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3G ?

From 2G to Practical Conductors – What Needs to be Improved?

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Bernhard Holzapfel, IFW Dresden, Germany
EUCAS 2013, Genova, Italy

Institute for Technical Physics

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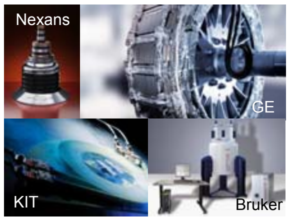
- And all members of CIGRE Working Group D1.38 „Emerging Test Techniques Common to HTS Power Equipment“

Motivation

„…there is a technology gap from 2G wire to practical applications…“



2G Manufacturer
AMSC, Bruker, d-nano, Fujikura, Sumitomo, Sunam, Superpower, STI, Theva, …

Industry
AMSC, Bruker, GE, Innopower, LS Cable, Nexans, nkt cables, Oswald, Siemens, Sumitomo, Southwire, …

„…there is a need for ready to use 2G conductor concepts…“

Motivation

„…there is a technology gap from 2G wire to practical applications…“

Industry needs

- Scalable currents and various geometries
- Reproducible quality and quantity within an acceptable time
- Mechanical and electrical stability
- Low degradation, long lifetime
- Reliable and specific electrical insulation
- Simple, low ohmic contacts and joints
- Low losses
- Competitive cost
- ….

Industry
Bruker, GE, Innopower, LS Cable, Nexans, nkt cables, Oswald Siemens, Sumitomo, Southwire, …

Motivation

Power System Applications	Present Favourite	Future Options
Cables	BSCCO	**REBCO**
Rotating Machines	BSCCO, **REBCO**	MgB_2
Transformers	**REBCO**	-
Fault Current Limiters	**REBCO**, BSCCO	-
SMES	NbTi	MgB_2, **REBCO**
Magnet Applications		
MRI Magnets	NbTi	MgB_2, **REBCO**
NMR Magnets	NbTi, Nb_3Sn	**REBCO**
Accelerator Magnets	NbTi	Nb_3Sn, **REBCO**, BSCCO
Fusion Magnets	NbTi, Nb_3Sn	**REBCO**
R&D and Industry Magnets	NbTi, Nb_3Sn	MgB_2, **REBCO**, BSCCO
Other Applications		
Current Leads	BSCCO	**REBCO**
Electrodynamic Levitation	NbTi	BSCCO, **REBCO**
Superconducting Levitation	**REBCO**	-

There is a big potential for 2G wire in nearly all large scale applications!

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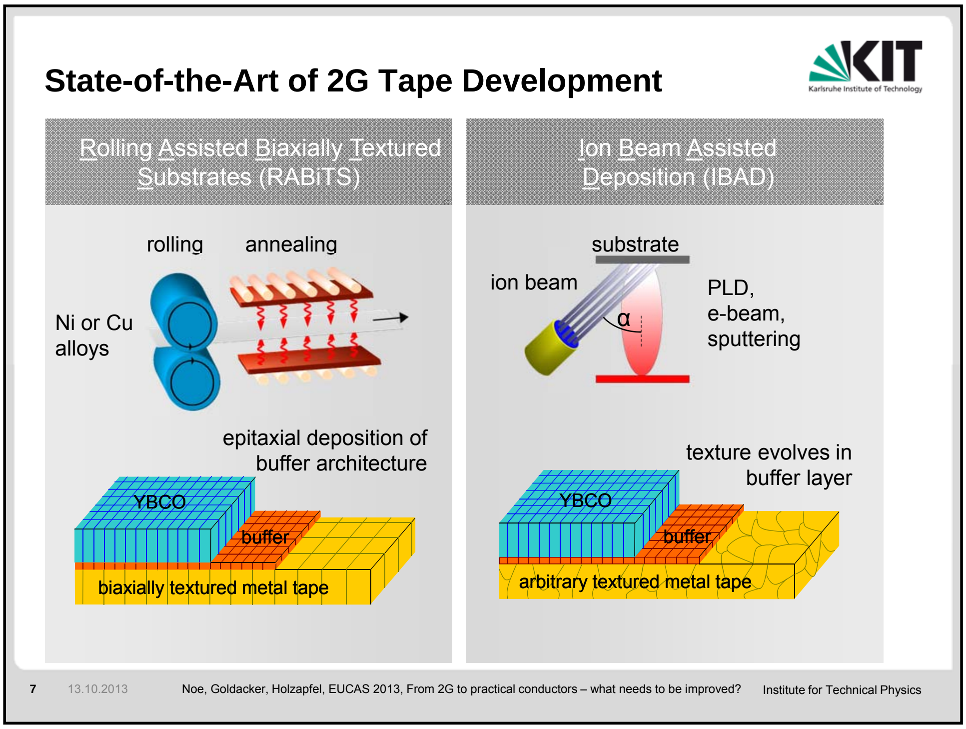
Which kind of 2G wire is needed for which application?


