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Siemens Activities in Superconductivity

PART I :

- **Large Scale HTS-Applications**
- **System Aspects, Design & Integration**

PART II :

- **Technical HTS-conductors and HTS-windings**
- **Is HTS Technology mature for Large Scale High Field Magnets ?**

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Siemens Corporate Technology
Erlangen, Germany

Power & Sensor Systems
Power Components & Superconductivity

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Large Scale HTS-Applications MRI Magnets

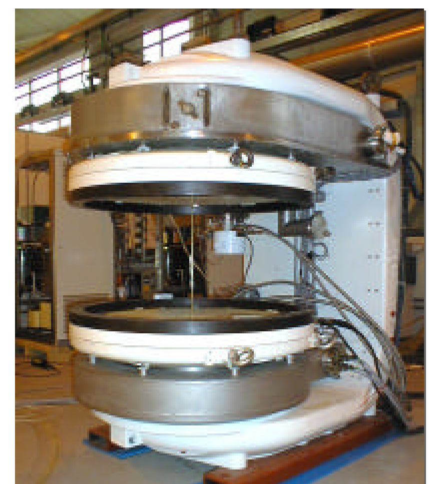
LTS Technology

- With first laboratory scale magnets in early 1980´s Siemens co-developed a multi-million dollar business
- Siemens Medical Solutions and Oxford Magnetic Technologies manufacture app. 1200 MRI-Magnets/yr.
- LTS MRI Magnet Systems from 0.5 T up to 3.0 T
- World market for MRI has a volume of ≈ 3 Mrd $/yr.


1.5 T MRI-Magnet

HTS Technology

- OMT OR10 - The world´s first MRI-magnet with HTS-magnet coils
- Cryofree conduction cooling with a GM-type refrigerator for T_{op}≈20K
- DC-pancake windings for a low field open MRI-system
- C/P ratio is essential to beat conventional electromagnets or permanent magnets


HTS-MRI Magnet 0.3T

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Large Scale HTS-Applications HTS-Transformer

Railway traction or distribution isle grid

- Weight = 50% - Volume = 50% - Efficiency = 92 → 99%
- Oil-free = environmental benefit, no fire hazard

Technical Characteristics

- P = 1 MVA, f = 50 Hz, U = 25 kV, single-phase
- I_{US} = 360 A, I_{OS} = 40 A , B_{HTS} < 500 mT, ≈ 7 km Bi-Tape
- Forced flow subcooled LN_2 (dielectric reasons) T_{op}=67K

Operational experience

- short circuit, no load experiments, frequency variation, load variations, asymmetric operation
- design-tools and loss-models predict measurement results
- Successful testing of operation with a converter (harmonics)
- Transformer executed a load characteristic experiment with a 1 hour drive cycle „Wunstorf-Lehrte“
- Proven ability to drive ONE hour without cryocooler

Development challenges

- low AC-loss conductor – twisted filaments, high j_e
- reliable compact cryogenic system – n*100W
- FRP Cryostat with long vacuum stability for a warm iron core

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Large Scale HTS-Applications
HTS-Motor / -Generator

First HTS-Industrial Motor (400kW) in Europe (2001) (BMBF funding)

- 3 yrs. continuous testing in a rough factory environment
- test with power converter passed in 4/02
- 4-pole, n = 1500 rpm, f = 50 Hz, x ...
- "invisible" cooling system ... yrs. operation)
- Test-Bed for scale-up of s... components

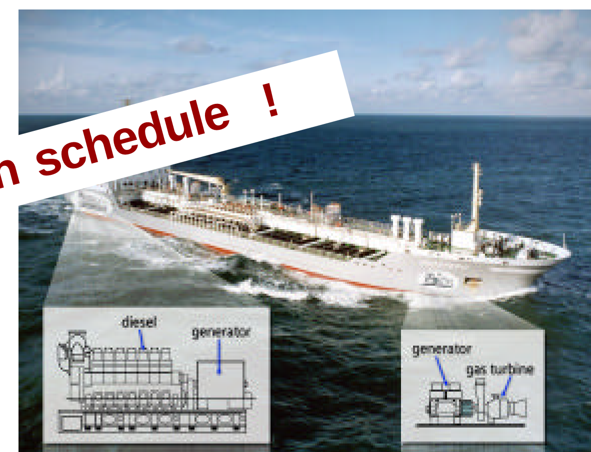
still in operation !!!

¨ **compactness** ¨ **efficiency** ¨ **stability**

4 MVA HTS-Generator (2002-2005) (BMBF funding)

- Development for application on-board of ships
- Rotor with HTS-windings and brushless excitation
- Stator with Air-core winding from Cu-Litz
- U = 6,6 kV, 2-poles, f = 60 Hz, n = 3600 ...
- Full-Load Testing with a ... converter and in the public grid in the new Siemens Systemprüfhaus, Nürnberg
- Testing with a gasturbine in discussion

entering Phase III - within schedule !



