Results of the Development of a High Current HTS Cable for Accelerator Magnet Applications

Presented by L. Bottura
on behalf of the EuCARD2 WP10 (Future Magnets) Collaboration

EUCAS 2017, Geneva, September 17th-21st, 2017

Outline

- Scope
- Baseline choices
- Tapes
- Cables
- Characterization
- Outlook

Scope of the program

- WP10: Develop a **5 T dipole** magnet with a bore of **40 mm diameter** with consideration of **accelerator quality** (ramping operation, field quality, protection)
- WP10.2: Develop a **10 kA-class conductor** suitable for the coil winding
  - High current density (J_E > 400 A/mm^2)
  - Flexible, for winding on a small radius (≈ 20 mm)
  - Long length (UL > 30 m)
  - Enough stabilizer for practical detection and protection times
  - Transposed (is this just common wisdom ?)

Initial targets (kick-off on 14 June 2013)

Tape

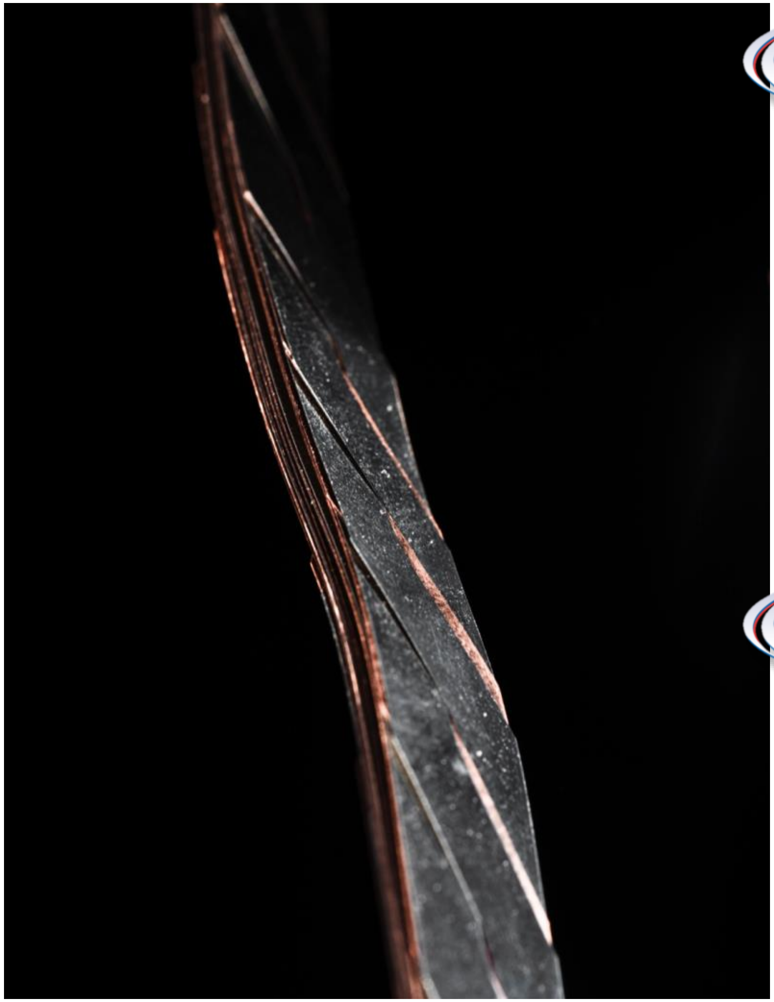
parameter	units	target
J_E (20 T, 4.2 K)	**(A/mm^2)**	**600**
σ (I_C) within a unit length	(%)	10
M(1.5 T, 10 mT/s)	(mT)	300
Range of $\sigma_{transverse}$	(MPa)	100
Range of $\varepsilon_{longitudinal}$	(%)	±0.3
Unit length	(m)	100

Cable

parameter	units	target
I_C (20T, 4.2 K)	**(kA)**	**10**
Provisional width	*(mm)*	*10*
Provisional thickness	*(mm)*	*1.5*
Effective contact resistance	(μΩ)	5

Material and geometry

EuCARD2 Roebel dummy



REBCO

- High J_E (≈ 800 A/mm^2) and steady improvement (BZO, stoichiometry control, SC layer thickness, smaller substrate)
- High mechanical strength substrate
- *Trivial* coil technology (conductor "ready-to-go", no HT processing)
- Available from several producers worldwide

ROEBEL cable

- Compact cable, high J_E
- Transposed cable vs. transverse field
- Easy bending in the parallel direction
- Can be produced automatically on long lengths (e.g. GCS, KIT)

Baseline cable designs

REBCO Tape

Tape width (before punching)	(mm)	12
SC layer	(µm)	1 … 2
Cu layer	(µm)	2 x 20
Substrate	(µm)	50 … 100
Tape thickness	(mm)	0.1 … 0.15
Critical current (4.2 K, 20 T perpendicular)	(A)	≥ 670

Protection !?!

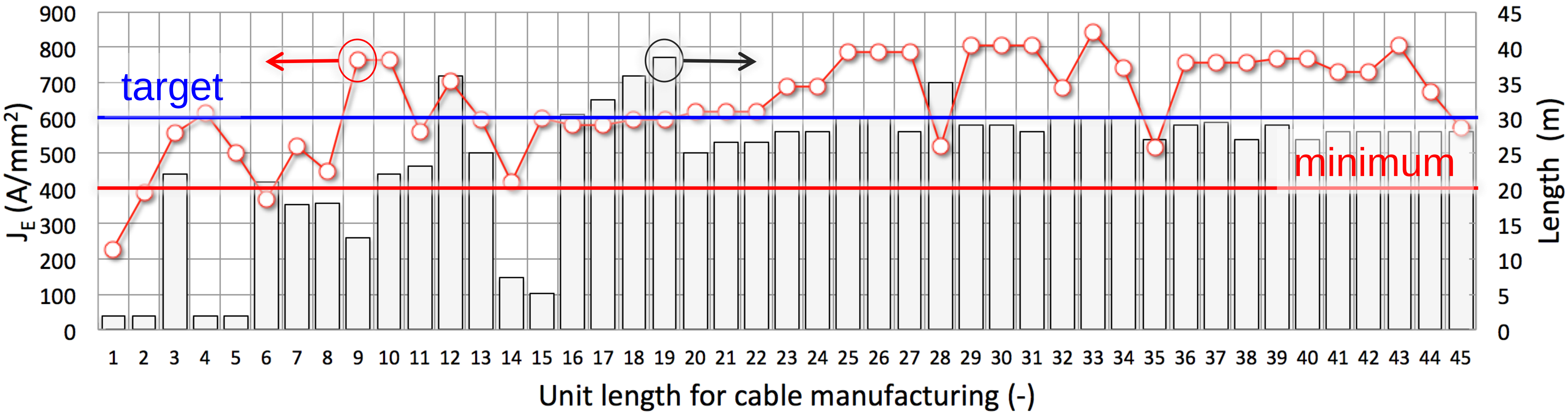
Roebel cable

Number of tapes	(-)	13 …15 *(17)*
Width	(mm)	12
Thickness	(mm)	0.9 … 1.1 ± 0.1
Transposition pitch	(mm)	~~226~~ 300
Critical current (4.2 K, 20 T perpendicular)	(kA)	≥ 4.8 … 5.8

Allow for tape *slippage* during winding

Tapes

Tape production for EuCARD2

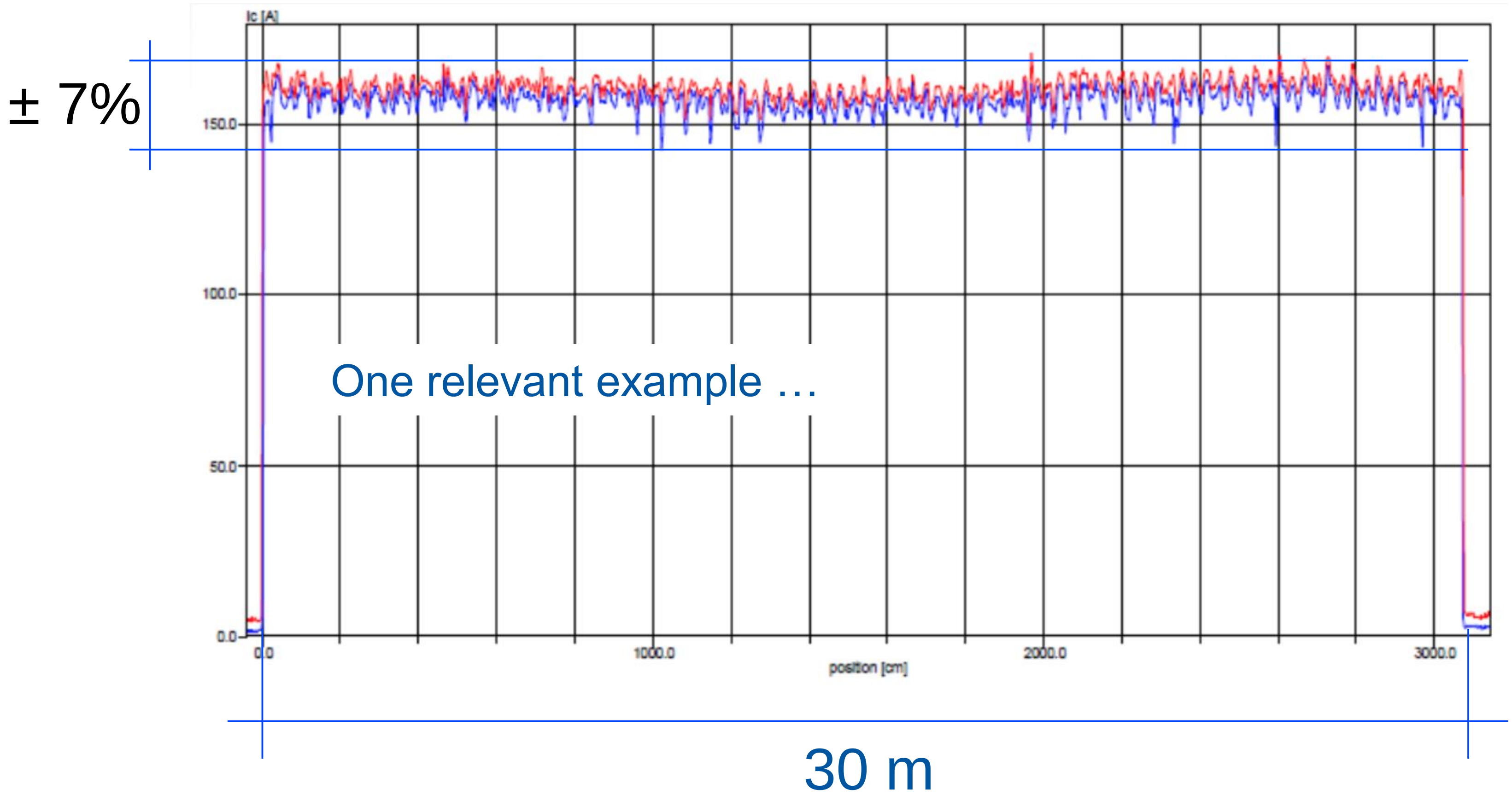


- A total of more than 1 km of 12 mm tape was produced:
  - All tapes above the minimum set J_E of 400 A/mm^2
  - most tapes, and especially present production, largely exceed the target J_E of 600 A/mm^2 (on a 100 μm substrate !)
  - Record J_E(4.2 K, 18 T) 956 A/mm^2 (not yet used in cable)
  - Production length is 90 m, cut for processing to 30 m
- An additional length of about 2 km procured by CERN (different producers) as complement material to the EuCARD2 program