State-of-the-Art of 2G Tape Development
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Rolling Assisted Biaxially Textured Substrates (RABiTS)
Ion Beam Assisted Deposition (IBAD)
rolling
annealing
Ni or Cu alloys
epitaxial deposition of buffer architecture
YBCO
buffer
biaxially textured metal tape
substrate
ion beam
α
PLD, e-beam, sputtering
texture evolves in buffer layer
YBCO
buffer
arbitrary textured metal tape
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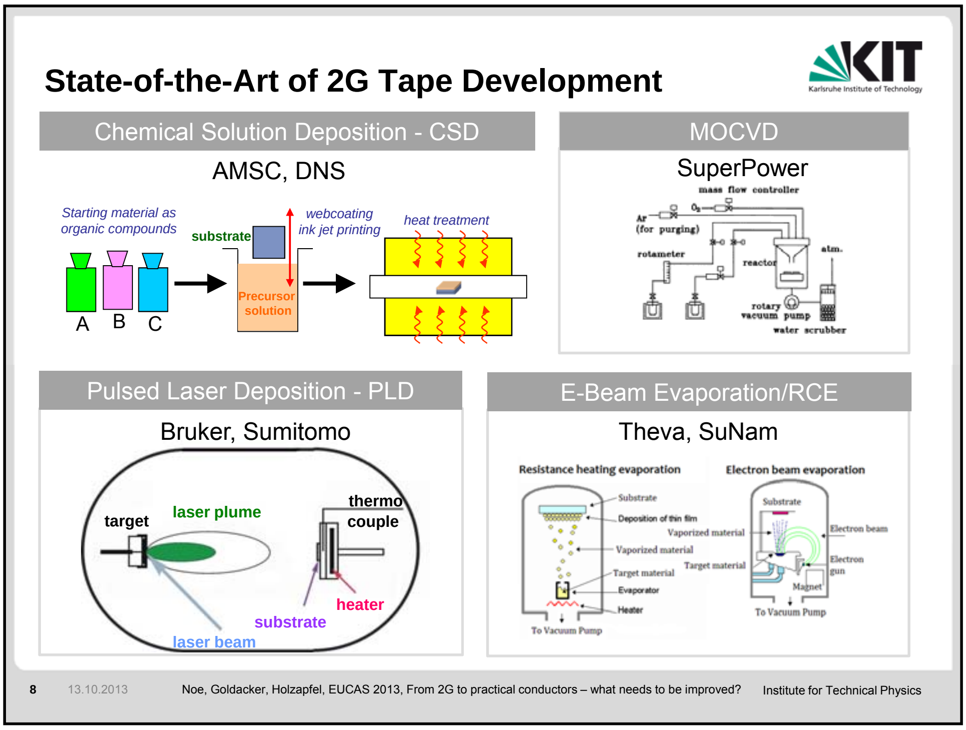
State-of-the-Art of 2G Tape Development
Karlsruhe Institute of Technology
Chemical Solution Deposition - CSD
AMSC, DNS
Starting material as organic compounds
substrate
webcoating ink jet printing
heat treatment
Precursor solution
A
B
C
MOCVD
SuperPower
mass flow controller
Ar (for purging)
rotameter
reactor
atm.
rotary vacuum pump
water scrubber
Pulsed Laser Deposition - PLD
Bruker, Sumitomo
target
laser plume
thermo couple
heater
substrate
laser beam
E-Beam Evaporation/RCE
Theva, SuNam
Resistance heating evaporation
Electron beam evaporation
Substrate
Deposition of thin film
Vaporized material
Target material
Evaporator
Heater
To Vacuum Pump
Electron beam
Electron gun
Magnet
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State-of-the-Art of 2G Tape Development

