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UDT 2019 – Technology trends and challenges for superconductor-based ship propulsion

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Abstract — The manufacturing of high-temperature superconductors (HTS) has reached a phase where large and continuous production of wires, coils and magnets allows for their commercialisation at competitive prices, leading them to become the game changers in all-electric and hybrid naval propulsion systems. In this work the use of HTS technology has been evaluated for propulsion systems with different technological maturity, i.e. podded systems, rim-driven propellers and MHD propulsion. Current trends and challenges on the development of HTS-based podded propulsion systems will be discussed. Rim-driven propulsion is an emerging technology offering higher controllability, efficiency and flexibility than systems with shaft. The use of HTS technology will reduce the size of the rim and consequently improve the hydrodynamic efficiency of the system. Thus, existing HTS-based Rim-driven concepts will be reviewed and discussed. Finally, HTS as a key enabling technology for disruptive approaches to ship propulsion such as the MHD will be evaluated.

1 Global Trends and Drivers for Electric Ship Propulsion

The need for propulsion systems that can provide high efficiency, compactness, high reliability and still offer low cost is ever-increasing. Current global trends are increasingly pushing naval markets to transition from traditional propulsion systems to electric-based systems. One such example is the movement towards 'Green Shipping', motivated by increasing energy prices, cost management and environmental awareness, which has seen the introduction of increasingly restrictive emission and particulate regulations, thus encouraging a shift to more sustainable electric propulsion.

In recent years manufacturers of commercial marine crafts, such as mega-yachts and cruise ships, have become aware that new propulsion systems can take great advantage of electric drives specifically designed for marine applications. Notable examples include the world' first cruise ship to be powered by liquid hydrogen, developed by Viking Cruises [1] and the world's first fuel cell powered passenger ship, the 'Alsterwasser'. The 50kW fuel cell means zero emissions and noiseless transport was built by Proton Motor Fuel Cell GmbH within the framework of the EU sponsored Zemship project [2] and embarked on her maiden voyage starting 2008.

Further drivers for the move to electric propulsion include changing shipping patterns brought about by shifting demographics, economic developments and increased shipping levels. This leads to operations in more extreme environments, as can be seen with the Arctic Challenge, which also allows for potential resource extraction via deep-sea mining and eventual Arctic oil and gas production. Thus, the need for vessels that can provide more efficient power and sailing is of high interest to naval markets [3].

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Fig. 1. Summer sea-ice extent and possible shipping routes in the Arctic sea [4].

Indeed, the Arctic Challenge presents a unique example of the need for high-power, efficient electric propulsion systems. Economic and geopolitical interest in the Arctic sea has risen in the last decade, becoming a major concern for neighboring countries such as Russia, Norway, Denmark, Canada, and the USA. The shrinking ice cap has opened new maritime routes and made previously inaccessible oil and gas reserves available, thus the region has become increasingly interesting. The Arctic sea is a vast and hostile environment where a small number of submarines and surface vessels need to cover large distances, leading to long lasting mission scenarios which require high-power, efficient propulsion systems. As the shift from conventional propulsion to electric becomes more of a reality, the need for a suitable alternative increase. High-temperature superconductors are key enabling technologies that have the potential to dramatically disrupt naval electric propulsion markets.

2. STATE-OF-THE-ART HIGH-POWER ELECTRIC NAVAL PROPULSION SYSTEMS

The current state-of-the-art electric propulsion solutions are characterised by a high level of flexibility and variance in terms of power production, transmission, and propulsion, depending on the type of ship, the operational profiles, and technology available at the time of construction [5]. While the majority of ship types using electric propulsion include cruise vessels and Icebreakers, the use of electric propulsion systems is gradually expanding to other vessel types such as dredgers, special construction vessels, and ferries. This is caused in part by specific operational requirements, such as those outlined above in the case of the Arctic challenge. Today, however, electric propulsion has three main application areas: ocean going vessels such as cruise ships and LNG carriers; station keeping vessels, such as DP drilling vessels, OSVs and OCVs; and icebreaking vessels.

Fig. 2. Examples of different marine electric propulsion systems [5].

Propulsion systems for ocean going vessels must be designed with the criteria of a specific vessel speed, but with the ability to operate at different speeds, and with the purpose of supplying one or two main propellers in the range of 20-25 MW. High-end cruise ships commonly use azimuth thrusters due to the improved efficiency and manoeuvrability they provide, as well as the low noise and vibration levels, and a certain degree of flexibility in the design of the engine room. The electrical power and propulsion for cruise ships is usually provided by medium voltage equipment with the main electrical power distribution performed on 11kV systems. Between four and six 11kV diesel generators feed the main switchboard, and subsequently the propulsion drive system, usually 3.3kV, is fed via propulsion transformers.

