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Experience, status and prospects of HTS rotating machines with 1G and 2G HTS at Siemens

Tabea Arndt,


M.Frank, J.Grundmann, P.van Hasselt,
H.-P.Krämer, P.Kummeth, W.Nick, M.Oomen

Siemens AG, CT RTC ENC SUC-DE
and colleagues by CT & I DT LD & E F PR GN

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**Energy conversion
nature**

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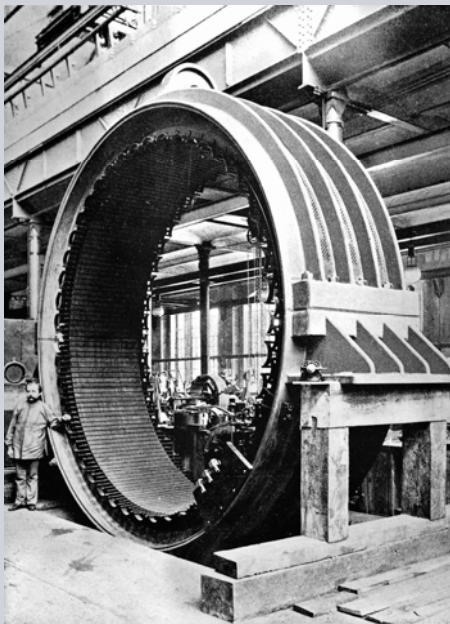
nature
widely distributed
 $\eta = 0.2...5\%$

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Energy conversion in nature is widely distributed („decentralized“), e.g. photosynthesis, but the efficiency is quite low.

Energy conversion technology

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technology

strongly localized

$\eta > 80\%$

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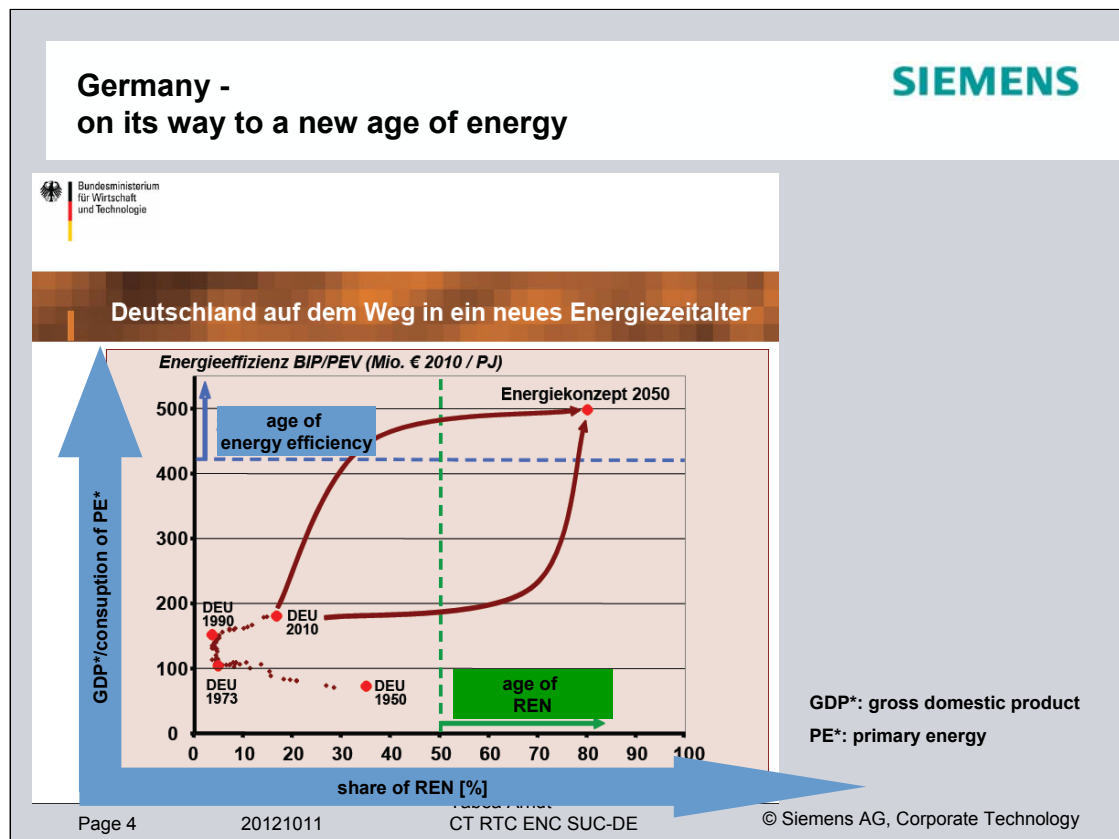
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Engineers usually have a different approach than nature:

highly efficient machines (e.g. energy conversion by rotating machines, in this case generators) at selected sites.

So if you are allowed to convert energy only at certain locations, it is mandatory to do this in the highest achievable degree of efficiency.



In Germany, the government realized that we have to follow two trends in energy technology:

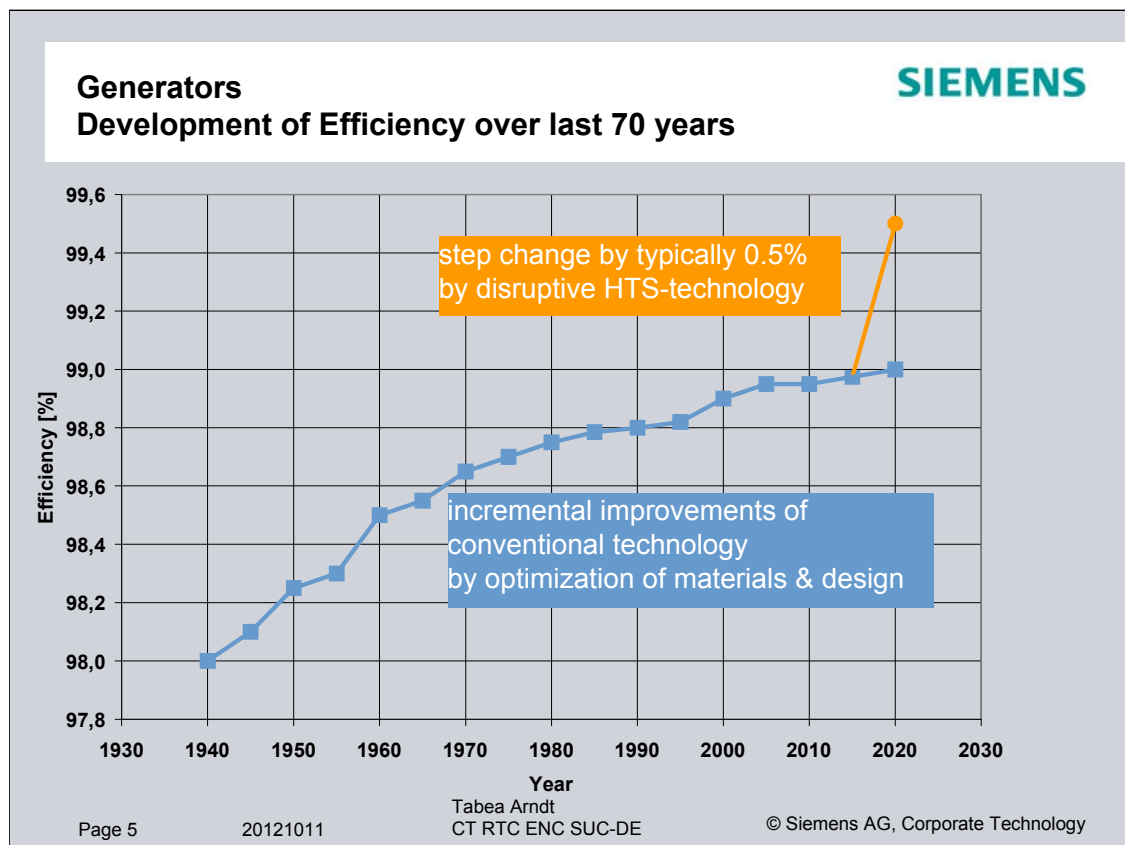
increasing the contribution of renewable energy (REN) to the total energy generation and