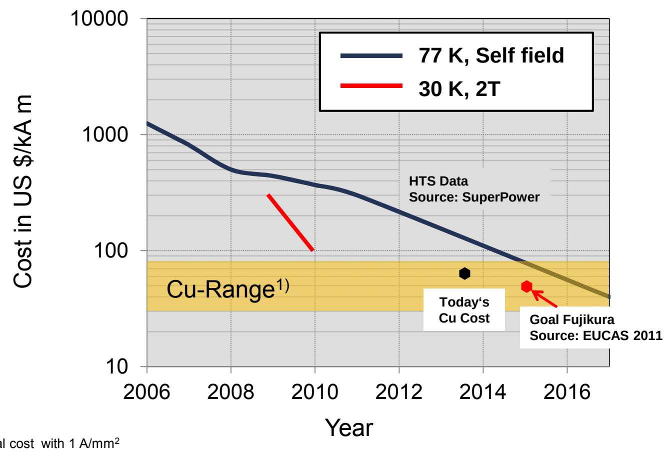
Manufacturer[1]	Width (mm)	Add. Stabilizer (µm)	Piece length [2] (m)	Critical Current A/cm @ 77 K, sf
AMSC	4.8/12/40	Cu, Brass, SS	a few 100 m	160-230
Bruker	4	Cu	120	250
Fujikura	4/12	Cu	?	up to 550
STI	10	Cu	?	300
Sumitomo Electric	2/4	Cu	100-200	300
Sunam	4/12	Cu, Brass	100 m	250-375
Superpower	3/4/6/12	Cu	100-300	250-300
Theva	≤12	Cu[3]	10 (200[3])	250 (350[3])

1) In alphabetical order
2) Maximum single piece length of available tapes
3) In 2014

All Data from homepage or private communication with manufacturer

The trend is towards more manufacturers, longer single piece length, higher critical current and lower cost.

2G Cost-Performance Ratio



1) Cu Material cost with 1 A/mm²

2 G tape has to beat the cost performance ratio of copper in the next few years!

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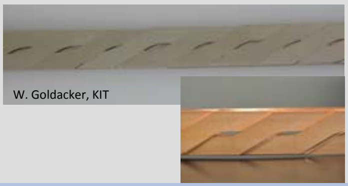
Overview on Multitape 2G Concepts

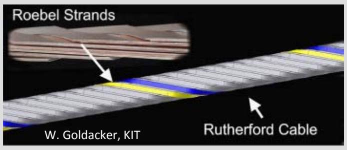
Stacks and Twisted Stacks

Cable on Round Core

Roebel



Roebel-Rutherford



Very good progress in the manufacturing and the characterization of multitape 2G concepts in the past few years!

Overview on Multitape 2G Concepts

Tested performance of multitape 2G short cable samples

Cable Type	Nr. of Tapes	Tape width	Critical current	Field	Temp.
CORC[1]	79	4 mm	7.56 kA	Self field	76 K
CORC[1]	52	4 mm	5.02 kA	19 T	4.2 K
Twisted stack [2]	32	4 mm	1.5 kA	Self field	77 K
Twisted stack [2]	50	4 mm	4 kA	19.7 T	4.2 K
Flat stack [3]	20	10 mm	45 kA	6 T	20 K
Flat stack [3]	20	10 mm	68 kA	1 T	4 K
Roebel [4]	15	5 mm[5]	10.8 kA	1 T	4.2 K
Roebel [4]	15	5 mm[5]	3.4 kA	9 T	4.2 K

1) D.C. van der Laan et. al. Supercond. Sci. Technol. 26 (2013) 045005
2) M. Takayasu et. al., IEEE Transactions on Applied Superconductivity, VoL. 23, No. 3, June 2013
3) N. Yanagi, et. al., « Progress of the Design of HTS Magnet Option and R&D Activities for the Helical Fusion Demo Reactor", The 23rd Magnet Technology July 14-19, 2013 @Boston, US
4) J. Fleiter et. al., Supercond. Sci. Technol. 26 (2013) 065014
5) Punched out of 12 mm tapes

