Abstract. An overview of the different approaches towards achieving a marketable application of a superconducting electrical machine, either as synchronous motor or generator, will be given. This field ranges from relatively small industrial drives to utility generators with large power ratings, from the low speed and high torque of wind power generators and ship propulsion motors, to high speed generators attached to turbines. Essentially HTS machine technology offers several advantages such as compactness (weight and volume reduction), increased efficiency, and other operational benefits. The machine features have to be optimized with regard to the specific application, and different concepts were developed by internationally competing teams, with Siemens being one of them. The achieved status in these fields will be summarized, pointing to the specific technical challenges to overcome. For this purpose we have not only to consider the technology of manufacturing the HTS rotor winding itself, but also to check requirements and availability of supporting technologies. This ranges from new challenges posed to the non-superconducting (“conventional”) components of such innovative HTS machines, manufacturing superconducting material in the coming transition from 1st to 2nd generation HTS tape, cryogenic technology including material behavior, to new and challenging tasks in simulating and predicting the performance of such machines by computational tools. The question of market opportunities for this technology obviously is a function of all these aspects; however, a strong tendency for the near future is seen in the area of high-torque ship propulsion.

1. Introduction: Features of HTS synchronous machines
HTS, like all superconductors, are perfect conductors in their cryogenically cooled operating environment. They offer the capability to conduct Direct Current practically without Ohmic losses at extraordinarily high current densities. This outstanding ability can be used very beneficial in the broad field of electrical machines.

The main features of large HTS synchronous machines have been demonstrated by laboratory machines of different internationally competing teams:

- compactness in volume and weight
- higher efficiency – up to a few percent increased efficiency because of reduced rotor Ohmic, iron, friction and windage losses - even if including additional power for refrigeration
- high over-load capacity and possibility of extended under-excited operation – due to large magnetic airgap and the resulting small synchronous reactance
stiff operational behavior – low variation of operational data during sudden load changes
reduced noise and vibrations – due to reduced harmonics in the airgap field because of omitted magnetic iron teeth.

However, it needs substantial technical input to facilitate these advantages. Technical solutions are available and have been managed successfully. These include specifically designed components (e.g. rotor winding) as well as supporting components like the refrigeration system including cold heads and compressors. These are off-the-shelf parts, however, they may require further development to improve or adapt to the specific requirements, as will be discussed below.

2. Design choices for HTS machines
Worldwide, researchers and engineers are engaged in developing superconducting machines using different design topologies. From a basic standpoint, the use of massive HTS could be considered as well as HTS tape together with magnetic material such as iron as well as with permanent magnet components. While looking at machines in the MW power range (in smaller size the additional effort to use superconductivity would hardly be profitable), we will focus on coil based windings made from commercially available HTS tapes.

As the HTS wires are sensitive to AC fields and AC currents, their use in electrical machines is economically viable only in DC rotor field windings of synchronous machines. Most of the teams concerned with design of superconducting machines deal with radial flux type synchronous machines. The principle design (on which we want to focus here) is given by a three-phase copper winding in the stator and an HTS field winding in the rotor. In order to really get size advantages derived from large SC current densities, the choice is to operate not at LN₂, but at lower temperature from 25 to 30 K. The precise operating point is determined by cooling system optimization.

In the following, several concepts are presented that are available for application to different machine types. The options for HTS machines can be differentiated by the design concepts of rotor and stator components, and electrical/mechanical and cooling concepts in both fields. Regarding the rotor there are machines with and without magnetic rotor iron core. The stator designs differ by the use of magnetic or non-magnetic stator teeth.

2.1. HTS rotor design
The rotor field windings are wound of HTS wires in race-track shaped coils. Due to the high current density the coils are quite compact and can produce high magnetic fields. The rotor can be designed smaller than with conventional machines, especially in diameter. Ironless rotors, also called air core rotors, have non-magnetic material in the active part of the rotor, which is used as support structure for the rotor field coils. A magnetic iron rotor core could be employed alternatively. Here two suboptions have evolved, to keep the rotor core at cryogenic temperature (“cold rotor iron”) or to use a rotor core at ambient temperature (“warm rotor iron”). Using iron in the magnetic circuit is often seen as a means to reduce the required quantity of expensive HTS tape. It has to be considered, however, that this choice causes a nonlinear no-load characteristic and results in an increased complexity of the analytical design. Advantages and disadvantages of using iron are sketched in the following table:
Table 1. Advantages and disadvantages: utilization of iron in rotor

