WAMSDO 2008 – Workshop on Accelerator Magnet, Superconductor, Design and Optimization

Karlsruhe Institute of Technology

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider

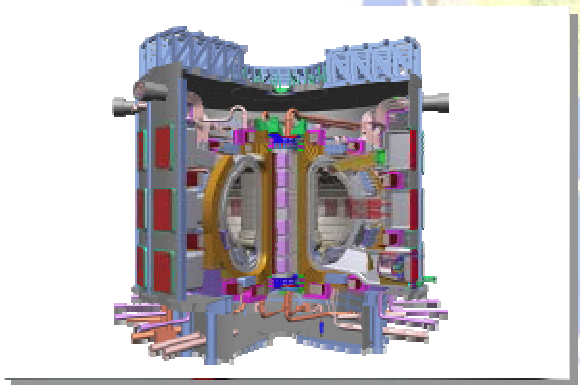
Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- HTS Wires and Tapes
- HTS for Power System Applications
- HTS for Current Leads
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

Applications of Superconductivity

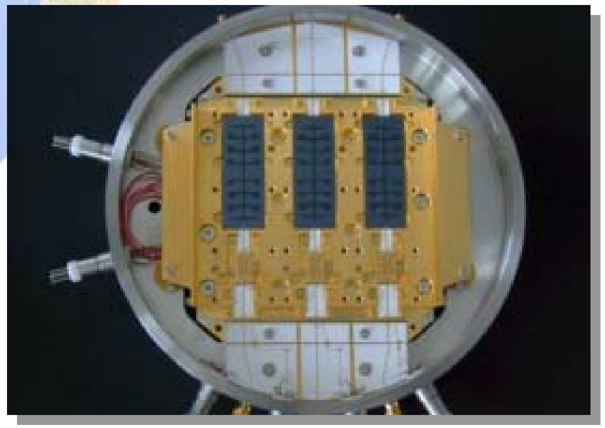
Medicine

Science



Power Systems

Engineering



Transport

Electronics

HELMHOLTZ GEMEINSCHAFT
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- **HTS Wires and Tapes**
- HTS for Power System Applications
- HTS for Current Leads
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

Main Requirements for HTS Tapes and Cables

	LTS	HTS Bi	HTS YBCO CC (now)
Availability • km batches • several manufacturers	☑	☑	☐ Soon available ☑
Stability • mechanically stable, reinforced • electrically, thermally stable	☑	☑	☐ ☑ ☐
Current carrying capacity • multistrand cable to adapt current	☑	☑	☐ First Roebel concepts
Low cost • less than 10 € per kA m	☑	☒	☐ Seems possible
Low AC loss • short twist • thin filaments • high transverse resistivity	☑	☑	☑

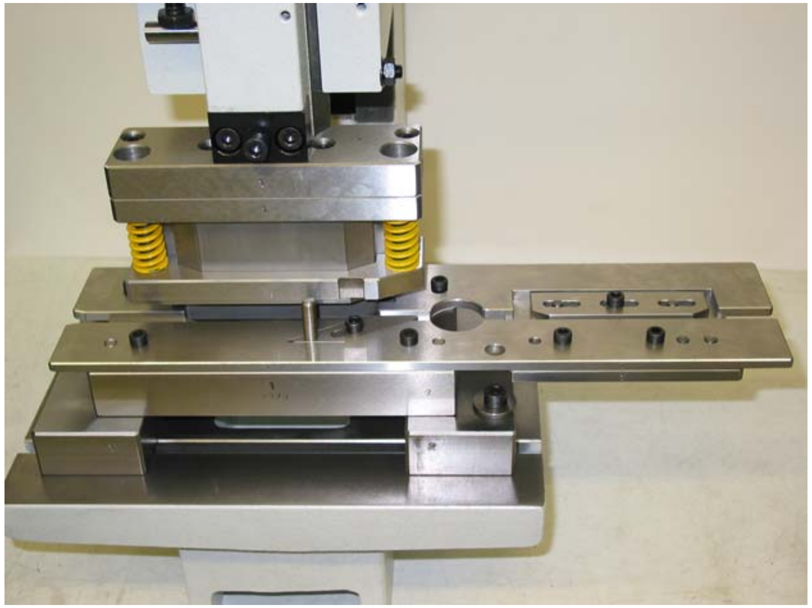
Multistrand HTS Cable Concept

Preparation of Roebel Cables at FZK

Single coated conductor

ROEBEL assembled coated conductor

Cable with interstrand connection



- Pure mechanical precision punching
- Tool optimized for material and thickness
- Very sharp clean cutting edges
- Sequential assembling to Roebel structure
- Upgrade to continous process

W.Goldacker et al. EUCAS-2005 Journal of Physics, Conf Series, Vol 43, 2006 p. 901

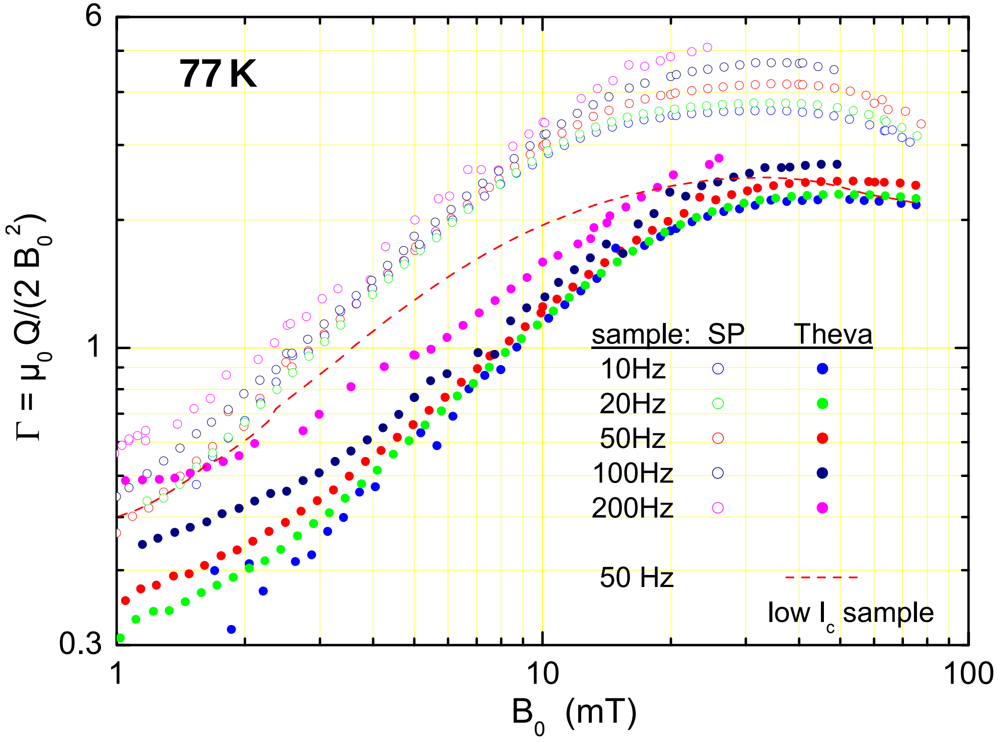
Multistrand HTS Cable Concept

Karlsruhe Institute of Technology

DyBCO and YBCO tapes and geometry of Roebel cable

Manufacturer	**Theva** (DyBCO)	**SuperPower** (YBCO)
Original tape width × thickness Mean I_c, self field at 77 K	10×0.1 mm² 317A ± 12A	12×0.1 mm² 230A ± 5A
Meander shaped strands width Mean I_c, self field at 77 K	4 mm 99.7A ± 9.5A	5 mm 89.5A ± 1.7A
N° of tapes in cable *N*	11	12
Cable cross section *d·h*	10×0.9 mm²	12×0.8 mm²
Cabling (= sample) length *L*	123 mm	127 mm

Loss function of Roebel Cables with YBCO coated conductors versus ac-field amplitude, with the frequency as a parameter



Main result: Coupling loss in Roebel cable is small in comparison to hysteresis loss

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- HTS Wires and Tapes
- **HTS for Power System Applications**
- HTS for Current Leads
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

HTS for Power System Applications

In present power systems

- **More powerful conventional devices**
  - Motors and Generators
  - Transformers
  - Cables
- **New devices**
  - Superconducting fault current limiters
  - Superconducting magnetic energy storage
  - Current limiting systems

In future power systems

  - Fusion power plants

"More power in a smaller size"

