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

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

Energy conversion nature

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nature

widely distributed

η = 0.2...5%

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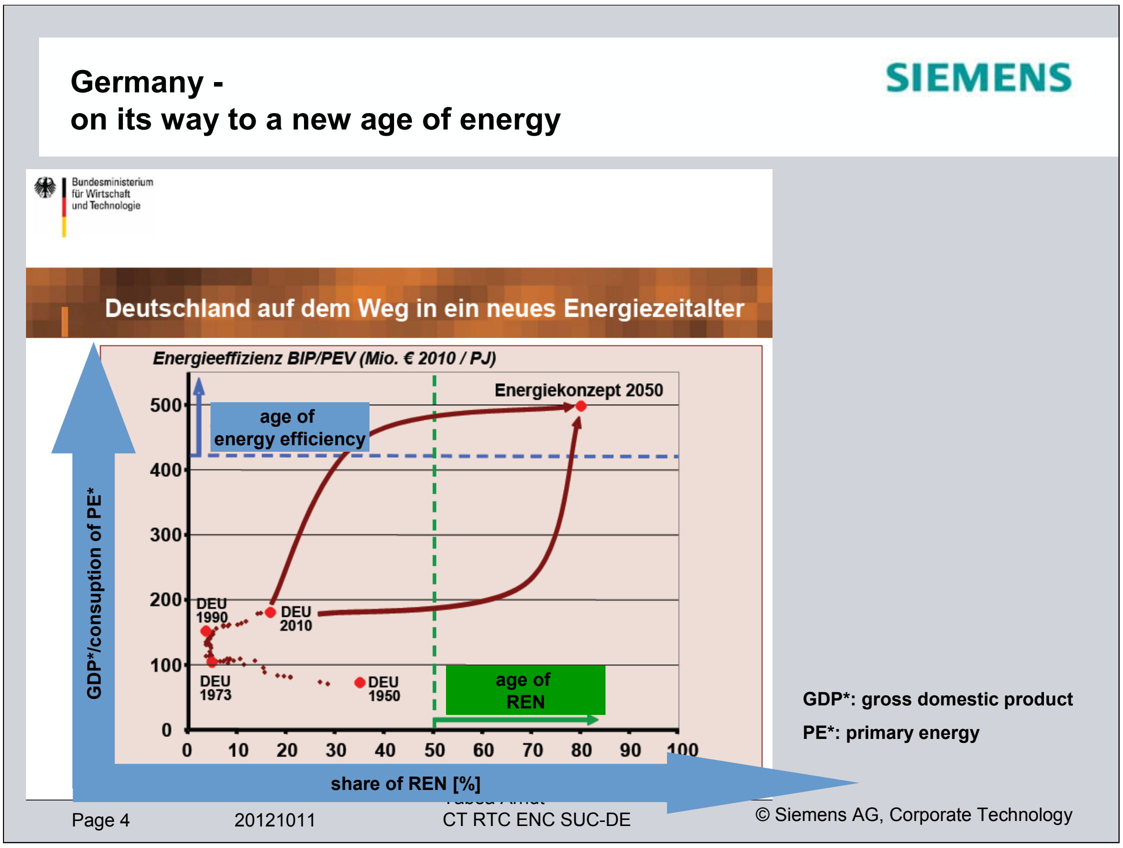
Energy conversion in nature is widely distributed („decentralized"), e.g. photosynthesis, but the efficiency is quite low.

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:

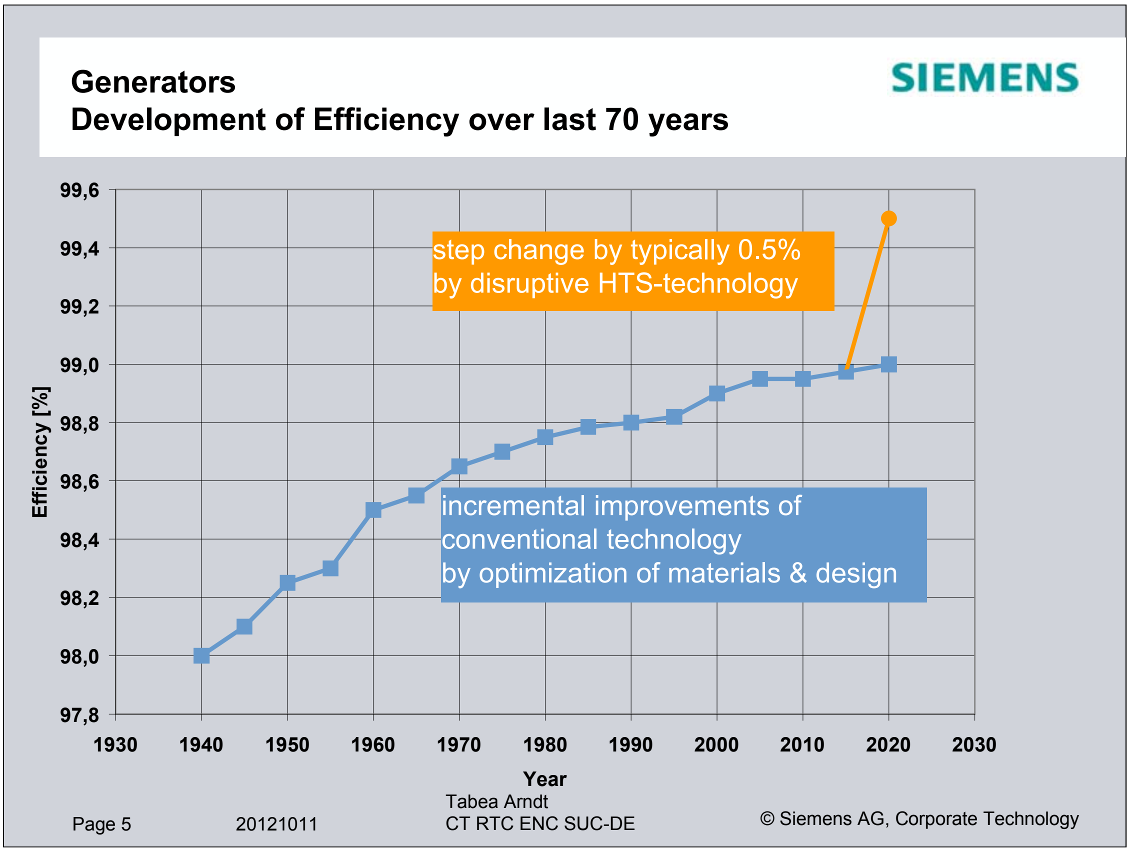
increasing the contribution of renewable energy (REN) to the total energy generation and

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

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

In the past Germany‘s path in the diagramm 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.

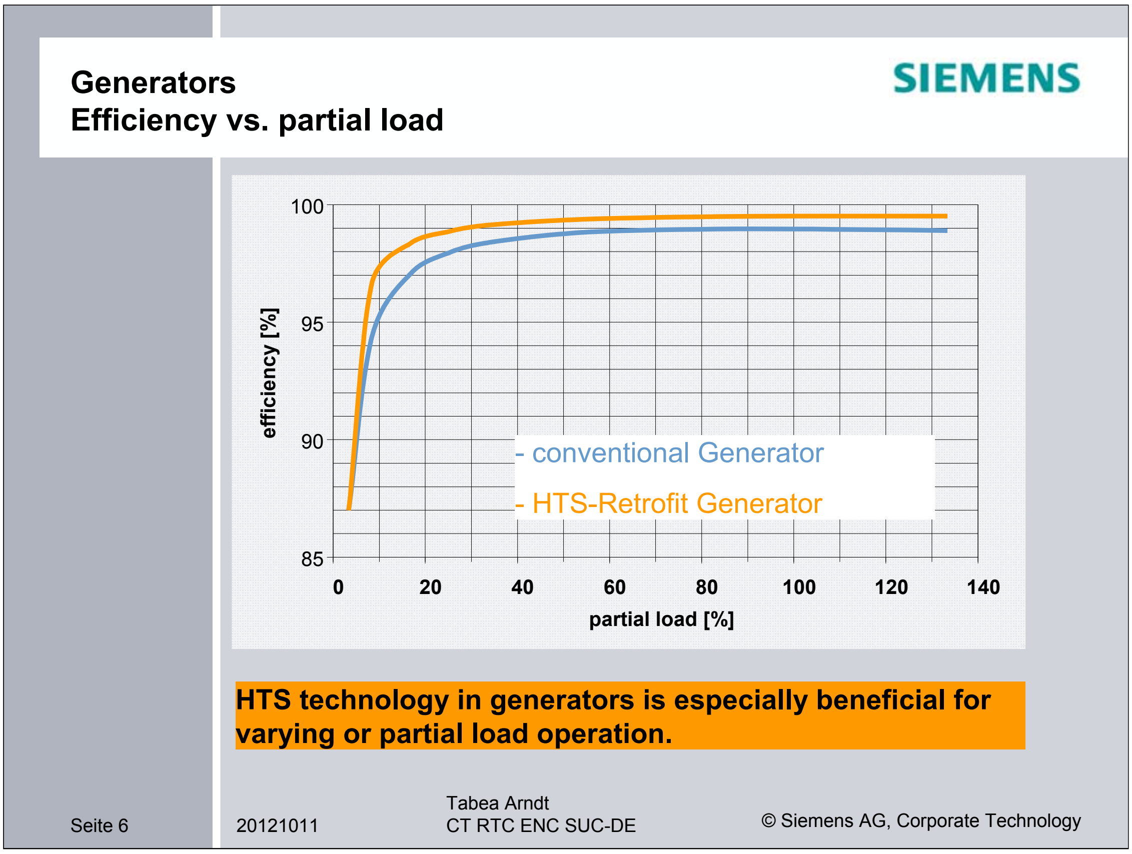


In the past 70 years, there have been considerable efforts and success to improve the efficiency of conventional generator.

This increase is mainly due to better use of sophisticated materials and optimized desigs 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.

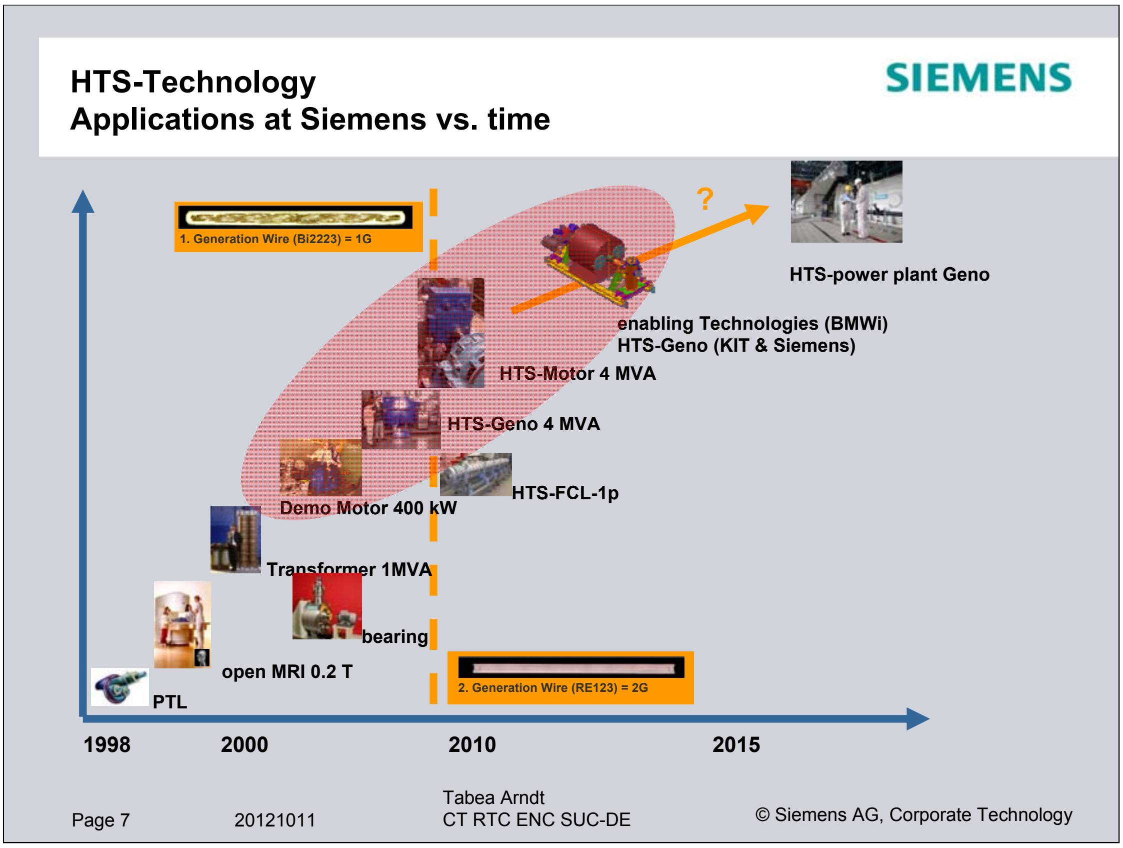
The HTS rotor retrofit apporach means that the conventional rotor of a existing generator is pulled out and replace by a compatible HTS rotor. In this case one will not benefit of all special advantages of HTS technology, but the resulting performance of the machine (power rating, power uprate, dynamic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



Even more important:

The preceeding 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.



