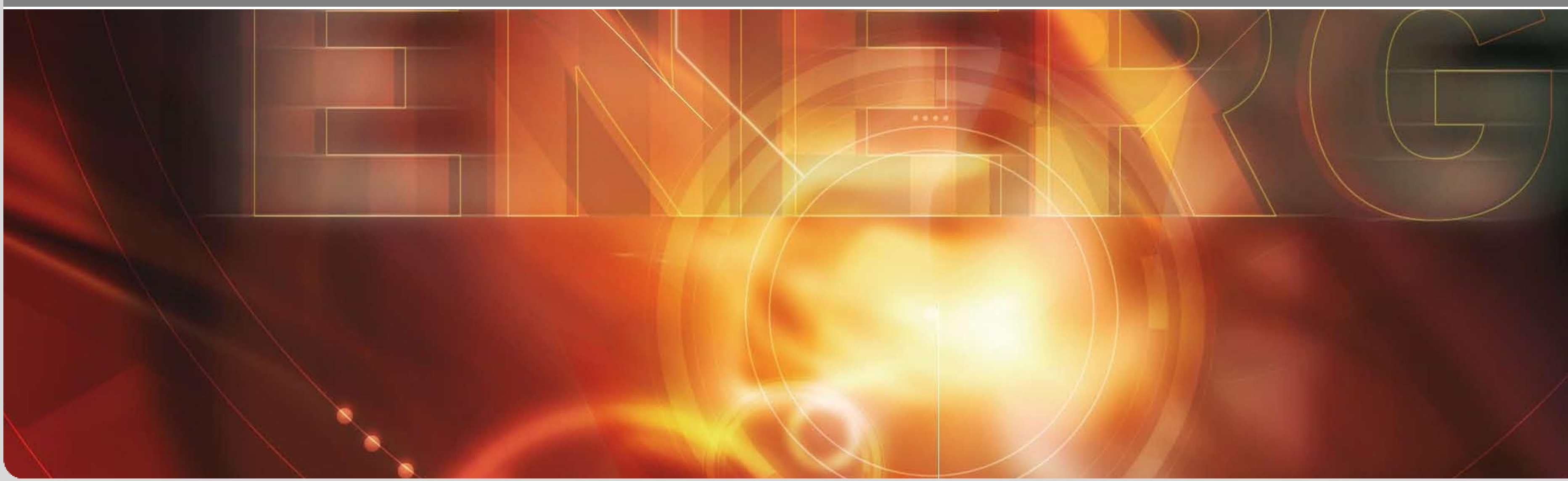
Karlsruher Institut für Technologie

Superconducting Materials and Applications R&D at Institute for Technical Physics at KIT

Prof. Dr.-Ing. Mathias Noe, Karlsruhe Institute of Technology (KIT), Institute for Technical Physics

Paul Scherrer Institut, Villigen, January 28th, 2019

KIT-ENERGY CENTRE



ITEP Research Topics

Superconducting and Cryo-Materials Bernhard Holzapfel	Energy Applications Mathias Noe	Superconducting Magnet Technology Walter Fietz	Fusion Fuel Cycle Technologies Christian Day	Physics and Techniques of Hydrogen Isotopologues Beate Bornschein
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Large Projects and Infrastructure
KATRIN, Energy Lab 2.0
Tritium Laboratory Karlsruhe, High Field Laboratory, Cryo Experiments and Infrastructure, CryoMak
Cryo-High Voltage Laboratory, CultKa, TOSKA, TIMO, SET-Laboratory, VACUUM Laboratory

Objectives and Approach

Holzapfel

Grilli

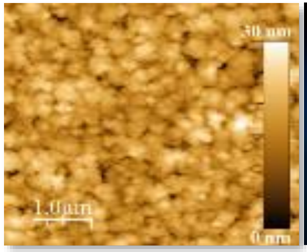
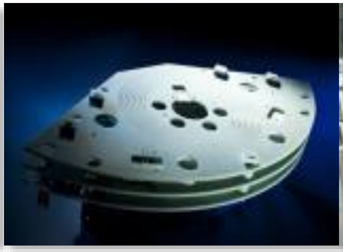
Weiss

Schlachter

Grohmann

Noe


Basic Science → Super-conducting Materials → Conductors and Coils → Equipment and Applications → Networks and Systems → Market

Develop fundamentally new and advanced superconducting technology with unsurpassed properties.

Manpower (11.2018)

Total	**203**
Academics	66
Engineers and Technicians	60
Others	21
PhD students in 2018	24
Master students in 2018	17
DH-students in 2018	9
Apprentices in 2018	6
In addition in 2018	**66**
Guests	18
Internships	5
HiWis	38
Bachelor students	15

Strategic Development – New Professorship on Superconducting Magnet Technology

- Helmholtz Recruitment of excellent female scientists

Status

- Person proposed and agreed by faculty
- KIT Senate decision in January 2019
- Q1 2019 invitation for concept discussion
- Q3 2019 start at KIT

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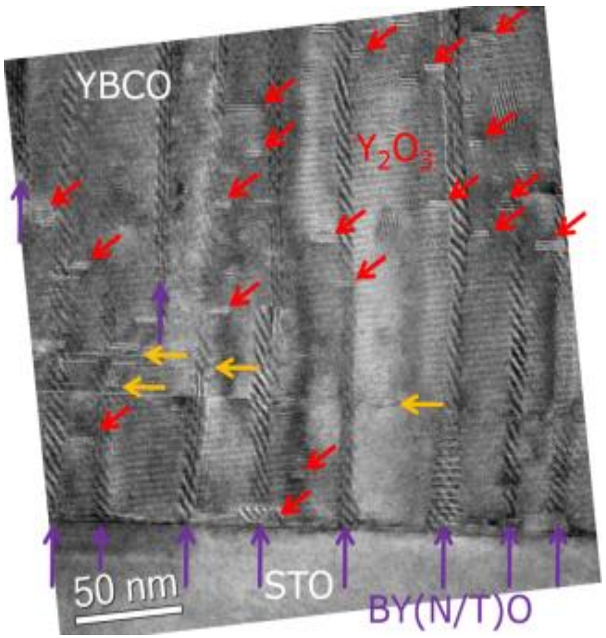
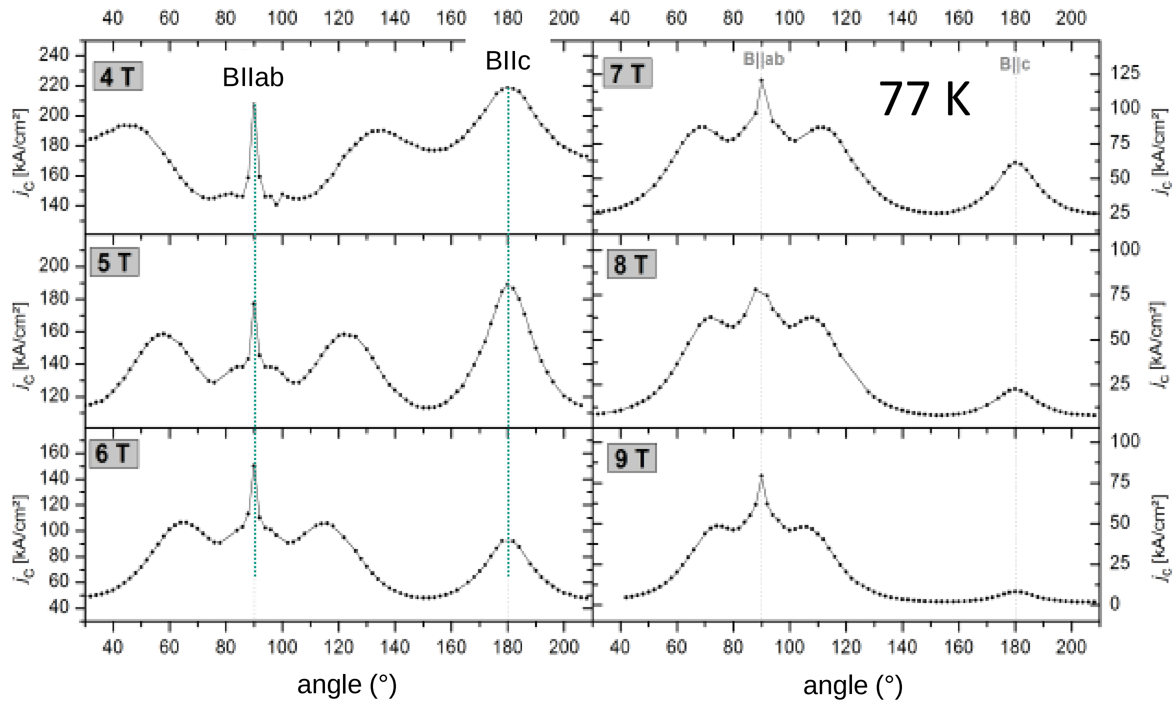
Enhanced J_c in $YBa_2Cu_3O_x$ by Controlled Nanoengineering

Leibniz Institute for Solid State and Materials Research Dresden

Karlsruher Institut für Technologie

- J_c *engineering* by self organized defect structure formation (here Ba_2YNbO_6/Ba_2YTaO_6-nanocolumns, Y_2O_3-nanoparticles, stacking faults) in Pulsed Laser deposited HTS films

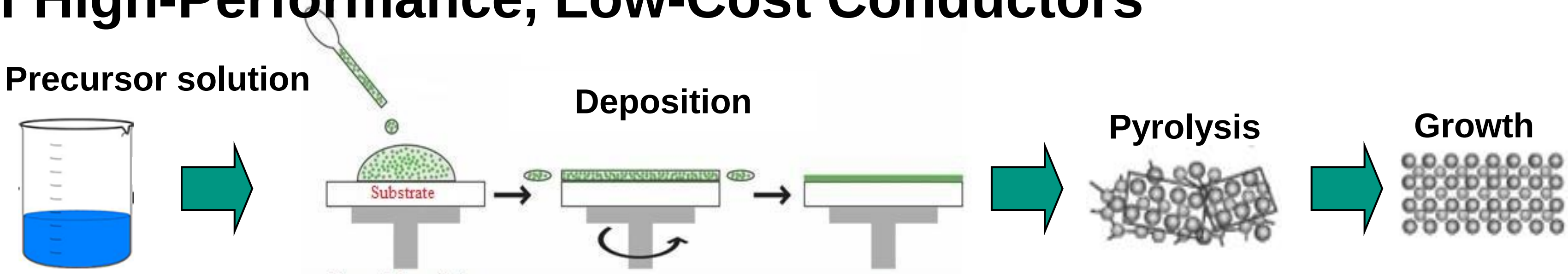




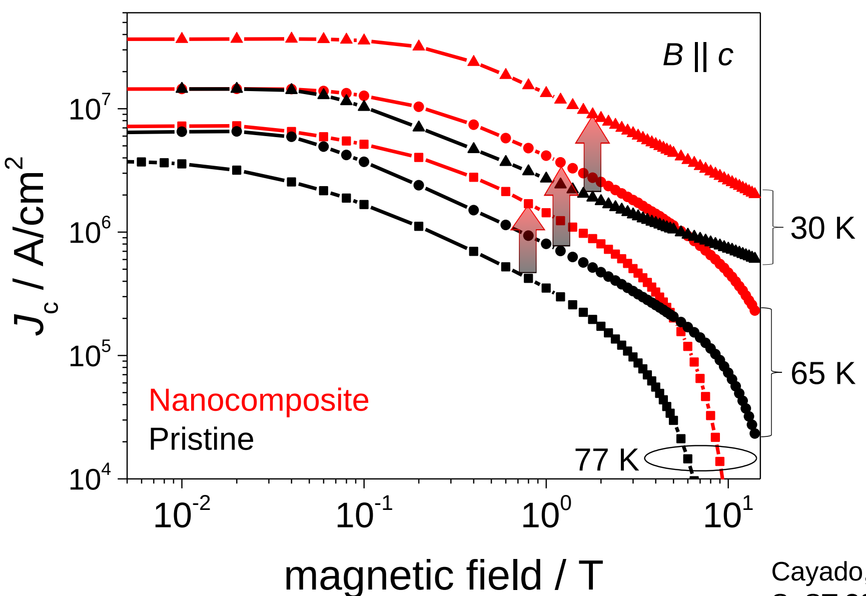
L. Opherden et al., Sci. Rep. **6**, 21188 (2016)

Well-controlled arrangement of nanoengineered defects enable strongest pinning and therefore highest critical currents

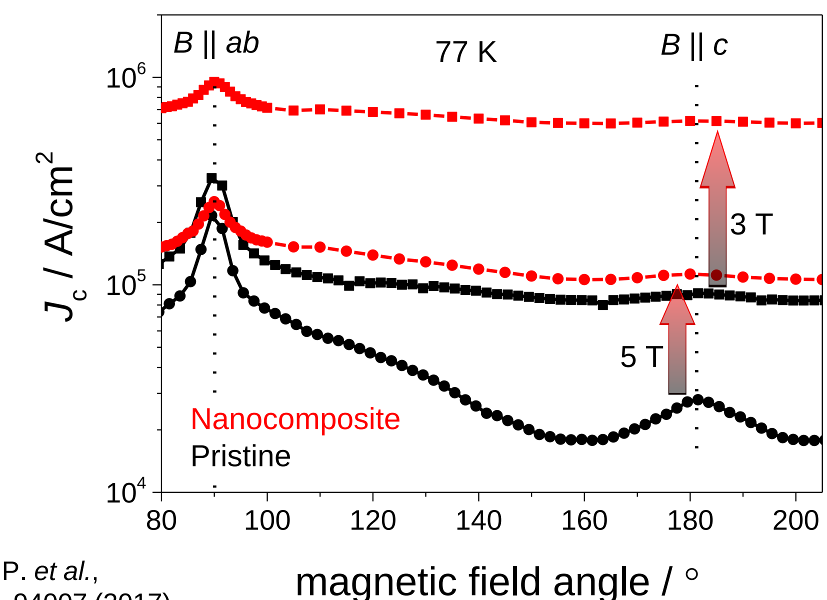
Chemical Solution Deposition of High-Performance, Low-Cost Conductors



$(Y,Gd)Ba_2Cu_3O_x$-$BaHfO_3$ nanocomposite films

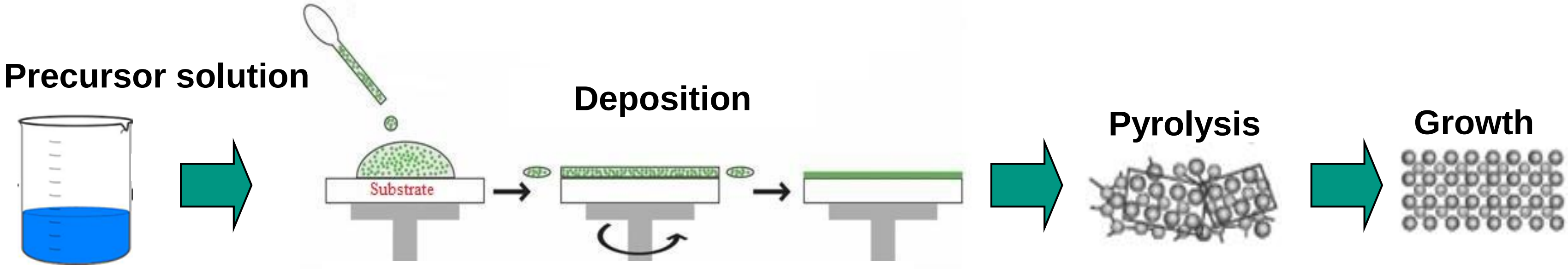


Cayado, P. *et al.*, SuST **30**, 94007 (2017).



