Karlsruher Institut für Technologie

ITEP – Institute for Technical Physics

Results of Research and Development
2020 Annual Report

Imprint

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Technology demonstrator of a 10 kW superconducting generator with no-insulation HTS excitation coils before assembly.

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Contents

Preface

The Institute of Technical Physics (ITEP) sees itself as a national and international competence centre for fusion, superconductivity and cryotechnology with the research fields

- Superconductor and cryomaterials
- Power engineering applications of superconductivity
- Superconducting magnet technology and
- Technologies of the Fusion Fuel Cycle

The work of the ITEP is anchored in the long-term programmes “Fusion”, “Storage and Networked Infrastructures” and “Matter and Universe” of the Karlsruhe Institute of Technology (KIT) and the Helmholtz Association of German Research Centres.

Very large and unique experimental facilities, laboratories and the corresponding technical infrastructure are available to deal with the complex and mostly multidisciplinary tasks. These are, for example, a laboratory for the development of superconducting energy technology components, a laboratory for the development of superconducting materials, the high-field magnet laboratory for the development of superconducting magnets of high fields, the cryogenic high-voltage laboratory for the investigation of the high-voltage strength of cryogenic insulating materials and the cryogenic material laboratories for the investigation of electrical and mechanical properties at very low temperatures.

In 2020, our institute achieved very nice scientific results, a large number of successful developments and some special challenges and events were mastered, which we will briefly discuss in the following. We would like to highlight two special awards.

Privatdozent Dr. habil. Francesco Grilli was awarded an Adjunct Professorship of the KIT Faculty of Electrical Engineering and Information Technology. With this award, the faculty honors the many years of excellent contributions of Dr. Grilli in research and teaching, which have already been honored several times in the past.

Figure 1: Dr. Grilli (center) is presented the certificate by the Vice Dean of the Faculty, Prof. Holzapfel (right).

Dr. Giovanni de Carne has succeeded in acquiring a Helmholtz Young Investigator Group for the development of multi-modal hybrid networks. This gives internationally outstanding postdocs the opportunity to establish their own research group and to increase the visibility of their own research.

In the **research field of superconductor and cryomaterials,** the investigation and further development of YBa2Cu3O7 tape conductors is an important focus. In 2020, definite screening design was applied and established as a new method in the fabrication of high temperature superconductors. This is a very effective method for narrowing the parameter space for the fabrication of complex materials whose quality depends on a large number of growth parameters. An enabling research project of FUSION for the development of high-strength structural materials for magnets was successfully completed. Materials were produced and characterized that have very high strength (>1000 MPa) and sufficient fracture toughness at temperatures of 4.2 and 77 K, respectively. Several new projects were started. These include a DFG project on the simultaneous description of the caloric and thermal properties of cryogenic mixtures of materials and a joint project within the framework of aeronautics research on the development of hybrid designs for high-performance electric motors by means of additive processes and fiber composite-metal hybrid designs for use in cryogenic environments in hydrogen atmospheres.

In the **research field of power engineering applications,** the design of a modular busbar was finalized and preparatory material characterizations carried out in a joint project for the development of a superconducting industrial busbar with a current strength of 200,000 amperes. Furthermore, a new joint project for the development of a very compact 110 kV, 500 MVA superconducting cable for the inner city of Munich was started. Our task here is the complete electromagnetic and thermal modeling of the cable system. Our power hardware-in-the-loop laboratory was further expanded after the first successful start-up in 2019 and high dynamic measurements were performed with a flywheel storage system. Furthermore, the modeling and real-time integration of a mini combined heat and power system and a micro gas turbine have progressed to the point where the hardware setup is largely complete and the first commissioning has already taken place.

An important task in the **research field of superconducting magnet technology** is the development of high-temperature superconducting magnets. As part of a joint project to develop and compare concepts for fully superconducting wind power generators, very precise models were developed to show how AC losses in the stator can be reduced by more than 80 % by optimizing the arrangement of the superconducting windings. In our own development of a superconducting wind power generator with direct current, the winding setup was built, pre-tested and assembled to such an extent that final tests can be carried out in 2021. As part of an international cooperation between the EU and China, a high-temperature superconducting conductor sample of the cross-conductor patented at ITEP was developed for quench investigations under fusion-relevant conditions, and a sample length of the cross-conductor of more than 50 m was successfully manufactured and tested. Furthermore, the winding laboratory was extended by a robotic winding technique with three multi-axis robots, in which superconducting 3D coils can be manufactured in the future.

In the **research field of fusion fuel cycle technologies,** we are developing fundamentally new vacuum technologies and processes for tritium extraction and recovery. In 2020, a great deal of preparatory work and reviews were carried out for the new European fusion program from 2021 to 2027. The detailed design of the cryopump system of the JT-60SA fusion facility was completed and tendered for fabrication. In the complex system, disturbances due to quench events and earthquakes were investigated in addition to normal load cases. A first application of our modeling tools took place in a stellarator, where the simulation and design of the transition flow in the divertor was performed for the W7-X plant. In the research field of vacuum hydraulics and hydrogen separation, a mercury ring pump from the THESEUS plant was removed and disassembled for the first time. This allowed very valuable experience to be gained in handling and maintenance. In the future, significantly longer service lives can be expected. In hydrogen separation, the HESTIA (Hydrogen Experiments for Separation with Temperature Initiated Absorption) facility for studying the separation of hydrogen isotopes within the fusion fuel cycle was completed.

In education, a total of 31 PhD students were supervised by members of our institute in 2020, as well as 5 master's students and 20 bachelor's theses.

In 2020, many special challenges arose due to the Corona pandemic and we would like to take this opportunity to sincerely thank all our staff members as well as all cooperation partners from universities, research institutions and industry for your understanding of the numerous restrictions and your prudence in taking the necessary measures. We look forward to further cooperation in 2021 and wish you all the best.

Yours Sincerely

Mathias Noe Bernhard Holzapfel

Tabea Arndt

Cabling of low-loss, high current HTSC ROEBEL cables within a joint KIT-CERN research collaboration to develop HTSC dipole magnets for accelerator storage rings

Results from the Research Areas

Superconductor and Cryogenic Materials

Coordination: Professor Dr. Bernhard Holzapfel

The understanding of superconducting materials, the the characterisation of material properties at cryogenic temperatures and the realisation of conductor structures form the basis of any superconducting power or magnet application. Within the research field of superconducting and cryomaterials the ITEP is currently working on the following research topics:

- Superconducting materials
- Conductor concepts and technologies
- Cryogenic properties of substances
- Materials for cryogenic applications

Superconducting Materials

The focal points of this research topic include basic material science tasks, such as the improvement of the electrical transport properties of established superconducting materials, as well as application-oriented investigations of promising superconductors and the industry-related technological development of HTS Coated Conductor synthesis

High-temperature superconductors

In a comparative study of different rare earth elements (RE) in $REBa_2Cu_3O_{7-x}$ films (REBCO, RE = Y, Nd, Sm, Gd, Dy, Ho, Er, Yb) produced by chemical solution deposition (CSD), their physical and microstructural properties were investigated in detail [Erbe et al. SuST 33 (2020) 094002]. Contrary to the general view in the literature, which postulates increasing T_c values with increasing radii of RE, most of the lanthanoid-based REBCO films investigated here showed a very similar level of at the highest T_c values of about 94 K. The self-field J_c values at 77 K showed a similar picture with values between 5 and 6 MA/cm². Only the very large and small lanthanoids neodymium and ytterbium showed larger difficulties in phase formation and were therefore excluded from the analysis. The same applies to yttrium itself, which as a non-lanthanoid showed slightly lower values despite similar ion radii. Another interesting finding was the strong binding of T_c of most RE to an ideal c-axis parameter; only Sm showed significantly more leeway with an increasing decrease of T_c with increasing values of c, whereas Dy showed almost no influence of c on T_c over a wide range, Figure 1.

In further studies related to possible pinning enhancement in CSD-grown REBCO films, samples with mixed rare earths and/or additional perovskite nanoparticles were investigated. For the first time, we have prepared such mixed-RE films by CSD with large RE ion size difference, in particular Sm and Yb [Cayado et al., R. Soc. Open Sci. 7: 201257] and showed that the mixed phases $Yb_{1-x}SmxBa_2Cu_3O_7$ can be especially beneficial at low temperatures. $BaHfO_3$-containing CSD-grown REBCO films were investigated thoroughly regarding growth, microstructure, and transport properties: For $BaHfO_3$ nanoparticles grown via the so-called ex-situ process, i.e. from preformed ZrO_2 nanoparticles in the precursor solutions, especially the pyrolysis process had to be adjusted for obtaining a homogeneous nanoparticle distribution necessary for enhanced pinning properties. Medium ramp rates and low pyrolysis temperatures are necessary to avoid large interfacial densities of nanoparticles, which deteriorate the microstructure and hence the transport properties of the REBCO matrix [Cayado et al., Sci. Rep. 10, 19469 (2020)]. The pinning mechanisms of such nanocomposites in high fields up to 20 T were elucidated on a GdBCO-$BaHfO_3$ nanocomposite grown by the in-situ phase formation method (i.e. with nanoparticles growing during the GdBCO growth process). Regions in temperature, field and orientation of ab-planar intrinsic pinning (vortex trapping and lock-in) as well as extrinsic pinning at the $BaHfO_3$ nanoparticles were identified [Iida et al., SuST 34 (2021) 015009].

Scanning transmission electron microscopy (STEM) in combination with chemical analysis by energy-dispersive x-ray spectroscopy (EDXS) is a powerful technique to investigate the microstructure of such nanocomposite thin films. Different types of defects on the nanometre scale have a direct influence on the superconducting

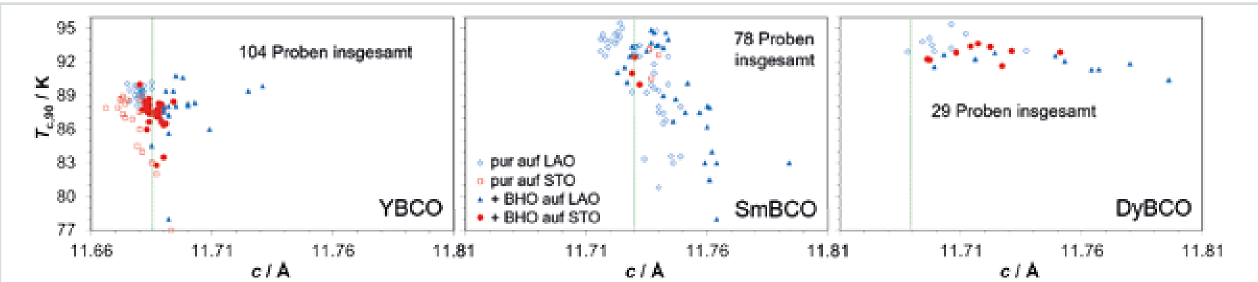

Fig. 1. Dependence of the critical temperature T_c on the c-axis lattice parameter for YBCO, SmBCO, and DyBCO.

properties. For example, the embedded $BaHfO_3$ nanoparticles can be identified by their Hf signal (red, Figure 2a) to determine their size, shape and distribution. The nanoparticles of roughly 20 nm size are homogeneously distributed within the film. In addition, RE-oxides (green, Gd) were observed near the interface to the SrTiO3 substrate (yellow). High-angle annular dark-field (HAADF) STEM imaging shows the atomic structure of such nanoparticles and the surrounding film. In HAADF-STEM, the image intensity directly correlates with the mean atomic number and heavier elements appear brighter. The RE-oxide does not directly grow at the substrate interface but after a single REBCO layer (Figure 2b). BaHfO3 nanoparticles are randomly oriented and can introduce additional planar defects (arrows, Figure 2c). Analysis by electron microscopy is done in cooperation with the Laboratory for Electron Microscopy (LEM) at Campus South.

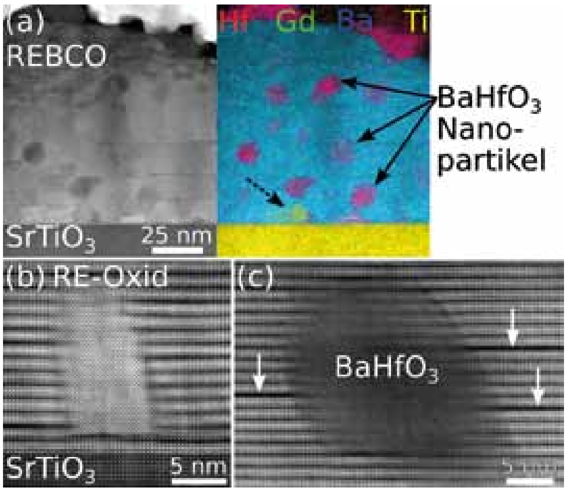

Fig. 2: Microstructural characterization of a ~200 nm REBCO-$BaHfO_3$ nanocomposite thin film on $SrTiO_3$ substrate by analytical and atomic-resolution STEM. (a) HAADF-STEM cross-section image and corresponding superimposed elemental distribution maps of Hf, Gd, Ba and Ti. The $BaHfO_3$ nanoparticles are evenly dispersed in the REBCO matrix. The formation of RE_2O_3 near the substrate interface is visible (dashed arrow). Atomic-resolution HAADF-STEM images of (b) RE_2O_3 near the substrate interface and (c) a $BaHfO_3$ nanoparticle. The latter introduced planar defects in the REBCO matrix (marked by arrows).

To improve CSD-grown $REBa_2Cu_3O_{7-\delta}$ thin films requires optimizing several process parameters such as crystallization temperature (T_{crys}), oxygen partial pressures (p_{O2}), total pressure, dew point and dwell time. A common method is the so-called one-factor-at-a-time experiment, where only one parameter is changed, while keeping all the others constant. This is not only very extensive but also incomplete, because interaction between parameters cannot be detected.

A novel method in the field of Design of Experiments (DOE) is Definitive Screening Design (DSD), where every parameter (factor) is set to three levels (high, mid, low). DSD enables estimating main effects (the first-order effect of a single factor), two-factor interactions (the correlation between two factors) and quadratic effects in a linear model, while reducing the necessary number of experiments as much as possible. We use this screening technique to investigate the improvement of self-field critical current density at 77 K ($J^{sf}_{c.77}$) for $ErBa_2Cu_3O_{7-\delta}$ thin films on IBAD substrate [Hayasaka et al., Sci. Rep. 10 (2020) 19934], which lead to the following model:

$J^{sf}_{c.77}$ = 2.737–0.417(T_{crys}–780)/10+0.531(p_{O2}–225)/75–0.623 (Dew–19)/3 –0.654{(p_{O2}–225)/75}^{2}

Fig. 3 (a) shows the dependency of $J^{sf}_{c.77}$ on dew point and T_{crys}: lower T_{crys} and lower dew points are crucial for improving $J^{sf}_{c.77}$. Fig. (b) confirms the validity of the model showing the $J^{sf}_{c.77}$ values of further samples (15-26) together with their 95 % prediction intervals (PI95%). Most of the data fall inside this prediction interval.

Similar optimizations via DSD have been undertaken for YBCO-$BaZrO_3$ nanocomposite films from solutions with preformed ZrO_2 nanoparticles [Rijckaert et al., submitted].

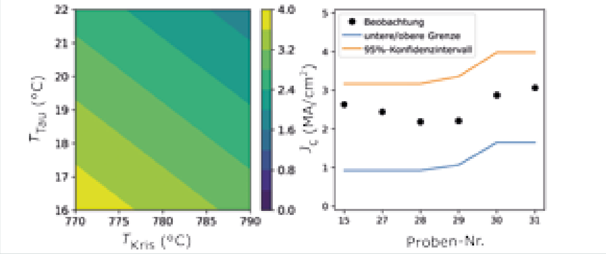

Fig. 3: Dependence of $J^{sf}_{c.77}$ on humidity and T_{crys} at fixed p_{O2} (left) and model confirmation for $J^{sf}_{c.77}$ (right).

In the field of superconducting REBCO films grown by pulsed laser deposition (PLD), we focused on the influence of the oxygen annealing procedure on structural and transport properties. Oxygen annealing is an important step during thin film preparation, since it is responsible for the formation of CuO chains and creation of the superconducting phase. To study in-situ (in PLD chamber) and ex-situ (in tubular furnace) oxygen annealing, PLD-grown GdBCO thin films were treated with different oxygenation routes with variation of parameters such as annealing temperature, annealing time, oxygen pressure, and cooling rate. The ex-situ oxygen annealing with an increase of in-field critical current densities by a factor of 2 showed a clear advantage compared to the in-situ route, Figure 4. For both processes, the highest self-field and in-field critical current densities are achieved at low oxygenation temperatures. For both loading methods, the highest critical current densities are achieved at low loading temperatures, whereas somewhat higher loading temperatures are required for nanocomposites (GdBCO-$BaHfO_3$).

These oxygenation studies were also extended to CSD-grown YBCO films on technical substrates. The films supplied by our partner Dnano were oxygenated during different holding times at 285 °C in order to study the kinetics of the oxygenation process. Some of these films were coated with silver in order to investigate its role in the oxygenation process.

During our investigations on PLD-grown $YBa_2Cu_3O_7$ films on different substrate materials, we observed a crack formation in films deposited on LSAT single crystals. The characteristic course parallel to the a- or b-di-

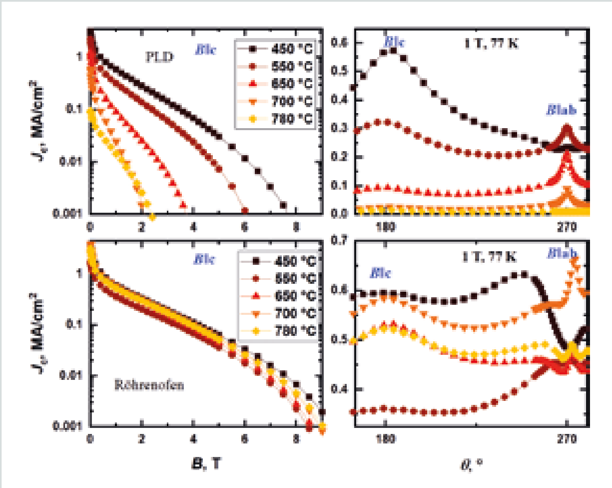

Figure 4: Field (B||c) and angular dependence (at 1 T) at 77 K for different oxygen annealing temperatures.

rection of the crystal structure indicated crack formation due to thermal stress during cooling after deposition, Figure 5. However, they only occur after annealing with oxygen, so that a connection with the formation of ab-axis twins seems to exist. The formation of the cracks is largely independent of the annealing temperature but only occurs during too fast a cooling process.

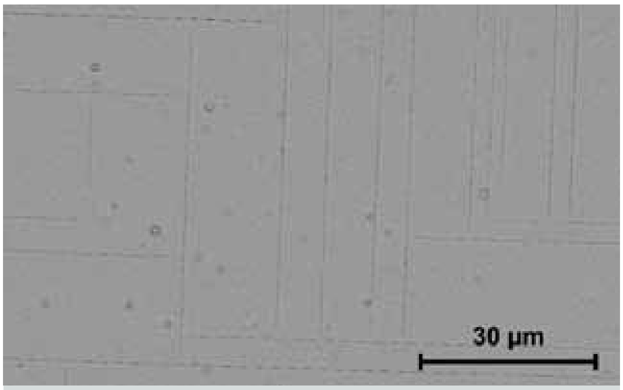

Fig. 5: Crack formation in $YBa_2Cu_3O_7$ on LSAT single crystal substrates during too fast a cooling process. The cracks are parallel to the a- and b-axis of $YBa_2Cu_3O_7$.

Fe-based superconductors

With the goal to improve the pinning properties in Fe-based superconducting materials, we continued our investigations on $Ba(Fe_{1-x}Co_x)_2As_2$ nanocomposite films. We prepared $Ba(Fe_{1-x}Co_x)$2As2-InAs nanocomposites in quasi-multilayer technique (typically ~140 layers, where the InAs content was varied via the pulse number on that target for each layer). Indium was detected by ICP and in TEM-EDXS investigations, although InAs nanoparticles were not observable. A medium nominal InAs concentration of ~ 1 mol% lead to strong c-axis pinning and an increase of J_c by a factor 6 [Meyer, PhD thesis 2020].

In an international collaboration, we investigated the anisotropic electrical transport properties of (Li,Fe)OHFeSe films [Hänisch et al., SuST 33 (2020) 114009]. These films were grown via matrix-assisted epitaxy by the group of Xiaoli Dong at Institute of Physics, Chinese Academy of Science. (Li,Fe)OHFeSe can be regarded in two ways: (1) as FeSe compound with heavily stretched c-axis, i.e. connecting low-anisotropy FeSe single crystals with T_c of ~8 K with FeSe single-unit-cell films with a T_c of up to 100 K, (2) as chalcogenide equivalent of the LnFeAsO pnictide compounds if the hydroxyl group is seen as single entity. The films with T_c of ~42 K, sharp biaxial texture and high phase purity showed extraordinarily high self-field J_c values at low temperatures (extrapolated to 16 MA/cm² at 0 K), explained by the short penetration depth λ ~ 200 nm, and a maximum pinning force density of ~ 115 GN/m³ at 4 K for B||c, Figure 6. An electronic anisotropy of ~11 near T_c (decreasing with decreasing temperature) lead to strong 2D effects, such as intrinsic pinning for field directions close to the ab-planes, a strongly temperature-dependent irreversibility field H_{irr}, and a 2D-3D transition in the vortex-liquid region.

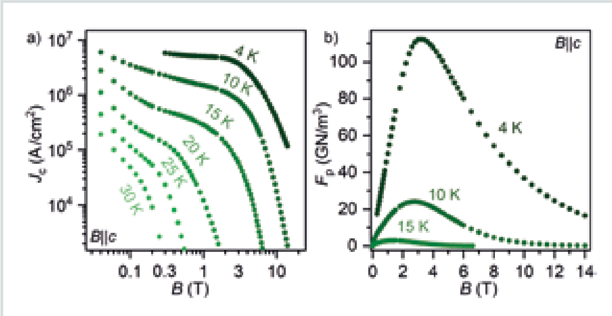

Fig. 6: Magnetic field dependence of J_c (a) and corresponding F_p (b) of a (Li,Fe)OHFeSe film for several temperatures.

