Karlsruher Institut für Technologie

Status of HTS Material and Application Development in Germany

Mathias Noe, Karlsruhe Institute of Technology
Institute for Technical Physics
IEA EXCO Meeting, July 2017

KIT-ZENTRUM ENERGIE

KIT – Die Forschungsuniversität in der Helmholtz Gemeinschaft

Acknowledgement

- Markus Abplanalp, ABB Corporate Technology
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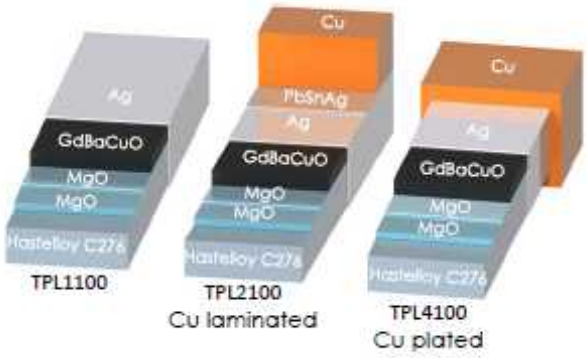
- Michael Bäcker, d-nano
- Wolfgang Reiser, Vision Electric Super Conductors
- Klaus Schlenga, Bruker
- Frank Werfel, ATZ
- My Co-workers at Institute of Technical Physics and many project partners from industry and academia

Status of HTS Material and Application Development in Germany

- Materials and tapes
  - *RE*BCO tapes
  - YBCO bulk material
- Conductor concepts
  - Roebel conductor
  - Cross-Conductor
- Energy Applications
  - Cable and busbars
  - Rotating machines
  - Current Limiters
  - Transformers

Pro-Line HTS wires

THEVA



Pilot line for industrial HTS wire production

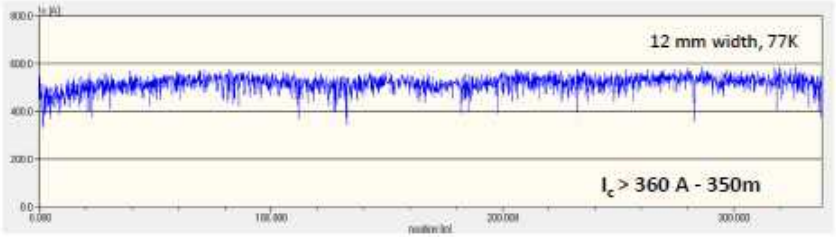
Capacity 150 km/yr (@ 12 mm-width)

Typical production tape length: 300 m

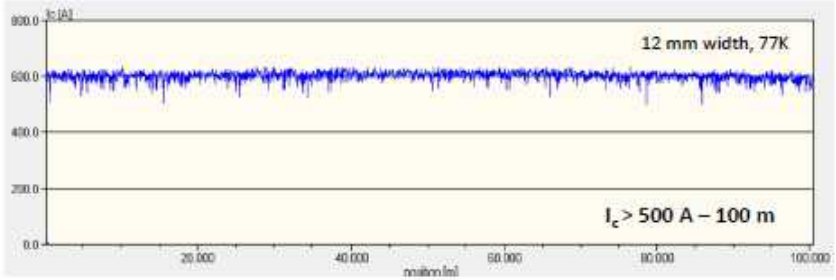
different wire types now available

Pro-Line HTS wires

THEV



Improved wire performance



deutsche nanoschicht

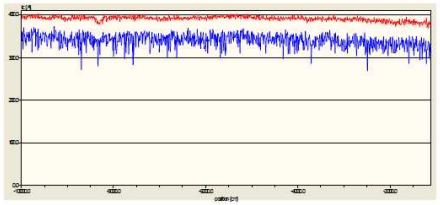
Expanded pilot line

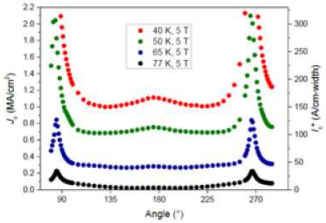
- Opening of expanded pilot line in Rheinbach in 2016
- Annual capacity > 200km technical HTS wire