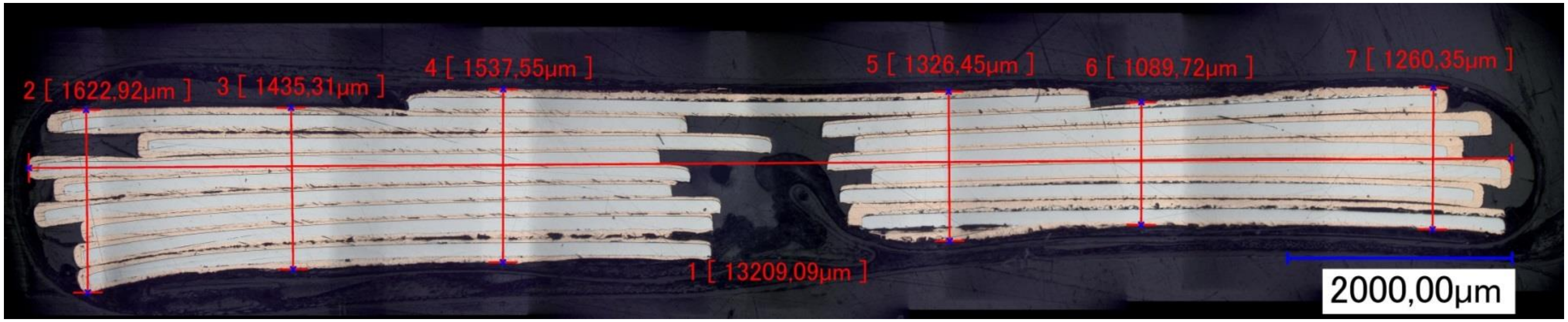
See: 2MO4-01

Courtesy of A. Usoskin

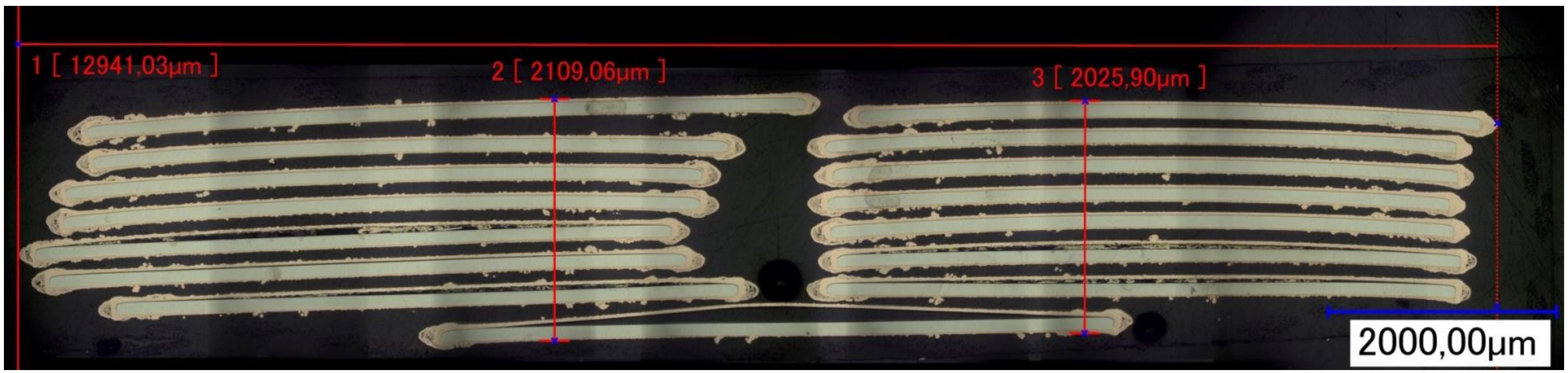
Homogeneity



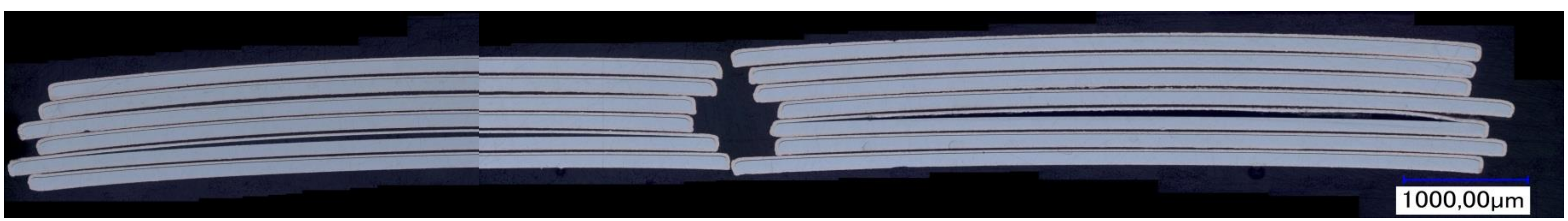
Cables



t = 1.6 mm
w = 13.3 mm



t = 2.1 mm
w = 12.9 mm



t = 1.1 mm
w = 12.3 mm

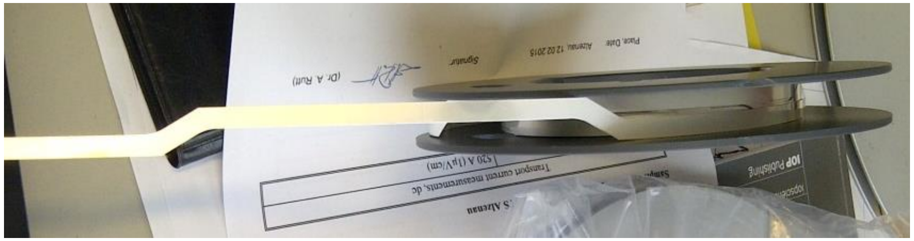
time

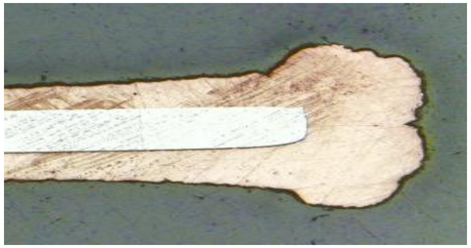
See: 4LP4-08

Punch-and-coat

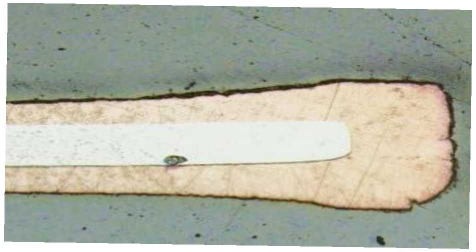
- Standard Roebel production sequence
  - Produce Cu-coated tape
  - Punch meanders
  - Assemble cable
- Modified Roebel production sequence
  - Produce Ag-capped tape
  - Punch meanders (less than 5% I_C degradation !)
  - Cu-coat (dog-boning !)
  - Assemble cable

