IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
EUCAS 2015 plenary presentation PL-ESAS Award.
Not submitted to IEEE Trans. Appl. Supercond.

WG10

12th EUropean Conference on Applied Superconductivity

6th - 10th September 2015 Lyon - France

KIT Karlsruher Institut für Technologie

HTS Roebel cable research from KIT and partners

(Award of excellence plenary)

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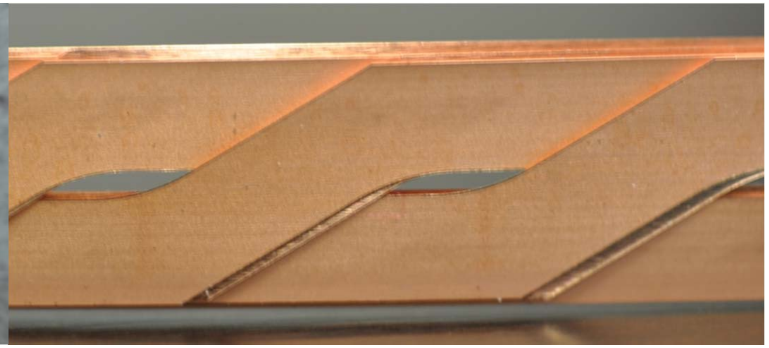
76344 Eggenstein-Leopoldshafen (Germany)

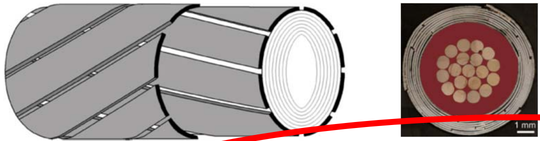


Slide 1

WG10 The numbers of references on the slides are indicating the talk and poster ID of EUCAS-2015 contributions.
Goldacker, Wilfried (ITEP); 29.10.2015

Our activities on high current cable concepts with CC

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

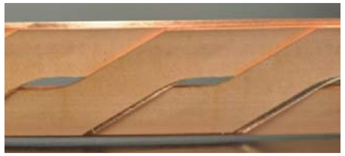


79 tapes, 4 mm wide:
7.56 kA @ 76 K, s. f.

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

- **Intelligent concept**
- **Perfect transposition**
- **The competitor !**

- **Roebel Assembled Coated Conductor (RACC)**



45 tapes, 5.8 mm wide:
2.7 kA @ 77 K, s. f.

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

- **The Roebel like transposition**
- **I_c anisotropic in fields**
- **I_c(B,T) like CC**

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

KIT
A.Kario unpubl.

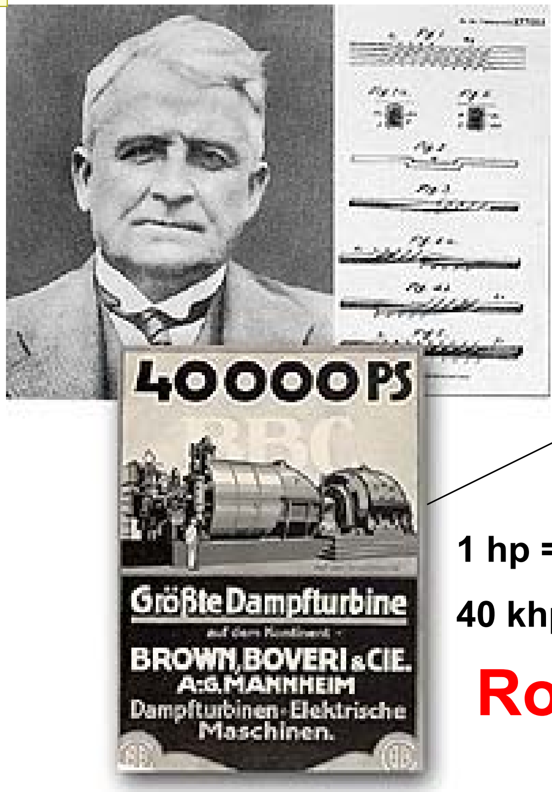
60 tapes, 5 mm wide:
2.50 kA @ 77 K, s. f.

- **Concept with transposition + transp. strands**

- **DC High Current power transmission bars for industrial applications (German project 3S)**

A short walk through history !

WG2



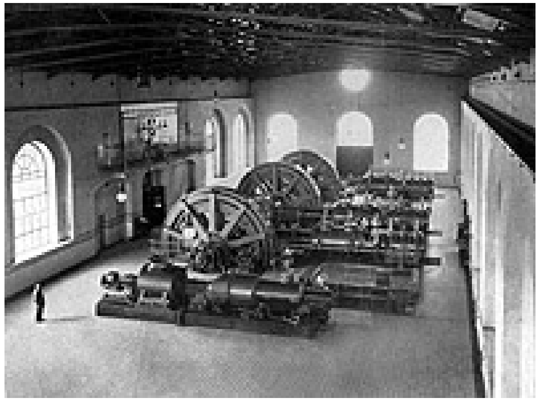
Begin !
1912-1914

1 hp = 0.7 kW

40 khp = 28.4 MW

Roebel Bar

Today !

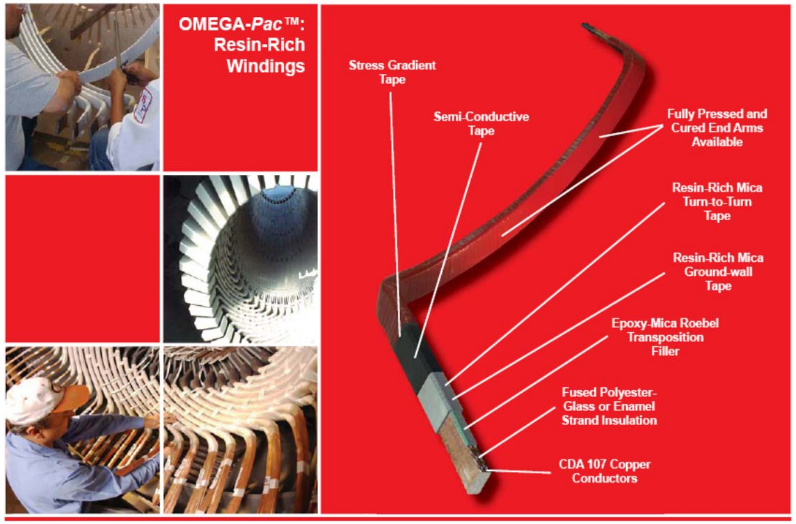


KIT Karlsruhe Institute of Technology

Elektricity plant at city of Mannheim 1899

power 5250 hp = 3.7 kW

WG WOOD GROUP **Generator Services, Inc.**



Slide 4

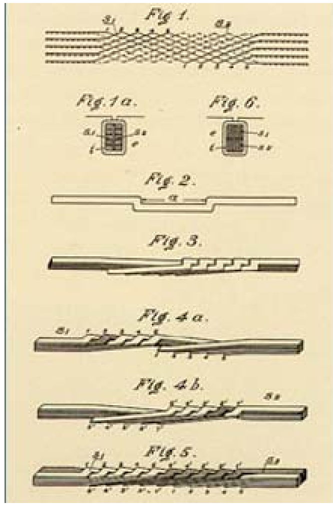
WG2 The Roebel bar was an invention of a cable with transposed Cu-wires reducing skin effect and Eddy currents. It was the revolution enabling very large generators due to drastically reduced AC losses. BBC company became world leader fabricating generators. The swiss BBC company built a fabrication plant at Mannheim because Mannheim equipped the electricity plant with BBC devices. In that new fabrication facility this qantum step was invented by Ludwig Roebel. Roebel bars are today standard parts in the stator windings of large generators.

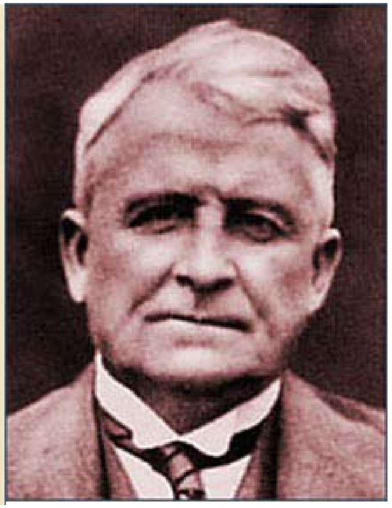
Goldacker, Wilfried (ITEP); 29.10.2015

WG3

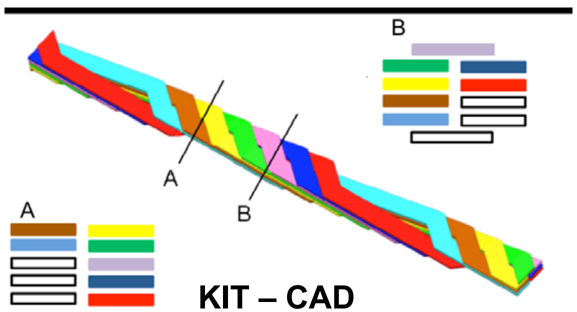
Roebel Assembled Coated Conductors (RACC)
100 years birthday of an old idea goes superconducting !

Karlsruhe Institute of Technology





Patent figure Ludwig Roebel (1878-1934)
BBC Mannheim (later ABB and Alsthom)



KIT – CAD

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

- **Invention 1912-1914 Ludwig Roebel (BBC)**
- **The LCT NbTi Roebel cable 1984/85**
- **Proposal for HTS-tape Martin Wilson 1999**
- **The Siemens BSCCO Roebel bar 2002-2004**
- **CC-Roebel bar (W.Goldacker et al.) 2005**
- **Commercialisation efforts IRL-GC 2008 f.**

Slide 5

WG3 One of the six D-shaped magnets of the large coil task (LCT) in the early 1980-s used a NbTi Roebel bar (EURATOM magnet) with transposed NbTi strands. The filaments of the strands themself were also transposed. The magnet properties regarding the losses were consistent with the calculations and loss estimations.

Martin Wilson proposed quite early the Roebel cable for HTS tapes in his talk 1998.

Successful shaping a REBCO tape to the Roebel structure by punching was the ignition for the first HTS cable. Important was simply to realize that the tape was robust enough for cutting and punching. This was claimed by AMSC company cutting 4 mm tapes from broader sizes. The very good bending ability of the tapes favored the assembling process.

Goldacker, Wilfried (ITEP); 29.10.2015

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. **9,** NO. 2, JUNE 1999 **111**

Karlsruhe Institute of Technology

Superconductivity and Accelerators: the Good Companions

Martin N. Wilson
Oxford Instruments, Tubney Woods, Abingdon, OX 13 5QX, UK.

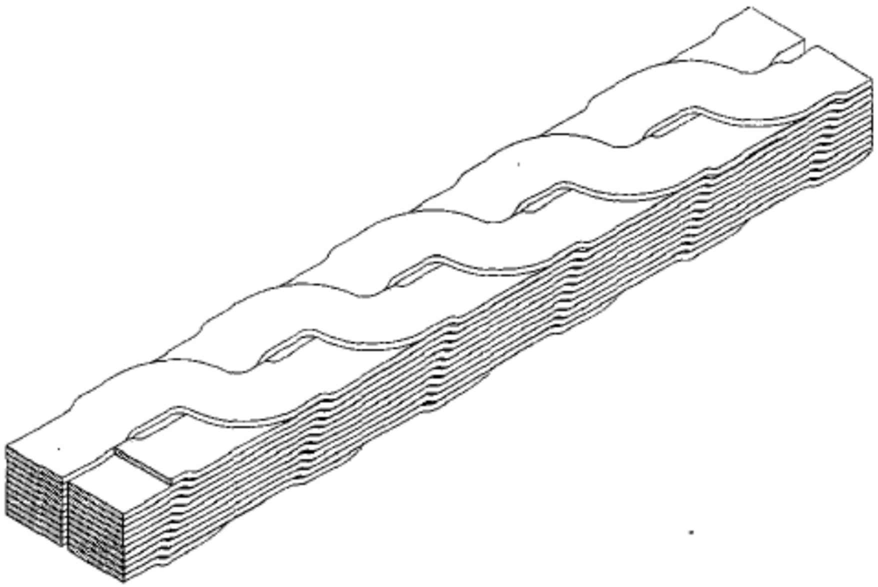


Fig 16: Idea for transposed Roebel bar cable made from HTS tape.

The begin in 2G HTS

Late Breaking News talk at CEC-ICMC
(beside official program)

High Current DyBCO – ROEBEL Assembled Coated Conductor (RACC)

W.Goldacker, R.Nast, G.Kotzyba, C.Schmidt, A.Frank, B.Ringsdorf, S.I.Schlachter

Keystone Resort and Conference Center
Colorado - USA
August 29th to September 2nd, 2005

WG4

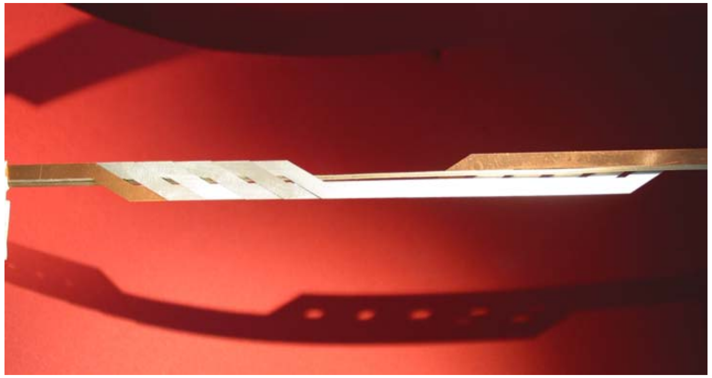
CEC-ICMC Keystone 2005

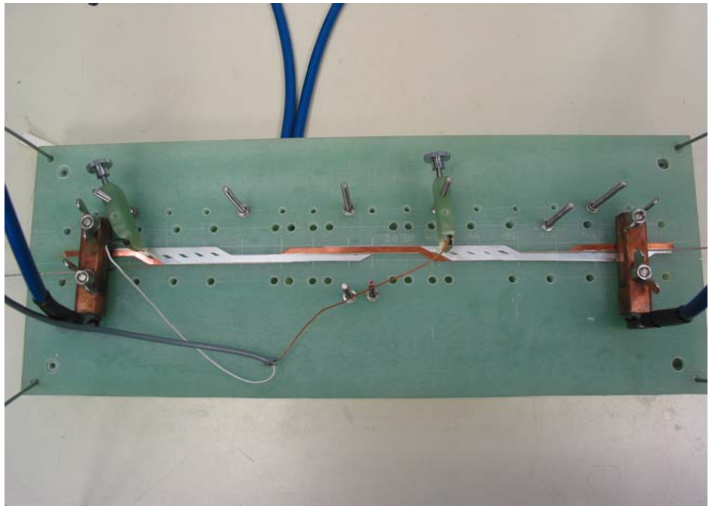
Karlsruhe Institute of Technology

1. Step RACC – Cable with 5 CC – Strands + 1 Cu - strand

Results

- Measured transport current I_c slightly above 300 Amps (approx. 305 Amps.)
- Calculated I_c was 294 A
- I_c onset was detected at 300 A (current source limit)
- Slight transport current increase through stabilising Cu strand ?
- Current sharing works !
- Ag cap layer (0.4 microns) seems to work sufficiently !
- External shunt of 1 mm^2 Cu ok !