increasing the efficiency of energy use measured by the ratio of GDP to PE (Gross Domestic Product and Primary Energy).

This led to the sketch of a „energy 2050 concept“.

In the past Germany's path in the diagram of GDP/PE vs. share of REN has been quite „curvy“ due to the not aligned growth of industry and support of renewable energy technology.

HTS technology might support our reaching out for a high GDP/PE ratio as shown in the following.

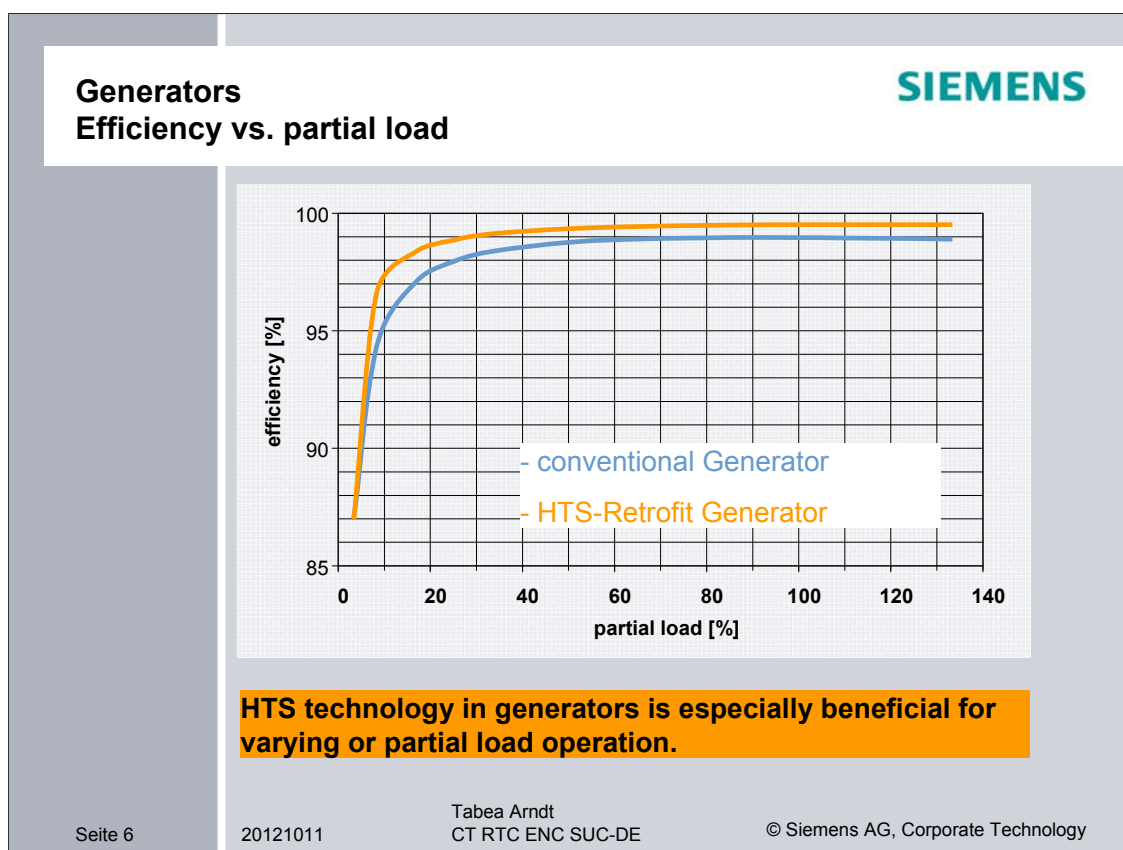


In the past 70 years, there have been considerable efforts and success to improve the efficiency of conventional generator.

This increase is mainly due to better use of sophisticated materials and optimized designs of the conventional generators and represents an evolutionary development.

HTS-technology –e.g. when using rotors of generators based on HTS technology for a retrofit approach- might yield a disruptive step change in efficiency. The magnitude of this step is nearly as high as the steady improvement due to 50 years of continued engineering on conventional designs.

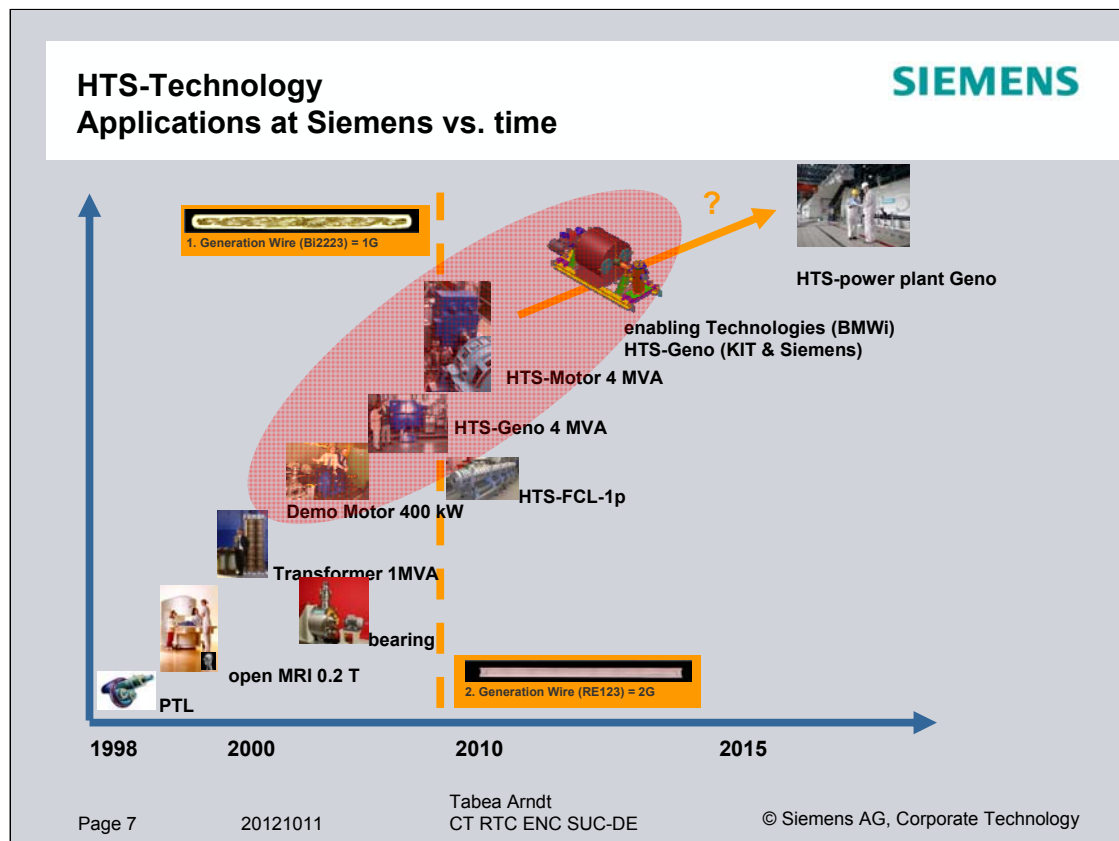
The HTS rotor retrofit approach means that the conventional rotor of a existing generator is pulled out and replace by a compatible HTS rotor. In this case one will not benefit of all special advantages of HTS technology, but the resulting performance of the machine (power rating, power uprate, dynamic behaviour, efficiency) will be improved clearly.



