IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation PL-4 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

Karlsruher Institut für Technologie

Application Driven Superconducting Wire and Cable Development and Application Activities / Prospects in Europe

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Content

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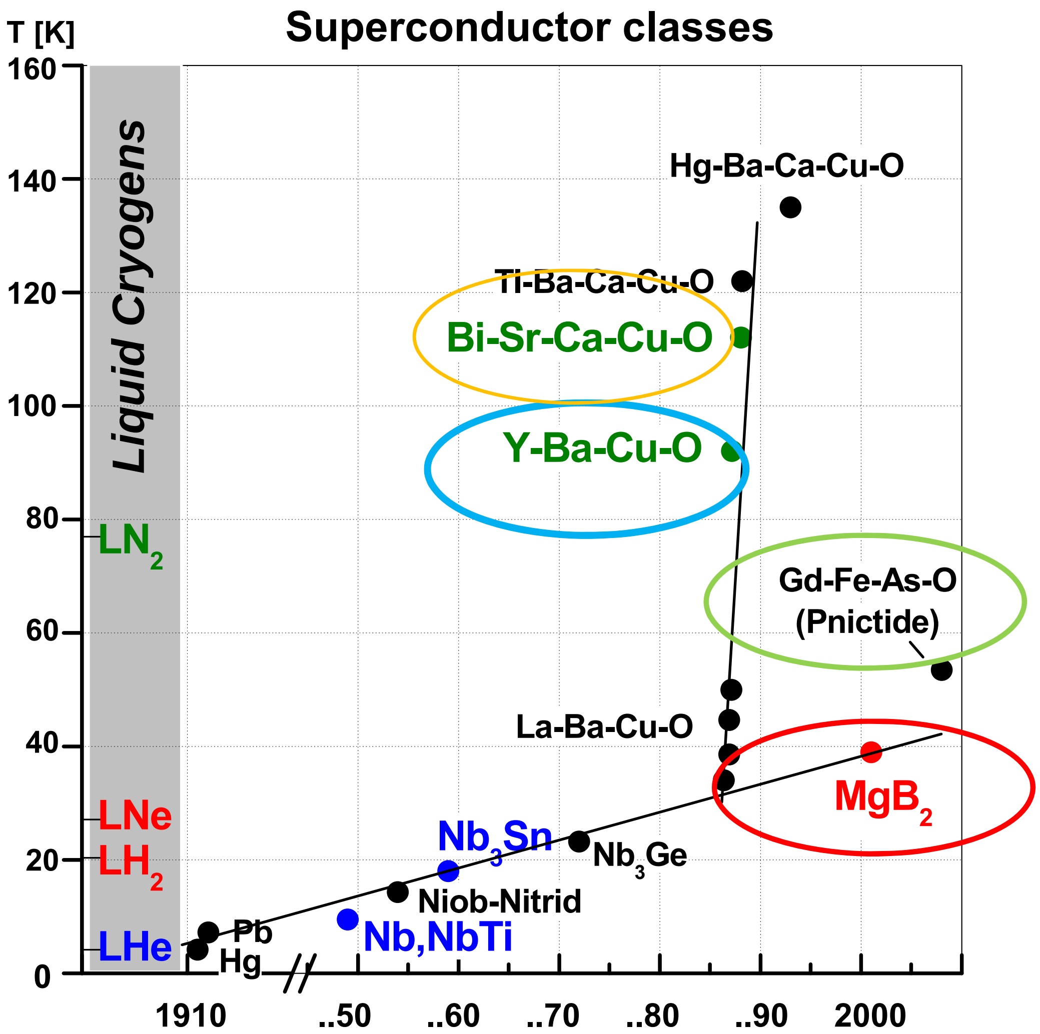
- Introduction comments to REBCO tapes
- Industries for REBCO tapes in Europe
- The REBCO HTS cable activities in Europe
- Application relevant features of REBCO cables
- Selected important applications and projects for HTS-REBCO-tapes and cables
- Final remarks

Investigated superconductors in Europe



- R&D by industries, Univ. and Research Institutions
- Academic university research
- Mainly industrial R&D, minor academic activities, applications !
- Poor research and no fabrication
- At university level a lot of research on more exotic systems like Heavy Fermions etc.
- Poor fundamental R&D on technical LTS materials, but intensive R&D on ITER Nb_3Sn magnet cable, interest in advanced Nb_3Sn wires (CERN, NMR)!

Motivation Energy Technology

integration of renewable energy, a save new grid structure, efficient energy use, future technology

- Power cables (HVDC, MVAC, HVAC)
- DC high power industry cables (also wind farms ?)
- Bus bar systems (CERN) (CC and MgB_2)
- Fault current limiters (resistive, inductive)
- Self limiting HTS transformer (MV/LV)
- Wind energy generators (AC and DC)
- Electrical Airplane short range (emission-free)
- Fly wheel storage systems (local grid solutions)
- Smart grid technology with HTS implementation

- Integration of renewable energy brings new grid structures, and requires storage, regulation and protection in very local dimensions
- So far no real market from energy sector, no significant driver as application, but pilot activities, demonstrators !
- Problem: costs & retrofitting of long term investments !

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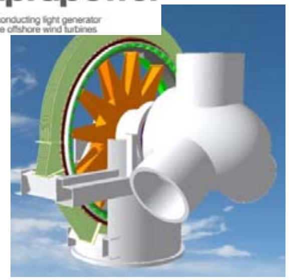
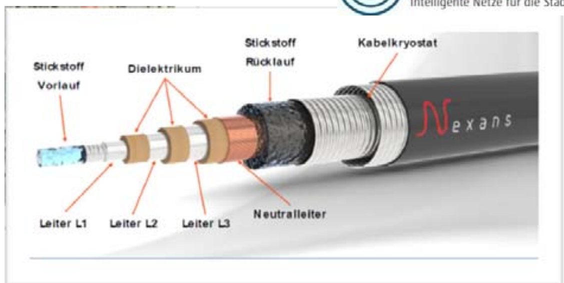
FCL

suprapower



AMPACITY Intelligente Netze für die Stadt



HTS Transformer KIT/ABB

Motivation Magnets

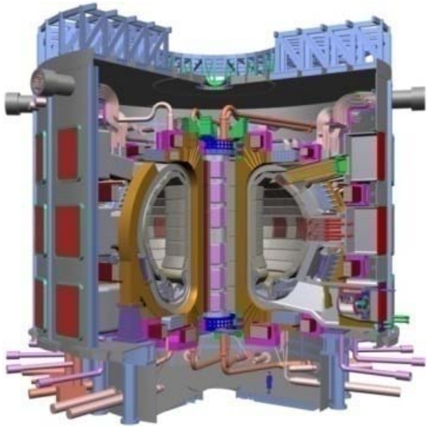
- Fusion magnets for DEMO*
- Accelerator magnets FCC CERN
- MRI (cryogen-free whole body)
- MRI (high resolution, high field)
- NMR (1.2 GHz + spectrometer)
- Magnets for space application
- Magnets for heat treatment, separation etc.
- High Field magnets (HTS inserts and stand-alone solutions) for research

* Marginal funding, HTS application Drivers !!!

Magnet applications are the drivers since HTS is an enabling technoly for increased fields, in the past the DEMO fusion plant

Now FCC (Future Circular Collider at CERN) is most important driver and may be booster for all HTS applications

NMR, MRI magnets is the big business



ITER & DEMO

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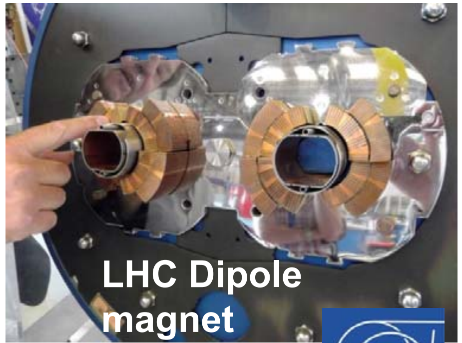
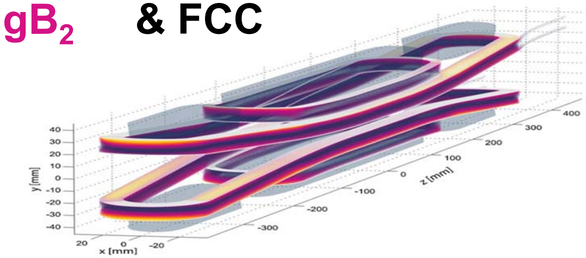


PARAmed MEDICAL SYSTEMS

Cryog. free MRI MgB_2

Hi-Lumi LHC & FCC



NMR & MRI

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The REBCO thin film tape the Coated Conductor (CC)

The new „working horse“ !

Characteristic features of REBCO coated conductors

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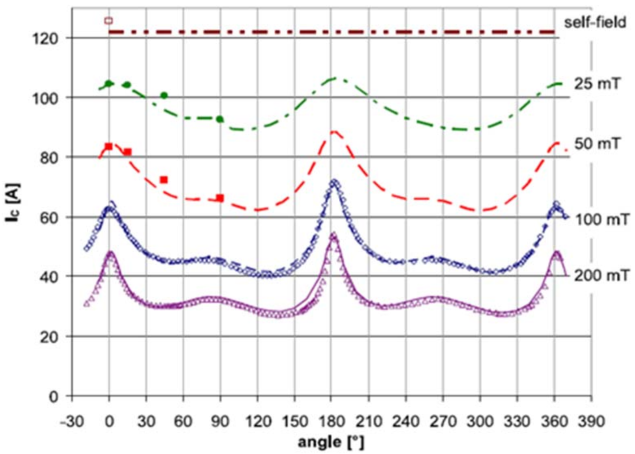
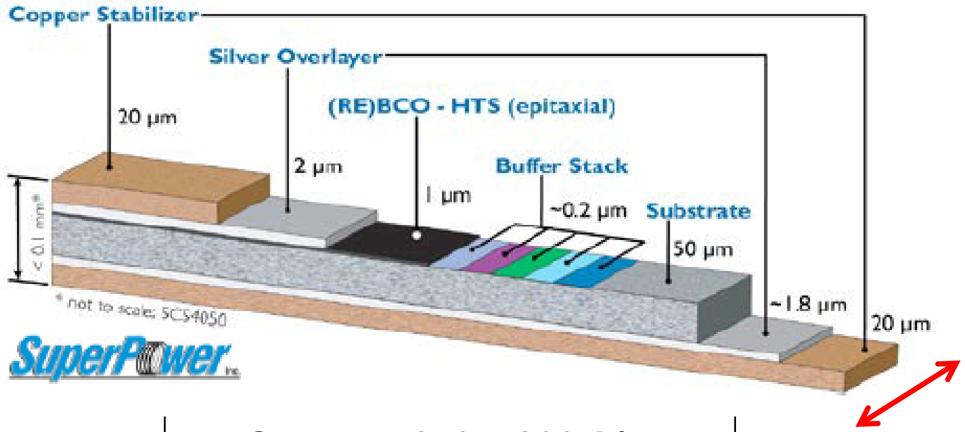
Current anisotropy 77 K

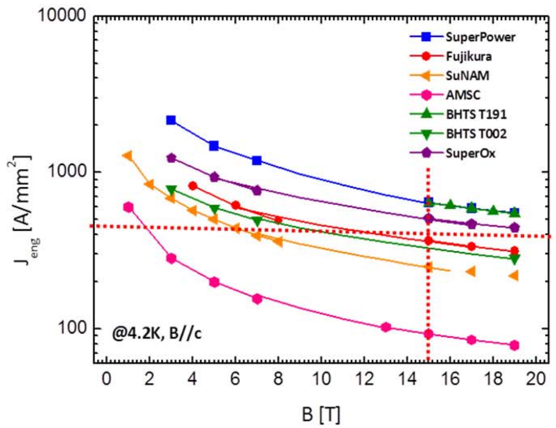




- Currents 250 – 800 A/cmw
- Width: 2-12 mm
- Thickness appr. 0.1 mm

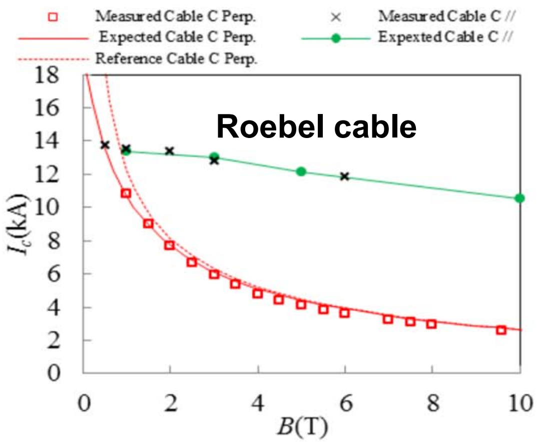
Very poor in-plane bending ability !

J_{ce} (B) at 4.2 K (pinning)



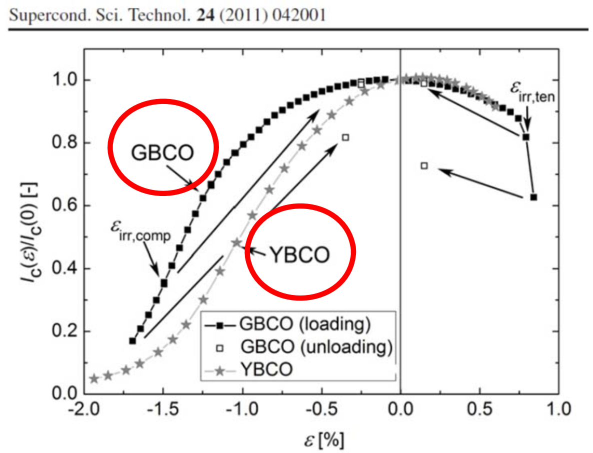
C. Senatore, et al., 1st Workshop on Accelerator Magnets in HTS, DESY, 21 - 23 May 2014.

Current anisotropy 4.2 K



J. Fleiter, A. Ballarino, L. Bottura, P. Tixador Superc. Science & Technoly.

Bending of REBCO-tapes



D.van der Laan Advanced Conductor Technologies.

Coated Conductor Manufacturers

Tier I

- AMSC, Mass. USA (RABiTS+MOD)
- SuperPower, NY, USA/ Japan (IBAD+MOCVD)
- SuNAM Co. Ltd, Korea (IBAD+RCE)
- SuperOx, Russia/Japan (IBAD+PLD)

Tier II

- Fujikura, Japan (IBAD+PLD)
- Bruker HTS, Germany (IBAD+PLD)
- Theva, Germany (ISD+RCE)
- STI, TX USA (IBAD+RCE)
- Shanghai Superconductor, China (IBAD+PLD)

Tier III

- d-nano (BASF), Germany (RABiTS+MOD)
- Shanghai Creative Superc, China (IBAD+MOD)
- SAMRI/CAS, Suzhou China (IBAD+MOCVD)
- Oxolutia, Spain (IBAD+MOD)
- Sumitomo, Japan (RABiTS+PLD)
- Metox, TX USA (RABiTS+MOCVD)

Table. Vladimir Matias, iBeam, CCA-2016, Aspen USA

Mainly focussing on:

Bruker: Magnet applications
THEVA: Energy applications

D-NANO: Cheap CSD CC-route
Oxolutia: Low cost CSD route
SuperOx: All applications

Wilfried Goldacker

ICMC- CSSJ Kanazawa – Japan – Nov. 7th. – 10th. 2016

Comparison and Specifications for REBCO-CC from European companies

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Company & Focus	REBCO	Deposition	Substrate & Buffer	Currents	Dimensions Capacity/y	Speciality
Bruker 4K high field applications: magnets	YBaCuO	**PLD** (pulsed laser deposition) Dynamic drum, reel-to-reel	**St-Steel** ABAD-YSZ Cap: Ag, Cu	I_c= 600-800 A/cm-w. at 4.2 K / 18 T (B//c) for long lengths I_c= 1250 A/cm-w. on 22m at 4.2 K / 18 T (B//c)	Dim.: 0.1 (0.06) x 4-12 mm 600 piece-length Capacity on own demands	Advanced high field pinning at T = 4 K
THEVA Economic route, simple architec-ture	GdBaCuO	**Consistent PVD** (thermal co-evaporation, e-beam)	**Hastelloy C276** ISD-MgO+MgO Cap: Ag, Cu	I_c> 500 A/cm-w. at 77 K s.f. for long lengths	Dim.: 0.1 x 12 mm 600 m piece-length (Dec 2016) Cap.: 150 km/Y @ 12 mm width	Lamination of Cu (Cu-alloy) tape (0.1 mm) Low resistance joints
SuperOx Customized solutions, cables	GdBaCuO	**PLD**	**Hastelloy C276** Al_2O_3, Y_2O_3 / , IBAD-MgO, LMO, CeO_2 Cap: Ag, Cu	I_c= 300-500 A/12mm-w. at 77 K s.f. I_c= 100-150 A/4mm-w. At 77 K s.f.	Dim.: 0.06-0.1 x 4-12 mm Piece length <500m Cap.: 150 km/Y ?	Customized stabilization, Insulations, laminations, HTS cables
D-NANO-BASF Low cost chemical route	YBaCuO	**CSD** (chemical solution deposition) Dip-coating technologies	**NiW – alloy** cube tectured LZO, CeO_2	I_c = 250 A/cm-w. 77K s.f. for 50 - 100 m	Dim.: 0.06 x 10 mm Piece length >200 m Cap.: approaching 200 km/Y	Doubled CC by back-to-back lamination
Oxolutia All solution approach, adv. nano pinning	YBaCuO	**CSD - Ink-Jet RTR** All solution process on ABAD	**Different approaches** mainly ABAD Bruker	I_c = 108 A/cm-w at 77 K s.f. on short samples	Short samples from Bruker buffered substrates	Nano-pinning by new approaches

Transport current capacity of industrial CC materials

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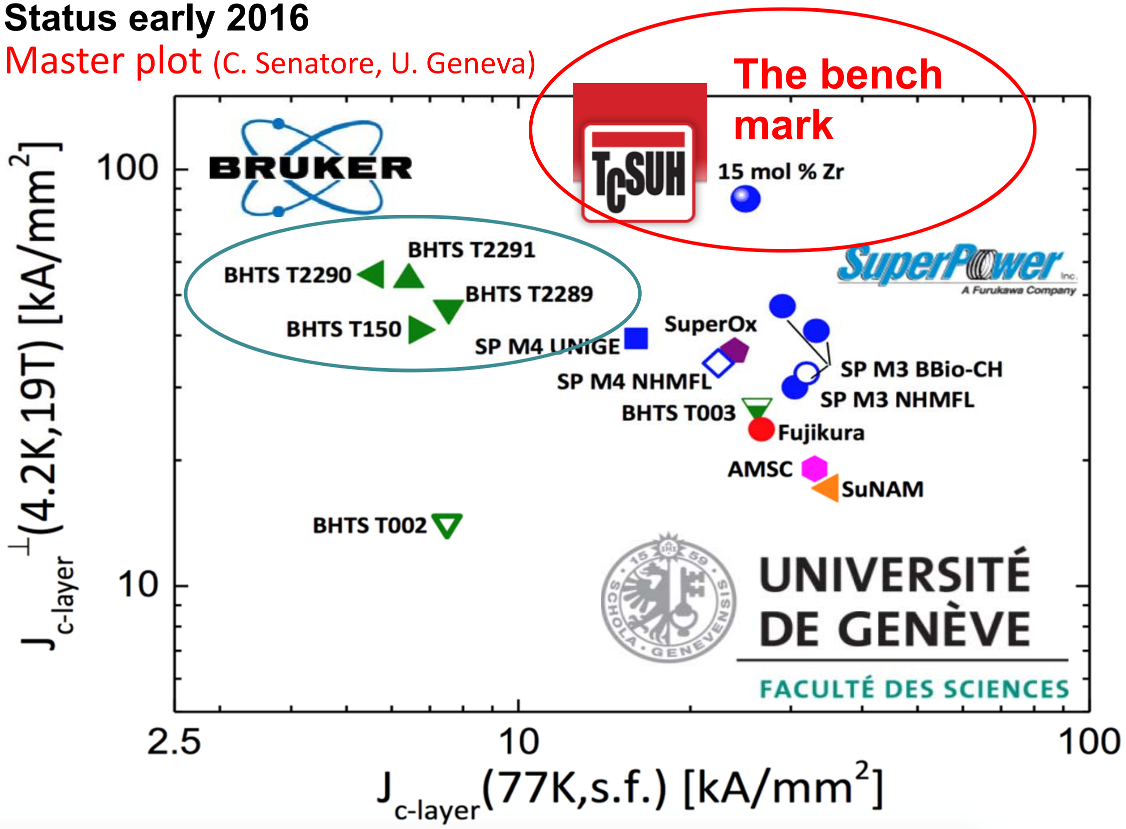
Activity under EU-project Eucard2 (CERN)