The technologies used for generating energy are characterized by relatively low efficiency ratios. Fuel cells may have a very high potential in this respect. Their development has enabled attempts to use them in all modes of transport. An important factor in the development of fuel cells is their relatively high efficiency and the strict emission norms from internal combustion engines used to power maritime transport. Several fuel cell technologies are under consideration to substitute or hybridise conventional gas or diesel turbines for the production of energy [6]. The efficiency of some of these systems for different power levels are shown in Figure 3.

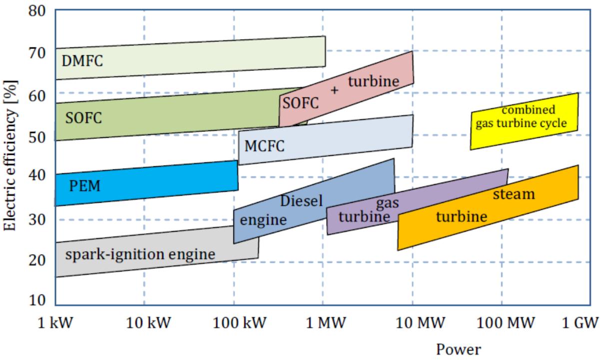

Fig. 3. Electric efficiency of the systems according to their production technology. (DMFC - direct methanol fuel cell; MCFC - molten carbonate fuel cell; SOFC - solid oxide fuel cell; PEM - proton exchange membrane) [6].

Due to changes in the LNG Carrier business, i.e. the shift from long-term chartered vessels on fixed routes to short term, spot trading of LNG, electric propulsion has become an attractive option. Here, electric propulsion is similar to that of cruise vessels, containing two independent converter lines supplied by a two-split switchboard. The main difference is that LNG Carriers mostly consist of a single propeller with a reduction gear between propeller and propulsion motors. This allows for the use of medium speed electric motors which are smaller than slow speed counterparts. LNG normally operate at around 6.6 kV with a cargo plant of approximately 10 MW.

As the name suggests, the main goal for station keeping vessels is to maintain their position to perform an operation. This requires that thruster units be designed and optimised so that the maximum thrust can be achieved at zero knots. Compared to the above criteria, this is remotely different from ocean going vessels, i.e. electric propulsion designed for a specific speed, thus showing the flexibility in architecture design offered by electric propulsion solutions. The main goal for station keeping ships is safety and redundancy, rather than efficiency. DP systems generally consist of three subsystems: the power system, the thruster system and the DP control system. The design aim is so that if a single fault within the DP system occurs, the loss of the affected component does not negatively impact the operation of the ship. The power plant is operated with an open transfer breaker between the main switchboards in order to increase safety and achieve 100% blackout free operation. The drawback of such systems is that the total power produced by the propulsion engines is higher than necessary and represents a lower overall efficiency than the optimal point of operation. Between five to eight thruster and propulsion units are installed into the vessel at both stern and bow and range from 1 to 6 MW.

DP drilling vessels have two basic designs: ship or rig, both with similar power and propulsion system architecture with six to eight thrusters, and six to eight generators. Usually, a drillship has six diesel generators with either one or two at each split, and a drill-rig has eight diesel generators in either 4 or 8 splits. The total installed power is typically in the range of 40 to 50 MW, and the voltage level is therefore usually 11kV on the main switchboard. The thruster drives can either be at 690 V or 3.3kW, depending on the thruster sizes, which range from about 3MW for rigs up to 5.5 MW for ships.

Offshore Support Vessels and Offshore Construction Vessels represent a wide range of variations in terms of operational characteristics, sizes and designs. They are considerably smaller than the ship types outlined above, falling around the 10 MW mark, with some examples up to 20 MW. Today, the majority operate on diesel-electric propulsion systems.

Icebreakers and other ships dealing with harsh arctic conditions have the main priority of being conditioned for navigation in icy territories, with the added need for certain oceangoing capabilities. Increased traffic in arctic areas leads to the need for a trade-off between a high bollard pull demand, propeller over-torque, and open water efficiency. Variable speed electric motor drives are the proven technology for icebreaking operations because of the high over-torque capabilities and accurate torque response of the electric motor drives.

