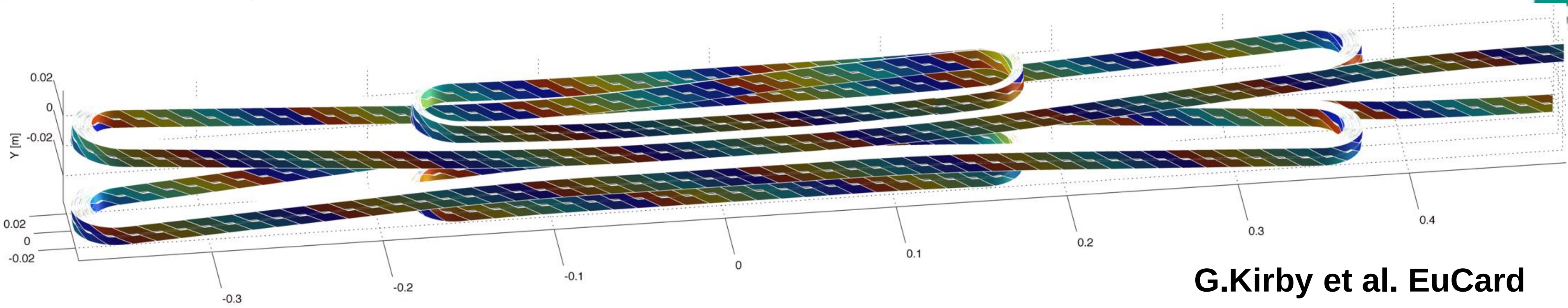
**Stresses average out when transposition length smaller than wound length or in solenoids**




**Stacked cable !**

**Strong stresses if not stacked during winding**

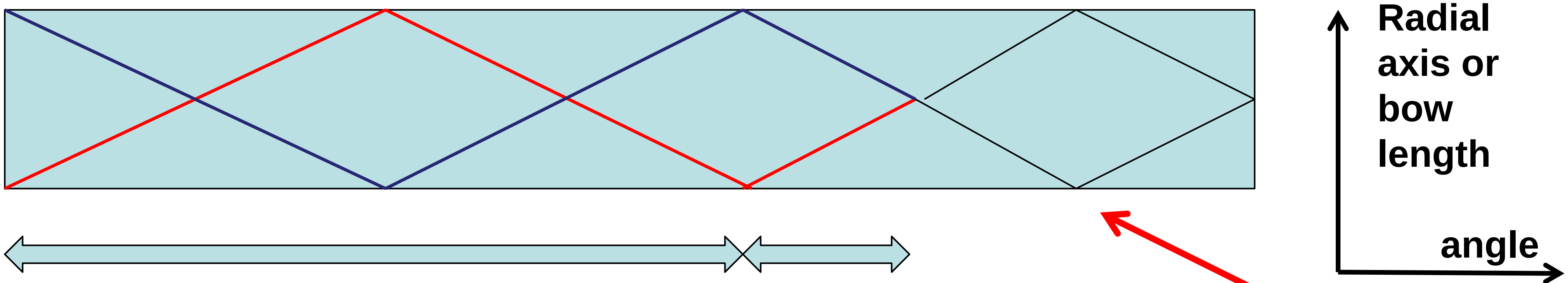
# Bending of a Roebel cable in non-solenoid shapes

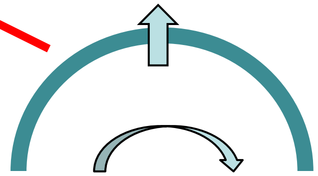



G.Kirby et al. EuCard

**The coil has straight and round sections**

**2 strands discussed in Roebel cable at end turn**



**Blue strand is longer than red one for 1.25 Lp ⟶ Stresses**

**Coils with many turns:**

- **Avoid cumulative deviations from bent strand lengths and resulting stresses**
- **Design the transposition length and coil dimensions together !**

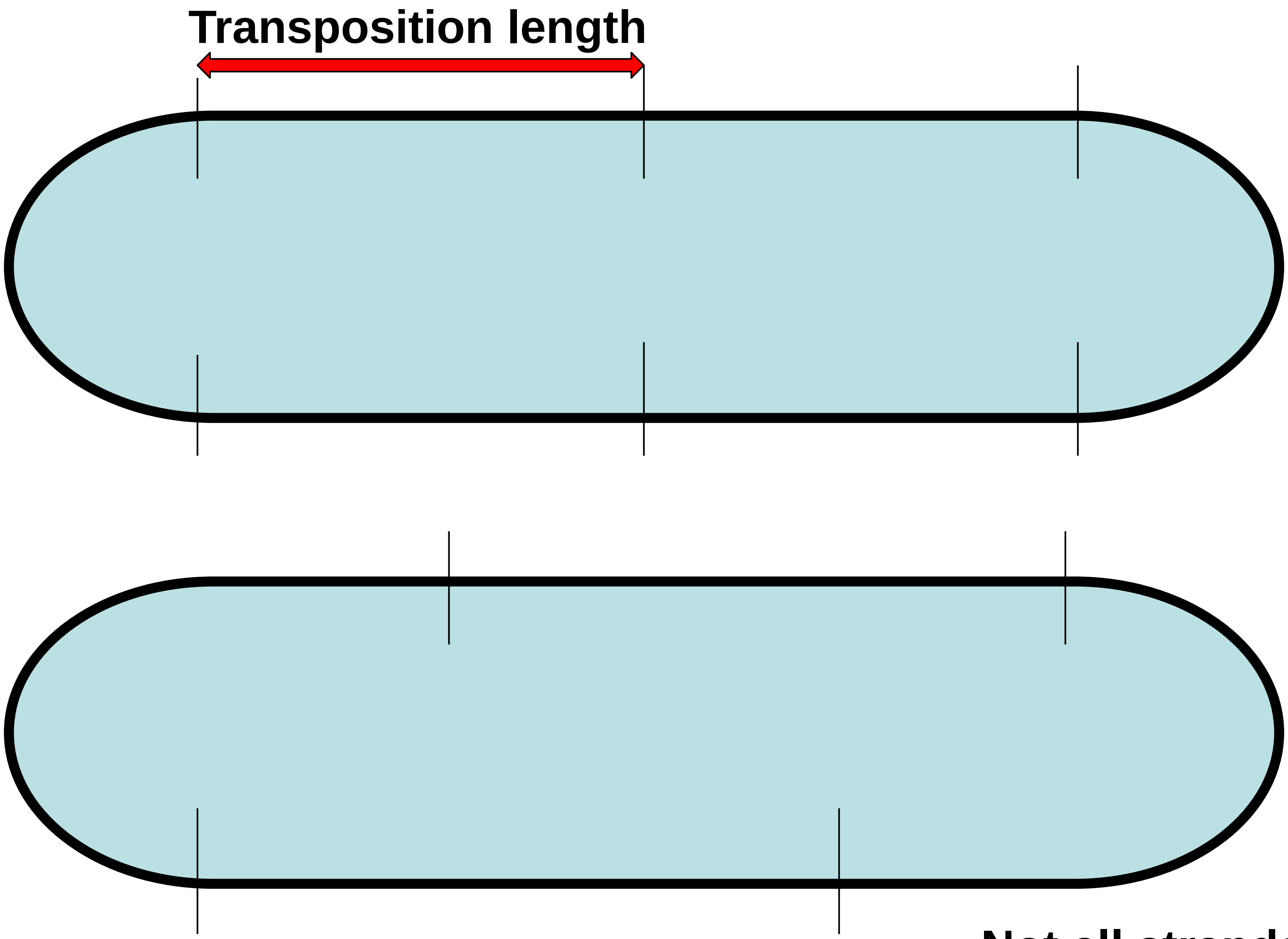
# Interplay of transposition length and magnet design

Case 1

$L_t$ = bent section

Case 2

$L_t$ > bent section




Find a way to unload the stress !