Status of HTS Cable Development

Karlsruhe Institute of Technology

Manufacturer	Year/Place [1)]	Type	Data	Superconductor
Furukawa	Yokosuka, 2004	CD	77 kV, 1 kA, 500 m, 1-ph.	BSCCO
Innost	Yunnan, 2004	WD	35 kV, 2 kA, 33 m, 3-ph.	BSCCO
Sumitomo	Albany, 2006	CD	34.5 kV, 800 A, 350 m, 3-ph.	BSCCO
Ultera	Columbus, 2006	Triax	13.2 kV, 3 kA, 200 m, 3-ph.	BSCCO
Sumitomo	Korea, 2006	CD	22 kV, 1.25 kA, 100 m, 3-ph.	BSCCO
LS Cable	Gochang, 2007	CD	22 kV, 1.25 kA, 100 m, 3-ph.	BSCCO
Sumitomo	Albany, 2007	CD	34.5 kV, 800 A, 30 m, 3-ph.	YBCO
Nexans	Hannover, 2007	CD	138 kV, 1.8 kA, 30 m, 1-ph.	YBCO
Nexans	Long Island, 2008	CD	138 kV, 2.4 kA, 610 m, 3-ph.	BSCCO
Ultera	New York, 2010	Triax	13.8 kV, 4 kA, 240 m, 3-ph.	YBCO
Ultera	New Orleans, 2011	Triax	13.8 kV, 2.5 kA, 1700 m, 3-ph.	YBCO ?
Ultera	Amsterdam, ?	?	50 kV, 2.9 kA, 6000 m, 3-ph.	?
Nexans	Long Island II, ?	CD	138 k	
LS Cable	Gochang, 2011	CD	154 k	
Sumitomo	Yokohama, 2010	CD	66 kV	

1) Year of first energization

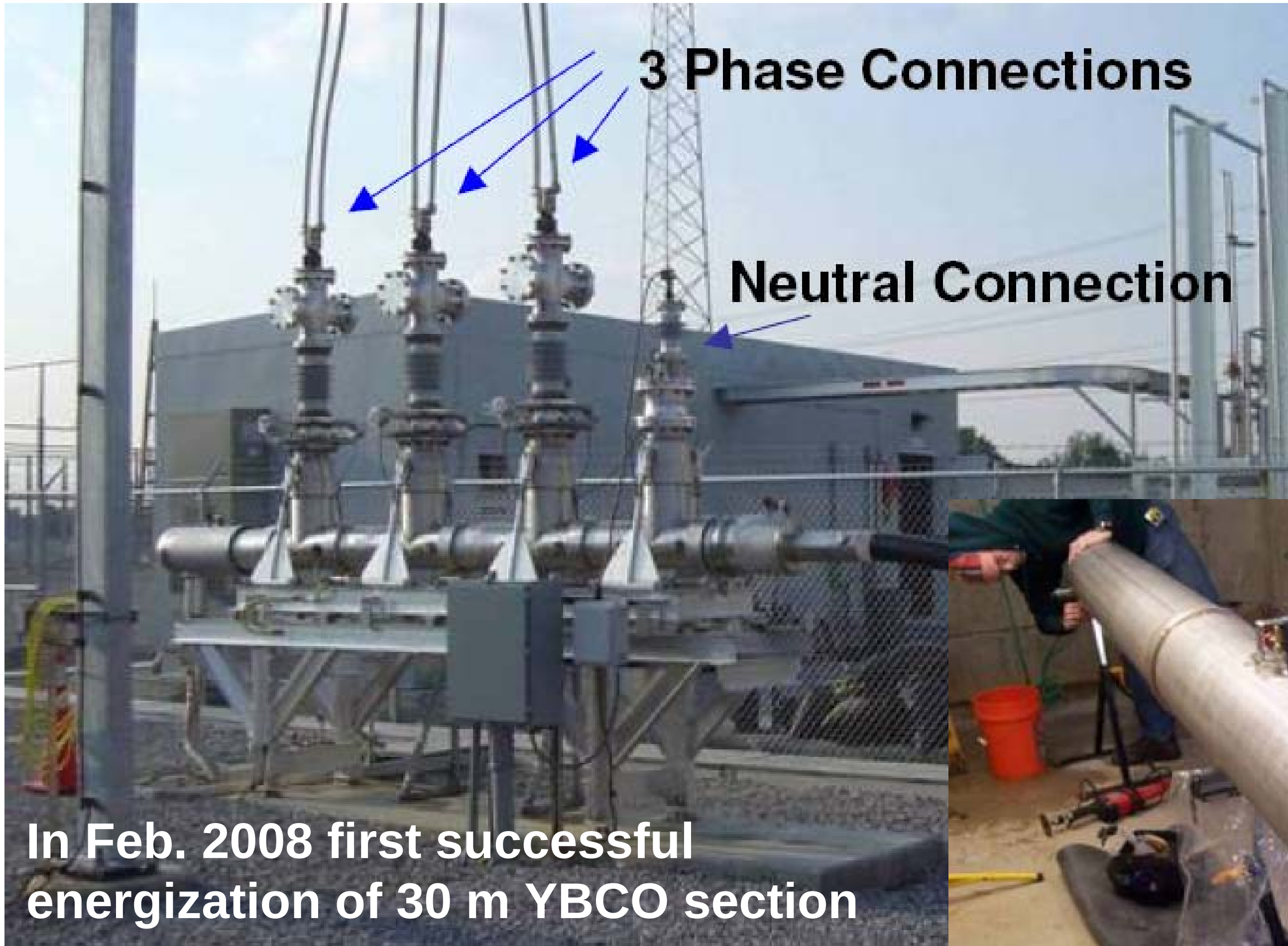
Future Trends

- YBCO coated conductor „2 G wire“
- longer lengths up to 6 km
- higher currents > 4 kA

13.2 kV, 3000 A, 200 m – Columbus Ohio

Partner
American Electric Power, nkt cables Southwire,
American SuperConductor, Praxair, ORNL

Successful energization July 2006
Bixby Substation, Columbus, Ohio



Picture: nkt cables

LIPA Cable (138 kV, 2.4 kA, 610 m)

Partner
Long Island Power Authority, Nexans,
American SuperConductor, Air Liquide, DoE

Courtesy: Nexans

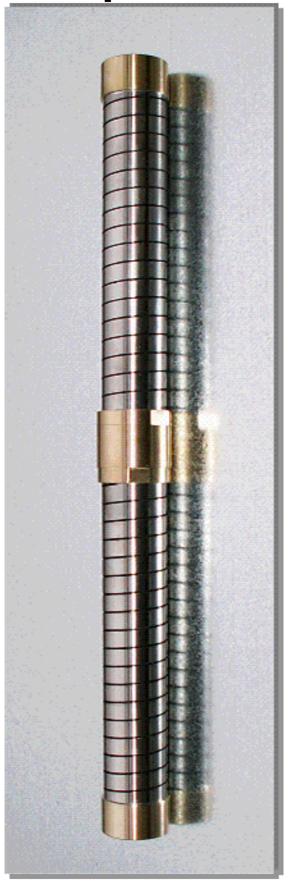
Status of SCFCL Development

Lead company	Year/Coutry 1)	Type	Data 2)	Superconductor	Field test
ACCEL/Nexans SC	2004	Resistive	6.9 kV, 600 A, 3-ph.	BSCCO 2212 bulk	+
KEPRI	2004	Resistive	3.8 kV, 200 A, 3-ph.	YBCO thin films	-
CRIEPI	2004	Resistive	1 kV, 40 A, 1-ph.	YBCO thin films	-
Mitsubishi	2004	Resistive	200 V, 1 kA, 1-ph.	YBCO thin films	-
Yonsei University	2004	Diode bridge	3.8 kV, 200 A, 3-ph.	BSCCO 2223 tape	-
CAS	2005	Diode bridge	6 kV, 1.5 kA, 3-ph.	BSCCO 2223 tape	+
CESI Research	2005	Resistive	3,2 kV, 215 A, 3-ph.	BSCCO 2223	-
KEPRI	2007	Res.-hybrid	13.2 kV, 630 A, 3-ph.	BSCCO 2212 bulk	-
Innopower	2007	DC biased iron core	20 kV, 1.6 kA, 3ph.	BSCCO 2223 tape	?
Toshiba	2008	Resistive	6.6 kV, -, 3-ph.	YBCO coated cond.	+
Siemens / AMSC	2007	Resistive	7.5 V, 267 A, 1-ph.	YBCO coated cond.	-
Hyundai / AMSC	2007	Resistive	13.2 kV, 630 A, 1-ph.	YBCO coated cond.	-
Nexans	2008	Resistive	6.9 kV, 800 A, 3-ph.	BSCCO 2212 bulk	+
Zenergy Power	2008	DC biased iron core	7.6 kV, 1.2 kA, 3-ph.	BSCCO 2223 tape	+
IGC Superpower	2009	Resistive	80 kV, -, 3-ph.	YBCO coated cond.	+
AMSC / Siemens	2011	Resistive	66 kV, -, 3-ph.	YBCO coated cond.	+
Rolls Royce	-	Resistive	6.6 kV, 400 A, -	MgB_2	-
KEPRI	2010	Resistive	22.9 kV, 3 kA, 3-ph.	YBCO coated cond.	+