Highest J_c and low J_c anisotropy in CSD nanocomposites achieved

Economic Coated Conductor Upscaling



Upscaling in cooperation with d-nano/BASF

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Cryogenic Materials Investigation & Testing

Karlsruher Institut für Technologie

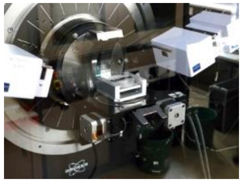
Various Test Platforms

ATLAS
axial ± 650 kN
Test of „Full-Size" components

PHOENIX
axial ±100 kN

PPMS
Heat capacity

X-Ray
Structural analysis



TORSION
axial ± 100 kN
torsion ±1000 Nm

INSTRON
Fall-Testing

GADALBINI
Charpy Testing

MTS25 & 50
cycling tests

Cryogenic Materials Investigation & Testing

CryoMaK is ITER reference lab

Examples for testing:

- Jacket (TF, PF, CC)
- Radial plates 316LN
- Winding Pack Mock-up
- TF-casing
- Helium HV-breaks
- TF He-inlet
- Insulation shear strength tests

PF Winding Pack Mockup

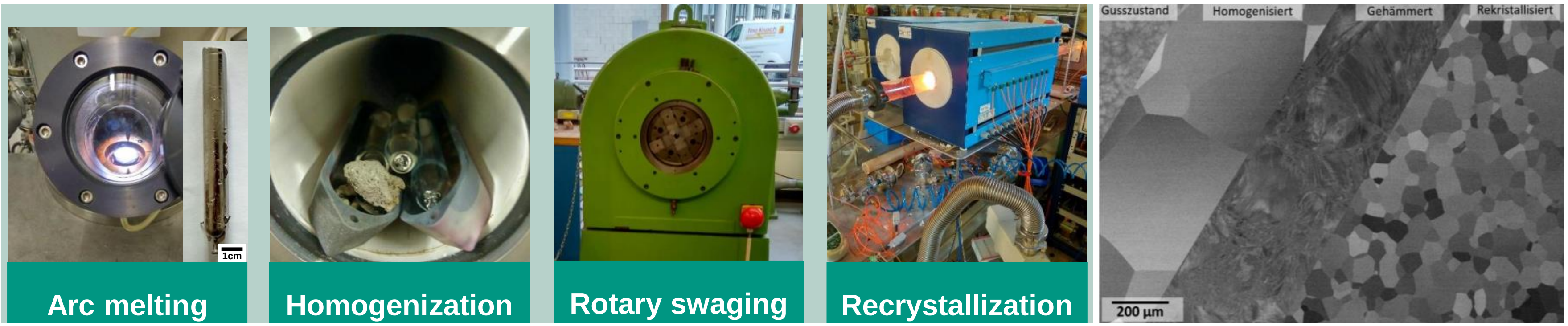
MTS 25 & 50 cycling tests

Radial Plate welding mock-up

Fatigue test at 4.2 K of TF coil He inlet

Cryogenic Materials Investigation & Testing

- **DFG focus program - High Entropy Alloy**
  Reference material (HfNbTaTiZr – bcc) produced



- **International Cryogenic Material Library (ICML)**
  ICML as main database for publications of cryogenic material database

Founding comittee in Boulder, USA (Nov.2018)
ICMC, NIST, NHFL (USA), NIMS, NIFS (Japan), **KIT** (Europe, Germany)

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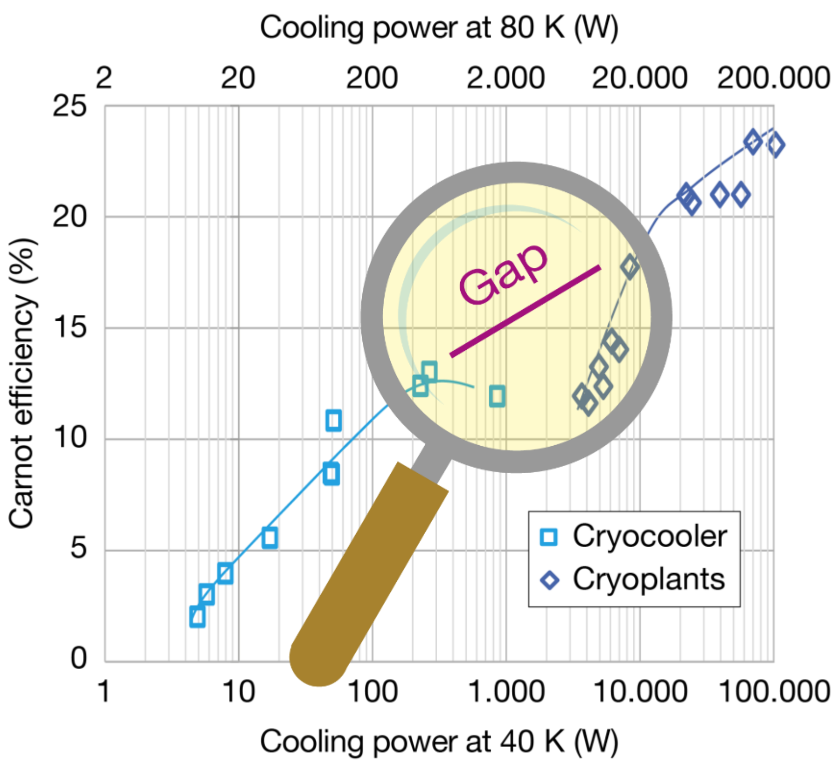
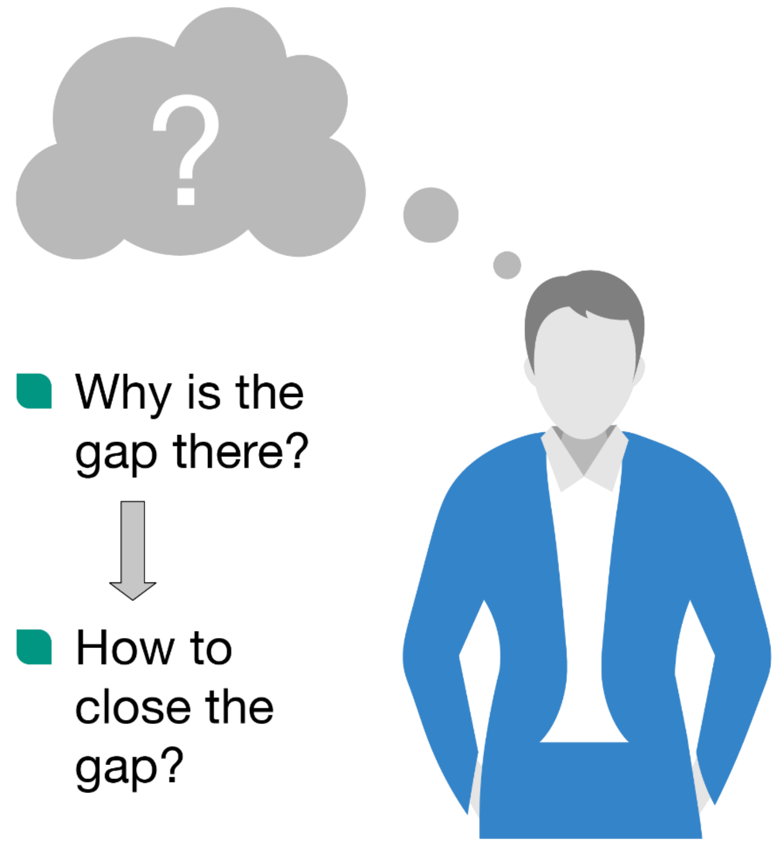
Cryogenic Technologies – Comparison

- State-of-the-art



Source: Decker, L.: Overview on cryogenic refrigeration cycles for large scale HTS applications. International Workshop on Cooling System for HTS Applications (IWC-HTS), October 14-16, 2015, Matsue, Japan

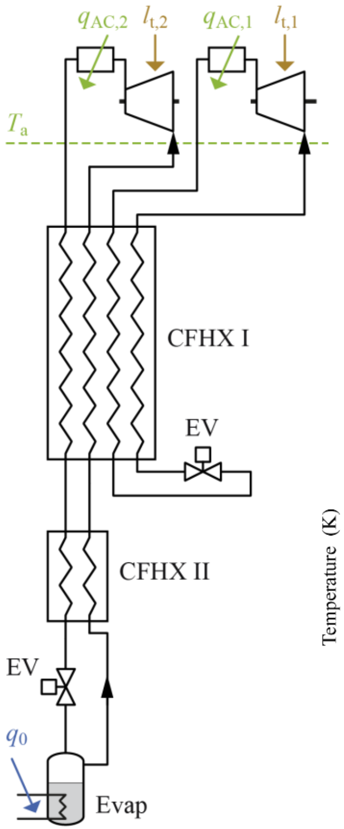


- Why is the gap there?

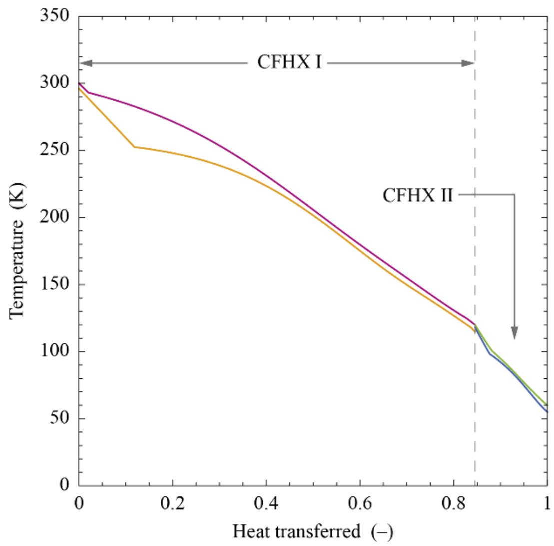
- How to close the gap?

Cryogenic Technologies

- Cryogenic mixed refrigerant cycles (CMRCs)



  - Wide-boiling mixtures for adaptation of capacity flow rates
    - **Molecular engineering** of fluid properties
  - Long-standing expertise of MRC-development at **KIT–ITTK** in **cooperation** with **IIT Madras**

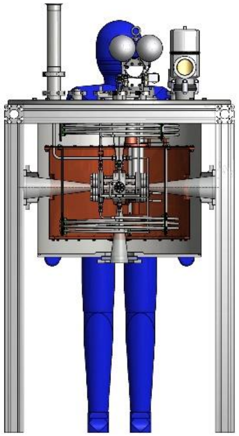


- Low pressure ($p \leq 20$ bar)
- No cold turbo-expanders
- **Inexpensive** (standard refrigeration components)
- **Scalable**
- **Good efficiency**

Properties of Cryogenic Fluid Mixtures

- **Systematic screening** of **non-flammable** refrigerant mixtures
  - Investigation of mixtures with **4th generation refrigerant** R1234yf
  - Measurement of vapor-liquid (VLE) and vapor-liquid-liquid (VLLE) equilibria **down to 150 K** (limitation of existing apparatus)
  - Modeling and publication of **equations of state**

- New **Cryo**genic **Pha**se **Eq**uilibria **T**est **S**tand (CryoPHAEQTS)
  - Temperature range **15 – 300 K**, maximum pressure **15 MPa**
  - Mixtures incl. flammable and oxidizing fluids (ATEX compliant)
  - Optical measurements in **cooperation** with **FAU Erlangen**
    - **Dynamic light scattering (DLS)** for measurement of thermal diffusivity, diffusion coefficient, speed of sound / sound attenuation
    - **Surface light scattering (SLS)** for measurement of viscosity and surface tension



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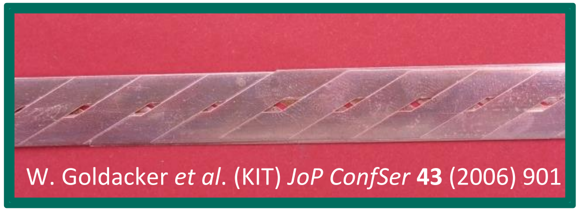
HTS High Current Cable Concepts

- Development and manufacturing of multistrand conductors for high current, low inductance, low AC loss applications

  - Stacks and Twisted Stacks

M. Takayasu (MIT) *et al.*, *IEEE TAS* **21** (2011) 2340; *IEEE TAS* **23** (2013) 4800104

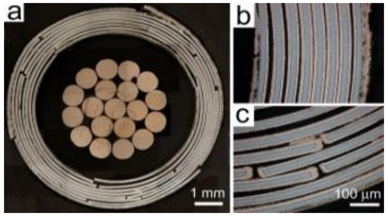
  - Roebel Cable



W. Goldacker *et al*. (KIT) *JoP ConfSer* **43** (2006) 901

  - Conductor on Round Core

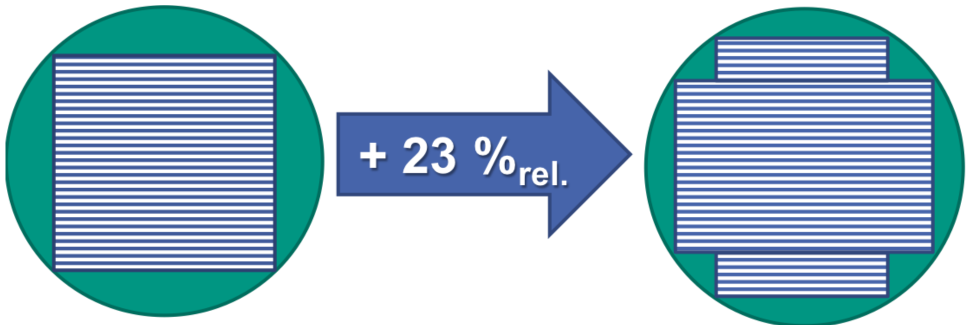
D.C. van der Laan, *SUST* 22 (2009) 065013.