W.Goldacker ICMC/CEC 2005 , Aug.28th.-Sept.2nd. Keystone - Colorado USA

5

Slide 8

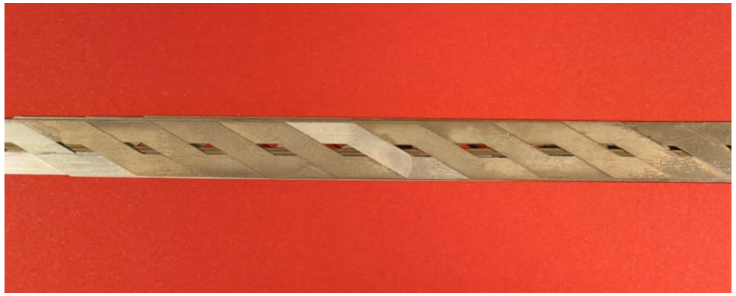
WG4 The gift of a piece of Ag-caped THEVA REBCO tape was used to try the first Roebel structure of a cable. A low cost but precise hand operated punching tool was used. One Cu-strand was added for external stabilisation because we didn't trust in the poor stabilisation of the very thin Ag cap and a central Constantan-wire was used as support during the assembling process. Some current sharing with the copper gave higher cable currents than the design value.

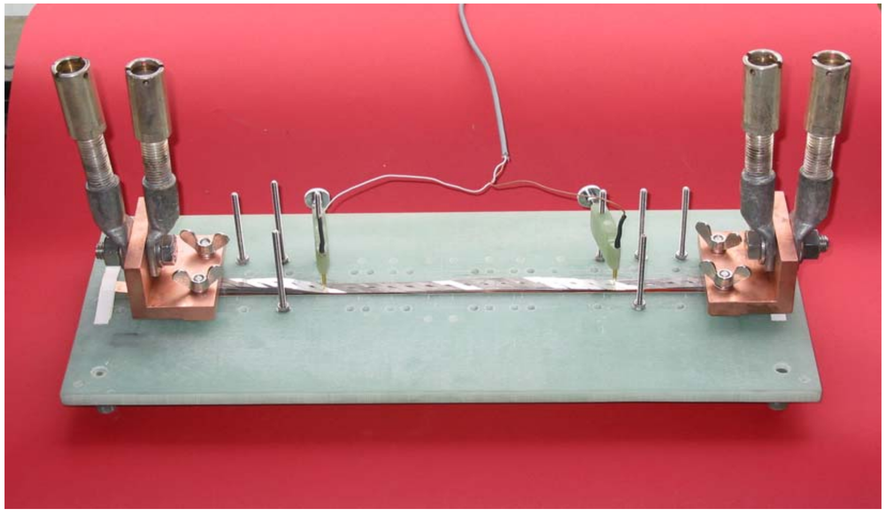
Goldacker, Wilfried (ITEP); 07.10.2015

WG7

CEC-ICMC Keystone 2005

2. Step Full 16 strand DyBCO-RACC sample (35 cm length)





pressed Indium sandwich contacts

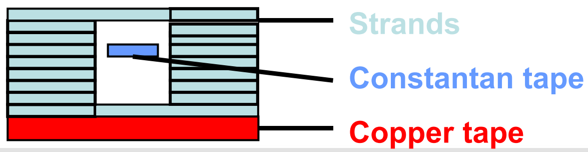
contact length 5 - 6 mm

No interstrand connection for first test !

Parallel ext. Cu stabilizer with 5 mm^2

Mixture of 2 CC batches: different Ag cap !

Scematical RACC cross section



Slide 9

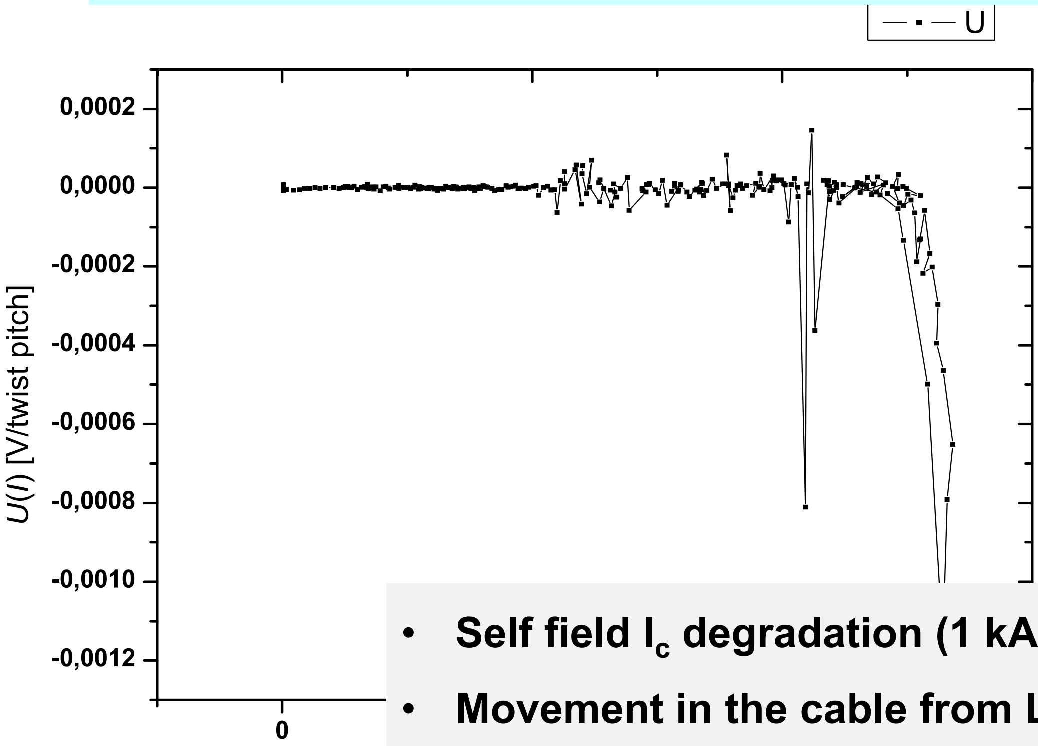
WG7 The whole cable was possible with a second gift of THEVA tape. The external Cu stabilisation was now a tape with the width of the cable placed below the cable. Contacts were made by In foils stacked alternating with CC tapes and pressed to a block.

Goldacker, Wilfried (ITEP); 29.10.2015

WG8

CEC-ICMC Keystone 2005

DC current measurement on 16 strand RACC-cable



Voltage contacts on strand No. 5

Measured transport current 500 A (1 µV/cm)

Indication of some instabilities, current sharing problems…..

- **Self field I_c degradation (1 kA expected)**
- **Movement in the cable from Lorentz Forces**
- **Current redistribution**

Slide 10

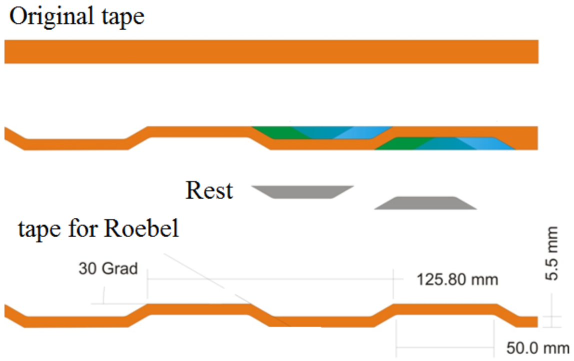
WG8 The first current measurement was chaotic, the self field effect was not recognized and higher currents expected. After a few runs a failure of the power supply led to overload and the whole cable finally burnt through at an overload of > 1.2 kA.

Goldacker, Wilfried (ITEP); 29.10.2015

Preparation issues of today

WG5

Roebel strand RTR punching with high precision



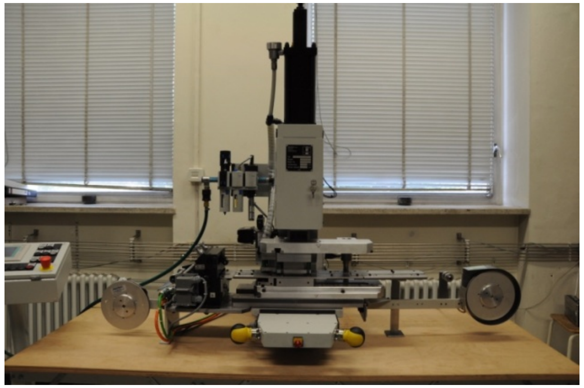
- **Uniformity of the CC geometry** is of most importance (positioning)
- **No drifts of punched dimensions** allowed for hundreds of meters !

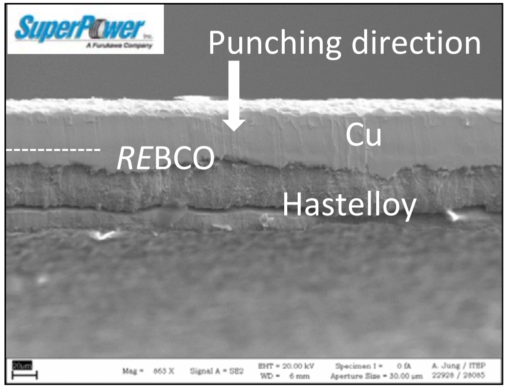
Challenge precise punching CC-tapes

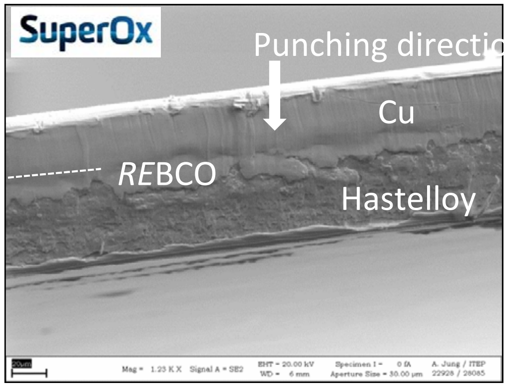
- Different conductor materials (SuperPower, Bruker, SuperOx, (THEVA)) and dimension !
- Delamination effects at the cutted edge
- Plastic deformations at the edge

KIT – RTR – punching device

- Very flexible with optimized tools
- Tools for different transposition lengths
- Tools for different tape materials and thickness







Slide 12

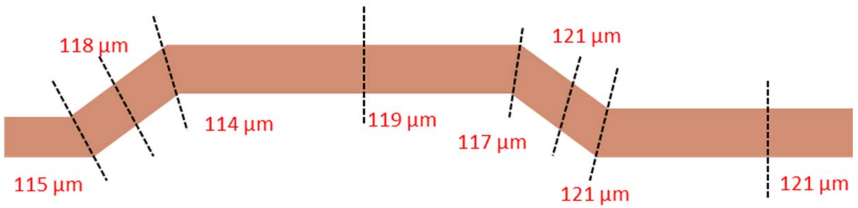
WG5 Perfectly designed punching tools provide a cutting edge where only the copper is smeared along the cut which is favorable closing the cut at the REBCO layer.
Beside of the uniformity no drifts of the cut dimensions are acceptable. The meander at the begin and at the end of long lengths need to be assembled and have to match in the cable!
Goldacker, Wilfried (ITEP); 29.10.2015

WG6

Actually improved process in work: Punch & Coat

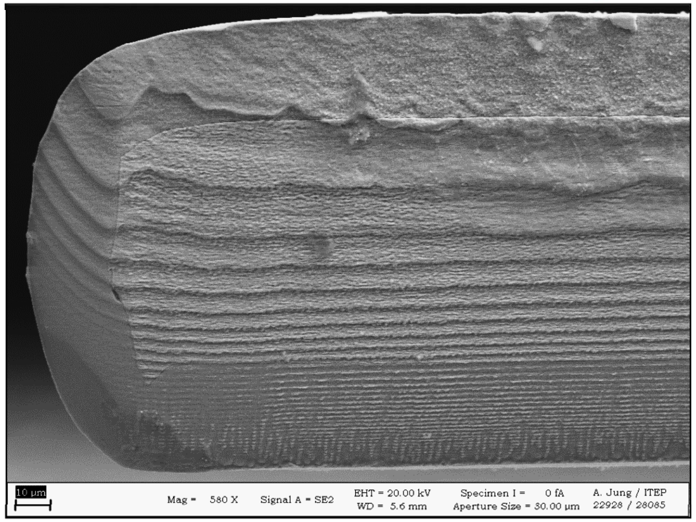
A. Kario, S. Otten et al unpublished

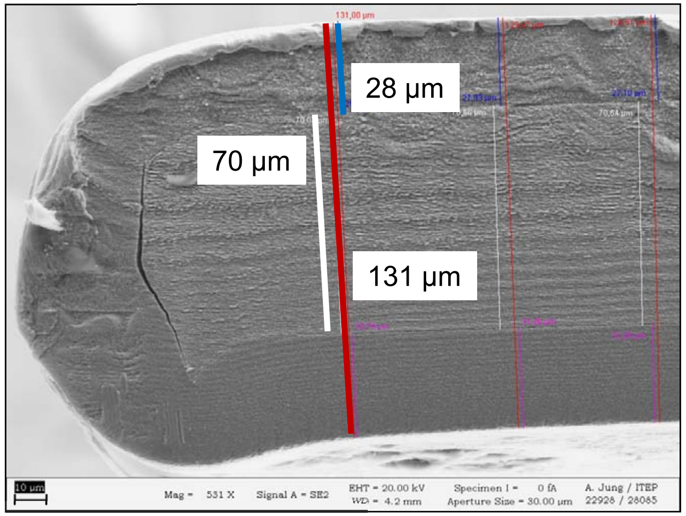
Cu-plated dummy tape after punching – SuperOx plating process:



Goal is to achieve an all around sealed strand

- **Suppressed delamination**
- **Sealed no access for IN2 / IHe**
- **No corrosion of CC layer from the open edge**





Anna Kario WAMHTS3
Lyon 2015
10-11.Sept. following EUCAS

Slide 13

WG6 A homogeneous Cu-plating is crucial since different thicknesses (in the worst case boning) of the tape cross section hinders dense packing and reduces the current density of the whole cable caused by the occuring voids.
Goldacker, Wilfried (ITEP); 29.10.2015

WG9

Punch & Coat: Towards a reliable Roebel performance

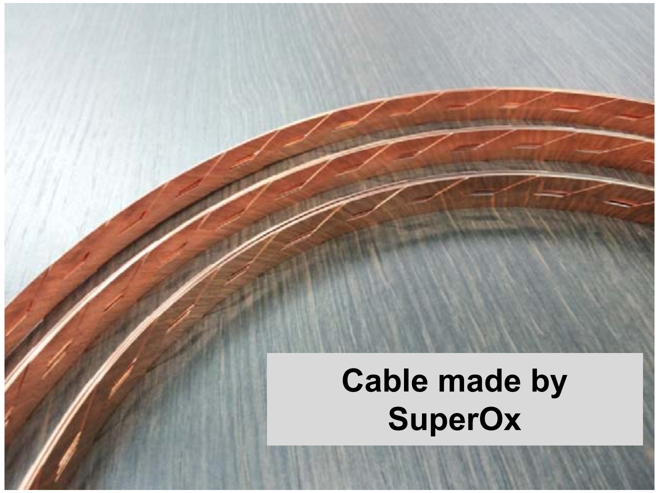
see EUCAS 2A-LS-P-07.03

"Development and characterisation of a 2G HTS Roebel cable for aircraft power systems"
FETISOV S, ZUBKO V, ZANEGIN S, NOSOV A, VYSOTSKY V, KARIO A, KLING A, GOLDACKER W, MOLODYK A, MANKEVICH A, KALITKA V, SAMOILENKOV S, MELYUKOV D

Karlsruhe Institute of Technology

SuperOx

Closed Joint Stock Company "SuperOx"
20-2 Nauchnyi proezd, Moscow, Russia, 117246
tel.: +7 495 669 79 95
fax: +7 495 669 79 96
info@superox.ru
www.superox.ru

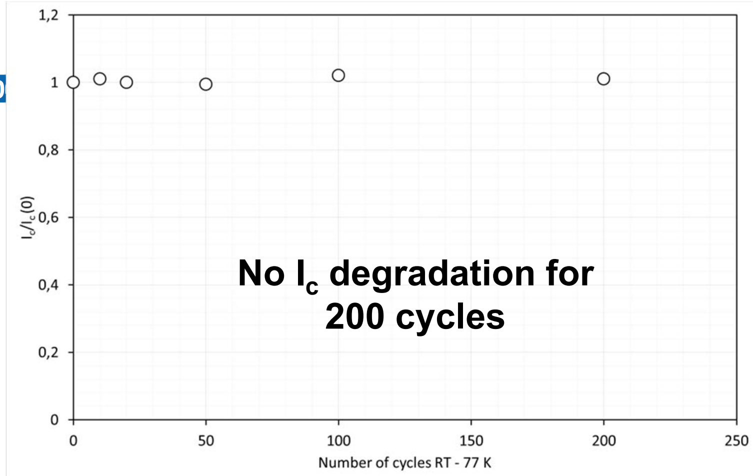


Cable made by SuperOx

One of the two first CC companies working on the „Punch & Coat“ process

- **Minimized material loss**
- **The optimum: hermetic Cu stabilisation**
- **No blow-up/delamination from thermal cycling**

SuperOx 2G HTS Roebel cable SR-5-15-300-PaC-20Cu-60H7	# SR-2015-0
Strand technology	Punch-and-Coat
Strand width	5 mm
Number of strands	15
Transposition length	300 mm
Cable length	2.4 m
Substrate	Hastelloy C276 (nonmagnetic), 60 µm
Copper layer, surround	20 µm
Original tape I_C (77K, s.f.)	300 A
Average strand I_C (77K, s.f.)	120 A
Original SuperOx 2G HTS wire ID	4F-21

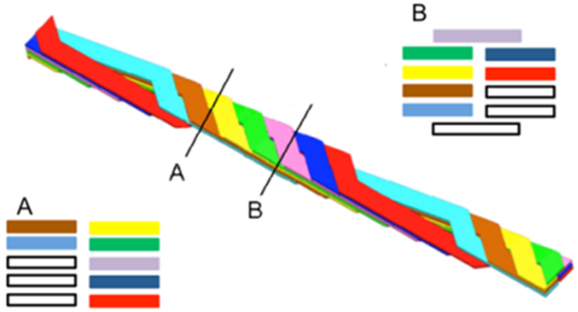


Slide 14

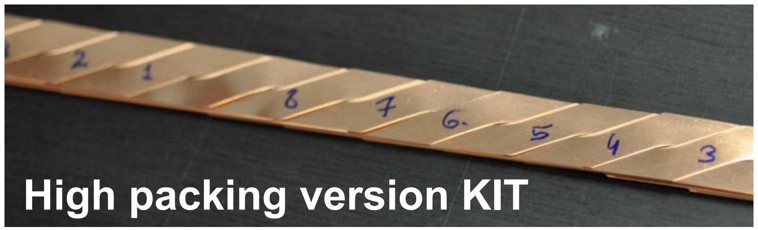
WG9 Best way is coating on the already shaped Roebel meander, in particular for the final step of the electroplated copper. The first cable which was done with that route was presented by SuperOx, an outcome of cooperation with KIT.
Goldacker, Wilfried (ITEP); 29.10.2015

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2015.
EUCAS 2015 plenary presentation PL-ESAS Award.
Not submitted to IEEE Trans. Appl. Supercond.

Assembling the cable

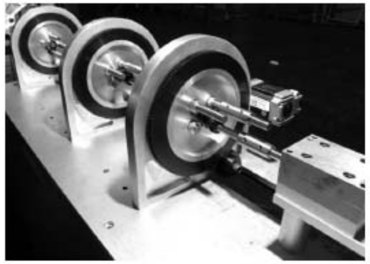


- Cabling = Complex twist bending and stacking of strands
- Method limits cable compaction



KIT half automatic assembling facility in work

Roebel cable assembling at IRL, GC, NZ



Winding machine for 10/2 cable

Winding machine for 15/5 cable

Slide 15

WG11 Assembling can be made with different machinery, the most advanced came from IRL at NZ. The densely packed cable of KIT (lower left side) can only be done by hand. KIT is using half automatic processing at this stage.

Goldacker, Wilfried (ITEP); 29.10.2015

Transport currents in Roebel cables

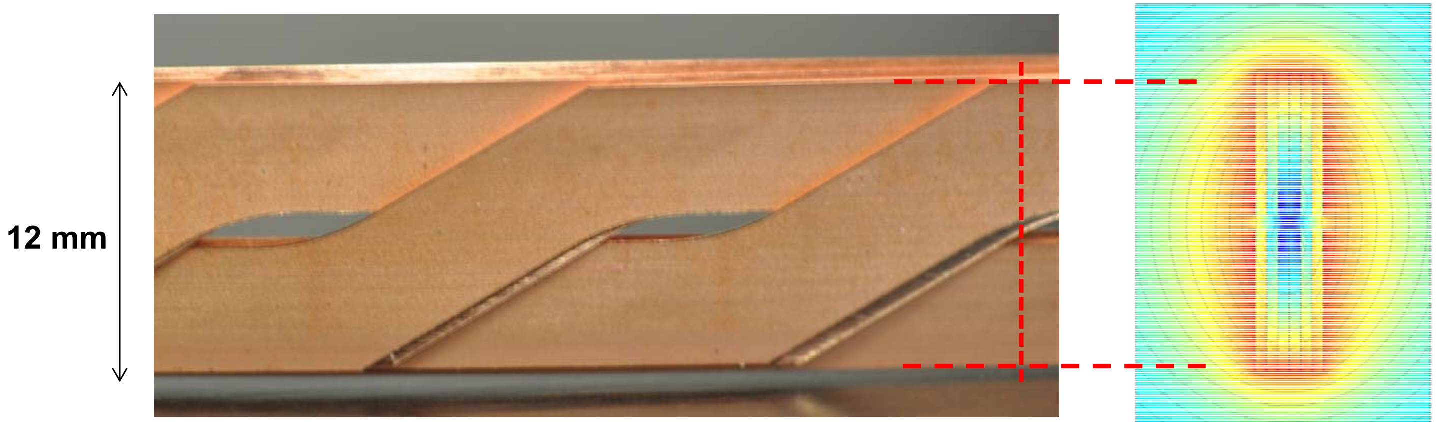
WG12

Features of a RACC sample in self field 77 K

KIT Karlsruhe Institute of Technology

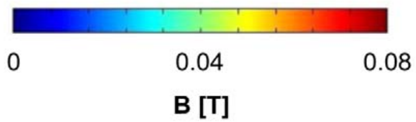
Non-homogeneous distribution of the magnetic self field in Roebel Coated Conductor cable cross section.

cross section

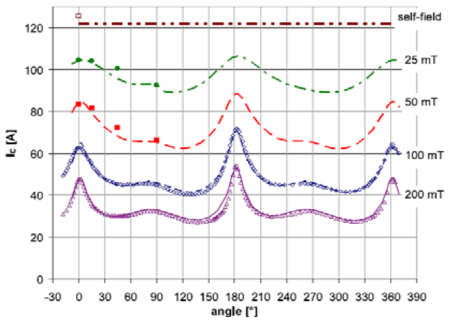


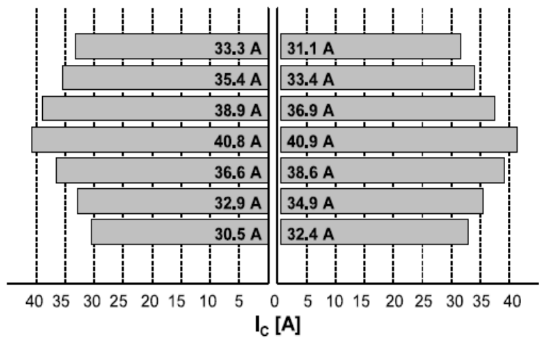
Modeled self field pattern

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



Current depends on local field, and orientation and on CC specific pinning (I_c anisotropy)





- **Strands pass all s.f. locations**
- **Current redistribution effect begins at $I > \frac{1}{2} I_c$**
- **Modeling explains I_c self field reduction by 40-60%**

Slide 17

WG12 Strands pass all locations in the cable cross section and are therefore in changing self fields which gives a modulation of the critical currents. Numerical modeling can describe this behavior perfectly. The self field induced current drop can reach 60-70% at 77 K depending on strand number and pinning mechanism of the CC. Strongest influence comes from perpendicular s.f. components.

Goldacker, Wilfried (ITEP); 29.10.2015

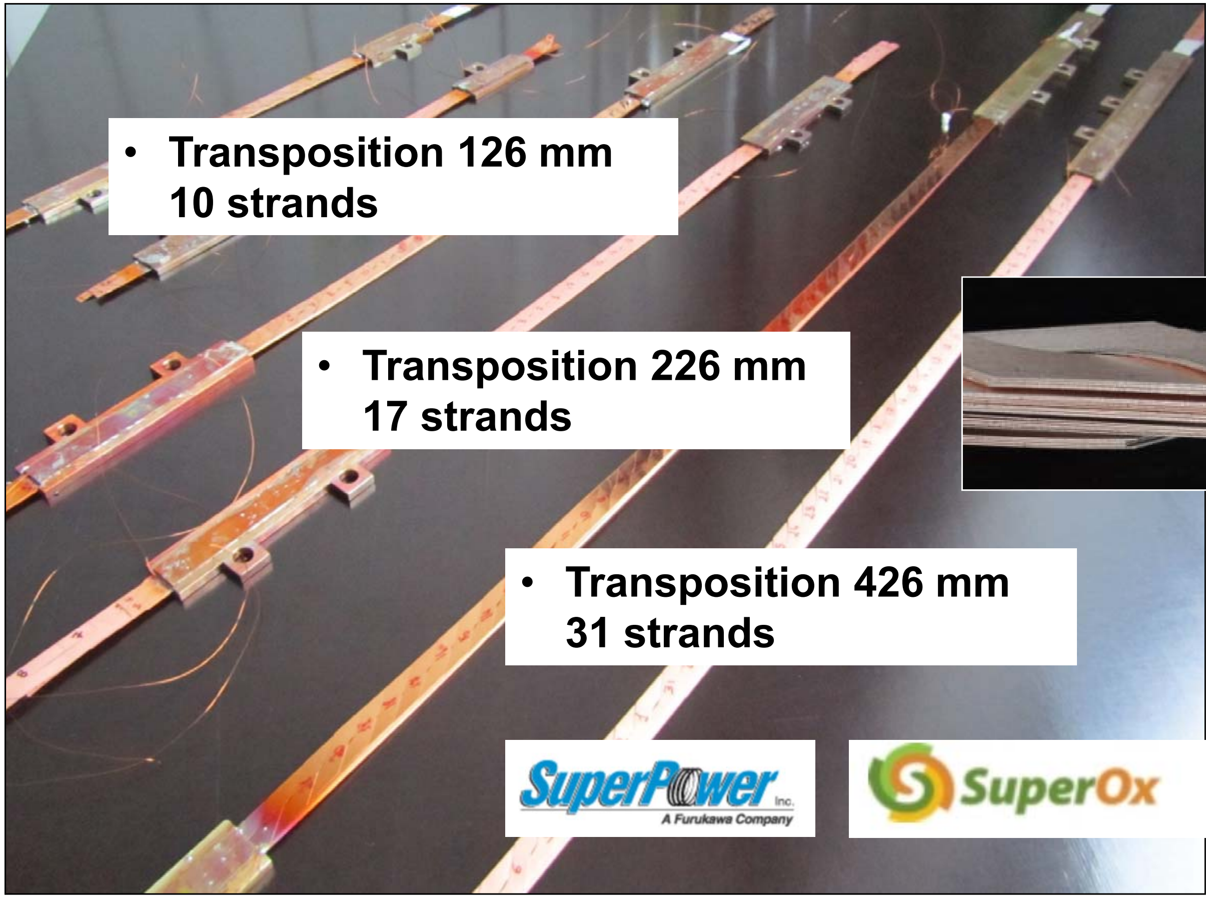
WG13

Currents in Roebel cable

A. Kario CCA-2014 unpubl.

KIT Karlsruhe Institute of Technology

Strands: Superpower with AP, SuperOx with no doping



Higher currents ?