Not all strands have the same length

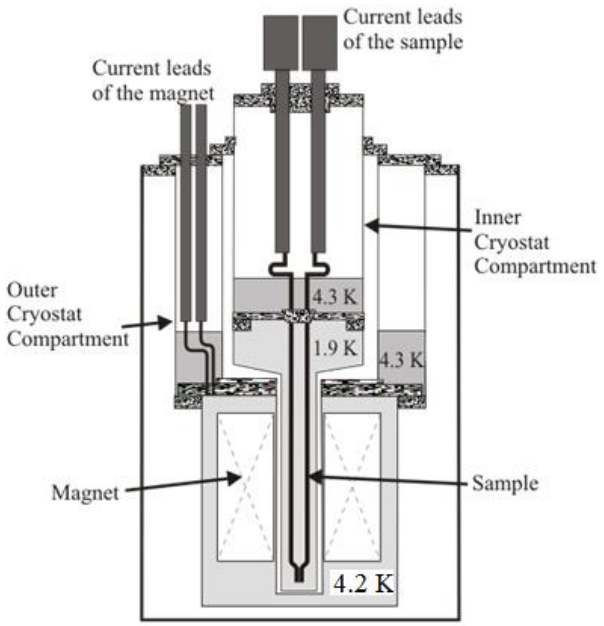
**It needs approved if it is a real problem !**

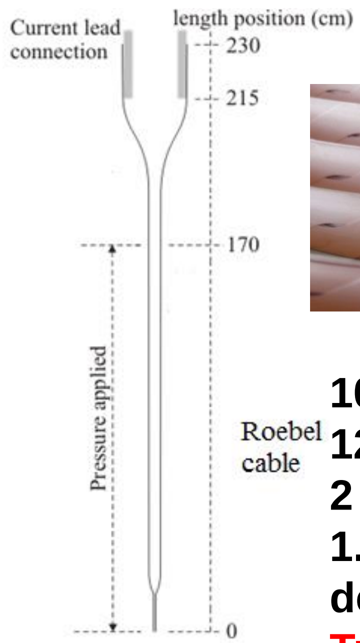
# How to increase transport current density at 4.2 K for Roebel cables

- **Increasing REYCO layer thickness in the CC (stabilisation issues need to be considered = Cu layer thickness !)**
- **Overall improved CC performance (homogeneity, tailored APC)**
- **Reduce substrate thickness to 25 - 30 microns ?**
- **Increasing  transposition length = more strands possible**
- **Applying multistacking = more strands = but worse bending !**

**The coil dimensions and shape (as bending radius) may restrict the potential of possible modifications**

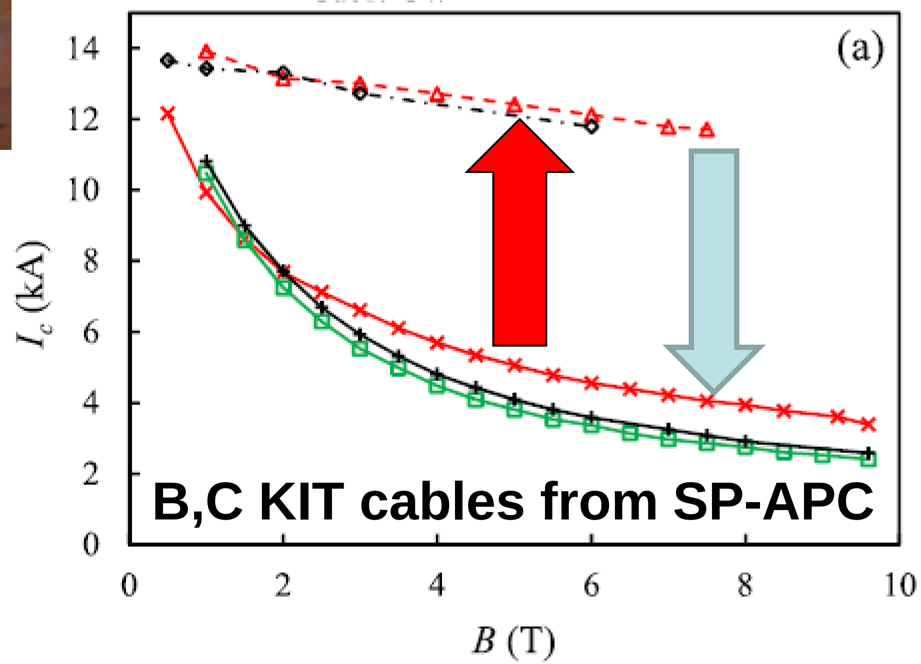
# Anisotropy & Currents at 4.2 K and B= 0 - 10 T (Test in FRESCA facility by CERN), CC from SuperPower




10 strands
12 mm cable width
2 m length
1.1 kA at 77K sf
dense packing
Transpos.: 126 mm

**Roebel cable can take advantage of anisotropy**




Electrical characterization of RE-123 Roebel cables
J. Fleiter[1], A. Ballarino[2], L. Bottura[2], P. Tixador[3], Superc. Science &Technol. 26 (2013) 065014

| | | |
|---|---|---|
| **Transport currents :** | **14 kA** | **at self field** |
| | **4 - 12 kA** | **at 6 T (4.2 K)** |
| **Enhancement factor** | **77K - 4 K** | **factor 12 !** |

**Anisotropy factor 3 - 5 ! at 4.2 K**

**$L_p$ = 0.4 m = 30 strands gives > 40 kA s.f. (in work)**

**$L_p$ = 1.8 m = 100 strands gives > 80 kA at 13.5 T, 4.2 K = DEMO cable ?**

**Cable designs with twisted CC along cable axis are in worst field orientation (as CORC)**

# Multistacking of strands in short straight samples

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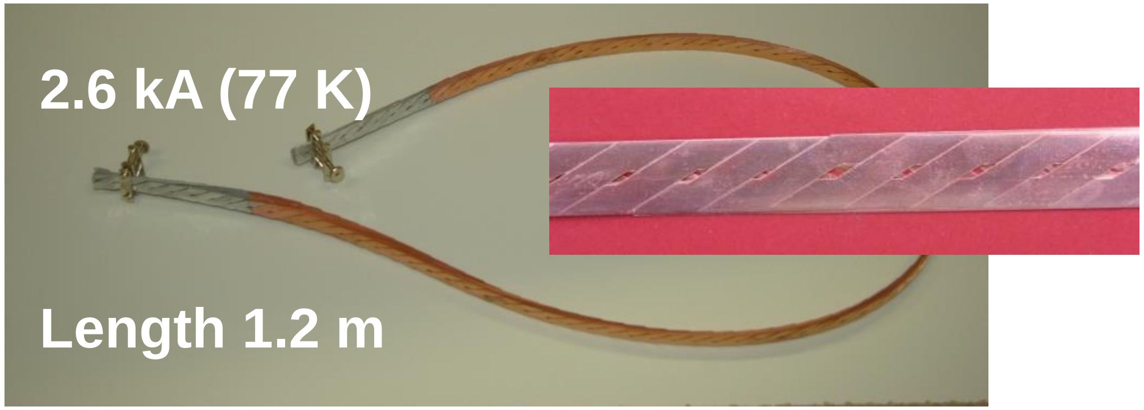
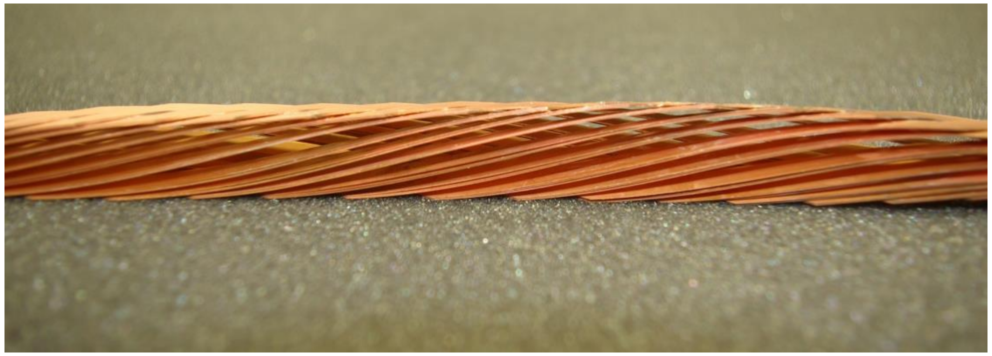



## 12 mm wide cables

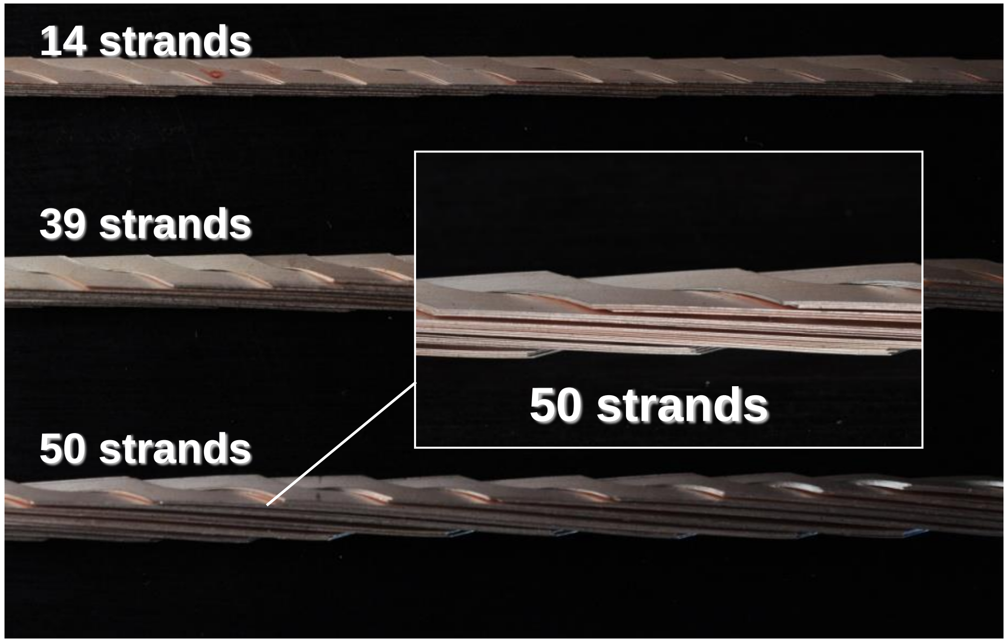
**10 – 12 mm width, 190 mm twist pitch, 3-fold stacks (Superpower CC)**