The HTS Cross Conductor - CroCo Concept

Twisted Stack
(one width)

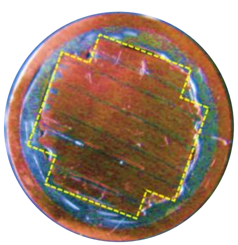
HTS CroCo
(two widths)

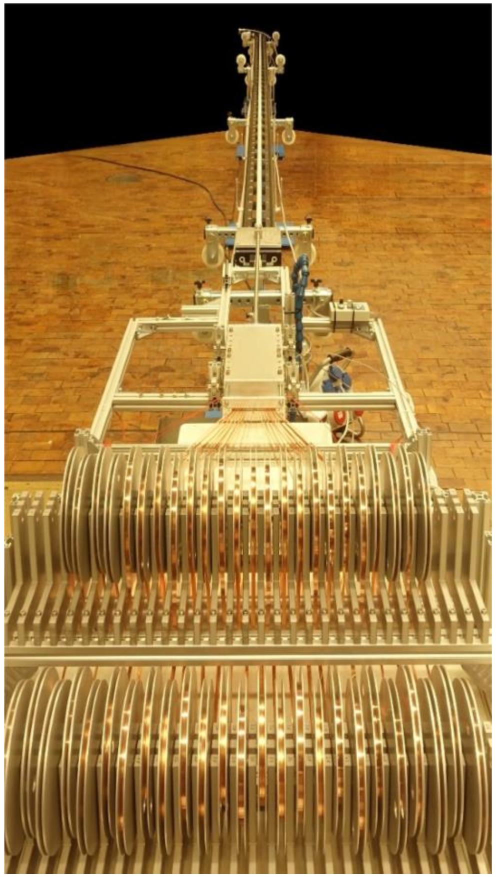


M. Takayasu et al.,
IEEE TAS 21(3), (2011) 2340

*W.H. Fietz et a*l., *IEEE TAS* 26(4), 2016, 4800705
M.J. Wolf et al., *IEEE TAS* 26(2), 2016, 6400106

- Continuous fabrication process including twisting





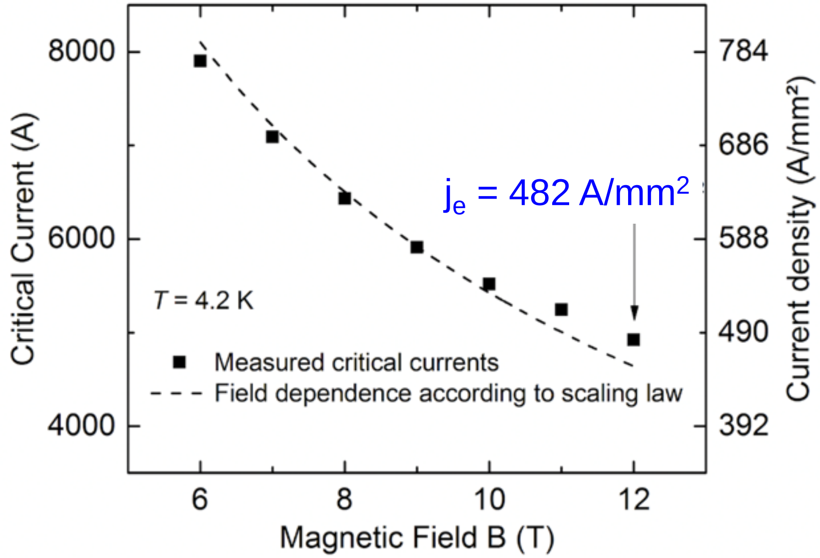
Successful demonstration and manufacturing of HTS CroCo´s up to 8 m

High-Current HTS CroCo Cables

- HTS CroCo is available as base strand in different sizes

	6/4 mm CroCo	4/3 mm CroCo	3/2 mm CroCo
Diameter incl. tube	9.3 mm	7.7 mm	5.8 mm
Min. Bending Radius R_{min}	~ 60 cm	~ 45 cm	~ 30 cm
I_c T = 77 K, sf	3.1 kA	2.1 kA	1.5 kA
I_c (4.2 K, B 12 T, || c)	> 10 kA	~ 9.5 kA	5.0 kA

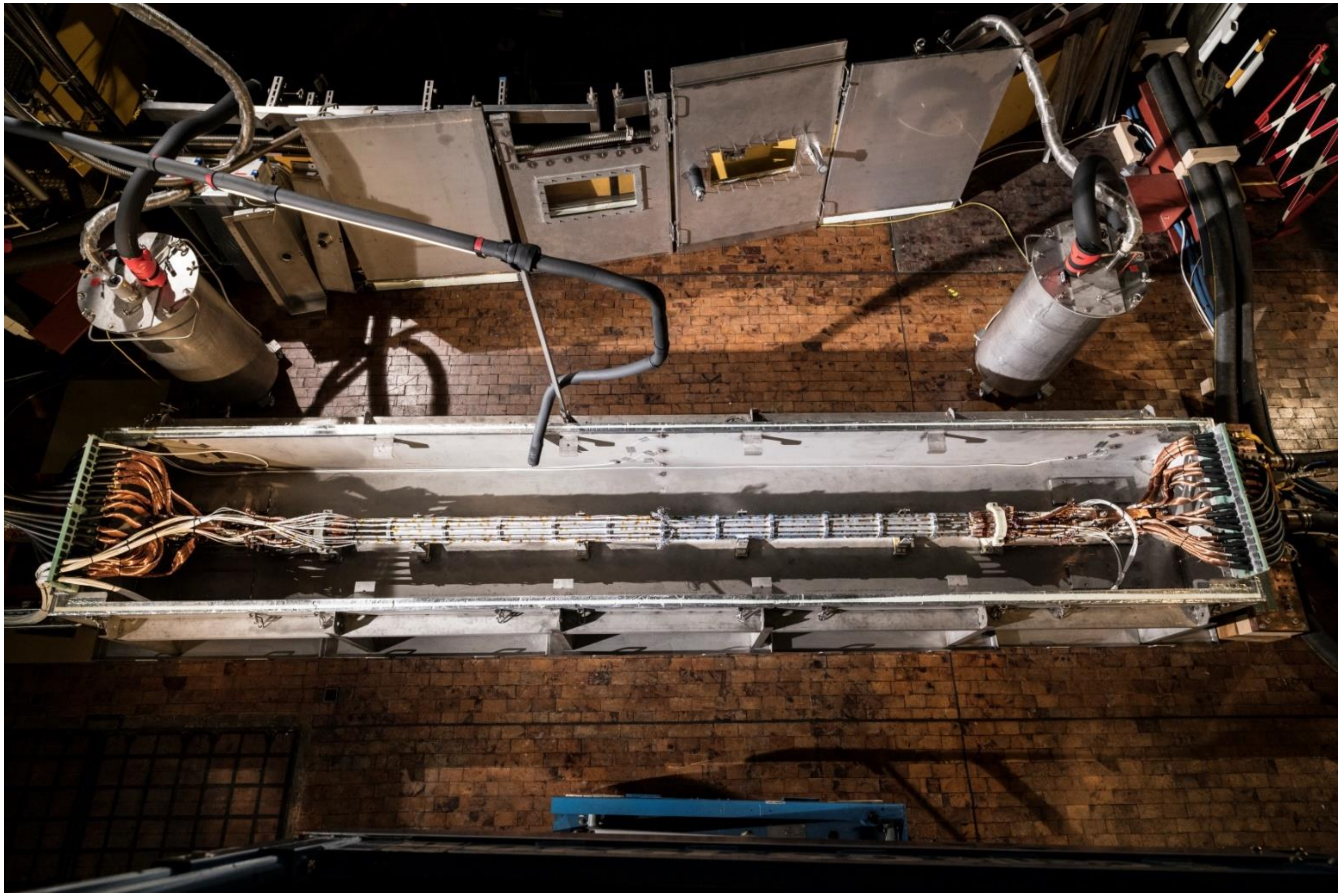
- Smallest 3/2 mm HTS CroCo **I_c (4.2 K, 12 T) ≈ 5 kA !**



High engineering critical currents in CroCo cables successfully demonstrated

High Current HTS CroCo Cables

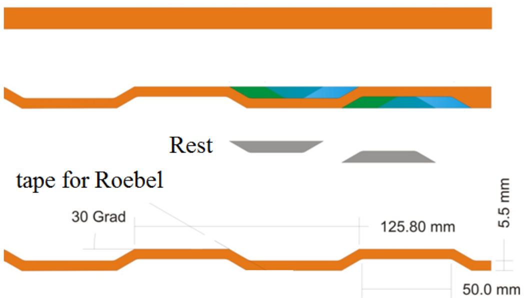
- Test of 35 kA DC test cable with 12 Cross Conductor Cables



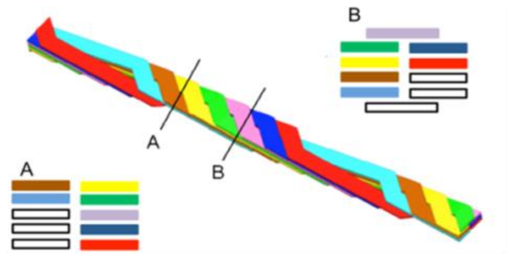
Manufacturing of HTS Roebel Cables

- Roebel cable concept requires complex fabrication steps

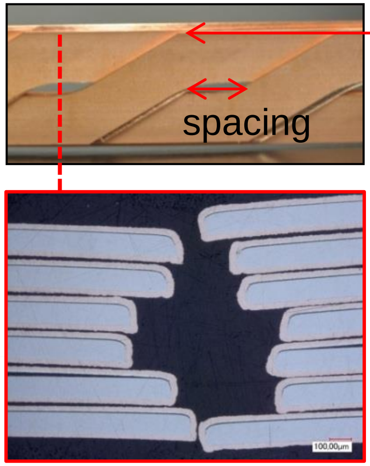
Multi- or one step punching process



Cable assembly

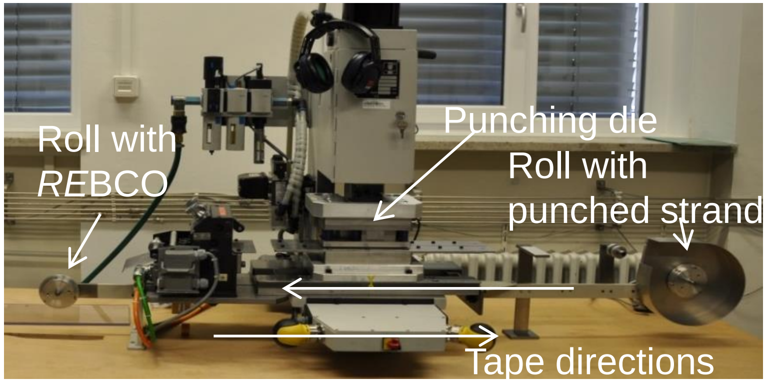


Transpositon length

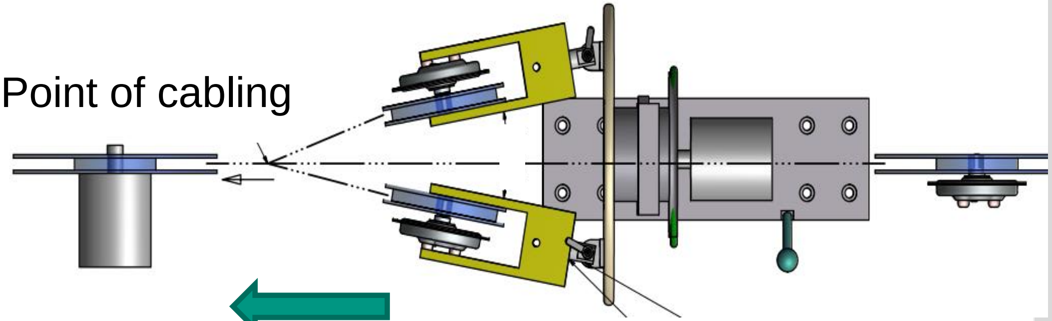


- Strand number
- Strand width

- Reel-to-reel manufacturing process



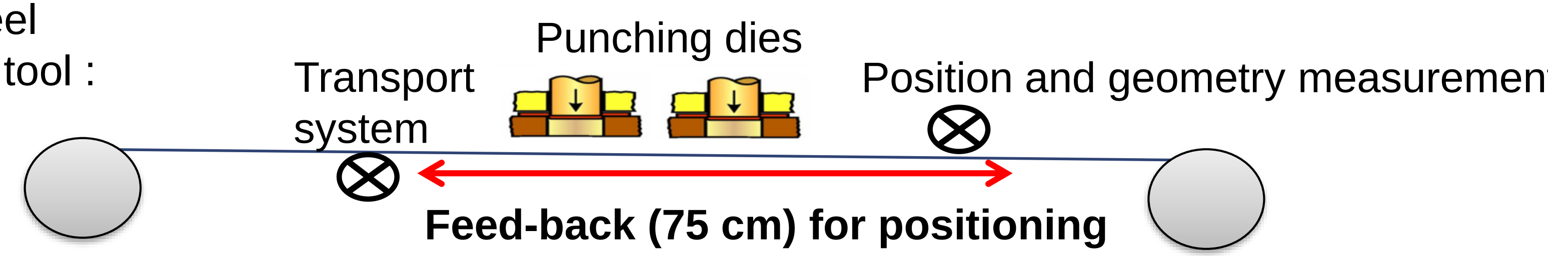
Point of cabling

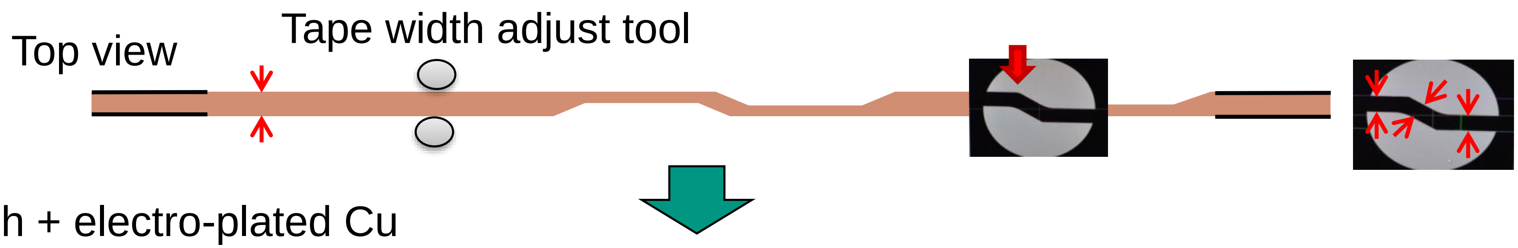


Cabling direction

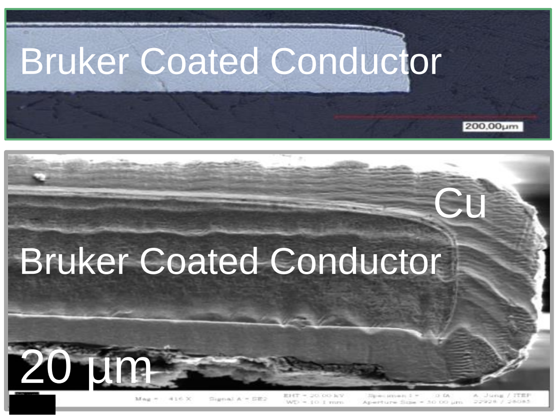
Manufacturing of HTS Roebel Cables

Reel-to-reel
Punching tool :