Nb_3Sn

Applications in high-energy physics such as the Future Circular Collider (FCC) at CERN require a performance increase of about 30 % to 50 % of state-of-the-art superconducting wires. The superconducting material in these wires is Nb_3Sn, a brittle intermetallic material that forms during a heat treatment after the wire has been wound into its desired shape. The performance of such wires can be improved by reducing the Nb_3Sn grain size. This is achieved by internally oxidizing an alloying element less noble than Nb in the Nb alloy precursor from which the Nb_3Sn forms. The so generated particles act as nucleation centers for the forming Nb3Sn and hinder its grain growth during phase formation. Recent publications suggest that grain refinement in the formed Nb_3Sn can also be achieved by retaining a fine grain size of the Nb alloy precursor during the reaction heat treatment. It had been suggested that this can already be achieved by alloying with a to-be-oxidized alloying element and without an internal oxidation.

We find that a suppression of the Nb-grain growth during heat-treating of a multi-filamentary wire can indeed be achieved by alloying the Nb precursor with a less noble alloying element. A complete suppression of the Nb alloy grain size (after 300 h at 640 °C), however, was only observed when this alloy was internally oxidized during the heat treatment, Figure 7. Nb_3Sn formed from this additionally oxidized alloy was significantly refined whereas the grain size of the un-oxidized reference remained unaffected. The Nb_3Sn grain size is therefore most likely not directly dependent on the grain size of the Nb alloy precursor but on the presence of nanoscale oxide precipitates in the alloy. The observed refinement of the Nb grain size is therefore correlated to but not the cause of the reduced Nb_3Sn grain size. Additional benefits of a refined Nb-grain size for the phase formation of Nb_3Sn as e.g. a facilitated Sn diffusion along grain boundaries are currently still under investigation.

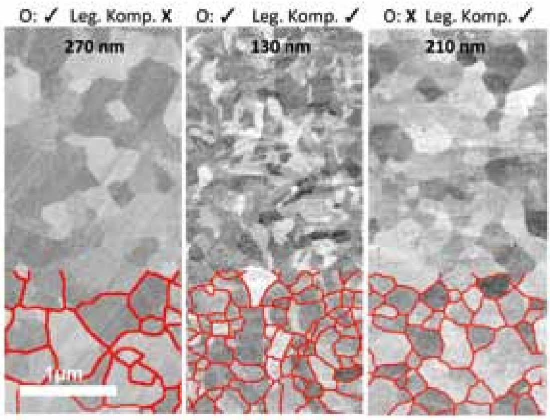

Fig. 7: Comparison of the grain size of remaining Nb alloy after 300 h at 640 °C. If either O or Zr is present, a reduction of grain growth is visible, indicating a successful oxygen transport into the Nb alloy. The recrystallization is fully suppressed only if both Zr and O are present in a filament.

Infrastructure

For depositing novel as well as application-relevant complex functional materials with increased throughput and improved growth control, a new UHV thin film deposition cluster by PREVAC has been installed, Figure 8. It consists of two deposition chambers (pulsed laser deposition and sputtering), an argon glove box, and a target/substrate storage unit, all connected by a central sample transfer. Sample sizes up to 4 inch diameter or 15 cm length, and sample temperatures up to 1200 °C are possible. The cluster is extendable in the future with a further UHV deposition or analysis chamber.

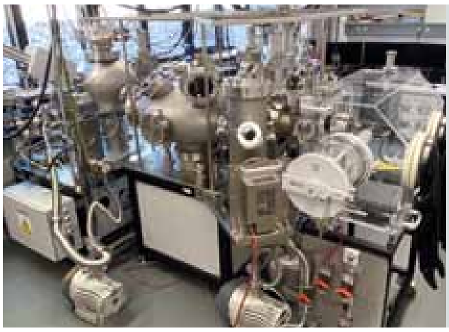

Fig. 8: UHV deposition cluster with PLD, sputtering, Ar glove box, and sample storage.

Contact: jens.haenisch@kit.edu

[1] M. Erbe et al., Supercond. Sci. Technol. **33** (2020) 094002
[2] P. Cayado et al., R. Soc. Open Sci. **7** (2020) 201257
[3] P. Cayado et al., Sci. Rep. **10** (2020) 19469
[4] K. Iida et al., Supercond. Sci. Technol. **34** (2021) 015009
[5] R. Hayasaka et al., Sci. Rep. **10** (2020) 19934
[6] S. Meyer, Introduction of quasi-multilayer pulsed laser deposition for enhanced superconducting properties of Ba(Fe0.92Co0.08)2As2 thin films, Dissertation 2020, KIT
[7] J. Hänisch et al., Supercond. Sci. Technol. **33** (2020) 114009
[8] C. Bühler et al., IEEE Trans. Appl. Supercond. **30** (2020) 6000805

Cryogenic properties of substances

In the context of the technology development of cryogenic mixed-refrigerant cycles (CMRC) for HTS applications, a second doctoral thesis was completed [9]. The work resulted in two patent applications in cooperation with the Institute of Technical Thermodynamics and Refrigeration (ITTK) and the Institute of Microprocess Engineering (IMVT). In a third doctoral thesis, prototype heat exchangers developed in [9] were successfully tested and a new test rig for the development of CMRC-cooled 10 kA current supplies was designed. The power source for this test bench was successfully obtained through a KIT Future Fields special investment program. Based on the use of the CryoPHAEQTS test facility (Cryoge-nic Phase Equilibria Test Stand) jointly built by ITEP and ITTK, the DFG project "Simultaneous Description of the Caloric and Thermal Properties of Cryogenic Mixtures" was successfully obtained, in which a precise inflow equation for neon-helium mixtures is to be developed. A European patent [10] was granted on the subject of heat transfer coatings (HTC). Basic physical investigations were carried out in the MTA-I magnet test facility at ITEP.

Contact: steffen.grohmann@kit.edu

[9] Gomse, D.: Development of heat exchanger technology for cryogenic mixed-refrigerant cycles. Dissertation, Karlsruhe Institute of Technology, 2020.
[10] Grohmann, S., Gomse, D. and Dutoit, B.: Use of a coating layer on a heat exchanger surface. EP 3 385 656 (B1). Sept. 2020

Cryo – Structural Materials

DFG Project „High Entropy Alloys"

Due to its outstanding ductility within a large temperature range, the equiatomic high entropy alloy HfNbTaTiZr is well-suited for investigating the influence of temperature and plastic strain on deformation mechanisms in concentrated, body-centered solid solutions. For this purpose, compression tests in a temperature range from 77 up to 1073 K were interrupted at varying plastic strains for comparison of plastic deformation behavior. High temperature tests were performed in collaboration with the partners of Institute for Applied Materials (IAM-WK) whereas microstructural investigations in terms of electron backscatter diffraction (EBSD) were partly carried out at the Karlsruhe Nano Micro Facility (KNMF). It was proven that, at room temperature, HfNbTaTiZr deforms by pencil glide as well as kink band formation. Figure 9 shows the orientation map of a longitudinal section of a HfNbTaTiZr sample deformed at 298 K. The map was generated by orientations determined by EBSD. The microstructure shows flattened grains due to pencil glide. Further kink bands are visible indicated by arrows. The color code of the orientation is given by an inverse pole figure of the inset. The same deformation mechanisms were revealed after plastic deformation at 77 K. In 2021, the focus is going to be on the investigation of deformation mechanisms at test temperatures below 77 K down to 4.2 K. For this purpose, compression tests accompanied with EBSD experiments are planned. [12]

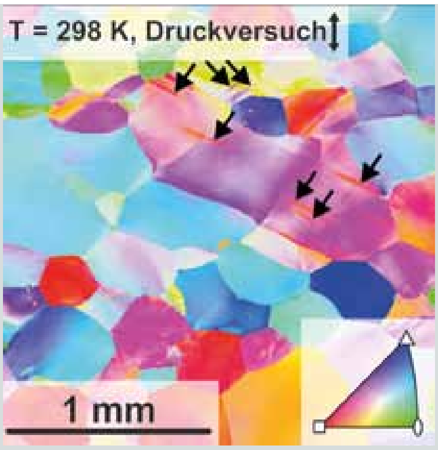

Fig. 9: Orientation map determined of a longitudinal section of a HfNbTaTiZr sample deformed at 298 K. Double-arrow in top of picture indicates pressure direction, arrows mark kink bands, inset shows orientation.

Determination of thermal contact resistance

The thermal contact resistance is a fundamental parameter in high-temperature superconsductor cables in order to predict and control their quench behavior. Especially with stranded HTS cables with an outer steel conduit (cable-in-conduit-conductor CICC), the heat transfer between individual parts of the conductor, such as HTS tapes and components made of normally conductive metals, determines the behavior in the event of a quench. Such a thermal contact can be realized by cutting thin sheets made of appropriate materials - copper or stainless steel - and stacking them together. Stacks can only be made of thin copper or stainless steel to characterize copper-copper or steel-steel contacts. In addition, with alternating stacking of copper and steel, the copper-steel contact can be assessed. Using the known thermal conductivity of the base materials, the thermal contact resistance was determined from the measurement in the temperature range from 2 K to 300 K. The investigations showed the essential dependency on the contact pressure that is exerted on the contact stack. For this purpose, a special measuring unit was developed to determine the contact pressure that acts on the stack using strain gauges (see Fig. 10). This unit is under preparation for measurements in the coming year.

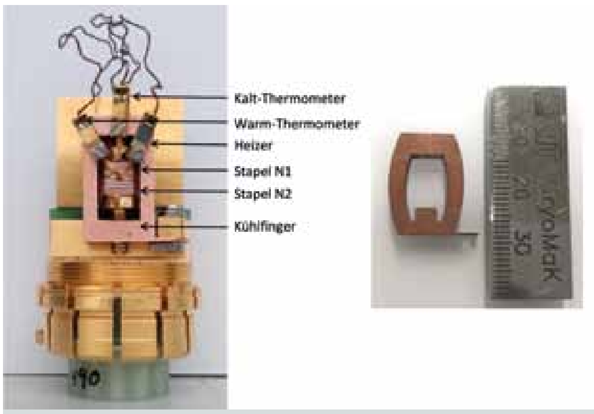

Fig. 10: Left: Copper frame mounted on probe platform with installed stack N1 and N2. Right: adapted frame to measure contact pressure simultaneously.

Project Enabling Research „High Strength Materials“

Due to the steadily increasing demands on structural materials used in superconducting magnets, the improvement of the mechanical properties of austenitic stainless steel at cryogenic temperatures was assessed in this project. The aim is to establish an industrially feasible thermomechanical processing method for the stainless steel 316LN in order to systematically adapt the mechanical properties for cryogenic applications. Based on the available process parameters and numerical simulations, specific forming processes were defined in order to tailor the grain size. Using the numerical simulation software DEFORM HT / 3D and the finite element method, the distribution of strain and temperature in the hot / cold processed material was determined and thus the resulting grain size in the structure. Mechanical experiments at room temperature, 77 K and 4.2 K show the expected increase in strength with reduced grain size in tensile tests. At the same time, the fracture toughness could be kept constant (see Fig. 11). [13]

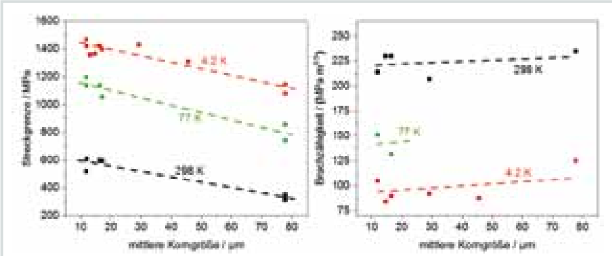

Fig. 11: Increasing yield strength with decreasing grain size on the left, constant fracture toughness at different temperatures on the right.

[12] Chen et al, “Influence of temperature and plastic strain on deformation mechanisms and kink band formation in homogenized HfNbTaTiZr”, to be published in Crystals
[13] Weiss et al. “Mechanical Properties after Thermo-mechanical Processing of Cryogenic High-Strength Materials for Magnet Application”, to be published in Fusion Engineering and Design

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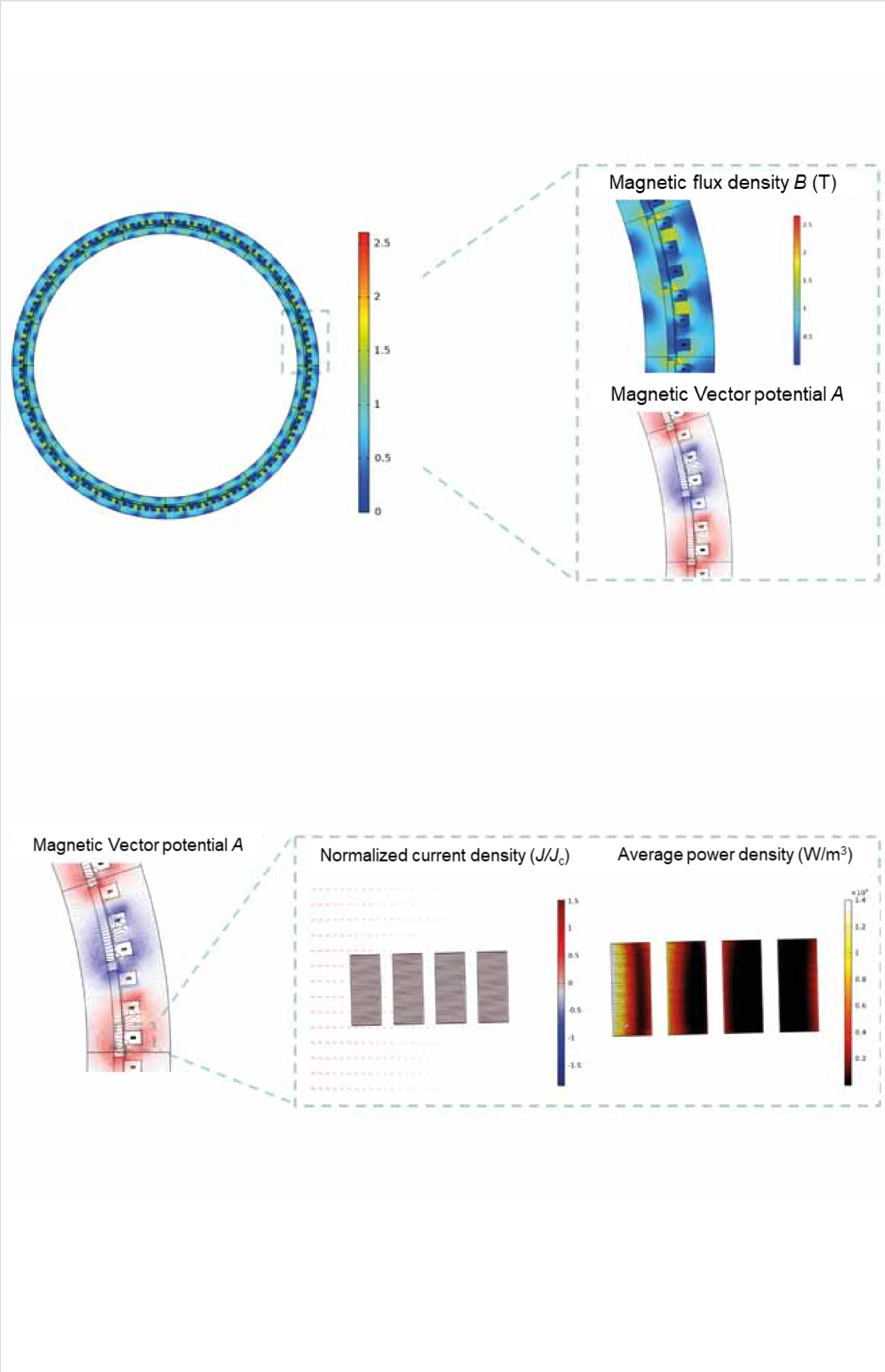

Simulation of the electromagnetic field of a fully superconducting wind turbine generator (top) with simultaneous calculation of the AC losses in the individual conductors (bottom).

Results from the Research Areas

Energy Applications of Superconductivity

Coordination: Prof. Dr.-Ing. Mathias Noe

In the research field of Superconducting Energy Technology Applications, ITEP scientists are working on the following topics:

- Superconducting power system and energy components
- Modelling of superconductors and components
- Real-time system integration

Superconducting power system and energy components

The focus in the area of superconducting network and energy components is on the development of novel equipment for electrical energy systems and the development of resource and energy efficient applications for energy technology. The researchers achieved the following results in 2020.

The **DEMO200 joint project** (Novel superconducting high-current system for 200 kA direct current), which was started in 2019 and is funded by the BMWi, aims to develop the technology for a compact and efficient industrial high current busbar with a current of 200,000 A and to demonstrate its functionality in a test together with the partners Vision Electric Superconductors, Messer, Trimet and Theva. This would mean a tenfold increase of the current compared to the state of the art of 20 kA and would enable a wide range of applications in industry. Within the project, the ITEP has taken on the task of characterising the superconducting coated conductors, co-developing the basic geometry and the contacts and carrying out a test on a subscaled busbar element. Figure 1 shows the basic structure of the test with three 20 kA sub-conductors (TL), which will be carried out at ITEP. In addition to two sub-conductors based on stacked coated conductors, a sub- conductor based on cross conductors (CroCo) will be set up. In both variants the expansions due to temperature changes are intrinsically compensated. The contacts between the superconductors and the copper and between each other are of crucial importance. Here a large number of tests were carried out and the contact design was specified in detail. Likewise, high forces between the superconductors must be absorbed. For this purpose, some preliminary tests were carried out on several conductor samples and real arrangements.

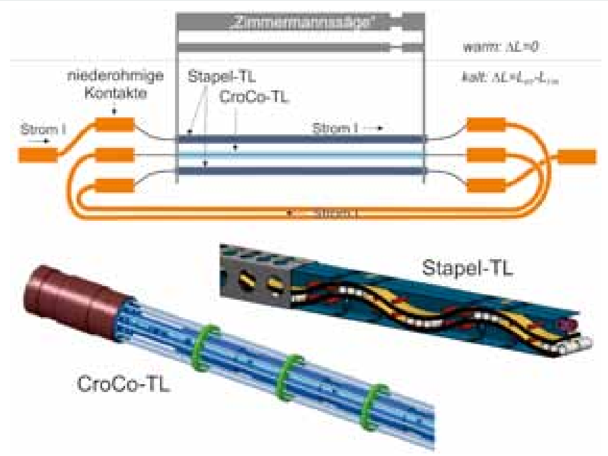

Fig. 1: Scheme of the Setup of the Subscale Tests

For the application in the city centre of Munich, the development of a very compact superconducting cable for a power of 500 MVA at a voltage of 110 kV was started with project partners. In the future, this superconducting cable can replace a conventional 380 kV cable and the necessary tunnel structure. Together, the consortium aims to meet all the necessary technical requirements and develop the most important components within two years, including a 200 m cable section, terminations and cooling. Once the project has been successfully completed, the twelve kilometres will then be tackled. KIT's research work mainly comprises the complex simulation of the electromagnetic and thermal behavior of the cable. The research is part of the **"SWM SuperLink"** project (Inner-city HTS high-voltage cable for safeguarding critical infrastructure in the course of the energy turnaround) funded by the Federal Ministry of Economics and Energy (BMWi). The project consortium includes KIT, the University of Applied Sciences of South Westphalia, Stadtwerke München, THEVA, NKT Cables Group and the Linde industrial gases group.

Electric flying is one of the technical alternatives for significantly reducing the CO_2 footprint of air travel. Within the framework of the German government's aviation research, the technology was further developed in the joint project **TELOS** (HTS conductor technology for thermally-electrically optimised aircraft propulsion systems). This includes light and compact power lines between the individual electrical components. As part of the development of a DC cable for hybrid-electric aircraft propulsion systems, various investigations were initially carried out on conductors and contacts. In addition, a demonstrator for the electrical test of a compact superconducting cable designed for an operating current of 13.3 kA at 20 K and 3.3 kA at 77 K was set up and various tests were carried out in liquid nitrogen. In parallel, a cryodemonstrator was developed to test the cooling behaviour of such cables at operating temperatures of 20-80 K. The construction of the cryodemonstrator was almost completed in 2020 (Figure 2). In this project, the ITEP is working closely with partners such as Airbus and Sie-

Fig. 2: Design of the valve box and cryodemonstrator for a 20 K high current line with high temperature superconductors

mens and is collaborating closely with Rolls Royce and Siemens in two other doctoral theses.

In 2020, a new EU project under the Horizon 2020 programme was launched with the participation of ITEP. The **MEESST** project (MHD Enhanced Entry System for Space Transportation) is concerned with the development of a novel system for plasma shielding during the entry of spacecraft into the atmosphere of Earth and other planets. With the aid of a superconducting magnet, the plasma created in the plsama in front of the space capsule during entry into the atmosphere is influenced in such a way that the temperature at the outer shell of the space capsule is significantly lower. In addition, the plasma is to be influenced by magneto-hydrodynamic effects in such a way that radio waves are not shielded and thus radio contact with satellites or earth stations is not disturbed. In the MEESST project, the ITEP has taken on the task of manufacturing and testing the superconducting magnet for experiments at the Institute of Space Systems at the University of Stuttgart and the Karman Institute for Fluid Dynamics in Belgium.

Superconducting magnetic heaters enable energy savings of more than 30 percentage points compared to previous methods when heating metals for industry and have already been built and operated in single units. However, not all operational requirements have yet been met. The main objective of the ITEP in the BMWi joint **project ROWAMAG** (Robust and low-maintenance magnetic heater with high-temperature superconductor coils for hot forming processes) for the construction and testing of a robust and low-maintenance magnetic heater with superconductors is therefore to develop a durable cryogenic system including the cryostat and the refrigeration systems. Together with the partners, Theva, Bültmann and Maschinenfabrik Beck, in 2020 the Kryodesign was finalised and all main components are in the workshop for production. As the magnet is cooled by conduction, a precise analysis of the temperature distribution in the superconducting winding package was carried out. Figure 3 shows a view of the cryostat in which the superconducting coil package is integrated. Furthermore, important pre-tests for the operation of the small coolers and the design of fixed and detachable connections were carried out in 2020.