- Chemical solution deposition (CSD) for all layers
  - Price performance ratio
  - Scalability
  - Reliability
- Customized electrical and mechanical stabilization

Performance

- Single piece length >100m
- Regular performance >300A/cmw (@77K,sf)





- Copper and stainless steel laminate
- Bridge-type joints <10nW

- Typical behaviour (B, T)
- Lift factors 0-5T, 20-77K available

BRUKER HTS GmbH

Milestones

- **BHTS milestones in HTS wire leng**
  - 2013 – 100m length
  - 2014 – 200m length

BRUKER HTS GmbH

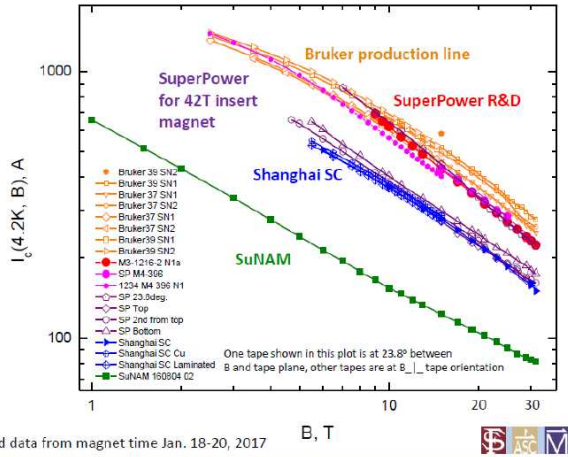
Applications

- **Application of BHTS coated cond**

BRUKER HTS GmbH

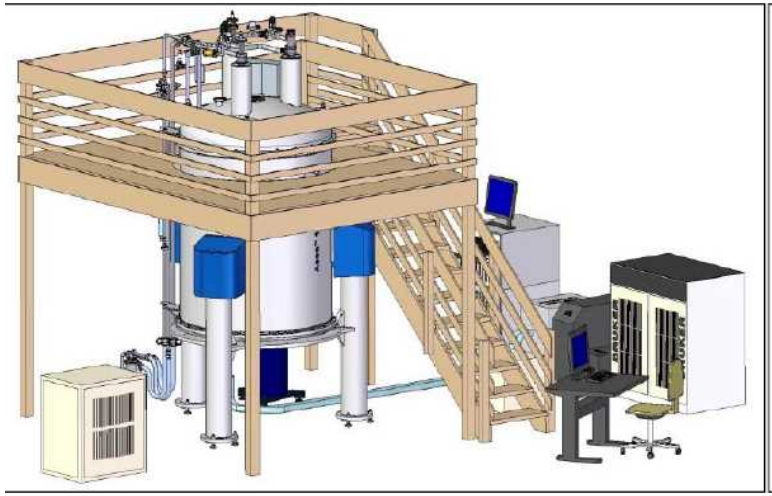
HTS wire performance

- **Ic in-field performance of HTS wires at 4.2K**
  - BHTS samples from HTS 600m tapes (tape ID# 16037, 16039)
  - I_c measured up to 30T B//c at 4.2K

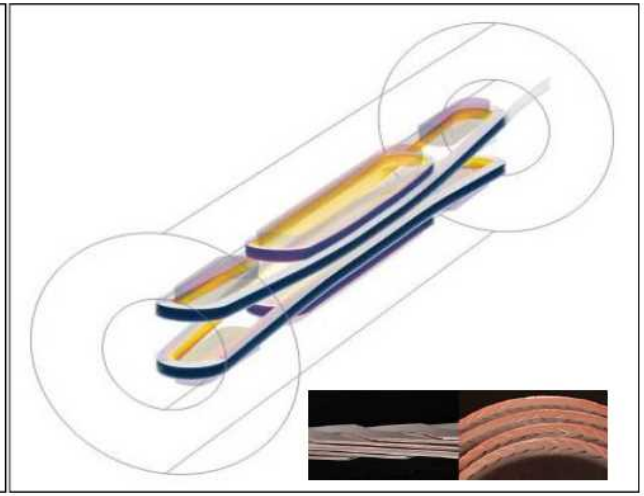


D. Abraimov, D.C. Larbalestier et al. (NHMFL) presented at WAMHTS-4 Barcelona in Feb. 2017

High field data from magnet time Jan. 18-20, 2017



Next generation of BRUKER BIOSPIN persistent super-conducting magnet for NMR spectroscopy



