CERN-ACC-SLIDES-2016-0021

EuCARD-2

Enhanced European Coordination for Accelerator Research & Development

Presentation

Latest developments and challenges in developing Coated Conductor magnets for accelerators within EuCARD-2

Goldacker, W (KIT) *et al*

11 September 2016

The EuCARD-2 Enhanced European Coordination for Accelerator Research & Development project is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453.

This work is part of EuCARD-2 Work Package **10: Future Magnets (MAG)**.

CERN-ACC-SLIDES-2016-0021

High-temperature superconductors towards applications

at SUPRA group,
Institute for Technical Physics
Karlsruhe Institute of Technology

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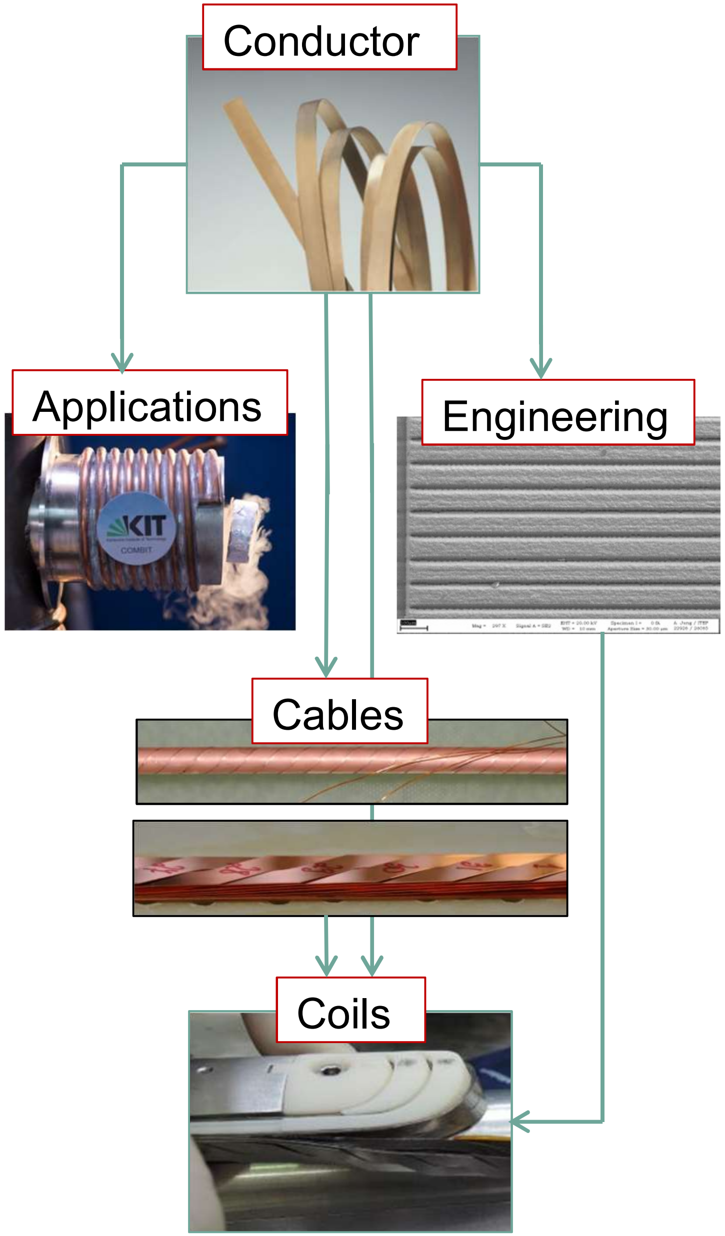
M. Vojenciak, SAV Institute of Electrical Engineering
D. van der Laan, Advanced Conductor Technologies
EuCARD[2] Project, WP10 Partners (listed in part 5)

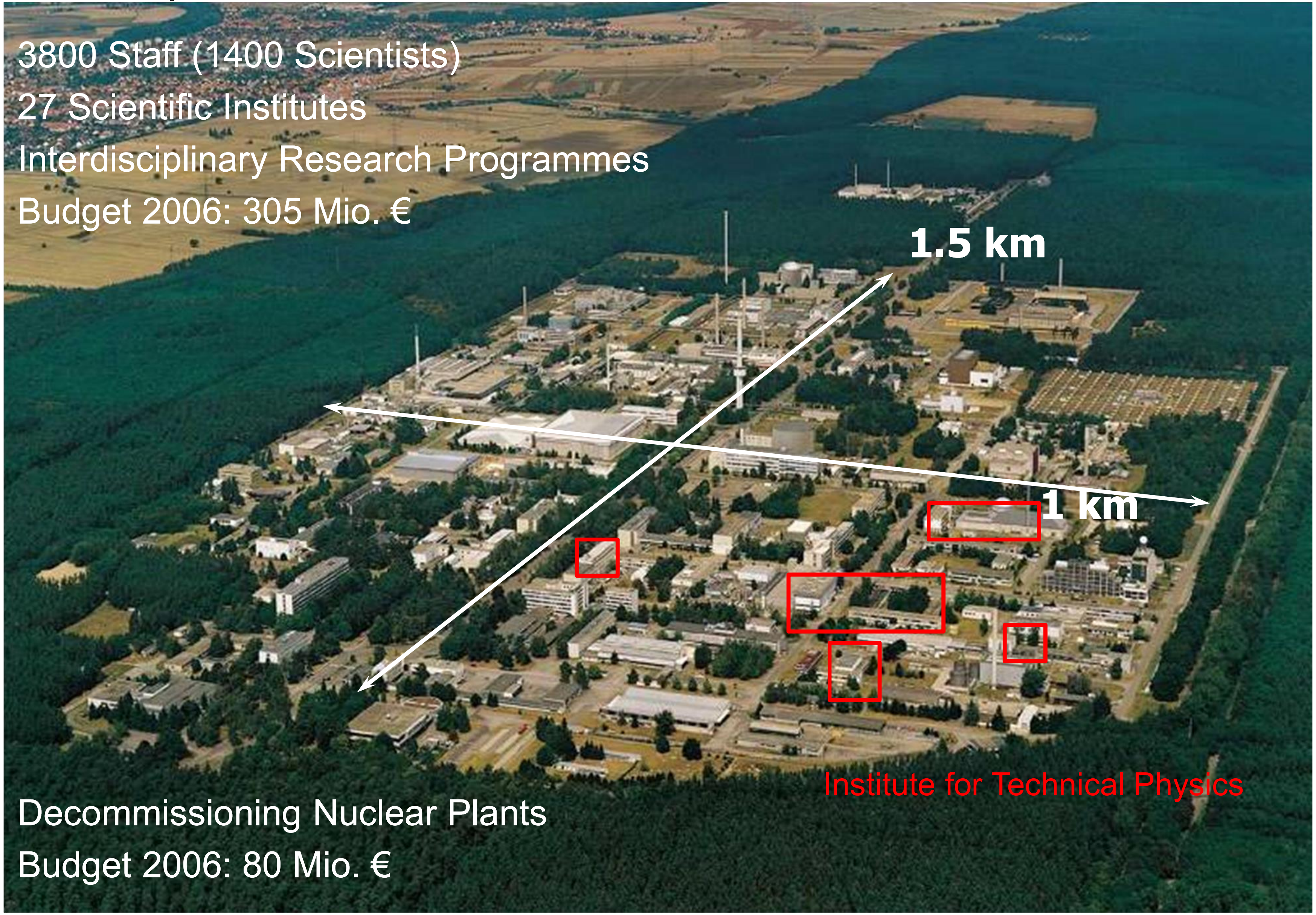
EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

Outline:

1. Institute for Technical Physics – Introduction
2. HTS – coated conductor materials
3. Examples of coated conductor applications at SUPRA
4. Engineering of Coated Conductor towards low AC loss
5. Roebel Coated Conductor cable in EuCARD^2 – future magnets program



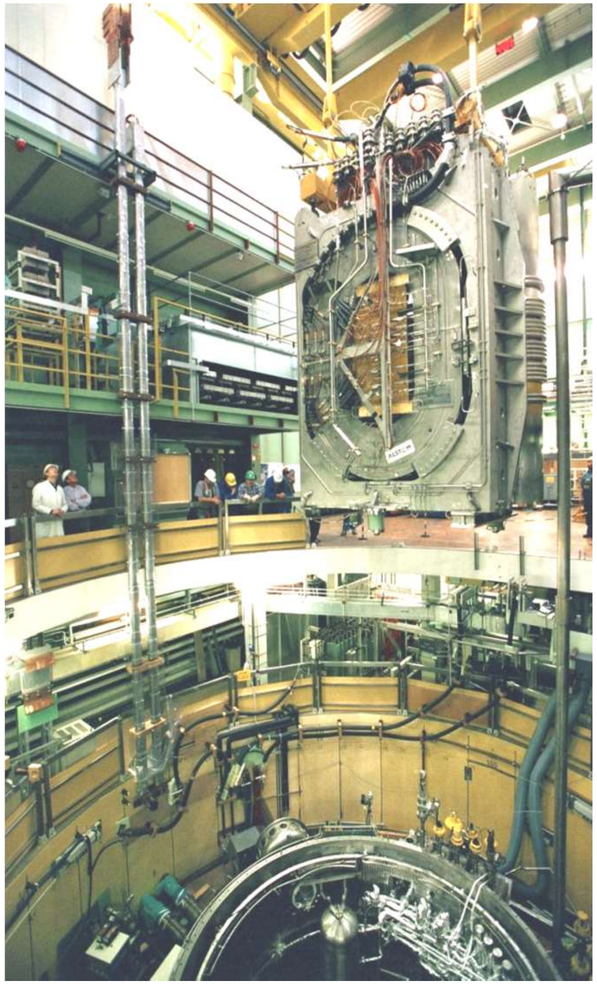
Karlsruhe Institute of Technology
- Campus North:



Institute for Technical Physics:

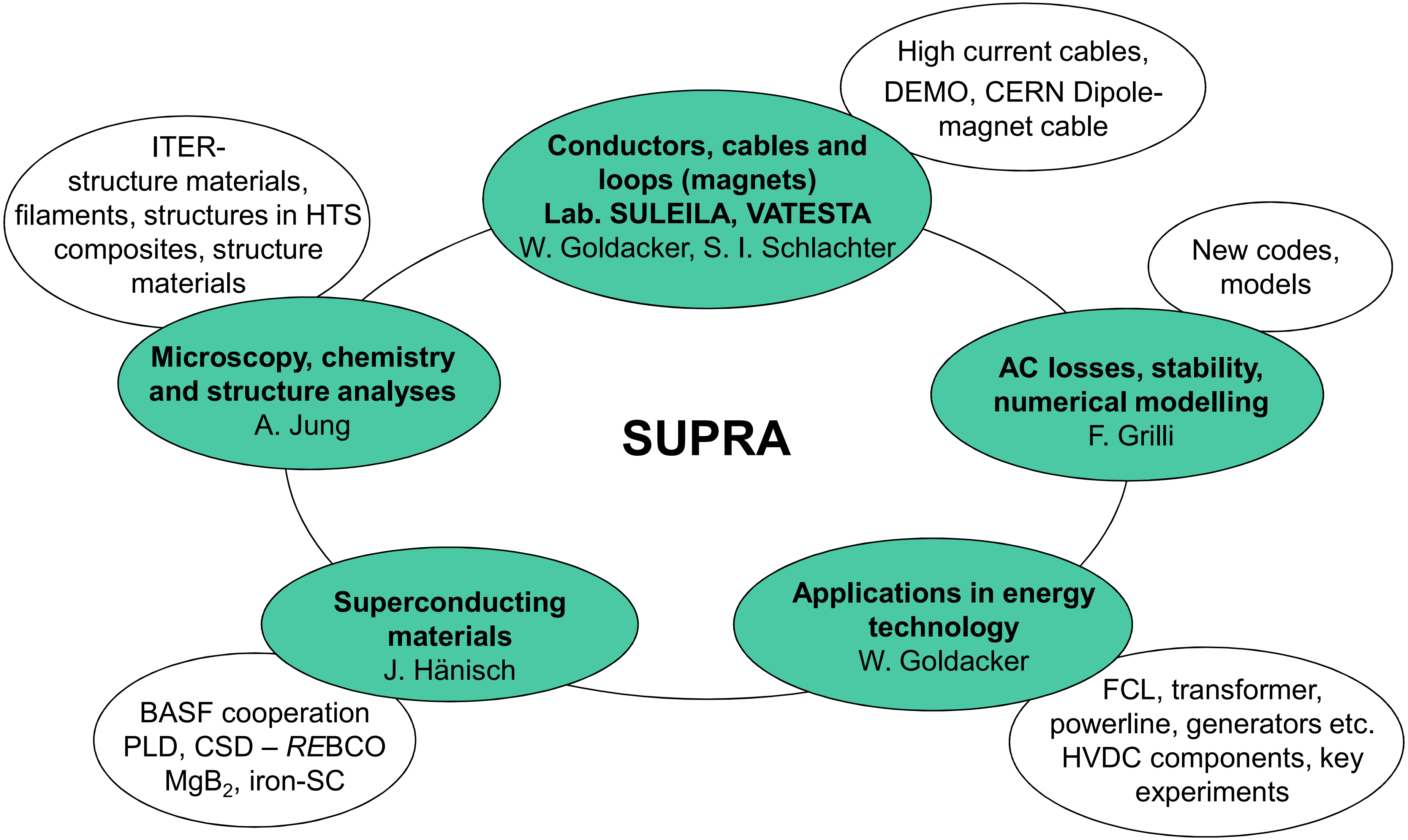
Institute directors: Prof. Mathias Noe
Prof. Bernhard Holzapfel

- Fusion magnet technology (Dr. Walter Fietz)
- Vacuum technology (Dr. Christian Day)
- **Superconducting materials and energy applications (Dr. Wilfried Goldacker)**
- High field magnets and special magnet systems (Dr. Theo Schneider)
- Cryogenics (Dr. Holger Neumann)
- Tritium technology (Dr. Beate Bornschein)



Department: Superconductor developments and energy applications

Head: W. Goldacker (S. I. Schlachter)



High-temperature superconductors towards applications (part of SUPRA):

Karlsruhe Institute of Technology

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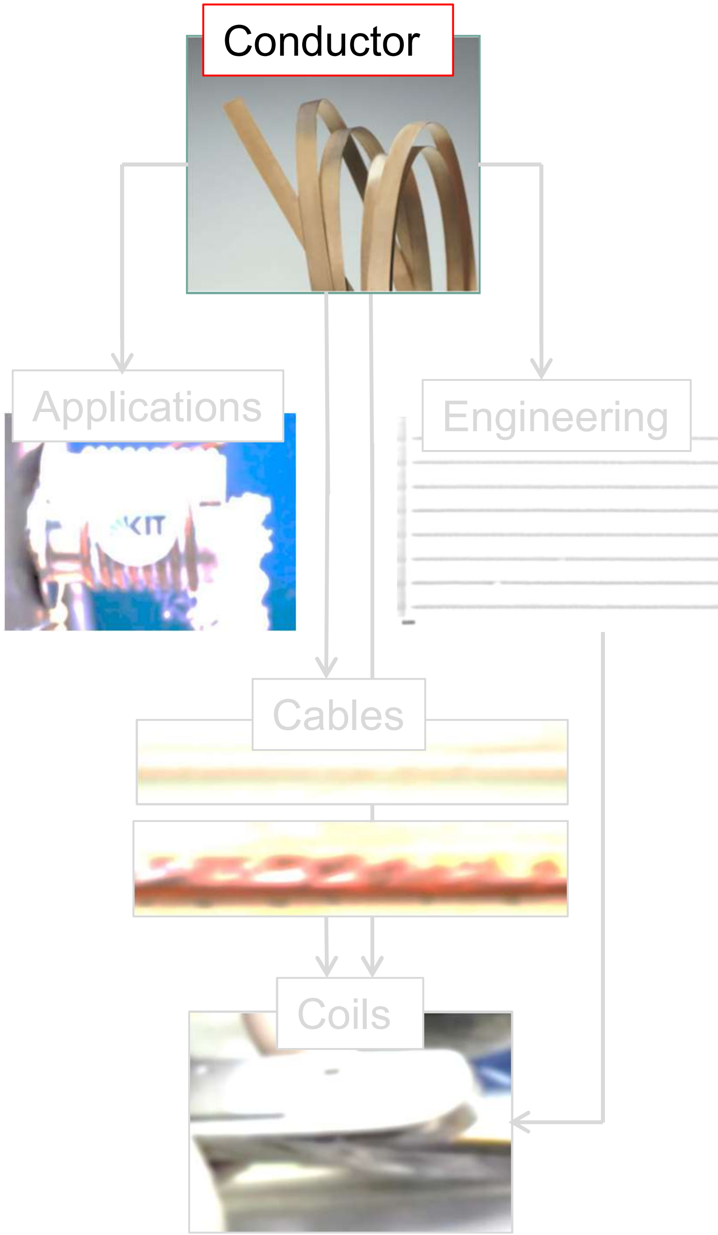
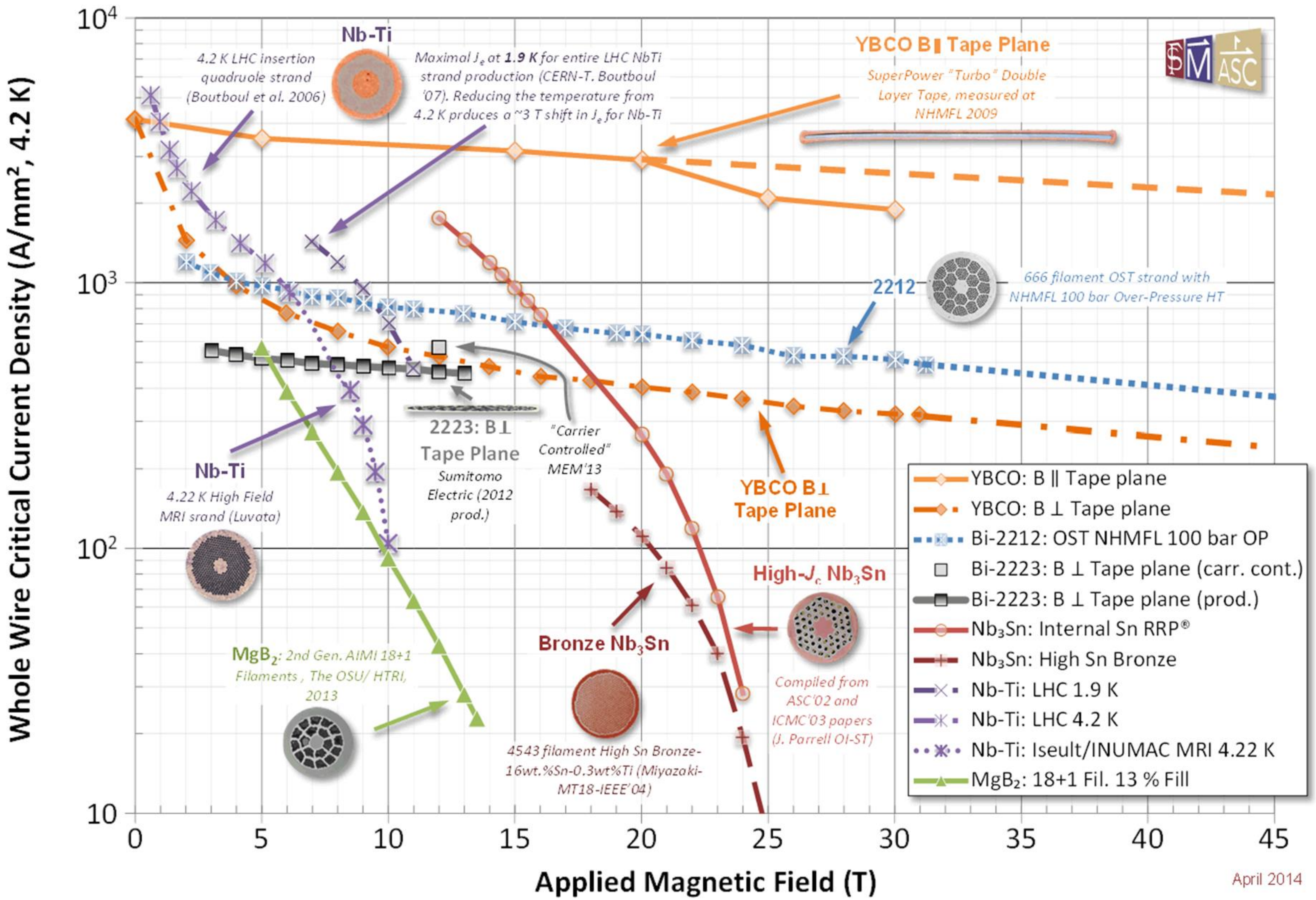
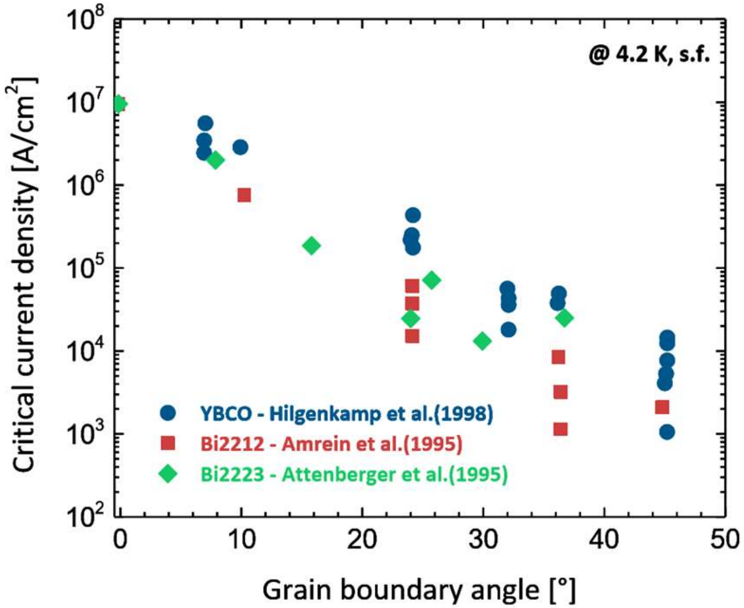


Superconducting materials for applications:



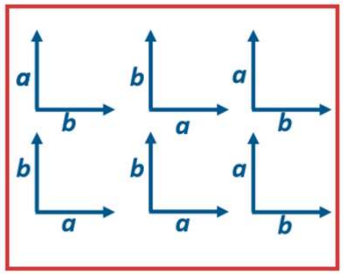
P. Lee. The expanded ASC “Plots” page. 2014. URL: http://fs.magnet.fsu.edu/ ~lee/plot/plot.htm.