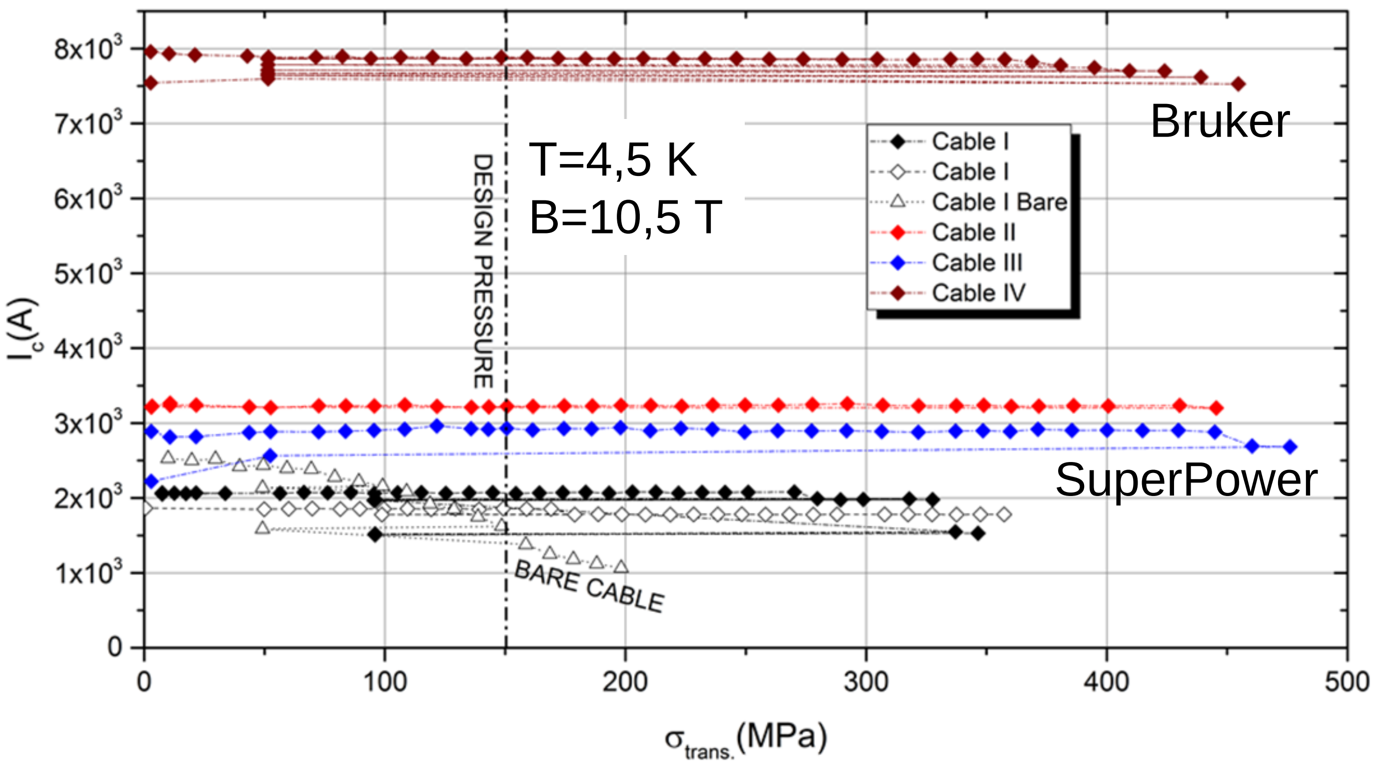


Punch + electro-plated Cu



Precise long-length cable punching (100 m demonstrated) for sharp damage-free cuts!

Roebel Cable Transport Properties



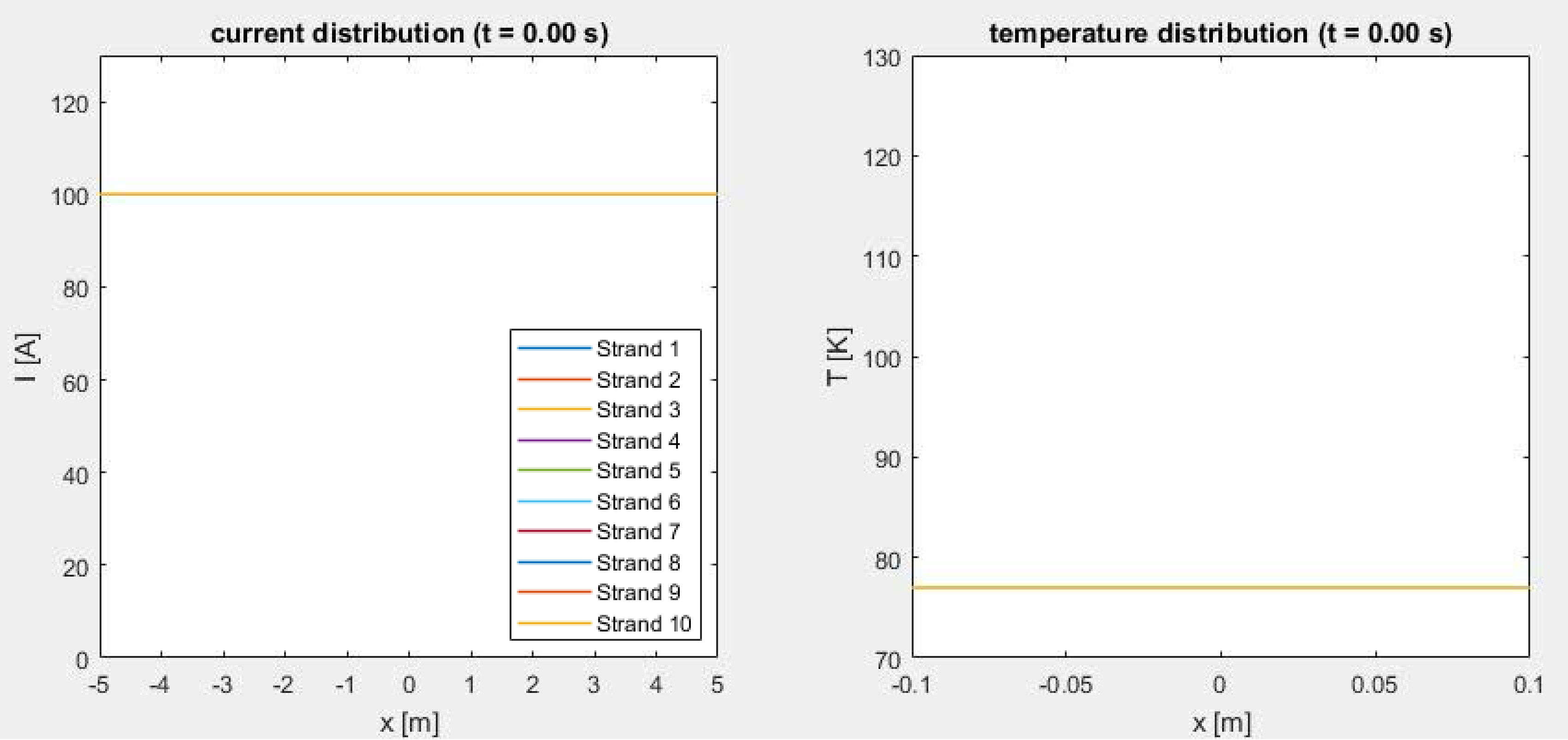
P. Gao et al. Effect of tape layout and impregnation method on transverse pressure dependence of critical current in REBCO Roebel cables. Presented at the 2016 ASC, Denver, USA. 2016

Impregnated Roebel cables show high critical currents and withstand transverse pressure in excess of 150 MPa

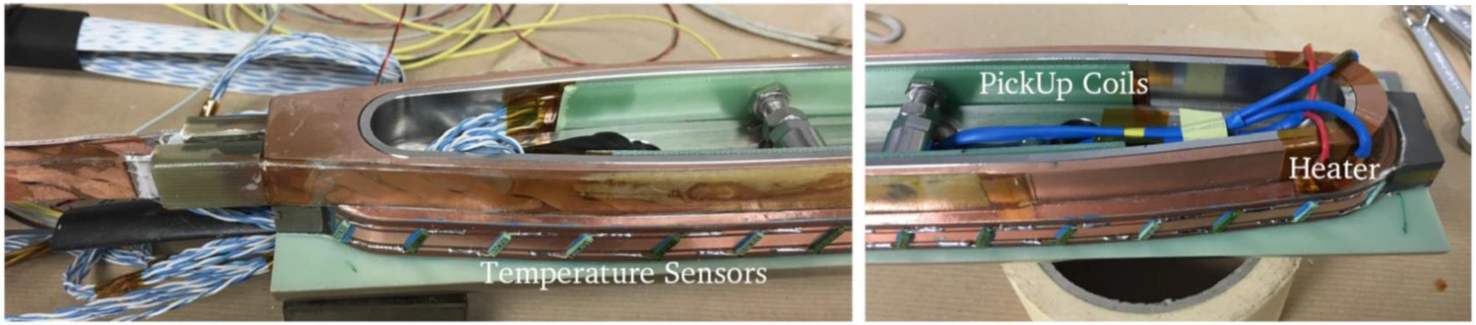
Quench Simulation of Roebel Cable

- 10 strands
- Applied current 10x100 A
- Temperature 77 K

	ρ_a	heat pulse	result
simulation 1	∞	0.2 J	quench
simulation 2	0.27 µΩm	0.2 J	
simulation 3	0.27 µΩm	0.3 J	

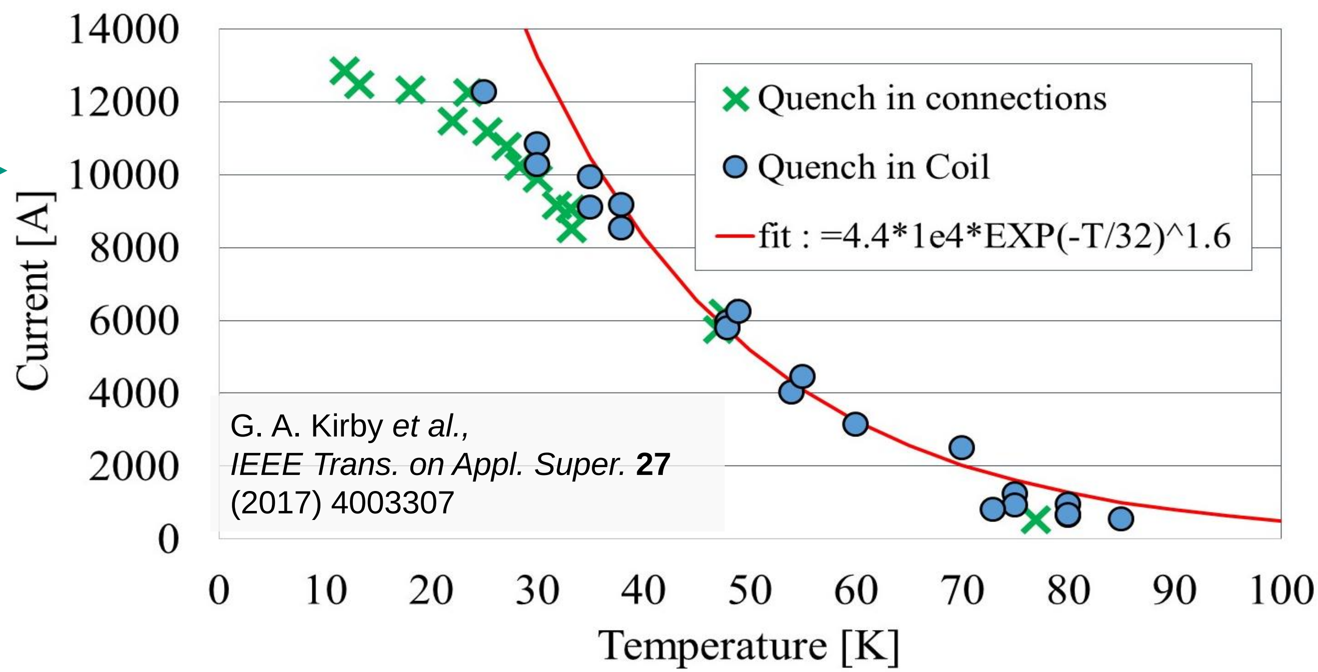


Roebel Cable Based Dipole Magnets



Subsize dipole magnet prototype coil (CERN)

Target current



Successful realization and test of prototype dipole magnet coils using Roebel cables

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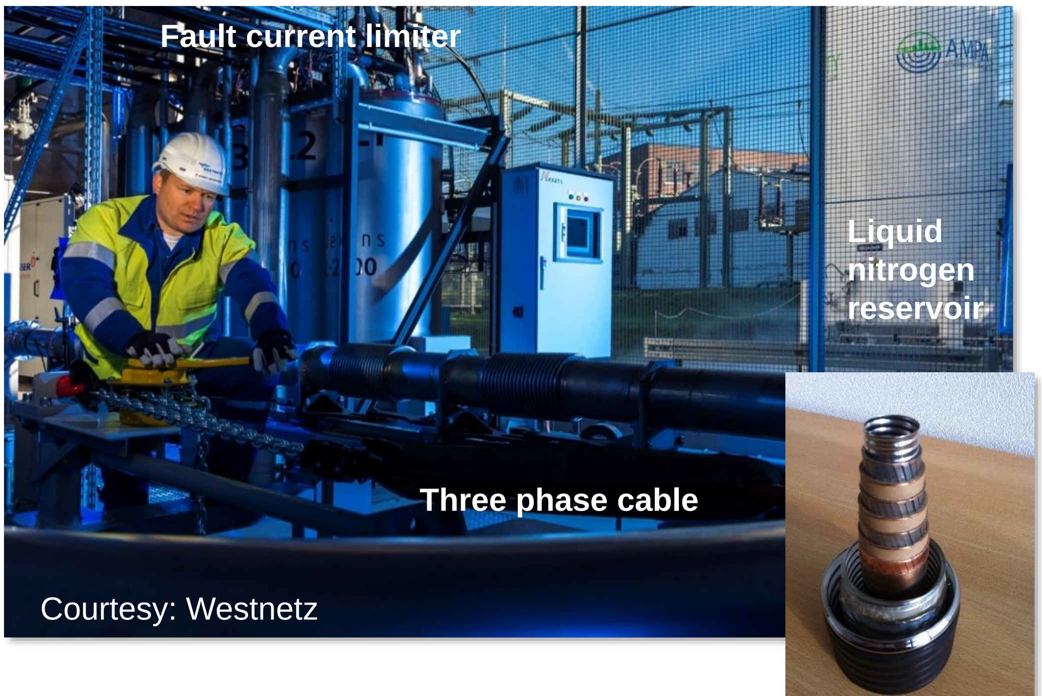
AmpaCity Cable

- Worldwide longest and fully operational superconducting cable (1 km, 40 MVA, 10 kV) with resistive-type superconducting fault current limiter
- KIT Tasks: Develop a three phase model cable with YBCO tapes, software tool for simulation and modeling, economic evaluation
- Successful continuous operation since April 2014, operation ongoing

Federal Ministry for Economic Affairs and Energy



Der Innovationspreis für Klima und Umwelt 2015

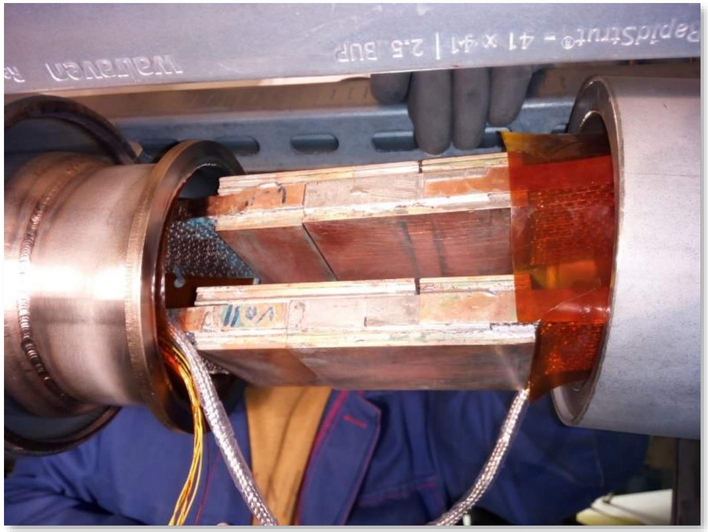
2015
German Prize for Innovation in Climate and Environment for the AmpaCity Project, Category Technologies

