Advances in the Development of a 10-kA Class REBCO cable for the EuCARD2 Demonstrator Magnet

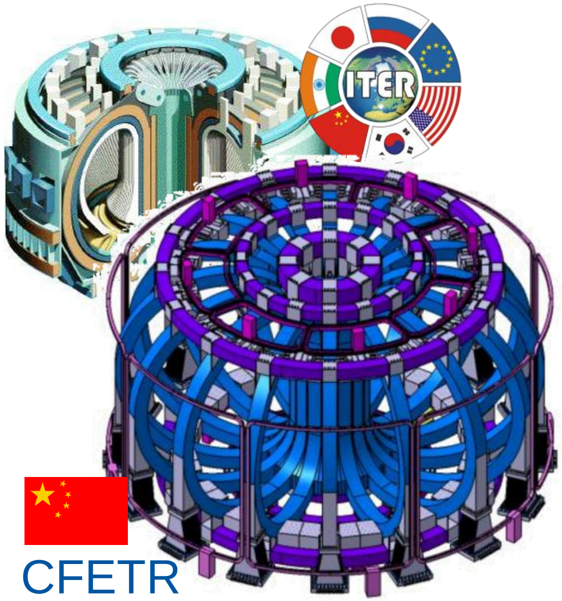
Presented by L. Bottura
on behalf of the EuCARD2 WP10 (Future Magnets) Collaboration

EUCAS 2015, Lyon, September 6th-10th, 2015

Outline

- Why HTS cables ?
- Which cable ?
- Highlights and plan

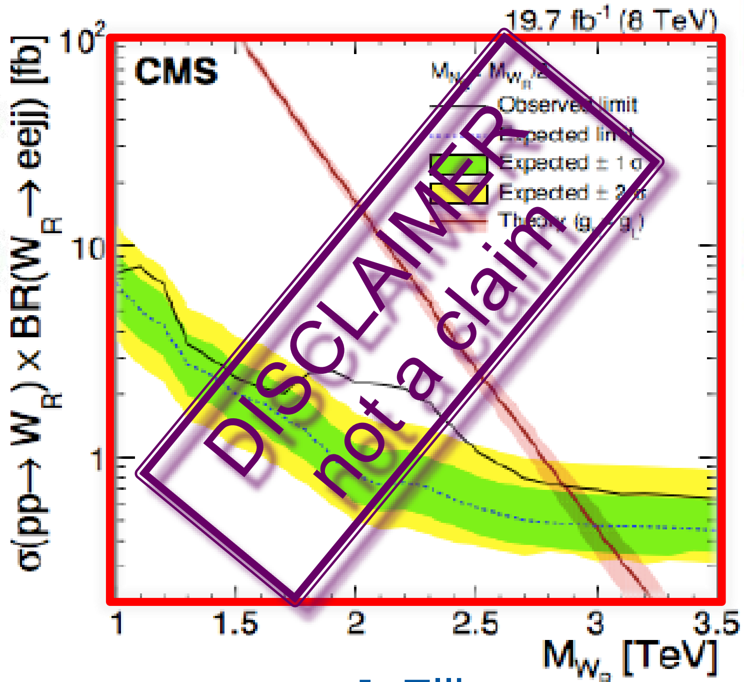
HTS, for what ?



CFETR

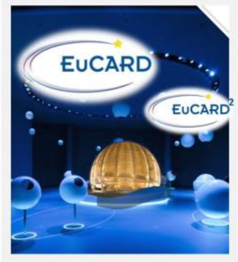
EUROfusion

Energy for the Future:
“a Life Beyond ITER”



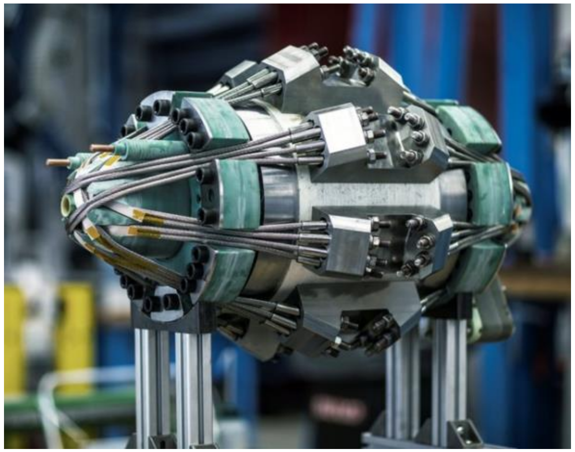
J. Ellis
“Is There Life after Higgs ?”