1) Year of test
2) Phase to ground voltage

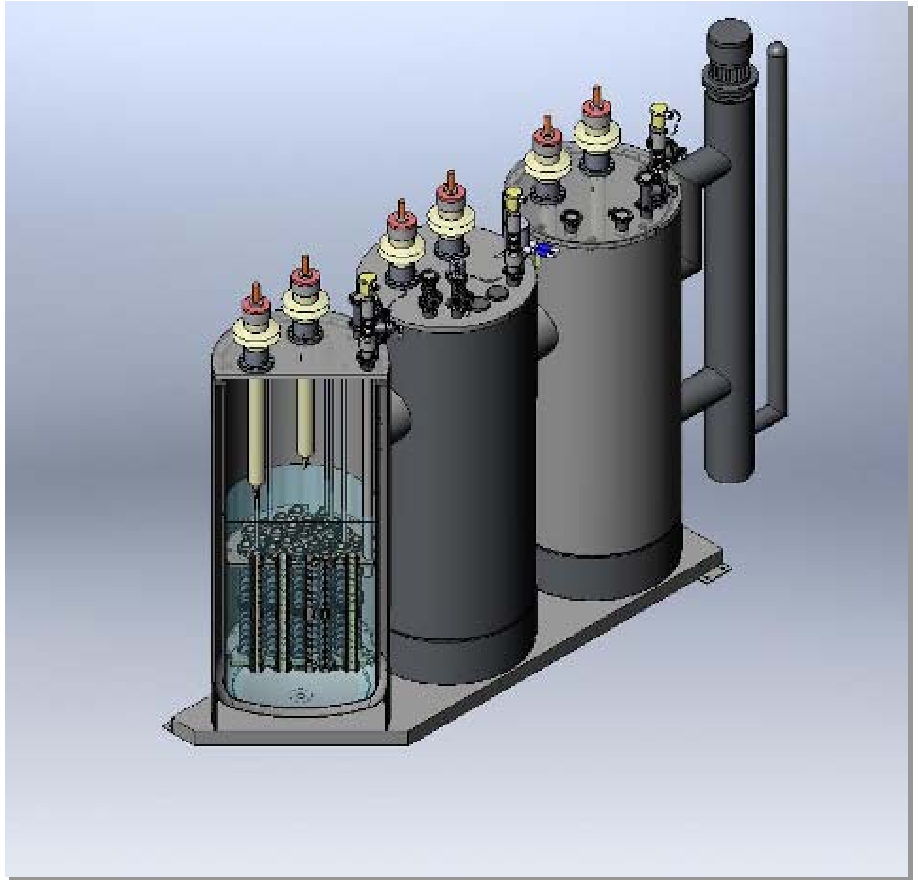
First Commercial SCFCL Installation

Bi 2212 component



Courtesy:
Nexans SuperConductors

3-phase arrangement



Courtesy:
Nexans SuperConductors

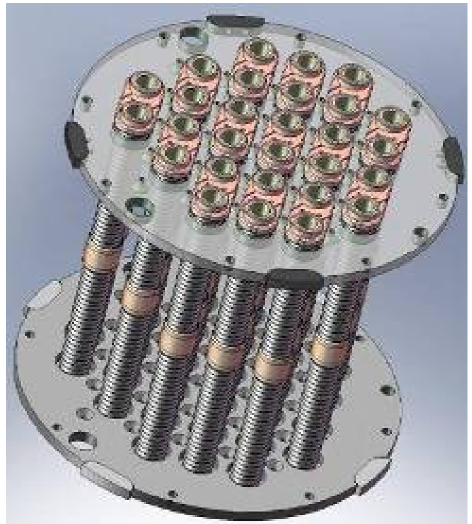
Rated voltage 12 kV

Rated current 800 A

Max. current 1.8 kA

Lim. time 120 ms

Lim. current < 27 kA



Courtesy:
Nexans SuperConductors

SCFCL Prototype 13 kV, 1.2 kA

Courtesy:
Zenergy Power

Short-circuit tests at Powertech Labs British Columbia, December 2007

Summary HTS for Power Systems

- Many demonstrator and prototype tests showed the technical feasibility of HTS in power system applications (Rotating machines, cables, transformers, current limiters, SMES)
- Superconducting cables and superconducting fault current limiters seem very close to commercialization
- Power system applications may open a continous demand for HTS and therefore accelerate the R&D for HTS material and tapes
- At a cost level of less than 10 k€ per kA and m a broad application of HTS devices seems very likely
- Power system industry needs low cost and low loss cables “ready to use”

Karlsruhe Institute of Technology

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

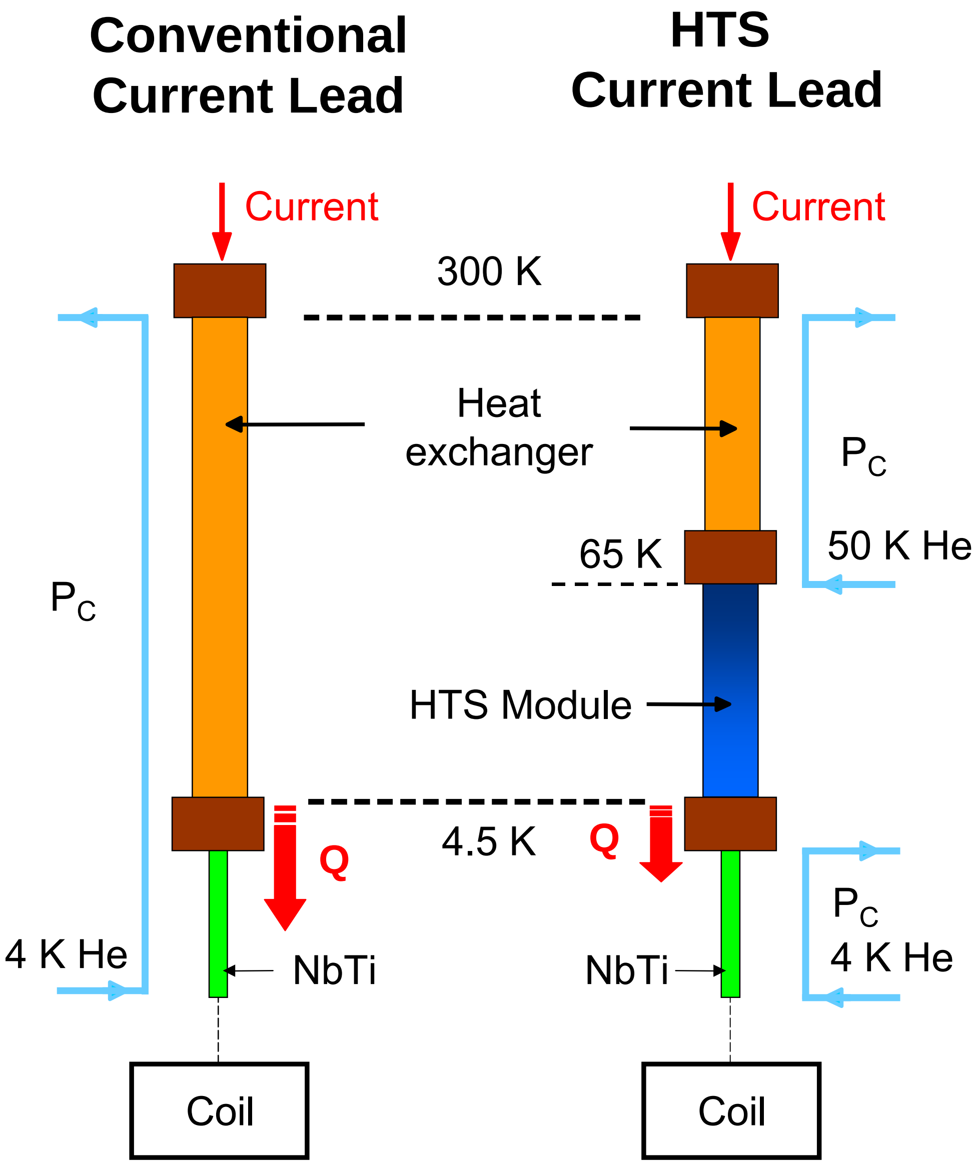
- Introduction to HTS Applications
- HTS Wires and Tapes
- HTS for Power System Applications
- **HTS for Current Leads**
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

Why HTS for Current Leads?

Cooling Power for ITER Current Leads

Type	Conv. CL
TF (18)	1.175 MW
PF (12)	0.530 MW
CS (12)	0.459 MW
Total	**2.164 MW**

Typ	HTS CL	Saving
TF (18)	0.37 MW	69%
PF (12)	0.14 MW	73%
CS (12)	0.12 MW	73%
Total	**0.63 MW**	**71%**



HTS Current Lead Design Principles

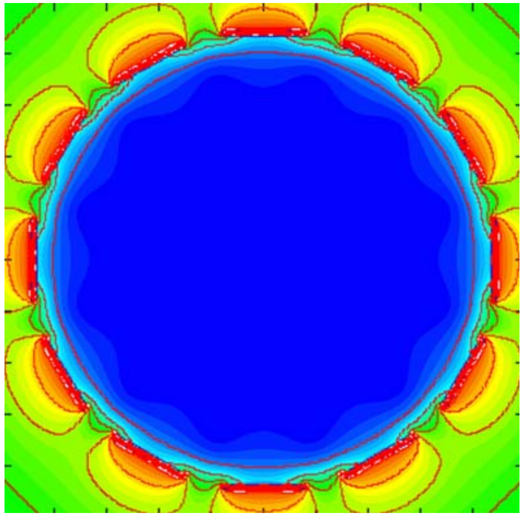
Karlsruhe Institute of Technology

Binary Current Lead

- HTS Part (4.5 K to 50 – 80 K), active or conduction cooling
- Heat Exchanger (50/80 K to 300 K), active cooling

