ICEC25-ICMC 2014 TWENTE

7th.-11th. July 2014

The Roebel Assembled Coated Conductor (RACC) cable, status of performance and prospects for further upgrades

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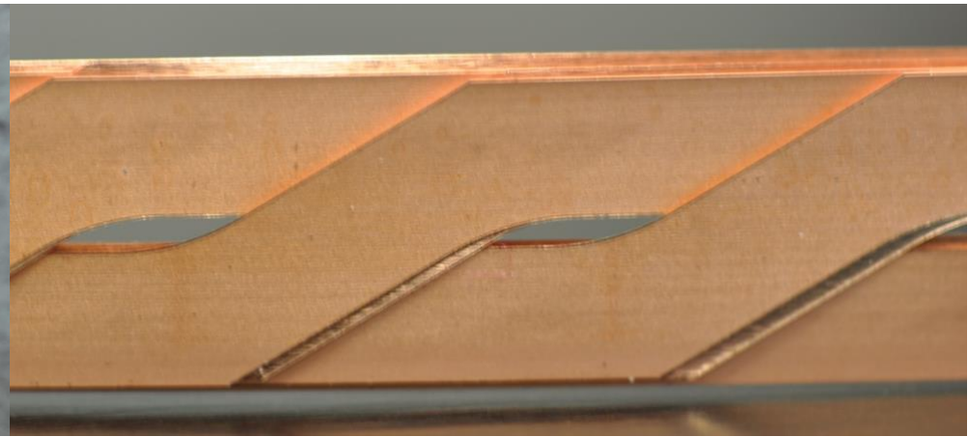


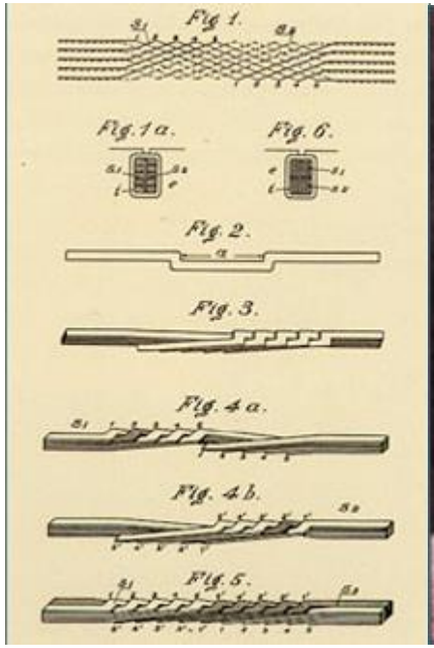
Contents

Roebel Cable (RACC)

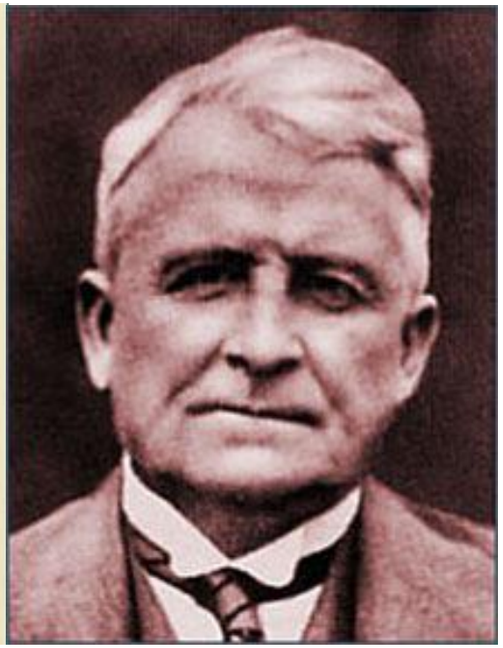
- **Introduction cable concepts**
- **Current capability / anisotropy at 4 – 77 K**
- **Parameters for current enhancement**
- **Solenoid and pancake coils**
- **Bending properties and coil shape**
- **Option: striations for lowered losses**
- **Filaments and Inhomogeneities**

Conclusions

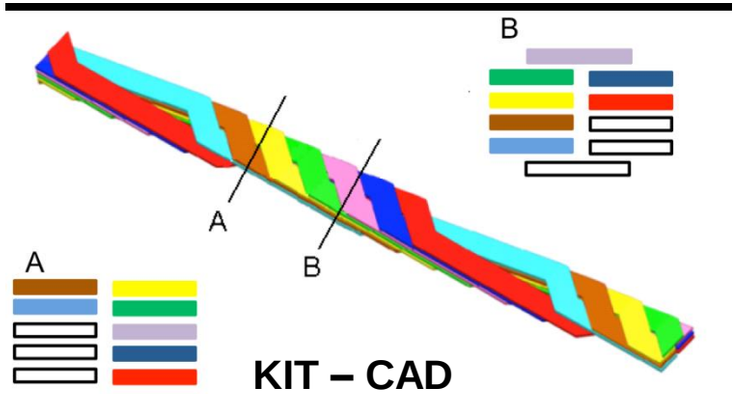
Roebel Assembled Coated Conductors (RACC)
100 years birthday of an old idea



Patent figure



Ludwig Roebel



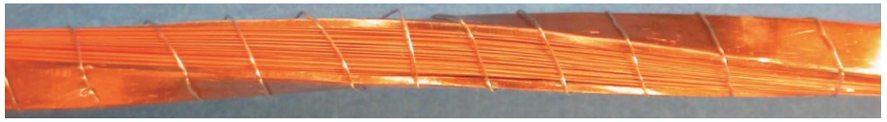
KIT – CAD

LCT EURATOM cable NbTi
Transposition in the cable and in the strands !!

- **Invention 1912-1914 Ludwig Roebel**
- **The LCT NbTi Roebel cable 1984/85**
- **Proposal for HTS-CC M.Wilson 1997**
- **Realisation KIT (W.G. et al.) 2005/06**
- **Commercialisation IRL-GC 2008 f.**

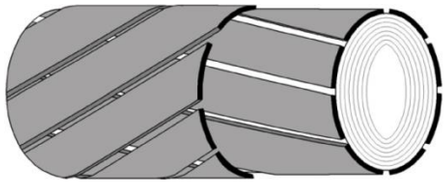
High current cable concepts with CC

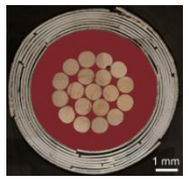
- **Twisted Stacked-Tape Cable (TSTC)**
-



M. Takayasu et al, Adv. Cryo. Eng., 54, Plenum, N.Y., 273-280, 2012

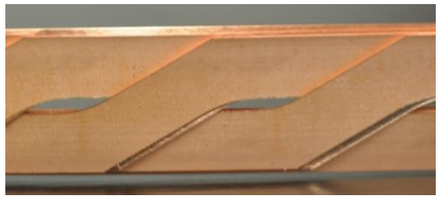
- **Conductor on Round Core (CORC) cable**





D.C. van der Laan et al, Supercond. Sci. Technol. 24, 042001, 2011

- **Roebel Assembled CC (RACC) at KIT**



The only concept with all CC axis aligned !!

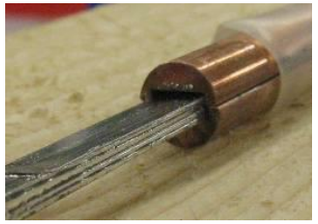
W. Goldacker et al, Supercond. Sci. Technol, 22, 034003, 2009

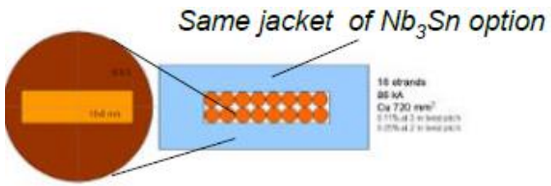
- **Rutherford Cable + Roebel strands (CCRF)**

KIT

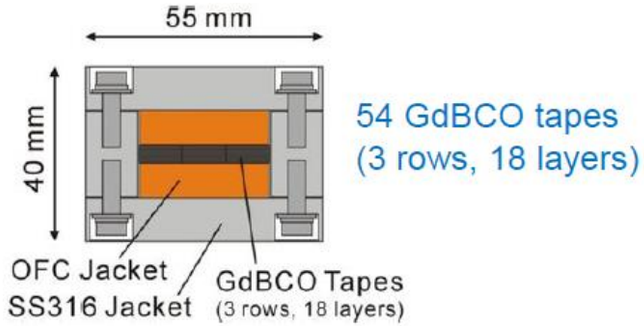
A.Kario unpubl.