$$E\,[\mathrm{TeV}] \approx 0.3\; B[\mathrm{T}]\; R[\mathrm{km}]$$



High Energy Physics

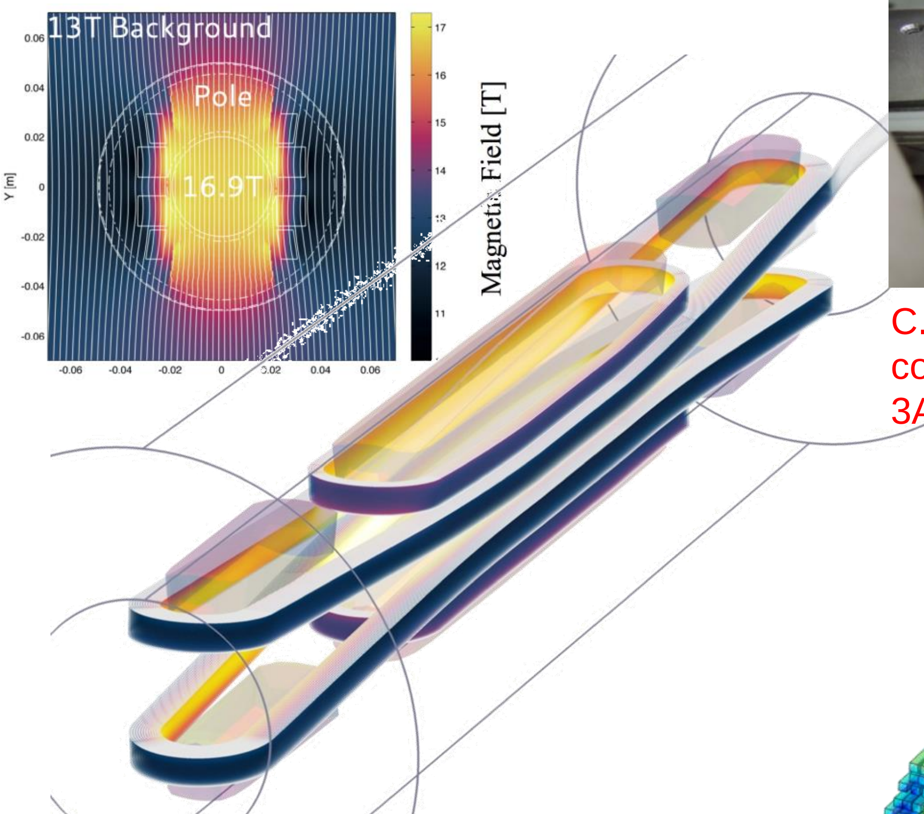
European Magnetic Field Laboratory



High magnetic fields:
“Life Science for Today”

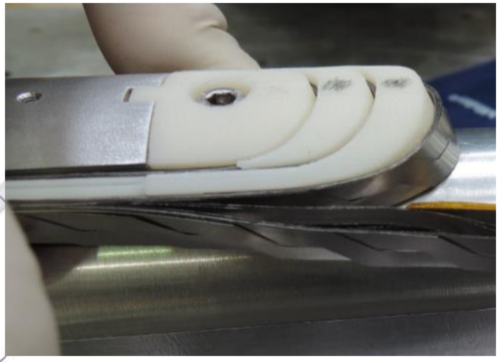
HTS for +5 T (REBCO)

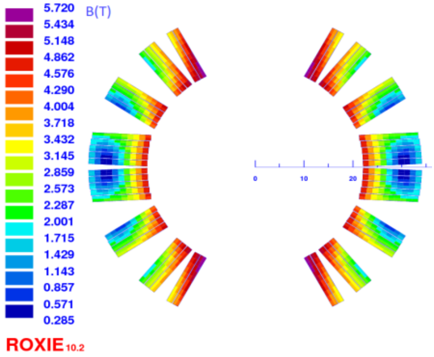
5 T HTS (YBCO) stand-alone dipole for test in FReSCa2 (40 mm bore)



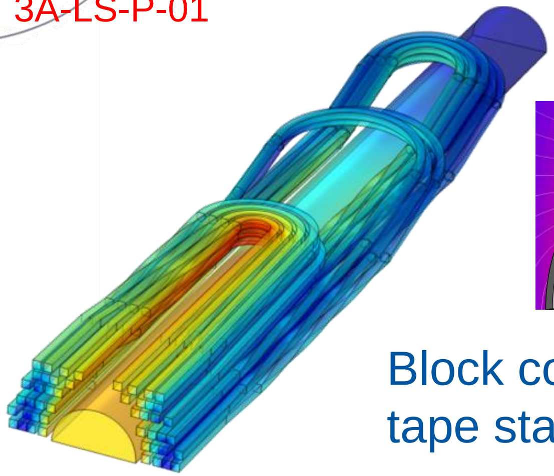
G. Kirby et al., “Design, construction and test of subscale coils with REBCO Roebel cable for the EuCARD-2 Future Magnets project”, 2M-LS-O2

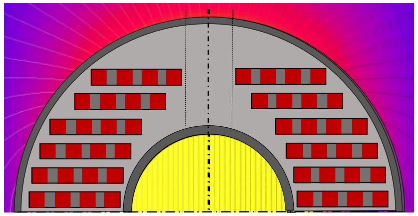
Cos-θ option for an HTS Roebel





C. Lorin et al., “Development of a Roebel-cable based cos-theta dipole: design and windability of magnet ends”, 3A-LS-P-01





Block coil with *lumped*-twist tape stacks

J. Himbele et al., “HTS dipole magnet for a particle accelerator using a twist stack cable”, 2M-LS-O2

Target performance

Parameter		R&D target	Minimum
J_E (4.2 K, 20 T)	(A/mm^2)	600	**400**
Unit length	(m)	100	**50**
$\sigma(I_c)$	(%)	10	
M (1.5 T, 10 mT/s)	(mT)	300	
Minimum $\sigma_{transverse}$	(MPa)		**100**
Range of $\varepsilon_{longitudinal}$	(%)		**±0.3**