HTS Part

- Circular arrangement to account for the anisotropic field dependence of Ic
- Heat sink made of stainless steel or similar to prevent fast thermal runaway in case of loss of coolant flow or quench



Heat Exchanger

- High efficient heat exchanger optimized for minimum coolant flow at nominal conditions and large thermal mass in case of loss of coolant flow
- Different types of heat exchangers are used

HELMHOLTZ GEMEINSCHAFT

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

13 kA HTS Current Lead for LHC (CERN)

Karlsruhe Institute of Technology

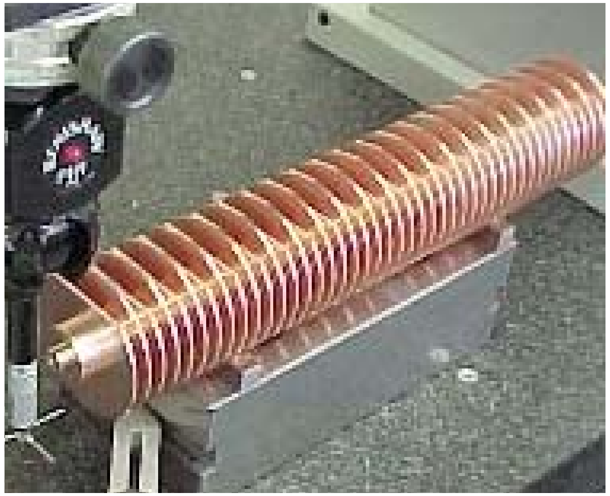
HTS Part

- Bi 2223 HTS tapes manufactured by AMSC and EHTS
- Active cooling with 4.2 K He
- Maximum operating temperature of HTS = 50 K

Heat exchanger

- Corrugated plates around a central Cu conductor
- Active cooling with 20 K He

HTS Part (CERN)



Heat Exchanger (CERN)

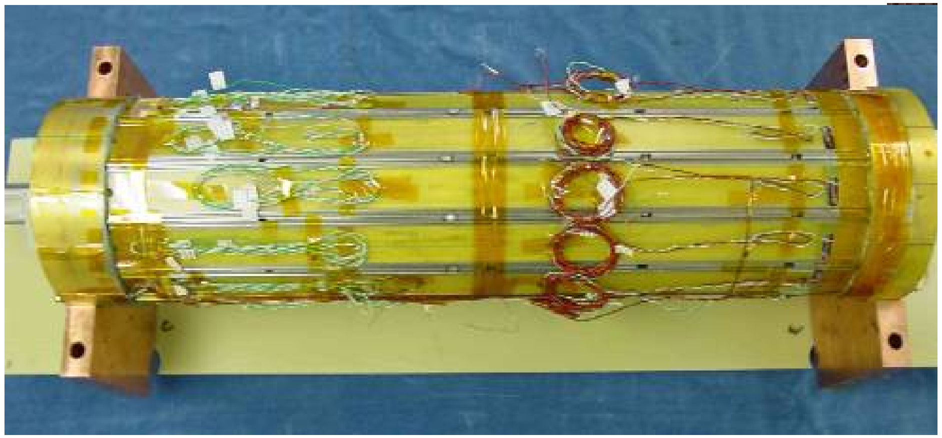
68 kA HTS Current Lead for ITER (FZK/CRPP)

HTS Part

- Bi 2223 HTS tapes manufactured by AMSC
- Conduction cooling from 4.5 K end
- Maximum operating temperature of HTS = 65 K

Heat Exchanger

- Perforated plates around a central Cu conductor
- Active cooling with 50 K He



HTS part (FZK)

Heat exchanger (FZK)

68 kA HTS Current Lead for ITER (FZK/CRPP)

Karlsruhe Institute of Technology

HTS Part

- Bi 2223 HTS tapes manufactured by AMSC
- Conduction cooling from 4.5 K end
- Maximum operating temperature of HTS = 65 K

Heat Exchanger

- Perforated plates around a central Cu conductor
- Active cooling with 50 K He

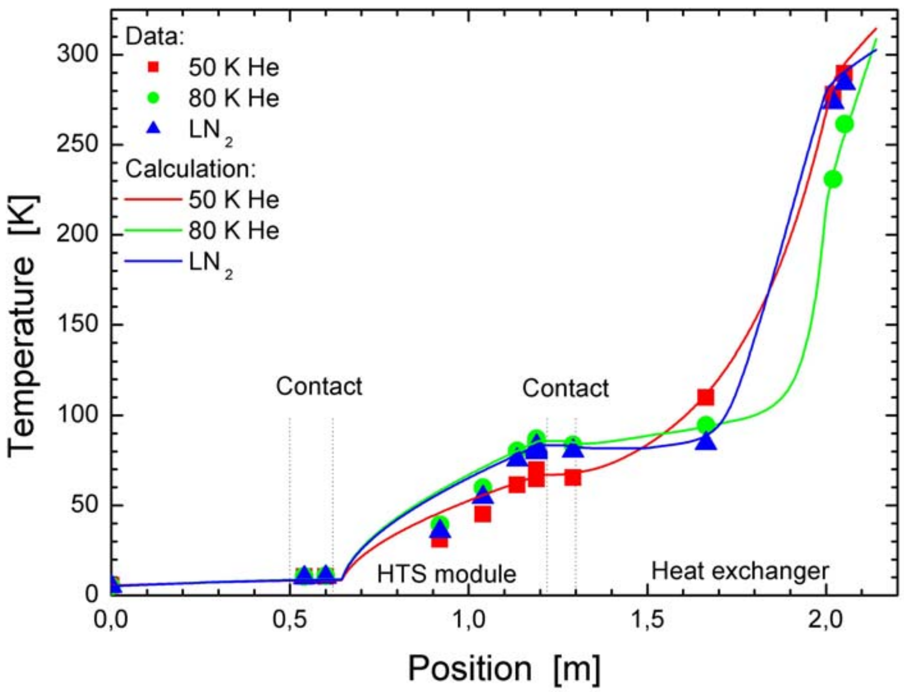
HELMHOLTZ GEMEINSCHAFT

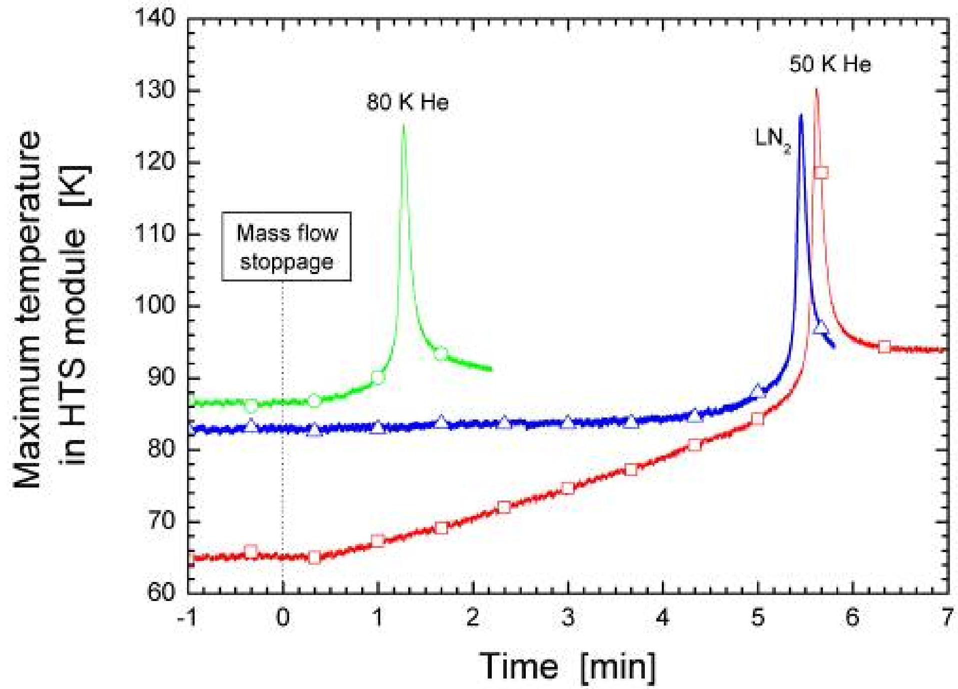
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

68 kA HTS Current Lead for ITER (FZK/CRPP)

Test Results

- Transport currents up to 80 kA (world record)
- Stable operation with 50 K He gas, 80 K He gas und LN_2
- Energy consumption is 20 – 30% compared to conventional current lead