Longer transposition = more strands

Stacking strands = 2x or 3x current

3-fold stacked strands = 45 strands 2009 SP tape quality 2.7 kA (77 K, sf)

For stacked strands limitation of bending ability like in stacked cables

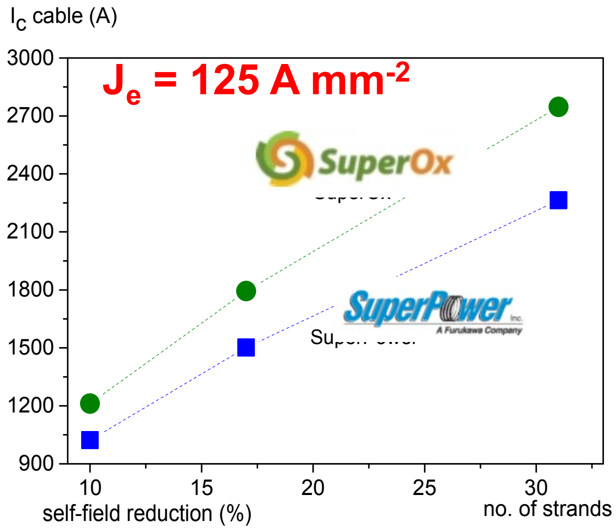
Slide 18

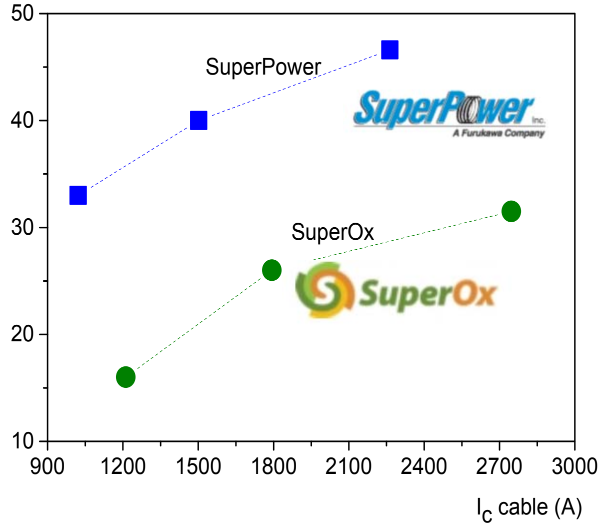
WG13 Parameters for enhanced critical current of the cables are increased transposition length enabling use of more strands and as second option stacking the strands. This was a systematic study of the changed transposition pitches on two CC materials of different layout.
Goldacker, Wilfried (ITEP); 07.10.2015

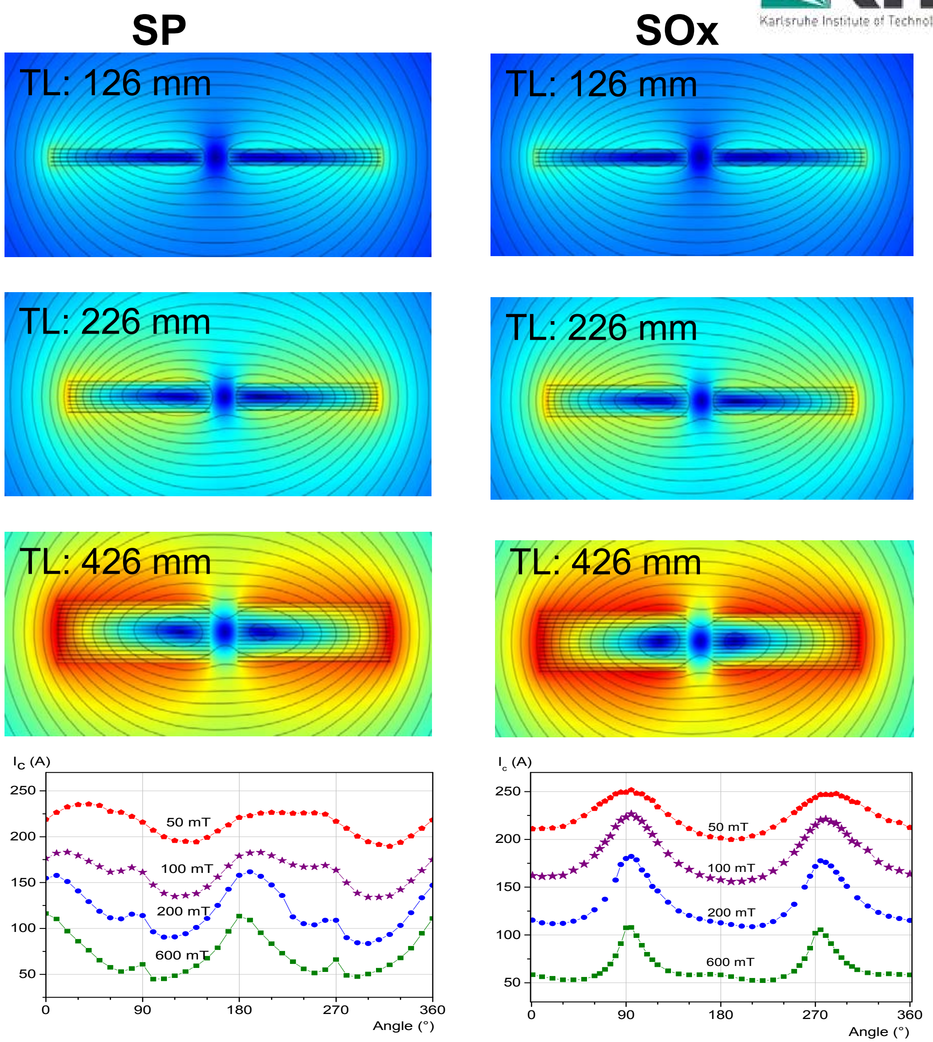
WG14

I_c = 2.7 kA (77 K, sf) SuperOx Roebel (31 strands, long transp.)

Karlsruhe Institute of Technology







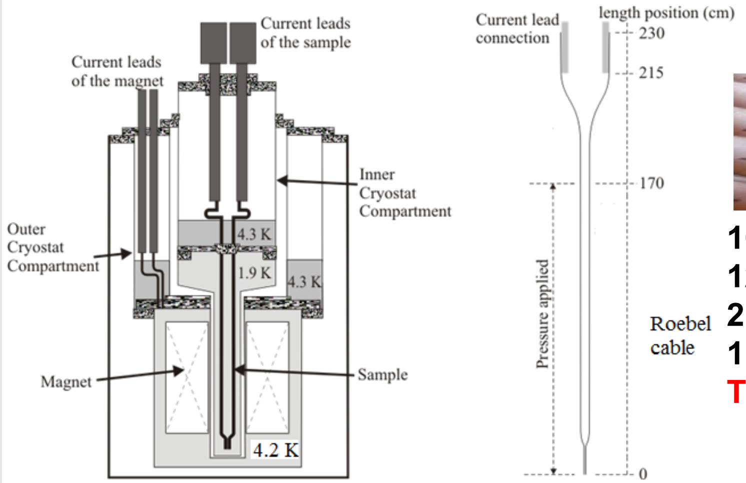
Slide 19

WG14 The pinning mechanism, no apllied pinning centers for SuperOx and advanced pinning in the case of SuperPower, determines the regime of optimized critical currents with regard to temperature and field. At 77K s.f. the SuperOx CC led to the best currents and lowest s.f. effects.

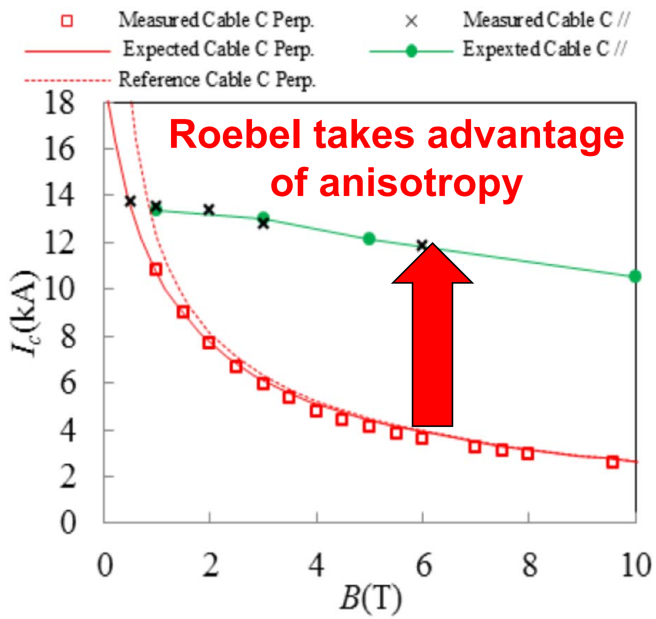
Goldacker, Wilfried (ITEP); 29.10.2015

WG15

Critical current and anisotropy 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, A. Ballarino, L. Bottura, P.Tixador,
Supercond. Sci. Technol. 26 (2013) 065014 (5pp)

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

L_p = 0.4 m = 31 strands gives > 40 kA s.f.

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

HTS-Robel cable is enabling high current applications in magnets at 4.2 K

Slide 20

WG15

Roebel cables are enabling low temperature applications in magnets, a nice lift factor of the currents being around 12, a preserved current anisotropy being favorable for solenoid structures, a high filling factor of >90% for high current density and excellent bending ability for performing windings.
Extrapolation of the currents of upgraded cables to higher fields at 4.2K show that they fulfill requirements of fusion magnets (DEMO).
Goldacker, Wilfried (ITEP); 29.10.2015

Roebel cables in windings and coils

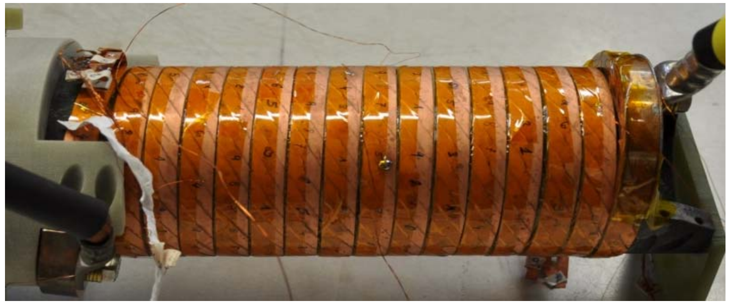
Geometry effects, modeling and measurement of currents and AC losses

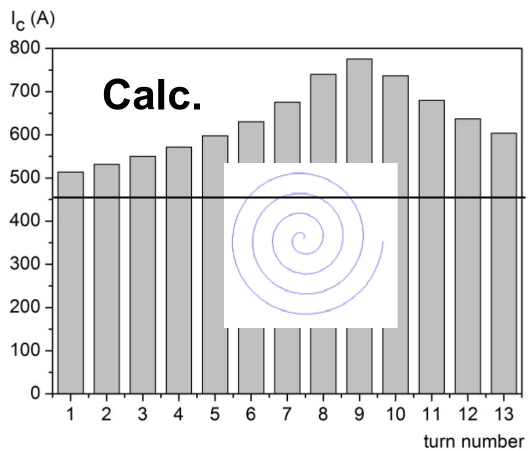
WG16

Magnets: pancake and layered coil

Changed spacings between layers

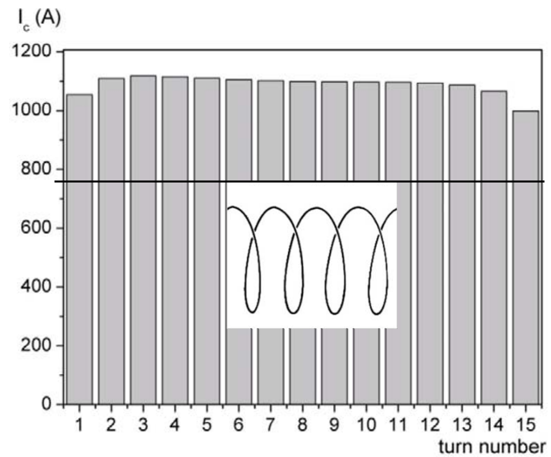
5 m sample





Design value	**1512 A**
Model with sharing	**1108 A**
Straight cable	**936 A (m.)**
Solenoid coil	**750 A (m.)**
Pancake coil	**460 A (m.)**

A Kario, M Vojenciak, F Grilli, A Kling, A Jung, J Brand, A Kudymow, J Willms, U Walschburger, V Zermeno, and W Goldacker, DC and AC Characterization of Pancake Coils MadeFrom Roebel-Assembled Coated Conductor Cable, IEEE TRANS ON APPL. SUPERCOND., VOL. 25, NO. 1, FEBRUARY 2015



Calculations use measured current anisotropy

Bending is excellent, Parallel and perp. field components play important role

Slide 22

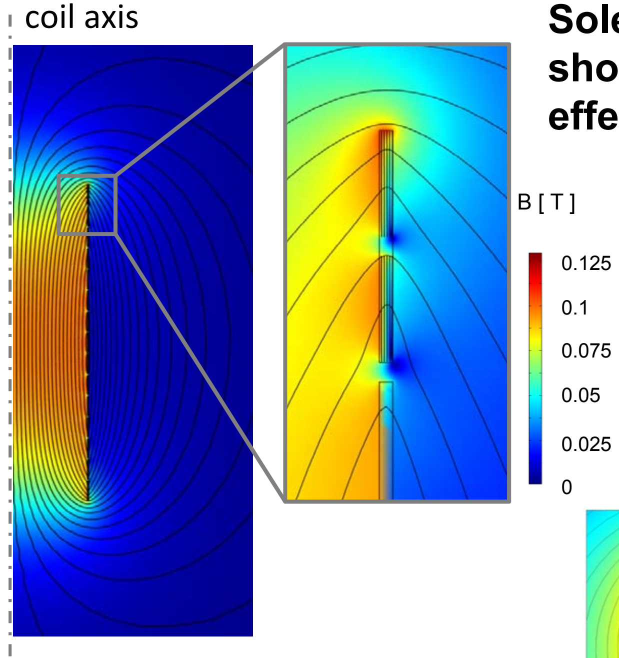
WG16 Pancake and layered coils were made with different spacings between the turns. The measured currents are always smaller than the ones calculated from numerical modeling. This is an indication of inhomogeneity of the CC which cause additional current degradation. The performance of the coils is depending very sensitively on the influence of perpendicular field components, as at the end of the solenoid.