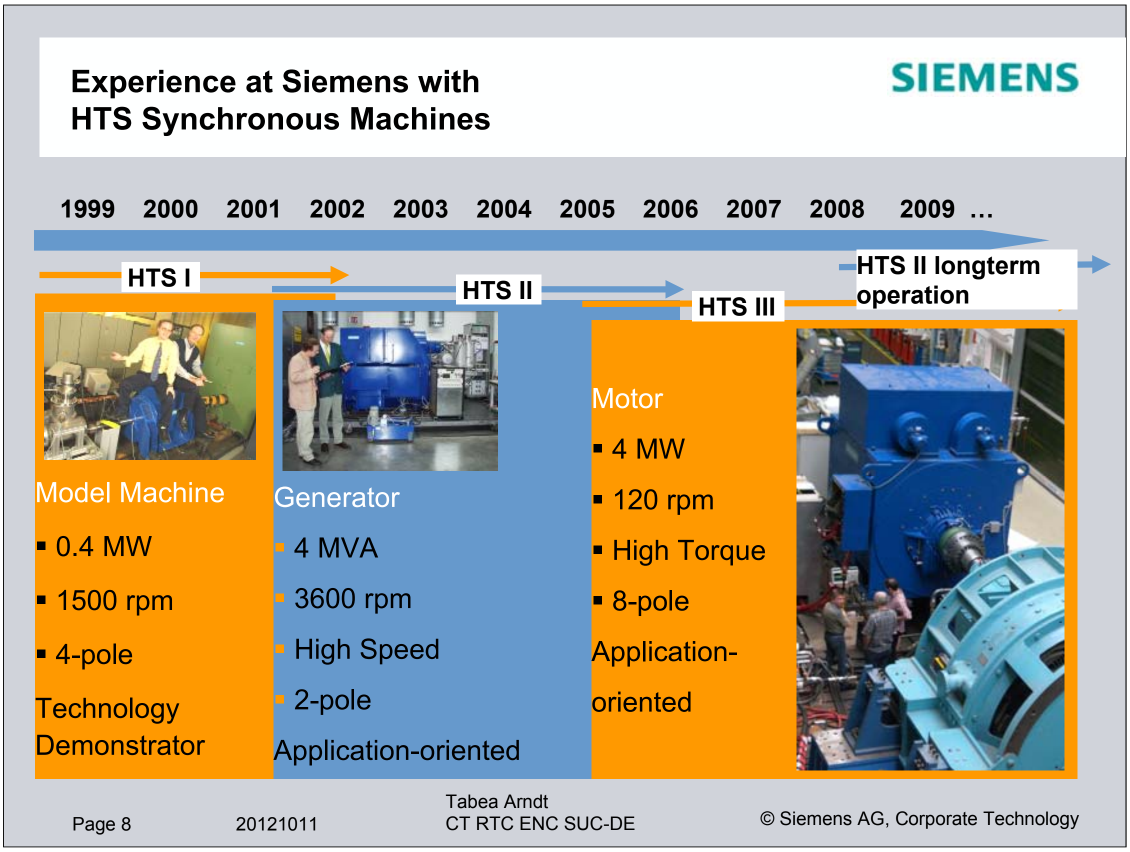
Siemens has built up quite an experience in different HTS applications.

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.



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).

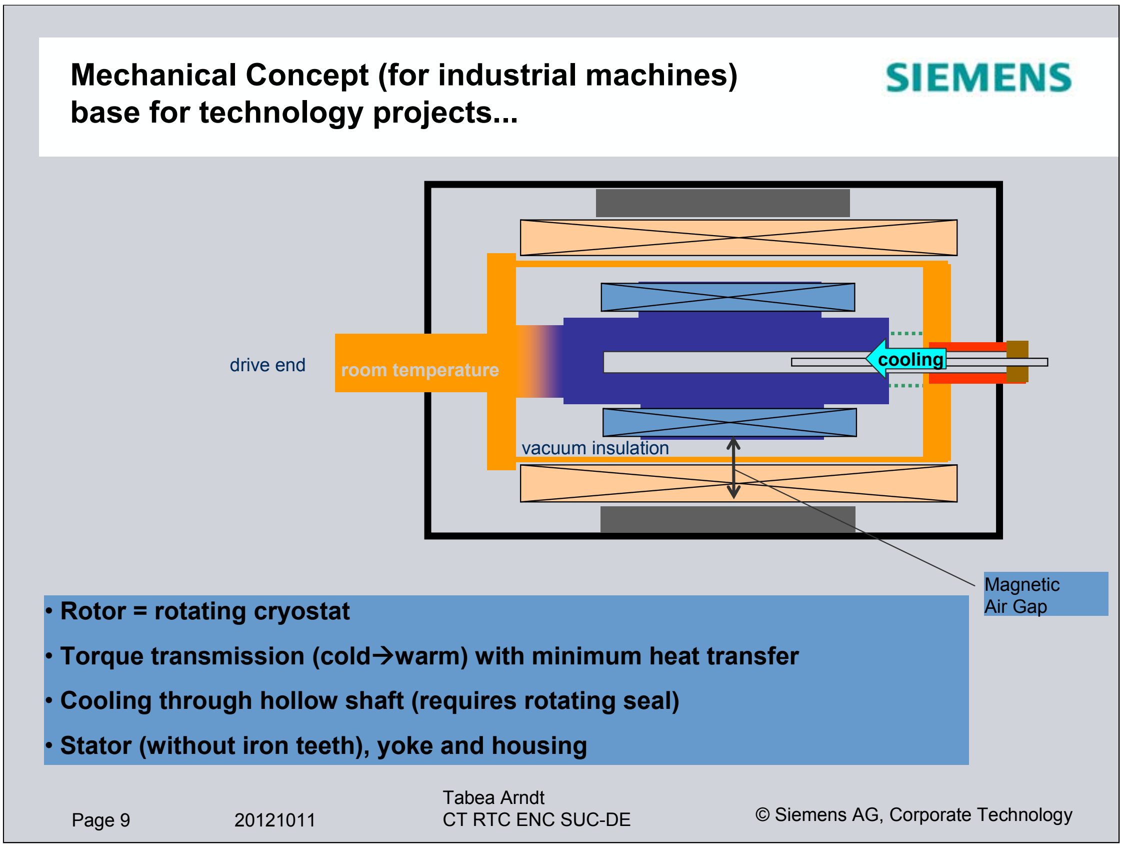
Then we built a generator with high rotational speed facing the necessities of 50/60 Hz operation (HTS-II).

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.



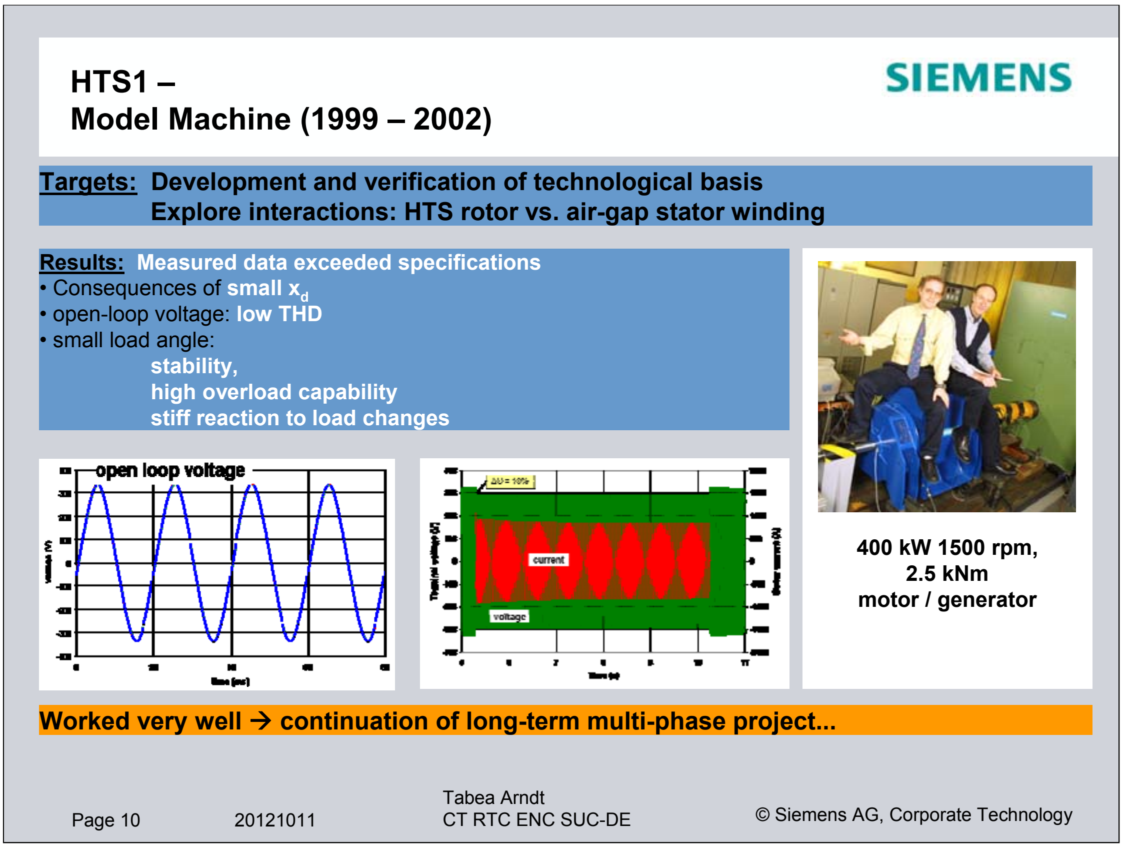
The superconducting wire is enclosed in a rotating cryostat and the superconducting coils are attached to the cold iron mass, enclosed within a rotating cryostat and cooled via the hollow shaft.

Therefore you will need some interfaces from cold to warm and this is done by a special device at the same time transfering 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 sheeth current in the stator.