Ag capped punched tape

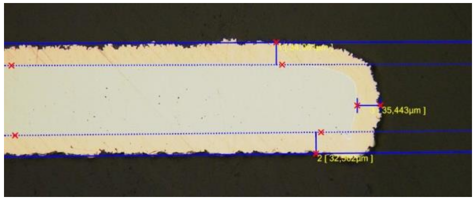




2x40 μm coating



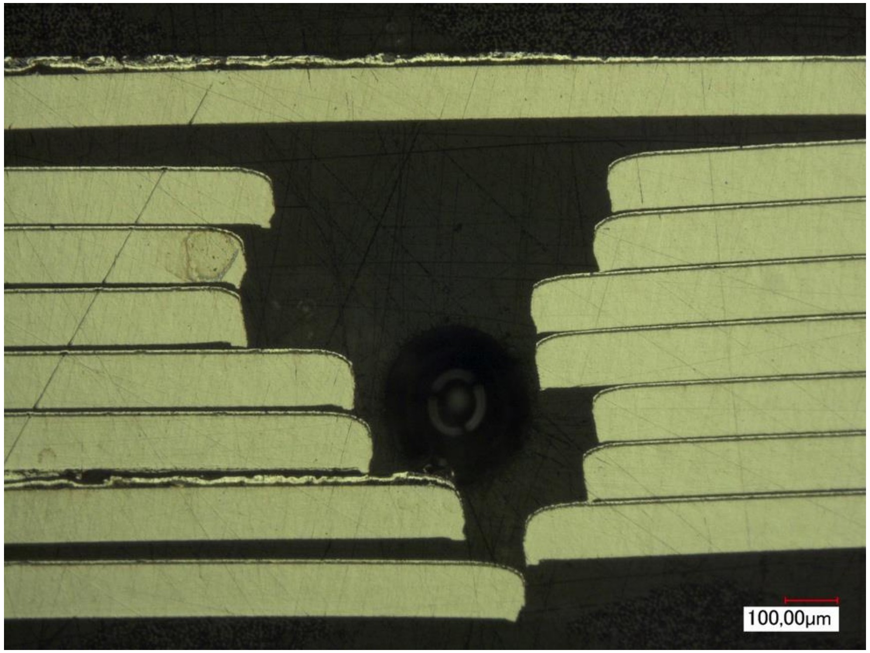
2x20 μm coating



Optimized 2x20 μm coating

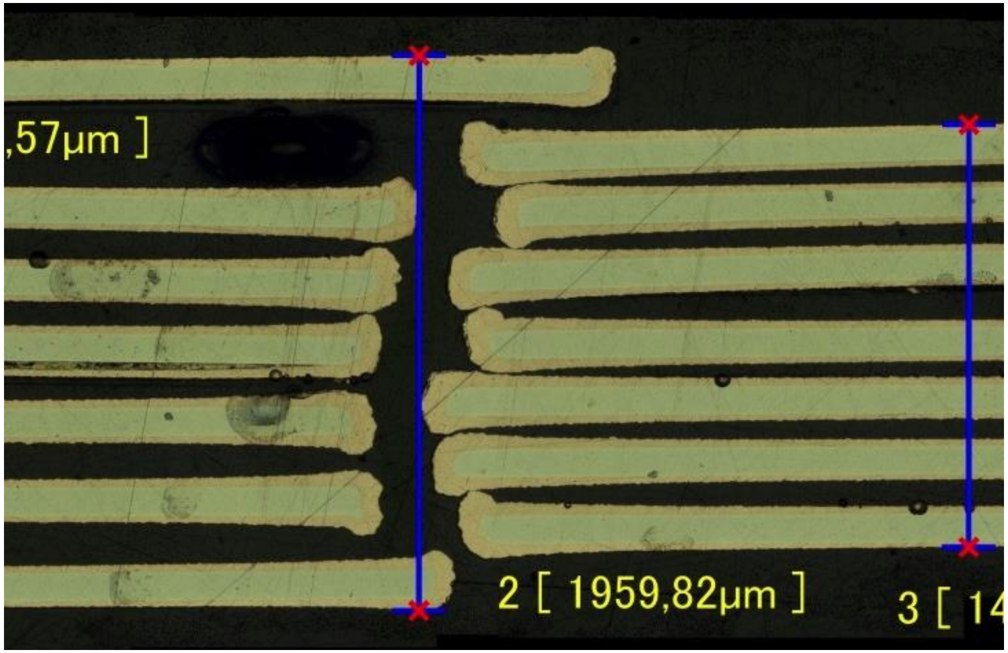
Cable technology

Punching of coated tape



Presence of burrs and danger of de-lamination

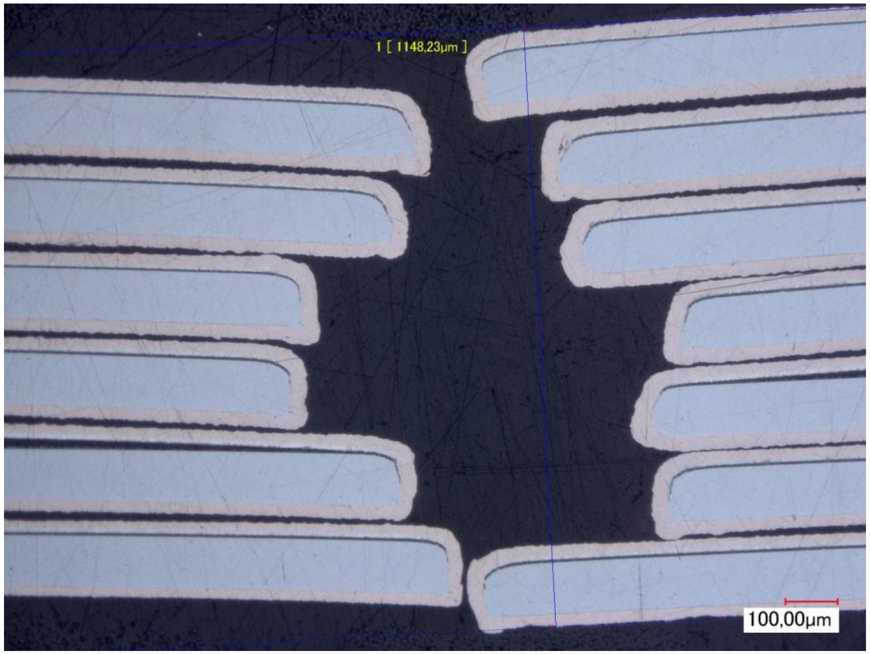
Punch-and-coat sequence



Tapes are enclosed in the Ag and Cu cap that seals them off

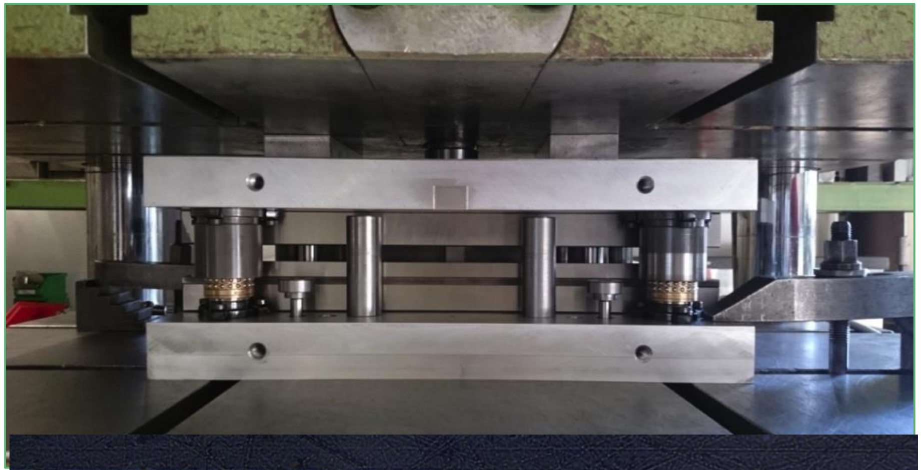
Cable technology

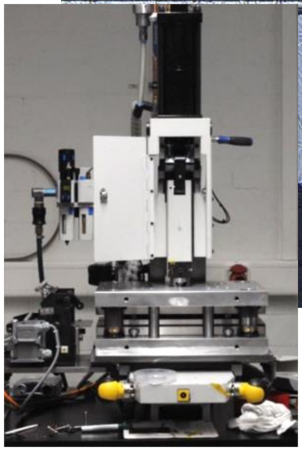
Flexible cutting tool

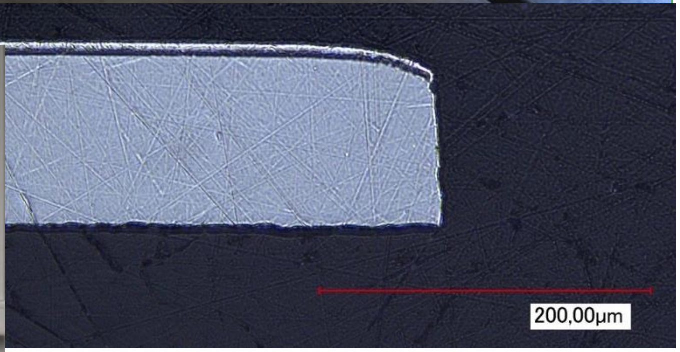


Multi-punching step, larger final tolerances

Optimized tool





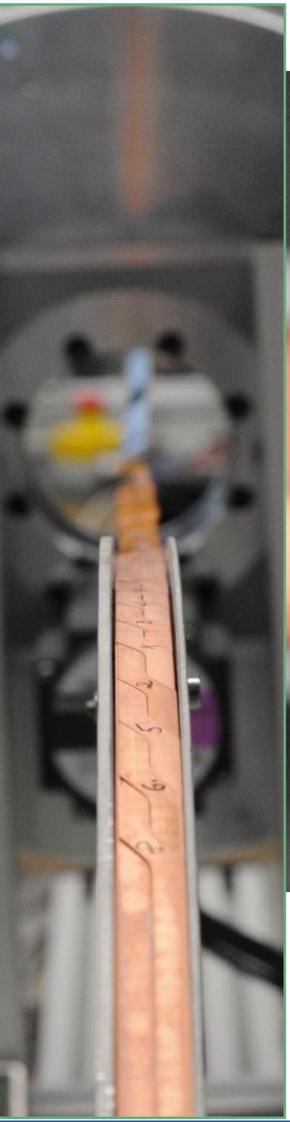


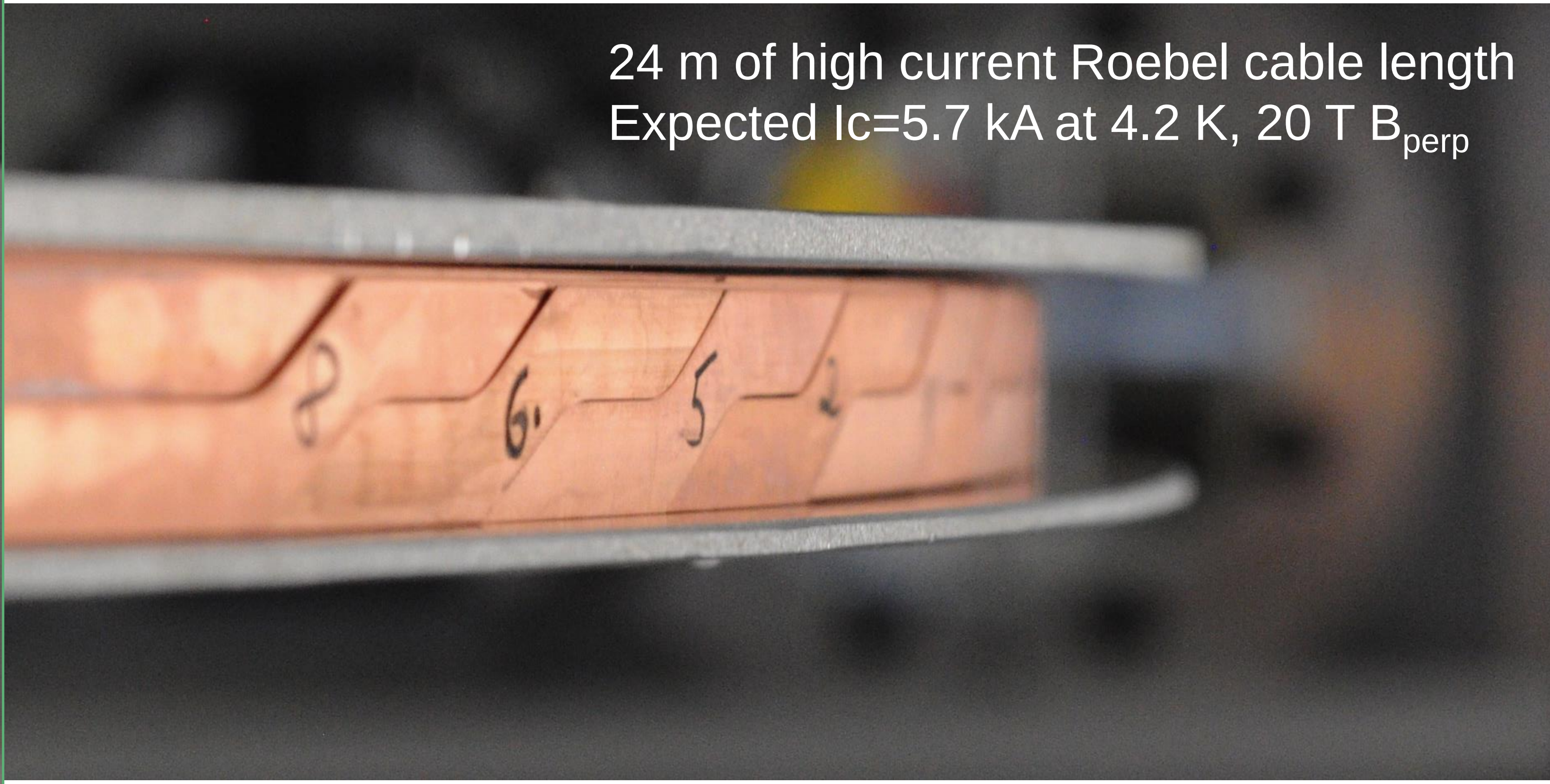
Single punching step, tight tolerances

See: 4LP4-08

First full length (January 2017)