- **Cable EPFL: CC stacks in Cu**

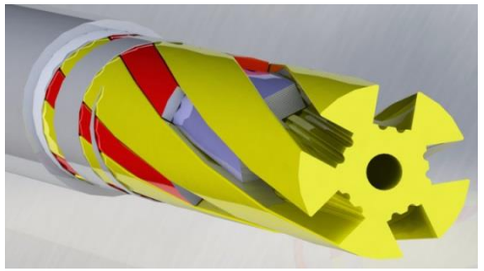


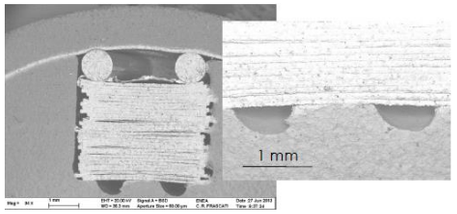


- **CC stacks in blocks (Tohoku Univ., NIFS)**



- **ENEA cable RF with stacks**



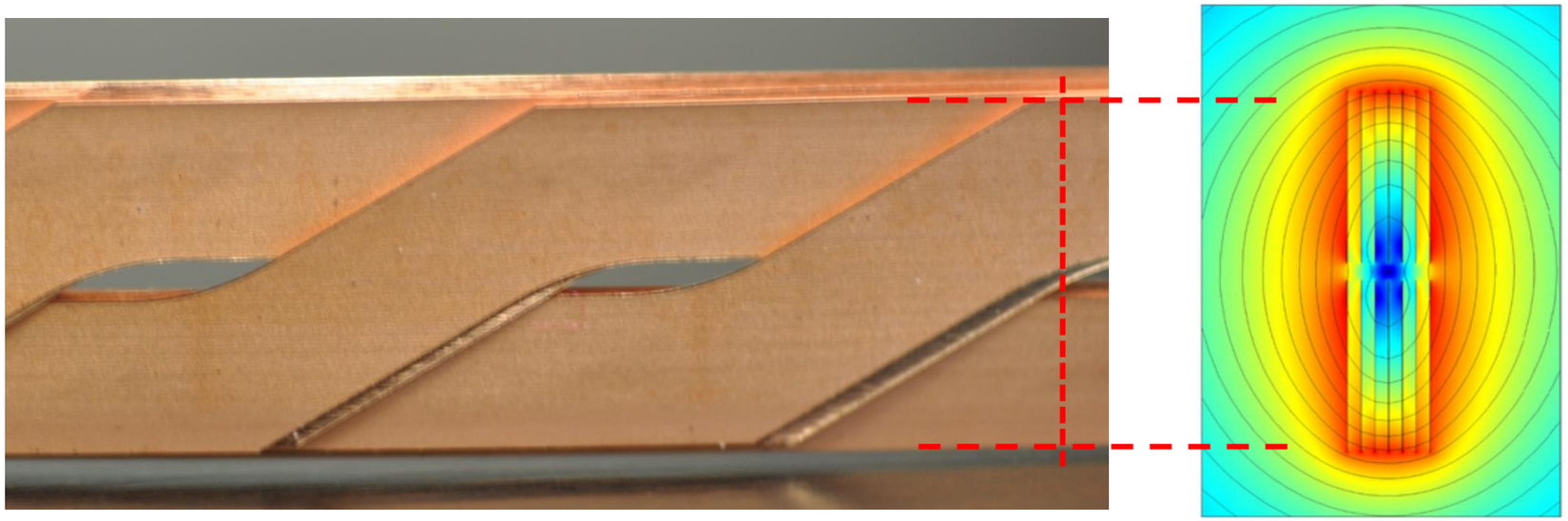


Short straight single RACC sample in self field 77 K

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

cross section

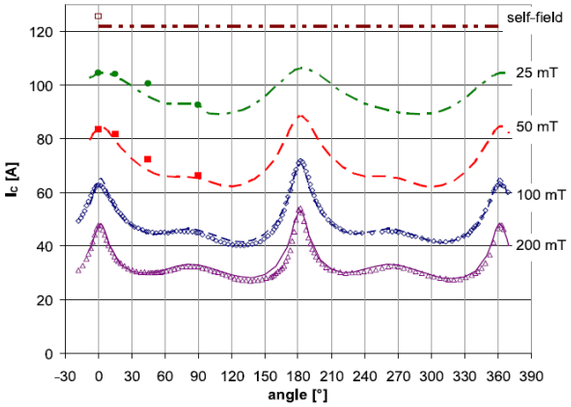
12 mm

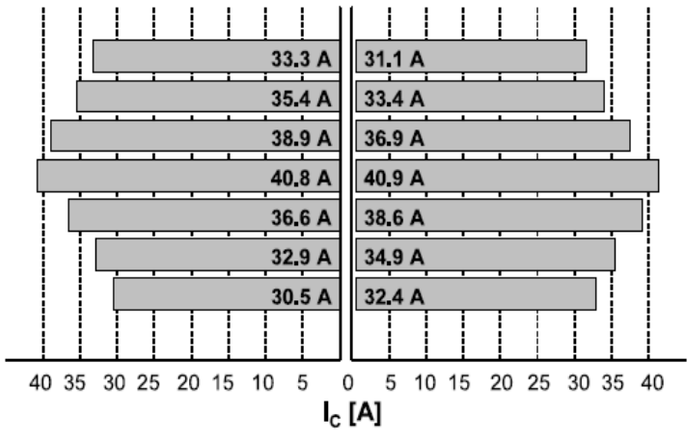


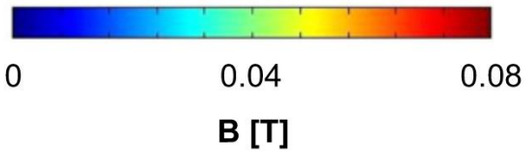
Modeled self field pattern

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

Current anisotropy not symmetric due to CC specific pinning, source of complex current distr.

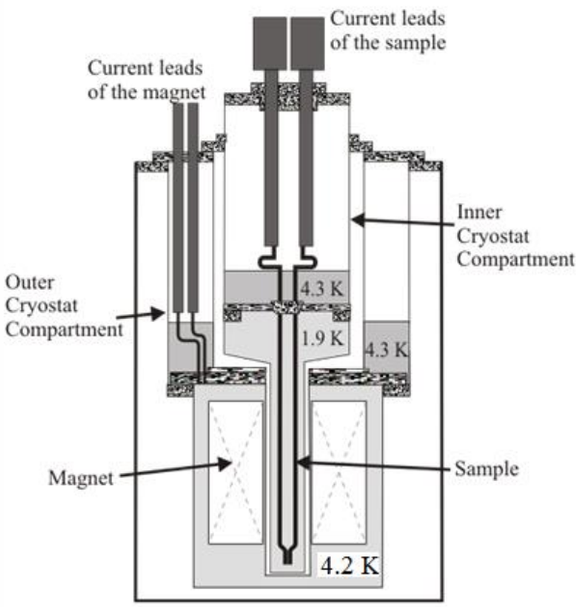


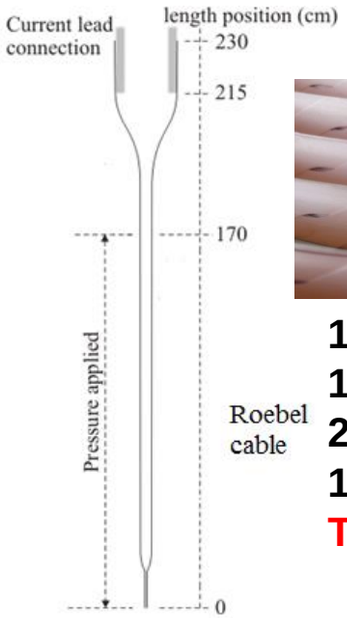




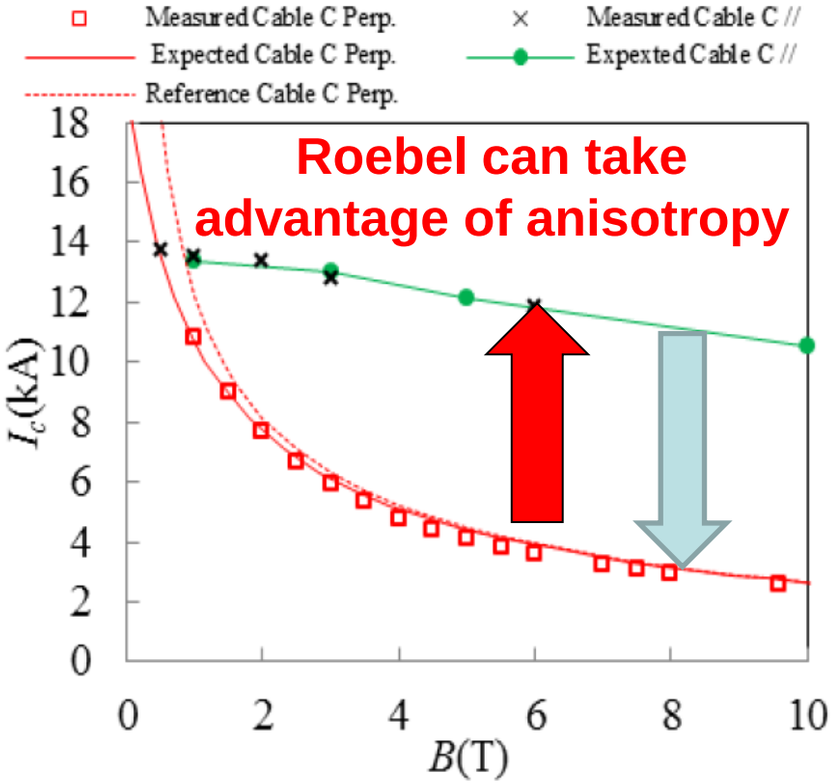
- **Current redistribution effects begin at $I > ½ I_c$**
- **Modelling shows influence of non-symmetric anisotropy**
- **I_c in s.f. reduced by 40-60%**

Anisotropy of Roebel cable 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
Transpos.: 126 mm



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

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

Cables with twisted CC along cable axis include worst field orientation (as CORC)