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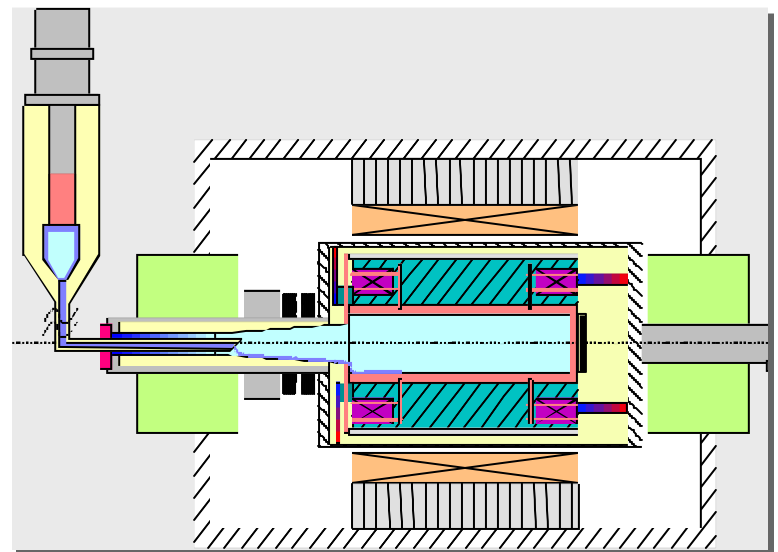
System Aspects, Design & Integration
Key Technologies for HTS-applications

- **HTS conductors**
  - physical application know-how : T_{op}, I_{op}, B_{op}
- **Winding Know-How** - Design & Manufacturing
  - mechanical, chemical & thermal tolerances
  - handling, contact & joining technology
  - qualitiy control
- **Electrotechnical system integration**
  - design and construction rules & tools
  - operation : converter-machine model
  - protection concept
- **Cryo and vacuum technology (rotating)**
  - closed cycle cooling system
  - possibility to exchange primary cooler
  - heat transfer by self-controlled thermosiphon



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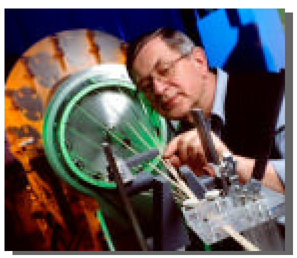
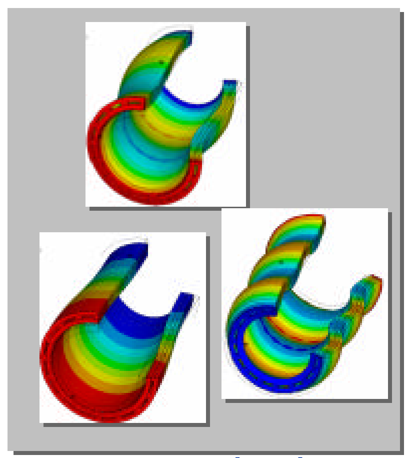
System Aspects, Design & Integration Development Process

Material, Cryog	Production of powe engineering equipme	System integration
Development of HTS-Material and Cryo-Equipment in cooperation with external partners	Design, systemengineering, and construction of components and power engineering equipment	Integration in systems, test of systems and development of a market entry with business units

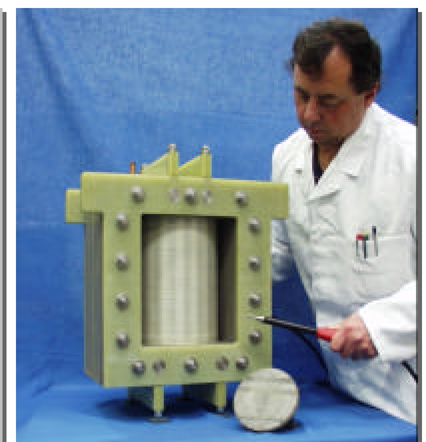


Technical Conductors

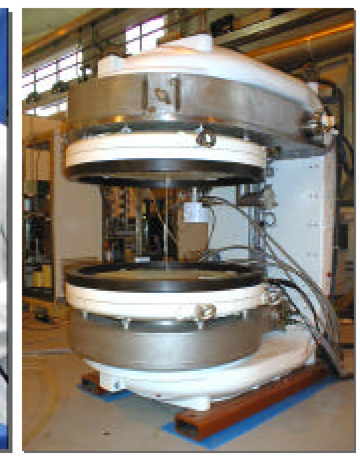
Design of windings



Systemengineering Multiphysics-Simulation



HTS-Choke Coil



HTS-MRI-Magnet

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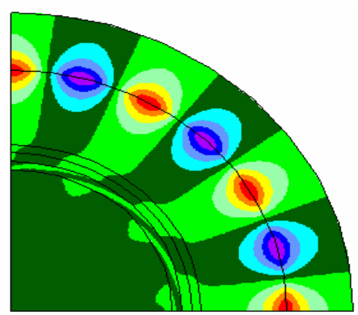
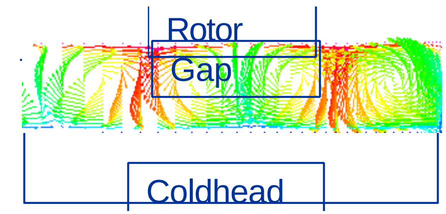
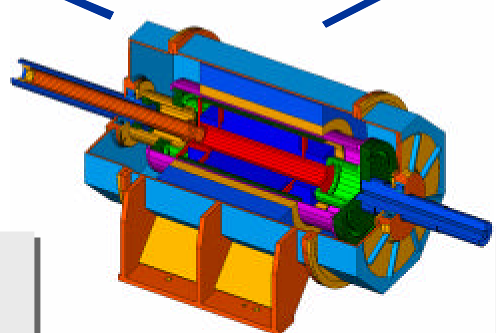
System Aspects, Design & Integration
Multiphysics Analysis

Electrodynamics
Shielding of Higher harmonics from the HTS windings with a damping shield