Karlsruhe Institute of Technology





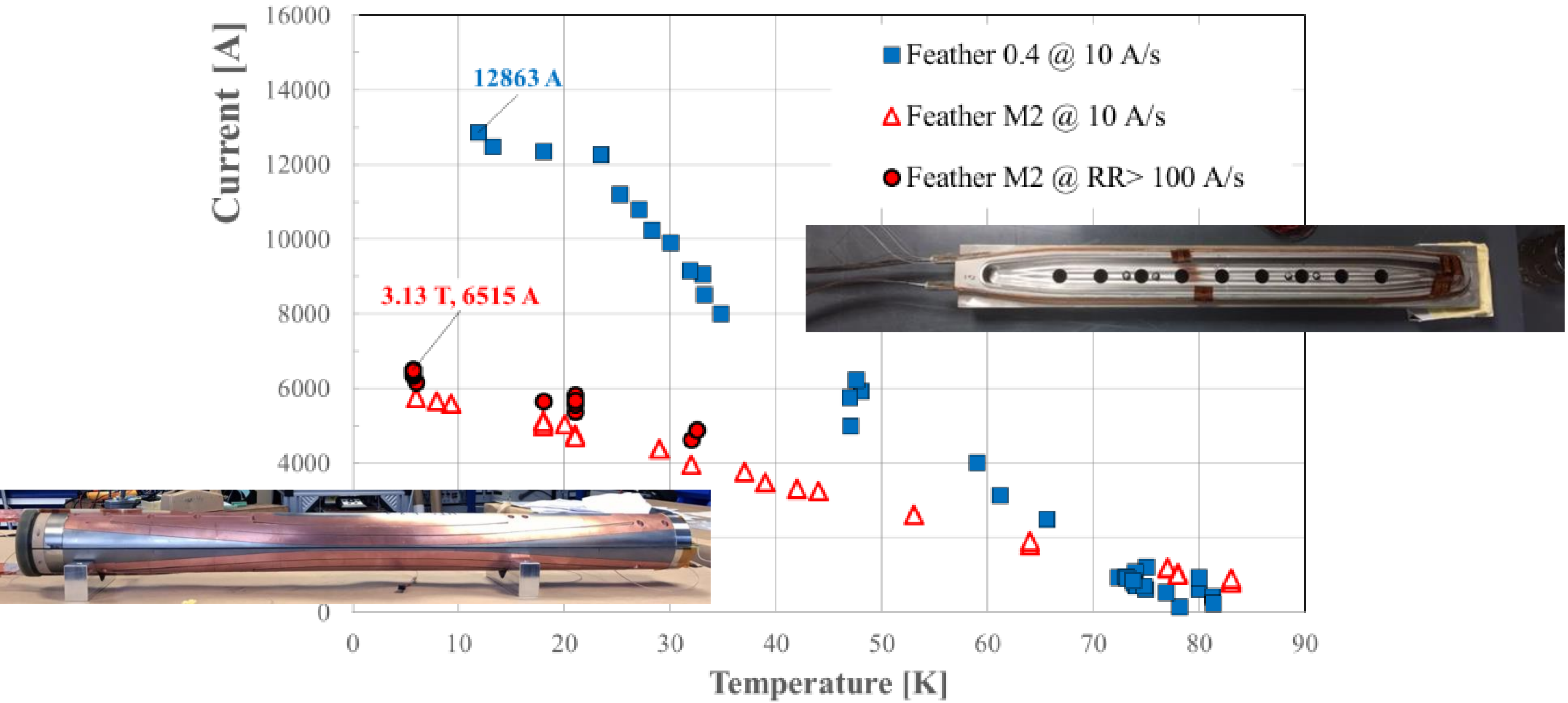
24 m of high current Roebel cable length

Expected Ic=5.7 kA at 4.2 K, 20 T B_{perp}

Semi-automatic Roebel cabling machine at KIT

Reel-to-reel system demonstrated up to **100 m**, with the possibility to upgrade the process to lengths in the range of 200…300 m

Coil I_C measurements



The cables reach I_C(B,T) (as far as we could tell from the data analysis)

Stability and training are not longer a feature (I am out of job)

Master plot

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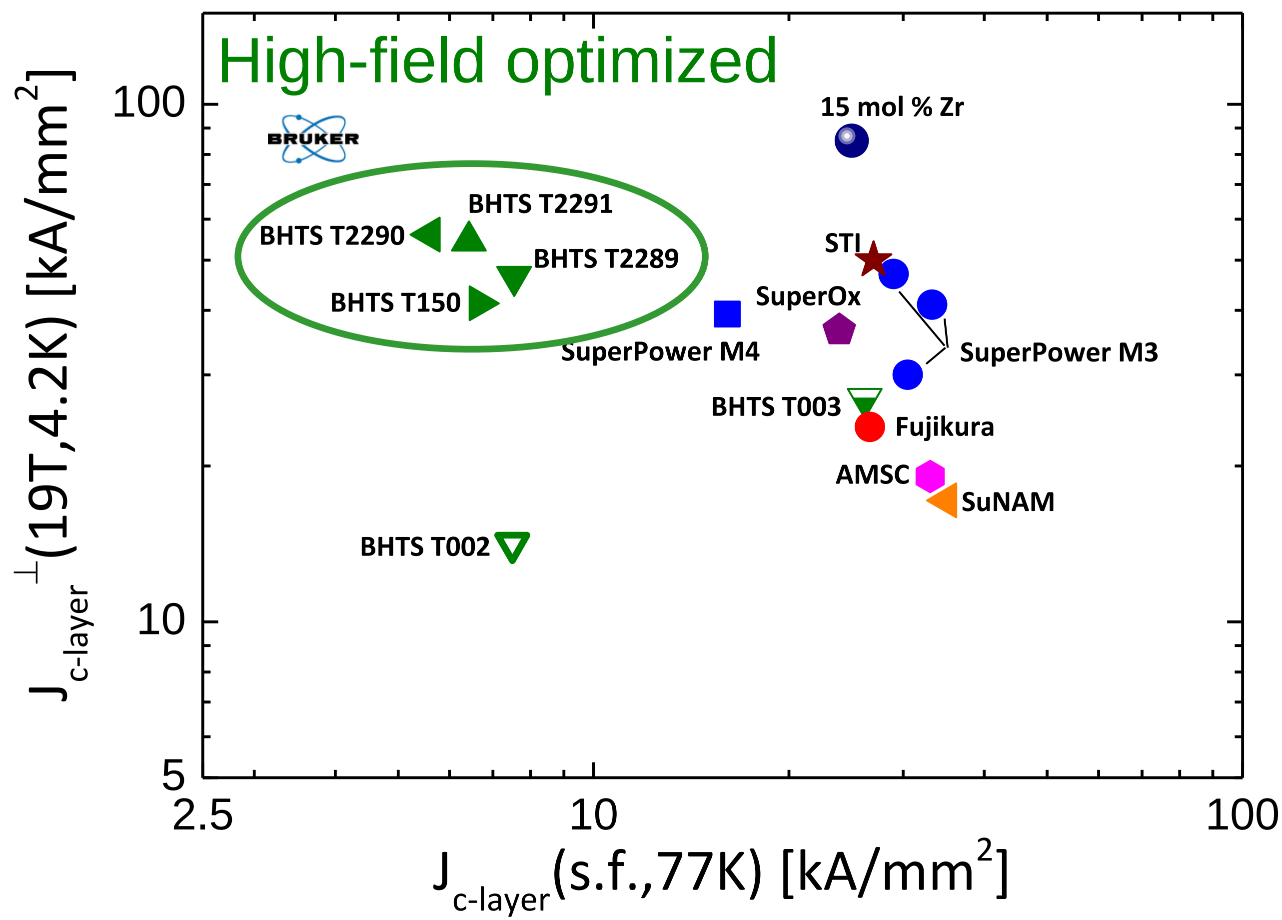
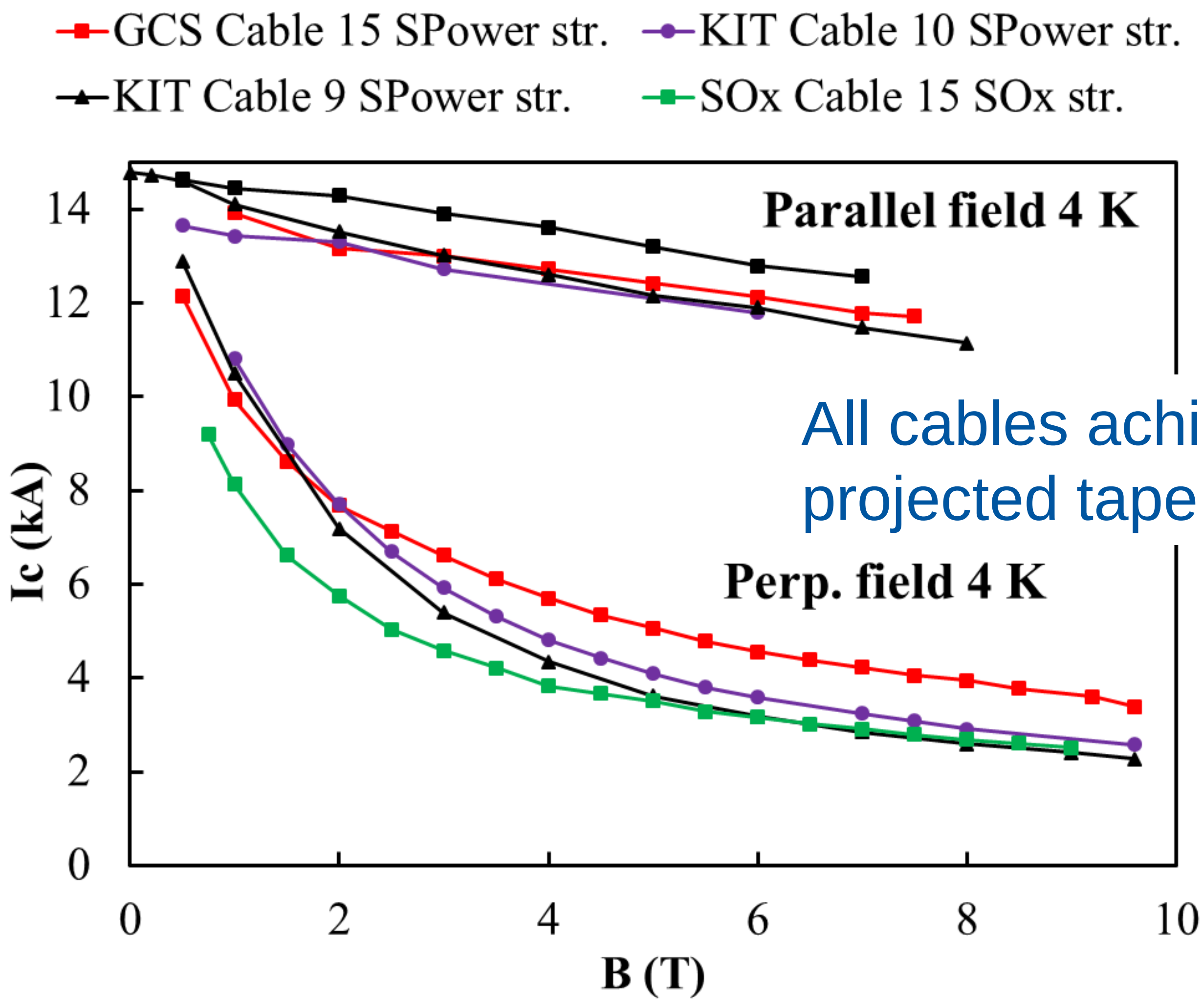
EuCARD²