- **Investigation of Bruker, SuperOx, SuNAM, THEVA, SuperPower, Fujikura, AMSC**
- **Application criteria: Current capacity at 4.2 – 77 K, current homogeneity, delamination sensitivity, customized stabilization !**

Status early 2016

Master plot (C. Senatore, U. Geneva)



BHTS: highest layer J_C at 4.2 K in field

- **Materials optmize via applied pinning for different temperature regimes**
- **Bruker qualifies as material with best 4.2 K in field performance**
- **Reason is a complex combination of different types of flux pinning sites (paper cited below)**
- **Substrate thickness of 100 microns is actually replaced by 50 micron for higher J_c^{eng} and improved bending**

IOP Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. **28** (2015) 114007 (8pp) — doi:10.1088/0953-2048/28/11/114007

Double disordered YBCO coated conductors of industrial scale: high currents in high magnetic field

D Abraimov[1], A Ballarino[2], C Barth[3], L Bottura[2], R Dietrich[4], A Francis[1], J Jaroszynski[1], G S Majkic[5], J McCallister[1], A Polyanskii[1], L Rossi[2], A Rutt[4], M Santos[1], K Schlenga[4], V Selvamanickam[5], C Senatore[3], A Usoskin[4] and Y L Viouchkov[1]

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
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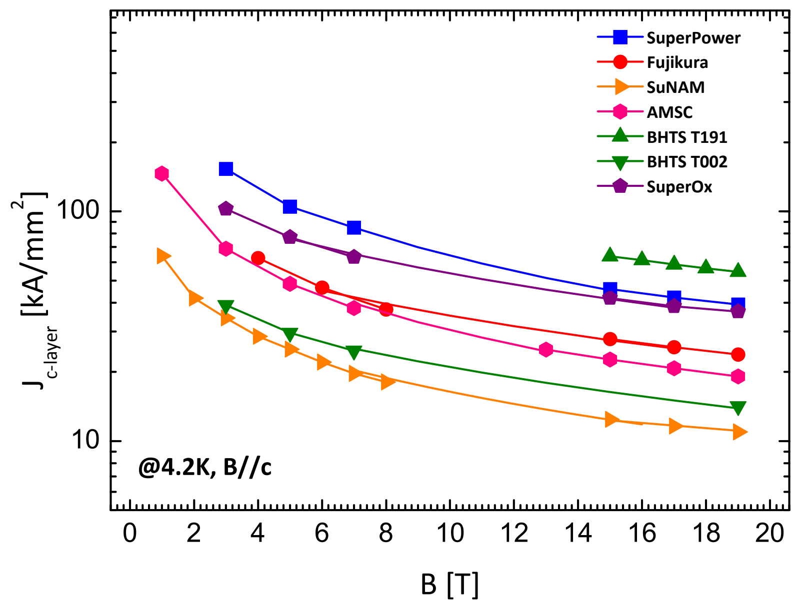
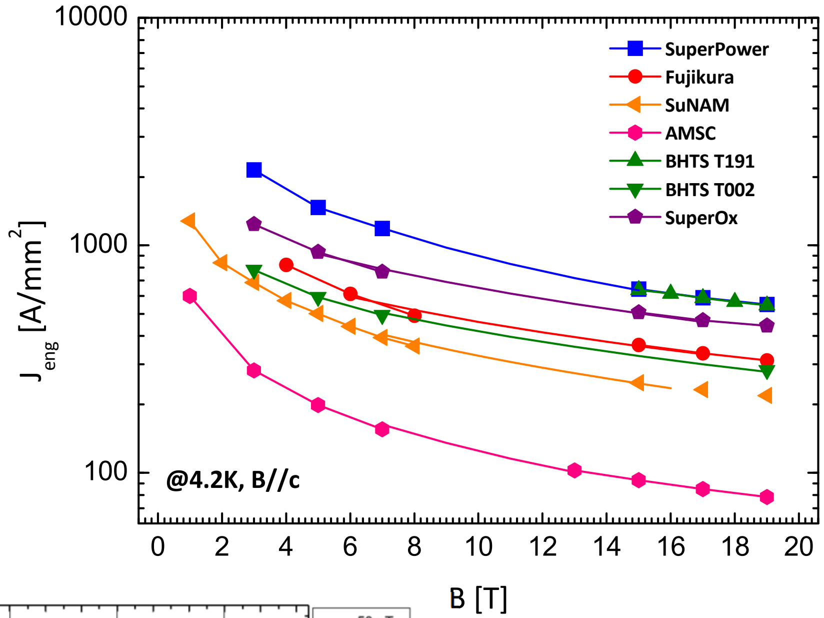
All industrial CC are proved for application specs.

Test and qualification for EU-project Eucard2



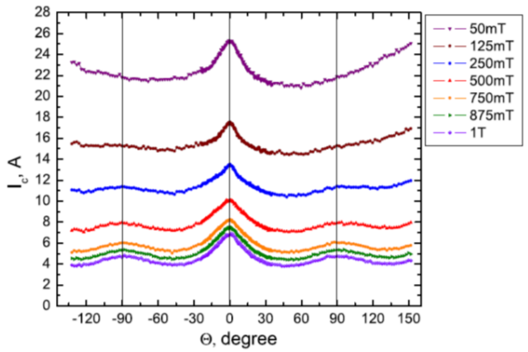


C. Senatore, C. Barth, M. Bonura, G. Mondonico, M. Kulich, 1st Workshop on Accelerator Magnets in HTS, DESY, 21 - 23 May 2014.

BHTS: highest layer J_C (4.2 K) obtained in an industrial process but thick substrate

Criteria for magnet applications

- **High engineering current density (50 micron substrate now at BHTS)**
- **Narrow angular dependency of I_c**
- **Advanced (artificial) pinning sites**



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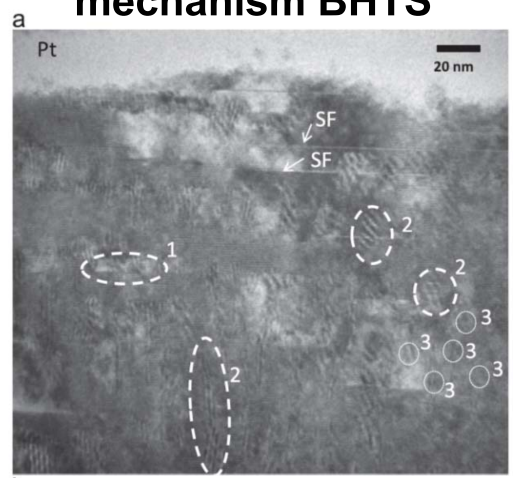
Complex flux pinning mechanism BHTS



Direct applications of HTS-tapes

- Small / medium magnets: Inserts for NMR, dipoles, etc.
- Pancake windings for motors/ generators
- Transformer, FCL and power transmission

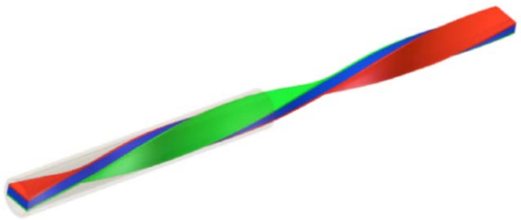
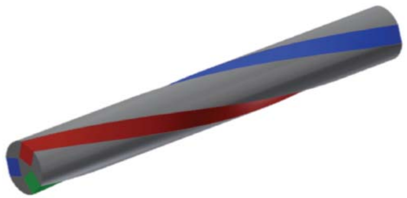
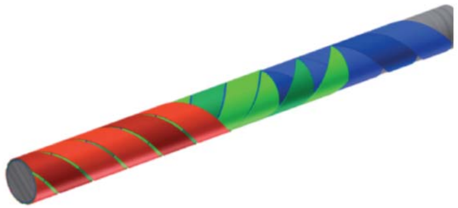
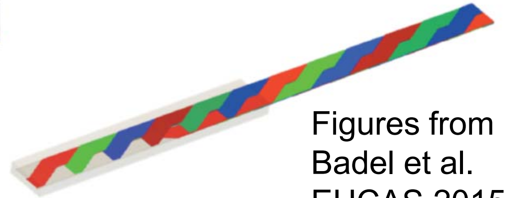
Conductors to be customized with Cu-layer, lamination, striations

HTS-cables for high operation current

- Large devices: Fusion, accelerator magnets, power lines
- High transport currents >> 1 HTS-CC-tape
- Stranded design with transposition for low AC losses

High current cables: different approaches possible

Transposition mandatory for AC use

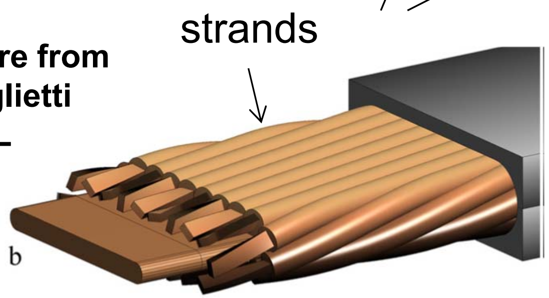
TST , EPFL-strand	HTST	CORC®	ROEBEL
			
CC Stack optional Cu tube & transposition	CC Stack in transposed groved rod (Cu, Al)	CC layers spirally wound on core, layer inside	CC cut in meander shape, stacked with transposition

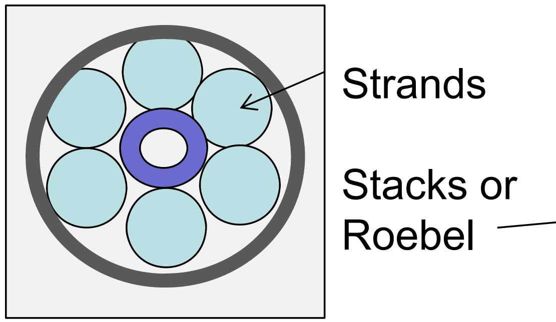
Figures from Badel et al. EUCAS 2015

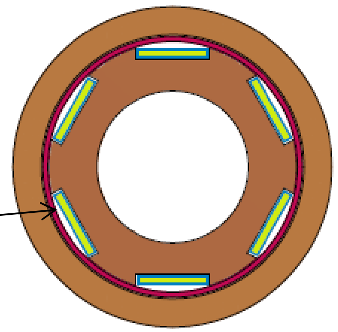
For higher currents

Option conduit

Figure from D.Uglietti EPFL







HTS cables used as strands !

HTS cables for large magnets I

- European activity
- US activity
- Asia activity

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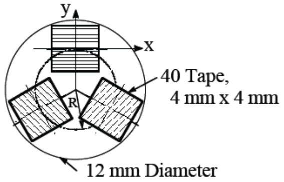
• Twisted Stacked-Tape Cable (TSTC)

MIT



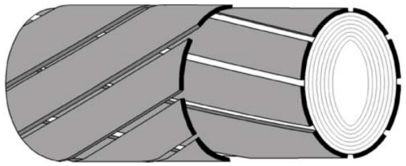
M. Takayasu et al, Adv. Cryo. Eng., 54, Plenum, N.Y., 273-280, 2012 & EUCAS 2013

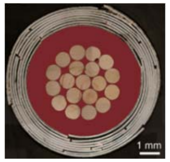
3x40 tapes, 4 mm wide:
5 kA @ 77 K, s. f.
40 tapes @ 4.2K, 12 T
9.4 kA

- **Very sensitive to bending**
- **Strand coupling not flexible**

• Conductor on Round Core (CORC®) cable

Advanced Conductor Technology





D.C. van der Laan et al, Supercond. Sci. Technol. 24, 042001, 2011
MT24 – Nov.2015 Seoul

79 tapes, 4 mm wide: **7.56 kA @ 76 K**
30 micron substrate
I_c (4.2 K, 17 T) = 7665 A
J_c (4.2 K, 17 T) = 372 A/mm^2

- **Perfect short transposition**
- **I_c (B) anisotropy averaged out**
- **High compressive prestress !**
- **Limited bending**

• Roebel Assembled Coated Conductor (RACC)

KIT

31 tapes, 5.5 mm wide: **2.75 kA @ 77 K**
10 tapes, 5.5 mm wide
I_c (4.2 K, 10 T) = 2.5 - 10.5 kA (depending on field orientation)

W. Goldacker et al, Supercond. Sci. Technol, 22, 034003, 2009, J. Fleiter[1], A. Ballarino[2], L. Bottura[2], P. Tixador[3], Superc. Science &Technol.

- **Full transposition**
- **I_c anisotropy**
- **I_c(B,T) like CC**
- **High J_c eng. and filling factor**

HTS cables for large magnets II

- European activity
- US activity
- Asia activity

KIT Karlsruhe Institute of Technology

- **Double-Core-Roebel-Cable (DOCO) KIT**

Subsize cable (1/2) demonstrated
22 tapes, 2.8 mm wide: **1.3 kA @ 77 K**
Arrangement: (8 inside, 14 outside)

W. Goldacker et al. ASC2016 Denver USA , unpublished

- Concept for higher current capacity and lower losses

- **KIT Rutherford Cable with Roebel strands (CCRC)**

KIT

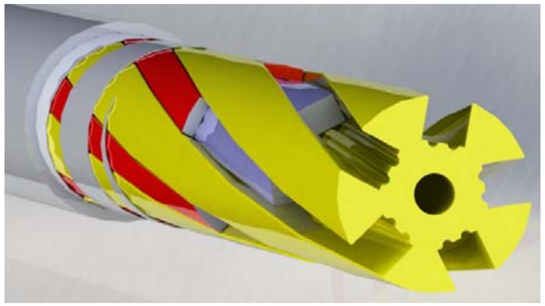
6 x 10 tapes, 5 mm wide:
2.6 kA @ 77 K, s. f.

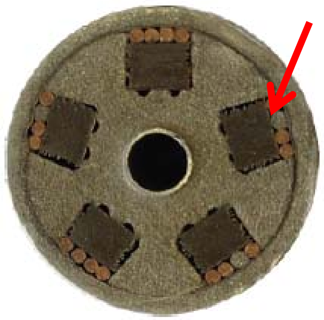
A.Kario et al. KIT unpubl. presented at ICSM Fethyie, Turkey 2016

- Concept with transposition + transp. strands
- Low filling factor

- **ENEA TRATOS cable, stacks as strands (Roebel strands as option)**

Luigi Muzzi et al. ASC2016 Denver USA





Filler from copper + CC stacks

6 x 20 tapes, 4 mm width
measured with 1 strand
1.95 kA @ 4.2 K, 12 T

- Function tested on 1 strand
- extruded Al core
- Similar to round Rutherford cable
- CC stacks now, option is Roebel

HTS cables for large magnets III

- European activity
- US activity
- Asia activity

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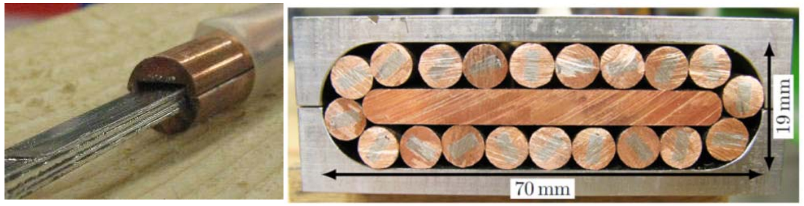
• Rutherford Cable EPFL: CC stacks in Cu

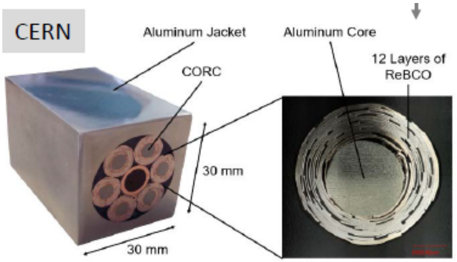


16 tapes, 4 mm wide:
3.2 kA @ 4.2 K, 10 T
Cable 20 strands
60 kA @ 7.8 K 12 T

D. Uglietti et al. HTS4Fusion WS Villigen Jan. 2014, and
Supercond. Sci. Technol. 28 (2015) 124005 (13pp)

- Test successful
- Stacks in strand
- transposition in
  Strand + Cable
  L_p > 1 m+ 0.32 m

• CORC® in Conduit CERN:

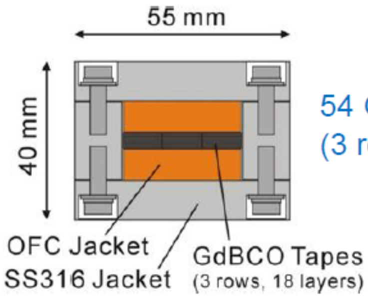


6 CORC strands a 38 CC tapes:
12.3 – 13 kA @ 77 K s.f.
>> 32 kA @ 4.2 K, 9 T (rated 47 kA at 10 T)

H. tenKate CCA-2016 Aspen-USA, Strands from Advanced Conductor Technology Boulder USA

- Test successful
  at 77K and 4.2K
- transposition in
  Strand + Cable
  L_p (cable): 0.4 m

• HTS STARS Conductor (CC stacks) (NIFS, Japan)



54 GdBCO tapes
(3 rows, 18 layers)

54 tapes, 10 mm wide:
100 kA @ 20 K, 5.3 T

Ito et al. HTS4Fusion WS Villigen Jan. 2014, N. Yanagi ASC2016 Denver USA

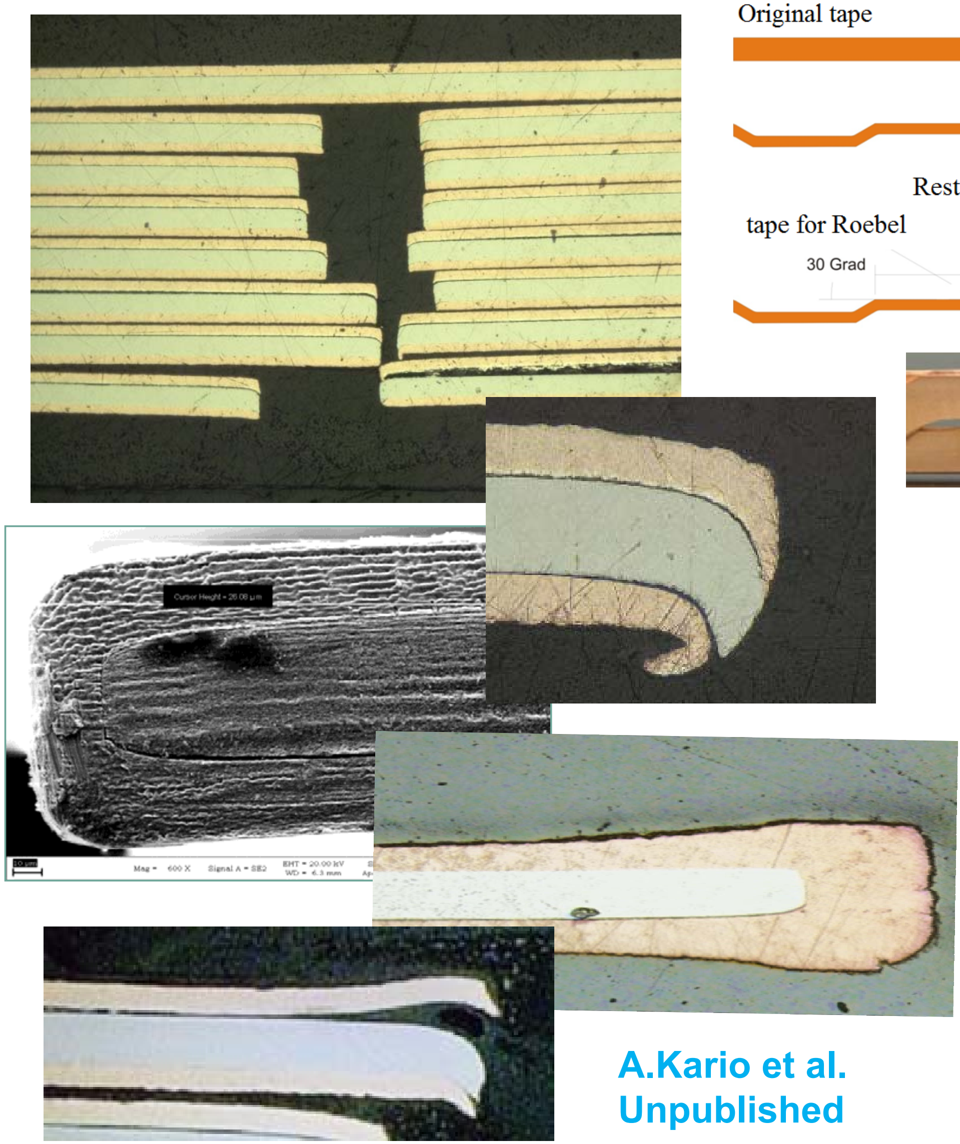
- Test successful
- Stacked CC
- Very stable !
- 100 kA class cable