| Ironless rotor (air-core) | Rotor with magnetic iron |
|--------------------------|-------------------------|
| **Cold rotor iron**      | **Warm rotor iron**     |
| • High flux densities possible | • Efficient use of magnetic iron limits flux |
| • Needs more HTS, due to large reluctance | • Needs less amount of HTS, as iron helps magnetizing the machine |
| • No saturation effects, linear open circuit characteristic, easy to calculate | • Iron saturation to be considered, nonlinear open circuit characteristic, more difficult to predict |
| • Low rotor mass (potentially) | • High thermal inertia (large mass) |
|                           | • Special cryogenic steel required |
| • Needs torque transmission tube, from operational temperature to room temperature | • Short cooldown (low cold mass) |
| • Simple cryostat design and coil suspension | • Conventional rotor steel useable |

Cooling of the HTS windings in the rotor can only be performed by using access through one of the shaft ends, thus, creating the principal restriction that only one shaft is available for torque transmission. Through a nonrotating pipe, inserted via a rotating feedthrough into the hollow shaft, the liquid coolant can be introduced, alternatively a gaseous coolant, that picks up the heat in the winding and then moves, via forced circulation, out of the rotor to a fixed cryogenic refrigerator where it is recooled. Both concepts can be developed to provide the robustness and redundancy that is needed from an application point of view. Table 2 shows the advantages and disadvantages of both types of cooling.

Table 2. Advantages and disadvantages: rotor cooling concept

| Forced convection (1-phase He gas) | Heat pipe (2-phase Ne) + conduction |
|-----------------------------------|-----------------------------------|
| • Technical standard solution, variable temperature (low spec. heat), depending on heat load and mass flow independent of orientation | • Very efficient, using latent heat, temperature depending on pressure (25 - 30K), liquid flow depending on gravity |
| • Requires transparent winding (→ voltage performance?) or sufficient number of cooling ducts | • Requires thermal conduction paths from evaporator to winding, possible difficulties with thermal contacts |
| • Enhanced mass flow needed to react to sudden heat loads | • Variable heat load → self-regulating behaviour good temperature constancy |
| • Capability to cool other components (e.g. leads) at higher temperature level | • Cooling capacity in limited temperature range (boiling curve) |
2.2. Stator design

Two different design principles exist for the stator winding. For a “low flux density machine” the conventional stator design may be applied. There, the stator Copper winding is embedded between magnetic iron teeth. The whole magnetic flux has to be carried by these teeth and the iron yoke and, as in conventional machines, the flux density is limited by the saturation of the stator iron. The HTS quantity used in the rotor field winding is low, as only few ampere-turns are needed to produce the necessary magnetic flux.

With HTS coils in the rotor, it is possible to design a “high flux density machine”, which generates larger excitation fields that exceed the limits of magnetic iron saturation. To achieve high power densities in the complete machine, the stator has to be down-sized, too. This is only possible using an airgap winding, meaning that the winding is situated in the airgap between rotor and stator yoke without any magnetic teeth. Only such a design will give the outstanding features of an HTS machine as stated above. Table 3 shows the advantages and disadvantages of the stator design options discussed above.

The characteristics of the machine are affected by the magnetic design of the machine, especially the magnitude of the exciter field and hence the quantity of HTS material. The excitation field will be limited no longer by saturation of iron and I²R losses of the windings. New freedom will be given for the electrical design: volume, weight, efficiency, and characteristic of the machine can be influenced by the dimensioning of the excitation field.

| Table 3. Advantages and disadvantages: stator magnetic design concept |

| Conventional: using iron teeth | Airgap winding, non-magnetic teeth |
|-------------------------------|-----------------------------------|
| • Proven, widely used, easily manufactured | • Innovative non-metallic (FRP) or non-magnetic teeth, no manufacturing and long-term performance experience, potentially expensive |
| • Airgap flux density limited, must not saturate teeth | • Airgap flux density not limited by saturable iron teeth |
| • Overall power density comparable to conventional machines | • Litz wire (many small, transposed, insulated strands) required to limit eddy and circulating current losses |
| • Teeth help in cooling the winding, however, must be well insulated | • Higher power density, i.e. volume reduction possible, limited by stator cooling capacity |
| • Voltage harmonics (slot harmonics) due to alternating slots and teeth | • Non-metallic teeth provide additional insulation capability, however, heat removal is more difficult without iron thermal conduction |
| • Concept to retrofit existing machines, only limited HTS machine advantages, no improved compactness | • No slot harmonics due to large magnetic airgap |
| | • Small synchronous reactance $\Rightarrow$ high overload capability, “stiff” load behaviour |
| | • Completely innovative machine, rotor + stator |
| | • Max. utilization of HTS machine advantages |