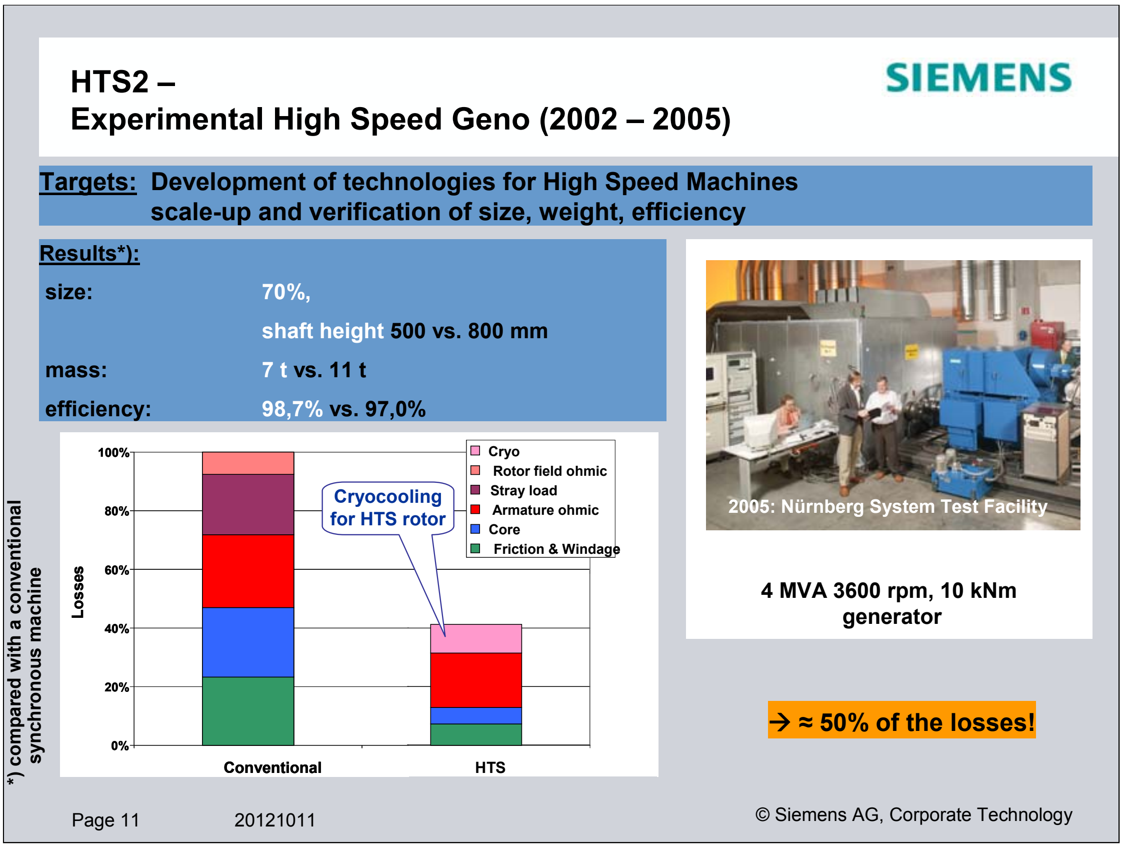
This arrangement will contribute to a large magnetic airgap of the machine delivering some of the special benefits of HTS-technology in rotating machines.

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



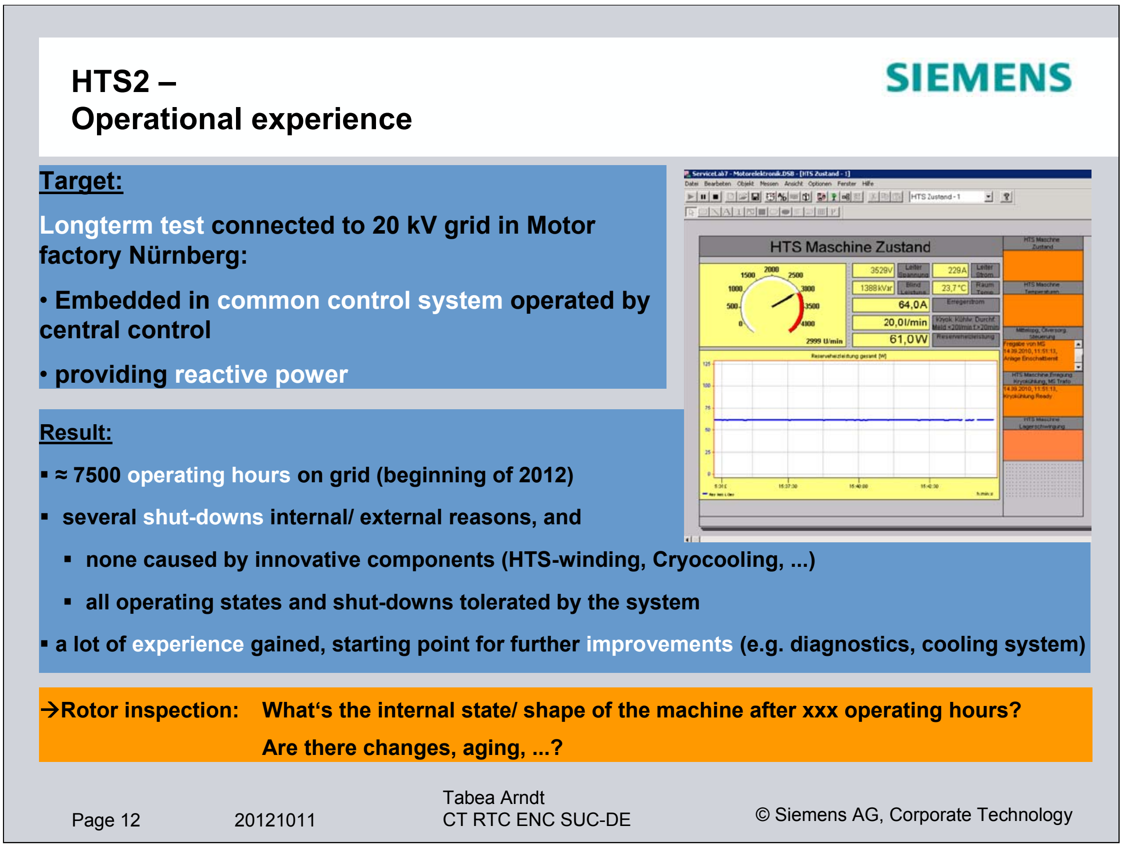
The large magnetic airgap contributes to a small x_d and leads to a very stiff behaviour of the machine. This can be seen in the central diagram of the slide: switching the current on/of has little effect on the voltage stability.

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.



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.

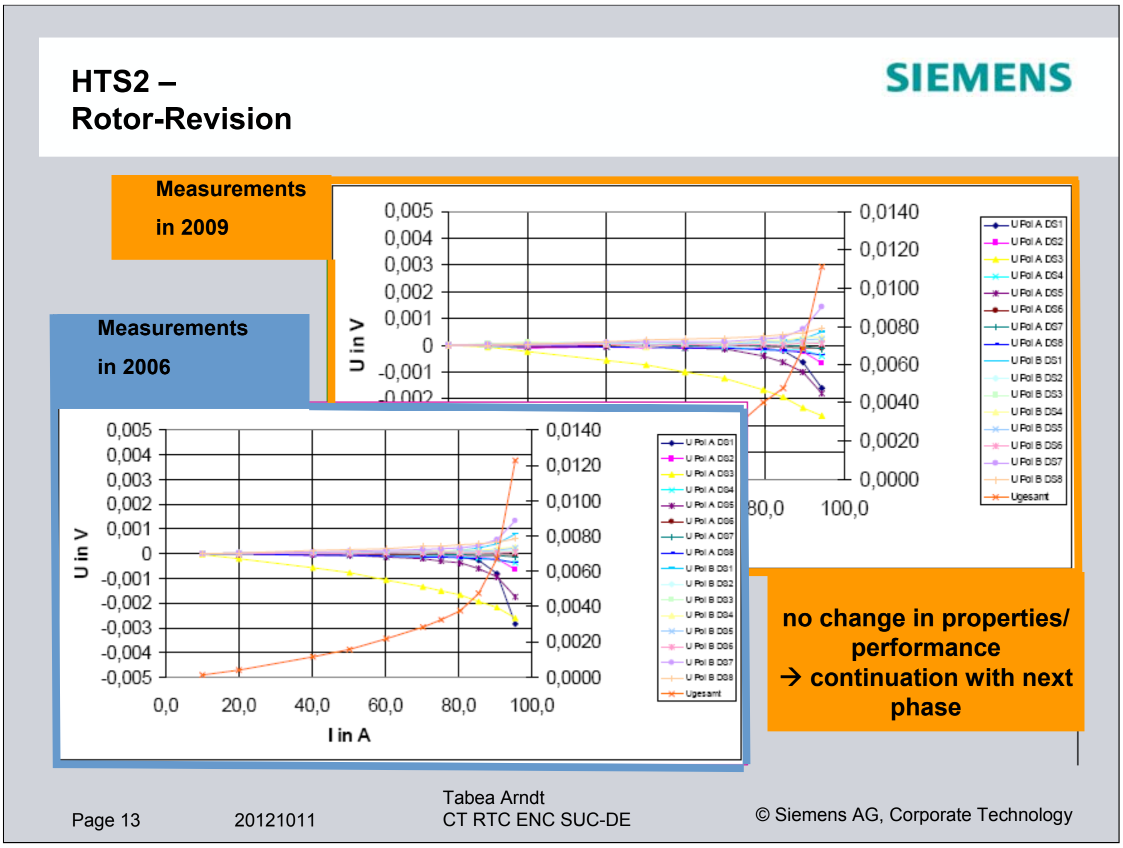


After commissioning the HTS-II machine is operated longterm at a Siemens plant in Nürnberg.