EuCARD-2: Next generation of accelerator magnets for High-Energy-Physics Collider at CERN

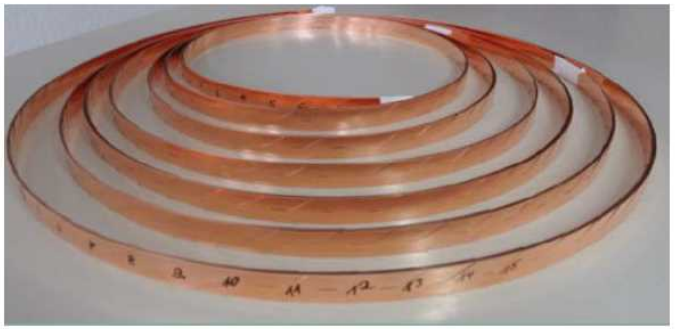
Status of HTS wire development

Manufacturer	Country	Width/ mm	Stabilizer	Piece length[1)]	I_c, 77 K, sf
AMSC	US	4, 12	Brass, Cu, SS	200	250 A/cm
Bruker	Germany	4, 12	Cu	600 m[2)]	High field tape
d-nano	Germany	4, 12	Cu, SS	> 100 m	~ 300 A/cm
Fujikura	Japan	4, 10, 12	Cu	300 m	> 500 A/cm
Shanghai ST	China	4, 12	Cu	up to 1 km	200-500 A/cm
Shanghai CST	China	4, 6, 12	Brass, Cu, SS	> 100 m	100-250 A/cm
STI	US	3,4,10	Cu	> 100 m	250-500 A/cm
Sunam	Korea	4, 12	Brass, Cu	200 m	500 A/cm
SuperPower	US	2,3,4,6,			
Superox	Russia/Japan	4, 12			
Theva	Germany	4, 12			

1) Single piece length without splices
2) 600 m for 4 mm

For each application several suppliers
- Width 2-12 mm
- Stabilizer Brass, Cu, SS
- Piece length up to several 100 m
- I_c mostly between 200-500 A/cm at 77 K, sf

HTS Röbelwire for Accelerator Magnets



15 strands Bruker 12 mm tape
20 μm Cu layer
Transposition pitch 226 mm
12.9 kA at 25 K

Worldwide first test of HTS Röbelwire in future Accelerator
from Bruker and Röbelwire from KIT)

G. Kirby et.al., "First Cold Powering Test of REBCO Roebel Wound
Coil for the EuCARD2 Future Magnet Development Project", IEEE TRANSACTIONS ON APPLIED SUPERCOND

Cross-Conductor High Current Conductor (KIT)

	6/4 CroCo	4/2 CroCo	3/2 CroCo
Number of *RE*BCO tapes	20 x 6 mm 10 x 4 mm	16 x 4 mm 16 x 2 mm	16 x 3 mm 8 x 2 mm
Ø incl. tube	9.1 mm	6.8 mm	5.7 mm
I_c(4.2 K, 12 T)	8000 A	4800 A	3200 A
I_c(77 K, s.f.)	3000 A	1800 A	1300 A

- Continous manufacturing
- Small twist pitch
- Low resistive terminations (30-50 nOhm)
- Applicable for AC and DC

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- Conductor concepts
  - Roebel conductor
  - Cross-Conductor
- Energy Applications
  - Cable and busbars
  - Rotating machines
  - Current Limiters
  - Transformers
  - Flywheel