Even more important:

The preceding slide showed the efficiency at nominal load.

When regarding the increase in efficiency by using HTS technology, this is generally even more pronounced when using a HTS machine in part load operation. This results from the fact that conventional generators have some steady loss contributions which are obsolete or at least drastically reduced for HTS generators. An example for that is windage loss (which is needed for conventional rotors for cooling reasons) at fixed frequency independent of excitation.




Siemens has built up quite an experience in different HTS applications.

Before 2G-HTS have become available in long length, the first demonstrators had to be built based 1G-HTS.

So, a series of three rotating machines has been realized using Bi-2223 HTS.


As 2G-HTS are now available in first promising lengths and performance, a funded project (partnering with KIT, partly funded by the german BMWi) has been started to analyze the potential of 2G-HTS and the corresponding enabling technologies for use in HTS generators for power plants.

The details of the HTS-I...-III machine are given in the next slide.



Experience at Siemens with HTS Synchronous Machines

1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 ...




HTS I

Model Machine

- 0.4 MW
- 1500 rpm
- 4-pole

Technology Demonstrator




HTS II

Generator

- 4 MVA
- 3600 rpm
- High Speed
- 2-pole

Application-oriented



HTS III

Motor

- 4 MW
- 120 rpm
- High Torque
- 8-pole

Application-oriented

HTS II longterm operation

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Summarizing the experience of Siemens in HTS synchronous machines, three 1G-HTS machines have been built; the characteristic data is given in the slide.

We started with a Model Machine with a moderate number of nominal rotations per minute demonstrating in a standard frame that the technology itself is working as expected (HTS-I).

Then we built a generator with high rotational speed facing the necessities of 50/60 Hz operation (HTS-II).

The HTS-III machine represents a ship propulsion motor following the rules of the Germanische Lloyd.

These three machines have been partly funded by the german BMBF/ BMWi.

But these machines have not only been built, the so-called HTS-II machine has entered a longterm operation after commissioning.

What is the general common design of these machines in MW-range? See next slide.

**Mechanical Concept (for industrial machines)
base for technology projects...**

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- Rotor = rotating cryostat
- Torque transmission (cold→warm) with minimum heat transfer
- Cooling through hollow shaft (requires rotating seal)
- Stator (without iron teeth), yoke and housing

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The superconducting wire is enclosed in a rotating cryostat and the superconducting coils are attached to the cold iron mass, enclosed within a rotating cryostat and cooled via the hollow shaft.


Therefore you will need some interfaces from cold to warm and this is done by a special device at the same time transferring the torque from the rotor body to the warm parts: the torque tube.

To benefit from the higher magnetic field produced by the HTS-coils in the rotor, one might omit the iron in the stator and fill the saved space with additional copper increasing the sheath current in the stator.

This arrangement will contribute to a large magnetic airgap of the machine delivering some of the special benefits of HTS-technology in rotating machines.

So, the target component for superconductivity is the rotor, being one of the parts determining the size and weight of the machine.

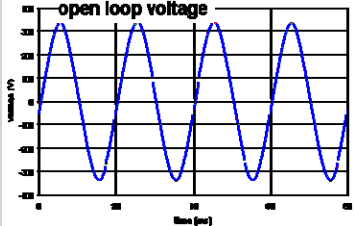
HTS1 – Model Machine (1999 – 2002)



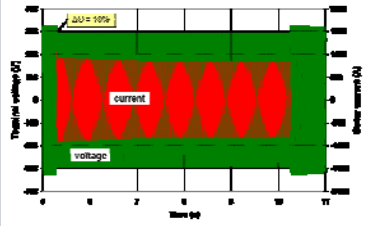
Targets: Development and verification of technological basis
Explore interactions: HTS rotor vs. air-gap stator winding

Results: Measured data exceeded specifications


- Consequences of small x_d
- open-loop voltage: low THD
- small load angle:
 - stability,
 - high overload capability
 - stiff reaction to load changes



open loop voltage



current
voltage



400 kW 1500 rpm,
2.5 kNm
motor / generator

Worked very well → continuation of long-term multi-phase project...

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The large magnetic airgap contributes to a small x_d and leads to a very stiff behaviour of the machine. This can be seen in the central diagram of the slide: switching the current on/of has little effect on the voltage stability. In addition, switching on/off has little effect on the voltage due to the small load angle of these machines. Furthermore this improves the capability to deal with overload.

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HTS2 – Experimental High Speed Geno (2002 – 2005)

Targets: Development of technologies for High Speed Machines
scale-up and verification of size, weight, efficiency

Results*):

size: 70%,
shaft height 500 vs. 800 mm

mass: 7 t vs. 11 t

efficiency: 98,7% vs. 97,0%

Loss Component	Conventional (%)	HTS (%)
Cryo	5	5
Rotor field ohmic	10	10
Stray load	10	0
Armature ohmic	25	15
Core	25	5
Friction & Windage	25	10
Total	100	50

2005: Nürnberg System Test Facility

4 MVA 3600 rpm, 10 kNm generator


→ ≈ 50% of the losses!

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When looking at the HTS-II machine, which is not just assembled in the next bigger housing of a standard machine, you see immediately the benefit of size & mass reduction compared to a conventional machine.

At the same time the efficiency is increased by 1.7%-pt. This is mainly due to absence of ohmic loss in the rotor, the reduction of friction and windage, of loss in the iron core, and this leads to (a rule of thumb for these types of HTS machines) only 50% of loss of a conventional machine. This increase of efficiency is stated when cryocooling is included.