**Bending not tested**

## 4 mm wide cables

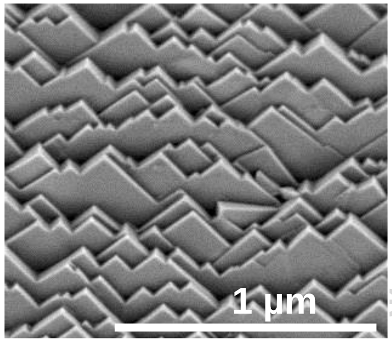
**4 mm wide, 109 mm tw. 3 and 5-fold stacks**



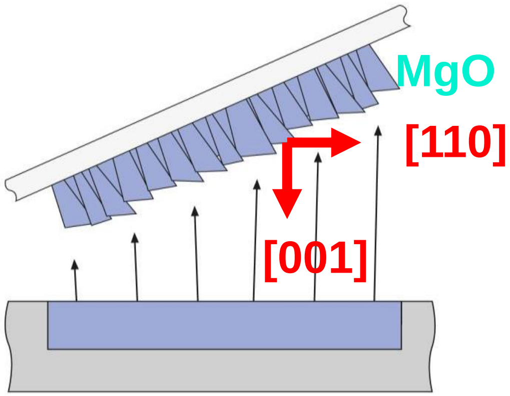

| Samples | No. of strands | Thick-ness (mm) | DC(A) 77 K |
|---|---|---|---|
| Roebel (14x1) | 14 | 1 | 465 |
| Roebel (13x3) | 39 | 2.7 | 1120 |
| Roebel (10x5) | 50 | 3.8 | 1320 |

- **Stacking leads to higher self field**
- **$I_c$ lift factor for 4.2 K not applicable**

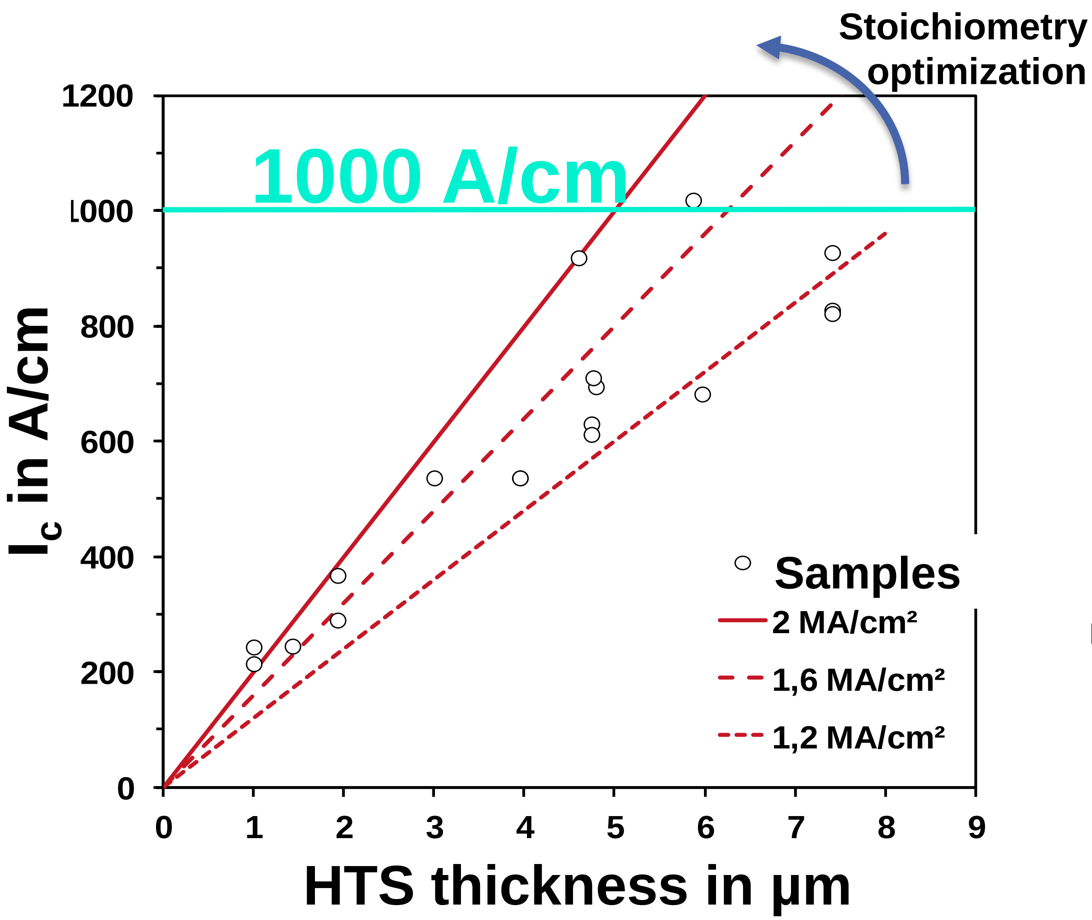
# Enabling high current tapes by increasing layer thickness

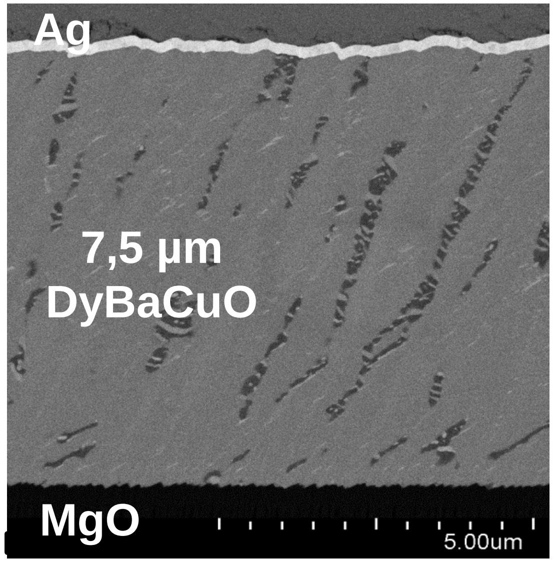



MgO buffer layer




Inclined Substrate Deposition (ISD)




Homogeneous growth of Thick HTS-layer

- The unique HTS growth mode on our stepped ISD buffer paves the way to 1000+ A/cm coated conductors!

Karlsruhe Institute of Technology

**Improved currents in REBCO layer is a very important parameter which allows:**

- **Most effectivly an increase of Engineering Current Density (Effect happens in 1-5% of conductor volume)**
- **But needs the required better stabilisation (electroplated Cu layer thickness)**
- **Defect = Hot Spot stabilisation !**

# Data and extrapolations for transport currents

Karlsruhe Institute of Technology

**Instead of applying lift factors (77k to 4.2 K), the 4.2 K data (Fleiter et al.) are used with enhancement factors for the cable modifications**
**Blue values are extrapolated, red are achieved, measured, all H II**

| | | |
|---|---|---|
| Cable 10 str., $L_t$ = 126 mm, | $I_c$ (4.2 K) = 14 kA, $J_c$ = 2.4 kA/mm$^2$ | $I_c$ (4.2 K, 20 T) = 9 kA, $J_c$ = 1.5 kA/mm$^2$ |
| Cable 30 str., $L_t$ = 430 mm, | $I_c$ (4.2 K) = 42 kA, $J_c$ = 7 kA/mm$^2$ | $I_c$ (4.2 K, 20 T) = 27 kA, $J_c$ = 4.5 kA/mm$^2$ |

Improved CC performance (300 A to 600 A): lift factor 2

2-fold stacked Roebel strands gives: lift factor 2

Increased Cu – stabilisation ( 40 to 140 micr.): lift factor 0.5 of less

Perpendicular field : lift factor down to appr. 0.2

Reduced substrate thickness (30-40 micr.) lift factor 1.2 – 1.35

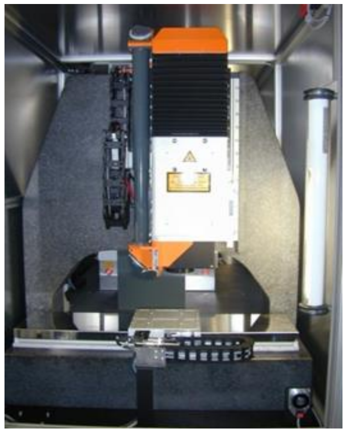
**Transverse stress > 100 Mpa, Bending radius > 15 mm (s. A Kario talk)**