Status of HTS DC cable and busbar development

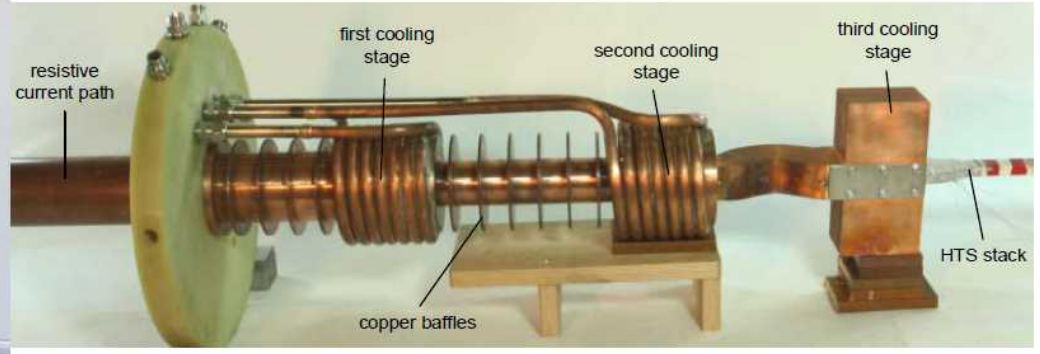
Year	Place	Country	Application	Length/ m	Current/ A	Voltage	HTS
2017	Ludwig						
2017	St. Pet						
2016	Ishi						
2015	Ishi						
2015	Jeju I						
2014	CE						
2013	Kuni						
2012	Gor						
2010	Chu						
2006	Chu						

Worldwide first

24 M. Noe, Stand der

3S-SupraStromSchienen
Supraleitendes Hochstromsystem für DC-Anwendungen

Current lead and connection CU-HTS



Projektpartner: VISION ELECTRIC Super Conductors, KIT Karlsruher Institut für Technologie, ILK Dresden

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

SUPRAPOWER project Outline

- Funded by the European Union's FP7 Programme under grant agreement 308793
- Time scope: Dic 2012 – May 2017
- Total Budget: 5.4 M€, EC funding: 3.9 M€
- TECNALIA leads a consortium of 8 partners:

Coordinator:

tecnalia Inspiring Business

Industrial Partners:

Columbus Superconductors

Ingeteam

solu+e

d2m GROUP

d2m Engineering
KNOWLEDGE, INNOVATION, SERVICE

Research centres and Universities:

ELÚ

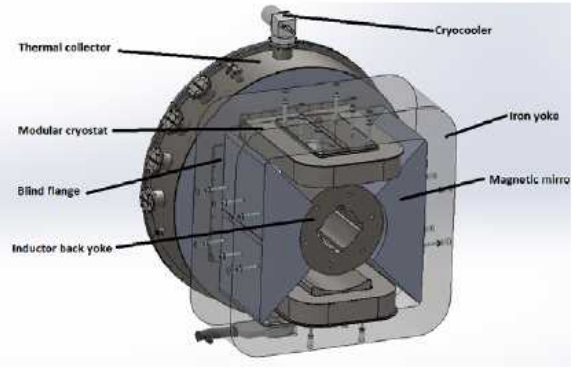
KIT Karlsruhe Institute of Technology

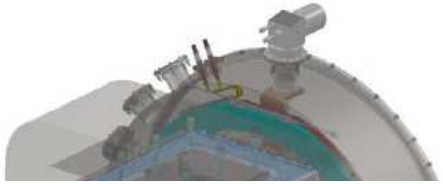
UNIVERSITY OF Southampton

suprapower

Scale Machine Validator: a comparison to full scale and scale generator (SG)

	10 MW	SG	SMV
Power	10 MW	550 kW	-
Speed	8.1 rpm	121.5 rpm	30 rpm
Torque	11.8 MN·m	43.2 kN·m	-
Number of poles	48	4	2
Frequency	3.24 Hz	4.05 Hz	-
Location of armature	External	Internal	-
Operating temperature	20 K	20 K	20 K
Armature winding	Copper	Copper	-
Magnetic core length	744 mm	528 mm	528 mm
Armature current density	3 A/mm^2	3 A/mm^2	-
Induction peak value in airgap	1.5 T	1.5 T	
Peak field in the superconductor	1.37 T	1.36 T	
Working point in the load line	65 %	65 %	





suprapower

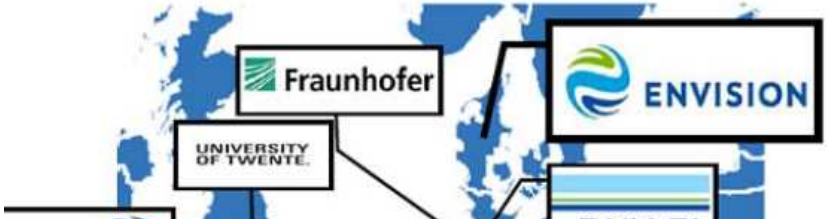
Scale Machine Validator: a comparison to full scale and scale generator (SG)

Double Pancake

Coil in Cryostat

Scale Machine Validator

Consortium



- Consortium of 9 institutions
  - Well defined responsibilities
  - Substantial development team

- The idea is to replace a PM generator with a superconducting generator

- This includes power conversion and refrigeration equipment.