3. Applications

During the last years, several demonstrators of synchronous electrical machines have been developed and tested [2], [4], [7], [8], [10]. In the following, 4 examples with different design concepts shall be introduced.
3.1. How it started – standard size, medium speed machines

First steps toward the application of HTS technology in electrical rotating machines were made in the standard-size, medium-speed machine segment. Such HTS machines had a power output of a few hundred kilowatts.

For example, the Siemens 400 kW HTS machine [2] had a 4-pole, 50 Hz design and, thus, a rated speed of 1500 rpm. Therewith, the centrifugal load on the winding was kept at a level that was regarded uncritical. This machine employed a rotor with cold magnetic rotor iron. In that way the amount of expensive HTS wire was limited by utilizing the iron magnetization, and also to obtain a simple cryostat design. The focus was on crucial design elements like HTS coils and connections, the FRP torque transmission element and cooling system. In case of the Siemens 400 kW machine, a single-pipe thermosyphon cooling system using Neon was introduced, that operated completely self-regulating [1]. The stator core of this machine employed nonmagnetic FRP teeth to hold the winding securely in place and allow for enhanced magnetic airgap fields compared to conventional machines. For this purpose a Litz wire winding was introduced. Additionally, new calculation tools were developed, tested and improved by comparison to the experimental results obtained.

In general it can be said that these HTS machines of the 1st generation were intended to demonstrate the feasibility of applying HTS technology. In fact we were surprised to find an increased efficiency, as the machine had not been optimized in any way. Highly valuable experiences were made by studying these machines and therewith, a foundation for further developments was laid.

3.2. A Step towards high power, high speed machines

With growing knowledge on HTS machine design and confidence gained from successful long term operation of demonstrators, manufacturers started to explore other, more challenging application fields for synchronous machines, with higher rated outputs and higher rotational speeds.

With these machines of the 2nd HTS machine generation another aspect came into play: these machines were built not only to demonstrate basic feasibility of HTS technology in approx. product size, but to optimize the design to achieve certain advantageous features like low mass and volume combined with high efficiency.

An example is the Siemens 4 MVA machine [4]. Designed as a generator for shipborne power generation, this machine delivers its rated power at 3600 rpm. The challenge with this machine was to manage high centrifugal forces on the winding and other components. Thus, design elements that were proven to be functional e.g. cooling system, torque transmission or FRP stator teeth were taken from the preceding 400 kW machine and focus was put on the winding and its suspension and connections. As its predecessor, the 4 MVA generator has a cold magnetic iron core rotor. Siemens found that mastering this rotor design provides a maximum degree of freedom in designing HTS machines, because from such a platform one can easily move in both directions: nonmagnetic iron core with maximum power per mass as well as magnetic iron core for maximum efficiency and power per HTS. The design goal for the 4 MVA machine was an optimum between power density i.e. mass and volume, efficiency and HTS wire costs which was achieved impressively. It was also demonstrated that HTS machines can be successfully designed and built for product-size power and high speed applications.

3.3. High torque, low speed motor/ generator

In contrast to high speed machines, another direction was selected with the latest developments. Worldwide a promising near-future application of HTS machines has been identified in the field of ship propulsion. There, one could highly benefit from extremely power dense and efficient propulsion motors. In this area, the huge dimensions of the machines’ components as well as processing of the large amount of HTS wire needed pose special challenges to the engineers.