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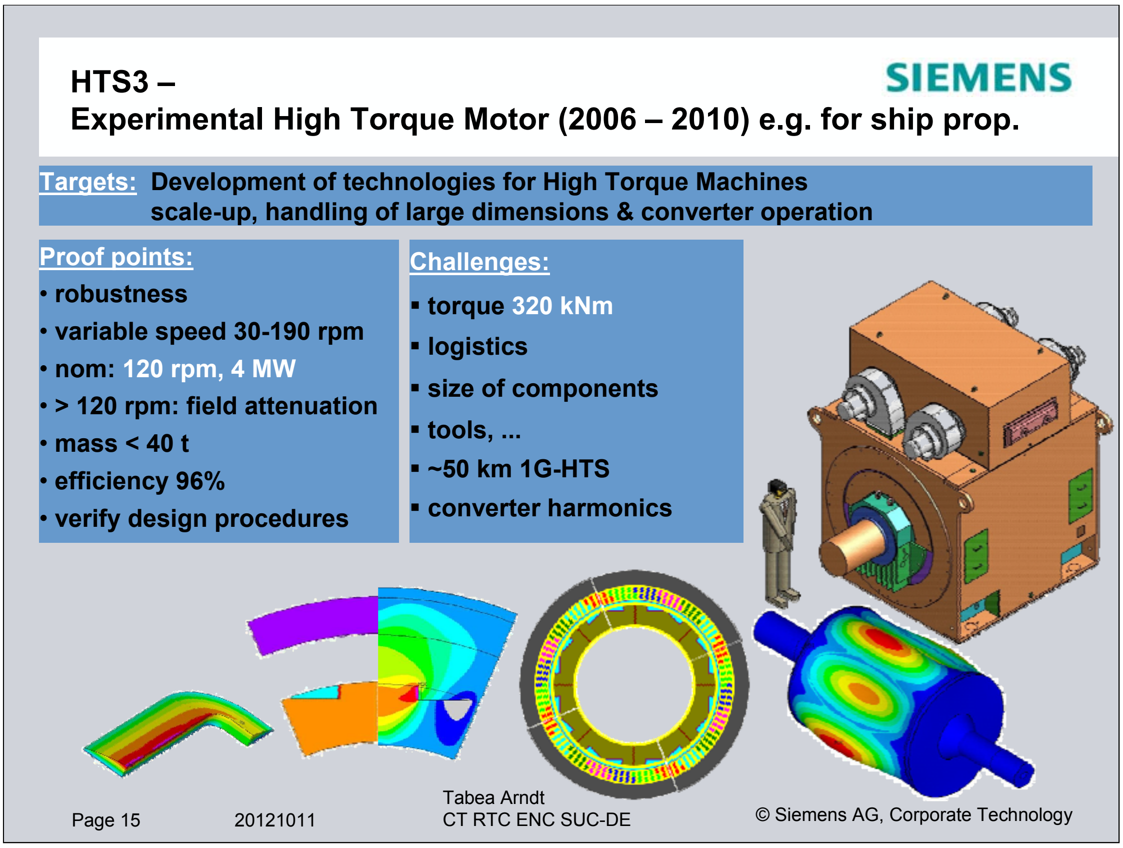
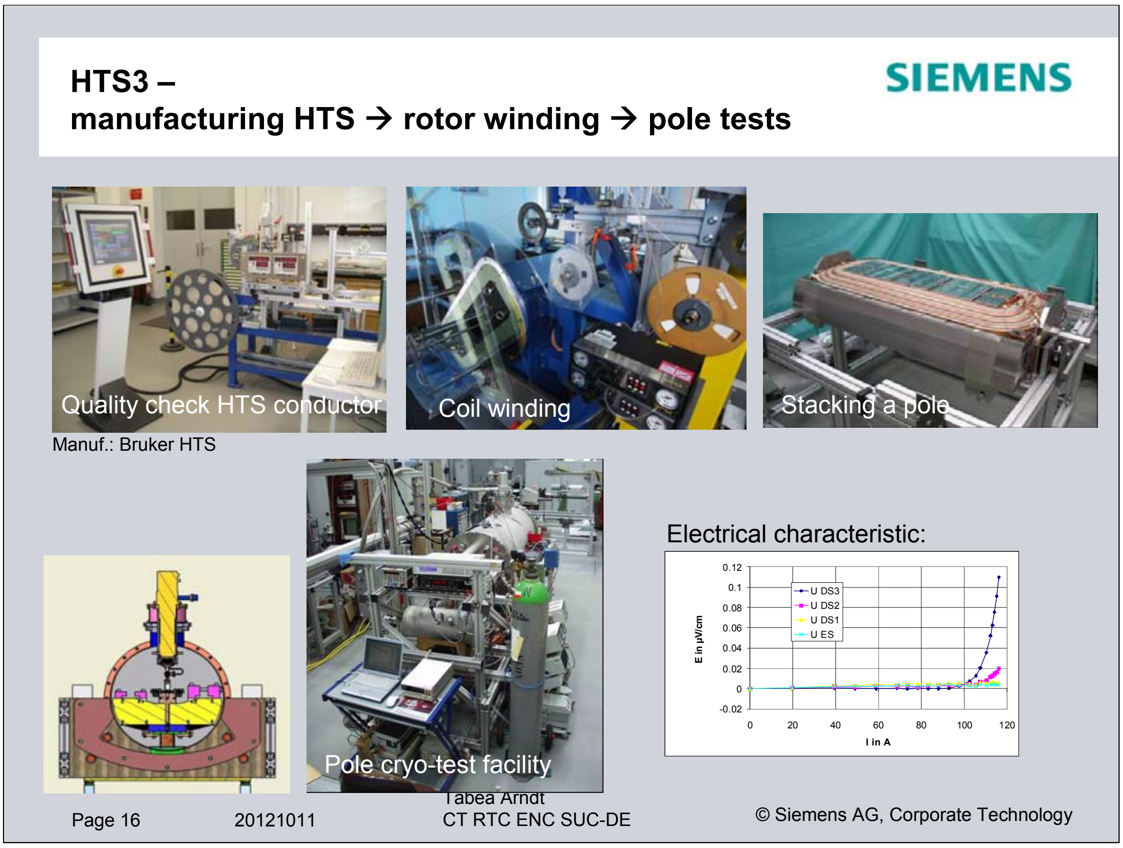
This slide shows the HTS-II machine located in a spare transformer box (other transformers are to the left and to the right of this photo) at the Nürnberg site providing reactive power on demand.

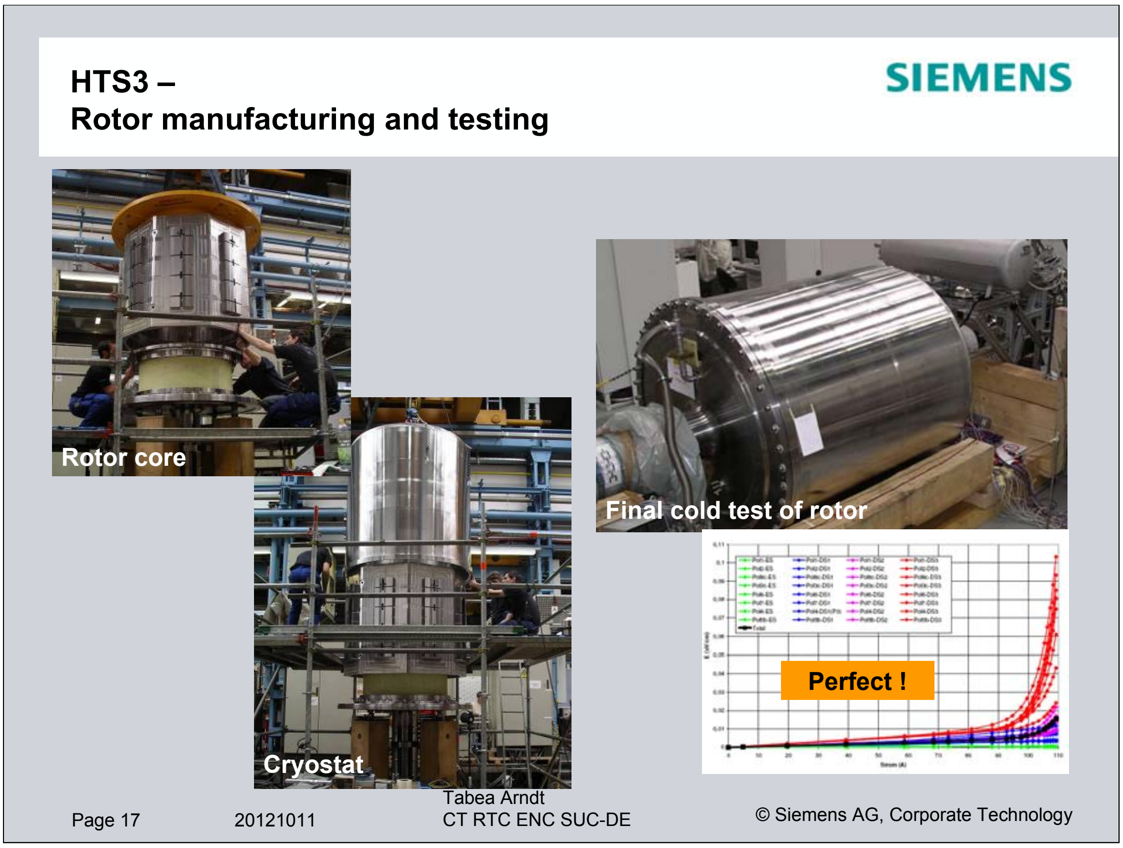
So it is not operated at a test site or in a lab, but in more or less rough industrial environment – and there is no reason to stop longterm operation.



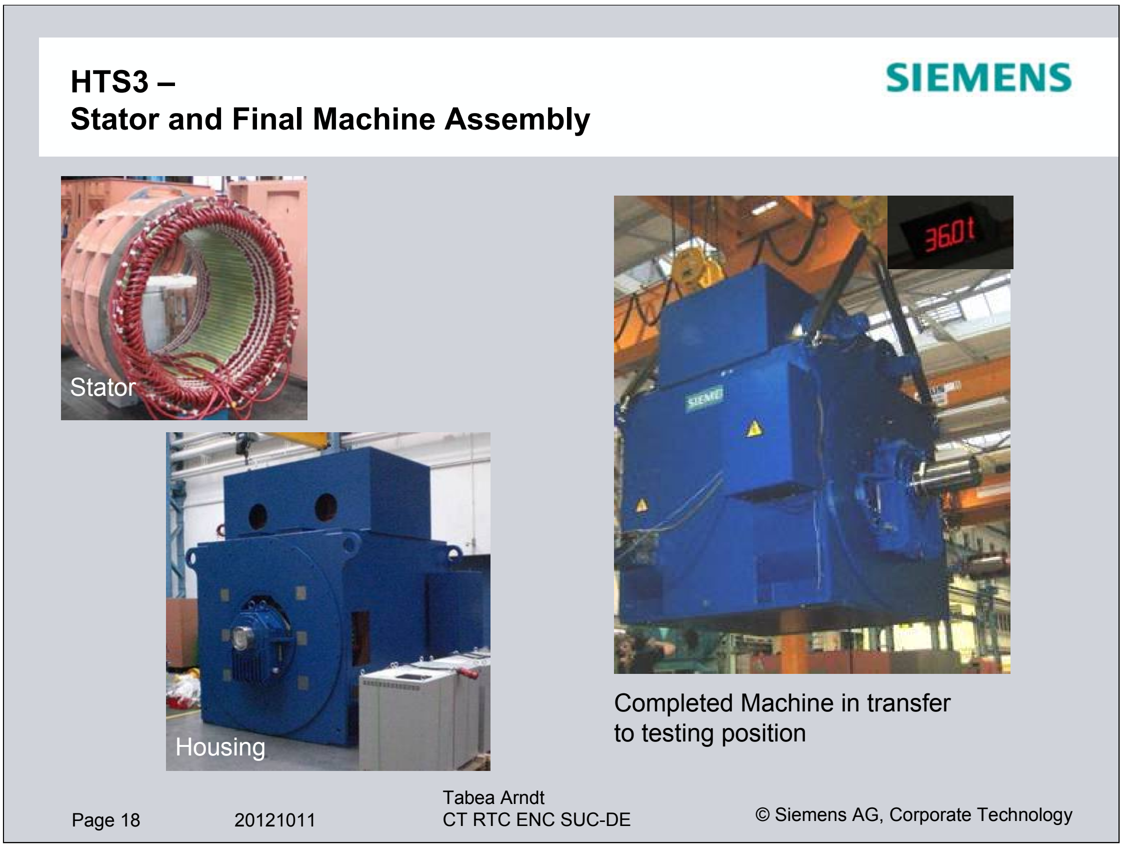
After addressing the high rotational speed application, we developed and built a low rotational speed and high torque HTS motor suitable for ship propulsion. The slide gives the targets and challenges, e.g. operation together with a standard converter and coping with the harmonics.