Cable Ic

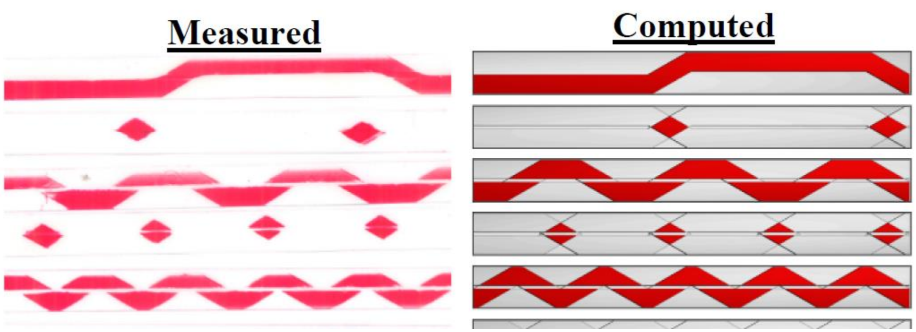


All cables achieve the projected tape IC

Courtesy of J. Fleiter

Transverse forces

Red=thicker spots =>stress

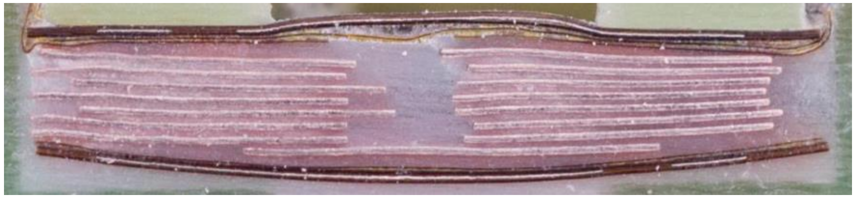


Grey =thinner spots =>no stress

J. Fleiter, C. Lorin. A. Ballarino

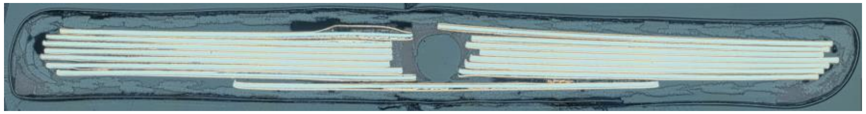
Impregnation as means to spread stress

Ch. Barth



KIT: 1:1 epoxy-fused silica

G. Kirby, J. van Nugteren



CERN: CTD101G

Ic vs. $F_{transverse}$

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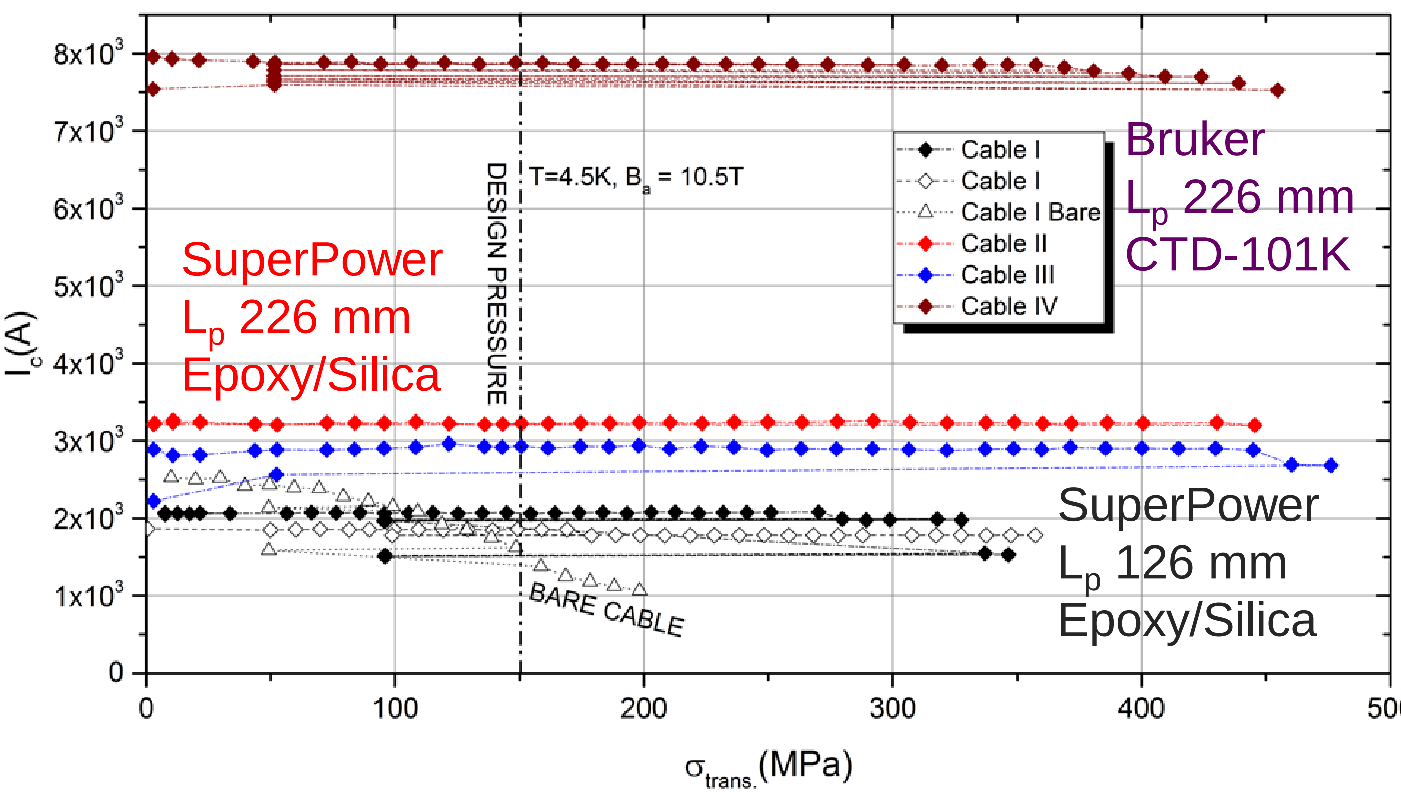
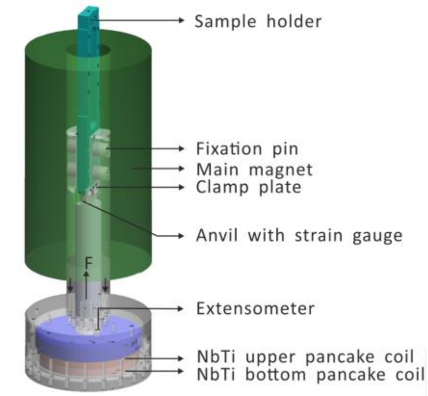
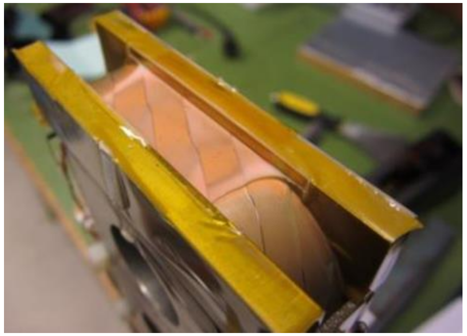




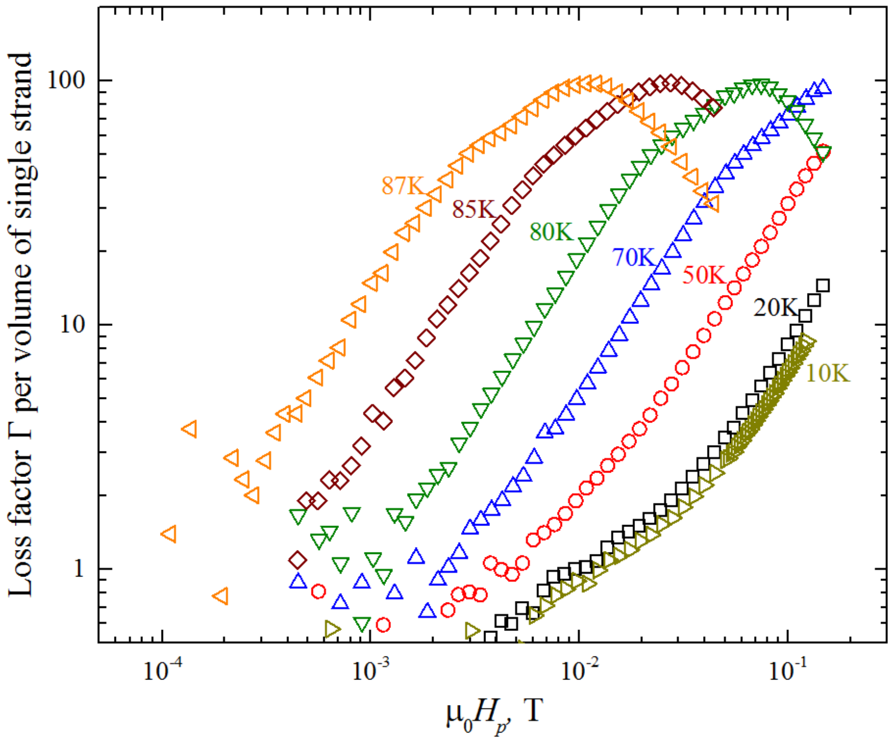
SuperPower
L_p 226 mm
CTD-101K

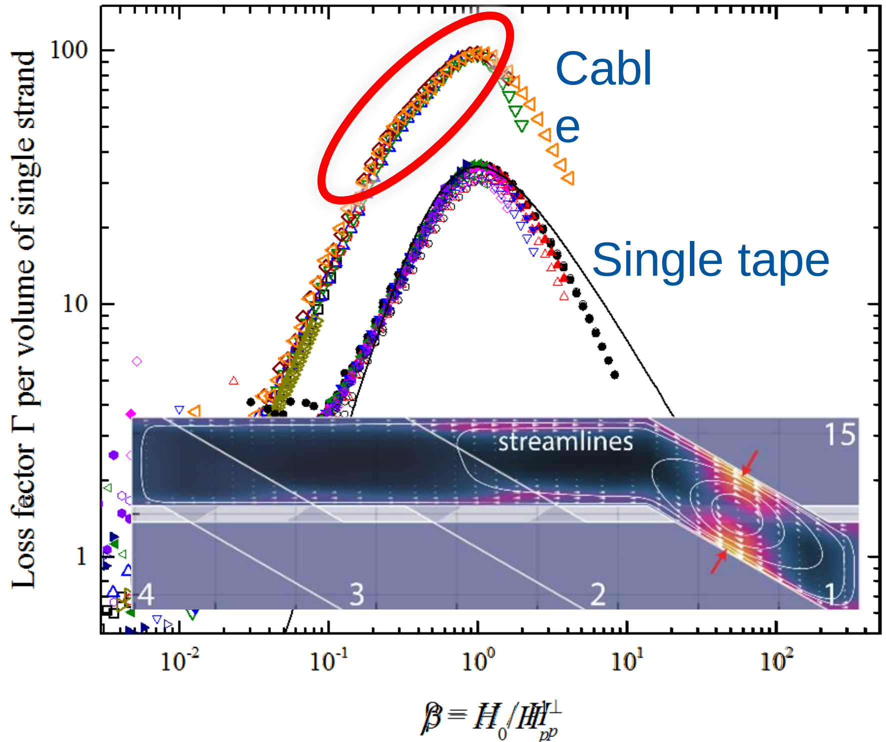


Impregnation provides a solution to stress concentration.
Impregnated cables withstand stress up to 400 MPa !