As examples, American Superconductor Inc. had built and tested at CAPS a 5 MW, 200rpm demonstrator for a ship propulsion motor [7], and has recently finished shop tests of a 36.5 MW HTS motor, and delivered to the US Navy for load tests [8]. The machine is designed to deliver a rated
torque of 2.9 MNm at 120 rpm speed. The design data allow the conclusion that the main focus was to achieve maximum compactness and minimum weight with this HTS machine. This can be figured e.g. by the choice of the machine’s rotor topology. The motor uses an air core rotor, which is relatively easy to calculate and exceptionally lightweight. On the down-side of this topology is the high quantity of HTS needed to achieve the necessary Ampere turns in the rotor. Due to the absence of iron the whole torque is transmitted via the rotor winding. The stator uses nonmagnetic teeth to support the stator winding. Thus, the airgap induction can be much higher than in conventional machines, which enables high power density. The stator winding can be operated with a very high utilization (current density) since the winding is oil-cooled and, therewith, also enables for a very power dense machine.

Also other manufacturers are developing such high torque, low speed HTS machines but may use somehow modified topologies. Siemens is working on a 4 MW HTS propulsion motor for 120 rpm while Converteam has presented plans for a directly drive HTS power generator applicable for wind turbines [11].

3.4. Utility power generator

Utility power generators are the largest and probably most complex electric synchronous machines with extraordinary high demands on reliability and availability. The application of HTS promises increased machine efficiency as well as the reduction of mass and generator size. To achieve the latter, an air core stator needs to be developed in addition to the HTS rotor. Since the simultaneous development of the two main generator components would require a fairly large and risky development program a more feasible way of development would be the subsequent development of HTS rotor and high power stator. This was already proposed by one manufacturer who started a development program for a power generator HTS rotor [3]. Retrofitting an HTS rotor into a conventional stator promises advantages like higher generator efficiency (typical 0.5 percent for a 500 MVA machine) and higher output with required power factor after a turbine upgrade. Additionally there would be operational benefits (capability to supply reactive power) and the avoidance of thermal ageing of the rotor winding insulation.

Using a conventional stator, the flux density provided by the HTS field must not be higher than in conventional generators. Thus, it makes sense to employ magnetic iron in the rotor core to benefit from its magnetic properties. Because of size and mass of the rotor (largest units have rotor body lengths of up to 8 meters and weigh more than 45 tons) a retrofit HTS rotor featuring a cold rotor core is not feasible. In such a case months would be required to cool such a large mass down to operating temperature. Thus, a “warm” rotor core is recommended for such HTS retrofit power generators, which is built on a closed cryostat structure around the HTS winding and its suspension system, allowing to keep the rotor iron at ambient temperature. In that way cool down times on the order of days are possible. In addition, the electromagnetic shielding of the rotor body is not necessary because eddy current losses due to e.g. negative sequence currents appear outside the rotor cryostat in the warm part of the machine. Also, the rotor body can be forged from conventional steel and bolted directly to the shaft ends. Special torque transmission elements, which transmit the rotor torque and connect the cryogenic part with the warm part, are not necessary.

Retrofitting an HTS Rotor into a conventional stator core represents the first step on the way to powerful, lighter and smaller utility generator. To fully apply the potential of HTS, the improvement of the stator core and especially the stator winding is necessary. Thus, the subsequent evolutionary step would be an air core stator, with non-magnetic winding support structure and a transposed Litz wire winding. This would allow for higher flux densities as offered from the HTS and therewith higher power densities, and enable to reduce the total size of these nowadays gigantic machines to about 1/3!

4. Challenges

It is well understood that the success achieved with these demonstrators and early prototypes is tremendous! However, if our goal is to progress towards a new commercial application of HTS that is
competitive to the existing technology, it is worthwhile to address those areas where special attention has to be focused.

4.1. HTS wire

Most of today’s HTS machines utilize so called first generation (1G) wires. These are produced by several manufacturers worldwide in lengths of kilometers and with production capacities of several 100 km/year. The ceramic superconductor (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{x}$ (BSCCO or Bi-2223) in form of many filaments is embedded in a soft pure silver matrix. Critical currents are ranging from about 100A to 180A (LN2, self field) in commercial wires for a cross-section of about 4mm x 0.3mm. The (PIT) manufacturing path is quite complex, thus, these products have shown to be very sensitive to deviations in material and processes, and their cost is too high from application standpoint.