- **Program:** EU Horizon 2020
- **Reference:** 656024
- **Start Date:** 2015-03-01
- **End Date:** 2019-03-01
- **Total Cost:** EUR 13,846,594
- **EU Contribution:** EUR 10,591,734

ion's Horizon 2020 research and innovation programme under
the author's view. The Commission is not responsible for any use

HTS coils

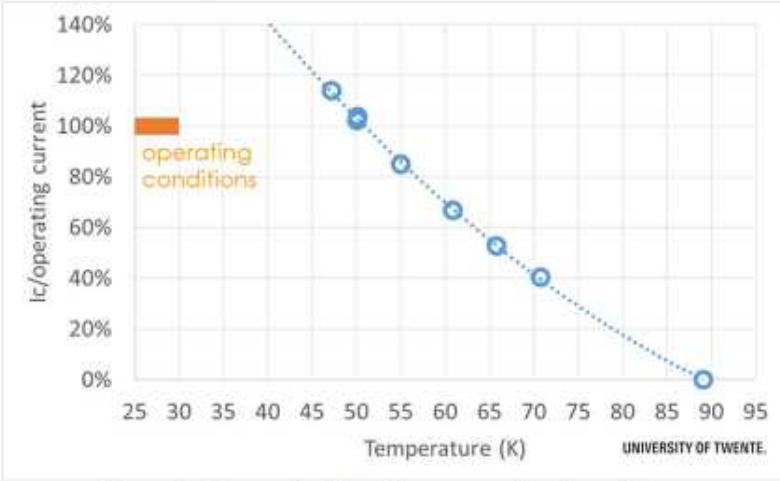
THEVA

Coil winding and casting technology was developed

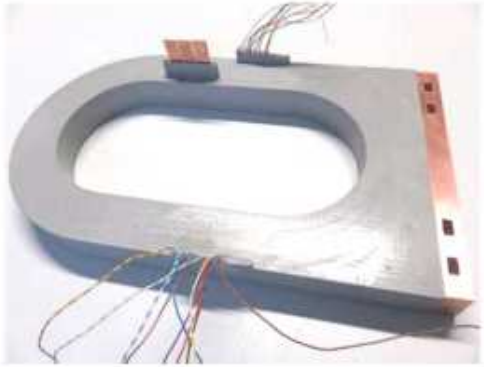
- Resin potted
- double pancake coils
- About 200 turns
- Operating at 30 K
- Conduction cooled

Ongoing:
Small series production of more than 30 coils for a 3.6 MW windpower generator within the EcoSwing project

Technology can be adapted for different size, number of turns and wire width.



Type test result showing expected performance



2 x 87 turn double layer test coil

ecoswing

"EcoSwing has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 656024." "Herein we reflect only the author's view. The Commission is not responsible for any use that may be made of the information it contains."

Rotating machines for electric aircrafts based on HTS technology

SIE

HTS technology as an enabler for sustainable electric aircraft propulsion

Details

- High power density
- High efficiency
- Power rating: several megawatt
- partnering with Airbus and others funded project “TELOS” in the german LuFo-Program

Airbus Group and Siemens Sign Long-Term Cooperation Agreement
in the Field of Hybrid Electric Propulsion Systems
Munich, 2016-Apr-07
Both companies take significant joint development decision
Assemble joint development team of some 200 employees
Target: breakthrough innovation in aerospace e-mobility

Press Release

http://www.siemens.com/press/en/feature/2016/corporate/2016-04-elect

ASuMED
Advanced Superconducting Motor Experimental Demonstrator (H2020, started May 2017)