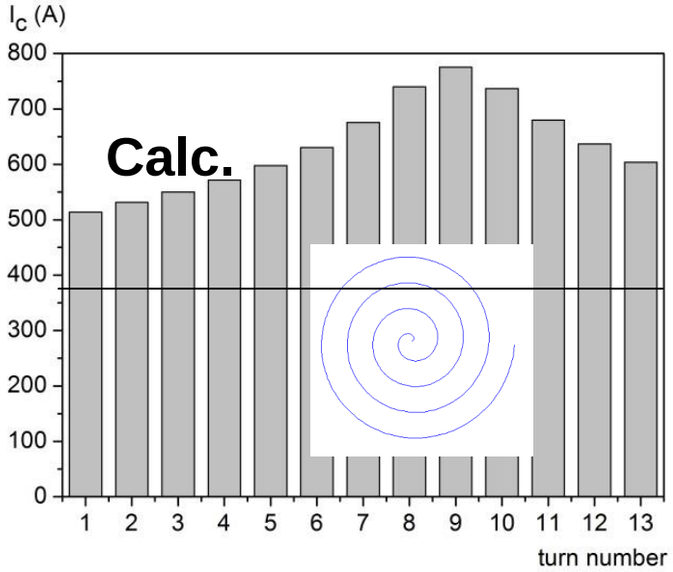
Solenoid and pancake coils

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



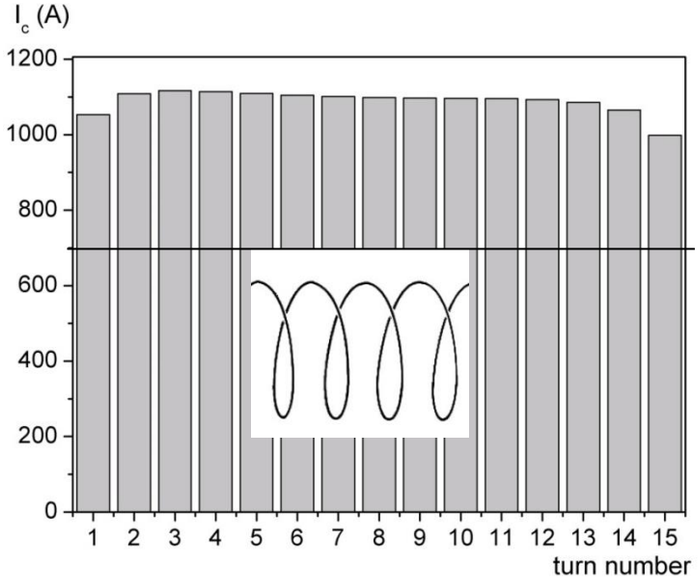
Design value 1512 A

Model with sharing 1108 A

Straight cable 936 A (m.)

Solenoid coil 750 A (m.)

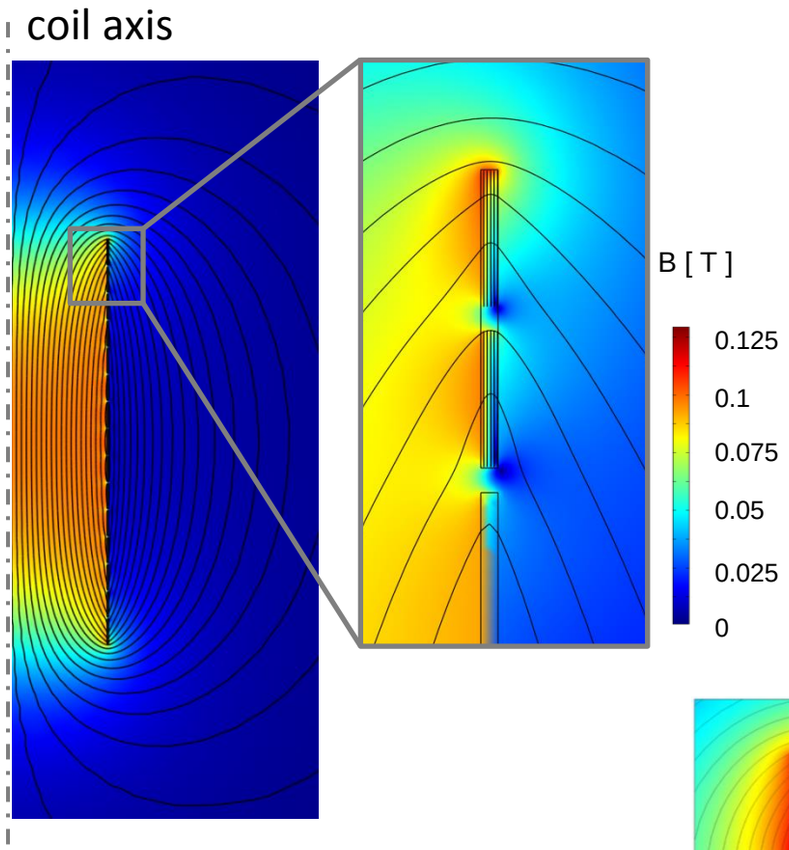
Pancake coil 460 A (m.)



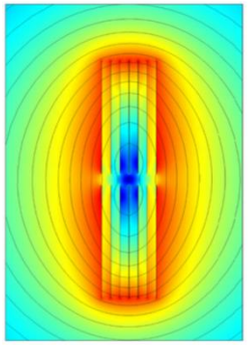
Bending is excellent, Measured degradation of current stronger than modeled
= Influence of CC Inhomogeneity + complex current path

Modelling of self field effects in the coil arrangement

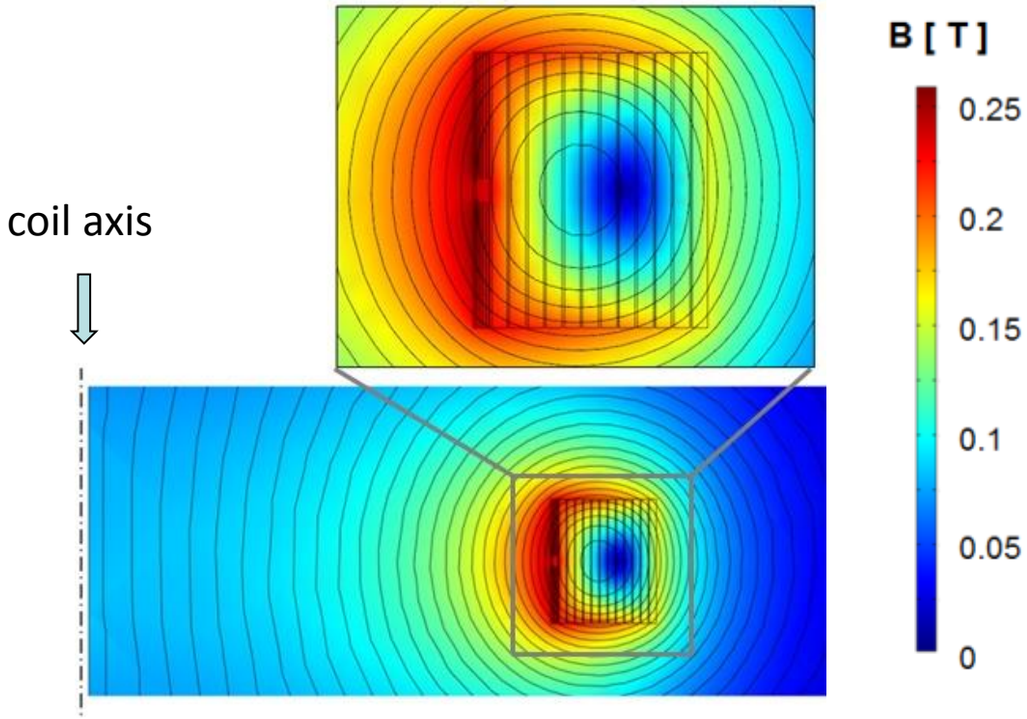
- **FEM Modeling confirms measured influence on transport currents**
- **Stronger self-field interaction occurs between turns in a pancake coil**
- **Strong influence of current anisotropy**