Coated conductor architecture:

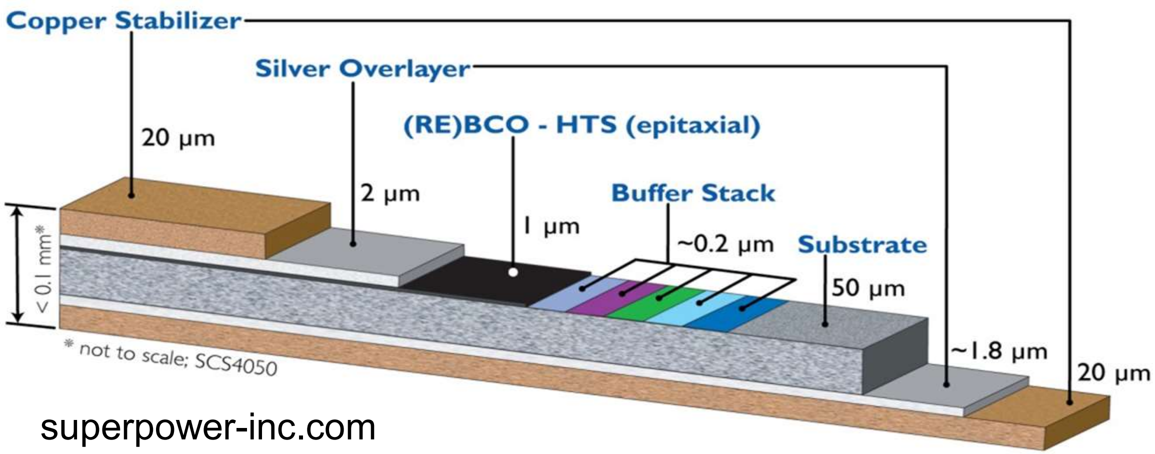


- Template – metallic substrate coated with a multifunctional oxide barrier
- Biaxial texturing – within < 3° is needed to overcome the grain boundary problem

C. Senatore, Plenary talk:
''30 years of HTS Status and perspectives'',
ASC 2016, Denver



Top view



superpower-inc.com

30 – 100 μm substrate:
Hastelloy C-276 or
stainless steel

Coated conductor preparation routes:

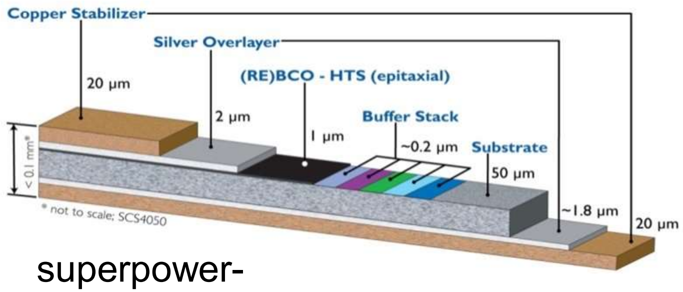
1. Substrate preparation

<u>RABiTS</u> – Rolling-Assisted, Biaxial Textured Substrates

(NiW substrate is textured)

<u>IBAD</u> – Ion Beam Assisted Deposition

(polycrystalline Hastelloy, biaxial textured MgO)



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2. *RE*BCO preparation

<u>Physical routes:</u>

PLD – Pulsed Laser Deposition

RCE Reactive Co-Evaporation

<u>Chemical routes:</u>

MOD Metal-Organic Deposition

MOCVD Metal-Organic Chemical Vapour Deposition

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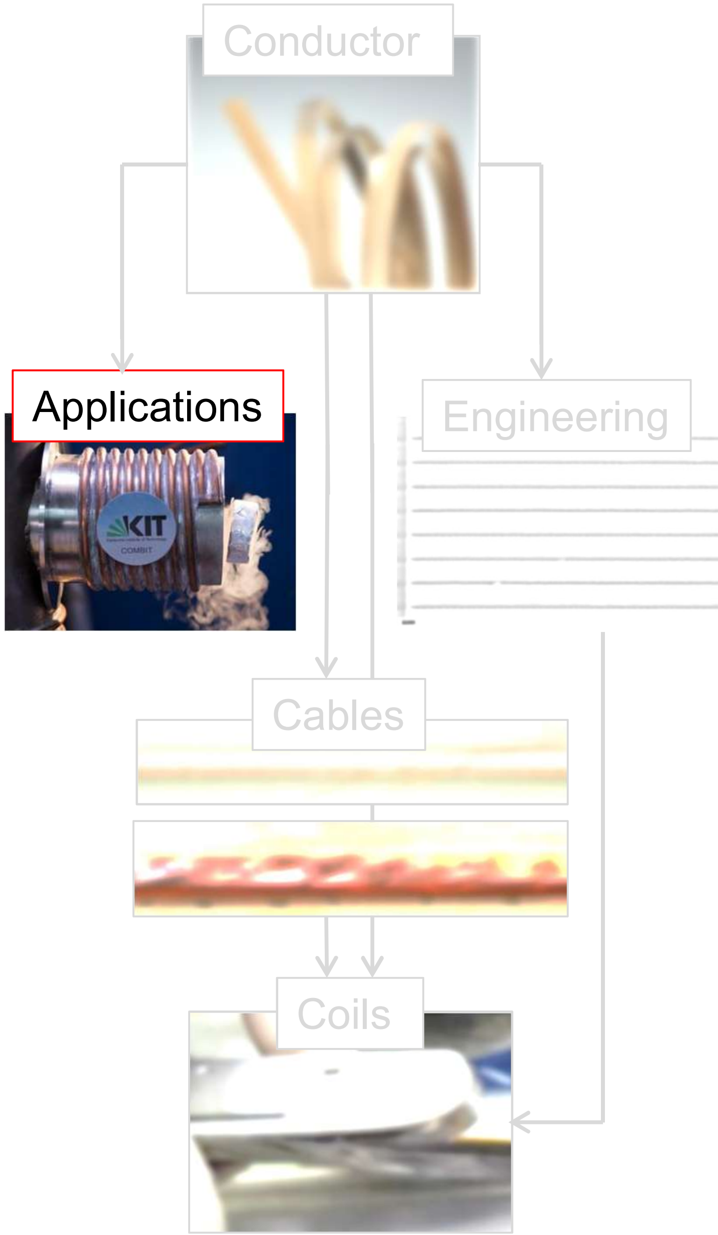
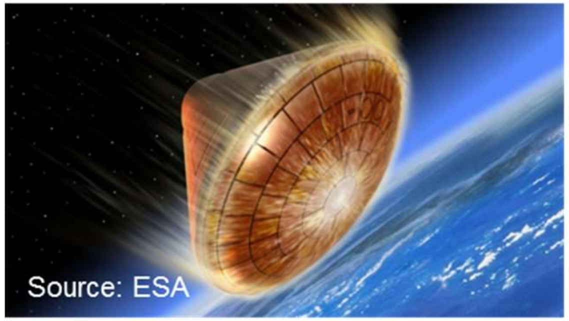
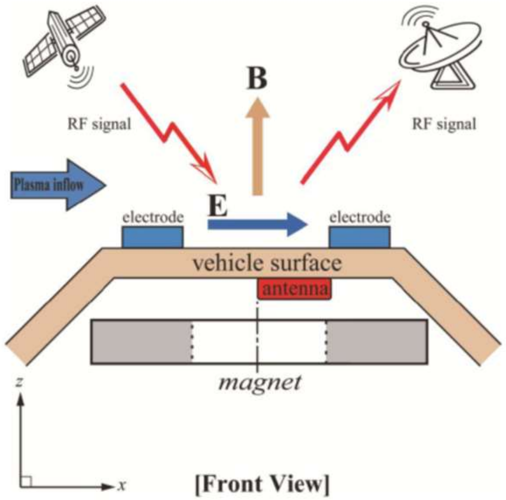


COMBIT - communication blackout mitigation

- Communication interruption due to attenuation and/or reflection of radio waves by plasma layer that is created during hypersonic or re-entry flight



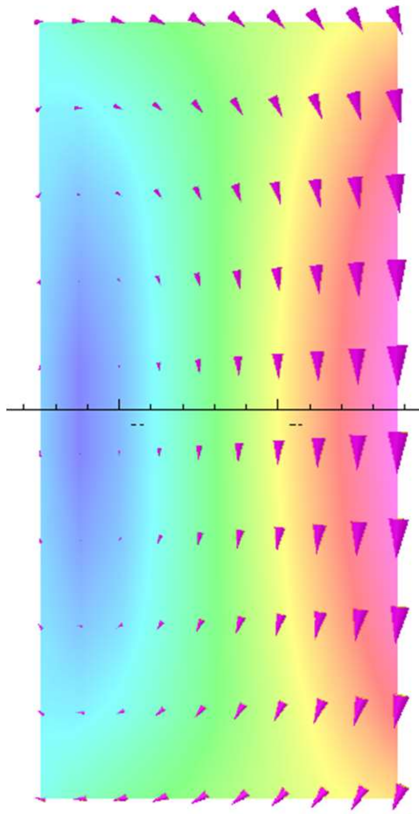


Courtesy of A. Gülhan, DLR Cologne, Joint Research Proposal, Helmholtz Russia Joint Research Group

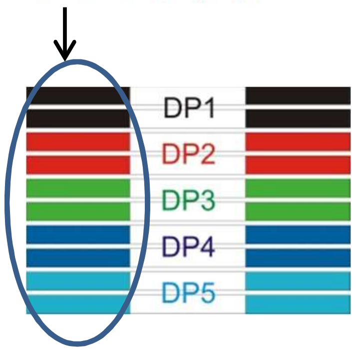
- Loss of communication with ground stations or satellites including GPS signals, data telemetry, and voice communication
- Examples:

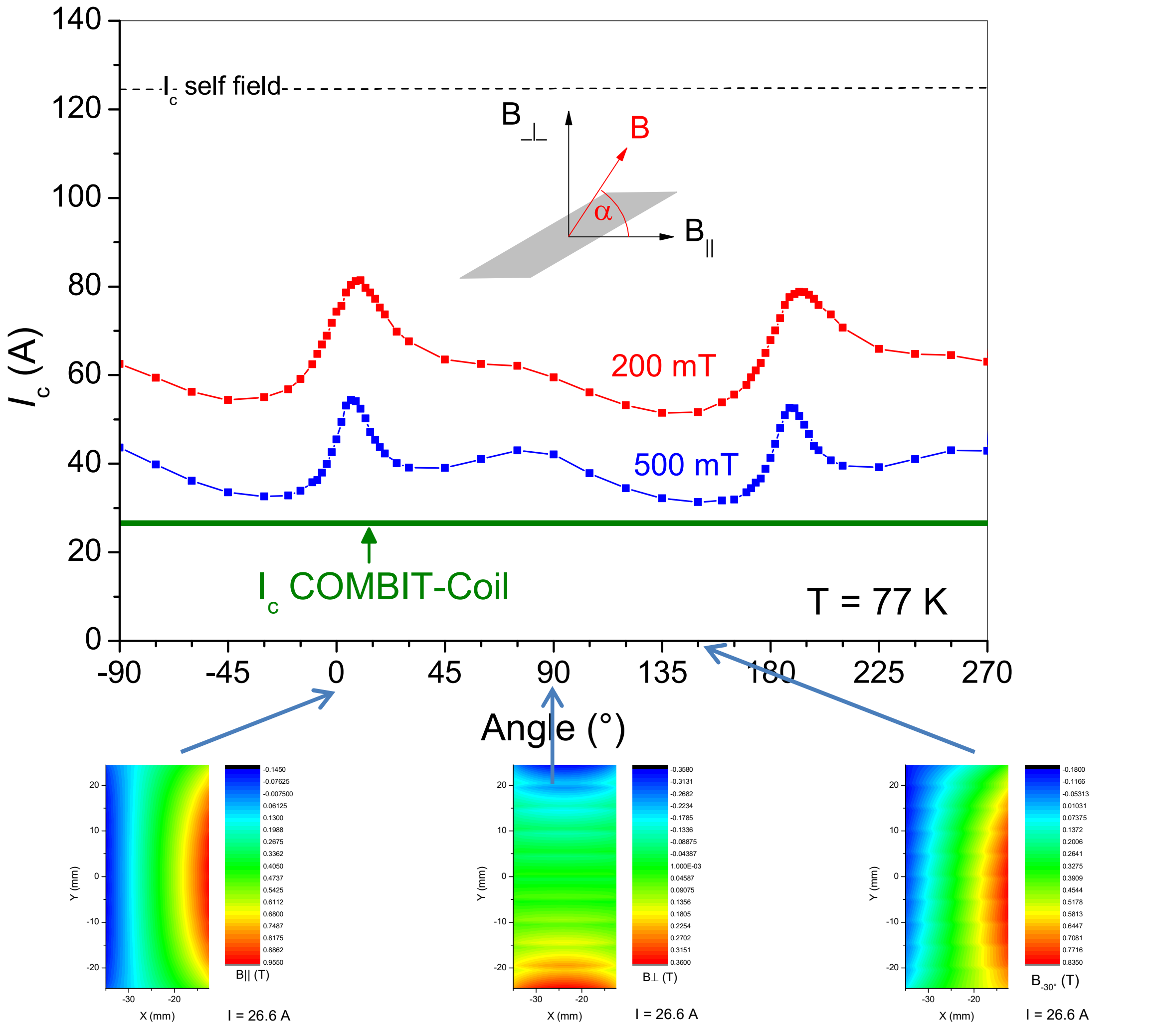
Mission	Duration of blackout phase
Gemini 2	~ 4 minutes
Apollo	~ 3 minutes
Mars Pathfinder	~ 30 seconds
Space shuttle (before creation of Tracking and Data Relay Satellite System)	~ 30 minutes

COMBIT - Angular field dependence of critical current:



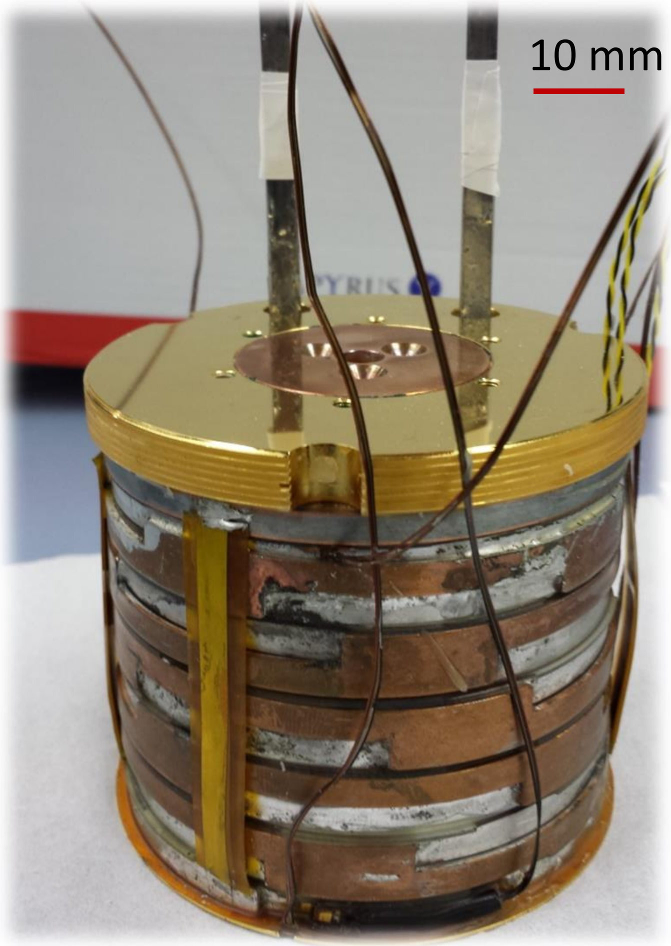
Magnetic field strength in the magnet

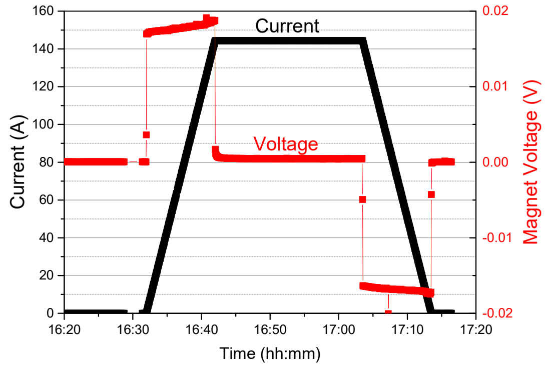


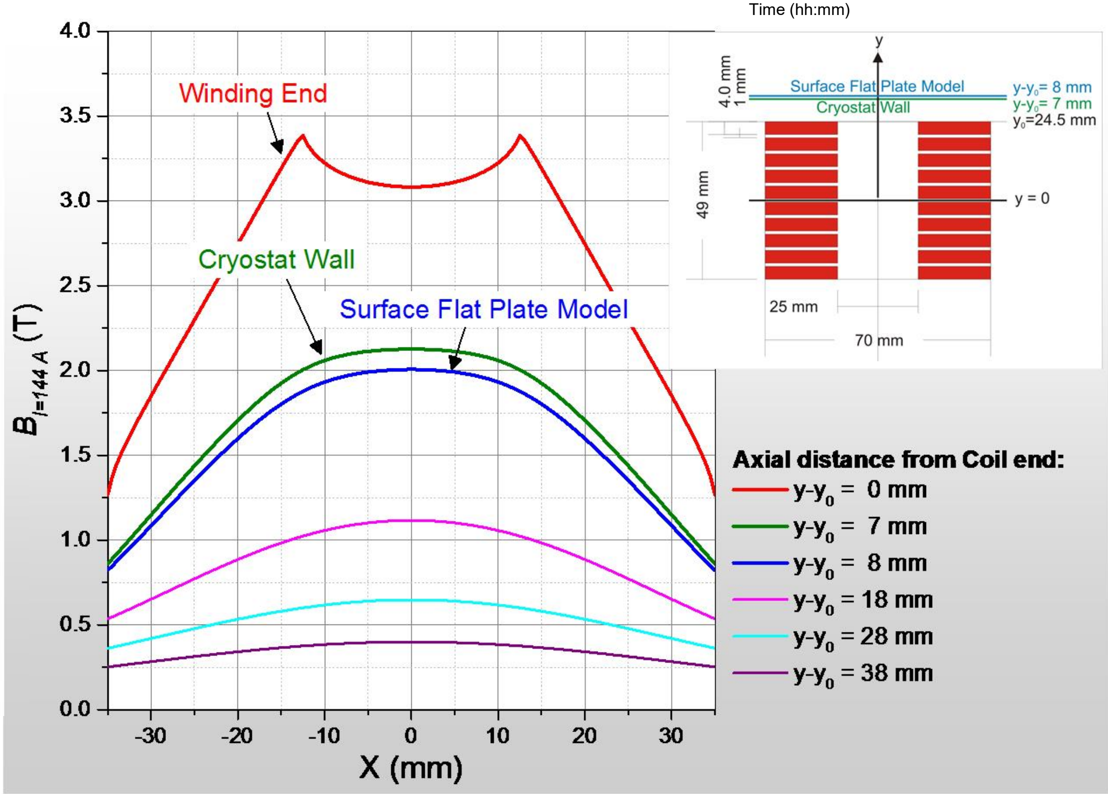


$B_{||,\,max}$ = 0.955 T $B_{\perp,\,max}$ = 0.36 T $B_{-30°,\,max}$ = 0.835 T

COMBIT - HTS magnet and produced field:

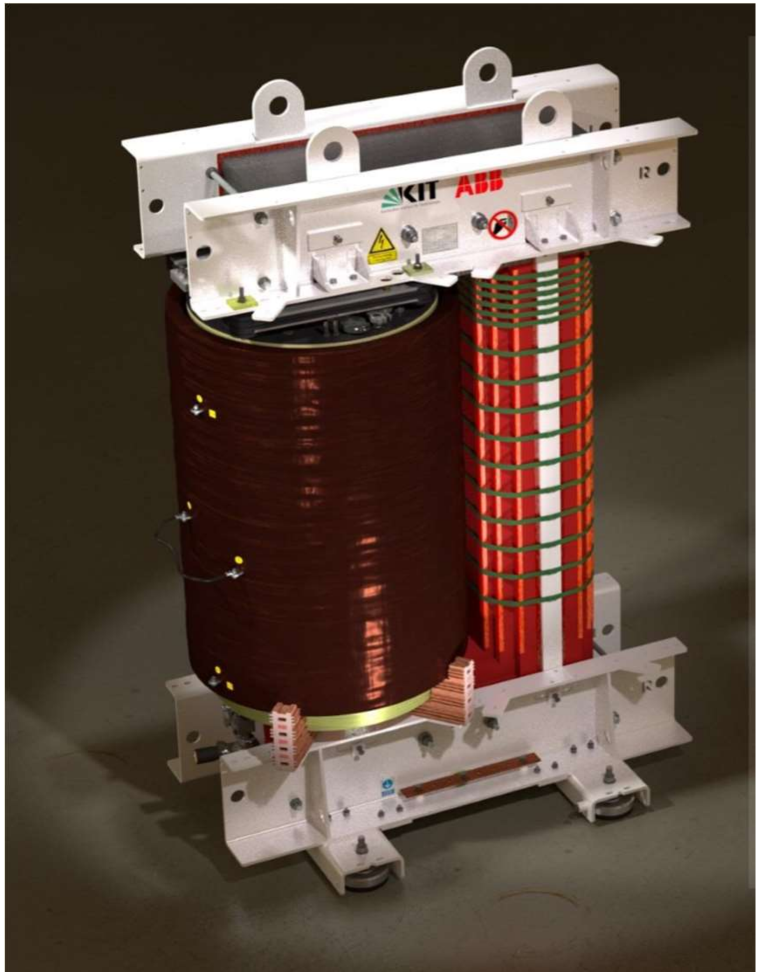




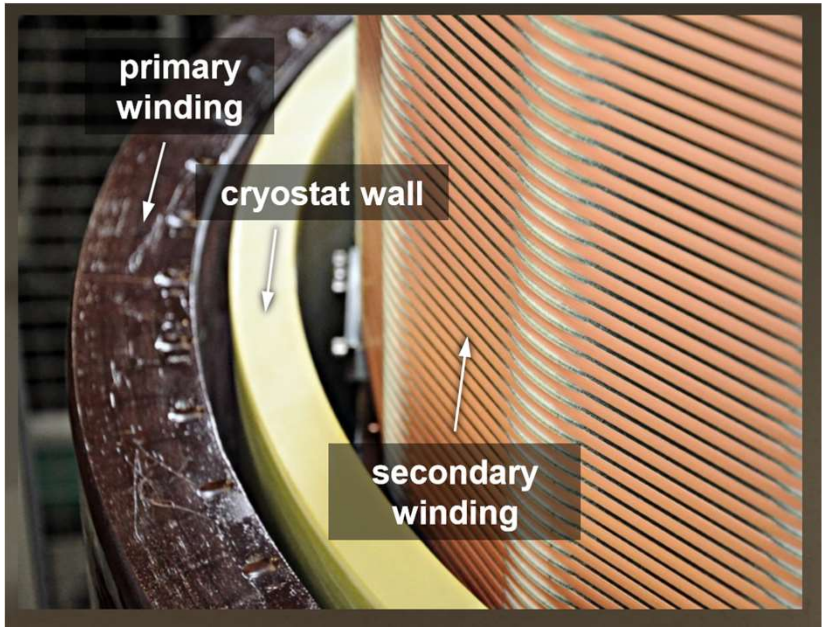


1MVA-Transformer Project KIT-ABB:

S. Hellmann, M. Noe

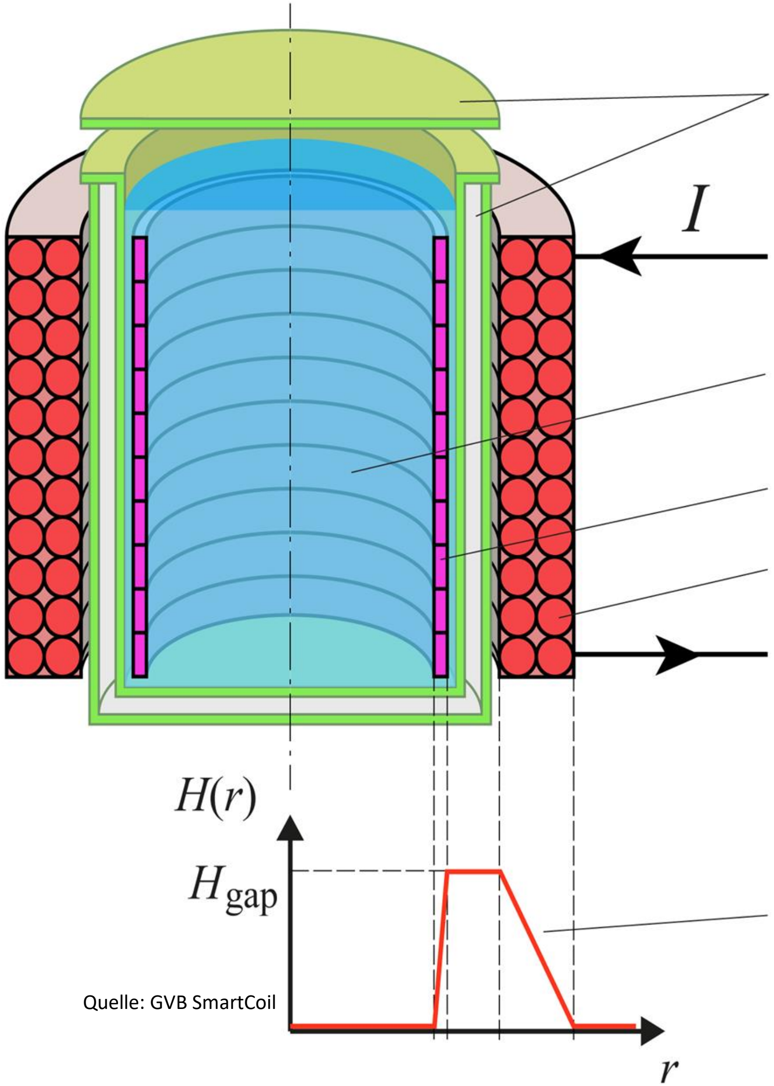


- Primary winding: 20 kV_{RMS} / 28.87 A_{RMS} (warm, copper)
- Secondary winding: 1 kV_{RMS} / 577.35 A_{RMS} (2G HTS)



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

SmartCoil – current limiter:



Cryostat with vacuum-isolation

Current in the reactance coil

Cooling medium LN_2 - 77K normal pressure

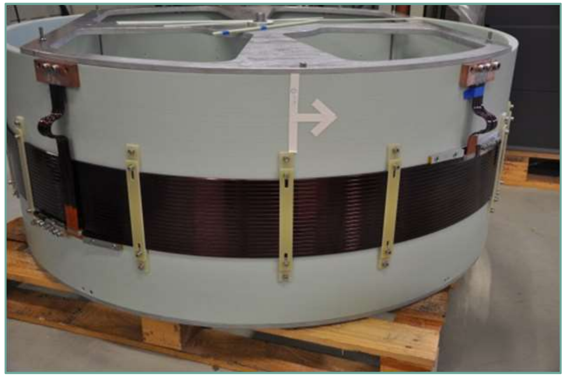
shortcut coil

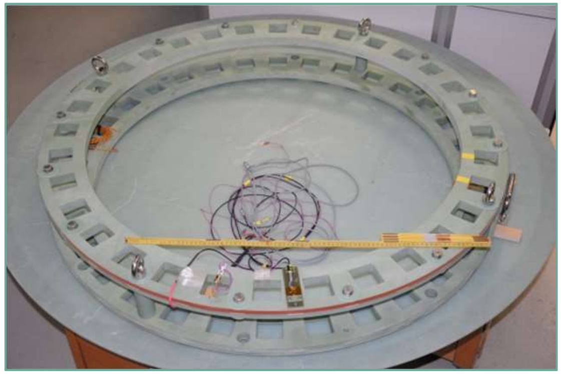
reactance coil

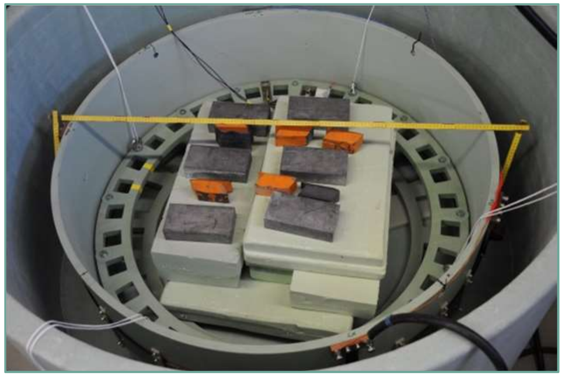
Magnetic field by nominal current (600 A_{RMS})

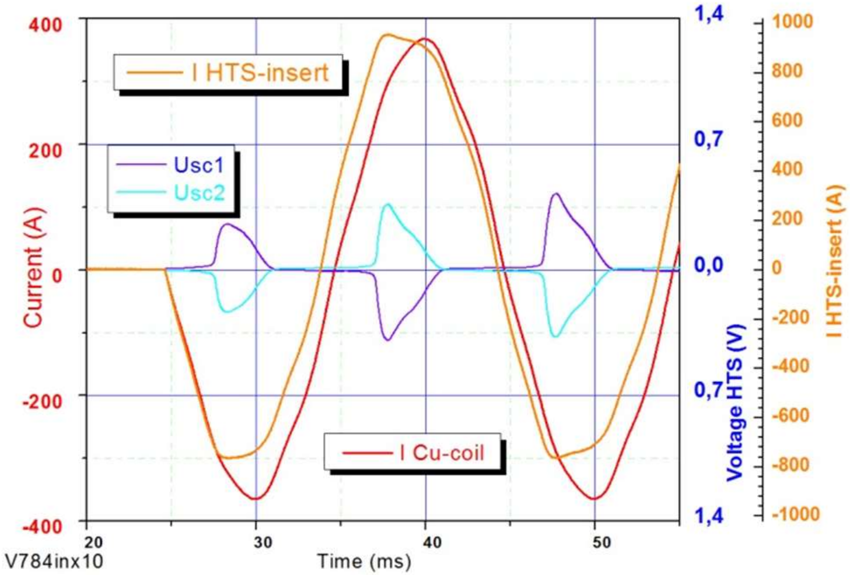
- Nominal voltage U_{nom} 5.77 kV_{RMS}
- Current limiting time 100 msec
- 80 ... 95 short-cut 2G HTS-rings (D=1.2 m)
- Soldered contacts

SmartCoil – current limiter:









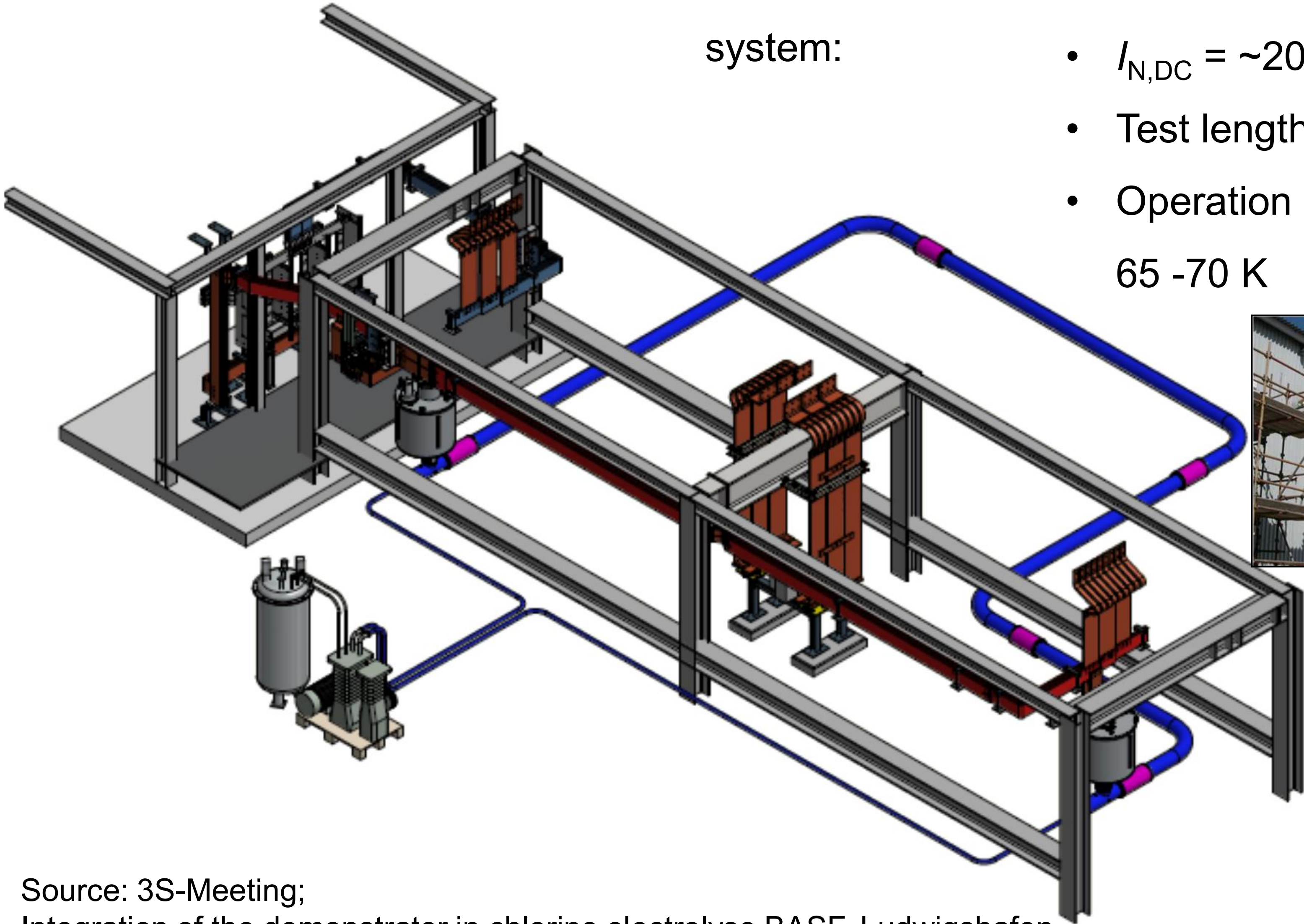
Conductor tests:

- Superpower SCS12100 und SCS12050 (1 m piece in 2 short-cuted rings)
- STI (1 m piece in 2 short-cuted rings)
- SuNAM (1 m piece in 2 short-cuted rings)
- THEVA (1 m piece)

3S – “SupraStromSchiene“ - superconducting current rail:

Modular construction and exchangeable rail system:

- $I_{N,DC}$ = ~20 kA
- Test length = 25 m
- Operation temperature: 65 -70 K



Source: 3S-Meeting;
Integration of the demonstrator in chlorine electrolyse BASF, Ludwigshafen

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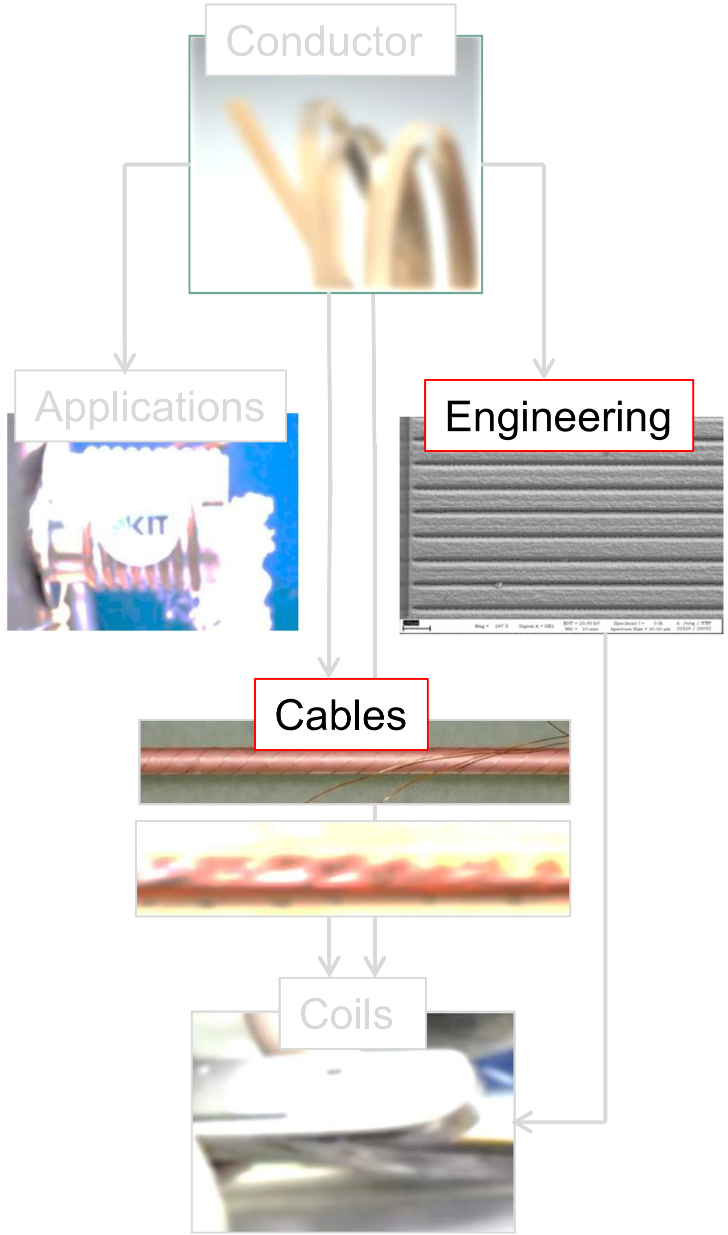


Engineering of low AC loss conductors and cables:

1. Applications with time varying magnetic fields:

- Reduction of AC losses (filaments)

Analytic solution for single strip:
E.H. Brandt (Phys. Rev. B vol.48 no.17, 1993)

$$\begin{cases} \boldsymbol{Q} = \boldsymbol{W}^{2} J_c B_0 g\left(\frac{\pi B_0}{\mu_0 J_c}\right) \\ g(x) = \frac{2}{x}\ln(\cosh(x)) - \tanh(x) \end{cases}$$