Courtesy of S. Otten, P. Gao, M. Dhallé

Hysteresis & coupling



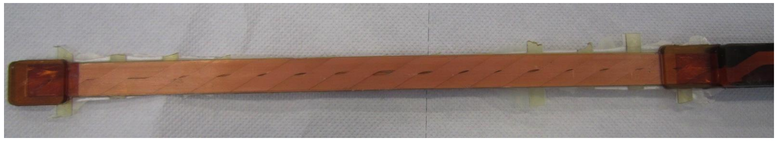


- Losses are dominated by hysteresis, coupling (inter-tape currents) are not visible
- Hysteresis scales with H_0/H_p as expected (Norris' strip)
- Assemblies of tapes are magnetically coupled, i.e. as a monolithic conductor, but not quite fully

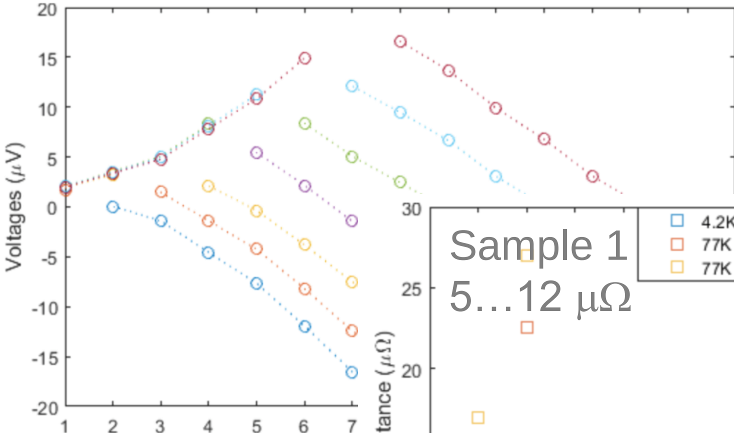
See: 4LP4-11

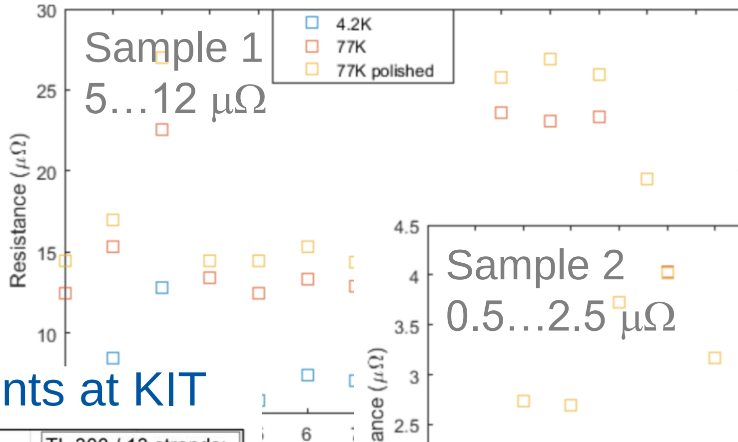
Courtesy of Y. Yang

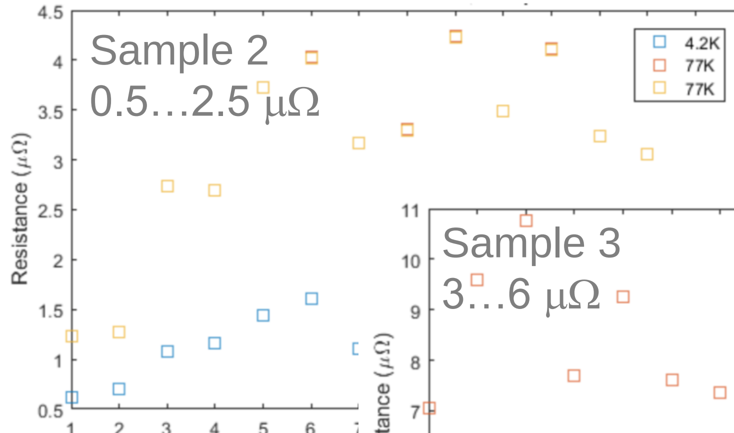
R_C

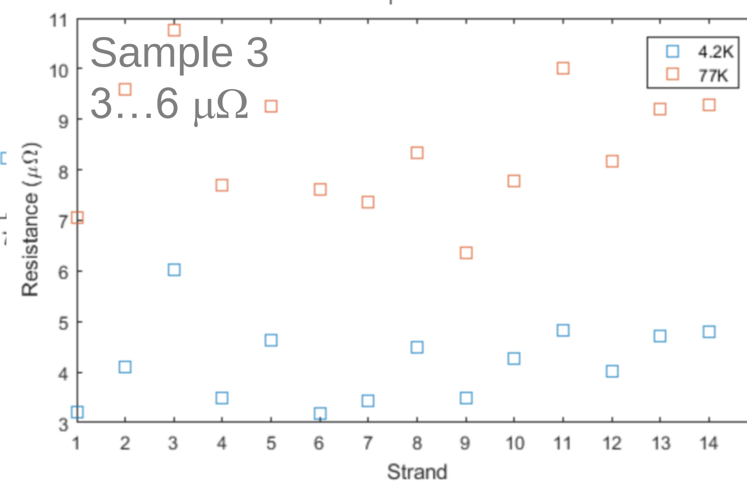


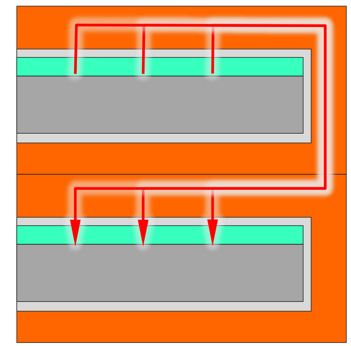
Strong effect of temperature observed, a factor 2 R_C reduction from 77 K to 4.2 K, consistent with large contribution from Cu



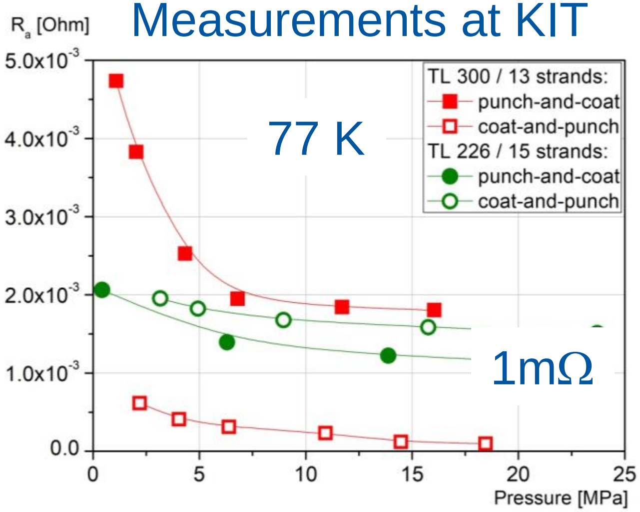








Measurements at KIT



a

es

from 1 to 10 µΩ,

g in the cable

Achievements (closing on 31 April 2017)

EuCARD²

Tape

parameter	units	target	
J_E (20 T, 4.2 K)	**(A/mm^2)**	**600**	✓
σ (I_C) within a unit length	(%)	10	✓
M(1.5 T, 10 mT/s)	(mT)	300	
Range of $\sigma_{transverse}$	(MPa)	100	✓
Range of $\varepsilon_{longitudinal}$	(%)	±0.3	
Unit length	(m)	100	✓

Cable

parameter	units	target	
I_C (20T, 4.2 K)	**(kA)**	**10**	✓
Width	(mm)	12 ± 0.1	
Thickness	(mm)	1.0 ± 0.1	
Effective contact resistance	($\mu\Omega$)	5	✓

CERN

What is left to do ?

- A few issues remain open:
  - Complete the validation of the final cable geometry in cable and magnet tests, especially including **thermal cycles and a check for degradation**
  - Verify **quench detection and protection**, measure temperatures, propagation speed and voltage development
  - Understand **magnetization values** (some surprising effect on field quality) and their control, including coupling and the effect of striation
  - **Define longitudinal strain limits** for winding and operation
  - **Joint technique** suitable for integration in a magnet construction

- EuCARD2 WP10 (Future Magnets) has provided a **strong focus** to the development of HTS cables for large-scale accelerator magnets. How to maintain momentum ?
  - On-going EU-FPT ARIES provides continuity
  - **More material is needed**, tapes and cables to feed the magnet program

A few references at EUCAS

EuCARD2 financed, supported or related

1LP3-01: S. Otten, “Inter-strand resistance in REBCO Roebel cables and effect on AC loss”
4LP4-11: Y. Yang, “Quench Characteristics of 2G YBCO Roebel Cable in a Pancake Coil”
1LP3-01: S. Otten, “Inter-strand resistance in REBCO Roebel cables and effect on AC loss”
2MO4-01: A. Usoskin, “Double-disordered HTS coated conductors and their assemblies aimed for ultra-high fields: large area tapes”
3LO3-08: P. Gao, “AC losses and inter-strand resistance in impregnated ReBCO Roebel cables”
3MP5-16: C. Petrone, “Measurement and Analysis of the Dynamic Effects in an HTS Dipole Magnet”
3MO2-07: Y. Yang, “AC Losses of Roebel Cables with Striated 2G YBCO Strands”
4LP4-08: A. Kario, “Advanced intermediate lengths of punch and coat processed HTS-Roebel cables in EuCARD2”
4LP1-01: G. Kirby, “An High Field Insert Accelerator Class Dipole Magnet Constructed with Roebel Multi-tape HTS Cable”
4LP3-11: X. Sarasola, “Test of the First HTS Demonstrator Coil in the 11 T Background Field of the SULTAN Facility”
4MP4-07: J. Murtomäki, “Investigation of REBCO Roebel Cable Irreversible Critical Current Degradation Under Transverse Pressure”