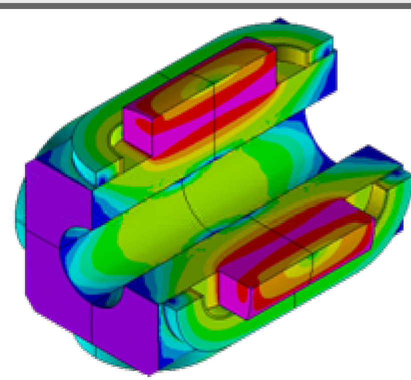


Cooling
Thermal Heat-Transfer between Coldhead and Rotor

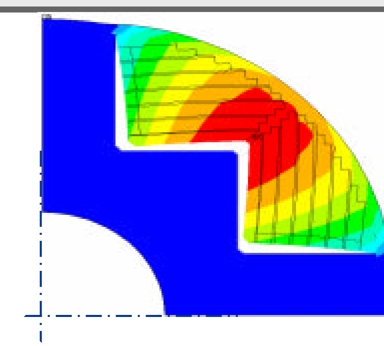




Magnetostatic Winding
Calculte magnetic fields for critical current, forces and moments in the conductors



Structural Mechanics
Dislocations, tensions induced by centrifugal and magnetic forces



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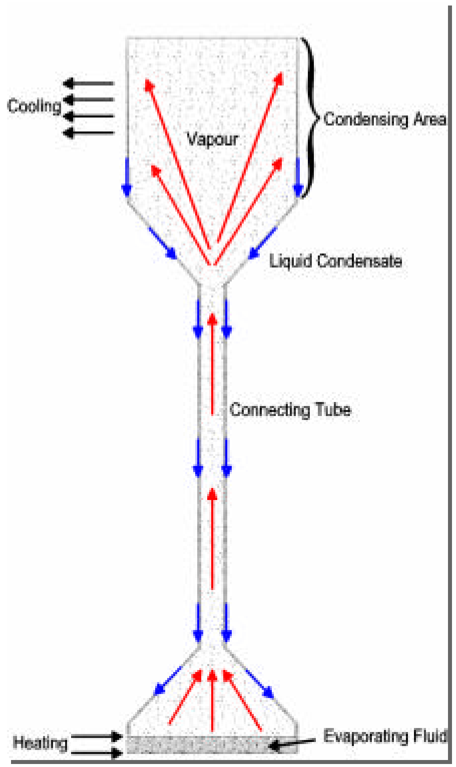
System Aspects, Design & Integration Cryogenics

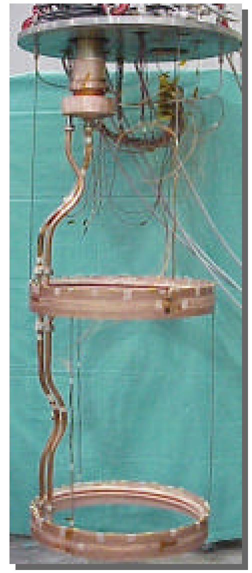
Thermosiphons comprise ...

... closed-cycle cooling system

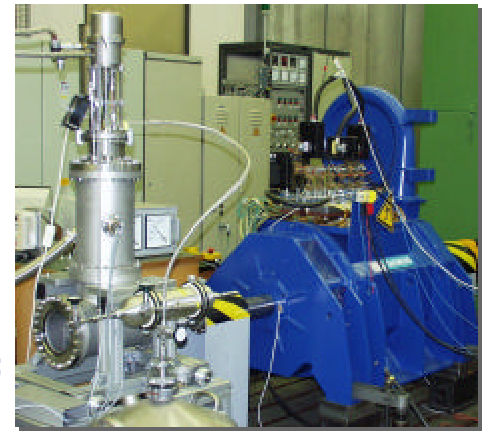
... Self-Control

... high thermal heat transfer capacity

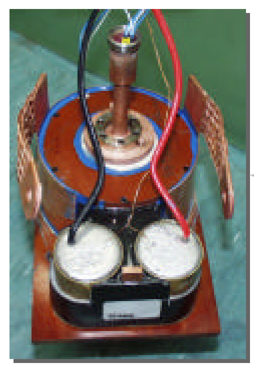




25-30K (Neon):
HTS MRI Magnet
(cooling testbed)



25-30K (Neon):
HTS Motor



4.2K (Helium):
Superc. Switch

4.2K (Helium):
MRI magnets

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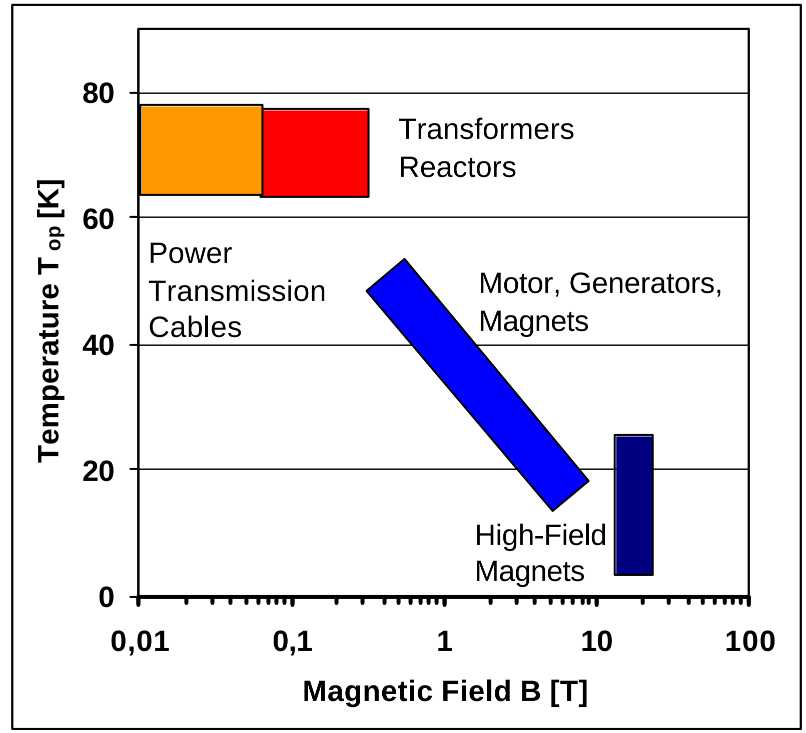
Technical HTS-Conductors & HTS-Windings Requirements