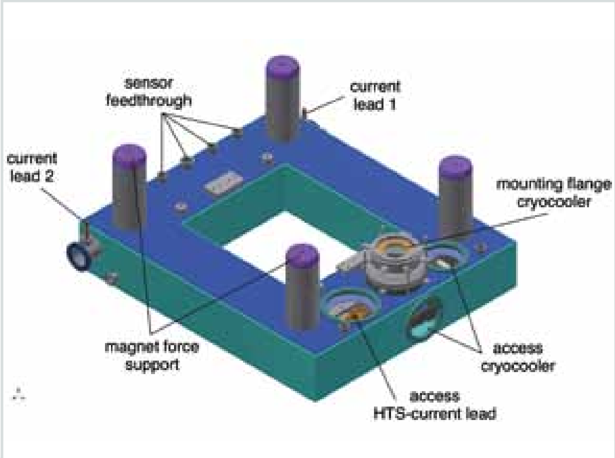

Fig. 3: Top view of the cryostats of the superconducting magnetic heater

A need for future superconducting current limiters for high voltage requires further experimental data for the **breakdown of liquid nitrogen,** which are not available so far. The facility "Fatelini 2" (FAcility for TEsting LIquid NItrogen) at ITEP has been used so far for breakdown voltage testing of saturated and supercooled liquid nitrogen with alternating voltage up to 230 kV (eff) and standard lightning impulse voltage up to 365 kV. For the European FASTGRID project, the facility was modified to be able to perform direct current tests up to a voltage of 325 kV. A bell-plate-electrode system was used (Fig. 4), which enables breakthrough and flashover tests. The liquid nitrogen space above the grounded plane can be examined with a webcam through windows of the cryostat to observe the boiling behaviour during the generation of heat pulses within the plate under high voltage application. The cryostat can be subjected to a pressure of up to 0.3

Fig. 4: On the left: Bell-plate arrangement to study the breakdown behaviour in liquid nitrogen. Right: Setup of the test cryostat in the cryogenic high voltage laboratory of the ITEP

MPa (absolute). Breakdown tests were started with a single initial one-hour step. Then 15-minute voltage steps were performed with increasing voltage until breakdown. In a test run with heater operation, five heater pulses with a duration of 10 s and a pause of 3 min were performed within each voltage step.

Clear outliers occurred during the breakdown tests, but all breakdowns occurred above an average field strength of 3.5 kV / mm. No significant reduction of the mean breakdown field strength with increasing voltage was observed, even up to 325 kV, which is very important for the high-voltage design of future superconducting current limiters. The high voltage tests showed a deterioration of dielectric strength under saturated conditions of liquid nitrogen in case of gas bubble formation.

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Modeling of Superconductors and Components

Within the project **SupraGenSys,** finite-element method simulations (based on the T-A formulation of Maxwell's equations implemented in COMSOL Multiphysics) were used to evaluate the losses in a wind turbine superconducting generator. The model allows calculating the time-dependent magnetic field distribution in the whole machine (Fig. 5) and the details of the current density evolution in the individual superconducting turns. The model is currently being used to optimize the shape and arrangement of the HTS stator coils, with the aim of reducing the energy dissipation and the cryogenic burden.

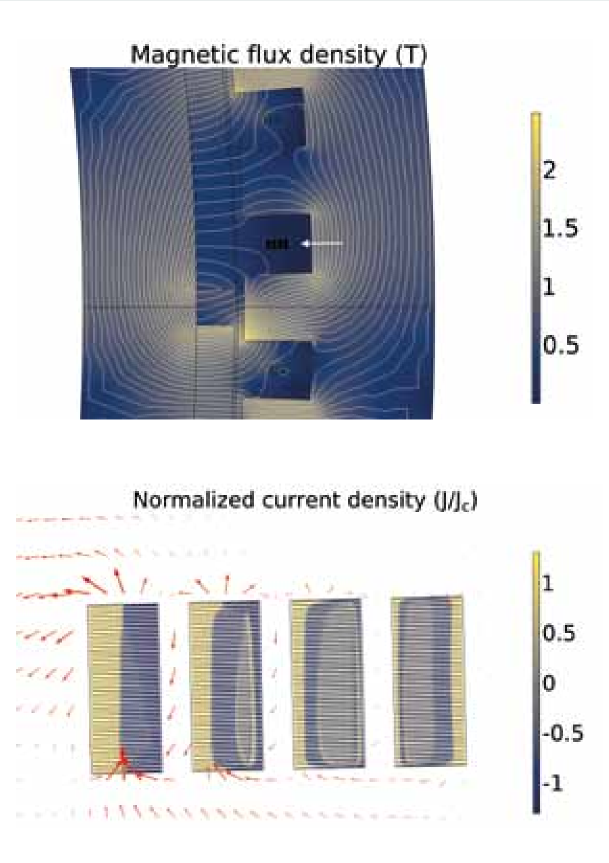

Fig. 5: Top: Distribution of magnetic flux density in one of the designs of the superconducting generator of a wind turbine. Below: Distribution of the normalised current density in four half coils (see white arrow). The red arrows indicate the direction and strength of the magnetic field. The left half of the coil, which is saturated with current and exposed to a high magnetic field, is the one with the highest losses.

The T-A formulation was also used to estimate the AC loss of the superconducting field coils in a 10 MW double-stator superconducting flux modulation generator. In this type of generators, both superconducting field coils and armature windings are placed in two separate stators, which enables a brushless current transfer and a stationary seal for coolants.

It was found that when there is a suitable margin to the critical current for the operating current, obtainable by reducing either the working temperature or the operating current, the energy dissipation in the superconducting coils is not very high. However, the eddy current loss of the copper thermal shield is significant. Therefore, efforts should be focused on methods to reduce eddy current loss in the thermal shield.

The introduction of no-insulation (NI) technique to high-temperature superconducting (HTS) coils has been regarded as one of the most innovative approaches for the development of magnet technology. Without turn-to-turn insulation, a NI coil can be self-protecting in case of a quench, thanks to the presence of turn-to-turn current paths. These turn-to-turn current paths are significantly influenced by the contact resistivity. In practice, it is very challenging to measure

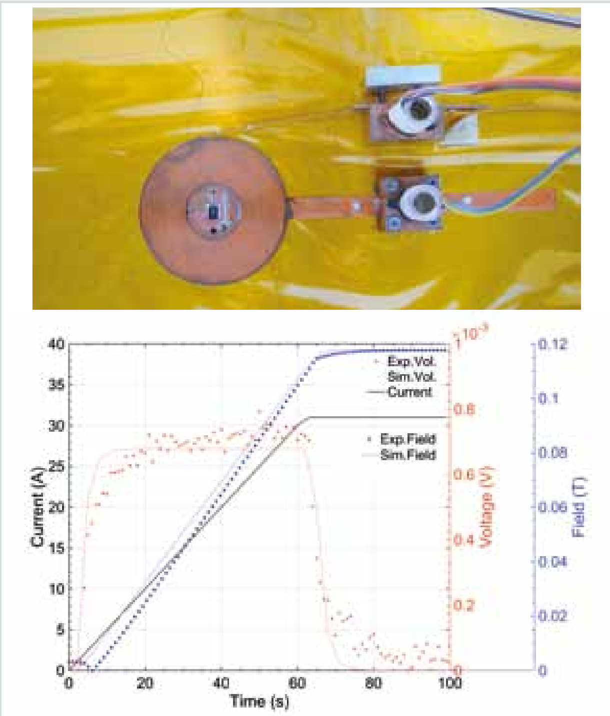

Fig. 6: Photo of a HTS-NI coil with 157 turns. The supply lines for the power supply are also visible. Below: Total voltage and central magnetic field with a ramp rate of 0.5 A/s and a specific contact resistance of 90 μΩ·cm2.

the contact resistivity of a NI coil by direct experiments of short HTS wires, since the contact resistivity of superconducting tapes is influenced by surface roughness and tolerance, stress, temperature etc. Hence, a distributed circuit model was employed to investigate the contact resistivity of a 157-turn NI coil with dedicated experiments (Fig. 6). It was found that the contact resistivity of the NI coil has an inhomogeneous distribution and that the equivalent contact resistivity calculated from sudden discharge cannot be reliably used as input for simulations aiming at reproducing experimental data.

At the level of the HTS numerical modeling community, we have participated in the definition and test of a simulation benchmark of an HTS dynamo (2020 Supercond. Sci. Technol. **33** 105009). We have also developed and distributed an open-source numerical model for introducing students to the calculation of AC losses in superconducotors (2020 Eur. J. Phys. **41** 045203).

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Real-time System Integration

In the Real Time System Integration research topic, the 2020 brought further development of the infrastructure and the realization of the first large experiments in the energy storage, sector coupling and superconductor area.

The **1 MVA Power Hardware In the Loop system** in Fig. 7 is currently in operation, with the acceptance test of the 5 Egston 200kVA Compiso power amplifiers carried out under different modes: AC and DC, series and parallel connections. The tests have validated the high voltage / high current capabilities of the Egston power amplifiers: the amplifiers group can work up to a voltage of 1.5kVdc injecting 650A current, and at 150Vdc they are able to inject a current of 4.5kA continuously, and up to 6kA for short term.

A first **realistic PHIL validation** has been performed with a 60kW high-speed Flywheel from the company Stornetic. The CIGRE microgrid benchmark has been implemented in the digital real time simulator OPAL-RT, and the flywheel has been "virtually" connected to a simulated busbar by means of the power amplifier interface. Two testing applications were targeted. Firstly, the compliance to the low voltage grids connection rules VDE-AR-N-4105 has been verified. Subsequently, the performance of the flywheel in providing grid frequency support services has been assessed. In the PHIL testing, several strategies to manage the frequency control in microgrids have been integrated in the flywheel controllers. As it can be seen in Fig. 8, the flywheel improves the grid frequency management, decreasing both the frequency derivative and deviation from the nominal value, with respect to a base-case without flywheel.

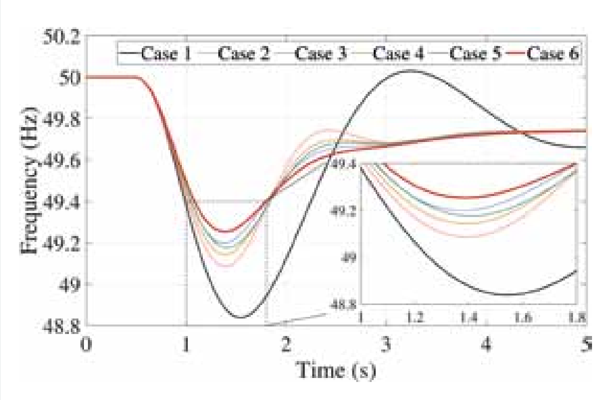

Fig. 8: Flywheel frequency support in microgrids under different controllers' actions.

Further investigations in the frequency control will be carried out next year in the BMWi-Verbundprojekts Flygrid. In the project a 500 kW, 5 kWh supercapacitor-based system will be installed in the Energy Lab 2.0 and connected to the PHIL lab. The main goal will be to demonstrate the competiveness of the supercapacitor technology in provide short-term (<5s) frequency support, and to compare and integrate it with the flywheel technology for longer frequency control strategies (up to several minutes)

In the BMBF-Verbundprojekt **Sektorkopplung (SEKO)** project, the micro-gas turbine in Fig. 9 is now in operation, and coupled with a cooling system and a gas supply. The turbine has an electrical power of 3kW and a thermal power of 15kW, that makes it suitable for

Fig. 7: PHIL Hall of the Energy Lab 2.0

Fig. 9: Micro-gas turbine experimental setup.

household applications. First experimental tests have been performed, applying variable power variations to the turbine, in both amplitude and frequency, in order to assess its dynamic behaviour. Further experiments are planned at the end of the year in connection with the 15kW PHIL setup. The gathered data are currently used to develop a black-box model of the turbine, that shall be used for digital real time simulation applications. In parallel to the black-model, a detailed analytical model of the system will be finalized at the beginning of the next year.

Together with the gas turbine, a Combined Heat and Power (CHP) system with 4kW electrical and 15kW thermal power has been built and brought in operation. The performance of the BHKW are currently investigated by means of the PHIL system.

In the superconducting area, the modelling of superconductive cables for real time applications has been optimized, developing new models that reduce the required execution time, while holding the initial accuracy.

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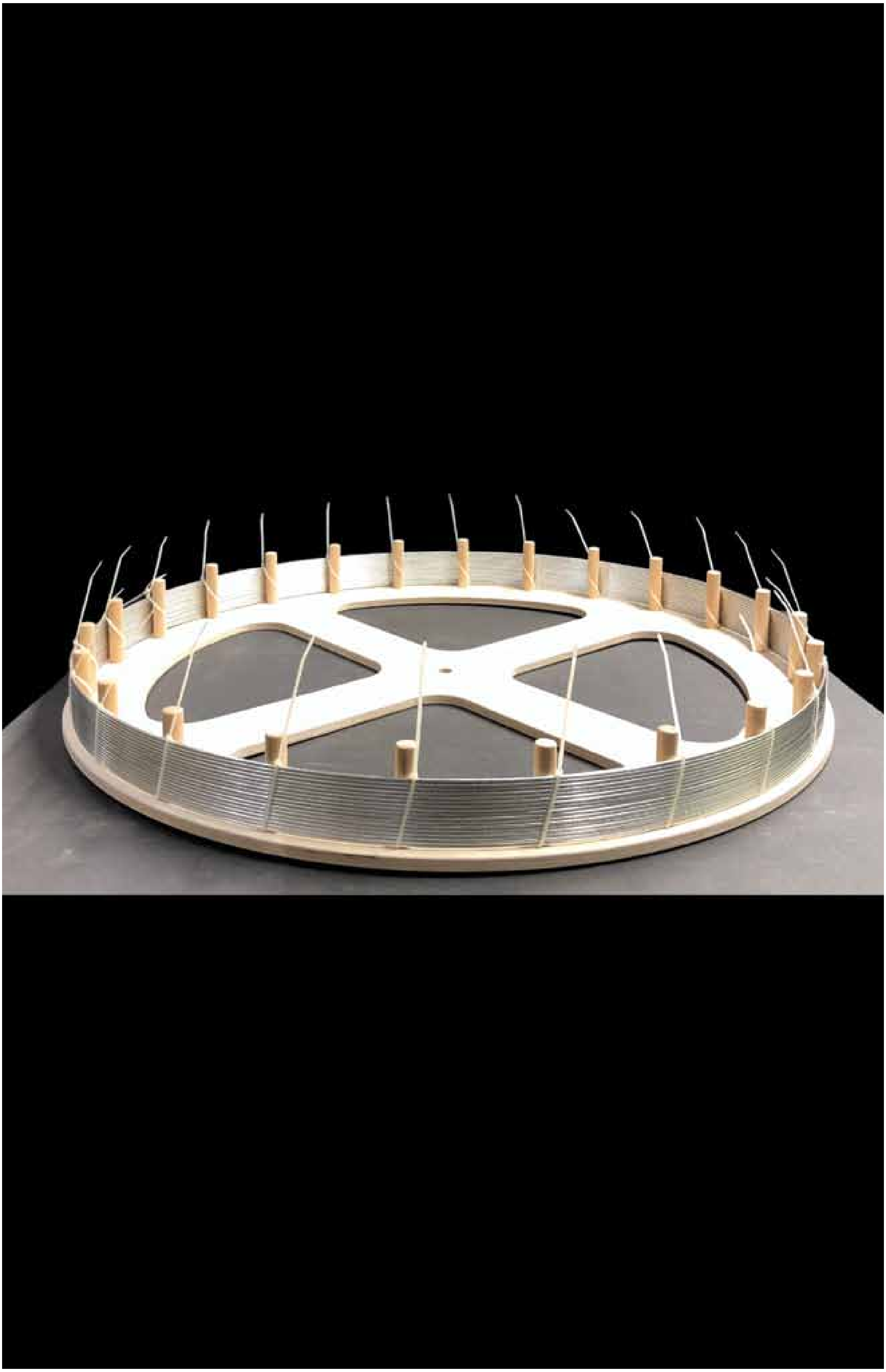

53 m winding of a HTS CroCo, made of 3mm/2mm REBCO tapes in a continuous manufacturing process

Results from the Research Areas

Superconducting Magnet Technology

Coordination: Dr. Walter Fietz

ITEP has many years of experience in the field of superconductivity and in the construction and testing of superconducting magnets.
Within the framework of the acquired know-how, the following current topics have developed in the research field "Superconducting Magnet Technology":

- Coil and magnet technology
- HTS fusion magnets
- Rotating machines

The research topic "Coil and Magnet Technology" was realigned in 2019 and now aims to develop optimized technologies for windings, coils and magnets. Here, the focus is on robotic winding with subsequent vacuum impregnation and advanced cooling technologies.

In the research topic "HTS fusion magnets", the focus is currently on the development of HTS high-current conductors as well as theoretical and experimental investigations into the quench problem. As part of this work, the production of an HTS CroCo over 50 m long, which was wound into a coil, was demonstrated.

In the research topic "Rotating Machines", components of electrical machines based on superconductor technology are modeled and developed. These include, for example, wind turbines, propulsion motors for ships and large land vehicles, and concepts for electric flying supported by superconductor components.

Coil and Magnet Technology

The research topic "Coil and Magnet Technology" changed its orientation in 2019. Whilst in the past the work concentrated on superconducting high-field magnets, relevant technologies are now being more broadly developed for the entire spectrum of coils, windings and magnets. Currently, the focus is on advancing concepts, robotic winding, functional vacuum-pressure impregnation and alternative cooling concepts, in particular the coupling of cryocoolers with thermosiphons.

Robotic Winding

Worldwide there is an increasing demand from laboratories, research institutions and (industrial) users for specific HTS coils, windings and magnets. The geometries required are becoming increasingly complex, to the extent of real three-dimensional coils. A winding system consisting of two industrial robots and a workpiece positioner from ABB was designed for the production of such complex coils. The coil former to be wound is held by the rotating and swiveling positioner. The two robots wind the superconductor. In order to be able to reach around and through, two robots are required. The HTS conductor itself is guided by means of a so-called winding hand. The winding hand carries the HTS supply reel and can be alternately docked to the flanges of the robots using a quick-change adapter. Since these robots operate non-collaborative, the system must be surrounded by a protective screen for reasons of occupational safety. During 2020, the robot chamber was designed, the required components selected and procured, and construction began. Figure 1 shows the advanced stage of the facility, as of December 2020.

Fig. 1: Advanced stage of the robot chamber with two robots, positioning table and partially constructed protective screen. In the foreground the electronic controls for the robots can be seen.

The disc-shaped winding hand (figure 2) is used to guide the conductor during the winding process. In order to guarantee a defined winding tension, the HTS supply reel is mounted on the shaft of a servomotor and its

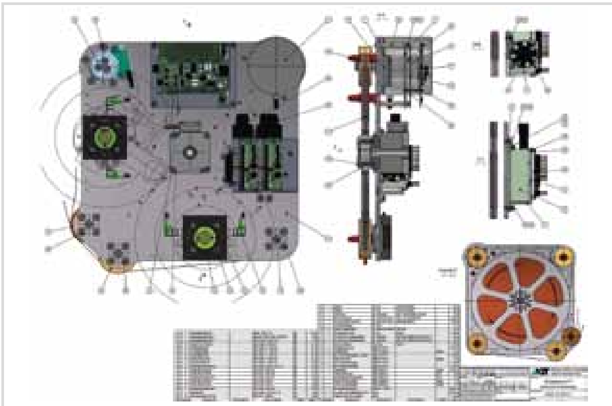

Fig. 2: Technical drawing of the winding hand for the robotic winding. On the front (left) is the servomotor, tensile force sensor and revolution counter with associated electronics as well as the two quick-change adapters. On the reverse side (lower right) is the HTS supply-reel.

tensile force is regulated by a tensile force sensor. A revolution counter determines the length of the wound conductor. The winding hand was designed, all required components were procured, and is now under construction.

Vacuum Pressure Impregnation

The development of new, more effective winding techniques goes hand in hand with the development of new impregnation technologies. For this purpose, the team procured a vacuum pressure impregnation system (VPI) (figure 3). The system consists of a vacuum batch mixing chamber and a vacuum potting chamber. In the batch mixing chamber, the components of a potting material are degassed with the aid of an agitator and mixed homogeneously. The potting takes place in a vacuum in the potting chamber located below the batch mixing chamber. The prepared potting compound is filled into the wound object via a dispensing valve within an evacuated potting chamber. The potting chamber has the dimensions 1 m x 1 m x 0.6 m, so that even large objects such as racetrack coils for accelerators or fusion can be potted.

Fig. 3: Newly-procured vacuum pressure impregnation facility.

Thermosiphon with cryocooler

Windings made of metallic superconductors are usually bath-cooled with cryogenic liquids (usually liquid helium at 4.2 K) because of their low transition temperature. Second generation HTS (REBCO) can be cooled with liquid nitrogen (77 K), but here the stability range of superconductivity is limited - especially in the presence of magnetic fields. With this in mind, an operating temperature of REBCO coils in the range below 77 K is advantageous, as it can be provided with cryocoolers. The coupling of the cooler to the object is mainly done via heat conduction through solid copper. However, the coupling by means of a so-called thermosiphon is more beneficial, since here the heat transport is about two orders of magnitude greater with comparable geometries. In its simplest form, a thermosiphon is a pipe or corrugated hose in which there is a small amount of a cryogenic liquid (e.g. neon with a boiling temperature of 27 K). At the warm end (object to be cooled) the neon evaporates and condenses again at the cold end (cold head of the cryocooler). With this circulating material flow and the phase transitions that occur, a comparatively large amount of heat is transported from the object to be cooled. To investigate this cooling mechanism, a concept was devised during 2020 (figure 4). A corresponding test stand was planned and most of the components required for this were procured. The construction of the actual thermosiphon in modular design with evaporator, condenser and connecting pipe is well underway.

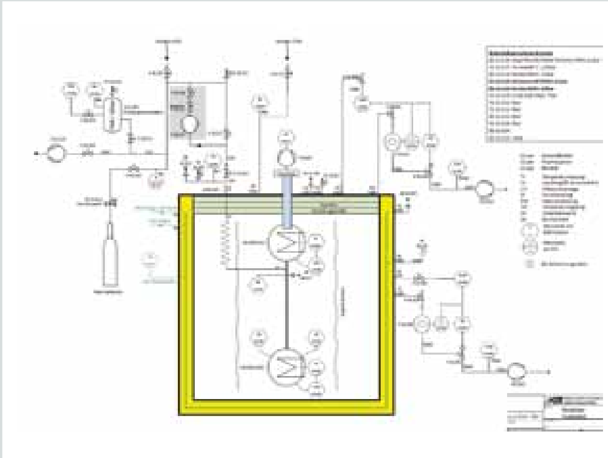

Fig. 4: Flow diagram of the planned test stand for the investigation of the thermosiphon cooling concept

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HTS-Fusion magnets

Development of a HTS CroCo Triplet sample for quench investigations.