Target cable I_C in the range of 10 kA

Material focus: REBCO

REBCO or Bi-2212

REBCO — strengths

- High J_E (≈ 800 A/mm2) 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

Bi-2212 — strengths

- High J_E (≈ 800 A/mm2)
- Magnetization control as for LTS wires (fine filaments, twisting)
- Cable as for LTS wires (Rutherford)
- Production as for LTS (PIT) in long lengths

REBCO — weaknesses

- Homogeneity in J_E demands tight QA
- High I_{OP}/J_E cable to be developed
- Sensitive to folding/twisting
- Large *magnetization* when exposed to perpendicular field
- Compatibility with impregnation
- Complex material production route, high cost and short available length

Bi-2212 — weaknesses

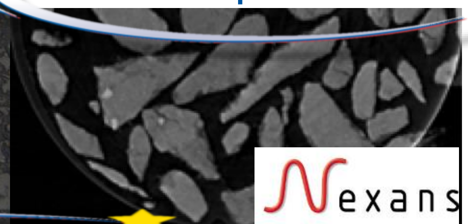
- J_E *stagnant* since the result of OPHT
- Low-strength wire matrix, modest electro-mechanical properties (degradation at 75 MPa ? C. Senatore et al.)
- Requires OPHT at 890 °C, controlled O_2 atmosphere at o(100 bar)
- Compatibility with insulation/structure
- Single vendor, exotic precursor, cost

Minimal Bi-2212 program

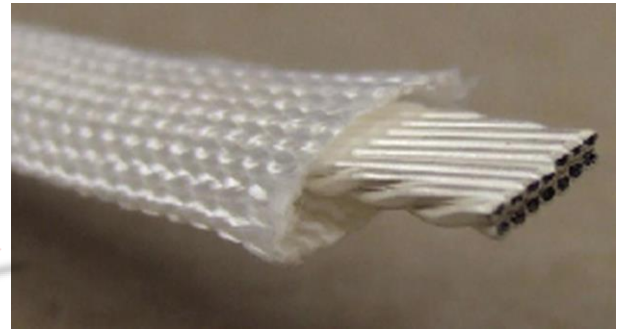
EuCARD²

BSCCO-2212 wire

Bi-2212 precursor



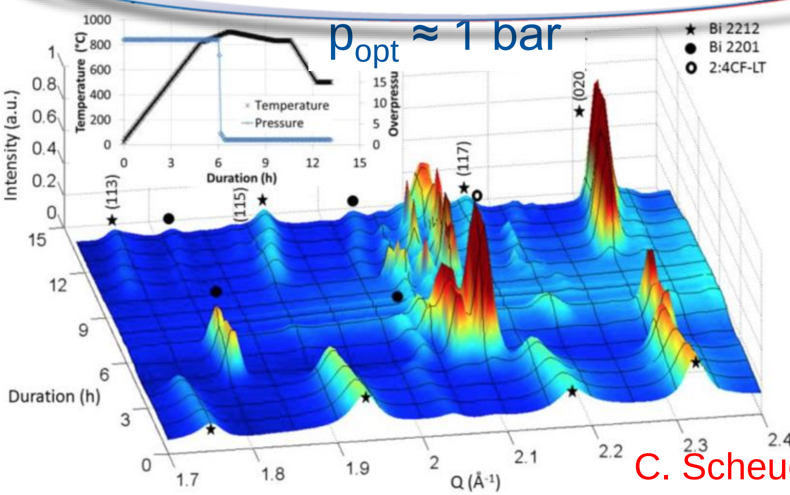
Sample of BSCCO-2212 cable



BERKELEY LAB

Analysis and characterization

$p_{opt} \approx 1$ bar



US-BSCCo program, testing alternative materials and coil configurations (CCT)

U. Trociewitz et al, Bi-2212 magnet technology, 2M-LS-O2
M. Matras et al, Bi-2212 heat treatment, 2A-WT-O1
F. Kametani et al., Bi-2212 microstructure, 3M-M-O2
C. Scheuerlein et al., Influence of the oxygen partial pressure, 3A-WT-P-01

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Cable options – 1/3

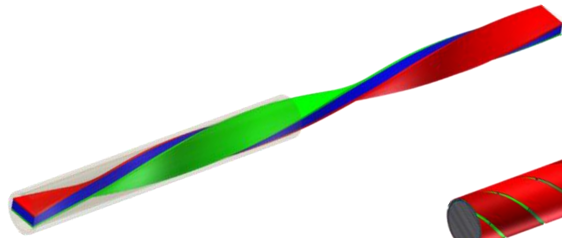
IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) October 2014
Plenary Presentation 4PLA-01 given at ASC 2014, Charlotte, August 10 – 15, 2014.