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Cables – Tape Requirements

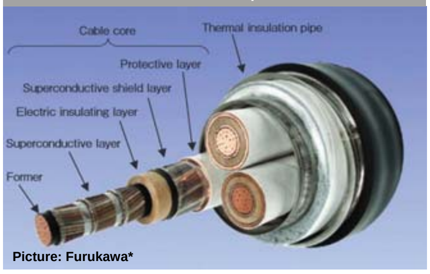
- Tape dimensions (2-4 mm) ☑
- Field and temperature (self field, at 68-80 K) ☑
- Multitape conductor arrangement (Coaxial wound layers) ☑

- Mechanical robust (tensile strength, min. bend radius, strain tolerance) ☑
- Critical current homogeneity over length ± 10% ☑
- Mechanical robust and flat splices ☑
- Low losses (magnetic substrates are not acceptable for 2G wire) ☑
- Overcurrent stability ☑
- No separate electrical insulation around 2G tape ☺

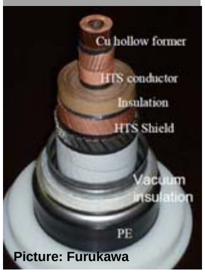
HTS tape should not be to thin in order to fit into existing cabling machines

Cables - Improvements

66/77-kV HTS Triplex Cable



275 kV, 3 kA



Further 2G tape improvements should focus on

- Cost/performance ratio
- AC losses

* Development of YBCO High-Tc Superconducting Power Cables, Shinichi Mukoyama et. Al. Furukawa Review, No. 35, 2009

Current Limiters – Tape Requirements*

* Resistive type SCFCL

- Tape dimensions (10-12 mm) ☑
- Field and temperature (self field at 77 K) ☑
- Multitape conductor arrangement (Bifilar coils or straight stacks in parallel) ☑

- Critical current homogeneity over length ± 5 % ☑
- Specific resistance, heat capacity and mass ☑
- Max. temperature at quench and thermal expansion ☑
- Mechanical robust (manufacturing and quench) ☑
- Short single piece length (no splices needed) ☺
- Low losses ☑
- Overcurrent stability ☑
- Electrical insulation

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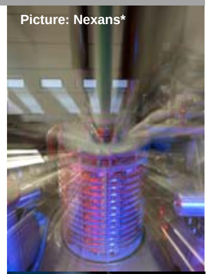
Current Limiters - Improvements

24 kV, 1000 A, 3 phase resistive type SCFCL (www.eccoflow.org)

Picture: Nexans*


Picture: Nexans*


Picture: Nexans*


Picture: KIT

* Private communication

Further 2G tape improvements should focus on
- Cost/performance ratio
- Better homogeneity→less stabilizer→smaller ratio of I_p/I_{op}
- Specific electrical insulation (no wrapping)

Rotating Machines – Tape Requirements*

* Fast rotating machines

- Tape dimensions (4 mm or wider?) ☑
- Field and temperature (1-3 T at 20-50 K) ☑
- Multitape conductor arrangement (racetrack coil) ☑

- Robust wire ☑ and mechanical robust winding concept (cycling forces and expansion coefficient)
- High Ampere/meters with more meters!
- Long single piece length (several 100 m, up to more than 1 km)
- Thermal stabilization with copper ☑
- Minor dependency on B-fields ($B^{\perp}$)
- Robust, thin walled electrical insulation

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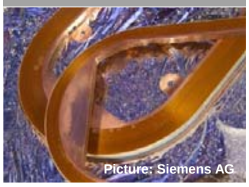
Rotating Machines – Power Generator