HTS2 – Operational experience



Target:

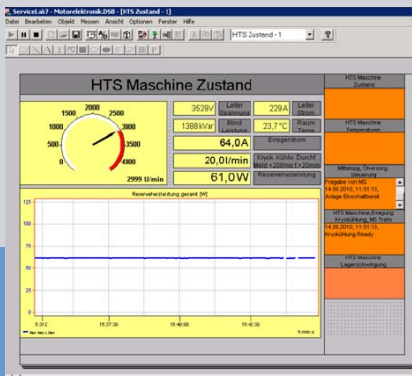
Longterm test connected to 20 kV grid in Motor factory Nürnberg:

- Embedded in common control system operated by central control
- providing reactive power

Result:

- ≈ 7500 operating hours on grid (beginning of 2012)
- several shut-downs internal/ external reasons, and
 - none caused by innovative components (HTS-winding, Cryocooling, ...)
 - all operating states and shut-downs tolerated by the system
- a lot of experience gained, starting point for further improvements (e.g. diagnostics, cooling system)

→Rotor inspection: What's the internal state/ shape of the machine after xxx operating hours?
Are there changes, aging, ...?



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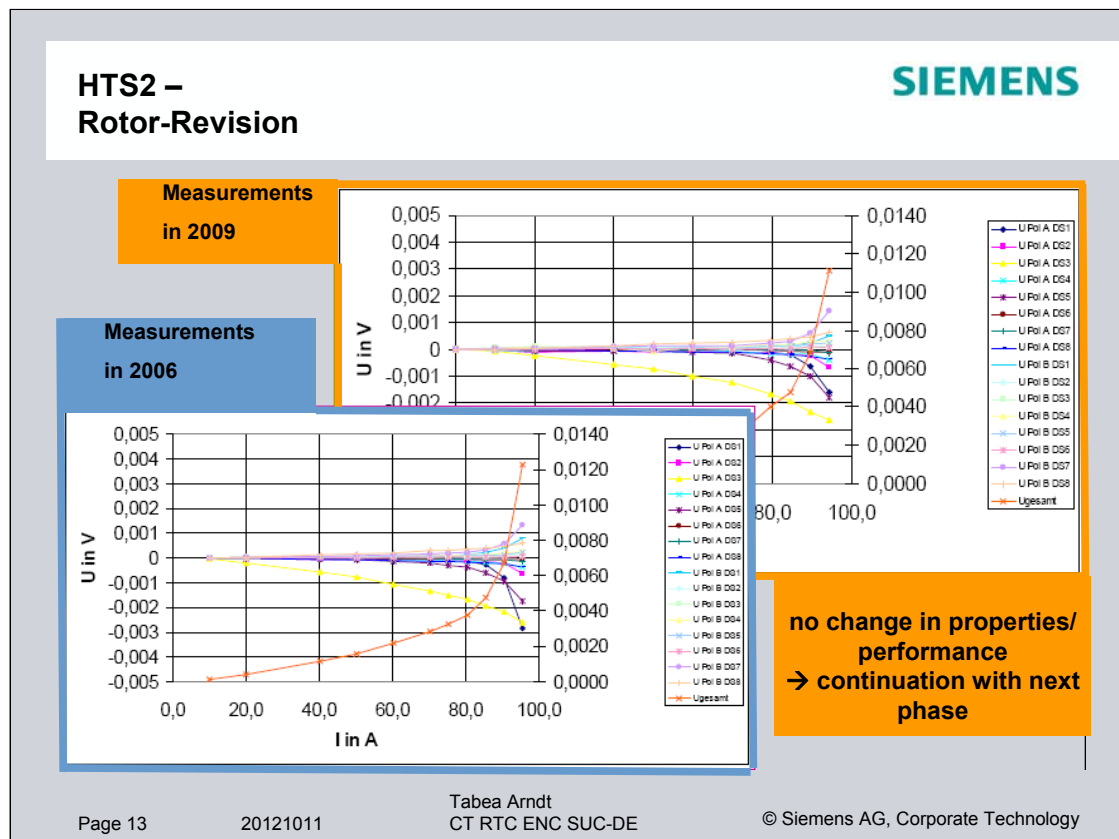
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After commissioning the HTS-II machine is operated longterm at a Siemens plant in Nürnberg.

It has been connected to the grid and is operated not by experts, but the common control system of the plant, and it is providing reactive power on demand.

This longterm operation resulted in considerable experience and confidence in HTS technology in rotating machines.

After some time of operation, a rotor inspection have been scheduled to check the performance and integrity of the new and innovative components.



For example, a voltage-current test of the coils of the rotor has been done in 2006 (before commissioning) and in 2009 at the time of the rotor inspection.

From the diagrams it is obvious that no change in properties could be observed. The HTS technology and the components are stable and not influenced by the operation, the design is robust and reliable.

HTS2- continued long term operation

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This slide shows the HTS-II machine located in a spare transformer box (other transformers are to the left and to the right of this photo) at the Nürnberg site providing reactive power on demand.

So it is not operated at a test site or in a lab, but in more or less rough industrial environment – and there is no reason to stop longterm operation.

HTS3 – Experimental High Torque Motor (2006 – 2010) e.g. for ship prop.



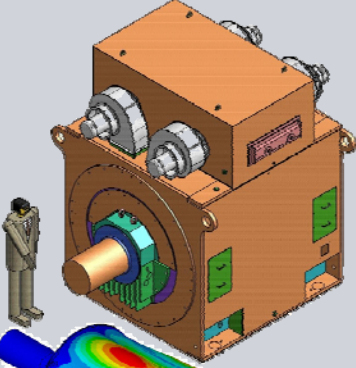
Targets: Development of technologies for High Torque Machines
scale-up, handling of large dimensions & converter operation

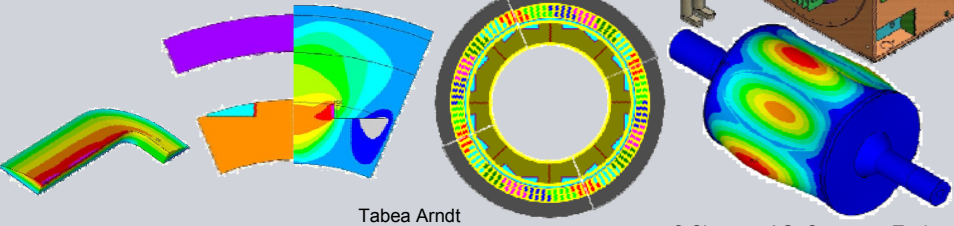
Proof points:

- robustness
- variable speed 30-190 rpm
- nom: 120 rpm, 4 MW
- > 120 rpm: field attenuation
- mass < 40 t
- efficiency 96%
- verify design procedures

Challenges:

- torque 320 kNm
- logistics
- size of components
- tools, ...
- ~50 km 1G-HTS
- converter harmonics







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After addressing the high rotational speed application, we developed and built a low rotational speed and high torque HTS motor suitable for ship propulsion. The slide gives the targets and challenges, e.g. operation together with a standard converter and coping with the harmonics.