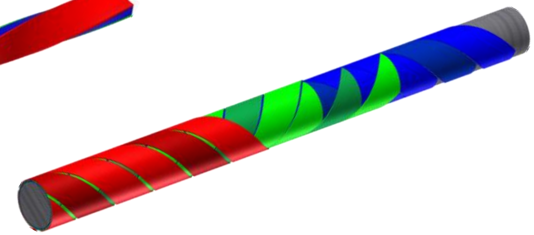
Cables Performance Summary

Cable concept	Rutherford	RACC	CORC	TSTC	RSCCCT	Slotted CIC
Conductor	Bi-2212	REBCO	REBCO	REBCO	REBCO/PIT	REBCO
Tape utilization	NA	mid/high	mid/high	high	high	high
Scale-up	easy	hard	possible	easy	easy	easy
I_{op} (kA) @4.2 K (possible >10 kA)	2.6 (s.f)	> 2 (8 T ⊥) > 10 (8 T //)	5 (19 T)	5 (12 T) 4 (19.7 T)	3 (12 T)	> 2 (10 T)
$J_{overall}$ (A/mm^2) @4.2 K	220 (s.f.)	400 (10 T)	114 (19 T)	100 (12 T)	100 (12 T)	~ 40 (10 T)
$\sigma_{transverse,ave}$ (MPa)	< 50	> 50	> 300	< 40	< 30	NA
$\varepsilon_{longitudinal}$ (%)	< 0.3	~ 0.4	> 0.6	NA	NA	NA
Bending radius (mm)		~10 (easy bend)	60 (-2.5%)	~140 (-3.6%)	300	NA
Comments	Transposed	Transposed	Partially transposed	Partially transposed	Partially transposed	Partially transposed

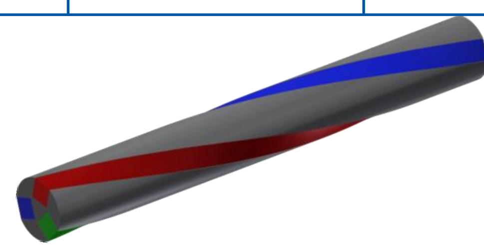
EuCARD2, 2014
Barth, 2014

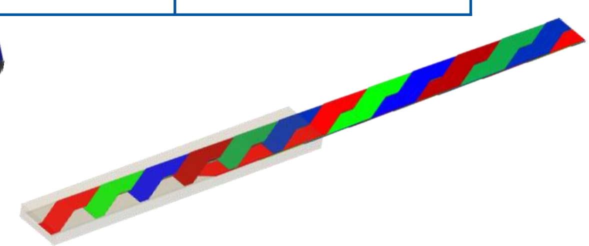
Cable options – 2/3





	Stacks	Twisted Stacks (TST)	Helically Twisted Stacks (HTST)	Conductor on Round Core (CORC)	Roebel
J_E (A/mm²)	*600*	**273** (@16 T)	**100** (@12 T)	**250** (@ 17 T)	**400** (@ 10T)
I_{OP} (A)	*3…5*	**4** (@19 T)	*10…20*	**7** (@ 17 T)	**10** (@ 10T)
ε (%)	as for tape	unknown	unknown	+0.8	unknown
σ (MPa)	as for tape	unknown	unknown	**> 300**	**> 170**





Cable options – 3/3

EuCARD2 Roebel dummy

- 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)

- More than 50% of the material is lost
- **Slit tape exposed to atmosphere**
- **No twisting (*scribing* not useful), large magnetization expected**
- **Mechanical sensitivity at cross-overs**
- Tensile behavior of cable is delicate
- Difficult bending in the transverse direction

Baseline cable design

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 !?!

3rd Workshop on Accelerator Magnets in HTS
Lyon, 10-11 September 2015

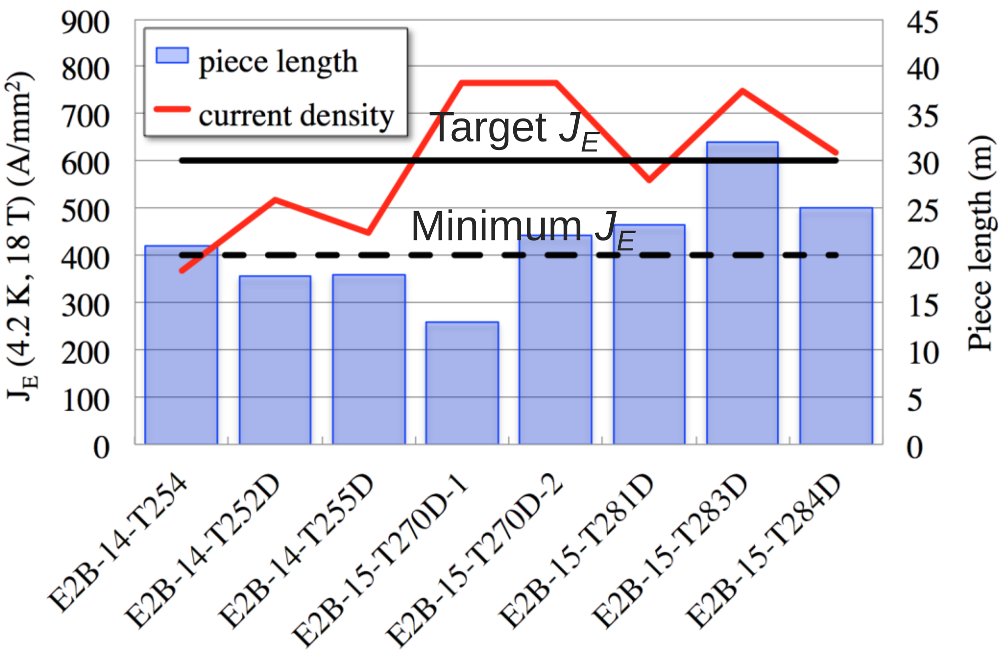
Roebel cable

Number of tapes	(-)	≤ 15 *(17)*
Width	(mm)	12
Thickness	(mm)	0.8 … 1.2
Transposition pitch	(mm)	226
Critical current (4.2 K, 20 T perpendicular)	(kA)	≥ 4.2