4 MVA Synchronous Generator (1G)

2G race track coil

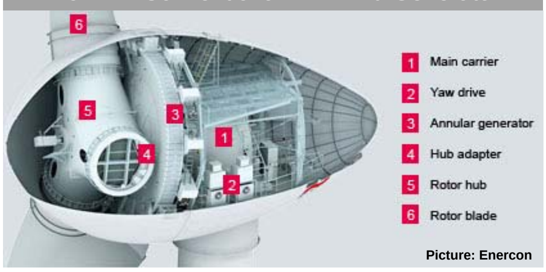


Further 2G tape improvements should focus on

- Longer single piece length
- Short-circuit stability in machine conditions (> 1000 gravity of earth in fast rotating power generators)

Rotating Machines – Wind Generator

7.5 MVA Conventional DD Wind Generator



Cu Rotor winding

Further 2G tape improvements should focus on

- Cost/performance ratio (at least several 100 km per 10 MW DD wind generator)
- High critical current at 2-3 T and 20-50 K

Transformer – Tape Requirements

- Tape dimensions (3-4 mm) ☑
- Field and temperature (stray field up to 100 mT at 68 -77 K) ☑
- Multitape conductor arrangement (solenoid coil with Roebel?)

- Robust wire ☑ and mechanical robust winding concept
- Long piece length with splices ☑
- Low AC loss configuration
- Current limitation and fast re-cooling under load
- Thermal stabilization with copper ☑
- Reliable electrical insulation for high voltages

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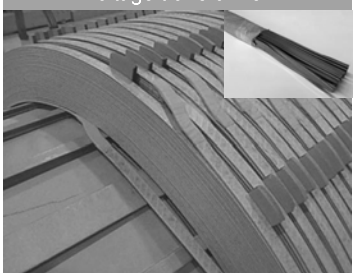
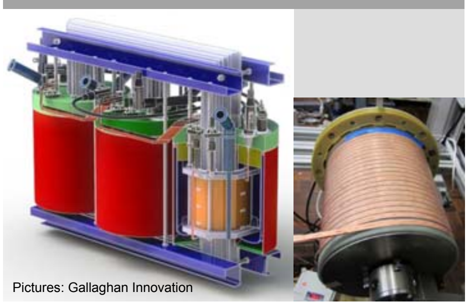
Transformer – Improvements

Disc Winding for conventional high voltage transformer



1 MVA HTS Transformer Demonstrator



Pictures: Gallaghan Innovation

First 2G Roebel Application!

Further improvements should focus on

- Low loss, high current conductor concept
- Suitable electrical insulation for the conductor not the single tape
- Adaptable cap layers to optimize current limitation, stability and recooling

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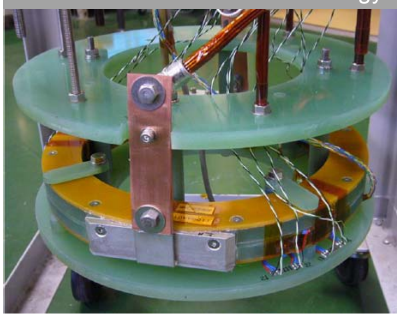
SMES – Tape Requirements

- Tape dimensions (4 mm-12 mm) ☑
- Field and temperature (≥ 5 T at 20-50 K) ☑
- Conductor arrangement (Pancake coil as solenoid or torus) ☑

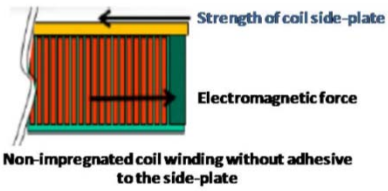
- High hoop stress of up to 600 MPa ☑
- Long piece length with splices ☑
- Coil stability at quench
- Low AC loss (for fast cycling only)
- Thin walled electrical insulation with high withstand voltage and good thermal conductivity for conduction cooled SMES
- High critical current at high magnetic fields

SMES – Improvements

2 GJ Class SMES Coil Technology



High Stress Tolerance



Tolerates a 1.7 GPa hoop stress

Reinforcement with non-impregnated coil and coil side-plate for reducing stresses during coil winding

Further 2G tape improvements should focus on

- Cost/performance ratio (100 km of 10 mm wide wire for 10MW, 20 MJ)
- AC loss for fast cycling

Source: Superconductivity Web21, September, 2013 Date of Issue: September 15, 2013