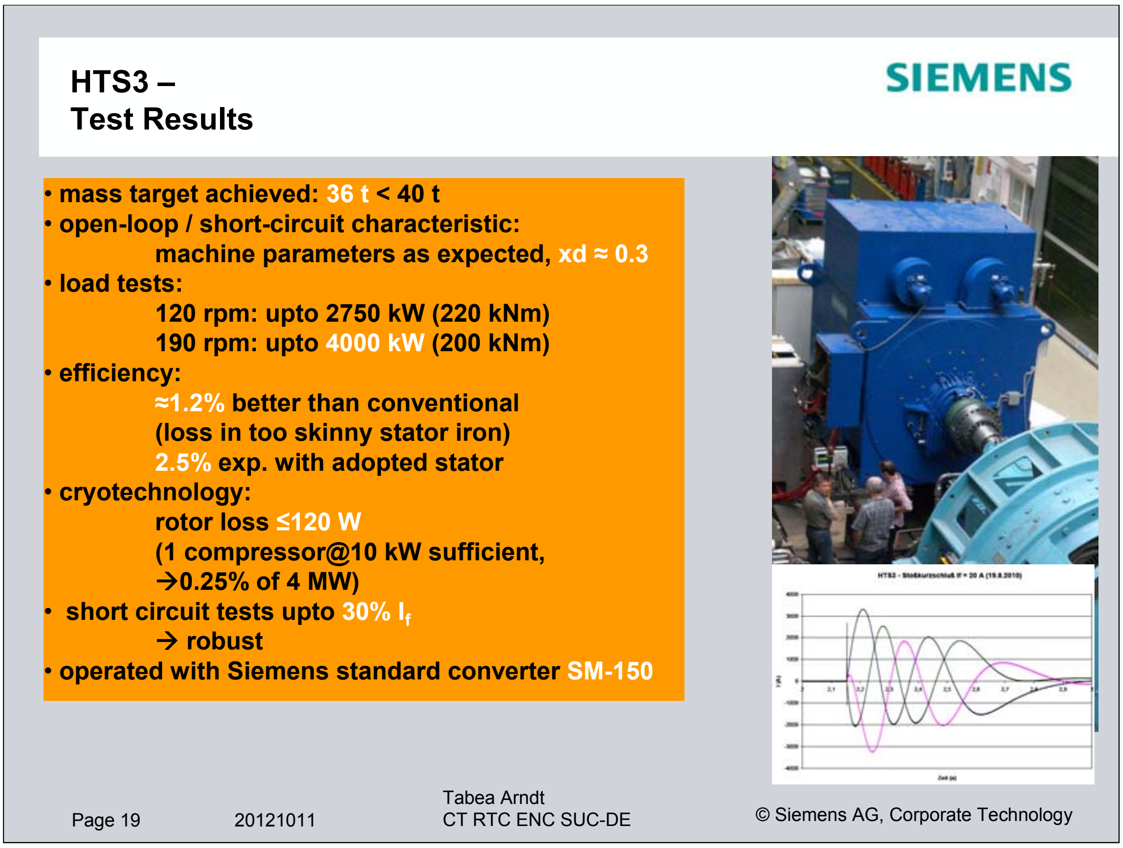
Before using the 50 km of Bi-HTS to built the coils, there was a quality check of the wire. The wire was then wound into coils, these coils are stacked to form poles. Each pole has been tested in a test rig to assure successful operation in the rotor.



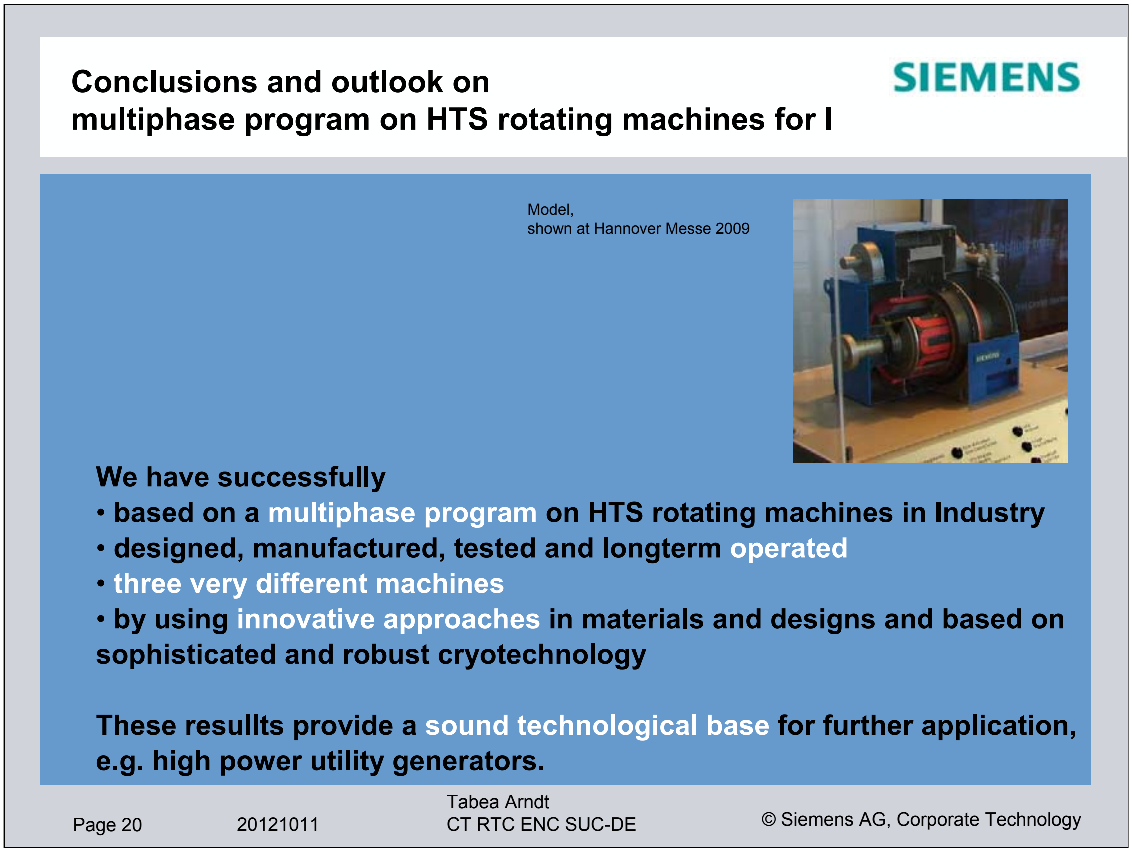
Finally the parts has been assembled and the rotor has been tested as a whole by cooling down and checking the performace of all poles/ coils.



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.



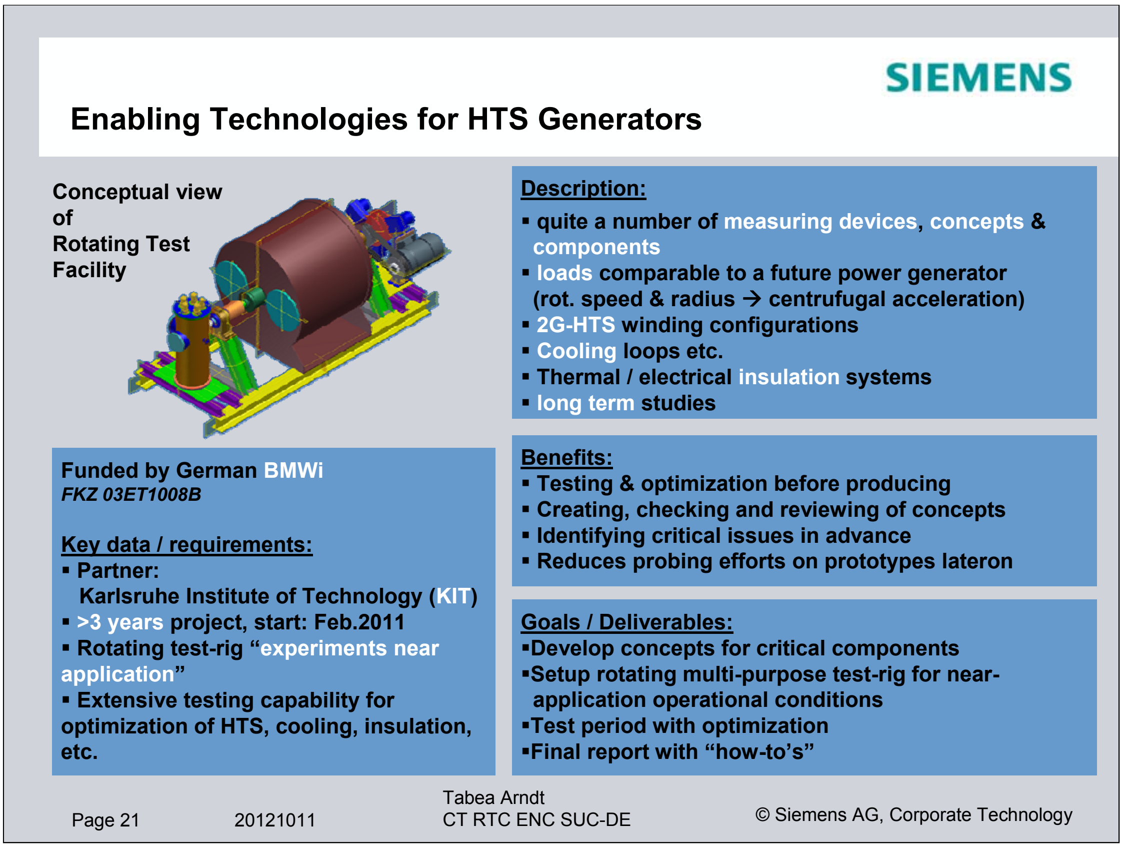
This slide summarizes the test results and shows the HTS-machine placed in the test field in operation with conventional machines (light blue). The diagram shows a consequence of the unique stiffness and load angle of this machine together with a robust design of components which allows to stop the rotor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



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.

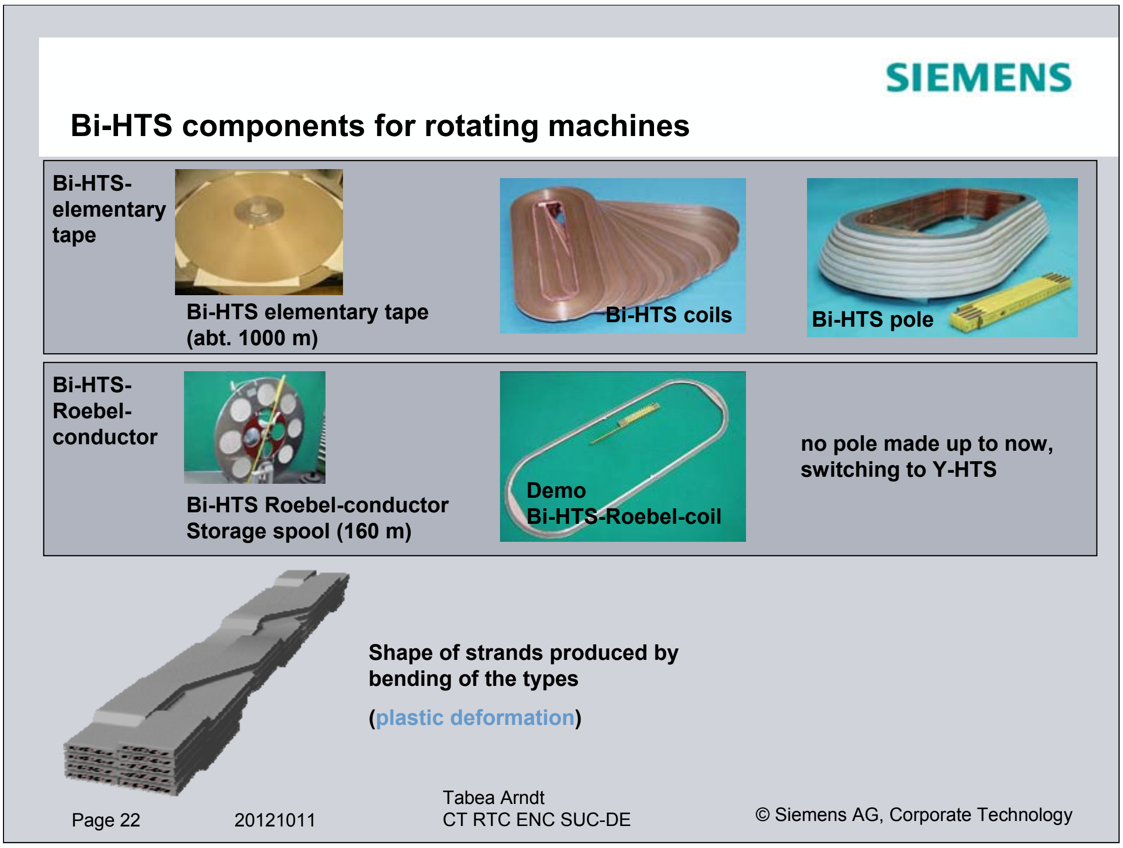
But today, it has to be checked that similar success and even more benefits can be achieved with 2G-HTS, too.