Allow for tape slippage during winding

Tapes

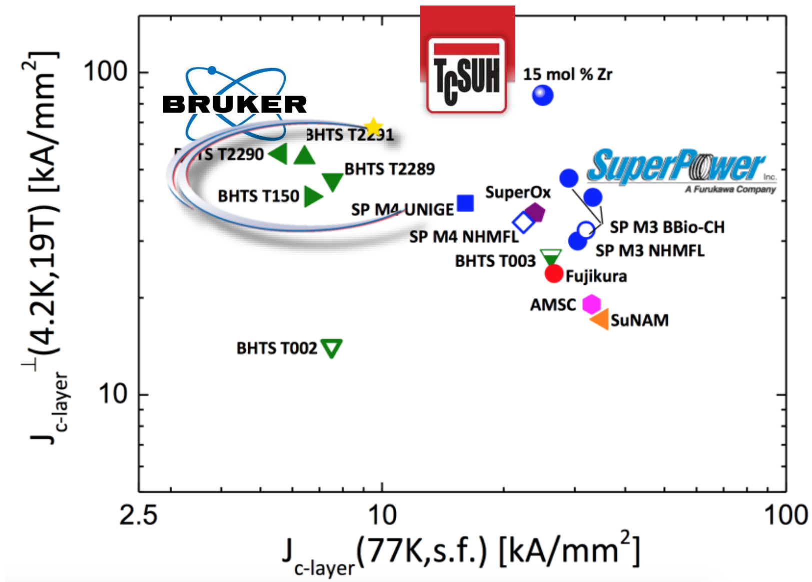
Tape production for EuCARD2



Approximately 250 m of 12 mm tape produced:

- all above minimum (400 A/mm²)
- most at target (600 A/mm²)
- some up to J_E (4.2 K, 18 T) ≈ 800 A/mm²

Master plot (C. Senatore, U. Geneva)