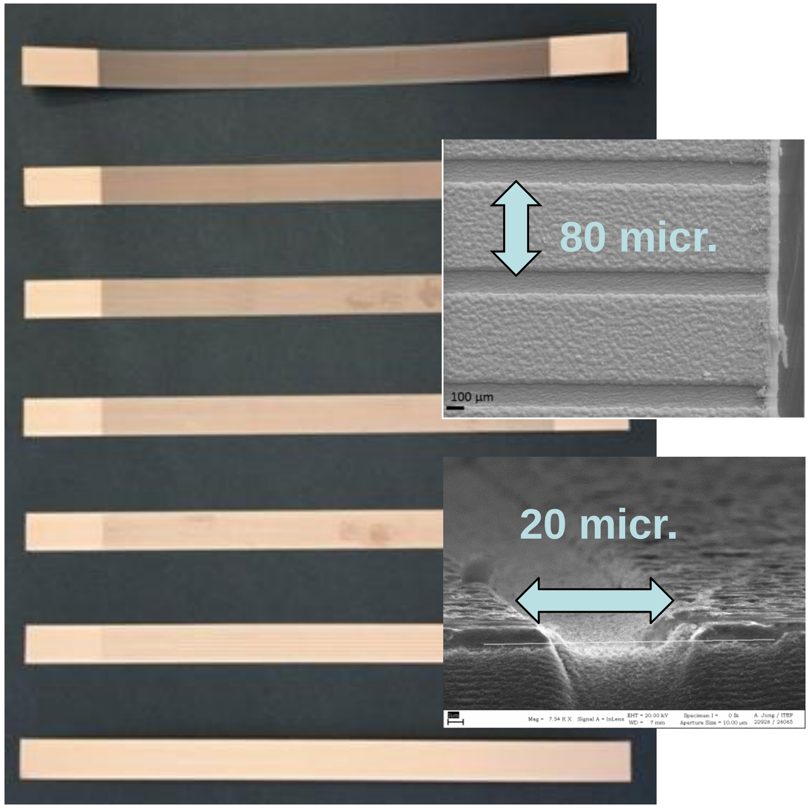
# Filaments in Roebel strands

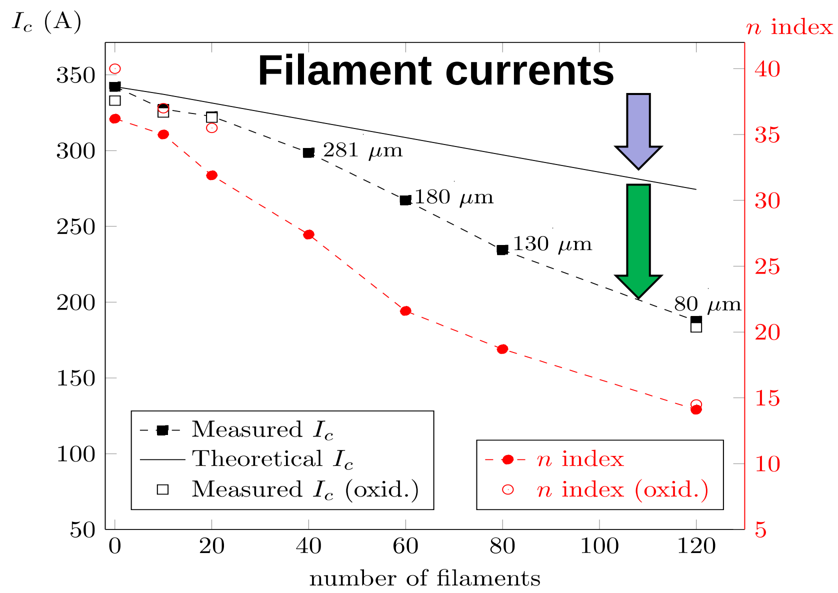
- **Effects on AC losses under investigation**
- **Effects on Transport Currents**
- **Resolution of CC performance in short scale**
- **Finger print of CC homogeneity !**
- **Quality test for CC material !**

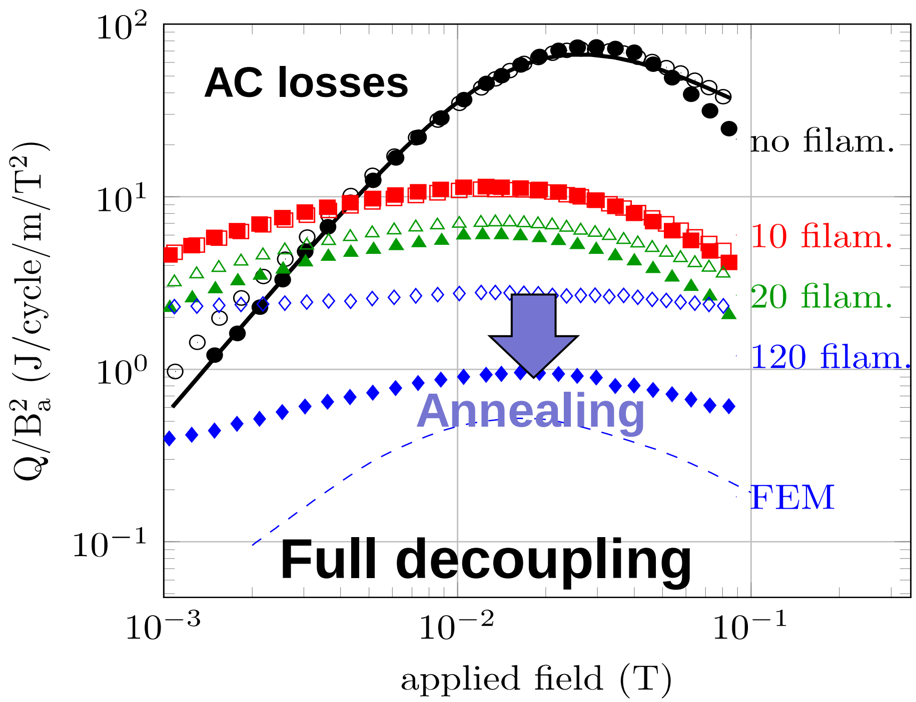
# Option for lower AC losses: Striated CC

- Up to 120 Filaments (12 mm width) prepared and analyzed,
- current degradation from material loss and CC inhomogeneity
- full separation with post annealing in $O_2$ (filled symbols in figure)





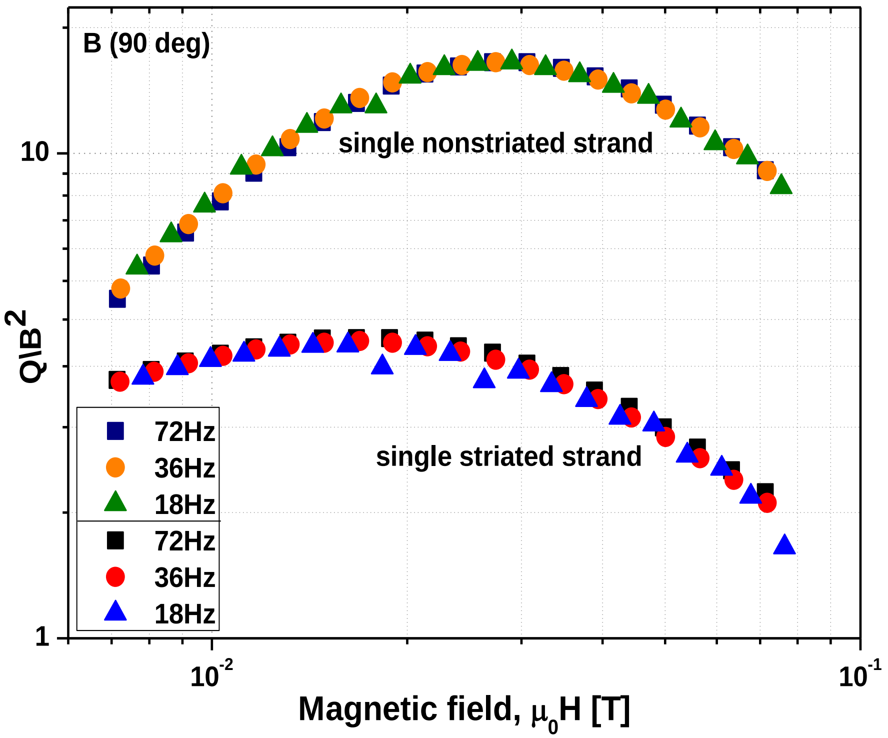



# Striated RACC cables (earlier results)

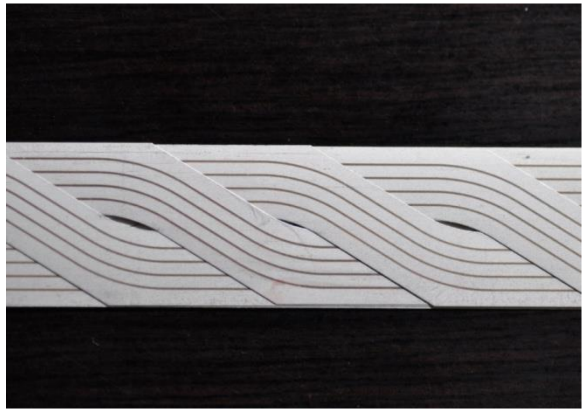
Magnetization AC loss measurements

**Terzieva S, Vojenčiak M, Grilli F, Nast R, Šouc J, Goldacker W, Jung A, Kudymow A and Kling A 2011 *Superconductor Science and Technology* 24 045001 and ASC 2010 Washington-USA**