For the use of high-temperature superconductors (HTS) in future fusion magnets, the behavior of an HTS fusion conductor in the event of a fault, the so-called quench, in which a piece of the conductor loses its superconducting properties and then exhibits a finite electrical resistance, is of particular interest. In contrast to low temperature superconductors (LTS) currently used in fusion magnets, such a resistive zone propagates very slowly and there is a risk that the HTS conductor will be locally overheated and destroyed. Therefore, samples based on different conductor concepts are currently being designed and fabricated in an international project, which will then be tested and selectively quenched in a test facility in Switzerland under conditions relevant for a fusion magnet.

The investigations already started in the previous year for the construction of a smallest possible stranded sample consisting of three HTS CroCos, i.e. an HTS CroCo triplet. They were continued this year and the design of the sample was finalized and first preliminary experimental investigations were performed.

Two different design options of the triplet cable were investigated, both differing in the way additional copper is added to the actual superconducting part, the HTS CroCo. In the first option, the HTS CroCo is encapsulated by a copper tube all around, while in the second option, the HTS CroCo is soldered into a copper profile.

The high currents and magnetic fields in a fusion magnet lead to high Lorentz forces. Finite element simulations were performed to assess the mechanical stresses in the two design variants at 180 kN/m, resulting from 15 kA at 12 T. The results of these simulations are shown in Figure 5. These show significantly lower stresses in the superconductor for the profile option, as can be seen in Figure 5, particularly for the lower conductor of the triplet.

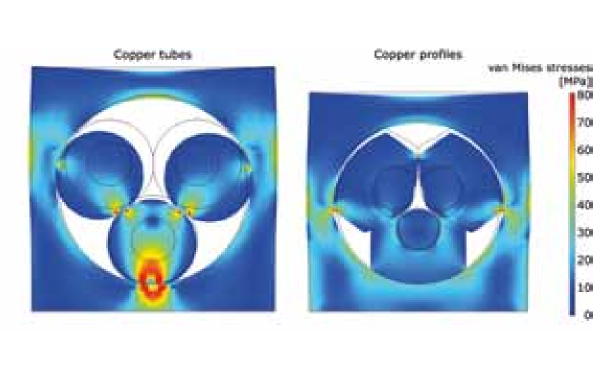

Fig. 5: Overview of the van Mises stresses of the two HTS CroCo sample options for quench investigations. The color scale is the same in both calculations.

Since numerical calculations of the quench behavior last year showed that the design with copper profiles also has advantageous properties in the case of quench, only this design will be implemented in the sample.

In addition to these conceptual investigations regarding the expected behavior of the sample under test conditions, the mechanical design of the specimen has been finalized. Analyses of the heat transfer in the quench case between copper-copper or copper-steel contact surfaces under variable contact pressure are in preparation. The sample geometry is defined by the facility and consists of a hairpin-shaped conductor arrangement in an approximately 9 cm x 14 cm cross section in 3.6 m length. Both electrical connections are located at the top end of the sample, and the sample is electrically connected at the bottom, effectively resulting in a series electrical connection, whereas both conductors are cooled by separate hydraulic circuits (also at different temperatures if necessary). The sample design provides for stainless steel half-shells to mechanically stabilize the superconductor with inserted copper parts at the required connection points. Both conductors are stabilized by a clamp frame against the Lorentz forces. The propagation of the quench is to be determined both electrically by measuring the development of the electrical voltage along the sample as well as by the resulting heating of different parts of the sample (HTS CroCo, helium, steel sheath) by various measurement techniques. This will allow comparison with the thermal-hydraulic modeling that has already been done and, if necessary, should serve the need to refine the model in order to predict the behavior of HTS fusion magnets with greater confidence in the future. Figure 6 shows an overview of the developed sample design.

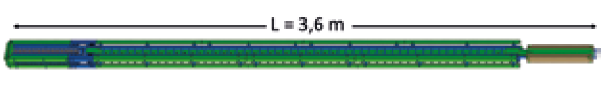

Fig. 6: Overview of the complete HTS CroCo sample for quench investigations. The electrical connection is on the right side, both conductors of the sample are cooled by supercritical helium flowing from left to right.

Bending properties of HTS CroCos

For the design of cables for fusion magnets based on the HTS CroCo concept, knowledge of the minimum bending radii to be maintained for the individual HTS CroCos is essential. Therefore, a combined study of the behavior of HTS CroCo conductors when bent to different radii was performed as part of a master's thesis. In this study, the behavior of HTS CroCo conductors was investigated both experimentally by measuring the critical current at T = 77 K and bending radii from 100 to 300 mm, and a mechanical model was developed to describe the degradation behavior based on the degradation behavior of the superconductors used in the HTS CroCo and the sample geometry and geometric manufacturing tolerances. Figure 7 shows the results of the study, the critical current when bent to a certain radius is normalized to the value in the straight state and plotted as a function of bending radius. In addition, the angle between the bending direction and the orientation of the superconducting tapes was varied. Here, 0° (Figure 7 left) corresponds to the case where the tape planes lie in the bending plane, while at 90° (Figure 7 right) the tape planes lie perpendicular to the bending plane. If we use a 5% decrease in the critical current (red line in Fig. 7) as a criterion for the onset of degradation of the superconductor, we determine a tolerable bending radius of about 250 mm, which is almost independent of the bending directions investigated. In all cases, there is very good agreement between the developed model and the experimental results.

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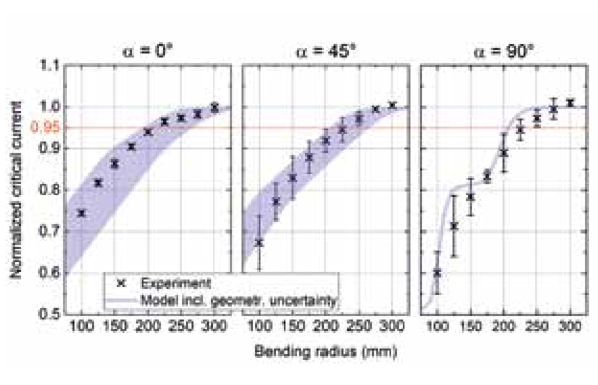

Fig. 7: Dependence of the critical current of HTS CroCos as a function of the bending radius for different orientations of the HTS strips to the bending plane.

HTS CrossConductor manufacturing in long lengths.

In 2018/19, as part of a KIT technology transfer preparatory project, the basis was created for fabricating HTS CroCos from 2 mm and 3 mm Cu and HTS tapes directly from the supply spools onto a receiver reel with a diameter of 100 cm. Now it should be demonstrated that this technique is also suitable for long fabrication lengths.

To keep costs reasonably low, instead of a complete equipment with HTS tapes, only two HTS tapes (shown in green in Fig. 8) in 3 mm width and two tapes in 2 mm width were used in the configuration shown in Fig. 8 (in a fully equipped HTS CroCo, all 0.1 mm thick Cu tapes (brown) would be replaced by HTS tapes with their superconducting side facing the respective central 0.2 mm thick Cu tape (red)).

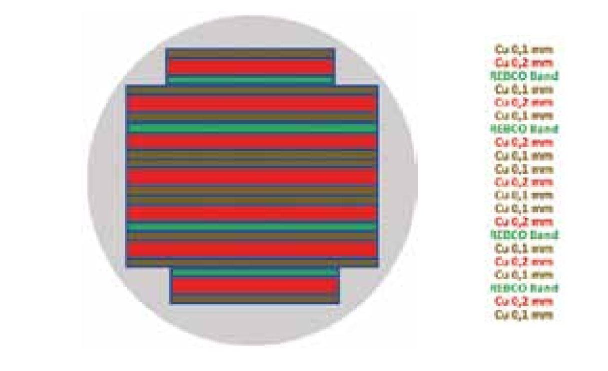

Fig. 8: Structure of the HTS CroCo, which was partially equipped with HTS REBCO tapes.

Although one of the 2 mm tapes was only available in about 47 m length, this was used in the fabrication run. This allowed to simulate whether the CroCo drawing process would be disturbed, e.g. by the rupture of an HTS tape.

It was found that the shorter 2 mm tape did not affect the drawing process, i.e. the drawing process was not affected by the transition from 21 to 20 tapes. Figure 9 shows the reel, which has a diameter of 1 m, during the production of the HTS CroCo spool. The cover picture of this part "Superconducting Magnet Technology" shows the winding with 17 turns (53 m conductor length) after transfer to the wooden frame.

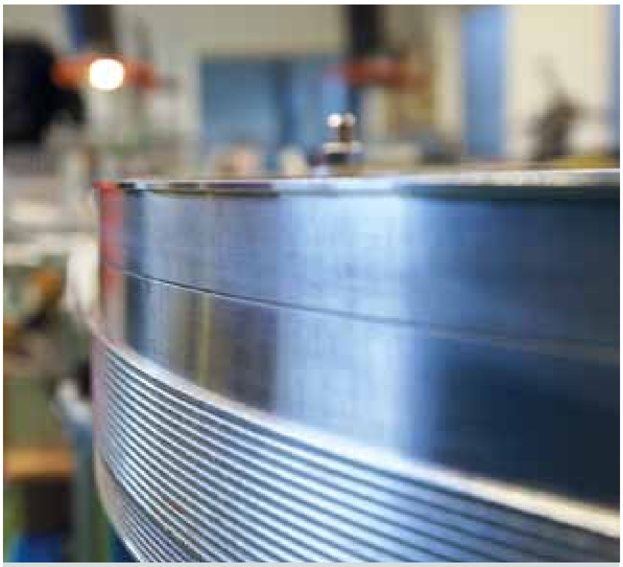

Fig. 9: Receiver reel with the first 14 turns of the HTS CroCos during the production of the winding.

For the further measurements, the area where only 3 HTS tapes were present was cut off, leaving a turn length of about 42 m, as shown in Figure 10.

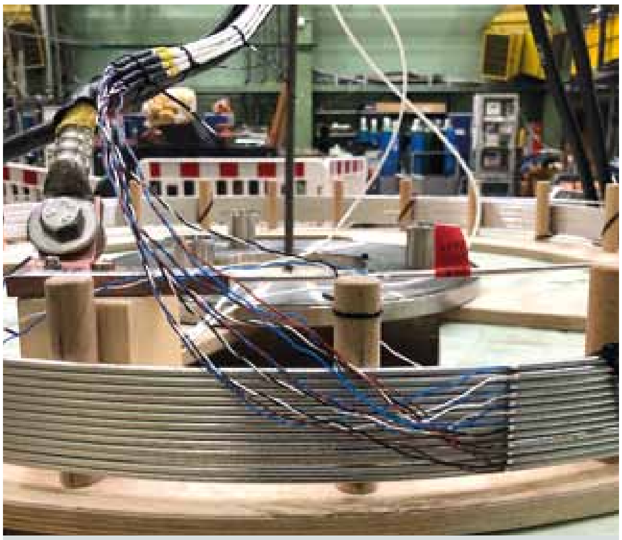

Fig. 10: Winding with 14 turns incl. current supply and voltage taps.

Initial measurements over the full length of the conductor appeared to actuate the expected performance, but relaxation effects appeared at faster current ramps.

However, it quickly became apparent that this was a result of the lack of insulation between the individual turns. Therefore, the measurement was repeated with insulated turns, and the results are described below under "Highlights".

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Rotating Machines

In the field of aviation, the international research activities in rotating machines continue despite the present economic difficulties due to the pandemic. The advantages in power-to-mass ratio and efficiency are prominent in turbo generators, for example in the 10 MW power rating, and for high-speed propulsion motors in the 1 MW class as well. When operating generators in (offshore-) wind-turbines, the rotational speed is reduced and a higher number of pole pairs is addressed. In both fields of application, the ITEP is contributing with research projects.

Other potential applications on mid-term timescale are in hydro power generators and –stimulated by the increased efforts in Hydrogen-technologies- propulsion motors for ships and large vehicles. To support this, ITEP is providing first feasibility documents; a continuation of these activities in 2021 by projects and contract research is expected.

Testrig for high-temperature superconducting rotors

In 2020, the project „HTS-Geno Testrig" has been kicked-off formally and first critical, already developed components have been received; in 2021 the technical project work will start. This undertaking will erect a test facility for high-speed, large (diameter up to about 1 m) rotating components of electric machines based on superconductor technology. Due to the high kinetic energy of the rotating parts, this testrig (see figure 11) will be installed in a spin bunker.

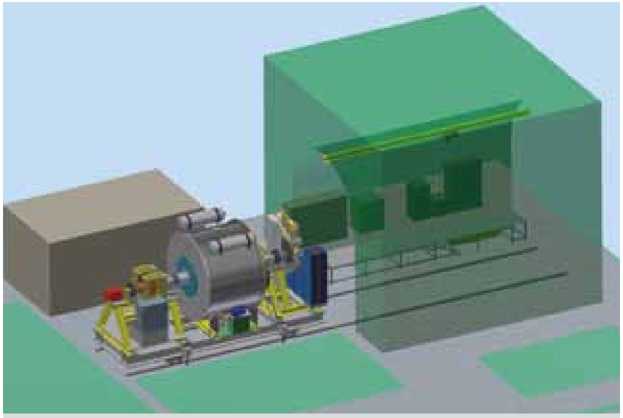

Fig. 11: CAD-picture of the testrig for cold rotor components based on superconductor technology. The cylindrical vacuum vessel has a diameter of about 2 m.

Superconducting generators for wind power

Generators for operation in offshore wind turbines have to be robust, lightweight, efficient and reliable in the power class of 10 MW+ – preferably in direct drive configuration to avoid high-maintenance gearboxes. The high current densities of superconductors facilitate compact and lightweight machines. Frequently the cooling technology appealing complex and sophisticated is a non-rational entry hurdle for the conventional industry. However, the low rotational speed and the electric frequencies in a wind turbine are motivating a use of superconductors even in the stator. This benefits from a more simple cooling technology (without cold feedthroughs). Therefore, ITEP and partners designed a superconducting stator system in the framework of the project SuperWind. This stator system was prepared in 2020. To achieve a high electrical stability, the coils have been manufactured in the so-called non-insulation winding technique.

The coil system (see figure 12) has been tested successfully in liquid Nitrogen. The characterization of the complete stator system at temperatures below 77 K is pending.

Another project in wind power called SupraGenSys started based on the hypothesis, that high-power offshore wind turbines and generators will exceptionally benefit from a fully superconducting electrical design. Following this thesis, a variety of concepts has been analyzed by ITEP and partners. As the superconducting wire in the stator winding has to be taylored and placed very specifically following the electromagnetic requirements and the need to keep the ac loss (hysteresis, coupling, feedback- and dynamic loss) low, considerable development efforts have been performed to meet both targets. A remarkable outcome is, that the AC-loss may be reduced extremely by a sophisticated configuration – see figure 13.

Fig. 12: Open stator system for a wind generator for the project SuperWind.

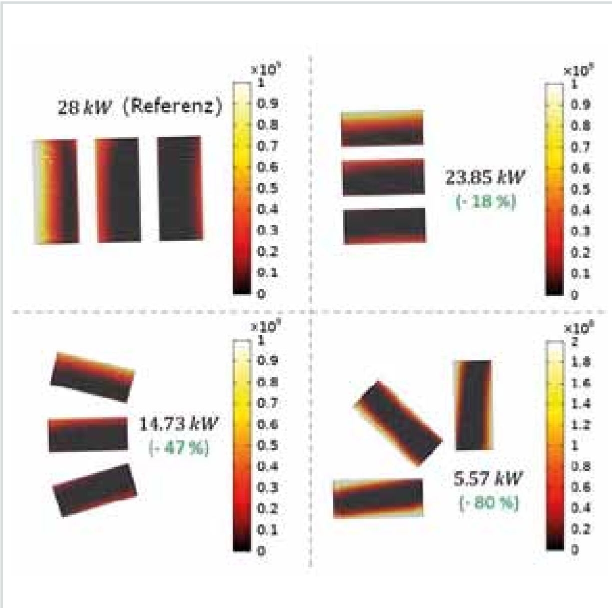

Fig. 13: Variations of a HTS stator winding. Compared to the reference configuration the ac loss can be reduced by 18%, 47% or 80% by specific orientations in the slot.

Superconducting motors for electric aircrafts

Distributed electric propulsion motors can benefit from a fully superconducting design, too. In the framework of the project ASuMED such a motor was developed and built-in collaboration with the partners. This machine will meet the requirements of large electric aircrafts for public transportation concerning power-to-mass ratio and efficiency (see figure 14). Having this demonstrated, the low emission targets of the roadmap Flightpath 2050 seem to be in reach.

The contributions of the ITEP to this project:

- Characterization of the HTS-wires and measurement of the critical current at different temperatures, magnetic fields and orientations,
- development of numerical models to calculate the ac-loss in the stator and to optimize the stator topology,
- numerical simulation and evaluation of the demagnetization effects of HTS-stacks in the rotor; these have been used instead of conventional permanent magnets.

The closing activities supported mainly works in the field of publication, transfer and dissemination and the further development of the models.

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Fig. 14: Motor with pod and fan for electric aircrafts having a distributed propulsion concept (1 MW, 6000 rpm, 1:1 Mockup).

Highlight: Coil made from a HTS CroCo produced in a single continuous process from 3 mm and 2 mm REBCO tapes.

After isolation of the individual turns, the single-layer HTS CroCo coil was measured in liquid nitrogen at T = 77 Kelvin. Figure 15 shows the insulated HTS CroCo coil made of 42 meters of HTS CroCo in 13.75 turns with a diameter of 97 cm. Here, the voltage drop was measured across each turn (W1 – W13) and additionally across a three-quarter turn (W0). The voltage taps for W1 to W13 and the negative current connection can be seen in the foreground in Fig. 15.

Fig. 15: Single-layer, insulated coil of 42 meters HTS CroCo before installation in the test equipment for measurement at T = 77 K. In the foreground a power connection and the instrumentation can be seen. The voltage along each individual winding was measured separately.

The magnetic flux density of this coil arrangement was calculated and is shown in Fig. 16. (a) shows the magnitude of the flux density and the flux lines for the complete coil, in (b) the normal component of the flux density relative to the orientation of the HTS tapes is plotted for the upper half of the coil. Its average value per band increases continuously from the coil center to the edge. Since the critical current of the used HTS tapes decreases with increasing flux density, one expects a smaller critical current for the outer turns than in the coil center.

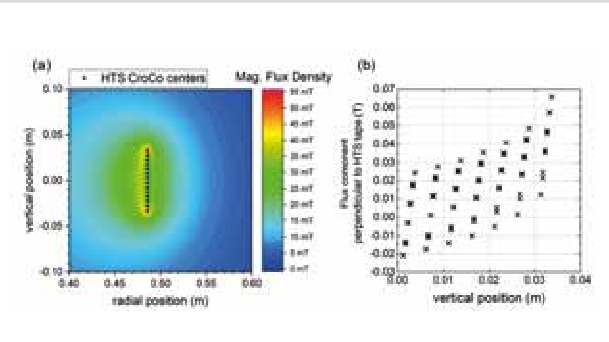

Fig. 16: (a) Calculated field geometry and flux density distribution near the HTS CroCo conductors. (b) Normal component of the flux density relative to the orientation of the HTS tapes.

Fig. 17(a) shows a schematic sketch of the HTS CroCo coil and its instrumentation, the colors and line styles correspond to the lines in Fig. 17(c). Equal colors correspond to an equal distance of the winding from the coil center. In Fig. 17(b), the electric field along the entire 13.75 turns is plotted as a function of coil current for a current ramp at 1 ampere per second. The horizontal red line marks the criterion for determining the critical current, which was determined in this way to be 305 A in good agreement with expectations. Similarly, the critical currents of the individual turns were determined and plotted in Fig. 17(c). A decrease in the critical current of the outer three turns is observed, which is due to the higher field component perpendicular to the HTS bands at the edge of the coil (cf. Fig. 16). In addition, a reduction of the critical current in turn 6 and a significant rounding of the transition from superconductivity to normal conduction can be seen in this turn, most likely due to degradation of one of the four superconductor bands in this turn. More detailed analyses of this turn are currently in preparation.

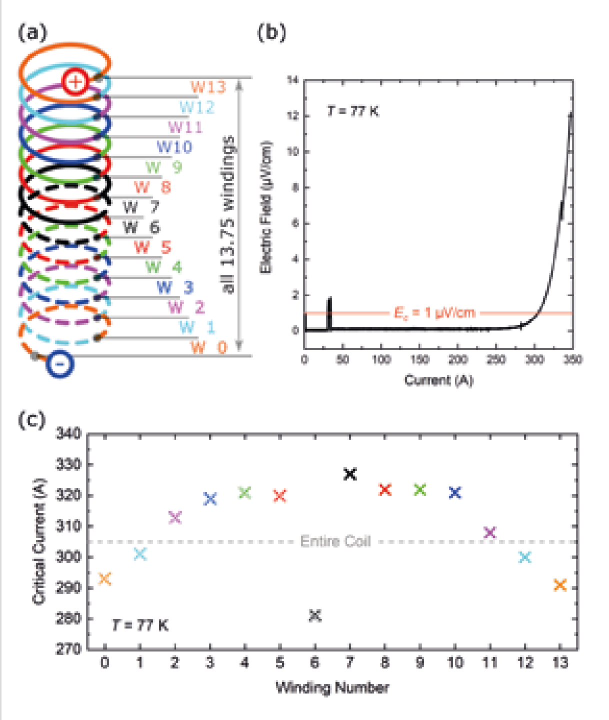

Fig. 17: Measurement results of the single-layer HTS CroCo coil in the liquid nitrogen bath (T = 77 K). (a) Schematic of the coil and its instrumentation. The top 7 turns are shown by solid symbols, the bottom 6.75 turns by broken symbols in (c). Equal colors correspond to equal distance of the winding from the coil center. (b) Electric field along the whole coil as a function of coil current. (c) Critical current of the individual windings.

In summary, the continuous winding process was successful. There is no length limitation of the process apart from the length of the superconducting tapes, i.e. coils with a conductor length in the range of several 100 m could also be produced.