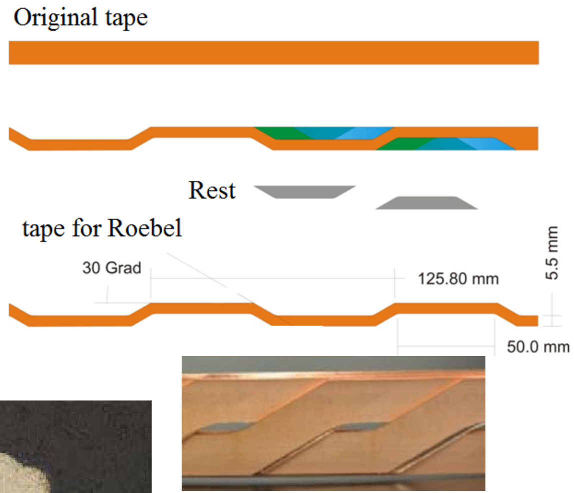
More details for 4 examples

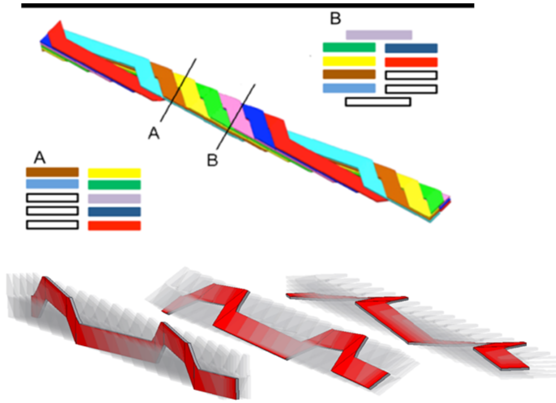
- Roebel HTS cable, first applications !
- DOCO cable the future upgrade
- CORC in CICC approach under first tests
- HTS Rutherford cables and strands from stacks

Preparation issues for HTS Roebel cables

Test of different coated conductors for Roebel approach (EUcard2-project)







A.Kario et al.
Unpublished

Key process: Strand punching !

- **Dimension accuracy of CC (width, straightness, dog boning from Cu)**
- **Delamination sensitivity !!**

- **High precision requires material specific punching tool (optimized gap tolerance)**

- **Switch to punch and coat process**

Stabilisation of Roebel strands successful with Punch & Coat (Cu plating on CC+Ag) strategy

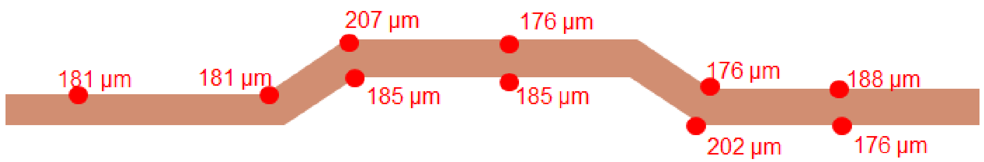
Karlsruhe Institute of Technology

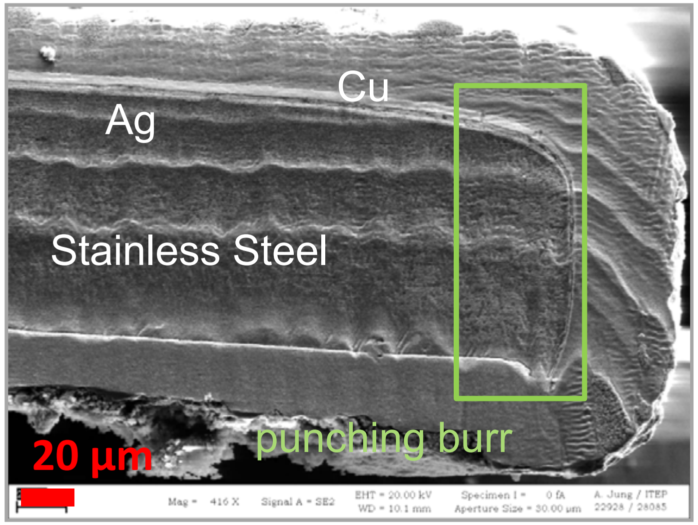
A.Kario et al. Unpublished

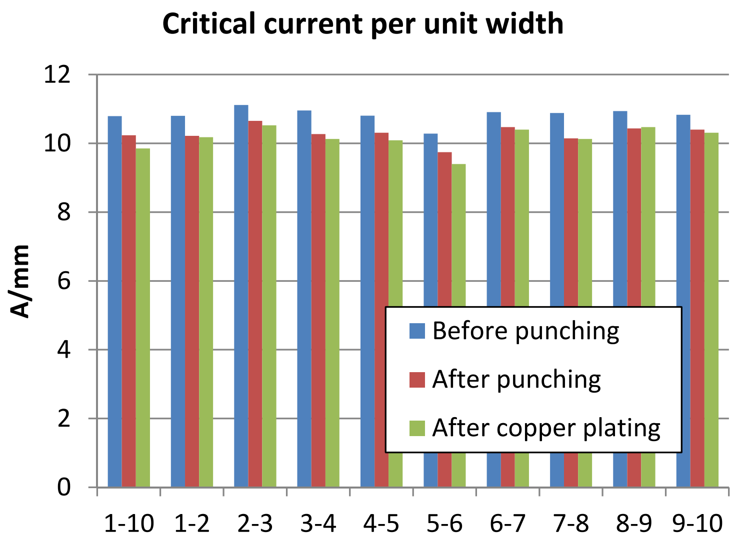
Delamination can be avoided, however some effects on geometry:

- width of this Cu plated tape is 5.46-5.67 mm and thickness 176 - 207 µm

Thickness measurements at different points:







- The average critical current per unit width degraded by 6% after punching and copper plating.
- No local defects were found.

Activity under EU-project Eucard2

In summary

P & C was applied for Bruker tape and demonstrated with SuperOx CC

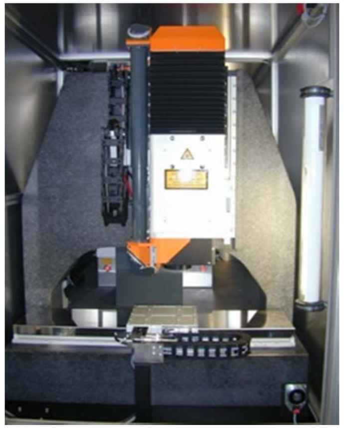
Materials stable against thermal cycling, no delamination

Method now mandatory for the Eucard2 cables !

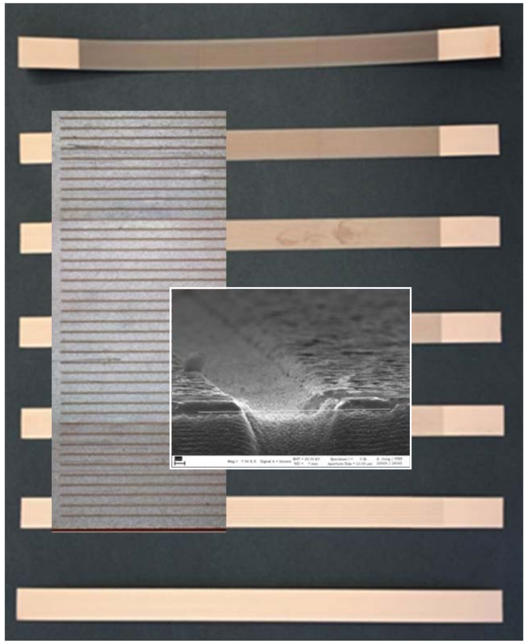
Homogeneity: CC with laser striations indicate defects

Karlsruhe Institute of Technology

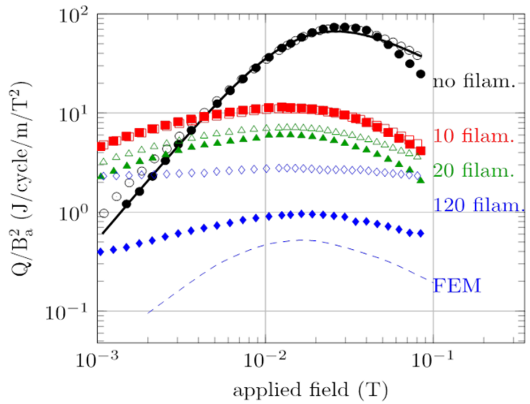
Now RTR ! free grove pattern

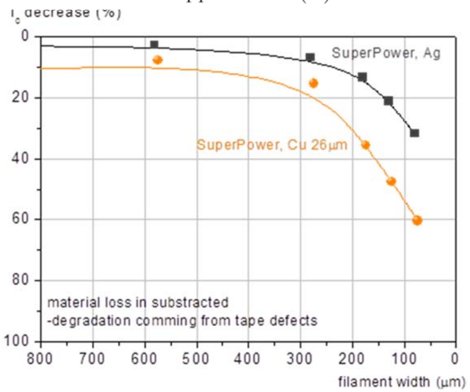


psec pulse NdYAG system up to 120 groves/12 mm

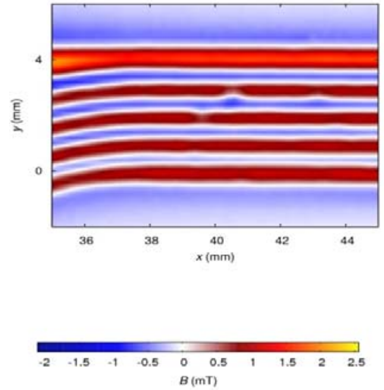


AC loss reduction with filaments



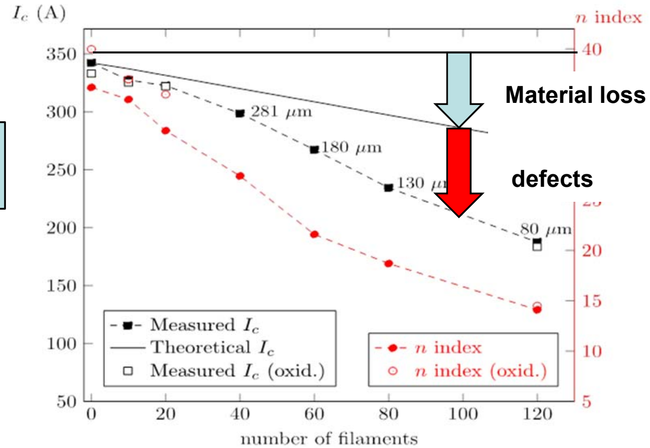


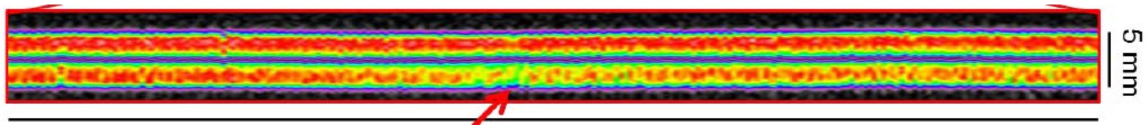
F. Grilli and A. Kario, Superc. Sci. Technol. 2016 Vol 29 No. 8



Defects can reach 300 micron size !

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



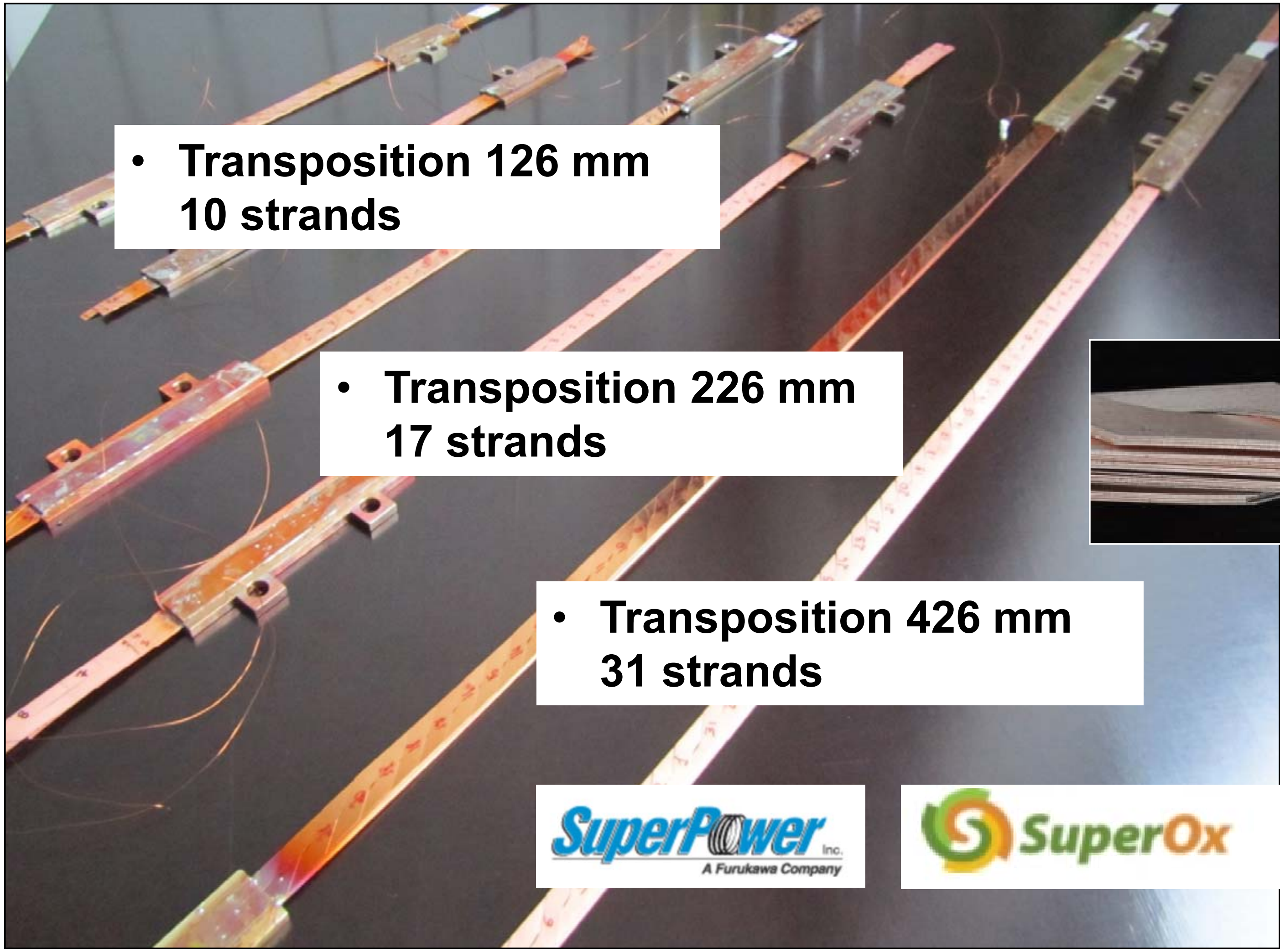


Local reduced currents: T.Kiss et al. MT24 Seoul 2015 2OrAC-04

Designed transport currents in Roebel cable

Karlsruhe Institute of Technology

Strands: Superpower with APC, SuperOx with no doping



A.Kario et al. Unpublished

Higher currents ?

- Longer transposition = more strands
- Stacking strands = 2x or 3x current

3-fold stacked strands
= 45 strands
= 2.7 kA (77 K, sf)

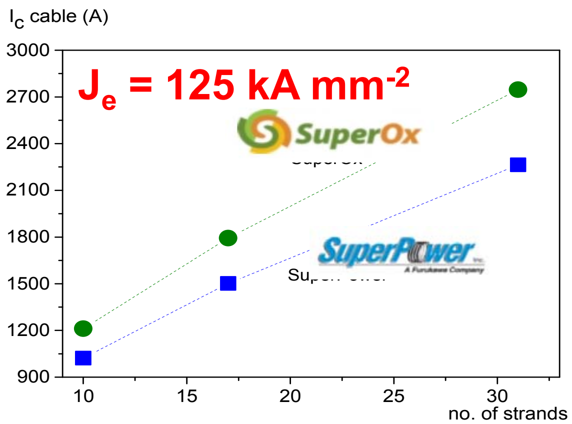
Increased limitation of bending ability like in stacked cables

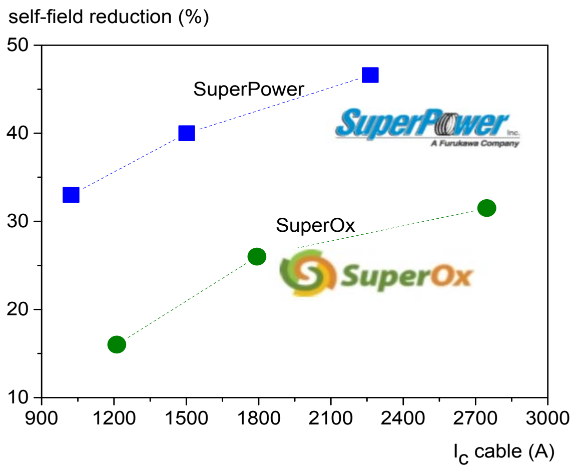
Roebel cable I_c(T, B) and flux pinning situation

Karlsruhe Institute of Technology

A.Kario et al. unpublished

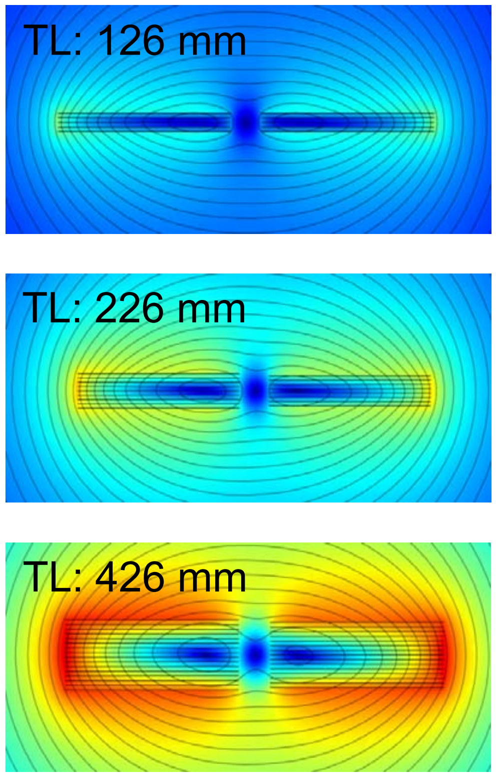
I_c = 2.7 kA (77 K, sf) SuperOx Roebel (31 strands, long transp.)