3. PRODUCTION OF 2G HTS WIRES, COILS AND MAGNETS

Since the development of Yttrium-Barium-Copper oxide YBCO in 1987, the improvement of second- generation (2G) rare earth barium copper oxide-coated conductors (CCs) has been a triumph of scientific insight, sophisticated processing and determined scale-up efforts. These CCs are promising for superconducting magnet applications because of their high Ic density, low dependency of the Ic on the external magnetic field, good mechanical properties and reasonable cost, which offer opportunities to develop ultra-high-field magnets [7]. For the CC made by THEVA, Yttrium is replaced by the rear earth element Gadolinium leading to improved properties of the CC. The superconductor tapes are produced as a multi-layer system on a substrate, which is a Nickel Chrome alloy. The layers consist of an initial MgO buffer layer applied with Inclined Substrate Deposition, followed by a second MgO buffer layer, an HTS film and a silver contact layer, see Figure 4.

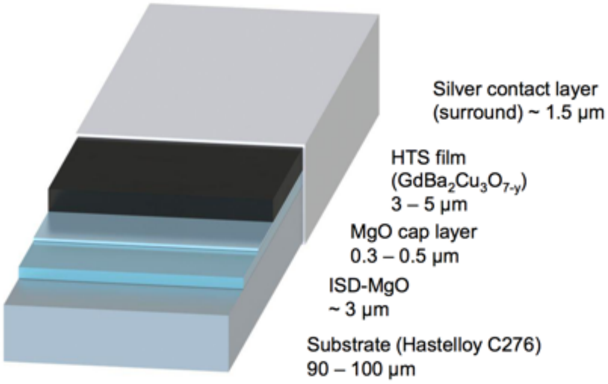

Fig. 4. THEVA's Type 2G HTS tape architecture.

All the layers are deposited by Electron Beam Physical Vapor Deposition (EB-PVD), which is a well-known and scalable technology for producing thin films on industrial scale. This technology offers advantages such as high evaporation rates, low substrate temperature, flexibility on selecting evaporation materials, a high performance due to quality consistence along the length of the tape and lastly, tunable performance enabled by varying the superconducting layer thickness.

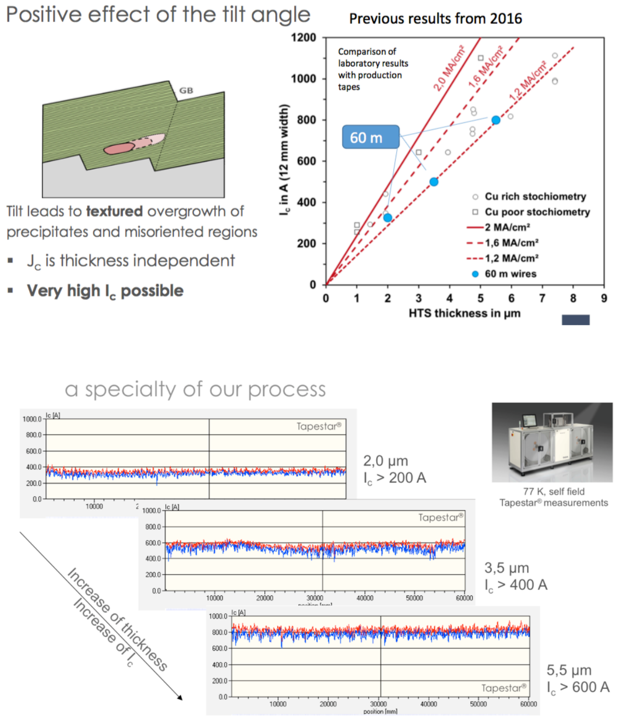

Fig. 5. Tunable performance of THEVA's HTS tapes © Copyright THEVA Dünnschichttechnik GmbH.

This high level of maturity has led to achieving a market situation of economies of scale. The worldwide installed capacity for 2G HTS tapes is around 1,000 km/year. THEVA, located in Munich, Germany, has the largest production capabilities in Europe, with a production capacity of 120 km per year (12 mm wide wire). High throughput, low material costs and a high yield, critical factors for success, were demonstrated with this production already. Further increase in demand is expected so that the price of the CC will decrease due to economy of scale as well as on-going improvements of production technology. An outline of the value chain for HTS materials is provided below:

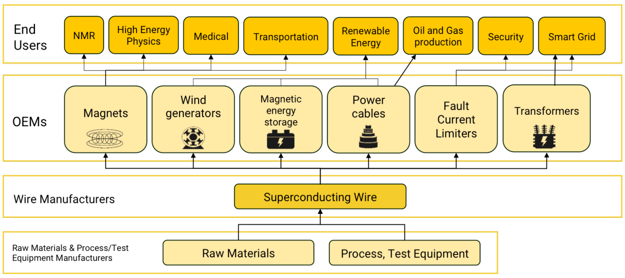

Fig. 1. © 2017 Copyright PI Integral Solutions based on Venkat Selvamanickam, (2014): Recent Advances in High Temperature Superconductors and Potential Applications, University of Houston.