- Solenoid with cable monolayer
- 1 mm turn distance



Reference straight cable

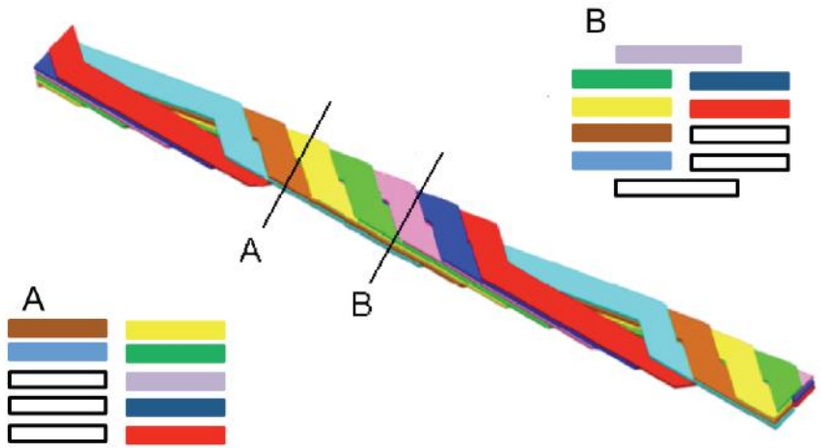


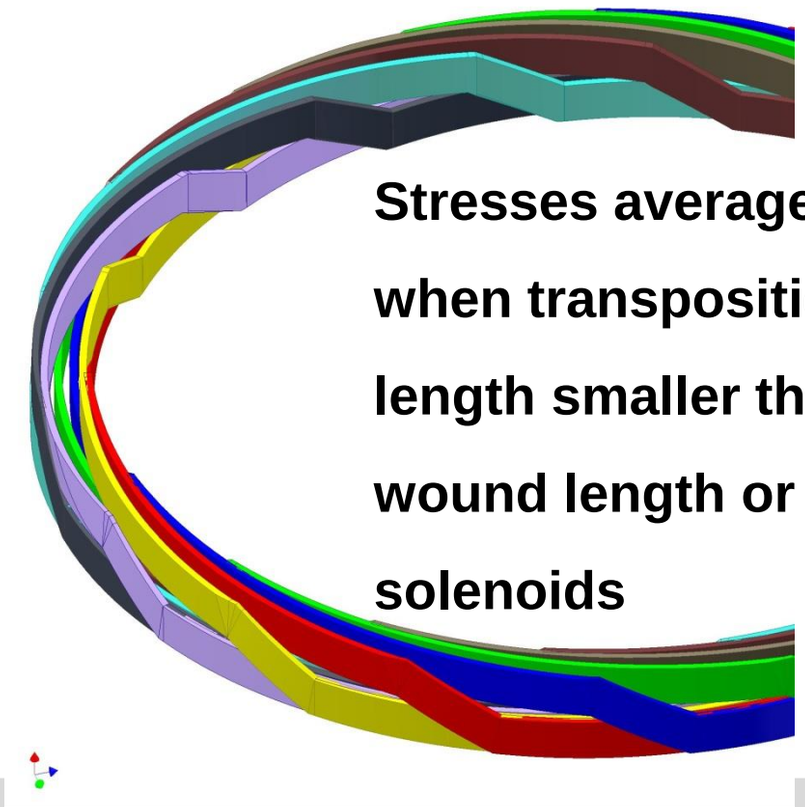
- Dense packed pancake version shown
- 0.1 mm turn distance

F. Grilli, M.Vojenciak et al.

Bending properties and coil shape

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

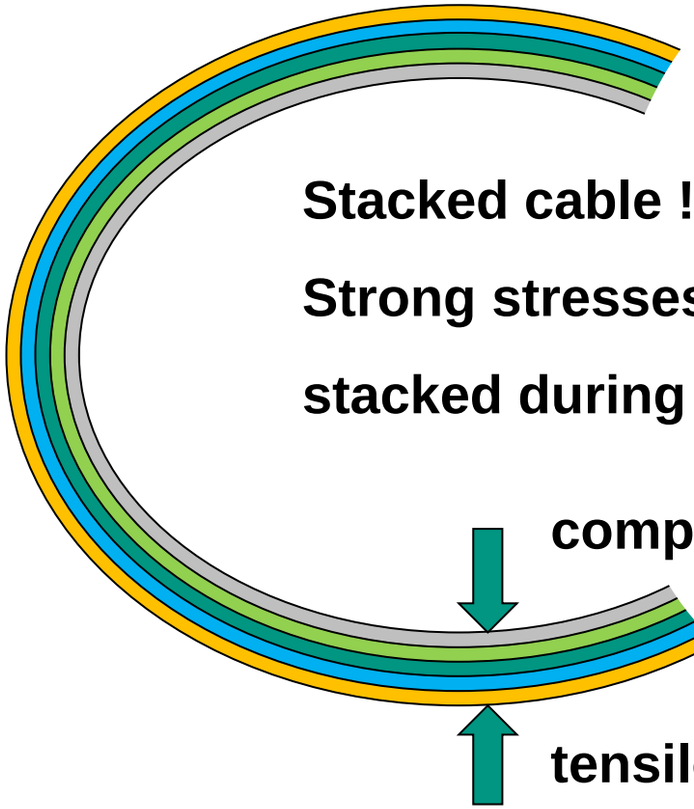




Stresses average out when transposition length smaller than wound length or in solenoids

Solenoid Case !

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



Stacked cable !

Strong stresses if not stacked during winding

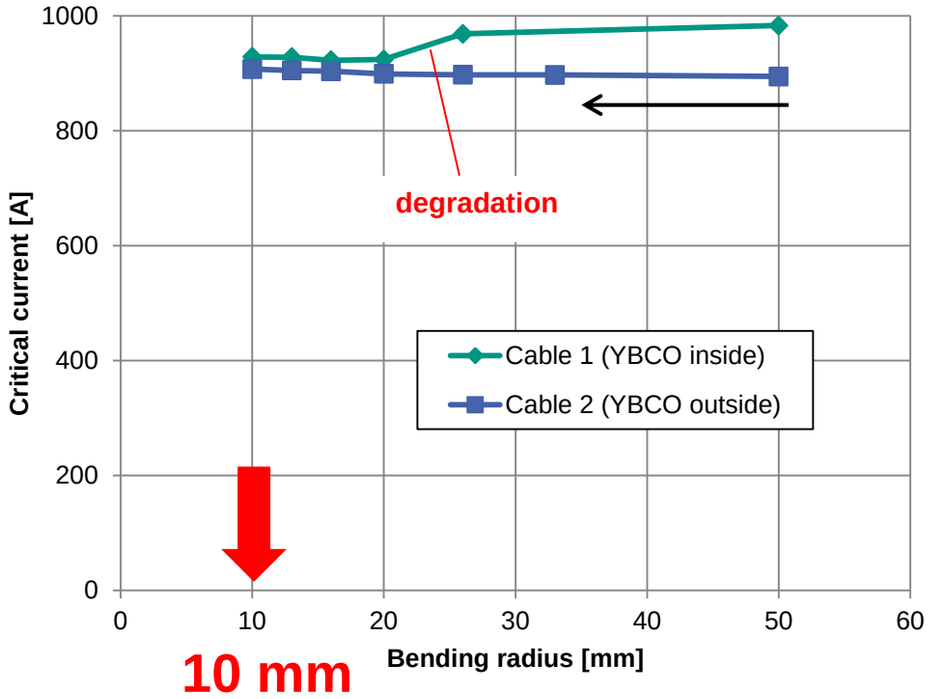
compressive

tensile

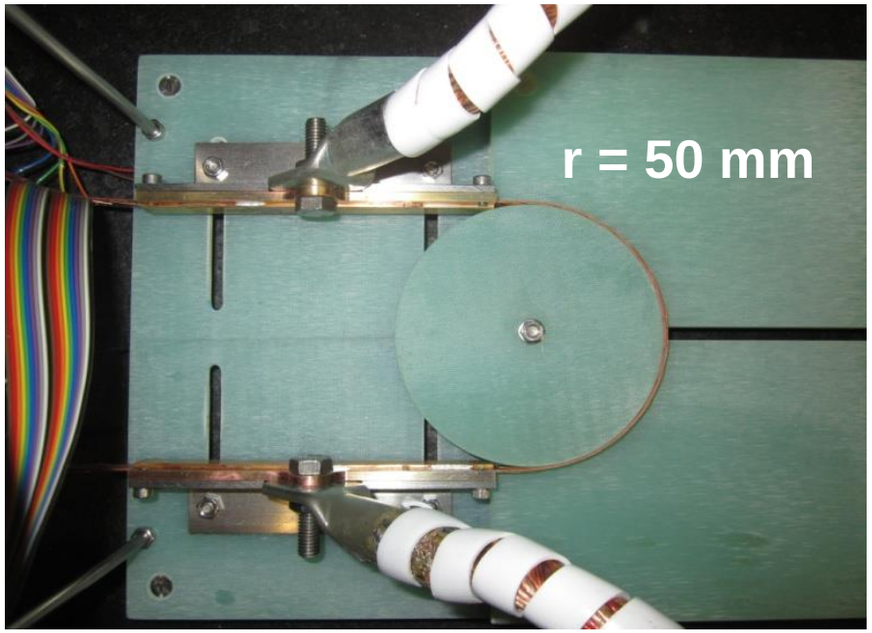
Bending of HTS Roebel cable in solenoid shape

S. Otten et al. KIT unpublished

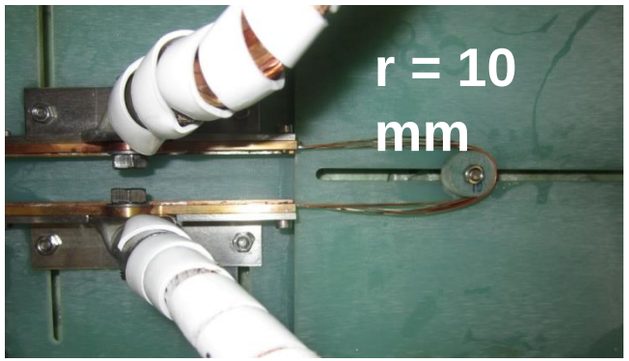
- Bending radii: 50, 33, 26, 20, 13, 10 mm
- Small degradation, < 6.5 % of total cable I_c
- Measurements on single strands show degradation in the bent section by < 1%
- Cable degradation was not caused by bending (current redistribution event !)



Bending like CC !