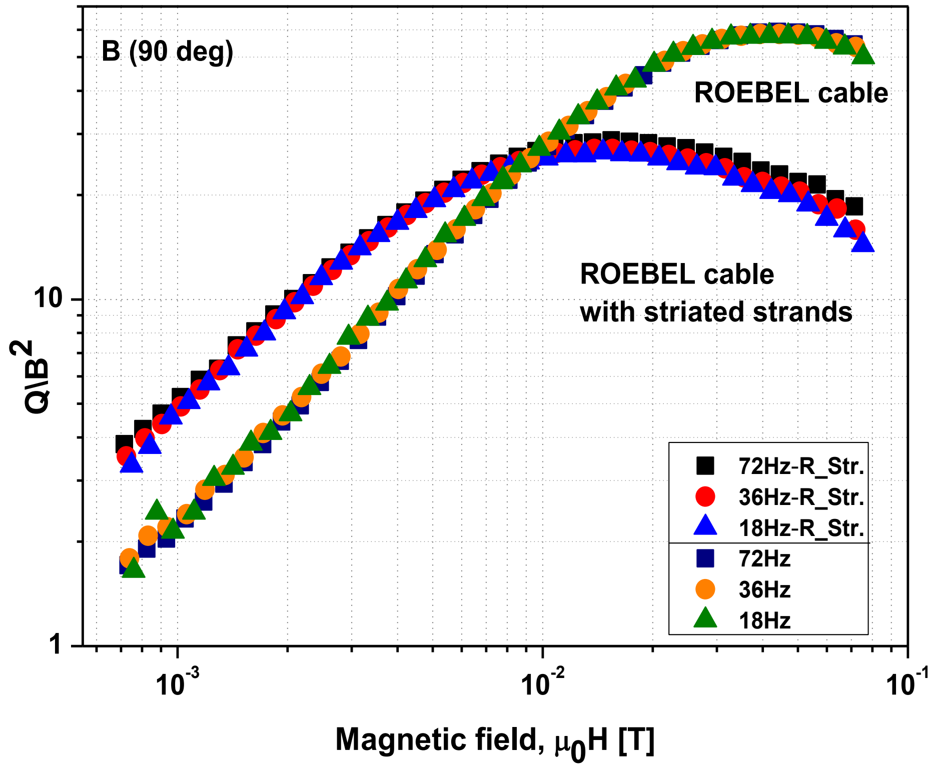
## Effect in strands




**Striations made by psec-IR laser at KIT**



## Effect in cable

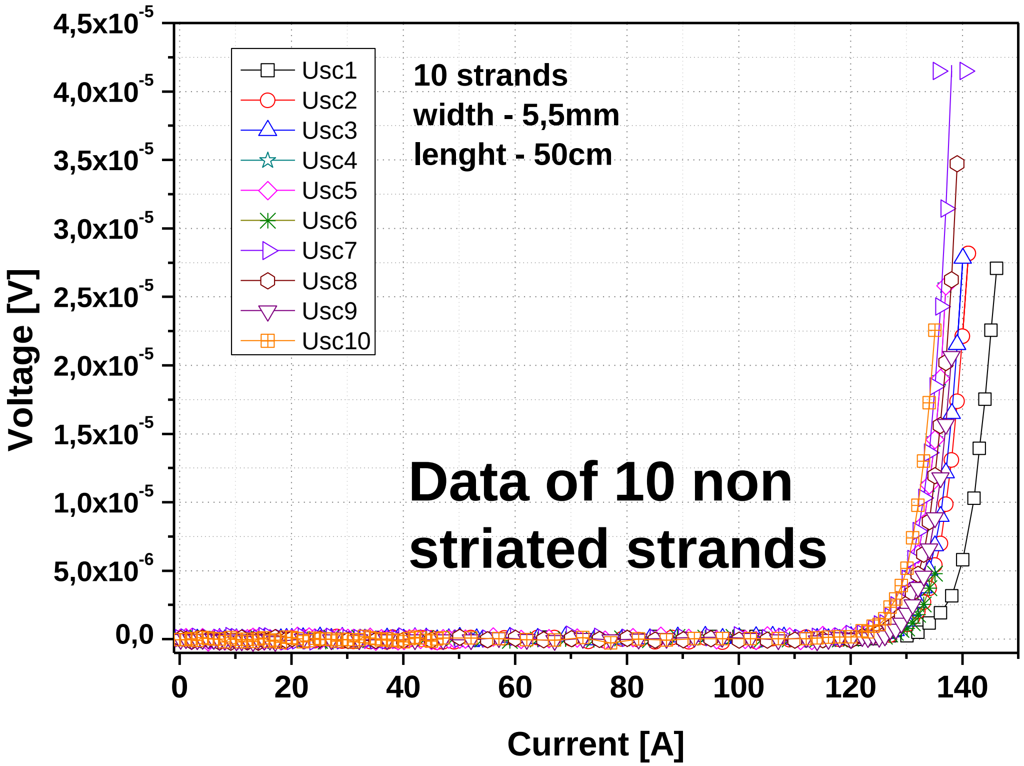


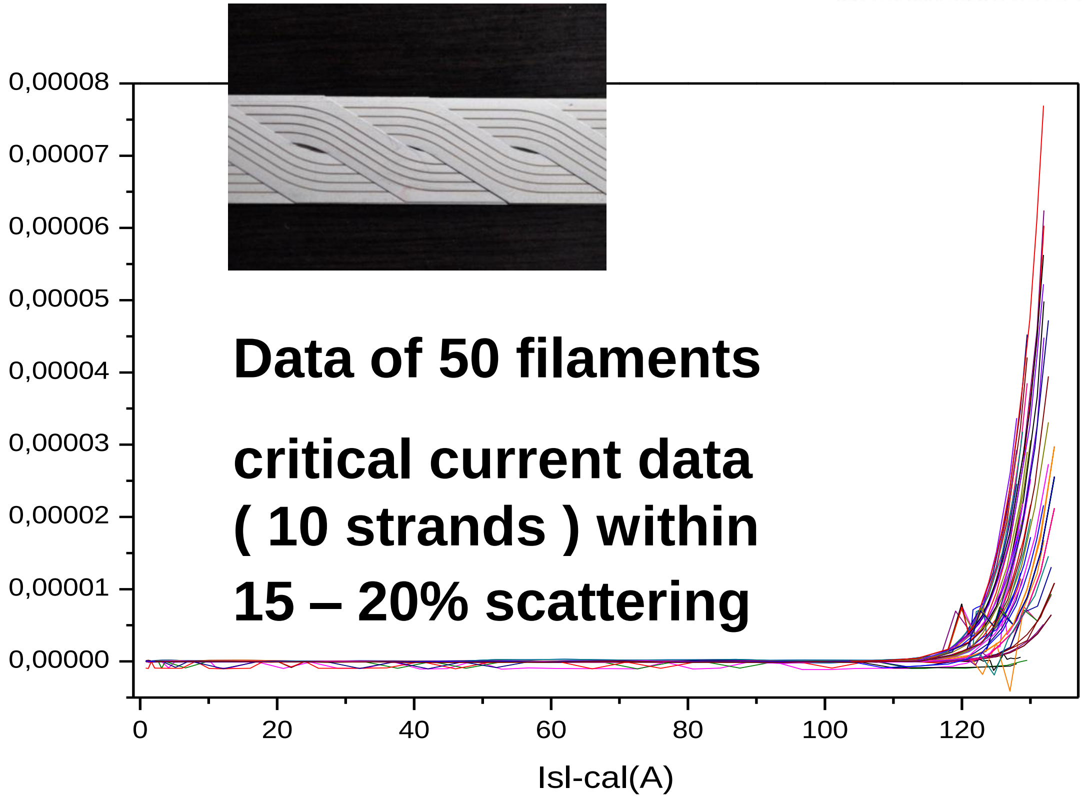

- **New Cables with up to 20 strands are already prepared for systematic res.**
- **AC loss investigations under way**
- **Modeling / theory will follow**