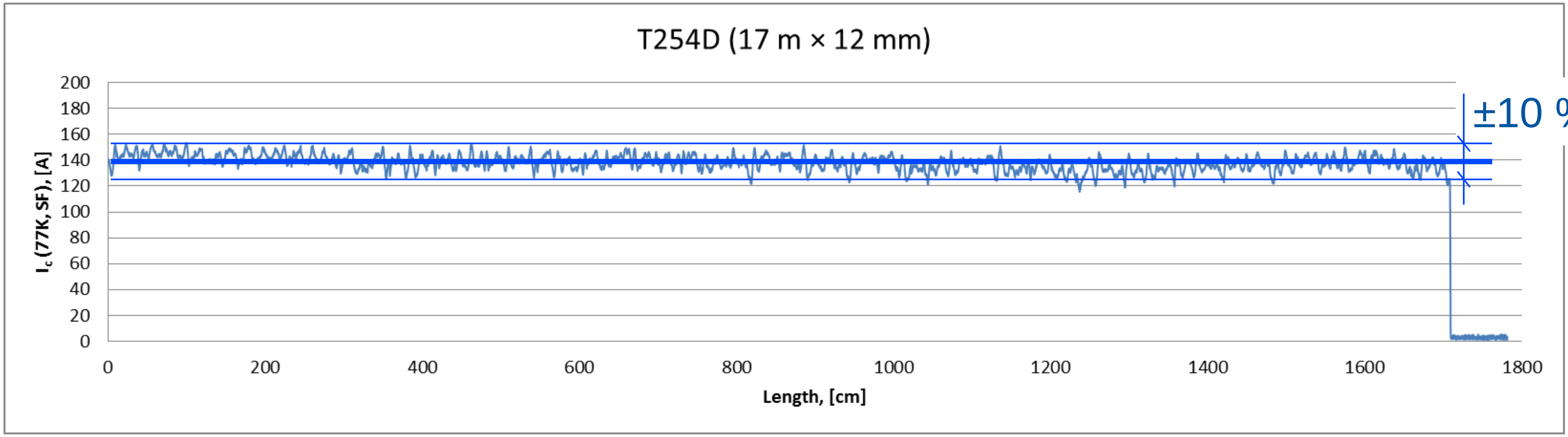


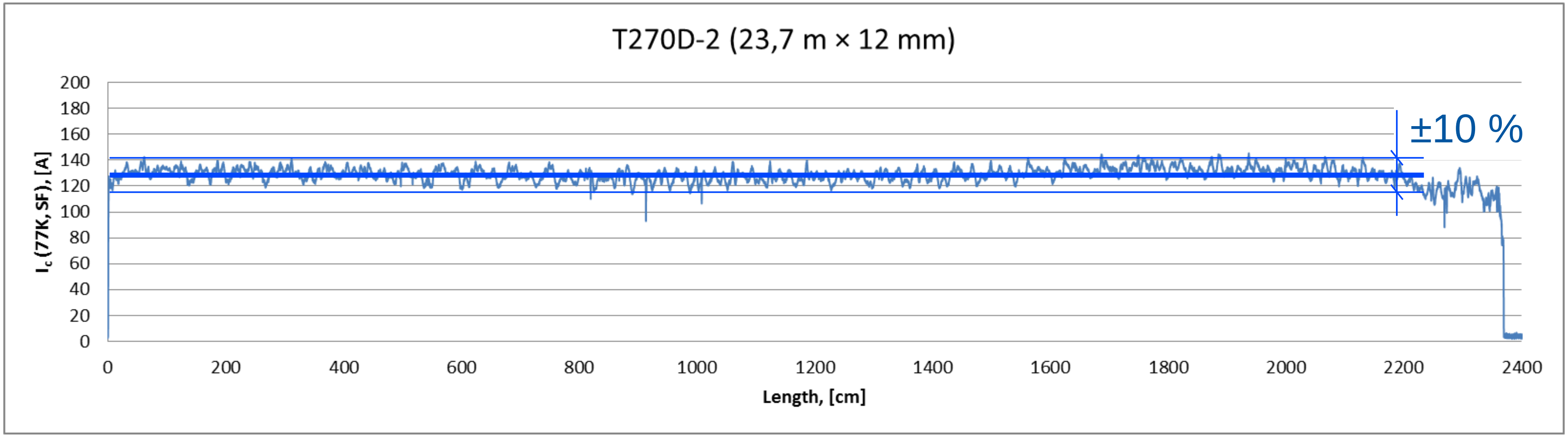
Highest layer J_C obtained in an industrial process

A. Usoskin, 12mm wide HTS coated conductors for high-field applications, 3A-WT-P-02

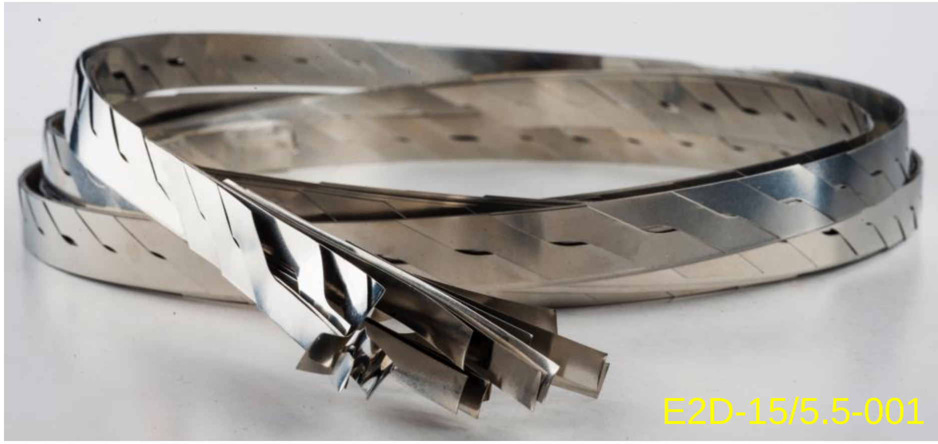
D. Abraimov, et al., “Double disordered YBCO coated conductors”, to appear in SUST, 2015

Homogeneity





Roebel cables



15 SS tapes (0.1 mm), 3 m

Total of ≈ 140 m produced/procured

15 SS+15 Cu tapes (0.1 mm), 3 m

15 BHTS tapes (0.14 mm), 5 m
Expected I_C (4.2 K, 20 T) ≈ 4.2 kA

Total of ≈ 10 m produced

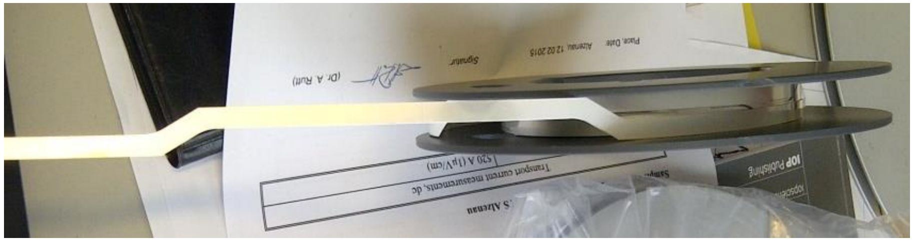
15 BHTS tapes (0.14 mm), 2 m
Expected I_C(4.2 K, 20 T) ≈ 5.1 kA

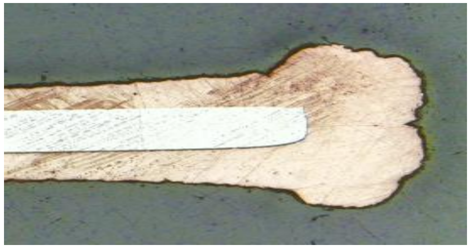
W. Goldacker et al, HTS-Roebel-cables in competition to the CORC approach, 3M-WT-O1

Punch-and-coat

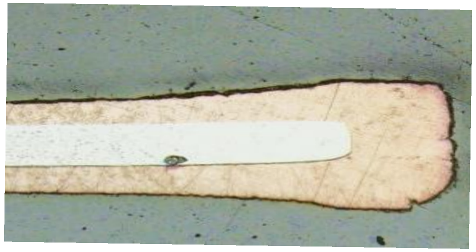
- Standard Roebel production sequence
  - Produce Cu-coated tape
  - Punch meanders
  - Assemble cable
- Modified Roebel production sequence
  - Produce Ag-capped tape
  - Punch meanders (less than 5% I_C degradation !)
  - Cu-coat (dog-boning !)
  - Assemble cable