Goldacker, Wilfried (ITEP); 29.10.2015

WG17

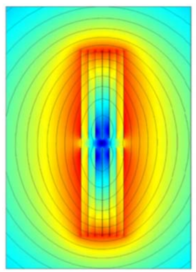
Modelling of field effects and AC losses in coils

- **FEM Modeling confirms and explains measured transport current effects**
- **Stronger anisotropic self-field effects occur between turns in a pancake coil.**

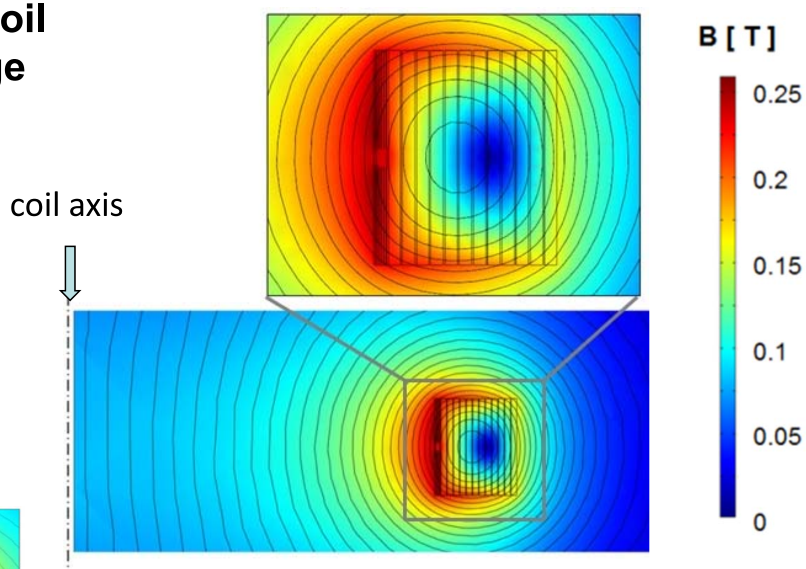


Solenoid coil shows edge effect

- Solenoid with cable monolayer
- 1 mm turn distance



Reference straight cable



- Dense packed pancake version shown
- 0.1 mm turn distance

more ⇒

F Grilli, V. M. R. Zermeño, E. Pardo
M. Vojenˇciak, J. Brand, A Kario, and W Goldacker
Self-Field Effects and AC Losses in Pancake Coils Assembled From Coated Conductor Roebel Cables
IEEE TRANS. ON APPL. SUPERCOND., VOL. 24, NO. 3, JUNE 2014 4801005

Slide 23

WG17 Modelling describes very well the coil properties. The measured current anisotropy is included in the calculations.
Goldacker, Wilfried (ITEP); 29.10.2015

The Roebel cable appraoch of Eucard2 Insert magnet for CERN LHC dipoles

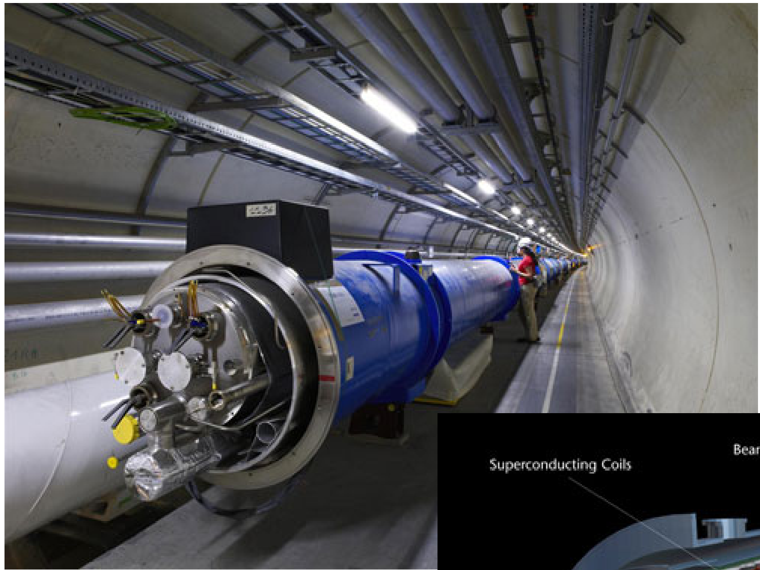
see Lucio Rossi 2M-LS-02.01

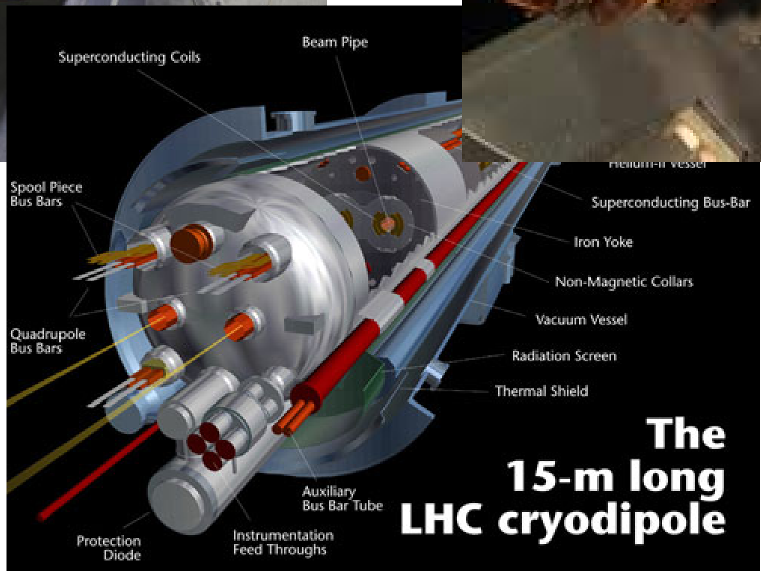
Technology driver for HTS Roebel Cable R&D

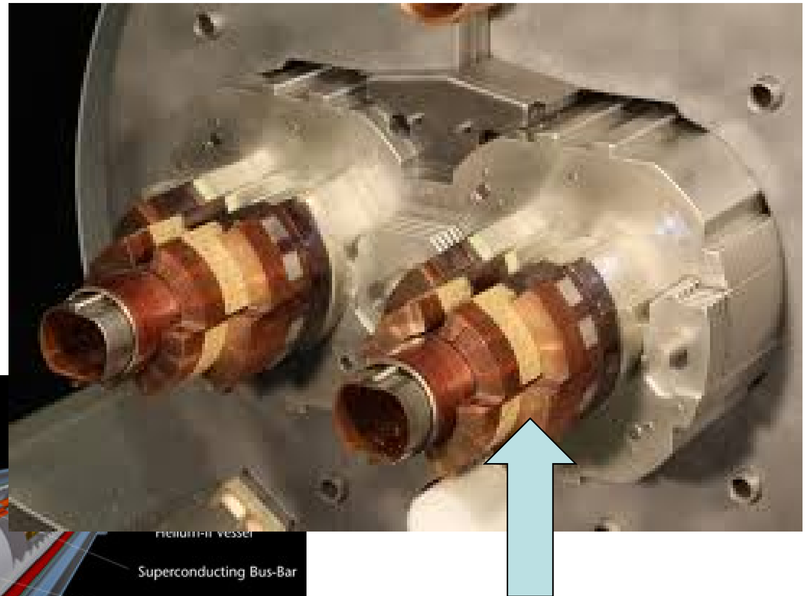
Decision for Roebel cable:

- **Highest achievable engineering current density**
- **Advantage from field anisotropy in magnets**
- **Very good bending ability (high tensile strength)**
- **Industrial production route available (in principle)**

Future LHC 20T dipoles need HTS insert magnets !







Pictures courtasy CERN

Final location inside LTS magnet part !

Eucard2 model magnet should be tested in upgraded FRESCA test facility (CERN)

WG18

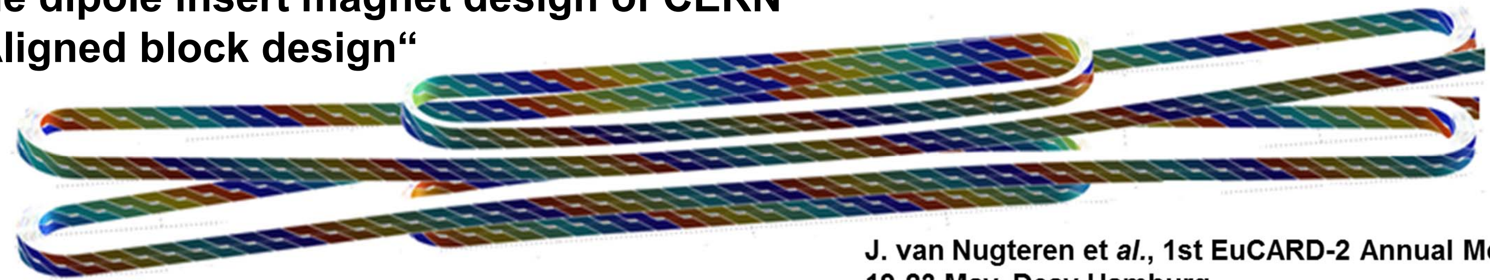
10-kA Class REBCO cable for EuCARD2 WP10 (Future Magnets)

KIT Karlsruhe Institute of Technology

see L. Bottura 3M-WT-01.01
and 2M-LS-02.03

The goal: 5 T dipole magnet for 4.2 K, 40 mm aperture
10 kA operation current at B = 20 T

The dipole insert magnet design of CERN „Aligned block design“



J. van Nugteren et *al.*, 1st EuCARD-2 Annual Meeting, 19-23 May, Desy Hamburg

Targets and minimum required performance for the HTS materials are crucial within the scope of the EuCARD2 magnet R&D

Decision for the HTS-Roebel cable approach, causing special ways of suitable magnet approaches

Parameter	units	target	minimum
J_E (20 T, 4.2 K)	(A/mm²)	≥ 600	≥ 400
s(I_c)	(%)	≤ 10	
m_0DM (1 T, 4.2 K)	(mT)	≤ 300	
Allowable $s_{transverse}$	(MPa)		≥ 100
Allowable $e_{longitudinal}$	(%)		≥ ±0.3
Unit Length	(km)	≥ 100	≥ 50

Slide 26

WG18 The Roebel cable is the approach coming closest to the demanded specs. of the dipole insert magnet. Due to very poor in plane bending ability of the cable, the magnet design has to be changed and modified regarding this limitation. The CERN approach shown here is the "block design".

Goldacker, Wilfried (ITEP); 29.10.2015

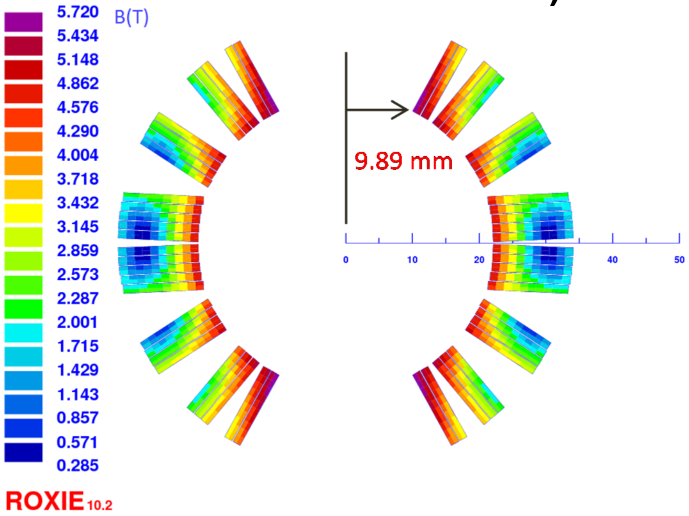
WG19

Alternative concepts: Classical *cosθ design*

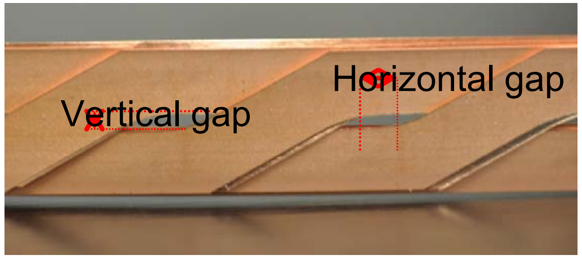
See Clement Lorin 3A-LS-P-01

Courtesy Maria Durante

Winding experiment with KIT Roebel Dummy (Stainless Steel) + Insulation performed



- **Test of 3D bending ability**
- **Handling of the winding process**
- **Is the cable design suitable to provide enough space for re-arranging the strands**



Options for changed design !

Slide 27

WG19 The CEA design follows the classical solution. Bending experiments were done with a KIT dummy cable from stainless steel. A success of this demanding route cannot be excluded from this first experience !