In the EU-funded EcoSwing project [8], aiming to develop and demonstrate the world's first superconducting, low-cost and light weight wind turbine drivetrain, HTS YBCCO tapes were provided by THEVA. The project designed, developed and manufactured a full-scale multi-megawatt direct-drive HTS wind generator. The generator will be installed in the GC-1, a 3.6 MW wind turbine with a rotor diameter of 128 m, full power converter and direct-drive permanent-magnet generator. The weight of the generator is expected to be reduced by 40% compared to commercial equivalents, and a reduction of 40% in cost is also expected. The aim is to advance the TRL of HTS generators from 4-5 to 6-7 and prove that large-scale superconducting drive train technology can be cost-competitive. As of December 2018, the HTS generator has become grid connected and is producing power, thus becoming the world's first wind turbine with a grid connected superconducting generator.

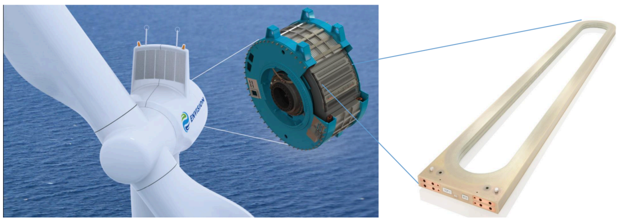

Fig. 2. Assembly schematic of HTS coils from TEHVA for the EcoSwing project [9].

The stator for EcoSwing was manufactured by Jeumont Electric, a key manufacturer of electrical motors and generators for various applications. For more than a century, Jeumont has been manufacturing motors for a broad range of applications. They have experience in manufacturing permanent-magnet synchronous motors and associated components. Their motors can run with variable speed drives up to 8,000 rpm and a rated power between 4 MW to 40 MW. Using HTS technology developed within EcoSwing, they managed to reduce the size of the reference permanent-magnet motor by 25%.

4. CURRENT TRENDS AND CHALLENGES FOR HTS-BASED PROPULSION SYSTEMS

HTS technology in ship propulsion is implemented in motors with a wide range of powers between 1 and 36.5 MW. Kawasaki developed a 1 MW-class HTS motor [10] operating at 190 rpm for podded ship propulsion, which led to a reduction of the size of the stern hull and improved the hydrodynamic efficiency. More recently, they build and tested successfully a 3 MW-class motor operating at rotating speeds between 20 and 160 rpm and loads up to 180 kNm with efficiencies of 98% [11].

Recently, in 2016, AMSC and Northrop Grumman Corporation successfully tested the most powerful HTS ship propulsion motor for the U.S. Navy with a power rating of 36.5 MW representing a 14:1 ratio increase over the previous 5 MW machine [12]. The motor is less than half the size of conventional motors and a third of the weight. The motor passed the full power test by the end of 2008, operating for 21 hours. The motor can operate at 120 rpm and produces 2.9 million Newton-meters of torque and is being successfully designed for naval propulsion in next-generation Navy warships with the possibility of direct commercial application in large cruise ships and merchant vessels.