Ag capped punched tape

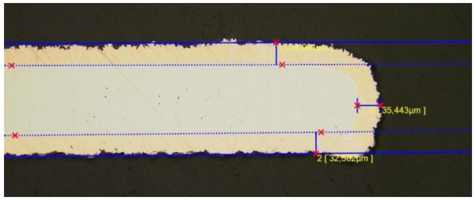




2x40 μm coating

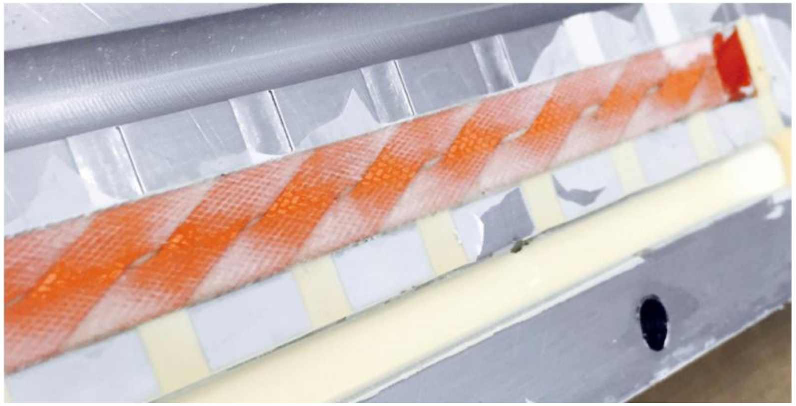


2x20 μm coating



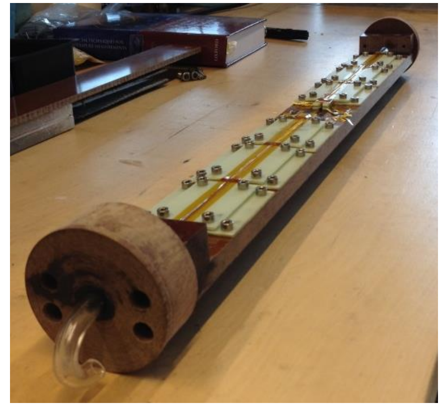
Optimized 2x20 μm coating

Magnetization



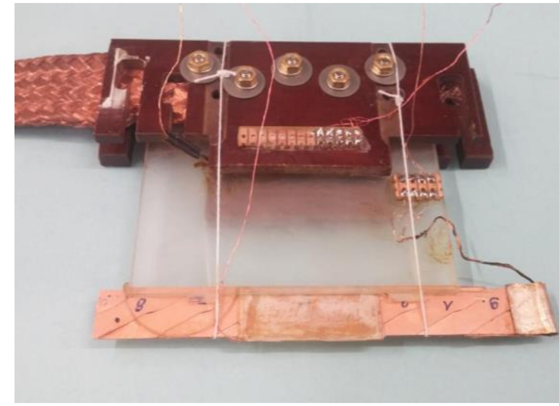
Impregnated (CTD101G)
Roebel cable sample, 226 mm

4.2 K, 400 mT



UNIVERSITEIT TWENTE.

4.2 … 100 K, 350 mT



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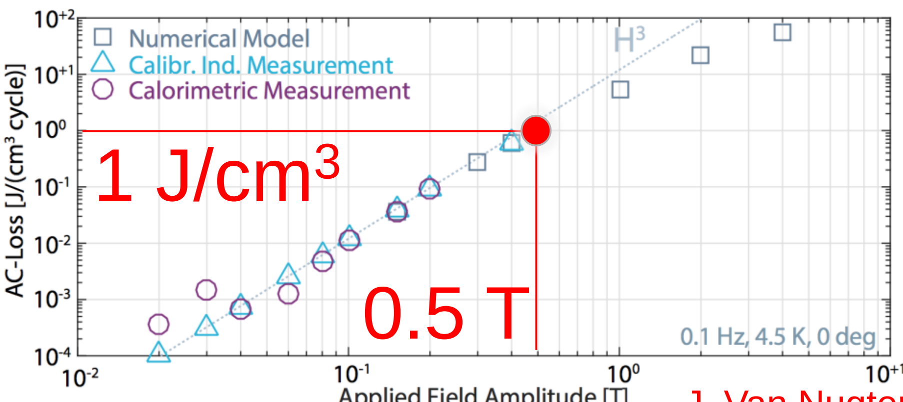
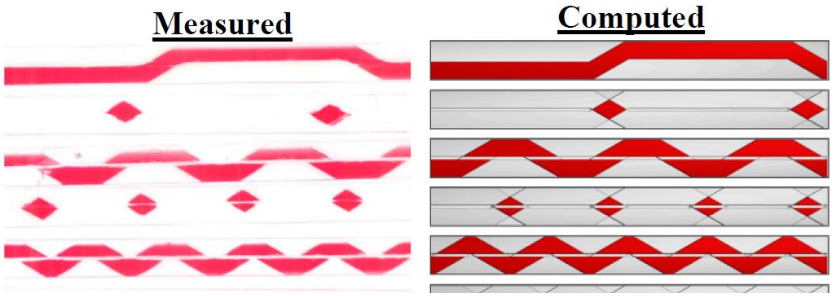