Goldacker, Wilfried (ITEP); 07.10.2015

KIT contributions to Eucard cables

- Optimization of strand and cable production for Bruker tapes see A.Usoskin 3A-WT-P-02.03 for tapes
- Optimizing cable design for magnet transposition length, spacings, stabilization technique etc.
- Providing test lengths up to 20 m (> 60 m provided for tests)
- Impregnation technology for transverse stress balance
- Diverse tests of superconducting properties
- Testing advanced or alternative materials and CC/strand conditioning
- Production of final 50 m cable

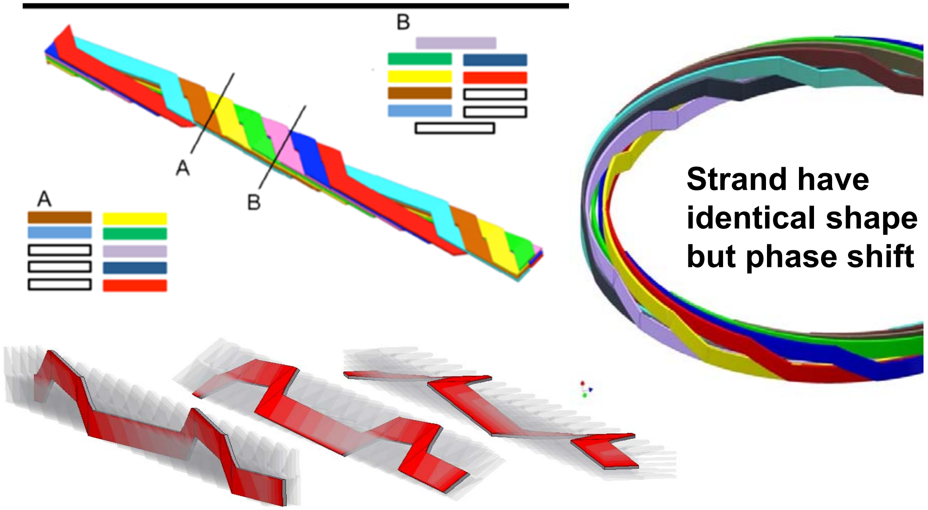
KIT Roebel dummies (stainless steel /copper) for winding process optim.

by courtesy of CERN

by courtesy of CERN

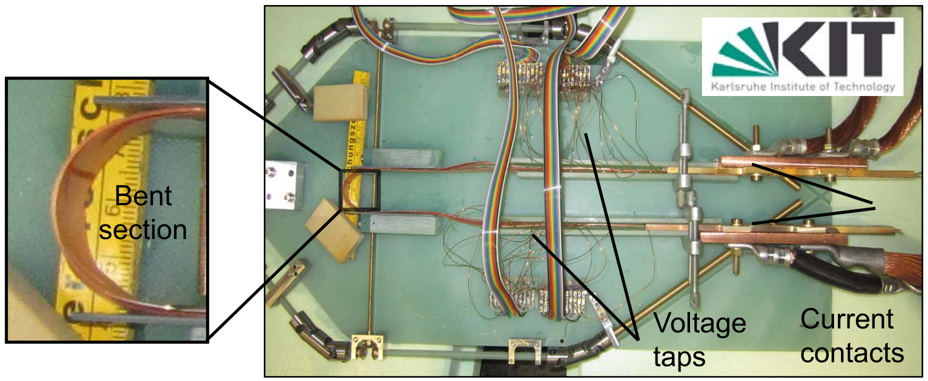
WG20

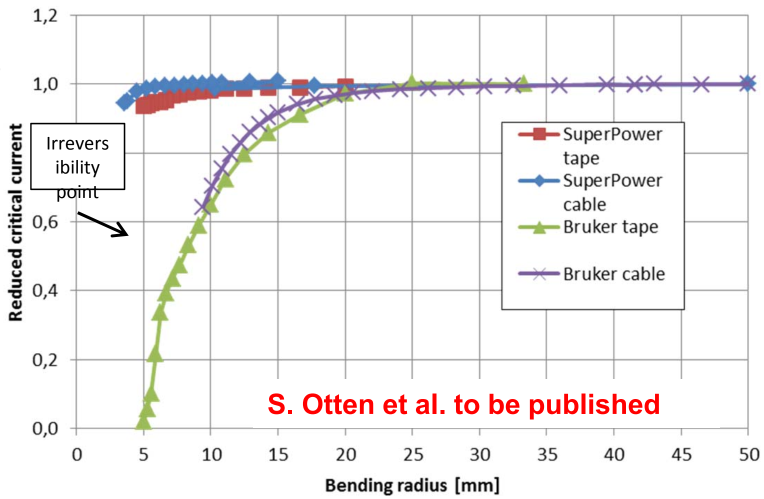
Excellent bending ability of HTS Roebel cables



- No pre-strain load from cabling !
- All strands have equal boundary conditions for sample lengths multiples of the transposition pitch
- Bending behaviour is uniform to the strands and identical to single CC tape (down to 10 mm !)
- Depends on tape material, substrate thickness (Bruker = 2x SP) and CC texturing route (IBAD, ISD etc.)

Contineous bending strain rig (CBSR) for cables (77 K)





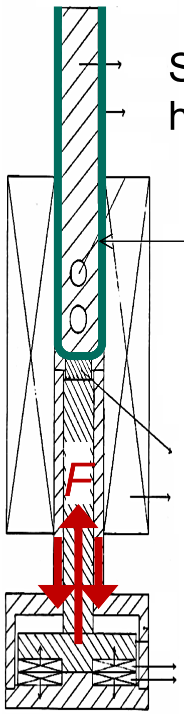
Slide 29

WG20 A new bending rig was built after the design of the "Goldacker bending method" used for CC. The out-of-plane bending ability of the Roebel cable is even slightly better than that of the used CC. This bending method applies changing bending radii at 77K without warm up.
Goldacker, Wilfried (ITEP); 07.10.2015

WG21

Transverse stress of impregnated Roebel cable

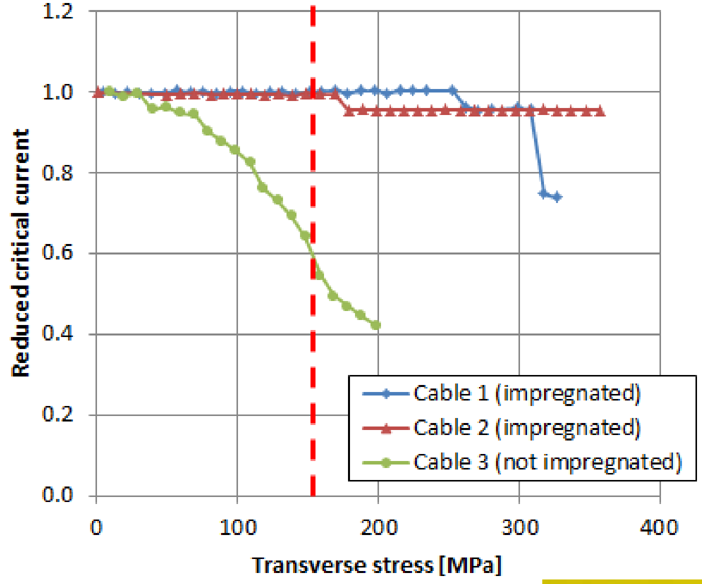
- T = 4.2 K
- I_{max} = 50 kA
- B_{max} = 11 T (perpendicular)
- F_{max} = 250 kN
- U-shaped samples

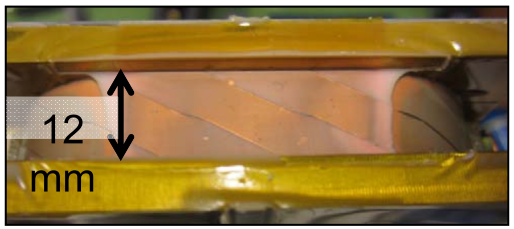


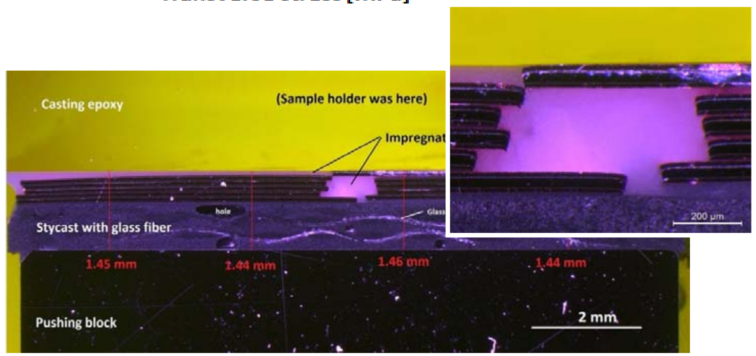
Thermal match of expansion coefficients by silica doped resin Ch. Barth ICMC 2013

Twente transverse stress rig

See Poster Simon Otten 2A-WT-P-03.05







Slide 30

WG21 Impregnation with silica filled resin enhanced the transverse stress toughness of the cables above the values necessary for the dipole insert magnets. This feature is necessary balancing the expected Lorentz Forces of up to 150 MPa.
Goldacker, Wilfried (ITEP); 07.10.2015

Laser burned Filaments in CC, Roebel and CORC cables

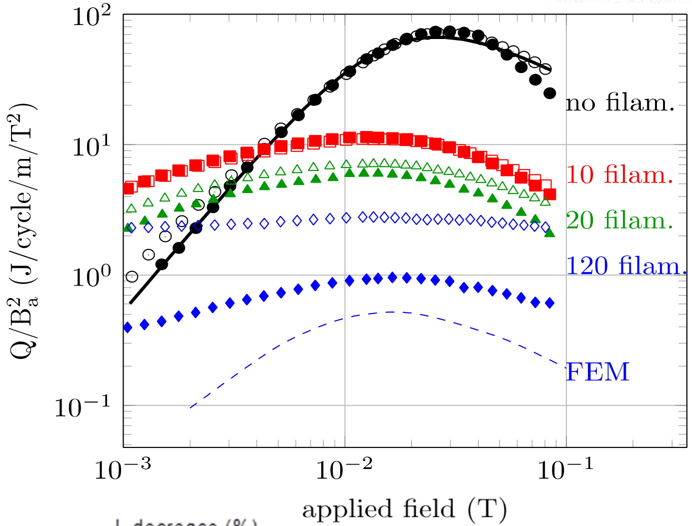
WG22

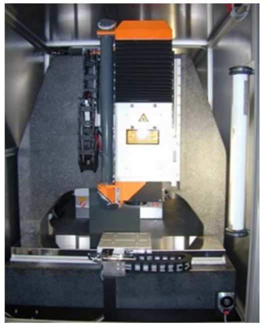
Option for reduced AC losses: Striated CC or strands

Karlsruhe Institute of Technology

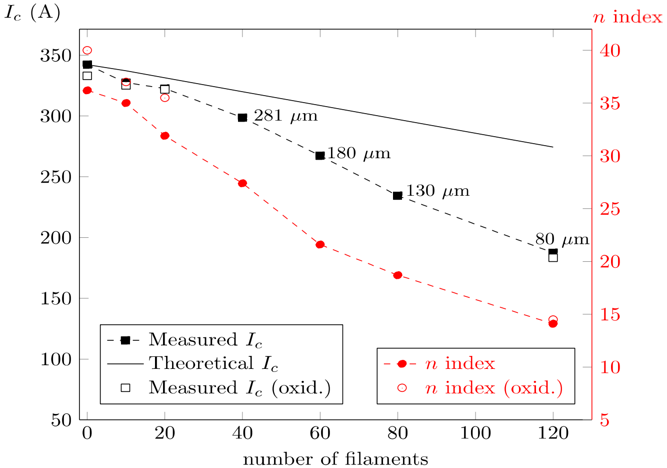
- **Up to 120 Filaments (12 mm) prepared and analyzed,**
- **current degradation from CC inhomogeneity,**
- **full separation with post annealing achieved**

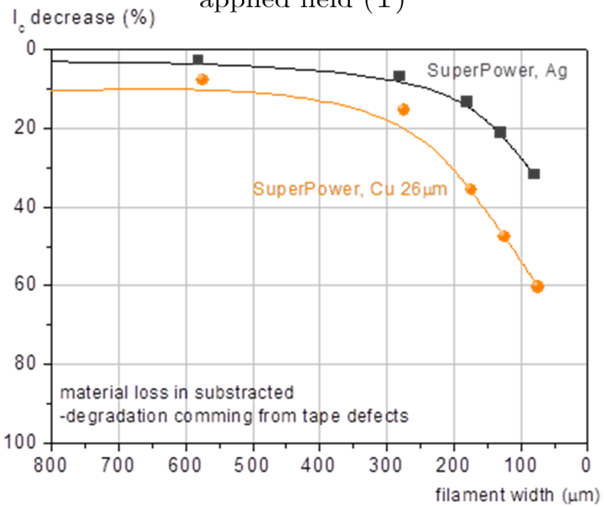
(filled symbols in figure)





psec YAG-L
2016 RTR !





Slide 32

WG22 The laser grooving method used is optimized for efficient material ablation and avoiding melting effects in the filaments. Beside the material loss additional current degradation is observed which is shown in the graph on the right lower picture. This is an indication of the role of defects in the REBCO layer with increasing influence at a filament size decreasing about 300 microns. This is a direct indication for the typical defect size.

Fall out of ablated material is causing some filament coupling seen in the AC loss level. Oxygen heat treatment is eliminating this coupling from deposited material which is seen in lowered AC losses (figure on right upper side, filled symbols).