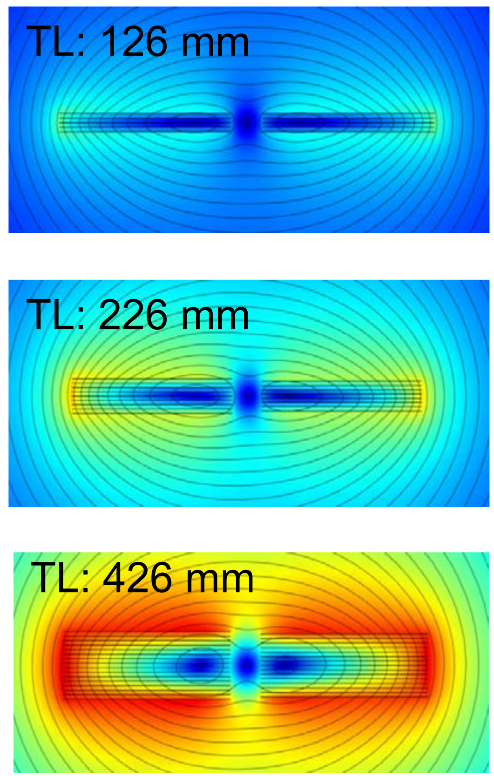


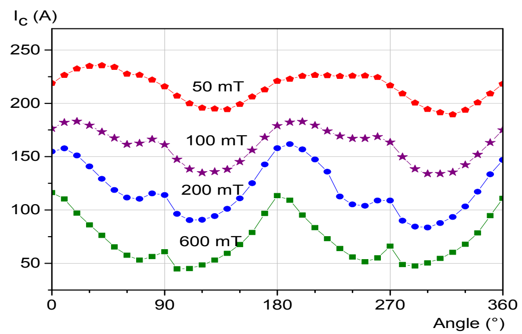


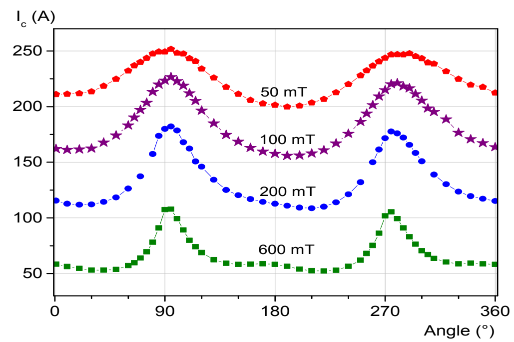
Pinning determines application regime

SuperPower Adv.Pg. **SuperOx no**





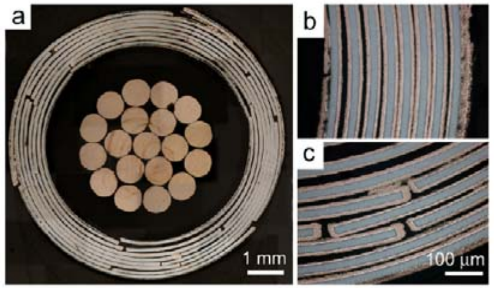


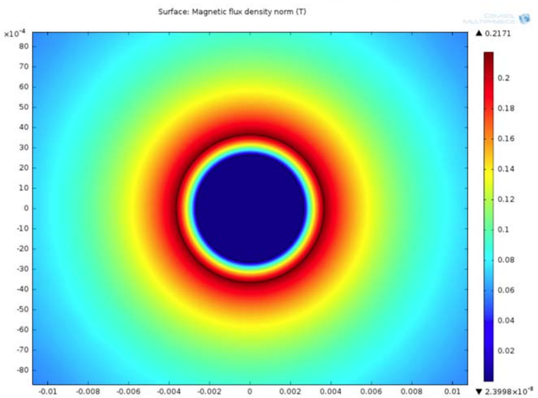


Low temperature transport currents

In comparison CORC cable or twisted stacks systems

- CC in cylinder shape
- No edge effects
- Anisotropy avered out

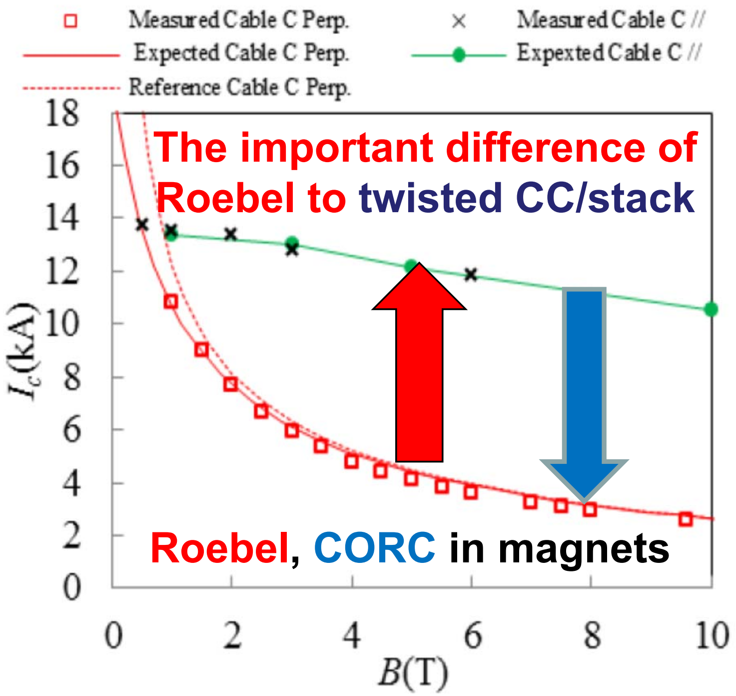




Anisotropy of Roebel cable at 4.2 K and B = 0 - 10 T

CC from SuperPower

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



J. Fleiter, A. Ballarino, L. Bottura, P. Tixador, *iopscience.iop.org/0953-2048/26/6/065014*.

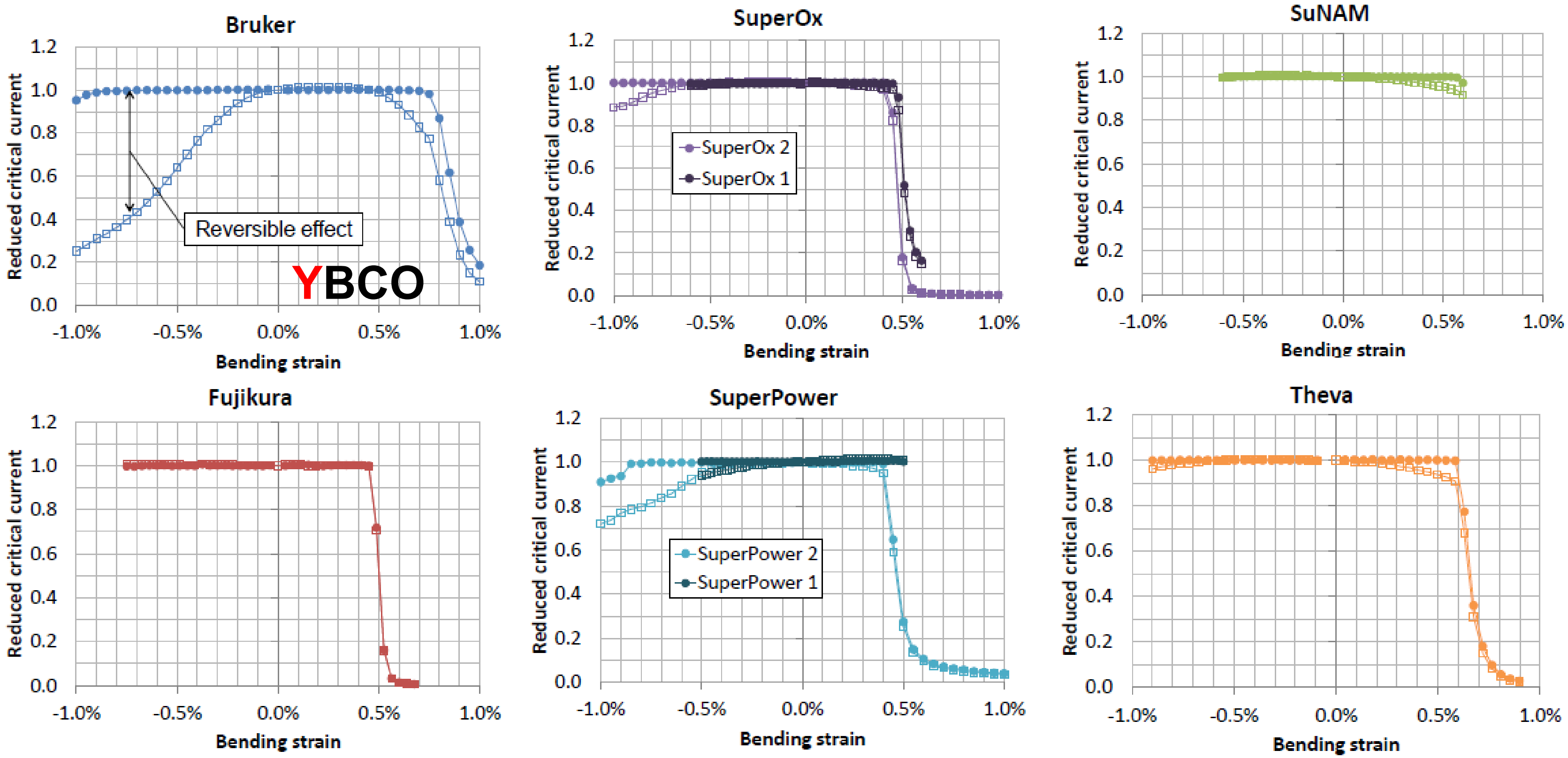
Transport I_c : 14 kA (35 kA) at self field

4 - 12 kA (10 – 30 kA) at 6 T (4.2 K)

Enhancement factor 77 K - 4 K factor 12 !

Red values: Extrapolated values for 31 strand cable !

Bending results for different coated conductors

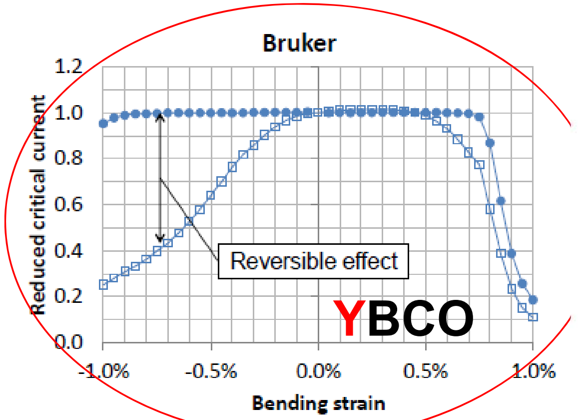


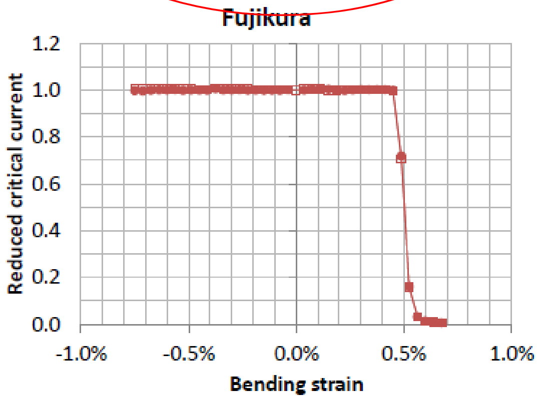
Tape	Substrate thickness	Stabilizer	$R_{min,comp}$	$R_{min,tens}$	ε_{min}	ε_{max}
Bruker	97 µm	20 µm Cu	< 5.0 mm	6.7 mm	< -1.0%	0.75%
Fujikura	75 µm	20 µm Cu	< 5.0 mm	10.0 mm	< -0.75%	0.45%
SuNAM	60 µm	20 µm Cu	< 5.0 mm	< 5.0 mm	< -0.6%	> 0.60%
SuperOx 1	60 µm	20 µm Cu	< 5.0 mm	6.7 mm	< -0.6%	0.45%
SuperOx 2	100 µm	only Ag	< 5.0 mm	12.5 mm	< -1.0%	0.40%
SuperPower 1	50 µm	20 µm Cu	< 5.0 mm	< 5.0 mm	< -5.0%	> 0.50%
SuperPower 2	100 µm	only Ag	5.9 mm	12.5 mm	-0.85%	0.40%
Theva	90 µm	10 µm Cu	< 5.0 mm	7.7 mm	< -0.9%	0.59%

- **Main difference in the reversible bending behaviour observed**
- **Choice of RE important !**

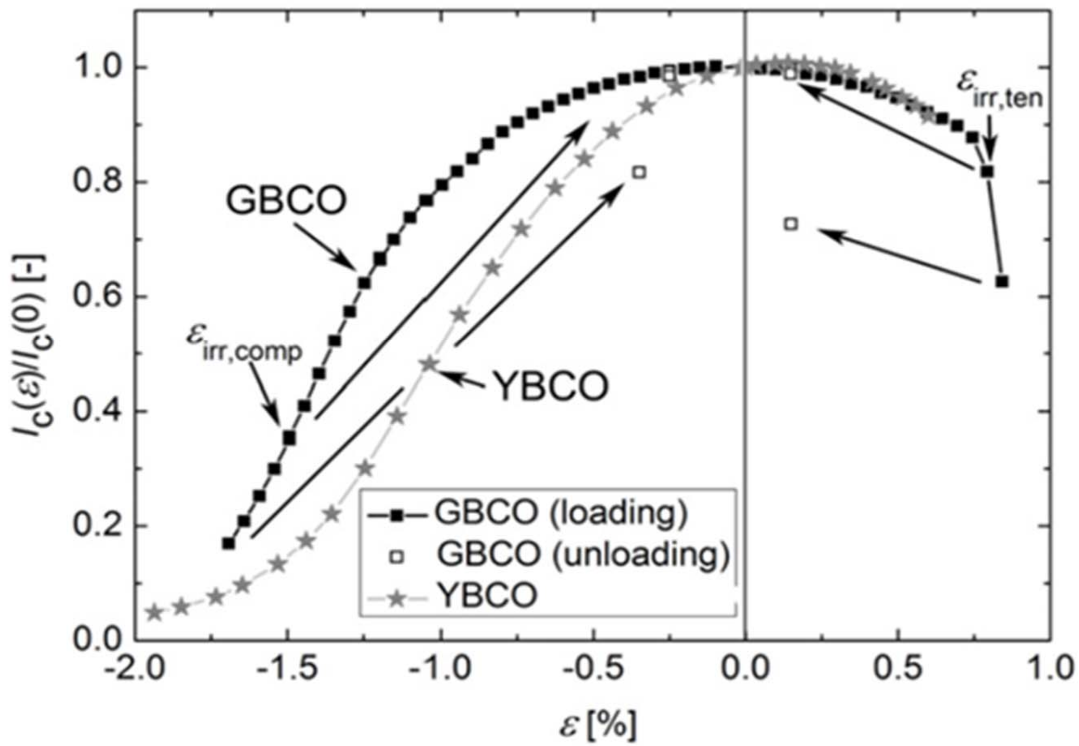
2LPo2D-09 [35] **ASC-2016 Denver**
Simon Otten, Anna Kario, Andrea Kling, Wilfried Goldacker

Bending results for different coated conductors





Supercond. Sci. Technol. **24** (2011) 042001



Danko van der Laan et al. Advanced Conductor Technol. Boulder

Tape	Substrate thickness	Stabilizer	$R_{min,comp}$	$R_{min,tens}$	ε_{min}	ε_{max}
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SuperPower 1	50 µm	20 µm Cu	< 5.0 mm	< 5.0 mm	< -5.0%	> 0.50%
SuperPower 2	100 µm	only Ag	5.9 mm	12.5 mm	-0.85%	0.40%
Theva	90 µm	10 µm Cu	< 5.0 mm	7.7 mm	< -0.9%	0.59%

- **Main difference in the reversible bending behaviour observed**
- **Choice of RE important !**

2LPo2D-09 [35] **ASC-2016 Denver**
Simon Otten, Anna Kario, Andrea Kling, Wilfried Goldacker

Bending results for 2 Roebel cables (SP, Bruker CC)

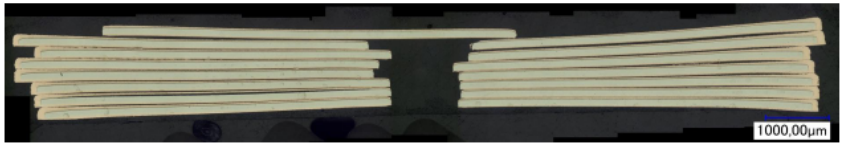
S.Otten et al. ASC-2016 Denver 2LPo2D-09, (acc. for publ. SUST)

KIT Karlsruhe Institute of Technology

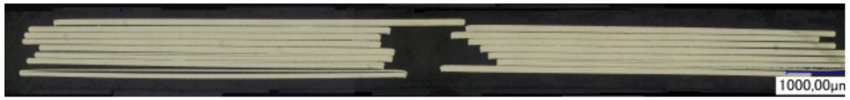
Samples

- 12 mm wide tapes from SuperPower and Bruker
- 15 strands (5.5 mm wide)
- 226 mm transposition length

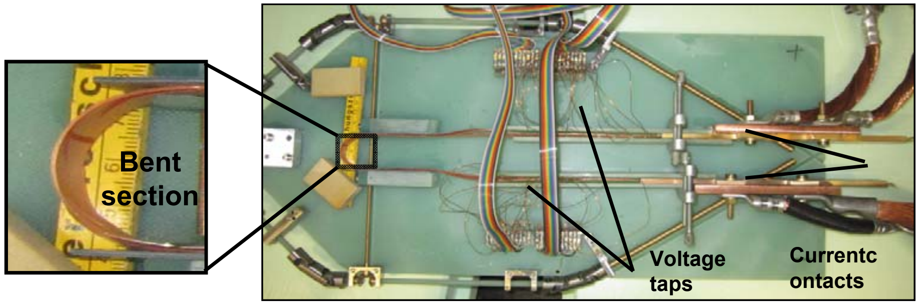
Cross-section of the cable with Bruker material (100 µm substrate)



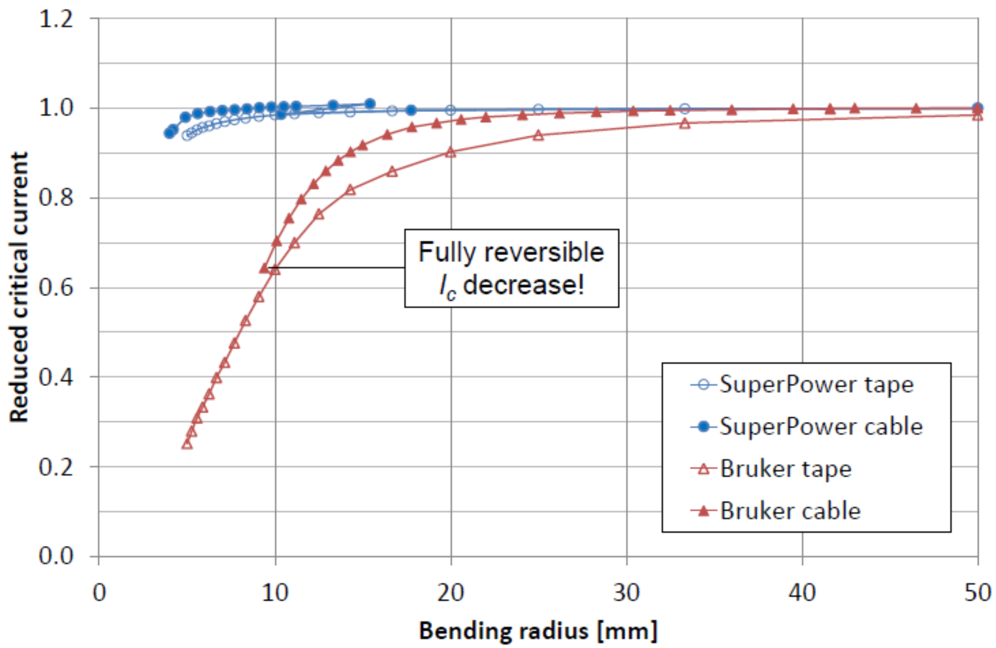
Cross-section of the cable with SuperPower material (50 µm substrate)



Roebel cable top view



Results



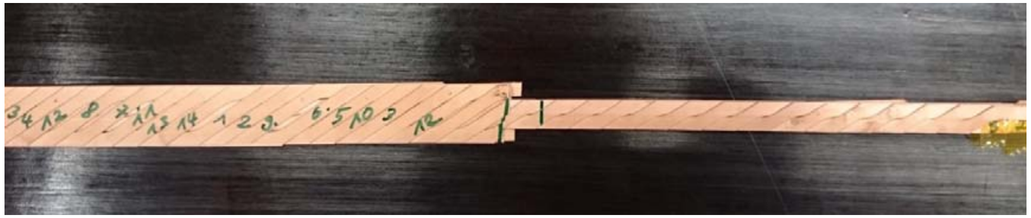
- **substrate thickness is important !**
- **Cables behave very similar as the single tapes**
- **No irreversible strains observed for smallest bending radius**
- **In cable some strand coupling is observed**
- **Systematic strand coupling still open issue !**

The DOCO-RACC-Cable, an approach for full-size magnets

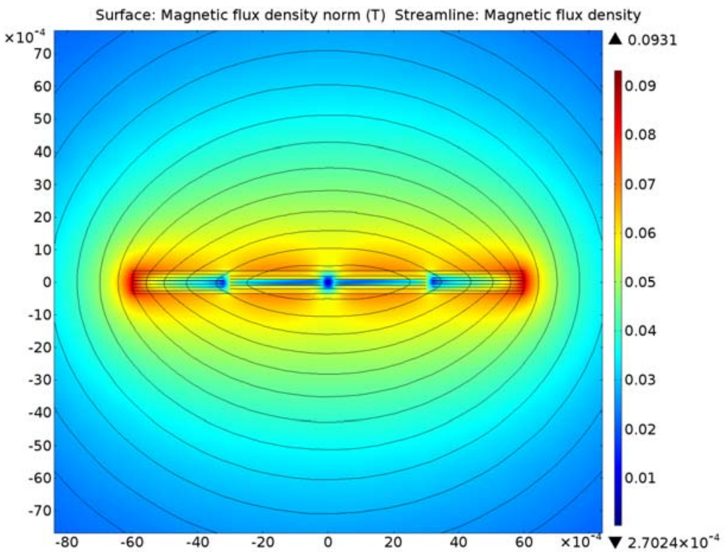
W.Goldacker et al. ASC 2016 4SPOr2A-05

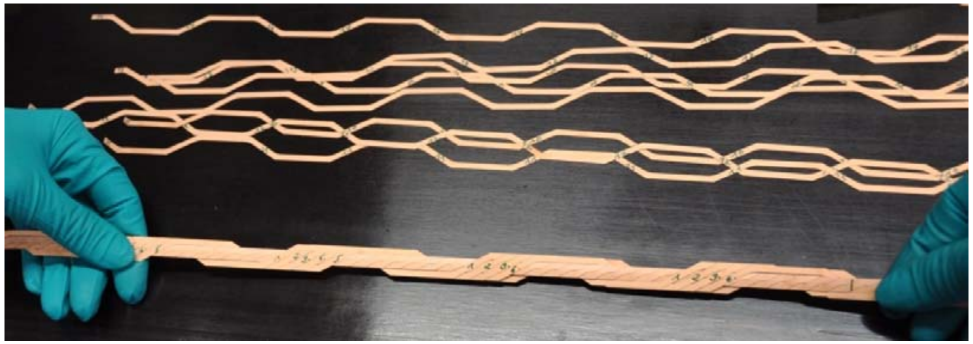
Karlsruhe Institute of Technology

The next Roebel – HTS for large devices !