Participants

OSWALD Elektromotoren GmbH, Germany
ROLLS-ROYCE PLC, United Kingdom
UNIVERSITY OF CAMBRIDGE, United Kingdom
KARLSRUHER INSTITUT FUER TECHNOLOGIE, Germany
HOCHSCHULE FUR ANGEWANDTE WISSENSCHAFTEN ASCHAFFENBURG, Germany
AIR LIQUIDE ADVANCED TECHNOLOGIES SA, France
DeMaCo Holland bv, Netherlands
SuperOx, Russian Federation
Institute of Electrical Engineering, Slovak Academy of Sciences, Slov
K & S GMBH PROJEKTMANAGEMENT, Germany

Purpose

- Demonstrate benefits of a new fully superconducting motor with a power density of **20kW/kg**. In particular:
  - design an appropriate motor topology
  - develop a **high-temperature superconducting (HTS) stator** with an electric loading of >450kA/m
  - develop a rotor using HTS stacks operating like permanent magnets providing an average magnetic loading of >2.5 T
  - integrate a magnetization system into the stator area
  - implement a highly efficient cryostat for motor combined with integrated cryogenic cooling system and associated power converter
- Demonstrate above technologies in a prototype with approximately **1 MW power at 10.000rpm and a thermal loss <0.1%**
- Design innovative modular inverter topology with enhanced failure protection, to realize highly dynamic and robust control of superconducting machines.

Current limiter Nexans

12 kV, 1600 A resistive FCL installed at busbar at Western Power Distribution, Chester Street, Birmingham, since End 2015

Quelle: Nexans

„ASSiST“ – SFCL for public 10 kV grid of Stadtwerke Augsburg, Bavaria, Germany

swa Netze

SFCL based Solution (SFCL+switchgear+control+DAQ) successfully installed and inaugurated in 03/2016.

gefördert
Bayerisches Staatsministerium
Wirtschaft und Medien, Energie und Technol

Details

- Collaboration of Siemens EM, CT & Stadtwerke Augsburg
- Integration of MTU’s extended testing facility of combined heat and power unit requires reduction of short-circuit current
- Combination of superconducting 15 MVA SFCL with ultrafast breaker and parallel series reactor
- Closed cooling system (cold heads included) – no blow-off during limitation
- Reduction of losses compared to conventional solution
- Increased system stability, no voltage drop
- Large area breaker up-grade dispensable
- Timeline:
  - Apr. 15, 2014: project start
  - Mar. 15, 2016: official inauguration

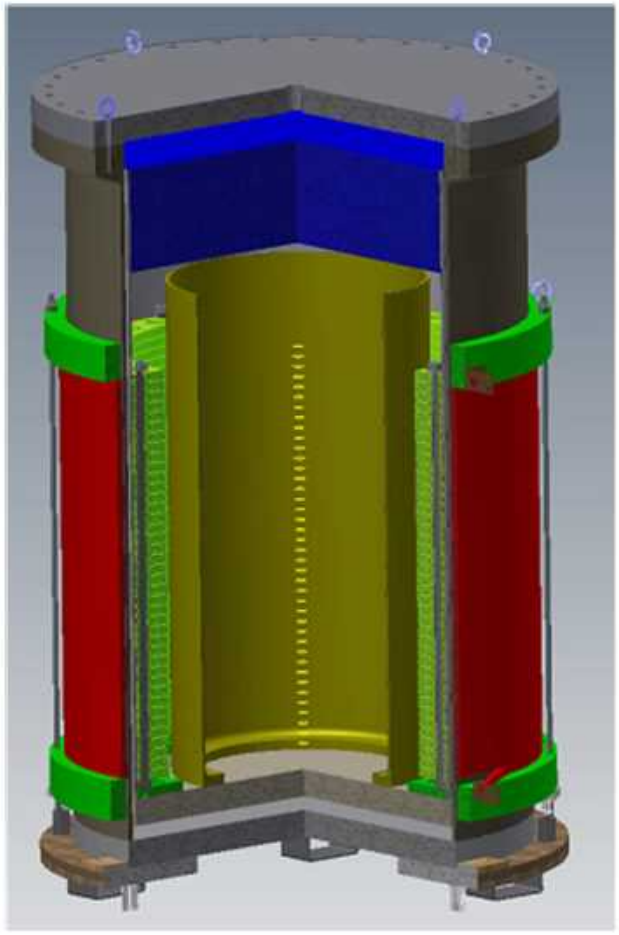
Visitors (IEA) at SFCL site


Install

Superconducting Current Limiter SMARTCOIL

- Siemens, KIT Project to develop a single phase FCL based on air coil limiter concept