Since about 2 years a new, second generation (2G) of HTS wires is commercially available. 2G wires comprise a layered architecture, with the superconductor Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ (YBCO) as a thin film being one of the layers. They are expected to be able to substitute 1G wire as a drop-in replacement in the near future with the prospect of lower prices. They also provide new technical options, like a broader range of available cross-sections or additional measures for mechanical, thermal and electrical stabilization. As a consequence, new degrees of freedom for the winding design will become available.

Due to these potential benefits some manufacturers of HTS wires already suspended the production of 1G wire, although, the transition to 2G has not been qualified by considerable real-size demonstrators yet.

Another aspect is the sufficient characterization of the HTS wire properties. Variations of performance have been found many times and thus, extended QA procedures had to be established. For the purpose of cost efficiency and reliability, internationally accepted standards are needed. This applies also to wire insulation, as for copper wires in classical technology. Defined insulation levels according to common line voltage levels and insulation test procedures should be included into those standards.

4.2. Excitation system

The system to excite the HTS field winding is a new challenge in general. As the coils obviously have negligible Ohmic resistance, the winding has to be powered by a relatively large current at only a few Volts under normal operation. In contrast, when ramping (i.e. exciting or de-exciting) the HTS coils, a large excitation voltage needs to be applied. This becomes necessary since windings assembled from coils wound from single HTS tape have an extraordinarily high inductance. To achieve field current changes within acceptable periods of time, excitation voltages in the range of 100 V or higher have to be applied for these incidences. Thus, it becomes clear that a control scheme using excitation current as regulation parameter is required rather than conventional voltage control. Such systems must be able to operate with solely inductive loads, in fact, for HTS machines utilizing iron in the rotor, the inductance depends on the excitation current. Additionally, unlike conventional machines with a resistive winding, HTS machines cannot dissipate the energy stored in the rotor inductance. So the exciter is also the key of the superconducting coils’ protection system.

Two solutions are currently in use: current transfer via brushes and slip rings, or brushless excitation via a rotating transformer with a complex control and protection device. Systems with brushes and slip rings are widely used within various fields of applications of electrical synchronous machines. However, for some applications e.g. on board of ships they are usually not tolerated because of the high maintenance effort.

Thus, contact free, wearless excitation systems are developed for HTS machines. The unavoidable rotating electronic components are subject to high mechanical stresses due to centrifugal forces e.g. for generators at 3000/3600 rpm. After all, an electronically controlled brushless exciter is a complex system with high requirements on the electrical (including EMC) and mechanical design as well as on the control system. Different approaches are known to brushless excitation systems for
HTS windings only by patent application publications. Although essential for the commercial success of HTS machines, there is no common development effort until today.

4.3. Refrigeration for rotor cooling system

Refrigeration to cryogenic temperatures is a major difference between HTS and conventional machines, and customers are unfamiliar with the required refrigeration/cooling systems. To overcome this burden, all interactions (vibration, noise, input power, EMC, maintenance, failure, costs, etc) of the refrigerator should be minor when compared with the total system (goal: an “invisible cooling system”).

However, HTS machines do operate at temperatures of about 30K with the need of a few hundred Watts of refrigeration power. Close to those parameters, there are no other commercial applications today. The best available fit are Gifford-McMahon (GM) refrigerators, which were originally developed for cooling thermal shields of LTS MRI systems, in order to reduce the boiloff of liquid Helium. Some (estimated) 10,000 applications are operating worldwide, so it is an industrially established technology offering attractive prices. However, as they were not designed for the parameters and rough operational conditions envisaged now, GM cryocoolers suffer from serious drawbacks:

- Standard GM refrigerators are provided with conventional oil-lubricated compressors. These compressors are comparably large and, most important, need maintenance about once a year. The oil is a continuous threat to the regenerator of the cold head because of contamination.
- The cold heads include a moving displacer, also needing maintenance, which is vulnerable to vibrations.
- Today, refrigeration power of available models is limited to about 100W at the temperature level of 25K. Thus, several GMs have to be operated in parallel within a cooling system for a rotating machine. Fortunately, compressors and cold heads can be connected via flexible transfer lines.
- The operation of today’s oil-lubricated compressors is dependent on orientation with respect to gravity, which is also true for the performance of the cold heads. Thus, for certain applications like ship propulsion, additional technical measures are required.