- **Concept for 24 mm width**
- **CC not available now**
- **Subsize shown: 12 mm width**





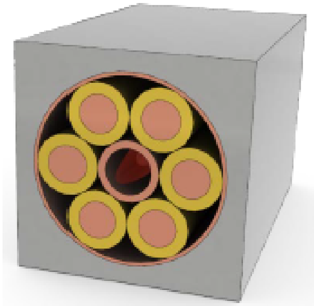
I_c = 1.3 kA / 77 K s.f. demonstrated successfully on 12 mm subsize width

CORC ® cable in conduit CERN – Univ. Twente

Strands from Advanced Superconductor Technologies

6.3 X-around-1 - CORC CICC variants

UNIVERSITY OF TWENTE.



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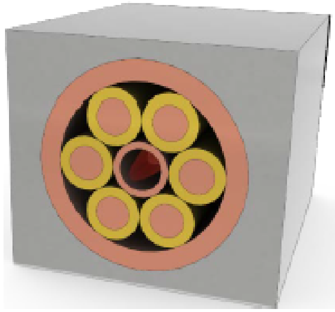
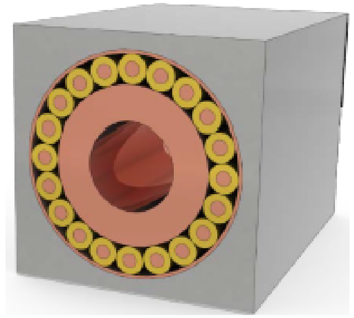
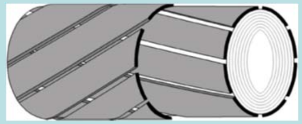
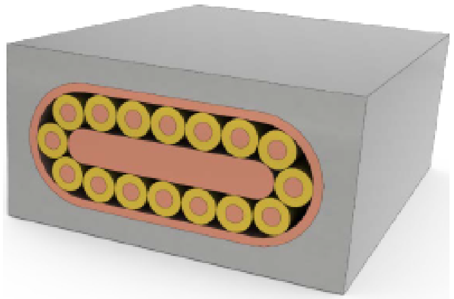


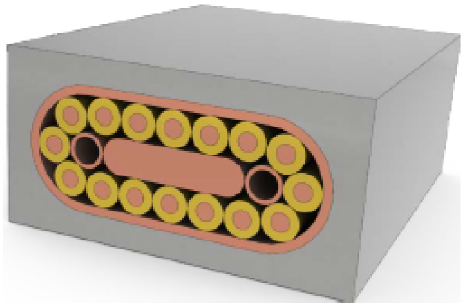




REBCO layer in strand (inside) under heavy compression

Flexible design, can add Cu for quench protection, vary cooling channels etc
Shown are 40 to 50 kA @ 4.2K/10T variants with 220 – 460 – 510 mm^2 Cu





- **Version A demonstrated**
- **Bending properties = open question**

Flexible design, or take thinner 4 mm strands and go rectangular or add dedicated cooling tubes with strands impregnated
Shown are 40 and 60 kA @ 4.2K/10T variants with 300 and 280 mm^2 Cu

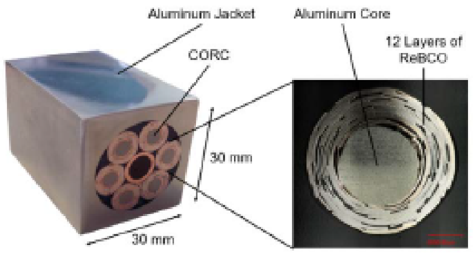
Herman tenKate
CCA-2016 Aspen USA

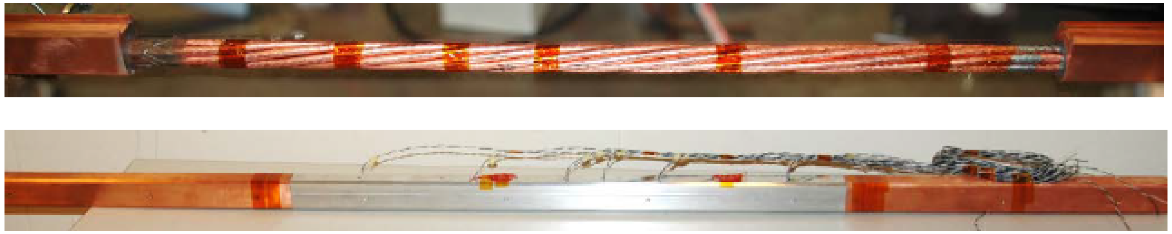
CORC® CICC First Test Results

UNIVERSITY OF TWENTE. Karlsruhe Institute of Technology

6.5 1st CICC - with Al-alloy conduit (1.7m)

2nd step, 1st CICC, Al-alloy conduit, test at CERN in FRESCA 9 T facility at 4 and 77K





CCIC with twisted 6-a-1 cable and 450 mm joint, bare and with jacket

- 6-around-1 CORC-CICC designed & assembled at CERN, tested first at FRESCA cable test facility at 4 K, and at SM18 test facility at 77 K.
- 6 CORC® cables of 7.5 mm diameter
- 38 tapes per CORC® cable (commercial order at ACT in 2014)
- Rated 47 kA at 4.2K/10T and 13 kA at 77K/self-field.
- ReBCO cable is 1.6 m long with a main section in Al5083 of 800 mm. Cable twist pitch is 400 mm.
- OFHC copper joint terminals are 450 mm long, same outer size as the conductor.
- Design resistances by simulation: 2.0 nΩ at 4.2 K and 6.5 nΩ at 77 K

Herman tenKate CCA-2016 Aspen USA

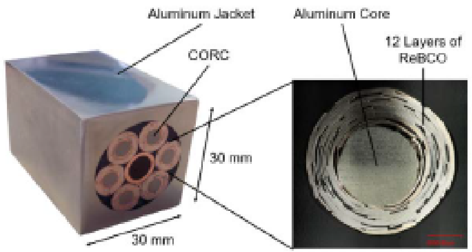
CORC® CICC First Test Results

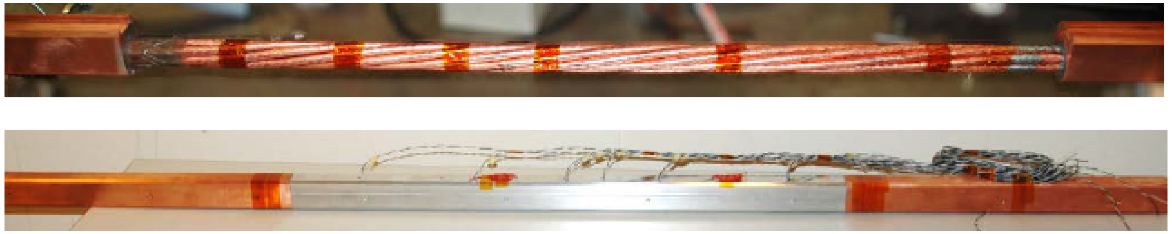
6.5 1st CICC - with Al-alloy conduit (1.7m)

UNIVERSITY OF TWENTE.

KIT Karlsruhe Institute of Technology

2nd step, 1st CICC, Al-alloy conduit, test at CERN in FRESCA 9 T facility at 4 and 77K





CCIC with twisted 6-a-1 cable and 450 mm joint, bare and with jacket

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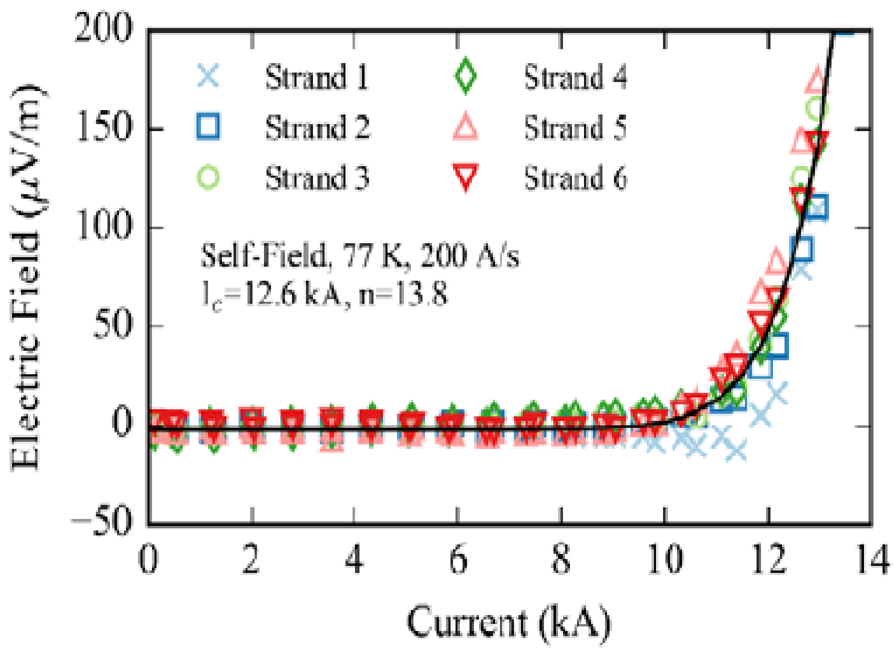

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Herman tenKate CCA-2016 Aspen USA

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation PL-4 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

ENEA/TRATOS HTS cable

TRATOS CAVI

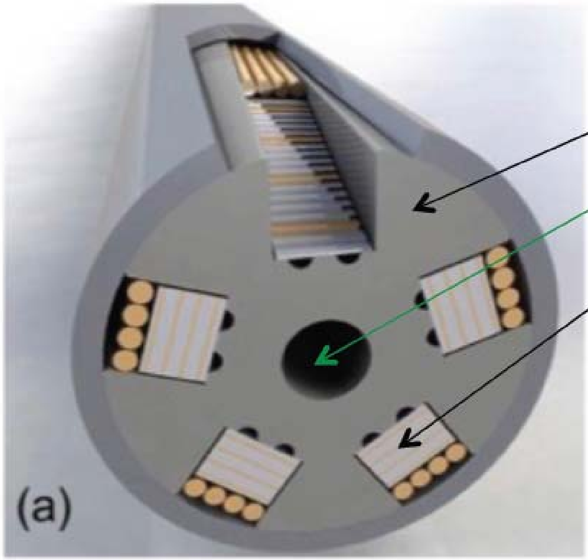
ENEA — AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

KIT Karlsruhe Institute of Technology

A) HTS for in-field applications

Al.-slotted Core HTS CICC

Fundamental design driver: ***industrial process feasibility***

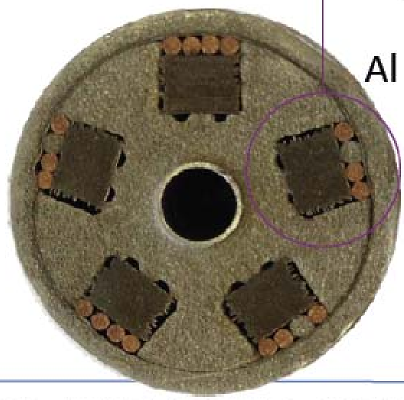


- Aluminum core, Φ = 19 mm
- Core central channel for coolant
- Duct 4.3 x 4.3 mm for tape stack with grooves for coolant
- 5 stacks of 2G-tapes

Target (@ 4.2K-12T) $I_c \approx$ 20 kA

$J_e \approx$ 70 A/mm^2

SC/non SC = 1.5 ‰



20 Tapes (150 μm thickness)

Tot Stab. = 206.49 mm^2 **57.4%**

Al = 47.4% Cu_{rods} = 4.4% Cu_{tapes} = 5.6%

Void = 38.9 mm^2 **10.8%**

SS tot = 40.0 mm^2 **11.1%**

Jacket = 74.6 mm^2 **20.7%**

ASC16 – Luigi Muzzi – Denver, Colorado - 8 September 2016

Fusion Unit EUROfusion

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation PL-4 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

ENEA/TRATOS HTS cable

TRATOS CAVI

ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

KIT Karlsruhe Institute of Technology

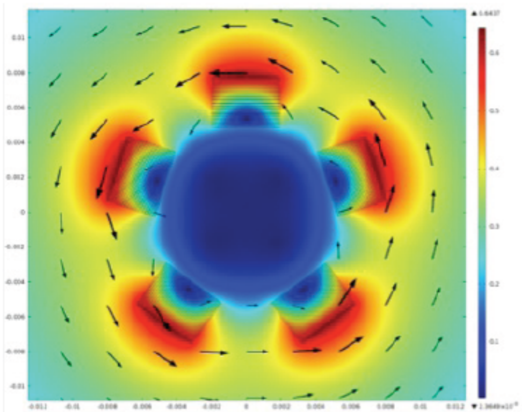
What has been done so far? **Al.-slotted Core HTS CICC**

KIT Karlsruhe Institute of Technology

Electrical tests at FBI Facility (@ LN2, LHe)

@ 12T, 4.2K	Measured
$I_{c,\ 1\ stack}$ - SUNAM	≈ 1952 A

- *Good performance wrt tape*
- *Good prediction capabilities*



Model prediction for fully equipped (5 stacks) cable (@ 12T, 4.2K):

$I_{c,cable}$ ≈ 10 kA (with the tapes here)

> 20 kA (can be achieved)

ASC16 – Luigi Muzzi – Denver, Colorado - 8 September 2016

Fusion Unit EUROfusion

ENEA/TRATOS HTS cable

TRATOS CAVI

ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

KIT Karlsruhe Institute of Technology

What has been done so far?

Al.-slotted Core HTS CICC

KIT Karlsruhe Institute of Technology

Electrical tests at FBI Facility (@ LN2, LHe)

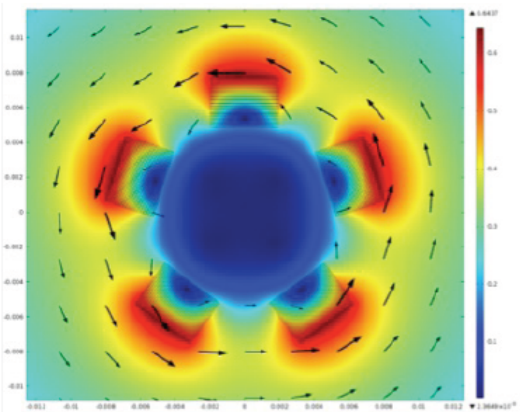
@ 12T, 4.2K	Measured
$I_{c,\ 1\ stack}$ - SUNAM	≈ 1952 A

Bending performance

Bending experiments on short samples:

Current degradations for R < 900 mm radius

Different single tapes from stacks measured



$I_{c,cable}$ ≈ 10 kA (with the tapes here)

> 20 kA (can be achieved)

ASC16 – Luigi Muzzi – Denver, Colorado - 8 September 2016

Fusion Unit EUROfusion

Bending of strands with stacked CC

Karlsruhe Institute of Technology

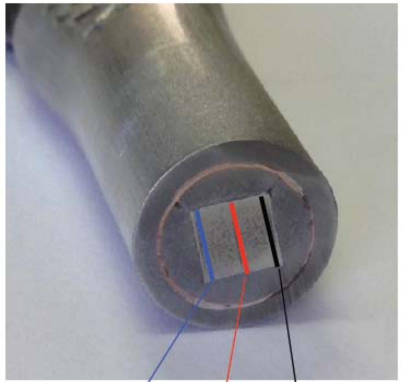
ENEA HTS MAST

TRATOS CAVI

ENEA — AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

Bending trials to diameter = 350 mm

$I_c/I_{c0} \approx 0.69$



CC tapes in dummy stack

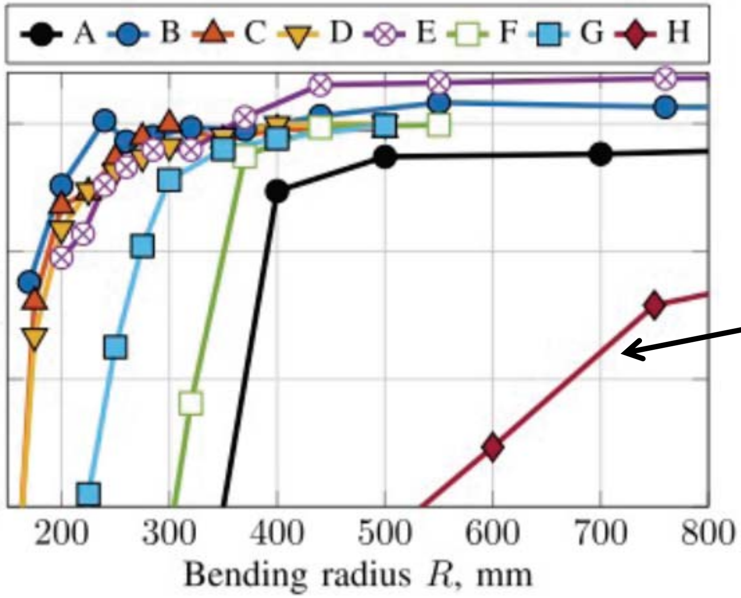
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 2, MARCH 2016 4201207

Design Optimization of Round Strands Made by Twisted Stacks of HTS Tapes

Nikolay Bykovsky, Davide Uglietti, Rainer Wesche, and Pierluigi Bruzzone

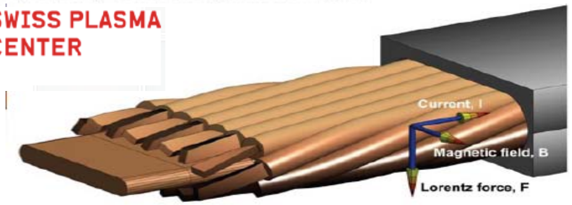
Abbreviation	A	B	C	D	E	F	G
Tape's manufacturer	SuperPower						SuperOx
Cross section							
Tape's width w, mm	4	4	4	4	3	4	4
Diameter D, mm	6.2	6.2	7	7	6	8	6.2
Number of tapes n	15	15	15	15	26	32	15
Twist-pitch h, mm	300	300	300	300	240	340	300
Profile annealing	No	Yes	Yes	Yes	Yes	Yes	Yes
j_e[a], A/mm^2	94	94	74	74	131	121	90
Copper area, mm^2	25 (81 %)	25 (81 %)	33 (85 %)	33 (85 %)	22 (79 %)	39 (78 %)	25 (81 %)
R_e[b], mm	420	180	190	190	205	360	275

[a] Engineering current density at (12 T, 4.2 K); [b] Critical bending radius @ 5 % I_c loss



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

SWISS PLASMA CENTER



ASC16 – Luigi Muzzi – Denver, Colorado - 8 September 2016

Fusion Unit EUROfusion

KIT Karlsruhe Institute of Technology

Summarized demands from applications for HTS properties in tapes and cables

- Optimized pinning for application temperature and field
- Homogeneity of material (no defects)
- Striations for low AC losses (option when necessary)
- Small bending radius (depends on device)
- Ballance of transverse stresses from Lorentz Forces
- Mechanical stability for cabling, shaping (Roebel, stacks etc.)
- Thermal stability for Quench events

KIT Karlsruhe Institute of Technology

Selected important applications and projects

EuCARD²

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

CAPACITIES

The activity towards the possible Future Circular Collider (FCC) at CERN

LHC upgrade in field and magnets or new Accelerator ring 80 km

WP 10 : Future Magnets: dipoles with 20 T (HTS inserts !)