Requirements for flexible HTS Conductor

- **availability in km-batches**
- **mechanical properties**
  - mechanically reinforced
- **high current capacity 0.1 – 5 kA**
  - large superconductor content
- **low Cost 10$/kAm (DoE)**
  - high engineering current density j_e
  - high critical current density j_c
- **low AC-losses (<0.45mW/Am /77K)**
  - short twist
  - thin filaments
  - High transverse resistivity



Operational parameters for Power engineering equipment

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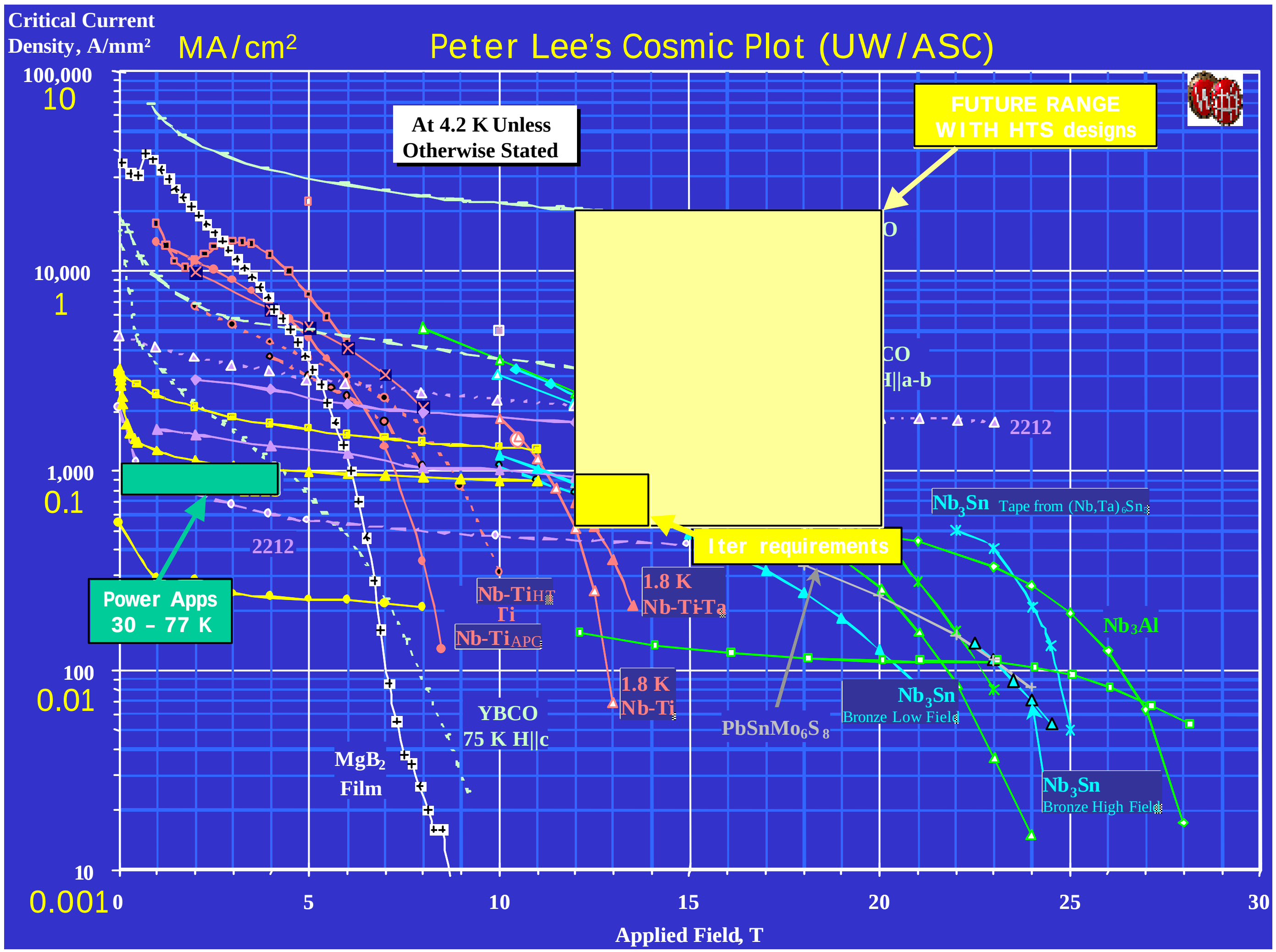
Technical HTS-Conductors & HTS-Windings Application Ranges - Material Selection



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Technical HTS-Conductors & HTS-Windings
HTS-Tape Conductor Properties