HTS3 – manufacturing HTS → rotor winding → pole tests






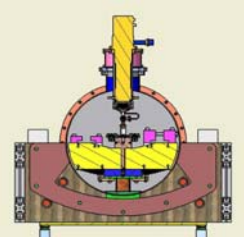
Quality check HTS conductor
Manuf.: Bruker HTS




Coil winding



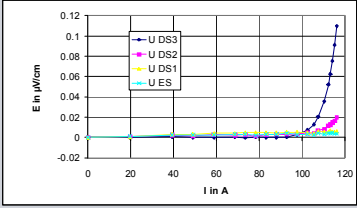
Stacking a pole





Pole cryo-test facility
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Electrical characteristic:



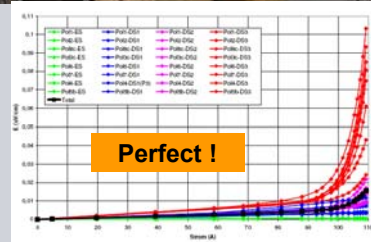
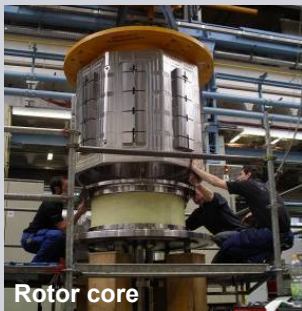
I in A	U DS3 (μV/cm)	U DS2 (μV/cm)	U DS1 (μV/cm)	U ES (μV/cm)
0	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
40	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00
80	0.00	0.00	0.00	0.00
100	0.00	0.00	0.00	0.00
110	0.00	0.00	0.00	0.00
120	0.10	0.02	0.01	0.00

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Before using the 50 km of Bi-HTS to built the coils, there was a quality check of the wire. The wire was then wound into coils, these coils are stacked to form poles. Each pole has been tested in a test rig to assure successful operation in the rotor.

HTS3 – Rotor manufacturing and testing

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Finally the parts has been assembled and the rotor has been tested as a whole by cooling down and checking the performace of all poles/ coils.

HTS3 – Stator and Final Machine Assembly


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The final assembly of HTS-rotor and stator has been done at the Dynamowerk Berlin and from the display of the crane you can easily see that we reached our goal of low weight.

HTS3 – Test Results

- mass target achieved: 36 t < 40 t
- open-loop / short-circuit characteristic:
machine parameters as expected, $x_d \approx 0.3$
- load tests:
120 rpm: upto 2750 kW (220 kNm)
190 rpm: upto 4000 kW (200 kNm)
- efficiency:
 $\approx 1.2\%$ better than conventional
(loss in too skinny stator iron)
2.5% exp. with adopted stator
- cryotechnology:
rotor loss ≤ 120 W
(1 compressor@10 kW sufficient,
 $\rightarrow 0.25\%$ of 4 MW)
- short circuit tests upto 30% I_r
 \rightarrow robust
- operated with Siemens standard converter SM-150



• mass target achieved: 36 t < 40 t

• open-loop / short-circuit characteristic:
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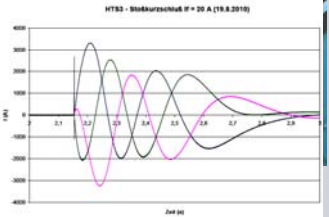
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This slide summarizes the test results and shows the HTS-machine placed in the test field in operation with conventional machines (light blue). The diagram shows a consequence of the unique stiffness and load angle of this machine together with a robust design of components which allows to stop the rotor out of nominal rotational speed to zero within less than half a rotation!

Conclusions and outlook on multiphase program on HTS rotating machines for I

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Model,
shown at Hannover Messe 2009



We have successfully

- based on a **multiphase program** on HTS rotating machines in Industry
- designed, manufactured, tested and longterm operated
- **three very different machines**
- by using **innovative approaches** in materials and designs and based on sophisticated and robust cryotechnology

These results provide a sound technological base for further application, e.g. high power utility generators.

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To sum up the activities on 1G-HTS rotating machines, we have successfully executed a multiphase program building three different machines with innovative approaches and components.

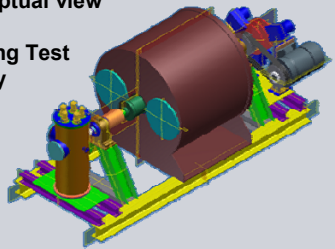
The achievements built a sound technological base to proceed to even larger machines.

But today, it has to be checked that similar success and even more benefits can be achieved with 2G-HTS, too.

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Enabling Technologies for HTS Generators

Conceptual view of Rotating Test Facility



Description:

- quite a number of measuring devices, concepts & components
- loads comparable to a future power generator (rot. speed & radius → centrifugal acceleration)
- 2G-HTS winding configurations
- Cooling loops etc.
- Thermal / electrical insulation systems
- long term studies

Funded by German BMWi
FKZ 03ET1008B

Key data / requirements:

- Partner: Karlsruhe Institute of Technology (KIT)
- >3 years project, start: Feb.2011
- Rotating test-rig “experiments near application”
- Extensive testing capability for optimization of HTS, cooling, insulation, etc.

Benefits:

- Testing & optimization before producing
- Creating, checking and reviewing of concepts
- Identifying critical issues in advance
- Reduces probing efforts on prototypes later on

Goals / Deliverables:

- Develop concepts for critical components
- Setup rotating multi-purpose test-rig for near-application operational conditions
- Test period with optimization
- Final report with “how-to’s”

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For this purpose, a BMWi-funded project addressing enabling technologies for HTS generators built with 2G-HTS has been started together with KIT.

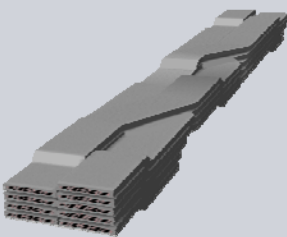
Within this project a test-rig for HTS, parts and components as well as for technologies will be installed at KIT.

The purpose of this test-rig is to proof and to improve designs and technologies and to evaluate these for possible future use in power plant generators.

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Bi-HTS components for rotating machines

Bi-HTS-elementary tape	 <p>Bi-HTS elementary tape (abt. 1000 m)</p>	 <p>Bi-HTS coils</p>	 <p>Bi-HTS pole</p>
Bi-HTS-Roebel-conductor	 <p>Bi-HTS Roebel-conductor Storage spool (160 m)</p>	 <p>Demo Bi-HTS-Roebel-coil</p>	no pole made up to now, switching to Y-HTS







 Shape of strands produced by bending of the tapes (plastic deformation)

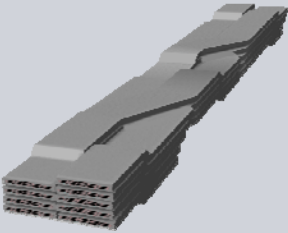
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This study on 2G-HTS is really necessary. With 1G-HTS there is considerable experience with wire and components and even compound conductors like Roebel cables. The latter ones are built by plastically deforming (bending) the 1G-tapes into the desired shape to produce S-zones and assembling them into the Roebel arrangement.