**Makes it sense for Roebel approach ?**

# Effect of striations on currents (older results)

Stanimira Terzevia et al. Unpublished

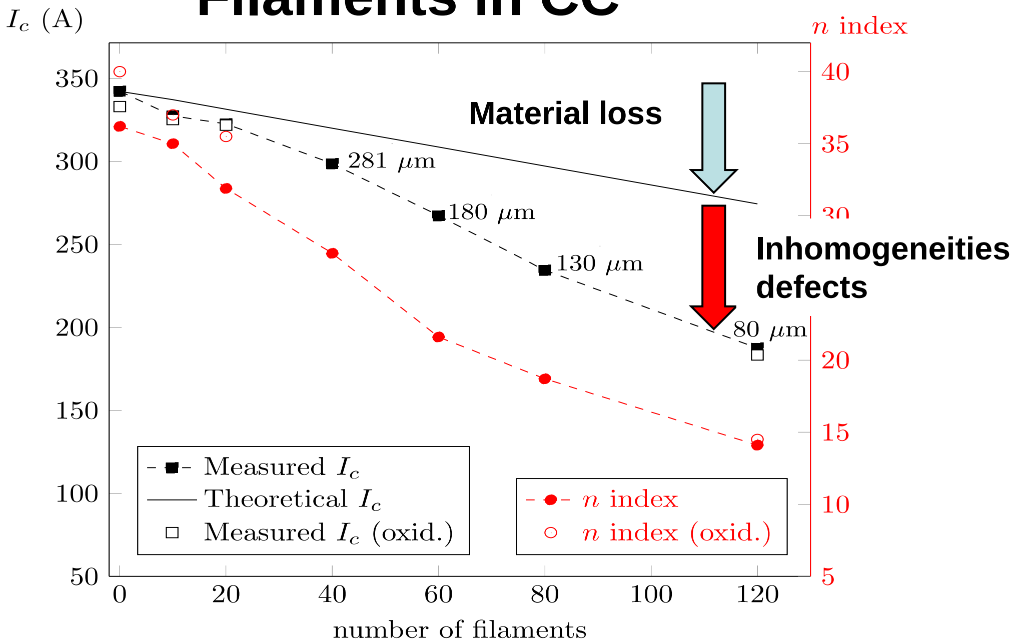


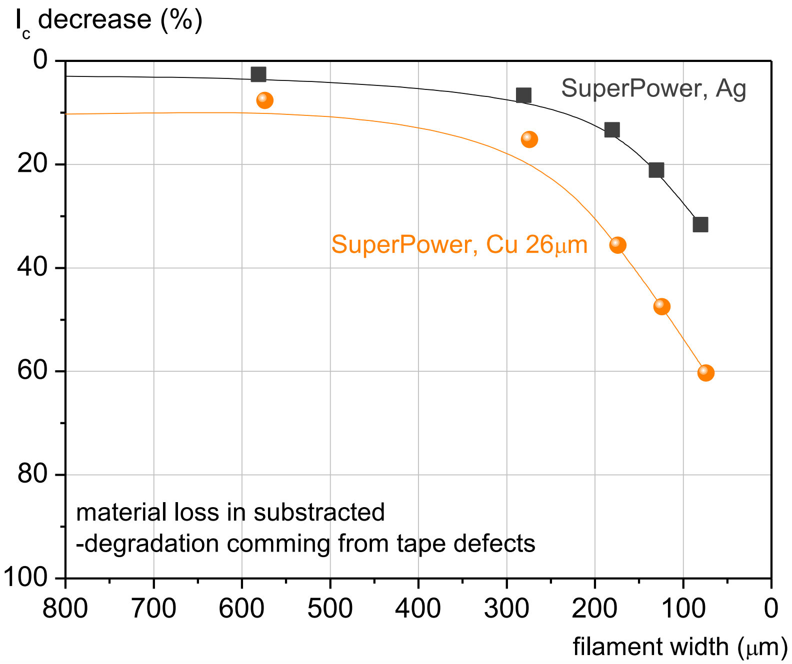




- $I_c$ of original CC = 270 A
- strand current around 133 A (scattering 14-15% Std.Dev.)
- Striated strands around to 125 A, scattering larger (15-20%)
- about 7-8 % loss in current from punching + grooving
- Material was Tapestar TM qualified for Roebel route by SuperPower !

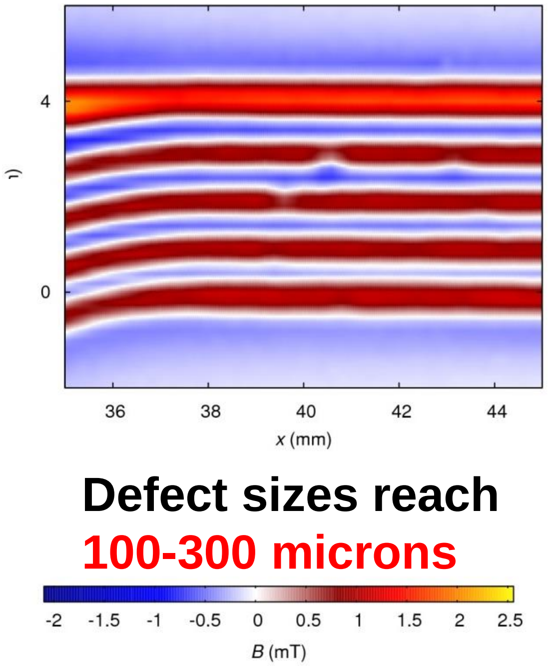
# Filaments as measure tool for CC homogeneity

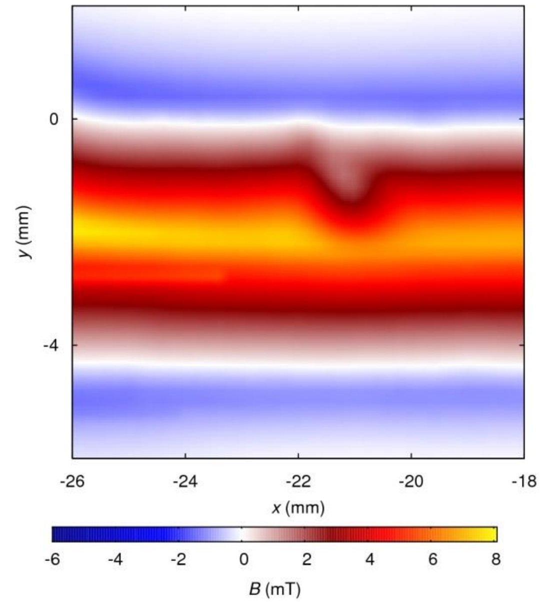
## Filaments in CC




## Filaments in Roebel strands



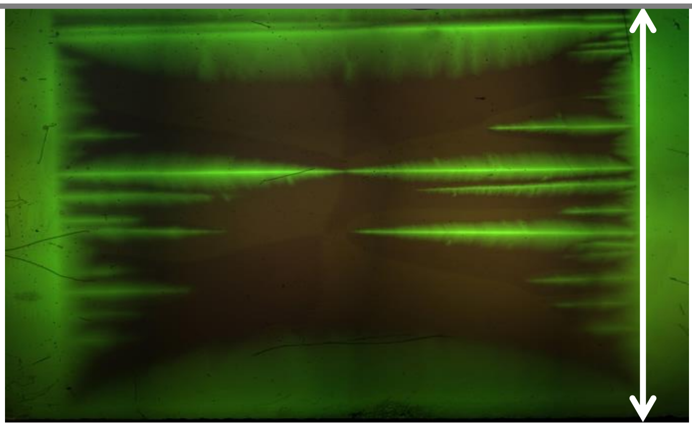




**Defect sizes reach**
**100-300 microns**

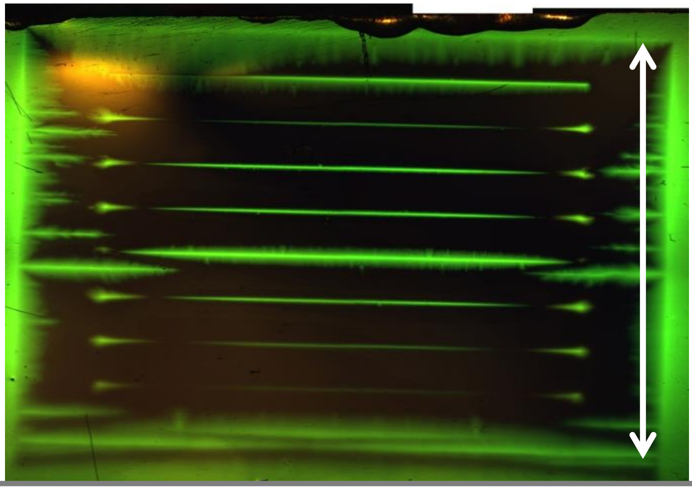
**Hall-probe scans: J Emhofer** IEEE Trans. Appl.Supercond.21(2011) p.3389.