HTS Current Leads under Construction

Outlook

FZK is constructing, manufacturing and testing HTS current leads for

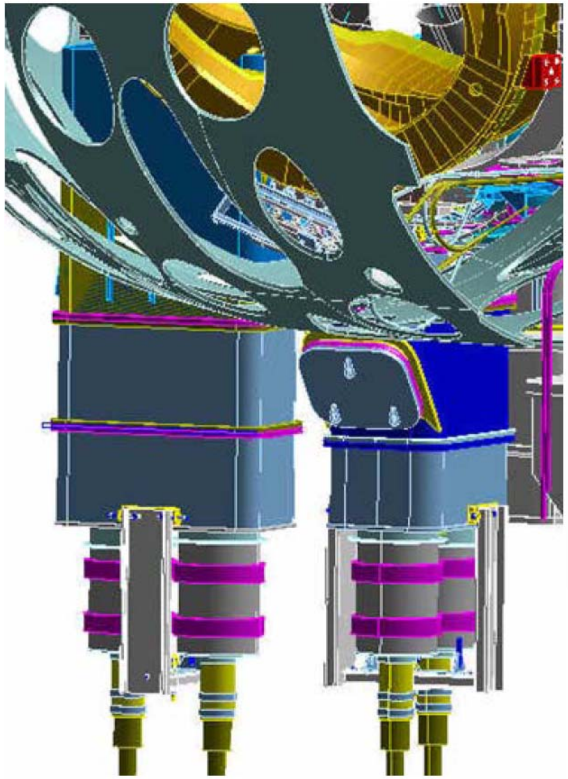
- W7-X
- JT60-SA

HTS Current Leads for W7-X

- 14 leads
- I_{max} = 18.2 kA
- U_{test} = 13 kV (Paschen tight)
- Orientation: upside-down
- Material: Bi 2223 stacks supplied by EHTS

HTS Current Leads for JT60-SA

- 26 leads
- I_{max} = 26 kA (TF) and 20 kA (CS/PF)
- U_{test} = 7/21 kV (Paschen tight)
- Orientation: vertical



CAD models of HTS current lead for W7-X

HTS Current Leads under Construction

Outlook

FZK is constructing, manufacturing and testing HTS current leads for

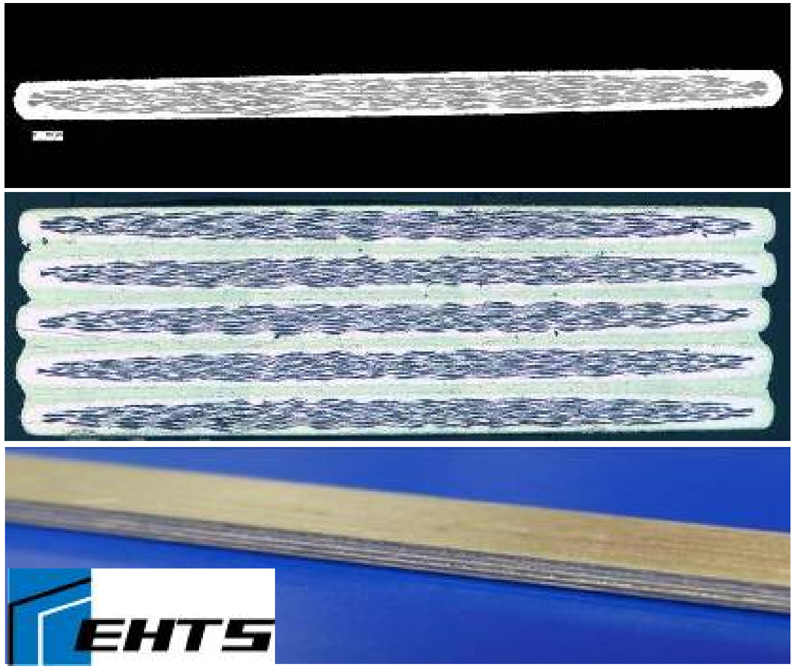
- W7-X
- JT60-SA

HTS Current Leads for W7-X

- 14 leads
- I_{max} = 18.2 kA
- U_{test} = 13 kV (Paschen tight)
- Orientation: upside-down
- Material: Bi 2223 stacks supplied by EHTS

HTS Current Leads for JT60-SA

- 26 leads
- I_{max} = 26 kA (TF) and 20 kA (CS/PF)
- U_{test} = 7/21 kV (Paschen tight)
- Orientation: vertical



Bi 2223 HTS stacks – components for HTS current leads by EHTS

Benefits

- High load cycling tolerance in strength
- High uniformity of tape geometry

Summary HTS for Current Leads

Karlsruhe Institute of Technology

- Current leads are the component of a sc magnet system where HTS material has been commercialized.
- This states for small magnet systems with current in the kA range as well as for large current capacity leads used or under construction in accelerators and fusion devices.
- First large scale application are the HTS current leads developed for LHC (up to 13 kA).
- Second example is the ITER HTS current lead demonstrator (68 kA) which led to the decision to use HTS current leads in ITER. But also other fusion devices in operation or under construction like EAST (China), W7-X (Germany) and JT60-SA (Japan) use HTS current leads.

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- HTS Wires and Tapes
- HTS for Power System Applications
- HTS for Current Leads
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

Why HTS for Fusion Magnets?

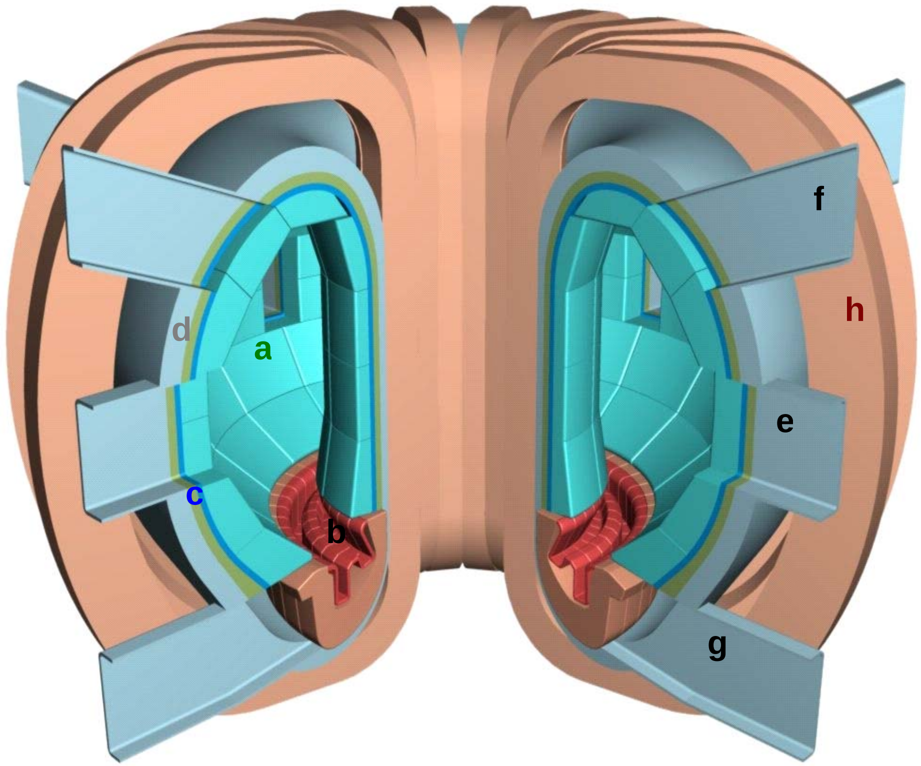
Cooling Power of Fusion Power Plant

Cooling Power

• at 4.5 K	74 kW
• at 80 K	1400 kW

RT Electric Power for Cooling

• at 4.5 K	19 MW
• at 80 K	14 MW
Total	33 MW



DEMO (EU-Study)

Why HTS for Fusion Magnets?

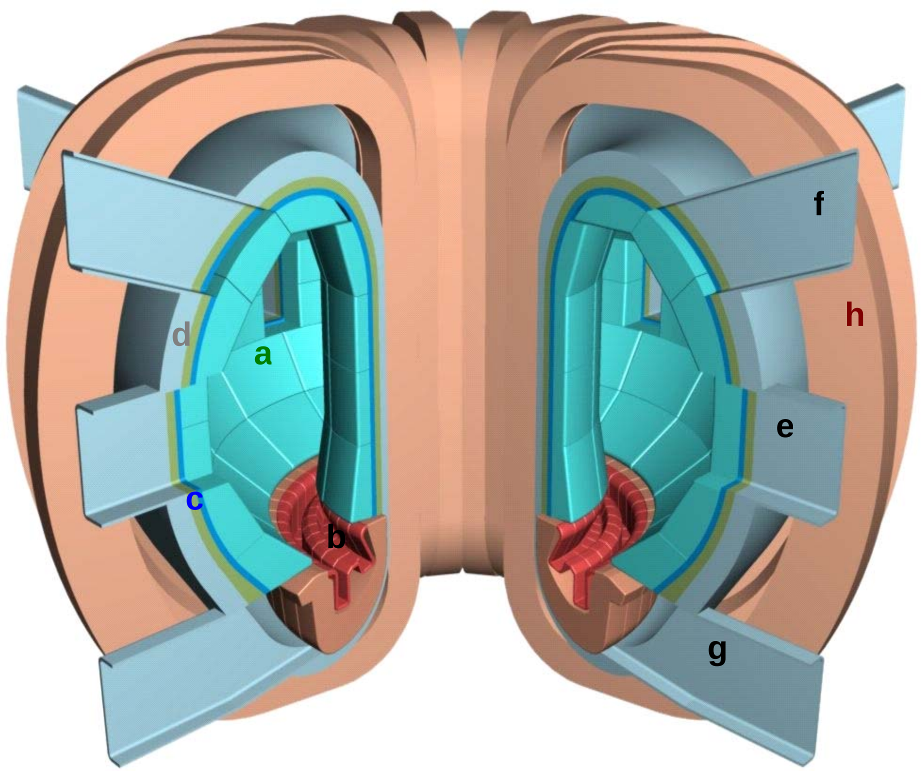
Cooling Power of Fusion Power Plant

Cooling Power

• at 4.5 K	74 kW
• at 80 K	1400 kW

RT Electric Power for Cooling

• at 50 K	12 MW (Δ 7 MW)
• at 80 K	14 MW
Total	26 MW



DEMO (EU-Study)