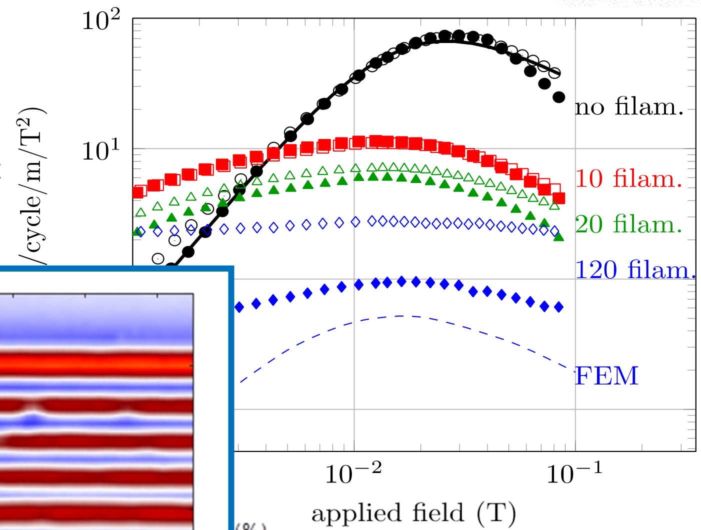
Goldacker, Wilfried (ITEP); 29.10.2015

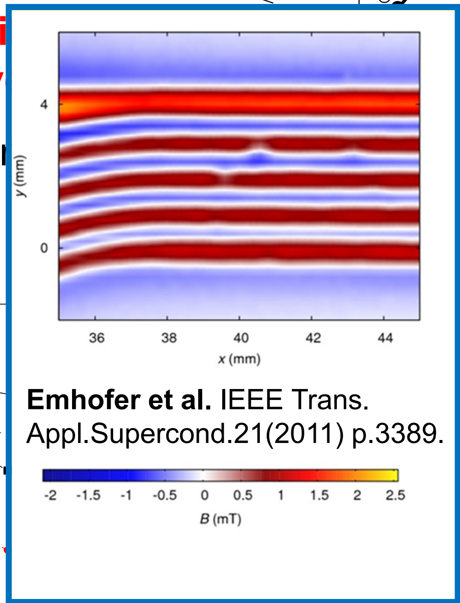
WG23

Option for reduced AC losses: Striated CC or strands

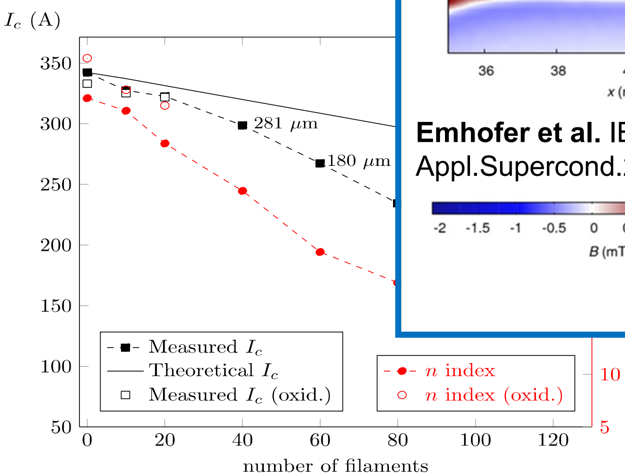
- **Up to 120 Filaments (12 mm) prepared and analyzed,**
- **current degradation from CC inhomogeneity,**
- **full separation wi... annealing achiev...**

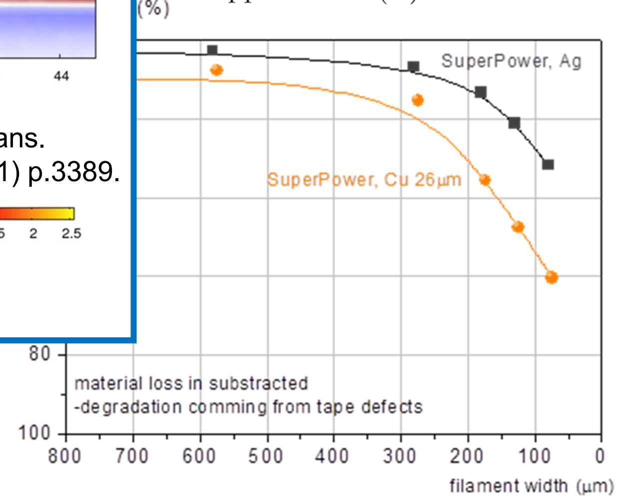
(filled symbols in figu...

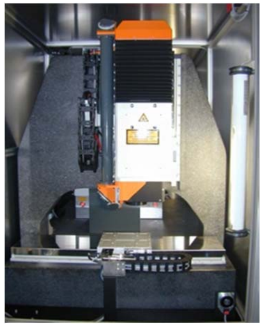




Emhofer et al. IEEE Trans. Appl.Supercond.21(2011) p.3389.







psec YAG-L 2016 RTR !

Slide 33

WG23 Hall probe scanning showed the defects in filaments corresponding to the findings and confirming the typical sizes of the defects.
Goldacker, Wilfried (ITEP); 29.10.2015

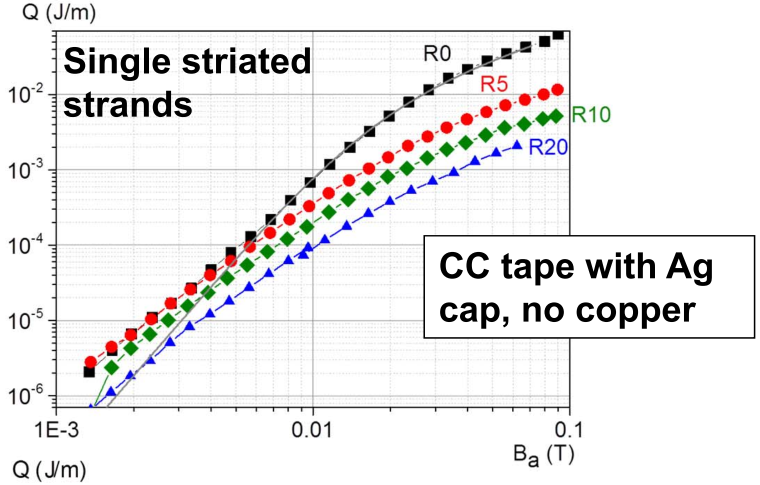
WG24

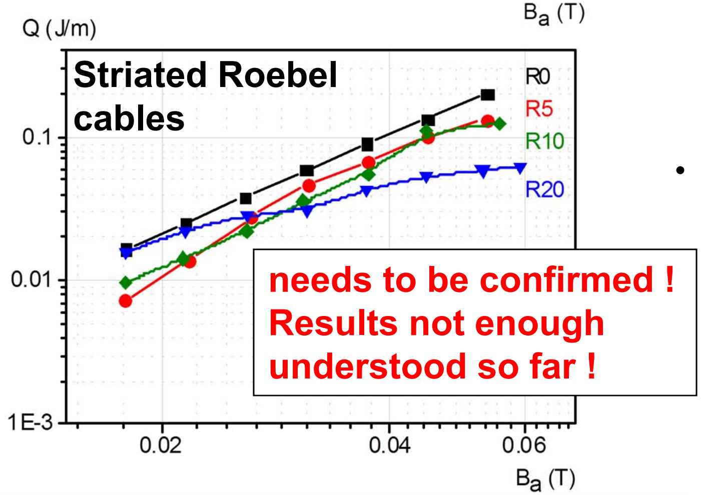
Calorimetric AC loss measurements on strands and Roebel cable with 0, 5, 10, 20 filaments

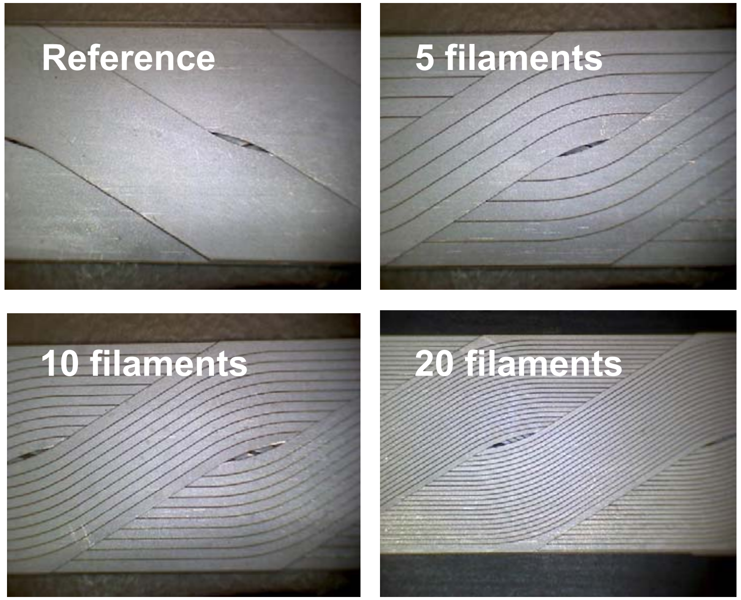
See A. Kario et al. 1A-WT-P-05.03

Karlsruhe Institute of Technology

A. Kario, M. Vojenciak, A. Kling, R. Nast, A. Godfrin, E. Demencik,
B. Ringsdorf, F. Grilli, W. Goldacker







- Inhomogeneous current shearing in Roebel cables due to soldering difficulties (non stabilised tapes)

Reduction of AC magnetisation loss with increasing filaments number on single Roebel strands

Indication of reduction of AC magnetisation loss with increasing filament number in Roebel cables at higher external field amplitudes ?

Slide 34

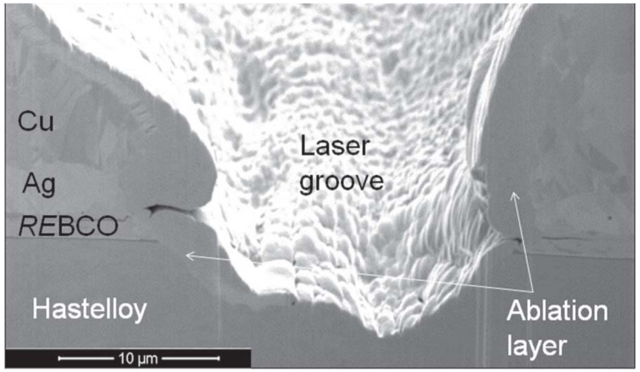
WG24 Filaments in Roebel strands were investigated. Preliminary results show some AC loss reduction. The interpretation is not finished and not completely understood and some verifyng experiments are under work.
Goldacker, Wilfried (ITEP); 29.10.2015

WG25

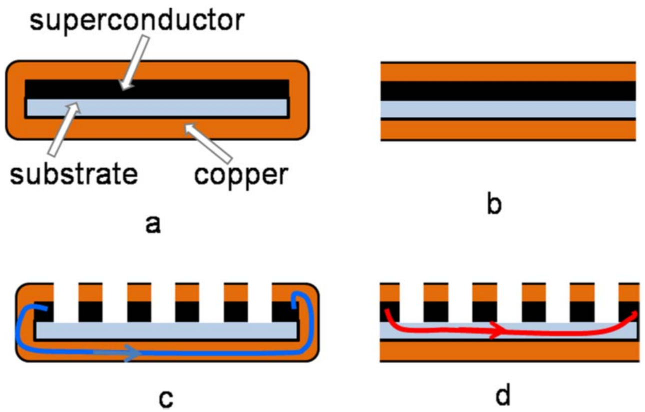
AC Loss Investigations on striated CORC – cables (advanced supercoductors) with 3,5,7,10 filaments

Ref. Magnetization ac loss reduction in HTS CORC cables made of striated coated conductors
M Vojenčiak, A Kario, B Ringsdorf, R Nast, D C van der Laan, J Scheiter, A Jung, B Runtsch, F Gömöry and W Goldacker; **accepted for publ. Supercond. Sci. Techn.**

SUST paper appears now !



Laser grove in CC with Cu clad



Effect of structuring on transport currents

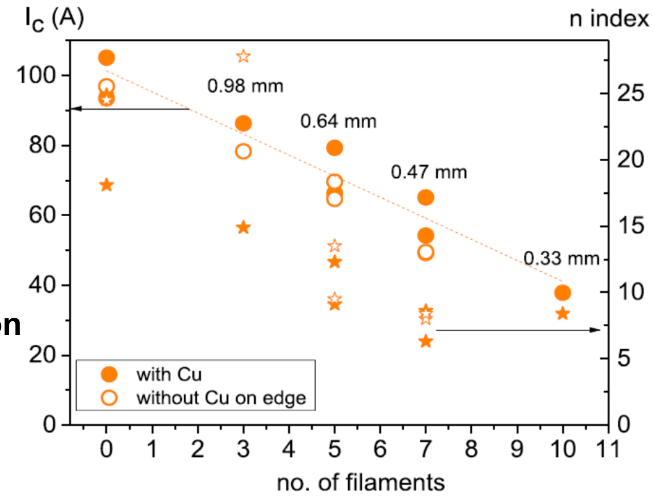


Figure 3. Critical current (circles) and n-index (stars) as a function of filament number. Solid symbols represent samples with Cu on edges, open symbols represent samples with cut edges. Numbers above symbols indicate filament width.

- **Laser grooving of standard SP-tapes with Cu clad**
- **Cut edges to eliminate coupling over substrate**
- **30 – 50% loss reduction at high fields !!!**

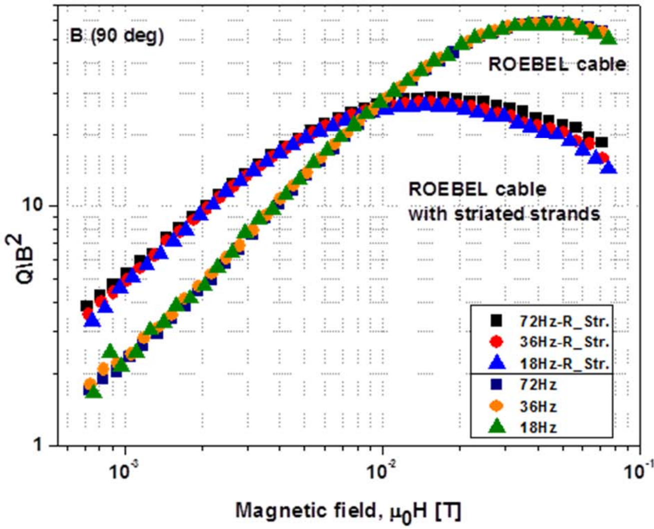
Slide 35

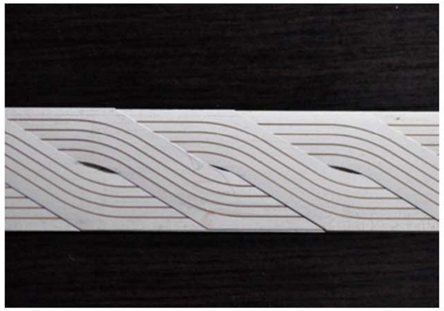
WG25 CORC cable are very suitable to apply filaments since they are fully transposed. The coupling of the outer filaments over the substrate and the Cu-plating under the substrate was found to be a strong contribution to the losses at higher fields. Laser cutted edges solved the problem eliminating the coupling.

Goldacker, Wilfried (ITEP); 29.10.2015

WG26

On-going work on striations and filament coupling





Slight coupling observed, * *

- **Fall-out from ablation**
- **Edge effect as in CORC**
- **Controlled moderate coupling is welcome !**

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

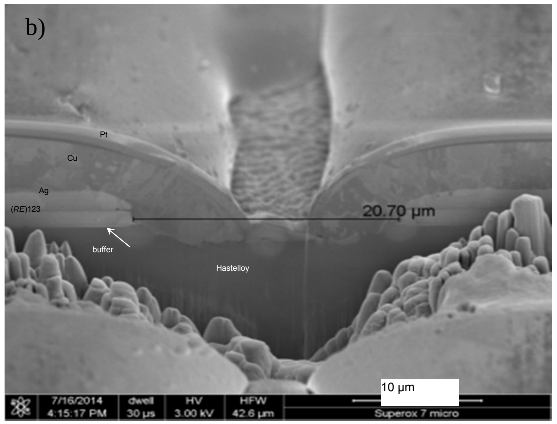
Striate and coat approach, KIT- SuperOx

See Posters R. Nast. 3A-WT-P-04.02 , A. Godfrin 3A-WT-P-04.02

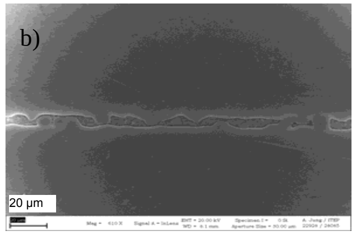
Next step is controlled filament coupling

1. **Striating (KIT)**
2. **Plating (SuperOx)**
3. **Interfilament resistance (KIT)**

Laser processing is minimized for Ag cap structuring !