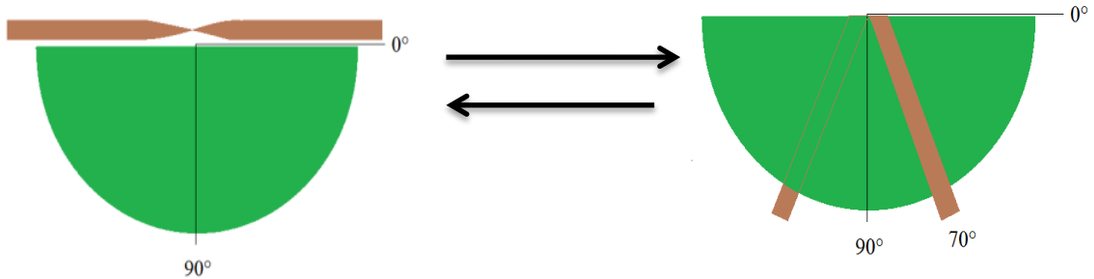


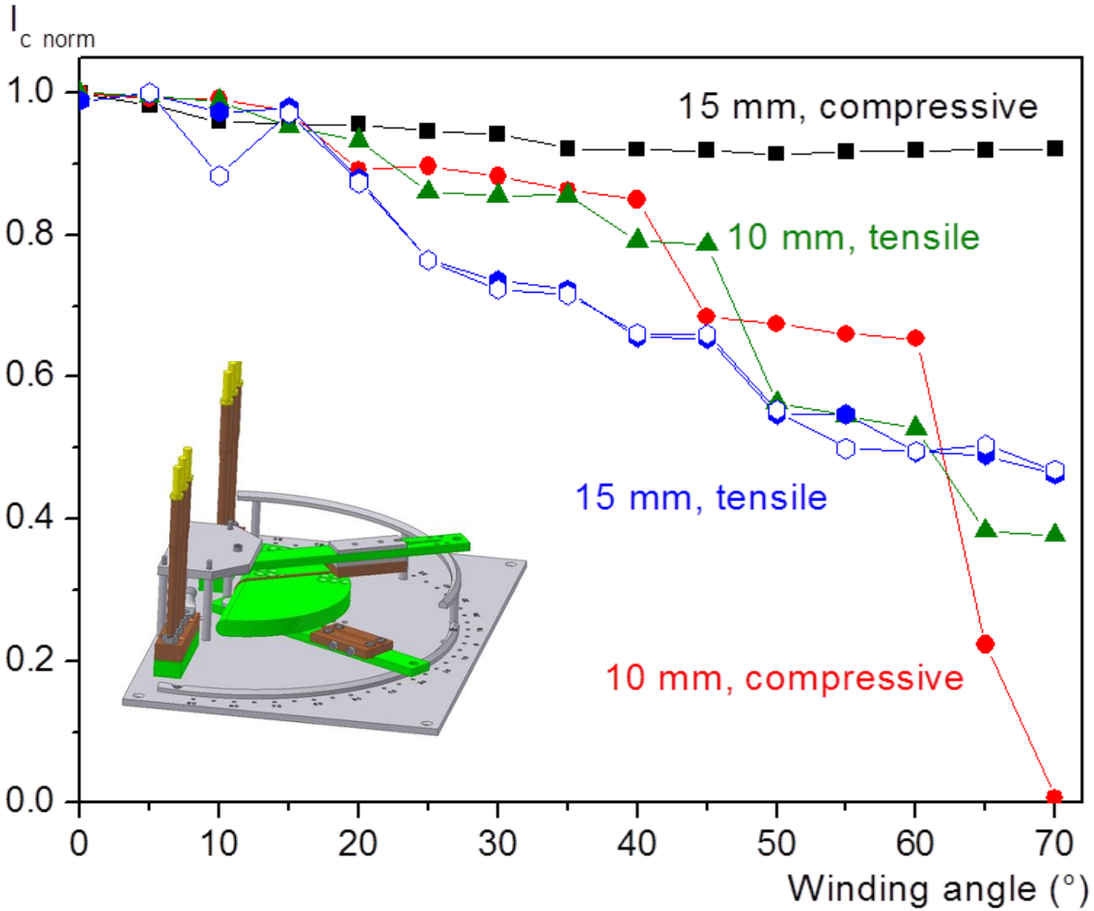
12 mm



Edge Bending of cable

- Variable angle between cable axis and bending direction
- Fixed beding diameter





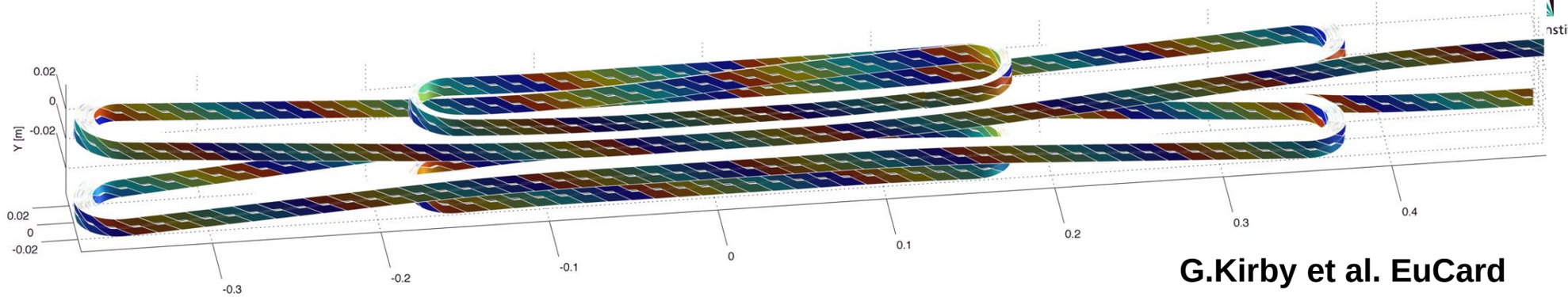
Roebel cable 4 mm width

For 0-5° no degradation

Degradations depend on orientation of cable (REBCO inside / outside)

CC layer orientation inside gives mechanical reserve

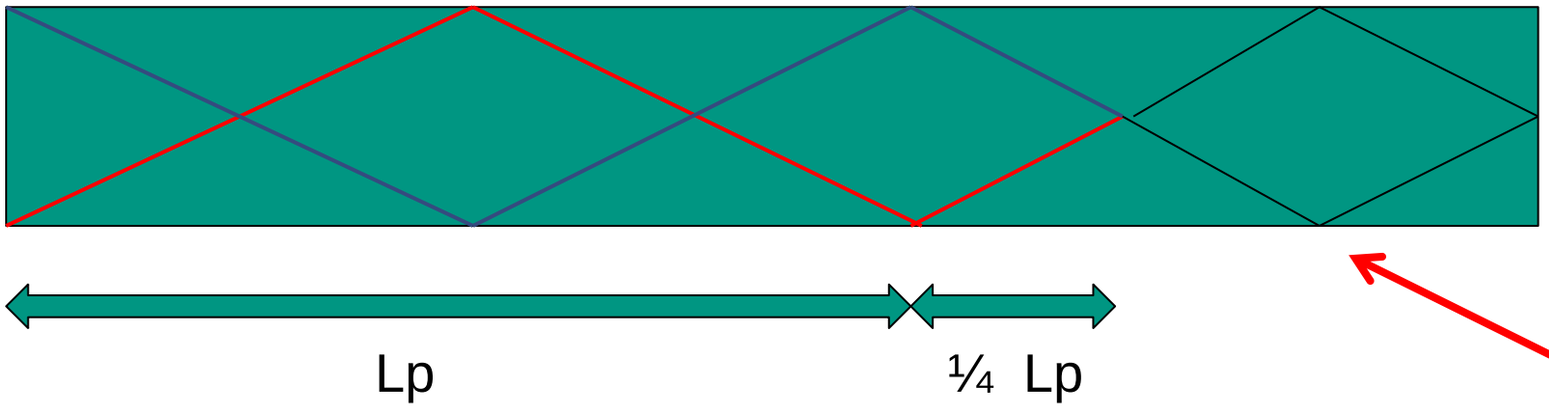
Bending of a Roebel cable in non-solenoid shapes

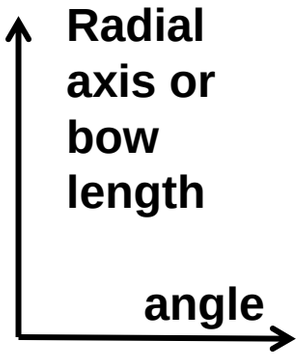


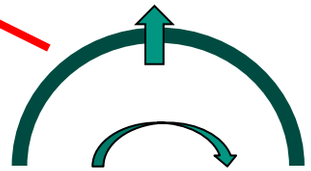
G.Kirby et al. EuCard

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:

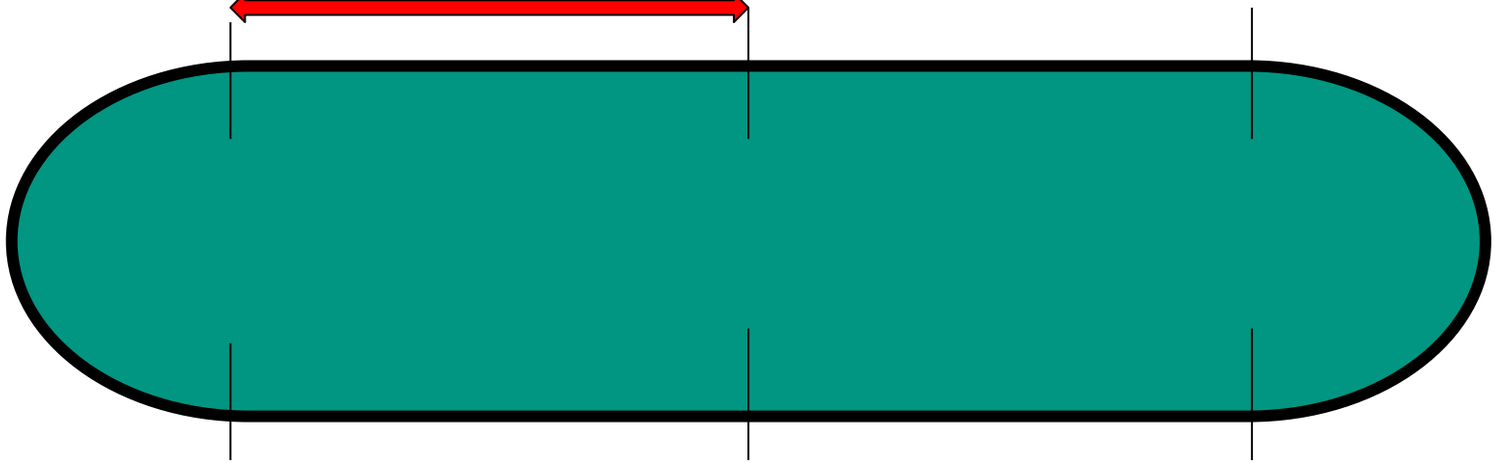
- **Avoid cumulative deviations from bent strand lengths and resulting stresses**
- **Designing the transposition length and coil dimensions together is necessary !**

Interplay of transposition length and magnet design

Transposition length

Case 1

L_t = bent section

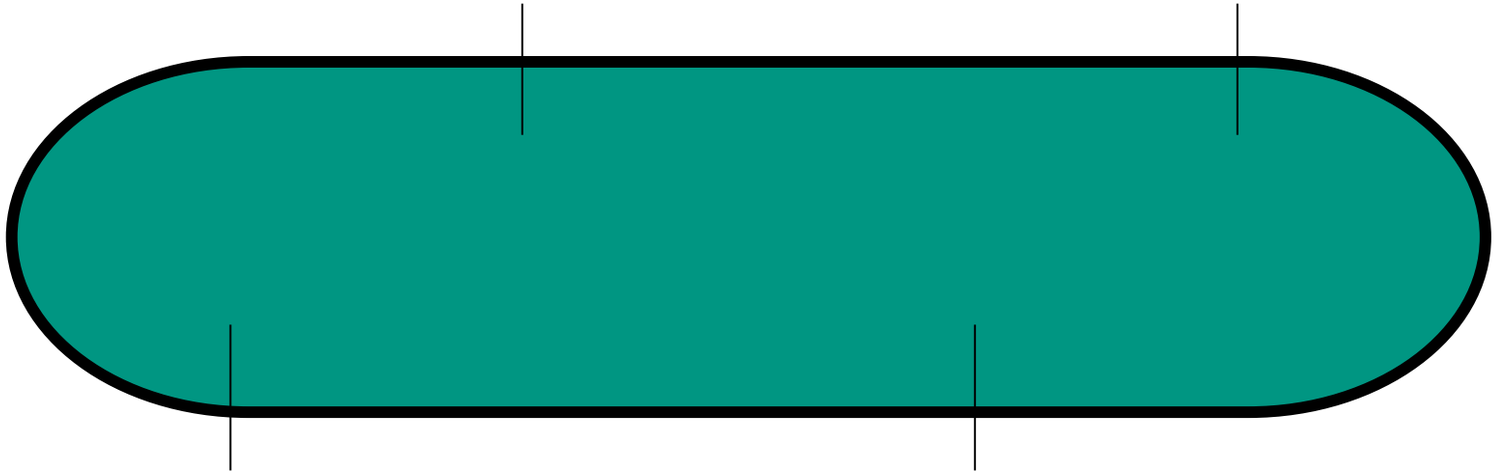


Find a way to unload the stress !

Cable design
Winding technology

Case 2

L_t > bent section



Experiments in work with dummy cables

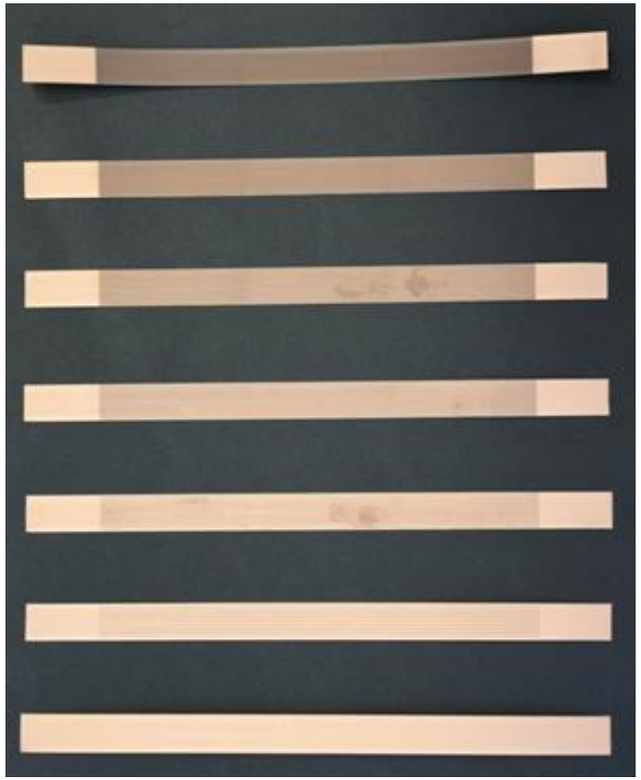
Not all strands have the same length
Situation changes turn by turn

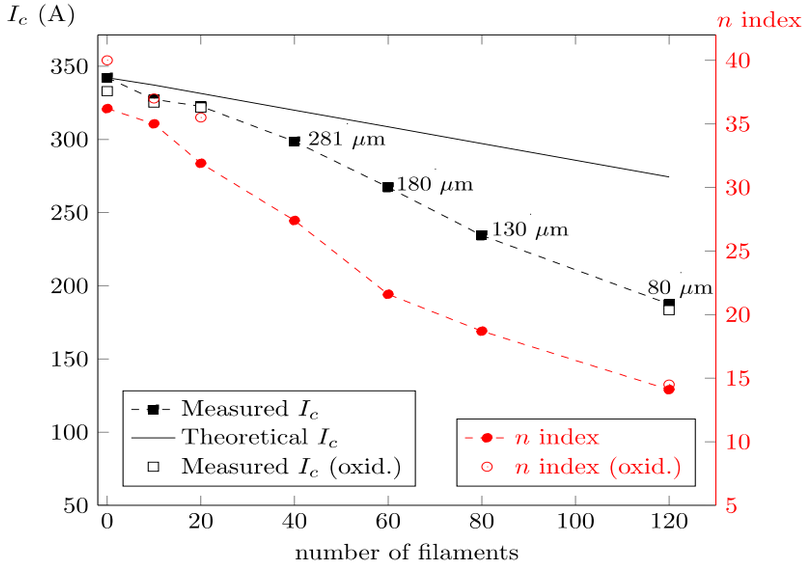
Winding experiments necessary!

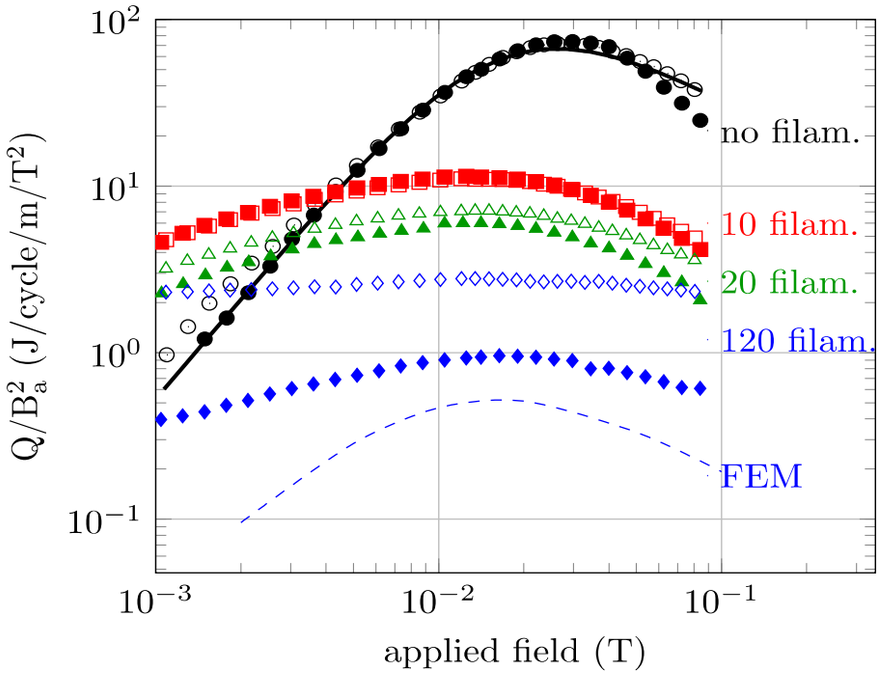
Option: Striations for lower Losses

Option for lower AC losses: Striated CC or strands:

Up to 120 Filaments (12 mm) prepared and analyzed, moderate current degradation from CC inhomogeneity, full separation with post annealing achieved (filled symbols in figure)





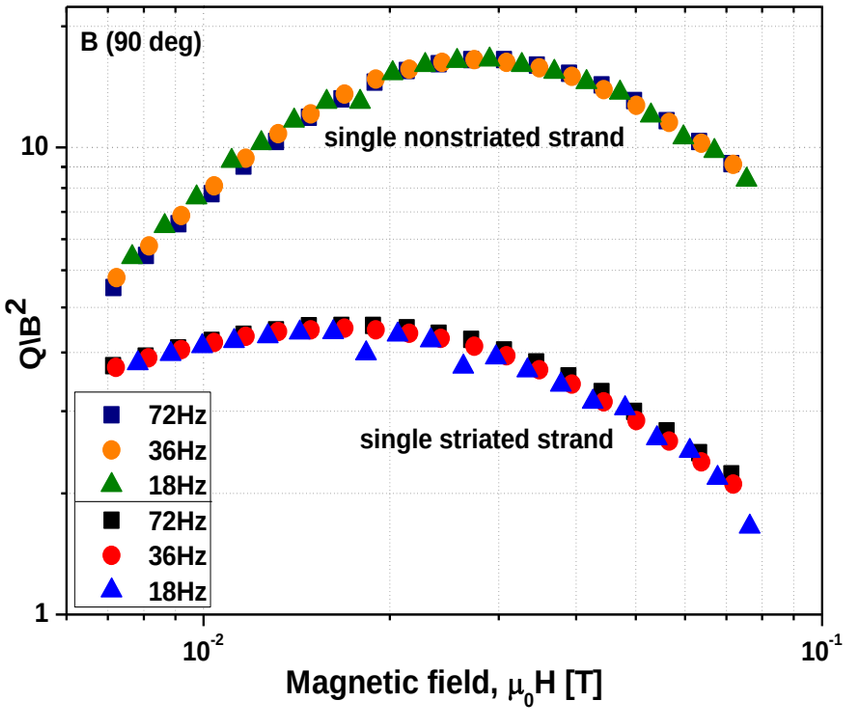


Striated RACC cables (earlier results)

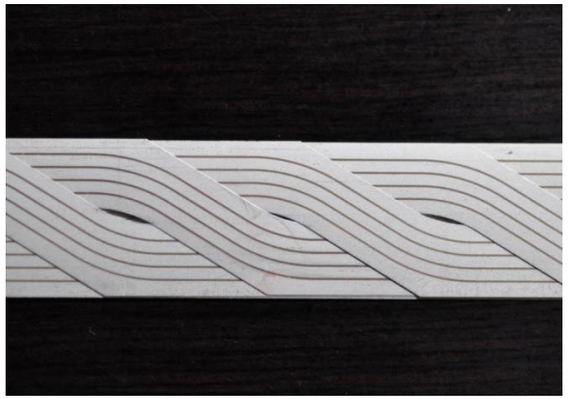
Magnetization AC loss measurements

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

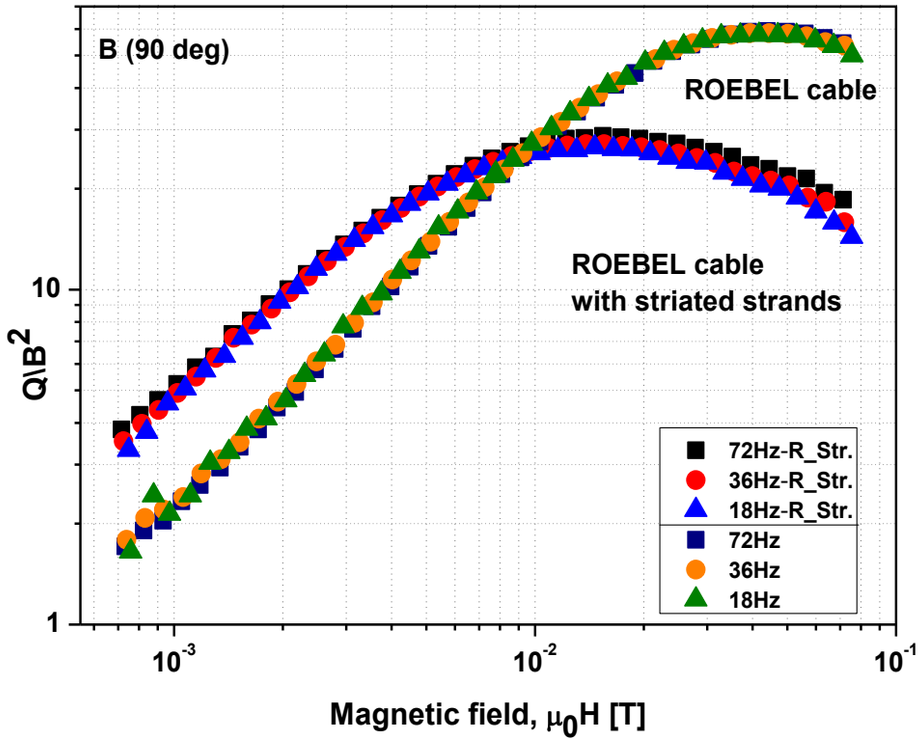
Effect in strands



Striations made by psec-IR laser at KIT



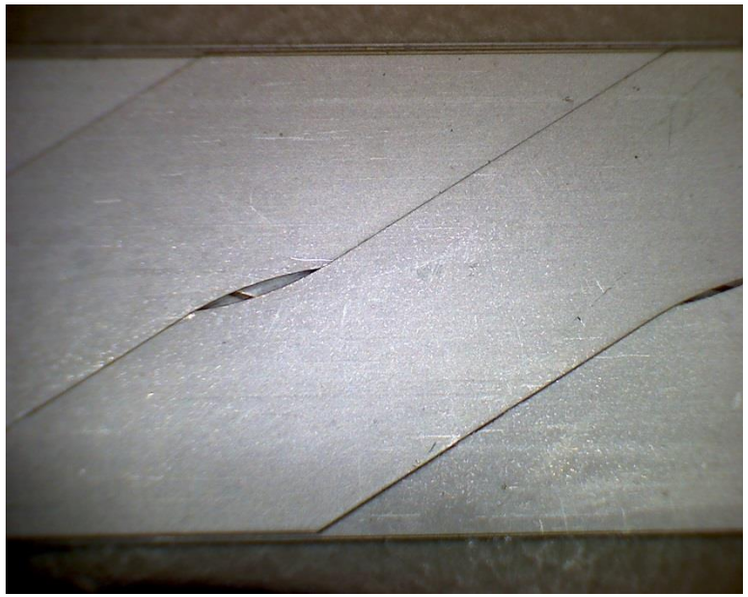
Effect in cable

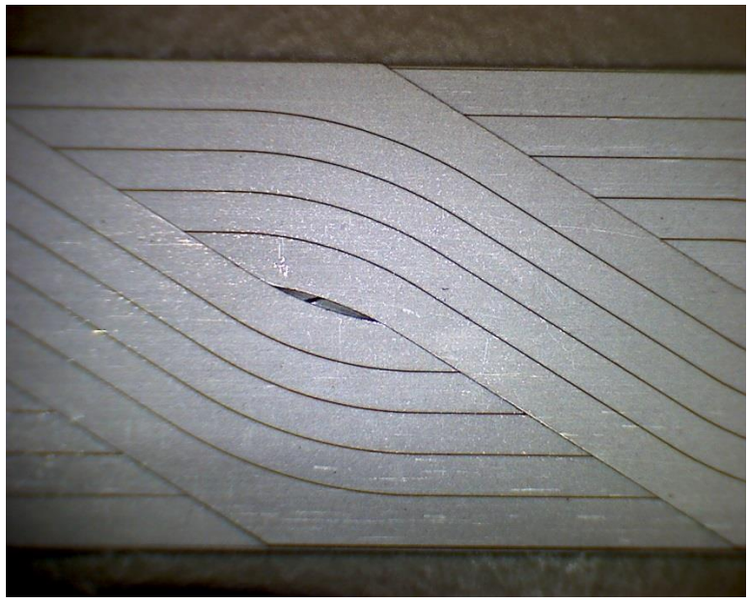


- **Systematic investigations with up to 20 filaments (samples exist) in work**
- **AC loss investigations**
- **Modeling will follow**

Striated RACC cables (under Investigation)