Parameter	Bi-2223/Ag-Tape	YBCO-CC-Tape	YBCO-CC-Tape outlook
Type	AgMg / Ag	IBAD / PLD	CSD
Available length	500-1500 m	10 m	>100 m
Width x thickness [mm^2] (typ.)	4 x 0.25	4 x 0.1	10 x 0.15
SC fill factor λ	25-35%	1-3 %	1-3 %
Critical current I_c(77K,0T)	80…140 A	120 A	+
Current Density j_e (77,sf)	100 A/mm^2	300 A/mm^2	125 A/mm^2
Current Density j_e (25,4T perp)	100 A/mm^2	340 A/mm^2	220 A/mm^2
Stabilized, insulated Current per width	200 A/cm	> 200 A/cm	+
I_c(66K)/ I_c(77K)	1.7	2.1	
$I_c(0.1T_{\|\|})$ / I_c(0T)	0.80	0.55	
$I_c(0.1_{\perp})/I_c$(0T)	0.31	0.47	
AC-loss $0.1T_{\|\|}$, 50Hz	0.3-1.0 mW/Am	<0.003 mW/Am	< 0.003 mW/Am
AC-loss $0.1T_{\perp}$, 50Hz	15 mW/Am	15 mW/Am	45 mW/Am
Critical bending radius	50 mm	< 15 mm	< 25 mm
Critical Tension (axial)	100…150 MPa	400 MPa	150
Handling	Robust	Sensitive	+
Insulation	wrapped, extruded	Not available	+
Stability, Normal resistance	High, < 10 mΩ/m	Low, > 1 Ω/m	+

Technical HTS-Conductors & HTS-Windings
Which critical current to use ?

Which critical current to use ?

- **High critical current I_c** keeps winding effort low (=cost) and keeps inductance low
- **High engineering current densities j_e** for compact windings (power density) in motors, generators, transformers, magnets, …
- **High current per width I_c/w** is required esp. in transmission lines (power cables)

From the I_c of the tape to the attainable current density J_w in a winding (M.Oomen)

- Critical current (density) at 77K in self field $I_{c,sf}$
- Critical current density at the operating point (Temperature, cooling technology , magnetic field) $j_e(T_{op},B_{op})$
- Critical current density of a stabilised tape (device depend requirements)
- Critical current density of an insulated tape (varnish, extruded, wrapped, process temperature ?)
- attainable current density in a winding (fill factor, cooling design, winding type) J_w

- **Final Results :**

	Bi2223	YBCO (PLD)	YBCO (MOD/CSD)	
j_e 77K, sf	100 A/mm^2	300 A/mm^2	125 A/mm^2	bare tape
J_w 77 K, 0.1 $T_{\parallel}$	35 A/mm^2	42A/mm^2	25 A/mm^2	winding
J_w 25 K, 4 $T_{\wedge}$	60 A/mm^2	204 A/mm^2	130 A/mm^2	winding

YBCO-tapes are comparable/better than Bi-2223-tapes for high power density windings

Technical HTS-Conductors & HTS-Windings AC-Current and High-current Applications

HTS Tapes for AC-applications - Twisted Tapes

Magnetisation Loss : $P_{mag}/I_c = p_{co} B^3 / (B_{co}^3 + B_{co} B^2) f / 50Hz + q_{co} (B / B_{co})^2 (f / 50Hz)^2$

- parallel field loss can be decreased by increasing w/l_p
- perpendicular field loss is independent of w/l_p – tape width determines AC-loss
- minimum parallel field loss (0.3 mW/Am) = hysteresis loss of filaments
- width / Twist- ratio > 0.3 causes degradation
- twist length typical : 8…14 mm
- engineering critical current density j_e = 50-65 A/mm^2
- Resistive matrix Ag-Pd possible – Barrier concept technical not mature

High-current conductors - Roebel bar conductor

- Critical current assembled conductors : $I_{c,design} = \Sigma I_{c,tape}$ = 673 A, $I_{c,cable}$ = 400 A (77K)
- Self-field induced I_c reduction to 60…70% of nominal $I_{c,design}$
- Self-field model for I_c reduction : increasing # of tapes and increasing critical current $I_{c,tape}$
- BUT : cabled conductors are designed for high field windings – self field is uncritical
- NO affection of tape properties (n-value, I_c) by cabling process
- AC-loss behaves as for a monoblock
- scaling of transport AC-losses for different conductors with Norris Ellipse model

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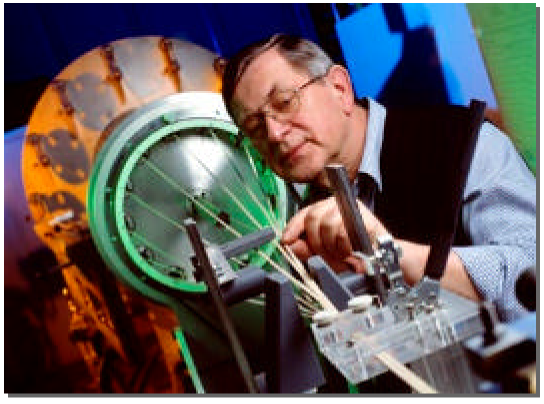
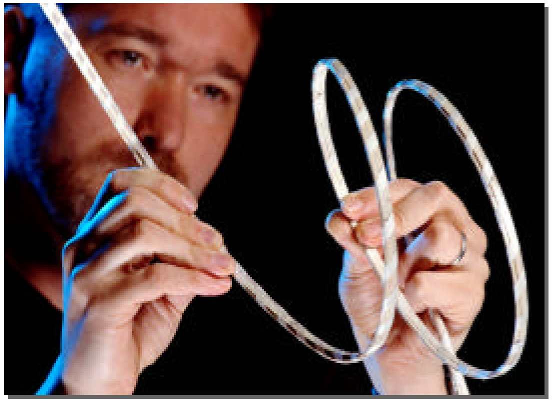
Technical HTS-Conductors & HTS-Windings
High Current Assemble