Actually a pulling activity for HTS applications !

EU-project EUCARD2 WP10 (Future Magnets)
with KIT 10-kA Class HTS Roebel cable

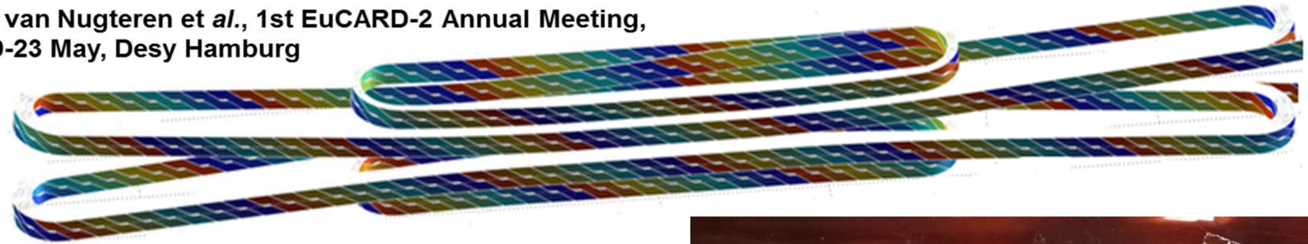
Karlsruhe Institute of Technology

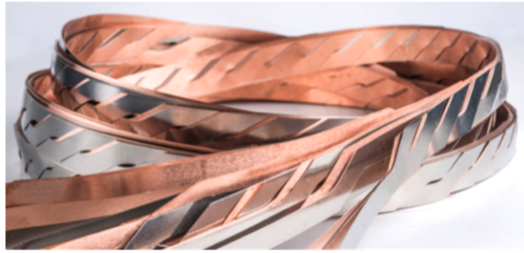
The dipole insert magnet design of CERN „Aligned block design“

CERN

The goal: 5 T dipole magnet for 4.2 K, 40 mm aperture
10 kA operation current at B = 20 T, length 0.5m
Cable length > 30 m

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





The Roebel cable provides excellent bending out-of-plane and for torsion !

cea

„CEA – cosϑ – design“
C. Lorint, M.Durante et.al.

Parameter	units	target	minimum
J_E (20 T, 4.2 K)	(A/mm^2)	≥ 600	≥ 400
s(I_c)	(%)	≤ 10	
m_0DM (1 T, 4.2 K)	(mT)	≤ 300	
Allowable $s_{transverse}$	(MPa)		≥ 150
Allowable $e_{longitudinal}$	(%)		≥ ±0.3
Unit Length	(km)	≥ 100	≥ 30

The engineering current density in HTS Roebel is > 90% of theory

The cable qualified for the dipole coil specified current density

The Roebel cable works for both concepts (tested with current)

Eucard2 HTS dipole: Feather M-0 prototype coils

- Several Feather 0 prototype coils manufactured (dummy and real Roebel cables from KIT up to 20 m)
- Development of winding and impregnation, Tooling
- High quench energy, low propagation speed
- New quench detection system with pickup-coils
- Test was performed, > 30 quenches applied
- I_c > 13 kA at 30 T s. f. achieved (Oct. 2016)

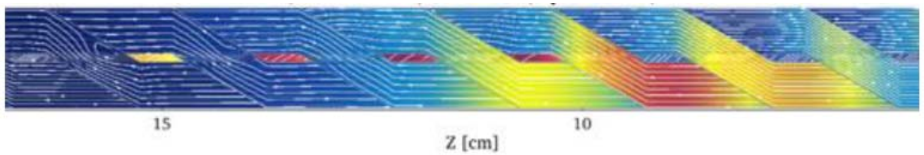
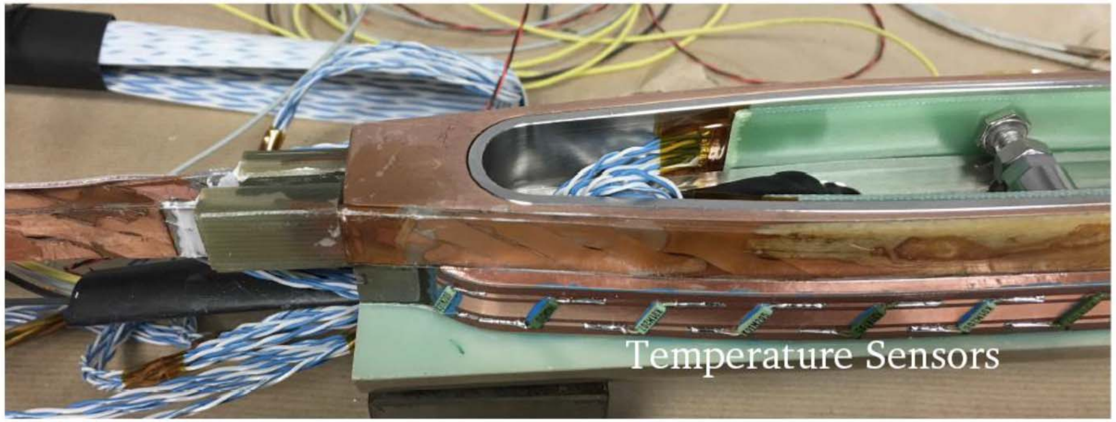
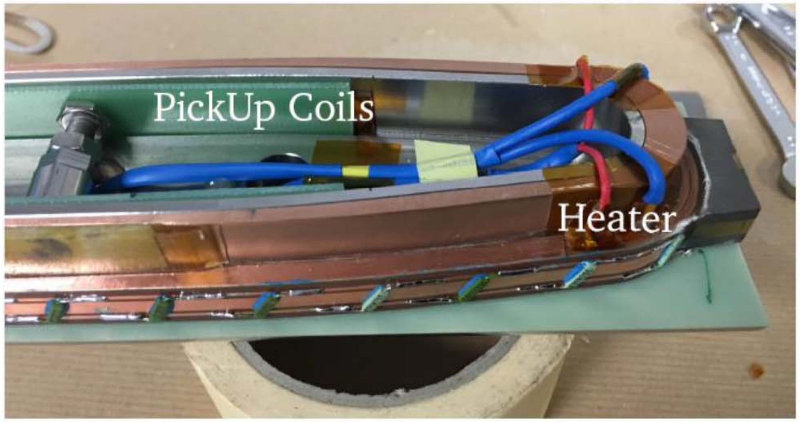


Fig. 2, Simulation showing thermal map of quenching Roebel cable, Blue 20K, Green 50 K, Yellow 65 K, Red 100K at 0.43 sec. in fig 5.

Lead End



Turn End

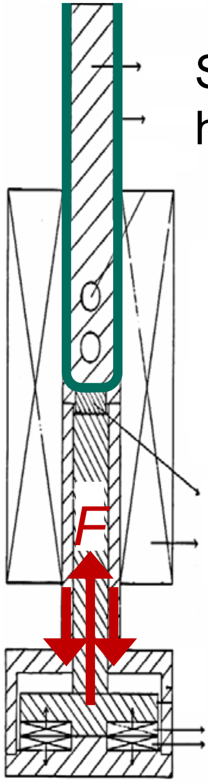


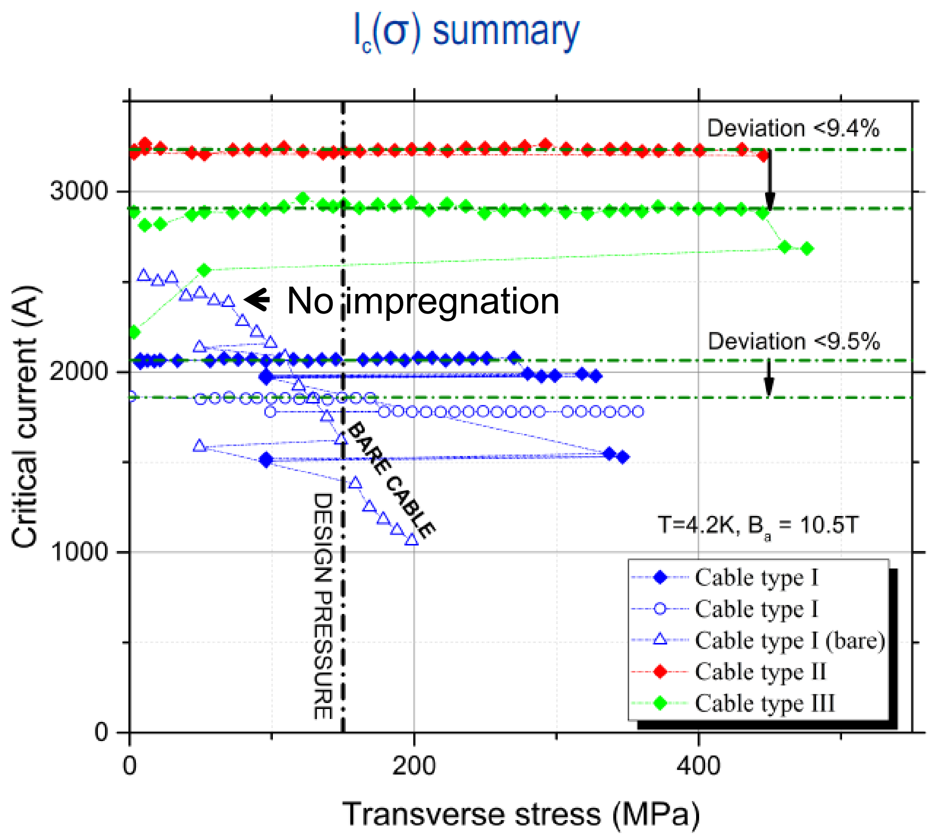
From Lucio Rossi@ EuCARD² 3rd annual meeting - 27/04/2016

G.A.Kirby et al. ASC 2016 (1LOr1B-01, paper submitted to IEEE

Transverse stress of impregnated Roebel cables

Peng Gao et al. Twente Univ. ASC-2016 Denver 2LPo2D-06





2 impregnations successful

KIT: Araldite CY5538 + Araldur HY 5571 + Silica Filler

CERN: CTD-101K ABC glass fibre rope glass sleeve

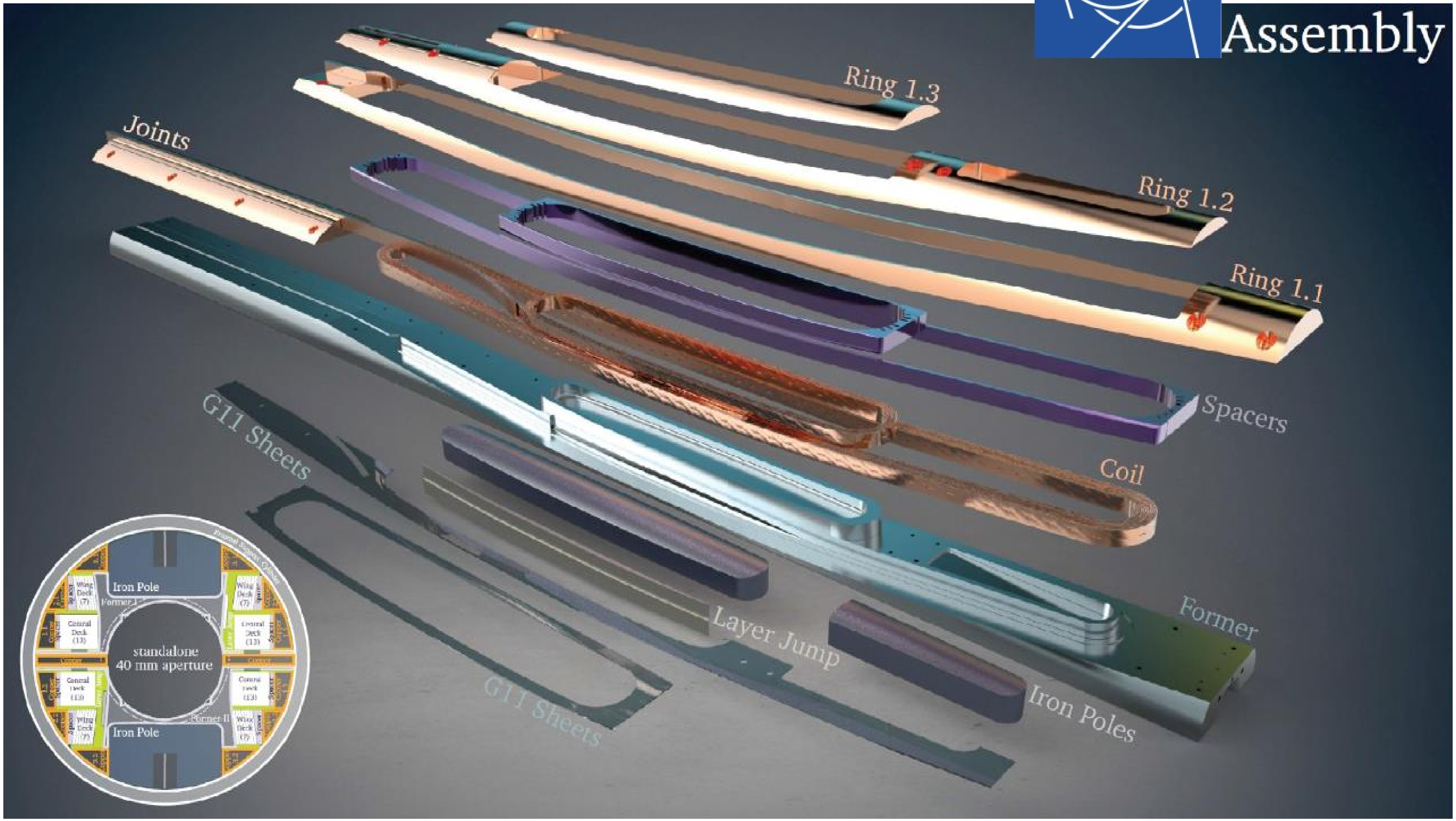
- T = 4.2 K
- I_{max} = 50 kA
- B_{max} = 11 T (perpendicular)
- F_{max} = 250 kN
- U-shaped samples

- **Shown: transverse stresses up to 450 MPa tolerable**
- **Local 500 MPa stress peaks expected (modeling)**
- **Impregnation of cable mandatory !**

Feather 2 (Full magnet) parts are ready

Cable comes begin 2017, Full magnet test in spring 2017

G. Kirby Appl.Superc. Conf. - 2016-USA

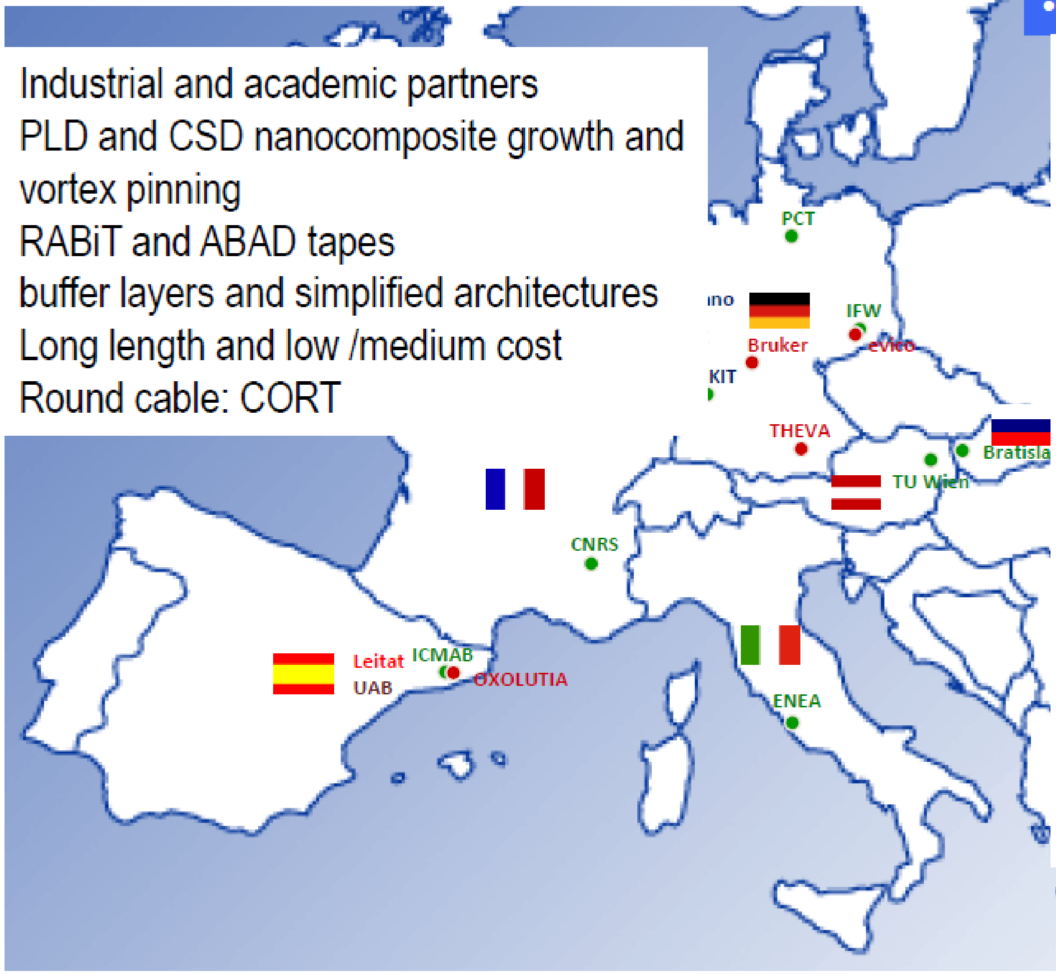


EU-project EURO-Tapes (ending 2017)

KIT Karlsruhe Institute of Technology

Consortium on CC Materials development

Industrial and academic partners
PLD and CSD nanocomposite growth and vortex pinning
RABiT and ABAD tapes
buffer layers and simplified architectures
Long length and low /medium cost
Round cable: CORT



EUROTAPES
http://www.eurotapes.eu/
- 21 EU partners (9 countries)
- ~20 M€ (13.5 M€ - EU)
- **09/2012-02/2017**

	Participant	Country
1 (Coord)	ICMAB- CSIC: COORDINATOR	ES
2	Bruker HTS GmbH	DE
3	Italian National agency ENEA	IT
4	Institute of Electrical Eng. Slovak	SK
5	La Farga la Cambra	ES
6	IFW Dresden	DE
7	Nexans SA	FR
8	Oxolutia, SL	ES
9	PerCoTech AG	DE
10	Technical University of Cluj-Napoca	RO
11	Vienna University of Technology	AT
12	Institute Neel	FR
13	University of Antwerp	BE
14	University of Cambridge	UK
15	University Autonoma de Barcelona	ES
16	University of Ghent	BE
17	Evico	DE
18	Nexans GmbH	DE
19	Leitat Technological Center	ES
20	Theva	DE
21	Deutsche-Nanoschicht	DE

T.Puig-CCA2016

9 companies

12 Research organisations or Universities

T. Puig
CCA-2016
Aspen USA

EU-Project EUROTAPES (ending 2017)

Karlsruhe Institute of Technology

Nanostructured Coated Conductors

Growth and performance

CSIC

ICMAB

EUROTAPES TARGETS:

- **Length** :+500 m ✓
- **Performance:**
- For low fields (B< 1 T):
  I_c (77K, sf) > 400 A/cm-w ✓
- For high fields (B ~3-5 T):
  F_p(60 K) > 100 GN/m^3 ✓
- For ultrahigh fields (B > 15 T):
  I_c(5K, 15 T) > 1000 A/cm-w
- **Pre-comercial cost**: ✓
  ~100 €/kAm (77 K)

High Energy Physics, Fusion, Ultrahigh Field NMR, ...