Field test demonstrated that all operational requirements are fulfilled

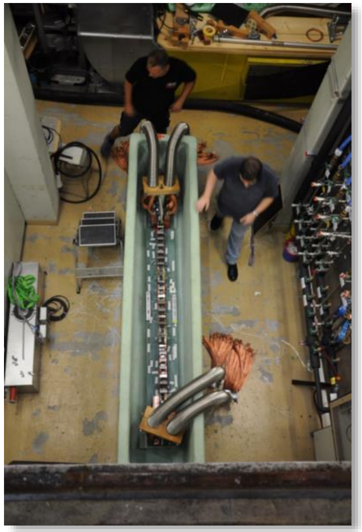
Modular High Current Busbar

- Development and test at industry fabrication site of a 20 kA, 25 m modular DC high current busbar system
- KIT Tasks: Electromagnetic design, joint manufacturing and busbar testing

Low-resistivity joint (1 nOhm at 20 kA)



Subscale test at 20 kA



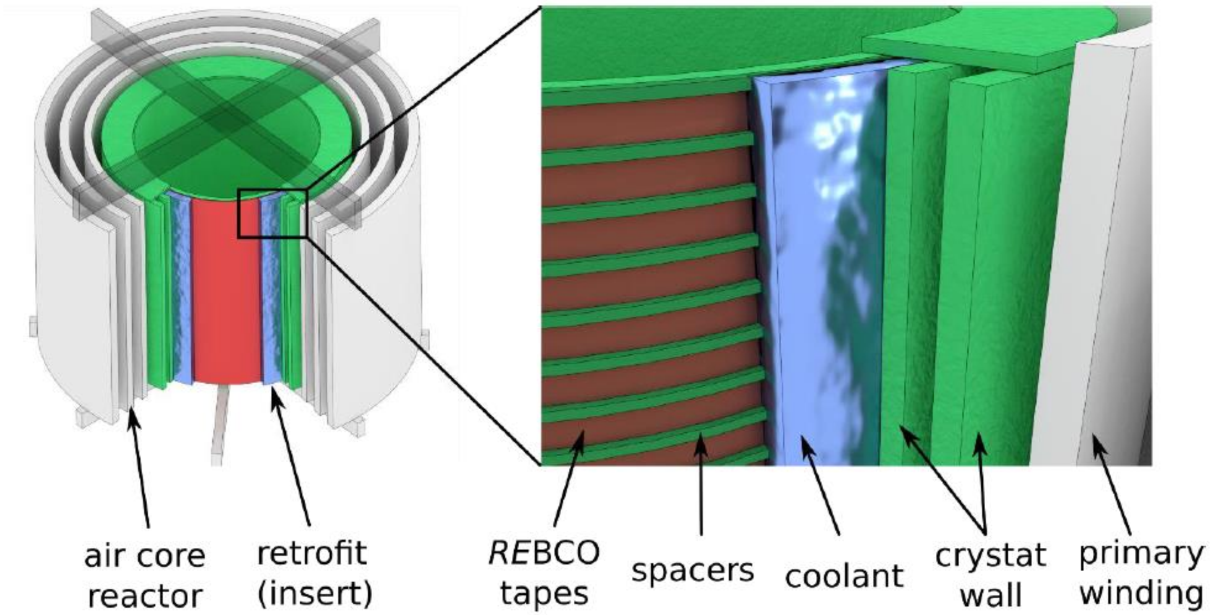
Mechanical test

Federal Ministry for Economic Affairs and Energy

Worldwide first HTS modular busbar industry installation

Air Coil Limiter

- Development and laboratory test of a 10 kV, 10 MVA air coil limiter type SCFCL
- KIT Tasks: Superconducting component test, cryostat design and real-time modelling



Advantages

- Low losses
- Retrofit
- Recovery under load
- Upscaling to high voltages

Federal Ministry for Economic Affairs and Energy

First-of-a-kind successful large-scale demonstration of patented fault current limiter technology

Air Coil Limiter

- Development and laboratory test of a 10 kV, 10 MVA air coil limiter type SCFCL
- KIT Tasks: Superconducting component test, cryostat design and real-time modelling

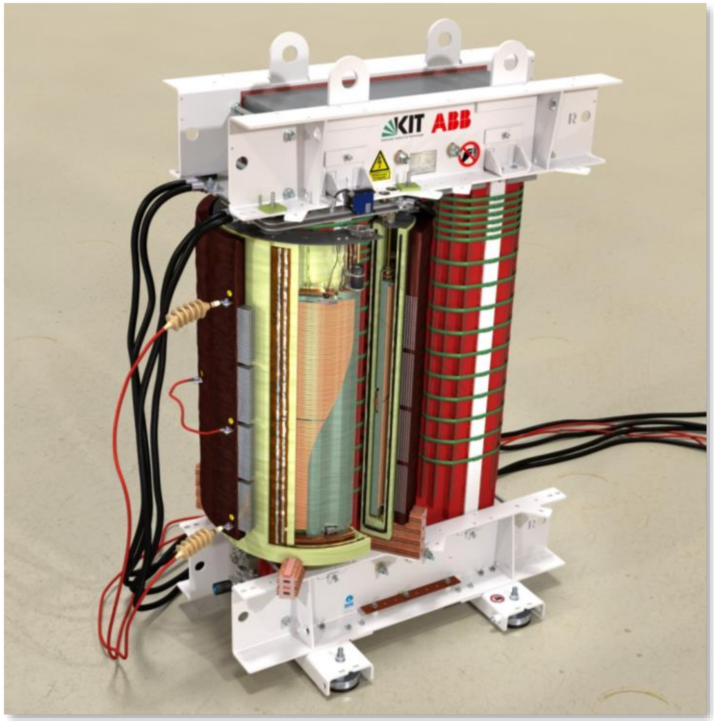
Current-limitation tests at Siemens Circuit Breaker Facilities in Berlin at 21-23 Feb. 2018

C. Schacherer, et. al. „SmartCoil—Concept of a Full-Scale Demonstrator of a Shielded Core Type Superconducting Fault Current Limiter, IEEE Transactions on Applied Superconductivity, Vol. 27, Nr. 4, June 2017, doi: 10.1109/TASC.2016.2642139

First-of-a-kind successful large-scale demonstration of patented fault current limiter technology

Fault Current Limiting Transformer

- Development and laboratory test of a 1MVA current limiting transformer with recovery under load
- KIT Tasks: Development of Superconducting winding and cryostat, transformer test



Name	Value
Nominal power	577.4 kVA
Voltage and current primary Cu winding	20 kV
	28.9 A
Voltage and current secondary superconducting winding	1 kV
	577.4 A
Fault duration	60 ms
Current limitation 1st HW	13.55 kA
Limitation 1st HW	71.4 %
Current limitation 6th HW	6.5 kA

S. Hellmann, M. Abplanalp, L. Hofstetter, M. Noe
Conceptual Design, Manufacturing and Test of a 1MVA Class Superconducting Fault Current Limiting Transformer with Recovery-under-Load Capabilities
IEEE Transactions on Applied Superconductivity, 27, 4, June 2017, DOI: 10.1109/TASC.2017.2652493

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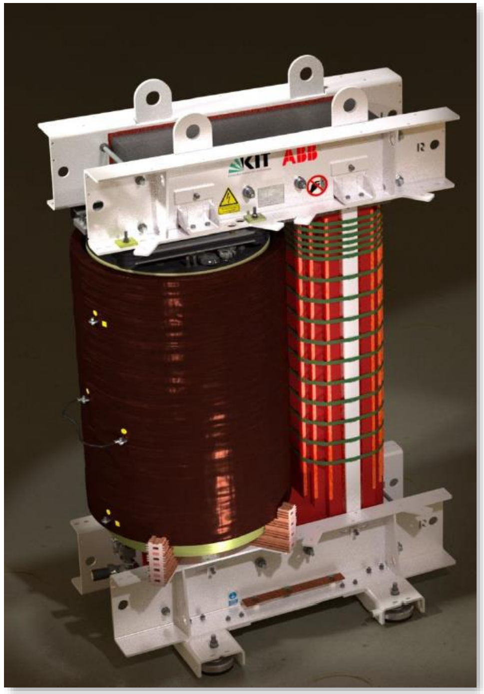
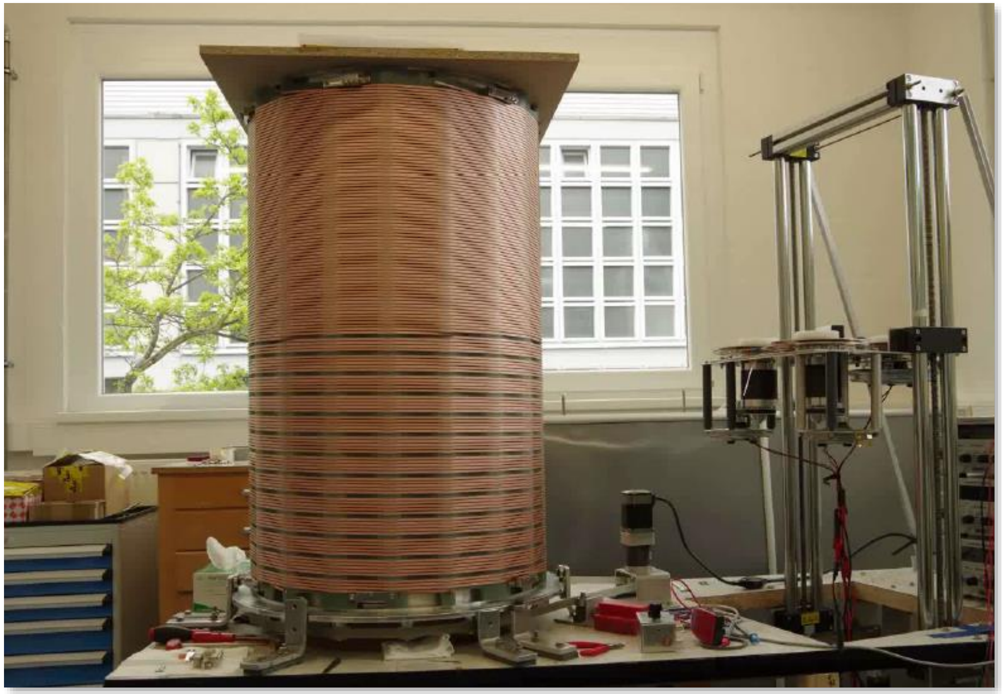
- Development and laboratory test of a 1MVA current limiting transformer with recovery under load
- KIT Tasks: Development of Superconducting winding and cryostat, transformer test





Patent Application: Transformator, Wickelkörper dafür und Verfahren zur Herstellung eines Wickelkörpers, Hellmann, Sebastian, DE 102015114208.2, WO PCT/EP2016/001412

Successful laboratory test of highly efficient demonstrator

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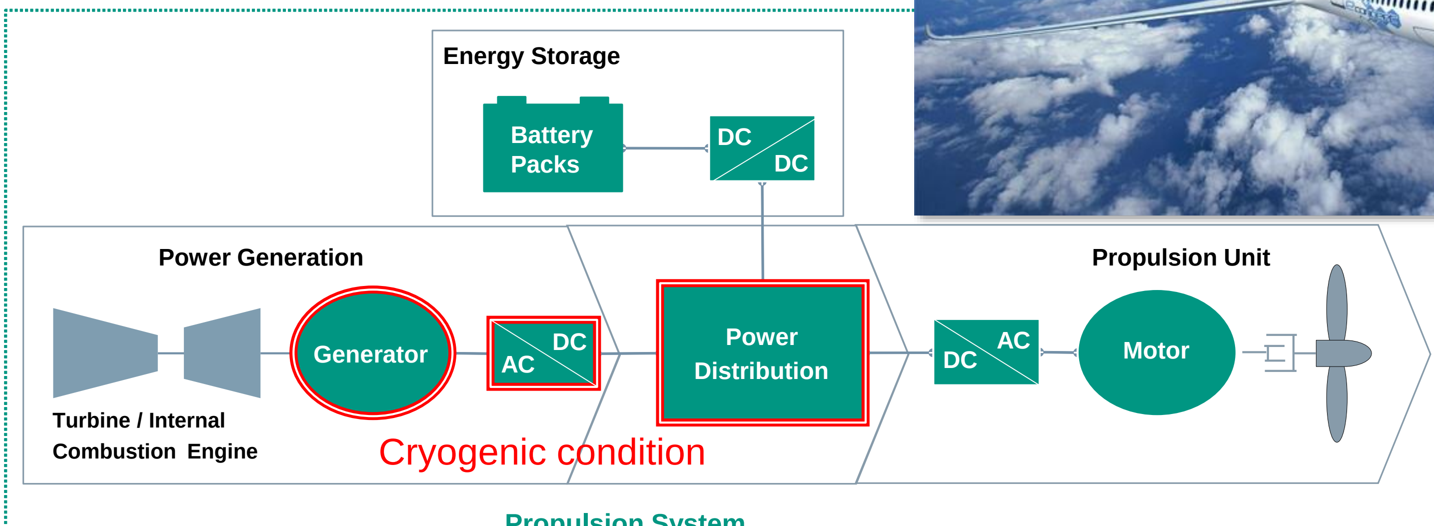
Electric Aircraft

AIRBUS SIEMENS KIT Karlsruher Institut für Technologie

- Develop and test key elements of superconducting infrastructure for future electric aircraft
- KIT Tasks: Design and demonstration of low-weight, high-current cable, support generator demonstrator application



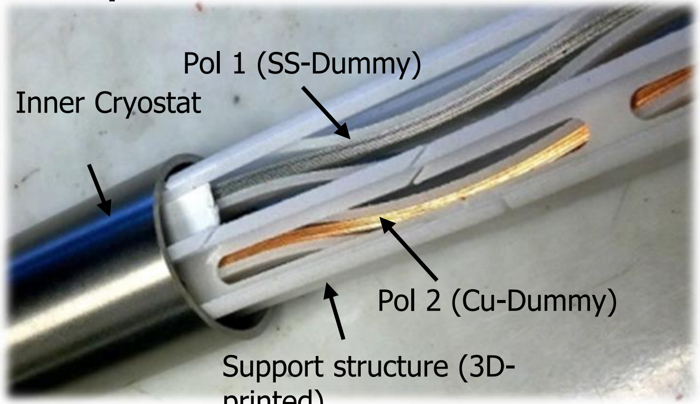
Federal Ministry for Economic Affairs and Energy

Pioneering R&D for key components of future electric aircraft
Setup of cable test facility for 40 MW, 20 m cable demonstrators at variable temperature

Electric Aircraft

- 40 MW compact cable development
  - Cable design finished
  - Lorentz force test successful
  - Low ohmic joints
  - Design for compact cryostat

Cable design as dummy with 10 Cu- and SS tapes



AC-Lorentz force test at 2 pole dummy cable, 10 half waves, I_{peak} = 19.5 kA, LN_2