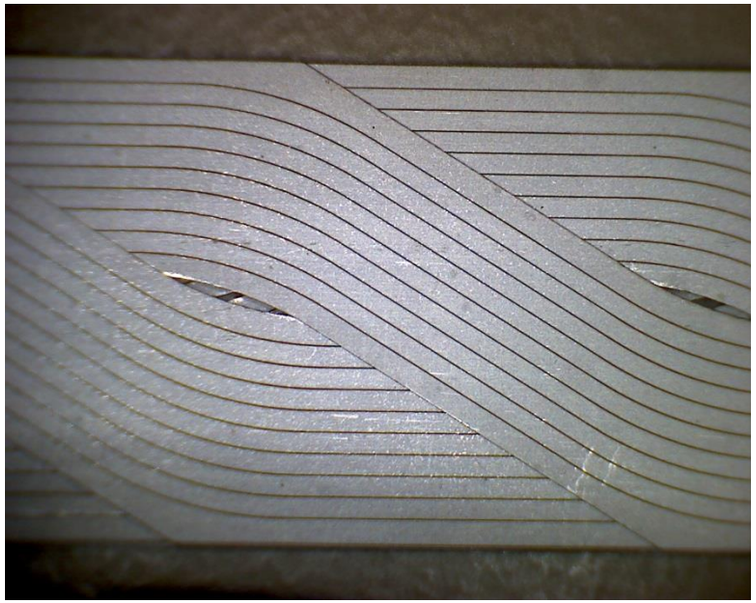
Magnetization AC loss measurements are actually performed

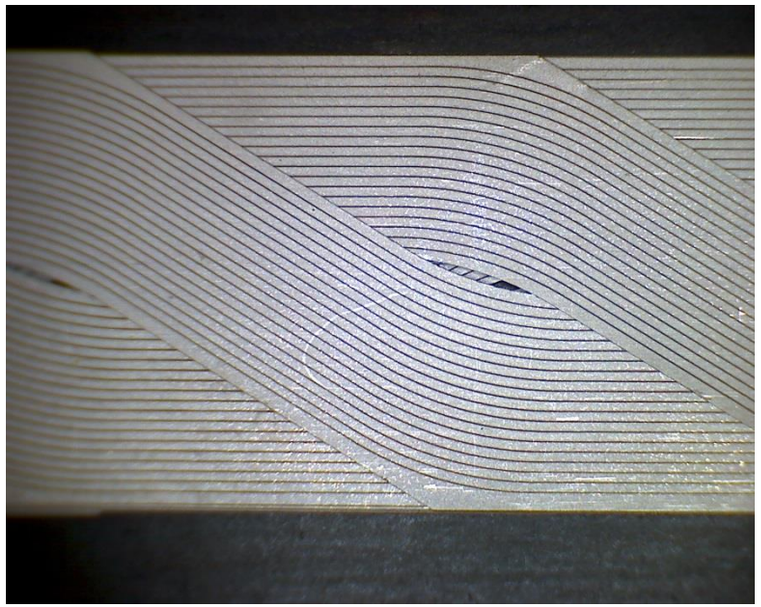




Filament numbers

0, 5, 10, 20





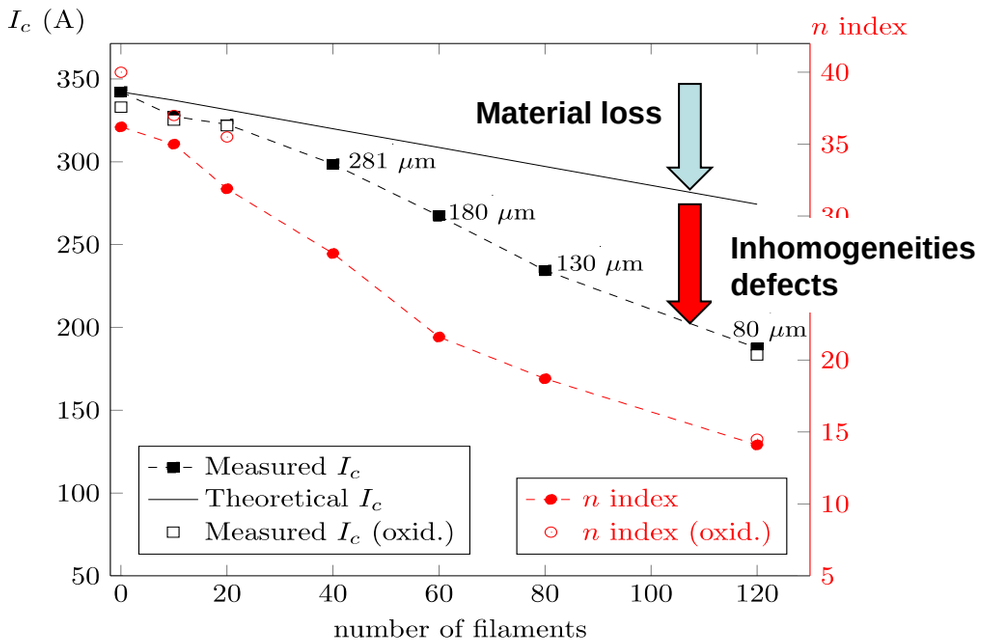
Shape oriented

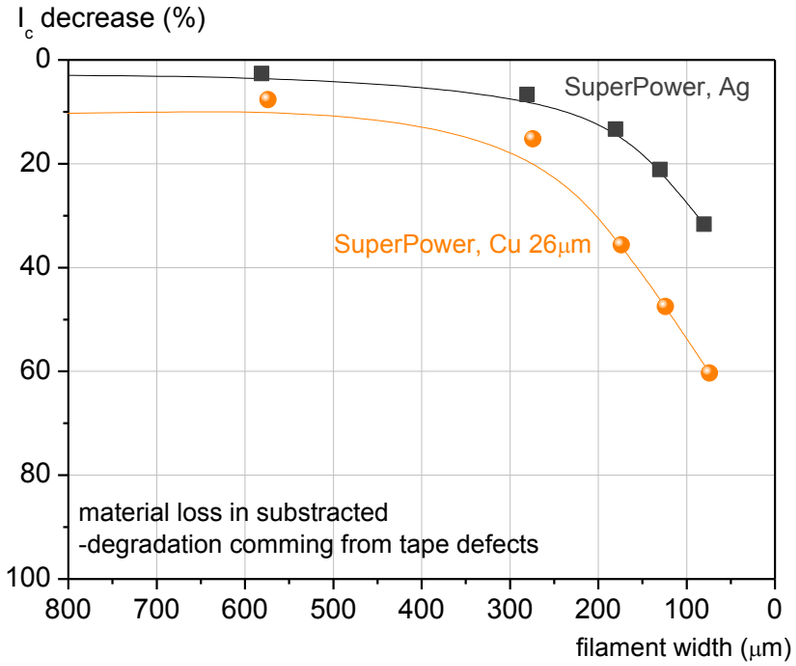
at inner

edge radius

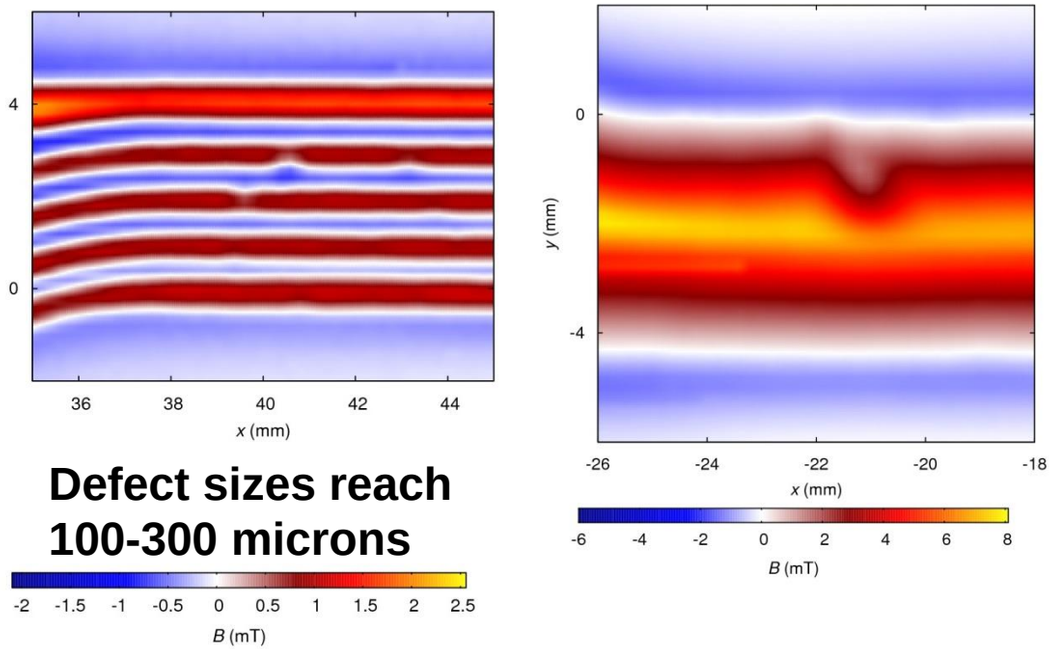
Filaments and Inhomogeneities

Filaments as measure tool for CC homogeneity





Filaments in Roebel strands



Defect sizes reach 100-300 microns

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

- **Defect size can reach 0.2-0.3 mm**
- **Narrow filaments reach defect size**
- **Defects are thermal hot spots**
- **Striations can be used as quality test**

Summary & Conclusions

- The only flat concept with full transposition
- High engineering current density
- Current anisotropy in fields still given
- Excellent bending behavior
- Current anisotropy as CC
- Longitudinal defects in CC a severe hint
- All CC suppliers actually under test
- Conduit as option is no problem (in the road map)
- Stabilisation can be applied as parallel Cu strand

Thank you for your attention !