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Summary

	Cable	SCFCL*	Machine**	Transformer	SMES
Width	2-4 mm	10-12 mm	4 mm	3-4 mm	4-12 mm
Magnetic Field	Self field	Self field	1-3 T	0.05-0.15 T	≥ 5 T
Op. Temperature	68-80 K	77 K	20-50 K	77 K	4-20 K
Conductor concept	✓	✓	✓	✋✋	✓
Crit. Current	✓	✓	✓	✓	↗
Homogeneity	± 10 %	± 5 %	✓	± 5 %	✓
Mechanical stability***	✓	✓	✓	✓	✓
Single piece length	✓	✓	↗	↗	↗
Losses	↘	✓	✓	↘	↘
Quench stability	✓	✓	✋	✋	✋
Electrical insulation	✓	✋	✋	✋	-

* Resistive type
** fast rotating machine
*** tape stability

✓ Fulfilled with commercially available 2G wire
✋ Needs more R&D
↗ Parameter should be increased
↘ Parameter should be decreased

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High Field Magnets – Tape Requirements*

* High Field HTS insert

- Tape dimensions (4-5 mm) ☑
- Field and temperature (≥ 20 T at 4.5 K) ☑
- Conductor arrangement (Pancake coil or layer coil) ☑

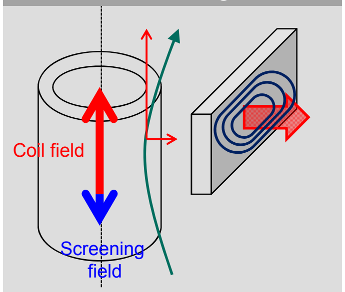
- Robust wire (high tensile stress, low cleavage and peel stress ☹)
- Deformation and stress during cool down
- High field homogeneity and stability (low drift, small screening currents)
- Superconducting contacts for persistent mode
- Coil stability and quench protection
- High critical current at high magnetic fields (small anisotropy)

High Field Magnets – Improvements

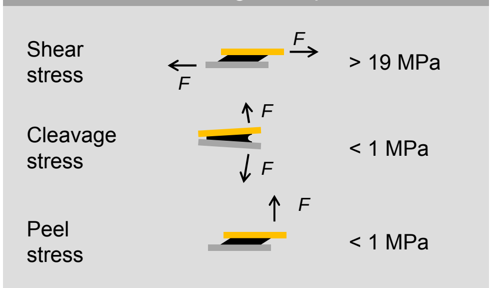
Basic technologies for HTS magnet[1)]

- Magnetic field distortion and drift : Effect of the screening current
- Degradations in the coil performance: Mechanical stress
- Stability and protection: Thermal runaway

Effect of screening current



Low shear, cleavage and peel stress [2)]



1) Hideaki Maeda, "Recent developments in high-temperature superconducting magnet technologies", RIKEN, Japan, 23rd MT Conference Boston 2013, US
2) Y. Yanagisawa, H. Nakagome, T. Takematsu, T. Takao, N. Sato, M. Takahashi, H. Maeda, Physica C 471, 480-485 (2011)

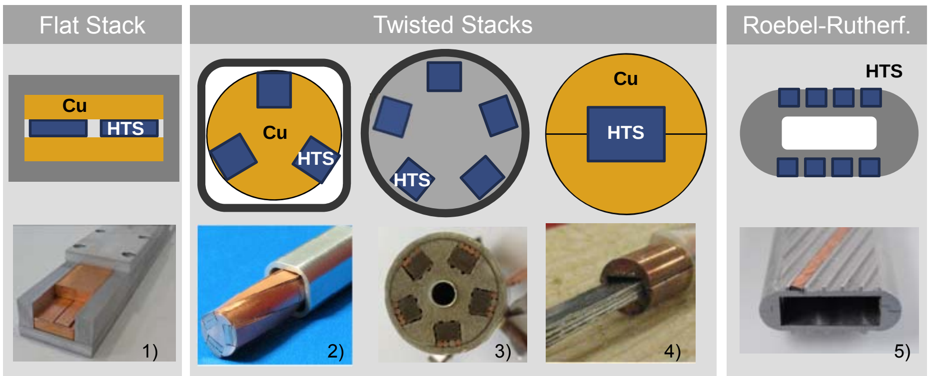
Fusion Magnets – Tape Requirements*

* Pulsed magnet

- Tape dimensions (4-5 mm) ☑
- Field and temperature (10-15 T at 50-70 K)
- Conductor arrangement (? in a large solenoid coil)