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Work on the open vessel on a large scale.

Results from the Research Areas

Technologies for the Fusion Fuel Cycle

Coordination: Dr.-Ing. Christian Day

In the research field of fusion fuel cycle technologies, ITEP is developing novel technologies to make the fuel cycle and associated neighbouring systems of a future fusion power plant more efficient, thereby ensuring that the tritium fuel produced in situ is optimally utilised. The research field covers all three key technologies of the fuel cycle: matter injection, vacuum technology and tritium technology. The new architecture of the fuel cycle developed at the Institute comprises three loops: The first returns unburnt fuel directly from the vacuum pumps to the pellet injectors, the second is a quasi-continuously operated bypass of the residual gas with isotope separation within the tritium plant, and finally the third is the loop equipped with cryo-distillation and water detritiation, which converts the remaining hydrogen isotopologues into the pure hydrogen isotopes for storage or delivery to the other loops.

On the basis of this architecture the following research topics have emerged in the research field:

- Vacuum technology and process integration
- Rarefied gas flows
- Vacuum hydraulics and hydrogen separation

This work is firmly embedded in the European fusion programme EUROfusion. As a highlight this year, the pre-conceptual design stage was successfully completed. The project is thus entering the next phase, which is scheduled for the period from 2021 to 2027 under the new European Research Framework Programme.

The year 2020 was a special one. Despite the special conditions of the Corona pandemic, extremely impressive results, especially experimental ones, were achieved, as every year. This was only possible because, in addition to ambitious and curious scientists, the team also includes skilled and highly dedicated technicians. To have maintained this team spirit in this difficult year is something we are particularly proud of.

Vacuum technology and process integration

This research topic addresses all vacuum technology issues related with a fusion plant and develops an integrative approach for describing them using a fuel cycle simulator. The activities go beyond the development of the technologies relevant for the corresponding subsystems of the fuel cycle and also include the vacuum systems outside the classical fuel cycle, for example the plasma chamber with outgassing and gas storage. Vacuum technologies for other large-scale fusion facilities, such as for the European neutron source IFMIF-DONES or the JT-60SA machine currently under construction in Japan, are also covered.

The Vacuum Technology Division at the Institute has been working for many years with the Japanese tokamak JT-60SA, which will go into operation in 2021. After an initial experimental campaign, the machine will be reopened in 2022 and completed with further in-vessel installations. These include a powerful cryopumping system that will be integrated directly into the divertor. The ITEP was charged to develop the complete design for this. This year, the design was completed and the manufacturing was finally put out to tender. This marks the end of many years of close cooperation with the Japanese team. Since 2012, we have been closely involved in the development of the research plan as part of an EU-JT-60SA Research Team. Over the years, we have been consulted in many technological questions, not only on vacuum systems, but also on matter injection, divertor physics, diagnostics and cryogenics.

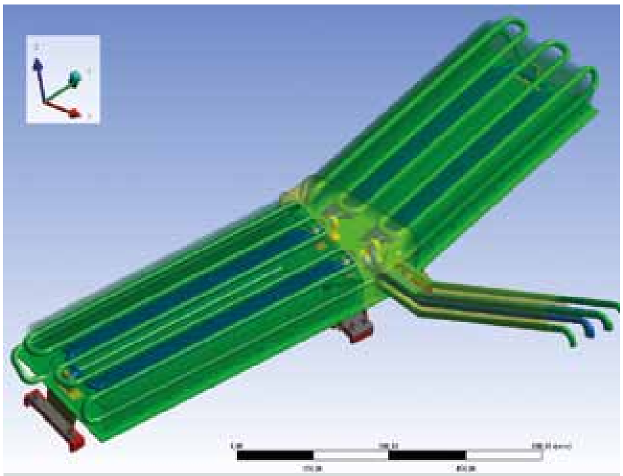

Fig. 1: Design of the cryopump for JT-60SA.

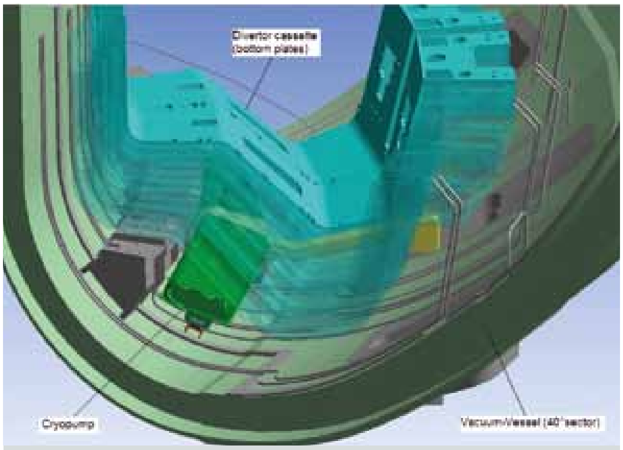

Fig. 2: View of the installation of one of the nine cryopumps in the JT-60SA plasma vessel.

Figure 1 shows the final design of our cryopump, which follows the proven cryosorption pump concept developed at the Institute of building the cryosurfaces modularly from hydroformed panels (blue) - two per pump wing. Figure 2 illustrates the installation situation.

For the design of the pump, extremely complex load combinations had to be considered. On the one hand, there were thermal stresses due to the fixed points on the vessel wall at room temperature and the cryogenic surfaces at 80 K and 3.7 K, respectively. Secondly, there were very strong electromagnetic forces acting on the pumps installed inside the plasma vessel in the event of plasma disruptions. Finally, there were seismic events to consider for earthquake-prone Japan.

Extensive vacuum modelling was carried out for the IFMIF-DONES materials test facility, which will be built in Grenada, Spain. DONES is an accelerator that produces a fusion-type neutron spectrum at a liquid lithium target, which can be used to test materials for applications in fusion. Our calculations have shown which pressure profile can be expected along the 90 m long facility (Figure 3). Furthermore, it became clear where the main contributions to the pressures come from, namely from beam losses in the first three sub-systems, from outgassing in the actual accelerator part (linac) and from argon gas injection in the plant part towards the target. The latter is necessary to suppress evaporation of the lithium at the free-flowing surface. As another important result, it was found that the total pressure in the linac is too high (a pressure of at most 5·10-8 mbar is required). Since the pumping speed cannot be increased significantly due to space constraints, the gas release rate (currently assumed to be about $4 \cdot 10^{-11}$ mbar·l/s·cm^2 and thus already relatively low) must be reduced significantly further. This will probably necessitate an elaborate conditioning step of the modules before installation, because in-situ bake-out will not be feasible.

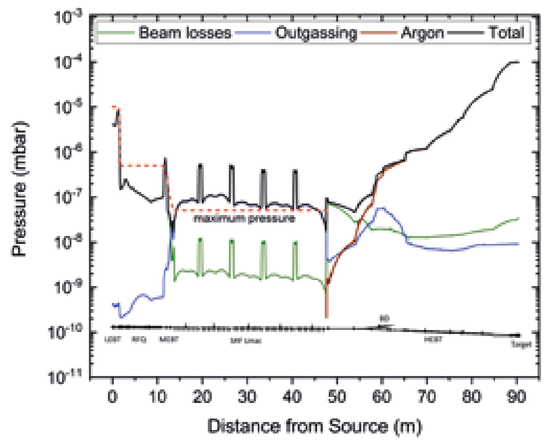

Fig. 3: Pressure profile at the IFMIF-DONES accelerator.

Another vacuum technology used at various points in the fuel cycle is based on getter materials (NEG). The leading company in this field, SAES Getters, has developed a new material in recent years with the trade name ZaO, which is produced in the form of discs with a diameter of 25 mm. To better understand the scaling of different disc arrangements, ITEP organised a multi-stage R&D programme in collaboration with SAES and Consorzio-RFX in Italy. Several disc arrangements at different scales were experimentally investigated. Building on this, a test pump with more than 4600 individual discs was built this year, installed in the TIMO test facility, commissioned and parametrically measured.

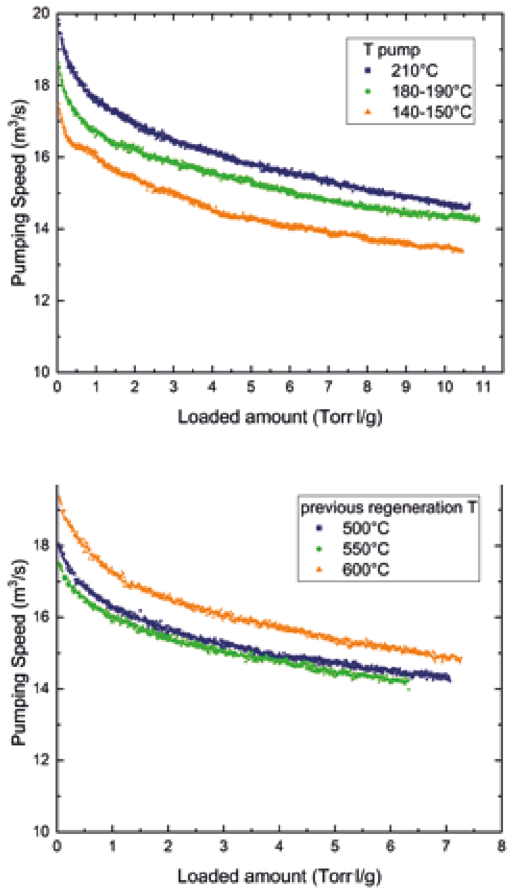

Fig. 4: Influence of getter temperature on the umping speed for H_2: during pumping (top) and in the regeneration step before pumping (bottom).

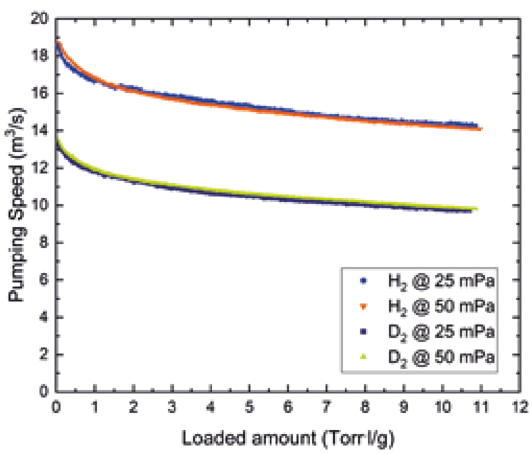

Fig. 5: Isotope dependence of the pumping speed for hydrogen, in comparison at two pressures in each case.

A typical result is illustrated in Figure 4. It shows the influence of the getter temperature on the pumping speed and the influence of different regeneration temperatures. The trend (higher temperatures lead to better pumping behaviour) could thus be quantified. Furthermore, the isotopic effect between H_2 and D_2 was extracted (Figure 5); an important correlation that can now be extrapolated to tritium and the other hydrogen isotopologues.

Finally, work on the new DTT fusion machine in Italy was continued. The design of DTT's divertor vacuum systems will become a new focus of work in the field of vacuum technology in the coming years.

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Rarefied gas flows

For the correct design of complex vacuum systems such as in the fusion fuel cycle, it is essential to be able to quantitatively calculate rarefied gas flows. This is done accurately by solving the Boltzmann equation, which describes the flow in the entire range of rarefaction. However, solving this equation for realistic applications (3D, complex geometries, gas mixtures) is very complex. Two different approaches are being pursued at the Institute for this purpose, on the one hand the DSMC algorithm, which uses stochastic methods, and on the other deterministic methods, which solve the equation directly. Particularly the latter approach was significantly elaborated in this reporting year.

This research topic focuses primarily on the physics of particle transport in the divertor of a fusion reactor. Alternative divertor configurations are currently being investigated for DEMO, and the so-called SX configuration shown in Fig. 6 was found to be particularly promising. Here we could show that the extracted particle flux is about twice as large as in the classical divertor over a wide range of parameters. Figure 6 shows the arrangement of the pumping duct relative to the position of the divertor.

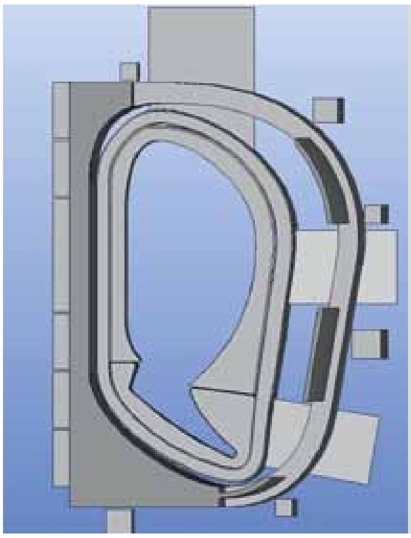

Fig. 6: The SX arrangement – a new divertor configuration with particularly good properties for extracting the helium formed in the fusion reaction.

In this reporting year, such calculations were applied for the first time for the divertor in stellarator geometry, namely for W7-X. Figure 7 shows the modelled plane of the complicated plasma vessel in W7-X.

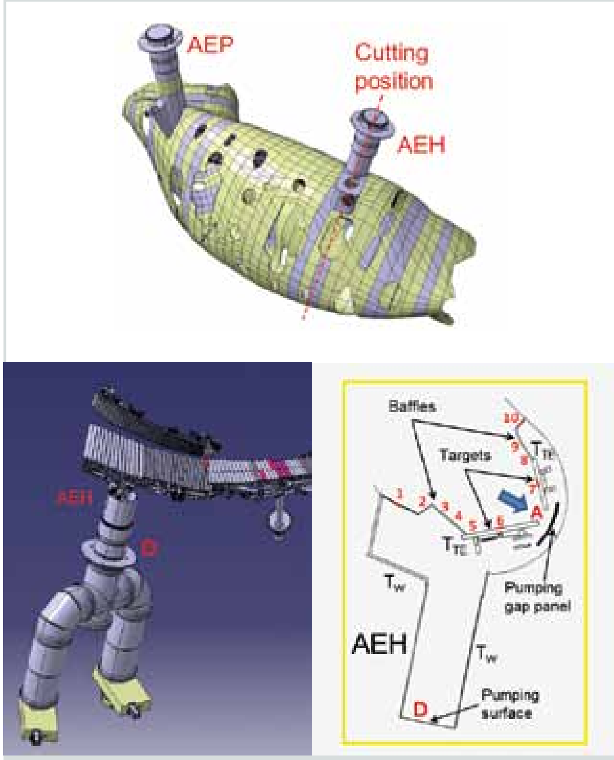

Fig. 7: Modelling of the pump sector (AEH) in W7-X.

Figure 8 below shows the distribution of the incoming particle flux to the different gaps and the pump aperture A, as well as the back-reflected particle flux.

Fig. 8: Distribution of the incoming particle flux to different openings (1-10) as well as the pump and the back-reflected flux.

The varied parameter c describes the pump efficiency. It is clearly visible which openings play a greater role. The influence of the pump efficiency is approximately linear, but with different slopes for each opening. Such calculations are important to develop an optimal design for the pump arrangement. The work for W7-X will be continued in the next few years.

For DEMO neutral particle heating, our modelling helped to establish a clear requirement for the pump efficiency needed. This resulted in the necessity to realise significantly higher efficiencies than originally planned. Figure 9 below shows the calculated pressure profiles along the injection direction of the neutral particle injector (neutraliser – residual ion dump (RID) and calorimeter), with the pump efficiency as a parameter. It becomes clear that an efficiency of about 20% is needed to reach the required pressure of maximum 3 mPa at the outlet of the calorimeter. It will be one of our main tasks in the next few years to develop such a pump.

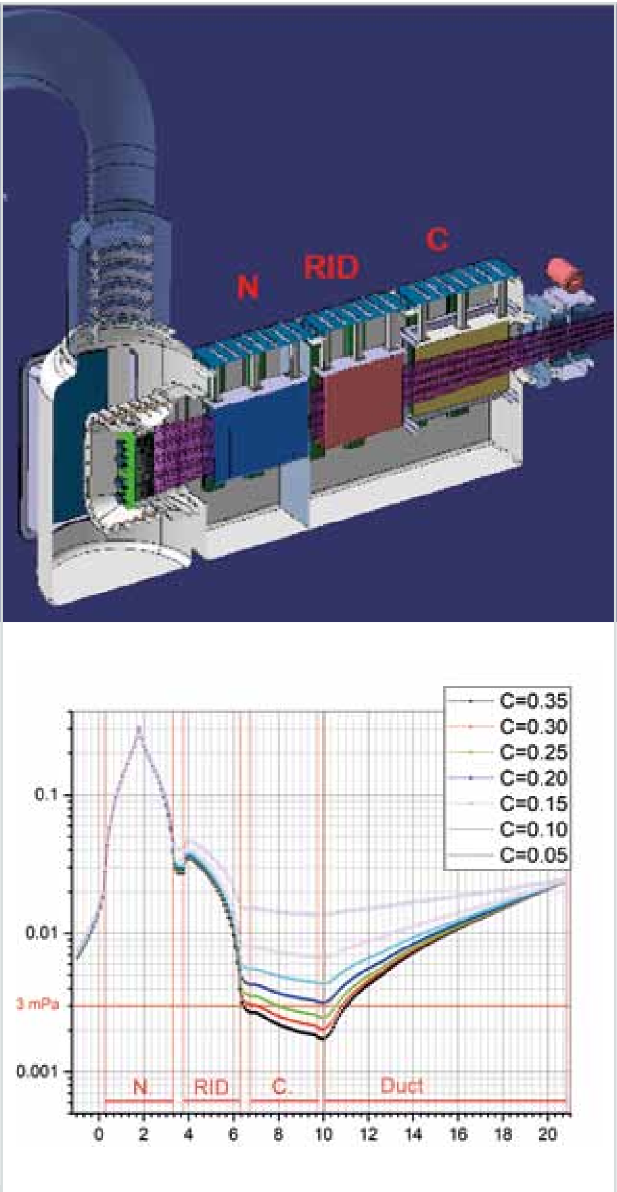

Fig. 9: Calculated pressure profiles along the DEMO neutral particle injector for different assumed pump efficiencies.

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Vacuum hydraulics and hydrogen separation

The research topic of vacuum hydraulics encompasses all activities that deal with the flow behaviour of liquid fluids, especially liquid metals, in machines and processes under vacuum. Accordingly, the Vacuum Technology Division at ITEP also works on processes for handling these working fluids, such as the purification and processing of mercury, as well as on the development of associated analytical procedures. Worldwide, this research topic is only being worked on at KIT. Due to the special safety and environmental requirements, all experiments on this topic are bundled in a common hall (Building 602).

The reference concept for the DEMO torus vacuum system is a combination of mercury-based high and rough vacuum pumps downstream of metal foil pumps (see below). Currently, a linear mercury diffusion pump is being developed for this purpose, which is designed to pump tritium in magnetic fields and with a minimum inventory of mercury as working fluid. Mercury-diven liquid ring pumps are to serve as backing pumps. In this reporting year, a mercury ring pump was removed from THESEUS and disassembled to find out why the pumping behaviour had deteriorated in recent years (Figure 10). This was also a very instructive exercise to practice handling such components. The activity was used together with MED (the medical department at KIT), the occupational health and safety service provider ias in Karlsruhe, and the Central Institute for Occupational Medicine, Hamburg to carry out biomonitoring. Finally, this successfully demonstrated that with appropriate protective equipment, such work can be carried out without any health concerns. The technical result of the dismantling was that there was probably a leakage due to penetrating cooling water, and due to the following corrosion, the valve seats at the control disc were no

Fig. 10: Disassembly of the mercury ring pump.

longer tight. In future, we will therefore provide the ring pumps with a modified sealing and drive concept.

In contrast to the cryovacuum pumps for ITER, the new vacuum concept of the fuel cycle developed for the European demonstration fusion power plant DEMO in recent years works continuously and without cryogen. It consists of three pump stages, with the ring pump described above representing the last stage. For the separation of the unburnt fuel DT, superpermeable metal foils are to be used in the first stage. This enables the separation of high-purity hydrogen from the fusion exhaust gas and provides compression at the same time. In order to develop a functional pump based on the metal foils, the Institute has started a systematic technology development that will last several years. A comprehensive R&D programme has been set up for this purpose.

In order to be pumped, the hydrogen must be converted into an energetic state. For this task, a microwave plasma source is being developed that should achieve a high degree of energisation. This development work is taking place on the basis of an industrial plasma in cooperation with industry source - Duo-Plasmaline from Muegge. One of the special requirements of DEMO is the operation of the metal foil pump in a locally non-constant magnetic field of high field strength of approx. 1 T (residual field of the magnetic coils of the plasma vessel), because the pump must be set up close to the divertor, cf. Figure 11.

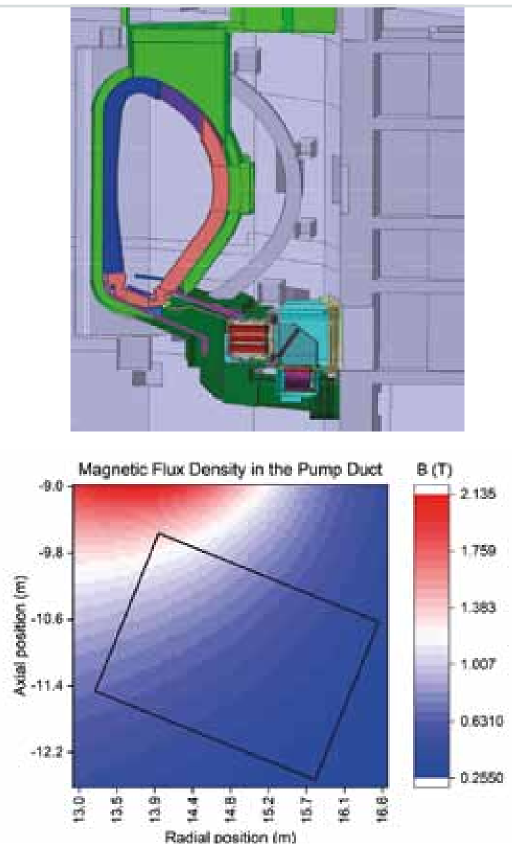

Fig. 11: Indication of the field strength conditions at the potential installation site of the metal foil pumps at DEMO.