Roebel bar conductor

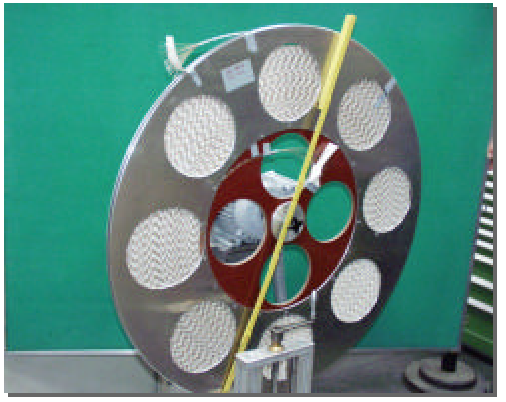
- modular concept for high-current conductors
- transposed strands for low ac-loss
- insulated strands - thin coated plastics
- flexibility for coil winding
- long-lengths production - semiautomatic
- developed for HTS transformers
- presently not applicable for YBCO



Laboratory Cabling Facility LARA



Flexible conductor



13-strand conductor, length=160m

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Technical HTS-Conductors & HTS-Windings
Solenoid Layer Windings – Traction transformer

Primary windings

- High voltage solenoid windings
- Bi2223/Ag-conductor, high-strength sheath
- thermoplastic coated insulation
- 9 Discs of solenoid layer windings with inter-coil connection
- 19 layer per disc, 2016 turns in total
- I_N = 40 A
- AC-operation, T_{op} = 67 K

Secondary windings

- Low voltage windings with high amperage
- 13-strand Bi2223/Ag-Roebel conductor
- thermoplastic coated insulation
- Internal or external (!) FRP-mandrel
- 1 layer with 56 turns
- I_N = 360 A
- AC-operation, T_{op} = 67 K

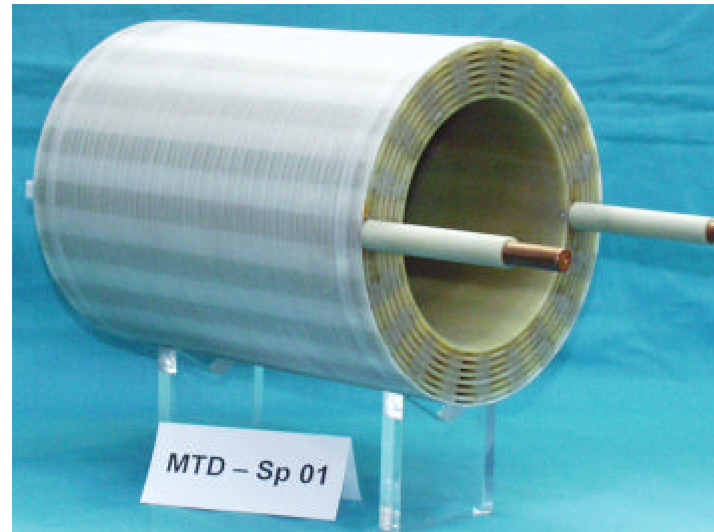
Technical HTS-Conductors & HTS-Windings
Roebel windings – HTS-Choke coil

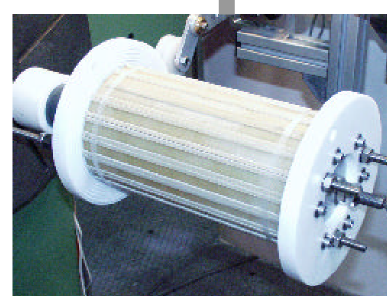
High amperage windings

for power engineering equipment with current 100...1000 A require assembled conductors

HTS-Choke coil

- Cable 13-strand fully-transposed, 105 m length, 13 x 0.9mm²
- $I_{c,sf,T_{op}=66K)}$ = 443 A, $I_{c,sf,77K}$ = 247A
- Elementary conductor 1362 m high-strength Bi-2223 tape
- winding with 6 layers and 192 turns
- Internal cooling channels for LN_2 bath cooling
- Dry winding and vacuum resin impregnation
- P = 208 kW (reactive) L = 5.5 mH, f = 50 Hz,
- Axial Field at $I_c(T_{op})$/50Hz = 585mT

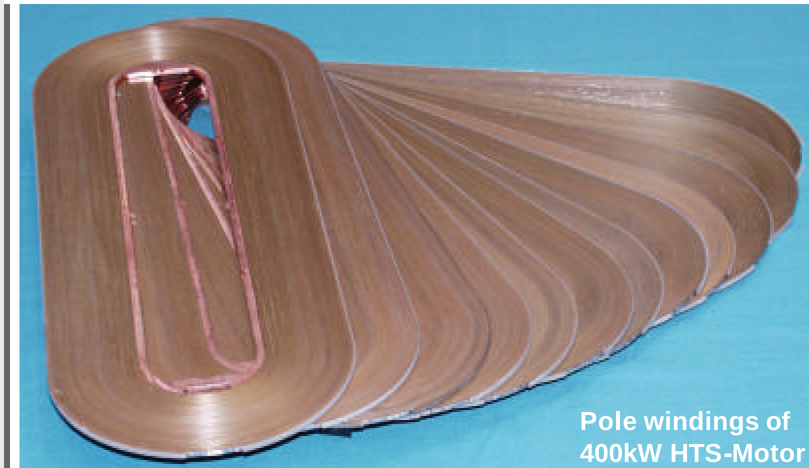




Technical HTS-Conductors & HTS-Windings
Racetrack Windings – Motor, Generator

HTS-Racetrack winding

- Bi2223/Ag-conductor, single-strand,
- thermoplastic coated insulation, Cu-mandrel
- Wet-winding with expoxy resin
- ≈ 100 windings
- conduction cooling, T_{op} = 20...30K
- DC-current operation with I = 40 A