- As expected, the cable has large loss and magnetic moment
- Penetration field is o(1T)
- **Work in progress** as to the understanding and evaluation of field quality in the various magnet design

J. Van Nugteren et al., “Measurement and Numerical Evaluation of AC-Losses in a ReBCO Roebel Cable”, 2M-LS-O2

Transverse forces



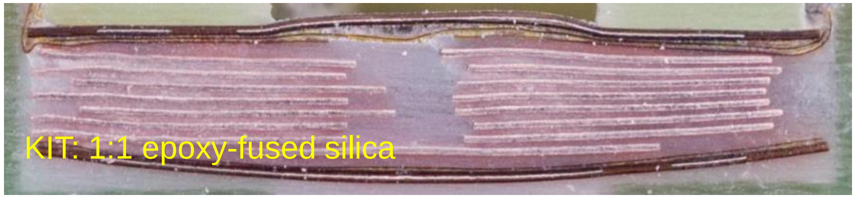
Red=thicker spots =>stress *Grey =thinner spots =>no stress*

Jerome Fleiter and Amalia Ballarino

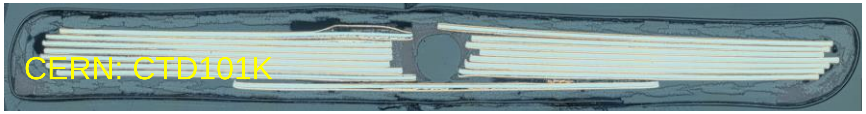
EuCARD2 Annual Meeting http://indico.cern.ch/event/364085/

Benefit of impregnation

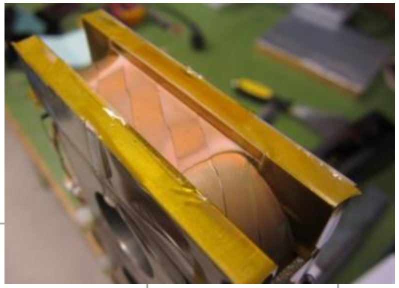
Ch. Barth

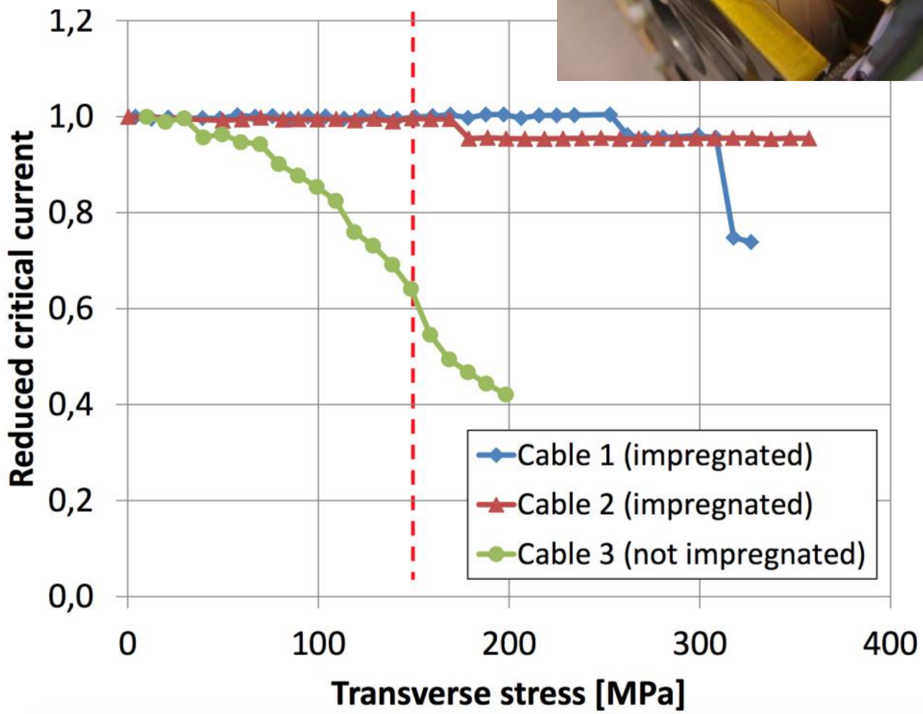


G. Kirby, J. van Nugteren



Measurement in the cable press at the University of Twente





S. Otten et al., "Transverse loading experiments on REBCO Roebel cables with and without impregnation", 2A-WT-P-03.05

Conclusions and plan

- EuCARD2 WP10 (Future Magnets) provides a strong focus to the development of HTS cables for large-scale accelerator magnets
  - Focused on REBCO tape based Roebel cable
  - Tape production and procurements on-going
  - Cable samples ready for characterization
  - Most performance targets are within reach !
- Critical steps in the next half term
  - Validate performance, and compare different materials (configurations ?)
  - Compatibility with coil winding technology, including resin impregnation, and joints
  - Quench detection and protection (!?!) WAMHTS-3 (https://indico.cern.ch/event/396905/)
  - Magnetization effects and control
  - Production for magnet winding

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EuCARD²
WP10.2

Nexans

Grenoble INP

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