The investigation of the influence of an external magnetic field on the mode of action of the plasma source was the focus of the work in this year. This activity is being carried out in collaboration with the Institute for Interfacial Process Engineering and Plasma Technology at the University of Stuttgart. Extensive measurements were made in a specially prepared test facility, in various field orientations. The measurements showed that the external field can significantly influence the plasma formation; thus, changes in the plasma volume, the plasma shape, the ignition readiness and the ignition location could be determined. As an example, Figure 12 compares the same operating condition with 3 kW microwave power (H_2 plasma) with and without magnetic field.

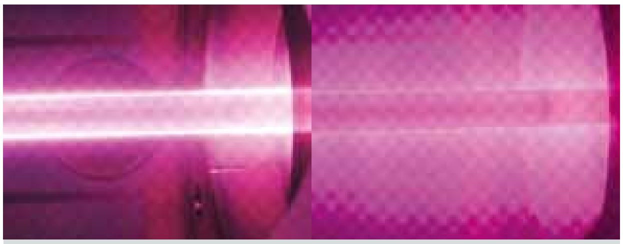

Fig. 12: Dependence of the plasma shaping at different external magnetic fields.

To interpret the measurement results, parametric electrodynamic calculations of the yield of energetic hydrogen particles are now running with the software package COMSOL-Multiphysics. This will also serve to support the scaling of the process to the application size in DEMO.

In order to characterise the integrated setup with source and foil, extensive measurement campaigns were run in the HERMESplus facility during the reporting period. Figure 13 shows how the performance data of the foil depend on the microwave power of the plasma source. For higher values, around 3 kW, one seems to run into a plateau. The permeation current found here is already sufficiently high to make this technology interesting for DEMO. This proves that the operating costs directly related to microwave power will thus also be of an acceptable order of magnitude.

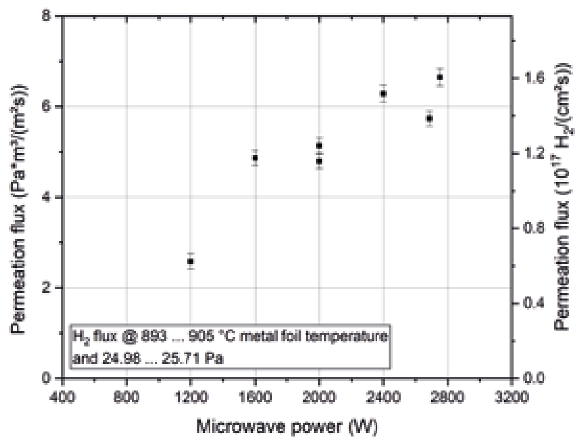

Fig. 13: Performance data of hydrogen through a niobium foil at about 900°C at a pressure of about 25 Pa.

The main task of the fuel cycle in fusion is to purify the exhaust gas and feed the fusion plasma with new fuel. Deuterium consumed by the fusion reaction is fed in from the outside, while the tritium is produced inside the plasma vessel in the so-called breeding blankets and supplied via the fuel cycle after a further extraction step. A major goal of the project to build a demonstration power plant is to show how this tritium self-sufficiency can be realised.

To provide the fuel in the desired composition, it is necessary to set the D:T ratio exactly equimolar. This requires a technology that can adjust concentration shifts within the incoming mixture of hydrogen isotopologues and extract the H that is unfavourable for the plasma reaction. The Vacuum Technology Division developed a new concept based on the coupling of a membrane process with a cyclic temperature change absorption, which exploits various hydrogen-metal interactions. The gas mixture is cyclically moved back and forth in portions between two columns in a semi-continuous process, whereby after a certain number of cycles – up to several 10 cycles depending on the desired shift in concentration – an enrichment of the isotopes takes place at the respective ends of the column. In the reporting year, a new TiCr alloy was extensively characterised as a promising material with inverse isotope effect (i.e. the heavier isotopologue is preferentially absorbed). A new test facility for demonstrating the entire process has been fully constructed and will soon go into operation (Fig. 14).

Figure 14: Photo of the new test facility HESTIA.

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Highlight: DEMO fuel cycle enters conceptual design phase

The year 2020 is the final year of the 7-year project to develop a new fuel cycle concept for DEMO. The related activities were organised in the European programme EUROfusion in the work package TFV Tritium - Fuelling - Vacuum, a consortium of several research Institutes with the aim of creating a design baseline, and were coordinated by ITEP across Europe. This is a good example of outstanding large-scale international research at KIT. In detail, these were the following Institutions:

- CEA, France: expertise in matter injection via pellets.
- Consorzio RFX, Italy: Expertise in neutral particle injector technology.
- ENEA, Italy: Expertise in membrane technology, pellet injection, and detritiation of the coolants helium and water.
- Max Planck Institute for Plasma Physics, Germany: expertise in plasma physics and matter injection.
- UKAEA, England: Expertise in tritium technology.
- University of Volos, Greece: Expertise in vacuum modelling.

Figure 15 shows the people involved at the beginning of the project (2014) and at the end (2020).

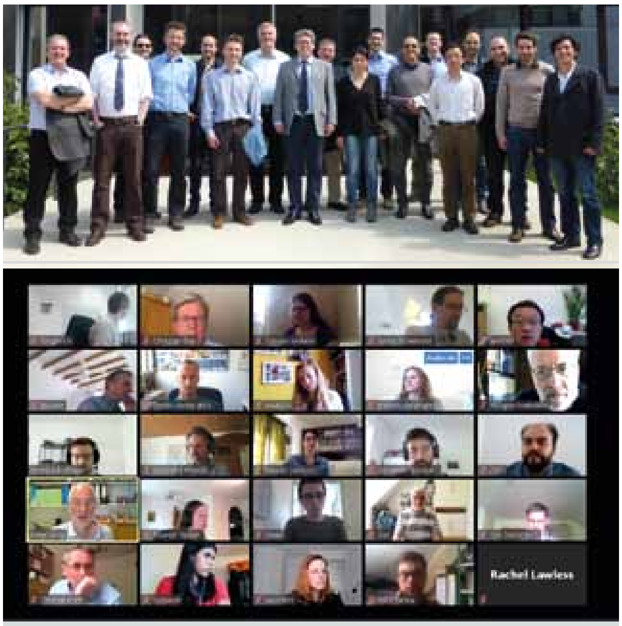

Fig. 15: TFV project team 2014-2020.

Over the 7 years of the project, the team grew from 15 to 35 people, with the proportion of PhD students increasing continuously. In the course of the project, a network has been established with a number of industrial companies, which is to be further expanded in the coming years (Figure 16).

In addition to the interesting new technical developments in this challenging project, there were a number of notable highlights. The 'Fusion Innovation Prize' for excellence and innovation in the field of fusion research was won twice by members of the TFV team. Namely by Christian Day and Thomas Giegerich (2014) for the concept of ‘Direct Internal Recycling’, and by Silvano Tosti and Alessia Santucci (2016) for significant advances in membrane technology. The TFV project was also awarded for promoting women in nuclear technology.

Fig. 16: Research and industry partners in the TFV project.

With the Mercury User Group Meeting (1st event March 2019, KIT), and the NEG for Fusion Seminar (1st event November 2019, Milano), two regular workshop series were launched, which will give the TFV work lasting special visibility in the scientific community.

Over the entire duration of the project, about 150 publications in scientific journals, lectures and poster contributions to international conferences were produced. A particular highlight is the publication of the 'Fusion Technology Textbook', which was created with a significant contribution from TFV and will be published by the IAEA by mid-2021.

During the TFV period to date, a new concept for the fuel cycle has been developed and established in such a way that it now represents the starting point for the conceptual design phase of DEMO (2021-2027) (Figure 17).

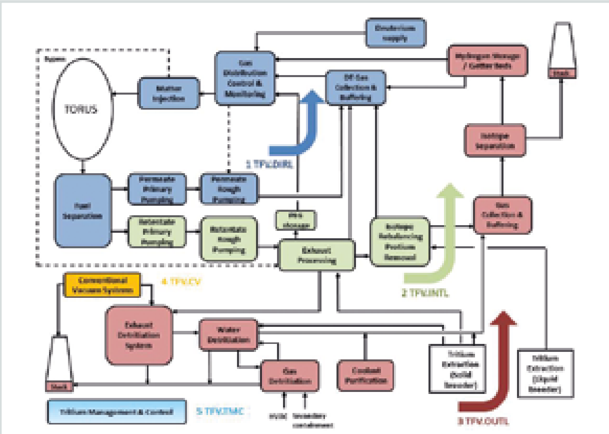

Fig.17: DEMO's new fuel cycle reference architecture.

In a series of external reviews, the new architecture was checked and found to be a very good solution. These reviews took place in various stages, and a total of about 450 pages of documentation were newly created for this purpose. This was a very challenging accomplishment in this special year 2020.

We are now looking forward to entering the next phase 2021–2027 with new strength, new ideas and new possibilities.

Prizes and awards

In 2020, the following awards and prizes were presented for work and to ITEP staff.

Dr. Holger Neumann was elected to the **board of the German Refrigeration and Air Conditioning Association.** The German Refrigeration and Air Conditioning Association (Deutscher Kälte- und Klimatechnischer Verein e.V.) is the only German technical-scientific association for the fields of refrigeration, air conditioning and heat pump technology. It was founded in 1909 in Berlin. The main objective of the association is to promote scientific and technical work in the field of refrigeration, air conditioning and heat pump technology.

Fig. 1: DKV board members with Holger Neumann (second from left) as new board member of the German Refrigeration and Air Conditioning Association.

The Energy Lab 2.0 building, Bau 668 was awarded the **Hugo-Häring Prize of the Association of German Architects (BDA)** as well as the **International Design Award Gold in the category Institutional Buildings.** Among other things, the Hugo-Häring Prize jury praised the very successful arrangement of the areas and the visual connection of the different rooms. Building 668 houses the ITEP's power hardware-in-the-loop laboratory and associated office workstations.

Fig. 2: View into building 668

Dr. Sonja Schlachter, Dr. Ralf Lietzow and Dr. Holger Neumann receive the **2018 Van Duzer Prize from the IEEE Council of Superconductivity** for their publication "Experimental Study on Superconducting Level Sensors in Liquid Hydrogen." The prize recognizes the best paper submitted to the journal IEEE Transactions on Applied Superconductivity in a given year and was awarded at the Applied Superconductivity Conference in 2020.

Dr. Giovanni de Carne has obtained a **Helmholtz Young Investigator Group on "Hybrid Networks: a multi-modal design for the future energy system"** and is participating in the **Helmholtz Mentoring Program.** This will give Mr. de Carne the opportunity to establish his own research group in the field.

Fig. 3: Giovanni de Carne

Privatdozent Dr. habil. Francesco Grilli has been awarded an **Adjunct Professorship of the KIT Faculty of Electrical Engineering and Information Technology.** With this award, the faculty honors the many years of excellent contributions of Dr. Grilli in research and teaching, which have already been honored several times in the past.

Fig. 4: Dr. Francesco Grill (center) receiving his certificate as Associate Professor.

We are very pleased with this recognition of the exceptional achievements of our staff and thank you all very much for your excellent work.

Completed PhD Theses

Dr. Sven Meyer

Introduction of quasi-multilayer pulsed laser deposition for enhanced superconducting properties of $Ba(Fe_{0.92}Co_{0.08})_2As_2$ thin films

This work focused on the implementation of artificial pinning centers by deploying the quasi-multilayer technique for pulsed laser deposition (PLD) in cobalt (Co)-doped $BaFe_2As_2$ (Ba122) compounds (see Fig. 1). The objective of this is to enhance the critical current densities and the pinning forces. By optimizing the epitaxial growth of Ba122 compounds, a reproducible process for experimenting with various amounts of artificial pinning centers was established, in order to obtain the optimal possible Ba122 film for the experimental setup, without intrinsic pinning centers, such as lattice defects or foreign phases. Co-doped films grown on CaF_2 showed the best results considering critical temperature, critical current density and low amount of intrinsic pinning centers.

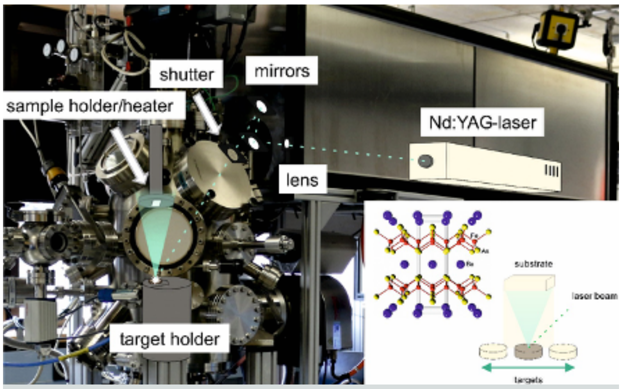

Fig. 1: Schematic view of the experimental setup, the structure of the Ba122 and the schematic principle of the multi-target PLD

Subsequent to various experiments with difierent numbers of pulses and target exchanges, the decision was made to focus on the implementation of BHO as the artificial pinning material, since BZO had already been investigated, although the investigated samples were not grown with quasi-multilayer technique. The investigated samples exhibited 0 mol%, 1.03 mol%, 1.59 mol% and 3.85 mol% of BHO. These contents were measured with inductively coupled plasma mass spectrometry (ICP-MS). The critical current density as well as the pinning force density could be enhanced to 106 A/cm2 respectively 50.6 GN/m3 for the highest tested doping level. Further investigations proved that nano-particles asided by nanocolumns were responsible for the pinning in lower doping levels. With increasing doping levels, more nanocolumns appeared. The nanocolumns could be identified to consist of BHO by energy dispersive X-ray spectroscopy measurements (EDX). Identical experiments with identical films grown on LAO showed an expected behavior. The critical current densities and pinning force densities scattered due to strong intrinsic pinning in the Co-doped Ba122. The additional artificial pinning centers led to more disturbance in the lattice, without enhancing the superconducting properties.

These investigations were repeated with the implementation of InAs as the artificial pinning material. The sphalerite semiconductor InAs has never been investigated before as an artificial pinning material. Several experiments were performed to obtain the optimal composition. The critical current densities showed a maximum at 468 pulses of InAs. It was found that the pinning mechanism was caused by point defects, which can only interact with solely one flux line at a time. Hence, an increase of InAs content in the film resulted in an increasing number of point defects interacting with one fiux line, until an optimum of critical current density was reached. Beyond this optimum, the increasing InAs content solely caused disorder in the lattice and the critical current density decreased again. The quasi-multilayered pulsed laser deposition was first used for the fabrication and improvement of iron-based superconducting thin films.

Dr. Matthias Corduan

Design of superconducting AC Machines for hybrid-electric aircraft

The aviation industry is challenged to develop environmentally and economically sustainable propulsion systems to deal with growing air traffic passenger demand and emission reduction goals. Electrification of the propulsion system offers benefits regarding this goals due to novel variable concepts such as hybrid-electric or distributed propulsion. Due to the multiple energy conversion, the propulsion system has to be highly efficient to achieve a fuel consumption benefit com-pared to a conventional propulsion system. Furthermore, a significantly reduced weight is required to reach the power-to-weight ratio of conventional engines. How-ever, state-of-the-art electric machines are unable to achieve this goals due to their thermal and magnetic limitations. Superconductors are promising to overcome these limitations due to the high current carrying capaci-ty and the negligible direct current (DC) resistance.

This thesis investigates superconducting alternating current (AC) machines as a part of a hybrid-electric propulsion system. A detailed machine design process is developed, that integrates the interaction between electromagnetics and thermics of the superconductor. Thus, the technical fields of superconductivity, electric machine and aircraft are combined in one tool under consideration of their respective requirements in order to investigate mutual dependencies. Various machine topologies create a large design space of synchronous radial flux machines and require for exploration fast holistic analytical approaches. In this work, the focus is on the modeling of superconducting coils based on magnesium diboride (MgB_2), which are penetrated by alternating magnetic fields in the stator. A 114 filament MgB_2 wire is characterized and the impact of its AC loss on the current carrying capacity is integrated in the machine design. Moreover, a two-phase flow of hydro-gen is implemented for the cooling of MgB_2 coils which also allows to determine the hydrogen consumption of machines. Hence, the design is subdivided into the analytical electro-thermal model and electromagnetic model. The flux density distribution is computed with high accuracy in all machine regions and is validated by finite element method. This allows to determine the field sensitive AC loss of stator coils. The mechanical and thermal support components within the magnetic air gap are adapted and designed according to the machine topology. Both active mass and passive mass from the main structural parts are calculated.

To evaluate the potential of fully and partially superconducting machines, the design of a 21. 6 MW machine shown in Fig. 1 is performed, which powers the conventional fan of an Airbus A321neo-LR.

These machine typologies based on superconducting as well as normal conducting coils and magnets are compared with each other by optimizing the number of pole pairs, the diameter of the machine as well as the coil and magnet thickness. This also includes the design of a tank for liquid hydrogen, which is integrated four times in the fuselage and stores 280 kg of liquid hydrogen per tank.

Furthermore, the range of this aircraft for a specific flight mission is calculated for a selection of optimized machines. Furthermore, the reduction of stator AC loss by an optimized control strategy of rotor and stator current is

studied. It is shown that the current density of a MgB_2 stator coil is up to 18 times higher compared to a conventional coil based on copper litz wires at ambient temperature. This leads to the fact that superconducting machines enable both high power-to-weight ratio and low stator AC loss. The lightest fully superconducting machine based on MgB_2 stator coils and high-tem-

Fig. 1: General topology of an hybrid electric aircraft (courtesy Siemens)

perature superconductor (HTS) rotor coils achieves a maximum power-to-weight ratio of 56 4 kWkg , which is also the lightest machine of all topologies. The most efficient machine of this topology reaches a minimal stator AC loss of 6 kW. Partially superconducting machines consisting of MgB_2 stator coils and Halbach rotor array generate even lower stator AC loss of mini-mal 3.9 kW. Moreover, low loss is required in order to avoid burdening the weight balance of the entire propul-sion system by a large liquid hydrogen tank or a heat exchanger, as necessary for copper stators. Hence, a maximum flight time of about 600 min is achieved with one liquid hydrogen tank, which is higher than the fuel range limit of the hybridized Airbus A321neo-LR.

It can be summarized that after reaching a minimum power-to-weight ratio in the machine design in order to fulfill requirements given by the installation space, the optimization of the stator AC loss becomes a priority. Finally, a design proposal is offered for detailed engi-nee-ring and manufacturing studies.

Dr. Aurélien Godfrin

AC Losses in HTS Tapes and Cables for Power Applications

Large scale applications such as transformers, mag-nets, and electric motors are being proposed with high-temperature superconductors (HTS) in the form of rare earth-based coated conductors thanks to their high current density, good in-field behavior and mechanical strength. However, these coated conductors have large AC magnetization losses because of their high aspect ratio between width (several millimeters) and the thickness (order of 1 μm), which hinders their use in these power applications.

A common way for reducing the AC losses of coated conductors is by striating the superconductor into narrow filaments. Laser ablation is one of the most used methods for making filaments. However, superconductors in power applications need indeed a sufficiently thick copper stabilization and but the best way of introducing filaments in copper-stabilized coated conductors is still to be found.

The focus of thesis is focused on two topics. The first is the investigation of producing filaments on copper-stabilized coated conductors, with striations made after or before electroplating the tape. Throughout the thesis, the samples produced with these two approaches are called Striated After Electroplating (SAE) and Striated Before Electroplating (SBE). Samples with different numbers of filaments (from 10 to 60) and copper thicknesses (5 μm and 10 μm) are investigated. The second topic is the applicability of the striations to reduce the AC losses of cables, in particu-lar the CORC® and RACC cables, which are made with HTS striated tapes.

The AC losses are measured with the calibration-free method for tapes and calorimetric method for cables, which are adapted for the investigation of HTS tapes and cables. Both methods operate at 77 K in a wide range of frequencies of the external magnetic field, which allows determining the onset of coupling currents and the importance of the coupling losses. Complemen-tary DC measurements of the transverse resistivity between filaments help to understand the path of the coupling currents.

Thanks to the variety of tested samples and operating conditions, the present work provides a direct comparison of the two striation processes in commercially available HTS coated conductors. For tapes, making filaments helps reduce the AC losses and the AC loss reduction is higher with higher number of filaments. However, the loss reduction strongly depends on the striation process and on the copper thickness. The presence of a path where the coupling currents can easily flow has been supposed, when higher AC losses were measured with higher frequencies, and has been confirmed by SEM images and by transverse resistance measurements. For both striation processes (SAE and SBE), a thinner copper layer allows reducing more ef-fectively the AC losses and limiting coupling. The use of SAE tape in applications can be hindered by delami-nation problems. Further investigations on this potential problem are therefore necessary. But if one considers the complexity and duration of the two processes and the AC loss results, the SAE process seems to be the preferable option.

Using filament reduces the losses of CORC® cables as well. However, the loss reduction of CORC® cables was smaller than that measured for single striated tapes. This can be probably ascribed to the fact that the inner layers are shielded by the outer layers. The AC losses were slightly reduced with the RACC cable made by striating strands. This fact is due to the fila-ment geometry on the RACC cable. The filament that is located on one of the edges of the strand does not go, at the half of the transposition length, to the opposite cable edge. The AC losses of CORC® and RACC ca-bles with similar critical current shows that for a given applied current the CORC® cables have smaller AC losses than those of the RACC cables. This is ex-plained by the fact that the strands of RACC cable are exposed to a perpendicular magnetic field whereas those of the CORC® cable are exposed to a field of various orientations. But, if the losses are normalized by the cable's current density, the RACC cables have smaller AC losses. This is explained by the fact that the former used in CORC® cable to wind the tapes reduces the engineering current density. In addition, if the former is reduced then the CORC® cable can be-come competitive.

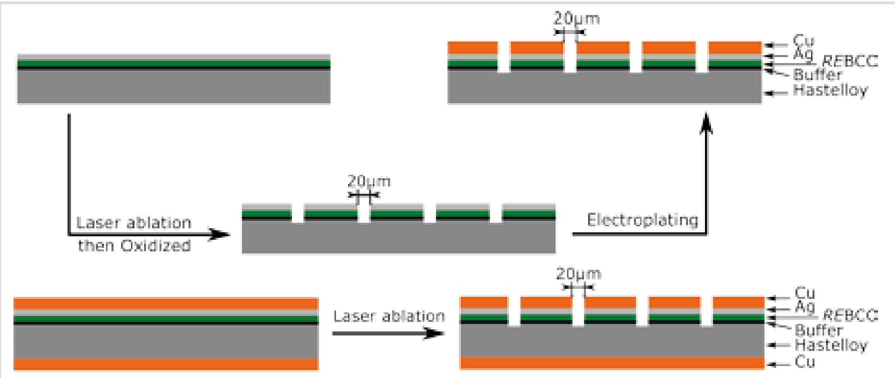

Fig. 1. Schematic illustration of tape striation before (top) and after (bottom) electroplating.