Alternatives to these standard systems are in development:

- Pulse Tube refrigerators (PTR) eliminate the need for a moving displacer within the cold head. Therefore, they are expected to be maintenance-free, will have a long lifetime, are almost orientation independent and less vulnerable to vibrations. However, their efficiency is worse than that of a GM refrigerator, so the required compressor must be larger.
- Oil-free linear compressors are available, but still expensive. However, they are larger then their oil-lubricated counterpart and not yet technically mature today.

In theory, any combination of cold head and compressor is possible. In reality, fine tuning and optimization is inevitable. Although this is an enabling technology for HTS-machines, the development progress is slow. On one hand, the developers of HTS-machines are focused on their technologies and challenges. On the other hand, for developers and sellers of cryorefrigerators, there is no addressable market for new products yet. Accordingly, the willingness to invest in developments particular to HTS machine requirements is limited.

4.4. Stator cooling

Effective stator cooling is the basis to achieve a stator winding with a large effective current density. To keep up with the goal of a compact machine, more intensive stator cooling is required for HTS machines with their down-sized rotor dimensions. Two different cooling schemes are in use. The more conservative method is the air-cooled stator as used in Siemens HTS machines. An innovative option is the liquid-cooled stator. Here, the complete stator winding is submerged into dielectric insulating oil. Another possibility is to run cooling water in cooling ducts through the stator winding. This method is already common with large utility power generators.
4.5. Development of Computational Tools
For conventional machines, analytic design routines are able to calculate the machine characteristics with good precision as the magnetic flux density is comparatively constant within discrete sections. It is not always reasonable to adapt such analytic routines to HTS design peculiarities, e.g., an airgap stator winding as typically applied for high power density machines. Hence, numerical simulations play a more significant role in HTS machine design. Major issues to be considered are:

- HTS materials are sensitive to AC fields. Usually, there are other metallic components in the cold parts of the machine. Thus, eddy-currents have to be regarded carefully. This is especially true for HTS motors that are operated in a drive configuration with a power converter. The harmonics generated by the inverter create eddy current/AC losses in the cryogenic part of the rotor and, therefore, should be shielded effectively.
- High-power HTS-machines are comparably short, with also a large magnetic airgap. This small ratio of active length vs. airgap length causes extreme fringing of the airgap field. Therefore, FE calculations using 3D modelling are required.
- Possible failure scenarios like short circuit have to be analyzed in order to guarantee mechanical and electrical integrity of the machines as required by common standards. Special attention is needed for specific components like the torque tubes and HTS windings, but also the stator airgap winding.
- Software tools for simulating drive systems consisting of HTS motors and power converters need to be updated with equivalent circuit models for HTS machines that e.g. consider frequency-dependent reactance or damping.

Further information regarding numerical calculation of HTS machines can be found in [12]. Many items are new and completely different to conventional machines. Experiences with HTS-machines for verification are limited. Each competitor works on own solutions for the benefit of a unique selling proposition. The ability to provide realistic performance predictions for prototypes under these difficult circumstances will be a key capability.

4.6. Development of Robust Manufacturing Processes and Acceptance Tests
HTS-machines have to evolve into products from today’s unique laboratory-manufactured items. To minimize production costs, the “off-the-shelf” HTS machine, or at least a standardized manufacturing process, has to be developed. This is required from the QA point of view of the manufacturer, but it is also in the interest of the customers that do not have to become specialists in HTS properties and cryogenic technology. There is a need for standardized factory acceptance tests that may be modified compared to those of conventional machines. Also special test procedures for the HTS-machines’ specific components, e.g. voltage testing for HTS windings which operate at “zero” voltage under regular conditions. Obviously, there are activities going on in this field, however, with little public recognition.

5. Conclusions
We tried to point to the essentials of different ongoing development approaches in worldwide competing teams trying to establish a HTS excited high power synchronous machine. A lot has been already achieved, many lessons have been learned. Also a couple of present technical challenges are addressed, whose solutions will be critical parameters when it comes to the competition of HTS machines as products on a market. Probably there is no single “best practice”, as there are different applications and customer interests.

With successful continuing developments in the areas of supporting technologies (HTS wire, cryogenic refrigeration, and power electronic rotating exciters) in conjunction with the machine manufacturers’ efforts to develop robust and reliable high-performance plus highly efficient HTS machines, we may see a first market entry of HTS technology in the niche of compact high-power ship propulsion in the years to come.
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