Ultra-High field, 4.2K
Design stage, some prototypes

Large Electrical Motors and Generators: Wind Mills, Airplanes, Ships,..

High field, 40-60K
Much activity with prototypes

Energy Future paradigm : cables, FCL, transformers, ...

Low and medium field, 77K
Devices already in grid

Major concerns: MARKETABILITY

-High I_c and J_e
(↑pinning,↑thickness,↓substrate thickness, simplified architectures)

-Low cost
(↑production rates, ↑yield, ↑growth rates, wide tapes, chemical methods)

Project goals

Bring advanced nano-structured APC to industrial CC routes:

- **Taylored CC properties**
- **Optimized CC for 3 application regimes**
- **Low cost CC**
- **Impact on all applications**

T. Puig
CCA-2016
Aspen USA

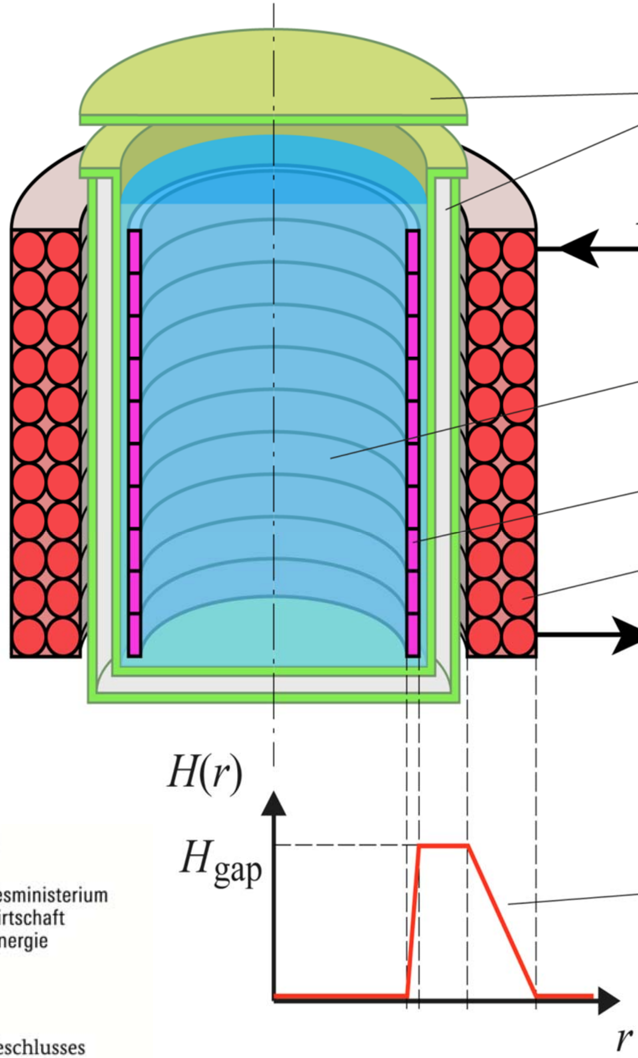
SmartCoil – inductive current limiter

SIEMENS
ILK Dresden
KIT - ITEP

KIT Karlsruhe Institute of Technology

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Closed loops of CC customized by Cu-layer thickness
As stacked modules, module function is verified



Cryostat with vacuum-isolation

Current in the reactance coil

Cooling medium LN_2 - 77K normal pressure

shortcut coil

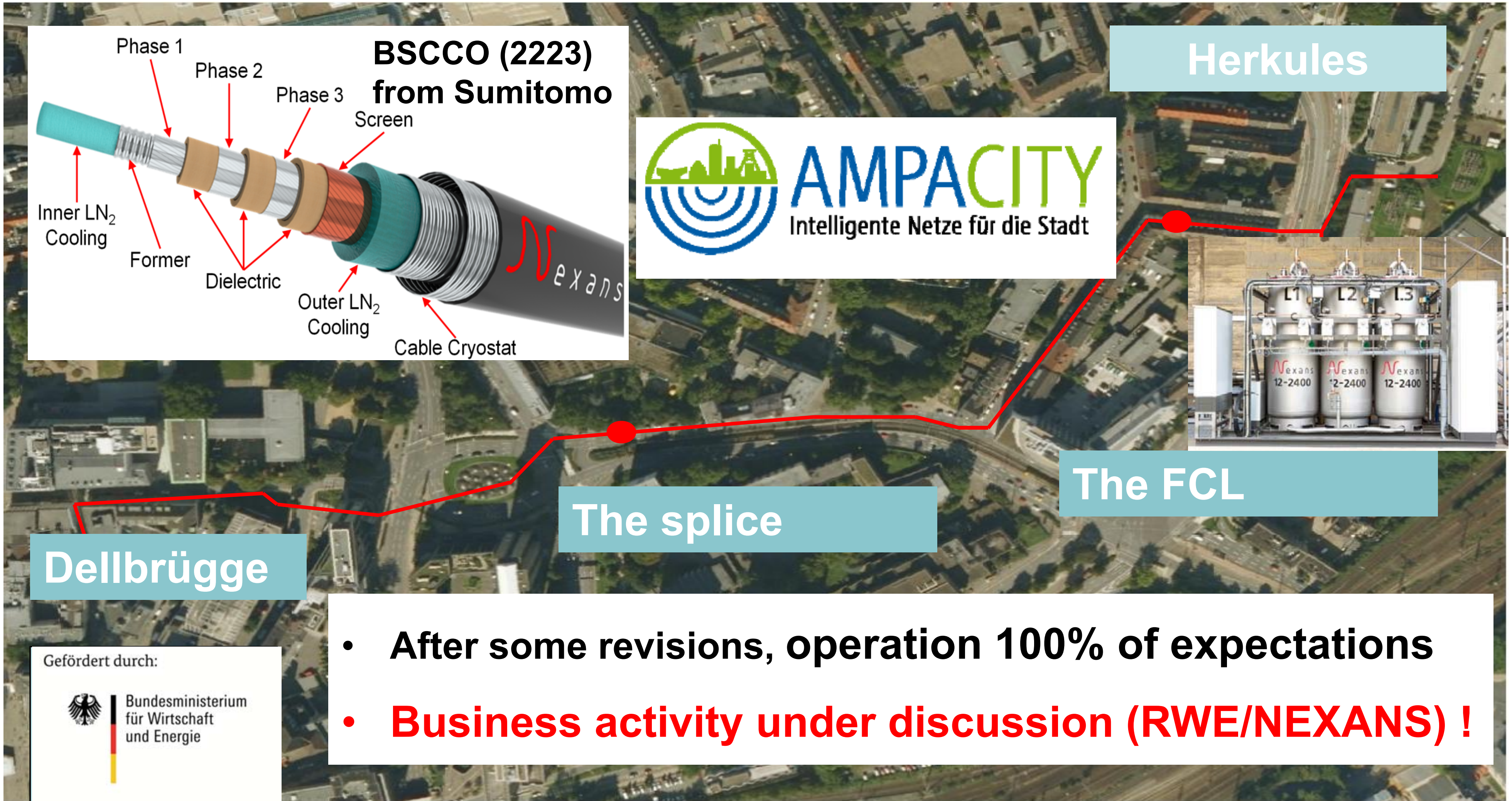
reactance coil

- Nominal voltage U_{nom} 5.77 kV_{RMS}
- Current limiting time 100 msec
- 80 short-cut 2G HTS-rings (D=1.2 m)
- Soldered low resistance contacts

600 A , 10 kV „air-coil“ sc - FCL

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

AMPACITY HTS power transmission cable ESSEN
1km, 2.3kA, 10kV, 3-ph. project finished, field test going on



- **After some revisions, operation 100% of expectations**
- **Business activity under discussion (RWE/NEXANS) !**

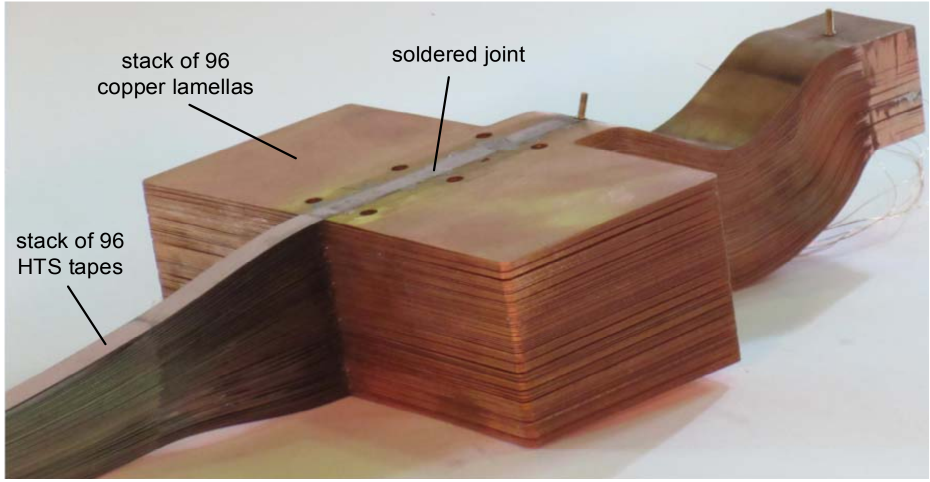
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Industrial power bar for high DC currents I (operation) > 10 kA

VISION ELECTRIC Super Conductors + KIT Karlsruhe Institute of Technology

Goal: Modular cable system (CC stacks) ready to use

Compact current lead



Flexible Copper to HTS contact with low resistance and high number of stacks.

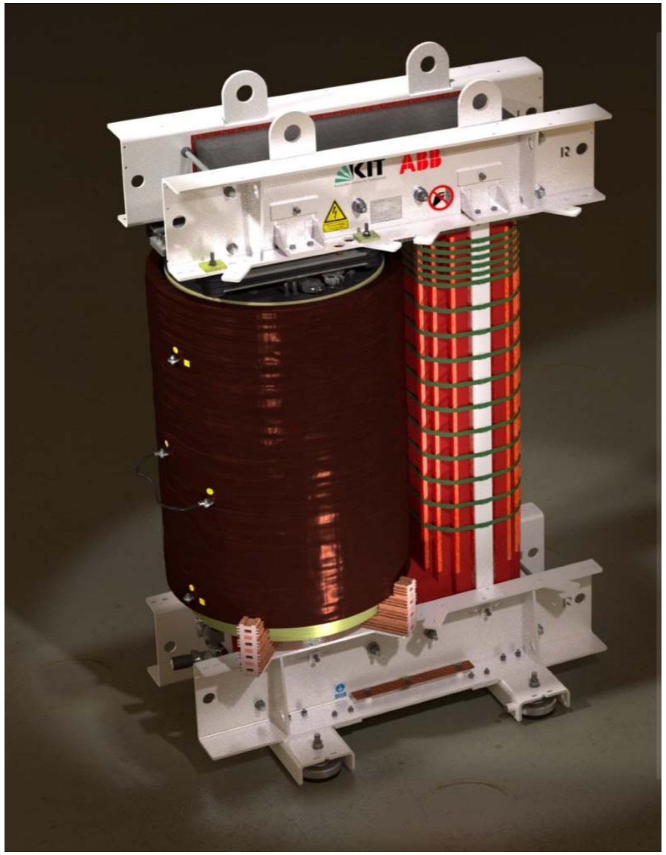
Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

Pilot demonstrator at BASF 2017 f Chlorine electrolysis plant
Under discussion: Aluminum Company

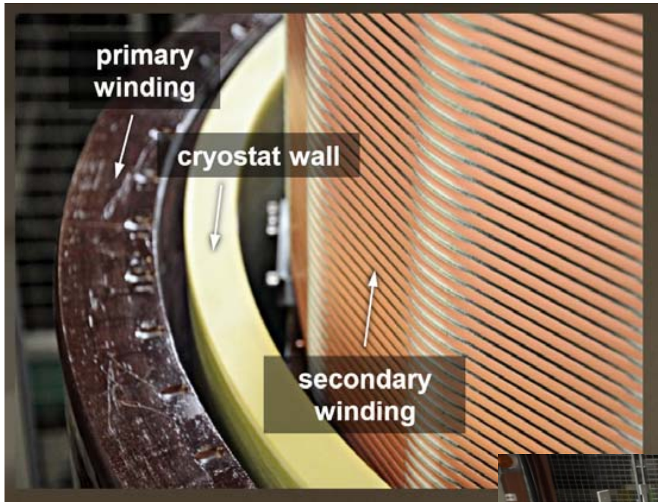
http://www.vesc-superbar.de/

1MVA - FCL - Transformer Project KIT- ABB

with recovery under load



- Primary winding: 20 kV_{RMS} / 28.87 A_{RMS} (warm, copper)
- **Secondary** winding: 1 kV_{RMS} / 577.35 A_{RMS} (2G HTS)



S. Hellmann et al.
ASC-2016 Denver
4LOr2A-02

IN2 only for HTS secondary coil

Patent applied for stress managing winding technology

- B_{max} in iron-core = 1.5 T, 77 K, LN_2 (normal pressure)
- **Solenoid, one layer winding (twins back-to-back), 4 mm, SuNAM and SuperPower SCS4050, Cu-plated**

EcoSwing Project

ecoswing

KIT Karlsruhe Institute of Technology

Full-size HTS-Wind generator

M. Bauer THEVA, ASC-Denver 2016

EcoSwing Ambition

- Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator
- **Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark**
- **(3.6 MW, 14 rpm, 128 m rotor)**

9 Partners from 5 countries working for a common goal:

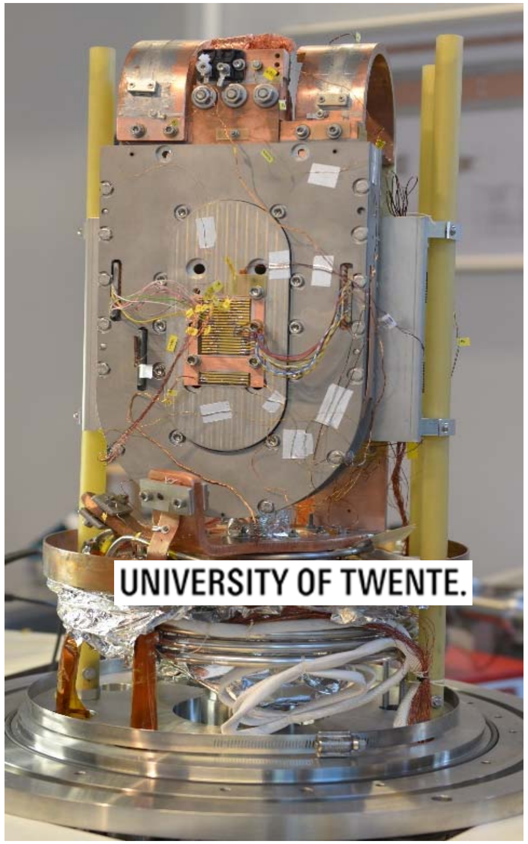
- **To prove that a superconducting drive train is cost-competitive.!**
- www.ecoswing.eu

World-wide first full scale HTS-CC wind energy device for field test in the grid

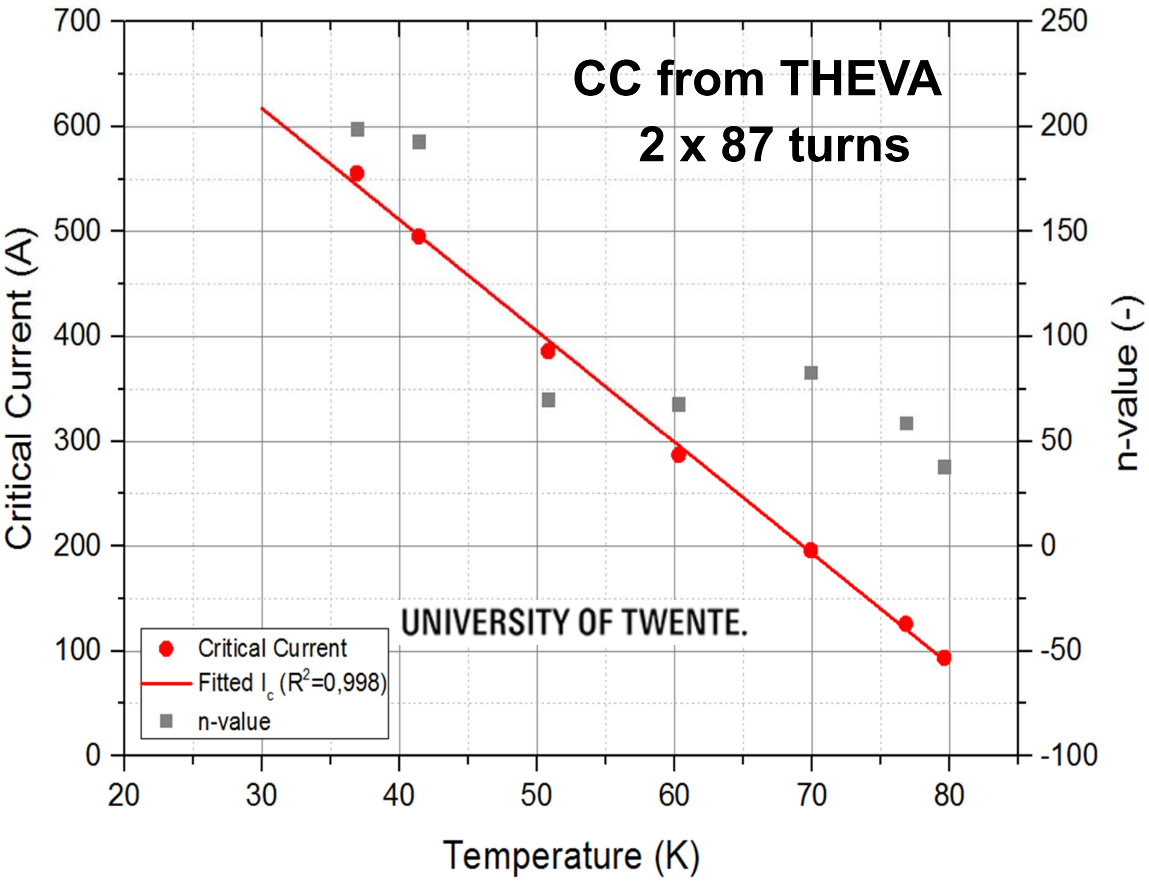
EcoSwing recent results

- Double Layer Subscale Test Coil
- test of full pole assembly
- CC material is fabricated

M. Bauer THEVA ASC-Denver 2016



coil mounted in the test rig



Critical current (red dots) as a function of the temperature (D2) and the corresponding n-values (grey). A linear relationship seems to hold (red line).

Design validation: Ic , joint & interconnect resistance, inductance, temperature distribution, quench behaviour, ...