Further programs and relevant work

4LO2-02: J. Van Nugteren, “ReBCO 20T+ Dipoles for Particle Accelerators”
3LO2-06 L. Rossi: “An HTS Magnet Demonstrator for Space Experiment”
4MP7-09: M. Matras, “Measurement at 4 K of normal zone propagation velocity in commercial REBCO conductors”

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KIT
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BRUKER

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EuCARD^2

WP10.2

UNIVERSITY OF Southampton

Grenoble INP

cnrs
dépasser les frontières

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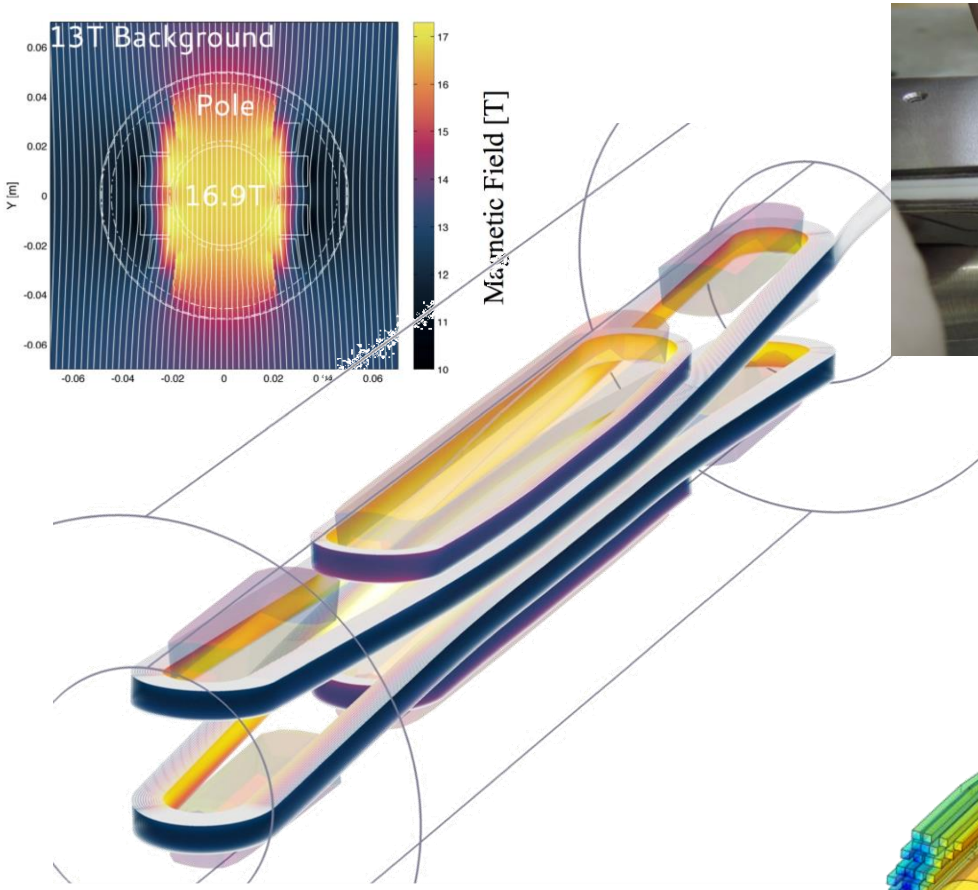
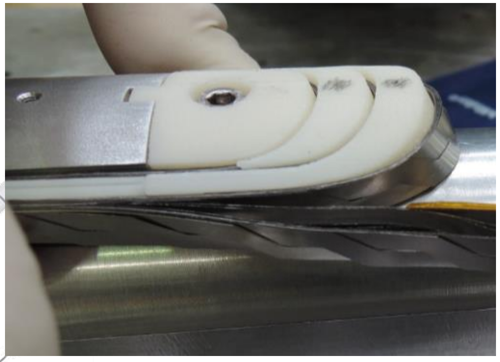
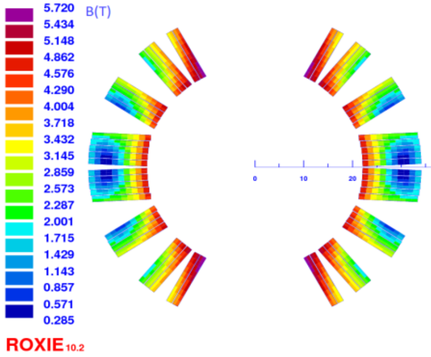
HTS for 5 T/40 mm

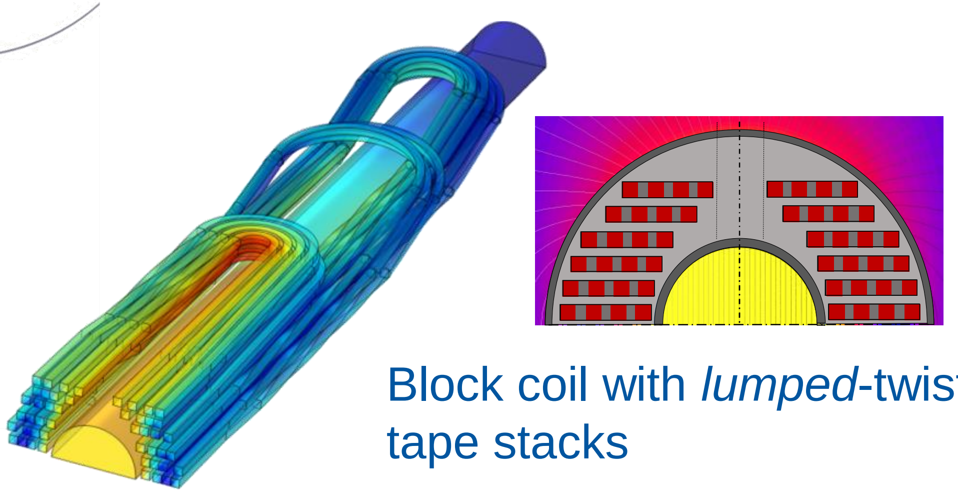
Aligned Blocks dipole (Roebel)



Cos-θ dipole (Roebel)







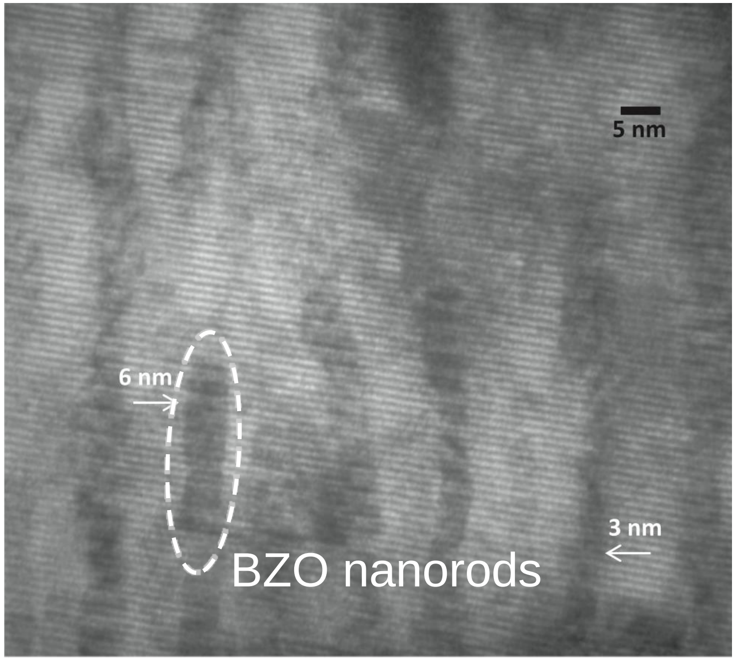
Block coil with *lumped*-twist tape stacks

PLD-300

IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. **28** (2015) 114007 (8pp)
doi:10.1088/0953-2048/28/11/114007

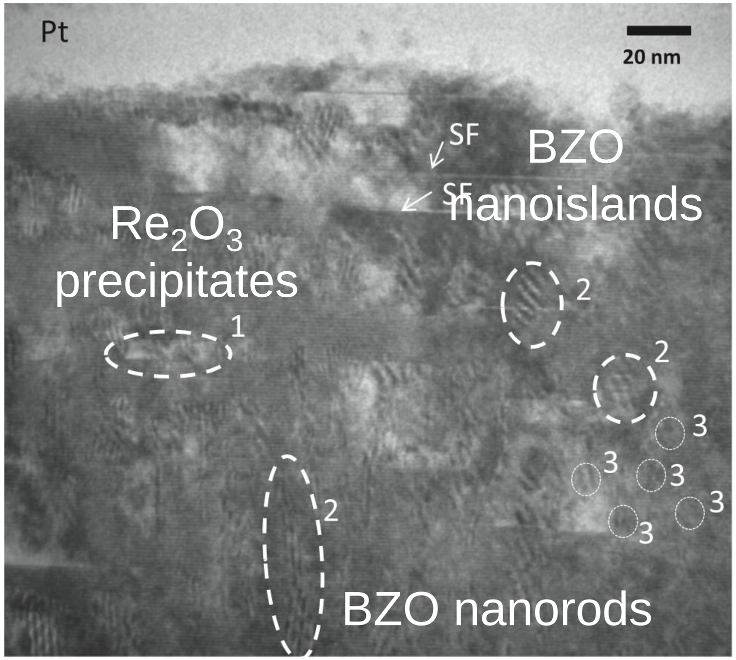
Double disordered YBCO coated conductors of industrial scale: high currents in high magnetic field

Extrinsic defects



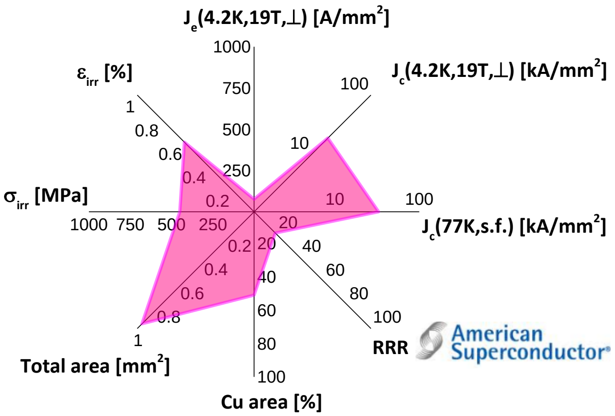
PLD deposition
5 wt% of BZO in the YBCO target