Y-HTS components for rotating machines

Y-HTS-elementary tape	 Y-HTS coil	poles to be built
Y-HTS-Roebel-conductor		cooperation with GCS & IRL (IP licensed to)
		 



Shape of strands produced by punching

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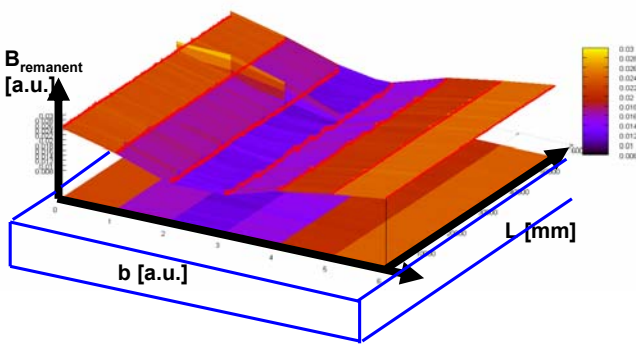

For 2G-HTS we still lack some experience in that. Furthermore, considering high-amperage Roebel-cables made out of 2G-HTS, the procedure is quite different: 2G-HTS can not be bend plastically, but have to be punched in the desired shape. So at least at this procedure, the new approach has to be confirmed.

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Quality Control & Assurance for Roebel-conductors

Roebel wires should

- withstand the punching process (no delamination, no degradation)
- withstand the centrifugal forces
- show sufficient 2D-homogeneity in I_c
 - show good longitudinal homogeneity in I_c
 - show good transverse homogeneity in I_c


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To produce high-amperage Roebel-conductors it is necessary that the wire used for that has not only a high homogeneity of critical current along the length, but along the width, too.

Otherwise you might punch away an essential (current-carrying) part of the tape and loose performance considerably.

The diagram shows the remanent magnetization of a tape very similar to a classical bean profile along the wire length L . But at one position, you can see that a half of the wire width is deviating considerably. This is a defect in the tape which can not be tolerated for Roebel-cable manufacturing.

Nevertheless, these difficulties can be overcome. The picture shows a long length of Roebel-conductor prepared for measurements on a drum.

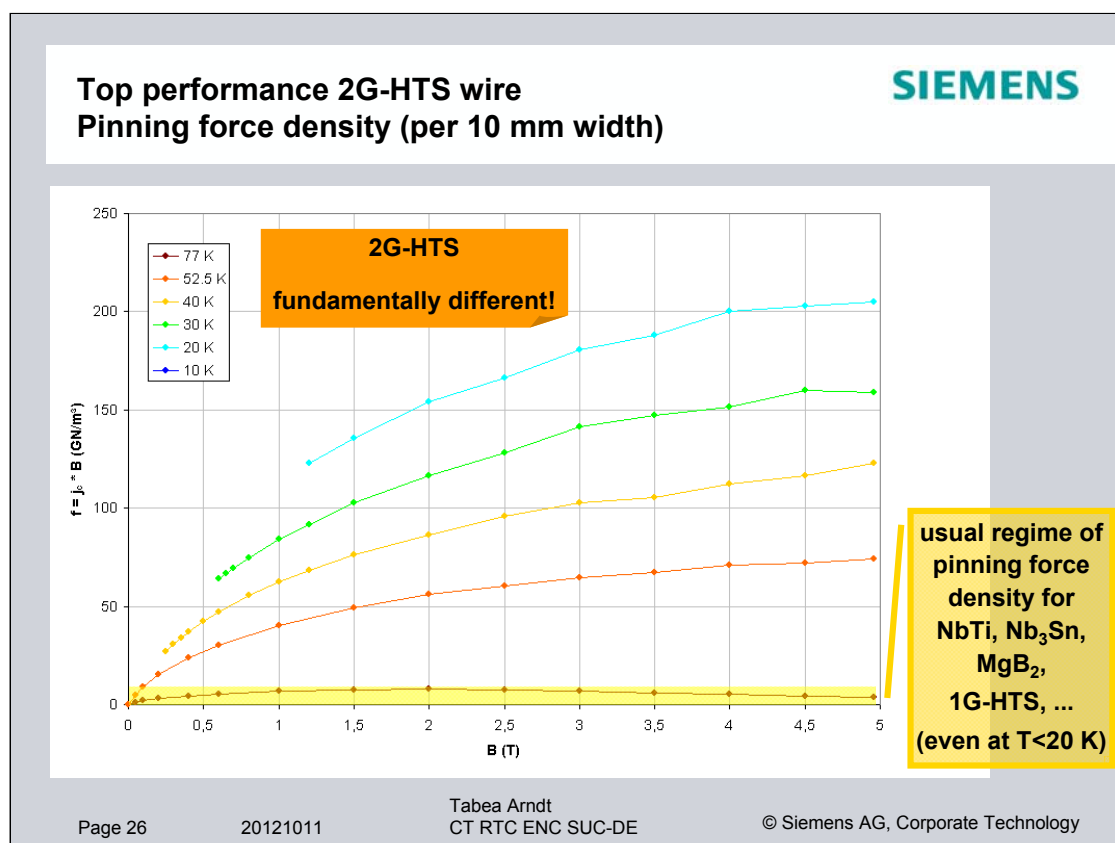


HTS wires for large rotating machines

- **HTS wire has to fulfill electrical & mechanical properties on long & homogeneous unit lengths**
- **In general, high currents, low ac-loss & high stress tolerance in longitudinal & transversal orientation is to strive for homogeneity.**
- **High tolerance to cycling/ fatigue.**
- **high amperage & low ac-loss may be achieved by Roebel-conductors out of suitable strands**
- **high stress tolerance may be achieved by laminations on to a suitable insert wire**
- **best overall performance results from sophisticated system & component design & preparation**

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This slide simply lists the key requirements on 2G-HTS wires for large rotating machines.