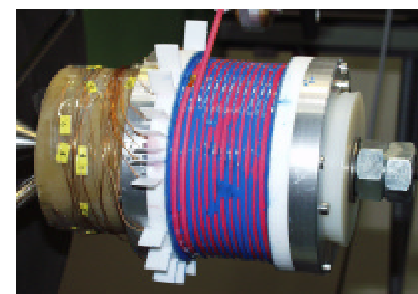


Pole windings of 400kW HTS-Motor

HTS-Experimental windings

- commercial winding machine adjusted for winding of HTS tapes
- measurement and control of winding tension
- flexible adjustment for any kind of coil
- HTS tape handling, guidance, co-winding
- dry-winding, wet winding and vacuum impregnation

1st pancake winding from 10m YBCO CC



Multi-layer solenoid from Bi2223-tape

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Technical HTS-Conductors & HTS-Windings Present Status

From the viewpoint of a magnet or power equipment manufacturer

HTS-Winding Technology (for Bi-tapes) is developed and proofed :

- applications in 4 K, 20...30 K, 60...80K temperature ranges
- winding adapted to flat tapes : 3...5 mm x 0.1...0.3 mm and assembled conductors (2n+1)-strand with typ. 7...10 mm x 1...4 mm
- wet winding or dry winding with vacuum resin impregnation (all React & Wind)
- low post-processing temperatures (insulation & tape)
- splicing and joining technology for elementary tapes (Bi - not CC)
- bath cooling or conduction cooling via eg. Mandrel
- intrinsic stabilization in Bi/Ag-tapes or co-winding with metal-tape

Further developments should preferrably allow a FORM-Fit replacement of the conductor by YBCO CC with a high engineering current density j_e

Whishes for the future :

no anisotropy, round wires, long batches, low C/P, tiny filaments, ...

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Is HTS Technology mature for Large Scale High Field (LSHF) Magnets ? - Design-Process

Replacement Approach

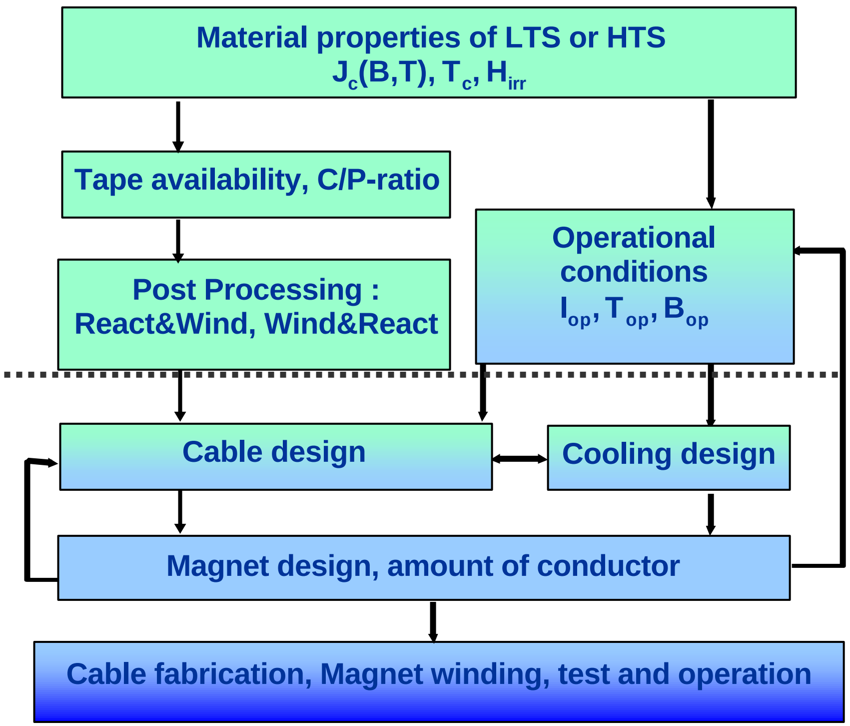
Substitute 1:1 LTS-Technology

- LTS : CICC, Compaction of jacket onto cable, W&R, LHe-coolant, $T_{op} = 4.2K$, $B_{op} \geq 13T$
- Performance as good as LTS
- Competitive C/P ratio drives replacement
- Improve performance and reduce process cost of HTS
- new mechanical concepts

Enabling Approach

Exploit advantages of HTS-conductor by Re-Design of Magnets

- performance under high fields B>20T
- enhanced T_{op} = 20...30 K enables cryo-free cooling and lowers cost of operation
- higher temperature margin ΔT - enhanced stability
- new mechanical concepts



Power & Sensor Systems
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Is HTS Technology mature for Large Scale High Field (LSHF) Magnets ?