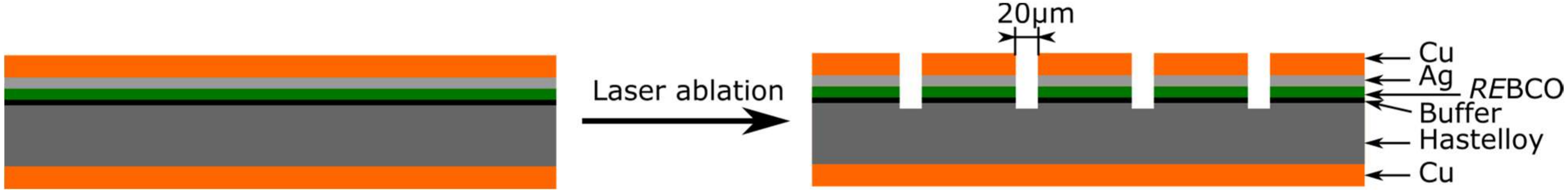
- Most often need a stabilizer (copper)

2. Challenge:

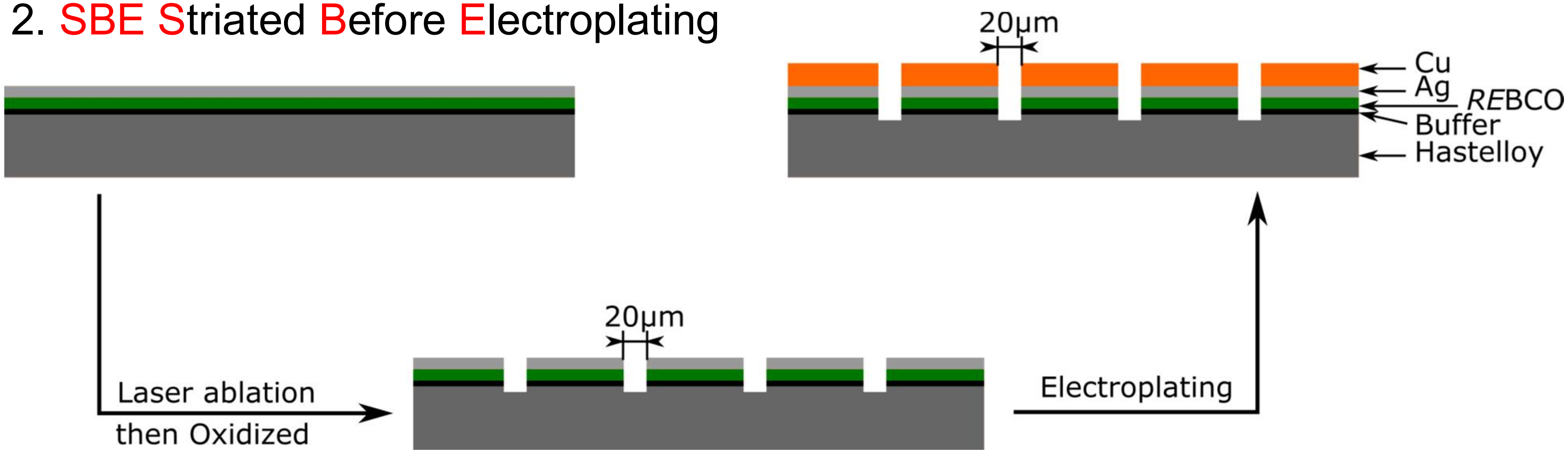
- Filaments with small deterioration of critical current
- Low losses with high number of filaments
- Application of coated conductors into cable structure

Engineering of low AC loss conductors:

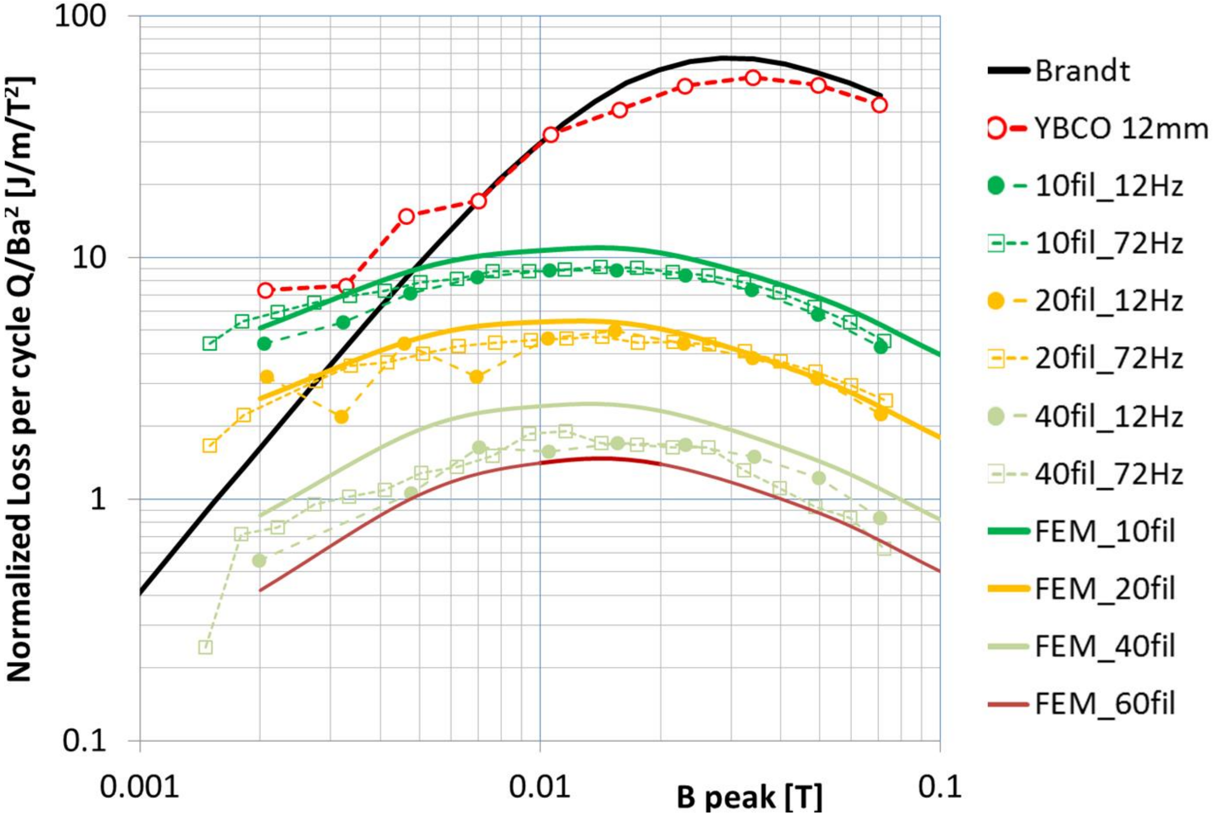
1. SAE - Striated After Electroplating

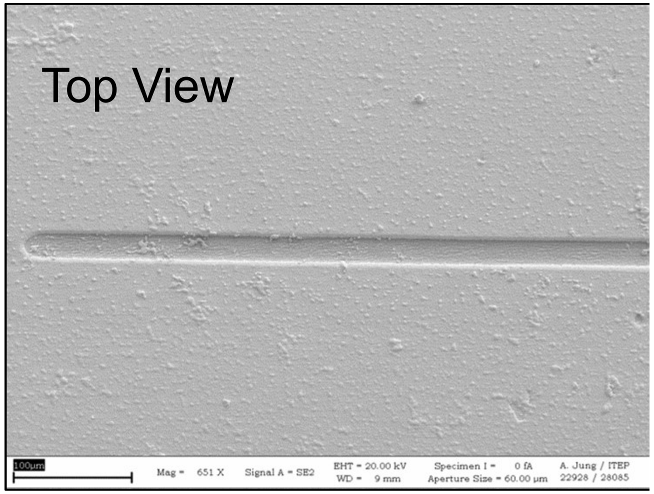


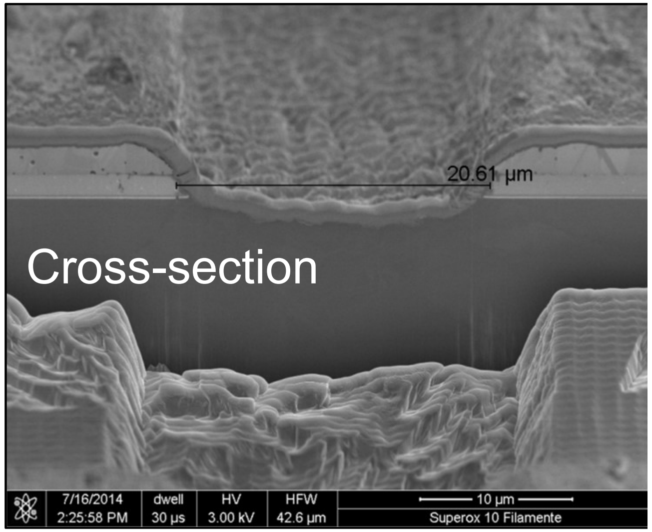
2. SBE Striated Before Electroplating



AC loss of Ag cap coated conductor after oxidation:



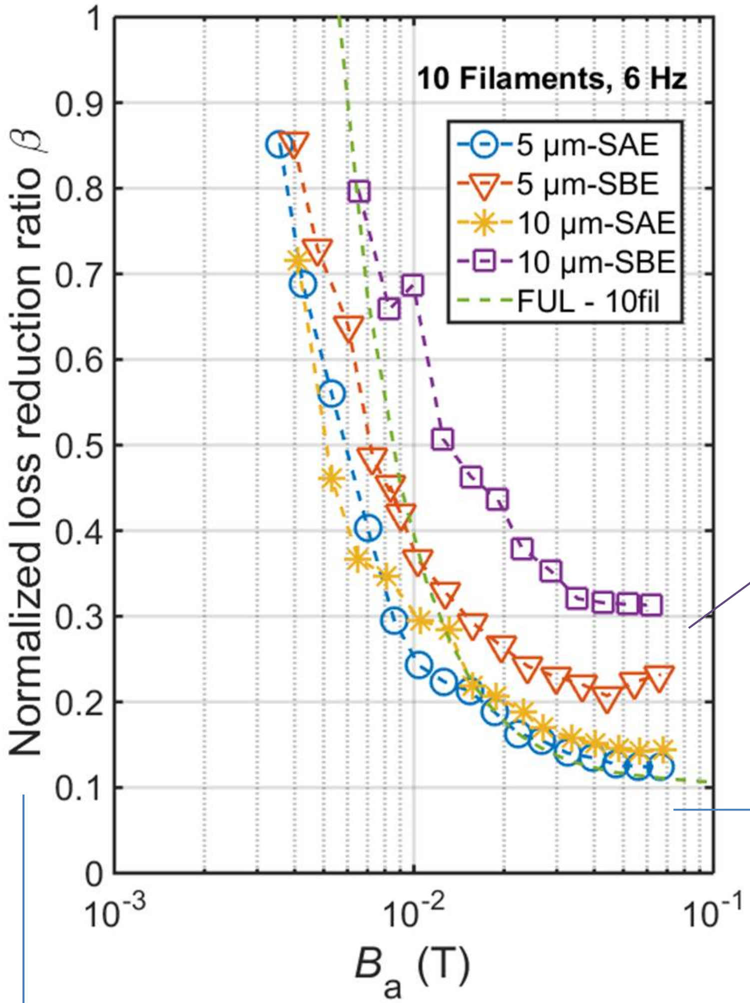


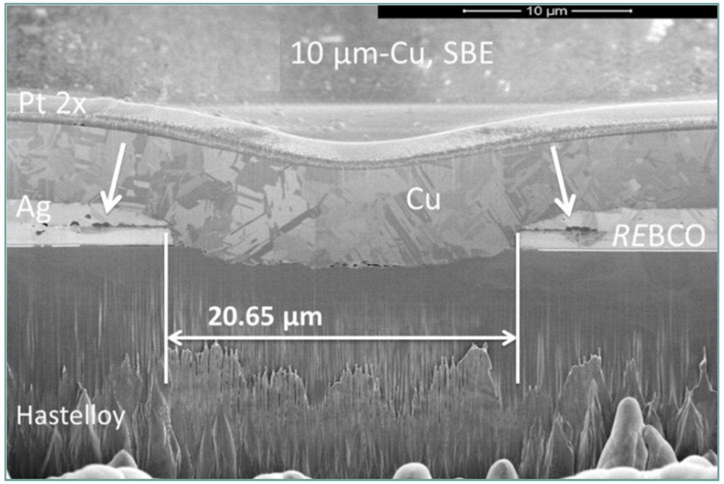


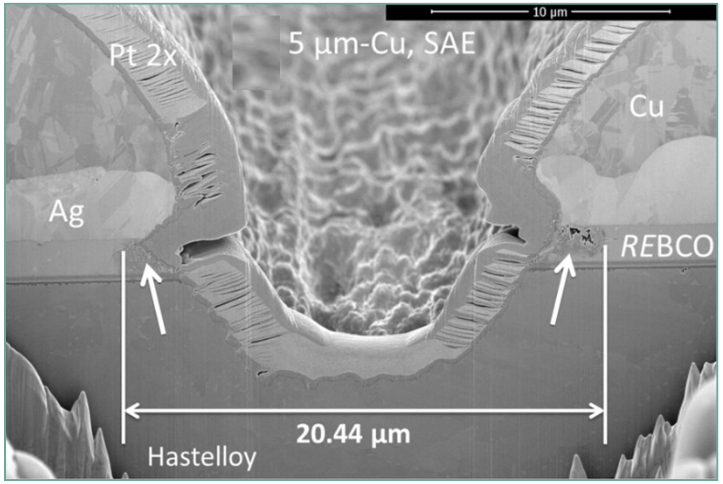
IFW Dresden, J. Scheiter

- LN_2, calibration free method
- 12, 72 Hz, SuperOx

AC loss of coated conductor with 5 an 10 µm Cu stabilisation:







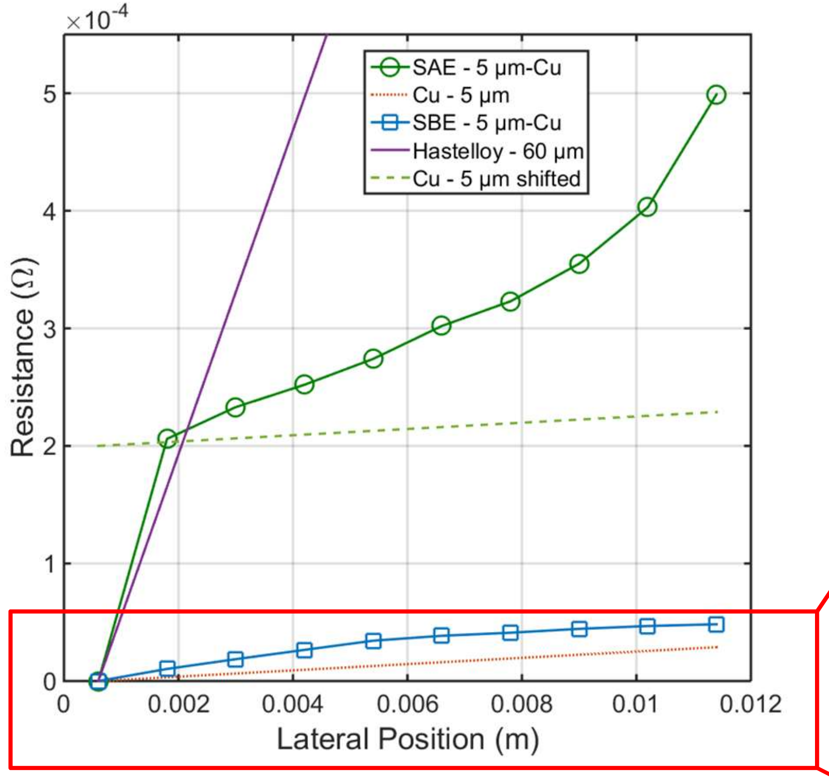
IFW Dresden, J. Scheiter

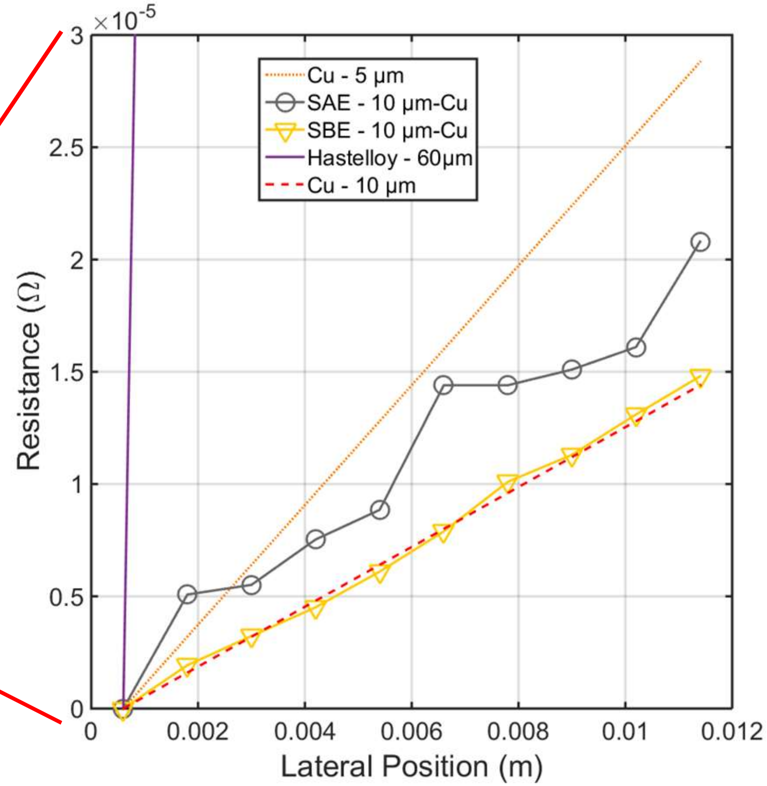
$$\beta = \frac{\alpha\, Q_{st}}{Q_{ref}} \qquad \alpha = \frac{I_{c,ref}}{I_{c,st}}$$

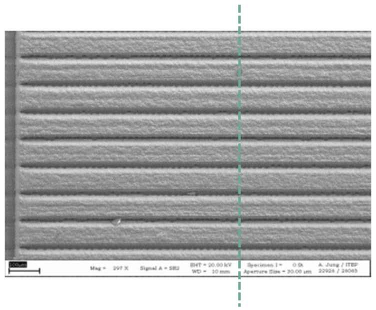
- LN_2, calibration free method
- SuperOx

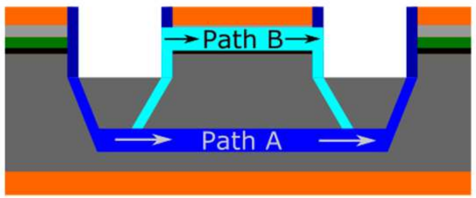
Transverse resistance and possible resistive current path across conductor:

- 10 filaments
- SAE & SBE
- 5 & 10 µm-Cu
- 77 K





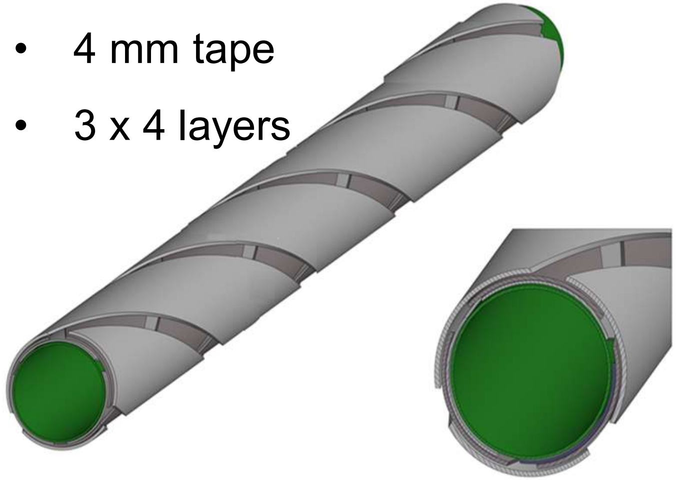




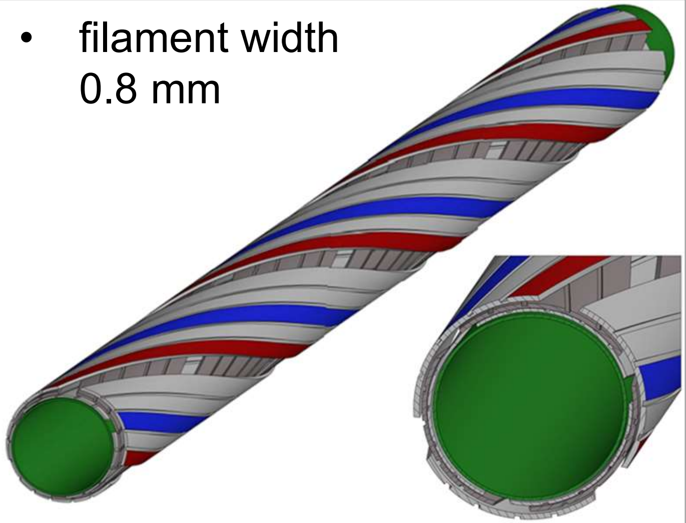
Engineering of low AC loss cables – CORC:

	CORC (Coated Conductor on Round Core)
Tape transpo-sition	• Determined by core diameter • Partial • Each layer has a different transposition length
Critical current	• Increases with the number of layers
J_e Enginee-ring current density	• Depends on used core
Anisotropy	• Averaged

- 4 mm tape
- 3 x 4 layers



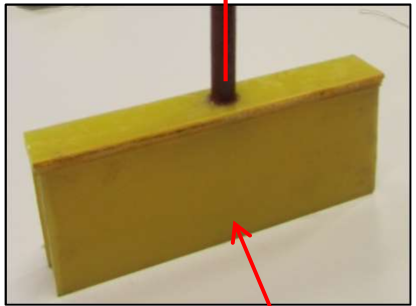
- filament width 0.8 mm



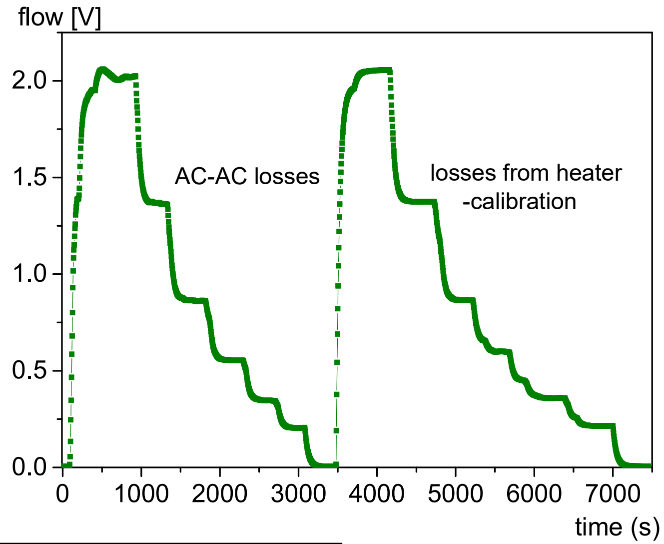
AC loss with AC field and AC current conditions:

- α = B/I
- 0.03, 0.07, 0.1 mT/A

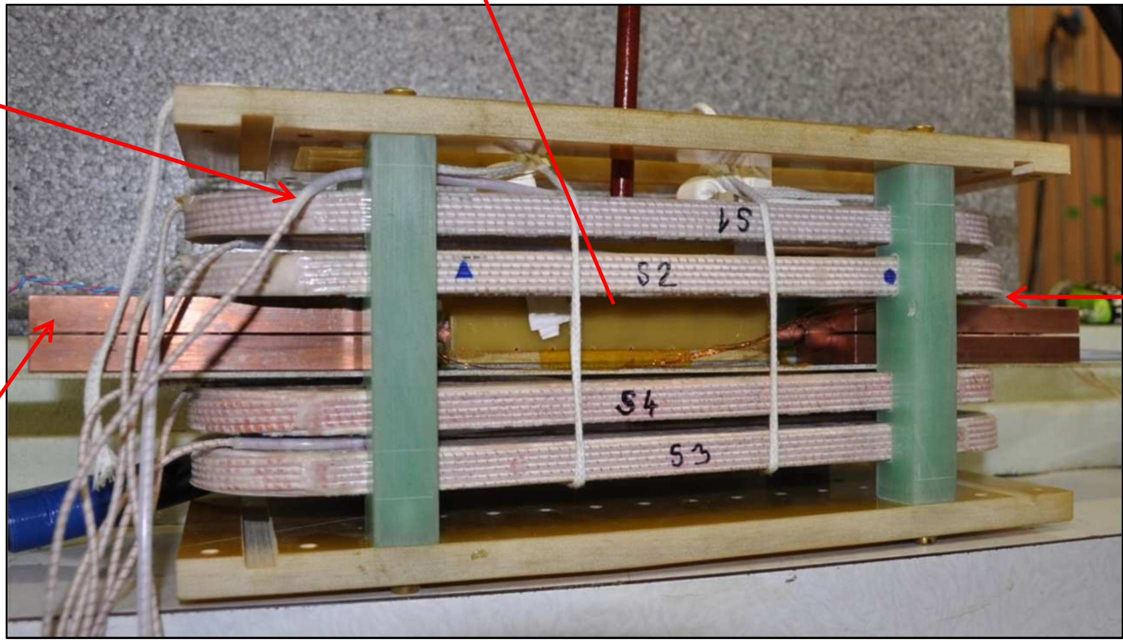
Gas flowmeter



Coils, transformer and bubble catcher are in LN_2



Copper racetrack coils
AC magnetic field

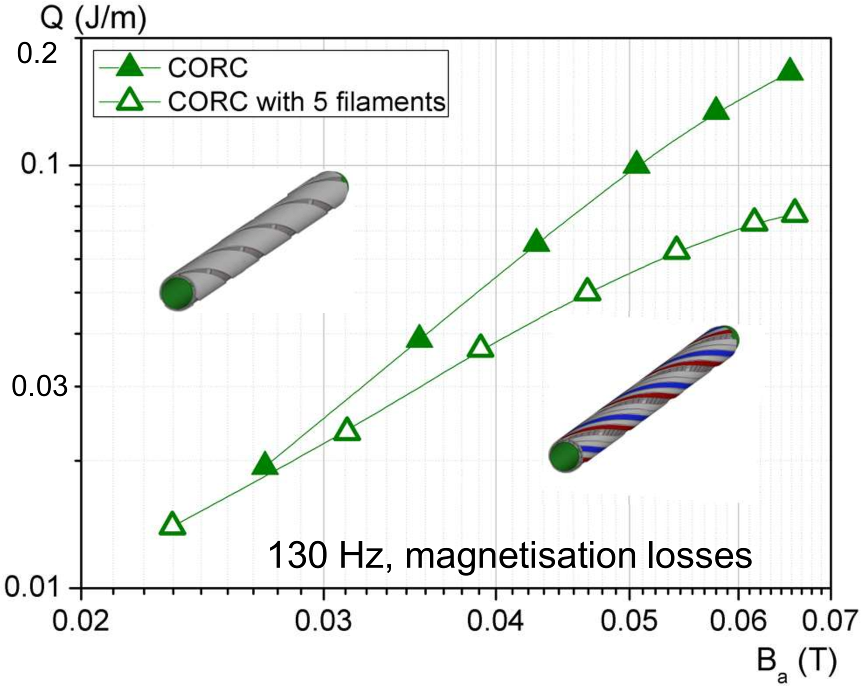


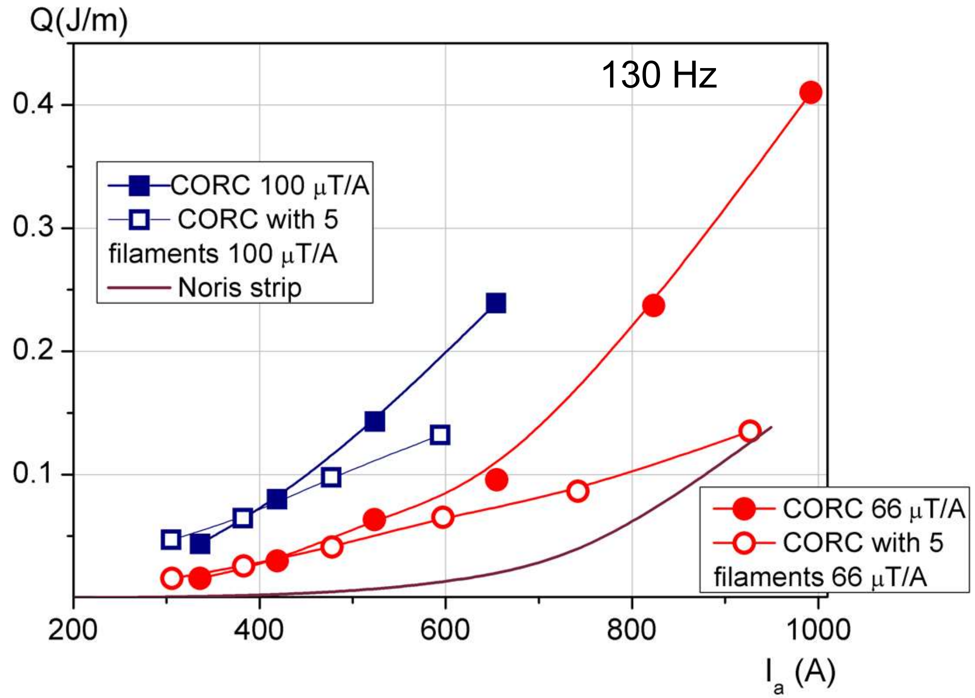
AC current

CORC Cable with resistive heater

Karlsruhe Institute of Technology

Reduction of the AC losses using striated tapes in CORC cable:





- Magnetisation losses
- Calorimetric method at 77 K
- $I_{c\ CORC}$ - 1043 A
- $I_{c\ CORC}$ with 5 filaments - 951 A (9% reduction)

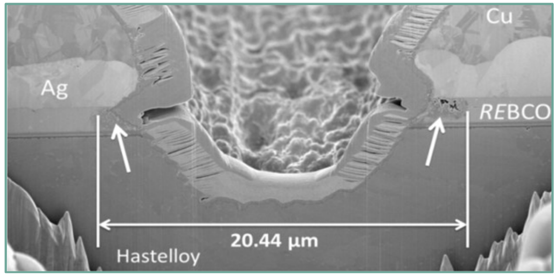
- AC-AC losses 0.07 and 0.1 mT/A
- Calorimetric method at 77 K

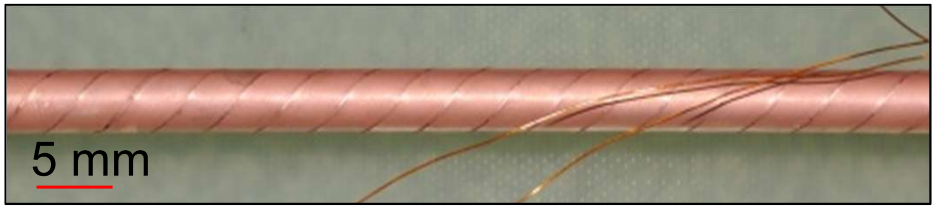
Engineering of low AC loss conductors and cables:

- Laser striation of Ag-cap conductors with additional oxidation leads to reduction of AC loss.

- Laser striation of Cu-cap conductors is not straightforward and the ‘ideal’ level of resistance between filaments need to be found.

- CORC cable structure is the ideal architecture for striated conductor – natural twist of filaments and AC loss reduction.





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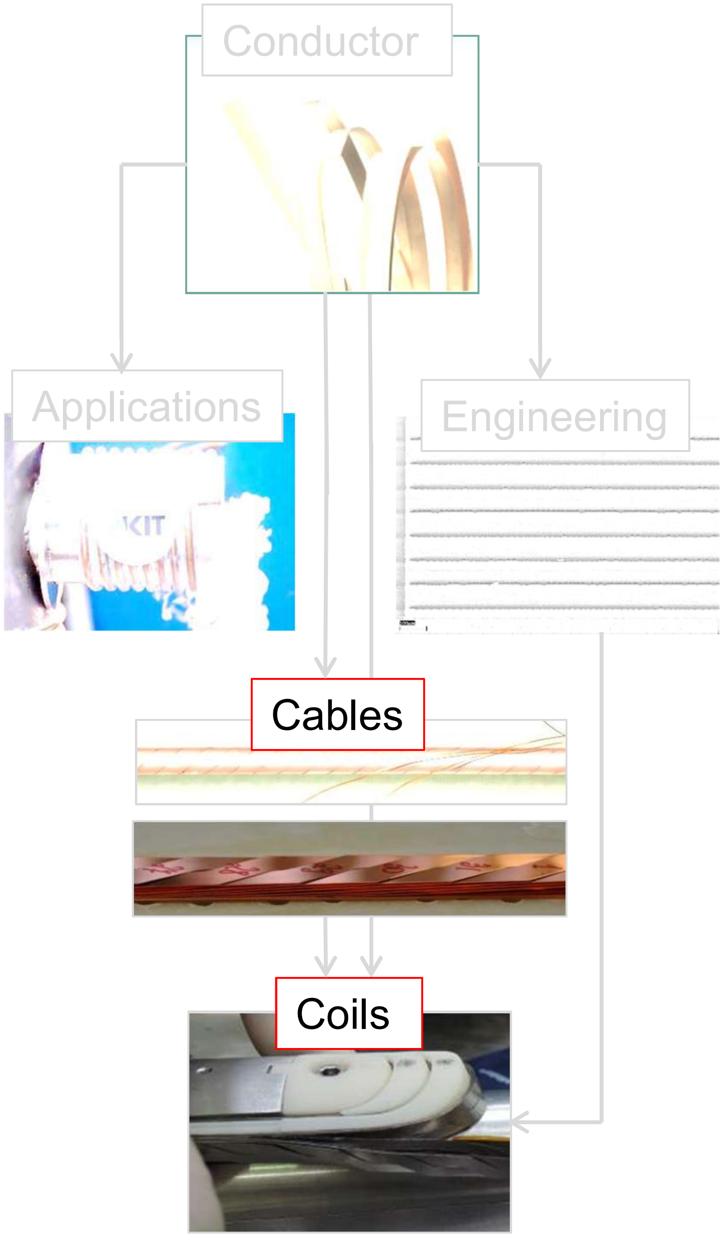


HTS magnet insert development and co-authors:

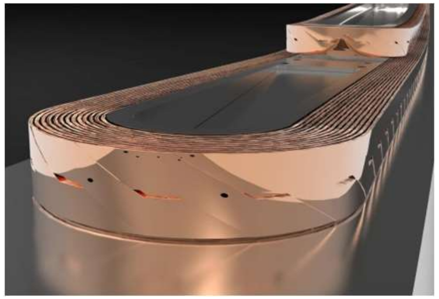
Conductor

⇨

Cable

⇨

Coil



- A. Rutt, A. Usoskin (BRUKER)
- C. Senatore, C. Barth, M. Bonura (Université de Genève, Faculté des Sciences)
- Y. Yang (University of Southampton)
- A. Stenvall (Tampere University of Technology)

- A. Kario, A. Kling, S. Otten, W. Goldacker (KIT Karlsruhe Institute of Technology)
- M. Dhallé, B. van Nugteren, P. Gao, S. Wessel (Universiteit Twente.)
- Y. Yang (University of Southampton)

- G. A. Kirby, J. van Nugteren, H. Bajas, V.Benda, A. Ballarino, M.Bajko L. Bottura, K. Broekens, M. Canale, A. Chiuchiolo, J. Fleiter, L.Gentini, N.Peray, J.C. Perez, G. de Rijk, A. Rijllart, L. Rossi, J. Murtomaeki, J. Mazet, F-O.Pincot (CERN)
- C. Lorin, M. Durante, P. Fazilleau (cea Saclay)

Future magnets program of EuCARD^2:

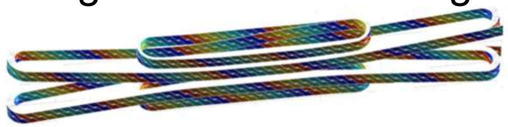
1. Develop a 10 kA-class cable in HTS suitable for accelerator magnets

- Large current to reduce magnet protection issues
- Cable properties suitable for accelerator
- Uniformity of properties over long lengths

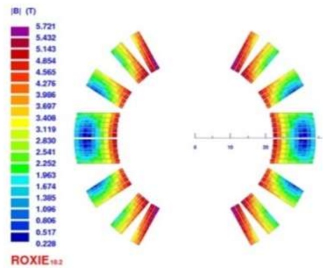
2. Design, manufacture and test a first accelerator quality, small prototype, dipole magnet:

- Bore diameter 40 mm, outside diameter 99 mm
- Length > 400 mm
- Field 5 T, good homogeneity (< 10^{-4}) stand-alone
- Field > 15 T in a high field magnet (Fresca2) – outside EuCARD^2

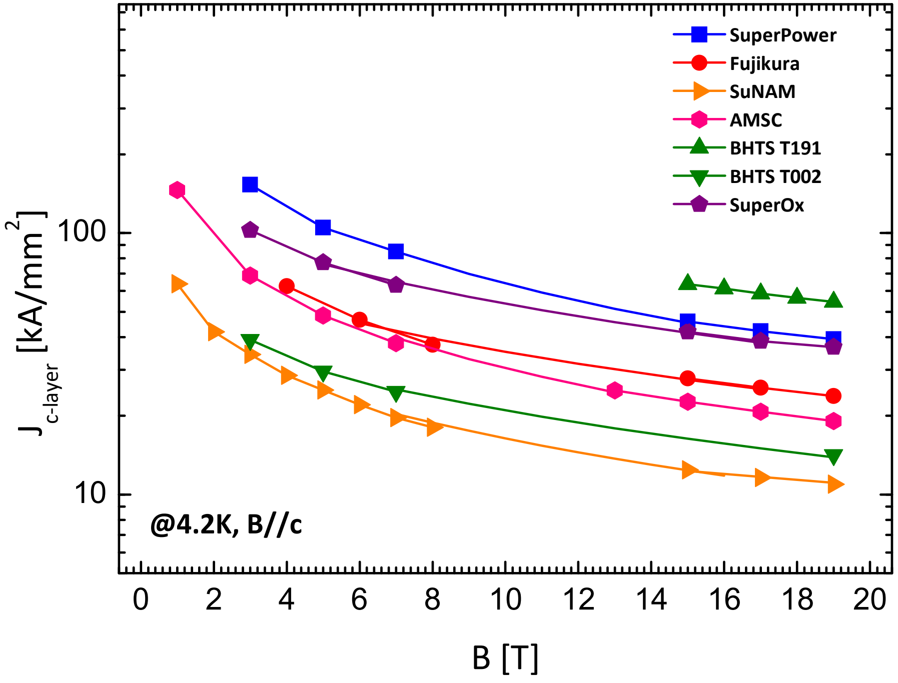
Aligned block coil design

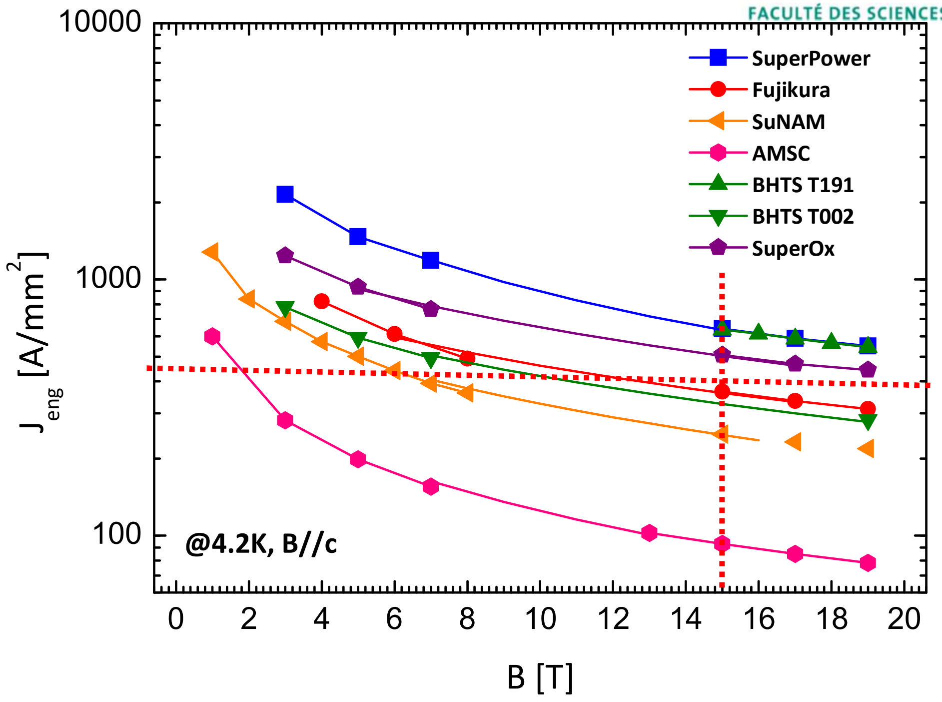


Cos-theta design



Coated conductor performance at 4.2 K:





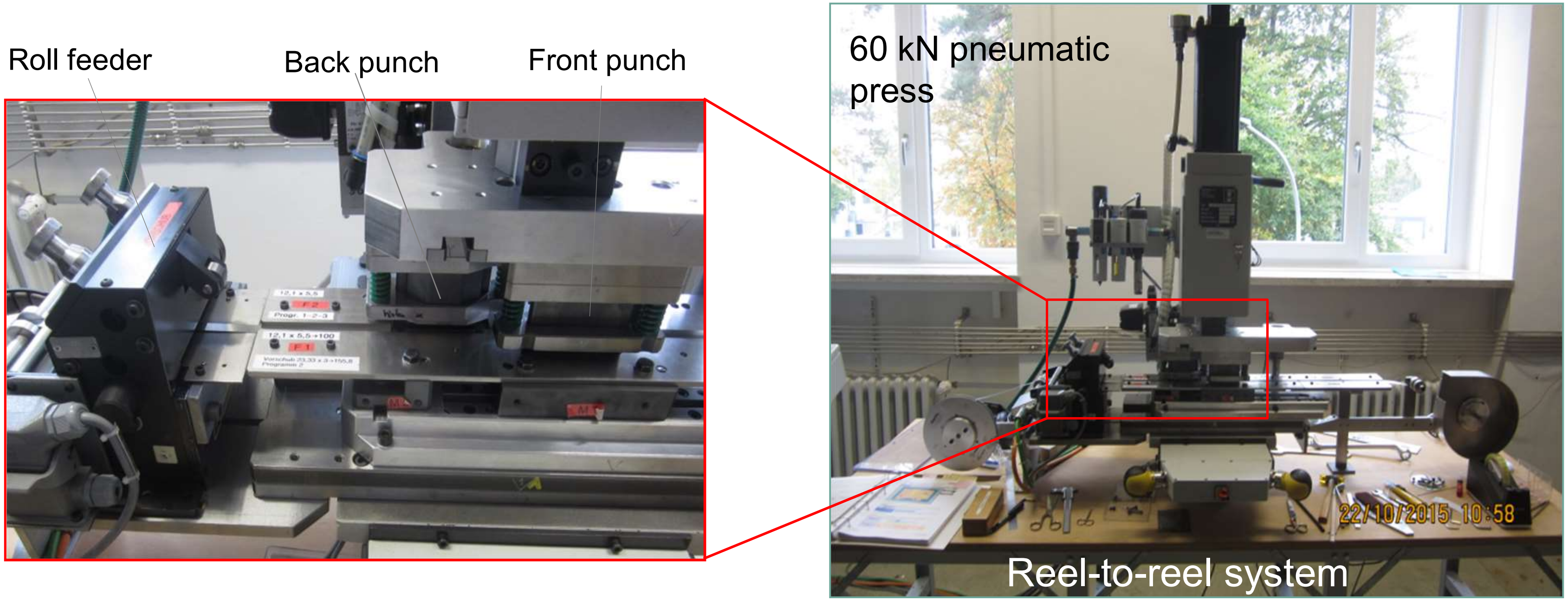
Target performance for *RE*123 tape at 4.2 K in perpendicular magnetic field:

- J_{eng} = 450 A/mm^2 at 15 T
- J_{eng} = 400 A/mm^2 – 600 A/mm^2 at 20 T

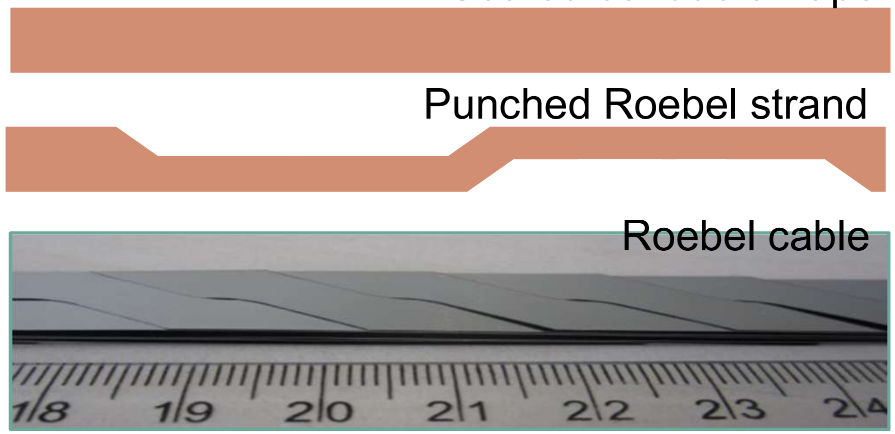
Manufacturer	*Substrate thickness / Cu thickness*
AMSC	75 µm/ 100 µm
BHTS	100 µm / 100µm
FUJIKURA	75 µm / 75 µm
SUNAM	60 µm / 40 µm
SUPEROX	60 µm/ 20 µm
SUPERPOWER	50 µm / 40 µm

Punching technology - fast reel-to-reel:

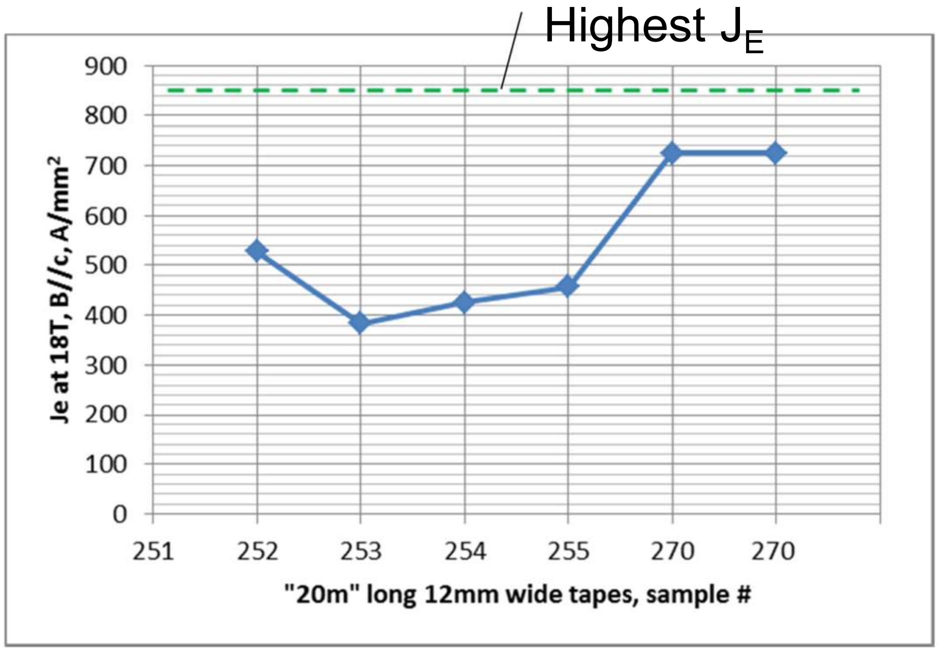
Karlsruhe Institute of Technology



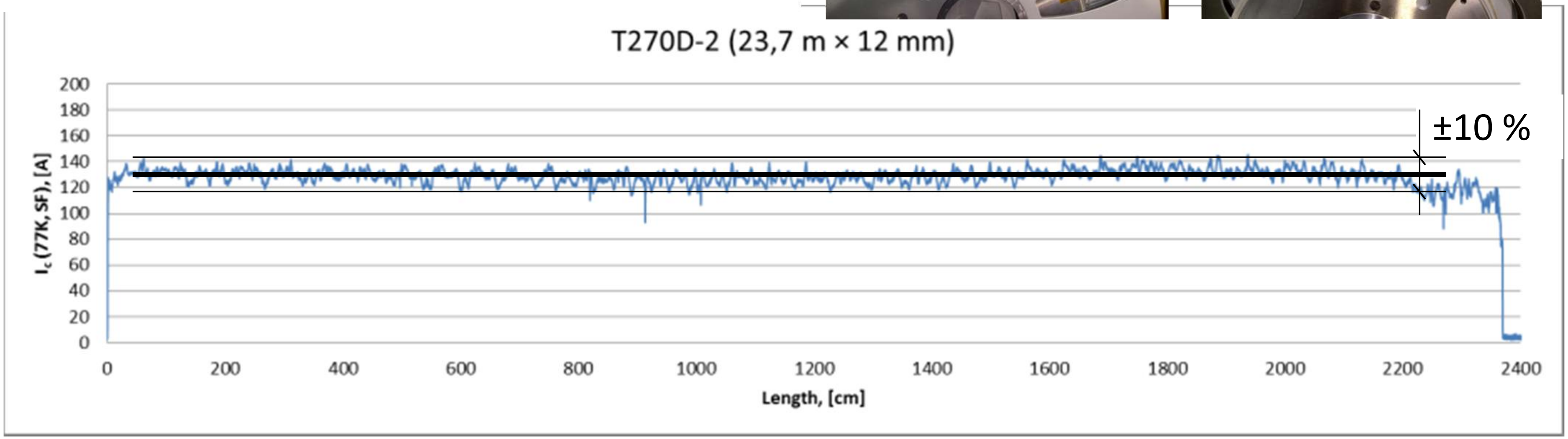
- 2 movable punches and dies
- Advantage: flexibility in punching geometry
- Disadvantage: Multiple steps per transposition needed



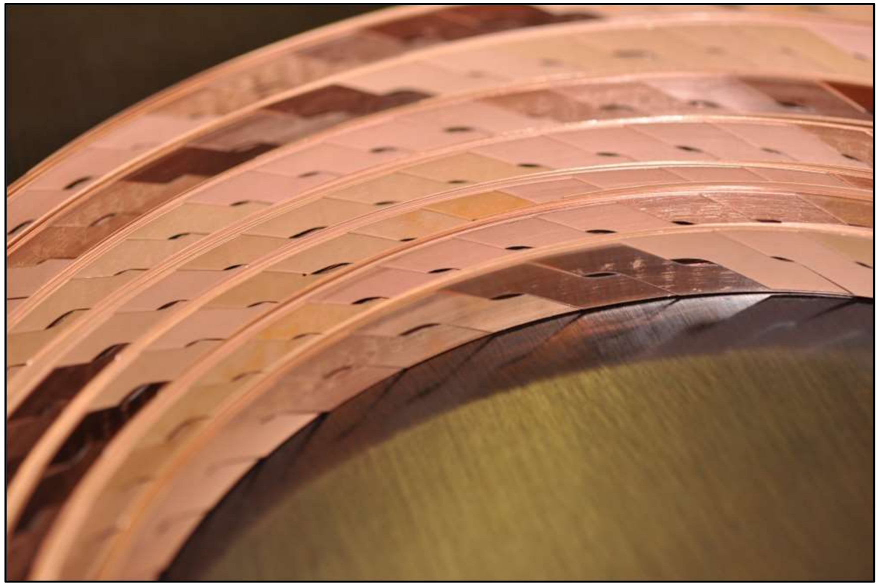
Long length tapes for Roebel cable have been delivered:



- 12 mm wide Bruker tape
- 10- 20 m long pieces
- Homogeneous I_c (+/-10%) along the length
- 20 micrometre (per side) Cu stabilisation



EuCARD^2 first Bruker Roebel cable – 5 m long:



EuCARD^2

CAPACITIES

Grant Agreement No: 312453

EuCARD-2

European Coordination for Accelerator Research and Development

Seventh Framework Programme, Capacities Specific Programme, Research Infrastructures, Combination of Collaborative Project and Coordination and Support Action

MILESTONE REPORT

PROTOTYPE CABLE LENGTHS AND REPORT

DELIVERABLE: D10.2

Document identifier:	EuCARD2-Del-D10-2-Final
Due date of milestone:	End of Month 24 (April 2015)
Report release date:	30/04/2015
Work package:	WP10: Future Magnets
Lead beneficiary:	CERN
Document status:	Final

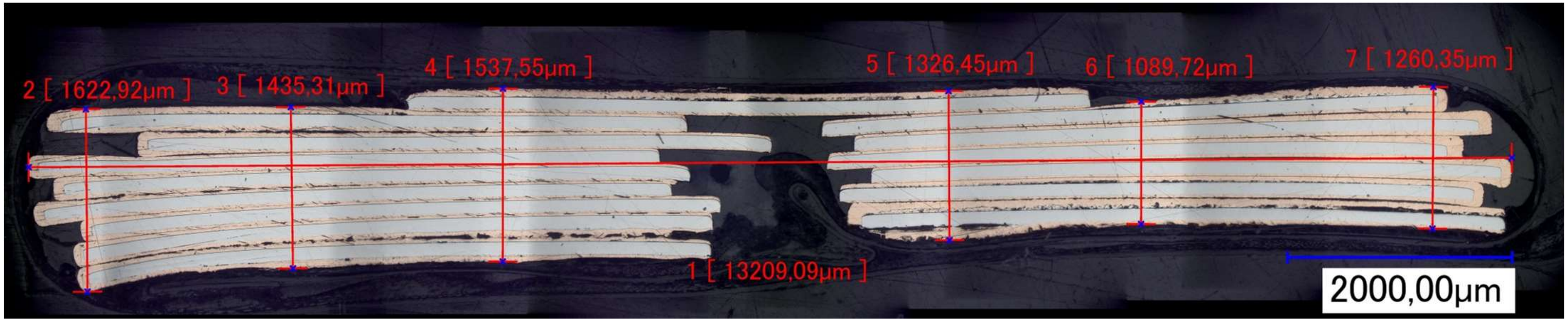
Bruker tape ID	Tape length [m]	Number of strands	I_c strand [A] (average, 77K)
254 D	14.1	2	51.5
255 D	18	3	52.6
270D-1	13	2	61.1
270D-2	22.1	4	56.9
281D	23.2	4	62.8

- 15 strands cable
- 226 mm transposition length
- 5.5 mm strand width

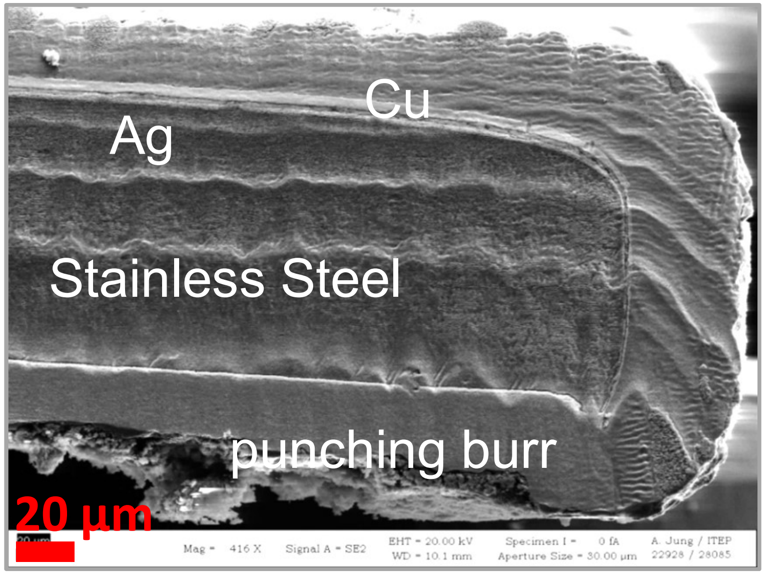
Cross-section of the first Bruker Roebel cable:

- Sum of all strands at 77 K, self-field - 861 A
- Roebel I_c predicted (with self-field, 77 K) – 749 A (13 % self-field reduction)
- Roebel I_c predicted (with self-field, 77 K) – 603 A (30 % self-field reduction)

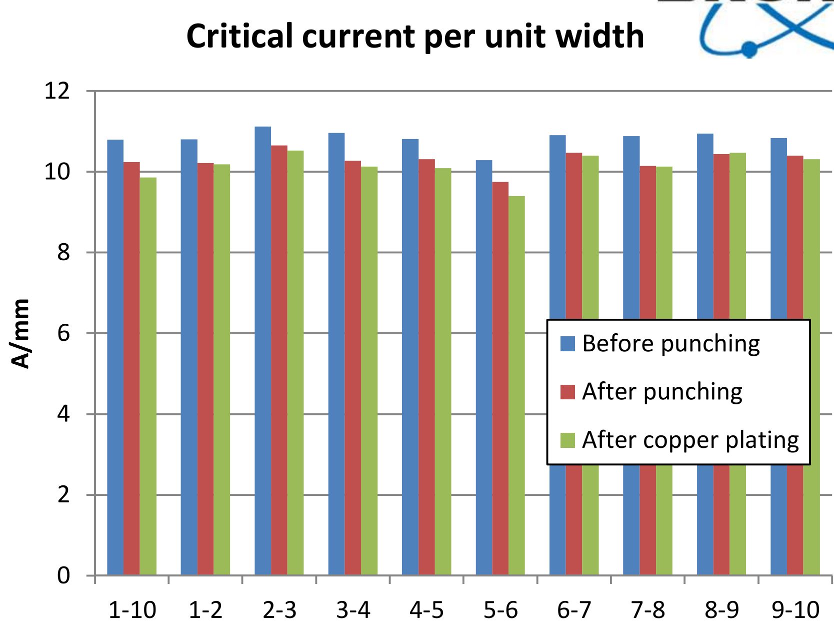
Cross-section



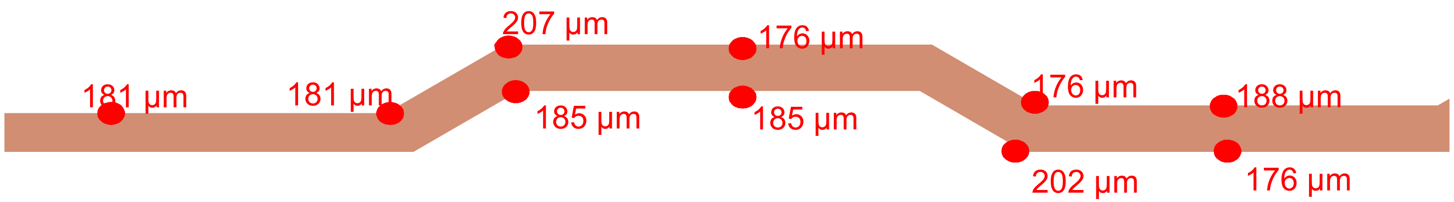
Cu-plated tape after punching – at Bruker:



A. Jung (KIT)



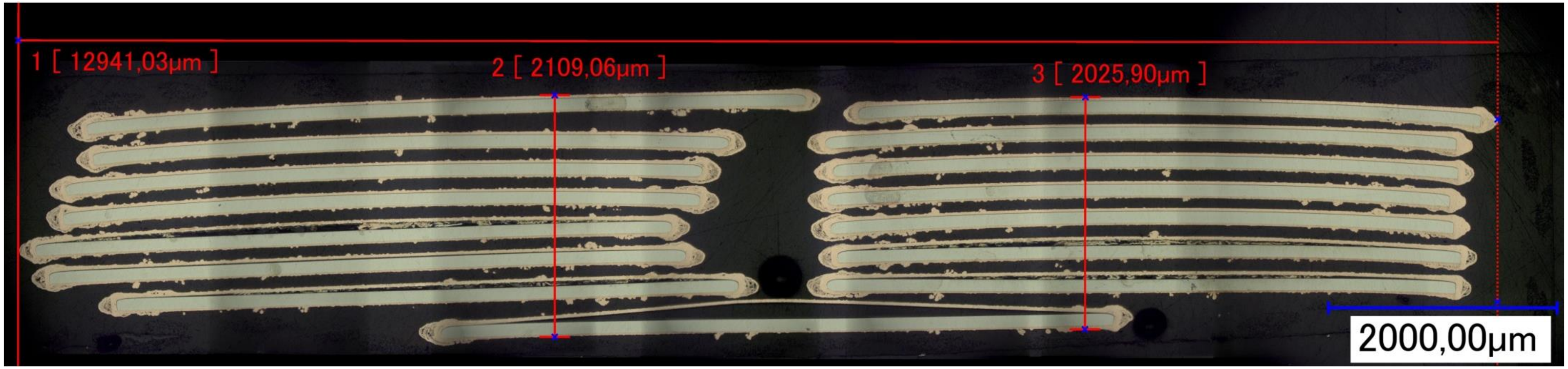
- Tape thickness after copper plating.