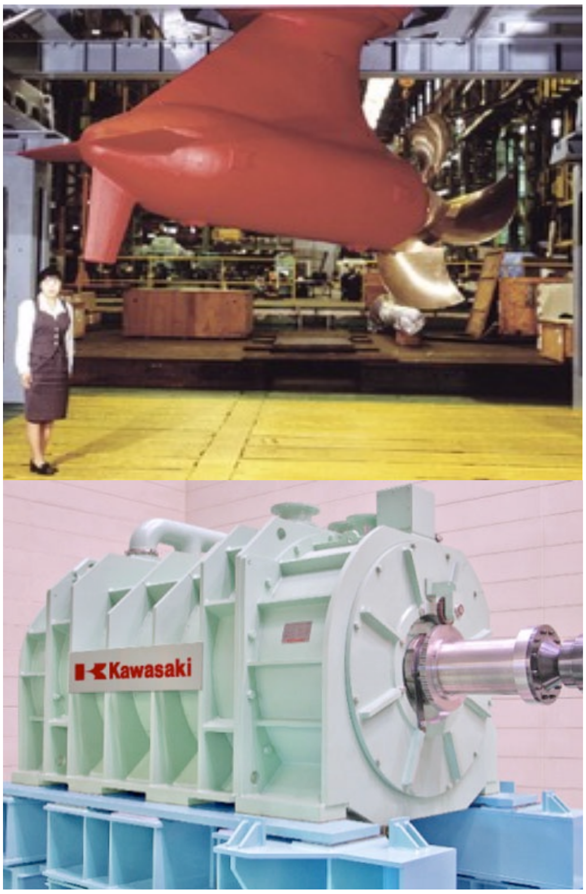

Fig. 3. (up) Pod from Kawasaki mounting the 1 MW-class HTS motor [10], and (down) external view of the 3MW-class HTS motor from Kawasaki [11].

Other such efforts in HTS motors are taking place at Siemens in Germany where a 380 kW (1500 rpm) motor was developed and tested in 2011 and later extended to a 4 MVA generator. The HTS motor successfully demonstrated the expected features, both mechanically and electrically. The cryogenic cooling input was low, leaving some margin for the capability to deliver excitation flux for 4.5 MW or more. Furthermore, the motor demonstrated around 25% reduced weight and size compared to conventional motors and the efficiency showed an improvement of 1.5% [13]. Two 4.7 MW HTS motors from Siemens are installed on German frigate 125 and they are combined with diesel and gas generators of 12 and 20 MW respectively [14].

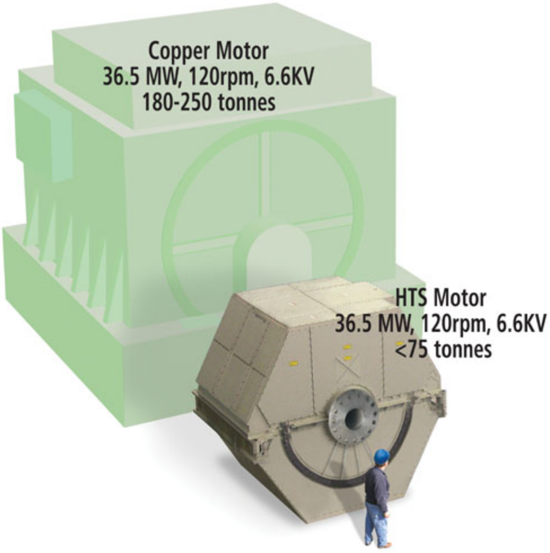

Fig. 4. Size comparison of conventional propulsion 36.5 MW motor and the equivalent using HTS technology tested for U.S. Navy [12].

A new class of marine propulsion motors, that achieves power density far superior from that obtained in conventional superconducting synchronous motor designs, was accomplished through the use of a novel coil design called the “double-helix” (DH) coil for the superconducting rotor of a synchronous machine in conjunction with a superconducting stator, and the use of a flux pump [15]. This led to high current excitation in a completely superconducting circuit without any external connection to the machine frame that penalizes the motor efficiency due to heat losses. A schematic of the DH coil and the flux pump mechanisms is shown in Figure 10.

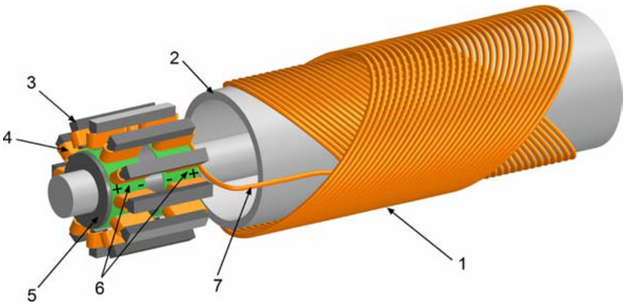

Fig. 5. 24-element drum type HTS flux pump connected to a double helix rotor (1). (2) Torque tube support for coils. (3) Stationary core for flux pump excitation magnet. (4) Externally controlled excitation coil (Permanent magnets are an option also.) (5) Rotating iron core of flux pump assembly. (6) Rotating HTS flux gates (thin cylinders, shown in green). Polarity of induced voltage shown and the elements are connected in parallel (not shown). (7) Coil lead (+) connected to flux gate. Other lead (-) is connected to the parallel connection (-) between flux gates (not shown) [15].