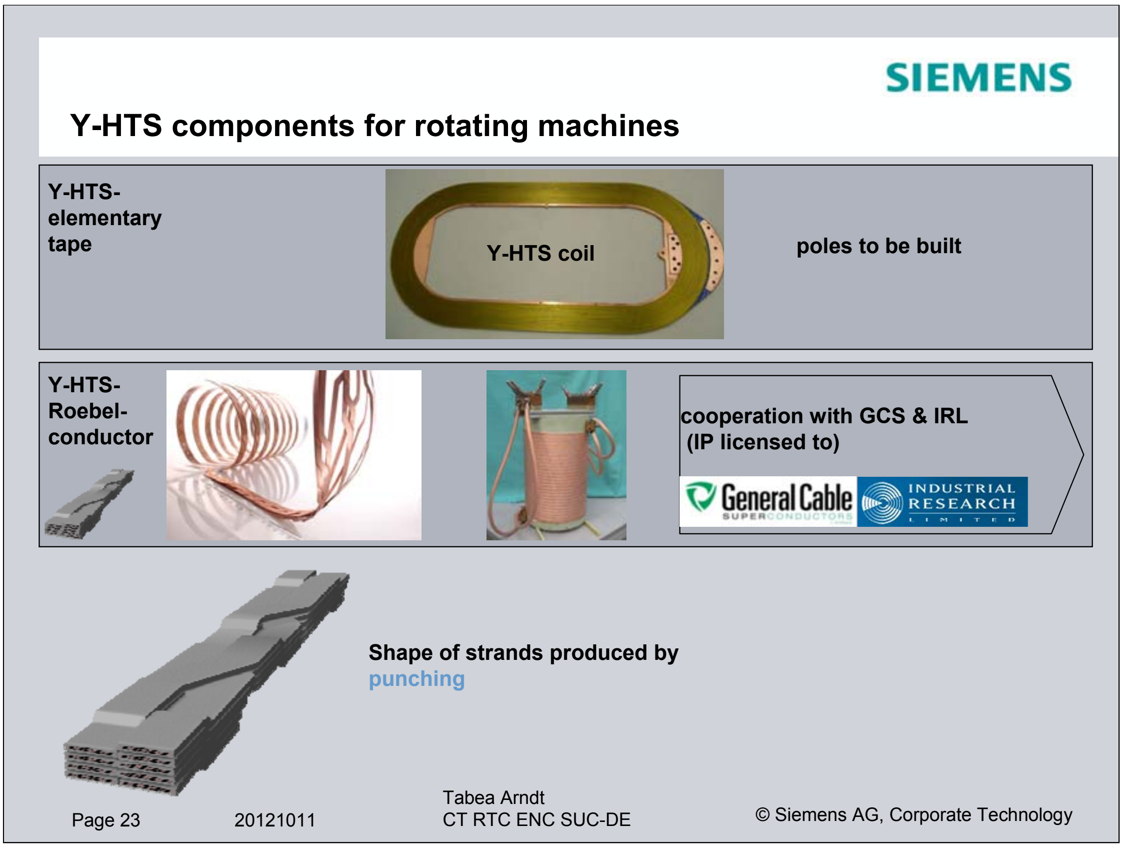
For this purpose, a BMWi-funded project addressing enabling technologies for HTS generators built with 2G-HTS has been started together with KIT.

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

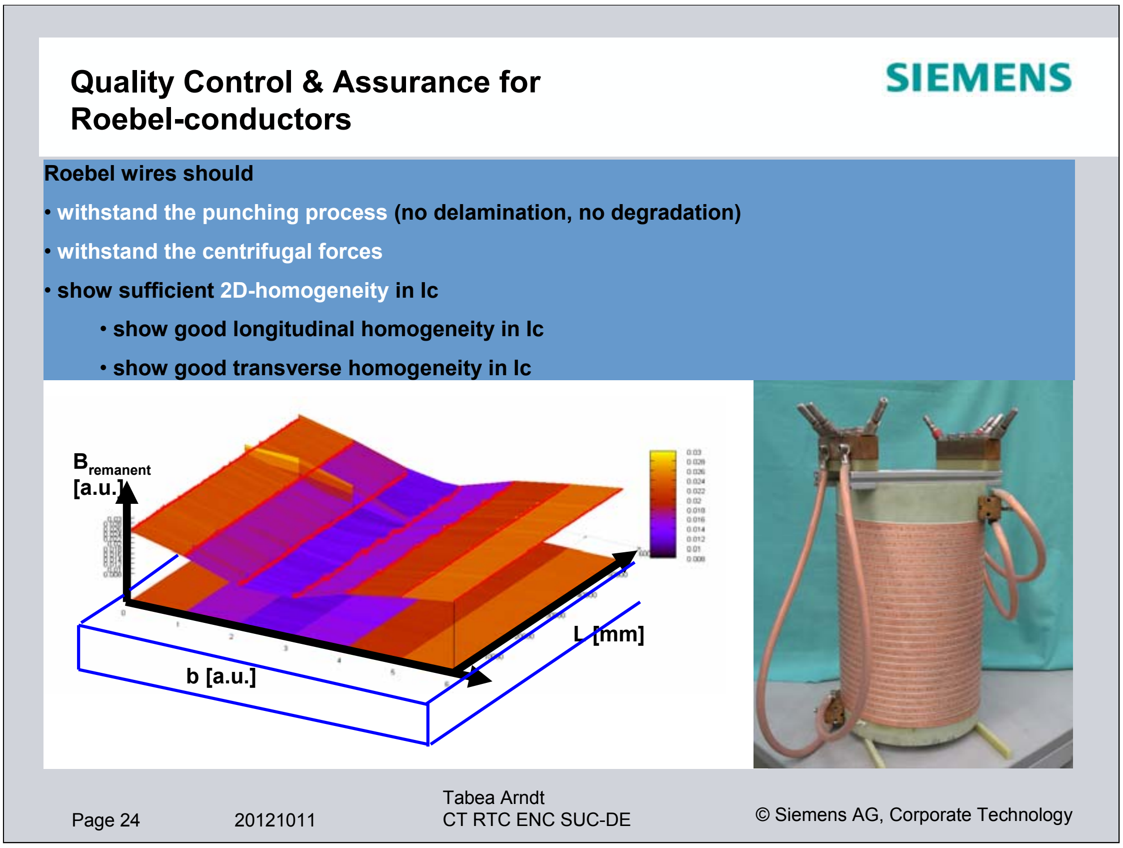
The purpose of this test-rig is to proof and to improve designs and technologies and to evaluate these for possible future use in power plant generators.



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.



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.

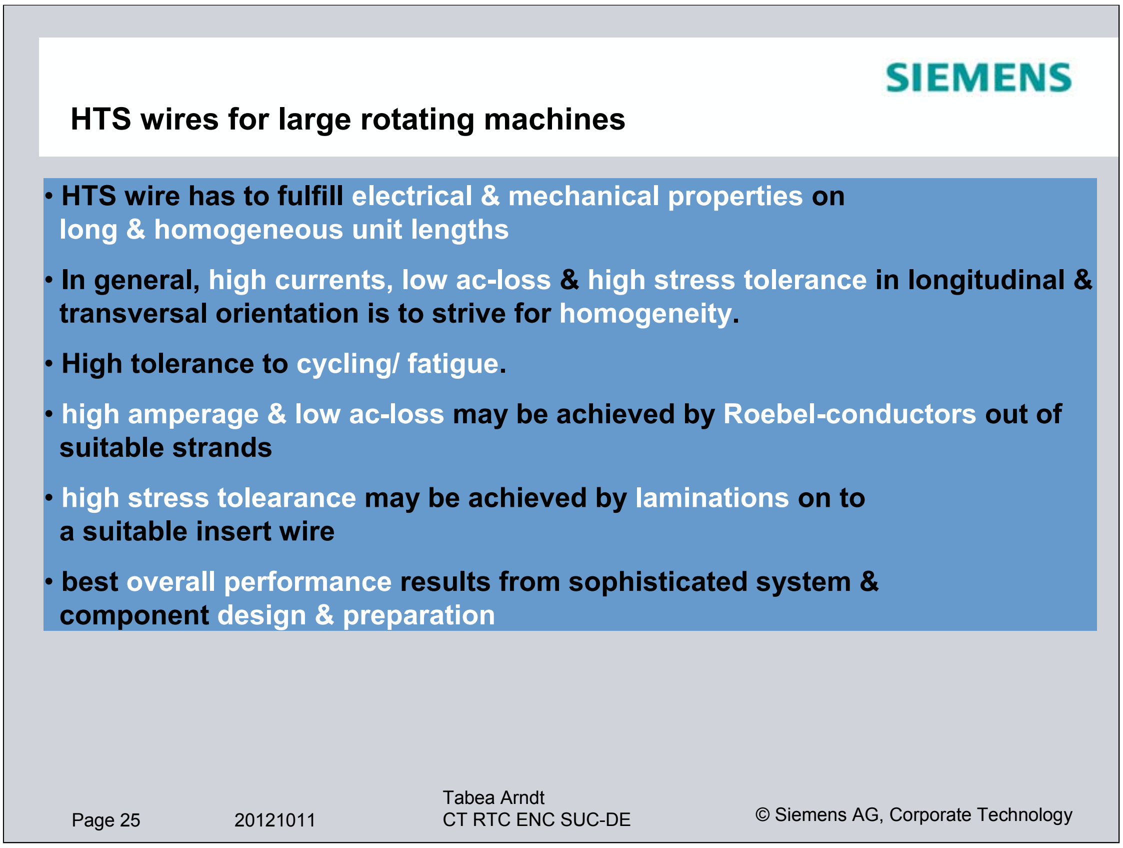


To produce high-amperage Roebel-conductors it is necessary that the wire used for that has not only a high homogeneity of critical current along the length, but along the width, too.

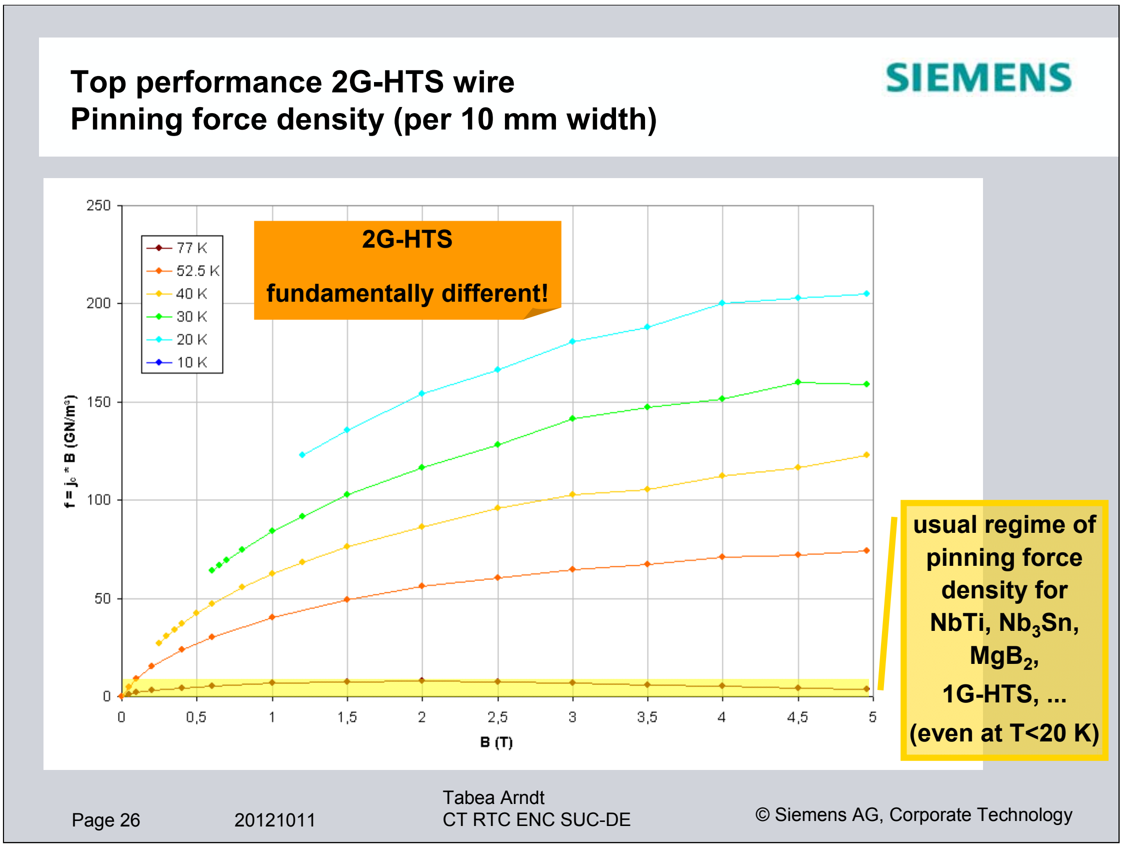
Otherwise you might punch away an essential (current-carrying) part of the tape and loose performance considerably.