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

First 2 m long Roebel cable made with punch-and -coat technique:

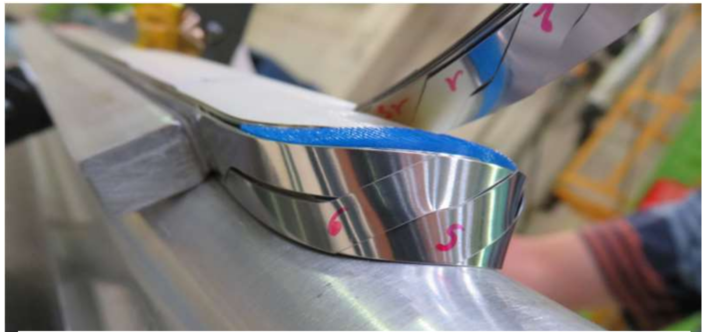
- Roebel cable: 226 TL, 15 strands
- Punch + Coat
- 2 m long



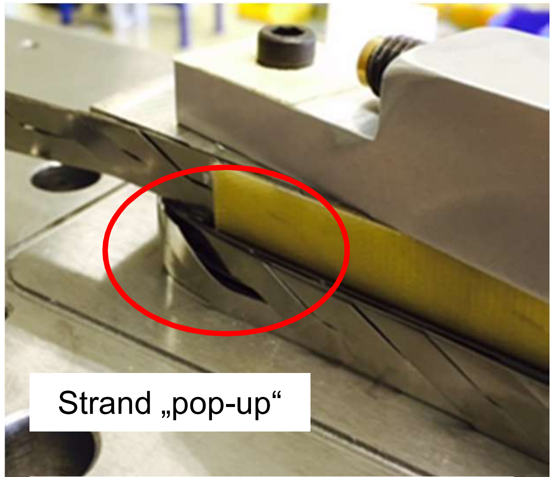
New design of the Roebel cable:

Karlsruhe Institute of Technology

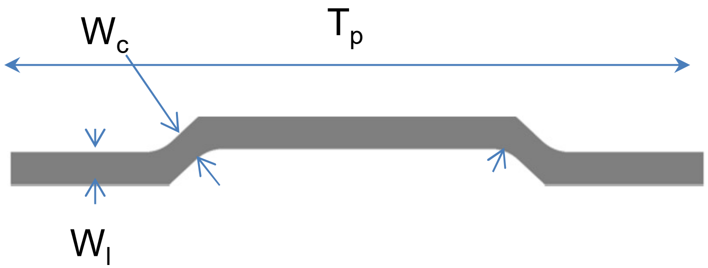
Unequal shift of tapes leads to problems in coil winding:

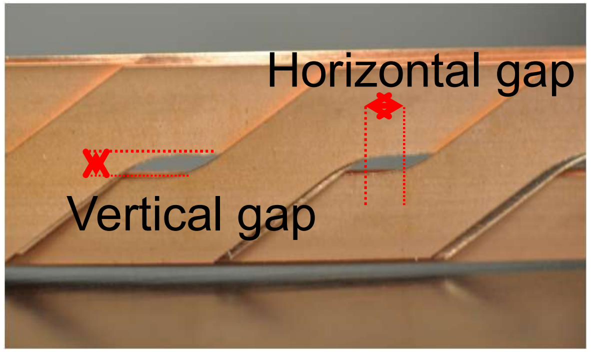


Similar effect in cos-θ coil at CEA Saclay (picture by M. Durante)



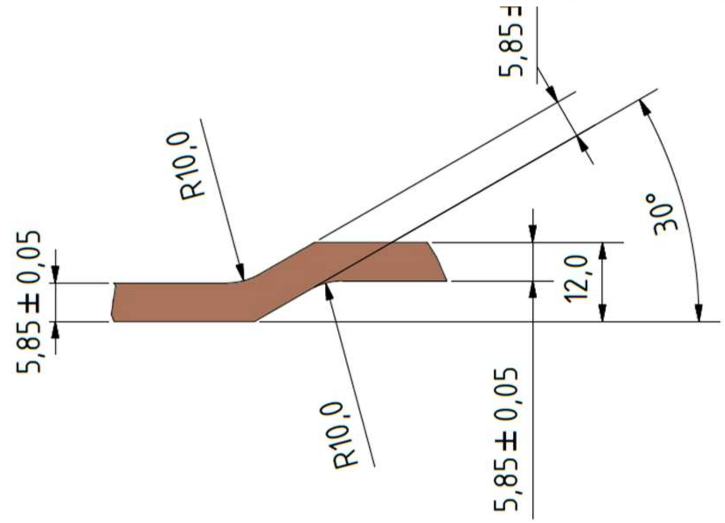
Aligned block dummy winding (G. Kirby)



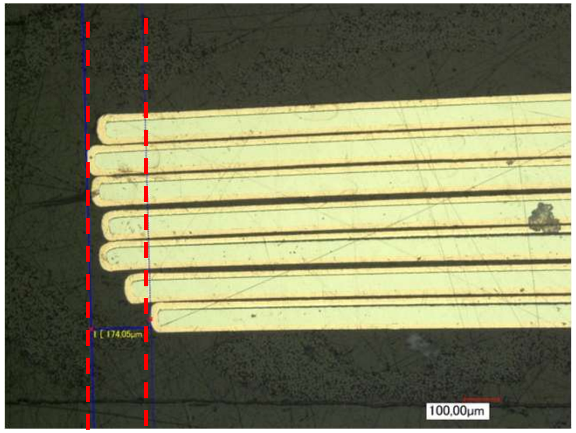


Transposition length (Tp) (mm)	Strand width (W_l) and bridge width (W_c) (mm)
226 (old)	5.5
300 (new)	5.85

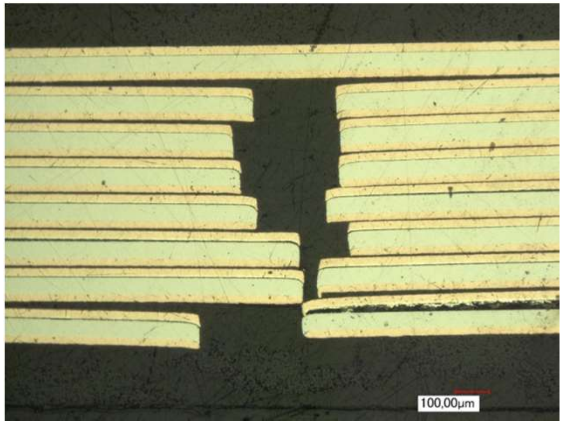
New punching tool and cable geometry:

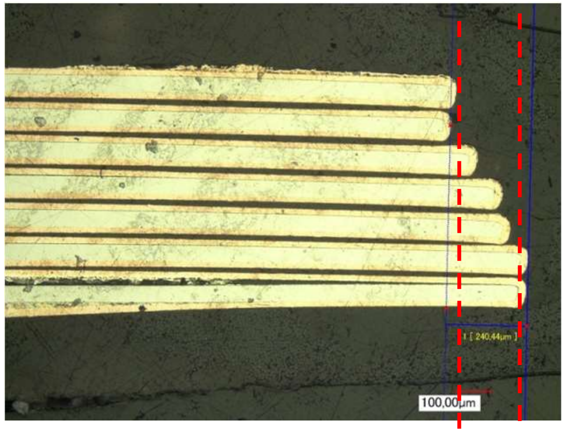


- New geometry now possible in punching tool
  - 5.85 mm strand width
  - 300 mm transposition length
- Baseline for next EuCARD² cables



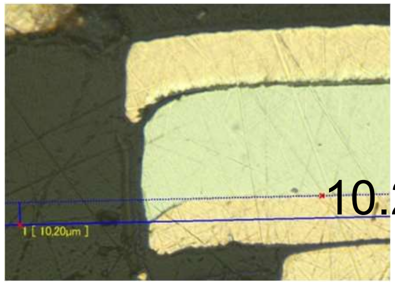
174 µm





240 µm

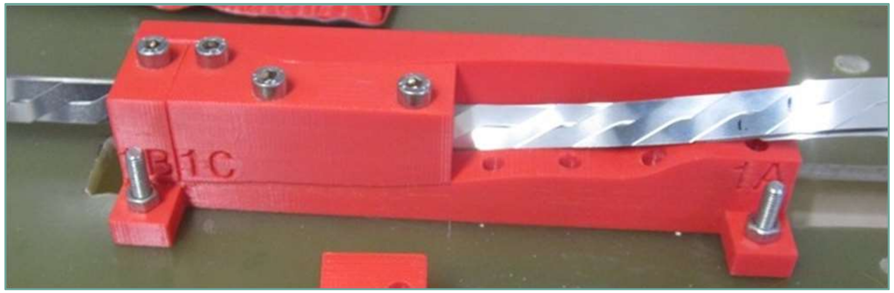
Cross-section of first punched cable with new geometry (15 strands).

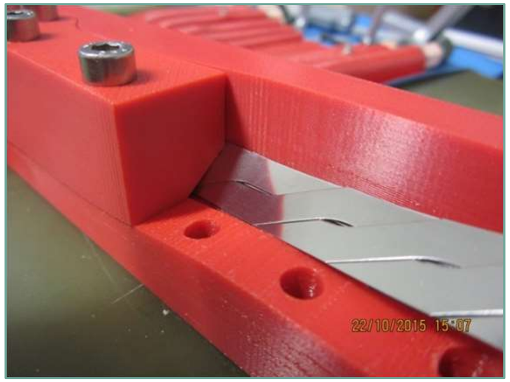


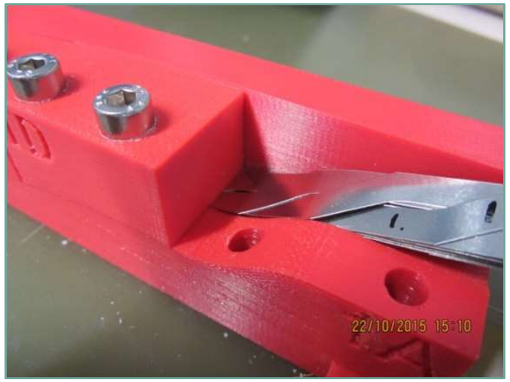
10.2 µm

Mechanical test of the cos-theta coil end geometry:

- Measurement at KIT with CEA Saclay (77 K, self-field)
- CERN and CEA -3D form print

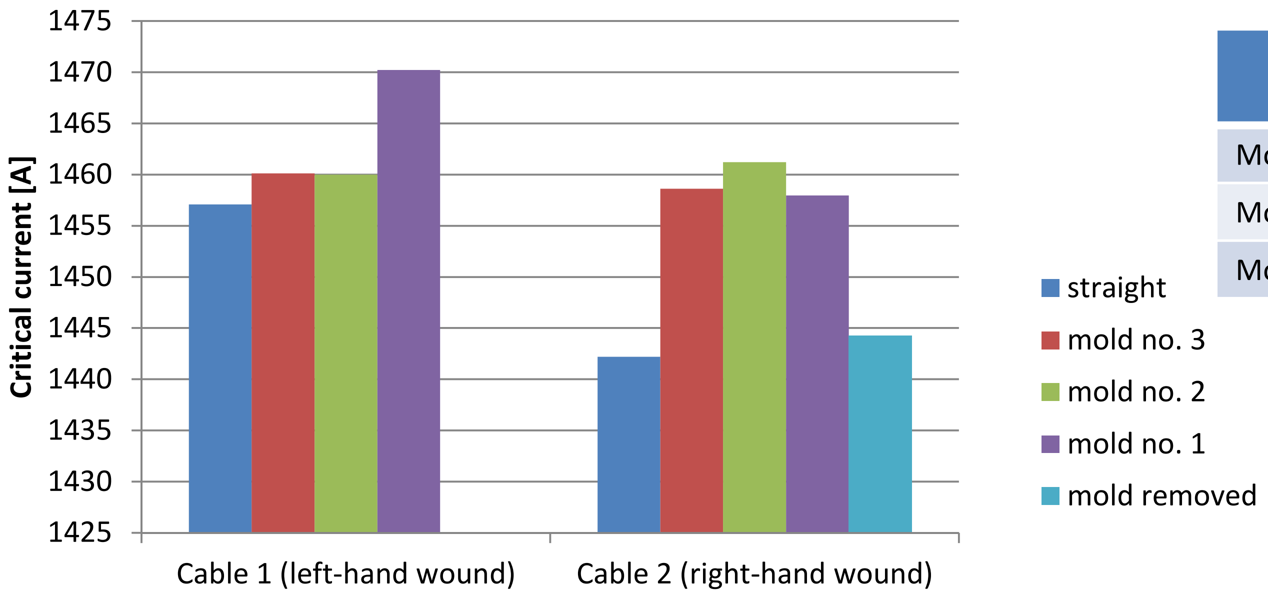




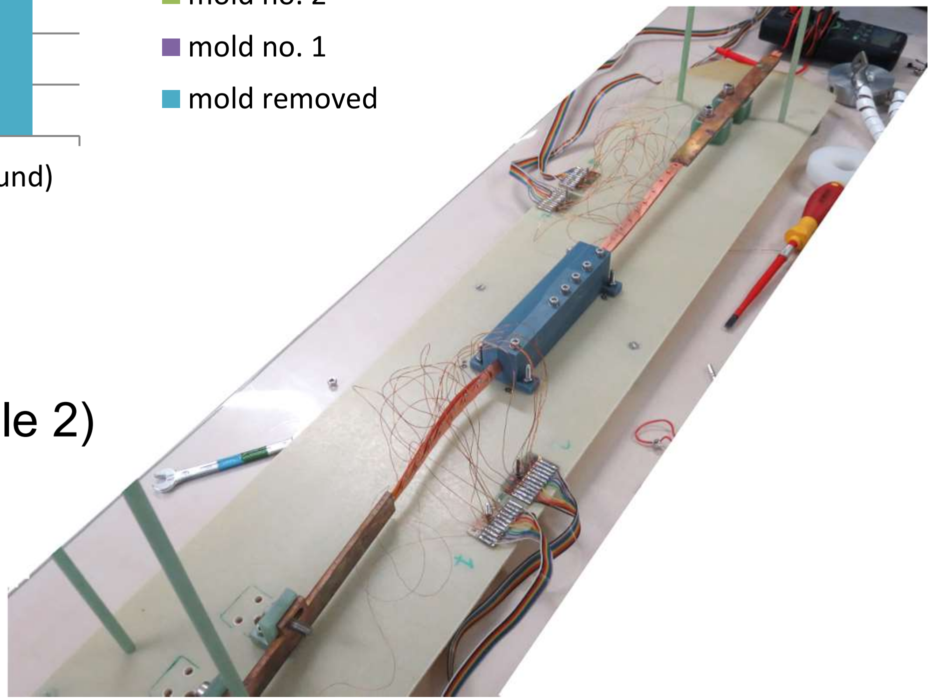


No degradation of I_c with all used molds:

Roebel cables in CEA torsion mold (*T* = 77 K, self-field)

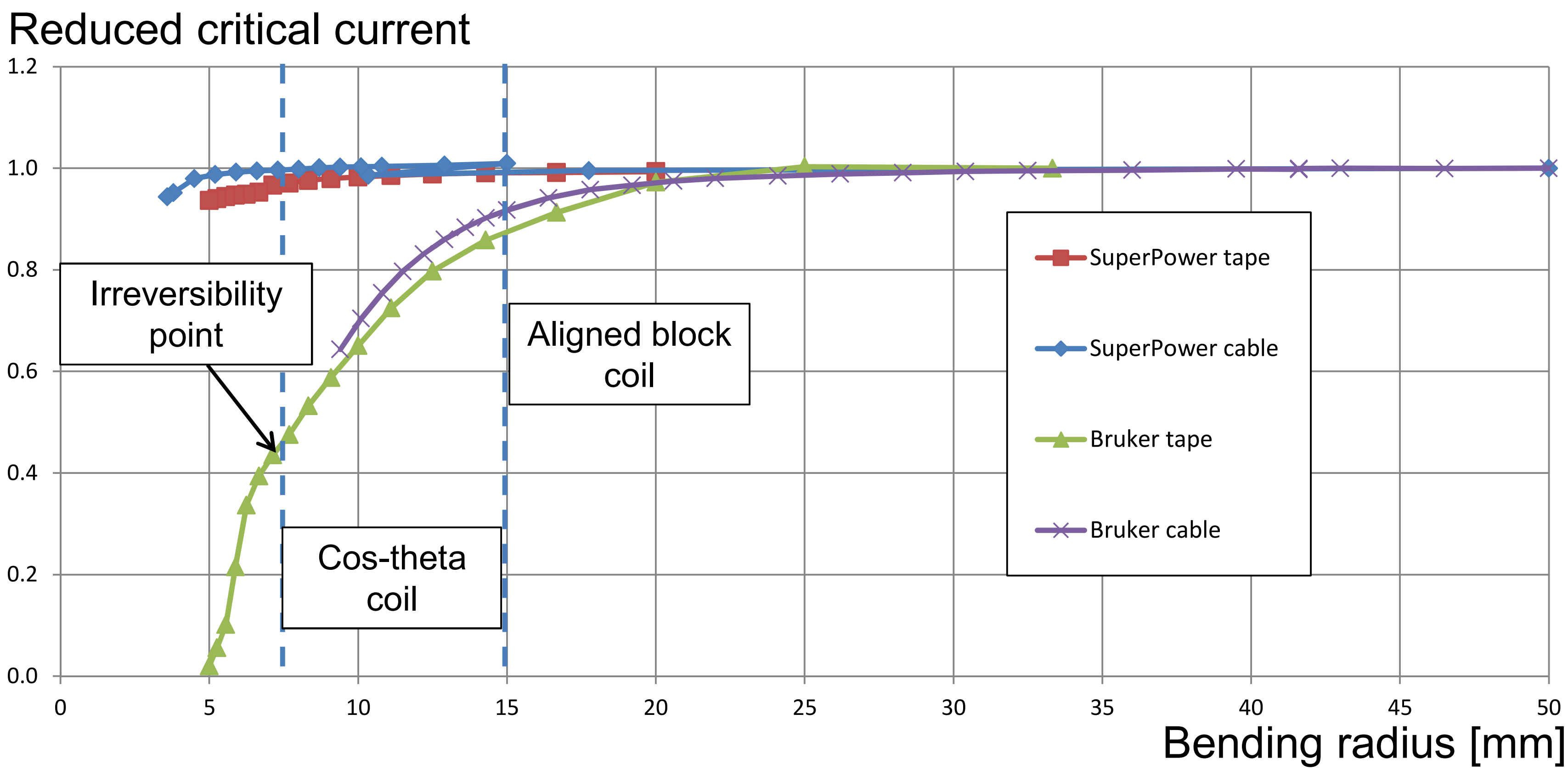


	Twist pitch [mm]	Bending radius [mm]
Mold 3	535	-
Mold 2	389	-
Mold 1	389	22



- No degradation observed
- Small I_c increase (reversible in cable 2)

Roebel cable bending – cable suitability for a coil:



- Measurements at LN_{2}, s.f.
- *RE*BCO inside / compressive bending
- I_c of the Roebel cables:

  SuperPower: 1427 A

  Bruker: 658 A

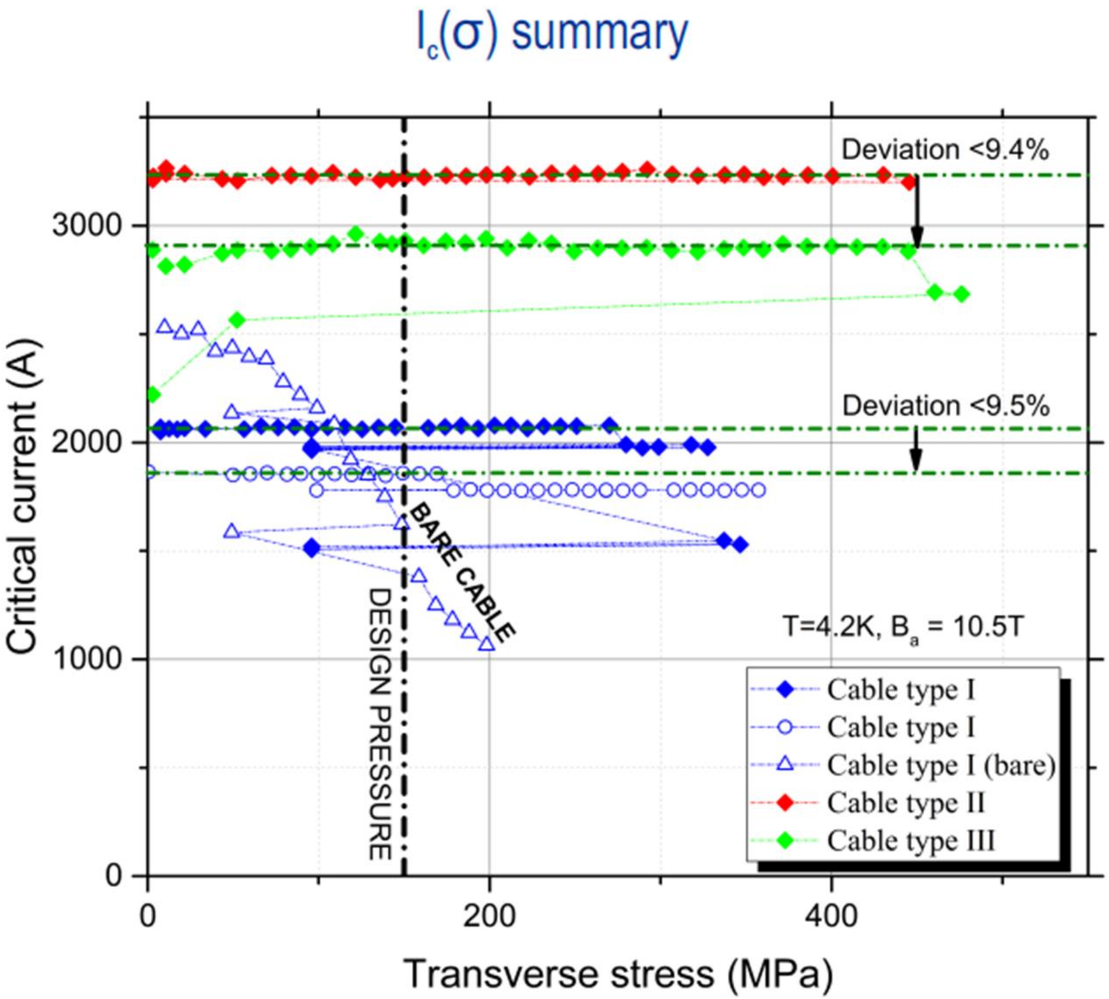
<u>SuperPower</u>

- 20 µm Cu, 50 µm Hastelloy

<u>Bruker</u>

- 20 µm Cu+, 100 µm SS

Transverse stress for advanced impregnations:



P. Gao et al., "Effect of tape layout and impregnation method on transverse pressure dependence of critical current in REBCO Roebel cables", presented at ASC2016, Denver

Cable type I & II: "KIT-type"

- Araldite CY5538 & Aradur HY5571
- Silica filler powder

Cable II

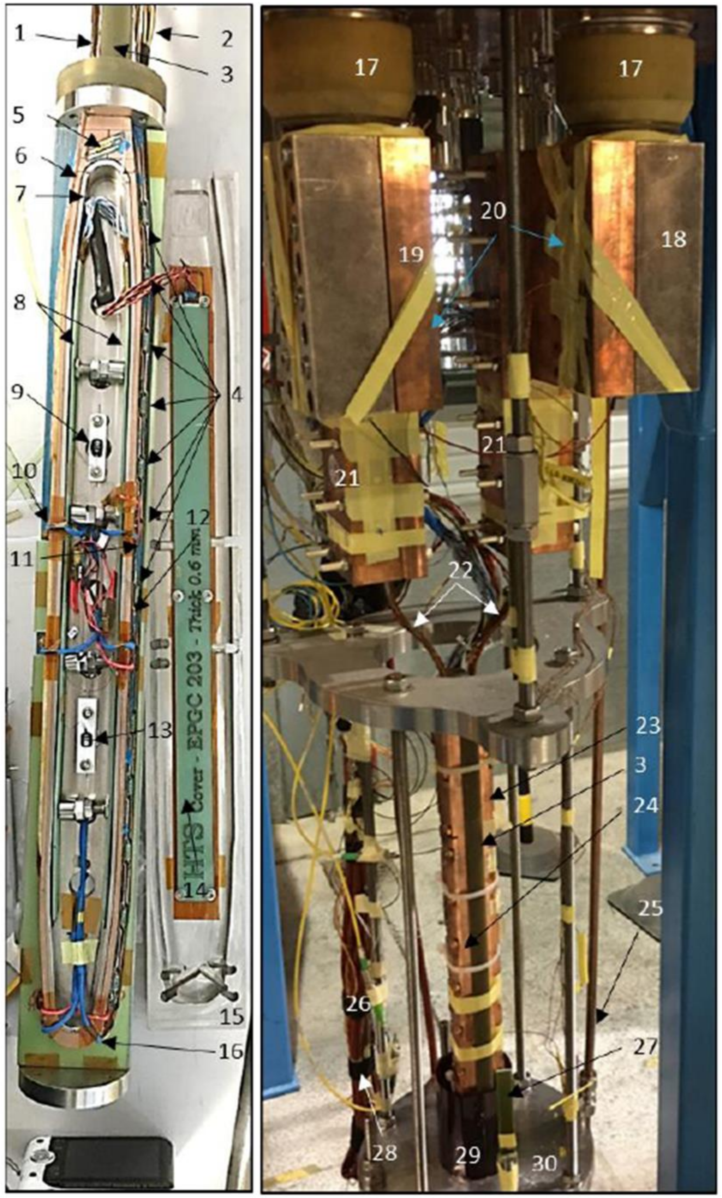
Cable type III & IV: "CERN-type"

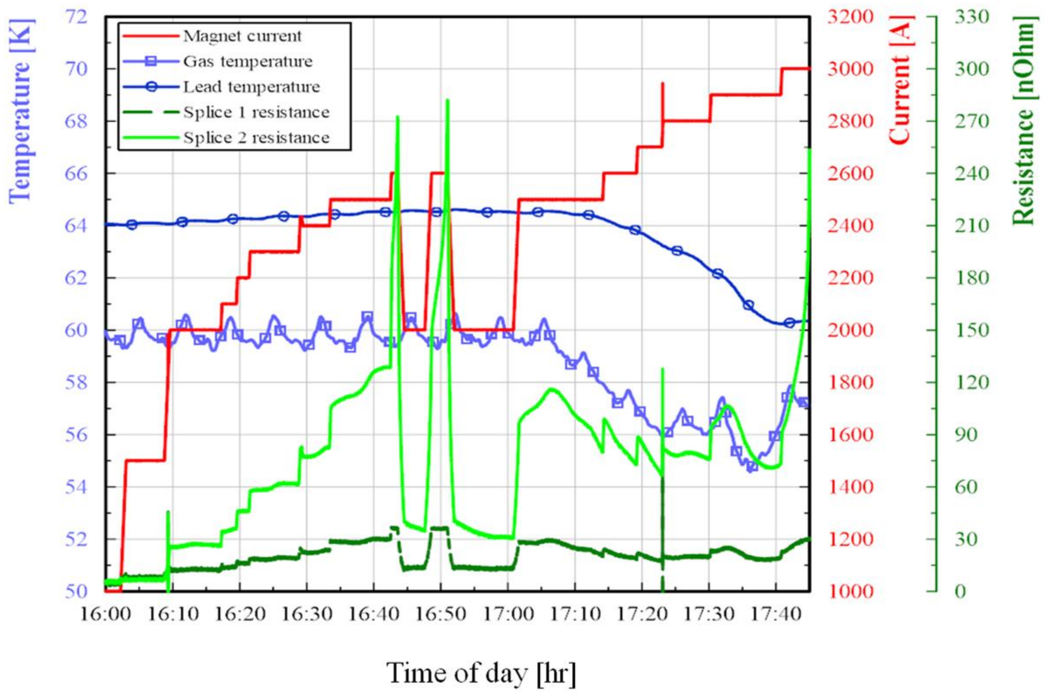
- CTD-101K part A,B, C
- Glass rope in central space
- Glass sleeve

Dummy cable

Cable III

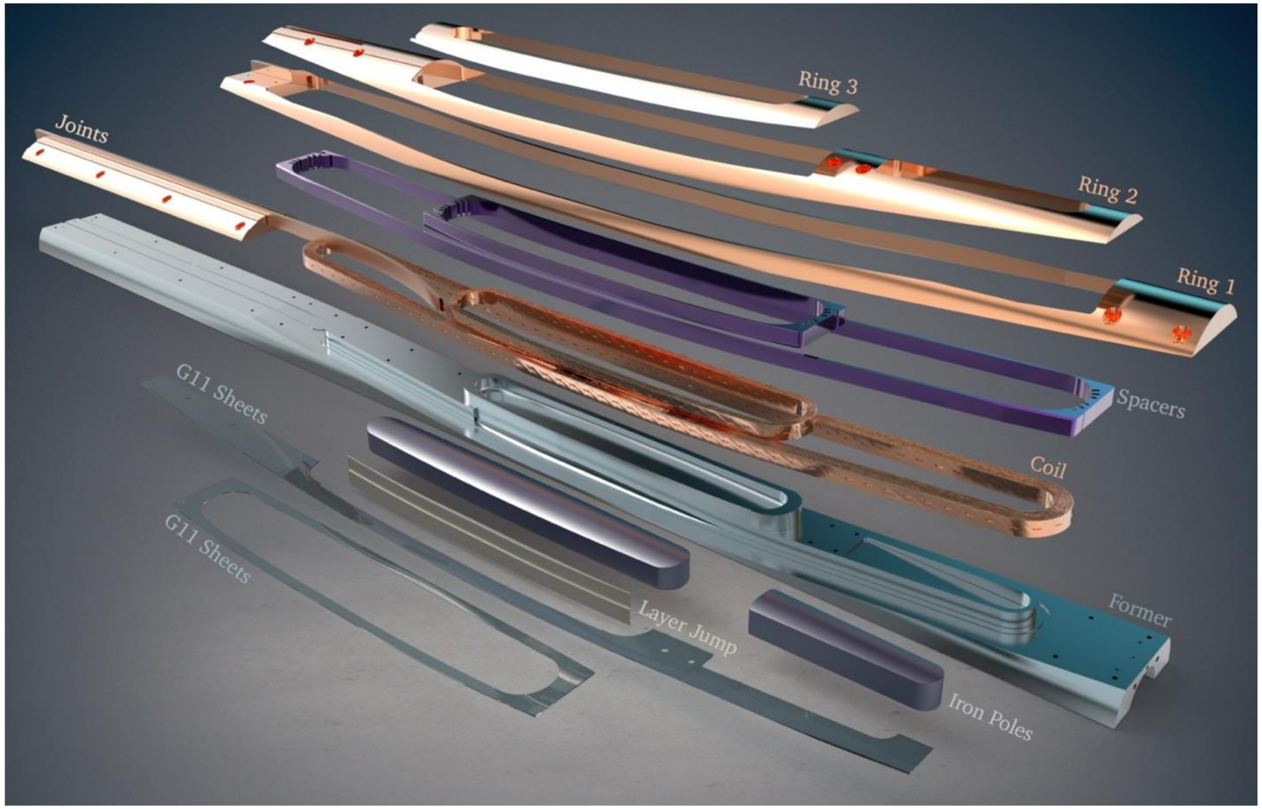
First cold test of subsize Feather M-0.4 coil:

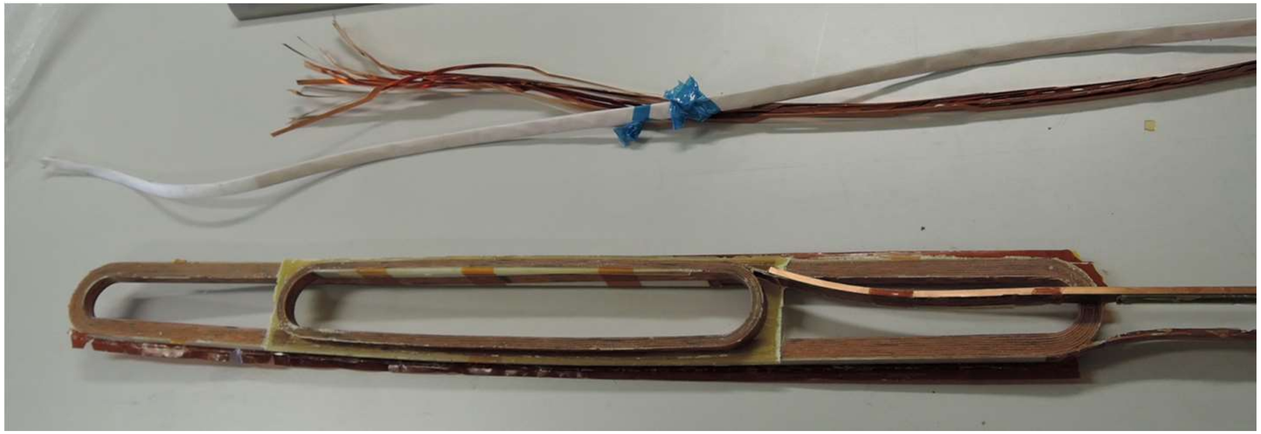




- Tests on Feather M0.x coils serve to advance production and testing instrumentation.
- Feather M-0.4 performance 100% of prediction from CC performance.

First winding and impregnation of Feather-M2 coil:





HTS Roebel cables for the EuCARD[2] "Future Magnets"

Karlsruhe Institute of Technology

Coated Conductor:

- Tapes for different supplies being tested (tape J_e, punching).
- Punch-and-coat process developed with Bruker.

Roebel coated conductor cable:

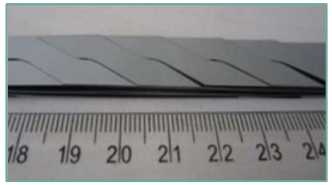
- First 5 m long cables were made and delivered for coil winding.
- Punch and coat technology used for first 2 m long cable.
- Cable design adopted to magnet design.

Roebel cable for the coil winding:

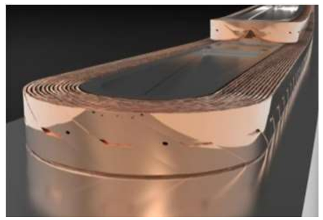
- It is possible to wind the cables into small radius coils without I_c degradation and test those at 77 K.
- Cos-theta end design tested-no I_c cable degradation.
- First successful test of Feather M0.4.

Conductor

Cable



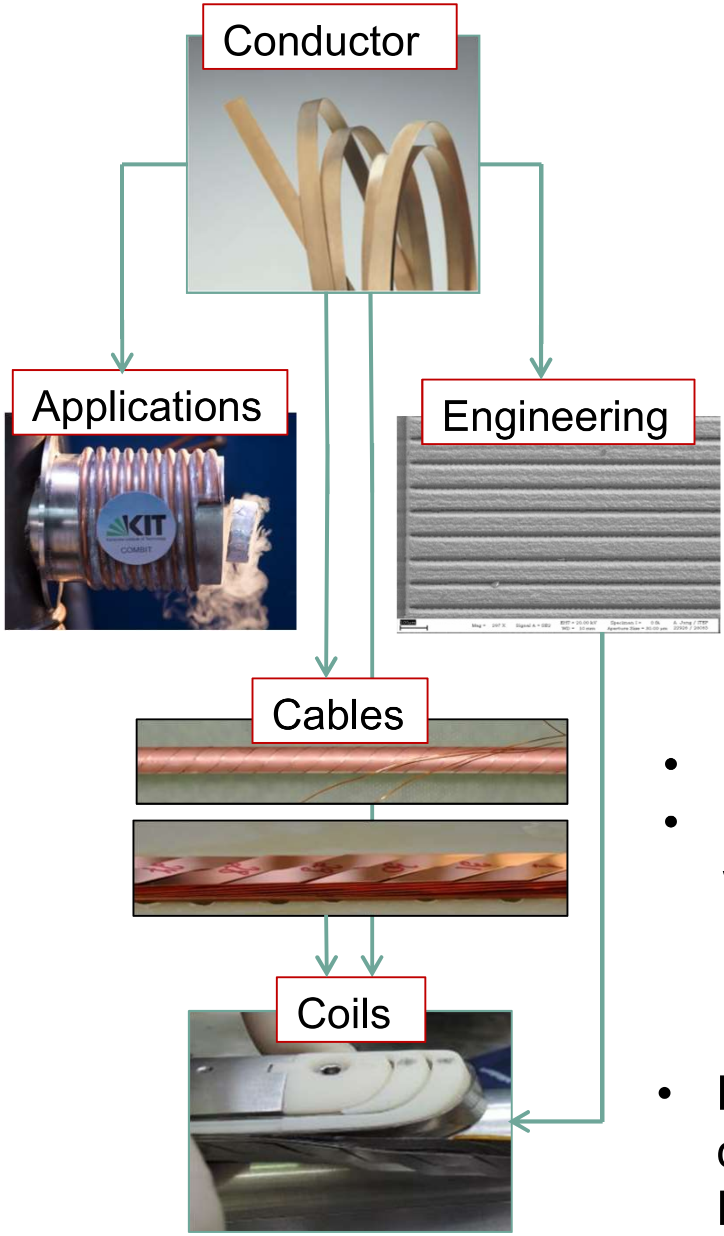
Coil



Summary:

- Special applications
- Electrical engineering applications:

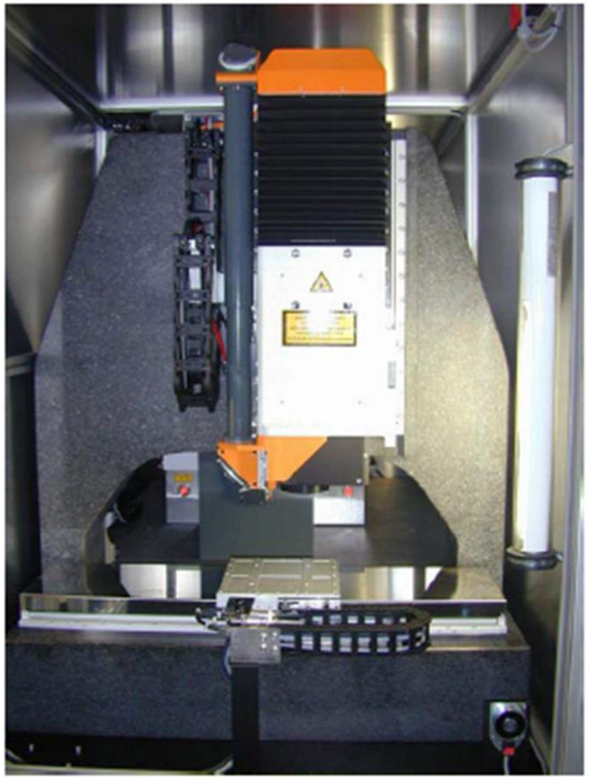
  - fault current limiter
  - transformer
  - superconducting current rails



- Low AC loss coated conductors with filaments
- Modulated resistance between filaments

- Roebel cable R&D
- Low AC loss CORC cable with filaments

- First HTS accelerator type coil demonstrator using HTS Roebel cable



KIT
Karlsruhe Institute of Technology

Optimized system in KIT TRUMPF TruMicro 5025:

- IR Wavelength 1030 nm
- Maximum Energy 25 W
- Pulse duration < 10 ps
- Max. Pulse energy 125 µJ
- Pulse frequency 400 kHz

Parameters for the scribing process

Energy	5 W (Ag, 10x),	12.5 W (Cu, 50x)
Repetition rate	400 kHz (Scanner),	100 kHz (Table)
Pulse energy	25 µJ (Ag, 10x),	62.5 µJ (Cu, 50x)
Speed	90 m/min (Scanner),	22.5 m/min (Table)
Spot diameter	18 µm (Ag),	30 µm (Cu)

Status

54 cm long samples

Future:

RTR long lengths