Dr.-Ing. Benedikt Peters

Development of a Hydrogen-Selective Vacuum Pump on the Basis of Superpermeation

This work is embedded thematically in the development of the fuel cycle for future fusion power plants, which has been pursued for years in the Institute's Vacuum Technology Division. A key element of this new concept for the fuel cycle is “Direct Internal Recycling" (DIR). This allows to downsize the required tritium inventory by more than 80 %. The quantification of the possible reduction is carried out for the first time in the doctoral thesis presented here.

However, the DIR requires a process unit capable of separating hydrogen from other gases at low pressure. The main part of the thesis deals with the development of such a unit based on the effect of superpermeation. Superpermeation makes use of the special property of hydrogen to be a molecule in the gas phase, but to dissolve atomically in metals. The splitting of hydrogen in the gas phase is supported by an energy source. In combination with a metal foil with suitable properties, the probability of a hydrogen atom hitting the surface of the foil penetrating can be almost 100%. This effect also works against a pressure gradient. Hydrogen can therefore be transported from a chamber with low pressure to a chamber with higher pressure. This characteristic has resulted in naming this process unit Metal Foil Pump (MFP).

In this thesis first the basic physical processes are described and material properties for possible films are compiled from literature. Based on these fundamentals a theoretical model for the assessment of superpermeation is derived. This model demonstrates that particularly high permeation probabilities can only occur in the surface-limited permeation regime. By combining the model with material data from literature it is shown that high hydrogen fluxes can only be achieved by materials with similar properties as niobium or palladium. These high fluxes are required for the DIR. The model predicts the formation of hydrogen blisters in the metal as a limiting boundary condition. As shown in Figure 1, this limitation could also be proven experimentally.

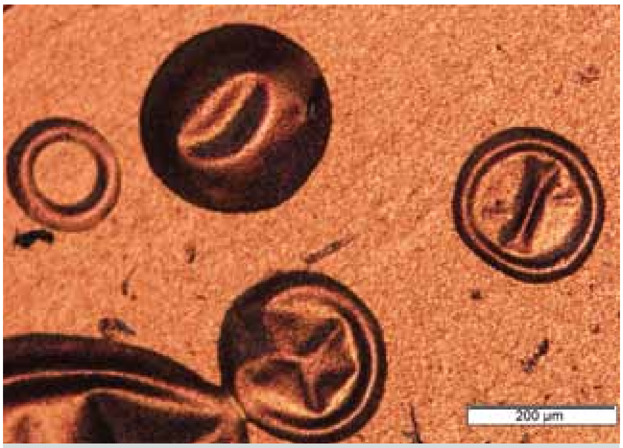

Fig. 1: Microscopic image of hydrogen blisters on a copper-coated iron membrane.

In the experimental part of the thesis two experimental facilities are employed. The facility HERMES (Hydrogen Experiment for Reseach on MEtal foils and Superpermeation) was used for the principal studies. In this facility the gas blisters from figure 1 were created. In this facility also a good separation effect between hydrogen and helium was proven. This separation effect is, as mentioned above, the main function of the metal foil pump in the DIR.

During these tests, the limitations of the HERMES test facility became apparent. In order to overcome these limitations, a new installation was designed, built and put into operation. Many parts of HERMES were reused.

This new setup, which has been named HERMESplus (Hydrogen Experiment for Reseach on MEtal foils and Superpermeation - PLasma Utilization Setup), allows the use of various devices to split the hydrogen molecules. An innovation of this setup is the use of a specialized plasma source. The plasma generated by this source is shown in Figure 2 on the left side of the photo. In comparison to other devices, this plasma source is capable of operating at exceptionally high pressures. Therefore, superpermeation at particularly high pressure could be shown. This demonstration is an important milestone for the concept of the DIR, since these pressures might be necessary for the operation in a fusion power plant.

Based on the findings, a first concept for the implementation of a metal foil pump for fusion was elaborated. The unresolved aspects of this concept were pinpointed and a further development path was outlined. I am glad to pass the further development into the hands of my two successors. I wish them all the best for their doctoral theses and look forward to their new findings.

Fig. 2: View into the vacuum chamber of HERMESplus during operation. On the left side the shining hydrogen plasma around the plasma source can be seen, on the right-side further installations are visible, among others a membrane, which was wound into a cylinder.

Teaching and Education

Lectures, Seminars, Workshops

Lectures

KIT-Fakultät Elektrotechnik und Informationstechnik

Supraleitende Systeme der Energietechnik (Holzapfel, Noe) WS 19/20, WS 20/21
Supraleitende Materialien (Holzapfel, Hänisch) WS 19/20, WS 20/21
Energy Storage and Network Integration (Noe, Grilli, De Carne) WS 19/20, WS 20/21
Übungen zu Energy Storage and Network Integration (Noe, Grilli, De Carne, Kottonau, Karrari) WS 19/20, WS 20/21
Projekt Management für Ingenieure (Noe, Day) SS 20
Grundlagen und Technologie supraleitender Magnete (Arndt) SS 20
Superconductors Materials for Energy Applications (Grilli) SS 20
Anleitung zum selbstständigen wissenschaftlichen Arbeiten (Holzapfel) SS 20
Electrical and Electronics Engineering for Mechanical Engineers (De Carne) WS 19/20, SS 20, WS 20/21

KIT-Fakultät für Chemieingenieurwesen und Verfahrenstechnik

Vakuumtechnik (Day) WS 19/20, WS 20/21
Übung zu Vakuumtechnik (Day, Varoutis) WS 19/20, WS 20/21
Kältetechnik A (Grohmann) WS 19/20, WS 20/21
Übungen zu Kältetechnik A (Grohmann, Mitarbeiter) WS 19/20, WS 20/21
Cryogenic Engineering (Grohmann) WS 19/20, WS 20/21
Cryogenic Engineering – Exercises (Grohmann, Mitarbeiter) WS 19/20, WS 20/21
Physical Foundations of Cryogenics (Grohmann) SS 20
Physical Foundations of Cryogenics – Exercises (Grohmann) SS 20
Kältetechnik B (Grohmann) SS 20
Übungen zu Kältetechnik B (Grohmann, Mitarbeiter) SS 20

KIT-Fakultät Maschinenbau

Fusionstechnologie A (Day, Demange, Fietz, Weiss, Wolf) WS 19/20, WS 20/21
Fusionstechnologiekolloquium* (Noe) SS 20
Magnet-Technologie für Fusionsreaktoren (Fietz, Weiss, Wolf) SS 20
Vakuumtechnik und Tritiumbrennstoffkreislauf (Day, Frances, Größle) SS 20

KIT-Fakultät Physik

Hauptseminar Astroteilchenphysik: Neutrinos und dunkle Materie (Größle) WS 19/20, SS 20

House of Competence

„Netzwerken – Verbindungen schaffen Freiheiten" (Arndt) WS 20/21
9005222 **Tagesworkshop** 25.11.2020

Kryo-Seminare

VDI-Wissensforum „Supraleitung: Hochfeldmagnete und andere Anwendungen" (Kläser) 07.–09.10.2020

Duale Hochschule BW – Fachbereich Maschinenbau

Arbeitssicherheit und Umweltschutz (Bauer) WS 19/20, SS 20
Thermodynamik 1 für Maschinenbauer (Neumann) WS 19/20, SS 20
Thermodynamik 2 für Maschinenbauer (Neumann) SS 20
Tieftemperaturtechnik (Neumann) WS 20

Zhejiang-Universität (China)

Cryogenics Online-Vorlesung; 10 Termine à 2 Zeitstunden; 14.07.–25.08.20 (Neumann) SS 20

* with participation of ITEP

Teaching and Education

PhD Theses – Master Theses – Bachelor Theses

PhD Theses 2020
(* Academic supervisor; ** completed)

Kai Ackermann (SUPRA)
Präparation und Charakterisierung atomar dotierter oxidischerSupraleiter
Betreuer: Prof. Dr. B. Holzapfel (KIT, ETIT)*, Prof. Dr. Matthieu Le Tacon (IFP)

Stefan Biser (SUPRA)
Entwicklung eines Tools zur analytischen Auslegung und Optimierung hybrid-elektrischer Luftfahrtantriebe
Betreuer: Prof. Dr. V. Hagenmeyer (IAI), Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Alexander Buchholz (SUPRA)
Prospective Life Cycle Analysis of high temperature superconductor tapes for future grid applications
Betreuer: Dr. M. Weil (ITAS), Prof. Dr.-Ing. M. Noe*

Carl Bühler (SUPRA)
Neue RRP Leiterkonzepte für verbessertes Pinning durch interne Oxidation
Betreuer: Prof. B. Holzapfel, Dr. S. Kauffmann-Weiss, Prof. M. Heilmaier (MACH)*

Matthias Corduan (SUPRA)**
Auslegung von supraleitenden AC-Maschinen für hybrid-elektrische Flugzeuge
Betreuer: Prof. Dr.-Ing. M. Noe, Pro. Dr. Martin Doppelbauer

Wolfram Freitag (SUPRA)
Optimierung eines kontinuierlichen Prozesses zur Herstellung $REBa_2Cu_3O_{7x}$-basierter supraleitender Bandleiter aus chemischen PräkursorenlösungenBetreuer: Prof. Dr. B. Holzapfel, Prof. Dr.-Ing. J. Sauer (IKFT)*

Cristian Gleason-González (VAKUUM)
Modelling of rarefied neutral gas flow
Betreuer: Dr. S. Varoutis, Prof. Dr. R. Stieglitz (KIT, MACH)*

Aurélien Godfrin (SUPRA)**
AC Losses in HTS Tapes and Cables for Power Applications
Betreuer: Dr. F. Grilli, Prof. Dr.-Ing. M. Noe (KIT, ETIT)

Lukas Grünewald (SUPRA)
Elektronenmikroskopische Untersuchung von eisen- und kupferbasierten Hochtemperatursupraleitern
Betreuer: Prof. Dr. B. Holzapfel, Prof. Dr. D. Gerthsen (LEM)*

Yannick Hörstensmeyer (VAKUUM)
Ein Prozess-Simulator zur Auslegung, Modellierung und Optimierung des inneren Brennstoffkreislaufs eines Fusionskraftwerks
Betreuer: Dr.-Ing. C. Day, Prof. Dr.-Ing. R. Stieglitz (INR)*

Harald Itschner (SUPRA)
Entwicklung von Modellen zur speichergestützten Versorgung von Inselnetzen mit erneuerbaren Energien
Betreuer: Prof. Dr.-Ing. K. Glöser (Hochschule Kaiserslautern), Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Shahab Karrari (SUPRA)
Integration von Energiespeichern in Elektroenergiesysteme
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Yannick Kathage (VAKUUM)
Entwicklung einer Metallfolienpumpe auf dem Prinzip der SuperpermeationBetreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Dustin Kottonau (SUPRA)
Echtzeitsimulation und Netzintegration von MikrogasturbinenBetreuer: Prof. Dr.-Ing. M. Noe*

Philip Kreideweis (SUPRA)
Entwicklung von Niederspannungsschaltanlagen
Betreuer: Dr. J. Geisbüsch, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Marco Langer (SUPRA)
Dünne Schichten pniktid-basierter Supraleiter für Detektoranwendungen
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel (KIT, ETIT)*

Sven Meyer (SUPRA)**
Introduction of quasi-multilayer pulsed laser deposition for enhanced superconducting properties of $Ba(Fe_{0.92}Co_{0.08})_2As_2$ thin films
Betreuer: Prof. Dr. B. Holzapfel, Prof. Dr. Matthieu Le Tacon (IFP)*

Cyra Neugebauer (VAKUUM)
Validation of a process for semi-continuous separation of hydrogen isotopes Betreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Daniel Nickel (FUSION)
Untersuchungen zum Quench-Verhalten und zur Degradation von HTS Hochstrom-Leitern für zukünftige FusionsmagneteBetreuer: Dr. M. Wolf, Prof. Dr. R. Stieglitz (KIT, Mach)*

Benedikt Peters (VAKUUM)**
Entwicklung einer auf Superpermeation basierenden, wasserstoffselektiven Vakuumpumpe
Betreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Quoc Hung Pham (SUPRA)
Untersuchung von schnellen Schaltvorgängen in Hochtemperatur-SupraleiternBetreuer: Prof. Dr.-Ing. M. Noe*

Ruslan Popov (SUPRA)
Stromtragfähigkeit und Pinningeigenschaften REBCO-basierter Dünnschichten und Bandleiter bei tiefen Temperaturen und in hohen Magnetfeldern
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel (KIT, ETIT)*

Carsten Räch (SUPRA)
Entwicklung von hocheffizienten modularen Hochstromsystemen auf Basis von Hochtempera-tursupraleitern zur Übertragung großer Leistungen von Windparks auf Mittelspannungsniveau
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Eugen Shabagin (KRYO)
Entwicklung einer 10 kA HTS-Stromzuführung mit kryogenem Gemischkältekreislauf
Betreuer: Prof. Dr.-Ing. S. Grohmann (CIW)*

Fabian Schreiner (SUPRA)
Aufbau eines supraleitenden DC Windkraftgenerators und Untersuchung der Netzanbindung
Betreuer: Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Jonas Schwenzer (VAKUUM)
Ein Prozess-Simulator zur Vorhersage und Optimierung des Betriebs des Brennstoffkreislaufs eines FusionskraftwerksBetreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Tim Teichmann (VAKUUM)
Entwicklung eines Berechnungsnverfahrens für quecksilbergetriebene Vakuumpumpen in einem weiten Bereich der KnudsenzahlBetreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Carlos Roberto Vargas-Llanos (SUPRA)
Numerical modeling and characterization of high-temperature superconductor coils for electrical machines-Betreuer: PD Dr. F. Grilli, Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Alejandro Vazquez-Cortes (VAKUUM)
Hydrogen Interaction with Superpermeable Metal Foil SurfacesBetreuer: Dr. C. Day, Prof. Dr. R. Stieglitz (KIT, Mach)*

Christina Weber (KRYO)
Dynamic modelling of incidents for the protection of helium cryostats against excessive pressure
Betreuer: Prof. Dr.-Ing. J. Schmidt (CIW), Prof. Dr.-Ing. S. Grohmann (CIW)*

Friedrich Wiegel (SUPRA)
Realisierung und Untersuchung der Bitübertragungsschicht unabhängiger Meshnetzwerke für Smart Grid Anwendungen
Betreuer: Prof. Dr. V. Hagenmeyer (IAI), Prof. Dr.-Ing. M. Noe (KIT, ETIT)*

Master Theses 2020
(* Academic supervisor; ** completed)

Arnaud Kraskowski **
Cryo-mechanical properties of high-strength-materials for fusion magnets after thermal deformation processingBetreuer: Dr. K.-P. Weiss, Prof. Dr. R. Stieglitz (KIT, MACH)*

Philipp Müller
Supraleitender Bahntransformator
Betreuer: Prof. Dr.-Ing. M. Noe*

Marco Öhl
Konzeptionierung einer Experimentierstation zum Thema Antriebstechniken in AutomobilenBetreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

Simone Pezzolato **
Modeling and Model Validation of Supercapacitors for Real-Time Simulations
Betreuer: Prof. Dr.-Ing. M. Noe, Prof. Dr. A. Morandi (University of Bologna)*

Pham Hung Quoc **
Modellierung elektrischer Maschinen mit HTS Statorwicklungen
Betreuer: M. Corduan (Siemens), Prof. Dr. B. Holzapfel*

Bachelor Theses 2020
(* Academic supervisor; ** completed)

Andreas Alexeenko
Untersuchung von geometrischen Einflüssen auf das Magnetisierungsverhalten von supraleitenden Bandstapeln
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Dominic Barthlott
Einfluß der Nanostrukturierung von supraleitenden Schichten und Bandleitern auf deren Stromtragfähigkeiten
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Nico Beisig **
Growth and characteriazation of InAs doped iron-based Ba122 superconducting thin films
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Leo Burger
Optimierung der Chemischen Lösungsabscheidung von $REBa_2Cu_3O_7$-δ-Schichten mit Hilfe des Definite Screening Designs (DSD)
Betreuer: W. Freitag, Dr. J. Hänisch*

Aslan Candas **
Untersuchung von Schaltvorgängen in Hochtemperatur-Supraleitern
Betreuer: Prof. Dr.-Ing. M. Noe, Prof. Dr. S. Elschner* (HS Mannheim – IES)

Leonhard Döring **
Herstellung, Charakterisierung und Simulation hochtemperatursupraleitender Permanentmagnete aus gestapelten YBCO-Bandleitern
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Michael Enns **
Herstellung und Charakterisierung von $BaFe_{2-x}CoxAs_2$-Targets
Betreuer: Dr. A. Jung, Prof. Dr. B. Holzapfel*

Nico Henkenhaf
Entwicklung eines didaktischen Konzeptes für die Experimentierstation „Klimaphysik" im KIT-Schülerlabor Energie
Betreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

Sebastian Hepp **
Entwicklung eines Konzepts für ein Arbeitsschutzmanagementsystem nach DIN EN ISO 45001
Betreuer: K. Bauer, Prof. Dr. D. Eidam (DHBW)*

Hendrik Löhr **
Induktiver Messstand zur Charakterisierung der kritischen Stromdichte und der kritischen Temperatur supraleitender Schichten bei tiefen Temperaturen
Betreuer: Dr. J. Hänisch, Prof. Dr. B. Holzapfel*

Jonas Pfob **
Entwicklung eines didaktischen Konzeptes für die Experimentierstation "Licht" im KIT-Schülerlabor Energie
Betreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

Simon Martz
Untersuchung von Schaltvorgängen in Hochtemperatur-Supraleitern (HTSL)
Betreuer: Q. Pham, Prof. Dr.-Ing. M. Noe

Jonas Mensinger
Optimierung der Prozessparameter zur Herstellung supraleitender REBCO-Dünnschichten auf IBAD-Substraten mittels statistischer Versuchsplanung
Betreuer: W. Freitag, Prof. Dr. Sauer (IKFT)*

Patrick Schäfer
Fertigung und Untersuchung gestapelter Supraleiterentwicklungen
Betreuer: Prof. Dr.-Ing. M. Noe*

Philipp Rembe
Optimierung der Prozessparameter zur Herstellung supraleitender ErBCO-Dünnschichten auf IBAD-Substraten mittels statistischer Versuchsplanung
Betreuer: W. Freitag, Prof. Dr.-Ing. Jörg Sauer (IKFT)*

Michael Temmen
Deposition und Charakterisierung von Strontium-Neodym-Nickelat-Schichten
Betreuer: K. Ackermann, Dr. J. Hänisch*

Romy Wüst **
Konzeptionierung einer Marketingstrategie für kryogene Extensometer
Betreuer: Dr. K.-P. Weiss, Dipl.-Ing. D. Kohl (DHBW)*

Jan Zudock **
Entwicklung eines didaktischen Konzepts für die Station "Photovoltaik" im KIT-Schülerlabor Energie
Betreuer: A. Rimikis, Prof. Dr. B. Holzapfel*

Teaching and Education

Colloquies

30.01.2020 Basic considerations and recent results in HTS device developments for electric aircrafts
Tabea Arndt
Safran-Group Scientific Day, Paris-Saclay, France

27.02.2020 Herstellung, Charakterisierung und Simulation hochtemperatursupraleitender Permanentmagnete aus gestapelten YBCO-Bandleitern
Leonard Döring
Fachvortrag Bachelorarbeit, IB SUPRA

27.02.2020 Herstellung und Charakterisierung von InAs-dotierten eisenbasierten Ba122-Supraleiter-Dünnschichten
Nico Beisig
Fachvortrag Bachelorarbeit, IB Supra

15.06.2020 Modellierung elektrischer Maschinen mit HTS Statorwicklungen
Quoc Hung Pham
Fachvortrag Masterarbeit, IB Supra

11.08.2020 Induktiver Messstand zur Charakterisierung der kritischen Stromdichte und der kritischen Temperatur supraleitender Schichten bei tiefen Temperaturen
Hendrik Löhr
Fachvortrag Bachelorarbeit, IB Supra

17.12.2020 Experimentelle Untersuchung des Kommutierungsvorgangs von Hochtemperatur-Supraleitern bei wechselndem Magnetfeld
Simon Martz
Fachvortrag Bachelorarbeit, IB Supra

Figures and Data

Chart of Organization

Superconducting and Cryomaterials (Holzapfel)	Energy Applications (Noe)	Superconducting Magnet Technology (Arndt)	Fusion Fuel Cycle Technologies (Day)
Superconducting Materials	Superconducting Power System Components	Coil and Magnet Technology	Vacuum Technology and Process Integration
Conductor Concepts and Technologies	Modelling of Superconductors and Components	Superconducting Components for Fusion Technology	Rarefied Gas Dynamics
Cryogenic Properties of Substances	Real-Time System-Integration	Rotating Machines	Vacuum Hydraulics and Hydrogen Separation
Materials for Cryogenic Applications			

Personnel Status (December 31, 2020)

Total	**139**
Academic staff	45
Engineers and technicians	42
Others	13
Doctoral students	22
Master's students	5
Students of the Baden-Württemberg Cooperative State University	8
Apprentices	4

Additional staff in 2020:

Guests	2
Trainees	4
Student assistants	15
Term papers, bachelor's theses	18

Figures and Data

Personnel Changes

Newly Recruited (Excluding Trainees, Guests, and Student Assistants)

Marcel Armbruster

Hans Chen

Jonas Emmerichs

Quoc Hung Pham

Harald Itschner

Pascal Kubis

Thomas Mack

Luca Tobler

Joschua Trapp

Sascha Westenfelder

Julian Würges

Leaving (Excluding Trainees, Guests, and Student Assistants)