5. DISRUPTIVE APPROACHES TO ALL-ELECTRIC SHIP PROPULSION

The HTS capability of generating extremely large magnetic fields in very compact systems opens the door to disruptive approaches for generating thrust.

The circulation of seawater within a volume with perpendicularly applied electric and magnetic fields accelerates the ions and generates a stream discharge, which produces the thrust, see Figure 11.

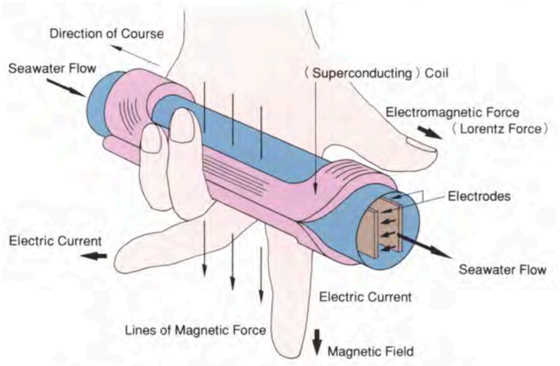

Fig. 11. Lorentz forces acting on the seawater ions when passing through perpendicularly applied electric and magnetic fields.

Already in 1985, the Japanese YAMATO-1 demonstrated the feasibility of an MHD thrusters for marine propulsion. It mounted two thruster units of six 3 m long HTS saddle coils generating a cross field of 4 T and producing a thrust of 16 kN. A schematic of the YAMATO-1 MHD thruster is shown in Figure 12.

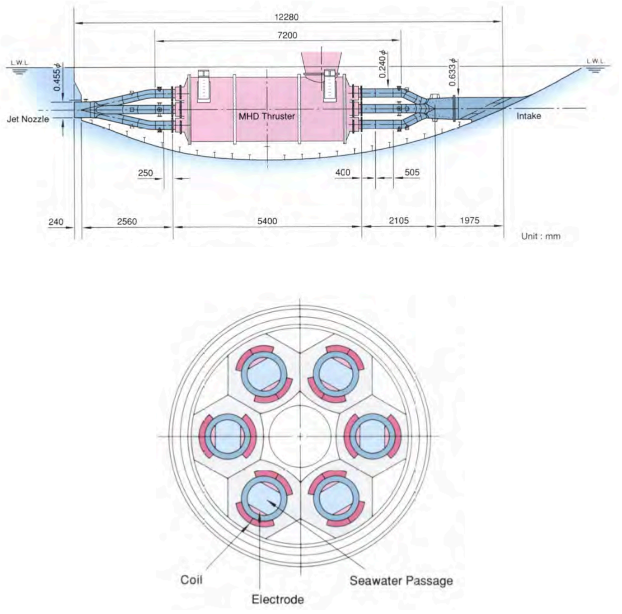

Fig. 12. MHD Thruster location in the Hull (top) and cross section view of the six discharge channels with the respective coils and electrodes (bottom).

Other MHD ship propulsion prototypes have been developed in China, where a 1 tone model ship operating at 4.7 kW and generating a field of 5 T achieved a modest thrust of bout 40-45 N [16]. Follow up experiments using up to 15 T where planned but not yet reported.

6. CONCLUSIONS

Electric propulsion systems allow for system architectures with higher flexibility, in particular for the use of pods, as well as the use of alternative power generation systems, such as fuel cells, and using liquid hydrogen as propellant. The use of HTS in electric propulsion systems is a key enabling technology to missions demanding efficient, compact, low noise and low electromagnetic signature high power propulsion systems. HTS-based motors provide higher mission success thanks to an important mass and volume reduction as compared to the conventional copper-based designs. The production capabilities of 2G HTS basic elements such as cables, bus bars, coils, magnets and foils has reached a state, where the deployment of this technology in transportation and defence is feasible and it is already included in the portfolio of the naval industry for the next generation of surface and underwater vessels.

High power density and efficiency can be achieved with the use double helix coil designs and integrating flux pumping systems for the magnetisation of the HTS coils.

The possibility with 2G HTS technology of generating efficiently very high magnetic fields, opens the door to disruptive technologies such as MHD propulsion, the development of which have been limited so far to a few technology demonstrators and laboratory prototypes.

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He is a senior expert in high temperature superconductors and studied physics at the Technical University Munich (TUM). He received his PhD at the physics department in 1998 for the development of bi-axially textured buffer layers on metal substrates. He is one of the founding members of THEVA. In 2010 he developed the coated conductor production line and now leads the business development. He was responsible for the development of the HTS coils within the EU funded EcoSwing project.