Influence of electroplated Cu-stabilization on laser-structured Ag-cap coated conductors,
R. Nast, A. Kario, A. Jung, A. Godfrin, R. Gyuraki, B. Ringsdorf, J. Scheiter, F. Grilli, W. Goldacker, A. Molodyk, A. Mankevich



Different metals under investigation

Slide 36

WG26

We work on methods of designed filament coupling going the following route:
First preparing filaments on CC with Ag cap.
Second applying the cu-plating.
The main challenge is to have a homogeneous procedure and constant depth of the grove along the filament.

Goldacker, Wilfried (ITEP); 29.10.2015

Karlsruhe Institute of Technology

Coated Conductor Rutherford Cable (CCRF) with Roebel strands

A cable concept for large magnets as DEMO (fusion reactor beyond ITER)

WG27

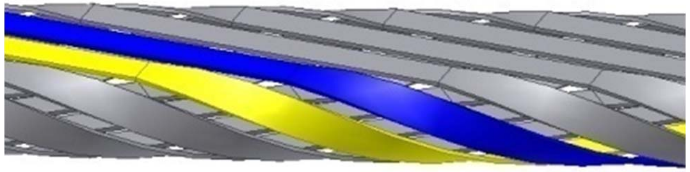
Flat and round Rutherford cable with Roebel-strands

Karlsruhe Institute of Technology

A Kario, M Vojenciak, F Grilli, A Kling, B Ringsdorf, U Walschburger, S I Schlachter and W Goldacker, nvestigation of a Rutherford cable using coated conductor Roebel cables as strands, Supercond. Sci. Technol. 26 (2013) 085019 (6pp)

Current degradation after transfer to cable 5-10 % (464.2 A to 423.2 A)

- **Degradation of 5-10 % current drop**
- **Bent strands beyond reversible regime**



The round concept

A. Kario, A. Kling, A. Jung, B. Runtsch, W. Goldacker, Round Rutherford cable concept with HTS Roebel Coated Conductors strands, ICEC25/ICMC2014, 7-11 July 2014, University of Twente, Enschede

Design features:

6 CC Roebel strands with 10 CC

Core diameter 15 or 17 mm

Conduit 2 mm wall thickness

Transposition of central former with l = 0.7 m

Commercial Roebel strands from General Cable / IRL NZ 5 mm width

Slide 38

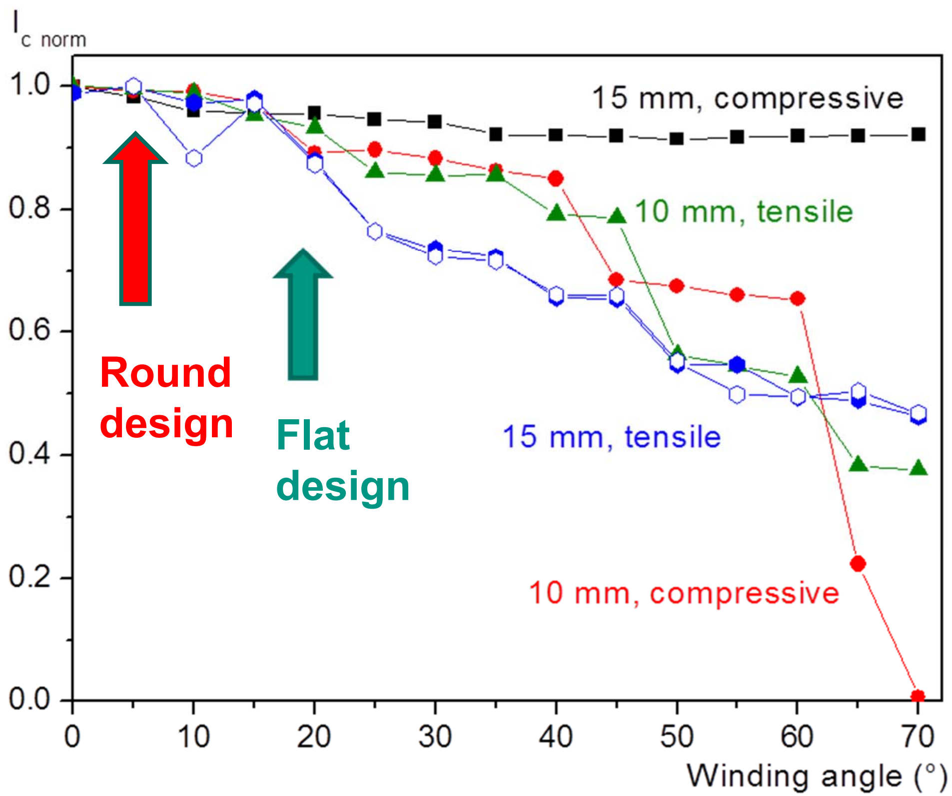
WG27 The Rutherford cable with Roebel strands is a very successful route for big magnets as Fusion magnets. A fully equipped cable was investigated measuring each step of preparation (adding one strand after the other).
Goldacker, Wilfried (ITEP); 29.10.2015

WG28

Bending of Roebel strands decides for round RFC

(parameter is ⟶ transposition length)

Karlsruhe Institute of Technology

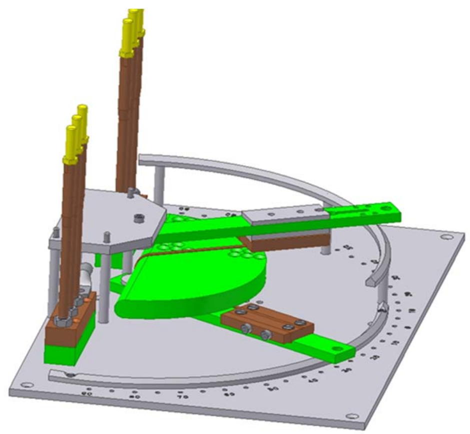


Transposition l_t = 0.7 m

Winding angle = 4°

Compare with graphs of 15 mm core thickness

Having CC layer orientation inside gives mechanical reserve



Slide 39

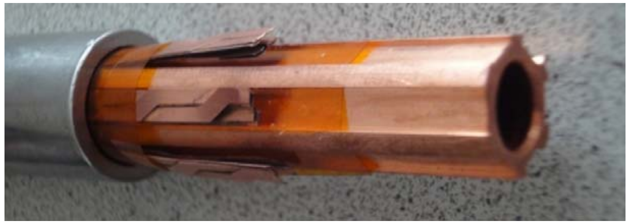
WG28 The round cross section design allows degradation free mounting of Roebel strands. The bending of the strands is in this case in the reversible regime of bending

Goldacker, Wilfried (ITEP); 07.10.2015

WG29

Transport currents in CCRF – Cable with 6 Roebel strands

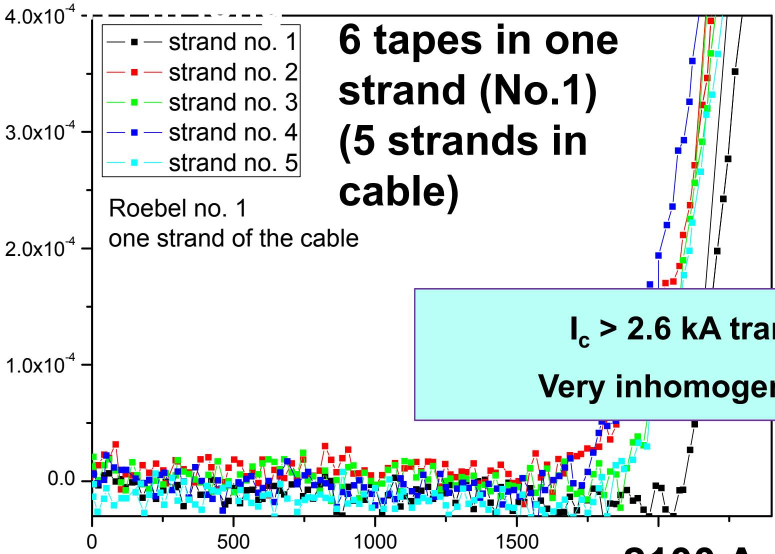
KIT Karlsruhe Institute of Technology



Cable length 1.4 m
Lp = 0.7 m

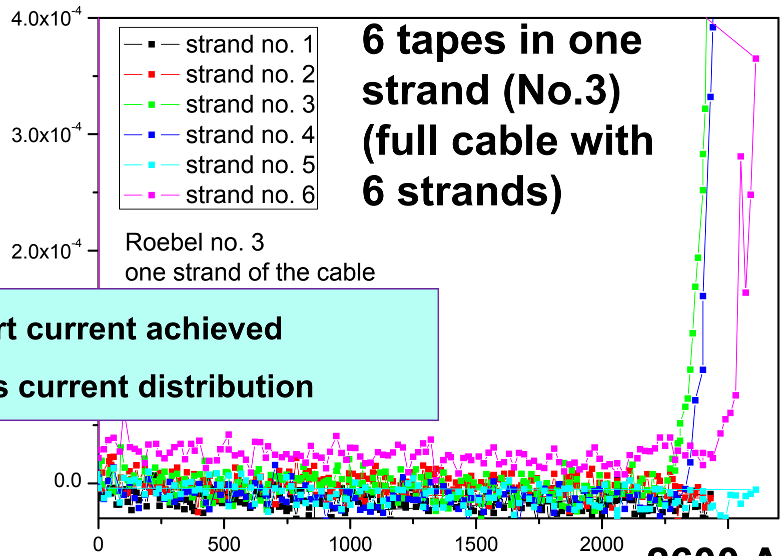
Very inhomogeneous current distribution and complex redistribution over the ends close I_c !

A.Kario et al. unpublished



6 tapes in one strand (No.1) (5 strands in cable)

2100 A



6 tapes in one strand (No.3) (full cable with 6 strands)

2600 A+

I_c > 2.6 kA transport current achieved

Very inhomogeneous current distribution

A stable cable behavior requires some current sharing and a compromise between strand or filament coupling and AC coupling losses level

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WG29 Strong redistribution of the currents in the strands and single CC was observed (Typical influence of scattering contact resistance for short samples). At 2.6 kA one of the last CC was still superconducting. The cable current can be estimated therefore being above 2.6 kA at 77K

Goldacker, Wilfried (ITEP); 07.10.2015

Final remarks !

What happens now with the Roebel waste (off- cuts)

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A kind of flat REBCO single crystal or MT-YBCO

They can be used constructing blocks or any other shape !

"Towards uniform trapped field magnets using Roebel cable offcuts to create stacks of tape with different stacking arrangements"

MITCHELL-WILLIAMS Thomas, PATEL Anup, BASKYS Algirdas, HOPKINS Simon, KARIO Anna, GOLDACKER Wilfried, GLOWACKI Bartek ***see 2A-WT-P-06.06 EUCAS-2015***

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Trapped fields greater than 7 T in a 12 mm square stack of commercial hightemperature superconducting tape

A. Patel, K. Filar, V. I. Nizhankovskii, S. C. Hopkins, and B. A. Glowacki

Applied Physics Letters **102**, 102601 (2013); doi: 10.1063/1.4795016

Maglev meets Roebel cable ?

But economy is always the final argument !

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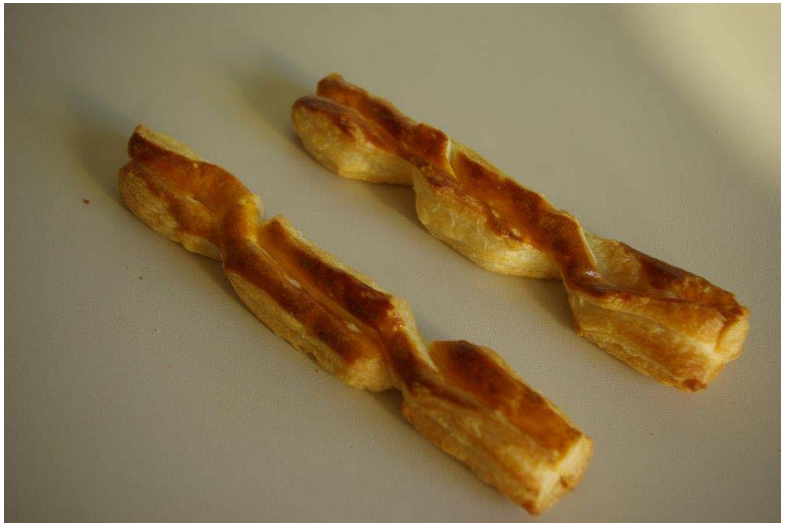

The Twisted Stack approach = simple

You can buy it !

The CORC approach = less simple

You can buy it !

The Roebel cookie = much more work

You cannot buy it !

You will have waste

But you can eat the waste !

Thank you for your attention !

Karlsruhe Institute of Technology

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Karlsruhe Institute of Technology

Colleagues contributing to Roebel, Rutherford, CORC cable research

Anna Kario	Responsible for Roebel R&D, Eucard2
Andrea Kling	Roebel punching, assembling
Antje Drechsler	Constructions
Alexandra Jung	SEM, microstructure
Sonja Schlachter	Rutherford cable
Simon Otten	Cable R&D
Brigitte Runtsch	Microscopy
Rainer Nast	Laser striations
Bernd Ringsdorf	Ic Characterisation
Francesco Grilli	Numerical modelling
Victor Zermeno-R.	Numerical modeling
Eduard Demencick	AC losses
Andrej Kudymow	Characterisation
Roland Gyuraki	Filament characterisation
Aurelian Godfrin	AC losses
Uwe Walschburger	Mechanics, workshop

The success is from an effective internal networking of a mostly „young and international research team“

I thank all my coworkers for the engagement and the contributions, it is always a big pleasure for me to see the outcome and progress !

External cooperations on Roebel (CORC) cable items

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