Possible reduction of cooling Power by 21 % with HTS Magnets

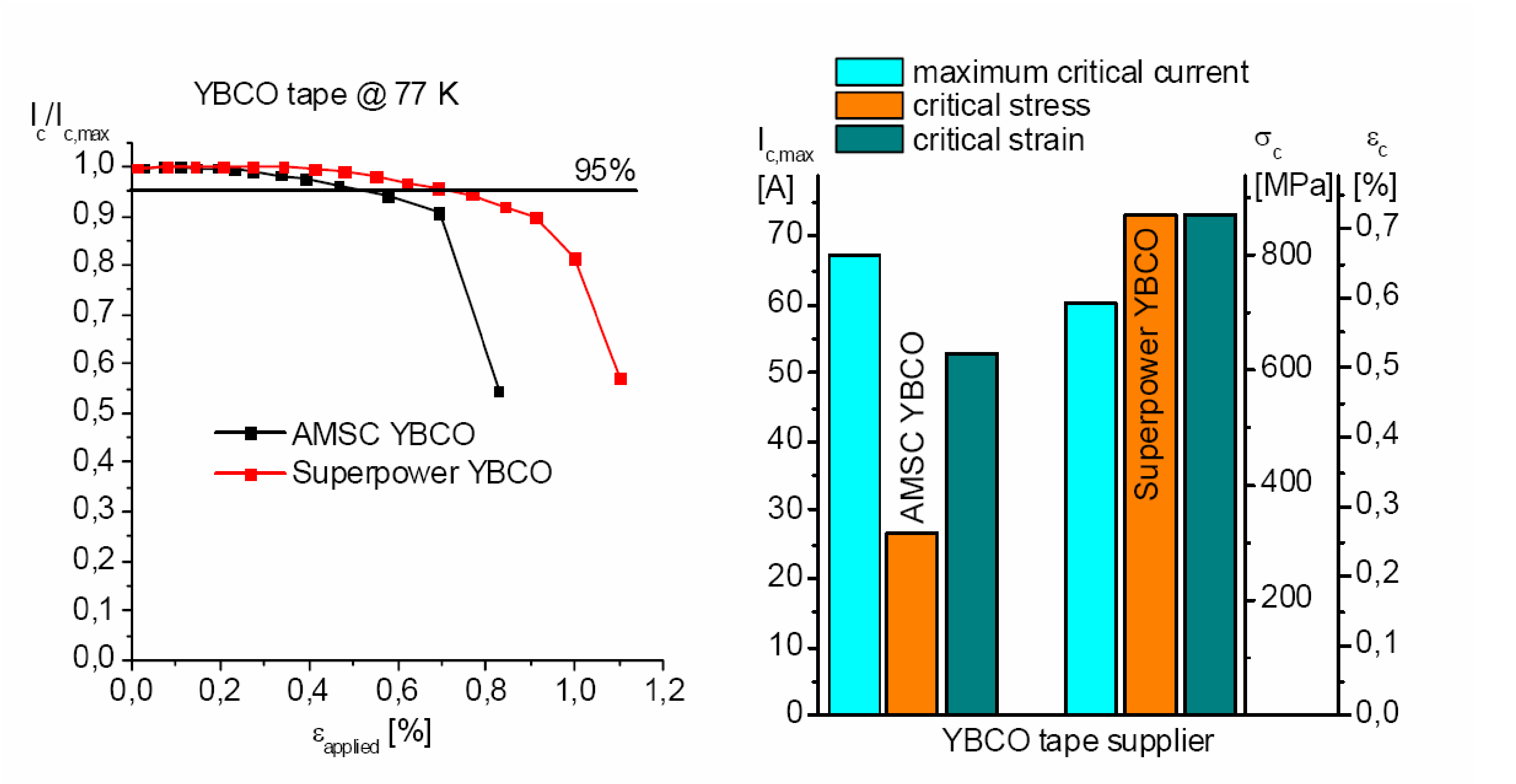
The complex radiation shield could be avoided

J.L Duchateau et al, EFDA Contract TW4-TMS-HTSMAG: First Intermediate Report, AIM/NTT-2006.004 (2006),

Main Requirements for HTS Fusion Magnet Conductors

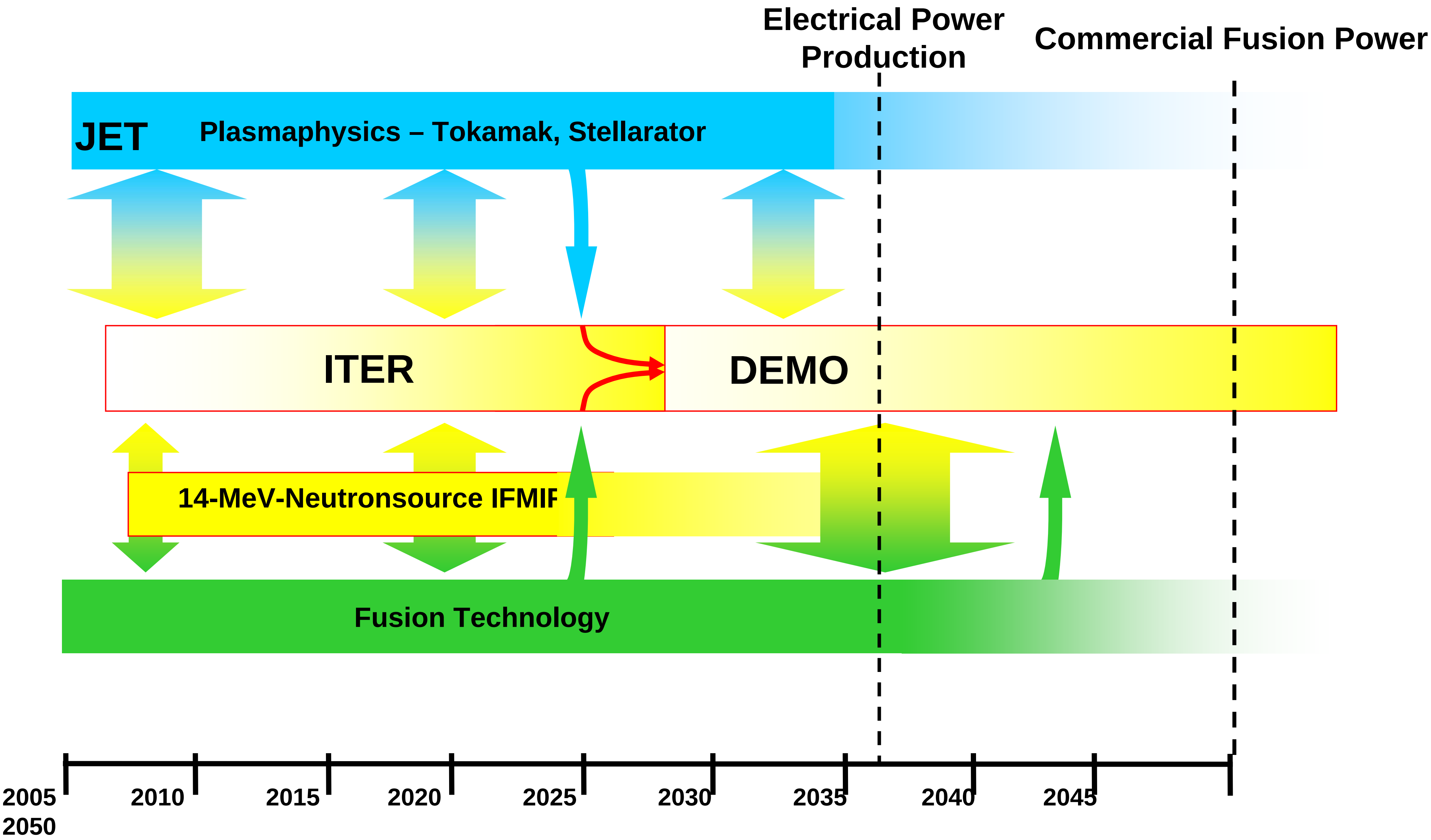
- High engineering current 10-20 kA in the conductor at the specific temperature 50-70 K and field 10-15 T.
- Sufficient mechanical strength (stress-strain characteristics) or option for reinforcement.
- Tolerable hotspot and quench behaviour of the HTS conductor (stabilisation).
- Optimized current distribution, i.e. feasibility of good joints and optimized inter-strand resistance and inductance.
- Possibilities to limit the AC losses.
- Cooling requirements.