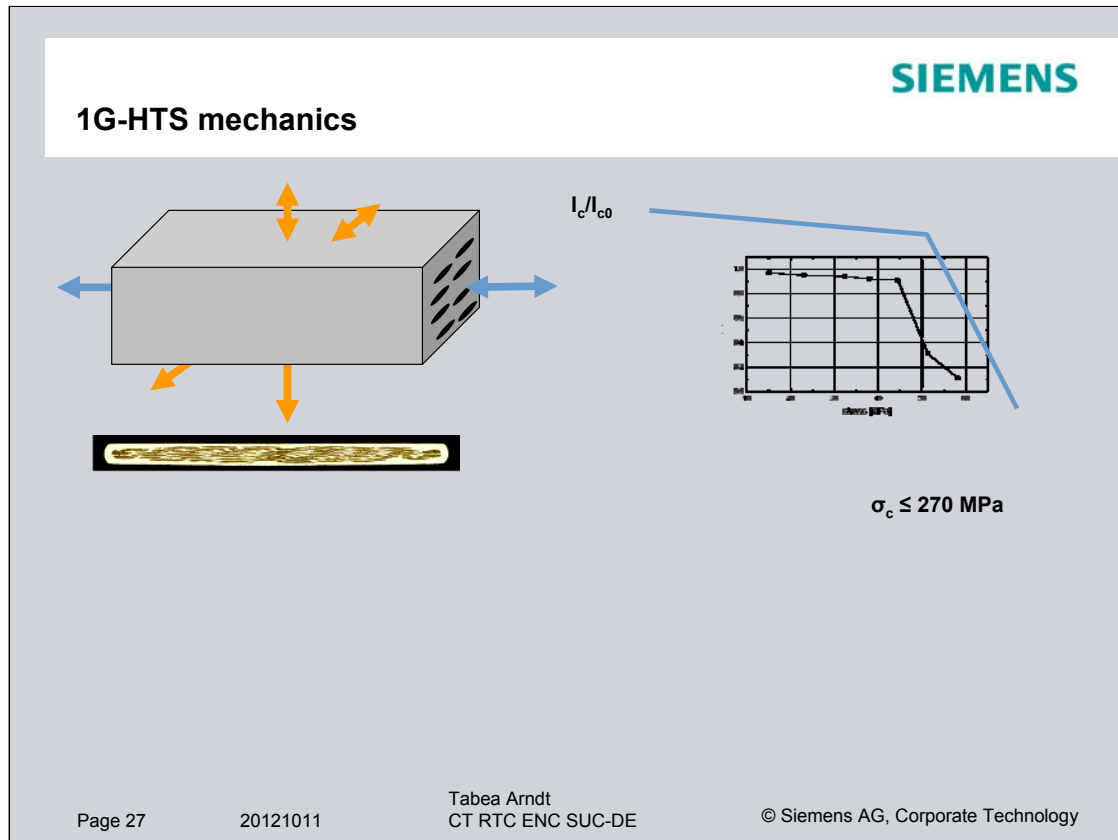
What's the reason for 2G-HTS being so attractive from a physicist's and an engineer's view?

With 2G-HTS one might overcome limitations of all other superconductors. This diagram shows the pinning force density of 2G-HTS at various temperatures.

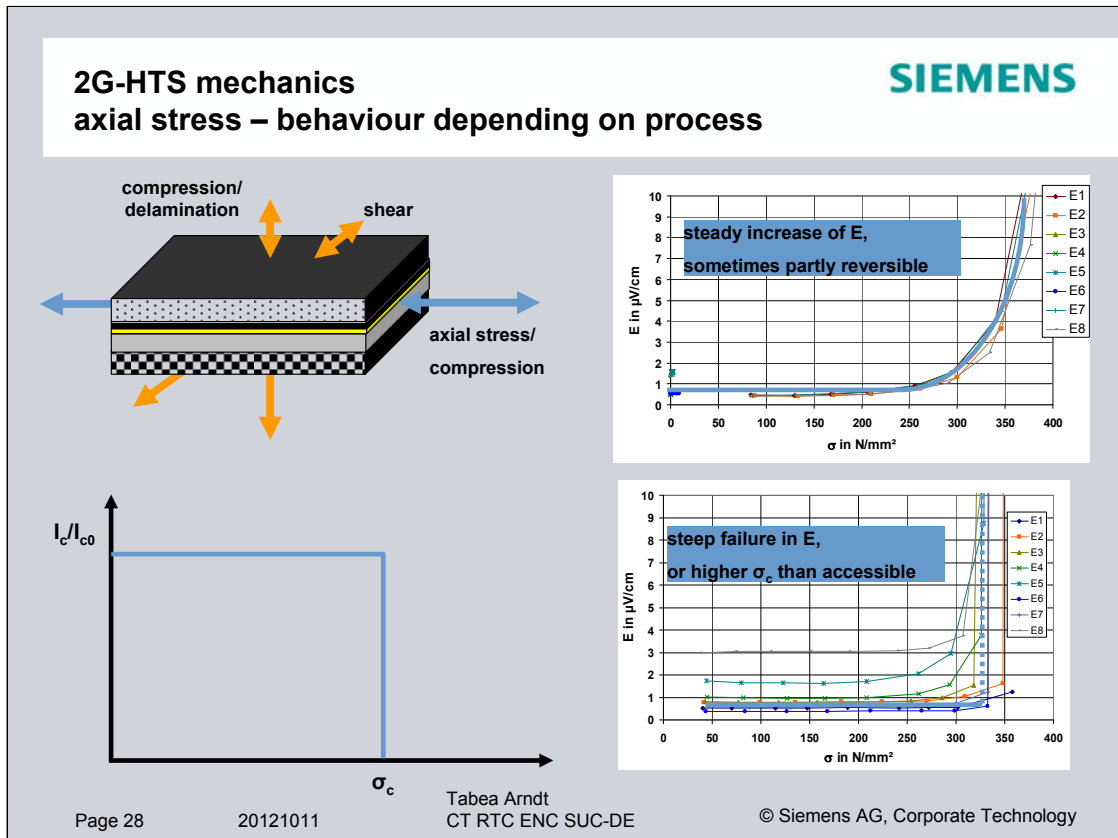
The regime of pinning force density for other superconductors is highlighted in yellow (even for low temperatures), too.

It's seen that when reducing the temperature below e.g. 52.5 K the 2G-HTS are superior to the other superconductors. This will mainly result out of the very thin layer thickness of the 2G-HTS, but in any case holds for long length 2G-HTS wires and makes it attractive for a lot of applications requiring some magnetic field.

If the cost and performance perspectives will follow the expectations of the suppliers, this might yield considerable design and cost advantages to possibly enable new applications.