Tara Benkel

Denis Bobrov

Lennard Busch

Pablo Cayado-Llosa

Jörn Geisbüsch

Steffen Grohmann

Roland Guyráki

Rainer Heger

Sebastian Hepp

Yannick Hörstensmeyer

Sandra Kauffmann-Weiss

Lukas Kneller

Marco Langer

Klaus Metzger

Sven Meyer

Santiago Ochoa-Guaman

Ruslan Popov

Claudia Ruf

Eugen Shabagin

Christina Weber

Romy Wüst

Figures and Data

Student assistants

Abraham Sunny

Alexeenko Andreas

Barthlott Dominic

Beisig Nico

Bobien Johanna

Frank Marius

Hetzler Sebastian

Kraskowski Arnaud

Lison Patrik

Löhr Hendrik

Mai Vadim

Pham Quoc Hung

Tekelioglu Emre

Temmen Michael

Zudock Jan

Figures and Data

Guest Researcher

Q. Meng
05.11.19–28.07.20 Hefei Institute of Physical Science, Hefei, China

M. Specchio
28.09.20–31.12.20 Politecnico di Bari, Italien

Damiano Paoletti
15.1.20–16.3.20 University of Roma Tor Vergata

Figures and Data

Memberships of relevant technical and scientific organisations

Tabea Arndt
- Programmausschuss-Konferenz „EUCAS 2020, Moskau 2020“
- Internationale Organisationskomitee-Konferenz „Magnet Technology 27, Fukuoka 2021“
- Mitglied DKE TC90

Wescley Batista de Sousa
- Mitglied der “HTS Modelling Workgroup”
- Mitglieder der CIGRE Arbeitsgruppe B4/A3.86 “Fault Current Limiting Technologies for DC Grids”
- Mitherausgeber des “IEEE Transactions on Applied Superconductivity”

Kai Bauer
- Mitglied im Helmholtz-Arbeitskreis HSE “Health, Safety and Environment”
- Mitglied der Prüfungsausschüsse der Dualen Hochschule Baden-Württemberg, Standort Karlsruhe in den Fachbereichen „Maschinenbau“ und „Wirtschaftsingenieurswesen“

Christian Day
- Mitglied des Vorstandsrates der Dt. Vakuumgesellschaft (DVG).
- Stellv. Vorsitzender des Fachverbandes Vakuumphysik und -technik der Dt. Physikalischen Gesellschaft (DPG).
- Projektleitung des Bereichs Tritium-Materiezufuhr-Vakuum (TFV) im Europäischen Fusionsprogramm EUROFUSION
- Mitglied im Fusion For Energy – Technical Advisory Panel
- Sprecher Topic 'Vakuum und Tritium' der deutschen DEMO-Initiative
- Mitglied im International Advisory Committee der RGD (Rarefied Gas Dynamics Conference)
- Mitglied des Programmkomitees der ISFNT (international Symposium of Fusion Nuclear Technology).
- Chartered Engineer der American Vacuum Society (AVS)
- Mitglied im Steering Committee JT-60SA

Giovanni de Carne
- Helmholtz Nachwuchsgruppe Leiter – 2020
- Sekretär und Mitglieder der CIGRE Arbeitsgruppe B4.91 “Power electronics-based transformer technology, design, grid integration and services provision to the distribution grid”
- Mitglieder der CIGRE Arbeitsgruppe A3.40 “Technical requirements and field experiences with MV DC switching equipment”
- Mitglieder der IEEE Arbeitsgruppe P2004 “Hardware in the Loop”.
- Mitglieder der IEEE Arbeitsgruppe “Modelling and Simulation with High Penetration of Inverter-Based Renewables”
- Assoziierte Editor der IEEE Zeitschrift “IEEE Industrial Electronic Magazine”
- Assoziierte Editor der Springer Zeitschrift “Electrical Engineering – Archiv für Elektrotechnik”
- Mitglied beim “Institute of Electrical and Electronics Engineers”
- Mitglied beim Verband der Elektrotechnik, Elektronik und Informationstechnik

Walter H. Fietz
- Mitglied des “International Organizing Committee of Symposium of Fusion Technology (SOFT) conference”
- Program Comittee Member of HTS4Fusion Conductor Workshop
- IEEE Senior Member
- Mitglied des “IEEE Council of Superconductivity”

Thomas Giegerich
- Vorsitzender des Fachverbandes Vakuumphysik und -technik der Dt. Physikalischen Gesellschaft (DPG).

Jens Hänisch
- Superconductor Science and Technology, Mitglied im Advisory-Board
- European Magnetic Field Laboratory EMFL, Mitglied im User Proposal Selection Committee
- Applied Superconductivity Conference, Mitglied im Programmkomitee Materialien
- Mitglied im KIT-Konvent

Reinhard Heller
- Computation of Thermo-Hydraulic Transients in Superconductors (CHATS-AS), Board member
- DKE/DIN K 184 – Supraleiter
- International Electrotechnical Commission (IEC TC90) – Superconductivity – Member WG 12 – “Superconducting Power Devices – General Requirements for Characteristic Tests of Current Leads designed for Powering Superconducting Devices”

Bernhard Holzapfel
- Applied Superconductivity Conference, Board member
- European Conference on Applied Superconductivity, Member of International Program Committee
- International Symposium on Superconductivity (ISS), Member of International Program Committee

Holger Neumann

- Member of the ICE Commitee
- Board member of the Cryogenic Engineering Conference CEC seit 2019 (gewählt auf der Tagung in Hartford)
- Vorsitzender des DKV
- Gastprofessur in China an der Zhejiang University in Hangzhou (China)

Mathias Noe

- Kurator des Forschungsnetzwerkes Hochtemperatur-Supraleitung des BMWi
- Internationaler Experte der CIGRE D1.69 Arbeitsgruppe" Assessing emerging test guidelines for HTS applications in power systems"
- Internationaler Experte der CIGRE Arbeitsgruppe D1.64 "Cryogenic dielectric insulation"
- Sprecher des Helmholtz Programmes Speicher und vernetzte Infrastrukturen
- Mitglied des Managementboards des Forschungsbereiches Energie der Helmholtz Gemeinschaft
- Deutscher Abgesandter der International Energy Agency, Technology Cooperation Programm Hochtemperatur-Supraleitung
- Mitglied des International Organizing and Scientific Program Committee of the International Conference on Magnet Technology
- Mitglied des Boards der Applied Superconductivity Conference
- Mitglied des Interessenverbandes Supraleitung (ivsupra)

Sonja Schlachter

- Mitglied des "International Cryogenic Material Conference (ICMC) Board of Directors"

Stylianos Varoutis

- Mitglied im wissensc haftlichen Komittee der NEGF (European Conference on Non-equilibrium Gas Flows).
- Mitglied im Auswahlkomittee des EU High Performance Computers MARCONI
- Mitglied der Deutschen Vakuumgesellschaft (DVG)

Klaus-Peter Weiss

- DKE Deutsche Kommission Elektrotechnik Elektronik Informationstechnik im DIN und VDE Referat K 184 „Supraleiter", Obmann
- IEC International Electrotechnical Commission/Technical Comittee 90 "Superconductivity", Mitglied WG 2 "Critical current measurement of Nb-Ti composite superconductors", WG 5 "Tensile test and electromechanical properties of composite superconductors", WG 7 "Critical current measurement method of Nb3Sn composite superconductors", WG 11 "Critical temperature measurement – Critical temperature of composite superconductors", WG 13 "General characteristics for practical superconducting wires"
- Sprecher der Arbeitsgruppe "Magnet Design" innerhalb der deutschen Koordination der Fusionsforschung für DEMO
- Member of the International Technical Program Committee – MEM18 9th Workshop on Mechanical and Electromagnetic Properties of Composite Superconductors/Organisator MEM20 10th Workshop in Karlsuhe
- Board Member ICMC (International Cryogenic Materials Conference) Subcommittee International Cryogenic Material Library
- Experte im EUROfusion Scientific & Technical Advisory Committee (STAC)

Publications

Fusion (* Wo Sand/or Scopus referenced)

Lecture

S. Varoutis, C. Tantos, GPU acceleration of DEMO particle exhaust simulations, 1st Spanish Fusion HPC Workshop Programme, virtual, Nov. 2020.

Journal article

* Tantos, Christos; Varoutis, Stylianos; Day, Christian
Effect of the internal degrees of freedom of the gas molecules on the heat and mass transfer in long circular capillaries;
Microfluidics and nanofluidics
doi:10.1007/s10404-020-02400-z

* Bauer, P; Ballarino, A; Devred, A; et al.
Development of HTS Current Leads for the ITER Project;
doi:10.1088/1757-899X/756/1/012032

A. Santucci, M. Incelli, L. Noschese, et al.
The issue of Tritium in DEMO coolant and mitigation strategies,
Fusion Engineering and Design
doi:10.1016/j.fusengdes.2020.111759

A. Frattolillo, L.R. Baylor, Chr. Day, et al.
Injection of high-speed solid D2 pellets using a "Direct-Line-of-Sight" (DLS)
guide tube, Fusion Engineering and Design 162 (2021) 112138.
doi: 10.1016/j.fusengdes.2020.1121138

C. Neugebauer, Y. Hörstensmeyer, Chr. Day
Technology Development for Isotope Rebalancing and Protium Removal in the EU-DEMO Fuel Cycle,
Fusion science and technology
doi:10.1080/15361055.2019.1704139

P.T. Lang, F. Cismondi, Chr. Day, et al.
Optimizing the EU-DEMO pellet fuelling scheme,
Fusion Engineering and Design
doi:10.1016/j.fusengdes.2020.111591

K. Sedlak, V. A. Anvar, N. Bagrets, et al.
Advance in the conceptual design of the European DEMO magnet system
Supercond. Sci. Technol. 33 (2020) 044013
doi: 10.1088/1361-6668/ab75a909

* Fischer, U.; Boccaccini, L.V.; Cismondi, F.; et al.
Required, achievable and target TBR for the European DEMO;
Fusion engineering and design
doi: 10.1016/j.fusengdes.2020.111553

* Hanke, Stefan; Day, Christian; Giegerich, Thomas; et al.
Progress of the R&D programme to develop a metal foil pump for DEMO;
Fusion engineering and design
doi: 10.1016/j.fusengdes.2020.111890

* Bidulský, Róbert; Bidulská, Jana; Gobber, Federico Simone; et al.
Case Study of the Tensile Fracture Investigation of Additive Manufactured Austenitic Stainless Steels Treated at Cryogenic Conditions
Materials
doi:10.3390/ma13153328

* Cismondi, F.; Spagnuolo, G.A.; Boccaccini, L.V.; et al.
Progress of the conceptual design of the European DEMO breeding blanket, tritium extraction and coolant purification systems;
Fusion engineering and design
doi: 10.1016/j.fusengdes.2020.111640

* Lewandowska, Monika; Dembkowska, Aleksandra; Heller, Reinhard; et al.
Hydraulic characterization of conductor prototypes for fusion magnets
Cryogenics
doi:10.1016/j.cryogenics.2019.103013

* Nickel, Daniel S.; Wolf, Michael J.; et al.
Mechanical and Electro-Mechanical Investigations of Assembled HTS CroCo Triplets
IEEE transactions on applied superconductivity
doi:10.1109/TASC.2020.2972226

* Tantos, Christos; Varoutis, Stylianos; Day, Christian
Deterministic and stochastic modeling of rarefied gas flows in fusion particle exhaust systems;
Journal of vacuum science & technology / B
doi: 10.1116/6.0000491

* Zappatore, A.; Heller, R.; Savoldi, L.; et al.
A new model for the analysis of quench in HTS cable-in-conduit conductors based on the twisted-stacked-tape cable concept for fusion applications
Superconductor science and technology
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* Reimerdes, H., Ambrosino, R., Innocente, P., et al.
Assessment of alternative divertor configurations as an exhaust solution for DEMO
Nuclear fusion
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* Ying, A., Riva, M., Ahn, M.-Y., et al.
Recent advances in tritium modeling and its implications on tritium management for outer fuel cycle
Fusion engineering and design
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* Tantos, Christos, Varoutis, Stylianos, Day, Christian
Effect of the internal degrees of freedom of the gas molecules on the heat and mass transfer in long circular capillaries
Microfluidics and nanofluidics
doi: 10.1007/s10404-020-02400-z

* Sirunyan, A. M., Tumasyan, A., Adam, W., et al.
Measurement of the top quark pair production cross section in dilepton final states containing one τ lepton in pp collisions at $\sqrt{s}$ = 13 TeV
Journal of high energy physics
doi:10.1007/JHEP02(2020)191

* Romaka, V V, Prikhna, T A, Eisterer, M, et al.
Structure and properties of MgB2bulks: Ab-initio simulations compared to experiment
IOP conference series / Materials science and engineering
doi: 10.1088/1757-899X/756/1/012020

* Giruzzi, G, Yoshida, M, Aiba, N, et al.
Advances in the physics studies for the JT-60SA tokamak exploitation and research plan
Plasma physics and controlled fusion
doi: 10.1088/1361-6587/ab4771

* Hohe, Jörg; Neubrand, Achim; Fliegener, Sascha; et al.
Performance of fiber reinforced materials under cryogenic conditions—A review;
Composites / A
doi: 10.1016/j.compositesa.2020.106226

* Hohe, J.; Schober, M.; Weiss, Klaus-Peter; et al.
Validation of Puck's failure criterion for CFRP composites in the cryogenic regime;
CEAS space journal
doi: 10.1007/s12567-020-00335-3

* Hörstensmeyer, Y. N.; Tosti, S.; Santucci, A.; et al.
Permeator Simulations for the EU-DEMO Fuel Cycle;
Fusion science and technology
doi: 10.1080/15361055.2019.1705690

* Kvackaj, Tibor; Rozsypalova, Alica; Kocisko, Robert; et al.
Influence of Processing Conditions on Properties of AISI 316LN Steel Grade;
Journal of materials engineering and performance
doi: 10.1007/s11665-020-04561-y

* Lang, Peter Thomas; Cismondi, Fabio; Day, Christian; et al.
Optimizing the EU-DEMO pellet fuelling scheme;
Fusion engineering and design
doi: 10.1016/j.fusengdes.2020.111591

* Neugebauer, C.; Hörstensmeyer, Y.; Day, C.
Technology Development for Isotope Rebalancing and Protium Removal in the EU-DEMO Fuel Cycle;
Fusion science and technology
doi: 10.1080/15361055.2019.1704139

* Obert, Susanne; Kauffmann, Alexander; Seils, Sascha; et al.
Microstructural and Chemical Constitution of the Oxide Scale formed on a Pesting-Resistant Mo-Si-Ti Alloy; Corrosion science
doi:10.1016/j.corsci.2020.109081

Poster

Day, C.; Davis, S.; Hajnal, N.; et al.
Design of the JT-60SA divertor cryopumps

Igitkhanov, Y.; Day, C.; Varoutis, S.; et al.
Analytical prediction of particle exhaust in DEMO divertor configurations

Kathage, Yannick; Hanke, Stefan; Vazquez Cortes, et al.
Utilization of a Cold Plasma Source for the Metal Foil Pump of a Fusion Reactor

Kathage, Y.; Vazquez Cortes, A.; Day, C.; et al.
Cold plasma source feasibility for a metal foil pump in DEMO

Merli, S.; Kathage, Y.; Hanke, S.; et al.
Self-consistent modelling of a linear microwave plasma source

Neugebauer, C.; Day, C.
Material characterisation experiments for isotope rebalancing and protium removal in the EU-DEMO fuel cycle

Schwenzer, J.; Ciattaglia, S.; Day, C.; et al.
Start-up and operational tritium inventories in the EU DEMO fuel cycle

Siviero, F.; Caruso, L.; Mura, M.; et al.
Robustness of the performances of NEG pumping solutions for fusion applications

Teichmann, T.; Day, C.; Giegerich, T.
Overview of the mercury diffusion pump developments for DEMO

Vazquez Cortes, A.; Kathage, Y.; Hanke, S.
Molecular Dynamics Simulation of Hydrogen Interactions with Group 5 Metals to characterize superpermeation process

Itschner, Harald
Entwicklung von Modellen zur speichergestützten Versorgung mit regenerativen Energien in Inselnetzen
doi: 10.5445/IR/1000119425

* Santucci, A.; Incelli, M.; Noschese, L.; et al.
The issue of Tritium in DEMO coolant and mitigation strategies;
Fusion engineering and design
doi: 10.1016/j.fusengdes.2020.111759

* Tirunilai, A.S.; Hanemann, T.; Weiss, K.-P.; et al.
Dislocation-based Serrated Plastic Flow of High Entropy Alloys at Cryogenic Temperatures;
Acta materialia
doi: 10.1016/j.actamat.2020.09.052

P. Bauer, A. Ballarino, A. Devred, et al.
Development of HTS Current Leads for the ITER Project
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Publications

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(* Wo Sand/or Scopus referenced)

Book essay

Kottonau, Dustin; Shabagin, Eugen; De Sousa, Wescley; et al.
Evaluation of the Use of Superconducting 380 kV Cable;
978-3-7315-1026-0
doi: 10.5445/KSP/1000117918

Hänisch, Jens; Iida, Kazumasa
Grain Boundaries in Fe-Based Superconductors in P. Mele et al. (eds.), Superconductivity, SpringerNature, Switzerland;
978-3-030-23302-0
doi: 10.1007/978-3-030-23303-7_10

Journal article

* Karrari, Shahab; Baghaee, Hamid Reza; De Carne, Giovanni; et al.
Adaptive inertia emulation control for high-speed flywheel energy storage systems;
IET generation, transmission and distribution
doi: 10.1049/iet-gtd.2020.0066

* Benkel, Tara; Lao, Mayraluna; Liu, Yingzhen; et al.
T-A-Formulation to Model Electrical Machines With HTS Coated Conductor Coils;
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* Berrospe-Juarez, Edgar; Trillaud, Frederic; Zermeño, Víctor M R; et al.
Screening Current-Induced Field and Field Drift Study in HTS coils using T-A homogenous model;
Journal of physics / Conference series
doi: 10.1088/1742-6596/1559/1/012128

* Berrospe-Juarez, Edgar; Trillaud, Frederic; Zermeño, Victor M. R.; et al.
Screening Currents and Hysteresis Losses in the REBCO Insert of the 32 T All-Superconducting Magnet Using T-A Homogenous Model;
IEEE transactions on applied superconductivity
doi: 10.1109/TASC.2020.2969865

* Boll, Martin; Corduan, Matthias; Biser, Stefan; et al.
A holistic system approach for short range passenger aircraft with cryogenic propulsion system;
Superconductor science and technology
doi: 10.1088/1361-6668/ab7779

* Cheng, Y.; Qu, R.; Gao, Y.; et al.
Comparison of electromagnetic performance of 10-MW HTS double-stator flux modulation wind generators with different topologies;
Superconductor science and technology
doi: 10.1109/TASC.2020.2975153

* Corduan, Matthias; Boll, Martin; Bause, Roman; et al.
Topology Comparison of Superconducting AC Machines for Hybrid Electric Aircraft;
IEEE transactions on applied superconductivity
doi: 10.1109/TASC.2019.2963396

* Filipenko, M.; Biser, S.; Boll, M.; Corduan, M.; Noe, M.; Rostek, P. et al.
Comparative analysis and optimization of technical and weight parameters of turbo-electric propulsion systems;
2226-4310
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doi: 10.3390/AEROSPACE7080107

* Grilli, Francesco; Benkel, Tara; Hänisch, Jens; et al.
Superconducting motors for aircraft propulsion: the Advanced Superconducting Motor Experimental Demonstrator project;
Journal of physics / Conference series
doi: 10.1088/1742-6596/1590/1/012051

* Grilli, Francesco; Pardo, Enric; Morandi, Antonio; et al.
Electromagnetic Modeling of Superconductors With Commercial Software: Possibilities With Two Vector Potential-Based Formulations;
IEEE transactions on applied superconductivity
doi: 10.1109/TASC.2020.3013028

* Grilli, Francesco; Rizzo, Enrico
A numerical model to introduce students to AC loss calculation in superconductors;
European journal of physics
doi: 10.1088/1361-6404/ab90dc

* Gyuráki, R.; Schreiner, F.; Benkel, T.; et al.
Fluorescent thermal imaging of a quench in insulated and non-insulated REBCO-wound pancake coils following a heater pulse at 77 K;
Superconductor science and technology
doi: 10.1088/1361-6668/ab6dc0

* Kottonau, Dustin; Wolf, Michael; Fietz, Walter; et al.
Feasibility of ultra-compact HTS CrossConductor based Power Transmission Cables;
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doi: 10.1088/1742-6596/1559/1/012084

* Otten, Simon; Kario, Anna; Demenčik, Eduard; et al.
Anisotropic monoblock model for computing AC loss in partially coupled Roebel cables;
Superconductor science and technology
doi: 10.1088/1361-6668/ab9939

* Riva, N.; Sirois, F.; Lacroix, C.; et al.
Resistivity of REBCO tapes in overcritical current regime: Impact on superconducting fault current limiter modeling;
Superconductor science and technology
doi: 10.1088/1361-6668/aba34e

* Ruebeling, Jascha; Grohmann, Steffen
Flow-induced noise generation at the outlet of a capillary tube = Génération de bruit provoquée par l'écoulement à la sortie d'un tube capillaire;
International journal of refrigeration
doi: 10.1016/j.ijrefrig.2019.11.021

* Schreiner, Fabian; Liu, Yingzhen; Zhang, Yuanzhi; et al.
Development of no-insulation racetrack coils wound with second generation high temperature superconductor tapes for a stator system for wind generators;
Superconductor science and technology
doi: 10.1088/1361-6668/aba34e

* Shabagin, E.; Raczka, K.; Grohmann, S.
Investigation of cryogenic mixed-refrigerant cooled current leads in combination with peltier elements;
IOP conference series / Materials science and engineering
doi: 10.1088/1757-899x/755/1/012138

* Shen, Boyang; Grilli, Francesco; Coombs, Tim
Overview of H-Formulation: A Versatile Tool for Modeling Electromagnetics in High-Temperature Superconductor Applications;
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doi: 10.1109/ACCESS.2020.2996177

* Shen, Boyang; Grilli, Francesco; Coombs, Tim
Review of the AC loss computation for HTS using H formulation;
Superconductor science and technology
doi: 10.1088/1361-6668/ab66e8

* Tamson, J.; Blanck, P.; Grohmann, S.
Commissioning of the Cryogenic Phase Equilibria Test Stand CryoPHAEQTS;
IOP conference series / Materials science and engineering
doi: 10.1088/1757-899x/755/1/012150

* Thomas, Ingo; Wunderlich, Bernd; Grohmann, Steffen
Pressure-driven dynamic process simulation using a new generic stream object;
Chemical engineering science
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