Mechanical properties of YBCO coated conductor



It is shown that YBCO coated conductor has the potential to fullfill the requirements for a fusion magnet cable

Road Map to the Fusion Reactor (Fast Track)



Outlook on HTS for Fusion Magnets

FZK has started a program HTS4Fusion to develop HTS conductors for fusion magnets

Conductor development (→ 2014)

- HTS material development
- Development of cabling/bundling techniques for both wires and tapes
- Develop HTS cable concept for 20 kA class 12 T, >50 K
- Characterisation of HTS strands and sub-size cables in upgraded FBI (warm bore)
- Conductor development

Structural material in the cryogenic lab (continuous)

- Prepare material database for structural materials beyond ITER
- Tests of advanced structural materials

Demo-Solenoid (2015 →)

- Demo-Solenoid Design & Construction
- Demo-Solenoid test in TOSKA

HTS TF-Demonstration Coil (2020 →)

HTS Applications

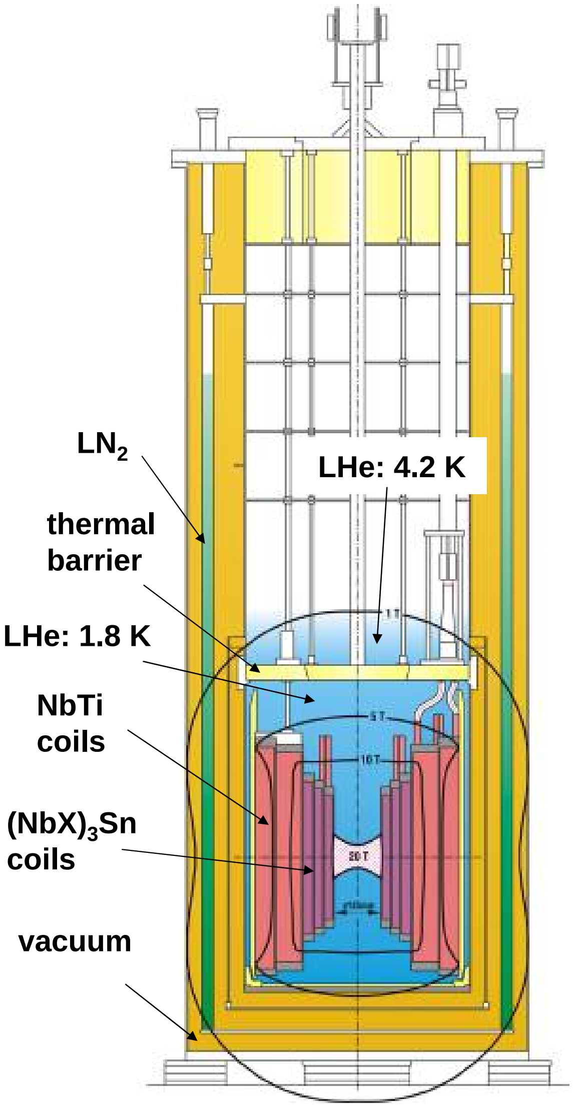
Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- HTS Wires and Tapes
- HTS for Power System Applications
- HTS for Current Leads
- HTS for Fusion Magnets
- **HTS for High Field Magnets**
- Outlook

HOMER II – High Field Test Facility at ITP

Karlsruhe Institute of Technology

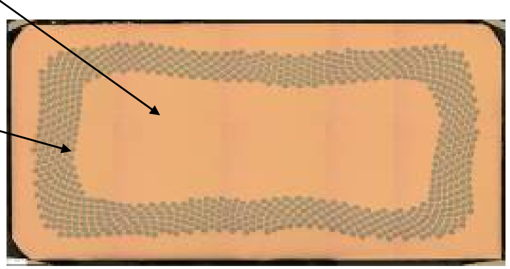
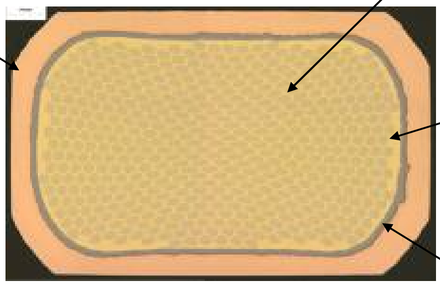


In 2006

20 T / ø185 mm / T = 1.8 K

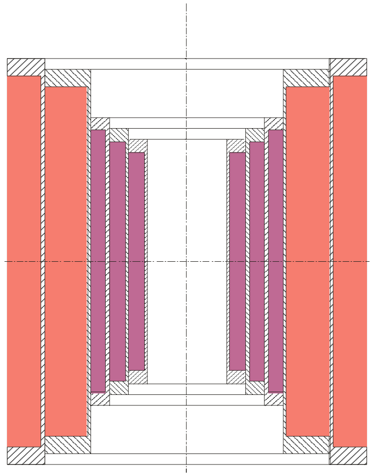
Data at 20 T
Flux: 0.54 Wb
Magnetic pressure: 160 MPa
Flux density: 20 Vs / m²
Stored energy: 24 MJ

HOMER II – High Field Test Facility at ITP
Superconductors and Coils

	NbTi	**$(NbX)_3Sn$**
		
Wire length:	15,000 m	8,000 m
Number of filaments:	846	up to123,000
Cross section:	up to 32 mm²	up to 6.3 mm²
Copper-superconductor ratio:	4	0.3
RRR:	80	> 100
Manufactured by:	EAS *	EAS *
Number of coils:	2	3
Field contribution:	12 T / 1.8 K	8 T / 1.8 K
Operating current:	~ 1,500 A	~ 500 A
Manufactured:	in house	in house

*: European Advanced Superconductors GmbH

HOMER II – Magnet Configurations

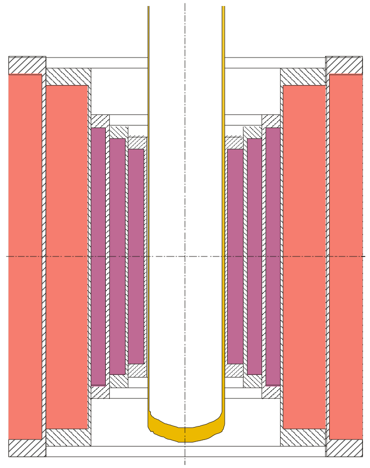


B_0 = 20 T; ∅ = 185 mm;

T = 1.8 K

⬇

Test of superconductors under increasing, simultaneous Lorentz force

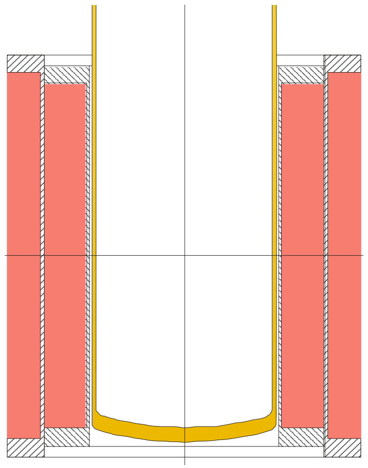


B_0 = 20 T; ∅ = 160 mm;

Temperature variable up to RT

⬇

HTS-characterisation



B_0 = 12 T; ∅ = 410 mm;

Temperature variable up to RT

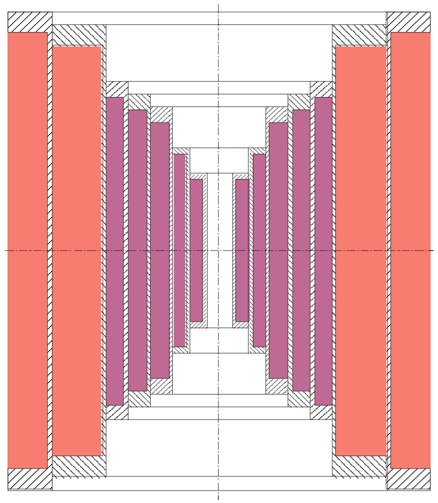
⬇

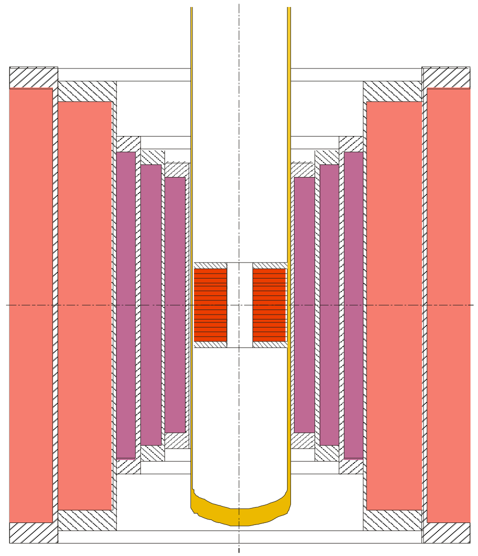
Testing of fusion conductors

HELMHOLTZ GEMEINSCHAFT
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

HOMER II – Future Magnet Configurations

Karlsruhe Institute of Technology





B_0 = 24 T; ∅ = 50 mm; T = 1.8 K

with $(NbX)_3Sn$ coils

↳ already in progress ✓

B_0 = 25 T; ∅ = 50 mm; T ≥ 4.2 K

with HTS insert coils

↳ Stability of HTS ?