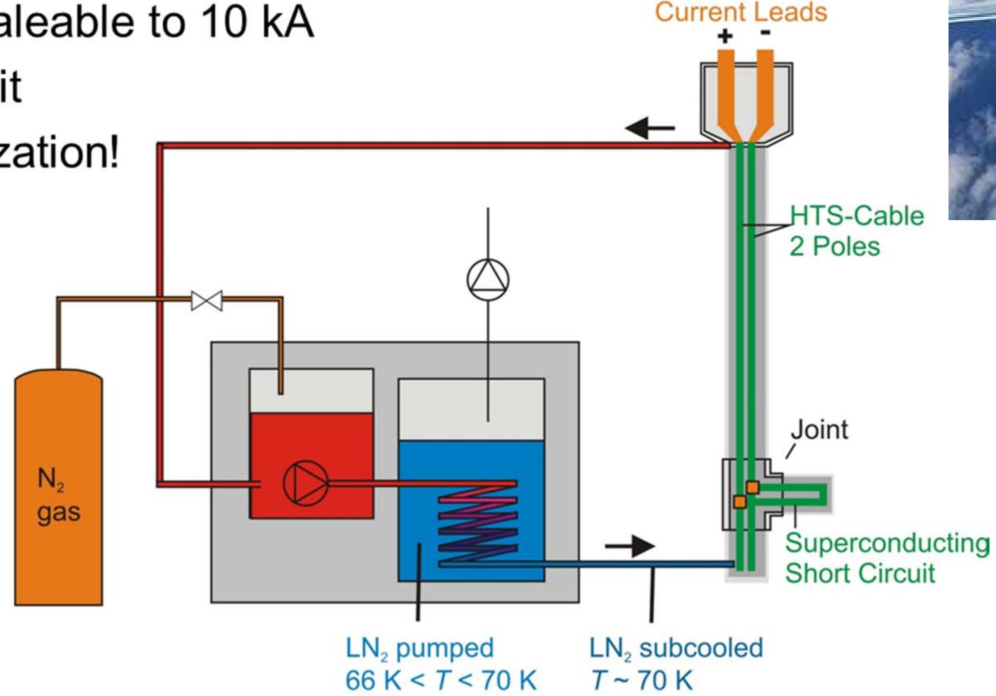
TELOS: Towards the all – electric airplane with HTS
Lightweight demo-cable with cryogenic system

Karlsruhe Institute of Technology

DC HTS-Cable:

- Number of poles: 2
- Rated voltage: 1 kV ≤ U ≤ 10 kV
- Rated current: 3 kA, scaleable to 10 kA
- Joint with sc short circuit
- Weight and loss optimization!

- **CC cable the most probable solution**
- **CL and payload biggest challenge**



Cryogenic system:

- Subcooled LN_2 (LH_2)

System:
+ HTS Generator
+ HTS thrust
+ HTS cable
+ energy storage !

AIRBUS
Defense & Space Operations Germany
SIEMENS
TECHNISCHE UNIVERSITÄT MÜNCHEN
Univ. Bayreuth

Sept. 12, 2016 Sonja Schlachter – "DC-HTS Cables for Power Distribution in Hybrid-Electric Aircraft"
Coated Conductors for Applications 2016, September 11-14, 2016, Aspen, Colorado, USA

Supported by: Karlsruhe Institute of Technology
Federal Ministry for Economic Affairs and Energy
Funded by on the basis of a decision by the German Bundestag

New EU-project on HTS airplane drive under final decision !!!

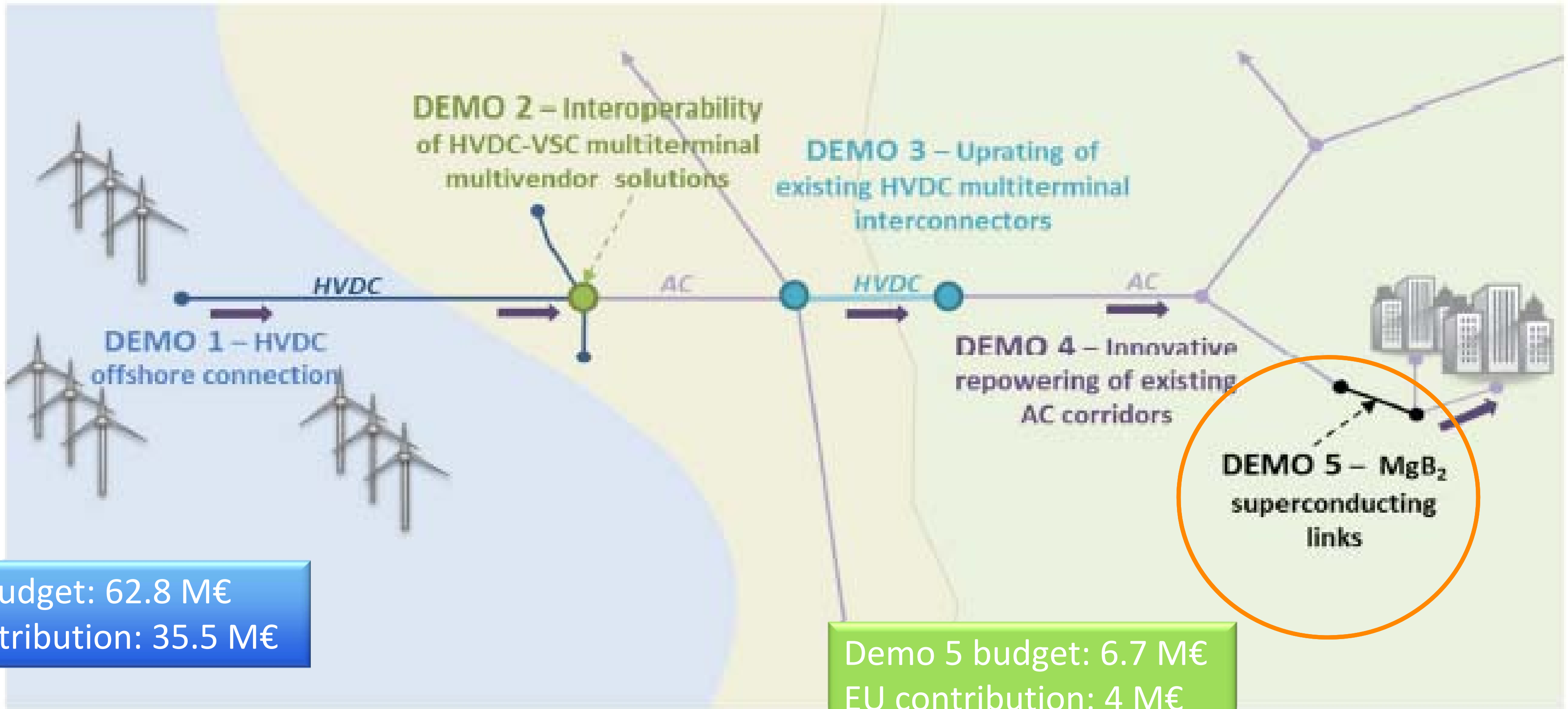
BestPaths EU-project: Demo 5: Supercond. MgB_2 HVDC link

KIT Karlsruhe Institute of Technology

EU FP7 Best paths project: http://www.bestpaths-project.eu/

BEST PATHS aims to develop and test high-capacity transmission technologies needed to meet Europe's long-term energy goals and the incorporation of renewable energy sources.

With 5 demonstration programs carry out by 39 partners



Total budget: 62.8 M€
EU contribution: 35.5 M€

Demo 5 budget: 6.7 M€
EU contribution: 4 M€

BestPaths DEMO 5, the partners

MgB_2 wires are the conductors of choice:

- Cheap wire technology
- Suitable for low field application at 25 K
- Industrial manufacturor
- Originally lH_2 cooling was planned but skipped from budget reasons

Information on Best paths project : http://www.bestpaths-project.eu

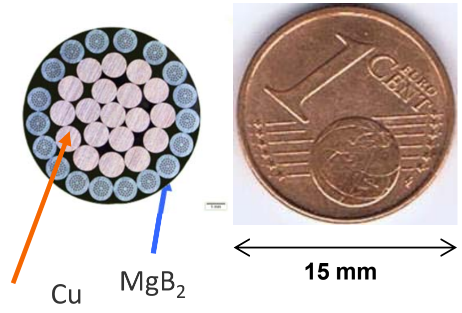
BestPaths: Experimental details

1. Objectives

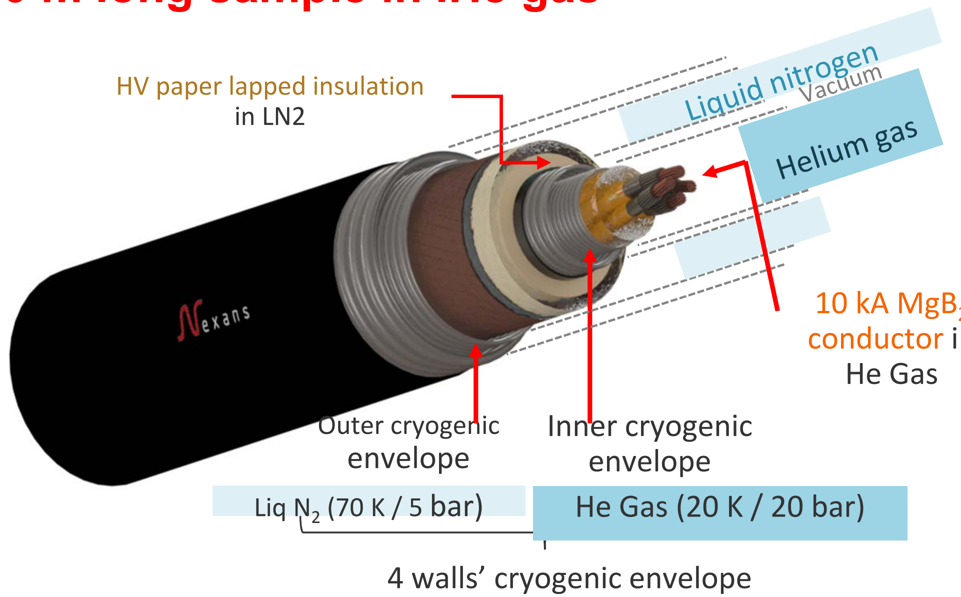
- **Demonstrate full-scale 3 GW class HVDC superconducting cable system operating at 320 kV and 10 kA**
- **Validate the novel MgB_2 superconductor for high-power electricity transfer**
- **Provide guidance on technical aspects, economic viability, and environmental impact of this innovative technology**
- **Test a 20 m long sample in lHe gas**

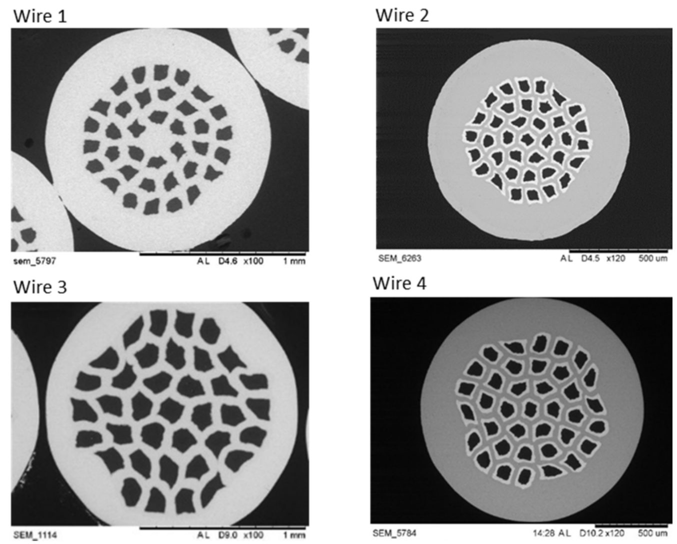
Karlsruhe Institute of Technology

10 kA MgB_2 conductor Columbus ex-situ



HVDC Cable characteristics
Monopole
3.2 GW
320 kV
10 kA





Columbus new round wire !

Columbus Superconductors

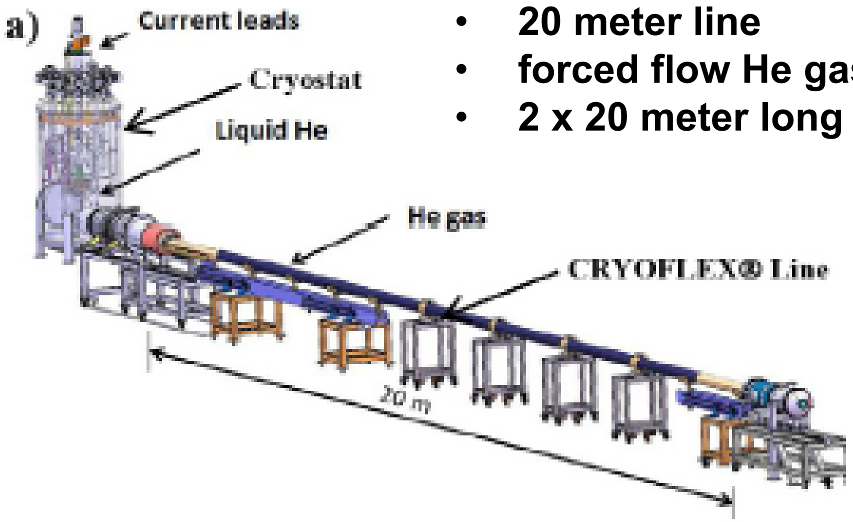
April 2014

CERN Bulletin

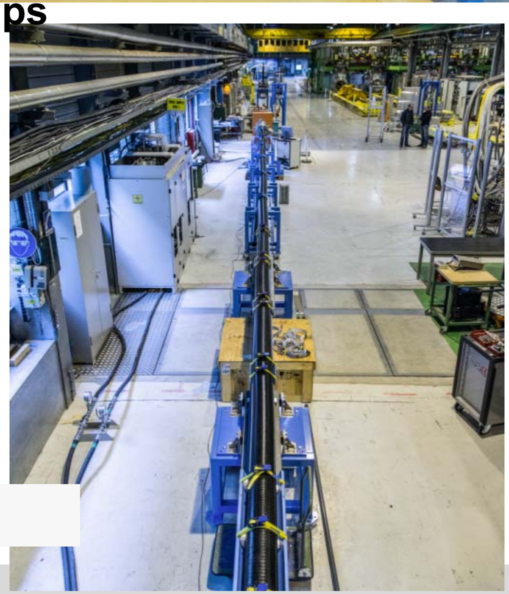
Issue No. 16-17/2014 - Monday 14 April 2014
More articles at: http://bulletin.cern.ch

WORLD-RECORD CURRENT IN A SUPERCONDUCTOR

In the framework of the High-Luminosity LHC project, experts from the CERN Superconductors team recently obtained a world-record current of 20 kA at 24 K in an electrical transmission line consisting of two 20-metre long cables made of Magnesium Diboride (MgB_2) superconductor. This result makes the use of such technology a viable solution for long-distance power transportation.



- 20 meter line
- forced flow He gas
- 2 x 20 meter long MgB_2 powered to 20KAmps



Long R&D effort started in 2008 between Columbus and CERN

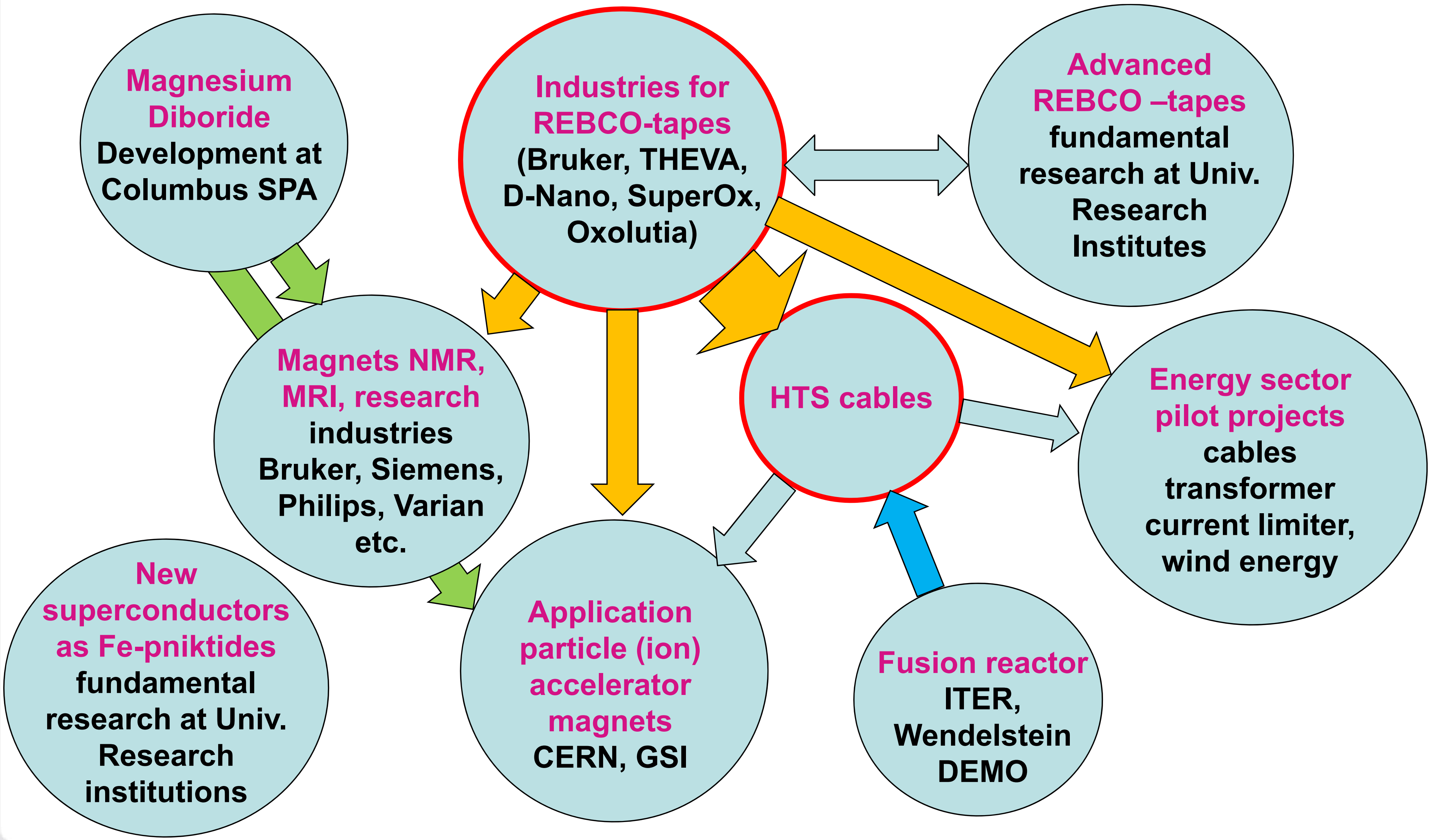
Matteo Tropeano Columbus

Other and upcoming activities, applications, projects

Karlsruhe Institute of Technology

- Ampacity energy cable: longer field tests, new cable ?
- New TENNET HV-cable 110 kV, 200 MVA, 3.4 km, NL, CC ?
- Fly-wheel storage (Industry proj.) for renew. energy
- CC for HVDC – FCL (EU-project)
- HTS Airplane motor-generator-layout (EU-project)
- HTS wind generator subsize (EU-project SUPRAPOWER)
- Cryogen-free MRI systems (industry)
- Several HTS insert magnet activities for high fields (NMR, Dipole magnets, Test fields etc.)
- CERN + partners: Nb_3Sn magnets 16 T, HTS inserts 20 T

HTS superconductivity: network in Europe



The roadmap to the market

New application fields

More demonstrators and prototypes

The „low cost“ REBCO-tape

The application customized REBCO-tape

Sustainable pulling application fields

Successful field tests and long term operation

PR to society, users, industries and politicians to convince them for new technologies

Many thanks to my colleagues providing me input !

Lucio Rossi
Glyn Kirby
Luca Bottura
Teresa Puig
Anna Kario
Simon Otten
Gao Peng
Marc Dhalle
Carmine Senatore
Markus Bauer
Michael Bäcker
Ron Feenstra
Alexander Usoskin
Christian Schacherer
Matteo Tropeano
Fedor Gömöry
Vladimir Matias
Matthias Noe
Amalia Ballarino
Luigi Muzzi
Sebastian Hellmann
Wolfgang Reiser
Stefan Huver
Luigi Bruzone
Herman tenKate
Danko vanderLaan

Thank you for your kind attention !