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Francesco Grilli

State of the Art and Open Challenges

Karlsruher Institut für Technologie

- 2D electromagnetic and thermal modeling well developed
  - Different formulations of Maxwell’s equations + thermal equations
  - Different software implementation (commercial, home-made)
- Challenges:
  - Integrate the superconductor model into simulation of complex devices (e.g. electrical machines)
  - Extend models to 3D and make them routinely usable
  - Make models reliable, available and benchmarked

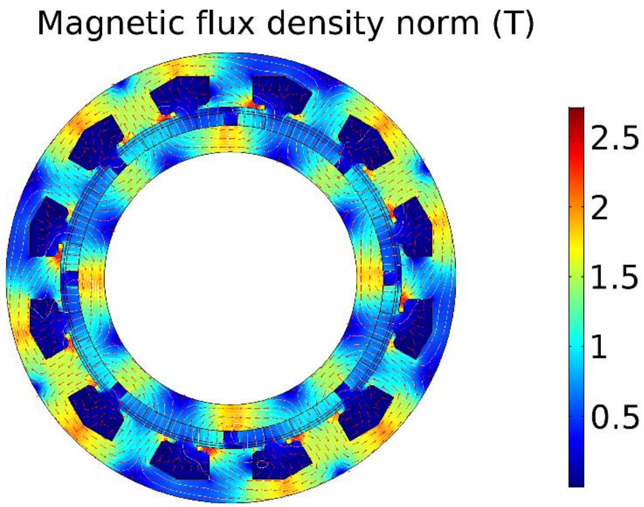
HTS MODELLING WORKGROUP | Modelling of high temperature superconductors (HTS)

www.htsmodelling.com

WELCOME! | BOARD | MODEL FILES | MATERIAL PROPERTIES | BENCHMARKS | WORKSHOPS | PUBLICATIONS

The ASUMED Project:
Modeling HTS Coils and Stacks for Aviation

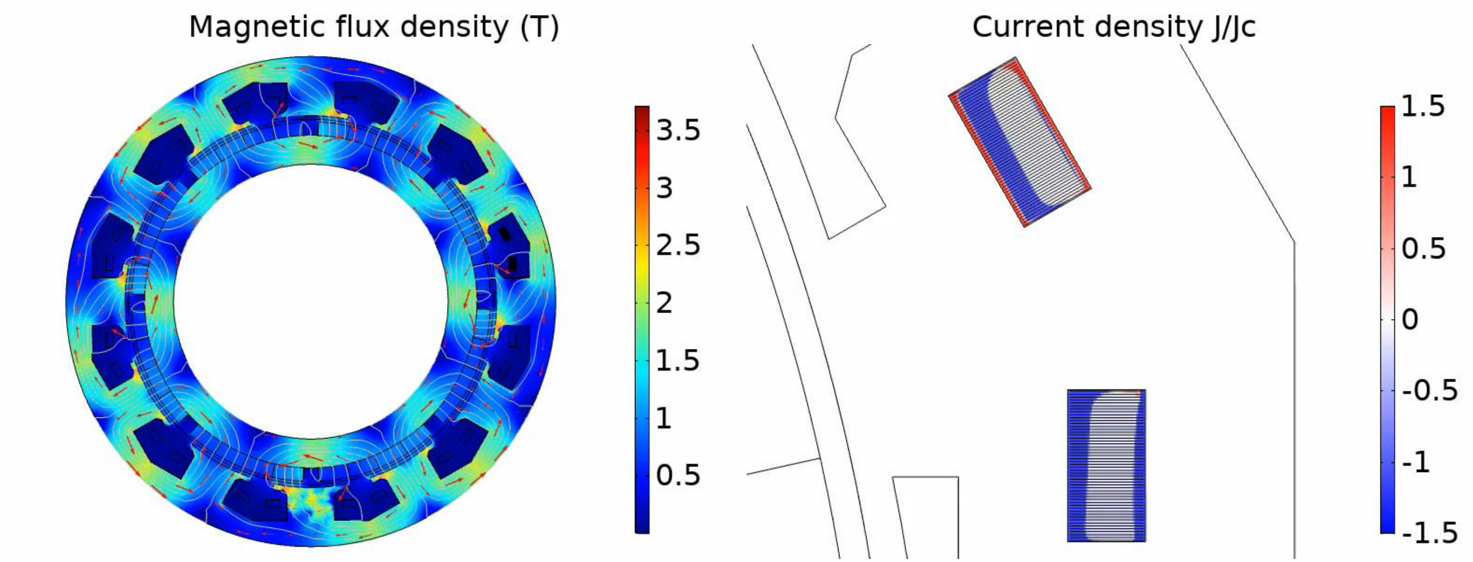
- Advanced Superconducting Motor Experimental Demonstrator
- Fully superconducting machine
  - Rotor: HTS coils
  - Stator: HTS tape stacks as permanent magnets (4 times higher than conventional)
- Power density 20 kW/kg
- Prototype:
  - ~1 MW power at 10,000 rpm
  - Thermal loss <0.1%
- http://asumed.oswald.de/



Numerical modeling will allow the first detailed AC loss evaluation in a fully superconducting machine

The ASUMED Project: Modeling HTS Coils and Stacks for Aviation

- Advanced Superconducting Motor Experimental Demonstrator
- Development of "Do it all" model



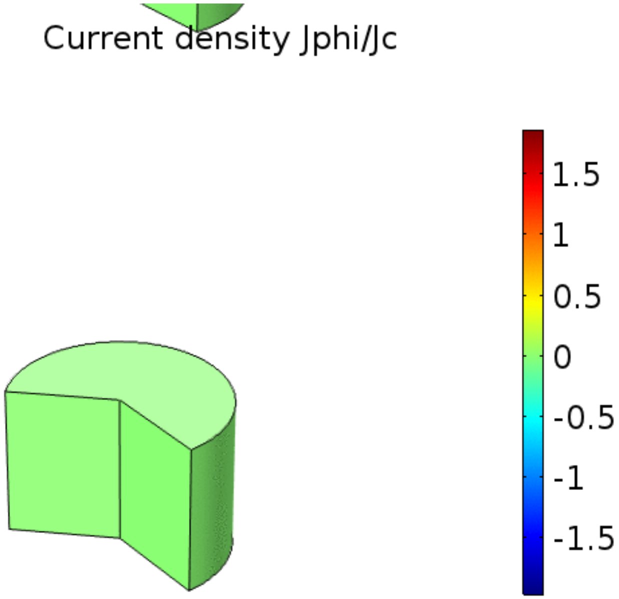
OSWALD
UNIVERSITY OF CAMBRIDGE
Air Liquide creative oxygen
KIT Karlsruhe Institute of Technology
hochschule aschaffenburg university of applied sciences
K·S
ELÚ
Rolls-Royce
DEMACO
SuperOx

Electromagnetic-Thermal Modeling

- Electrodynamic behavior of HTS magnets (homogenized *T-A* formulation)

Current density and magnetic field distribution in a 400-turn magnet (90 min charge/discharge).

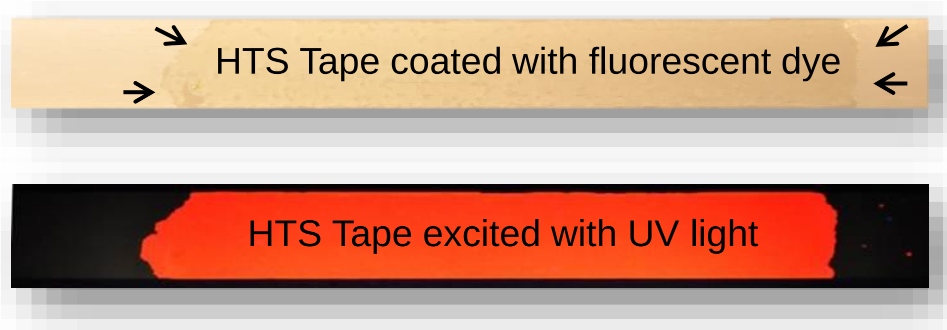
- Modeling of magnetic levitation with deforming mesh

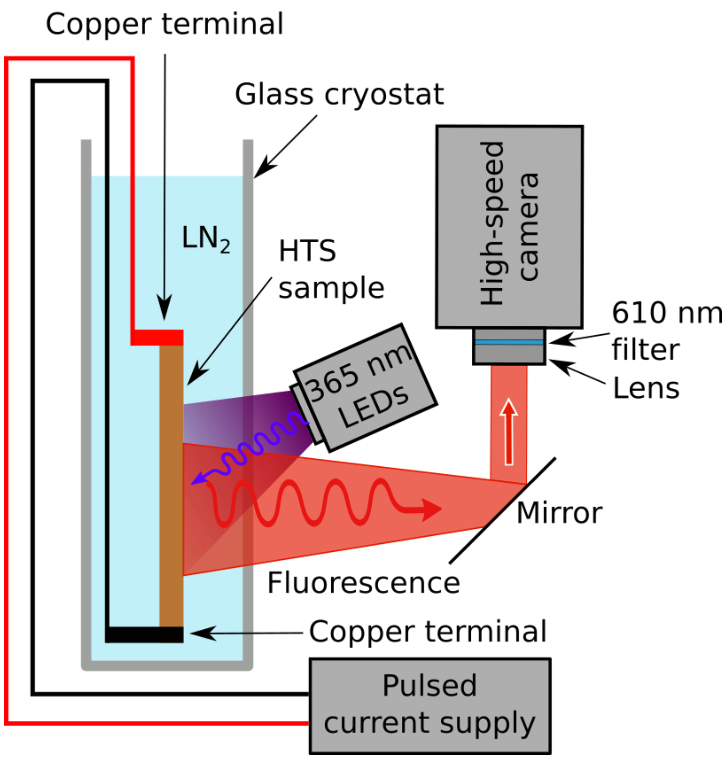


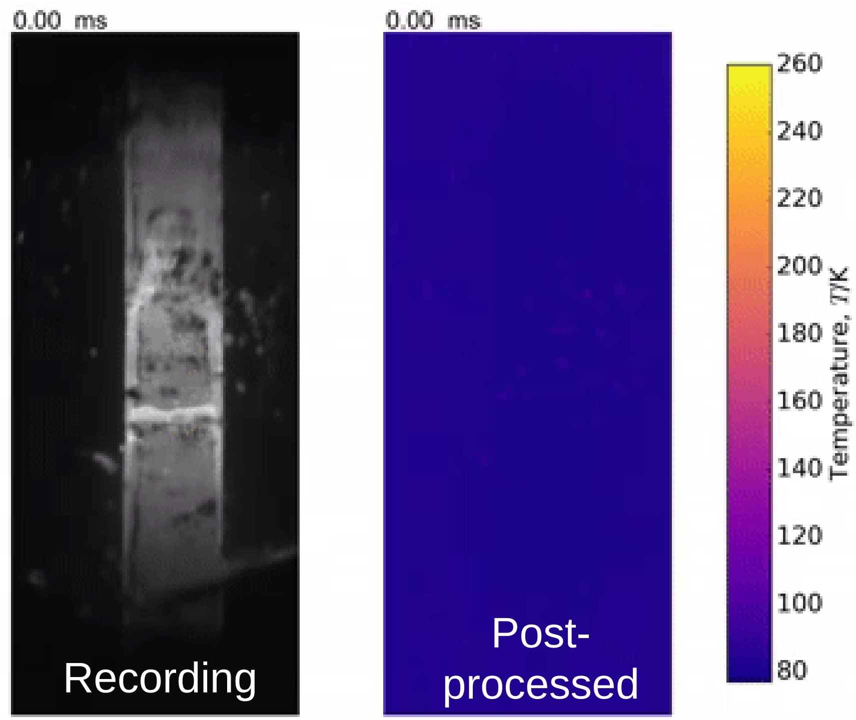
Levitation of a permanent magnet above a superconducting bulk. Currents induced in the bulks are displayed.