HELMHOLTZ GEMEINSCHAFT

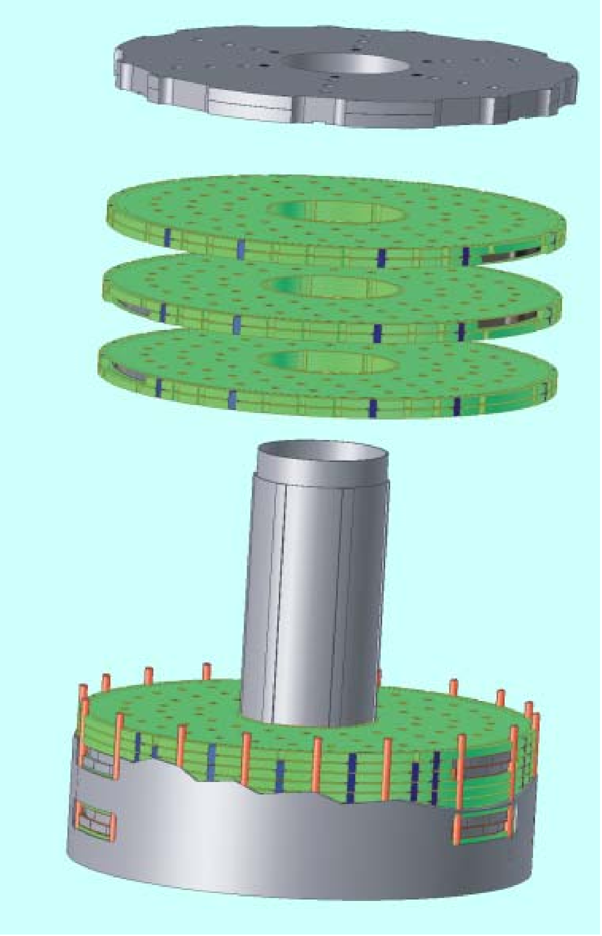
Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

HTS High Field Insert Coils

Forschungszentrum Karlsruhe Bi2223 double pancake coil 2004

Design of 5 T Bi-2223 Insert Coil → Stacked double pancake layout

Design:	stacking of 16 double pancakes
HTS material:	reinforced AMSC Bi-2223 tapes
Technique:	react & wind
Joints:	made of copper
Height incl. flanges:	177 mm
Free bore:	50 mm
OD incl. jacket tube:	185 mm
Number of turns:	5402
Coil constant:	35.41 mT/A



We reached 5 T in a background field of 10 T but after warming up, ballooning of the tape was observed presumably due to the penetration of superfluid helium.

HTS High Field Insert Coils

Bi2212 insert coil NHFML-Tallahassee-2004

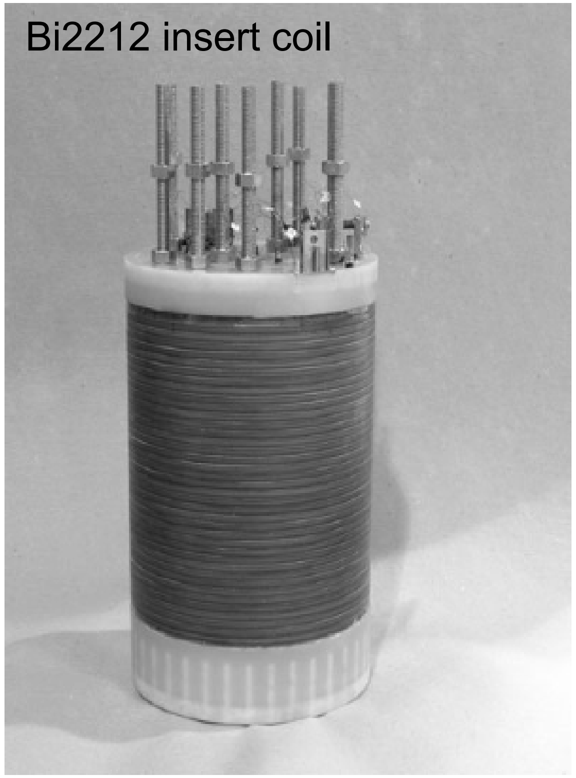


Table 1. Geometric and related parameters of the Bi2212 insert coil.

	Unit	A section	B section	C section
Inner radius	mm	20.5	53	78
Outer radius	mm	48	73	82.5
Total height	mm	185	185	209
Construction	—	17 DP	17 DP	14 layers
Total no. of turns	—	3723	2611	532
Conductor length	m	801	1034	269
Coil constant	mT A−1	23.7	14.7	2.5
Self inductance	H	0.23	0.39	0.03
Packing factor[a]	—	0.74	0.71	0.57
Resistive joints	—	16	16	3

[a] Total conductor cross-section as a fraction of the winding cross-section.

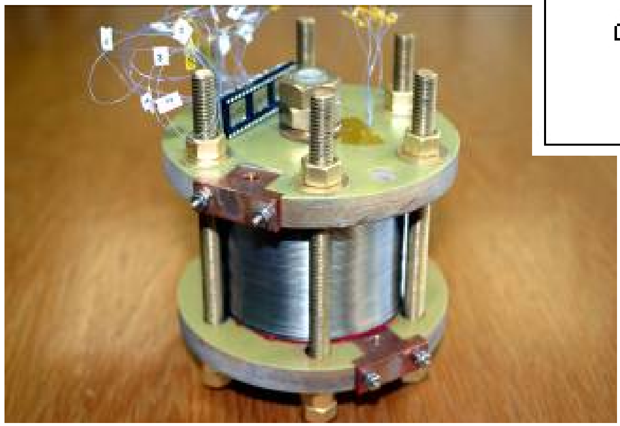
The generation of 25.05 T using a 5.11 T Bi2Sr2CaCu2O*x* superconducting insert magnet
H.W.Weijers et al.; Supercond. Sci. Technol. 17 (2004) 636–644

HTS High Field Insert Coils

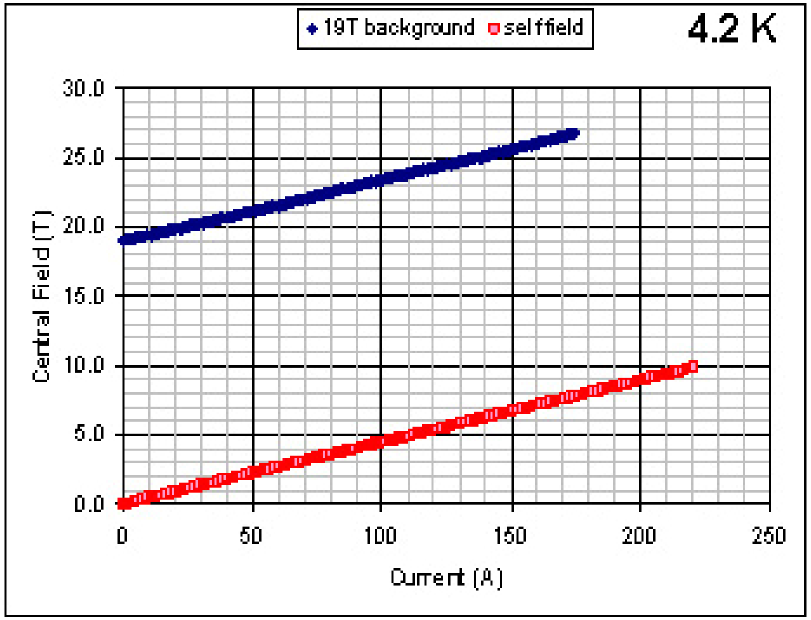
SuperPower YBCO double pancake coil 2007

Average Ic of Tapes in Coil	~ 78 A (77K, sf)
4.2 K Coil Ic - Self field	221 A
4.2 K Amp Turns @ Ic- self field	612,612
4.2 K Central Field – self field	**9.81 T**
4.2 K Coil Ic – 19 T Background (axial)	175 A
4.2 K Amp Turns @ Ic – 19 T Background (axial)	485,100
4.2K Central Field – 19 T Background (axial)	**26.8 T**

Coil ID	9.5 mm (clear bore)
Winding ID	19.1 mm
Winding OD	~ 87 mm
Coil Height	~ 51.6 mm
# Pancakes	12 (6 x double)
2G Wire Used	~ 462 m
# Turns	~ 2772
Coil Je	~1.569 A/mm² per A
Coil Constant	~ 44.46 mT/A



Measurement at NHFML



http://www.superpower-inc.com

WAMSDO 2008 – Workshop on Accelerator Magnet, Superconductor, Design and Optimization

Karlsruhe Institute of Technology

HTS Applications

Mathias Noe, Wilfried Goldacker, Reinhard Heller, Walter Fietz, Theo Schneider,

Forschungszentrum Karlsruhe, Institute for Technical Physics

- Introduction to HTS Applications
- HTS Wires and Tapes
- HTS for Power System Applications
- HTS for Current Leads
- HTS for Fusion Magnets
- HTS for High Field Magnets
- Outlook

HELMHOLTZ GEMEINSCHAFT

Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft

Outlook HTS Magnet Applications

	LTS now	HTS now	HTS future
MRI Magnets	☑	-	?
NMR Magnets	☑	-	☑ HTS insert
Accelerator Magnets	☑	-	☑ High fields
Fusion Magnets	☑	-	☑ Long term
SMES Magnets	☑	-	☑
Induction Heater Magnets	-	☑	☑
Current Leads	-	☑	☑

Many thanks for your attention!