The diagram shows the remanent magnetization of a tape very similar to a classical bean profile alon 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.



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 physicists and an engineers view?

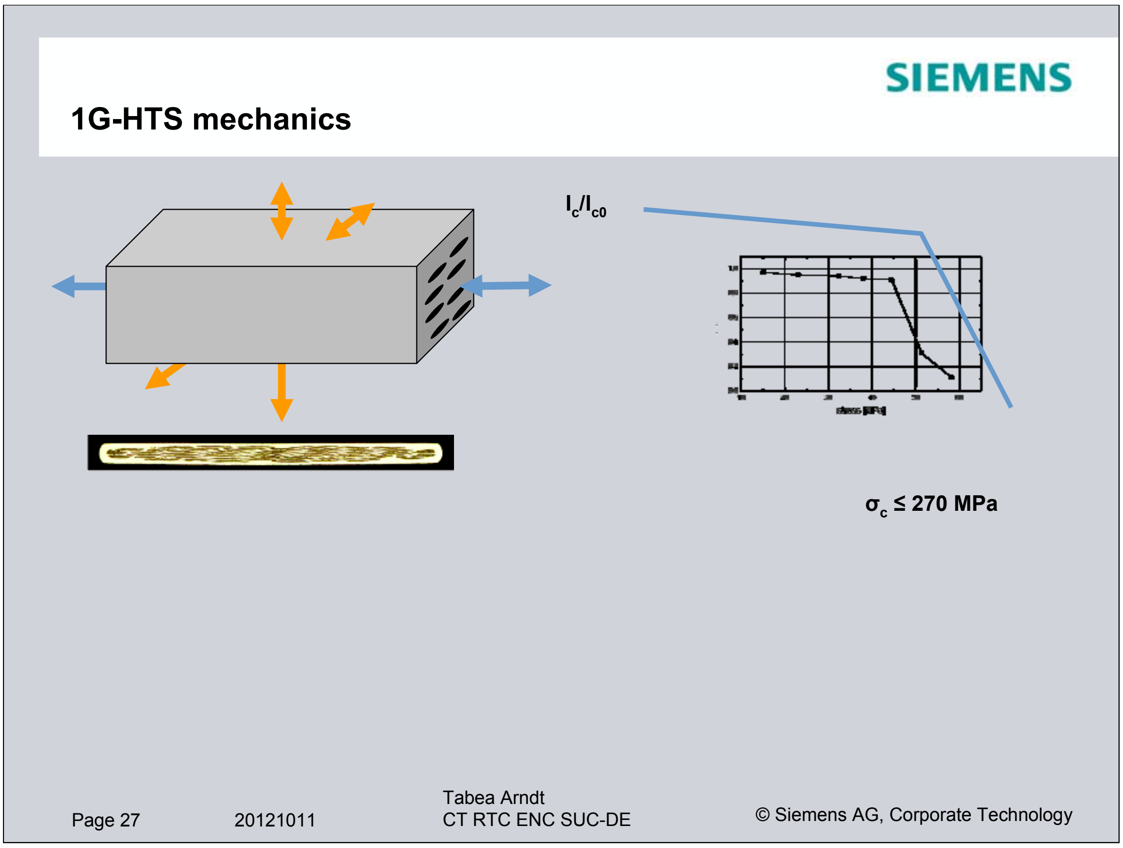
With 2G-HTS one might overcome limitations of all other superconductors.

This diagram shows the pinning force density of 2G-HTS at various temperatures.

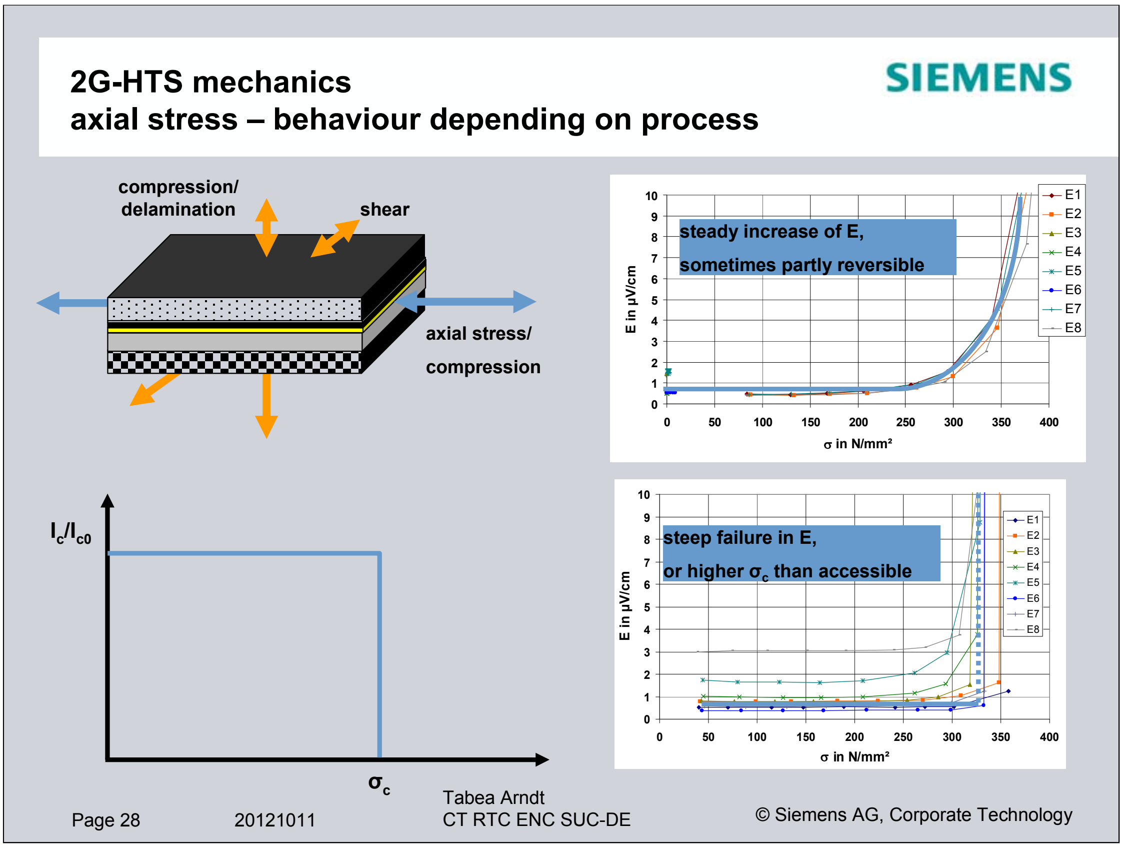
The regime of pinning force density for other superconductors is highlighted in yellow (even for low temperatures), too.

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



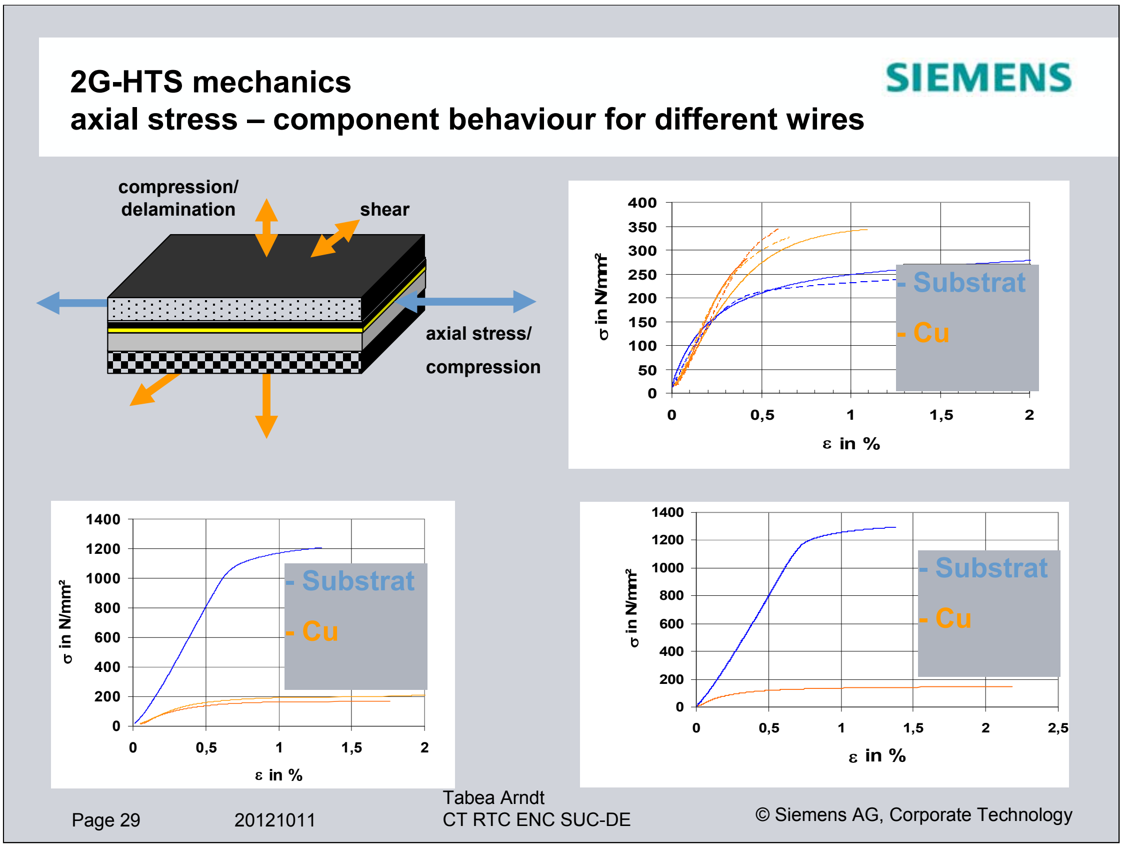
Considering the mechancial properties of HTS, and in this case 1G-HTS, the critical stress is quite limited and furthermore, a degradation/ reduction of properties starts at quite low values of axial stress.



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.