Current limiting Coil	
Current	600 A
Voltage (Phase-Ground)	5.77 kV
Height of coil	1170 mm
Inner diameter	1318 mm
Number of turns	45
Number of layers	1
Nominal impedance	1.95 mH (0.60 Ω)
Short-circuit voltage	6%
Max. Op. Temp.	< 155 °C



Cost effective **F**CL using **a**dvanced **s**upercon. **t**apes for future HVDC **grids**

FastGrid

Significant advances of the economical attractiveness of SCFCLs by improving REBCO tapes, especially in their current limitation mode

- **Advanced REBCO tape**
  - Low standard deviation in term of critical current (I_c) over the tape length
  - Electric field higher than 100 V/m (50 ms)
  - Critical current higher than 1000 A/cm-w at 65 K (self-field)
- **Emerging REBCO tape**
  - Tape with enhanced propagation velocity (CFD concept)
  - Sapphire substrate REBCO tape with ultra high electric fields
- **Smart module of a HVDC apparatus**
  - Current and voltage in the range of 0.5/1 kA and 30/50 kV
  - New functionality such as quench detection through optical fiber
  - Extensive testing of the module in relevant operating conditions

- H2020 project
- 42 months
- Starting: 01/2017
- Coord.: CNRS (FR)
- Total budget: 9 M€

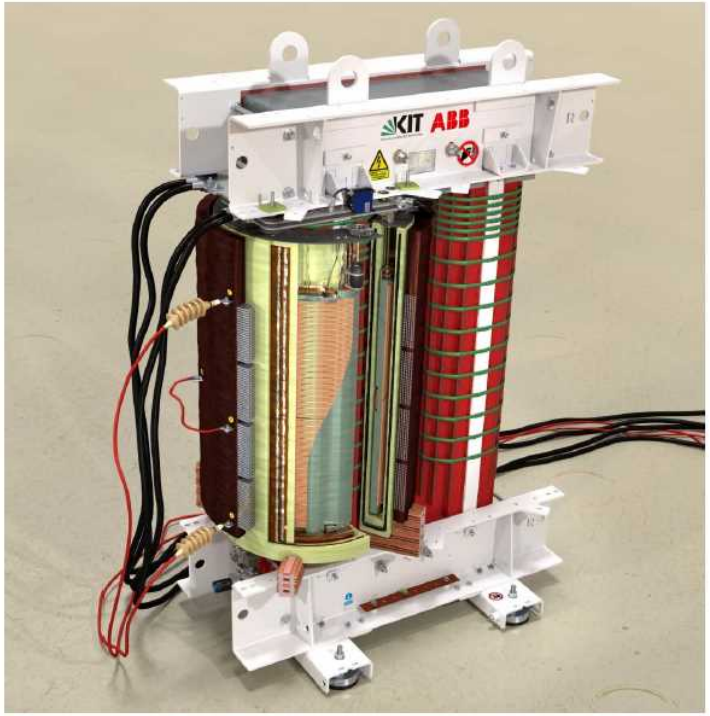
Staus of FCL development (> 100 kV)

Lead Company	Year/Country [1]	Data [2]	Type	Phase	HTS
Innopower	China /2011	220 kV, 300 MVA	DC biased iron core	3-ph.✓	BSCCO
AMSC / Siemens	US / D / 2012	115 kV, 1.2 kA	Res.	1-ph.	YBCO tape
KEPRI	Korea/2015	154 kV, 2 kA	Res.	1-ph.	YBCO tape
Applied Materials	US / 2016	115 kV, 550 A	Res.	3-ph. ✓	YBCO tape
IEE CAS	China /2017	220 kV	Res.		YBCO tape
IEE CAS	China /2017	500 kV	DC biased iron core		BSCCO
IEE CAS	China/	160 kV DC	Res.		YBCO tape
Superox	Russia /2018	220 kV	Res.		YBCO tape