Francesco Grilli

High-Speed Fluorescent Thermal Imaging of HTS Tapes



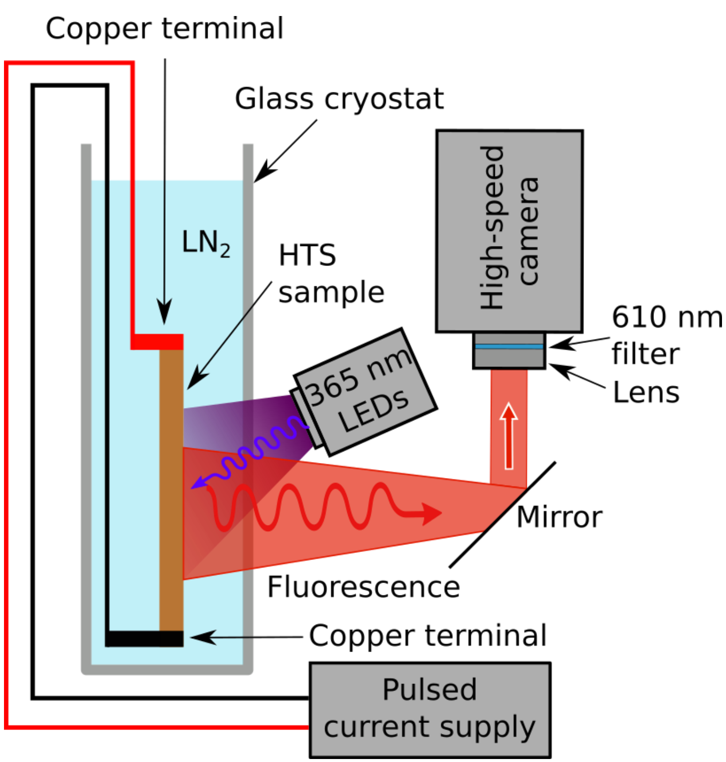


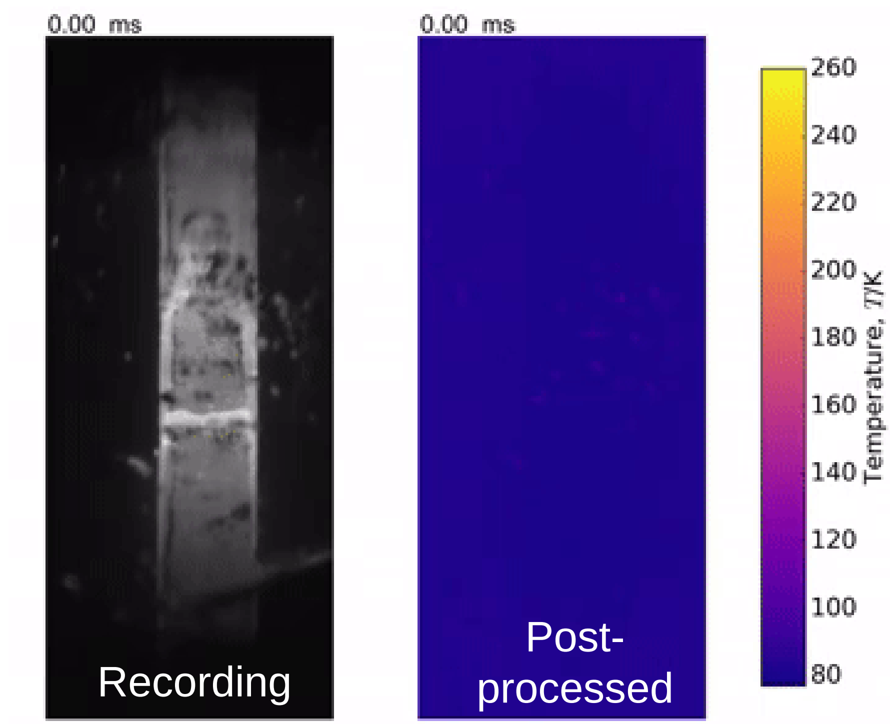


Francesco Grilli

High-Speed Fluorescent Thermal Imaging of HTS Tapes

Fast imaging of temperature evolution in HTS tapes





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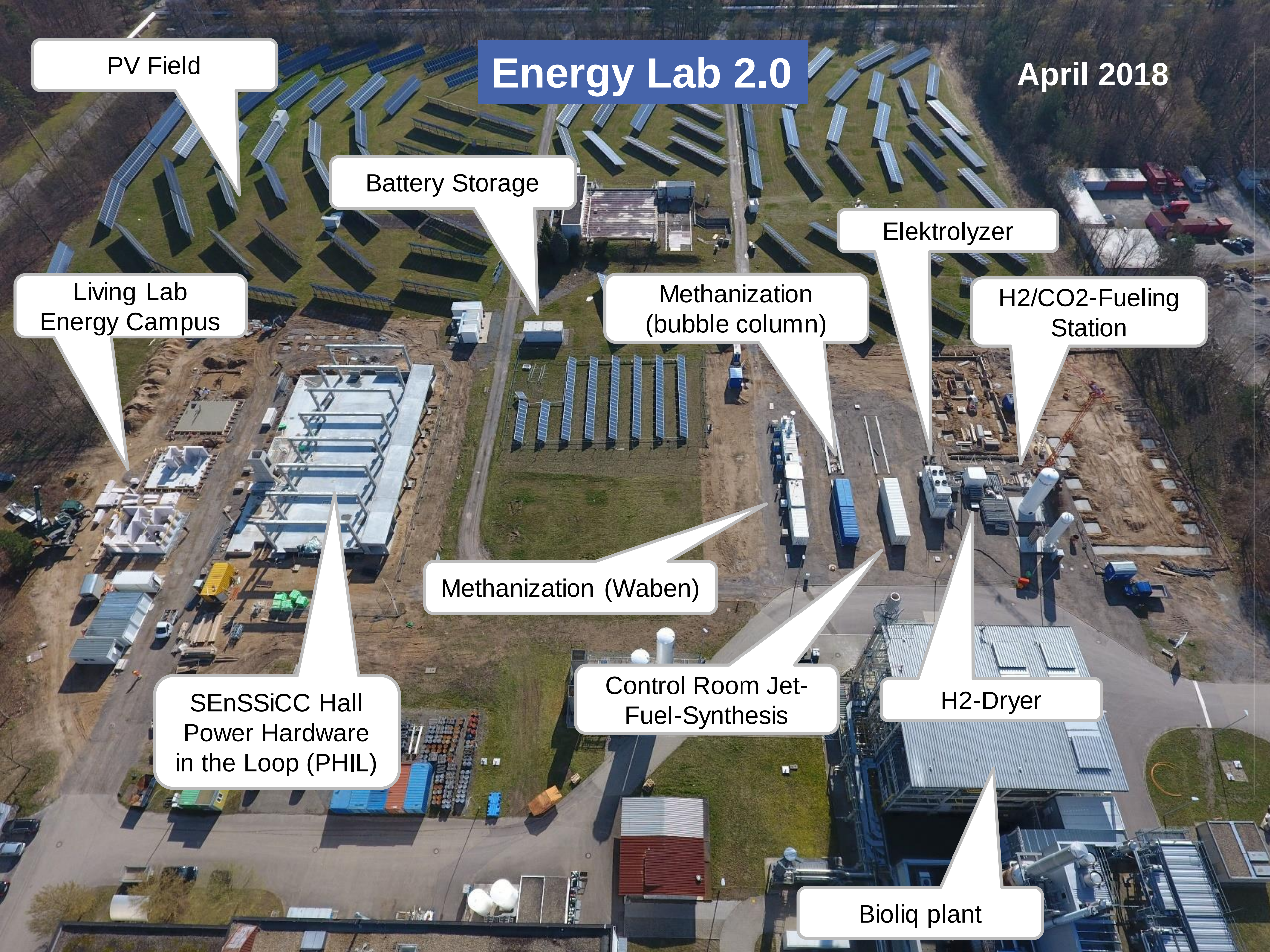
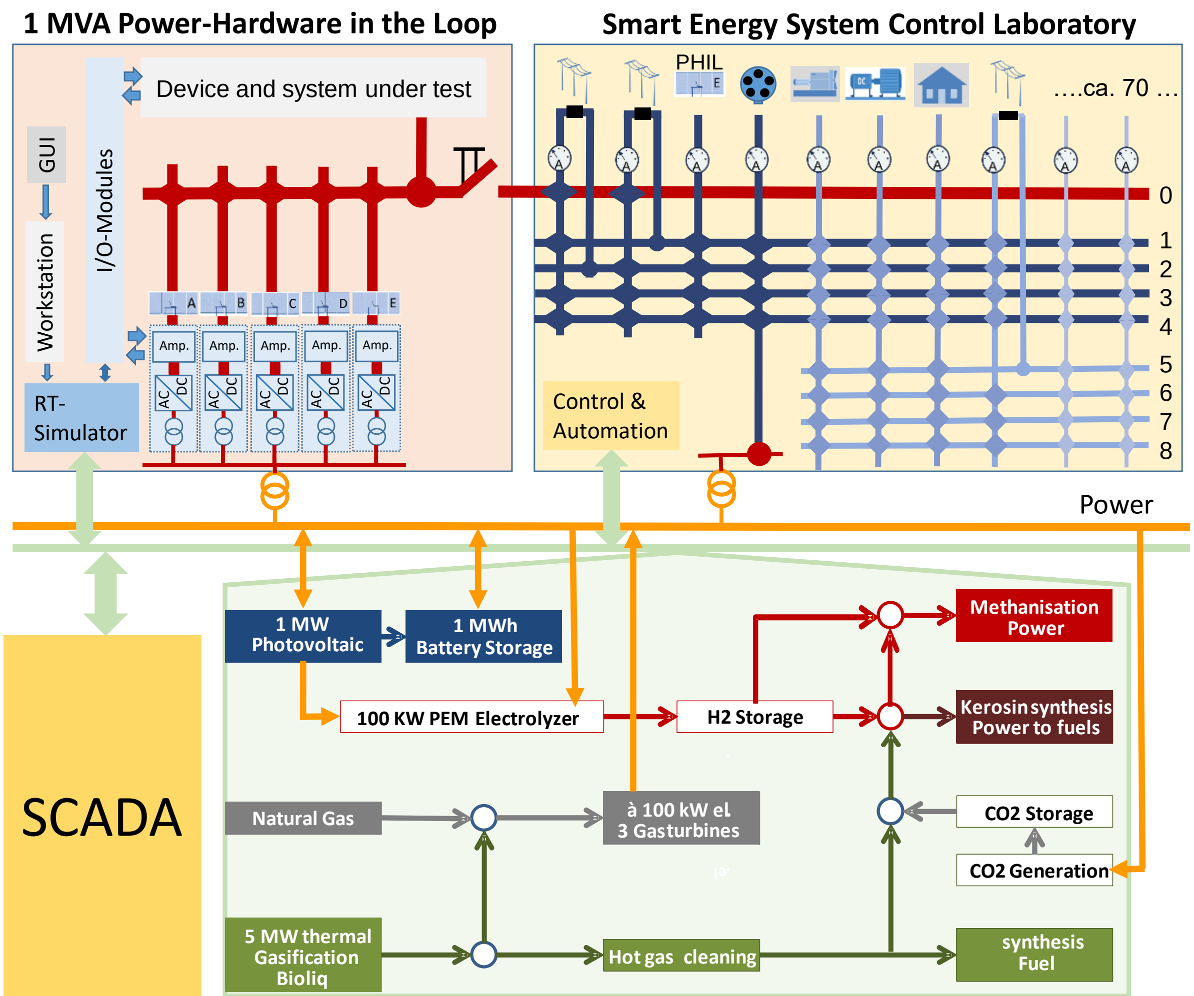

Energy Lab 2.0
April 2018
PV Field
Battery Storage
Elektrolyzer
Living Lab
Energy Campus
Methanization
(bubble column)
H2/CO2-Fueling
Station
Methanization (Waben)
SEnSSiCC Hall
Power Hardware
in the Loop (PHIL)
Control Room Jet-
Fuel-Synthesis
H2-Dryer
Bioliq plant

Energy Lab 2.0 at KIT: Microgrid and Power Hardware in the Loop



Main features

- Modular
- Fully interconnected
- Sector coupling
- Big data

Plus separate

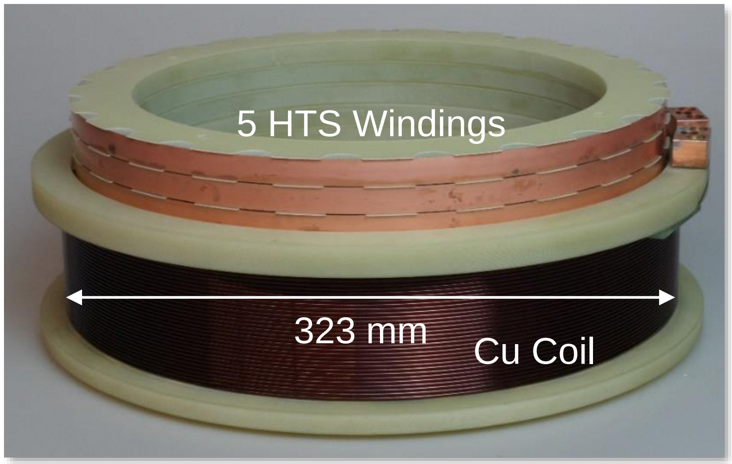
- PHIL training station

and

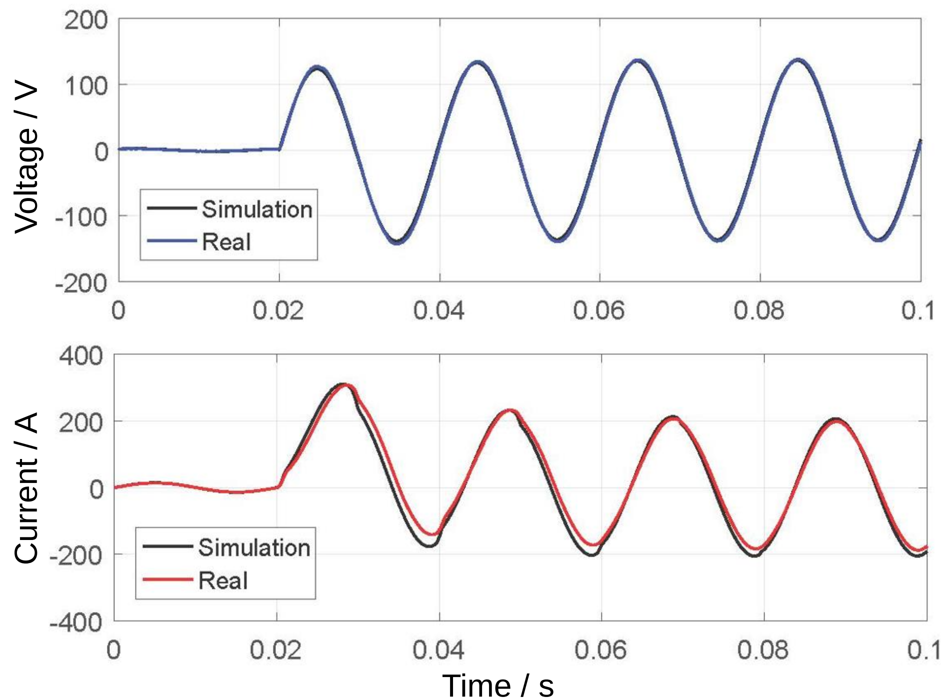
- Residential Smart Home PHIL Lab

System Integration with Air Coil Limiter

- Accelerate system integration of new power network technologies
- KIT Tasks: Development of real-time models and Power-Hardware-in-the-Loop Tests



Parameter	Value
Operating temperature	77 K
Voltage$_{RMS}$	100 V
Current$_{RMS}$	10 A
Limiting impedance	600 mΩ



Real-time modeling and Power-Hardware-in-the Loop test agree very well

First real-time modeling of superconducting fault current limiters

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Coil Technology

- High Field High Temperature Insert Coil
  - YBCO Layer Winding
  - 5 T insert in 20 T LTS background field
  - Test coils confirmed mechanical stability and current carryig capability

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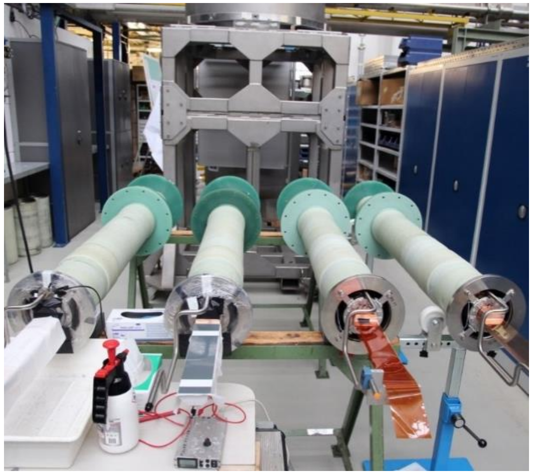
HTS Fusion Magnets and Current Leads