- **Defects limit the current capability**
- **Narrow filaments reach defect size**
- **Defects are thermally weak points**
- **Striations can be used as quality test**

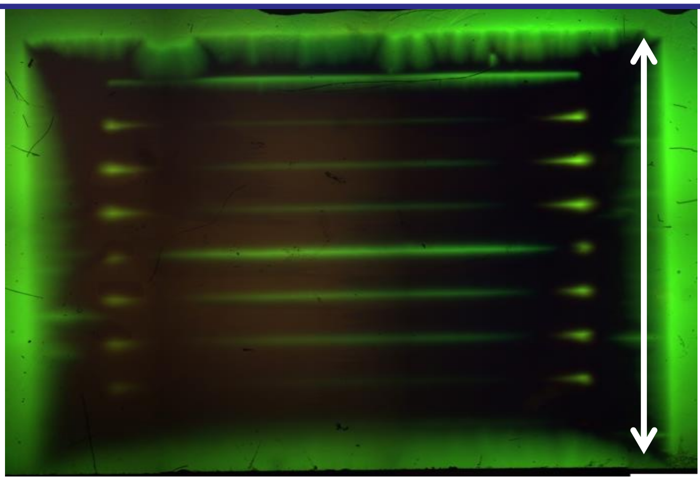
# MOI (made at KIT) of defects on SuperPower CC



12 mm width
across tape
Ag cap
42.7 mT
50 K



12 mm width
across tape
Ag cap
10 filaments
42.7 mT
50 K

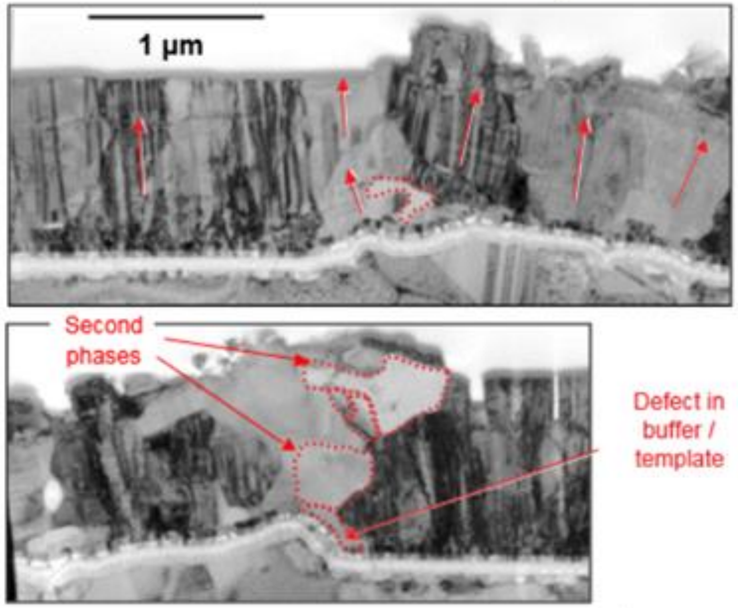


12 mm width
across tape
Cu cap
10 filaments
42.7 mT
23 K

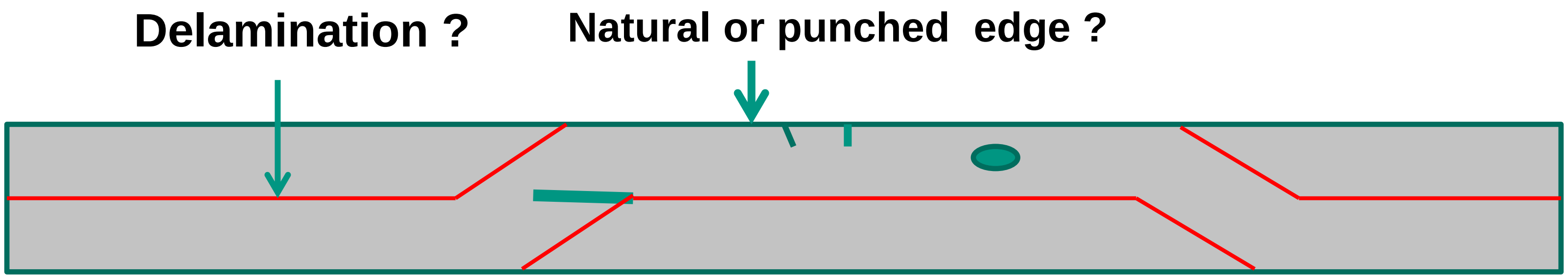
**Longitudinal defects are crucial penalty for Roebel shaping**

D.J. Miller et al.,
http://www.superpower-inc.com/files/
2006_ASC+4MI12+ANL+Poster.pdf

TEM reveals **misoriented YBCO** due to topography, loss of integrity of buffer/template



# Impact of defects in Coated Conductors for the Roebel route

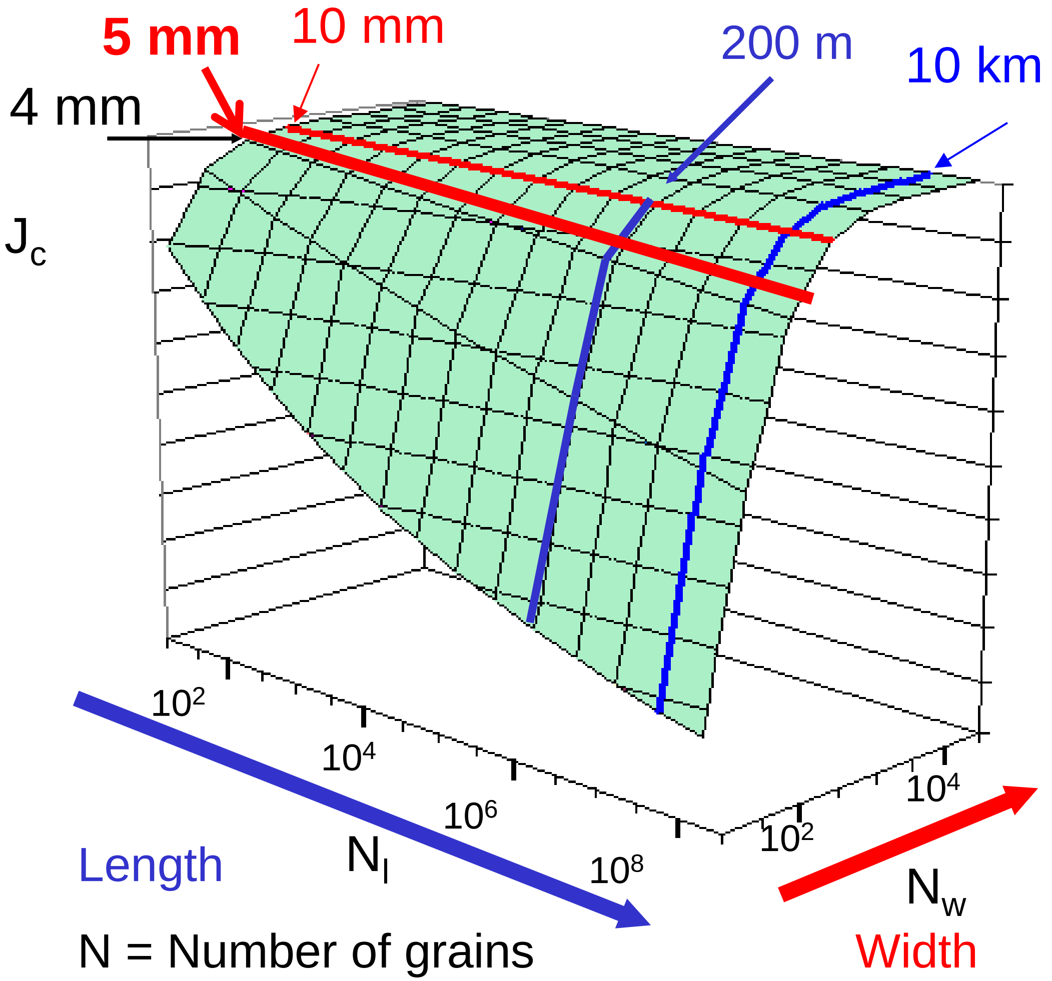



- Longitudinal defects in the crossing section most critical
- Transverse defects (less common, but at edge observed)
- Point defects (Hot Spots) , larger inhomogeneities