Status of

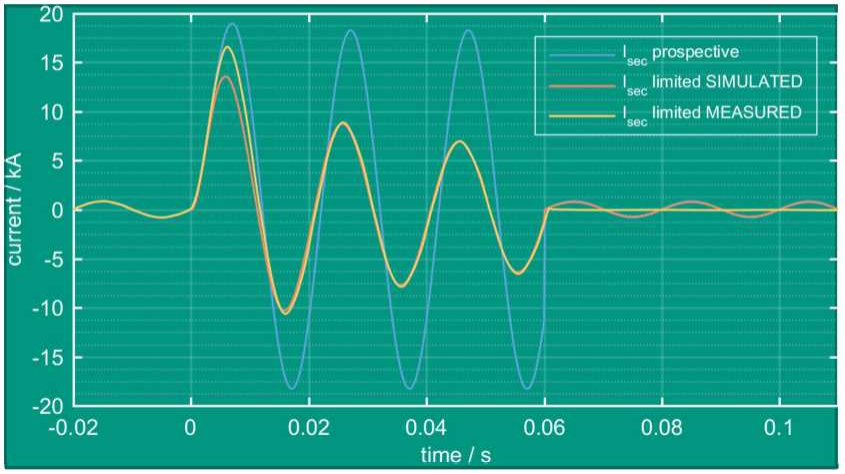
Lead Company				
ACCEL/NexansSC				
CESI RICERCA				
Siemens / AMSC				
LSIS				
Hyundai / AMSC				
KEPRI				
Toshiba				
Nexans SC				
Nexans SC	D / 2009	12 kV, 800 A	3-ph.✓	Bi 2212 bulk
RSE	I / 2011	9 kV, 250 A	3-ph.✓	Bi 2223 tape
RSE	I / 2012	9 kV, 1 kA	3-ph.✓	YBCO tape
KEPRI	Korea / 2011	22.9 kV, 3 kA	3-ph.✓	YBCO tape
Nexans SC	D / 2011	12 kV, 800 A	3-ph.✓	YBCO tape
Rolls Royce	UK / -	11.5 kV, 400 A	3-ph.	MgB_2 wire
Nexans SC	D/2013	10 kV, 2.4 kA	3-ph. ✓	YBCO tape
Nexans SC	EU 2013	24 kV, 1 kA	3-ph. ✓	YBCO tape
Applied Materiaks	US /2013	15 kV / 1kA	3-ph. ✓	YBCO tape
Nexans SC	UK/2015	12 kV/1.6 kA	3-ph. ✓	YBCO tape
Siemens	D / 2016	10 kV / 15 MVA	3-ph. ✓	YBCO tape

Strombegrenzender Transformator (ABB-KIT)



Name	Value
Nominal power	577.4 kVA
Primary winding Cu	20 kV
	28.9 A
Secondary winding HTS	1 kV
	577.4 A
Fault duration	60 ms
Current lim. 1st HW	13.55 kA
Limitation 1st HW in resp. to prosp. Current	71.4 %
Current limitation 6th HW	6.5 kA
Limitation 6th HW in resp. to prosp. current	35.7 %

Strombegrenzender Transformator (ABB-KIT)



Stand der Entwicklung supraleitender Transformatoren (> 500 kVA, seit 2000)

Karlsruher Institut für Technologie

Country	Inst.	Application	Data	Phase	Year	HTS
Japan	Fuji Electric	Demonstrator	1 MVA, 22 kV/6,9 kV	1	2001	Bi 2223
Germany	Siemens	Railway	1 MVA, 25 kV/1,4 kV	1	2001	Bi 2223
Korea	U Seoul	Demonstrator	1 MVA, 22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	Bi 2223
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	Bi 2223
China	IEE CAS	Demonstrator	630 kVA, 10.5 kV/400 V	3	2005	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6,6 kV	1	2009	P-Bi 2223/S-YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA, 11 kV/415 V	3 Dy	2013	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3 Yyn0	2014	Bi 2223
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2016	P-Cu/S-YBCO

END