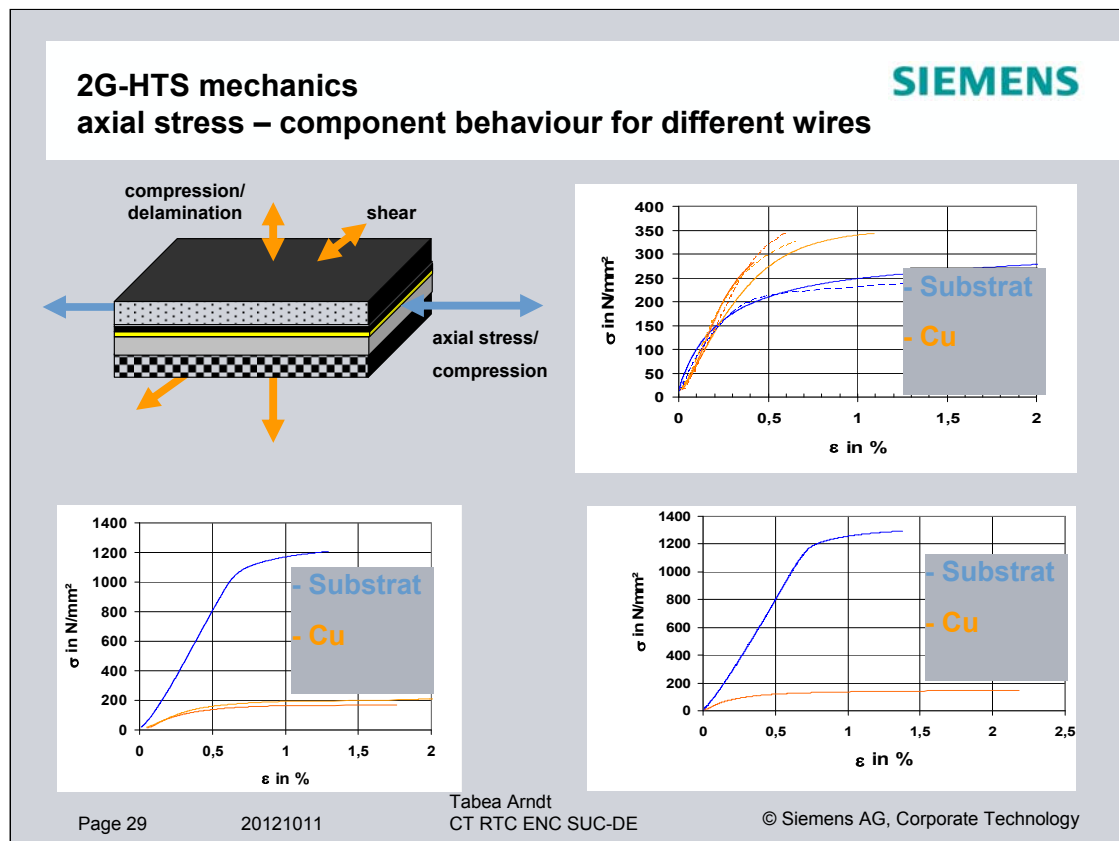
Considering the mechanical properties of HTS, and in this case 1G-HTS, the critical stress is quite limited and furthermore, a degradation/ reduction of properties starts at quite low values of axial stress.



When looking at 2G-HTS the behaviour is different.

The material of some suppliers shows a unchanged performance until a critical stress is reached, other's material shows an (sometimes reversible) increase of resistivity when going beyond a certain threshold, and again there is material having even higher critical stress values than can be accessed by usual equipment found in labs.

In any case, 2G-HTS offer much improved mechanical robustness in axial direction compared to 1G-HTS.



When looking at the wire components, the picture becomes even more detailed.

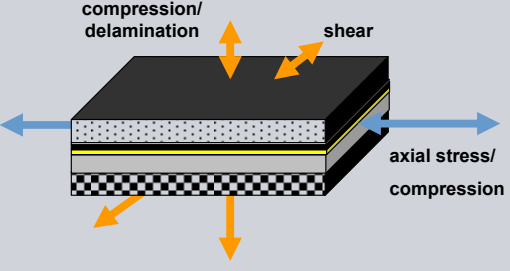
There are wire architectures available, where the substrate is stronger than the copper shunt and vice versa.

And Young's Modulus might be similar or different of substrate and shunt.

This and its effect in the specific application have to be considered for different wire architectures and suppliers as well as by the manufacturers of applications.

2G-HTS mechanics
axial stress – cycling properties

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compression/
delamination

shear

axial stress/
compression

Good news:
2G-HTS did not show any effect of cycling ($\leq 10000\#$)
given that $\sigma < \sigma_{c,ab}$ to some extent

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When looking at the mechanical performance of 2G-HTS under cycling, there is good news – look at the text box of the slide.

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2G-HTS mechanics transverse stress – ultimate value, cycling properties

compression/
delamination

shear

axial stress/
compression

F [N]

E [a.u.]

F in N, E in A

time

Bad news:
spread of small $\sigma_{c,c} = 15 \dots 90$ MPa

Good news:
no degradation after 10000 cycles with appropriate σ_c

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When looking at the mechanical performance of 2G-HTS in transverse direction, the situation becomes more difficult again. Due to the layered architecture of the tapes, the bonding of the layers becomes crucial.

Finally the critical stress in transverse direction becomes quite small, but when restricting the stresses below a certain threshold, there will be no degradation when cycling the tapes. But this strongly depends on manufacturing processes, wire architecture, and many other properties under control of the suppliers.

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2G-HTS „wanted poster“

Practical 2G-HTS wires for large rotating machines show...

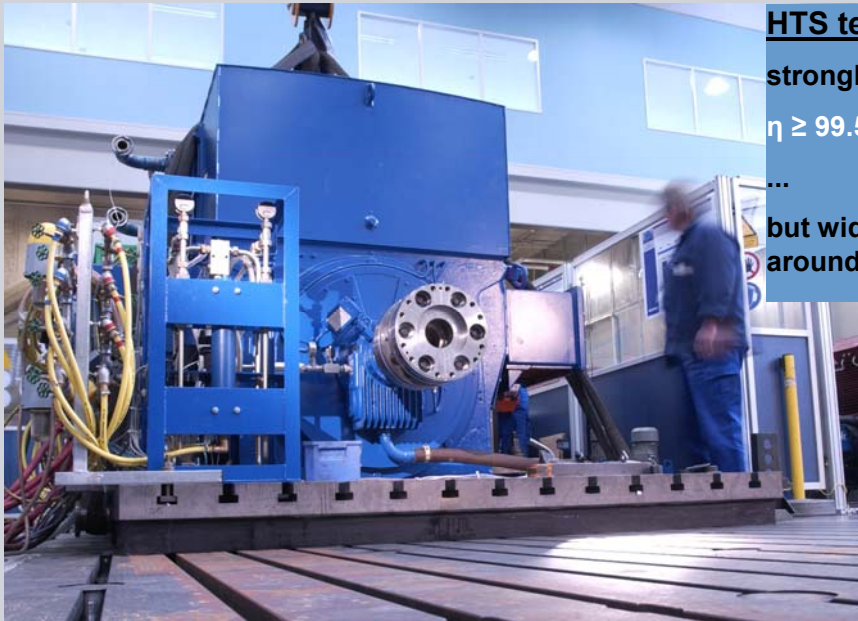
- **large piece length** **> ≈600 m**
- **high currents** **$I_c(30\text{ K}, 2\text{ T}_{\perp}) \geq 600\text{ A}$**
- **high current densities** **(to reduce mass of winding)**
- **electrical stabilization** **$\geq 100\ \mu\text{m Cu}$**
- **maybe some insulation**
- **mechanical properties**
 - tensile strength**
 - delamination strength**
 - tolerance to cycling**
 - low internal shear stress**
- **low prices & reliable delivery**

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This slide simply summarizes the requirements on 2G-HTS for use in large rotating machines.

Energy conversion technology

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HTS technology
strongly localized
 $\eta \geq 99.5\%$
...
but widely spread around the world

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When these requirements on 2G-HTS wire are fulfilled, then energy conversion with HTS technology and high efficiency might become strongly localized (with even reduced footprints of the machines) as well as widely used and spread around the world.

It's really worth to aim for that to save the worlds energy and CO₂ and to deliver the special operational benefits mentioned before to the end user.





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