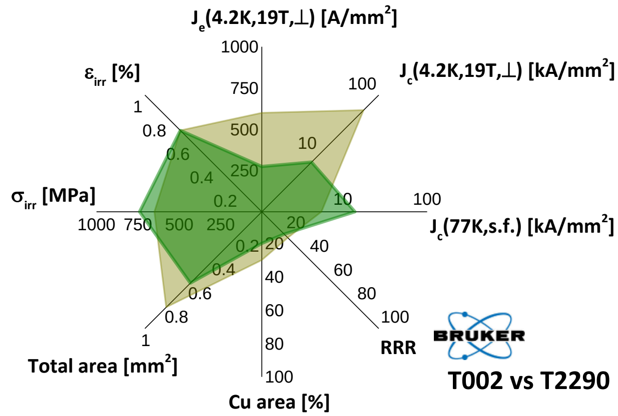
Intrinsic and extrinsic defects

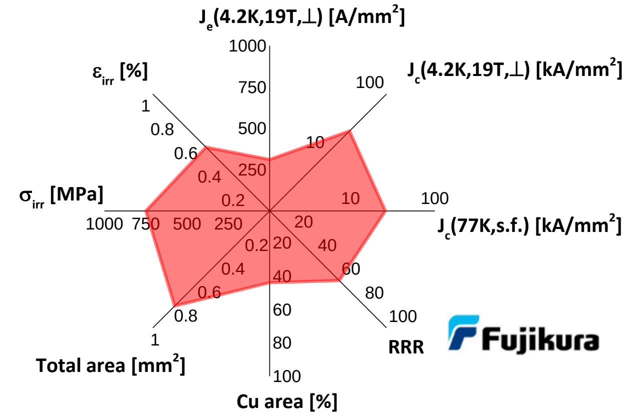


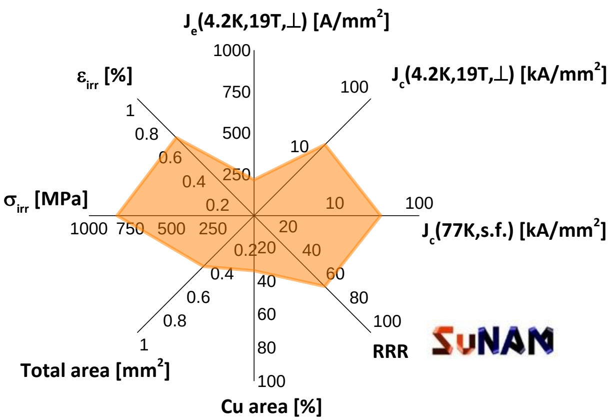
PLD deposition
5 wt% of BZO in the YBCO target
0.2…0.5 mbar O_2 pressure variation

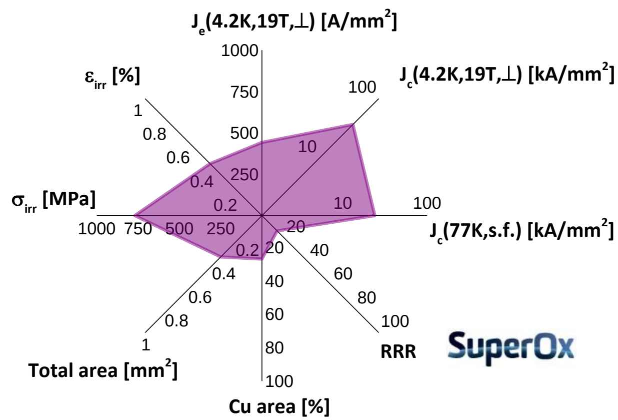
Zoo of tapes

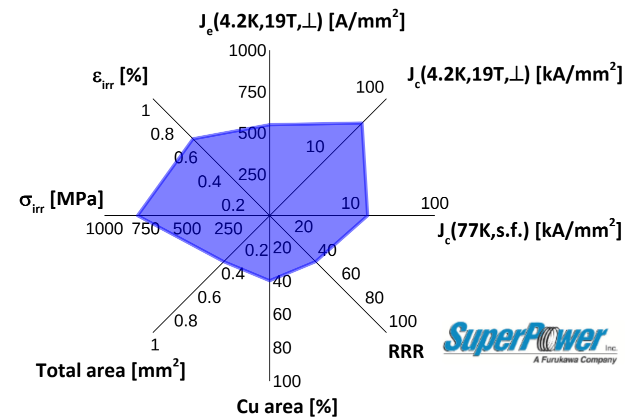

J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
American Superconductor


J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
BRUKER
T002 vs T2290


J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
Fujikura


J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
SuNAM


J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
SuperOx


J_e(4.2K,19T,⊥) [A/mm²]
J_c(4.2K,19T,⊥) [kA/mm²]
J_c(77K,s.f.) [kA/mm²]
RRR
Cu area [%]
Total area [mm²]
σ_{irr} [MPa]
ε_{irr} [%]
SuperPower
A Furukawa Company

Magnetization

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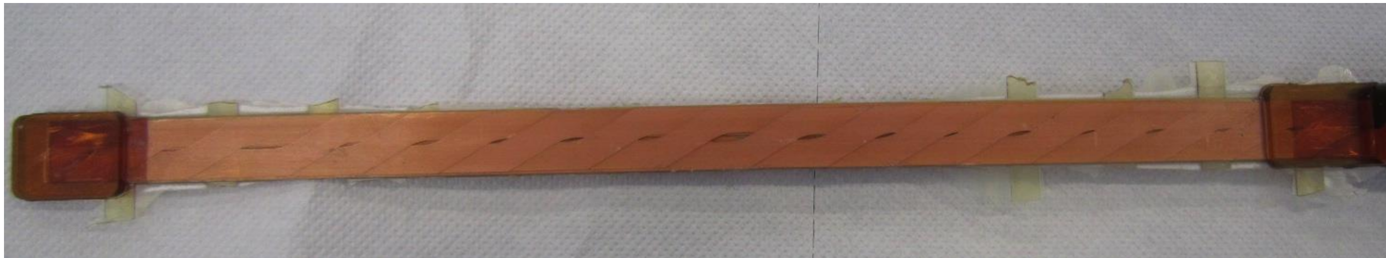
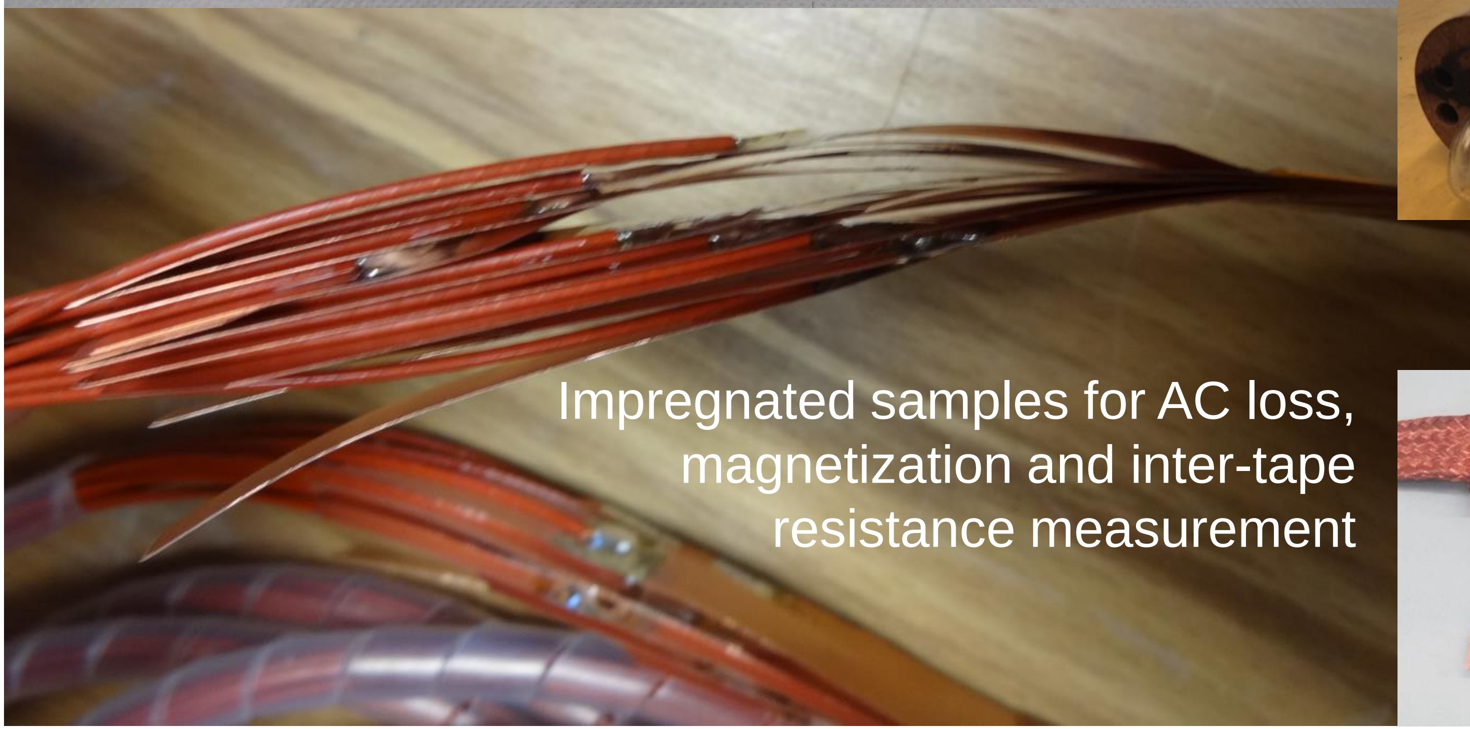
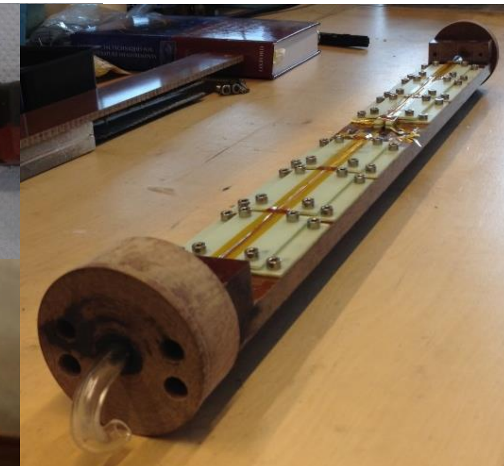
CERN
EuCARD²
UNIVERSITEIT TWENTE.







4.2 K, 400 mT

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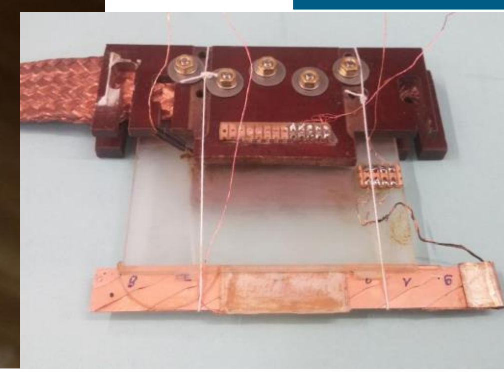

4.2 … 100 K, 350 mT