- Development and Test of Current Leads for JT60-SA

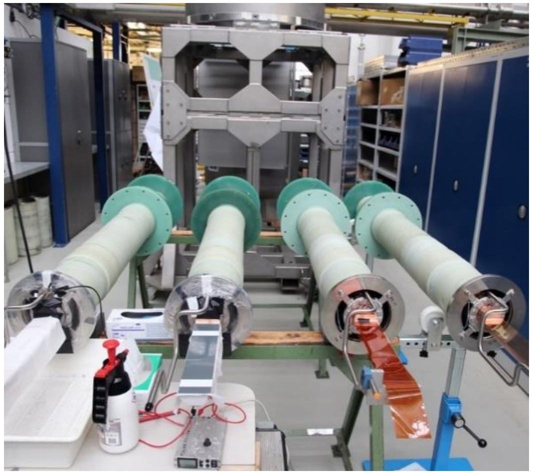


6 CLs with 26 kA

20 CLS with 20 kA

HTS Fusion Magnets and Current Leads

- Development and Test of Current Leads for JT60-SA



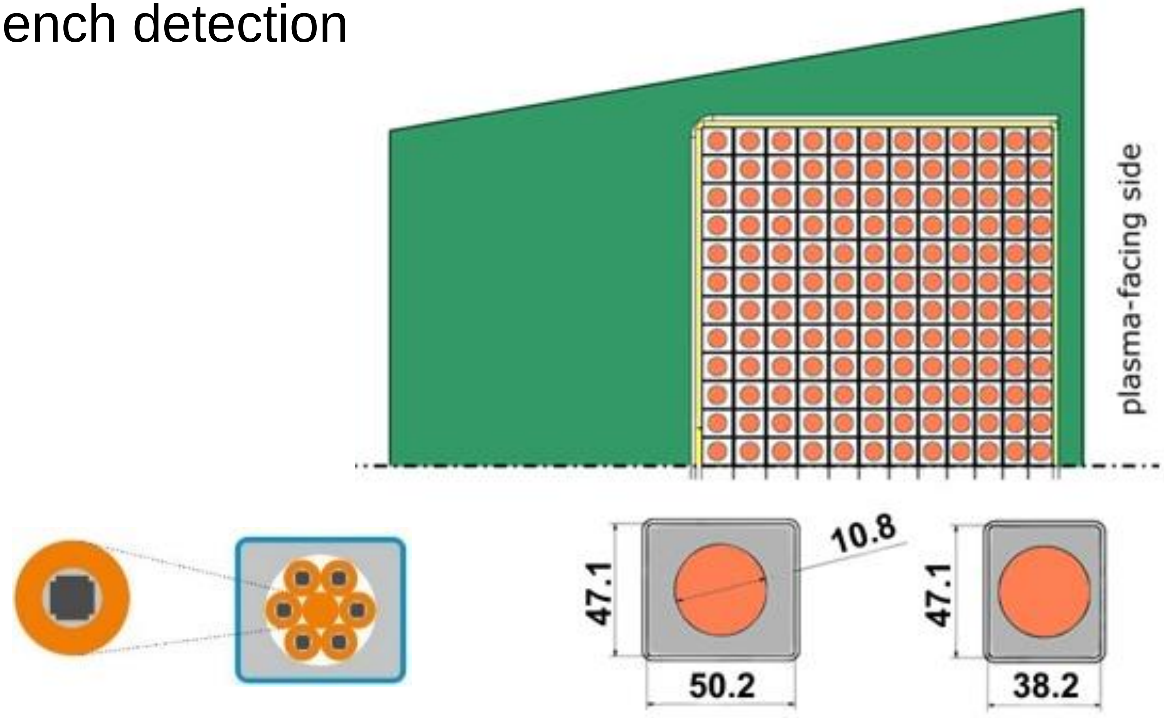
6 CLs with 26 kA

20 CLS with 20 kA

- Development of REBCO HTS Current Lead

HTS Fusion Magnets and Current Leads

- HTS Conductor Concept and Winding Pack
  - Mechanical, electrical and hydaulic simulation okay
  - > 10 K temperature margin
  - Challenging quench detection



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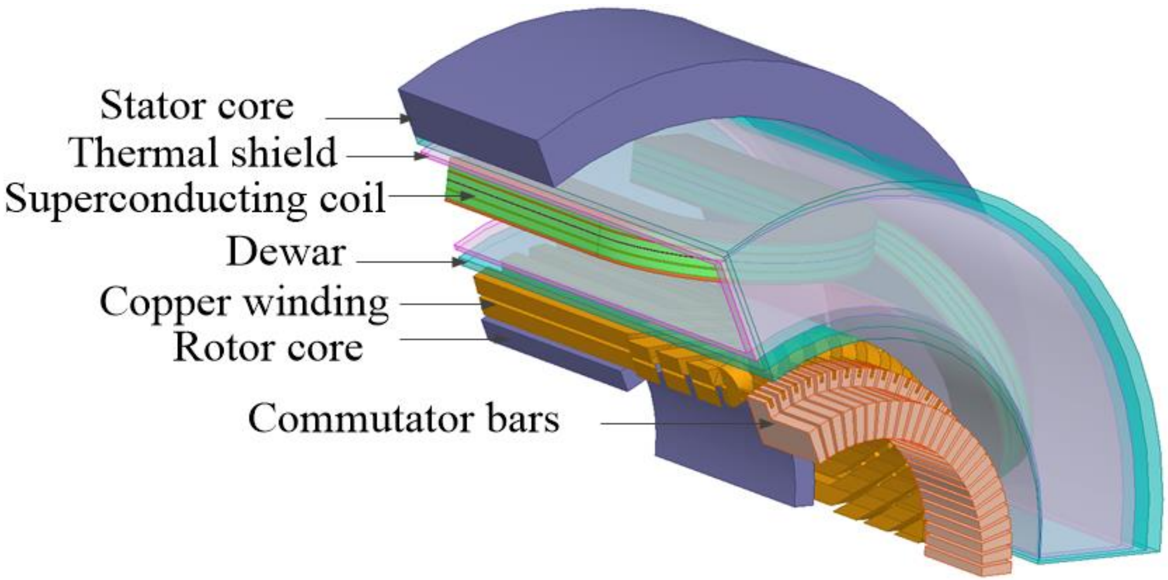
Wind Generator

- Development and laboratory test of a 10 kW superconducting DC wind generator
- KIT Tasks: Design, built and test of the demonstrator

Motivation
- Smaller volume and weight
- High efficiency

Advantages
- DC in superconductor
- Cryogenfree non-rotating cryostat



First-of-a-kind laboratory demonstrator for a superconducting DC wind generator

Y. Liu, M. Noe, M. Doppelbauer
Feasibility Study of a Superconducting DC Direct-Drive Wind Generator
IEEE Transactions on Applied Superconductivity, 26, 4, 1-6, 2016, DOI: 10.1109/TASC.2016.2536103

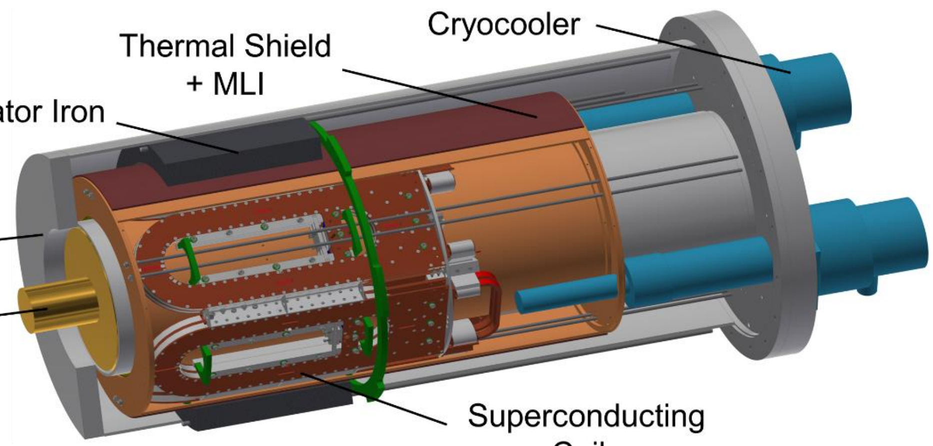
Wind Generator

- Development and laboratory test of a 10 kW superconducting DC wind generator
- KIT Tasks: Design, built and test of the demonstrator

Demonstrator data

Name	Data
Torque	275 Nm
Rated speed	389 rpm
Air gap flux density	Mag. 0.75 T Avg. 0.52 T
Stator outer diameter	486 mm
Stack length	220 mm
Air gap	5 mm
Pole number	6
Target temperature	30 K
SC coils current	147 A
SC tapes	3.2 km

Laboratory demonstrator



DFG funded Sino-German project since January 2018 to further develop basic technology for superconducting wind generators

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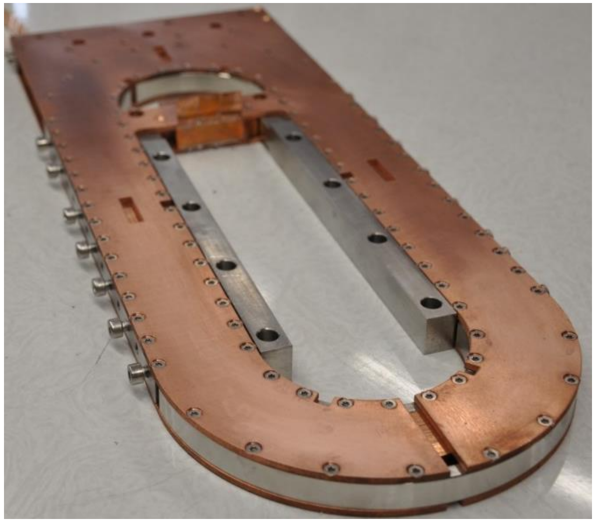
YBCO non inulation test coil



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ITEP Research Topics

Superconducting and Cryo-Materials Bernhard Holzapfel	Energy Applications Mathias Noe	Superconducting Magnet Technology Walter Fietz	Fusion Fuel Cycle Technologies Christian Day	Physics and Techniques of Hydrogen Isotopologues Beate Bornschein
Superconducting Materials Jens Hänisch	Superconducting Power System Components Andrej Kudymow	Coil Technology Frank Hornung	Vacuum Technology and Integration Christian Day	Tritium Facilities and –processing Stefan Welte
Cryo-Structural Materials Klaus-Peter Weiss	New Applications of Superconductivity Sonja Schlachter	HTS-Fusion Magnets and Current Leads Walter Fietz	Tritium Extraction and Recovery Laetitia Frances	Tritium and Hydrogen Analytics Marco Röllig
Cryogenic Properties of Substances Steffen Grohmann	Modelling of Superconductors and Components Francesco Grilli	Rotating Machines Yingzhen Liu	Rarified Gas Dynamics Stylianos Varoutis	Physics of Hydrogen Isotopologues Robin Größle
Conductor and Wire Concepts Michael Wolf	Real-time System Integration Jörn Geisbüsch	**Industry Applications** Marion Kläser	Vacuum Hydraulics Thomas Giegerich	Search for New Physics Magnus Schlösser

Large Projects and Infrastructure
KATRIN, Energy Lab 2.0
Tritium Laboratory Karlsruhe, High Field Laboratory, Cryo Experiments and Infrastructure, CryoMak
Cryo-High Voltage Laboratory, CultKa, TOSKA, TIMO, SET-Laboratory, VACUUM Laboratory

Magnetic Heating

- Industrial DC magnet heater ➩ Forming of non-ferrous metals (Al, Cu, …)

- **Motivation**
  - Worldwide 1st / 2nd industrial HTS magnet heaters installed in Al pressing plant in 2008 / 2013
  - +30 % energy efficiency
  - +10% production throughput
  - Performance/cost targets and maintenance not yet competitive

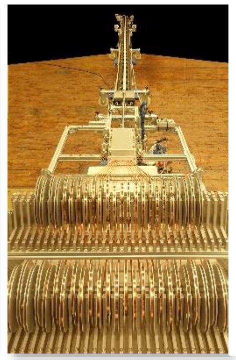
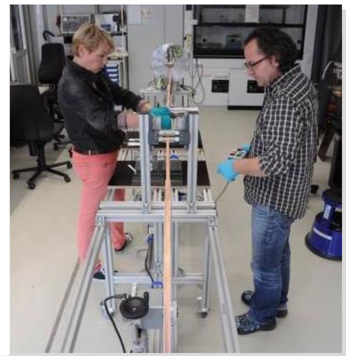
- **New project starts soon**
  - Application of **second generation** HTS tapes
  - Proof of **economic viability**
  - **Industrial-suited** machines
  - Qualification of DC magnet heaters for **commercialisation**

Important Infrastructures

Karlsruher Institut für Technologie

Cryogenic Material Test Karlsruhe

Conductor Manufacturing

Power Hardware in the Loop

Superconducting Materials | **Conductors and Coils** | **Equipment and Applications** | **Networks and Systems**

Chemical Solution Deposition

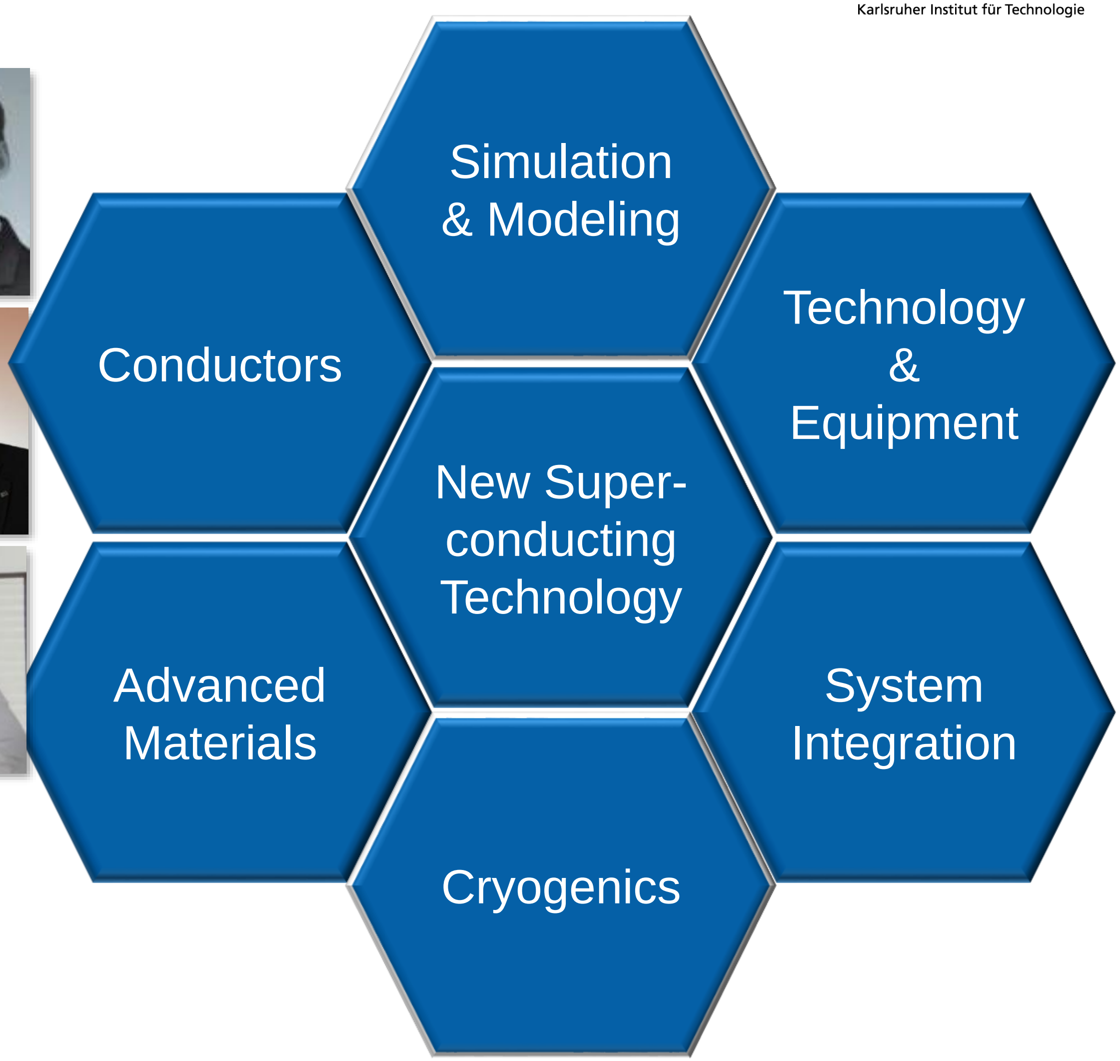
Component Testing

High-Field Magnet

Cryogenic High Voltage

Unique combination of infrastructure aligned to core competences

Competences



Many thanks for your attention!