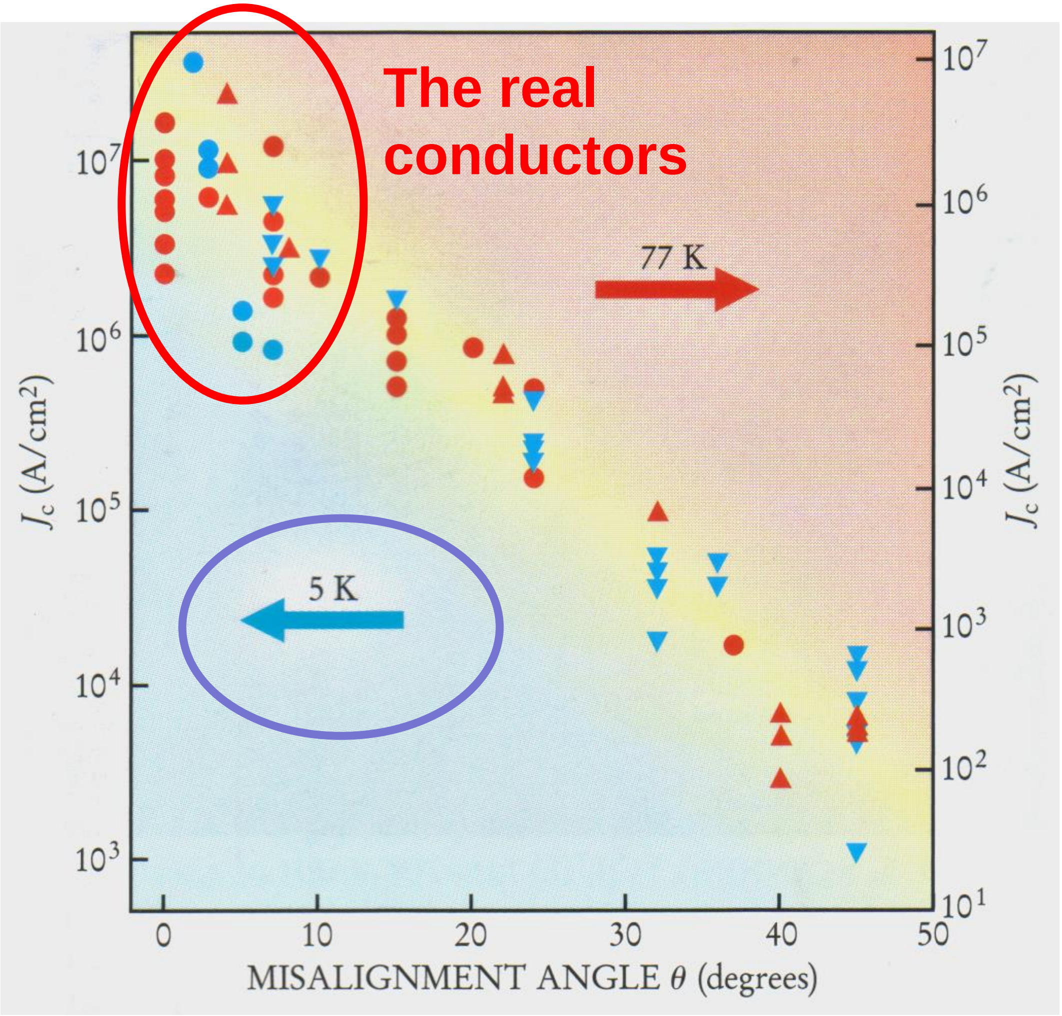
- Hall probe scan (Tapestar™) can provide first qualification test !
- Test & qualification of each CC material necessary !

# Effect of grain boundary angles on $I_c$

## The old story of effect from weak links (statistics of grain orientation)



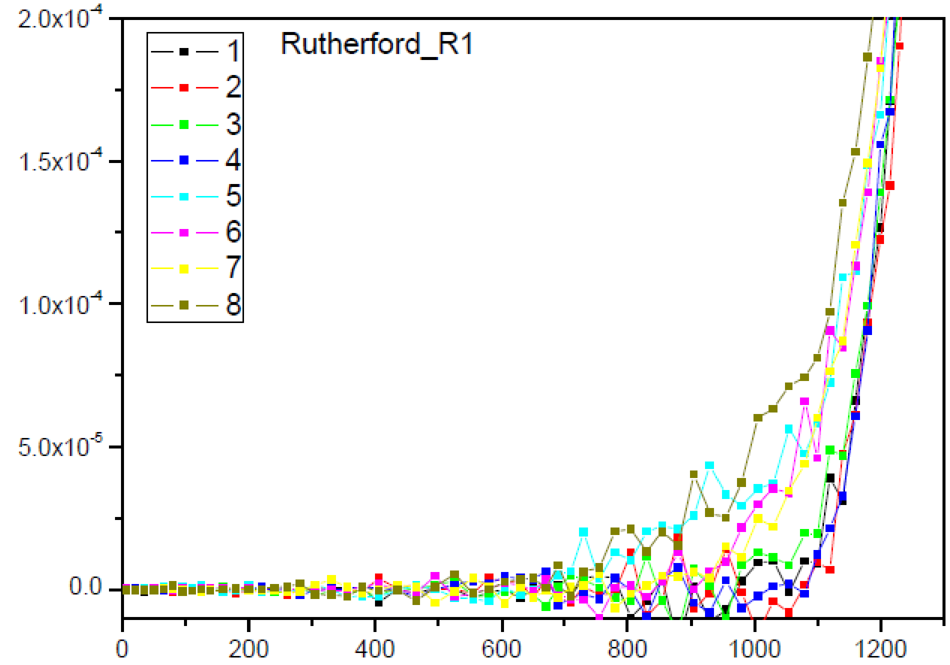

B.Zeimetz, A.Campbell et al. SUST 14 (2001) 672

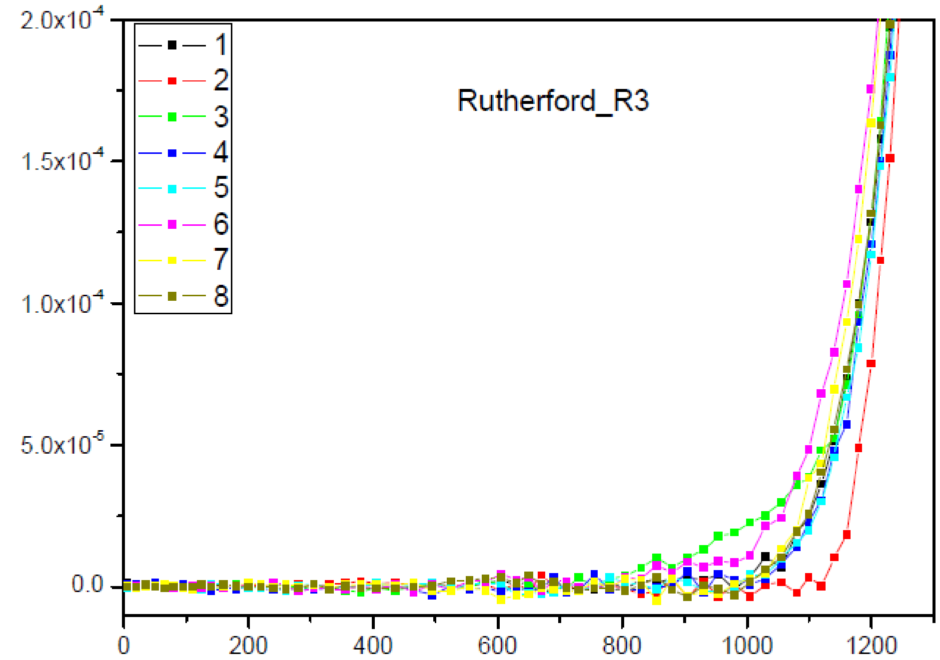



H. Hilgenkamp and J. Mannhart Rev. Mod Physisc

**Narrow CC width not suitable for high perfromance over long lengths**

# Issue: Current sharing in Roebel cables




- **From work on 1.4 m RF - cable**
- **Cables with 10 strands, 4 mm width**
- **Current redistributes over the ends**
- **Contact resistance dominant**
- **Negligible current sharing directly between strands**

- **In magnet winding moderate current sharing is requested**
- **But impregnation too ( see A.Kario talk this WS )**
- **Solution necessary !**

# Conclusions

- HTS CC Roebel cable is a promising choice for dipole inserts
- Provides full transposition and excellent bending
- Current anisotropy like CC
- Design is flexibel for transposition, strand number, can meet Specs
- Provides parameters for drastic current density scale-up
- Current sharing, stabilisation, impregnation not solved
- Optimize cable design (packing density, $L_t$ ) + magnet design !

**Qualification of all Coated Conductor materials for the Roebel cable process is absolutely mandatory !** ➔ **What can provide industry**

**KIT provided 4 cables of 2 meter for FRESCA, changed cable designs, SS Roebel dummy cables with 20 m length for winding process experiments and cooperation in technical issues like impregnation**

# The end, thank you

# !