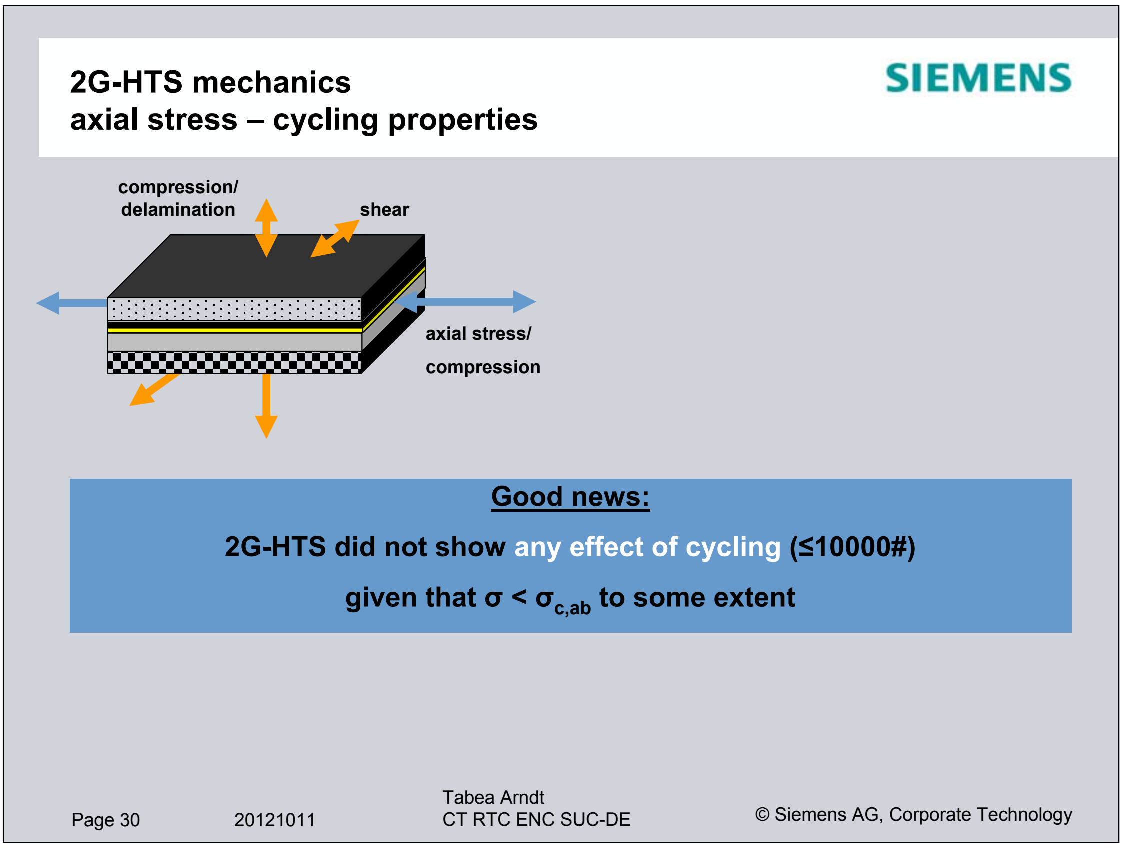


When looking at the wire components, the picture becomes even more detailed.

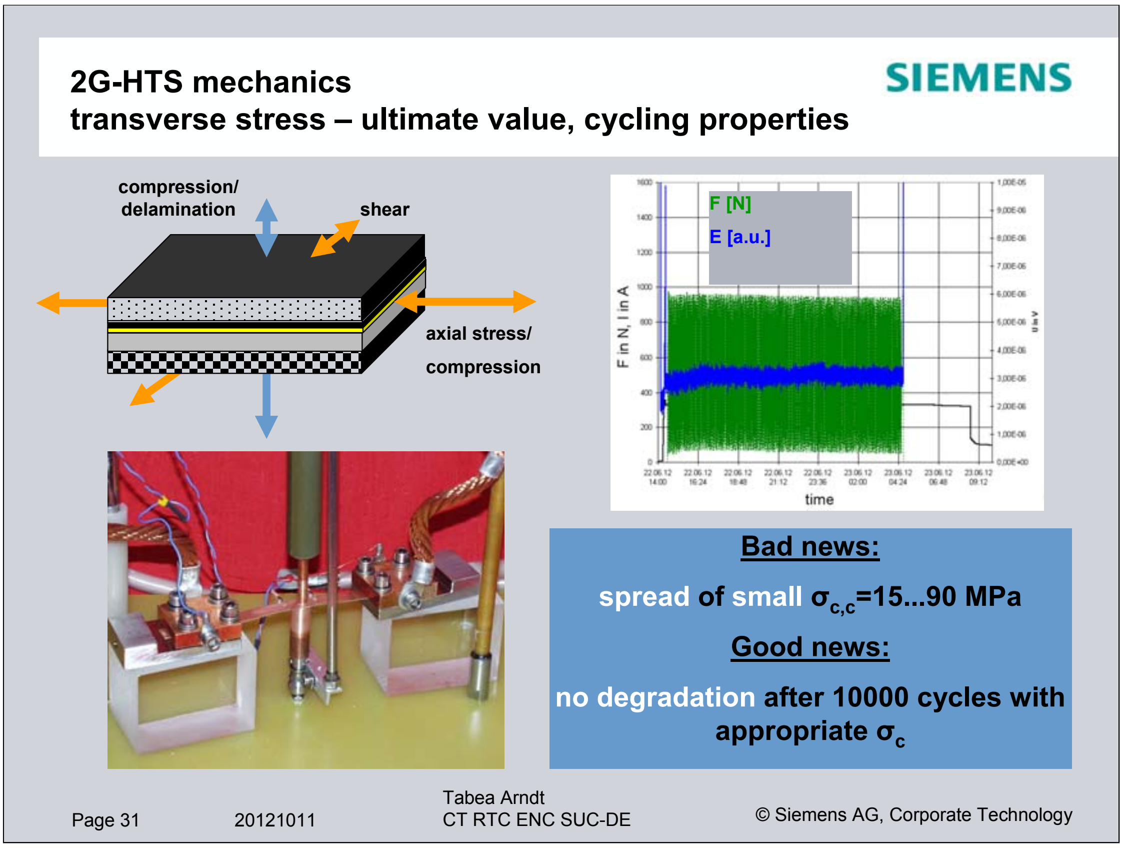
There are wire architechtures available, where the substrate is stronger than the copper shunt and vice versa.

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 architechtures and suppliers as well as by the manufacturers of applications.

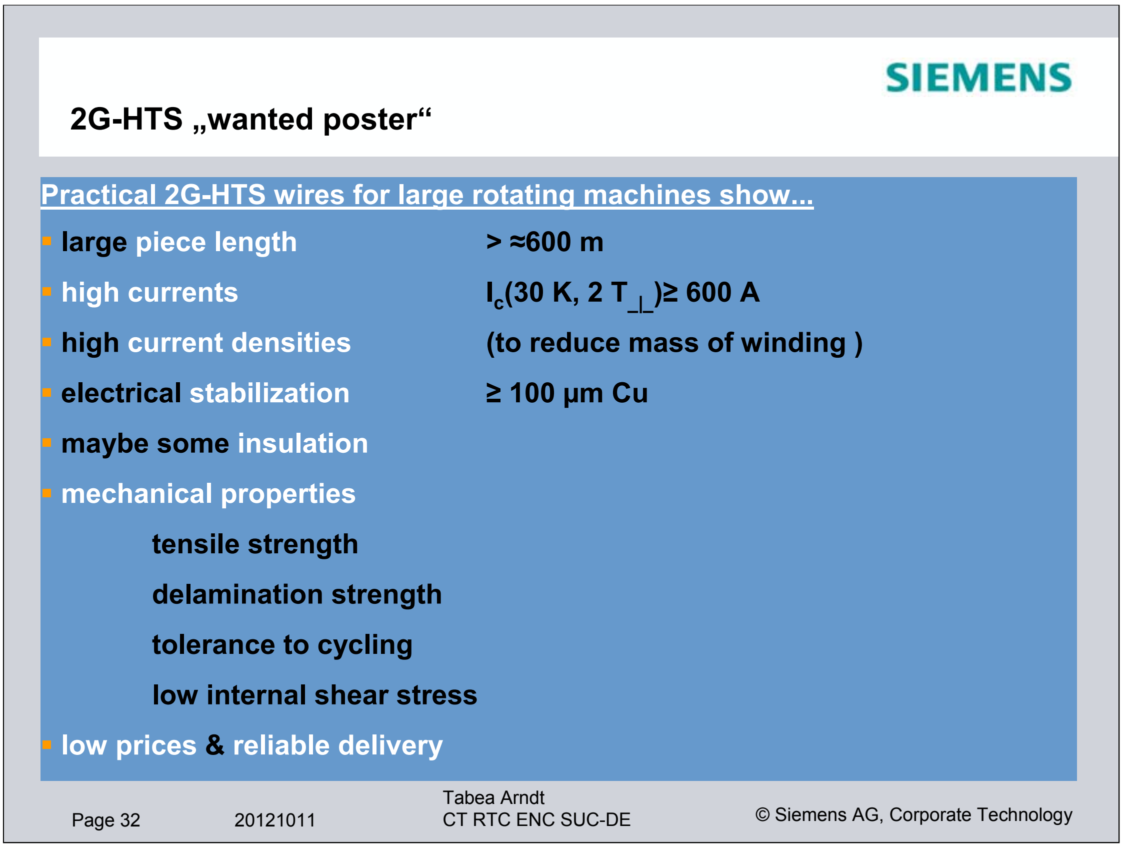


When looking at the mechanical performance of 2G-HTS under cycling, there is good news – look at the text box of the slide.

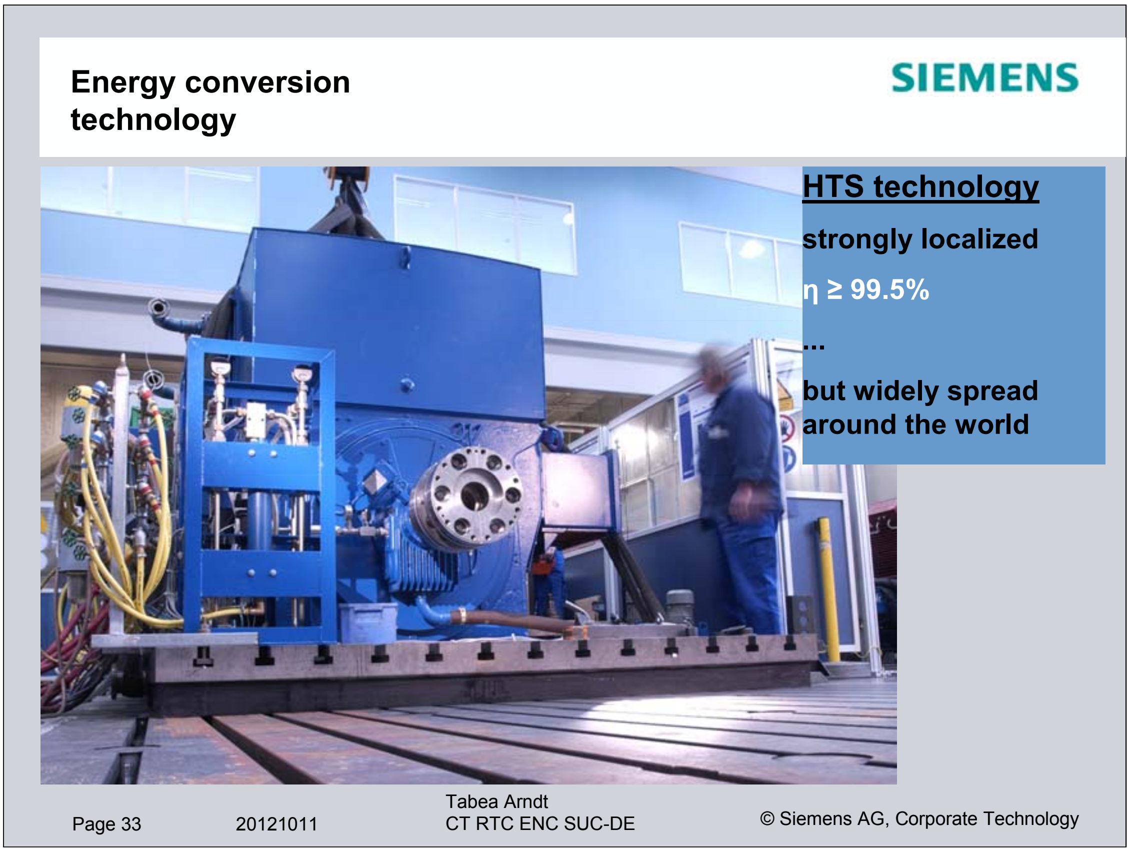


When looking at the mechanical performance of 2G-HTS in transverse direction, the situation becomes more difficult again. Due to the layered architecture of the tapes, the bonding of the layers becomes crucial.

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.



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



When these requirements on 2G-HTS wire are fullfilled, 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 CO_2 and to deliver the special operational benefits mentioned before to the end user.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