- Robust wire (high tensile stress, low cleavage and peel stress ☹)
- Deformation and stress during cool down
- Coil stability and quench protection
- Optimized interstrand resistance
- Possibilities to limit AC losses
- High critical current at high magnetic fields (small anisotropy)

Fusion Magnets – Conductor Arrangements



Various conductor concepts have been proposed in recent years and first test and simulation results are available. A full qualification still needs to be done.

1) N. Yanagi, Progress of the Design of HTS Magnet Option and R&D Activities for the Helical Fusion Demo Reactor, MT2013, Boston
2) M. Takayasu et. al. ,"Investigation of twisted stacked-tape cable conductor", Advances in Cryogenic Engineering,AIP Conf. Proc., 1435, 273-280 (2012)
3) G. Celentano, et. al. "HTS conductor design for fusion magnets application", MT2013, Boston
4) D. Uglietti, R. Wesche, and P. Bruzzone, «Design and Strand Tests of a Fusion Cable Composed of Coated Conductor Tapes", MT2013, Boston
5) A. Kario, et. al., "Investigation of a Rutherford cable using, coated conductor Roebel cables as strands", Supercond. Sci. Technol. 26 (2013) 085019

Fusion Magnets – Next Steps

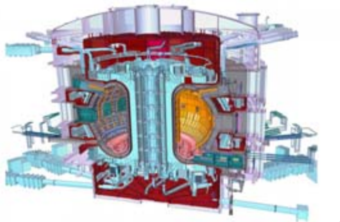


Figure: www.iter.org

Prototype coil

Demonstrator coil

Manufacturing tools

Coil concept

Small demonstrator coil

Wire concepts

Feasibility of 2G HTS ✓

Time →

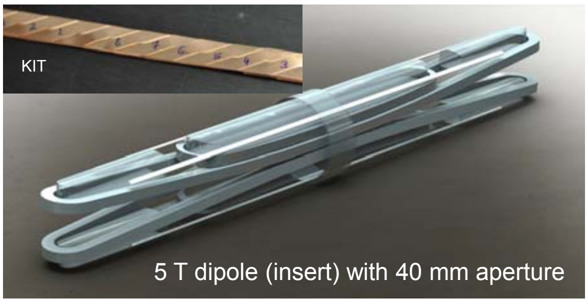
Accelerator Magnets – Tape Requirements

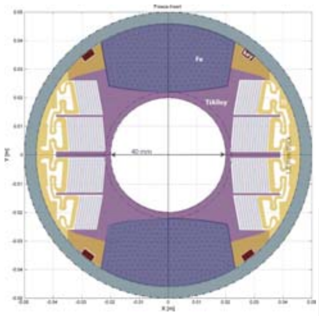
- Tape dimensions
- Field and temperature (≥ 20 T at 4.5 K) ☑
- Conductor arrangement (racetrack coil) ☑

- Robust wire (high tensile stress, low cleavage and peel stress)
- Deformation and stress during cool down
- High field homogeneity and stability (low drift, small screening currents)
- Coil stability and quench protection
- High critical current at high magnetic fields (small anisotropy)

Presently under investigation for high field inserts for future accelerator magnets are CORC, twisted stacks and Roebel cables

Accelerators – Example





Pictures: J. van Nugteren (CERN)

Ideas for the future exist but still a lot of R&D ahead.

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Summary

	Cable on Round Core	Flat Stack	Twisted Stacks	Roebel Cable
Overall current density	Mid	High	High	High
Self field direction to tape	parallel	perpendicular	perpendicular	perpendicular
Manufacturing	OK	OK	OK	OK but difficult
Tape transposition	partial	no	partial	full
Possible Applications	Accelerator magnets, High current cables	DC only	Fusion magnets, Accelerator magnets, High current cables	Transformers, Machines, Fusion magnets, Accelerator magnets

Thank you very much for your attention!