Parameter	LTS Magnet	HTS Magnet
Conductor	Nb3Sn CCIC	Assembled Conductors of Bi/Ag-Tapes or YBCO CC
Current density j_e	Reference	Multiple - no strain dependence below e_c
C/P ratio	Reference	Lower (YBCO-CSD)
Insulation	External wound prepregs	Bi : available YBCO-CC : tbd
Magnet construction	Self-supporting	Supporting plate/mandrel
Magnet fabrication	Wind & React (high risk)	React & Wind (minized risk)
Stability	Low Stability Internal Cu and Cryogenic stabilization	Intrinsic (Ag), Impregnation (Pb) or Add-on conductor (Cu) Bi : high stability YBCO : low stability
Stability margin DT	mK Range	10 K Range = reduced quench risk
Cooling	Direct internal He-Cooling	Indirect via separate (He-)channel, conduction cooling
Operation	Pulsed mode possible	Small field change rates dB/dt
Magnetic field B	Limited B	Very small dj_c/dB for B>>13T
Investment	High	Medium (2nd Gen CC)
Cost of operation	High (4K)	Medium (20K)
R&D needs	Small	Concept for 20K Magnets, C/P-improvement, low cost process (CSD)
Status	Close to Saturation	Development with potential

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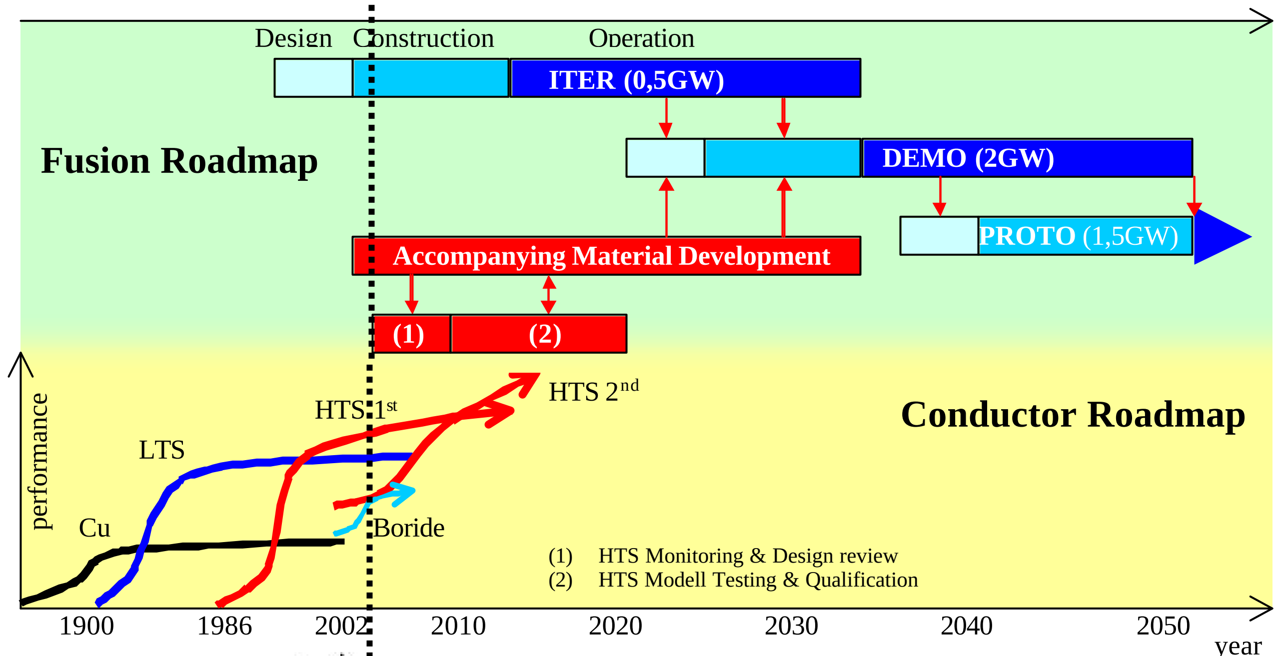
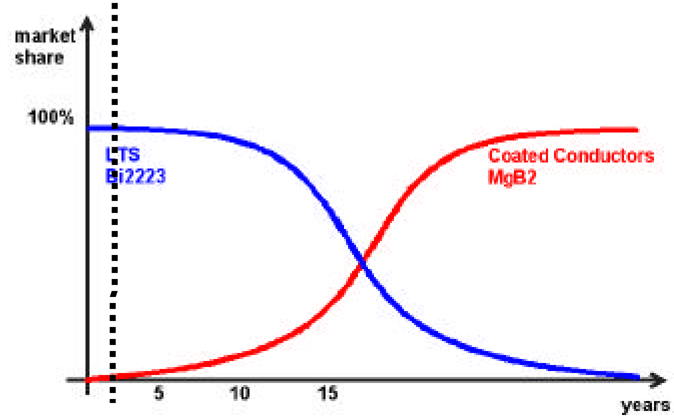
Is HTS Technology mature for Large Scale High Field (LSHF) Magnets ? - Roadmap Matching ?





Status : 5/2002

Accelerator Magnets should accelerate the Development speed for HTS-Conductors !

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Summary

Status

- HTS is economically not competitive at the moment to substitute (1:1) Nb_3Sn in LSHF-magnets
- HTS wire meet most j_e and mechanical requirements, AC-loss dependent on field ramp rate requirements
- **A Redesign of the magnets (T»20..30K, high B-field) will fully exploit the advantages of HTS**
- Winding technology for Bi/Ag-Tapes is well developed and 1st transfers for form-fit YBCO CC are successful
- Modelling tools for the design of HTS-windings regard the specific field and temperature j_c(B,T), n(B,T) etc.

Outlook

- **Develop new Magnet concepts for the use of HTS in LSHF applications**
  including concepts for mechanical forces, cooling, thermal and electrical stabilization.

- Monitor and drive further progress in the **development of secondary key components**
  (Cryocoolers, Cryostats, sealings, bearings etc.)

- **Monitor and drive the HTS-material development constantly**

Bi2212	low cost production process, fine filamentary high current wires
Bi2223	lower process cost by production ramp up, performance increase j_e, low AC-loss
YBCO	long length production with low cost process, stabilization, joining, insulation
MgB_2	(4.2K application ?) current density, preparation progress, multifilamentary wires

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